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華中師範大學

博士学位论文

在 LHCb 上首次发现 $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$

衰变以及 Z 玻色子极化的研究

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DOCTORAL DISSERTATION

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Dissertation

First observation of decay mode

$\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ and study of Z

**boson polarization at the LHCb
experiment**

By

Meng-Lin Xu

Supervisor: Prof. Hang Yin

Specialty: Particle Physics and Nuclear Physics

**Research Area: Quark Model, Electroweak physics,
LHCb detector upgrade**

College of Physical Science and Technology

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摘 要

标准模型是粒子物理学中最成功的理论模型之一，对三种基本相互作用力（强相互作用力、弱相互作用力、以及电磁相互作用力）以及物质世界最根本的组成粒子，做出了非常成功的理论描述，同时对绝大多数实验现象做出了有效的预言和解释。夸克模型是它的重要组分，夸克模型自建立以来成功的预言了超过一百种强子态的存在。在夸克模型中， $SU(4)$ 理论预言存在含有两个粲夸克的重子，即双粲重子，但是长久以来并未有任何实验观测到此类粒子的存在。根据理论预言，该粒子的质量在 $3500\text{--}3700\text{MeV}/c^2$ 范围内，寿命在 $110\text{--}250\text{fs}$ 之间，是一个长寿命粒子。不同于由较轻的上夸克、下夸克以及奇异夸克所组成的重子，双粲重子更容易被理论模型所描述。在理论计算中双粲重子可以被描述为一个轻夸克和一对重夸克组成的重子体系，这种体系不会受到经典力学中三体动力学的困扰。在实验上寻找双粲重子 Ξ_{cc}^{++} 并测量其性质可以直接检验量子色动力学，尤其是非微扰论中的各种不同的理论预言模型，从而加深对量子色动力学中非微扰理论计算的理解。

在过去的几十年中，多个实验组使用不同的探测器尝试对双粲重子进行搜索，其中最著名的是 2003 年 SELEX 实验组宣布他们通过 $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ 衰变道发现了双粲重子信号，并对其性质进行了测量，测量到的质量为 $3520\text{MeV}/c^2$ 。虽然这一测量结果也与大部分理论预言值在误差范围内相符合，但是 SELEX 实验所测量得到的 Ξ_{cc}^+ 的寿命远小于理论预言值。而且，在 SELEX 的结果中，相当大比份的 Λ_c^+ 重子是来源于 Ξ_{cc}^+ 重子衰变，这个性质和各种理论预言都不符合。随后，FOCUS、Belle 和 BaBar 等实验组都尝试使用同样的衰变道寻找 Ξ_{cc}^+ 重子，但是都没有在 SELEX 实验组测量得到的 Ξ_{cc}^+ 质量区间内观察到任何信号。LHCb 探测器是大型强子对撞机 LHC 上的一个专为重味物理研究而设计建造的大型探测器，和 LHC 上的其他大型实验相比，LHCb 探测器具有良好的径迹和粒子鉴别系统，为寻找双粲重子 Ξ_{cc} 提供了十分有利的实验条件。LHCb 实验也曾利用 RunI 期间采集到的数据，尝试通过与 SELEX 实验相同的衰变道去寻找 Ξ_{cc}^+ 重子，但是同样也未能观察到任何 Ξ_{cc}^+ 信号。

随着 LHC 上各个探测器的不断升级和统计量的持续增加，LHCb 实验利用 RunII 数据再次尝试寻找双粲重子 Ξ_{cc} 。2017 年，LHCb 实验组宣布利用 2016 年探测器所记录的数据，通过 $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ (\rightarrow p^+ K^- \pi^+) K^- \pi^+ \pi^+$ 衰变道首次观测到了双粲重子 Ξ_{cc}^{++} 的信号，并对这一粒子的性质进行了测量，测量得到的质量为 $3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst})\text{MeV}/c^2$ ，其中第一项误差为统计误差，第二



项误差为系统误差。这一测量结果能够与绝大多数的理论预言吻合，并且通过对 Ξ_{cc}^{++} 的寿命测量证实这是一个弱衰变过程。在此基础上，如何利用其它衰变模式寻找并确认这个发现的双粲重子 Ξ_{cc}^{++} 变的尤为重要。根据中国理论学家的计算和预言， $\Xi_{cc}^{++} \rightarrow \Xi_c^+(\rightarrow p^+ K^- \pi^+) \pi^+$ 这一衰变道同样是寻找 Ξ_{cc}^{++} 的黄金衰变道。这一衰变道和发现道有着相同的拓扑衰变结构且末态粒子都是带电粒子。LHCb 实验能够很好的观测到带电径迹，无法探测中微子，并对所有中性粒子探测效率偏低。因此，虽然这个道的衰变分支比略微低于发现道，但是该衰变道的末态只有 4 条带电径迹，低于发现道的 6 条末态带电径迹，意味着在实验上和 $\Xi_{cc}^{++} \rightarrow \Lambda_c^+(\rightarrow p^+ K^- \pi^+) K^- \pi^+ \pi^+$ 衰变道相比，该衰变道有着更高的探测效率。因此本论文同样使用 LHCb 2016 年记录的质子-质子对撞数据，通过 $\Xi_{cc}^{++} \rightarrow \Xi_c^+(\rightarrow p^+ K^- \pi^+) \pi^+$ 这一衰变道来寻找双粲重子 Ξ_{cc}^{++} 。这个分析的难点在于如何在海量的本底中找到真实的信号，相较于 $\Xi_{cc}^{++} \rightarrow \Lambda_c^+(\rightarrow p^+ K^- \pi^+) K^- \pi^+ \pi^+$ 衰变道， $\Xi_{cc}^{++} \rightarrow \Xi_c^+(\rightarrow p^+ K^- \pi^+) \pi^+$ 有着更庞大的本底。在总的分析流程上，该分析采用和双粲重子发现道相同的方式，即盲分析的策略：利用本底事例和蒙特卡罗信号事例对筛选条件进行研究和优化，在确定最终的筛选条件前不打开双粲重子 Ξ_{cc}^{++} 所在的质量范围的信号窗口，以避免实验中任何的人为偏差的引入。具体流程如下：首先利用简单的初步选择条件去除部分本底，然后利用多变量分析法进一步去除本底，在最大程度上去除完所有可能存在的本底后，将所有的筛选条件、分析步骤、实验细节都提交到合作组进行审核。在合作组审核同意后再打开信号窗口。将审核通过后的筛选条件应用到 2016 年的数据上后，我们在 Ξ_{cc}^{++} 信号窗内观测到了明显的质量峰，其信号显著度为 6.8σ 。通常，在实验上某个信号的显著度大于 5σ 则认为发现了这一衰变模式。因此接下来在本论文中，对通过 $\Xi_{cc}^{++} \rightarrow \Xi_c^+(\rightarrow p^+ K^- \pi^+) \pi^+$ 这一模式所观测到的双粲重子 Ξ_{cc}^{++} 的性质进行了深入研究，通过拟合测量得到双粲重子 Ξ_{cc}^{++} 的质量为 $3620.56 \pm 1.45(\text{stat}) \pm 0.49(\text{syst}) \text{ MeV}/c^2$ ，其中第一项误差为统计误差，第二项误差来源于系统误差，这一结果在误差范围内与发现道测量得到的结果一致，从而在实验上再次确认了双粲重子的发现。最后，我们利用 BLUE 的方法可以将通过两个衰变道测量得到的 Ξ_{cc}^{++} 的质量进行合并，合并结果为 $3621.24 \pm 0.65(\text{stat}) \pm 0.31(\text{syst}) \text{ MeV}/c^2$ 。合并的结果和大部分理论预言相吻合。与此同时基于这两个衰变道都能观测到双粲重子，以及同个粒子的不同衰变道之间的分支比之比能够为理解双粲种子相关性质提供重要的信息，本文对两个衰变道的衰变分支比之比也进行了测量。这一测量有一个难点：这一分析是在 LHCb 实验上首次使用 Turbo line（实时在线刻度、修正、重建，无需离线完全重建）触发收



集得到的数据进行相关的效率研究。因此在这一分析中，不能简单的按照传统的方法来测量相关触发效率，需要先对触发效率的有足够的研究和理解，具体步骤为：首先利用参考道证实利用蒙特卡洛事例计算得到触发效率是可靠的，再利用蒙特卡洛事例计算得到 $\Xi_{cc}^{++} \rightarrow \Lambda_c^+(\rightarrow p^+ K^- \pi^+) K^- \pi^+ \pi^+$ 衰变道和 $\Xi_{cc}^{++} \rightarrow \Xi_c^+(\rightarrow p^+ K^- \pi^+) \pi^+$ 衰变道中相关的触发效率，然后将其应用到衰变分支比之比的测量中。本论文中对该方法进行了细致的研究和讨论，这一研究过程为后续 LHCb 实验上其他利用 Turbo line 采集数据进行的分析提供了非常有价值的参考。最终测量得到两个衰变道的衰变分支比之比为 $0.035 \pm 0.009 (\text{stat}) \pm 0.003 (\text{syst})$ ，这一结果也在误差范围内和理论预言相一致，为更好的理解双粲重子的衰变性质提供了重要的信息。

虽然标准模型已经给出了非常出色的理论描述，同时可以对绝大多数实验现象做出有效的预言和解释，但是现有的标准模型仍然没能做到四种相互作用力统一，仍无法解释暗物质和暗能量等相关物理现象。因此物理学家们一直致力于寻找能够解释这些问题的新物理理论。实验上对于新物理的寻找有两种途径：一. 对新粒子以及新产生机制的直接实验寻找；二. 通过对一些基本物理量的精确测量，对比理论预言值，同样也可以用来检验标准模型、间接寻找新物理。在精确测量中，任何测量物理量与理论预言值间的微小偏差都能预示新物理的存在，这也就是通常说的间接寻找新物理。在第二种途径中，通过对电弱物理中的基本观测量进行精确测量也是其中重要的方向之一。因为标准模型已经对电弱物理有着非常精确的理论预言，那么如果实验上测得的相关参数与标准模型预言值存在了一定的偏差，那么这些偏差可能就是由于一些尚未发现的新的物理过程在其中发挥了作用所造成的。比如对 Z 玻色子衰变中末态轻子的角度分布进行精确测量能够严格检验它的产生机制所涉及到的量子色动力学 (QCD) 理论预言，同时利用 $q\bar{q} \rightarrow \gamma^*/Z \rightarrow \mu^+\mu^-$ 这一物理过程来测量 Z 玻色子的前后不对称性，也为研究 Z 玻色子和费米子之间的耦合提供了重要的信息。对 Z 玻色子衰变的精确测量也是 LHC 电弱物理最为重要的精确测量之一。

在大型强子对撞机上，和 ATLAS, CMS 实验相比，LHCb 探测器非常独特的前向探测接受度。因此，在 Z 玻色子相关性质的测量上有着独一无二的优势，这一独特的接受度意味着 LHCb 的实验结果能够在独特的范围内对部分子分布函数提供重要约束。LHCb 实验测量得到的结果同时也能够与其他有着不同接受度范围的实验所测量得到的结果进行互补。相较于其他强子衰变和半轻衰变过程， Z 玻色子的产生以及它的轻子衰变过程是一个非常独特、干净的物理过程，且有较为充足的统



计量。其中 $Z \rightarrow \mu\mu$ 这一物理过程的产生截面较高、且末态非常干净，尤其是在 LHCb 实验上，其事例纯度能够达到 99% 以上，这为 Z 玻色子截面的精确测量提供了非常好的实验环境。

本文使用 LHCb 实验在碰撞中心能量为 13 TeV 下采集到的 5.2 fb^{-1} 的质子-质子碰撞数据，利用 $q\bar{q} \rightarrow \gamma^*/Z \rightarrow \mu^+\mu^-$ 事例细致研究这一物理过程中末态轻子的运动学微分分布，对规范玻色子 (Z) 的极化进行直接探测。理论上， $q\bar{q} \rightarrow \gamma^*/Z \rightarrow \mu^+\mu^-$ 这一过程的角度微分分布可以用 8 个 $A_i = 0, \dots, 7$ 角度参数来表示，这些参数是轻子对不变质量、横向动量和快度的相关函数。本文对其五个最重要的角度参数 (A_0 到 A_4) 进行精确测量，分别测量了这些参数关于横向动量以及 Z 玻色子快度的依赖关系。并将测量结果与不同的理论预言进行对比，从而对标准模型进行检验，为理解 Z 玻色子的产生机制提供重要的信息。

这个电弱物理精确测量依赖于一个探测器相关的服务性工作：LHCb 实验上高动量 μ 子的能量修正。LHCb 实验在数据采集过程中，各个子探测器的校准工作是在线取数时研究并应用的。在这一校准过程中，主要用到 $D^0 \rightarrow K\pi$ 事例的径迹、衰变顶点以及质量等相关信息。在线校准程序通过对已知粒子质量限制，从而改进了带电粒子的动量测量精度，最大程度上消除了探测器校准所带来的影响，这一校准程序适用于 LHCb 绝大多数的物理分析。然而，电弱物理中所涉及到的带电径迹动量要远远大于校准中所使用径迹动量，因此目前的在线校准流程无法完全解决电弱物理中所存在的相关问题，所以 W/Z 玻色子衰变产生的高动量 μ 子仍会受到探测器微小位移效应的影响。这一效应最直观的表现：在 LHCb 收集到的 $Z^0 \rightarrow \mu^+\mu^-$ 数据中的质量分辨率比蒙特卡洛模拟事件中 Z^0 的质量分辨率差，这会影响到 W 玻色子的质量测量。此外，在 Z/γ^* 前后电荷不对称测量 (A_{FB}) 中，我们发现在真实数据中， A_{FB} 的分布在磁极向上和磁极向下的两个样本中有较大的差异。这一差异并不来自于物理层面，而是由于探测器的校准问题或磁场的模型化不够准确所造成的，这会为相关的电弱测量带来较大的系统误差。为了解决这一问题，在本文中，我们对 $Z^0 \rightarrow \mu^+\mu^-$ 事例中的高横动量的 μ 子构建了离线层面的两步能量校准。首先在探测器层面上对于 μ 子的能量将进行对准修正，尤其是修正 Z 玻色子质量与 μ 子空间角的依赖关系，并将修正后的 μ 子进行重新拟合，因为这一步本质上还是在探测器层面上的修正，因此在本文中称之为 ‘improved-alignment’ 修正。通过 ‘improved-alignment’ 修正能够有效的消除探测器不完全准直效应，较大的提高了 Z 事例的质量分辨率，很好的修正了 Z 玻色子质量与方位角的依赖关系，并在很大程度上消除了磁极向上和向



下数据中的 A_{FB} 差异。但是这个修正并不能完全消除残余的探测器准直效应：在 Z^0 玻色子峰值附近，不同磁场状态下收集的样本中 A_{FB} 仍存在大约 0.05 的差异，远超统计误差所能覆盖的范围。在 ‘improved-alignment’ 修正中，我们假设了 Z^0 玻色子的质量峰中心值位置在不同的相空间区域是稳定的值，但是通过进一步的后续研究发现，这一假设并不十分准确。由于 LHCb 探测器是一个单臂前冲的实验装置，它只能探测到前冲产生的 Z^0 玻色子，这些事例通常位于整个相空间的特殊区域内。通过对产生子层面的事例的研究发现，在相空间的不同区域内， Z^0 玻色子的质量依赖性是有较大波动。尤其是在探测器边界的事例， Z^0 玻色子的质量平均值位置不再与 Z^0 玻色子的世界平均值相同。因此在 ‘improved-alignment’ 修正的基础上，我们围绕 Z^0 玻色子的质量平均值位置构建了 ‘post-alignment’ 对 μ 子能量做进一步的修正。最终通过 ‘Improved-alignment’ 以及 ‘post-alignment’ 修正完成了对 $Z^0 \rightarrow \mu^+\mu^-$ 中高横动量 μ 子的能量修正，有效的消除了磁极向上和磁极向下样本中 A_{FB} 的差异，提高了 Z^0 玻色子的质量分辨率，且将蒙特卡洛样本中的 Z^0 玻色子的质量分辨率和真实数据的质量分辨率调整为一致。这一工作是目前在 LHCb 实验上能够消除 Z^0 玻色子 A_{FB} 在不同磁场样本中差异的最好方式，其相关技术细节在下文中将会做具体讨论。针对这个工作的 LHCb 内部技术细节文档已经整理完成，并通过了合作审核，这一工作不仅对本文中所涉及到的 Z 玻色子的角分布测量非常重要，对其他 Z^0 玻色子的相关研究（例如截面测量）也有着重要意义。

除了能量修正外，在 Z 玻色子相关精确测量中，测量高横动量 μ 子相关重建、鉴别以及触发效率也是非常重要的组成部分。同样也是系统误差的重要来源，本文对此也做了非常细致的研究。本论文中电弱物理相关的 μ 子效率研究是在 LHCb 实验上首次使用 2016, 2017 和 2018 年所采集到的数据，对高横动量 μ 子的重建效率进行系统的研究。包括 μ 子的触发效率， μ 子径迹的重建效率以及 μ 子的粒子鉴别效率。通常情况下，LHCb 实验上利用蒙特卡洛模拟事例通过 ‘truth-match’ 的方法来研究效率。虽然蒙特卡洛事例不能完全准确的描述探测器的响应，但这种效率测量方式可以用于大部分寻找新粒子以及统计误差占主导的分析。而精确测量的分析需要更为细致的效率研究，因此在本文中采取另一种常见的效率计算方法：‘tag-and-probe’ 方法。这种方法的优点是利用真实数据中的 Z 玻色子事例来计算 μ 子的各种效率，以此来避免蒙特卡洛事例无法准确描述探测器响应而带来的系统偏差。同时利用蒙特卡洛事例，比较使用以上两种方法所得到效率值的差别，来得到来自效率计算方法的系统误差。因为 $q\bar{q} \rightarrow \gamma^*/Z \rightarrow \mu^+\mu^-$ 事例有较为充足的统计量，且纯度非常高，



因此本文选用 $q\bar{q} \rightarrow \gamma^*/Z \rightarrow \mu^+\mu^-$ 事例作为测量效率的样本。该衰变道的末态有两个 μ 子，在效率分析中，要求其中一个 μ 子完全重建，即必须通过 μ 子鉴别以及通过触发的要求，后面将其称之为‘tag’。另一个 μ 子只需要被部分重建，后面将其称之为‘probe’。通过研究‘probe’是否能够被完全重建、被鉴别为一个真实的 μ 子、以及是否能被触发，来分别计算 μ 子的重建效率、鉴别效率、和触发效率。本文还详细研究了 μ 子效率是否存在电荷和磁场依赖的关系，来确保得到的效率真实可靠，并对各项效率的计算详细的研究了其系统误差。该项工作不仅适用于本文中所讨论的电弱物理中的 Z 玻色子的角度分析，也同样适用于 W, Z 玻色子的产生截面测量，以及前后不对称性等精确测量，因此对于 LHCb 电弱相关物理有着重要的意义。和 μ 子能量修正一样，该项工作相关的技术细节也已经整理成文，并且通过了合作组审核，作为合作组内部技术细节文档。

除了上述的两个物理分析外，本文也描述了我对 LHCb 探测器升级所做出的软件和硬件方面的研究和贡献。如上文所诉，目前标准模型仍然无法解释所有的物理现象，比如暗物质、暗能量等，增大实验数据是检验标准模型、以及寻找新物理最有效、最直接的方式。世界上对撞能量最高的大型强子对撞机 LHC 在 2019 至 2021 年间正在进行硬件升级。升级之后，LHCb 实验对应的瞬时亮度将提高 5–7 倍，以期通过统计量的增加来观察到更多稀有衰变物理现象以及寻找新粒子、发现新物理。同时，LHCb 实验将对探测器进行重大升级。这次升级将使探测器能够在更高的瞬时亮度下运行，并以软件触发的方式来处理 LHC 40 兆赫兹的束流对撞频率。新的运行条件对探测器提出了更高的技术要求，导致很多之前的子探测器无法在新的运行条件下工作。以 LHCb 径迹探测器为例，整个径迹系统都需要被更换，来处理升级后产生的大量数据。其中最主要的升级是磁铁下游的径迹探测器将被 SciFi 径迹探测器所取代。SciFi 径迹探测器是一种大型、高颗粒度闪烁光纤径迹探测器，信号由硅光电倍增管（SiPMs）阵列读出。探测器读出信号由名为 PACIFIC 的定制的 64 位通道芯片处理。每个通道包含一个模拟信号处理链和三个比较器，并具有可调的数字化阈值。每个通道的阈值都需要根据连接的 SiPM 信道进行校准，以确保探测器的高性能。SciFi 径迹探测器的组件已经生产完毕，并完成了大部分的组装工作。但是在正式使用前需要对其各项性能进行测试，以确保组建完成后能够正常工作。2018 年 7 月，LHCb 实验在欧洲核子研究中心（CERN）利用组建好的 SciFi 探测器模块进行了 SPS 束流测试，获得了大量测试数据。基于这一期间内获得的束流测试数据，LHCb SciFi Testbeam 小组对 SciFi 径迹探测器的击中效率、击中分辨率以及溢出效应的相关性能进



行了研究。在研究过程中我们发现一个难以理解的问题：虽然 SciFi 径迹探测器的探测效率是整体上大于 99% 的，但是在同样的测试环境下，部分模块 (Mat3) 相较于其他模块的击中效率明显偏低。在 SciFi 径迹探测器正式组装到 LHCb 探测器上之前，急需理解并解决这一问题，找到效率降低原因。我在海德堡大学交流合作期间，对这一问题进行了细致的研究，最终通过研究发现 Mat3 这一模块上击中效率的下降并不是由硬件本身的问题造成的，而是在入射光系统的时间校准算法中对不同模块的标度选取存在差异造成的。因此在 SciFi 径迹探测器后续对应的软件开发中，需要对不同模块之间的计时差异做更细致的研究，找到一种更好的方法来优化入射光系统校准计时。此外，我在研究中发现，现有的 SciFi 径迹探测器的软件模块下击中分辨率不够好，并且在不同的区域内有较大的差异：分辨率在 $[60\mu\text{m}, 100\mu\text{m}]$ 之间变化。随后发现，而 SciFi 击中分辨率其光学镜部件密切相关，而光学镜的校准与否会对分辨率带来很大的影响。在海德堡大学交流合作期间，我们针对光学镜部件构建了一套新的校准方案，来改善各个区域内的分辨率，从而能够有效的消除不同区域内分辨率的差别。将不同模块上的击中分辨率从 $[60\mu\text{m}, 100\mu\text{m}]$ 降低到 $[50\mu\text{m}, 60\mu\text{m}]$ ，最终达到了 SciFi 径迹探测器的设计目标。

LHCb 探测器有着高精度的径迹探测系统，能够很好的探测和重建带电粒子的径迹。对于低动量的粒子，动量的测量误差只有 0.1%，对于高动量的粒子 (200 GeV)，动量的测量误差也只有 1.0%。但是仍有一小部分的‘假径迹’存在，‘假径迹’指的是通过电子学信号与算法重建出来的带电径迹，但是没有任何真实粒子与之对应，在下文中称之为‘幽灵径迹’。有效的去除幽灵径迹能够提高 LHCb 探测器在径迹重建方面的性能。与此同时 LHCb 实验在 RunII 数据采集阶段 (2015-2018) 采用了一种新的触发方式，即在线对数据完成实时重建和校准。通过触发器的事例可以直接用于物理分析，不需要再进行离线重建。LHCb 的触发系统由三个阶段组成：能够通过硬件实现的阶段称之为‘L0’，通过软件实现的两个阶段称之为高级触发器，分别是‘HLT1’和‘HLT2’。在 HLT1 这一阶段完成部分重建，而 HLT2 包含数百个算法，这些算法更加耗时。新的触发方式能够大大的提高数据处理速度，更有效的完成数据处理。以上的现状要求我们在线取数时，要降低幽灵径迹存在率，进一步的提高径迹重建效率，节约在线数据处理时间。为了适应这个改变，LHCb 提出了一种基于神经网络的模式识别幽灵迹算法，原理是利用各子探测器中的相关径迹信息，通过神经元网络模式训练出一个更能分辨幽灵径迹和粒子真实径迹的变量。经测试，该算法能够在保留 99% 以上的



真实径迹基础上, 减少 60% 的幽灵径迹。并且通过大量的算法优化, 该算法能够显著减少需要处理的径迹数目、事例重建中的误组合本底, 并且该算法的速度足以适应软件触发时所保留的 CPU 时间, 这对 LHCb 实验在 RunII 取数阶段中的在线重建具有重要意义。正如上面所提到的, LHCb 探测器目前正在处于重大的硬件升级过程中, 以应对 RunIII 中更高统计量的数据。在软件层面, 由于 LHCb 将采用无硬件触发读出系统, 即全软件触发的取数模式, 这对在线径迹重建提出了更高的要求。RunIII 运行中瞬时亮度的增加同时也意味着幽灵径迹的增加, 因此幽灵径迹算法也需要进一步的升级, 来更有效的去除本底以及降低算法所需要花费的 CPU 时间。我们通过研究发现该算法中 90% 的 CPU 时间被用于寻找各子探测器上预期的击中率, 因此在本文的研究中我们尝试在多变量分析中去掉这一部分相关的变量, 来加速算法。根据离线分析的结果显示, 去掉这一部分变量不会对该算法去除幽灵径迹的能力有很大影响, 同时还能够减少 96% 的 CPU 使用时间。在此基础上, 本文还同样对激励函数做了更细致的研究, 研究结果表明采用采用更简单的激励函数也能够保证去除幽灵径迹能力的基础上提高算法运行速度。最终, 我们根据以上离线测试的结果对该算法进行了升级, 包括去除耗时变量、更改激励函数等。这些改变能够减少该算法 97% 的 CPU 时间的同时能够有效的去除幽灵径迹, 适应升级后的在线取数。新版本的幽灵径迹算法已经被 LHCb 官方所采纳, 并将用于 RunIII 的在线取数中。

我在攻读博士期间主导了两个 LHCb 实验的物理分析, 是这两个物理分析的第一作者, 完成了一个探测器升级方面的硬件方面工作, 以及负责一个在线软件算法的维护、升级工作。其中第一个物理分析, $\Xi_{cc}^{++} \rightarrow \Xi_c^+(\rightarrow p^+ K^- \pi^+) \pi^+$ 衰变道的发现验证了双粲重子的发现, 检验了夸克模型, 有助于加深对强相互作用本质的了解, 这项工作已经发表在 PRL 上。第二个物理分析, Z 玻色子的极化测量是 LHCb 上首次对这一过程进行角度分析, 且在该项工作中提出了目前在 LHCb 实验上唯一能够消除 Z^0 玻色子 A_{FB} 在不同磁场样本中差异的方式, 同时在 LHCb 实验上首次使用 2016, 2017 和 2018 年所采集到的数据, 对高横动量 μ 子的重建效率进行系统的研究。这一工作产生一个物理分析文章以及两个合作组内部技术细节文章, 其中物理分析文章已近进入物理分析组审核, 两个合作组内部技术细节文章已经通过合作组审核。与此同时我还对 LHCb 探测器的硬件和软件升级部分做了贡献, 其中硬件升级主要是指径迹系统的升级, LHCb 将采用一个全新的径迹探测器: SciFi。本文对其性能做了相关研究和讨论, 我参与了 LHCb SciFi Testbeam 小组为研究 SiciFi 性能有关的文章撰写。软件升级指的是在原有的幽灵径迹算法的基础上做了相关的研究, 对其算法进行了升级。在保证去除幽灵径迹的能力基础上, 极大的缩短了算法所需要花费的 CPU 时间。更新后的算法已经被 LHCb 官方采用, 这一工作对即将到来的 LHCb RunIII 取数阶段有着重要意义。



关键词: 标准模型, 双粲重子, 电弱物理, 极化测量, 轻子能量修正, 效率测量, 探测器升级, 幽灵径迹



Abstract

The Large Hadron Collider (LHC) is the most powerful and energetic particle accelerator in the world. The LHCb experiment is a single-arm forward spectrometer situated at the LHC, which is primarily designed for the precision study of beauty and charm flavoured hadrons. In this thesis, the observation of a new decay mode for the doubly charmed baryon Ξ_{cc}^{++} , the study of the angular coefficient of the Z boson, using the pp collision data collected by the LHCb detector, are presented. Besides physics analyses, I also made contributions to the SciFi detector upgrade and ghost probability algorithm for LHCb RunIII data taking.

The Standard Model (SM) predicts the exist of the doubly charmed baryon Ξ_{cc}^{++} . It was firstly observed by the LHCb collaboration in 2017, using the decay model $\Xi_{cc}^{++} \rightarrow \Lambda_c^+(\rightarrow p^+ K^- \pi^+) K^- \pi^+ \pi^+$. Following the previous discovery of Ξ_{cc}^{++} , this thesis presents an observation of new decay model $\Xi_{cc}^{++} \rightarrow \Xi_c^+(\rightarrow p^+ K^- \pi^+) \pi^+$ for the first time, with a statistical significance of 5.9σ , which confirmed the previous observation of the Ξ_{cc}^{++} . The data sample used in this observation is corresponds to an integrated luminosity of 1.7fb^{-1} , collected by the LHCb experiment in pp collisions of 2016 at a center-of-mass energy of 13TeV. The mass of the Ξ_{cc}^{++} state was measured to be $3620.56 \pm 1.45 \text{ (stat)} \pm 0.49 \text{ (syst)} \text{ MeV}/c^2$, where the first and second uncertainties are statistical and systematic, respectively. The result is consistent with the previous result. The ratio of branching fractions between the decay model $\Xi_{cc}^{++} \rightarrow \Xi_c^+(\rightarrow p^+ K^- \pi^+) \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Lambda_c^+(\rightarrow p^+ K^- \pi^+) K^- \pi^+ \pi^+$ is measured to be $0.035 \pm 0.009 \text{ (stat)} \pm 0.003 \text{ (syst)}$.

Another physics topic presented in this thesis is a measurement of the angular coefficients of $\mu^+ \mu^-$ pairs in the Z boson mass region at LHCb. Measurements of the five most significant angular coefficients, A_0 through A_4 , for Z bosons produced in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ and decaying to $\mu^+ \mu^-$ are presented as a function of the transverse momentum and rapidity of the Z boson. The dataset used in this analysis is collected with the LHCb detector, corresponds to 5.2 fb^{-1} of integrated luminosity. These measurements provide stringent tests on the SM, and comprehensive information about the Z boson production mechanisms, and are compared to different theoretical predictions.

The LHCb experiment is performing a major upgrade of the detector during the LHC Long Shutdown 2 from 2019 to 2021. This upgrade will enable the LHCb detector to operate at an increased instantaneous luminosity, and to record data at the LHC bunch crossing rate of 40 MHz. Besides the physics analyses, this thesis also includes two studies for this upgrade, for both the software and hardware upgrade.



The new operating conditions require the replacement of the complete tracking system. The tracking stations downstream of the magnet will be replaced by the SciFi Tracker, which is a large and high granular scintillating fibre tracker. The performance of a full detector slice of the SciFi Tracker regarding the hit efficiency, hit resolution, and spillover has been studied using the data obtained during a test beam campaign at the CERN SPS in July 2018.

For the software development in the LHCb, a neural-network based algorithm to identify fake tracks in the LHCb pattern recognition is presented. This algorithm, named ghost probability, is fast enough to fit into the CPU time budget of the software trigger farm and thus reduces the combinatorics of the decay reconstructions, as well as the number of tracks that need to be processed by the particle identification algorithms. For the upgrade, this algorithm is expected to be improved to deal with the highly increasing of online statistics in LHC Run-III, this thesis presents the latest updates on this algorithm.

Key Words: Standard Model; Doubly charmed baryon; Electroweak physics; Polarization measurement, Lepton momentum calibration; Lepton efficiency measurement; Detector upgrade; Ghost track probability

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Preface

This thesis documents all of the works carried out during my PhD period, in the LHCb collaboration. It includes a result of the searching for $\Xi_{cc}^{++} \rightarrow \Xi_c^+(\rightarrow p^+ K^- \pi^+) \pi^+$ using the proton-proton collision data collected by the LHCb detector in 2016, and a result of studying of the angular coefficient of the Z boson using LHCb 2016, 2017 and 2018 datasets. The thesis also discusses the SciFi detector upgrade and ghost probability algorithm for LHCb Run-III data taking.

Chapter 1 reviews the theory that relate to the properties and decays of doubly-charmed baryons and the angular coefficient of Z boson. This chapter includes a review of the current best theory of particle physics, the Standard Model, then an overview of the quark model, flavour physics, parton distribution functions and a discussion on the electroweak unification. This chapter concludes with a detailed descriptions of the theoretical and experimental status of doubly-charmed baryons and angular coefficient measurement.

Chapter 2 describes the design and operations of the Large Hadron Collider beauty (LHCb) detector. The detector systems that makes the LHCb becomes to an excellent laboratory, its data can be used to search for doubly-charmed baryons and study the angular coefficient of Z boson. Then, this chapter shows a brief description of the data processing work-flow at LHCb and an explanation of signal simulation at the LHCb. In the end of this chapter, an introduction of the upgrade of the LHCb detector is presented.

Chapter 3 describes a study of the ghost probability for LHCb Run-III data taking. The LHCb experiment is planning to collect data at a very high instantaneous luminosity in the LHC Run-III period. As ghost probability has been used in HLT for the online data taking of Run-II, the timing will be main concern for any improvement on this algorithm. For the ghost probability study for upgrade, several potential improvements are explored. The updated algorithm is approved and used as default one in the LHCb official software release.

Chapter 4 describes a study of the performance of the LHCb scintillating fibre tracker (SciFi), which will be installed in the current LHCb upgrade. This chapter gives a short introduction of the design of the SciFi detector, and shows a detailed studies of the performance of the full SciFi detector. The study on the puzzle of a drop of single hit efficiency, which is figured out and an dedicated algorithm to improve the single hit resolution performance is presented.

Chapter 5 presents one of the two physics analyses in this thesis, the first observation of the $\Xi_{cc}^{++} \rightarrow \Xi_c^+(\rightarrow p^+ K^- \pi^+) \pi^+$ decays at the LHCb. This chapter gives a detailed discussions on the selection of the data, the background studies, mass measurement and branching fraction ratio



measurements. The result is consistent with the previous result and the theoretical predictions.

Chapter 6 describes a measurements of the five most significant angular coefficients, A_0 to A_4 for Z bosons decaying to $\mu^+\mu^-$. The measured results are presented as a function of the transverse momentum and rapidity of the Z boson. These measurements provide stringent tests on the SM, and comprehensive information about the Z boson production mechanisms, and are compared to different theoretical predictions.

Chapter 7 presents a determination of high- p_T muon reconstruction efficiency for the LHCb Run-II data-sets, which is a very important component of the angular coefficient measurement. In this chapter, it is the first time to use the data collected in 2016, 2017 and 2018 in the LHCb experiments to systematically study the reconstruction efficiency of the high transverse momentum μ , the trigger, track reconstruction and identification efficiency studies of μ are included.

Chapter 8 is dedicated to the design of a two step offline procedure of muon momentum alignment for the LHCb Run-II datasets. It is the first time in the LHCb, we develop an algorithm to alignment the high momentum muons from W and Z^0 decays, to decrease the detector performance differences between *MagUp* and *MagDown* data samples.



1 Introduction

1.1 The Standard Model

Particle physics studies the basic constituents of matter and interactions between them. A remarkably successful theory: Standard Model (SM) [1] gives the best understanding of laws governing the fundamental particles and interactions to date.

The leptons have six flavors and are arranged into three generations, *i.e.* electron (e) and electron neutrino (ν_e), muon (μ) and muon neutrino (ν_μ) and tau lepton (τ) and tau neutrino (ν_τ), according to their charge (Q), lepton flavour numbers (L_e , L_μ , and L_τ) as summarized in Table 1. The e , μ and τ are massive particles and carry a negative elementary electric charge, while the neutrinos have small but non-zero masses and carry zero electric charge. Each lepton has a corresponding antiparticle which has the same mass and opposite quantum numbers so there are totally twelve leptons.

Table 1: Types of lepton in the SM. The names, charges, lepton flavour numbers, and masses are shown.

Leptons (spin = $\frac{1}{2}$)					
Flavour	Electric Charge	L_e	L_μ	L_τ	Mass (MeV/ c^2)
e	-1	1	0	0	0.511
ν_e	0	1	0	0	< 0.002
μ	-1	0	1	0	105.6
ν_μ	0	0	1	0	< 0.17
τ	-1	0	0	1	1777.8
ν_τ	0	0	0	1	< 18.2

Similarly six quarks are grouped into three generations according to their flavors. Up quark (u) and down quark (d) form the first generations, charm quark (c) and the strange quark (s) form the second generations, top quark (t) and the bottom quark (b) form the third generations. Each quark and antiquark has three colors, so there are totally thirty-six quarks. Quarks carry fractional electric charge and an additional quantum number called color charge, are introduced to describe strong interaction. The quark type is summarised in Table 2.

The four fundamental interactions include gravity, weak, electromagnet (EM) and strong interactions. The strong interaction occur through the exchange the gluon, the EM occur through photons, while $W^\pm$ and Z carries the weak force. The gravity force is described by Einstein Theory of General Relativity.



Table 2: Types of quark in the SM. The names, charges, and masses are shown.

Quarks (spin = $\frac{1}{2}$)		
Flavour	Electric Charge	Mass(MeV/ c^2)
u	+2/3	2
d	-1/3	5
s	+2/3	100
c	-1/3	1200
b	2/3	4200
t	-1/3	174000

1.2 The Quark Model

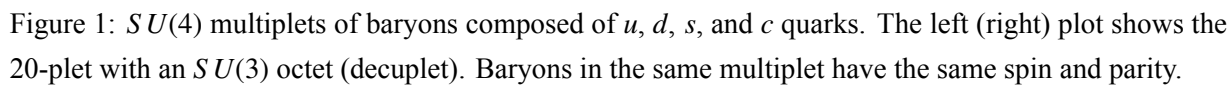
The quark model [2, 3] classifies and predicts the hadron structures. In this theory, hadron is consistent of basic components (particles): quarks. There are two types of composition:

- Baryons are composite subatomic particles that have three quark particles.
- Meson is made of a quark and an antiquark.

Considering the three light quarks (u , d , and s) and one heavy quark (c), the quark model predicts the existence of two $SU(4)$ multiplets of baryon states as Figure 1 shows, with a structure determined by the symmetry properties of the hadron wave functions. Baryons on inclined lines have the same charge, while baryons on horizontal lines have the same strangeness number. All the ground states with the charm quantum number $C = 0$ or $C = 1$ have been discovered. Weakly decaying $C = 2$ states are expected: a Ξ_{cc} isodoublet (ccu, ccd), each with $J^P = 1/2^+$.

1.3 Quantum chromodynamics

The quark model discusses the properties, production and decays of hadrons. However, it cannot describe the dynamical properties. Quantum Chromodynamics (QCD) [4] is a non-Abelian gauge field theory based on the gauge group $SU(3)$, and describe the strong interaction sector of the SM. The theory of QCD does not only describe quarks and gluons, but also the interactions between them. In terms of the dynamics within the QCD framework, a quark may emit or absorb a gluon, as well as vice versa, and any two gluons may directly interact, all of which can lead to the exchange of momentum and colour. This means a gluon and quark in isolation are still described by the Lagrangians respectively:



$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}. \quad (2)$$

But the full QCD Lagrangian has additional terms to account for the interactions between these elementary particles, which also maintain the gauge symmetry of the Lagrangian. The QCD Lagrangian is simply written as:

$$\mathcal{L}_{QCD} = \overline{\psi}_q^i (i\gamma^\mu D_\mu - m) \psi_q^i - \frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu}, \quad (3)$$

where

- ψ_q^i is the Dirac field of the quark with flavour q and color index i .
- γ^μ is the Dirac matrix.
- $G_a^{\mu\nu}$ is a tensor denoting the gluonic field strength.
- The subscript a in the $G_a^{\mu\nu}$ tensor runs from 1–8 to represent the different possible gluon states.
- D_μ is the gauge covariant derivative, it is defined as

$$D_\mu = \partial_\mu + ig_s t_a G_\mu^a, \quad (4)$$



where g_s is the effective color charge, which determines the strength of interaction between the colour-charged particles, t_a are the generators of the $SU(3)$ group and G_μ^a represents the field of the gluon.

Following the examination of QCD, the picture of baryons as bound systems of only three quarks should also be slightly refined. A baryon should be viewed as a system of three valence quarks within a ‘sea’ of virtual quarks and gluons that are allowed to exist within the permitted dynamics of QCD.

In quantum field theories all quantities that are held fixed within the theory actually depend upon the wavelength of the tool being used to measure them, even the number of particles is not conserved in a quantum field theory. Instead, these quantities are renormalised by processes involving virtual-particles. The coupling constants depend on the energy scale at which one observes them.

The strength of the nuclear strong interaction, characterised by the strong coupling constant, α_s , becomes logarithmically weaker as the energy E at which the hadron is probed at increases

$$\alpha_s(E) \simeq \frac{g_s}{\ln(\frac{E}{\Lambda_{QCD}})}, \quad (5)$$

where Λ_{QCD} is the QCD scale parameter. When the coupling constant becomes larger and the perturbative formalism starts to break down. If the energy scale goes to infinity (or the distance approaches zero), the strong coupling decreases to zero, the quarks and gluons behave as a free non-interacting particles. This remarkable feature is called ‘asymptotic freedom’ [5], which implies that the perturbative formalism is legitimate at energy scale much higher than Λ_{QCD} .

Conversely, the strong coupling α_s also increases with decreasing energy. This trend is expected to be responsible for the principle of ‘colour confinement’ [6], whereby quarks and gluons cannot be separated from their parent hadron without producing new hadrons. Colour confinement is hitherto an empirical fact, has not been mathematically proven.

Although QCD seemingly does not allow quarks and gluons to be free, it was expected a signature of their existence could come in the form of narrow-cone-like shapes of hadrons or ‘jets’ being produced when an original hadron system becomes fragmented during an energetic collision. The gluon was discovered in this manner following the observation of three-jet events by the TASSO experiment [7] at the PETRA collider [8].



1.4 Scattering and factorisation

Nucleus and nucleon both have a certain size and internal structure. In experiment, high energy leptons on nuclear targets to determine the hadron structure. Not being affected by the strong nuclear force, leptons can penetrate deep into the hadron to interact with the quarks. In experiments during the 1960s, the rate of large angle electron scattering from a hydrogen target was measured. The rate was expected to be small, since previous proton-proton collision experiments resulted in the production of hadrons colinear to the beam axes, supporting the hypothesis that the constituents of the proton disfavoured partaking in hard collisions. The rate was found to be large, suggesting that elastic collisions were taking place between the electron and proton. However, for the vast majority of these large-angle scattering events, the proton broke up.

In the high energy scattering, there are three regions: the elastic scattering region, resonance excitation region and the elastic scattering region. In the inelastic scattering region, the proton-neutron is either excited to a separated energy level resonance state, or has a higher excitation energy to reach the continuous excited state. In the case of large momentum transfer, the shape factor of elastic scattering is very small and the probability of inelastic scattering is larger.

1.4.1 Deep inelastic scattering

The electron-proton scattering process is represented by the Feynman diagram in Figure 2. The initial proton and electron have momenta P and k , the exchanged photon has momentum $q = k - k'$, and the final state electron momentum is k' . Deep inelastic scattering occurs when $-q^2 \equiv Q^2 \gg m_p^2$ (deep), where the proton is being probed at energies much larger than its mass, and $(P + q)^2 \equiv W^2 \gg m_p^2$ (inelastic), where the struck proton obtains energies that are also much larger than its mass, causing it to break up.

Consider the centre-of-mass frame, where the proton constituents are travelling toward the electron at relativistic velocities, colinear to the proton velocity. Any transverse momentum that the constituents may have is suppressed by α_s . The constituent momentum p is thus a fraction x of the proton longitudinal momentum P such that $p = xP$. The probability that a proton contains a parton with this momentum cannot be computed from perturbation theory since it depends on processes that take place in an energy regime where perturbative expansions do not converge; it must be determined from experiment instead. This probability is also called parton density function (PDF). For a particular parton species q , the PDF is a function of x and Q^2 , $f_q = f_q(x, Q^2)$, in agreement with data. The original parton model considered the PDFs as

functions of x only, to reflect the data at the time. This phenomenon is known as Bjorken scaling, which is a good approximation at low Q^2 .

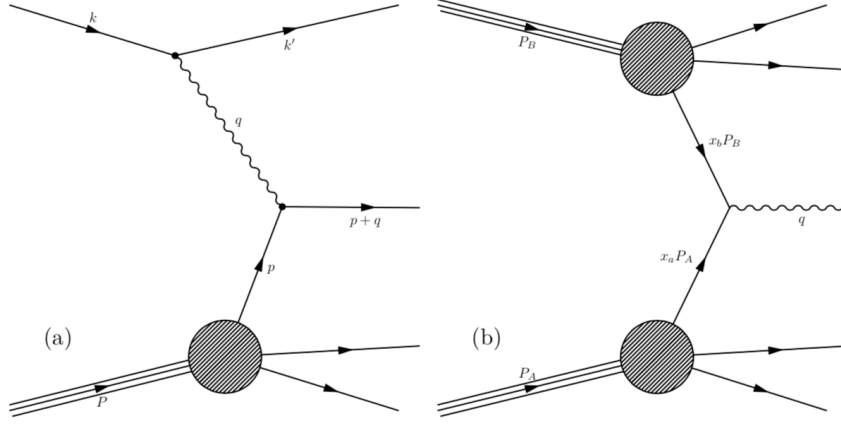


Figure 2: Feynman diagrams representing (a) ep and (b) pp deep inelastic scattering.

1.5 Parton distribution functions

Based on the deep inelastic scattering of high energy leptons and nucleons, parton distribution functions is proposed. In general, a PDF takes the form

$$f(x, Q^2) = F(x, Q^2) x^{m(Q^2)} (1 - x)^{n(Q^2)} \quad (6)$$

The function F is polynomial in x , whose coefficients and powers are given by parameters that depend on Q^2 . The values of the parameters at various Q^2 must be constrained empirically using data. The energy reach of the experiment, and indeed the particular process under study, determines the values of Q^2 that the hadron structure is probed at. Different experiments can also probe different regions of the PDF phase-space due to differing geometric acceptances. Figure 3 shows how various experiments cover their phase-space, where the coverage is due to the geometry of each experiment and the energy scale of the processes studied. The green domain represents fixed target data, which probe PDFs in the low- Q^2 and quite a broad range of x . Experiments at the Tevatron have a higher Q^2 but do not encompass as broad a range of x . The LHC experiments are represented by the orange and blue domains. These cover a broad range of both x and Q^2 . The regions accessible to the LHCb detector are indicated by the orange domains. Due that LHCb is detecting the W , Z bosons generated in the forward region, so the LHCb data is particularly sensitive to the small x and large x regions of bjorken- x , and has been

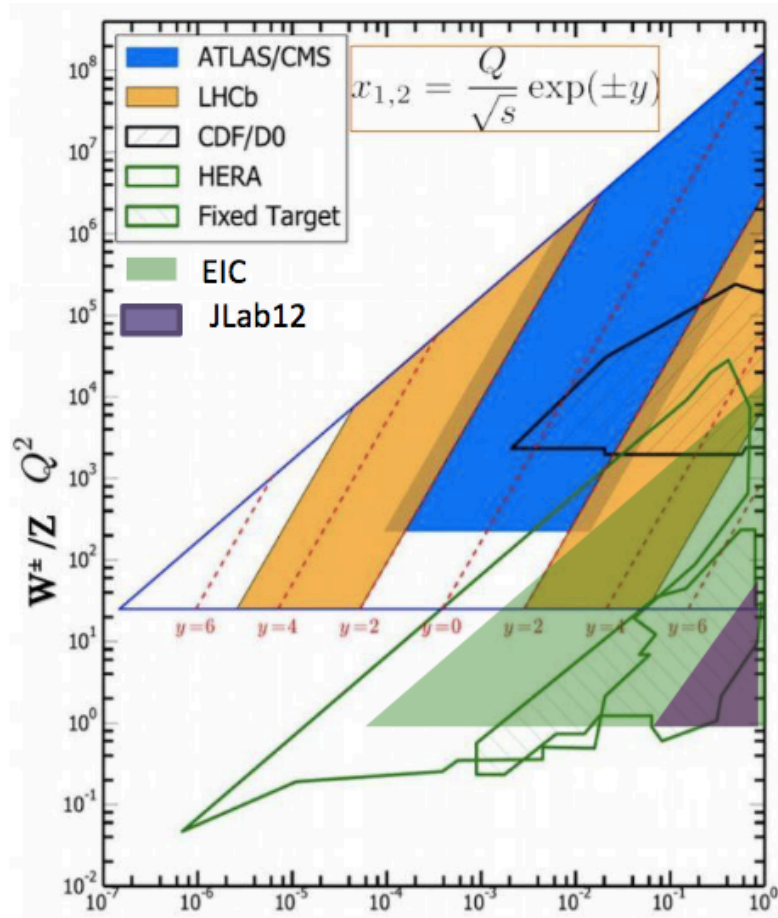


Figure 3: The (x, Q^2) plane and where it is covered by experiment. The LHCb covers two distinct regions at low- and high- x .



used for global PDFs fitting. The 13 TeV pp collision allow LHCb to explore lower x region than 7 and 8 TeV.

1.6 Electroweak unification

The weak force is one of the four fundamental forces that govern all matter in the universe. Most subatomic particles are unstable and decay by the weak interaction. For example, $\mu \rightarrow e + \nu_\mu + \bar{\nu}_e$. The weak force is transmitted by two charged ($W^\pm$) and one neutral (Z) force carrier. The lifetimes for particles that decay via the weak interaction is expected to be long. The effectiveness of the weak interaction is confined to a distance range of [10, 17] metre [9], about 1% of the diameter of a typical atomic nucleus.

The following typical experimental findings promote the understanding of electric-weak interaction.

- β -decay processes like hadronic $\nu \rightarrow pe^- \bar{\nu}_e$ and leptonic $\mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu$ couple to the weak force with the same strength.
- In the measurement of angular distribution of electrons in ^{60}Co β decay, it is found that parity is not conserved in weak interaction.
- The charged weak current only couples to left-handed fermions and right-handed anti-fermions. This implies a breaking of the discrete symmetries of parity P and charge conjugation C .
- The neutral weak current couples to left- and right-handed charged fermions, with different interaction strengths. This current differs from the photon in that it also couples to neutrinos.
- The vast majority of neutrinos are left-handed. Right-handed neutrinos must exist to account for neutrino oscillations and masses, but these are not included in the SM.

$SU(2) \times U(1)$ electricweak unified theory [1] is developed to account for these experimental findings. The unified electricweak interaction satisfies the internal gauge symmetry of $SU(2) \times U(1)$. Due to the chirality of particles, the coupling modes of neutral force carriers with left-handed and right-handed fermions are different. With respect to the charged weak force, of up- and down-type left-handed fermions, the corresponding fields are arranged in doublets like



Equation 1.6 to highlight the fact that these fields transform into one another under $SU(2)$ transformations. The couplings of right-handed fermions to the neutral force carrier can be accounted for by an additional $U(1)$ symmetry. Letting f denote fermion fields, and ν neutrino fields, the free and massless fermion Lagrangian is then could be written as:

$$\mathcal{L}_0 = \mathcal{L}_0^L + \mathcal{L}_0^R. \quad (7)$$

The discovery of non-conservation of parity in weak interaction shows that γ_5 term must be included in weak interaction flow. Defining the projection operators as:

$$\psi_L = \frac{1 - \gamma_5}{2} \psi, \quad (8)$$

$$\psi_R = \frac{1 + \gamma_5}{2} \psi. \quad (9)$$

The left-handed fermions can be categorizd into the following:

$$\begin{bmatrix} u \\ d \end{bmatrix}_L \quad \begin{bmatrix} u \\ s \end{bmatrix}_L \quad \begin{bmatrix} t \\ b \end{bmatrix}_L$$

$$\begin{bmatrix} \nu_e \\ e^- \end{bmatrix}_L \quad \begin{bmatrix} \nu_\mu \\ \mu^- \end{bmatrix}_L \quad \begin{bmatrix} \nu_\tau \\ \tau^- \end{bmatrix}_L.$$

The imposition of $SU(2)$ local gauge invariance on the left-handed part of the lagrangian requires the introduction of three additional vector fields. The vector boson should have different properties from photons. Firstly because β decay is a charged process, the particle should be charged. Secondly, due to the short range of weak interaction, the particle should have heavy mass. Finally, they should not have definite parity to allow weak flows to have $V - A$ structures. The left-handed Lagrangian becomes

$$\mathcal{L}^L = \sum_f \overline{\psi_L(x)} \gamma^\mu (\partial^\mu - ig \frac{\vec{\tau}}{2} \times \vec{W}(x)) \psi_L(x) - \frac{1}{4} F_i^{\mu\nu} F_{i\mu\nu}, \quad (10)$$

where $\vec{\tau}$ encodes the generators of the $SU(2)$ group and the weak interaction strength g has been factored out, similar to what was done for QCD. The weak field strength tensor is

$$F_i^{\mu\nu} = \partial^\mu W_i^\nu(x) - \partial^\nu W_i^\mu(x) + g \epsilon_{ijk} W_j^\mu(x) W_k^\nu(x). \quad (11)$$

The $W_{1,2}(x)$ vector fields combine to give the observed $W^\pm$. The $W_3(x)$ only couples to left-handed fields so it cannot be interpreted as the Z boson. A new $U(1)_Y$ symmetry is invoked.



Table 3: Properties of elementary particles under gauge transformation $SU(2)_L \times U(1)_Y$.

Particles	boson		lepton			quark			Higgs	
	W	B^0	ν_e	e_L	e_R	μ_L	d_L	μ_R	d_R	ϕ
I	1	0	1/2	1/2	0	1/2	1/2	0	0	1/2
Y	0	0	-1	-1	-2	1/3	1/3	4/3	-2/3	1

The properties of each particle under $SU(2)$ gauge transformation can be described by the weak isospin (I). While the properties under the $U(1)$ gauge change can be described hypercharge (Y). This new charge is defined in terms of other charges as the difference between the electric charge Q and the charge associated with transformations of the $W_3(x)$ field, I_3 , which is called the third component of weak isospin, as

$$\frac{Y}{2} = Q - I_3. \quad (12)$$

Properties of elementary particles under gauge transformation $SU(2)_L \times U(1)_Y$ are given in Table 3.

The left- and right-handed Lagrangians are amended to include the interactions between the field B_μ and the spinor fields, as

$$\mathcal{L}^G = -\frac{1}{4}F_i^{\mu\nu}F_{\mu\nu}^i - \frac{1}{4}B^{\mu\nu}B_{\mu\nu}, \quad (13)$$

where $F_{\mu\nu}^i (i = 1, 2, 3)$ is the second-order field strength tensor corresponding to the $SU(2)$ gauge field, while B is the second-order field strength tensor of $U(1)$ gauge field. The four massless bosons derived from this Lagrangian:

- $W_3(W^+, W^-, W^0)$: $SU(2)$ gauge field
- B^0 : $U(1)$ gauge field

By considering admixtures of the B and W_3 fields, one obtains the physical photon and Z boson. The admixture is parameterised by the weak mixing angle θ_W .

In summary the $SU(2)_L \times U(1)_Y$ symmetry requires four fields, W_3 and B . Some of the properties of the observed the W , Z and photon are obtained by superpositions of these fields. But until now the most important property of the observed W and Z bosons, their large mass, has not been accounted for yet. The gauge invariance will be broken after considering mass.

To solve these problems, spontaneous symmetry breaking (SSB) [10] is introduced. Suppose a system has an infinite family of degenerate ground states due to some symmetry. If one of these



states is chosen to be the unique ground state, then the original symmetry is broken. Involving a complex scalar field, the expression of the Langrange is:

$$\mathcal{L} = \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi), \quad (14)$$

where $V(\phi)$ is the scalar potential and could be written as

$$V(\phi) = \mu^2 \phi^\dagger \phi + h(\phi^\dagger \phi)^2. \quad (15)$$

This Lagrangian is invariant under the global phase transformation

$$\phi(x) \rightarrow \phi'(x) \equiv e^{i\lambda} \phi(x), \quad (16)$$

Where ϕ is the field quantity of Higgs field, the transformation property of Higgs under $SU(2)_L \times U(1)_Y$ gauge transformation, is $(I, Y) = (\frac{1}{2}, 1)$. So the transformation property of $\phi^\dagger$ is $(I, Y) = (\frac{1}{2}, -1)$. The $SU(2)_L \times U(1)_Y$ symmetry requires the transformation property of $V(\phi)$ must be $(0, 0)$.

To express $V(\phi)$ by power series of ϕ and $\phi^\dagger$, the express should satisfies the following two restrictions:

- The renormalizability require the field quantity of Higgs can not exceed the fourth power.
- $Y = 0$ and I has the possibility equal to 0

So $V(\phi)$ can only have square and the 4th power terms, usually written as:

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2. \quad (17)$$

The minimum value of potential energy or vacuum state is determined by the following conditions:

$$\begin{aligned} \frac{\partial V}{\partial \phi} &= \mu^2 \phi^* + 2\lambda \phi^{*2} \phi = 0, \\ \frac{\partial V}{\partial \phi^*} &= \mu^2 \phi + 2\lambda \phi^* \phi^2 = 0. \end{aligned} \quad (18)$$

The situation that $\mu^2 > 0$ and $\phi^\dagger = \phi = 0$ corresponds to the minimum energy of the whole space. For this mode the vacuum is invariant under the transformation Equation 16, the vacuum is nondegenerate and this model has strict symmetry. When $\mu^2 < 0$, $\phi^\dagger = \phi = 0$ corresponds to the maximum energy of the whole space, and there is an infinite set of ground states:

$$\begin{aligned} |\phi| &= \frac{v}{\sqrt{2}} \\ v &= \sqrt{-\mu^2/\lambda}, \end{aligned} \quad (19)$$



and if a particular ground state is chosen, at $\lambda = 0$, the entire symmetry is broken.

For $\phi_0 \neq 0$, the ground state is excited to:

$$\phi(x) = \frac{1}{\sqrt{2}}(v + \phi_1(x) + i\phi_2(x)), \quad (20)$$

then the potential becomes:

$$V(\phi) = V(\phi_0) - \mu^2 \phi_1^2 + h\nu \phi_1(\phi_1^2 + \phi_2^2) + \frac{h}{4}(\phi_1^2 + \phi_2^2)^2, \quad (21)$$

where ϕ_1 has a mass term, but ϕ_2 does not. The massless excitation is called a Nambu-Goldstone boson [11]. In the SM, it is extended to the symmetry group governing electroweak interactions $SU(2)_L \times U(1)_Y$. This is done such that the weak part is broken and the electromagnetic part remains unbroken, a choice motivated by the experimental fact that W and Z bosons are massive while the photon is massless. A new field arises, the Higgs boson, as well as three Goldstone bosons (two charged, one neutral). The example above considered the global symmetries. In the case of the SM, the symmetry is a local one and the Goldstone bosons can be removed from the Lagrangian by a suitable choice of gauge. Their degrees of freedom remain, but are now interpreted as longitudinal polarisation states of the W and Z bosons. Longitudinal polarisation states are characteristic of all massive particles.

The mass of $W^\pm$ and Z boson could be written as

$$\begin{aligned} m_W^2 &= \frac{1}{4}g_2^2 v^2, \\ m_Z^2 &= \frac{1}{4}(g_2^2 + g_1^2)v^2, \end{aligned} \quad (22)$$

Where g_1 and g_2 are two independent gauge coupling constants, g_1 corresponds to $SU(2)$ group and g_2 corresponds to $U(1)$ group.

One parameter of the SM specified in Weinberg-Salam theory of the electroweak interaction named Weinberg angle, also known as the weak mixing angle, which is used to determine the relationship between the W and Z boson masses. It is defined as:

$$\begin{aligned} \sin\theta_w &= \frac{g_1}{g_2^2 + g_1^2}, \\ \cos\theta_w &= \frac{g_2}{g_2^2 + g_1^2}. \end{aligned} \quad (23)$$

So the W and Z masses could be expressed as

$$\begin{aligned} m_W &= \frac{ev}{2\sin\theta_w}, \\ m_Z &= \frac{ev}{2\sin\theta_w \cos\theta_w}, \\ m_W &= \frac{m_Z}{\cos\theta_w}. \end{aligned} \quad (24)$$



After the spontaneous symmetry breaking, only Higgs field eigenvalues are not zero, while the vacuum eigenvalues of other fields are still 0. Higgs field bring the influence and changes from the spontaneous breaking of symmetry into the interaction.

Like the fermion mass term in Lagrangian's quantity is the multiplication of left-handed and right-handed field quantities, it does not satisfy the requirements of $SU(2) \times U(1)$ invariant in the electric weak unified theory. But after considering the interaction between Higgs field and fermion, the fermions gain mass from the spontaneously symmetry breaks.

1.7 Doubly charmed baryon

Doubly charmed baryons (DCBs) are baryons composed of two heavy charm quarks in combination with another valence quark. They are firmly predicted by the quark model that has to date predicted over a hundred baryon states discovered in different experiments. Searches for DCBs are important because DCBs provide a unique system for testing different methods used in chromodynamics, particularly non-perturbative techniques. While baryons composed of the lighter up, down and strange quarks suffer from the classical three-body problem of dynamics, DCBs are much easier to model. They can be described in calculations as a single static and heavy cc diquark structure with a lighter quark orbiting. This type of simplification facilitates many theoretical approaches, particularly in Heavy Quark Effective Theory. Improvements in QCD techniques would in turn help aid progress in understanding exotic hadrons, such as the tetraquark and pentaquark candidates. This section will describe the expected properties of doubly-charmed baryons based on recent theoretical work that has then also motivated the strategies of the search analyses. Equally, this section will discuss the variety of searches for doubly-charmed baryons performed by different research groups, prior to any of the analyses detailed in this thesis had began.

1.7.1 Theoretical predictions

Mass

The mass of the Ξ_{cc}^+ baryon is considered by various methods, *e.g.* relativistic quark model [12, 13], non-relativistic quark mode [14–17], QCD sum rules [18–20] and MIT bag mode [20]. Most calculations yield mass predictions in the range $3500 - 3700 \text{ MeV}/c^2$ [14, 20–24]. Additionally, the masses of the the Ξ_{cc}^+ and Ξ_{cc}^{++} baryons are expected to be very similar because of the isospin symmetry between the up and down quarks. On the other hand, the ω_{cc}^+ is expected

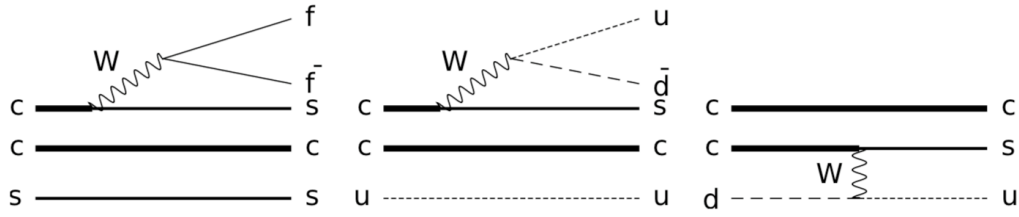


Figure 4: Quark diagrams of general decay of different doubly-charmed baryons, where the form of the weak decay is (left) W^- external emission in a semi-leptonic decay, (middle) W^- external emission to a quark-antiquark final state and (right) W exchange.

to be $100 \text{ MeV}/c^2$ heavier than the Ξ_{cc} baryons as it contains the more massive strange quark.

Lifetime

QCD methods can also be used to calculate the lifetime of a particle. The probability that a quasi-stable particle will decay is governed by the rules of Relativistic Quantum Field Theory. As such, the decay rate, Γ , of a particle is given by the sum squared of the amplitudes (terms from each Feynman diagram contribution) of all possible ways in which the particle can decay. The decay rate then gives the probability that the particle decays in a unit of time with the lifetime of a particle given as $\tau = \frac{1}{\Gamma}$. The decay rate Γ also contributes to the width of any signal peak in the distribution of mass measurements of a particle due to the Heisenberg's Uncertainty principle. When it comes to the lifetimes of the spin-1/2 DCBs, there is a large spread in their predicted values. For instance, the predicted lifetime of the Ξ_{cc}^+ baryon spans the range 50-250 fs [25–28], while the Ξ_{cc}^{++} baryon is expected to be three to four times longer lived with a predicted lifetime between 200-1050 fs [25–28]. The predicted larger lifetime of the Ξ_{cc}^{++} baryon over the Ξ_{cc}^+ baryon can be qualitatively explained by the destructive Pauli interference of its charm-quark decay products and its valence up quark in the initial state acting as a spectator, whereas the lifetime of the Ξ_{cc}^+ baryon should be shortened due to an additional contribution from W -exchange between the charm and down quarks. A combination of these effects, leads to following generally well accepted hierarchy of lifetimes; $\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^+) \gg \tau(\Xi_{cc}^+)$, for the spin-1/2 DCBs. Quark diagrams illustrating the exchange and spectator contributions for the Ξ_{cc}^+ , Ξ_{cc}^{++} and Ω_{cc}^+ baryons are shown in Figure 4.

Production cross-section

The cross section, a measure of the rate of production, of a DCBs can also be predicted using



Table 4: Properties of the $SU(4)$ doubly-charmed baryons with $J^P = +\frac{1}{2}$. The values are taken from a variety of different sources.

State	Valence quarks	Mass (MeV/ c^2)	Lifetime (fs)	$I(J^P)$
Ξ_{cc}^+	ccd	3500–3800	50–250	$\frac{1}{2}(\frac{1}{2}^+)$
Ξ_{cc}^{++}	ccu	3500–3800	200–1050	$\frac{1}{2}(\frac{1}{2}^+)$
Ω_{cc}^+	ccs	3600–3900	200–500	$0(\frac{1}{2}^+)$

QCD techniques. In general, the formation is divided into three steps:

- 1) Computing the production of two c quarks using perturbative QCD in the pp collision
- 2) Binding of the two c quarks into a diquark structure
- 3) Hadronization of the diquark structure into a light quark to create a DCB.

However, the predicted cross-sections are generally associated with sizeable uncertainties since charm quarks have large non-perturbative contributions. The theoretical calculations for the production cross section of the Ξ_{cc} baryons in proton-proton collisions at $\sqrt{s} = 14\text{TeV}$ are between 60–1800 nb [29, 30], while the Ω_{cc}^+ cross section is expected to be a factor of three smaller due to the fragmentation fractions of u , d and s quarks in p - p collisions [31–34]. It is interesting to note that some theorists suggest searching for DCBs in heavy-ion collisions, since the cross sections of DCBs might be enhanced by a few orders of magnitude when quark gluon plasma is produced [35–37]. Experimentally, cc quark production from proton-proton collisions is found to be dominated by double-parton scattering according to the double-heavy production measurements performed by the LHCb collaboration. Double-parton scattering (DPS) is when two independent hard scattering processes occur in two independent collisions that each produces a $c\bar{c}$ pair. There is no experimental evidence to suggest that DPS is the dominant mechanism for DCBs production or whether it is suppressed in the hadronization process such that single-parton scattering leads.

From theoretical expectations, it is clear that the spin-1/2 Ξ_{cc}^{++} state is the DCBs with the most promise for discovery, given the combination of its relatively long lifetime and its high production cross section, compared to the other two states. All the properties of the spin-1/2 $SU(4)$ DCBs that discussed above are summarised in Table 4.

Search Modes

Like most hadrons, doubly-charmed baryons are quasi-stable systems and will decay to more



stable particles, typically charged kaons ($K^\pm$), protons (p) and charged pions ($\pi^\pm$), which can be detected by high-energy physics detectors to infer their existence. The states of doubly-charmed baryons of lowest mass with $J^P = +\frac{1}{2}$ can only decay via the nuclear weak interaction and as such they should be conveniently displaced for their production point. This is one of the key signatures of signal in the search analyses of Section 5. However, their hadronic weak decays usually lead to multiple detectable particles in the final state. This can negatively impact the ability of the detector to reconstruct the full decay. Then in the case of doubly-charmed baryons with $J^P = +\frac{3}{2}$, these will decay almost instantaneously to their $J^P = +\frac{1}{2}$ state, either electromagnetically or via the strong nuclear force, emitting a photon in the former case and pions in the latter. Hence, searches for these doubly-charmed baryons will be difficult due to the challenge of reconstructing even more tracks (from the PV). Any signal will also have a broad decay width making it challenging to disentangle from background.

In hadronic multi-body decays, intermediate and strongly decaying particles can be produced, such that the final state is topologically similar were the decay to proceed in a non-resonant fashion. In the past decades, searches of doubly charmed baryon decays were focused on cases where the baryon weakly decays to two such intermediate particles. The $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ (\rightarrow p^+ K^- \pi^+) K^- \pi^+ \pi^+$ decay mode was predicted to be the most promising for discovery [38]. Recently, the LHCb experiment reported a significant structure in $\Lambda_c^+ K^- \pi^+ \pi^+$ final state, using 13 TeV data corresponding to an integrated luminosity of 1.7 fb^{-1} . The signal yield is measured to be 313 ± 33 , corresponding to a local statistical significance in excess of 12σ , consistent with a weakly decaying particle, which is Ξ_{cc}^{++} . Therefore, it would be very interesting to confirm this structure with other decay modes. In the theoretical calculation Ξ_{cc} decays shows that the $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ decay [38], as shown in Figure 5, has a branching fraction that is comparable to that of the $\Lambda_c^+ K^- \pi^+ \pi^+$ decay mode. Although the branching fraction of $\Xi_c^+ K^- \pi^+$ is estimated to be $(1.6 \pm 0.5)\%$, which is about a factor of 4 smaller than that of $\Lambda_c^+ p K^- \pi^+$, $(6.35 \pm 0.33)\%$. But there are only 4 tracks in the final states for the $\Xi_c^+ K^- \pi^+$, compared to 6 tracks for the $\Lambda_c^+ K^- \pi^+ \pi^+$ mode, the reconstruction/trigger/selection efficiency is expected to be higher. Therefore, a search for Ξ_{cc}^{++} baryon using the $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ decay mode is very promising. This analysis aims to search for the $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ using the 2016 data, with an inclusive Ξ_c^+ Turbo line.

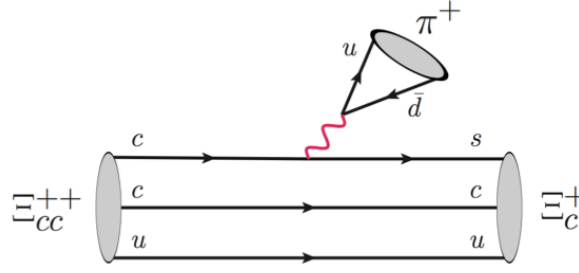


Figure 5: An example Feynman diagram of the $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ decay.

1.7.2 Various experiments searched DCBs in the past decades

In 2002, SELEX collaboration at the Fermi National Accelerator Laboratory claimed that they found the signals of the Ξ_{cc}^+ through $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ decay mode [39]. Following in 2004, SELEX collaboration reported signals of the same state via the $\Xi_{cc}^+ \rightarrow D^+ p K^-$ decay mode [40]. These reported results as Figure 6 shows. But the measured properties are not agree with most of theoretical predictions. The reported lifetime was found to be compatible with zero within the experimental resolution, which is less than 33 fs at the 90% Confidence Level (C.L.). This is not consistent with most theoretical expectations for a weakly decaying Ξ_{cc}^+ state as Table 5 shows. Furthermore, SELEX estimated that 20% of $\Lambda_c^+(udc)$ yield originated directly from decays of Ξ_{cc}^+ baryons, but it is not consistent with a fact that the production of doubly-charmed baryons is suppressed by several orders of magnitude with respect to singly-charmed baryons.

Table 5: Properties of the $SU(4)$ doubly-charmed baryons with $J^P = \frac{1}{2}^+$.

State	Valence quarks	Mass (MeV/ c^2)	Lifetime (fs)	$I(J^P)$
Ξ_{cc}^+	ccd	3500–3800	50–250	$\frac{1}{2}(\frac{1}{2}^+)$
Ξ_{cc}^{++}	ccu	3500–3800	200–1050	$\frac{1}{2}(\frac{1}{2}^+)$
Ω_{cc}^+	ccs	3600–3900	200–500	$0(\frac{1}{2}^+)$

Since then, several other experiments in different production environments, like FOCUS [41], BaBar [42] and Belle [43] experiments, try to search for the same state reported by the SELEX group. All of these groups failed to confirm such a particle. The LHCb collaboration also try to search for the Ξ_{cc}^+ state through the $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ decay using proton-proton collision data in 2013 [44]. Unfortunately, the LHCb experiment also did not find any significant signal in the mass range 3300 – 3800 MeV/ c^2 , as shown in the left plot of Figure 7. In the end, the LHCb

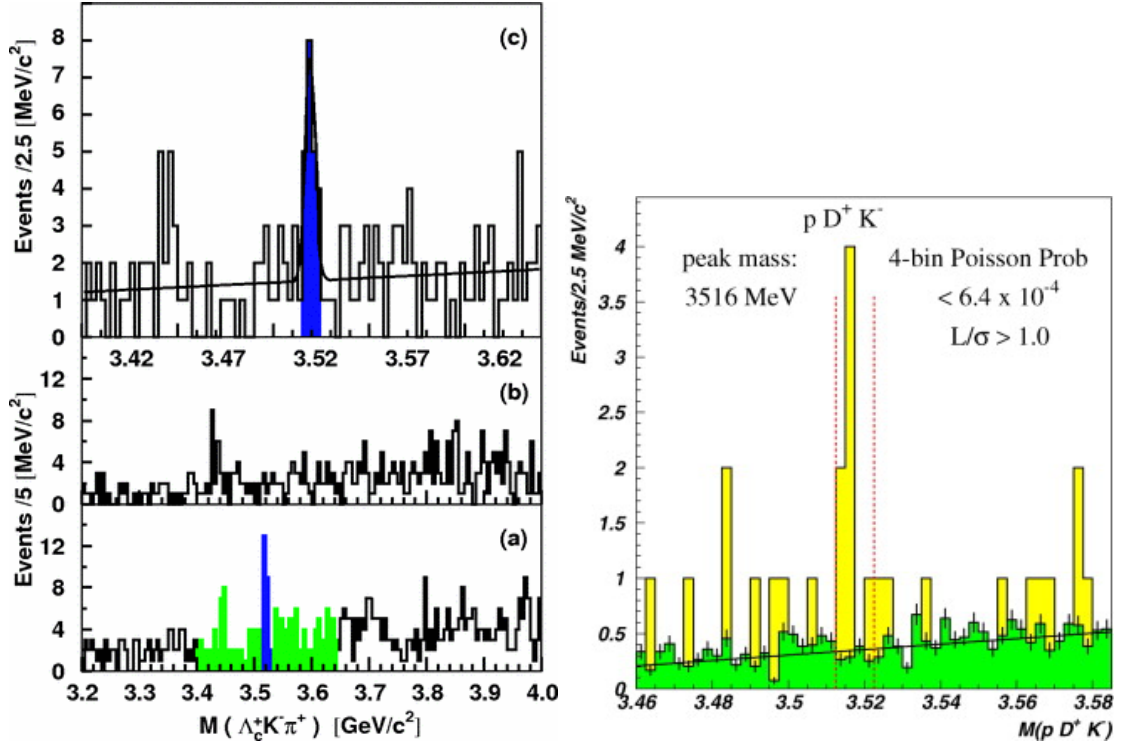


Figure 6: $\Lambda_c^+ K^- \pi^+$ and $D^+ p K^-$ peaking structure in SELEX reported results.

experiment set upper limits at the 95% CL on the production ratio:

$$R = \frac{\sigma(\Xi_{cc}^+) \times \mathcal{B}(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)}, \quad (25)$$

where σ and $\mathcal{B}$ denote production cross section and branching fraction quantities, respectively. The value of the upper limit on R as a function of the mass and lifetime of the Ξ_{cc}^+ baryon is shown in the right plot of Figure 7. In the LHCb publication, the upper limit on this ratio R is determined to be in the 10^{-4} to 10^{-2} range, with the value being dependent on the lifetime of the Ξ_{cc}^+ baryon. The value reported by the SELEX for the same ratio is not consistent with this region.

However, considering the production environments are different between these experiments, it is still possible that the hyperon beams could enhance the production cross section of Ξ_{cc}^+ baryons. These inconsistent results remain a longstanding puzzle in the Ξ_{cc} sector. The increased statistics and improved trigger conditions in the LHCb experiment will contribute to the studies of the doubly-charmed baryons.

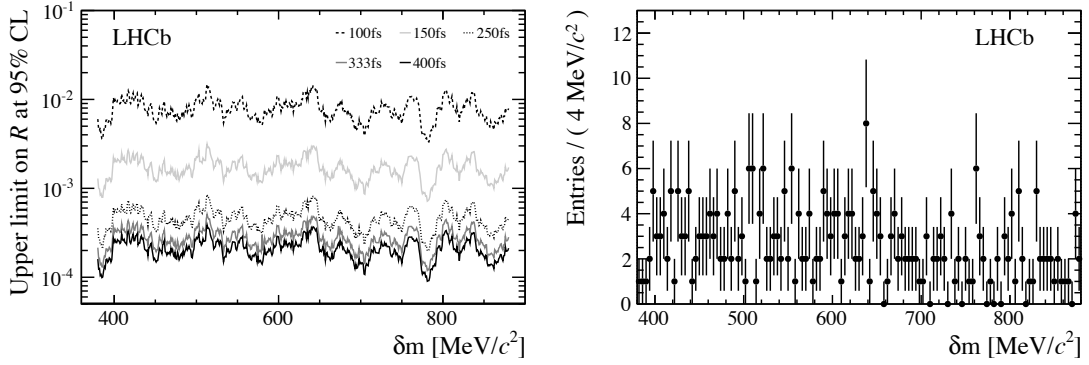


Figure 7: Results for the search of the $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ decay by the LHCb collaboration. (Left) The $\delta(m)$ distribution for Ξ_{cc}^+ candidates, where $\delta(m)$ is a mass difference variable defined as $m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) - m(K^-) - m(\pi^+)$. (Right) The upper limit ratio of $\sigma \Xi_{cc}^+ \times B(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)$ relative to $\sigma(\Lambda_c^+)$ under different $\delta(m)$ and lifetime, τ , hypotheses.

1.8 Angular Coefficient

1.8.1 Introduction

The production of Z boson followed by subsequent leptonic decay is a benchmark process at hadron colliders. The production rate for this process is close to 200 pb [45] in the LHCb fiducial region for the 13 TeV pp collision and combined with the fact that the final state is clean experimentally, it has allowed precise (multi-) differential Z boson cross section measurements been performed at the LHC [45–48]. Typically, these measurements are performed with respect to the kinematic information of the gauge boson decay and have a wide range of phenomenological applications, including Parton Distribution Functions (PDFs) and luminosity determinations.

Additional tests on the Quantum Chromodynamics (QCD) for Z boson production can also be performed by explicitly studying the angular distributions of the final-state leptons. An example is the measurement of the forward–backward charge asymmetry in Drell-Yan lepton pair production, differential in the lepton polar angle, provides important information on the coupling of the Z boson to fermions [49]. However, more information is accessible by looking at the full differential information of the leptons kinematics. With an assumption that the lepton pair is produced through the exchange of a gauge boson, the reconstructed lepton kinematics provide a direct probe of polarisation of the intermediate gauge boson, which in turn exposes the underlying QCD production mechanisms. The QCD dynamics of the $Z \rightarrow \ell^+ \ell^-$ process can be expressed in terms of a set of eight frame dependent angular coefficients $A_i = 0, \dots, 7$, which depend on the



invariant mass, transverse momentum, and rapidity of the lepton pair.

At tree level, the angular distribution of the final state leptons in the quark-antiquark ($q\bar{q}$) annihilation process ($q\bar{q} \rightarrow \gamma^*/Z \rightarrow \ell^+\ell^-$) can be written as [50, 51]

$$\frac{d\sigma}{d\cos\theta} \propto A(1 + \cos^2\theta) + B\cos\theta, \quad (26)$$

where θ is emission angle of the negatively charged lepton relative to the incoming fermion momentum, and A and B are functions dependent on the weak isospin, charge of the incoming fermions, and Q^2 of the interaction. When quarks are bound in a nucleon (*e.g.* in $pp \rightarrow \gamma^*/Z \rightarrow \ell^+\ell^-X$), the γ^*/Z is in general produced with a finite transverse momentum. In QCD this occurs either through the quark anti-quark annihilation process with a gluon (g) in the final state ($q\bar{q} \rightarrow \gamma^*/Z g$), or via the Compton process with a quark in the final state ($qg \rightarrow \gamma^*/Z q$). The Feynman diagrams for these two processes are shown in Figure 8.

The Collins-Soper (CS) frame [52] rather than the laboratory frame is used in this analysis. In the laboratory frame, the pp collision axis is the z axis, with the positive z axis oriented along the direction of the quark. The transverse component of any vector, such as the momentum vector, is defined to be relative to the z axis. The transverse component of vectors in other reference frames is defined to be relative to the z axis in those frames. The rest frame is reached from the laboratory frame via two Lorentz boosts, first along the laboratory z axis into a frame where the z component of the lepton-pair momentum vector is zero, followed by a boost along the transverse component of the lepton-pair momentum vector. Within the CS frame, the z axis for the polar angle is the angular bisector between the quark direction and the reverse of the anti-quark direction. The positive x axis for the azimuthal angle is along the direction of the transverse boost. A view of the CS frame is shown in Figure 9. By construction, the CS frame angles θ and ϕ are invariant with respect to boosts along the pp collision axis. When the transverse momentum of the lepton pair is zero, the CS and laboratory coordinate-system axes are the same.

In the CS frame, the angle θ is reconstructed using the following laboratory-frame quantities: the lepton energies, the lepton momenta along the beam line, the dilepton invariant mass, $M_{\ell\ell}$, and the dilepton transverse momentum, p_T . The polar angle of the negatively charged lepton is calculated as:

$$\cos\theta = \frac{\ell_+^-\ell_-^+ - \ell_-^-\ell_+^+}{M\sqrt{M^2 + p_T^2}}, \quad (27)$$

where $\ell_{\pm} = (E \pm p_z)$ and the $+$ ($-$) superscript represent lepton charge. The ϕ is calculated with

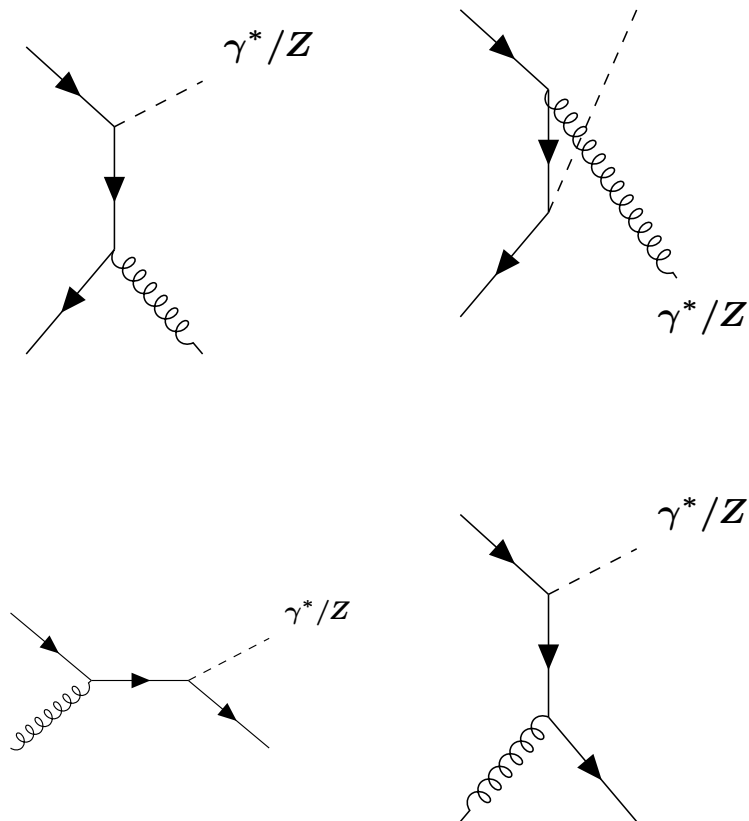


Figure 8: Leading order (top) annihilation ($q\bar{q} \rightarrow \gamma^*/Z g$) and (bottom) Compton Feynman diagrams ($qg \rightarrow \gamma^*/Z q$) for the production of Z bosons with finite transverse momentum.

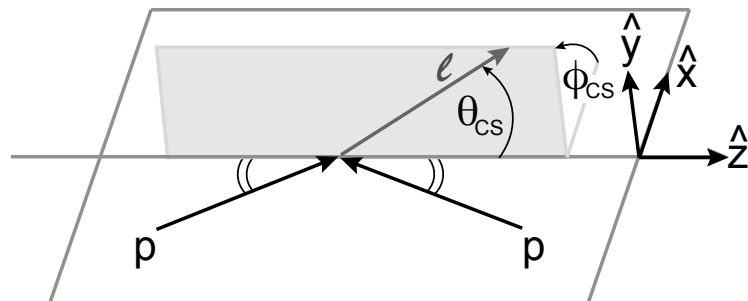


Figure 9: Sketch of the Collins-Soper reference frame [53].



the laboratory-frame quantities, as:

$$\tan \phi = \frac{\sqrt{M^2 + p_T^2} \vec{\Delta} \cdot \hat{R}_T}{M \vec{\Delta} \cdot \hat{p}_T}, \quad (28)$$

where $\vec{\Delta}$ is the difference between the ℓ^+ and ℓ^- laboratory-frame momentum vectors; $\hat{R}_T$ is the unit vector along $\vec{p}_p \times \vec{p}$, with $\vec{p}_p$ being the proton momentum vector and $\vec{p}$ the lepton-pair momentum vector; and $\hat{p}_T$ is the unit vector along the transverse component of the lepton-pair momentum vector.

The general expression [50, 51] for angular distribution of the final state leptons for $q\bar{q} \rightarrow \gamma^*/Z \rightarrow \ell^+\ell^-$ process is given by:

$$\begin{aligned} \frac{d\sigma}{d\cos\theta d\phi} \propto & (1 + \cos^2\theta) \\ & + \frac{1}{2}A_0(1 - 3\cos^2\theta) + A_1\sin 2\theta\cos\phi \\ & + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi \\ & + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi \\ & + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi, \end{aligned} \quad (29)$$

Perturbative QCD (pQCD) calculations make definite predictions for all of the angular coefficients, except for low Z $p_T \lesssim 10$ GeV/c, where effects from nonperturbative transverse momentum of the partons within the protons may contribute to the A_2 coefficient [54, 55]. For $pp \rightarrow \gamma^*/Z \rightarrow \ell^+\ell^-X$, the parameters A_0 , A_1 , and A_2 are related to the polarization of the Z boson, whilst A_3 and A_4 are also sensitive to the $V - A$ structure of the couplings of the muons. Perturbatively, at leading-order (LO), all angular coefficients vanish as the Z boson transverse momentum approaches zero except for A_4 , which is the electroweak (EW) parity violation term. As noted above, nonperturbative contributions to A_2 are possible for small Z boson transverse momentum. At next-to-leading-order (NLO), A_0 to A_3 become non-zero, while at next-to-next-to-leading-order (NNLO), the angular coefficients A_5 , A_6 and A_7 become non-zero, but still close to zero. If we integrate over positive and negative rapidity (y), the angular coefficients A_1 and A_3 are small.

1.8.2 Dilution effects

The sign of $\cos\theta$ and $\tan\phi$ are defined with respect to the direction of the quark, which is ambiguous in pp collisions. It is therefore chosen by measuring the longitudinal boost of



the final-state dilepton system in the laboratory frame, and assuming that this is in the same direction as that of the quark in the initial state. This assumption leads to a fraction of events with wrongly assigned quark direction, causing a dilution of the observed angular distributions. The probability of correct quark direction assignment increases with the boost of the dilepton system, thus reducing the dilution for dileptons produced at large rapidities. With this assumption, $\cos \theta$ can be written as a function of the lepton momenta in the laboratory frame,

$$\cos \theta = \frac{p_z}{|p_z|} \frac{\ell_+^- \ell_-^+ - \ell_-^- \ell_+^+}{M \sqrt{M^2 + p_T^2}}, \quad (30)$$

and $\tan \phi$ can be written as

$$\tan \phi = \frac{p_z}{|p_z|} \frac{\sqrt{M^2 + p_T^2}}{M} \frac{\vec{\Delta} \cdot \hat{R}_T}{\vec{\Delta} \cdot \hat{p}_T}, \quad (31)$$

Considering direction of quark could be wrongly determined, we defined and used θ_d, ϕ_d in this analysis, which represents θ and ϕ angle in CS frame with dilution effects. When quark carries larger momentum than anti-quark, the direction of quark is along Z boosted direction, θ_d is equal to θ , and ϕ_d equal to ϕ . While, for the reversed case, θ_d is equal to $\pi - \theta$, and ϕ_d is equal to $\pi - \phi$. Therefore, the terms with θ and ϕ in Equation 29 are affected by the dilution. For events with wrongly determined quark direction, corresponding θ terms can be modified as:

$$\begin{aligned} \sin \theta_d &= \sin(\pi - \theta) = \sin \theta, \\ \cos \theta_d &= \cos(\pi - \theta) = -\cos \theta, \\ \sin^2 \theta_d &= \sin^2(\pi - \theta) = \sin^2 \theta, \\ \cos^2 \theta_d &= \cos^2(\pi - \theta) = \cos^2 \theta, \\ \sin 2\theta_d &= \sin 2(\pi - \theta) = -\sin 2\theta, \end{aligned} \quad (32)$$

which indicates the A_1, A_4 , and A_6 are affected by the $\cos \theta$ dilution effect. For ϕ terms in the formula can be modified as:

$$\begin{aligned} \sin \phi_d &= \sin(\pi - \phi) = \sin \phi, \\ \cos \phi_d &= \cos(\pi - \phi) = -\cos \phi, \\ \sin 2\phi_d &= \sin 2(\pi - \phi) = -\sin 2\phi, \\ \cos 2\phi_d &= \cos 2(\pi - \phi) = \cos 2\phi, \end{aligned} \quad (33)$$

which indicates the A_1, A_3 , and A_5 are affected by the ϕ dilution effect.

The dilution factor, f , is defined as the fraction of $Z \rightarrow \ell^+ \ell^-$ events with quark direction wrongly determined, which can be estimated from generator, and depends on the input PDFs. In



the LHC, as a pp collider, θ_d and ϕ_d are the observables in reality, instead of θ and ϕ . Take the dilution effects into account, the Equation 29 can be rewritten as

$$\begin{aligned} \frac{d\sigma}{d\cos\theta_d d\phi_d} &= f \times \frac{d\sigma}{d\cos\theta d\phi} \Big|_{\theta=\pi-\theta_d}^{\phi=\pi-\phi_d} + (1-f) \times \frac{d\sigma}{d\cos\theta d\phi} \Big|_{\theta=\theta_d}^{\phi=\phi_d} \\ &\propto (1 + \cos^2\theta_d) \\ &\quad + \frac{1}{2}A_0(1 - 3\cos^2\theta_d) + A_1 \sin 2\theta_d \cos \phi_d \\ &\quad + \frac{1}{2}A_2 \sin^2\theta_d \cos 2\phi_d + (1-2f)A_3 \sin \theta_d \cos \phi_d \\ &\quad + (1-2f)A_4 \cos \theta_d + (1-2f)A_5 \sin^2\theta_d \sin 2\phi_d \\ &\quad + (1-2f)A_6 \sin 2\theta_d \sin \phi_d + A_7 \sin \theta_d \sin \phi_d. \end{aligned} \quad (34)$$

In reality, the A_i parameters extracted from $\cos\theta_d$ and ϕ_d distribution are named as A'_i , with $A'_0 = A_0$, $A'_1 = A_1$, $A'_2 = A_2$, $A'_3 = (1-2f)A_3$, $A'_4 = (1-2f)A_4$, $A'_5 = (1-2f)A_5$, $A'_6 = (1-2f)A_6$, and $A'_7 = A_7$, where A_i is the angular coefficient in BORN level, A'_i is coefficient with dilution effects, and f is the average dilution in specific phase-space.

As expected, a data sample with a large dilution factor f does not have good sensitivity on the A_i measurement. With $f = 0.5$, the data sample cannot be used to extract A_3 , A_4 , A_5 , and A_6 . The LHCb is a forward detector, the collected Z events are highly boosted. Therefore, the dilution effect is smaller than that of ATLAS and CMS. The dilution can be determined from the generator level events, the estimated dilution $(1-2f)$ and purity $(1-f)$ are shown in Figure 10. In the LHCb fiducial region, the average purity is determined to be 0.842 ± 0.002 , while the average dilution factor is determined to 0.686 ± 0.004 .

The dilution is one of important elements in angular coefficient measurement at the LHCb, which should be considered in the A_i measurement. In this analysis, the measured results has include the dilution effects. If we want to get A_i in the BORN level, then it can be calculated by dividing the measured A'_i with dilution efficiency. But since dilution efficiency has strong dependents on the input PDFs, we will not report the BORN level results, instead both data and theoretical predictions are presented with dilution effects.

1.8.3 The Lam-Tung relation

For the $q\bar{q} \rightarrow \gamma^*/Z g$ annihilation process, pQCD in LO predicts that the angular coefficients A_0 and A_2 are equal, independent on Parton Distribution Functions (PDFs), and are described by $A_0^{q\bar{q}} = A_2^{q\bar{q}} = \frac{p_T^2}{M_{\ell\ell}^2 + p_T^2}$ [56–59].

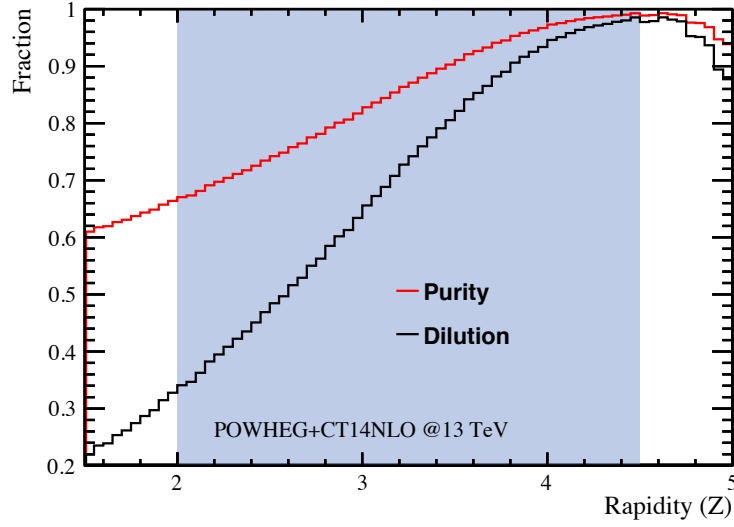


Figure 10: The purity ($1 - f$) of quark direction is correct in the CS frame, and the dilution efficiency ($1 - 2f$), estimated using Powheg generator with CT14NLO PDFs, as a function of Z boson rapidity in LHCb detection region.

For the $qg \rightarrow \gamma^*/Z q$ Compton process, A_0 and A_2 depend on PDFs and rapidity. However, in pQCD at LO, when averaged over y , A_0 and A_2 are approximately described by $A_0^{gq} = A_2^{qg} \approx \frac{5p_T^2}{M_{\ell\ell}^2 + 5p_T^2}$ [60].

The equality $A_0 = A_2$ [61] is known as the Lam-Tung relation. At LO, it is valid for both $q\bar{q}$ and gq processes. Fixed order pQCD calculations in next to leading order (NLO), as well as QCD resummation calculations to all orders [62] indicate that violations of the Lam-Tung relation are small. The Lam-Tung relation is only valid for vector (spin=1) gluons. It is badly broken for scalar (spin=0) gluons [63]. Therefore confirmation of the Lam-Tung relation is a fundamental test of the vector gluon nature of QCD and is equivalent to a measurement of the spin of the gluon.

1.8.4 The Boer-Mulders function

In the past decades, study of the transverse momentum dependent (TMD) parton distribution functions of the nucleon is one of hottest topics in the high energy physics, as it provides new perspectives on the hadron structure and QCD [64]. There are two types of TMD distribution functions, as the Sivers function [65] and the Boer-Mulders function [64].

The Sivers function, $f_{1T}^\perp(x, k_\perp^2)$, where x is the fraction of proton's momentum carried by the



quark, $k_{\perp}$ is the transverse momentum of the quark. The Sivers function is used to represent the correlation between $k_{\perp}$ and the transverse spin of the nucleon, $S_{\perp}$. It is time-reversal odd (T -odd) and can arise from initial- or final-state interactions. Measurements of the semi-inclusive deep-inelastic scattering (SIDIS) from the HERMES [66] and COMPASS [67] collaborations have shown clear evidence for the presence of the T -odd Sivers functions, and the magnitude and flavor structure of the Sivers functions are determined accordingly [68, 69].

The Boer-Mulders function [54, 64] is another the T -odd TMD function, $h_1^{\perp}(x, k_{\perp}^2)$, which signifies the correlation between $k_{\perp}$ and the quark transverse spin, $s_{\perp}$, in an unpolarized nucleon. It is the chiral-odd analog of the Sivers function and also owes its existence to the presence of initial/final state interactions [70]. As the Sivers function is beginning to be quantitatively determined from the SIDIS experiments, the Boer-Mulders function is still unexplored.

The Boer-Mulders functions can be extracted [71] from the azimuthal angular distributions in the unpolarized Drell-Yan process. As shown in Equation 29, the $\cos 2\phi$ term (A_2) is proportional to the convolution of the quark and antiquark Boer-Mulders functions in the projectile and target [71]. As the Drell-Yan cross section depends on the transverse spins of the initial-state quark and antiquark, a correlation between the transverse spin and the transverse momentum of the quark, as represented by the Boer-Mulders function, would affects the angular distributions of final-state leptons.

Unlike pion-induced Drell-Yan or semi-inclusive DIS, in the Drell-Yan production of pp collision in the forward region, the event has one quark with relatively large- x value annihilating with a sea quark with relatively small- x . It is a convolution of two Boer-Mulders distributions, and the Boer-Mulders distribution for small- x sea quarks remains completely unconstrained, which could be a small effects, but also could lead to significant impacts to the LHCb data. Therefore, it would be interesting to constraint Boer-Mulders function by measuring A_2 with the events in lower Z p_T region ($p_T^Z < 10 \text{ GeV}$), and lower dimuon invariant mass region ($50 < M_{\mu^+\mu^-} < 70 \text{ GeV}$).

1.8.5 The weak mixing angle

$A_4 \cos \theta$ term is parity violating, and is due to the interference of the amplitudes of the vector and axial-vector currents. Its presence induces an asymmetry to the ϕ -integrated $\cos \theta$ cross section. Two sources contribute: the interference between the Z -boson vector and axial-vector amplitudes, and the interference between the photon vector and Z -boson axial-vector amplitudes.



The asymmetric component from the $\gamma^* - Z$ interference cross section is proportional to g_A^f . The asymmetric component from Z -boson self-interference is proportional to a product of g_V^f from the lepton and quark vertices, and thus is related to the weak mixing angle ($\sin \theta_W$). g_A^f and g_V^f are the couplings of Z boson interact with vector and axial-vector current components.

The forward-backward charge asymmetry of Z boson events are used to measure the weak mixing angle, and is defined as:

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}, \quad (35)$$

where σ_F (σ_B) is the integrated cross section for events with $\cos \theta > 0$ ($\cos \theta < 0$). In addition, the relationship between A_{FB} and A_4 can be write as:

$$A_{FB}(M) = \frac{3}{8}A_4(M) \quad (36)$$

However, in this analysis, we are focus on testing of QCD calculation on A_4 parameter, will not measure the weak mixing angle. Also, there is a ongoing analysis aiming to extract this angle, using the LHCb RunII dataset.

1.8.6 Previous studies

The CDF Collaboration at the Tevatron published a measurement [72] of the angular coefficients of lepton pairs produced near the Z -boson mass pole, using 2.1 fb^{-1} of $p\bar{p}$ collision data at a centre-of-mass energy $\sqrt{s} = 1.96 \text{ TeV}$. These measurements were later used by CDF [73] to infer an indirect measurement of $\sin \theta_W$, or equivalently, the W -boson mass in the on-shell scheme, from the average A_4 coefficient. Measurements of the W -boson angular coefficients at the LHC were published by both ATLAS [74] and CMS [75] Collaborations. Later, a measurement of the Z -boson angular coefficients with $Z \rightarrow \mu^+\mu^-$ decays was published by CMS [76] Collaboration, which is the first five coefficients were measured with 19.7 fb^{-1} of pp collision data at $\sqrt{s} = 8 \text{ TeV}$. The measurement was performed in two y_Z bins, $0 < |y_Z| < 1$ and $1 < |y_Z| < 2.1$, each with eight bins in p_T^Z up to 300 GeV . The violation of the Lam–Tung relation was observed, as predicted by QCD calculations beyond NLO. Then, the ATLAS collaboration [53] polished a measurement of these coefficients, for the complete set of angular coefficients A_0 to A_7 .

1.8.7 Strategy

The data samples used in this analysis and event selection for the $Z \rightarrow \mu^+\mu^-$ candidates are discussed at first, followed by detailed background studies. Then after several corrections



applied to remove detector effects, the angular coefficients measurements are performed. The angular coefficients, A_0 , A_1 , A_2 , A_3 , A_4 , and $A_0 - A_2$ are measured, as a function of Z boson p_T and rapidity y . Due to the A_4 is relative to the A_{fb} , the A_4 measurement will not show the absolute measured values, instead of a ratio of measured results to the A_4 value in the first Z p_T bin. It is the first test of the Lam-Tung relation in the forward detector region, and for the first time provides information to constrain the Boer-Mulders function at the LHC.

In the extraction of results, the measured A_i values are corrected to the Born level (without FSR effects), not the Bare level (with FSR effects), as the Equation 29 and 34 only valid in the Born level. Events in different invariant mass range are used in this study, as the lower Z mass region ($50-75 \text{ GeV}/c^2$) and the central Z mass region ($75-105 \text{ GeV}/c^2$). The lower mass region is used to study the Boer-Mulders function, with less contribution from the Z pole events. While the central mass region is used to extract the A_i values, with small contributions from the Drell-Yan process and interference between Drell-Yan process and Z events.

For the Z boson events, non-zero p_T comes from the QCD effects. Therefore, the measured A_i observables as a function of Z boson p_T , with other phase-spaces been integrated out, could probe corresponding QCD calculations. In principle, the measured A_i results as a function of Z boson rapidity, with p_T information been integrated out, should not affected by the QCD effects. However, in reality the LHCb detector only cover very forward detector region, the integration of Z boson p_T is not performed for the full phase-space, resulting A_i measurements as a function of Z rapidity becomes very interesting. As it can be used to test the Z p_T resummation effects.



2 The LHCb Detector

The data used to make measurements in this thesis all were collected by the Large Hadron Collider beauty experiment (LHCb), a fundamental particle detector housed on the Large Hadron Collider (LHC) ring. This chapter describes both the LHC and LHCb.

2.1 LHC

The LHC is a two-ring super-conducting proton-proton collider, the most powerful and energetic particle accelerator in the world. The LHC is a colliding beam facility; particle beams are accelerated to velocities close to the speed of light in a circular ring, whose circumference is 27 km, before being brought into collision at various interaction points on the ring.

Four main experiments are installed along the LHC ring for different physics purposes. Two general purpose experiment, ATLAS and CMS, have been designed to discover the Higgs boson and search for new physics directly. The LHCb is a dedicated heavy flavor physics experiment, whose primary goals are to perform precise CKM measurements and to search for new physics in CP symmetry violation and rare decays via processes involving loops. The ALICE is optimized for heavy-ion physics to study the physics of strongly interacting matter at extreme energy densities.

When the LHC was commissioned, one of the main goals was to look for experimental confirmation of a mechanism to explain electroweak boson masses, as well as fermion masses. One such mechanism involves the existence of a hitherto unknown, massive, scalar particle, the so-called Higgs boson. Collision experiments involving hadrons can be used to produce Higgs bosons via gluon fusion, vector boson fusion. The discovery of the Higgs boson was announced during the first LHC run period (RunI). The achievement of this primary objective has ensured that the LHC project will be forever considered a success. The LHC continues to test the SM to its limits, and indeed look for evidence of new physics beyond the SM (BSM).

LHCb is an experiment designed to precisely test the SM and to search for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons. The SM is a very successful theory, which explains almost all experimental observations. The only source of CP violation in the SM is the CKM mechanism. However, it is believed to be insufficient to explain the observed baryon asymmetry in the universe. New sources of CP violation are needed. Numerous new physics models produce additional contributions to CP violation and permit decay modes, which are forbidden or highly suppressed in the SM. Precise measurements of the CP

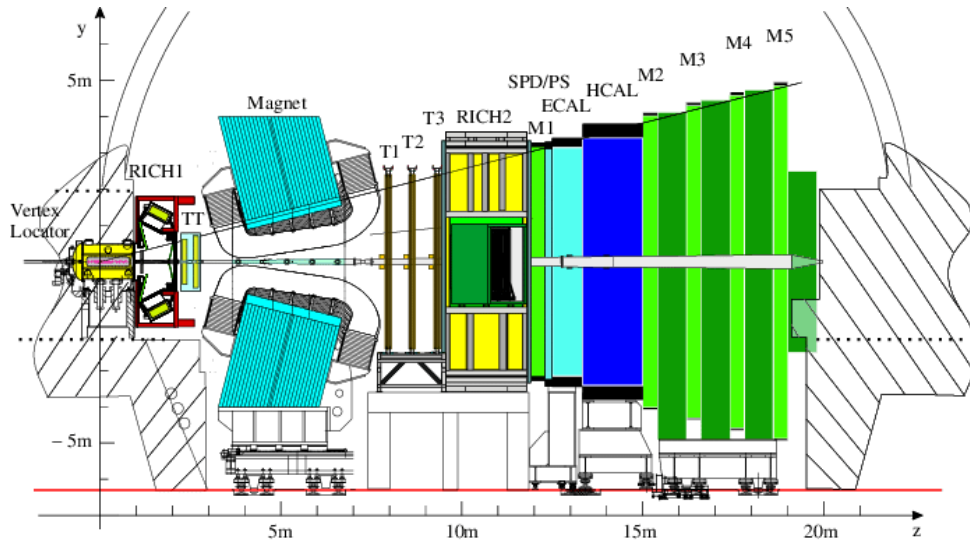


Figure 11: Side view of the LHCb detector from inside of the LHC machine loop. Image from [77]

violation parameters and the search for rare decays can potentially unveil new physics. Physical processes involving b quarks are theoretically cleaner in the SM, which makes the separation of the SM and new physics easier. Therefore it is an ideal place for the new physics search at LHC energies. With the large samples of beauty hadrons and an optimized detector, LHCb is able to determine the SM parameters to an unprecedented precision.

2.2 The LHCb Detector

LHCb is an experiment designed to precisely test the SM and to search for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons. The SM is a very successful theory, which explains almost all experimental observations. The only source of CP violation in the SM is the CKM mechanism. However, it is believed to be insufficient to explain the observed baryon asymmetry in the universe. New sources of CP violation are needed. Numerous new physics models produce additional contributions to CP violation and permit decay modes, which are forbidden or highly suppressed in the SM. Precise measurements of the CP violation parameters and the search for rare decays can potentially unveil new physics. Physical processes involving b quarks are theoretically cleaner in the SM, which makes the separation of the SM and new physics easier. Therefore it is an ideal place for the new physics search at LHC energies. LHCb profits from large cross-sections for $b\bar{b}$ ($288 \pm 4(\text{stat.}) \pm 48(\text{syst.}) \text{ mb}$). With the large samples of beauty hadrons and an optimized detector, LHCb is able to determine the



SM parameters to an unprecedented precision. To primarily reconstruct B-mesons that decay in the forward region, the LHCb detector is designed as a single arm spectrometer with a forward angular acceptance of 10 mrad to 250 mrad vertically and 10 mrad to 300 mrad horizontally. Covering only 4% of the full solid angle, LHCb collects 27% of b or c hadrons.

Since B-mesons are relatively long-lived, their experimental signature is a decay vertex that is significantly displaced from the primary interaction vertex. Reconstruction of these secondary decay vertices is best achieved in a low occupancy environment.

Figure 11 is a side-view of the LHCb detector; the beam pipe (grey) passes through the middle of the detector, and most of the detector instrumentation/material (coloured) is located after the magnet. A precise tracking system, an efficient particle identification (PID) system and a flexible trigger system are essential for precise measurements of heavy flavor physics. At LHCb The particle tracking system consists of the Vertex Locator (VELO), Tracker Turicensis (TT), magnet and T-stations (T1, T2, T3). The calorimeter system consists of the Scintillating Pad Detector (SPD), Pre-Shower detector (PS), the Electromagnetic Calorimeter (ECAL) and the Hadronic Calorimeter (HCAL). The particle identification system consists of the Ring Imaging Cherenkov detectors (RICH) and the muon system (M1-M5). These components are explained in more detail in the following sections.

2.3 Tracking system

The path of any particle created in a pp collision at LHCb, which is stable on the time-scale of the detector and is within its acceptance, is tracked by a combination of a vertex locator, a series of tracking stations and a dipole magnet. Each particle leaves behind different signatures in all or some of these sub-detectors with the magnet's field causing certain tracks to bend if they originate from electrically charged particles. Then through use of a Kalman Filter process, these detector hits are iteratively group together to determine the likely trajectory of many particle as possible. Each track is also given a χ^2 per degree of freedom ($\chi^2_{\text{vtx}}/\text{ndf}$) to determine the quality of the reconstructed track. The combined tracking system must be able to reconstruct the trajectory of particles and their associated points of decay with high spatial resolution, such that the momenta of tracks can be determined to great accuracy. With the knowledge of these track trajectories and points of decays at hand, full decay chains of particles of interest can be assembled and decay topologies understood. This makes the tracking system fundamental to all physics analyses at LHCb.



2.3.1 Vertex Locator

The VELO provides information to reconstruct primary vertices and displaced secondary vertices, which provide a signature of heavy flavor decays, and is therefore an important part of the LHCb tracking system. It is a silicon micro-strip detector capable of precise tracking near the LHCb pp interaction point. The VELO gathers information from electronic hits in its micro-strips to reconstruct the trajectories of particles. Primarily, the VELO is used to distinguish between locations where pp interactions occur in bunch crossings, known as the Primary Vertices (PVs), and points in space where long-lived hadrons decay, which are referred to as Displaced Vertices (DVs). The number of PVs from a single bunch crossing is kept relatively low at LHCb through the process of luminosity leveling. The active region of the VELO is large enough to reconstruct the majority of heavy-flavoured hadrons, which typically travel a few mm to a few cm from a PV. Combining the momentum measurements made by the downstream tracking stations with knowledge of the positions of the PVs and DVs in an event, then the time before a particle decays, its decay time, can be determined by LHCb. An event is defined as the complete detector readout for a proton bunch crossing. Due to the short Flight Distance (FD) of the particles of interest to LHCb and their close proximity to the beam line, it is important that the VELO is situated as close to the pp collisions as possible to minimise the extrapolation distance between the first hit of a reconstructed track and the interaction point. However, if the VELO is too close to the beam line then it will incur radiation damage. For this reason, the VELO is constructed as two structures with the ability to separate from one another. During the beam injection from the SPS to the LHC, the VELO is retracted to 29 mm away from the beam into two composite halves, one either side of the LHC beam pipe. When the beams are declared stable during a physics fill, the halves are carefully brought together by a mechanical system that leaves the halves overlapping slightly such that the pp interaction point is fully enclosed. At this point the VELO is centred around the beam-line and is ready for data taking. When fully closed, the VELO has a 7 mm aperture in the through without interacting with and damaging the silicon-strips. The closest active region of the micro-strips then begins 8.2 mm from the beam line. At these close proximity, the VELO material is still inside the radius nominally covered by the LHC pipe. Therefore, to maintain a good vacuum within the beam pipe, to shield against electromagnetic activity from the beams and to provide a continuous path for the mirror currents of the beam through the VELO, the micro-strip detectors are mounted within a structure covered by aluminium foil, known as the Radio Frequency box (RF-box). On the side of the RF-box that is facing the beam, the foil is slighter



thinner at only $300\ \mu\text{m}$ to minimise the amount of material the tracks see but is still thick enough to separate RF-box from the beam vacuum. As a result, a vacuum pressure of approximately 10^{-7} mbar is achieved inside the VELO.

The VELO halves both contain twenty-one identical detector modules positioned along the beam line in each half. The temperature of the modules are maintained below zero degrees by a bi-phase cooling system. Each module contains two semi-circular shaped sensors composed of $300\ \mu\text{m}$ thick silicon wafer with implanted aluminium micro-strips. The sensors measure the radial coordinate, R , and the azimuthal angle coordinate, Φ , of the tracks of particles passing the VELO. The z -coordinate is determined from what module along the beam line registered the hit. As shown in Figure 12, the VELO modules are packed more closely together near the interaction region; this is to give an improved PV resolution. Each time the VELO is closed the alignment of the R sensor is required to have an accuracy smaller than $100\ \mu\text{m}$ relative to the other half of the detector. In Run II, the alignment is checked at the end of every Fill, while in Run I the alignment was updated a few times during the year. A schematic of the R and Φ sensors is shown in Figure 13 for one VELO module. The pitch, the distance between the sensor strips, increases further from the beam line, starting at around $40\ \mu\text{m}$ and going up to roughly $100\ \mu\text{m}$. In total, each sensor has 2048 readout channels.

The VELO can also determine the Impact Parameter (IP) of track. The IP quantity is the distance of closest approach with respect to a reconstructed PV. The increase in pitch ensures that the measurements along the track contribute to the precision of the IP value approximately equally. An associated quantity of the IP variable, the χ^2_{IP} of a track, helps determine the likely PV from which a particle originated. The χ^2_{IP} is defined as the difference in χ^2_{IP} of a given PV reconstructed with and without the considered track. Decays of heavy-flavoured hadrons generally have larger FD and IP values than the decays of light hadrons at LHCb. This makes the FD and IP quantities particularly useful for separating these two different classes of decays in an event. The performance of the VELO can be quantified by its excellent IP resolution, which was found to be less than $35\ \mu\text{m}$ for particles with transverse momentum (p_T) greater than 1 GeV for 2012 data. The same data set showed that for a typical pp event, the vertex resolution was between 10 and $20\ \mu\text{m}$. This accuracy means LHCb is more precise at locating vertex objects than any other LHC experiment thanks to the VELO. In the left plot of Figure 14, the IP resolution in the x and y directions are given as a function of the momentum of a track. The right plot of Figure 14 shows the dependency of the IP resolution projected in the x -axis, on the inverse of a track's transverse momentum.

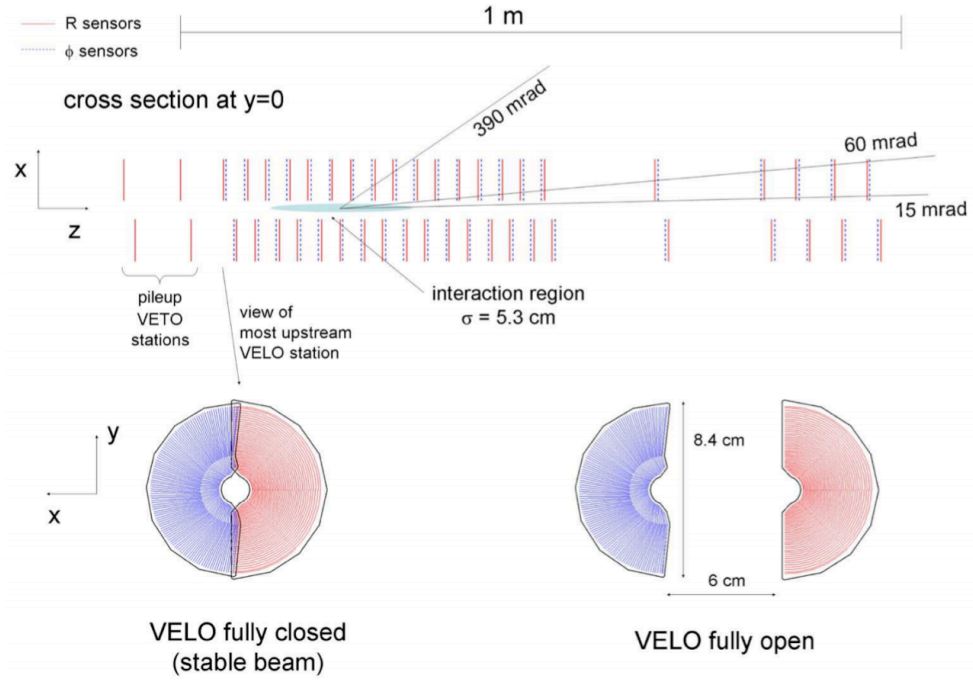


Figure 12: An overview of the layout of the VELO modules with the R sensors (red) and Φ sensors (blue), reproduced from [78]

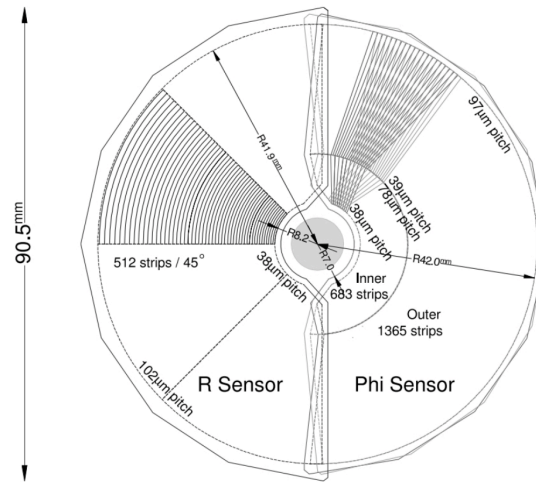


Figure 13: The layout of the silicon micro-strips on the R and Φ sensors of a singular VELO module, reproduced from [78].

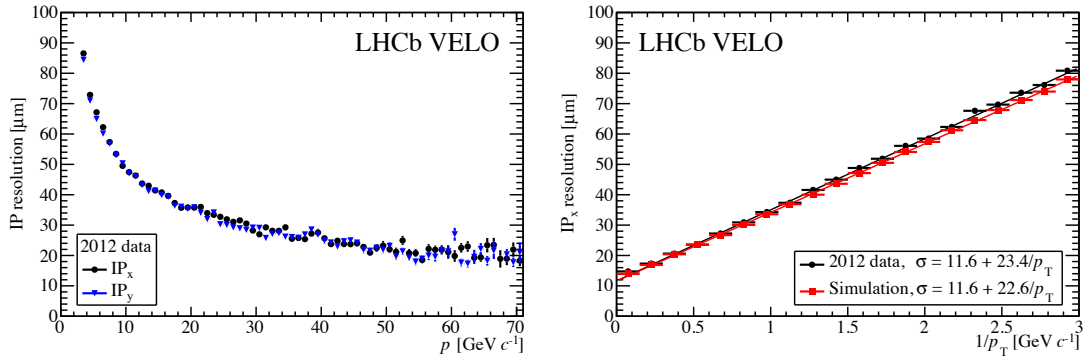


Figure 14: (Left) The IP resolution, in μm , as a function of the momentum of a track, in GeV . (Right) The IP_x resolution, in μm , as a function of the inverse of the momentum of a track, in GeV , for 2012 data (black) and simulated pp events (red), plots are from [79].

2.3.2 Tracking Detectors

Assisting the VELO subdetector in tracking particles through LHCb are a further four planar detectors; the Tracker Turicensis (TT) and three tracking stations (T1-T3). The high levels of radiation close to the beam line means the TT and the inner regions of T1-T3 are built of radiation-hard silicon strips. They are thus collectively known as the Silicon Trackers (ST). The ST have a high granularity to keep hit occupancy at a low enough level to allow for effective track reconstruction. The outer regions of T1-T3, relative to the beam line, are referred to as the Outer Tracker (OT). The OT is situated in a region of the detector that is subject to a lower number of particles per unit area compared to the ST. The lower particle flux means the OT is set up as a drift-time detector with cost-effective gas filled straw tubes. Despite their different locations and constructions, the ST and OT ultimately both serve the same purpose - to measure the trajectories of charged particles such that their momenta can be measured. The TT is a silicon detector located between the RICH1 detector and the dipole magnet and performs fast momentum measurements for trigger decision using residual magnetic field. It consists of four rectangular detection layers, which are approximately 150 cm in width and 130 cm in height to cover the full LHCb acceptance. The layout of the third TT detection layer is shown in Figure 15. The four layers are settled in the sequence of $x-u-v-x$ with strips in the x layers arranged vertically, while strips in the u and v layers rotated $+5^\circ$ and -5° , respectively. The reason for this arrangement is that it maximises the resolution in the x -direction, which is the direction responsible for the momentum resolution; the resolution in the y -direction is only needed for pattern recognition and is less critical. This angled orientation of the layers leads to an excellent single-hit spatial

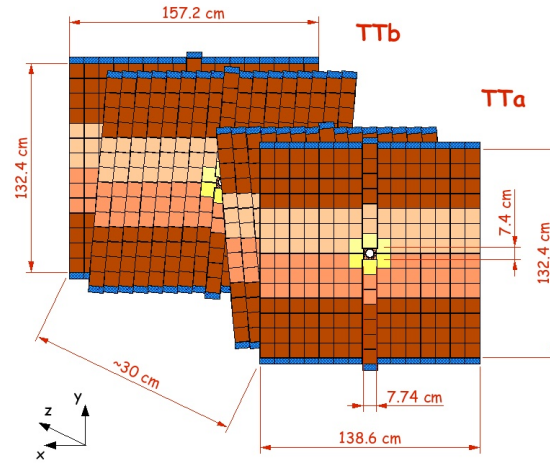


Figure 15: The layout and dimensions of the four detection layers of the Tracker Turicensis subdetector, reproduced from [80]

resolution of $50\mu\text{m}$. The detection layers are separated by approximately 30 cm in the z-axis and each TT sensor carries 512 readout strips. To facilitate tracking finding, the four layers are divided into two groups, (x, u) and (v, x) . The detector layer consists of two half modules, an upper half and a lower half, each comprised of a row of seven silicon sensors organized into two or three readout sectors depending on their position relative to the beam pipe. The organization of a half module close to the beam pipe is shown in Figure 16.

The performance of the tracking system at LHCb was evaluated during Run I. The track hit efficiency of the ST was measured using a pure sample of $J/\psi \rightarrow \mu^+\mu^-$ decays. The muon tracks must pass some basic kinematic requirements and need to have a momentum greater than 10 GeV to reduce multiple scattering. The hit efficiency is defined as the ratio of the number of hits found against the number of hits expected, for a given sector of the tracking system. For the TT, this efficiency was measured to be greater than 99.7% (99.8%) in 2011 (2012) data. Similarly, T1-T3 also had a very high hit efficiency of 99.8% (99.9%) according to 2011 (2012) data. The performance of the tracking system can also be evaluated in terms of its hit resolution. The resolution is determined using data from the unbiased residuals of the measured hit position and the extrapolated track position when the hit is removed from the fit.

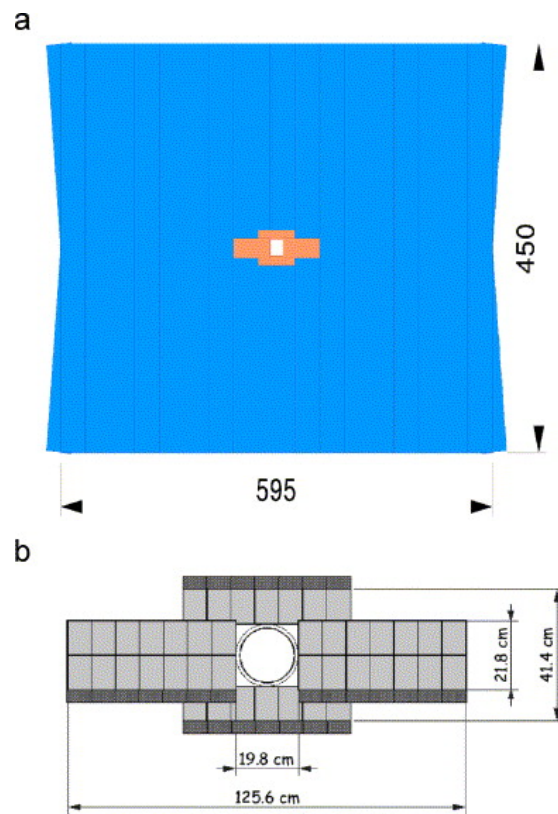


Figure 16: The layout of one of the three tracking stations. The center region is covered by a silicon strip detector, (right) which is surrounding the beam pipe. The outer region (left) is covered by a straw tube detector (the dimensions are given in cm).



2.3.3 Spectrometer Magnet

The LHCb tracking system exploits a dipole magnet to bend the tracks of charged particles. The curvature of the tracks and precision knowledge of the magnet's field at all points allows the particle's momentum to be determined. Thanks to the magnet and the rest of the tracking system, the relative uncertainty on the momentum resolution varies from 0.5% at low momentum to 1.0% at 200 GeV.

The magnet is situated immediately after the TT as shown in Figure 11. The centre of the magnet is 5.3mm from the pp interaction point, along the z-axis. It is composed of a 1,500 ton iron yoke and two conical saddle shaped coils located above and below the beam line. The coils are made of aluminum and weigh in at around 27 tonnes. A schematic diagram of the magnet, showing its design, is given in Figure 17. This is a warm magnet capable of producing an integrated magnetic field strength of approximately 4Tm between the interaction point and the tracking stations, with the principal field component directed along the y-axis.

A precise knowledge of the magnetic field is required to ensure a good momentum resolution can be achieved. This is particularly important for the LHCb detector, since its tracking stations are fairly spaced apart compared to other high energy physics experiments. The integrated field was measured using an array of Hall probes and is found to give a very high relative precision of 4×10^{-4} across the measured volume. Data is collected at LHCb for both *MagUp* (field pointing in +y direction) and *MagDown* (field pointing in -y direction) configurations for an approximately equal amount of time during data taking to cancel out potential asymmetry effects caused by the magnetic field. For instance, the performance of the drift tubes in the OT are very sensitive to the direction of the magnetic field. This detector effect could be misinterpreted as signs of CP-violation if not treated correctly. However, the polarity of the magnet is only flipped a few times per year of data taking so not to damage the magnet.

2.3.4 Track finding algorithm

Charged particles produce signal in one or more of the tracking sub-detectors. Depending on the path through which the charged particle traverses the detector, the following classes of tracks are defined, as illustrated in Figure 18.

- Long tracks: pass through the complete tracking system, from the VELO to T stations. They have the highest reconstruction quality and are the most important tracks for physics analysis.

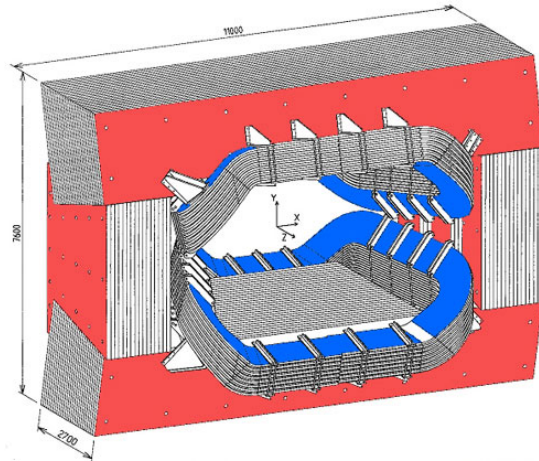


Figure 17: A perspective view of the magnet with dimensions given in units of mm and electrical connections and water cooling system also shown, reproduced from [78].

- Upstream tracks: traverse only the VELO and the TT. They are usually low momentum tracks swept out of the detector acceptance by the magnetic field, and have relatively poor momentum resolution. However, they can be used to understand the background in the RICH PID algorithm since they pass through RICH1 and may generate Cherenkov photons if having large enough momentum. They can also be used for flavor tagging and b-hadron decay reconstruction.
- Downstream tracks: pass through the TT and the T stations. Typically they are daughters of long-lived particles, such as K_S^0 or Λ .
- VELO tracks: leave hits solely in the VELO, and have large angles with respect to the beam axis or move backward. They can be used to reconstruct primary vertices and veto non-exclusive events.
- T tracks: only leave hits in the T stations. They help to perform RICH2 global pattern recognition.

The reconstruction procedure begins with a search of track seeds in the VELO, where the magnetic field is sufficiently low and tracks can be considered as straight lines. The seeds are also searched in the T stations. The VELO seeds are extrapolated to the TT and T stations to form long tracks. This algorithm, called forward tracking, already find a large fraction of long tracks. The hits used by forward tracking are removed from further track finding to save computing time.

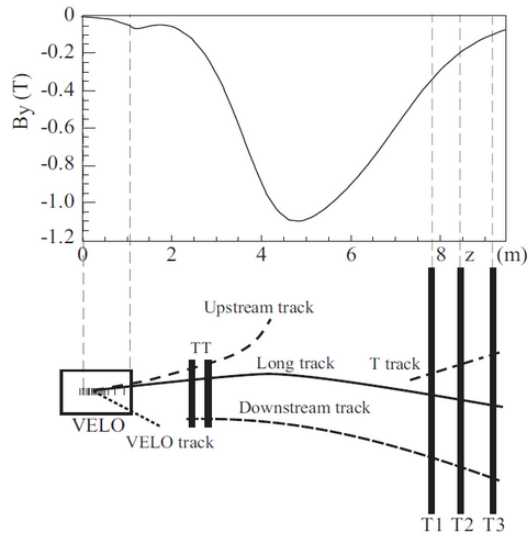


Figure 18: Illustration of the LHCb track types. For reference the y component of the magnetic field is also plotted.

To increase track finding efficiency for long tracks, a second algorithm called track matching is performed. T seeds are matched to the VELO seeds left from the forward tracking using the Kalman filter[74]. VELO seeds not used by the forward tracking or track matching are extrapolated to TT stations to form upstream tracks. Downstream tracks are reconstructed by adding the TT hits to the T seeds. The VELO and T seeds that have not been used for a long, upstream or downstream track are classified as a VELO or T track.

2.3.5 Track finding efficiency and momentum resolution

The track finding efficiency is measured using a data-driven method called ‘tag-and-probe’. This method employs two-body decays with one daughter particle, the ‘tag’ leg, reconstructed using the full detector information, while the other daughter particle, the ‘probe’ leg, reconstructed only using information from part of sub-detectors. The information carried by the tag leg and the probe leg is sufficient to reconstruct the mother particle, thus the number of mother particles can be obtained from fit. The probe leg is then matched to fully reconstructed tracks, and the number of the mother particle after matching can again be obtained. The track finding efficiency is defined as the ratio of the number of mother particles after and before matching.



2.4 Particle Identification

To determine what tracks pass through the detector to an outstanding level of accuracy, a combination of two Cherenkov radiation detectors, a calorimeter system and a set of muon chambers are used in LHCb.

2.4.1 Ring Imaging Cherenkov Detectors

Two Ring Imaging Cherenkov detectors (RICH-1 and RICH-2) contribute towards efficient particle identification (PID) at LHCb. PID refers to the determination of the species of a track reconstructed in the detector, namely e , μ , π , K and p in the case of the RICH subdetectors. The RICH systems offer the best means of identifying charged hadrons at LHCb but the calorimeter and muon systems provide complimentary information, which further enhance PID capabilities of LHCb. Information from RICH-1 and RICH-2 ultimately help reduce the chances of wrongly misidentifying decays as ones of interest in any particular analysis. The RICH subdetectors exploit the phenomenon of Cherenkov radiation to extract PID information. This situation occurs when a charged particle traveling through a dielectric material emits a cone of coherent light if its velocity is greater than the phase velocity of light in the dielectric. The opening angle, θ_c , of this light cone is dependent on the particle's velocity according to

$$\cos\theta_c = \frac{1}{n\beta} \quad (37)$$

where n is the refractive index of the dielectric material that the particle passes through and β is the ratio of the particle's velocity to the speed of light in a vacuum, v/c . The value of θ_c is relative to the inducing particle's trajectory. By making use of some basic relativistic kinematics, Equation 37 can be rearranged in terms of the mass and momentum of the particle inducing the Cherenkov radiation as

$$\cos\theta_c = \frac{1}{n} \sqrt{1 + \left(\frac{mc}{p}\right)^2} \quad (38)$$

In essence, this means that if the momentum of the particle can be measured, along with the Cherenkov angle of its emitted light cone, then the rest mass of the particle can be inferred. Figure 20 shows the dependence of θ_c on the momentum of a particle for different species of particles. RICH-1 is located between the VELO and the TT. It covers the full angular acceptance of the LHCb, 25 mrad to 300 (250) mrad in the horizontal (vertical) plane and is designed to perform PID for tracks with momentum between 1 and 60 GeV. RICH-1 is divided into two

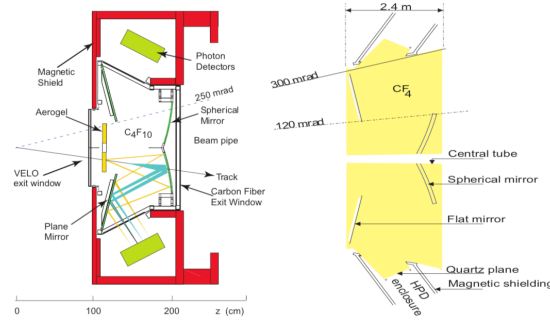


Figure 19: Schematic of the RICH-1 (left) and RICH-2 (right) sub-detectors at LHCb. Plots are from [78].

halves set above and below the beam pipe, which are referred to as the 'Up' and 'Down' sections. RICH-2 is positioned between the magnet and the T3 tracking plane. It provides PID for higher momentum tracks which are between 15 to 100 GeV. Since high momentum tracks are not swept out to wide angles by the magnetic field, they predominantly stay close to the beam line. Therefore, RICH-2 covers a smaller angular region of 15 mrad to 100 (120) mrad in the vertical (horizontal) plane. RICH-2 is also similarly divided into two sections, named 'A' and 'C', and in the horizontal in this case. Section A is closer to the centre of the LHC ring with Section C further away. Figure 19 shows the layout of RICH-1 and RICH-2 in the vertical and horizontal planes, respectively

Every track object with an associated momentum measurement from the tracking system and travelling through the RICH sub-detectors, has its expected θ_c angle calculated under five different mass hypotheses (e, K, μ, π and p) according to Equation 38. The radius of the photon ring corresponding to this expected value of θ_c is then compared to a fit of the detector responses simultaneously. Under each mass hypothesis the log-likelihood of the RICH detector response fit compared to the expected photon ring radius is calculated. However, instead of computing the absolute log-likelihood values, the RICH PID software calculates the difference in log-likelihood (DLL) between the pion hypothesis and each of the four remaining mass hypotheses, x , where $x \in e, K, \mu, p$, such that $DLL_x \equiv DLL_x - DLL_\pi$. The choice of pions as the reference hypothesis is somewhat arbitrary and based on the fact they are the most abundantly produced particle at LHCb.

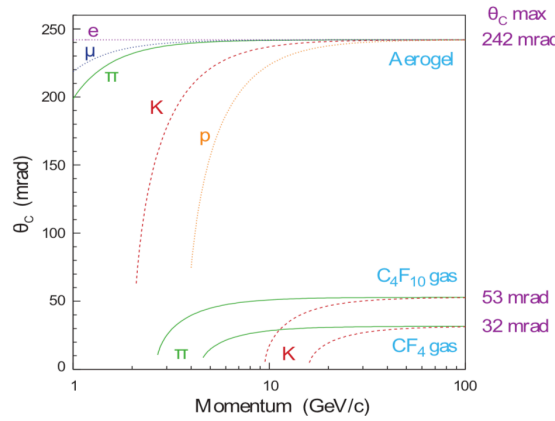


Figure 20: The Cherenkov angle in mrad, of photos produced in the RICH subdetectors by electrons (purple), kaons (red), pion (green) and protons (orange) as a function of particle momentum in GeV. Plots are from [78].

2.4.2 Calorimeter System

Electron and hadron candidates can also be identified by a calorimeter system at LHCb. The purpose of this system is the identification of hadrons, electrons, photons, and the measurement of their energies and positions. The calorimeter system consists of four sub-detectors, the Scintillating Pad Detector (SPD), the Pre-Shower (PS), the Electromagnetic Calorimeter (ECAL) and the Hadronic Calorimeter (HCAL). They also allow particles with high transverse energy to be identified; such energetic particles usually originate from decays of heavy-flavoured particles.

Electrons and positrons moving through dense materials emit photon radiation via bremsstrahlung. If the emitted photon is energetic enough, it may decay into an electron-positron pair, which in turn may radiate due to bremsstrahlung. This cascade effect is called an electromagnetic shower. Electromagnetic calorimeters induce these showers with layers of dense material, such as Pb. The thickness of these materials is usually expressed in interaction lengths, denoted by X_0 , defined as the distance over which the particle is reduced to $1/e$ of its original energy.

The energy loss due to bremsstrahlung is inversely proportional to the mass of the accelerating particle, and is thus relatively large for the lightest particles, i.e. electrons. For heavier particles like muons and hadrons, energy loss due to bremsstrahlung is small compared to energy loss due to interactions with the nuclei in the material. The effect of these interactions with nuclei is to produce secondary hadrons with lower energies, which in turn interact with other nuclei and so on, producing a hadronic shower. Hadronic calorimeters induce these showers with layers of dense material. The thickness of these materials is usually expressed in hadronic



interaction lengths Λ_I , defined as the mean distance that a hadron travels before interacting.

For both electromagnetic and hadronic calorimeters, the dense layers that induce the showers are interwoven with scintillating material. These absorb the energy of ionising particles and re-emit it as light, which gets collected in a photo multiplier tube (PMT). The energy of the collected radiation is roughly proportional to the original energy of the particle.

The ECAL and HCAL are both situated between the first and second muon tracking stations, as shown in Figure 11. The ECAL is used to record the position and energy of particles that interact primarily via the electromagnetic interaction (electrons and photons) while the HCAL serves the equivalent purpose but for hadrons, which interact via the strong force. The HCAL is particularly important for identifying neutral hadrons, since they are not picked up by the tracking stations or identified by the RICH systems. In order to distinguish electrons from hadrons, the ECAL is preceded by a Scintillator Pad Detector (SPD), which identifies charged hadrons and allows neutral ones to be rejected, then a Pre-Shower (PS) detector, which detects electromagnetic showers, and thus identifies electrons only. The information recorded by the calorimeters is particularly important in the hardware stage of LHCb's trigger. In general, all four components of the calorimeter system operate similarly; particles are stopped in flight by metallic materials, which absorb all the energy of incident particles and then produce cascade showers of secondary particles which generate light in the scintillation pads. The photons released by these scintillating pads are then read out by wavelength-shifting (WLS) fibres.

2.5 Muon System

The outermost layers of the LHCb detector are dedicated to muon identification by measuring the position and energy of tracks left by muons. Due to the comparatively large mass of muons, they emit far less energy through the process of Bremsstrahlung radiation compared to the other particles. Muons then typically penetrate the full length of the detector and thus this system is placed furthest from the pp interaction point.

The muon system consists of five rectangular stations (M1-M5) with M1 in front of the SPS/PS and M2-M5 behind the HCAL, as shown in Figure 11. The position of the M1 station before the calorimeter is specifically chosen to enhance the momentum measurement of a muon track, which is useful for muon-specific triggers. Placed between each muon station are 80cm thick iron absorbers, which are used to ensure only high momentum muons, above 6 GeV, reach the final M5 station. The surface area of each station also increases further along the z-axis



to ensure an angular acceptance between 20 (16) mrad and 306 (258) mrad in the horizontal, (vertical) plane, respectively. The M1-M3 muon stations are primarily used for tracking and momentum measurements so they have relatively fine granularity along the x-axis to give good spatial resolution. Instead M4-M5 are much coarser as they are intended for accurate PID.

2.6 Triggering at LHCb

The LHC operates with a pp bunch crossing rate of 40 MHz. Beauty and charm hadrons are produced inside the detector acceptance at rates exceeding 50kHz and 1MHz, respectively. It is too difficult to record each of these interesting interactions, it would sum to an overwhelming amount of data, which is too much for the detector to process and for the storage systems to record. The trigger is developed to reduce the data down to a manageable storage rate by using simple selection criteria. Three level trigger: initial hardware trigger and two-stage high-level trigger is used to achieve this reduction. Firstly, during a physics Fill at LHC, the hardware trigger runs synchronously with the frequency of the pp collisions.

Trigger system operates in a consecutive manner whereby the first software trigger only processes events that pass the hardware trigger and likewise for the second software trigger with respect to the first software trigger. Only events passing all three stages of the trigger are sent to permanent storage where this data is processed further for use in offline physics analyses.

2.6.1 Level-0 trigger

The Level-0 (L0) hardware trigger is required to reduce the retention rate of data down from 40 MHz to 1 MHz after which the software triggers can then apply a more thorough event selection to the remaining data. This essentially means the L0 trigger removes 97% of the inelastic pp interactions at LHCb. It decides what events to retain based on information gathered from a combination of the VELO, calorimeter and muon systems. The L0 trigger only retains events containing tracks that have large transverse energy, ET. The measurement of ET is based on the hadron, electron and photon clusters in the calorimeters. Additionally, L0 only keeps events with pairs of high pT muons, since high ET and pT tracks indicate the likely presence of heavy-flavoured hadrons in an event. Furthermore, the L0 trigger vetoes events that have a large number of tracks, since large track multiplicities worsen reconstruction capabilities at LHCb. All this type of event information is sent to the front-end electronics of a custom built decision unit (L0DU). The L0DU then takes the decision whether to keep the event or not, around 6 μ s after



the associated pp collision took place.

2.6.2 High level trigger

The HLT trigger is implemented on farm of PCs adjacent to the detector. The HLT is divided into two stages called HLT1 and HLT2. During data-taking in 2011, HLT1 processed the L0 rate and used a partial event reconstruction to reduce the rate to 43 kHz. HLT2 then performed a more complete event reconstruction, reducing the rate to 3 kHz.

The first-stage High Level Trigger (HLT1) receives information on the entire detector from events passing the L0 trigger. The software is run on the event filter farm, which is located in the LHCb cavern and is comprised of thousands of computing nodes. Using simple and fast reconstruction algorithms, HLT1 identifies tracks from charged particles passing the VELO and tracking stations to confirm the decisions made by L0. It matches the clusters in the calorimeters or hits in the muon stations to these reconstructed tracks, or identifies clusters as from photons and neutral hadrons if there is no associated tracks. HLT1 reduces the retention rate of events to approximately 30kHz (110kHz) during RunI (II). The remaining events are fed to the second-stage software trigger.

The second-stage High Level Trigger (HLT2) performs an event reconstruction based on all detector information available from the surviving events. With this full reconstruction capability, the HLT2 trigger looks for specific decays of heavy-flavoured hadrons, applying many and different selection algorithms to do so. The algorithms make use of a variety of selection criteria including requirements on PID (only in RunII) and the aforementioned FD and IP variables of a decay. HLT2 also has access to kinematic and topological information of a decay, such as the invariant mass of the reconstructed heavy-flavour hadron and its direction with respect to a PV of an event. The decays that HLT2 select are formed by combining sets of tracks under the assumption that they are the decay products, or ‘daughters’, of a single heavy-flavoured hadron, referred to as the ‘mother’ particle. The decays can also be of an ‘explicit’ nature where a mother particle is fully reconstructed or the decay can be selected in the more general ‘inclusive’ sense whereby a partial reconstruction of the mother particle is performed. The final decision of HLT2 is formed from a logical OR of these exclusive and inclusive selections; the events then just need to be accepted by one of these selection algorithms to pass HLT2. During RunI (II), events accepted by HLT2 are sent to permanent storage with an output rate of roughly 5 kHz (12.5 kHz). A flow diagram showing the processing path of data through the trigger system at LHCb during

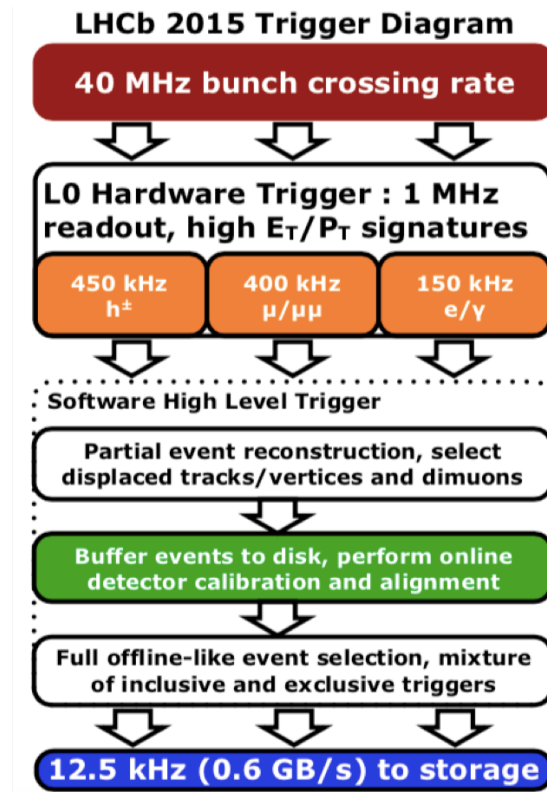


Figure 21: An overview of the LHCb trigger system in RunII showing the processing of events.

RunII is shown in Figure 21.

2.7 LHCb software framework

The data processing at LHCb proceeds in several steps. The Monte Carlo (MC) simulation samples are processed in a similar way to data. It is based on the assumption that events can be treated nearly independently of each other. This idea is encoded in the GAUDI framework. Several software packages allow to handle different parts of the data flow.

- Gauss: MC simulation. Pythia generates pp collisions, EvtGen describes the decay of simulated b - and c - hadrons, and Geant4 simulates the propagation and interaction of particles through and with the detector. The output is 'hits' in the sub-detectorsections
- Boole: digitises the simulated sub-detector hits to the same output formats the readout electronics and adds L0 decisions.
- Moore: adds HLT decisions to the event information by running the same applications used during real data-taking.

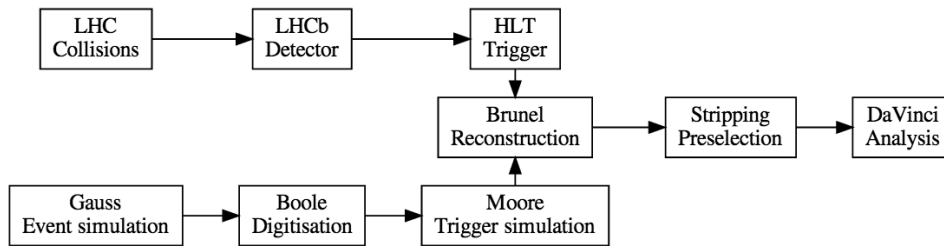


Figure 22: Different LHCb software stages in the Gaudi framework.

- Brunel: reconstructs raw data to transform detector hits into objects such as tracks and clusters. The output is stored in Data Summary Tape (DST).
- DaVinci: offline physics selection framework. Events are separated into different physics streams so that they can be used in different analyses. The application reconstructs primary vertices, assigns particle identification hypotheses to tracks and calorimeter events, and stores the output also in DST files. The application provides several tools that can be used for analysis, e.g. constrained vertex fitting, determination of the signal flavour, and calculation of decay angles.

2.8 LHCb Upgrade

The upgrade of the LHCb detector, which will take place during the Long Shutdown 2(LS2), from the end of 2018 until the end of 2020, will extend significantly the physics reach of the experiment by allowing the detector to operate at a higher instantaneous luminosity of $2 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$.

At the same time a triggerless 40MHz readout with a very flexible software-based trigger will increase the efficiency for a wide range of hadronic B decay channels. This will allow the data rate to be increased substantially, as well as the trigger efficiency, leading to improvements in annual signal yields compared to those obtained by LHCb in 2011 by a factor of around ten for muonic B decays and twenty or more for heavy-flavour decays to hadronic final states. In addition to the significant increase in sensitivity for flavour physics, the experiment will be capable of triggering on other interesting signatures, such as long-lived particles, and thus act as a general purpose detector in the forward region.



3 Ghost probability study for LHCb RunIII

3.1 Introduction

As Section 2 said, The LHCb detector is designed to perform high efficiency track reconstruction ($\geq 95\%$) with an excellent momentum resolution (0.5% for $p \leq 20\text{GeV}/c$). In RunII of the LHC (2015–2018), a scheme for the LHCb software trigger allows splitting the triggering of the event into two stages, giving room to perform the alignment and calibration in real time.

A major achievement of LHCb's operations in RunII is that the full offline reconstruction is run in the second stage of the software trigger. In combination with the final offline calibration available in the software trigger, this results in the best possible reconstruction quality for online event selection. One of the challenges to run the full offline reconstruction in the software trigger is the limited CPU time budget of the computing farm. The reconstruction time of events depends strongly on the number of reconstructed charged particle tracks in an event in two ways. Firstly, the particle identification (PID) is evaluated for every reconstructed long track in the second stage of the software trigger. Secondly, there are more possible track combinations to consider in the reconstruction of decay vertices with more reconstructed tracks.

A key ingredient to fit the offline reconstruction into the software trigger is the reduction of the fake track rate prior to the PID and decay reconstruction in the second software trigger stage. Ghost (fake) tracks are defined as those reconstructed tracks which do not correspond to the trajectory of a true particle but instead are due to the mismatch of hits from separate particles or from detector noise. A neural network is deployed to identify these fake tracks, called the 'ghost probability'.

3.2 Track reconstruction

Section 2.3.4 shows an overview of different track types defended in the LHCb reconstruction. Long tracks are the highest quality tracks comprising all available information from the trackers and are therefore used in most physics analyses. Downstream tracks mainly play a role in the reconstruction of daughters from long-lived particles which have decayed after the VELO (usually weakly decaying strange hadrons, such as Λ^0 or K_S^0).



3.3 Reconstruction sequence in RunII and the upgrade

The RunII trigger, schematically shown on the Figure 21, uses different track reconstruction sequences in the fast (HLT1) and full (HLT2) stage of the software trigger. In HLT1, all VELO tracks are reconstructed and fitted with a simplified Kalman filter, allowing for single rescattering at the sensor planes, and then used to find the primary vertices. VELO track trajectories are then extrapolated to the TT to reconstruct upstream tracks. In addition, the charge of the track can be estimated due to the magnetic fringe field in the TT. The upstream track candidates are then used as input to a fast version of the forward tracking algorithm, where only long track candidates with $p_T \geq 500\text{MeV}$ are accepted. The found long track candidates are fitted with a Kalman filter.

In RunIII, the LHCb experiment will take data at an instantaneous luminosity of $2 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$, five times as high as in RunII. At this luminosity, the rate of potentially interesting physics would be too high to have a reasonable compromise of event reduction and efficiency with the simple selections of L0 hardware trigger. It was therefore decided to move to a trigger-less readout system and a full software trigger as Figure 23 shown. This puts strong constraints on the execution time of the tracking sequence in the fast trigger stage, which at a higher occupancy is expected to be reduced by a factor ≈ 2.5 compared to the current sequence. It will thus require massive use of cost effective parallel computing techniques as well as finding an optimal working point in the trade-off between timing and track reconstruction efficiency at a low fake rate.

3.4 Fake track

Fake long tracks can occur at different places in the pattern recognition. Figure 24 shows ghost types for long tracks, most of the fake long tracks originate from particles which cannot be tracked through the entire detector due to a hadronic interaction with the detector material, followed by fake track segments in the T stations and tracks where two different particles were reconstructed in the upstream and downstream parts of the detector. Fake reconstruction of VELO segments occurs at a lower rate. Mismatched track segments are due to the long lever arm between the tracking stations up- and downstream of the magnet and remain to be the most abundant category after fake track rejection.

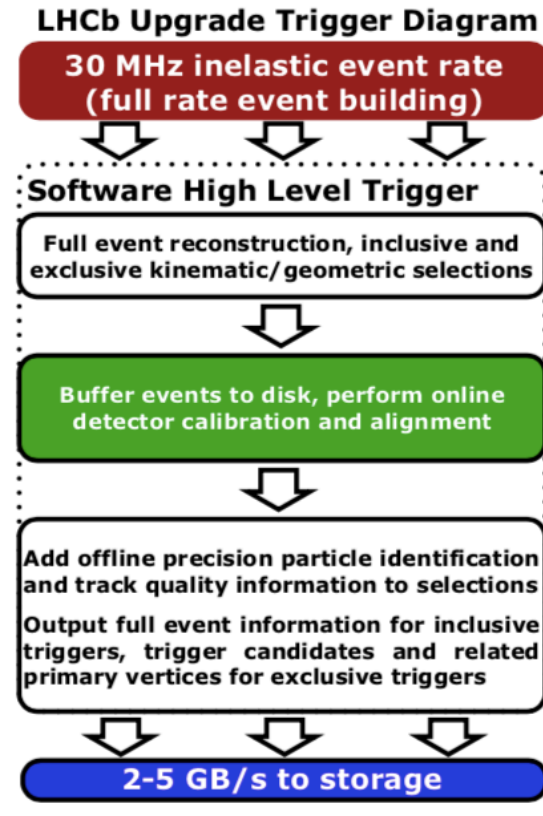


Figure 23: An overview of the LHCb trigger system in RunIII showing the processing of events.

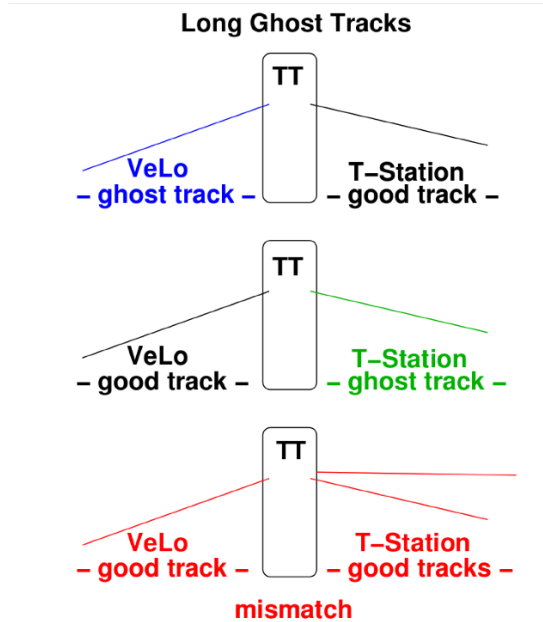


Figure 24: Ghost types for long tracks.



3.5 The ghost probability classifier for long tracks

3.5.1 Introduction

To discriminate between good and fake tracks, a fast artificial neural network classifier in form of TMVA's MultiLayerPerceptron (MLP) is used in both stages of the software trigger after track fitting. While the 'ghost probability', the name of the MLP's response, was an offline quantity during Run I, a huge speed-up by a factor ≈ 90 allowed for its processing in HLT2 in 2015. A cut on the track χ^2/nDof of the track fit was used to reject ghost tracks in Run I and in HLT1 in 2015. Since 2016 the fake track rejection also runs in the HLT1 reconstruction sequence, leading to a significant speed-up of subsequent algorithms.

3.5.2 Previous works

An earlier version of the work presented here, referred to as the 'old ghost probability', was already used in analyses of Run II data. The network was trained on all reconstructed tracks in simulated events with at least one $b\bar{b}$ pair produced in the pp collision.

Training sample

The input to the ghost probability classifier was defined with an B inclusive sample. Samples of good tracks, which could be associated to a generated particle, and 'ghost tracks', for which this association failed, were used.

Input variables

An optimal set of discriminating variables was chosen so that a neural network using these variables has a maximal separation power, i.e. cuts on the resulting classifier are highly efficient on the good tracks, while rejecting as many ghost tracks as possible. The input variables for the GP classifier were restricted to be tracking variables, potentially discriminating PID information was not used. It can be utilized in a different classifier which will be trained at a later stage. A set of 22 input variables for the neural network was found to be optimal:

- the total track fit χ^2 and the corresponding number of degrees of freedom
- the track fit χ^2 contribution from the VELO and T-station segments and the corresponding numbers of degrees of freedom



- the track fit χ^2 contribution from the match between VELO and T-station segments
- the number of observed hits assigned to the track in each of the VELO, TT, IT, and OT detectors
- the excess of the observed number of hits over the number of hits expected from geometry in each of the VELO, TT, IT, and OT
- the sum of the number of OT hits that were rejected by the track fit ('outlier') and the number of OT hits where the measured drift time was inconsistent with the track hypothesis and therefore not used for the fit ('bad drift time')
- the total hit multiplicities in the VELO, TT, IT and OT
- the pseudorapidity η
- the transverse momentum p_T

These variables contain separation power between good tracks and ghosts. For some of the variables, alternative parameterisations have been examined. Instead of the separate use of χ^2 and number of degrees of freedom, the use of reduced χ^2 values or prob (χ^2) values has been tested and leads to a worse performance. Other quantities that have been tested as input variables include the type of the track reconstruction algorithm (PatForward or PatMatch), the hit multiplicity in the SPD, the polar angle φ and the track position (x, y) at the T stations. Including any or all of these has been found not to lead to a gain in performance, hence these variables are not used in the classifier.

There are separate networks for each track type, where input variables are removed if they are not defined for that track type (e.g. VELO hits for downstream tracks).

Architecture

The ghost probability classifier is based on a multilayer perceptron (MLP) neural network. It is implemented using the ROOT framework TMVA. Other classifier types, including boosted decision trees, have been tested, but did not give a better performance.



3.6 Ghost probability study for LHCb RunIII

As Section 3.5.1 said, in RunIII LHCb experiment will take data at a very high instantaneous luminosity and as ghost probability has been used in HLT, so the timing will be main concern for any improvement. For the ghost probability study for upgrade several, potential improvement are expected.

3.6.1 Input variables

During studies, it is found that 90% of the process time is spent looking for expected hits. The comparison for all track types of the comparison between with and without expected hits information as Figure 25 shows. The red one labels the performance with expected his information, while the blue one labels the performance without expected hits information. For the Long track and Downstream track which used in most physics analyses and detector studies, the performance does not have a significance change.

For the CPU time, the Timing Auditor is used to check the average time in milliseconds it takes per event. A 96% ($70.80 \rightarrow 2.70$) improvement for CPU time by removing the expected hits information is founded. At the same time, by using the Valgrind tool, it is also founded that about 90% of process time spent on finding the expected hits, the result as Figure 26 shows.

Considering that by removing expected variables, the CUP time is obviously much reduced, and only Velo Track performance becomes worse, so the expected hits information is removed in MVA for upgrade.

Adding more variables in MVA training to increase the separation power is also studied like adding the total observed hits in FT information in MVA . But including it has been found not to lead to a gain in performance, hence these information will be not used in the classifier.

3.6.2 Active function - hidden layer

In a neural network, an activation function normalizes the input and produces an output which is then passed forward into the subsequent layer. Activation functions add non-linearity to the output which enables neural networks to solve non-linear problems. In other words, a neural network without an activation function is essentially just a linear regression model. Common activation functions include Linear, Sigmoid, Tanh, and ReLu, the function distribution as Figure 27 shows.

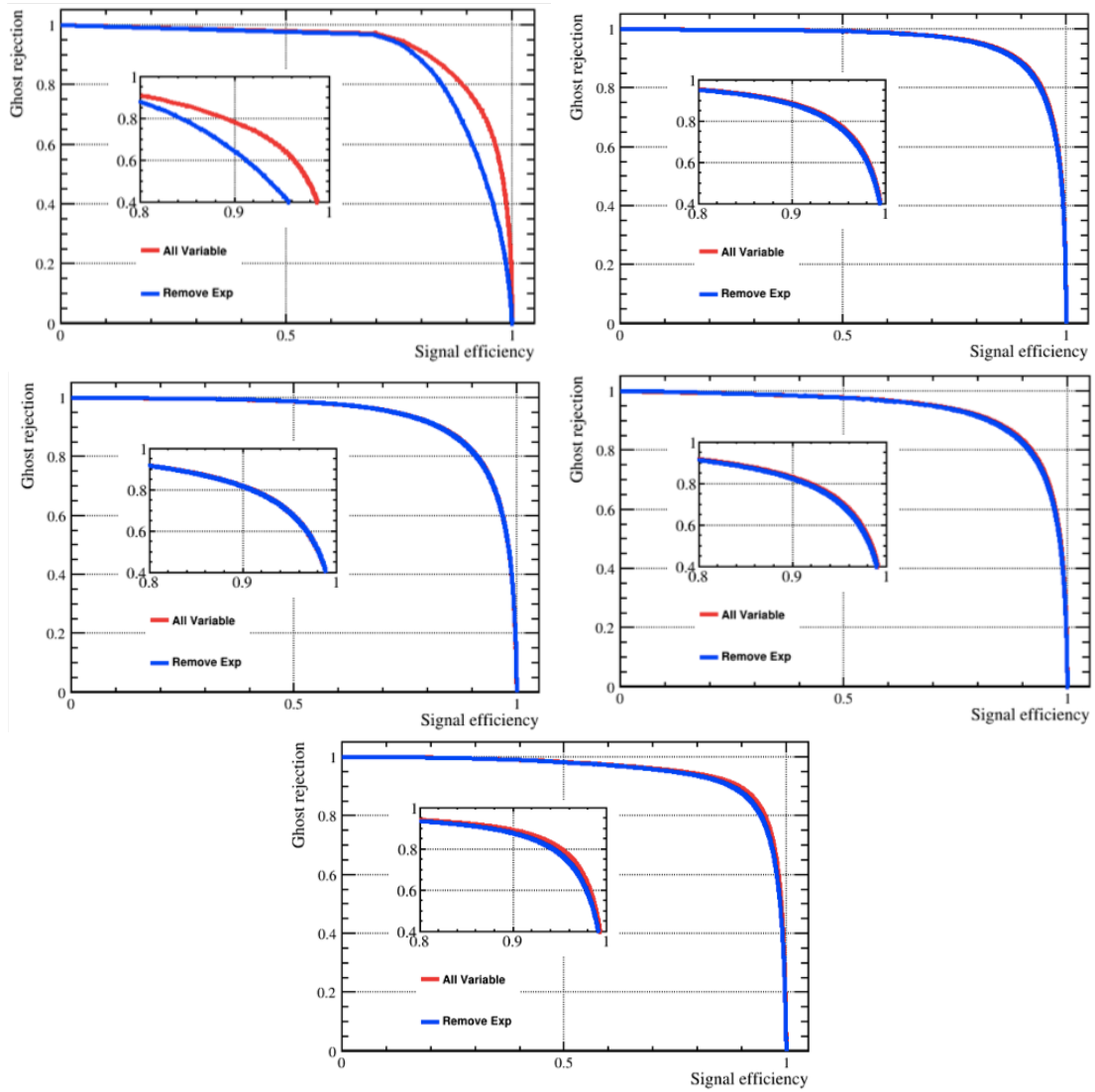


Figure 25: The comparison of the performance between with and without hits information for Velo Track (top left), Long Track (top right), Downstream Track (middle left), Upstream Track (middle right), T Track (bottom left).

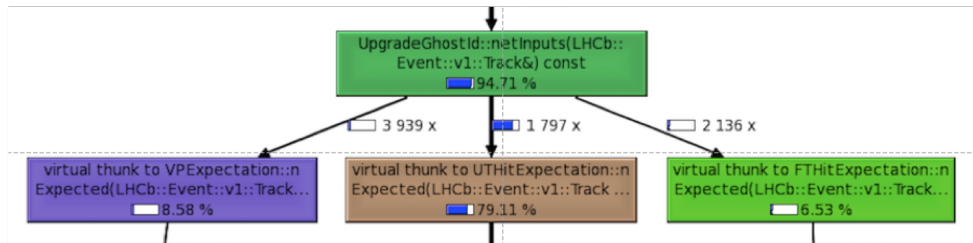


Figure 26: A program diagram of function call.

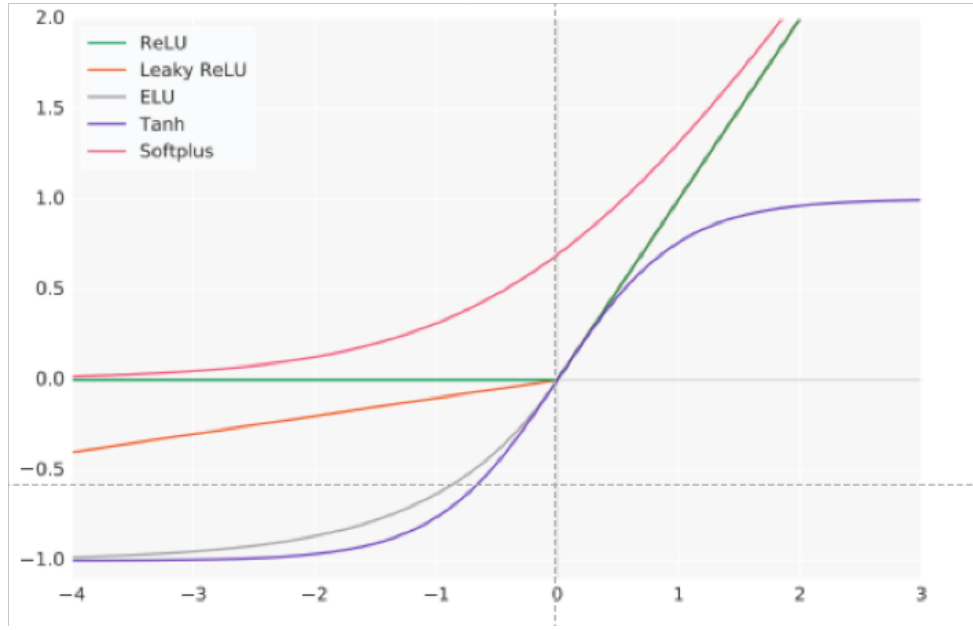


Figure 27: Common activation functions distribution.

RunI choose Tanh function as the hidden layer activation function, the function expression is

$$\frac{e^x - e^{-x}}{e^x + e^{-x}} \quad (39)$$

RunII use a simpler function: Sigmoid function, the function expression is

$$\frac{1}{1 + e^{-x}} \quad (40)$$

For the update, the ReLU function is used as activation function to ensure fast computation of the net work response. The function expression is

$$\max(0, x) \quad (41)$$

The simpler function expression is expected to contribute to the faster processing speed. By using Timing Auditor, it is found there is about 10% improvement of the training time and application average cost time, i.e. for long track, the training time could be decreased from 2815 sec to 2431 sec, the application average cost time could be decreased from 13×10^{-6} sec to 11×10^{-6} sec. And this change do not hurt the performance as Figure 28 shows.

3.6.3 Active function - last layer

For the last layer activation function, the default one is the exponential function. In upgrade, it will be replaced by fast exponential function. In the fast exponential function, the exponential

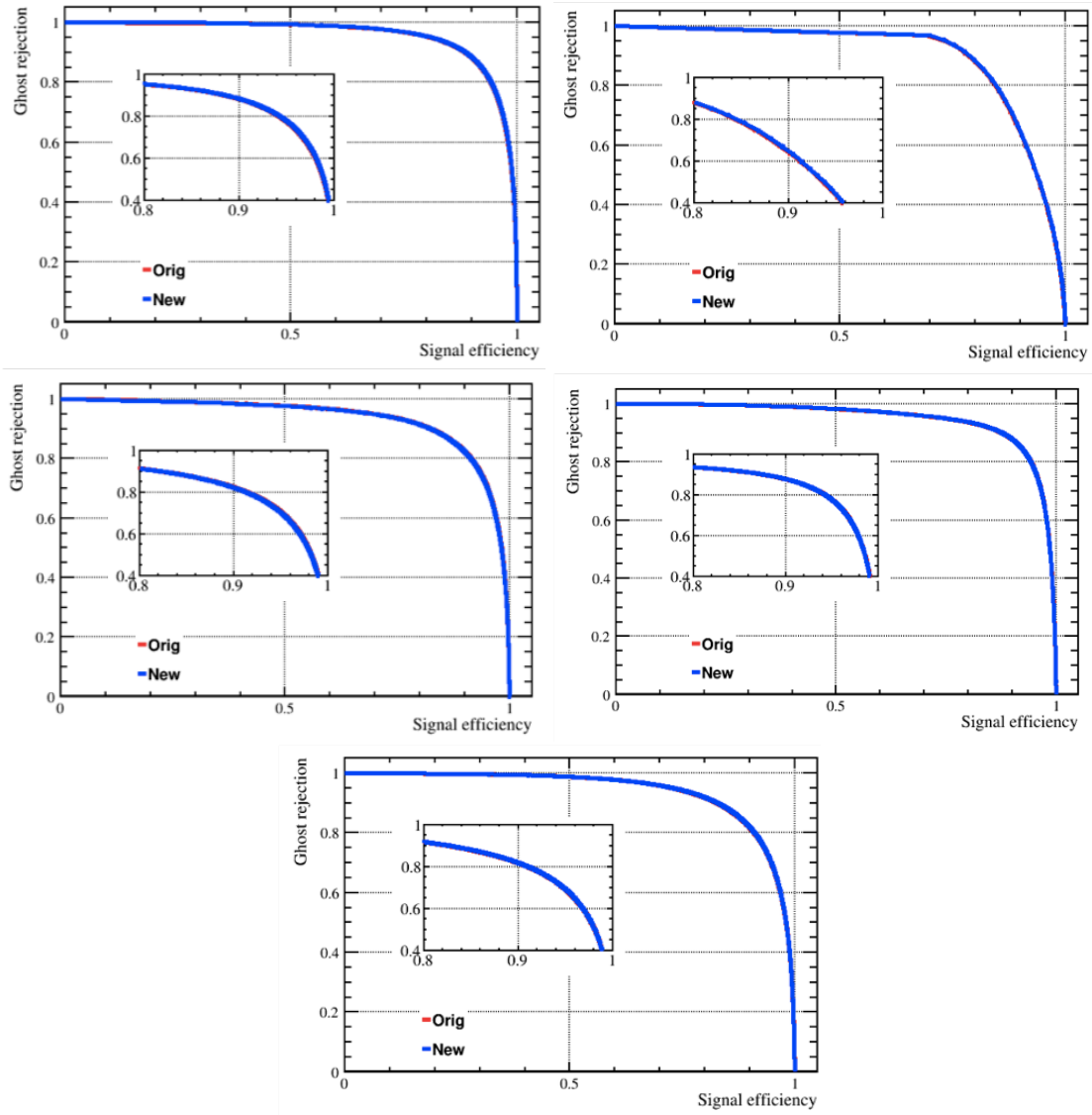


Figure 28: The comparison of the performance between Sigmoid function and ReLu function as the active function in hidden layer for Velo Track (top left), Long Track (top right), Downstream Track (middle left), Upstream Track (middle right), T Track (bottom left).



operation is replaced with the finite number of multiplications, so it is expected to be faster. The improvement is about 0.1%, i.e. for long track, the training time could be decreased from 2815 sec to 2813 sec, while application average cost time could be decreased from 1303×10^{-4} sec to 1301×10^{-4} sec. The physics performance is also be checked to make sure it is reasonable.

3.6.4 Output transformation

To ease the usage of the ghost probability, a transformation of the network response is applied. A probability integral transform commonly referred to as ‘flattening’ or ‘rarity transformation’ is implemented as a linear spline fit to the cumulative network response for fake tracks in simulated events. The discriminating behaviour of any classifier is invariant under monotonous transformations and so is the physics performance under the probability integral transform. Motivations for this transformation are primarily to give a physical interpretation to the response: rejecting tracks with a ghost probability of larger than $x\%$ will retain $x\%$ of all fake tracks.

In addition any update of the ghost probability training will have the same behaviour and thus the optimal working points of algorithms using the ghost probability algorithm will remain unchanged to a good approximation.

3.7 Conclusion

The comparison of the performance between before optimizations and after optimizations in the upgrade need to be checked to make sure that all above optimizations are reasonable. The comparison of the physics performance between before and after optimization as Figure 29 shows. The performance for the Velo track become worse, but Velo tracks is not critical as there are hardly any ghosts. The comparison of the CPU time between before and after optimization as Figure 30 shows. Optimisations bring about about 97% ($60.8 \text{ sec} \rightarrow 1.83 \text{ sec}$) improvement in the CPU time.

Based on all above results, in the upgrade ghost probability algorithm, the expected variables will be removed, ReLU function will be used to replace the Simoid function for the activation function in the hidden layer, and for the activation function in the last layer the fast exponential function will be used. All these optimisations have been involved in the LHCb official software package.

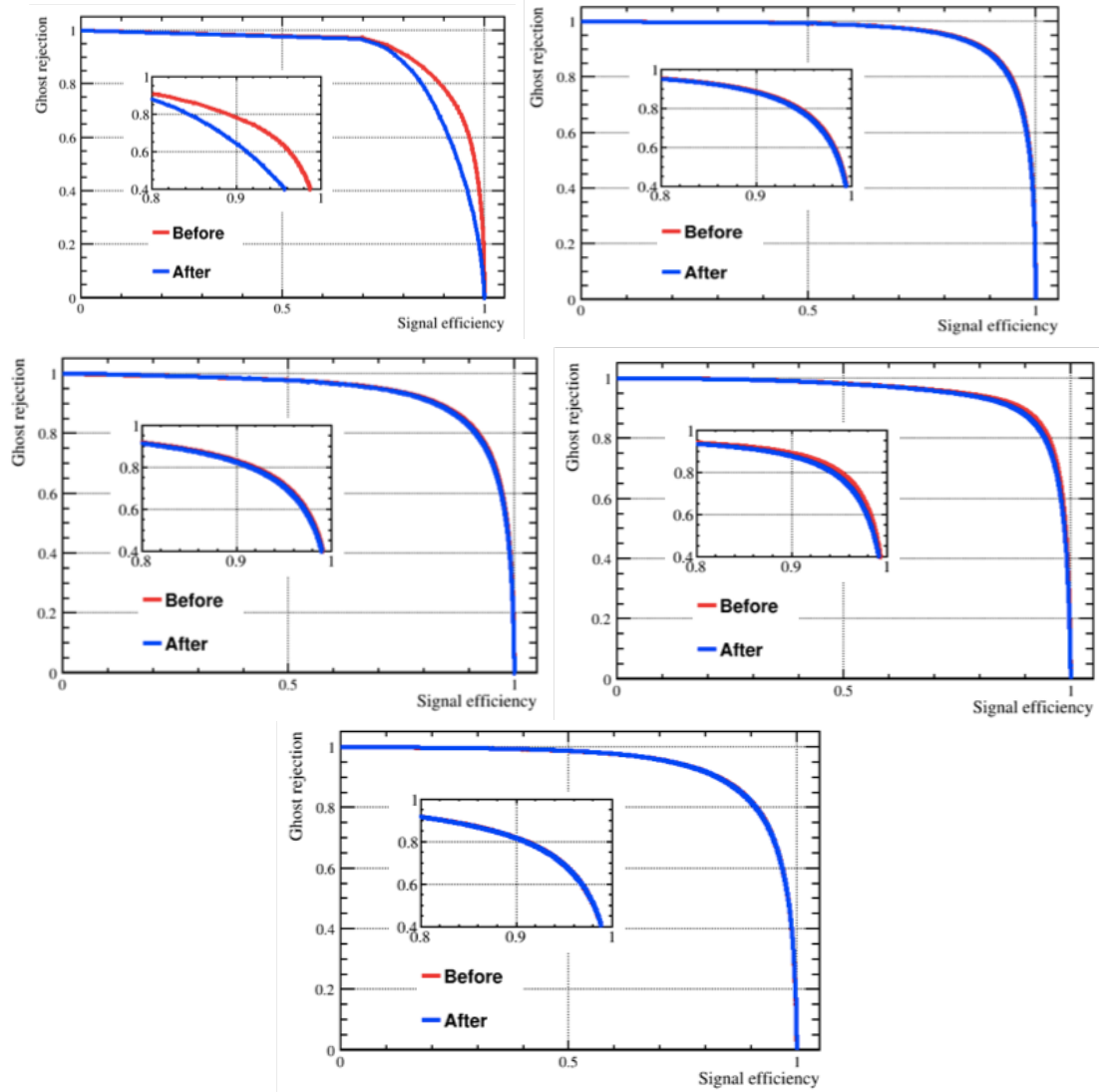


Figure 29: The comparison of the performance between before optimization and after optimization for Velo Track (top left), Long Track (top right), Downstream Track (middle left), Upstream Track (middle right), T Track (bottom left).



TimingAuditor.T...	INFO	RecoTrBestSeq	1298.133	1297.385	69.783	10688.1	1111.24	300	389.192
TimingAuditor.T...	INFO	PrForwardTrackingBest	52.733	53.338	0.215	833.3	88.34	300	16.082
TimingAuditor.T...	INFO	PrHybridSeedingBest	47.408	47.664	0.917	783.1	84.01	300	14.299
TimingAuditor.T...	INFO	PrMatchNNBest	2.808	2.786	0.184	24.9	2.77	300	0.836
TimingAuditor.T...	INFO	PrLongLivedTrackingBest	38.466	38.954	0.570	458.4	48.33	300	11.686
TimingAuditor.T...	INFO	BestTrackCreatorSeq	1087.866	1093.015	47.194	8294.1	866.93	300	327.985
TimingAuditor.T...	INFO	TrackConverterSeq	1.766	1.968	0.279	8.7	1.06	300	0.590
TimingAuditor.T...	INFO	DownstreamConverter	0.266	0.287	0.034	7.0	0.42	300	0.086
TimingAuditor.T...	INFO	ForwardBestConverter	0.333	0.232	0.020	0.8	0.15	300	0.070
TimingAuditor.T...	INFO	ForwardFastConverter	0.100	0.085	0.011	0.2	0.04	300	0.026
TimingAuditor.T...	INFO	MatchConverter	0.100	0.243	0.024	0.5	0.11	300	0.073
TimingAuditor.T...	INFO	SeedingConverter	0.100	0.260	0.031	1.0	0.15	300	0.078
TimingAuditor.T...	INFO	UpstreamConverter	0.166	0.150	0.027	0.6	0.07	300	0.045
TimingAuditor.T...	INFO	VeloConverter	0.333	0.375	0.045	0.9	0.14	300	0.113
TimingAuditor.T...	INFO	VertexConverter	0.266	0.285	0.012	4.9	0.33	300	0.086
TimingAuditor.T...	INFO	TrackBestTrackCreator	1086.033	1091.017	46.867	8288.7	866.10	300	327.305
TimingAuditor.T...	INFO	TrackAddExtraInfoSeq	68.833	61.459	3.932	294.2	34.49	300	18.438
TimingAuditor.T...	INFO	TrackAddNNGhostId	68.800	61.435	3.916	294.2	34.49	300	18.431
TimingAuditor.T...	INFO	RecoTrBestSeq	1338.766	1347.187	53.839	11798.1	1228.34	300	404.132
TimingAuditor.T...	INFO	PrForwardTrackingBest	54.708	55.848	0.258	879.2	90.55	300	16.515
TimingAuditor.T...	INFO	PrHybridSeedingBest	49.066	48.954	1.038	808.8	86.06	300	14.686
TimingAuditor.T...	INFO	PrMatchNNBest	2.708	3.085	0.082	27.2	3.06	300	0.926
TimingAuditor.T...	INFO	PrLongLivedTrackingBest	40.508	41.141	0.231	472.3	51.71	300	12.342
TimingAuditor.T...	INFO	BestTrackCreatorSeq	1189.833	1196.821	51.833	9596.1	996.93	300	359.046
TimingAuditor.T...	INFO	TrackConverterSeq	2.980	2.460	0.284	9.6	1.34	300	0.738
TimingAuditor.T...	INFO	DownstreamConverter	0.233	0.346	0.033	4.4	0.33	300	0.104
TimingAuditor.T...	INFO	ForwardBestConverter	0.200	0.285	0.017	1.0	0.19	300	0.086
TimingAuditor.T...	INFO	ForwardFastConverter	0.166	0.138	0.009	7.4	0.46	300	0.042
TimingAuditor.T...	INFO	MatchConverter	0.366	0.297	0.019	1.4	0.16	300	0.089
TimingAuditor.T...	INFO	SeedingConverter	0.266	0.314	0.017	1.3	0.18	300	0.094
TimingAuditor.T...	INFO	UpstreamConverter	0.233	0.183	0.015	1.0	0.09	300	0.055
TimingAuditor.T...	INFO	VeloConverter	0.800	0.515	0.035	6.1	0.38	300	0.155
TimingAuditor.T...	INFO	VertexConverter	0.466	0.313	0.014	1.8	0.23	300	0.094
TimingAuditor.T...	INFO	TrackBestTrackCreator	1186.866	1194.310	51.592	9589.0	995.89	300	358.293
TimingAuditor.T...	INFO	TrackAddExtraInfoSeq	1.866	1.900	0.139	14.3	1.56	300	0.570
TimingAuditor.T...	INFO	TrackAddNNGhostId	1.833	1.880	0.127	14.2	1.55	300	0.564

Figure 30: The comparison of the costed CPU time between before optimization (top) and after optimization (bottom) obtained from the Timing Auditor.

4 LHCb Scintillating Fibre Tracker: the CERN-SPS July 2018 test beam studies

4.1 Introduction

4.1.1 LHCb Upgrade

As Section 2.8 talked, LHCb experiment will perform a major upgrade of the detector during the LHC's Long Shutdown II from 2019 to 2020. The complete tracking system is required to be replaced with the new operating condition. The LHCb main tracking system now consists of an Inner Tracker, built from silicon strip sensors, and an Outer Tracker, using 5 mm straw-tubes for the particle detection. To cope with the expected high particle multiplicities after LS2, both Inner and Outer tracker will be replaced by a highly granular, uniform, low-mass Scintillating Fibre Tracker (SciFi) Tracker. The location of the new SciFi detector within LHCb is shown in Figure 31.

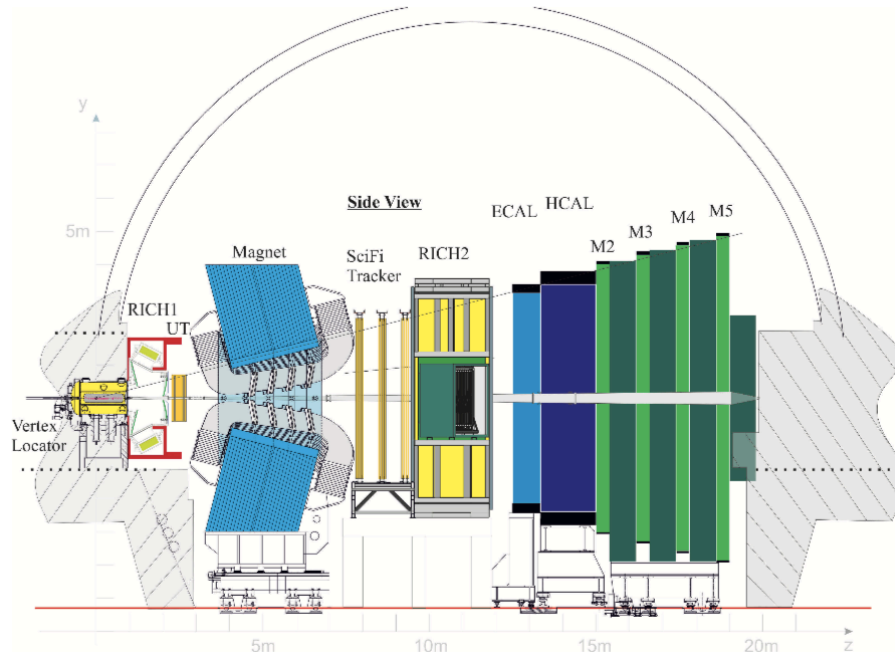


Figure 31: Schematic side-view of the planned upgraded LHCb detector. UT = Upstream Tracker. SciFi Tracker = Scintillating Fibre Tracker, reproduced from [81].

4.1.2 Requirements

The track reconstruction requires that the detector has high hit efficiency, good spatial resolution in the bending plane of the magnet, and low material budget in the acceptance. The LHCb



upgrade requires that the read-out electronics operate with 40 MHz sampling frequency. The detector must be able to operate for the full lifetime of the upgraded LHCb detector to ensure that the performance of the track reconstruction is good enough for the duration of the experiment.

The main requirements on the upgraded tracking detector are summarised as follows:

- The hit detection efficiency should be as large as possible ($\approx 99\%$), while the fake hit rate should not exceed 10% of the signal rate at the same location.
- The single hit spatial resolution must be less $100\ \mu\text{m}$ in the bending plane of the magnet. A better resolution is not necessary as the extrapolation of tracks from the VELO would be dominated by multiple scattering in the detectors upstream of the magnet.
- The material in the acceptance region should be minimised such that the effects of multiple scattering in the tracker are smaller than those due to the material upstream of the magnet. This requirement is achieved when the radiation length is such that $X/X_0 \leq 1\%$ per detection layer.
- The read-out electronics should be able to run at a frequency of 40 MHz, and the recovery time of the read-out channels should be short to minimise inefficiency due to dead-time.
- The detector should be able to operate with the required performance for an integrated luminosity up to $50\ \text{fb}^{-1}$.

4.1.3 Test Beam

The performance of a full detector slice of the SciFi Tracker regarding the hit efficiency, hit resolution, and spillover has been studied on data obtained during a test beam campaign at the CERN SPS in July 2018. For the SciFi tracker, the hit efficiency is the parameter of greatest interest and is a product of the threshold cuts applied on the signal clusters and the light yield distribution in each channel. This thesis mainly talk about the performance of the single hit efficiency and the hit resolution.

4.2 LHCb SciFi detectors design

4.2.1 Layout of the LHCb SciFi

The LHCb SciFi Tracker will occupy the same space as the OT and also follow the same layout of three stations composed of four layers in an $x-u-v-x$ geometry where the two stereo

layers (u, v) are tilted by $\pm 5^\circ$. Each detection layer covers an area of approximately $6 \times 5\text{m}^2$ and is made up of ten to twelve modules that each contain eight fibre mats. In total 128 modules will be used to construct the SciFi Tracker, covering an active area of more than 320m^2 . Figure 32 shows the layout of one SciFi Tracker station. The fibre mats consist of six staggered layers

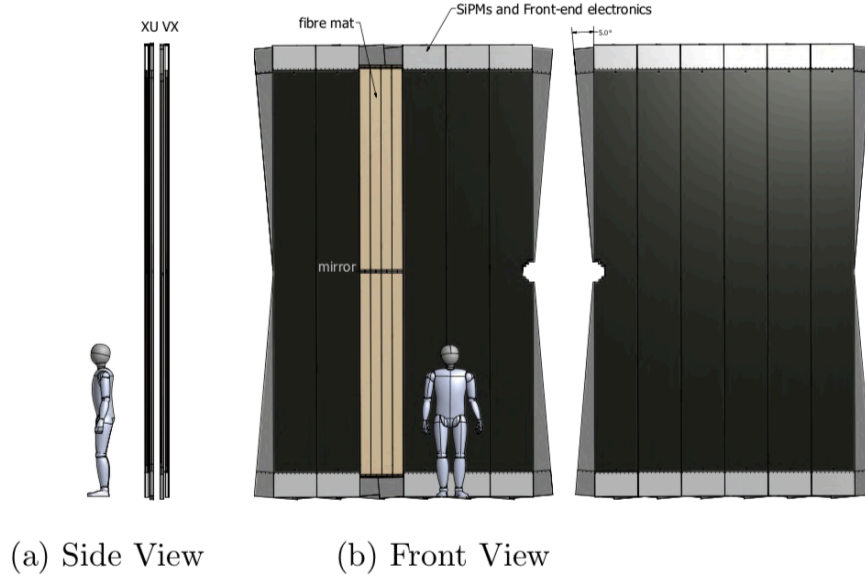


Figure 32: Layout of an LHCb SciFi Tracker station. Image are from [80]

of diameter scintillating fibres. The mats are readout by multichannel arrays of silicon photo multipliers (SiPMs) on one side, whereas a mirror is glued to the other side, facing the centre of the detector. All fronted electronics and services are located at the top and bottom of the detector outside of the acceptance.

4.2.2 Working principle

The process of the signal generation in SciFi Tracker as Figure 33 shows. When a charged particle crosses the scintillating fibres, the energy is deposited through ionisation which be subsequently transformed into light by the scintillation process. The light is fractionally trapped inside the fibres and transported via total internal reflection to the SiPMs. The signal in each SiPM channel is proportional to the number of detected photons so the particle position will be calculated by using the weighted mean of the channel signals.

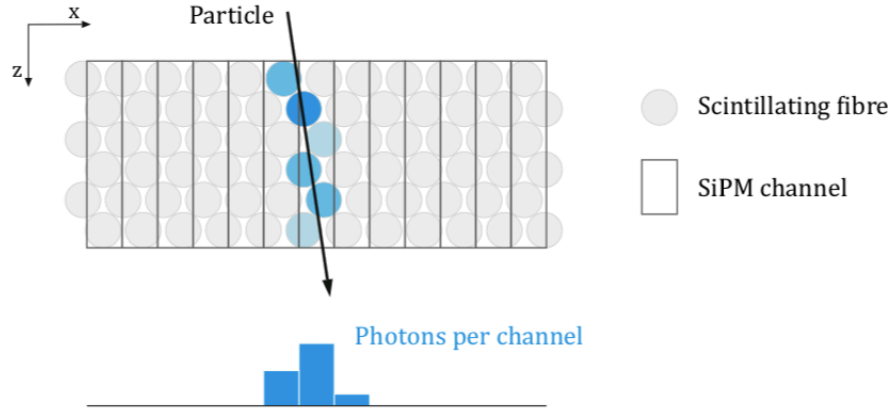


Figure 33: Illustration of the signal generation of a particle crossing a fibre mat. The coordinates corresponds to the right-handed coordinate system of LHCb, images from [82]

4.2.3 Scintillating fibres

Scintillating fibres are used as the active component of the SciFi Tracker. When a charged particle traverses a fibre it deposits energy through ionisation which leads to the isotropic emission of scintillation light that is generated in a multi-step process

4.2.4 Fibre mats and modules

SciFi Tracker's each detection layer contains ten to twelve modules that each contain eight fibre mats, as well as all the necessary interfaces for the SiPMs and electronics.

4.2.5 Silicon photomultipliers

SiPM characteristics

Silicon photomultipliers (SiPM) are solid state photon detection devices that combine all the necessary features needed for the detection of photons in a high resolution scintillating fibre tracker. The amplitude of a SiPM signal is commonly given in units of photoelectrons (pe), where 1 pe corresponds to the signal of a single pixel. SiPM are characterised by a variety of different parameters, the most two relevant parameters are Breakdown voltage and Gain.

Breakdown voltage

The breakdown voltage (V_{BD}) is defined as the bias voltage (V_{BIAS}) where the electric field of

the multiplication area becomes strong enough to trigger the creation of an avalanche. The over voltage is defined as $\Delta V = V_{BD} - V_{BIAS}$.

Gain

The gain (G), is the multiplication factor of the primary photoelectron in the avalanche. It is proportional to δV and the capacitance of the pixel (junction capacitance, C_J)

$$G = \frac{Q_{Avalanche}}{e} = \frac{C_J \times \delta V}{e} \quad (42)$$

SiPM plus height spectrum

The SiPMs's main performance parameters generally is determined by Pluse height (PH) spectra which is recorded either in the dark or under pulsed illumination. And the PH spectra recorded with light could be used to calibrate the fronted ASIC. The PH spectrum of a SiPM as Figure 34 shows, is characterised by distinct peaks corresponding to 0, 1, 2 ... N geiger avalanches.

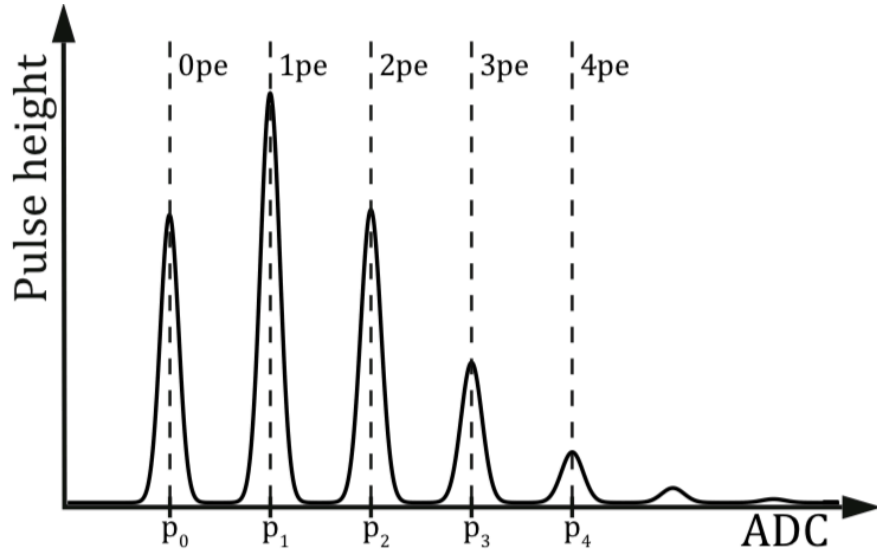


Figure 34: illustration of the SiPM pulse height spectrum. The lines indicate the positions of the peaks p_k , images from [82]

4.2.6 Fronted electronics

The fronted electronics are connected to the fibre modules to process the SiPM signals with a readout frequency of 40 MHz and transform the data. The schematic view of the fronted electronics as the Figure 35 shows.

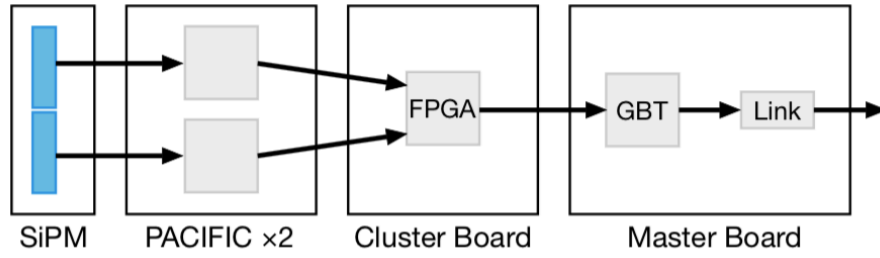


Figure 35: The schematic view of the fronted electronics.

4.2.7 Light injection system

The light pluses are injected into the fibre mats by the light injection system (LIS) which could be used to calibrate the detector in particular the thresholds of the PACIFIC. The schematic view of the LIS as Figure 36 shows.

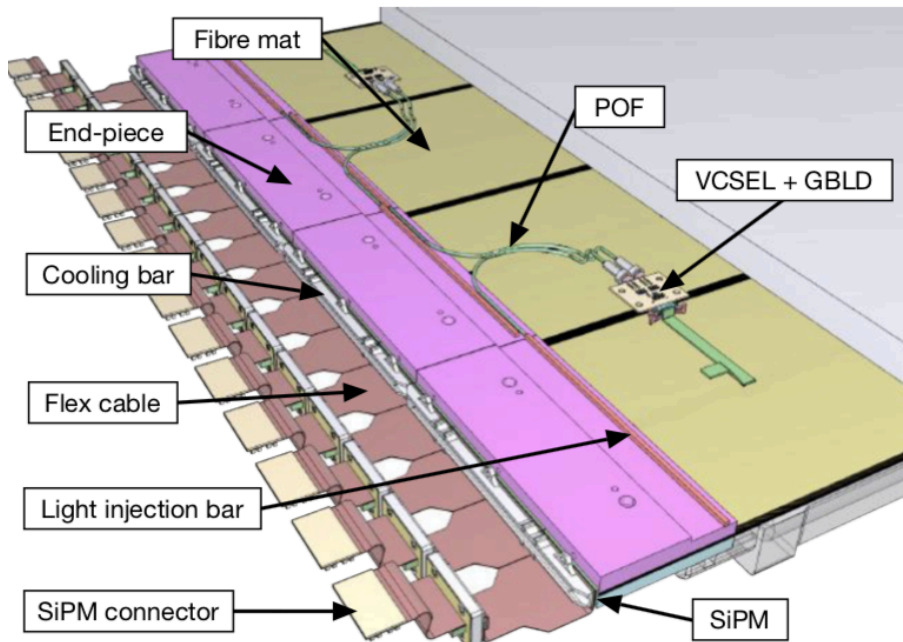


Figure 36: The schematic view of the LIS, from [83]

4.2.8 Hit reconstruction

At Scifi reconstruction system, a clustering algorithm based on three thresholds is developed to reconstruct the hit position and reduce the noise.

Considering a particle traversing the detector typically leave the signal more than one neighbouring SiPM channels, so the hit position is reconstructed by combing the signals whose ampli-

tude exceed certain comparator thresholds into clusters. Three thresholds in order is defended as: $neighbour \leq seed \leq high$. By this way, the amplitude in every channel can be represent by three bits according to which thresholds have been passed like (000) or (001) as left plot in Figure 37 shows. But there are four combinations (000, 001, 011, 111), so they also could be encoded in a 2-bit number to further reduce the size of the data.

The cluster find algorithm starts by searching for cluster candidates where the channel pass the seed threshold, then include signals from adjacent channels that pass the neighbour threshold into the cluster. Finally the cluster in which one channel exceeds the high threshold or it contains at least on channel above the seed and one above the neighbour threshold. The hit position($\bar{x}$) is

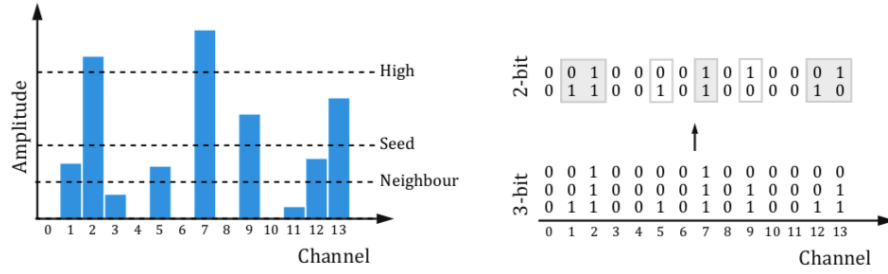


Figure 37: Illustration of the cluster finding algorithm based on the amplitude information given by three thresholds. Left plot shows the analogue SiPM signals and set thresholds, while right plot shows the corresponding digital output. The grey boxes illustrate found clusters and the open boxes rejected clusters. Image inspired from [84]

determined by calculating the cluster's centre by using the weighted average:

$$\bar{x} = \frac{\sum x_i \times w_i}{\sum w_i} \quad (43)$$

x_i is the channel i in the cluster position, w_i is the corresponding weights calculated according to threshold passed.

4.3 The PACIFIC ASIC

The PACIFIC ASIC is the frontend ASIC of the LHCb SciFi Tracker and includes all elements to amplify, shape, and digitise the SiPM signals. It is a 64 channel ASIC designed for a 40 MHz triggerless readout of SiPMs. Each channel of the PACIFIC contains the analog processing chain shown in Figure 38.

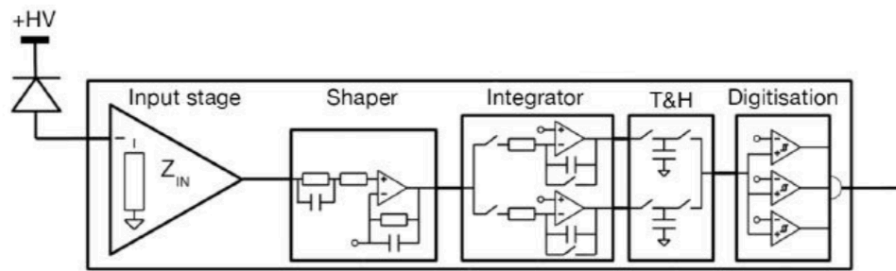


Figure 38: PACIFIC channel block diagram, image from [85]

4.3.1 Input stage

For each SiPM channel, the input stage is within a same range to compensate for differences in the breakdown voltage. By this way, every channel could operate at the same over voltage and thus has the same gain and photon detection efficiency.

4.3.2 Fast shaper

The light generation and propagation in the fibres and the long tail of SiPM pulse could cause the SiPM signals extend over several LHC bunch crossing periods. The fast shaper is needed to reduce the signal tail in order to minimise spillover into the next bunch crossing.

4.3.3 Integration

The shaped SiPM signals are integrated by two interleaved gated integrators switching at 40MHz in order to avoid any dead time during acquisition. It could be achieved by the strategy that at the same time, only one integrator work, the other is disconnected from the input and being reset.

4.3.4 Digitisation

Then three adjustable comparators are used to digitise the integrated signal, which could provide the necessary amplitude information for the clustering algorithm described in Section 4.2.8. The comparator thresholds are configurable for each channel individually.

4.4 Test Beam in July 2018

The individual components of the SCiFi Tracker have been intensively studied in previous years during several test beam campaigns. Since the development of all subcomponents has been

effectively finished, the latest test beam campaign aims to study the full system performance of prototypes of the SciFi Tracker. It was conducted at the CERN SPS North Area in July 2018.

4.4.1 Experimental setup

The experimental setup of the test beam campaign in May 2015 is shown in Figure 39. The detectors-under-test are two production version full width but half length modules, each assembled with a cold-box with 16 SiPMs and a full set of front-end electronics, which named ROB0 and ROB1. The TimPix3 telescope trigger was used to provide the reference tracks for the performance studies of the SciFi Tracker modules, as well as a fine timestamps which records the trigger time relative to the 40 MHz readout of the SciFi Tracker. The beam was set to a width of about 1 cm and contained mainly pions and protons with a momentum of around 180 GeV.

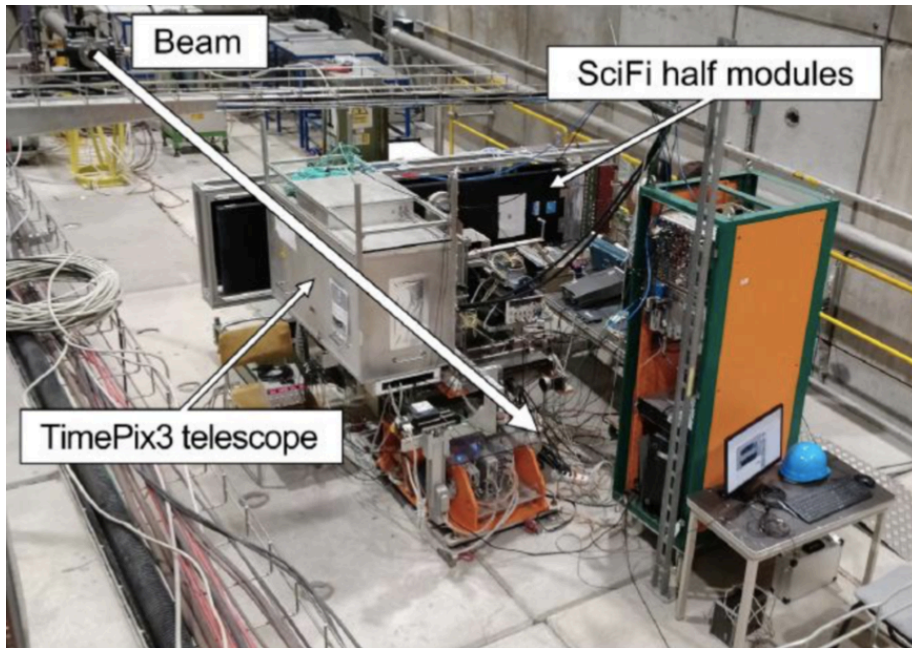


Figure 39: Picture of the test beam setup at the CERN North Area in July 2018

4.4.2 Calibration of the PACIFIC threshold

The calibration of the PACIFIC comparators is a very vital step, which provide the conversion from a signal measured in units of DAC values to photoelectrons using three comparators with adjustable thresholds. And before taking data the thresholds to the values required by the clustering algorithm a calibration is needed.

The calibration consists of two parts, a threshold scan for every channel and comparator, and a fit to extract the calibration constants.

Threshold Scan

The threshold scan is performed under pulsed illumination provided by the light injection system (LIS). Figure 40 (left plot) shows an example of a complete SiPM spectrum under illumination. The complete amplitude information of each SiPM pulse could be only obtained by measuring this spectrum under a full ADC. And the PACIFIC digitises the signals with three comparators, where the only information about the signal is, whether it is above or below a previously set threshold. So to measure the complete spectrum, scanning through the threshold values and each time counting how many signals pass it. The strategy is When the threshold is set below the pedestal peak all signals pass it, the ratio is set to one. Each time a peak is being traversed fewer signals pass the threshold and the ratio continuously decreases until the threshold is in between two peaks giving rise to the characteristic stair case shape. Figure 40 (right plot) shows an example of the threshold scan result, which is called $S - curve$. The $S - curve$ gives the probability that a signal X will exceed a certain threshold value x : $P(X \geq x)$, which corresponds to the complementary cumulative distribution function of the SiPM spectrum.

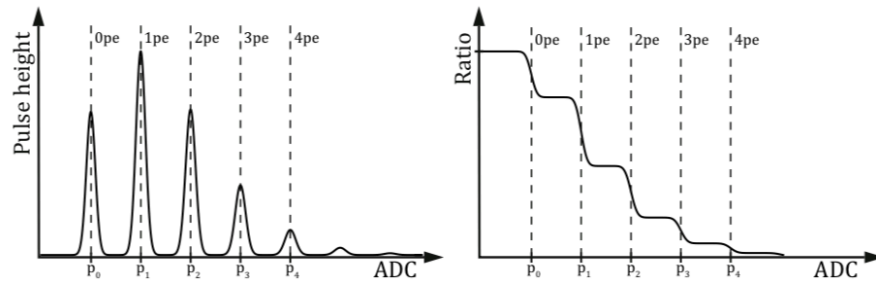


Figure 40: SiPM spectrum under pulsed illumination recorded with a full ADC and a single comparator. The dashed lines indicate the photoelectron peak (step) positions p_k , images from [82]

Threshold determination

The distinct peaks of the SiPM spectrum allow for excluding certain amplitudes by setting the threshold of the comparator in between two peaks, which in terms of the PACIFIC corresponds to the centre of a plateau. These positions, which are denoted as $p_{k.5}$ could be obtained by fitting the $S - curve$ like Figure 41. Then these step positions are used to calculate the centre of the plateaus.

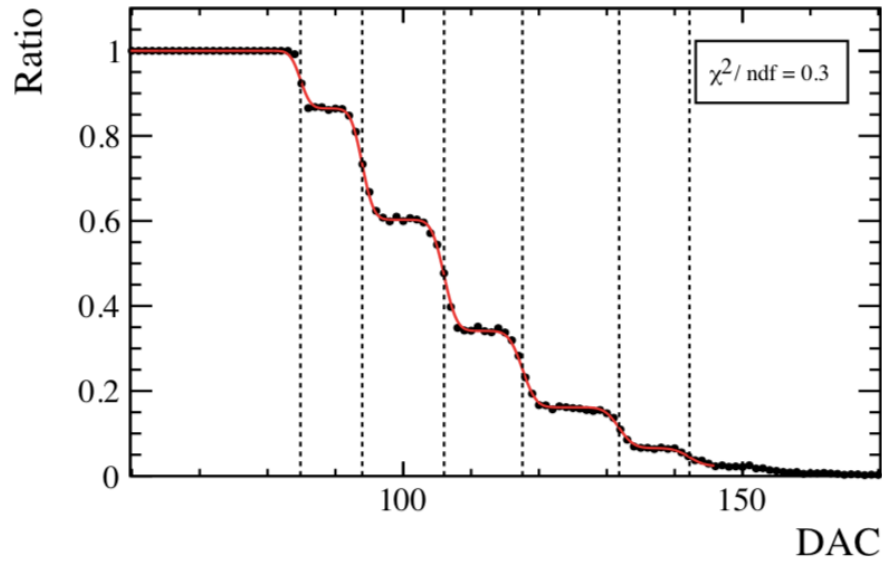


Figure 41: S-curve distribution and fit result, images from [82].

4.4.3 Event selection

The readout electronics are designed to operate in sync with the LHC bunch crossing, so the arrival time of the particles could be precisely determines which is recorded by the TimePix3 telescope trigger. The delay between the trigger and the DAQ was adjusted such that most signals could be recorded in one bunch crossing as Figure 42 shows. Figure 43 shows the number of signals in all channels over the high threshold for different signal arrival times in the signal bunch crossing corresponding to BX2 of left picture. Within BX2 bunch crossing the signals need to be further selected based on their arrival time to ensure that they are properly integrated by the PACIFIC. Because like these two sideband region in this plot, if the signals arrive either too late or too early are only partially integrated therefore have a lower probability to pass a fixed threshold.

4.4.4 Fine Timestamp Selection

For further analysis a fine time selection is applied, which only selects events that fall within a certain time window inside of 25ns long BXs. The window of allowed fine time bins is determined based on the number of events above the PACIFIC thresholds as a function of the fine timestamp. The normalised fine timestamps distribution is shown in Figure 44.

The maximum of this distribution characterises the events where the detector integrates most

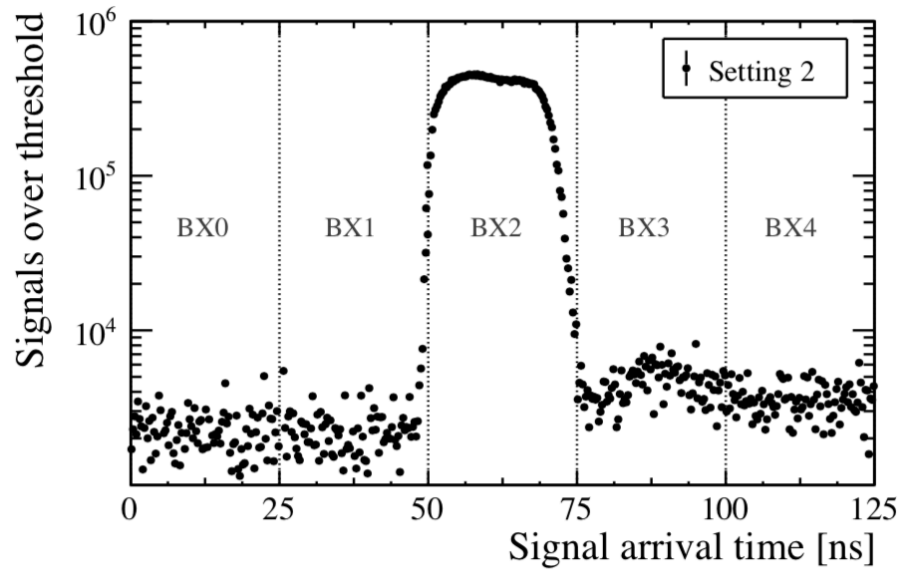


Figure 42: Distribution of signals over the high threshold for five consecutive bunch crossings, images from [82].

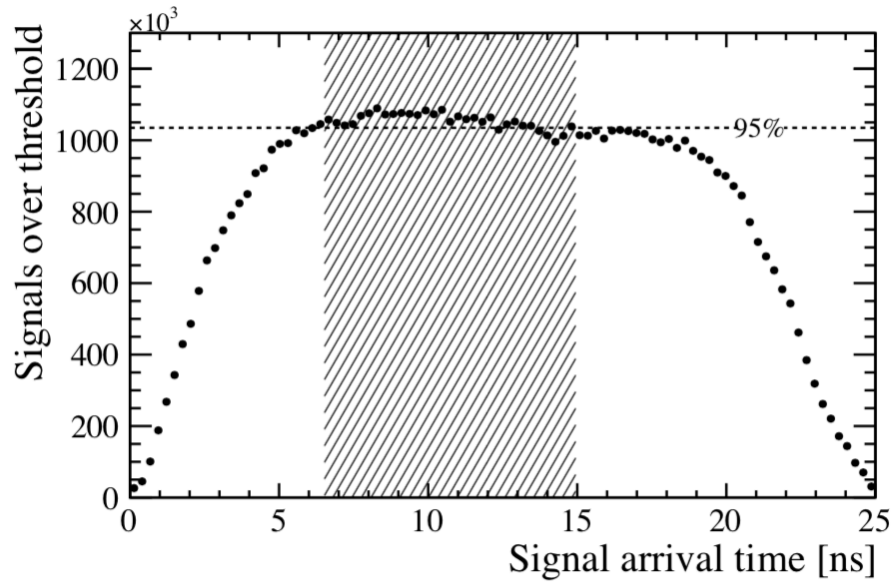


Figure 43: Distribution of the number of signals over the high threshold in the signal bunch crossing. The 95% level, relative to the maximum number of events, is shown as dotted line and the range of selected arrival times is indicated by the hatched box, images from [82]

deposited signal of the incoming particles and would be the working point in a synchronised setup in order to maximise hit efficiency. It is favourable to choose the selection window as tight as possible to emulate having a synchronised beam, while retaining enough events for further statistical analysis. Figure 44 shows an exemplary fine time selection where the window is chosen such that the selection where at least 90% of the events, relative to the maximum, have passed the highest PACIFIC comparator threshold.

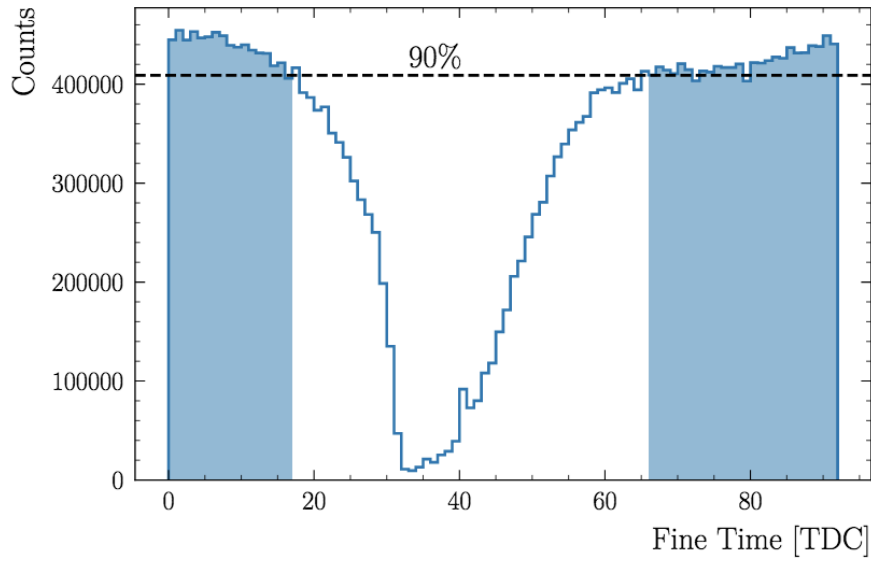


Figure 44: Distribution of signals over the highest threshold in different fine time bins and selected events, images from [82]

4.4.5 Single Hit Efficiency

The single hit efficiency is a very crucial parameters which directly affects the tracking efficiency and the eventually physics performance of the LHCb experiment. It is defined as the efficiency to detect a charged particle traversing one detector layer:

$$\epsilon_{hit}(x) = \frac{N_{SciFi}(x)}{N(x)} \quad (44)$$

where N_{SciFi} is the number of detected particles, *i.e.* reconstructed clusters. $N(x)$ is the total number of particles passing the detector at a certain position x which is given by extrapolating the telescope tracks to the position of the SciFi modules. Figure 45 shows the measured hit efficiency as a function of the channel number for the two ROB at nominal setting, the automatic finetimestap selection is used. The beam was incident close to the mirror side of the mat and

pointed at nine different positions along its width. Since the beam was only about 1 cm wide there are channels where no data was recorded. Every 64 channels a drop in the efficiency, due to the gaps between the two dies of one SiPM and between different SiPMs, is observed. For the two channels around the small gap in between the SiPM dies the efficiency drops to around 85% and for the large gap ($460\ \mu\text{m}$) between two SiPMs it drops to 64%. The efficiency in the plateau region, *i.e.* all channels except the ones right next to the gaps, is found to be 99%.

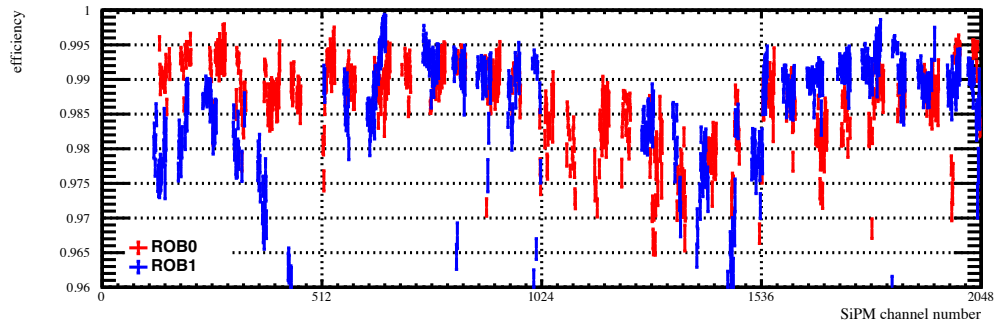


Figure 45: Efficiency profiles of the two ROBs at nominal settings (152545 / 3.5V)

Studies of the efficiency drop

As Figure 45 shows, the efficiency in both modules almost follow the same trend and almost efficiency could be greater than 99%, which meet the goal of SciFi tracker design. But the efficiency at Mat 3 for both modules and the efficiency at Mat1 for ROB1 are still with lower efficiency, in these regions there is about 1% efficiency drop compared with others. There are four possible reasons, mats have intrinsically lower efficiency, calibration light intensity, fine time selection and calibration timing.

Light Yield Checks

Figure 46 shows the light intensity distribution for both ROBs. The light yield does not have the same trend like single hit efficiency has a drop at Mat3 for both ROBs, which means Mat3 does not have intrinsically lower efficiency for both ROBs.

Compare with the calibration light intensity

Figure 47 shows the light yield profiles distribution for both ROBs taken from different calibration. No similar drop structure at Mat3 could be observed in this distribution.

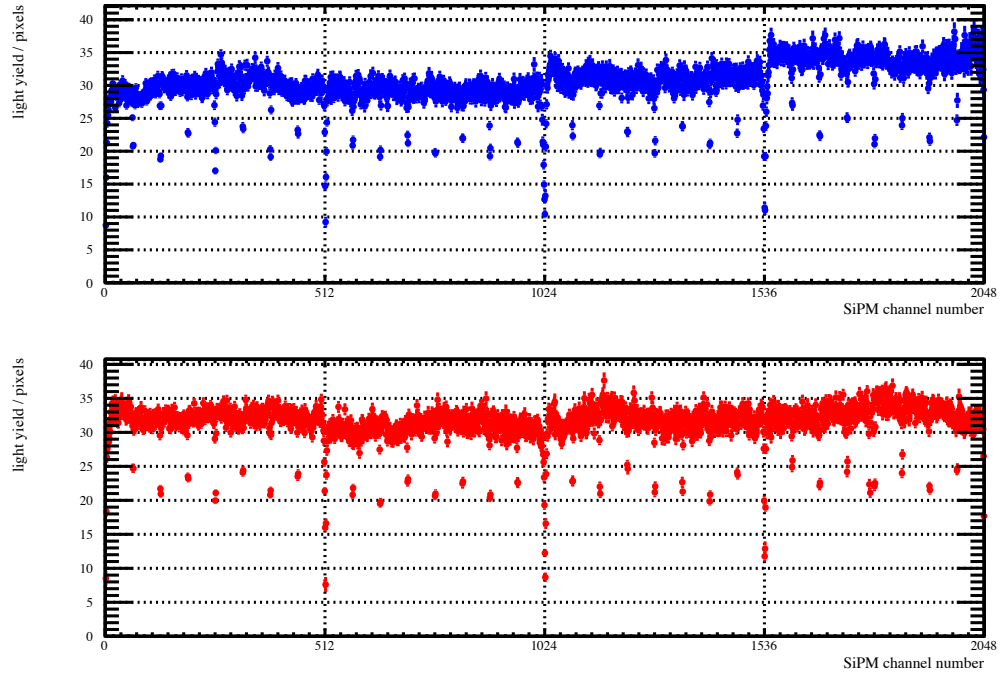


Figure 46: The light yield distribution as a function of the channel number for ROB0(top) and ROB1(bottom)

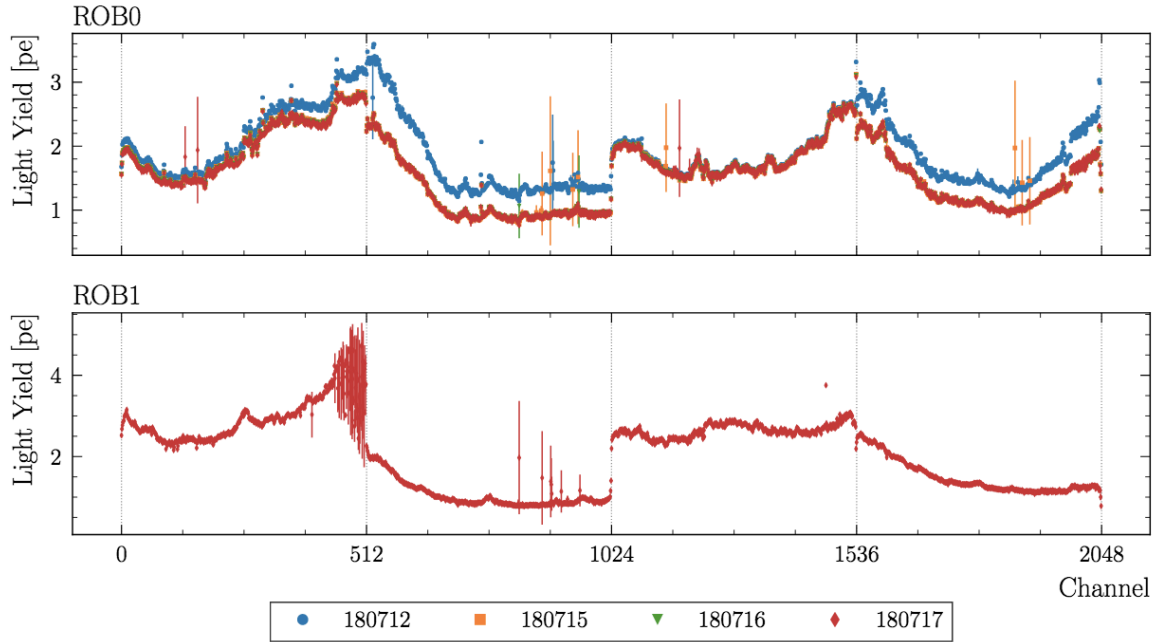


Figure 47: Light yield profiles for both ROBs taken from different calibration

Influence of the finetimestamp selection

As Section 4.4.4 described, the current fine time window is determined automatically by using 90% level as a selection criterion. The 90% level is applied for all channels which means that this fine time selection method is the fair for all channels. It is theoretically a very reasonable way of analyzing data. But there is still a possibility that the time window corresponding 90% level is still too large for some channels especially for Mat3.

In order to avoid this possibility, another test that smallest possible fineTimestamp slice and find the maximum efficiency profile is necessary. Firstly the time window is modified to be 2 ns which is a very narrow window compared to the normal value of 10-20 ns. Then use this time window to scan the whole fine time region with 0.5 ns per step for each channel to evaluate their maximum efficiency. If the maximum efficiency for each channel is almost same, it means the drop comes from the time window selection bias. While if the maximum efficiency is different, it means no matter how to optimize the fine time selection, the drop could not be removed. The result as Figure 48 shows. In this plot the blue line labeled the efficiency by using the automatically fine time selection, the read one labeled the maximum efficiency. The efficiency just have about a very small improvement about 0.01% on the whole by using maximum efficiency. And the drop shape at Mat3 still remains. It means that any deviation of efficiency in the different channel caused by fine time selection could be excluded.

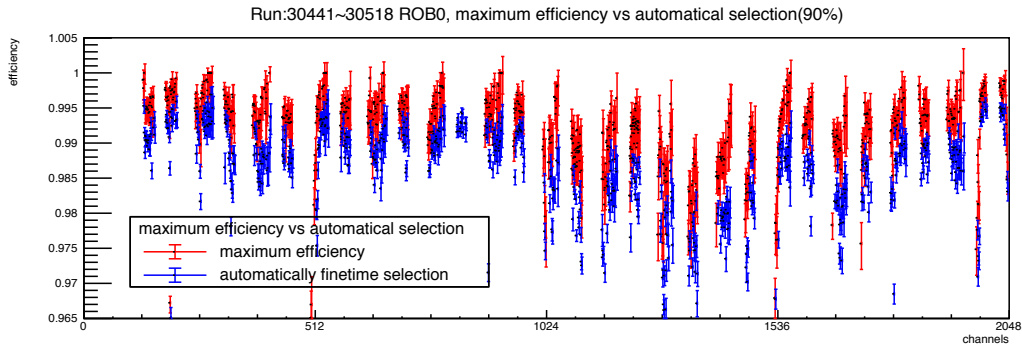


Figure 48: smallest possible fineTimestamp slice, maximum efficiency profile, images from [82].

OverThreshold Ratio profile vs light yield profile

If assume the gain is consistent for each channel, the shape of the over threshold ratio and light yield should be the same. Firstly, the cosmic data is used to verify that if this statement is correct. Figure 46 shows the signal light yield distribution for ROB0 and ROB1 while Figure 49 and Figure 50 show the over 3.5pe threshold ratio distribution. So for cosmic data, the light yield



distribution and over threshold ratio distribution have the same trend.

And considering cosmic data and SciFi data have the same trend of the particle light yield. Just for cosmic data the particle incoming angle is smaller than SciFi data so the cosmic data's light yield is larger than SciFi overall but the trend should be the same. But by comparing Figure 49 and Figure 50 with the Figure 51 and Figure 52, the over threshold ratio trend is very different between cosmic data and verify data. These means that during testbeam, for the same threshold setting, the gain is different for each channel. And this difference comes from the timing.

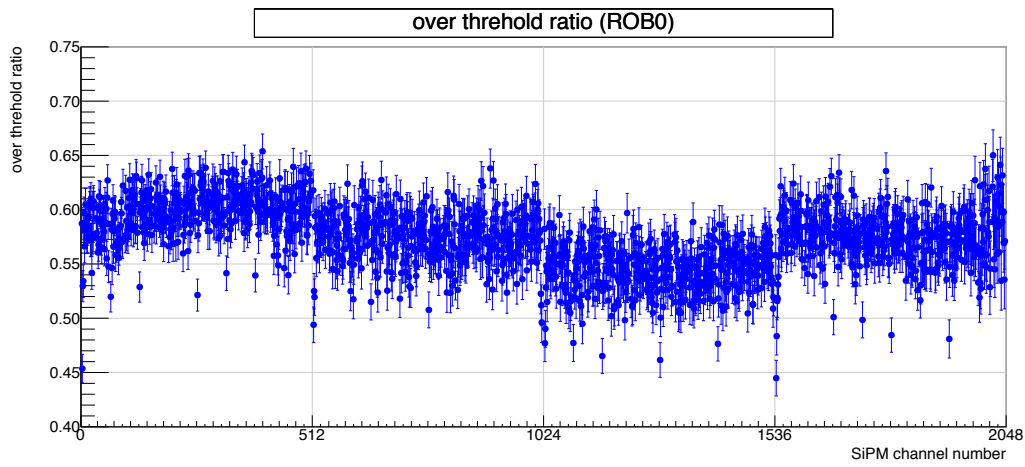


Figure 49: overThreshold Ratio profile of ROB0 using cosmic data

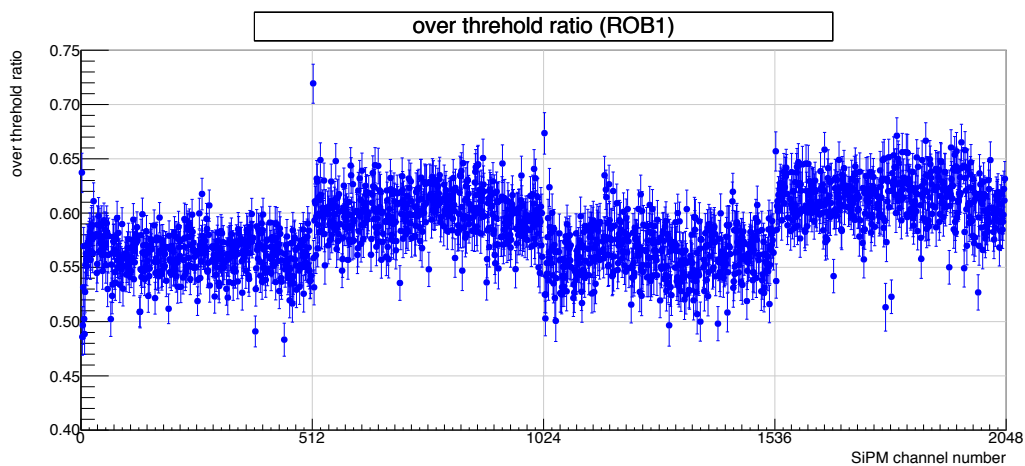


Figure 50: overThreshold Ratio profile of ROB1 using cosmic data

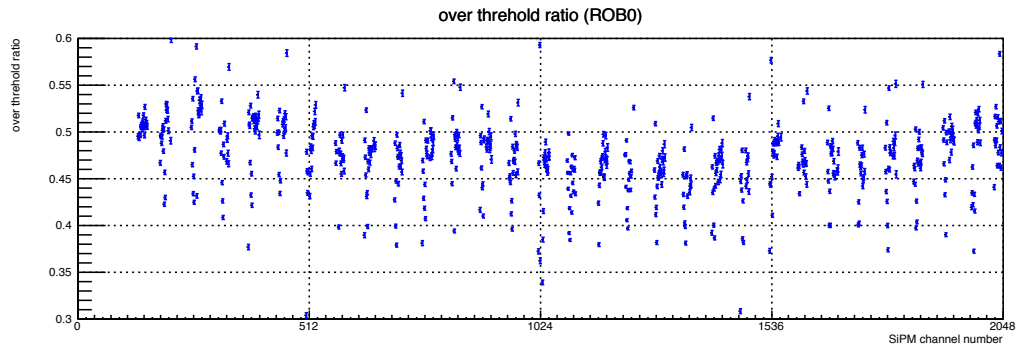


Figure 51: overThreshold Ratio profile of ROB0 using SciFi data

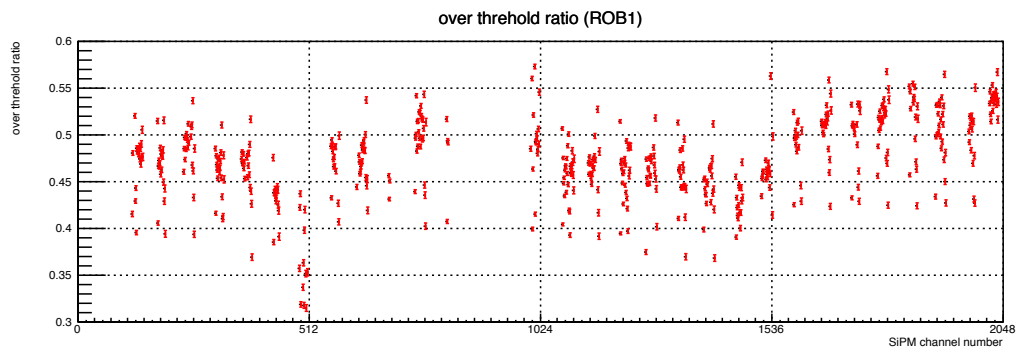


Figure 52: overThreshold Ratio profile of ROB1 using SciFi data



Conclusion

The drop of the single hit efficiency at Mat3 is due to the LIS calibration timing. It would be nice to investigate how much timing varies across modules and to think about a better way to optimize LIS calibration timing in the next development of the SciFi software.

4.4.6 Studies of the single hit resolution

Introduction

The residuals are calculated using the predicted hit position of the telescope tracks and the reconstructed hit position in the SciFi module.

$$R = x - x_{\text{SciFi}} \quad (45)$$

Figure 53 shows an example of the resulting residual distribution. The width σ residual of the distribution is the quadratic sum of the track resolution σ_{track} and the single-hit resolution of the SciFi Tracker module σ_{SciFi}

$$\sigma_{\text{track}}^2 = \sqrt{\sigma_{\text{track}}^2 + \sigma_{\text{SciFi}}^2} \approx \sigma_{\text{SciFi}} \quad (46)$$

The resolution of the telescope is so small (about $10 \mu\text{m}$ at the location of the SciFi Tracker modules) relative to the SciFi that it does not contribute much to the residual. So the residual width is approximately equal to the resolution of the SciFi Tracker which could be parameterised with a double Gaussian

$$R \propto f \cdot \exp\left[-\frac{(R - \mu)^2}{2\sigma_{\text{inner}}^2}\right] + (1 - f) \cdot \exp\left[-\frac{(R - \mu)^2}{2\sigma_{\text{outer}}^2}\right] \quad (47)$$

where f denotes the percentage of entries in the inner Gaussian and is typically around 98%. The two contributions to the double Gaussian can be combined to an effective resolution defined as

$$\sigma_{\text{eff}} = \sqrt{f \cdot \sigma_{\text{inner}}^2 + (1 - f) \cdot \sigma_{\text{outer}}^2} \approx \sigma_{\text{SciFi}} \quad (48)$$

alignment to the Telescope

The SciFi resolution is strongly correlated to the telescope so any misalignments of the telescope are crucial for the resolution. At first, an offset correction between the telescope and the SciFi tracker is needed then an additional rotation alignment between telescope coordinate and SciFi coordinate is applied. The rotation misalignment could be corrected by using Equation 50 and

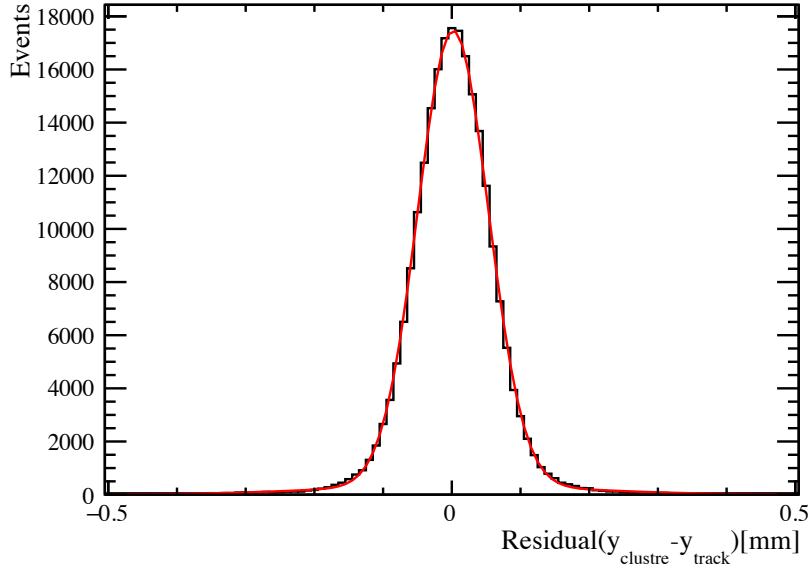


Figure 53: Run 30464 ROB1 residual distribution

Equation 51. There y_i means the track position in y axis (along fiber) for each event while the x_i means the track position in x axis (cross fiber) for each event. and the θ means the angle rotation between two coordinate, y_{init} means the initial track position in the y axis. The θ and y_{init} value for each run could be extracted by using TMinuit tool which corresponding the mini χ^2 value.

$$\chi^2 = \sum_i^n (y'_i - y_i)^2 \quad (49)$$

$$x'_i = x_i \cdot \cos\theta + y_i \cdot \sin\theta \quad (50)$$

$$y'_i = y_i^{init} + x_i \cdot \sin\theta + y_i \cdot \cos\theta \quad (51)$$

An example corrected residual distribution in y is shown in Figure 53. The residual distribution is centred around zero which means any offsets have been corrected. Figure 54 shows the unbiased residual distribution in y depending on the track position in x (x_{track}). This distributions is parallel with respect to the horizontal axis, it suggests there the rotation misalignments has been corrected. Both plots indicate that the alignment procedure was successful.

Resolution at normal setting (close to mirror)

Figure 55 shows the measured spatial resolution as a function of the channel number for the width of four fibre mat. The variations across module is in the region $[50\mu\text{m}, 60\mu\text{m}]$ and the best resolution so far is $51\mu\text{m}$ which meet the goal of SciFi tracker design.

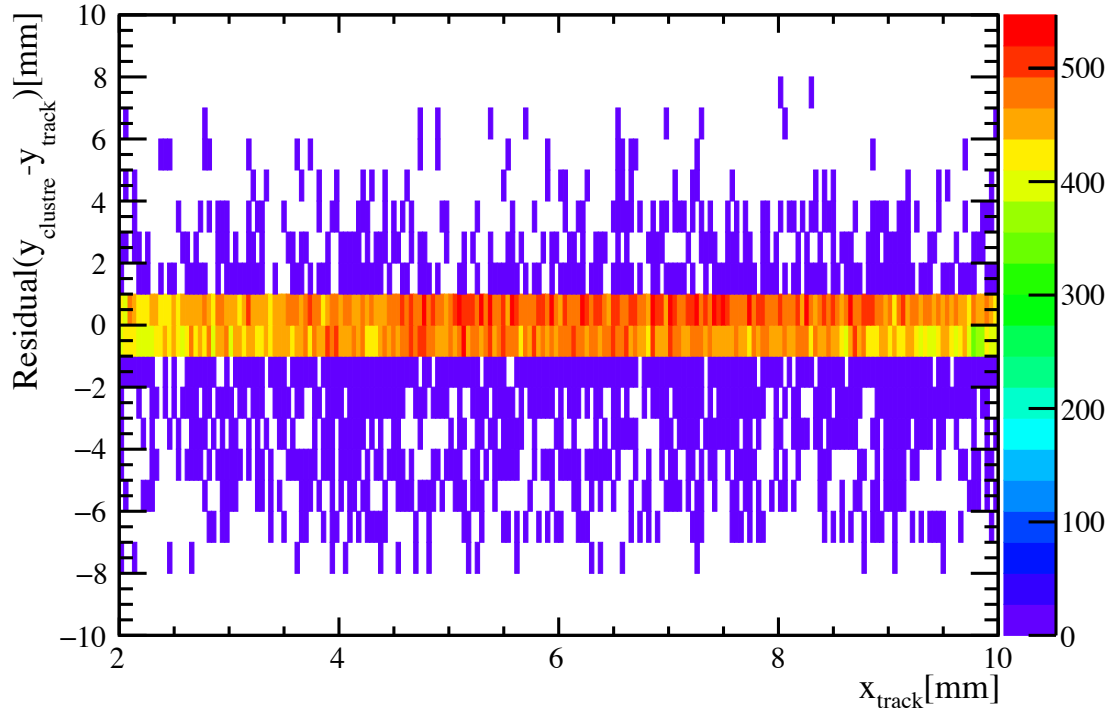


Figure 54: unbiased residual distribution in y depending on the track position in x (x_{track})

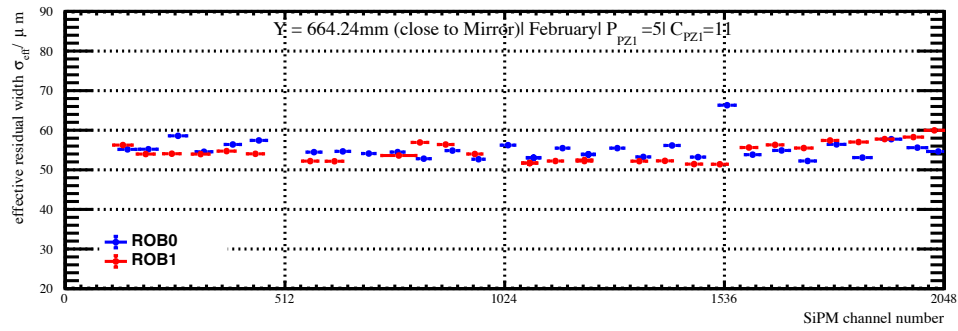


Figure 55: Spatial Resolution at the mirror side across module



5 Search for the doubly charmed baryon Ξ_{cc}^{++} with the $\Xi_c^+\pi^+$ decay

5.1 Data and simulation

The `Hlt2CharmHadXiCpToPpKmPipTurbo` turbo line in the Turbo++ stream CHARMMULTIBODY of 2016 data is used for this analysis. The bookkeeping paths of the 2016 data samples are

`/LHCb/Collision16/Beam6500GeV-VeloClosed-MagDown/Real Data/Turbo03/94000000/CHARMMULTIBODY.MDST`

`/LHCb/Collision16/Beam6500GeV-VeloClosed-MagUp/Real Data/Turbo03/94000000/CHARMMULTIBODY.MDST`

In the simulation, pp collisions are generated using Pythia [86] with a specific LHCb configuration [88]. A dedicated generator, GENXICC2.0¹ is used to simulate Ξ_{cc} baryon production [89]. The mass and the lifetime of the Ξ_{cc}^{++} baryon in the simulation were set to be the same as those in Pythia *i.e.*, $m(\Xi_{cc}^{++}) = 3597.98 \text{ MeV}/c^2$ and $\tau(\Xi_{cc}^{++}) = 333 \text{ fs}$. The Ξ_{cc}^{++} MC samples has been re-weighted to have a lifetime of 260 fs, which is more close to the measured one [90]. The Ξ_{cc}^{++} decay products are distributed according to phase space, while the Ξ_c^+ decay according to a pseudo-resonant model. The number of simulated events is approximately 2 M for each magnet polarity. The bookkeeping locations of the 2016 MC samples are:

`/MC/2016/Beam6500GeV-2016-MagDown-Nu1.6-25ns-GenXiccPythia8/Sim09b/Trig0x6138160F/Reco16/Turbo03/`

`Stripping28NoPrescalingFlagged/26264053/ALLSTREAMS.DST`

`/MC/2016/Beam6500GeV-2016-MagUp-Nu1.6-25ns-GenXiccPythia8/Sim09b/Trig0x6138160F/Reco16/Turbo03/`

`Stripping28NoPrescalingFlagged/26264053/ALLSTREAMS.DST`

for *MagDown* and *MagUp*. The truth matching is done using the true IDs. As the decay descriptor for this channel is $\Xi_{cc}^{++} \rightarrow \Xi_c^+(\rightarrow p^+K^-\pi^+)\pi^+$, then each track is required to have the correct true ID and comes from the corresponding mother or grandmother, as shown in Table 6. The truth matching defined above is referred as the tight MC truth matching. For the candidates selected by the truth matching filter, we do see signal peak with BKGCAT=10 and 50. The category 10 refers to signal with Ξ_c^+ intermediate resonances, and the category 50 refers to low-mass background². The fraction of MC matched events in category 10 is about 53%, and the fraction of MC matched events in category 50 is around 2.6%. The MC sample with Ξ_c^+ intermediate resonances is a very

¹GENXICC2.0 is a generator for hadronic production of Ξ_{cc} based on three mechanisms via gluon-gluon fusion, gluon-charm collision and charm-charm collision, based on NRQCD framework.

²A MC event is marked as ‘low-mass background’, if it passed the following requirements, as: (1) there is at least one final state particles of the candidate had been misidentified; and (2) the mass of MC-truth mother is $100 \text{ MeV}/c^2$ lesser than the average mass of the candidate particle.



Table 6: The MC match used in this analysis. The first column is the name of the particle, the second column is the true ID that required the particle to match, and the third column is the true ID of the mother particle or grandmother particle must to match.

particles	abs(ID)	abs(Mother/Grandmother ID)
Ξ_{cc}^{++}	4422	
Ξ_c^+	4232	4422
$\Xi_{cc}^{++}-\pi^+$	211	4422
$\Xi_c^+-p^+$	2212	4232
$\Xi_c^+-K^-$	321	4232
$\Xi_c^+-\pi^+$	211	4232

important component of signal, we will keep these events in this analysis. For the MC events in category 50, with roughly half of these events in the signal region, the MC matched events not in the signal region is $\sim 1.3\%$, the effects can be ignore in this analysis.

5.2 Selection

5.2.1 Overview

The selection has been developed with a blinded procedure. The blinded region, $[3571, 3671] \text{ MeV}/c^2$, which is $\pm 50 \text{ MeV}/c^2$ of the measured Ξ_{cc}^{++} mass, will not be looked until the green light from the reviewer committee is given to unblinding.

To reconstruct Ξ_{cc}^{++} candidates, a Ξ_c^+ from the Hlt2CharmHadXicpToPpKmPipTurbo turbo line is combined with a same-sign π^+ , which is referred as RS (right-sign). The wrong-sign (WS) background candidates are reconstructed with a Ξ_c^+ from the Turbo line, combined with an opposite-sign π^- . The corresponding decays are:

RS: $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$

WS: $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^-$

The selection has been developed and optimized with signal from MC samples, and background from the far upper side-band (SB) $[3800, 4000] \text{ MeV}/c^2$ in the right-sign data sample, as in the lower side-band region, there could be contamination from wrong-sign Ω_c^{**} or $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \rho^+ (\rightarrow \pi^+ \pi^-)$ decays. Furthermore, the MVA performance (Section 5.2.4) with lower SB events is worse compared to that of upper SB only MVA (Appendix A.5). The wrong-sign sample is



used for cross-checks, with potential contamination from particle mis-identification (mis-ID) background, it has been found to have worse performance compared to that of the far upper side-band of the RS sample (Appendix A.4). To make the signal MC samples more close to data, the PID cuts were not applied directly for MC samples but their effect was emulated via PIDCalib, and the signal MC samples has been re-weighted to have a lifetime of 260 fs, which is more close to the measured one [90]. More detail studies on the choice of background can be found in Appendix A.5.

The selections are done in four steps, the trigger selection, the offline preselection, the MVA-based final selection, and a further proton PID cut, which are described in the sub-sections 5.2.2 5.2.3 5.2.4 5.2.5 respectively.

5.2.2 Selections in the trigger

The `Hlt2CharmHadXicpToPpKmPipTurbo` were developed ahead of time and remained fixed throughout the 2016 data-taking. We summarise them here and give more detailed cut values in Table 7.

- $\Xi_c^+ \rightarrow p^+ K^- \pi^+$ candidates are reconstructed from three long tracks that pass appropriate hadron PID requirements, as well as quality requirements to reject soft and/or prompt tracks ($p_T > 200 \text{ MeV}/c$, $p > 1000 \text{ MeV}/c$, $\chi_{\text{IP}}^2 > 6$). The proton track is required to have momentum $p > 10000 \text{ MeV}/c$ (to ensure that it would be above the Cherenkov threshold in RICH1 under the kaon mass hypothesis, otherwise there is no kaon/proton discrimination). To further suppress background, cuts are placed on combinations of the tracks: at least one of the three tracks must have $p_T > 1000 \text{ MeV}/c$ and $\chi_{\text{IP}}^2 > 16$, at least two of them must have $p_T > 400 \text{ MeV}/c$ and $\chi_{\text{IP}}^2 > 9$, and the scalar p_T sum of the three tracks must be greater than $3000 \text{ MeV}/c$. The Ξ_c^+ candidate must have a good vertex fit quality with $\chi_{\text{vtx}}^2/\text{ndf} < 10$. It must point back to the primary vertex (within 0.01 radian, *i.e.* $\cos^{-1}(\text{DIRA}) < 0.01$), and the vertex should be displaced from primary vertex such that the estimated Ξ_c^+ decay time is more than 0.15 ps.
- Ξ_c^+ candidates are reconstructed from three tracks that pass appropriate hadron PID requirements, as described in Table 7.
- The candidate must be TOS on `Hlt1TrackMVA` or `Hlt1TwoTrackMVA`³ for Ξ_c^+ . The line `Hlt1TrackMVA` selects tracks with large χ_{IP}^2 and p_T , while `Hlt1TwoTrackMVA`

³The thresholds of these two triggers had been slightly changed during the 2016 data taking, but in this analysis,



selects two tracks with reasonably large χ_{IP}^2 and p_T , and requires the two tracks to form a good vertex with large invariant mass. For `H1t1TwoTrackMVA`, the candidates are further required to pass a Boosted Decision Tree (BDT) trained variable, where the input variables of the training are p_T , vertex χ^2 , and flight distance χ^2 information. The detailed selection criteria are given in Table 8.

- For the L0 selection, the candidate must pass a combined TIS/TOS requirement, as `C_L0Global_TIS || Xic_L0Hadron_TOS`.

In the Ξ_c^+ data sample, we selected around 3.9×10^8 candidates from the Turbo stream. For MC events, with the Turbo requirements except those PID cuts, the approximate yield in the signal MC sample is around 2.6×10^4 . Weights from the PIDCalib package are used later to emulate the PID cuts, whose efficiency is around 80%.

5.2.3 Offline reconstruction and preselection

DecayTreeFitter (DTF) is used to refit to the Ξ_{cc}^{++} candidates. This is necessary for the mass measurement studies (see Section 5.4) and also improves the resolution. With DTF, various constraints are possible (such as to constrain the Ξ_c^+ mass to its known value, or to constrain the Ξ_{cc}^{++} to originate from the PV). By default we will use a PV constraint but no mass constraints, unless stated.

The Ξ_c^+ is required to have reconstructed mass in the range (2450, 2488) MeV/ c^2 , which corresponds to about $\pm 3\sigma$. The Ξ_c^+ mass distributions of WS and RS sideband events after Turbo selection are shown in Figure 56. To keep as much signal as we can, the offline selection for π is very loose, only require $p_T > 200$ MeV/ c , and necessary PID cuts.

Similar to the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ analysis the hadron PID cuts (since PID variables will not be included in the multivariate selector that follows) as well other Ξ_{cc}^{++} cuts to ensure that the reconstructed Ξ_{cc}^{++} candidate is sensible. The cuts are chosen to have high overall efficiency while cleaning up some of the background. The PID efficiencies of different hadrons are shown in Appendix A.2, calculated using PIDCalib package.

The details of the cuts used are given in Table 9. PID requirements are applied to all final tracks; these requirements use the multivariate `ProbNNx` variables, and include a loose cut on

we are aiming to a mass and branching fraction measurements or upper limit measurement, which will not be affected by the different trigger thresholds. As the trigger efficiency will not be used in the mass measurement, and it will be cancelled out in the branching fraction or upper limit measurement.



Table 7: Hlt2 trigger selections.

Particle	Variable	Cuts
Ξ_c^+	Cosine of decay angle (DIRA)	$> \cos(0.01)$
	Mass	$\in [2392, 2543] \text{ MeV}/c^2$
	Arithmetic sum of daughter p_T	$3000 \text{ MeV}/c$
	Decay time	$\tau > 0.15 \text{ ps}$
	Vertex quality	$\chi^2_{\text{vtx}}/\text{ndf} < 10$
	Maximum p_T	$> 1000 \text{ MeV}/c$
	Second maximum p_T	$> 400 \text{ MeV}/c$
	Maximum χ^2_{IP}	> 16
	Second maximum χ^2_{IP}	> 9
p	Transverse momentum	$p_T > 200 \text{ MeV}/c$
	Momentum	$p > 10000 \text{ MeV}/c$
	Impact parameter significance	$\chi^2_{\text{IP}} > 6$
	Track quality	$\chi^2/\text{ndf} < 3.0$
	particle ID	$\text{DLL}_{p\pi} > 5.0, \text{DLL}_{pK} > 5$
π	Transverse momentum	$p_T > 200 \text{ MeV}/c$
	Momentum	$p > 1000 \text{ MeV}/c$
	Impact parameter significance	$\chi^2_{\text{IP}} > 6$
	Track quality	$\chi^2/\text{ndf} < 3.0$
	particle ID	$\text{DLL}_{K\pi} < 5.0$
K	Transverse momentum	$p_T > 200 \text{ MeV}/c$
	Momentum	$p > 1000 \text{ MeV}/c$
	Impact parameter significance	$\chi^2_{\text{IP}} > 6$
	Track quality	$\chi^2/\text{ndf} < 3.0$
	particle ID	$\text{DLL}_{K\pi} > 5.0$



Table 8: Hlt1 trigger selections.

Trigger	Selections (p_T in GeV/c)
Hlt1TrackMVA	$p > 5 \text{ GeV}/c$, $\chi^2/\text{ndf} < 2.5$, $P(\text{ghost}) < 0.2$ $\{p_T > 1 \text{ GeV}/c, \log \chi_{\text{IP}}^2 > (\frac{1}{(p_T-1)^2} + \frac{1.1*(25-p_T)}{25} + \log(7.4))\}$ or $\{p_T > 25 \text{ GeV}/c, \chi_{\text{IP}}^2 > 7.4\}$
Hlt1TwoTrackMVA	Tracks: $p > 5 \text{ GeV}/c$, $\chi^2/\text{ndf} < 2.5$, $P(\text{ghost}) < 0.2$ Tracks: $p_T > 0.6 \text{ GeV}/c$, $\chi_{\text{IP}}^2 > 4$ Vertex: $\chi_{\text{vtx}}^2 < 10$, $M(\pi\pi) > 1 \text{ GeV}/c^2$ BDT: > 0.95

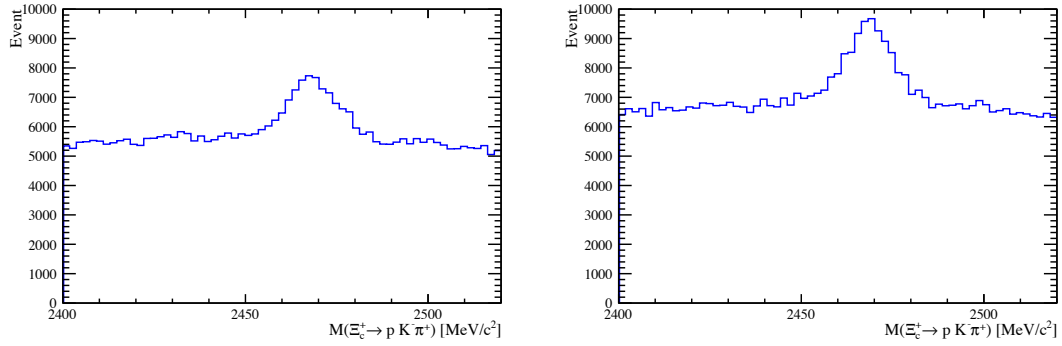


Figure 56: The Ξ_c^+ mass distributions of (left) RS-sideband and (right) WS events after Turbo selection, without any other preselection and MVA selection.

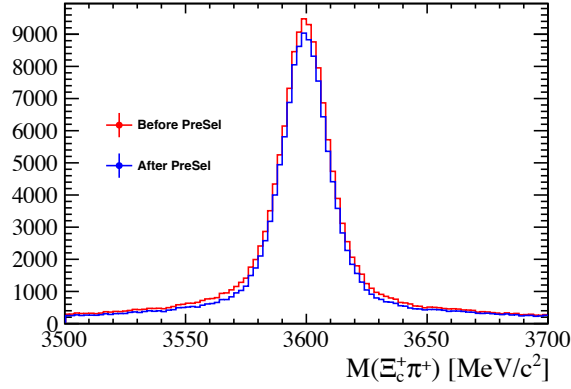


Figure 57: The invariant mass distribution of signal events, before and after preselection cuts.

ProbNNghost. The tracks are also required to have $2 < p < 150 \text{ GeV}/c$ and $1.5 < \eta < 5.0$. In addition, the Ξ_{cc}^{++} is required to originate from the PV ($\chi_{\text{IP}}^2 < 25$), DIRA greater than 0.9, to have a good vertex $\chi_{\text{vtx}}^2/\text{ndf}$ from the initial vertex fit, to have a reasonable χ^2 from the DTF refit, and to have a transverse momentum $p_T > 2 \text{ GeV}/c$. The mass distributions of signal before and after preselection are shown in Figure 57.

Within the given Ξ_c^+ and Ξ_{cc}^{++} mass windows, the efficiency of the cuts described above with respect to the Turbo output is evaluated with the signal MC sample (using PIDCalib for the PID cuts) and found to be around 82%. The background rejection efficiency is tested with the SB sample and is found to be around 97.5%.

5.2.4 Multivariate selection

With preselection applied onto data, there are still a huge number of background events (combinatorial background, as shown in Figure 62). In order to suppress the background and get higher signal purity, a multivariate analysis (MVA) selection is used here. In the training, simulated $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ events after preselection are used as signals, while the SB (WS) sample from the data with the preselection applied is used as the default (cross-check) background. Due to the large statistics of the background, only 10% of the background is chosen uniformly over the whole data taking period, and used in the MVA training and evaluation test, the remaining 90% of background events is used for the MVA cut optimization described below. Following the standard TMVA approach, both the signal and background samples were split randomly into two equally sized disjoint subsamples, one for the training and the other for the test.

The charm hadrons has a relatively long lifetime, and their daughters have relatively hard



Table 9: Offline preselections.

Particle	Selections
all tracks	$2 < p < 150 \text{ GeV}/c$
all tracks	$1.5 < \eta < 5.0$
all tracks	$\text{ProbNNghost} < 0.9$
p	$\text{ProbNNp} > 0.1$
K	$\text{ProbNNk} > 0.1$
all π	$\text{ProbNNpi} > 0.1$
Ξ_c^+	$m \in (2450, 2488) \text{ MeV}/c^2$
bachelor π p_T	$p_T > 200 \text{ MeV}/c$
Ξ_{cc}^{++}	$\text{DIRA} > 0.9$
Ξ_{cc}^{++}	$\chi_{\text{IP}}^2 < 25$
Ξ_{cc}^{++}	$\chi_{\text{vtx}}^2/\text{ndf} < 25$
Ξ_{cc}^{++}	$p_T > 2 \text{ GeV}/c$
Ξ_{cc}^{++}	$\text{DTF refit } \chi^2 < 80$

p_T distribution due to their high mass. The lifetime and p_T related variables, and the vertex fit quality, are used to train the MVA. The variables used in the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ analysis [91] (Section 3.2.3) have been considered as a starting point for this analysis. Unlike the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ analysis, here we have enough MC statistics (2.6×10^4 events after preselection) to utilize more input variables in the training. Also, for Ξ_c^+ the background level in data is higher than that from Λ_c^+ . Therefore, more variables have been employed in this analysis. The final 19 variables used for the training are listed in Table 10, with their correlation matrices shown in Figure 58.

The input variables include p_T and χ_{IP}^2 of p , K , π , Ξ_c^+ , Ξ_{cc}^{++} , π , and Ξ_{cc}^{++} ; $\sum \chi_{\text{IP}}^2$ among final-state daughters of Ξ_{cc}^{++} ; angular information (DIRA); χ_{FD}^2 and $\chi_{\text{vtx}}^2/\text{ndf}$ of Ξ_c^+ and Ξ_{cc}^{++} ; and χ^2 of the Ξ_{cc}^{++} vertex fit (DTF, with PV constraint). More details on the input variables can be found in Appendix A.3.

Several different selector algorithms were considered, and the boosted decision tree (BDT) based and the multilayer perceptron (MLP) based selectors were found to give the best performance. The Receiver Operating Characteristic (ROC) curves of the four selectors are shown in Figure 59, and the MVA output distributions are shown in Figure 60. Figure 60 shows there is no over-training in these four selectors, and all of them are acceptable.

The Punzi figure of merit (FoM) is used to quantify the performance of the selectors and to



Table 10: The 19 variables finally used in the multivariate selector.

$\sqrt{\chi_{\text{IP}}^2}$ of Ξ_c^+ daughters (p, K, π) to its PV
$\sqrt{\chi_{\text{IP}}^2}$ of Ξ_c^+ to its PV
$\sqrt{\chi_{\text{IP}}^2}$ of Ξ_{cc}^{++} daughter π to its PV
$\sqrt{\chi_{\text{IP}}^2}$ of Ξ_{cc}^{++} to its PV
$\sqrt{\sum \chi_{\text{IP}}^2}$ among the daughters ($p, K, \pi, \Xi_{cc}^{++} - \pi$) of Ξ_{cc}^{++}
$\log(p_T)$ of Ξ_c^+ daughters (p, K, π)
$\log(p_T)$ of Ξ_c^+
$\log(p_T)$ of Ξ_{cc}^{++} daughter π
$\log(p_T)$ of Ξ_{cc}^{++}
$\cos^{-1}(\text{DIRA})$ of Ξ_{cc}^{++} to its PV
$\sqrt{\chi_{\text{FD}}^2}$ of Ξ_{cc}^{++} from its PV
$\sqrt{\chi_{\text{FD}}^2}$ of Ξ_c^+ from its PV
$\chi_{\text{vtx}}^2/\text{ndf}$ of the Ξ_c^+ vertex fit
$\chi_{\text{vtx}}^2/\text{ndf}$ of the Ξ_{cc}^{++} vertex fit (non-DTF)
χ^2 of the Ξ_{cc}^{++} vertex fit (DTF, with PV constraint)

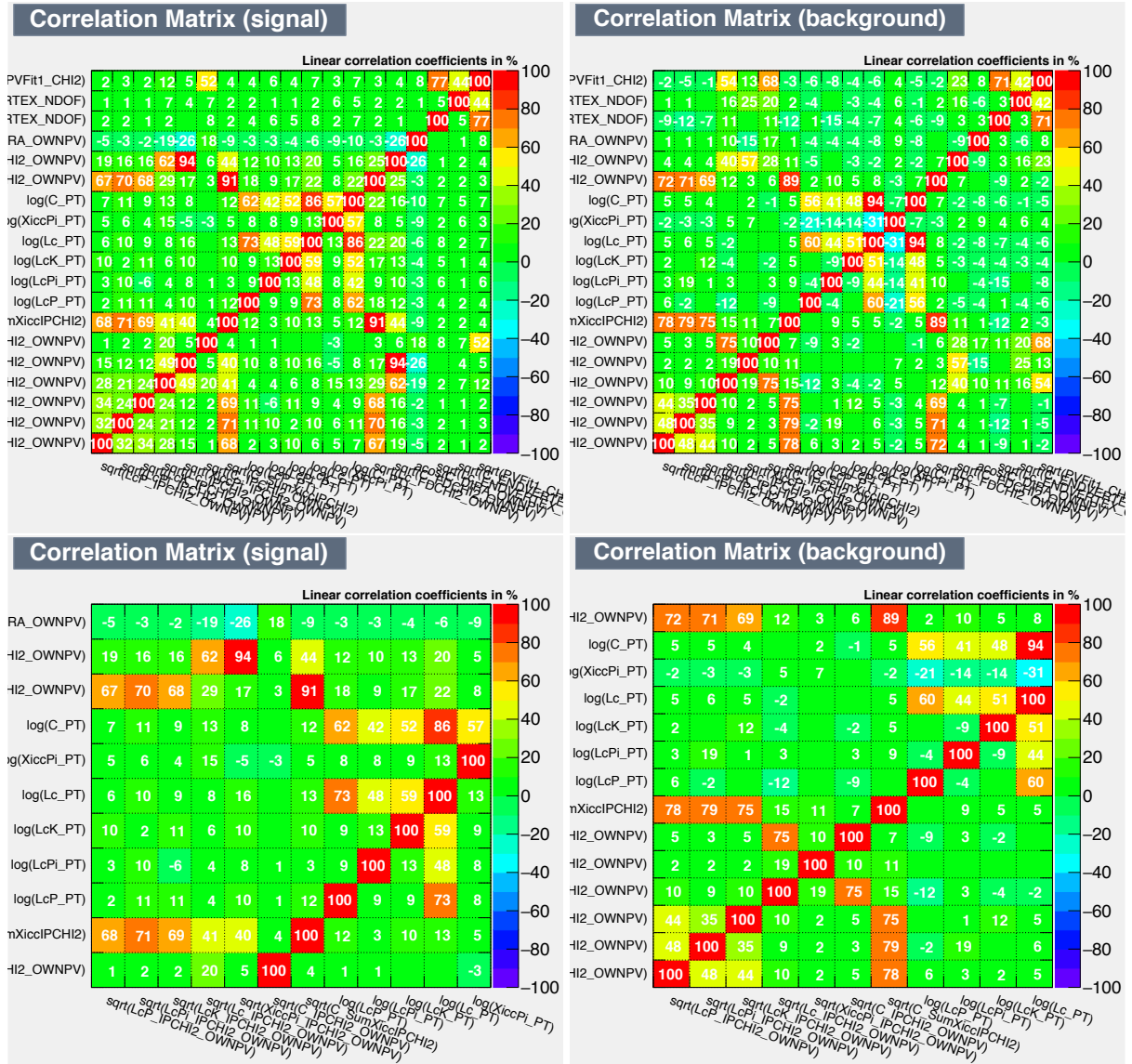


Figure 58: Correlation matrices for the 19 variables used in the multivariate selector, for (top-left) signal and (top-right) background. The zoomed figures are shown in the bottom two plots.

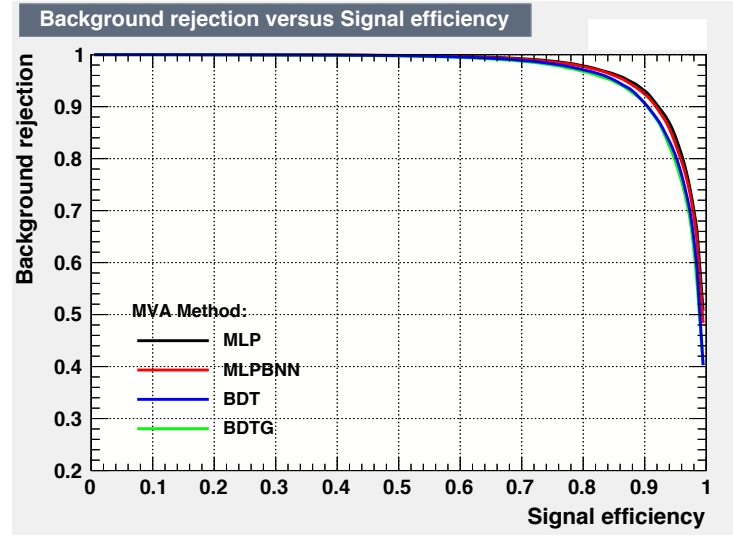


Figure 59: ROC curves for four selectors. The vertical axis shows the background rejection fraction, and the horizontal the signal efficiency. Good performance is obtained, with a signal efficiency of 50% corresponding to a background rejection of around 99.85%.

choose a working point. For a cut t on the output, the figure of merit is defined as

$$F(t) = \frac{\varepsilon(t)}{\frac{a}{2} + \sqrt{B(t)}}, \quad (52)$$

where ε is the signal efficiency, B is the expected background in the signal region, and $a = 5$ is the desired significance. These are evaluated as

$$\begin{aligned} \varepsilon(t) &= \frac{\text{No. of signal candidates passing full selection}}{\text{No. of signal candidates generated}} \\ B(t) &= \frac{\text{No. of background candidates passing full selection}}{C_{\text{scaling}} \times C_{\text{window}}}. \end{aligned}$$

Thus, $\varepsilon(t)$ is the full efficiency after generator-level and offline cuts. For example, when applying no cut on the MVA output the numerator would be $\approx 26,000$ (the effect of the PID cuts emulated via PIDCalib) and the denominator would be $\approx 4M$. Since $B(t)$ is the expected background underneath the signal but what we measure is the number of background events in our control sample, we need to apply various scaling factors:

- C_{scaling} corrects for any downscaling used in the background sample: in this analysis it is 0.9, since 10% of background sample was used for the training and the test.
- C_{window} corrects for the mass window used. In this analysis, the upper side-band data events are used in this optimization, and wide range of $3300 < m(\Xi_{cc}^{++}) < 3800 \text{ MeV}/c^2$ are

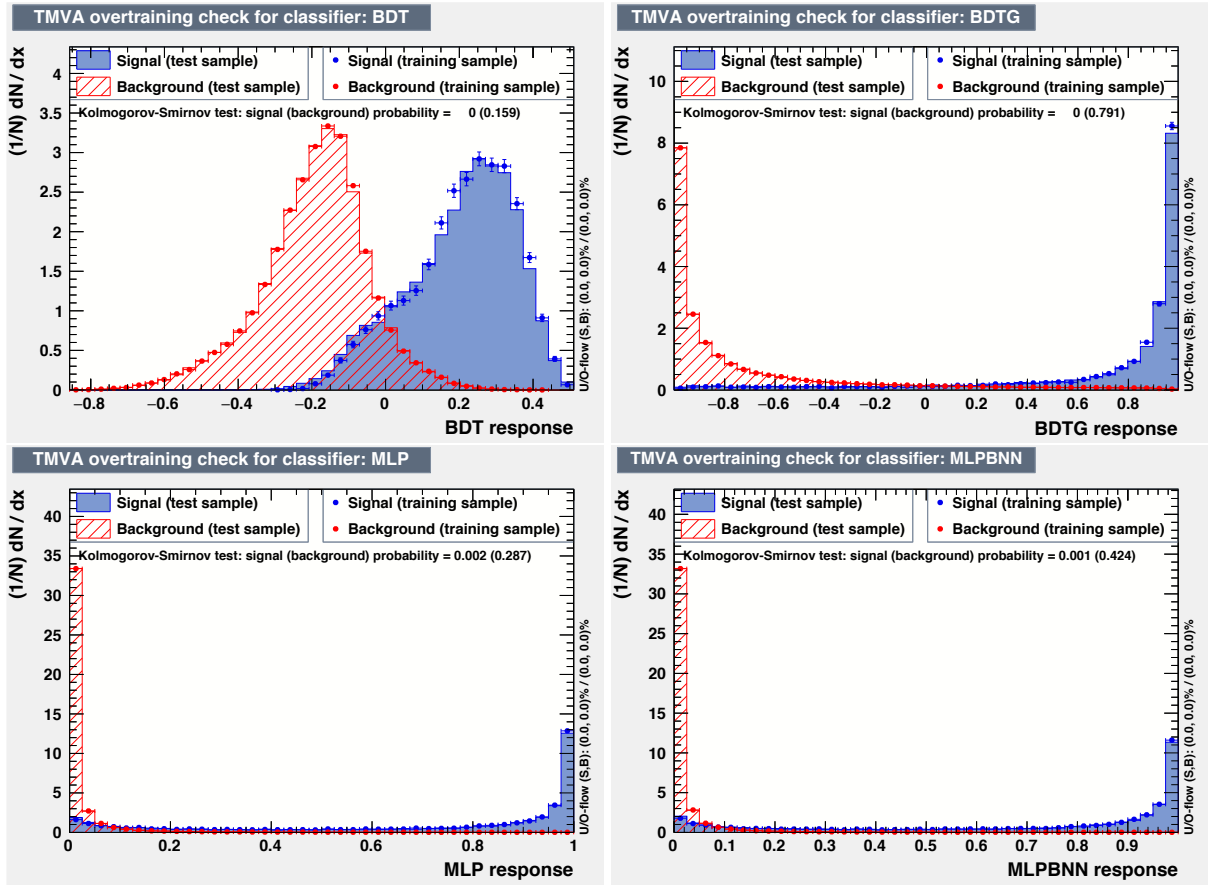


Figure 60: Response curves for four selectors: (top left) BDT, (top right) BDTG, (bottom left) MLP, (bottom right) MLPBNN . For each plot, the horizontal axis shows the MVA output and the vertical axis shows the normalized distribution. The output for the training sample is shown as points with error bars and the output for the test sample is shown as a shaded/hatched histogram.

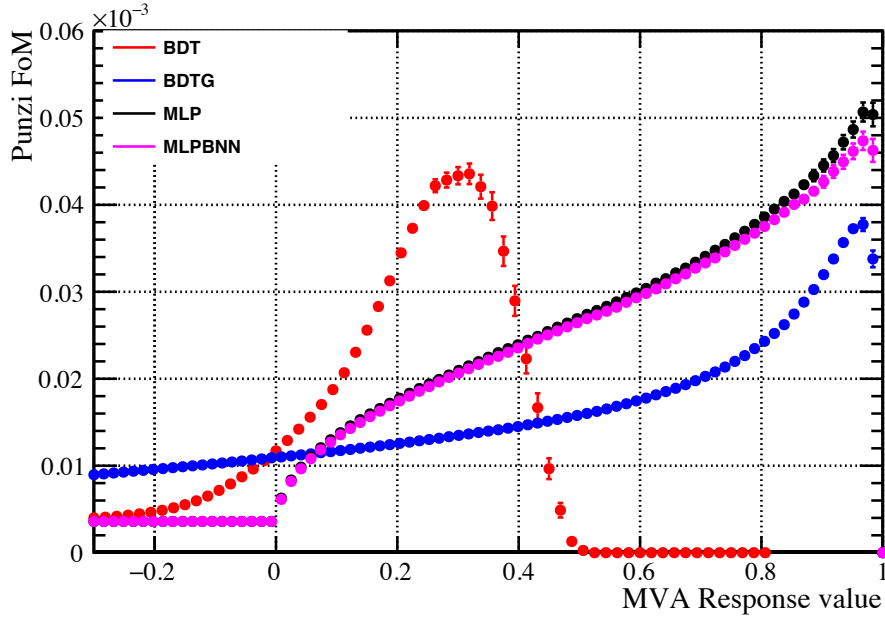


Figure 61: Dependence of the Punzi figure of merit $F(t)$ on the cut applied, for four different selectors. The SB sample is used as background.

used for Ξ_{cc}^{++} search. The expected resolution depends on the Ξ_{cc}^{++} mass and is measured to be around $10.0 \text{ MeV}/c^2$ using MC events. We suppose that the relevant range is $\pm 3\sigma$. For each cut t the invariant mass distribution of upper sideband events was fitted by an exponential function, and the ratio of the number of the background in the wide range to that underneath the signal peak ($m(\Xi_{cc}^{++}) = 3620 \text{ MeV}/c^2$) is calculated, and it is found that $C_{\text{window}} \approx 2.13$.

For example, when applying no cut on the MVA output, $B(t)$ would be around 1.49×10^6 , and thus $F(t)$ would be 6.7×10^{-3} .

The variation of $F(t)$ is shown for different selectors in Figure 61, and the optimal values are shown in Table 11. We find that the working points are broadly similar between the different selectors. The MLP has been chosen, on the ground that it appears more robust against overtraining. The working point we use is a cut $t > 0.9775$. The MLP selection efficiency with respect to preselection is around 32.2%, as compared with other MVA selection criteria given in Table 11.

Two-step MVA method has been also considered in this analysis, which training a MVA for Ξ_c^+ at first, and then combined Ξ_{cc}^{++} information, a second MVA is used for event selection. The two-step MVA has potential to get a better Ξ_c^+ background rejection compared to one-step



Table 11: The optimal working points for various MVA selectors, and the relative efficiencies and FOM values at those working points. Here ε_{MVA} is defined as the relative efficiency of the selector with respect to the preselection.

Selector	Optimal cut t	ε_{MVA}	$F(t) (\times 10^{-5})$
BDT	0.3188	0.251 ± 0.003	4.36 ± 0.12
BDTG	0.9650	0.369 ± 0.003	3.77 ± 0.07
MLP	0.9775	0.322 ± 0.003	5.15 ± 0.11
MLPBNN	0.9725	0.315 ± 0.003	4.77 ± 0.11

MVA, as the first MVA could be used to suppress the Ξ_c^+ background, resulting a Xic sample with higher purity. But after detailed study on this in Appendix A.6, we found the one-step MVA has similar performance compared to that of two-step MVA, by using same sample to perform TMVA training and evaluate the FoM performance. As the one-step MVA even has a slightly better performance, therefore, the one-step MVA is chosen as the default one. The signal MVA efficiency check is discussed in Appendix A.7.

Finally, we perform several cross-checks to ensure that the MVA training is reasonable.

Checks for mass peak in WS sample

First, we check that the selector does not create any strange structures in the background mass distribution (the mass with PV constraint). To do this we look at the yield and retention in bins of mass for the WS sample after applying the optimized MVA selection (MLP used), as shown in Figure 62. No significant peaking structures are seen.

Checks for MVA performance with different lifetime

Second, we check that the behavior varies in a reasonable way with the Ξ_{cc}^{++} lifetime. To do this, we reweight the sample of signal MC to emulate different lifetime hypotheses. We checked this by applying the default MVA algorithm without re-training to the reweighted sample and re-optimize the working point. The results are shown in Figure 63, where the y-axis shows the Punzi FOM $F(t)$. There is a directly proportional to the overall efficiency, as numerator is $\varepsilon(t)$, in the meanwhile, the denominator is unaffected by the reweighting. As expected, longer lifetimes have better overall efficiency. We can see that the efficiency is roughly linear over most of the

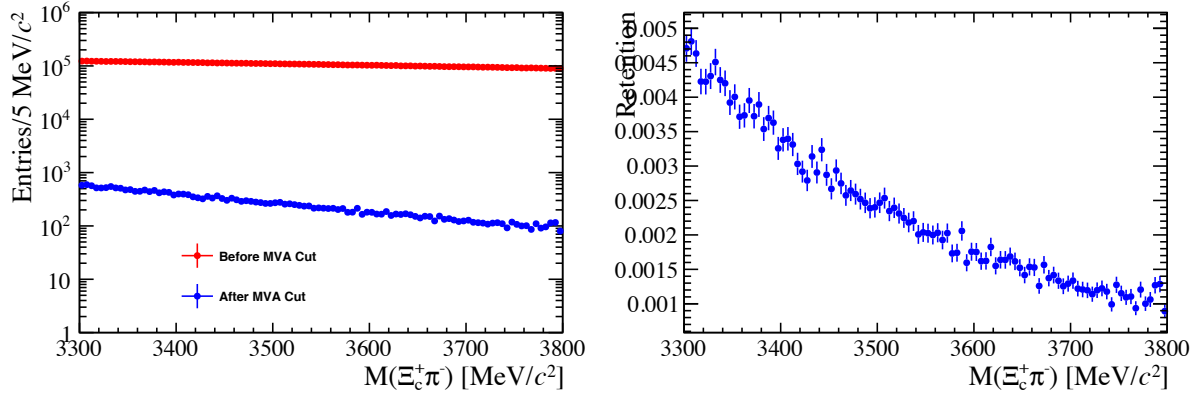


Figure 62: (left) the mass distribution before and after the MVA selector, and (right) the background retention rate of that selector. The MLP selector and the cut value obtained with the SB sample is applied to the WS samples.

working range (200–350 fs), which demonstrate our MVA method works well across a range of lifetimes.

Checks for FoM as function of PID cuts

When reasonable PID cuts are applied usually tighter PID cuts will not improve the FoM value. We checked this with tighter PID cuts on top of the MVA cuts applied. Since a multiple dimensional optimization will be very difficult, we made two quick checks. Without a proper study on different MC PID cuts efficiency, these two tests are just used to demonstrate there is no large PID dependence on the MVA. For events with larger PID values, PID efficiency is over-estimated compared to that in data, therefore, the FoM distributions are over-estimated in the high PID value region.

In the first check, we applied the same cut value to the corresponding `ProbNNx` variables for all final tracks. The FoM as a function of the cut value is shown in Figure 64. In the second check, we made 1D scans of the `ProbNNx` cut for each track while leaving other tracks' cut values untouched. The scans was done for each track, and the results are shown in Figure 65. These plots show that tighter PID cuts will improve the FoM. Also, considering the mis-ID background mainly arise from proton mis-ID, we decided to use a tighter proton PID cut, and keep the PID cuts for kaon and pion as `ProbNNx` > 0.1. More details on the PID optimization are shown in Appendix A.8.

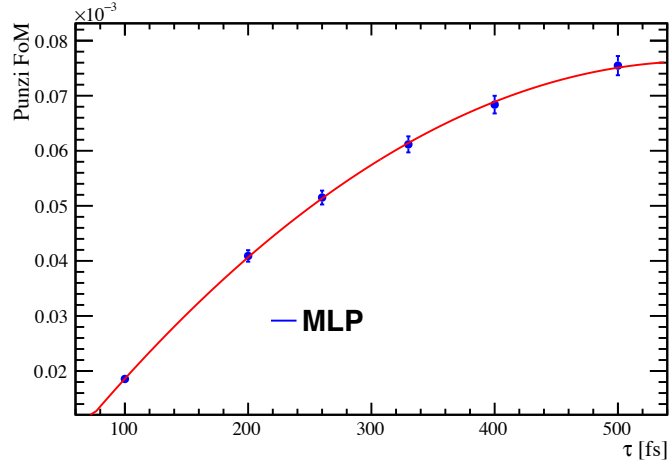


Figure 63: The $F(t)$ distributions obtained after reweighting the signal MC sample to different lifetime hypothesis. In this plot, the default training and working point are used. The red curve is fitting results with a polynomial function.

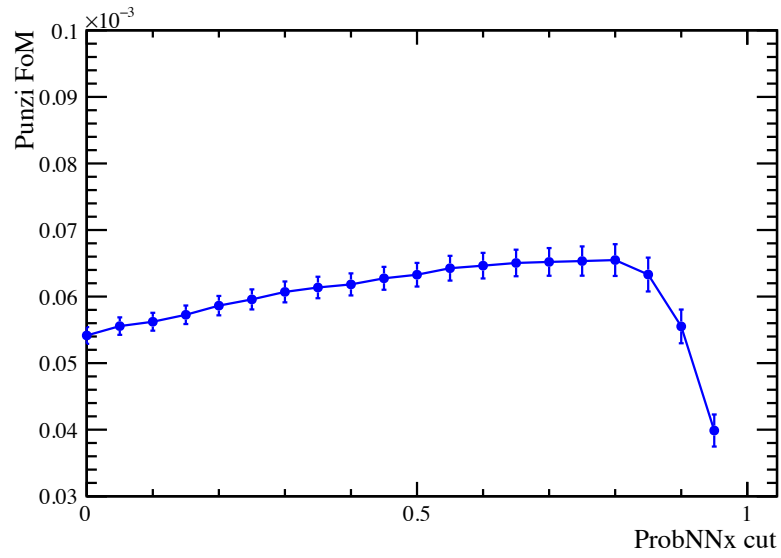


Figure 64: The Punzi FoM as a function of the cut value which is applied to the corresponding ProbNNx variables for all final tracks.

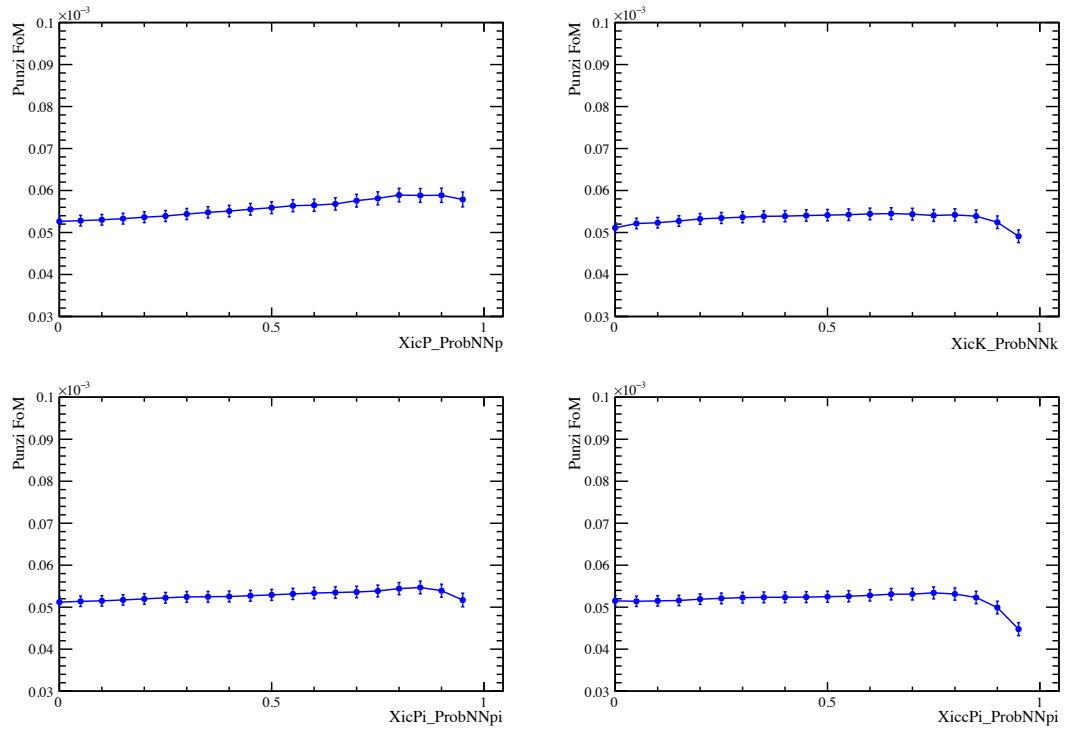


Figure 65: The Punzi FoM as a function of the cut value which is applied to the ProbNN $\times$ variables for each corresponding track, while cuts on other variables remain.

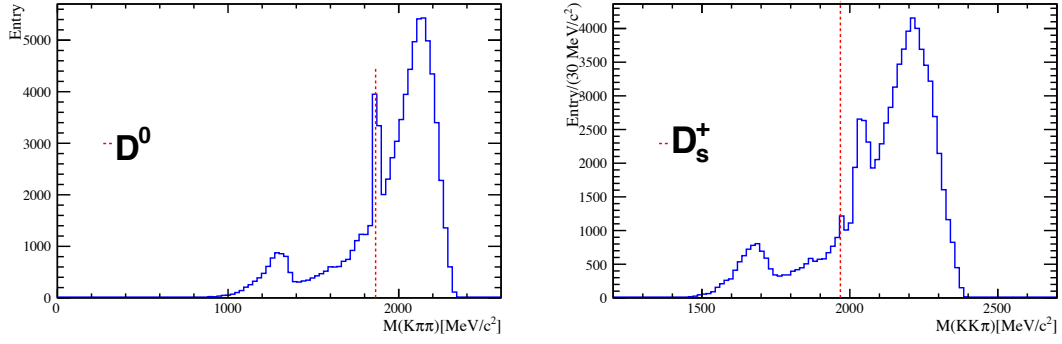


Figure 66: The Ξ_c^+ mass distribution with different mass different mass hypotheses for final-state particles. (left) is treat p as π , (right) is treat p as K . There are peaking backgrounds from D hadrons.

Tighter proton PID cut

As shown in the Figure 65, after preselection, the Punzi FoM has proton PID dependence. Furthermore, in the Ξ_c^+ mass distribution and WS Ξ_{cc}^{++} mass distribution, there are sizable contributions from proton mis-ID, as shown in Figure 66 for proton mis-ID background in Ξ_c^+ candidates, and Figure 67 for proton mis-ID background in Ξ_{cc}^{++} WS candidates, which means for the selected Ξ_c^+ with loose PID ($\text{ProbNN}_x > 0.1$), the physics contributions from low mass D mesons cannot be ignored. As shown in Figure 68, the Ξ_c^+ mass distribution has a large background contribution. These physics backgrounds can be removed by applying a tighter proton PID cut ($\text{ProbNN}_p > 0.8$). Therefore, the $\text{ProbNN}_p > 0.8$ is further required on the candidates after the trigger, preselection and MVA selection. The Ξ_c^+ mass distribution with tighter PID cut applied is shown in Figure 69. More details on the mis-ID background are discussed in Appendix A.4.

The procedure that with $\text{ProbNN}_p > 0.8$ applied before MVA selection had been checked, and the Punzi FoM is worse than that of default procedure, therefore, we decided to apply the tighter proton PID cut after MVA selection.

5.2.5 Removal of internal track clone candidates

Candidates with any same charge track-pairs closer than 0.5 mrad in angle are removed to eliminate clones, as described in Section 5.3.3.

5.2.6 Duplicate candidates

As discussed in $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ analysis [91] (Section 3.4), the level of multiple candidates is not expected to be small, where the duplicated events are from multiple combinations

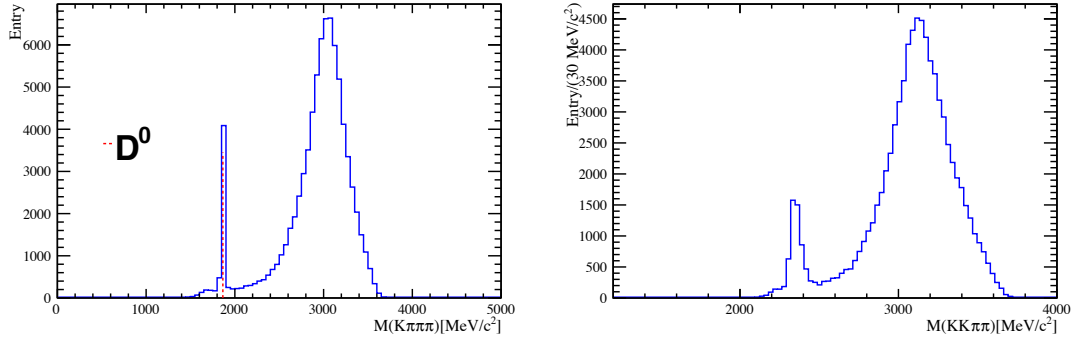


Figure 67: The Ξ_{cc}^{++} mass distribution with different mass different mass hypotheses for final-state particles. (left) is treat p as π , (right) is treat p as K . There are peaking backgrounds from D hadrons.

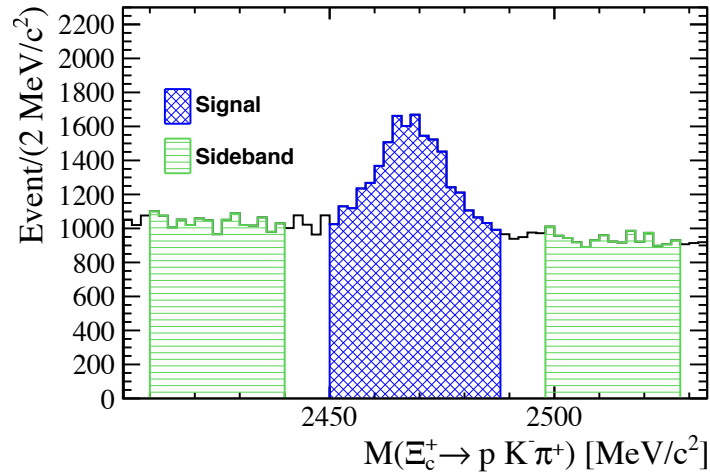


Figure 68: Ξ_c^+ invariant mass distribution, selected with loose proton PID cut ($\text{ProbNNp} > 0.1$). The shaded area indicating (blue crossed) the signal region and (green horizontal) the sideband regions. Events are taken from the WS sample with MVA cuts applied.



of a lot of tracks in the same events. More details on the different types of duplicate events is discussed in Section 5.3.2.

5.3 Studies of the backgrounds

In this section, we summaries the studies of background components using the WS sample, including: Ξ_c^+ backgrounds, track clones and multiple candidates. We try to illustrate that these specific background contributions do not create fake narrow structure in the $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ invariant mass distribution. In the following, candidates reconstructed in either WS or SB are referred to Ξ_{cc}^{++} decay for simplicity and without confusion.

5.3.1 Ξ_c^+ background

As mentioned in the previous section, the Ξ_c^+ signal window is defined as $[2450, 2488] \text{ MeV}/c^2$, shown in the middle cross-shaded region of Figure 69. The Ξ_c^+ sideband regions are defined as $[2410, 2440] \cup [2498, 2528] \text{ MeV}/c^2$, which are also shown in Figure 69. Figure 70 shows comparisons of the $\Xi_c^+ \pi^-$ mass distributions in different Ξ_c^+ mass regions. In the WS sample without any MVA selection, the $\Xi_c^+ \pi^-$ mass distribution in the Ξ_c^+ signal region (labeled as ‘Signal’), after the background subtraction, is consistent with that in the Ξ_c^+ sideband region (labeled as ‘Sideband’). After applying the MVA cut, the $\Xi_c^+ \pi^-$ mass distributions in the Ξ_c^+ signal region is slightly different from that in the Ξ_c^+ sideband regions. Such small difference might be caused by that several Ξ_c^+ variables are used in the MVA training, which could have different impact on the Ξ_c^+ signal and side-bands. However, the results suggest the combinatorial background candidates from either signal Ξ_c^+ or Ξ_c^+ combinatorial background don’t cause narrow peaking structures.

5.3.2 Multiple candidates

In this analysis, for Ξ_{cc}^{++} candidates, we have four tracks in the final state. In the Ξ_{cc}^{++} candidates after the Turbo stream selection, we observed on average 5.6 candidates per event in the WS sample. Then after the full offline selections, this number reduces to 1.015, around 1.5% of the events have multiple candidates.

Here, using the WS samples we demonstrate that for background events, multiple candidates do not created narrow fake peaks. So we tend not to reduce random combinations of multiple

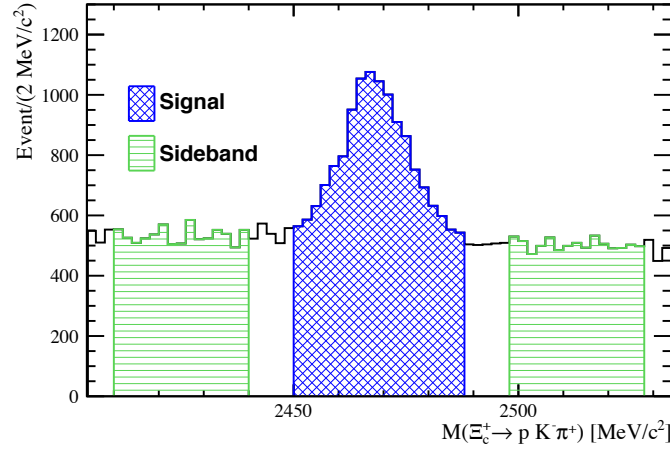


Figure 69: Ξ_c^+ invariant mass distribution, selected with tighter proton PID cut ($\text{ProbNNp} > 0.8$). The shaded area indicating (blue crossed) the signal region and (green horizontal) the sideband regions. Events are taken from the WS sample with MVA cuts applied.

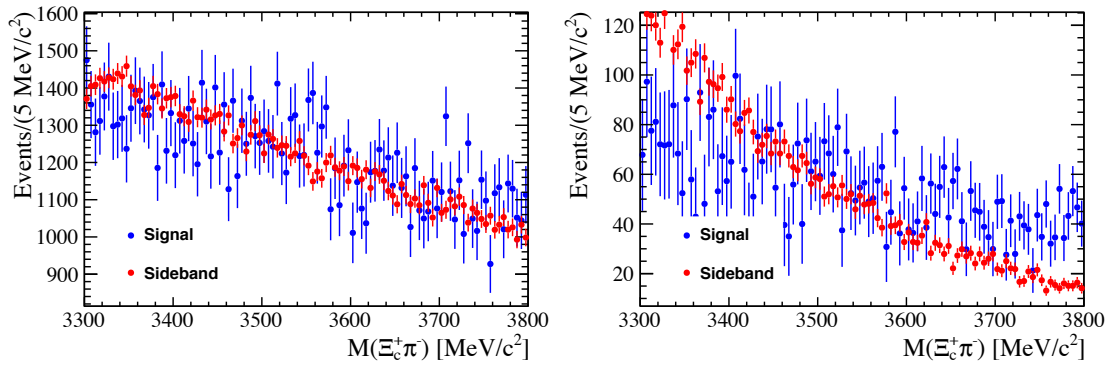


Figure 70: Invariant mass distributions of Ξ_{cc}^{++} candidates in the WS samples. The left histogram represent the invariant mass distribution in the Ξ_c^+ signal region and Ξ_c^+ sideband region, using partial WS sample before applying the MVA selection. The right histogram represent the Ξ_{cc}^{++} mass distribution in the Ξ_c^+ signal region and Ξ_c^+ sideband region, using entire WS sample after applying the MVA selection. The ‘signal’ distribution is estimated using the sideband subtraction method with Ξ_c^+ mass information.



candidates, in order not to accidentally reduce our signals, or create any bias due to the removal procedure.

Several multiple candidates scenarios are considered in this analysis:

- Two (or more) candidates in the same event share all four tracks with the same corresponding mass (ID) assignments among the candidates, where the same event is identified by using unique runNumber and eventNumber at the same time.
- Two (or more) candidates in the same event share a few but less than four tracks in the final states, and the shared tracks have the same mass assignments.
- Two (or more) candidates share either all final state tracks of a fraction of them, but at least one shared track have different mass assignments in different candidates.

The first scenario, namely duplication (track-exchange). Duplicate candidates are constructed with exactly the same final tracks, and they have exactly the same Ξ_{cc}^{++} invariant mass by definition, but the Ξ_c^+ mass could be very different. Also, the selections could help to suppress these duplicate candidates, including the Ξ_c^+ mass window requirement, the vertex fit quality etc. Figure 71 shows the invariant mass distributions for the duplicate candidates in the MC sample and the WS sample. The duplicate candidates in the MC sample show a peak around the true mass (as expected), while for pure combinatorial background the duplications do not create fake narrow peak (also as expected). In the WS sample, after the event selection, the multiple candidates from the swap of tracking is around 1.0006, which means only 0.06% events had been reconstructed twice with exactly same final state tracks. Considering the small rate of this type of events, and most of swapped candidates are located in the lower mass region, the effect can be ignored in this analysis, so we will not discuss this background in this analysis. The second scenario is naturally expected, for example a Ξ_c^+ is combined with one additional pion to form a Ξ_{cc}^{++} , while the third case corresponds to mis-ID backgrounds, and is highly suppressed by the tight PID selections, as discussed in Appendix A.4. In WS data sample, we found that the second type of multiple candidates dominates ($\sim 70\%$) the multiple candidates contributions; especially, the same Ξ_c^+ candidate is used by two or more candidates. We now demonstrate that the last two scenarios are not expected to create significant narrow fake peaks.

For each unique event, we study the mass distribution for those containing a singly selected candidate and those with multiply selected candidates after final selections, as shown in Figure 72. In the plot, the duplication candidates (the first category) have been removed already.

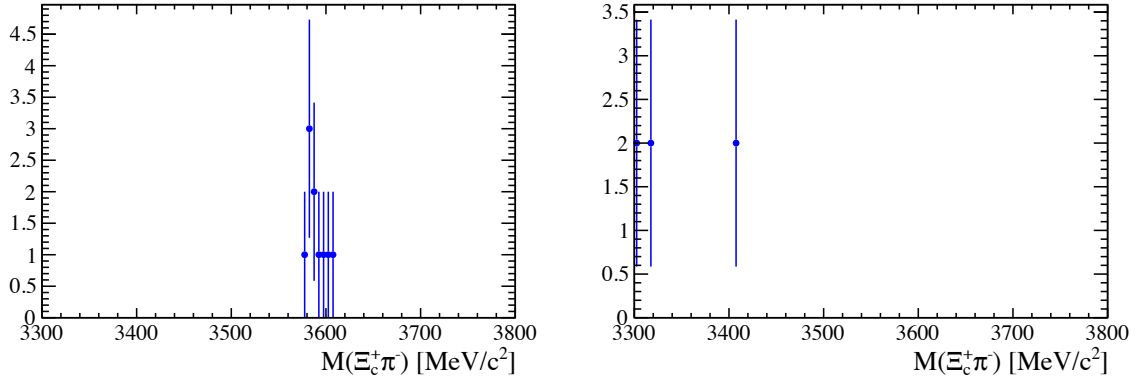


Figure 71: Distributions of the (left) MC RS Ξ_{cc}^{++} mass, and (right) WS Ξ_{cc}^{++} mass ($M(\Xi_c^+, \pi^-)$) for duplicate candidates due to track exchange after the final selection.

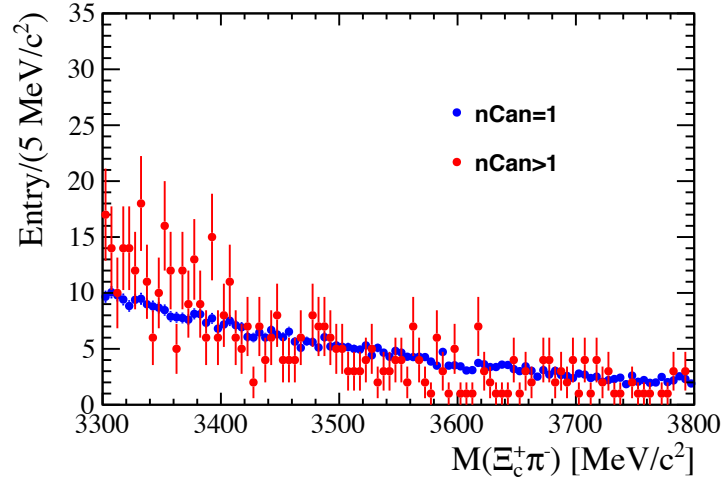


Figure 72: Invariant mass distributions of WS Ξ_{cc}^{++} candidates for events with exactly one candidate passing final selection and for those in events that have multiple candidates selected. The one candidates events distribution has been normalized to that of multiple candidates distribution.

The mass distributions for one candidate and multiple candidate events are very similar, with no significant narrow peaking structure identified, also, as discussed before, the contribution from the multiple candidates is around 1.0%.

In conclusion, multiple candidates are not removed as part of the selections, since the removal procedure could cause bias. On the other hand, only 1.0% event has multiple candidate, and they doesn't cause obvious narrow peaks.

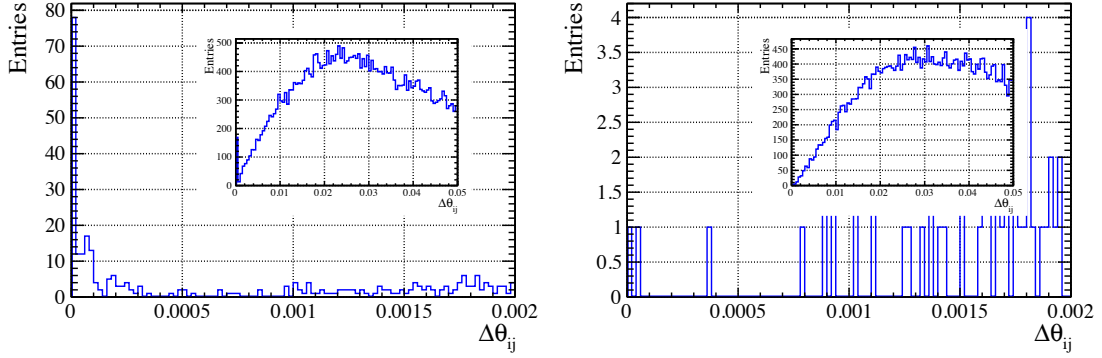


Figure 73: Angles of tracks with same charge in (left) WS, and (right) truth matched Ξ_{cc}^{++} MC samples. The insert for each plot gives the same distribution but in a larger region.

5.3.3 Clone tracks

Since the Ξ_{cc}^{++} candidates in this analysis are reconstructed from four tracks, the decay is expected to suffer from contamination from clone candidates. A clone candidate has at least one track which is cloned from another track of the same candidate, defined for this particular case. Two tracks which are clones of each other have relative angle accumulated around zero.

In 2016 Turbo data, there is potential problem that pick up one bachelor pion twice from PerstistReco, for both Ξ_c^+ and Ξ_{cc}^{++} reconstructions. The contribution from this scenario has been largely suppressed, by adding a function ‘CheckOverlap’ of ‘LoKi’ in the DaVinci scripts.

In Figure 73, we plot the angles for any pairs of tracks (among all the four tracks) with the same charge in the WS and truth matched MC samples. In WS samples, a peak around zero angle is seen, consistent in the two samples, which is understood to be clone tracks. The same peak is not seen in simulation, as these candidates are removed by the MC-Match algorithm. By applying a cut at $\delta\theta_{i,j} > 0.5$ mrad, the clone contributions can be almost fully removed, without affecting the signal decays in a large amount. If a candidate has at least one pair of clone tracks in the final states, we remove it; and this procedure removes around 0.7% for WS, and rejects only 3 candidate in signal MC among 26,000 candidates. In Figure 74, the mass of Ξ_{cc}^{++} candidates for the clone candidates are shown compared with the nominal distributions after the MVA selections, for WS samples. The clone candidates have averagely smaller mass due to smaller open angle of final state tracks. No significant peaks are identified in the clone candidates.

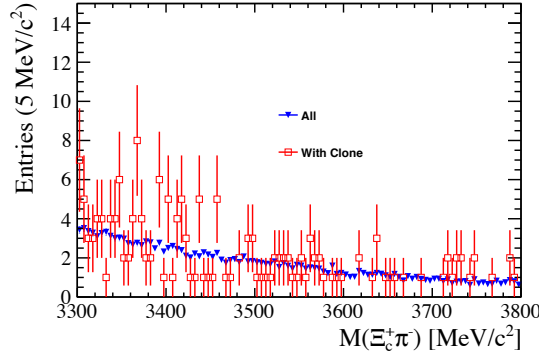


Figure 74: Ξ_{cc}^{++} invariant mass distribution of WS for (blue triangle) default selections and (red square) clone candidates.

5.4 Measurement of Ξ_{cc}^{++} mass

In this section, we describe the analysis of measuring Ξ_{cc}^{++} mass using the mode $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$.

5.4.1 Mass fitting

The Ξ_{cc}^{++} mass is measured from the invariant mass distribution of $\Xi_c^+ \pi^+$ fitted with signal plus combinatorial background components. As will be discussed later in Section 5.4.3, the mass difference between the Ξ_{cc}^{++} and Ξ_c^+ has been measured, then the known Ξ_c^+ mass [92] is used to determine the Ξ_{cc}^{++} mass. To do that, the variable $DM \equiv M(\Xi_{cc}^{++}) - M(\Xi_c^+) + M_{PDG}(\Xi_c^+)^4$ is used in the study, where $M(\Xi_{cc}^{++})$ and $M(\Xi_c^+)$ are the reconstructed mass after applying kinematic/geometrical fit (DecayTreeFitter) with the primary vertex constraint. The kinematic refitting helps to improve the mass resolution, and the momentum scaling calibration is applied in such fit.

The shape of the signal mass distribution is obtained from the fully simulated Ξ_{cc}^{++} sample with selection described in Section 5.2.⁵ The DM distribution could be well described by a Gaussian distribution plus double sided crystal ball function (DSCB) sharing the same mean value μ , as shown in Figure 75 for the simulated sample⁶. The width of DSCB is scaled from the width of the Gaussian. The fitted parameters are given in Table 12 for the fit to the candidates with MVA selection applied in simulation. The effective mass resolution is defined as $\sigma = \sqrt{f \cdot \sigma_1^2 + (1 - f) \cdot \sigma_2^2}$, where σ_1 (σ_2) is the width of Gaussian (DSCB) and f

⁴Without specific statement, the DM is used as default mass variable, include previous Sections.

⁵MC truth match applied everywhere if not specified.

⁶Based on $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ study [93], the shape of data/signal DM could be well described by Gaussian plus DSCB. Therefore, we use them to model the signal DM shape, empirically. Additional systematic uncertainty has been assigned to the signal modelling, as discussed in Sec. 5.4.6



is the fraction of Gaussian. Due to strong correlations of f with other parameters, it is fixed to $f = 0.3$. The resolution estimated in simulation, $(6.45 \pm 0.14) \text{ MeV}/c^2$, has to be scaled with the Q value, $Q(\Xi_{cc}^{++}) \equiv \mu(\Xi_{cc}^{++}) - M_{\text{PDG}}(\Xi_c^+) - M_{\pi^+}$. The resolution has linear dependence with Q values. In the MC events, the Ξ_{cc}^{++} mass is fixed to $3597.98 \text{ MeV}/c^2$, which is about $20 \text{ MeV}/c^2$ from the measured value, therefore, we scaled the MC resolution to get data resolution, using Q values of MC and data. In the end, the resolution σ for Ξ_{cc}^{++} in data is estimated to be $(6.45 \pm 0.14) \cdot Q_{\text{Data}}(\Xi_{cc}^{++})/Q_{\text{MC}}(\Xi_{cc}^{++}) \text{ MeV}/c^2$, where $Q_{\text{MC}}(\Xi_{cc}^{++}) = 990.5 \text{ MeV}/c^2$ and $Q_{\text{Data}}(\Xi_{cc}^{++}) \text{ MeV}/c^2$ is fixed by fitting to data. When we fit to the right-sign sample, the μ value of the signal component is a free parameter to be determined from data, same for the resolution parameter in fit. Other parameters are fixed to values obtained in Ξ_{cc}^{++} simulation as shown in Table 12, and their uncertainties will be considered as a source of systematic uncertainties, studied by varying the parameters according to their uncertainties (details given in subsection 5.4.6).

The background mass distribution can be well described by an exponential function. The wrong-sign mass distribution, and the right-sign mass distribution in the Λ_c^+ sideband region after applying all the event selection, together with wrong-sign mass distribution fit result are shown in Figure 76, where both wrong-sign and the right-sign mass distribution in the Λ_c^+ sideband region shapes can be well modelled with the exponential function.

In the following, we study the possible sources of systematic effects on the mass measurements, including the uncertainty on the momentum scaling calibration, the bias of the reconstructed Ξ_c^+ mass, the bias of Ξ_{cc}^{++} mass due to offline selections, the final state radiation, the uncertainty on the known Ξ_c^+ mass, the uncertainty due to Ξ_{cc}^{++} invariant mass fit model and the uncertainty coming from track-exchange candidate. We also discuss the possible contributions from mis-ID backgrounds from other physical decay signals.

5.4.2 Momentum scaling calibration

Due to non-perfect alignment of tracking system and uncertainty on magnetic field, the measured track momenta need to be calibrated to correct for possible biases. For the Run II data, the momentum scaling is calibrated using large samples of detached J/ψ in $J/\psi \rightarrow \mu^+\mu^-$ decays and $B^+ \rightarrow J/\psi K^+$ decays reconstructed in the stripping [94, 95]. In the calibration procedure, track momenta are scaled with $1 - \alpha$, with α being the momentum correction factor, to bring the observed J/ψ and B^+ masses to the known value. The momentum correction is performed according to data taking period, magnet field polarity and track charge. The overall correction

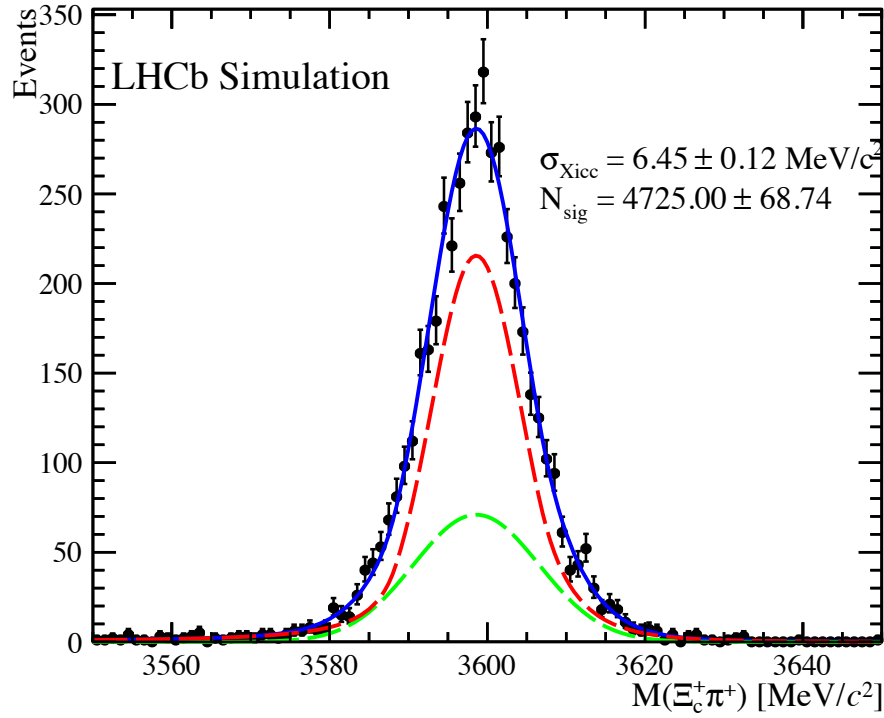


Figure 75: Invariant mass distribution DM in Ξ_{cc}^{++} simulation, fitted with Gaussian plus double sided crystal ball function. The fit is used to validate the model and to estimate the parameters that are to be fixed when fitting data.

Table 12: The resulted parameters from the fit to the Ξ_{cc}^{++} invariant mass distribution in simulation, with a Gaussian function plus a DSCB.

Parameter	Value
μ	$3598.62 \pm 0.09 \text{ MeV}/c^2$
σ (resolution)	$6.50 \pm 0.10 \text{ MeV}/c^2$
$R = \frac{\sigma(\text{DSCB})}{\sigma(\text{Gaussian})}$	0.75 ± 0.04
$f(\text{Gaussian})$	0.3(fixed)
a_L	1.89 ± 0.34
n_L	1.82 ± 0.08
a_R	6.58 ± 1.40
n_R	1.47 ± 0.08
If other parameters fixed to values above	
μ	$3598.59 \pm 0.08 \text{ MeV}/c^2$
σ	$6.45 \pm 0.14 \text{ MeV}/c^2$

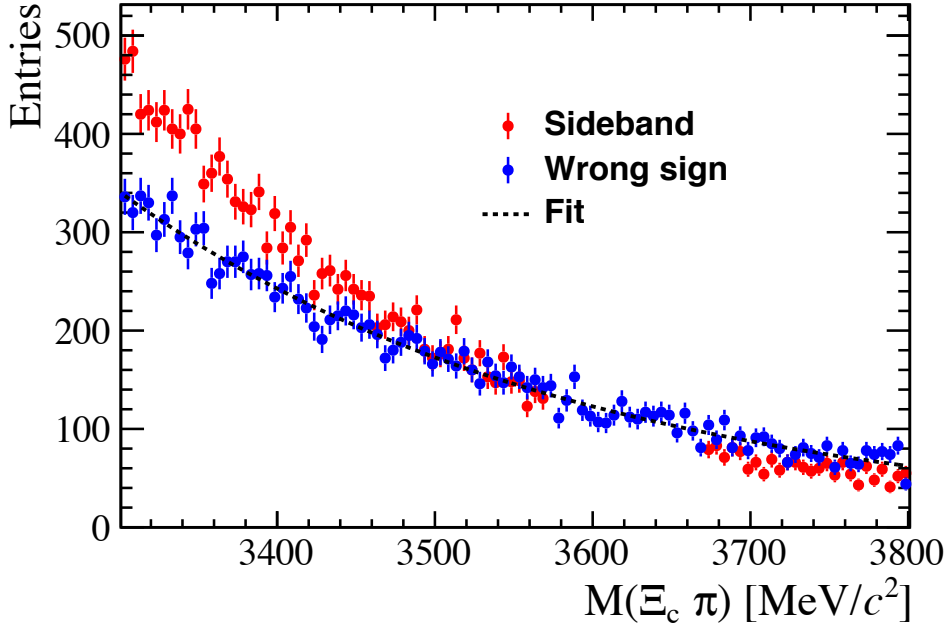


Figure 76: Invariant mass distribution of wrong-sign background and the right-sign in the Λ_c^+ sideband region. The wrong-sign mass distribution is fitted with an exponential function.

factor α is at the level of $0.3 \text{ GeV}/c^2$. Accordingly, the correction also shifts the observed mass for a particle, reconstructed in a particular decay, by an amount of $\Delta\mu \approx Q \cdot \alpha$, where Q is the energy release for that decay, and this is how the momentum calibration brings observed J/ψ mass to its known value.

As discussed in the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ analysis [91] (Section 6.1), the momentum scaling calibration is cross-checked with masses of many other resonance with well known mass, i.e., $K_s^0 \rightarrow \pi^+ \pi^-$ (both long-long tracks, and down-down tracks), D^+ , D^0 , D_s^+ , Λ_c^+ , $\psi(2S) \rightarrow (\mu^+ \mu^-, J/\psi \pi^+ \pi^-)$, $B^+ \rightarrow (J/\psi K^+, J/\psi K^+ \pi^+ \pi^-, \psi(2S) K^+, p \bar{p} K^+)$, $\Lambda_b^0 \rightarrow (\Lambda_c^+ \pi^+, \Lambda_c^+ 3\pi^+)$, and $\Upsilon(nS)$. The measured masses after the calibration agree with their known values within $\pm 0.03\%$, which is quoted as systematic uncertainty of the momentum scaling. The uncertainty on the final state track momentum introduce uncertainty to observed invariant mass of Ξ_{cc}^{++} candidates. The effect is studied by changing the momentum scaling correction factor by one standard deviation, 0.03% , and measuring the per candidate shift of DM (i.e. to calculate the mass shift for each candidate individually), shown in Figure 77. The distribution is fitted with a Gaussian function, resulting a mean value of $0.368 \pm 0.002 \text{ MeV}/c^2$. The study is performed using the Ξ_{cc}^{++} simulation sample, which has input value for Ξ_{cc}^{++} mass as $3597.98 \text{ MeV}/c^2$, and need scaled by the data Q value once unblinded, as $0.368 \cdot S_Q = 0.375 \text{ MeV}/c^2$.

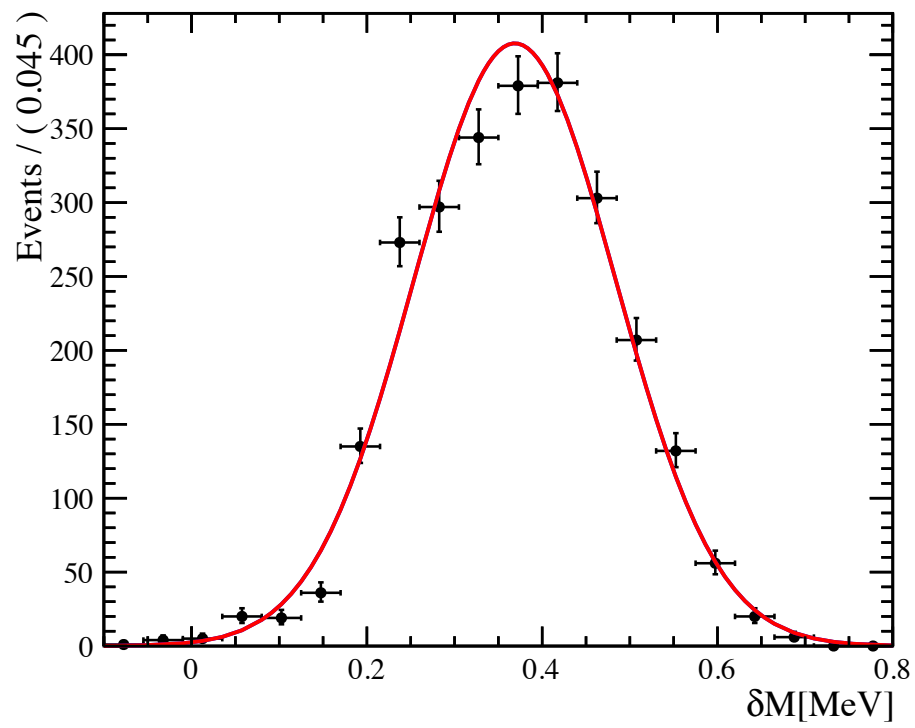


Figure 77: Distribution of event by event mass shift for additional momentum scaling correction of $0.3 \text{ GeV}/c^2$

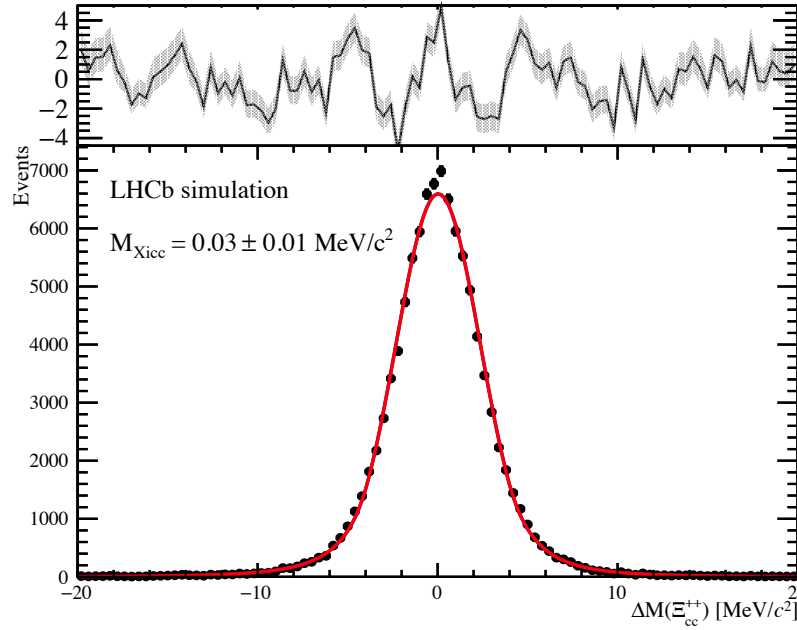


Figure 78: Distribution of Ξ_{cc}^{++} mass bias (reconstructed value subtracted by true value) when the measured Ξ_c^+ mass is constrained to its known value.

5.4.3 Bias of the Ξ_c^+ mass

As discussed in the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ analysis [91] (Section 6.2), the observed Λ_c^+ mass is biased due to selection favoring longer decay time by a value around $0.8 \text{ MeV}/c^2$, so we also make a similar study here. As in simulation, the reconstructed Ξ_{cc}^{++} mass is biased by a similar amount to the bias of Ξ_c^+ mass, so the mass difference $DM \equiv M(\Xi_{cc}^{++}) - M(\Xi_c^+) + M_{\text{PDG}}(\Xi_c^+)$ can be used as an approximately unbiased estimator of Ξ_{cc}^{++} mass.

To check whether the effect of Ξ_c^+ mass bias on the Ξ_{cc}^{++} mass is removed/reduced, the Ξ_c^+ momentum is recalculated with the Ξ_c^+ mass constrained to its known value using the kinematic fit. In this case, the Ξ_{cc}^{++} mass is calculated using the refitted Ξ_c^+ momentum combined with one additional track. The validation is studied by comparing the $DM \equiv M(\Xi_{cc}^{++}) - M(\Xi_c^+) + M_{\text{PDG}}(\Xi_c^+)$ with M_{TRUE} , where M_{TRUE} is the MC input Ξ_{cc}^{++} mass, calculated using truth kinematics of Ξ_c^+ and π^+ , on a candidate by candidate basis. The difference of the two is shown in Fig. 78, with an average value of $-0.03 \pm 0.01 \text{ MeV}/c^2$. For this Ξ_{cc}^{++} mass estimator, the bias is also quite small. The difference is so small that we don't consider it as a systematic uncertainty.



5.4.4 Bias of Ξ_{cc}^{++} mass due to offline selections

The reconstructed Λ_c^+ mass is found to depend on the decay time [91] after applying the momentum scale calibration, and would affect the Ξ_{cc}^{++} mass in an event selection dependent way. A similar effects is expected here, as a lifetime-biased criteria is required to select Ξ_c^+ (see Section 5.2 for details), and such bias need to be corrected.

The effect of the offline selections on the Ξ_{cc}^{++} mass is studied with Ξ_{cc}^{++} MC samples, for which we intentionally remove all the offline selection cuts, except the ‘MC-Matching’. The difference between the DM and the MC input Ξ_{cc}^{++} mass for this ‘unbiased’ sample is shown in the left plot of Figure 79, there is small bias due to effects as the un-calibrated momentum scale, and the final state radiation effects. In the right plot of Figure 79, the distribution for events after applying all the offline selections (including MVA) is shown. Comparing the mean values in these two plots, it can be seen that an additional bias of $\delta\mu = 0.104 \pm 0.078 \text{ MeV}/c^2$ is observed, where the uncertainty, coming from limited statistics in the simulation sample, is calculates as $\sqrt{\sigma_1^2 - \sigma_2^2}$ [93]. σ_2 and σ_1 are the uncertainties of the mean mass before and after the offline selections. The observed bias, $0.104 \text{ MeV}/c^2$ after MVA selection, corresponds the lifetime of 0.333 ps in simulation. As discussed above, this bias comes from the offline selection, specially the lifetime-related cuts. This bias generally depends on the lifetime of the particle in question. The effect of unknown lifetime is studied by using other lifetimes obtained by reweighting the Ξ_{cc}^{++} simulation sample to match other lifetime value τ' , with weight $\frac{1/\tau' \exp^{-t/\tau'}}{1/\tau_0 \exp^{-t/\tau_0}}$, where τ' (τ_0) is the target (MC input) lifetime and t is the reconstructed decay time. For each target lifetime, the mean mass bias is studied in the same way as for nominal case (i.e. $\tau = 0.333 \text{ ps}$). Using the default MVA selections, the bias as a function of lifetime is shown in Figure 80, which is very stable in the lifetime region. For the result, the largest variation of measured mass bias for lifetime in the range $0.1 < \tau < 0.5 \text{ ps}$, which covers theoretical predictions, is $0.03 \text{ MeV}/c^2$. Without exact knowledge of lifetime, $0.03 \text{ MeV}/c^2$ is quoted as systematic uncertainty on the mass measurement due to unknown lifetime.

In the end, concerning the selection related bias and its dependence on Ξ_{cc}^{++} lifetime, $0.104 \text{ MeV}/c^2$ is used to correct the measured Ξ_{cc}^{++} mass with an uncertainty of $0.078 \text{ MeV}/c^2$ due to limited statistics in simulation for this study, and an uncertainty of $0.03 \text{ MeV}/c^2$ due to lifetime dependence.

We followed the method described in Reference [95], to estimate the uncertainty from the final state radiation (FSR), by using simulated Ξ_{cc}^{++} signal events (generator level events from Gauss).

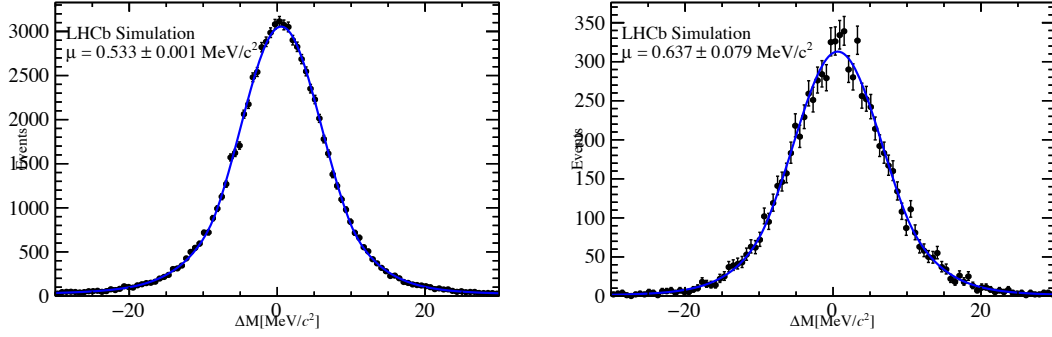


Figure 79: Distribution of observed Ξ_{cc}^{++} mass, using the mass difference estimator, subtracted by its true value in the simulation sample (left) without applying cuts relating to decay time of Ξ_{cc}^{++} , (right) after all offline selections, including the MVA variable.

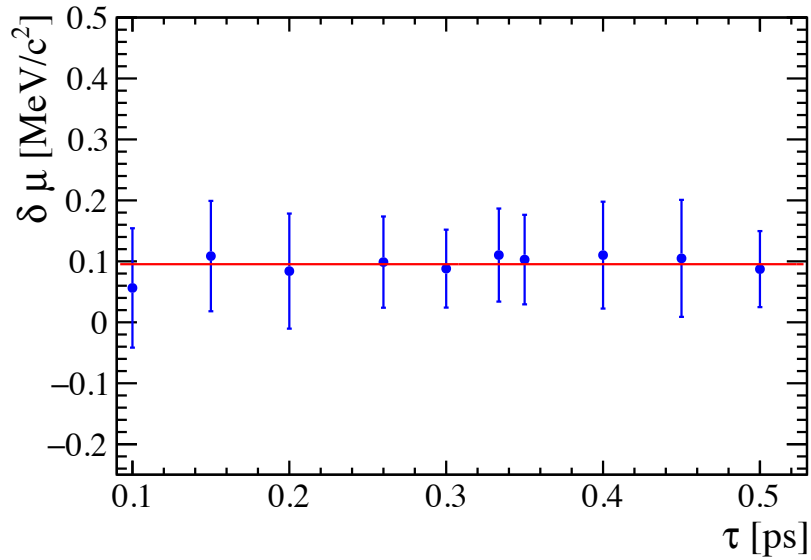


Figure 80: Bias of measured mean mass for different Ξ_{cc}^{++} lifetime hypotheses, obtained by fitting to samples reweighting the decay time distribution to match other lifetimes.

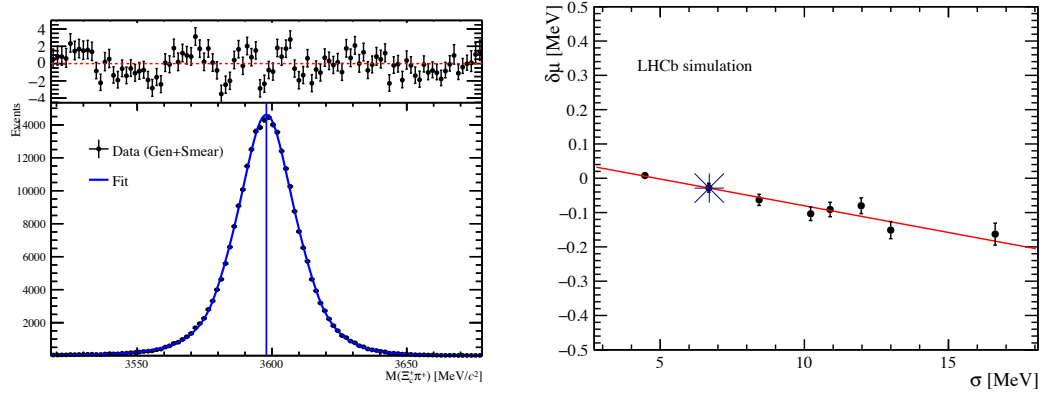


Figure 81: LHCb simulation. (Left) Ξ_{cc}^{++} mass, calculated from final state track momenta smeared with a Gaussian function for resolution, corrected by reconstructed Ξ_c^+ mass calculated in the same way. (Right) Fitted Ξ_{cc}^{++} mass as a function of the resolution.

The smearing procedure is used to simulate the LHCb detection resolution. In the smearing procedure, for each of the final state tracks (from Ξ_{cc}^{++} and Ξ_c^+), the momentum magnitude is varied by a value randomly drawn from a Gaussian distribution. The Gaussian function has a mean equals zero and sigma corresponding to LHCb measured momentum resolution scaled by a factor. The LHCb momentum resolution divided by the momentum itself (i.e. relative uncertainty $\delta p/p$) varies from 0.5% at low momentum to 1.0% at 200 GeV/c. On top of that, the track slopes $tx = p_x/p_z, ty = p_y/p_z$ are then smeared following similar procedure using a Gaussian function with mean of zero and sigma of $\sqrt{(6.2 \times 10^{-5})^2 + (2.1 \times 10^{-1}/p)^2}$ scaled by the same factor as for the momentum, where the formula and parameters are get from RapidSim [96]. By choosing different scale factors, we study the mass deviations within different detector resolution.

The Ξ_{cc}^{++} and Ξ_c^+ masses are calculated using the summed momenta of the corresponding final state tracks. Then the mass difference defined previously is fitted to obtain the Ξ_{cc}^{++} mean mass, with the same model used to describe the signal in data. An example of the fit is shown in the left plot of Figure 81. In the right plot of Figure 81, the bias as a function of mass resolution $\sigma = \sqrt{f \cdot \sigma_1^2 + (1 - f) \cdot \sigma_2^2}$ is shown, suggesting the effect is quite small. The distribution is fitted with a linear function, and the bias is 0.03 ± 0.01 MeV/c² for the resolution observed in simulation. With larger detector resolution, the FSR contribution becomes larger, which will shift the mass distribution into the lower mass region, resulting a larger mass peak deviation.

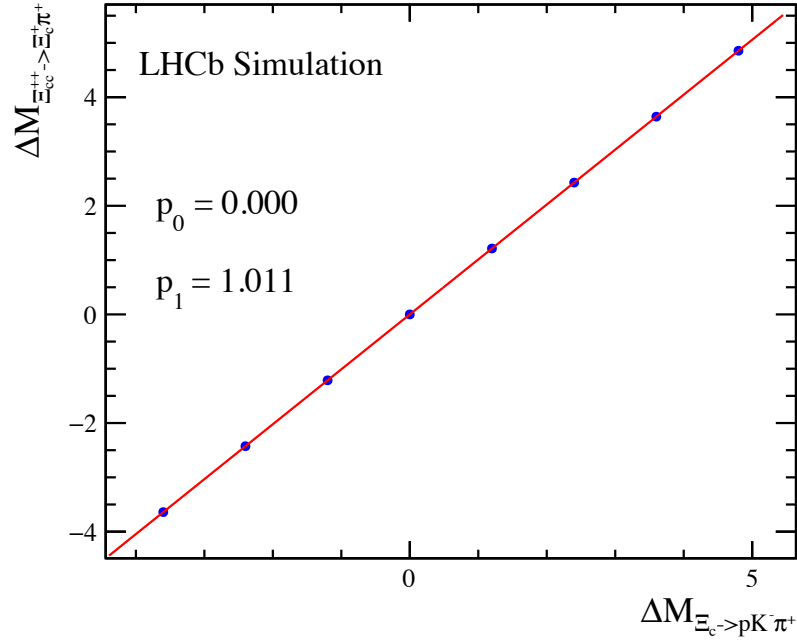


Figure 82: Variation of Ξ_{cc}^{++} mass as a function of change of known Ξ_c^+ mass.

5.4.5 Uncertainty on Ξ_c^+ mass

The known Ξ_c^+ mass has an uncertainty of $0.30 \text{ MeV}/c^2$ [92], which should be propagated to measurement of Ξ_{cc}^{++} mass. The study is performed using kinematic fit, where we modify the known Ξ_c^+ mass slightly and study the corresponding change of Ξ_{cc}^{++} mass candidate by candidate. The spread of the Ξ_{cc}^{++} mass change among different candidate due to a fixed amount of Ξ_c^+ mass shift is quite small (less than 2% of resolution), and in Figure 82, the mean Ξ_{cc}^{++} mass variation is shown as a function of Ξ_c^+ mass change. As can be seen, Ξ_{cc}^{++} mass change is almost identical to Ξ_c^+ mass change. For the uncertainty of $0.30 \text{ MeV}/c^2$ on Ξ_c^+ mass, the corresponding Ξ_{cc}^{++} mass uncertainty is estimated to be $0.30 \text{ MeV}/c^2$, which is quoted as systematic uncertainty. This uncertainty is assigned to the absolute mass measurement.

5.4.6 Invariant mass fit model

The fit model could introduce effects on the measured mass. For the signal model, alternative models include those by changing the shape parameters in Table 13, by using a single DSCB to describe the signal. The largest variation of fitted mass, which is $0.05 \text{ MeV}/c^2$.

For the background model, alternative fits include changing the mass range in the fit, using shapes that obtained or constrained from wrong sign data, using a first order Chebychev



Table 13: Variation of fitted Ξ_{cc}^{++} mass for alternative fit models

Alternative	Mean mass change (MeV/ c^2)
Signal model	
Single DSCB function	0.05
Background model	
Mass fit range ($\pm 150 \rightarrow \pm 100$ MeV/ c^2)	0.05
First order Chebychev	0.02
Second order Chebychev	0.01

polynomial function (for a smaller mass window). The change of mass fit regions from 3620 ± 150 MeV/ c^2 to 3620 ± 100 MeV/ c^2 changes the fitted result by 0.05 MeV/ c^2 . If we fit the background with a second order Chebychev polynomial function, the fitted mass is only different by a value of 0.01 MeV/ c^2 . If a first order Chebychev polynomial (a linear function) is used as the model for the background, the fitted mass changes by value of 0.02 MeV/ c^2 .

Since same data sample is used in these tests, which are fully correlated, the maximum variation from different models, for which if the fit quality is acceptable, is quoted as systematic uncertainty. In the end, the result for these alternatives are shown in Table 13, and the uncertainty is quoted as 0.05 MeV/ c^2 .

5.4.7 Stability with respect to MVA selection

As discussed in section 5.4.4, the observed Ξ_{cc}^{++} mass is biased due to those offline selections (including the MVA cut) exploring reconstructed decay-time. Now we study the mass change with small variation of MVA cut around the nominal cut. In Figure 83, the change of fitted mass with respect to the change of MVA cut is shown for simulation. The variation of signal yield is in the range $\pm 25\%$.

We don't quote systematic uncertainties due to the variation of MVA cut, since it double counts statistical fluctuation.

5.4.8 Unblinded results

In Figure 84, the invariant mass distribution in data for events passing all selection cuts is shown. The fit use the signal model described in Section 5.4.1, and exponential function for

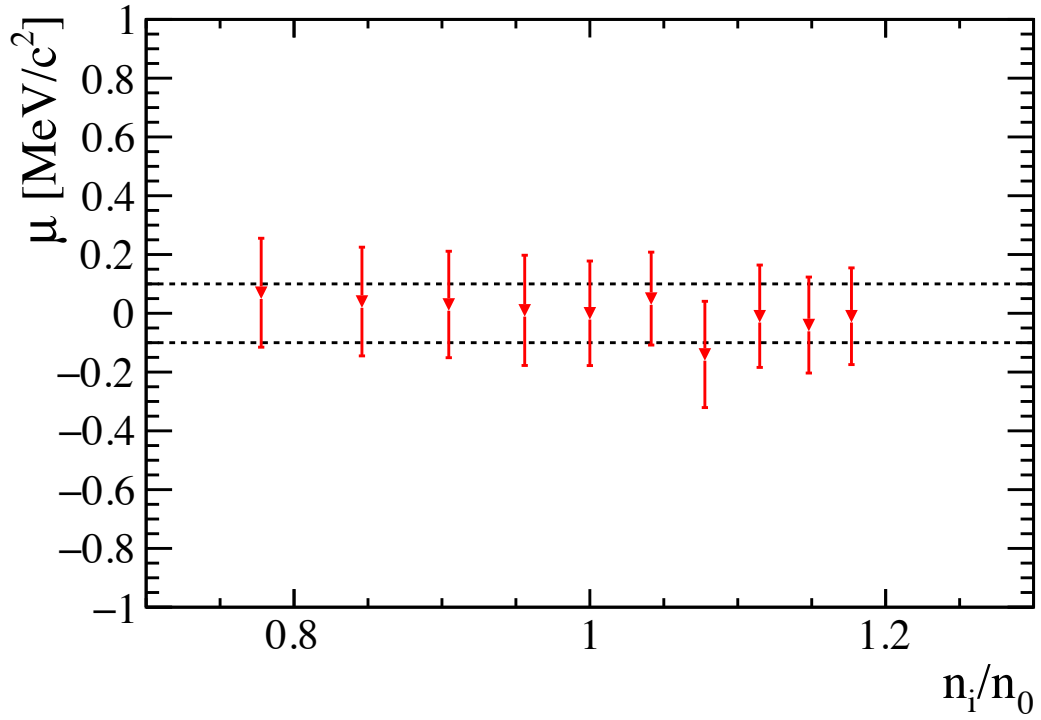


Figure 83: Variation of fitted E_{cc}^{++} mass μ with variation of the MVA selection, in simulation and data. The x-axis represents the number of signal yield relative to the one for nominal cut while the y-axis represents the change of μ w.r.t. to nominal value. As same data/MC samples are used in the n_i/n_0 tests, the uncertainties in this figure are correlated with each other.

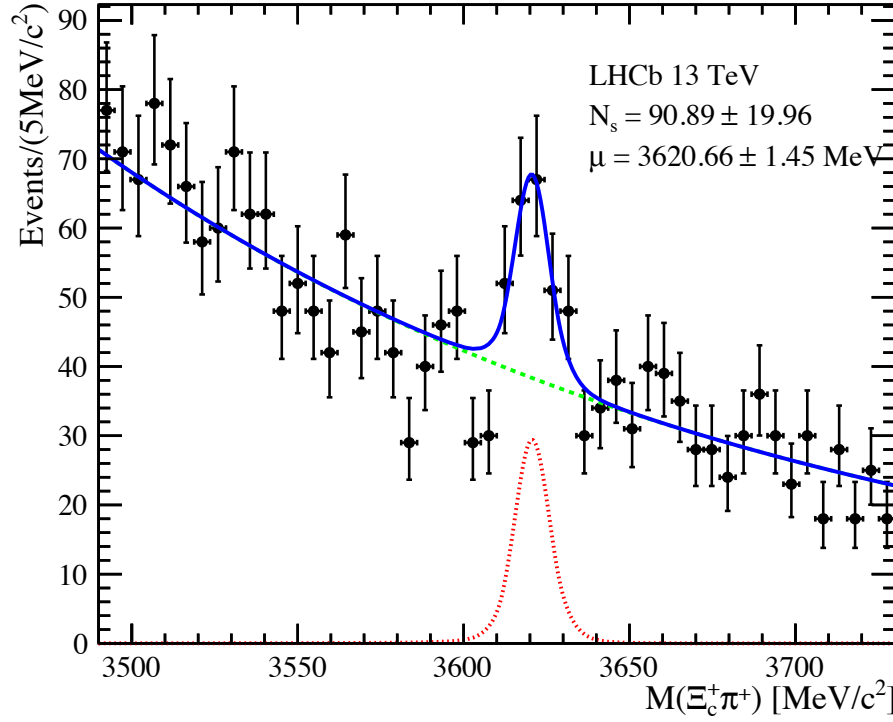


Figure 84: The invariant mass distribution for the 2016 RS sample around the mass peak. The data is fitted with the Gaussian plus DSCB function for the signal, and exponential for the background.

background. The mean value of the signal after the mass fitting is

$$\mu = 3620.66 \pm 1.45 \text{ MeV}/c^2 \quad (53)$$

and resolution width is

$$\sigma = 5.5 \pm 1.3 \text{ MeV}/c^2 \quad (54)$$

where the uncertainties are statistical uncertainty get from the fitting. The `Likelihood` scan and profile `Likelihood` scan for these two parameters are shown in Figure 85. The observed mass resolution in data is agree with expectations from scaled simulation value. The signal yield is 91 ± 20 , the local significance is 6.00σ .

With the measured Ξ_{cc}^{++} mass, the Q -value of this decay mode is 1013.2 ± 1.2 , $S_Q = Q_{\text{Data}}(\Xi_{cc}^{++})/Q_{\text{MC}}(\Xi_{cc}^{++}) = 1.02$ times of the simulated value 990.5.

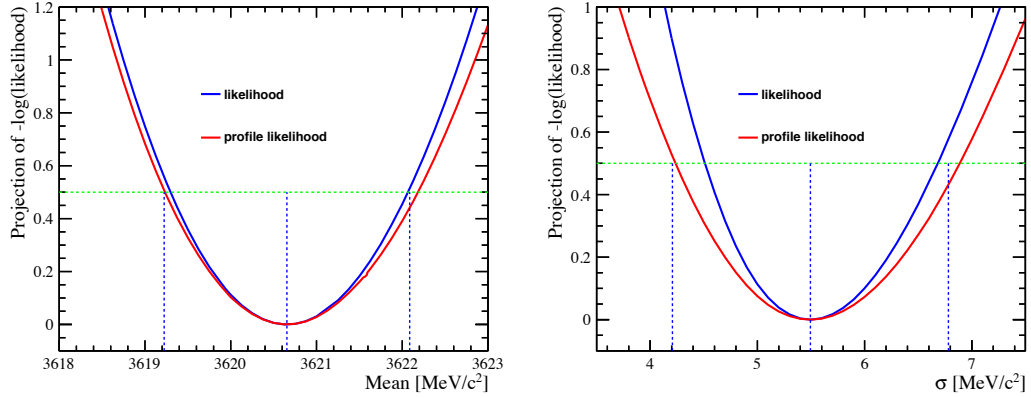


Figure 85: The Likelihood scan (blue) and profile Likelihood scan (red) of mean value (left plot) and resolution (right plot) in the $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ mass distribution fitting. The green dashed lines represent the one standard deviation (1σ) line, the black lines represent the central value in the fitting, the blue dashed lines represent the corresponding 1σ region for mean value and resolution.

5.4.9 Summary of mass measurement

The search of Ξ_{cc}^{++} using $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel of 2016 data, the Ξ_{cc}^{++} mass is $3620.66 \pm 1.45 \text{ MeV}/c^2$, which is corrected by bias due to offline selections on Ξ_c^+ as $-0.03 \text{ MeV}/c^2$ and on Ξ_{cc}^{++} as $-0.10 \text{ MeV}/c^2$, and due to FSR of $+0.03 \text{ MeV}/c^2$, resulting $3620.56 \pm 1.45 (\text{stat}) \pm 0.49 (\text{syst}) \text{ MeV}/c^2$. The measured Ξ_{cc}^{++} mass using $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel is $3621.40 \pm 0.72 (\text{stat}) \pm 0.31 (\text{syst}) \text{ MeV}/c^2$. Good agreement had been found between these two measured Ξ_{cc}^{++} mass.

Then, we combined these two measured Ξ_{cc}^{++} mass results, with assumptions that the systematic uncertainties from momentum scale and lifetime are 100% correlated between two channels, and other systematic uncertainties are uncorrelated. With BLUE method [97, 98], the combined results is $3621.24 \pm 0.65 (\text{stat}) \pm 0.31 (\text{syst}) \text{ MeV}/c^2$, as shown in Figure 86.

5.5 Ratio of branching fraction measurement

For this analysis, as discussed in Section 5.7, if the signal significance is greater than 3σ , we will measure the Ξ_{cc}^{++} mass and the branching fraction ratio relative to that of the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decay mode. If the signal significance is smaller than 3σ , we will set a upper limit on the relative branching fraction of this decay. In this section, we will discuss the procedure for the ratio of branching fraction measurement.



Table 14: Systematic uncertainties on mass measurement.

Source	Value(MeV/ c^2)
Momentum-scale calibration	0.38
Ξ_c^+ bias due to selections	0.01
Ξ_{cc}^{++} bias due to selections	0.08
Ξ_{cc}^{++} unknown lifetime	0.03
FSR	0.03
Uncertainty of Ξ_c^+ mass	0.30
Mass fit model	0.05
Total	0.49

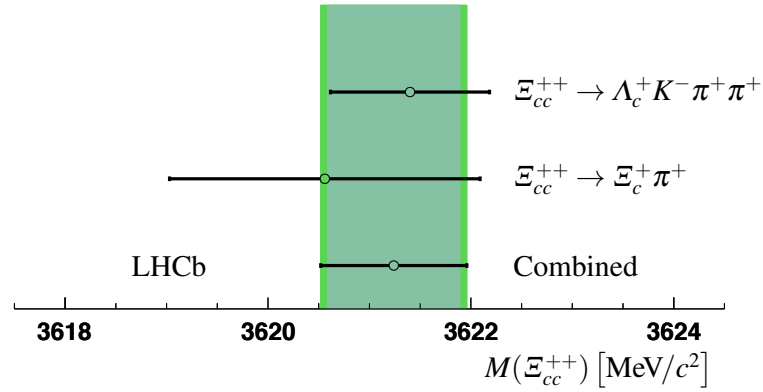


Figure 86: The measured Ξ_{cc}^{++} mass using $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channels, and the combined mass value.

The ratio of branching fraction ($\mathcal{R}$) is a ratio of the $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ branching fraction to that of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decays, times the ratio of Ξ_c^+ decay to $p^+ K^- \pi^+$ to that of Λ_c^+ , is defined as,

$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ (\rightarrow p^+ K^- \pi^+) \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ (\rightarrow p^+ K^- \pi^+) K^- \pi^+ \pi^+)} \quad (55)$$

$$= \frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} \times \frac{\mathcal{B}(\Xi_c^+ \rightarrow p K^- \pi^+)}{\mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+)} \quad (56)$$

$$= \frac{N(\Xi_c^+ \pi^+)}{N(\Lambda_c^+ K^- \pi^+ \pi^+)} \times \frac{\varepsilon(\Lambda_c^+ K^- \pi^+ \pi^+)}{\varepsilon(\Xi_c^+ \pi^+)} \quad (57)$$

where $N(\Xi_c^+ \pi^+)$ and $N(\Lambda_c^+ K^- \pi^+ \pi^+)$ are the $\Xi_{cc}^{++} \rightarrow \Xi_c^+ (\rightarrow p^+ K^- \pi^+) \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ (\rightarrow p^+ K^- \pi^+) K^- \pi^+ \pi^+$ signal yields, $\varepsilon(\Xi_c^+ \pi^+)$ and $\varepsilon(\Lambda_c^+ K^- \pi^+ \pi^+)$ are total efficiencies for these two decay modes, including efficiencies of the acceptance, reconstruction, event selection, PID selection, and trigger selection. As there is no experimental measurement of the $\Xi_c^+ \rightarrow p^+ K^- \pi^+$ branching fraction, therefore, we include the ratio of $\Xi_c^+ \rightarrow p^+ K^- \pi^+$ branching fraction to that of Λ_c^+ in our measured results. As discussed in Section 5.2.2, only the events triggered by the TOS (Trigger Of Signal) of the L0Hadron, or the TIS (Trigger Independent of Signal) of the all L0 trigger lines (L0Gloal) are used, i.e., `C_L0Global_TIS || Xic_L0Hadron_TOS` (or `C_L0Global_TIS || Lc_L0Hadron_TIS`) is used in this analysis, to have better estimate of the L0 trigger efficiency. Such requirement is also applied to the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decay. The signal yield of the $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ decay has been determined in Section 5.4 to be 91 ± 20 . The $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ mass distribution after applying this L0 requirements further is shown in Figure 87, and the number of signal yields is determined to be 289 ± 35 .

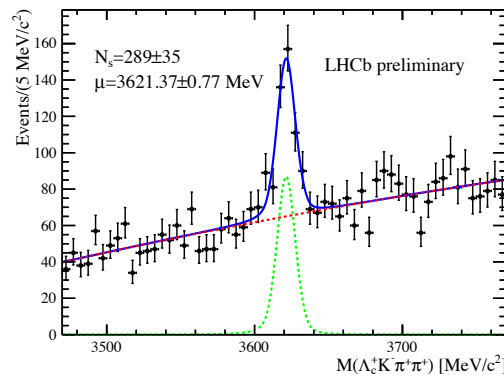


Figure 87: The $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ mass distribution in 2016 data, together with the fit results.



5.5.1 Signal modeling

The MC signal sample was generated with GENXICC generator, with the mass of Ξ_{cc}^{++} baryon is set to $3.59798 \text{ GeV}/c^2$, and lifetime is set to 0.333 ps . These input parameters are different from what we observed in Ξ_{cc}^{++} discovery, and the Ξ_{cc}^{++} lifetime measurement [90], which may result in a different kinematic and geometric distributions, and affect the branching fraction ratio measurement. As discussed in the following, the p_T distribution in data is found to be slightly softer than in simulation, therefore, we consider to use a p_T reweighting, and a lifetime reweighting, to make MC more close to data.

As Ξ_{cc}^{++} lifetime analysis [90] (using $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel) is performed parallel to this analysis, we have two scenarios for the lifetime reweighting. The first scenario is that the Ξ_{cc}^{++} lifetime result published before $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel publication, then we will directly quote a published lifetime result, as 0.260 ps . The second scenario is reversed case, and in that case, we will use a binned reweighting method to make the MC lifetime distribution agrees with that of data. Currently, we are using the second lifetime scenario, and will make a final decision during the coming review process.

For $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel, the comparisons of $\Xi_{cc}^{++} p_T$ and y distributions between background-subtracted data and MC simulation are shown in Figure 88, the other kinematic distributions comparisons and the MVA input variables comparisons are shown in Appendix A.9. Even with limited statistics of Ξ_{cc}^{++} candidates, there are still some sizable disagreement between data and simulation for the p_T distribution, therefore, two steps reweighting is performed to get a better data and MC agreement. First, a p_T correction (Data/MC) is studied and applied, which is aiming to correct kinematic difference between data and MC. As shown in Figure 89, the correction factor (Data/MC) is calculated as functions of $\Xi_{cc}^{++} p_T$, where the p_T binning is (4, 8.8, 11, 13.2, 17.4, 35) GeV/c . In order to get the lifetime agreement between data and MC, a lifetime correction is studied and applied. In Figure 90, data and MC lifetime comparison and the reweighting factor (Data/MC) are shown. The lifetime correction factor is calculated using the data lifetime distribution after background-subtraction and that distribution of simulation.

For $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$, as the number of signal is very limited, so only p_T correction is applied. The comparisons between s-weighted data and signal MC for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ are shown in Figure 91, and the p_T correction is shown in Figure 92. The lifetime comparison for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel is shown in Figure 93.

It is known that the event multiplicity (SPD hits) distribution (n_{SPD}) in MC is different from

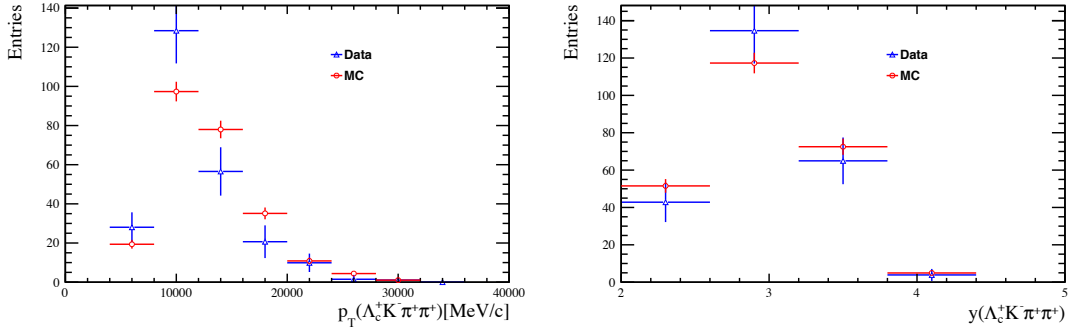


Figure 88: Comparisons of Ξ_{cc}^{++} p_T (left) and y (right) distributions between s-weighted data and simulation using $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel.

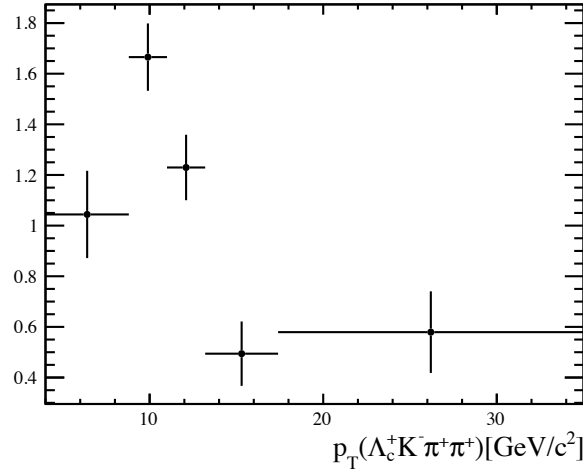


Figure 89: The Ξ_{cc}^{++} p_T reweighting factor of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel.

that in data. However, as shown in Figure 94, the SPD distribution for the signal and control decays agree well, for both the L0TOS and the L0TIS category. Therefore, such difference should mostly be canceled in the branching fraction ratio. As the measured results are totally dominated by statistical uncertainty, and with such limited number of signals, it is not possible to have a precise estimate of the SPD weight, no SPD reweighting is applied for the nominal value.

5.5.2 Efficiencies

The total efficiencies of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ are studied with simulated signal events, including the geometrical acceptance of detector and generator level cuts efficiency (ϵ_{Acc}), the combined reconstruction and selection efficiency ($\epsilon_{Reco\&Sel}$), the trigger efficiency

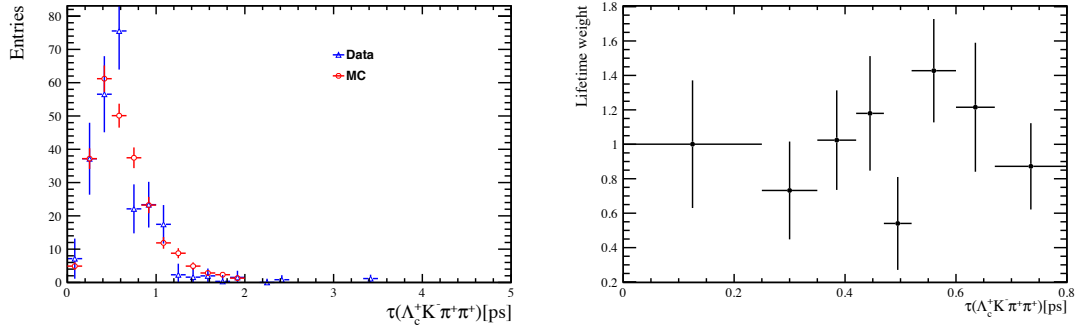


Figure 90: The Ξ_{cc}^{++} lifetime comparison (left) between data and simulation, and the lifetime reweighting factor (right) of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel.

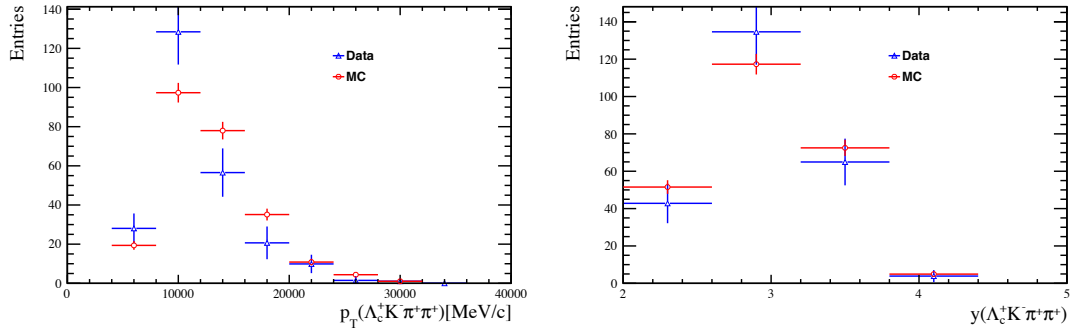


Figure 91: Comparisons of Ξ_{cc}^{++} p_T (left) and y (right) distributions between s-weighted data and simulation using $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel.

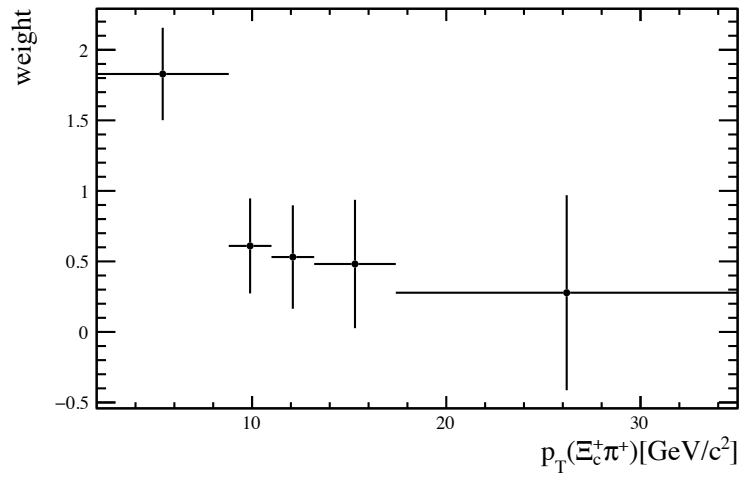


Figure 92: The Ξ_{cc}^{++} p_T reweighting factor of $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel.

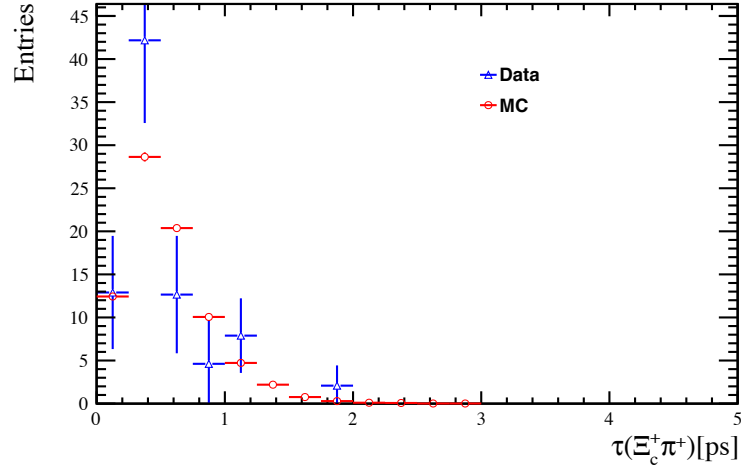


Figure 93: The Ξ_{cc}^{++} lifetime comparison between data and simulation of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel.

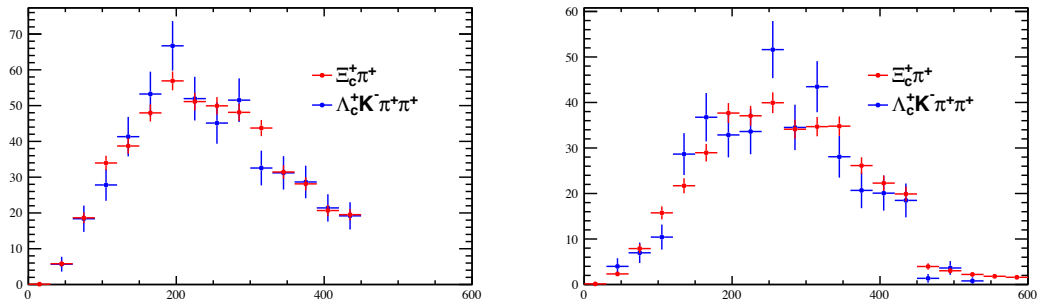


Figure 94: The comparison between nSPD distributions of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channels, L0TOS (left) and L0TIS (right) events.



(ε_{Trig}), and the PID efficiency for final state hadrons (ε_{PID}), as:

$$\varepsilon = \varepsilon_{Acc} \times \varepsilon_{Reco\&Sel} \times \varepsilon_{Trig} \times \varepsilon_{PID} \quad (58)$$

Acceptance efficiency of different modes is calculated from the GENXICC generator level events, the ε_{Acc} is calculated as:

$$\varepsilon_{Acc} = \frac{\Xi_{cc}^{++} \text{ generated in } 4\pi \text{ and all tracks in LHCb detector}}{\Xi_{cc}^{++} \text{ generated in } 4\pi} \quad (59)$$

where the denominator is the number of generated Ξ_{cc}^{++} events in the 4π space, and the numerator is the number of Ξ_{cc}^{++} events with all the final state tracks with polar angles of momentum direction in the region between 10 to 400 mrad. The obtained individual generator level efficiency for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ decays are 0.0987 ± 0.0002 and 0.1364 ± 0.0002 . The $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decay has six tracks in the final state, while $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ decay only has four tracks. Therefore, the acceptance efficiency of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ is smaller than that of $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$.

The reconstruction and selection efficiency are obtained from simulation, including particle reconstruction efficiency and event selection (described in Section 5.2), with applying of the corrections described in Section 5.5.1. The ratio of branching fraction measurement is a ratio of four-body decay branching fraction to that of six-body decay, where the decay topology and kinematic of these two modes are different from each other. It does not make any sense to use either same selection cuts, or same TMVA training input variables in the efficiency studies. The reconstruction and selection efficiency for each mode is studied independently, using simulated events. The efficiencies are measured to be $(0.58 \pm 0.01) \times 10^{-3}$ for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel (statistics only), and $(4.56 \pm 0.03) \times 10^{-3}$ (statistics only) for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel. The PID efficiencies are determined using the PIDCalib package [99]. PID efficiencies for proton, kaon, and pion are determined separately, according to the PID cuts used in this analysis, as functions of momentum and η , for both *MagDown* and *MagUp* polarities. Then, the PID efficiency for each event is calculated by combining efficiency for each final states particle. The PID efficiencies are measured to be 0.714 ± 0.013 (statistics only) for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel, and 0.680 ± 0.003 (statistics only) for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel. In $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel, even with lesser tracks in final state, with tighter `ProbNNp` cut applied on proton, the calculated PID efficiency is lower than that of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel.

The trigger efficiency is very complicated for this analysis, and is discussed in Section 5.5.3.

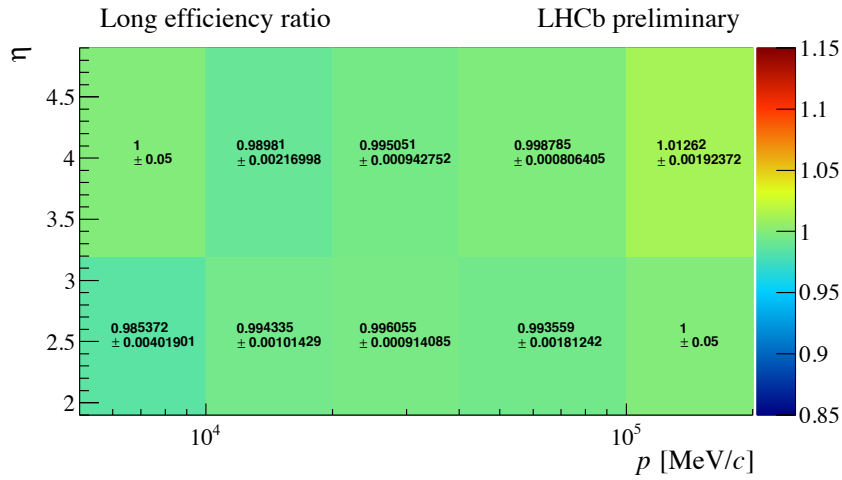


Figure 95: The track efficiency correction table for 2016 data.

Tracking efficiency

The tracking efficiency correction has been applied to the simulated events according to momentum and pseudorapidity value of each final state particle [100], the tracking efficiency correction for 2016 data is shown in Figure 95.

MC-Match efficiency

As discussed in the Reference [101], the MC truth match is defined as a reconstructed particle matched to an MC particle if there is an overlap of at least 70% between the hits created by the reconstructed particle and these created by the MC particle. The arbitrary of the percentage threshold will leads to an inefficiency in the truth matching. Therefore, this inefficiency need to be corrected in the reconstruction efficiency, as $\varepsilon_{Reco\&Sel}^{New} = \varepsilon_{Reco\&Sel} / \varepsilon_{MC-Match}$.

The $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ has six tracks in the final states, while $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ only has four tracks. In the simulation, different number of final state tracks could gives a different performance of MC-match efficiency.

The MC matching efficiency is calculated as the ratio of the number of MC-matched signal events to the number of signal events obtained by fitting the mass distribution (without MC-matching), both numbers are after applying all the event selection, including MVA selection. It is determined to be 0.883 ± 0.007 for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel, and 0.962 ± 0.003 for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel. The unmatched events mass and BKGCAT distributions are shown in Figure 97. The contribution from ‘ghost’ tracks (BKGCAT==60) of the MC events that failed MC-match is determined to be 100% for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel, and 87% for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel.

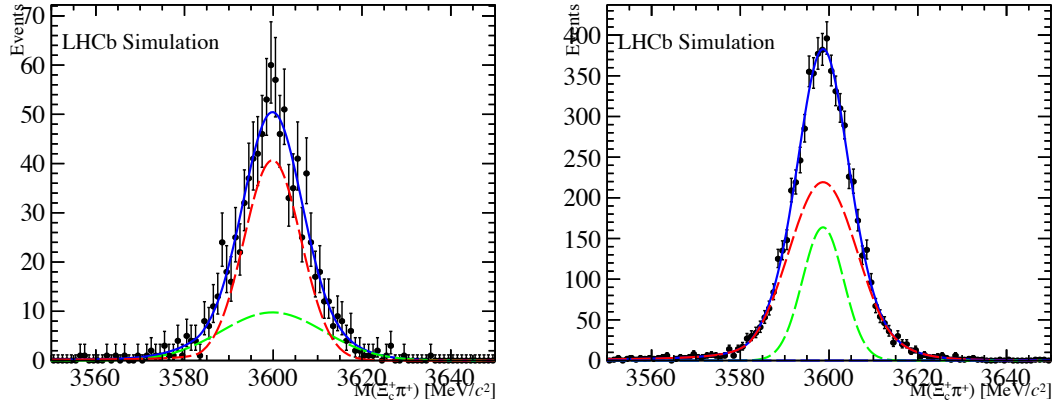


Figure 96: Ξ_{cc}^{++} candidate mass distribution in simulated signal sample, after applying all the event selection (including PID cuts), without requiring MC-matching, for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ (left), and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ (right).

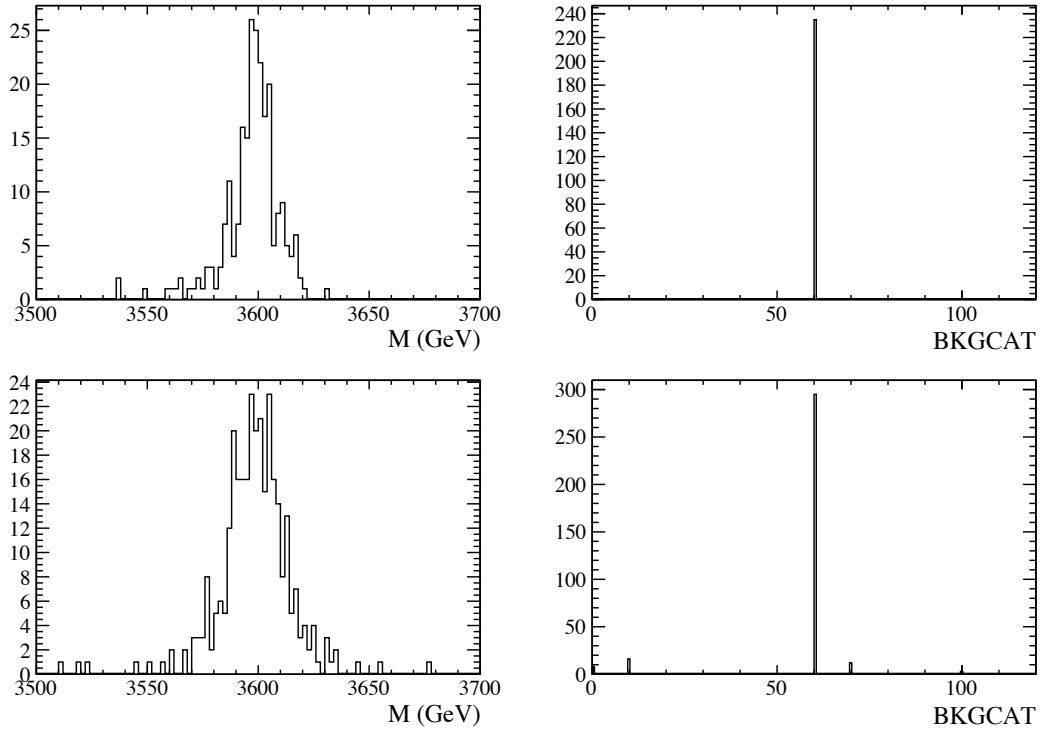


Figure 97: Ξ_{cc}^{++} candidate mass (left) and BKGCAT distributions of MC events that failed MC-match, after applying all the event selection (including PID cuts), for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ (top), and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ (bottom).



5.5.3 Trigger efficiency

For the trigger efficiency, as Turbo lines are used in both analyses, where the Turbo selection is equal to offline selection. Therefore, only L0 and HLT1 trigger efficiencies are studied.

In this analysis, the L0 trigger efficiency requirements includes L0Hadron_TOS and L0Global_TIS. In order to study the L0 trigger efficiency, the data/MC sample is split into two disjoint subsamples, as:

- L0TOS: (L0Hadron_TOS on Λ_c^+ or Ξ_c^+)
- L0TIS: !(L0Hadron_TOS on Λ_c^+ or Ξ_c^+) & (L0Global_TIS on Ξ_{cc}^{++})

In this section, without particular definitions, the L0TOS and L0TIS are used to refer these subsamples. We will measure the branching fraction with L0TOS and L0TIS subsamples, and combine them later. If two measured results away from each other more than 3 standard deviation, we will considered to use L0TIS events, as the modeling of L0TIS efficiency is more straight forward. A validation test for this method using two Λ_b^0 channels ($\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$) is presented in Appendix A.10, where good agreements between the measured ratio of branching fraction of Λ_b^0 by using L0TOS and L0TIS events had been found, which are also consistent with PDG values.

Control channels

The L0 trigger efficiency estimation is more difficulty to study, compared to that of HLT1 efficiency. At L0, C_L0Global_TIS || Lc_L0Hadron_TOS requirement is applied to the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel, and C_L0Global_TIS || Xic_L0Hadron_TOS is applied to the $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel. The most reliable way to determine trigger efficiency is uses data TIS-TOS method, directly. But with limited statistics of both Ξ_{cc}^{++} decay modes in current data set, it is impossible to determine the trigger efficiency using TISTOS method with real data. Alternatively, we could use simulated events to study L0 efficiency, but the performance of ‘L0Hadron’ TOS triggers had not being well understood, therefore, the trigger efficiencies measured using MC events cannot be simply used in the analysis. Here, we proposed a method to measure the L0 trigger efficiency for different Ξ_{cc}^{++} decay modes, using two Λ_b^0 control channels. The ratio of two control channels L0 efficiency is calculated, and compared with the ratio in Λ_b^0 MC samples, to develop a correction for MC events. Then, we apply the correction to the Ξ_{cc}^{++} modes (MC events).



In this method, two control channels of Λ_b^0 decays are used, as $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$. These two channels have similar decay topology compared to that of Ξ_{cc}^{++} decays ($\Lambda_b^0 \rightarrow \Xi_c^+ \pi^-$ channel is not used in this study, due to this decay mode is not been observed in the data, and there is no $\Lambda_b^0 \rightarrow \Xi_c^+ \pi^-$ simulation sample available). With the 2016 stripping data, we have enough statistics to perform a L0 trigger efficiency study. The candidates after stripping selection are required to pass the preselection cuts described in Section 5.2, then we fit the Λ_b^0 mass distribution to extract the number of signal for samples passed different trigger requirements. Furthermore, MC events of these two control channels are used to estimate the trigger efficiency, too. The discrepancies between data and MC events need to be suppressed by using several corrections, as a function of the number of SPD hits (n_{SPD}), and kinematic distributions (p_T and y). The n_{SPD} correction is applied into the MC events at first. The n_{SPD} correction factors are calculated using the MC n_{SPD} distribution and the s-weighted data n_{SPD} distribution (Data/MC), for L0TOS and L0TIS samples, separately. Then, the kinematic correction is applied to MC to reduce the difference between data and MC. The two-dimension correction factor, as a function of Λ_b^0 p_T and y , is calculated using the Λ_b^0 s-weighted data and MC (Data/MC).

More details for the Λ_b^0 mass fitting and MC corrections are shown in Appendix A.10.

L0 trigger efficiency

To make a reliable estimation on L0 trigger efficiency, ratios ($R_{\Xi_{cc}^{++}}^{\text{TOS}}, R_{\Xi_{cc}^{++}}^{\text{TIS}}$) of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ L0 trigger efficiency to those of $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ are determined and used in the analysis.

To correct MC, $R_{\Xi_{cc}^{++}}^{\text{TIS}}$ and $R_{\Xi_{cc}^{++}}^{\text{TOS}}$ are studied. The ratios ($R_{\text{Data}}^{\text{TOS}}, R_{\text{Data}}^{\text{TIS}}, R_{\text{MC}}^{\text{TOS}}, R_{\text{MC}}^{\text{TIS}}$) of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ L0 trigger efficiency to those of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ are calculated. Furthermore, the correction factors $\mathcal{R}^{\text{TOS}}$ ($\mathcal{R}^{\text{TIS}}$) are calculated using $R_{\text{Data}}^{\text{TOS}}$ and $R_{\text{MC}}^{\text{TOS}}$ ($R_{\text{Data}}^{\text{TIS}}$ and $R_{\text{MC}}^{\text{TIS}}$), to describe the trigger efficiency discrepancies between data and MC, which will be further applied into the $R_{\text{MC}, \Xi_{cc}^{++}}^{\text{TOS}}$ and $R_{\text{MC}, \Xi_{cc}^{++}}^{\text{TIS}}$ (determined from Ξ_{cc}^{++} MC events). The formulas used to calculate $R_{\Xi_{cc}^{++}}^{\text{TOS}}$ and $R_{\Xi_{cc}^{++}}^{\text{TIS}}$ are

$$\begin{aligned} R_{\Xi_{cc}^{++}}^{\text{TOS}} &= \mathcal{R}^{\text{TOS}} \cdot R_{\text{MC}, \Xi_{cc}^{++}}^{\text{TOS}} \\ R_{\Xi_{cc}^{++}}^{\text{TIS}} &= \mathcal{R}^{\text{TIS}} \cdot R_{\text{MC}, \Xi_{cc}^{++}}^{\text{TIS}}, \end{aligned} \quad (60)$$

where $\mathcal{R}^{\text{TOS}}$ and $\mathcal{R}^{\text{TIS}}$ are determined as:

$$\mathcal{R}^{\text{TOS}} = \frac{R_{\text{Data}}^{\text{TOS}}}{R_{\text{MC}}^{\text{TOS}}} = \frac{\varepsilon_{\text{Data}}^{\text{TOS}}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-)}{\varepsilon_{\text{Data}}^{\text{TOS}}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} \cdot \frac{\varepsilon_{\text{MC}}^{\text{TOS}}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)}{\varepsilon_{\text{MC}}^{\text{TOS}}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-)} \quad (61)$$



Table 15: Measured L0TIS, L0TOS trigger efficiencies from Ξ_{cc}^{++} MC events, after corrections.

	$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$	$\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$
TOS	0.176 ± 0.010	0.153 ± 0.003
TIS	0.205 ± 0.010	0.188 ± 0.004

$$\mathcal{R}^{\text{TIS}} = \frac{R_{\text{Data}}^{\text{TIS}}}{R_{\text{MC}}^{\text{TIS}}} = \frac{\varepsilon_{\text{Data}}^{\text{TIS}}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-)}{\varepsilon_{\text{Data}}^{\text{TIS}}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)} \cdot \frac{\varepsilon_{\text{MC}}^{\text{TIS}}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-)}{\varepsilon_{\text{MC}}^{\text{TIS}}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-)}. \quad (62)$$

In the two control channels, the L0 trigger efficiency in L0TOS ($\varepsilon_{\text{Trig}}^{\text{TOS}}$) and L0TIS ($\varepsilon_{\text{Trig}}^{\text{TIS}}$) are studied using TISTOS method, for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ channels. The $\varepsilon_{\text{Trig}}^{\text{TOS}}$ is the L0 TOS trigger efficiency (Lc_L0Hadron_TOS), calculated as:

$$\varepsilon_{\text{L0}}^{\text{TOS}} = \frac{N^{\text{TIS\&TOS}}}{N^{\text{TIS}}} \quad (63)$$

where $N^{\text{TIS\&TOS}}$ is the number of events passed both L0 TIS and Lc_L0Hadron TOS trigger requirements, and N^{TIS} is the number of events passed L0 TIS requirements. Here, the TIS events are required to pass either of the following L0 TIS triggers, as: ‘L0Photon’, ‘L0Electron’, ‘L0Muon’, ‘L0DiMuon’. Similarly, the L0TIS efficiency (C_Global_TIS), $\varepsilon_{\text{Trig}}^{\text{TIS}}$, is calculated as:

$$\varepsilon_{\text{L0}}^{\text{TIS}} = \frac{N^{\text{TIS\&TOS}}}{N^{\text{TOS}}} \quad (64)$$

where N^{TOS} is the number of events passed ‘L0Global_TOS’ requirement. The measured L0TOS and L0TIS efficiencies as a function of p_T are shown in Figure 98 and 99, for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ channels. The data and MC efficiency ratios ($R_{\text{Data}}^{\text{TOS}}$, $R_{\text{Data}}^{\text{TIS}}$, $R_{\text{MC}}^{\text{TOS}}$, $R_{\text{MC}}^{\text{TIS}}$) are compared in Figure 100. The calculated $\mathcal{R}^{\text{TOS}}$ and $\mathcal{R}^{\text{TIS}}$ are shown in Figure 101. The correction factor in Figure 101 will be used to correct both $R_{\Xi_{cc}^{++}}^{\text{TOS}}$ and $R_{\Xi_{cc}^{++}}^{\text{TIS}}$, as a function of p_T .

With $\varepsilon_{\text{Trig}}^{\text{TOS}}$ and $\varepsilon_{\text{Trig}}^{\text{TIS}}$ measured from these two Ξ_{cc}^{++} channels, using the formula as:

$$\varepsilon_{\text{L0}}^{\text{TIS/TOS}} = \frac{N(\text{passed all selections \& passed TIS/TOS cuts})}{N(\text{passed all selections})} \quad (65)$$

the measured efficiencies are summarized in Table 15. For the systematic uncertainty, we take the differences between the measured efficiencies by using the MC-Match method and that of TISTOS method as a systematic uncertainty, using two Λ_b^0 channels. For instance, the uncertainties is determined to be 0.8% for L0TOS events, and 0.7% for L0TIS events.

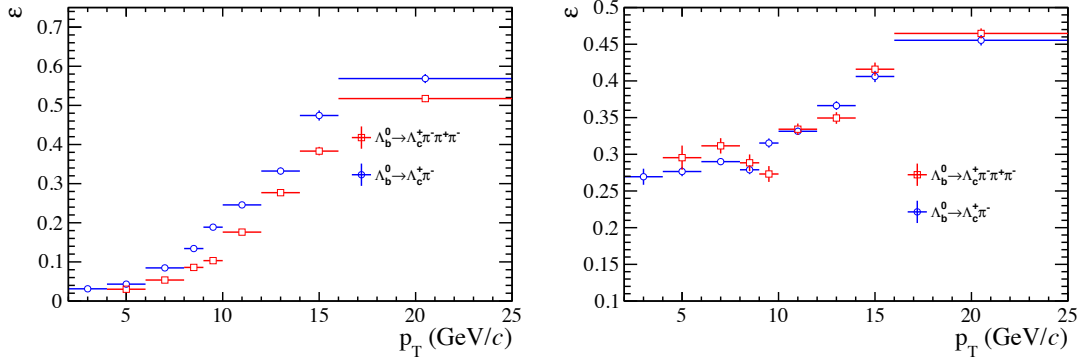


Figure 98: The measured (left) L0TOS and (right) L0TIS trigger efficiency using TISTOS method, using Λ_b^0 data.

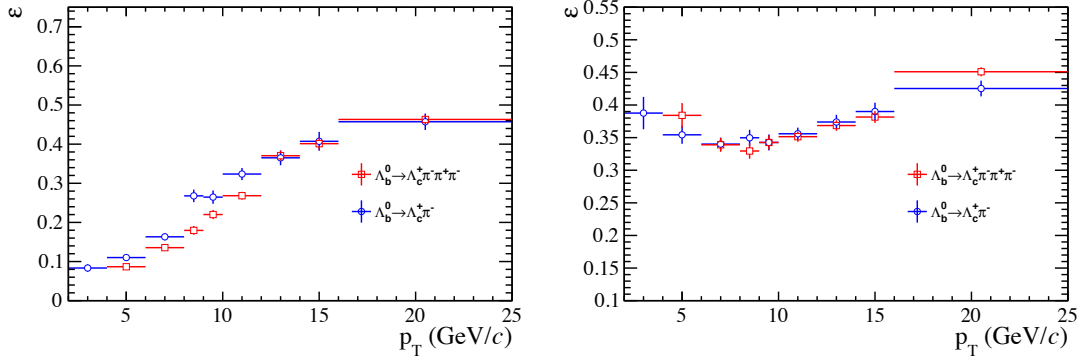


Figure 99: The measured (left) L0TOS and (right) L0TIS trigger efficiency using TISTOS method, using Λ_b^0 MC.

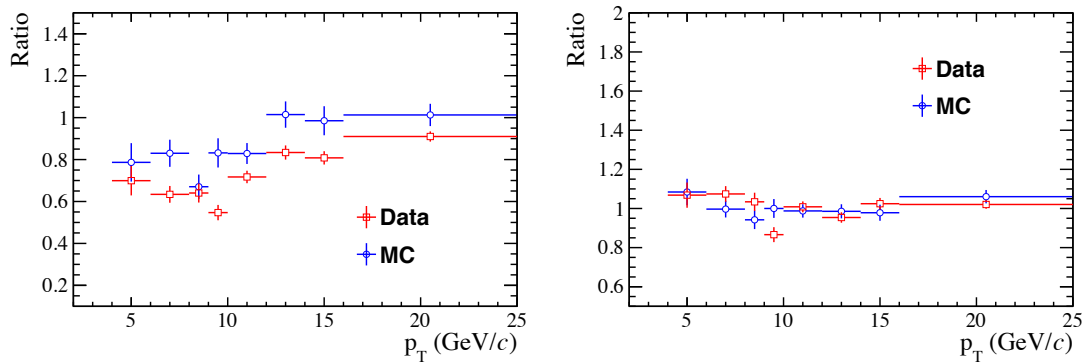


Figure 100: The measured $R_{\text{Data}}^{\text{TOS}}$ and $R_{\text{MC}}^{\text{TOS}}$ (left) for L0TOS events, and $R_{\text{Data}}^{\text{TIS}}$ and $R_{\text{MC}}^{\text{TIS}}$ (right) for L0TIS events.

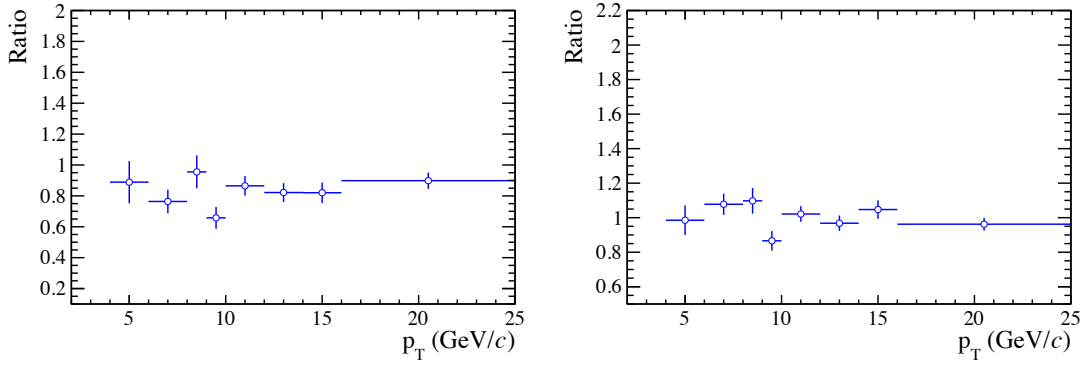


Figure 101: The measured $\mathcal{R}^{\text{TOS}}$ (left) for LOTOS events, and $\mathcal{R}^{\text{TIS}}$ (right) for LOTIS events.

HLT1 trigger efficiency

The HLT1 triggers⁷, ‘Hlt1TrackMVA’ and ‘Hlt1TwoTrackMVA’ have been used. The HLT1 efficiencies are directly estimated using the MC-Matched simulation events, as

$$\varepsilon_{\text{HLT1}} = \frac{N^{\text{HLT1}}}{N^{\text{Sel}}} \quad (66)$$

where N^{Sel} is the number of events passing event selection and L0 requirements, and N^{HLT1} is the number of events passing event selection, L0 and HLT1 requirements.

With tight Turbo selection cuts, the $\varepsilon_{\text{HLT1}}$ is expected to be very high for both channels. Using TISTOS method, the $\varepsilon_{\text{HLT1}}$ is determined to be 0.939 ± 0.015 for LOTOS, and 0.922 ± 0.015 for LOTIS in $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel. The $\varepsilon_{\text{HLT1}}$ is determined to be 0.950 ± 0.005 for LOTOS, and 0.940 ± 0.005 for LOTIS in $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel.

5.6 Total efficiency and ratio

The efficiencies and ratios of each selections for both channels are summarized in Table 16 and 17 for LOTOS and LOTIS events.

5.6.1 Ratio of branching fraction results

Signal yields

The selected LOTOS and LOTIS candidates for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channels are shown in Fig. 102. The $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ signal yield is 141 ± 23 for LOTOS candidates,

⁷The thresholds of these two triggers had been slightly changed during the 2016 data taking. In the branching fraction measurements, as same data sample is used in both Ξ_{cc}^{++} channels, the trigger efficiency should not be affected by the different thresholds, as the cancellation in the first order.



Table 16: Measured efficiencies and ratios for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ L0TOS events.

	$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$	$\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$	R
Acc	0.0987 ± 0.0002	0.1364 ± 0.0002	0.724 ± 0.002
Reco	$(5.77 \pm 0.12) \times 10^{-4}$	$(45.6 \pm 0.34) \times 10^{-4}$	0.127 ± 0.003
PID	0.714 ± 0.013	0.680 ± 0.003	1.050 ± 0.013
L0	0.176 ± 0.010	0.153 ± 0.003	1.148 ± 0.068
HLT1	0.939 ± 0.015	0.950 ± 0.005	0.988 ± 0.016
MC-Match (1./)	0.883 ± 0.007	0.962 ± 0.003	0.918 ± 0.008

Table 17: Measured efficiencies and ratios for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ L0TIS events.

	$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$	$\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$	R
Acc	0.0987 ± 0.0002	0.1364 ± 0.0002	0.724 ± 0.002
Reco	$(5.77 \pm 0.12) \times 10^{-4}$	$(45.6 \pm 0.34) \times 10^{-4}$	0.127 ± 0.003
PID	0.714 ± 0.013	0.680 ± 0.003	1.050 ± 0.013
L0	0.205 ± 0.010	0.188 ± 0.003	1.090 ± 0.058
HLT1	0.922 ± 0.015	0.940 ± 0.005	0.981 ± 0.017
MC-Match (1./)	0.883 ± 0.007	0.962 ± 0.003	0.918 ± 0.008

144 ± 22 for L0TIS candidates. The $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ signal yield is 33 ± 13 for L0TOS candidates, 56 ± 14 for L0TIS candidates. These numbers are get from a simultaneous fitting of both L0TOS and L0TIS events for each channel, using same mass mean value and resolution parameters.

Measured results

As shown in Equation 55, with determined efficiencies and signal yield, the ratio of branching fraction can be calculated accordingly. The measured ratios for L0TOS and L0TIS are:

$$\mathcal{R}_{\text{TOS}} = 0.028 \pm 0.011, \quad (67)$$

$$\mathcal{R}_{\text{TIS}} = 0.045 \pm 0.013, \quad (68)$$

where the uncertainty is statistical uncertainty only.

Systematic uncertainties

Sources of systematic uncertainty and their effects on the measured ratio of the total branching fractions are summarized in Table 18.

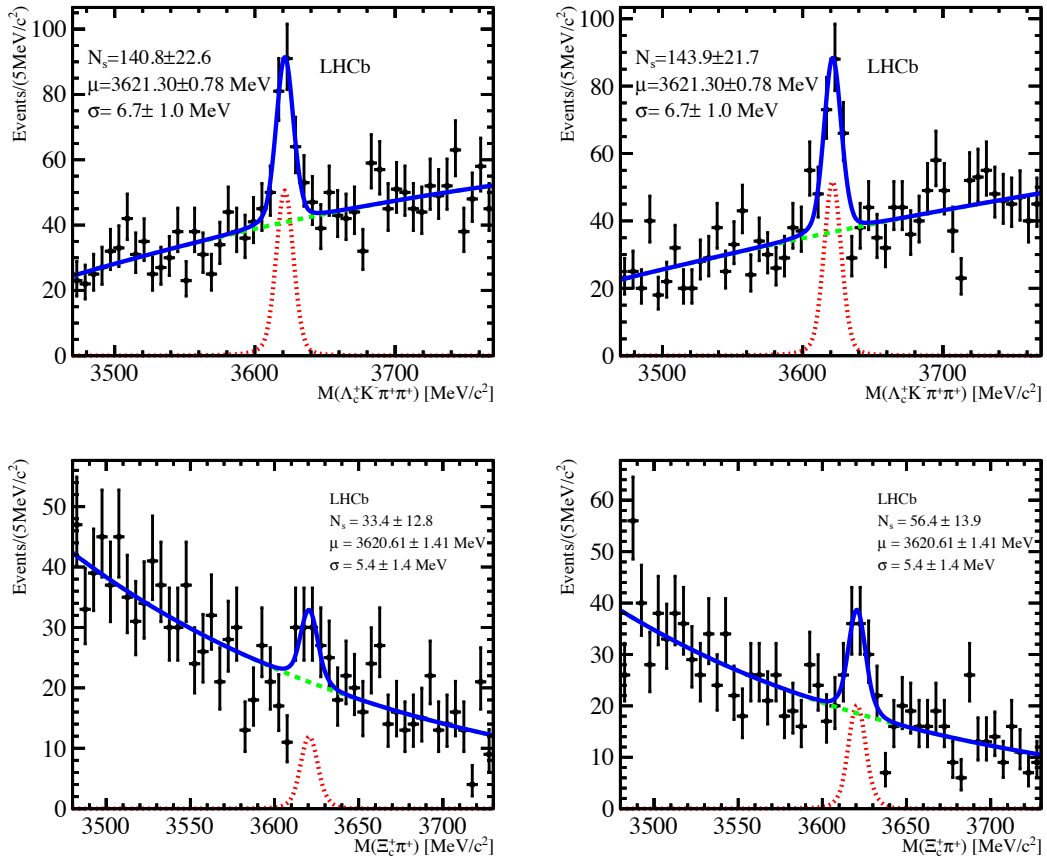


Figure 102: The Ξ_{cc}^{++} L0TOS candidates (left), and Ξ_{cc}^{++} L0TOS candidates (left). $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ distributions are shown in the top two figures, and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ distributions are shown in the bottom two figures.



The signal yields of both the signal and the normalization decays can be affected by the signal and background line shapes, and by the fit range. Such effects are studied by using alternative signal and background models, and by performing the mass fits in different mass ranges. For the signal model, a two-Gaussian functions have been tried, to replace the nominal one Gaussian function plus one crystal ball function. For the background model, the nominal exponential function has been changed to an first-order polynomial function. The fit range have been changed from $3620 \pm 150 \text{ MeV}/c^2$ to $3620 \pm 100 \text{ MeV}/c^2$. Using the MC toy method, as described in Reference [102], the differences between the new ratio and the nominal one, which are 3.8% for the fit range, 2.6% for the signal modelling, and 2.3% for the background modelling. Combined above uncertainties, 5.2% is taken as the systematic uncertainty from the mass fitting.

The input Ξ_{cc}^{++} mass used in the MC sample is different from the measured value using $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel. As discussed in Appendix A.1, after detailed study on this effect, a systematic uncertainty of 1.2% is assigned for this effect.

The GENXICC2.0 generator is used to simulate Ξ_{cc}^{++} production, a slightly different p_T spectrum in simulation and in data is seen. This has been reweighted to match that in data. However, the kinematic cut on $\Xi_{cc}^{++} p_T$ is slightly different for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ ($> 2 \text{ GeV}/c$) and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ ($> 4 \text{ GeV}/c$). In order to estimate any remaining effects, the p_T cut in $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ study has been tightened to be the same as used in $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ ($> 4 \text{ GeV}/c$). The ratio is measured again, and a difference of 0.7% is found w.r.t. to the nominal one. Conservatively, 0.7% is assigned as a systematic uncertainty. The uncertainties from p_T -y reweighting, and life-time reweighting are studied using the toy MC method, by varying the correction within one standard deviation. The uncertainty from efficiencies correction, are also studied with the toy MC method.

Additional systematic uncertainty arises from tracking reconstruction efficiency, with limited knowledge of the material budget of the detector, which gives a 1.1% (1.4%) [103] uncertainty on the the kaon (pion, proton) reconstruction efficiency due to modelling of hadronic interactions with detector material. Also, there is an additional uncertainty on the tracking efficiency from the method, which amounts to 0.8% for each track at 13 TeV. As the final states of the Ξ_c^+ and Λ_c^+ are the same, such effects are expected to cancel out at the first order. Basically the remaining effects are due to that there are two more tracks in the normalization decay $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ than in the signal decay $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$, so $1.1\% (\text{kaon}) + 1.4\% (\text{pion}) + 0.8\% \times 2 (\text{two more tracks}) = 4.1\%$, is assigned as the systematic uncertainty.

For the uncertainty from the particle ID, the bin size of the PID efficiency could be not



Table 18: Statistical and systematic uncertainties in the ratio of branching fraction measurement.

Source	L0TOS	L0TIS	Combined
Stat.	41.2%	29.4%	24.8%
Syst.			
Input Mass	1.2%	1.2%	1.2%
p_T cut	0.7%	0.7%	0.7%
Mass fit	5.2%	5.2%	5.2%
MC reweight	0.2%	0.2%	0.1%
MC match	1.3%	1.3%	1.3%
Lifetime	0.1%	0.1%	0.1%
Efficiency	2.2%	2.2%	2.2%
Trigger	6.2%	5.7%	4.2%
Tracking	4.1%	4.1%	4.1%
PID	1.3%	1.3%	1.3%
Total	9.6%	9.3%	8.5%

small enough, then a wrong average efficiency is taken due to the potentially different kinematic distribution between signal/normalization samples, and the calibration samples. Such effects are studied by doubling/halving the number of bins, the PID efficiency is recalculated. The largest deviation from the nominal result, 1.3%, is taken as the systematic uncertainty.

For ratio of the total branching fractions measurement, which is not sensitive to the fitted mass, so the energy scale and other uncertainties related to the mass measurement are negligible.

The uncertainty from trigger is discussed in Section 5.5.3 and Appendix A.10. The uncertainty from acceptance, reconstruction efficiency is calculated using the MC samples, with the uncertainty from MC-Match efficiency included (Section 5.5.2).

Combined results

The measured branching fraction ratio ($\mathcal{R}$) using L0TOS and L0TIS events are

$$\mathcal{R}_{\text{TOS}} = 0.028 \pm 0.011(\text{stat}) \pm 0.003(\text{syst}), \quad (69)$$

$$\mathcal{R}_{\text{TIS}} = 0.045 \pm 0.013(\text{stat}) \pm 0.004(\text{syst}), \quad (70)$$

Using BLUE method [97, 98], and taking the systematic uncertainties from trigger and MC reweight as uncorrelated, and other systematic uncertainties as 100% correlated between L0TOS

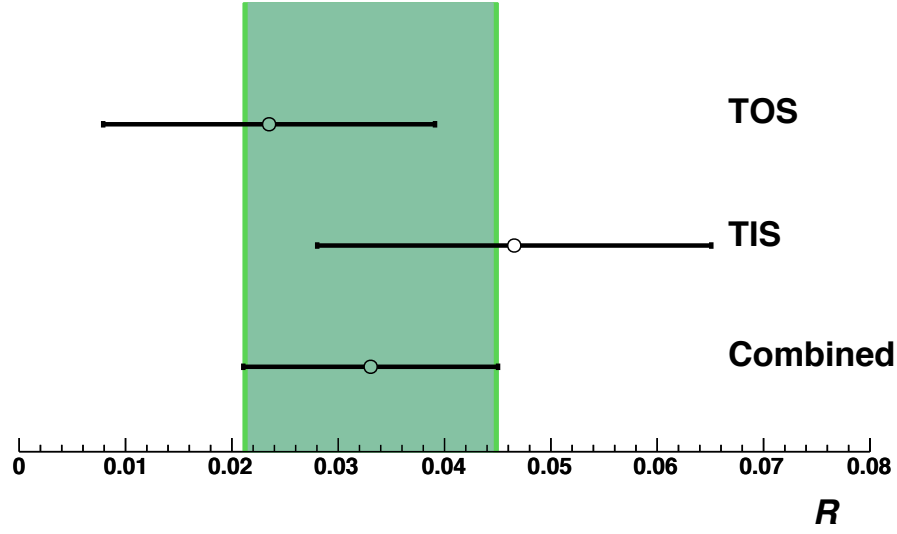


Figure 103: The measured branching fraction ratio using L0TOS and L0TIS, and the combined results.

and L0TOS, the combined result is

$$\mathcal{R} = 0.035 \pm 0.009(\text{stat}) \pm 0.003(\text{syst}), \quad (71)$$

The comparison between the measured ratio results using L0TOS and L0TIS events, and the combined result is shown in Figure 103.

5.7 Procedures for evaluating significance and setting limits

5.7.1 Strategy

In this chapter, we are following similar procedures which has been discussed in the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ analysis [91] (Section 7). Considering the Ξ_{cc}^{++} has been discovered, so in this analysis, we only refer to ‘local’ significance, without any discussion on the ‘global’ significance. The ‘local significance’ means the significance of a signal evaluated for one particular δm hypothesis. (There are various different ways to compute a number for this; see below.) And the ‘global significance’ means the significance of a signal in the whole δm range taking into account the look-elsewhere effect (LEE)—that is, the global significance reflects the probability under the null hypothesis for such a signal to pop up anywhere in the mass range scanned.

Depending on what we see in data, we will need to choose one of a few different paths:

- If there is a peak whose local significance is above 3σ , we will quote that local significance (along with how it was evaluated) but will not fuss with a LEE correction. We will measure



its mass and yield in a fit (and of course carry out crosschecks to see if it could be faked by another process).

- If there is no peak at even 3σ local, we will quote upper limits as above, together with a branching fraction estimation.

5.7.2 Local significance estimates

There is no one single, universally accepted way of estimating the local significance of a peak. In practice, this doesn't matter too much for us: if the significance is high then its exact value is immaterial, and if the significance is low then we will set upper limit for the measurement. If we have a clear signal which we are able to fit, obtaining a yield of $Y \pm \sigma_Y$, the log-likelihood ratio method will be used to estimate the significance. In the method, we will fit the mass distribution in the signal region, with background only hypothesis and signal plus background hypothesis, calculate the log-likelihood for each of hypotheses, and convert log-likelihood ratio into significance using Wilks' theorem.

Also, if there is no peak structure in the data, after unblinding. We will evaluate the significance with same procedure describe above. In this test, all fit parameters will be fixed, except the signal yield.

5.7.3 Global significance estimates

As we are not planning to evaluate global significance in this analysis, so there is no discussion on this.

5.7.4 Upper limits

If no signal is seen, we can set upper limits using the CL_s procedure, as was done for the 2011 analysis (see Section 10 of ANA-2012-094). If the signal yield is not enough to perform the kinematic corrections discussed in Section 5.5.1, even with $\sim 3\sigma$ significance, we will use a larger bin size when studying these corrections, or use one-dimensional correction to ensure there are enough statistics in each bin.

For all of the discussion of the significance tests, all that matters is whether a peak is present in the signal mode so all we really need is the signal mode in data (though we get some help from control samples to estimate the background shape when generating toys). To set an upper limit,



however, we need two more ingredients: the efficiency (from signal MC), and a normalization mode. This will enable us to quote limits on

$$R \equiv \frac{\sigma(pp \rightarrow \Xi_{cc}^{++} X) \mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+)}{\sigma(pp \rightarrow \Xi_{cc}^{++} X) \mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} = \frac{N_{\text{sig}} \varepsilon_{\text{norm}}}{N_{\text{norm}} \varepsilon_{\text{sig}}}, \quad (72)$$

where σ is a cross-section, $\mathcal{B}$ is a branching fraction, N is a yield, ε is an efficiency, sig indicates the Ξ_{cc}^{++} signal decay, and norm indicates the $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ normalization mode. Note that ε_{sig} depends on the assumed Ξ_{cc}^{++} lifetime, so we will check the lifetime dependence of the ratio of ε_{sig} ($R(\varepsilon_{\text{sig}})$) in two channels, if there is a strong lifetime dependence of $R(\varepsilon_{\text{sig}})$, we will need to quote limits for several lifetime hypotheses; if not, we will assign a proper systematic uncertainty on this, and only report one limit. ε_{sig} also depends on δm in general, but this is easier to take into account; also in the previous analysis it was found that this dependence was quite weak.

Most of systematic uncertainties for the upper limit setting on the branching fraction, are similar to the uncertainties discussed in Section 5.5. The uncertainties from acceptance and reconstruction efficiency in upper limit measurement are exactly same as that in branching fraction measurement, similar for the uncertainties from input mass, lifetime, mass fit. The uncertainty from trigger and MC reweight will be slightly different, since we do not have data to perform the reweighting.

5.8 Conclusions

With 2016 data, we search for Ξ_{cc}^{++} using $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel, and in this note, we established entire analysis procedure, including the mass measurement, ratio of branching fraction measurement, and significance calculation. After unblinding the data, a structure is observed in 2016 data, with 5.9σ local significance, which is consistent with previously discovered Ξ_{cc}^{++} , with a mass of 3620.56 ± 1.45 (stat) ± 0.49 (syst) MeV/ c^2 . The $\frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)} \times \frac{\mathcal{B}(\Xi_c^+ \rightarrow p K^- \pi^+)}{\mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+)}$ is measured to 0.035 ± 0.009 (stat) ± 0.003 (syst).



6 Measurement of the angular coefficients of $\mu^+\mu^-$ pairs in the Z boson mass region at LHCb

6.1 Data and simulation samples

DaVinci v44r10p1 is used to produce the ROOT [104] ntuples for the fully reconstructed simulation and data samples at $\sqrt{s} = 13$ TeV centre-of-mass energy.

6.1.1 Data samples

The 2016, 2017, and 2018 data were taken at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. The integrated luminosity of three data sets is 5.2 fb^{-1} .

The magnetic field deflects oppositely charged particles in opposite directions and this can lead to detection asymmetries. Periodically reversing the magnetic field polarity throughout the data-taking almost cancels the effect. The data samples are split into two independent sub-samples, as *MagUp* and *MagDown*.

6.1.2 Simulation

To reduce discrepancies between real data and simulation events, backgrounds with largest contributions are estimated with a data-driven method. However, two different types of Monte Carlo (MC) samples are used in the analysis, as MC events with detector simulation and generator-level events. The MC events with detector simulation are used to study efficiencies, to get a better understanding on detector response, and to estimate background contributions, which are passed through the LHCb full detector simulation chain and reconstructed with the same algorithms as data. The MC events with detector simulation are summarized in Section 6.1.3. The generator-level MC events are used to estimate the high order correction, to study final state radiation (FSR) effects.

6.1.3 MC with detector simulation

These samples are produced using Pythia 8 generator [105], configured as described in Reference [106], using the CTEQ6L1 [107] Parton Distribution Function (PDF) set. The MC samples with detector simulation used in this analysis are summarized in Table 19. These MC samples are used to understand the background contributions and efficiency modelling.



In $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow \tau^+\tau^-$ MC samples, the interference effects between the Z boson and the photon are included. The $gg \rightarrow t\bar{t}$ and $q\bar{q} \rightarrow t\bar{t}$ samples are treated independently to estimate the background contributions, accordingly to the production cross-section and luminosity, then combined together with label $t\bar{t}$.

Table 19: Decay channels, event type numbers, and generator level cuts for MC samples used in this analysis, with detector simulation.

Process	LHCb number	Generator level requirements
$Z \rightarrow \mu^+\mu^-$	42112001	$p_T^\mu > 4 \text{ GeV}, \eta^\mu > 1.6, m_{\mu\mu} > 40 \text{ GeV}$
$W^+W^- \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$	41922002	$p_T^\mu > 15 \text{ GeV}, \eta > 1.6$
single top	41900003	$p_T^\mu > 17 \text{ GeV}, \eta > 1.6$
$gg \rightarrow t\bar{t}$	41900006	$p_T^\mu > 17 \text{ GeV}, \eta > 1.6$
$q\bar{q} \rightarrow t\bar{t}$	41900007	$p_T^\mu > 17 \text{ GeV}, \eta > 1.6$
$Z \rightarrow \tau^+\tau^-$	42100000	$p_T^\mu > 4 \text{ GeV}, \eta > 1.6$

6.1.4 Generator level MC

As discussed in Reference [108], the theoretical calculations for the Drell-Yan process with QCD radiation, usually do not include the full EW radiative corrections. Fortunately, the QCD, the quantum electrodynamics (QED), and the weak corrections can be organized independently, which can be studied and applied, separately. Following the strategy used in Reference [108], we used an enhanced QCD prediction for Drell-Yan process, by implementing the EW corrections to the QCD calculation.

For the QED radiative corrections, which are related to the final state photons, are not considered in the calculation. However, these effects are included in the signal MC ($Z \rightarrow \mu^+\mu^-$) events with LHCb detector simulation, via Pythia 8 formalism. In this analysis, as the measured results are correct to the Born level, so the effects from the FSR are removed, the measured results can be directly compared with any theoretical predictions in Born level.

The virtual EW radiative corrections are implemented into QCD calculations of Drell-Yan process, via form factors of fermion-pair production in e^+e^- collision, $e^+e^- \rightarrow Z \rightarrow f\bar{f}$.

The Z -amplitude form factors are calculated by ZFitter [109–111] generator, which were widely used in the LEP-1 and SLD collaborations for various precision tests of the Standard Model [112]. It is a semi-analytical calculation for fermion-pair production and radiative corrections for high energy e^+e^- collisions. Corrections to fermion-pair production via the virtual



photon include weak-interaction W boson loops in the photon propagator, and Z boson propagators at fermion-photon vertices. The weak and QED corrections in ZFitter are organized to be separately gauge invariant. Consequently, weak corrections to fermion-pair production via the virtual photon are included with the Z amplitude form factors. The renormalization scheme used in ZFitter is the on-shell scheme [113], where particle masses are on-shell. In this scheme, the $\sin^2\theta_W$ is defined as

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}, \quad (73)$$

The form factors calculated by ZFitter are stored for later use in Drell-Yan QCD calculations. The calculated form factors are $\rho_{\ell q}$, κ_ℓ , κ_q , and $\kappa_{\ell q}$, where the label ℓ denotes a lepton and q denotes a quark. As the calculations use the massless-fermion approximation, the form factors only depend on the charge and weak isospin of the fermions. Therefore, the calculated form factors are categorized with three labels: ℓ (lepton type), u (up-quark type), and d (down-quark type), which are complex valued, and been presented as a function of the $\sin^2\theta_W$ and the Mandelstam $\hat{s}$ variable of the $e^+e^- \rightarrow Z \rightarrow f\bar{f}$. The first three of them for the Z amplitude are important, which can be reformulated as corrections to the Born-level g_A^f and g_V^f couplings, as

$$\begin{aligned} g_V^f &\rightarrow \sqrt{\rho_{\ell q}} (T_3^f - 2Q_f \kappa_f \sin^2\theta_W) \\ g_A^f &\rightarrow \sqrt{\rho_{\ell q}} T_3^f, \end{aligned} \quad (74)$$

where $f = \ell$ or q , where T_3^f and Q_f are the third component of the weak isospin and the charge of the fermion.

The Drell-Yan QCD calculations are improved by the implementation of the calculated form factors by the ZFitter into the process amplitude, which provides an enhanced Born approximation (EBA) to the EW terms of the amplitude. The QED photon self-energy correction is included as part of the EBA. The cross section of $\gamma - Z$ interference is proportional to $(\hat{s} - M_Z^2)$, which dominates the total interference cross section away from the Z pole. As the $\gamma - Z$ interference dilutes $\sin^2\theta_W$, photonic corrections are also included. The ZFitter form factors $\rho_{\ell q}$, κ_ℓ , and κ_q are implemented to the Born g_A^f and g_V^f couplings for the Drell-Yan process, while $\kappa_{\ell q}$ form factor is used as an amplitude correction. The measured Z boson resonant line shape from the LEP experiments and the total decay width calculated by ZFitter are used in the calculation.

Different theoretical predictions are considered in this analysis, including analytic resummed calculations (ResBos, dyturbo), fixed-order calculations (Powheg-BOX, MCFM).

The enhanced QCD prediction is obtained from a generator-level $Z \rightarrow \mu^+\mu^-$ sample, which is generated with ResBos [114] using the CT14HERA2NNLO PDFs [115], with the form fac-



tors calculated by ZFitter implemented. The ResBos calculation combines a NLO fixed-order calculation at high boson p_T with the Collins-Soper-Sterman resummation formalism [116–118] at low boson p_T , which is an all-orders summation of large terms from gluon emission.

The Powheg-BOX [119–122] is a NLO generator, and can be interfaced with Pythia for QCD and EW showering. It is a fully unweighted partonic-event generator for Drell-Yan process at NLO. Although Pythia is a LO generator, it approximates higher order effects in initial and final states via a parton showering algorithm [105]. In this analysis, Powheg-BOX is used to generate $Z \rightarrow \mu^+\mu^-$ events, followed by hadronization using Pythia.

The dyturbo [123] is a NNLO generator, for the calculation of the QCD transverse-momentum resummation of Drell-Yan cross sections up to NNLL accuracy combined with the fixed-order results at NNLO order ($O(\alpha_s^2)$), including the full kinematical dependence of the decaying lepton pair with the corresponding spin correlations and the finite-width effects.

The MCFM [124] is a NLO generator, it is used to estimate the cross section of $t\bar{t}$ processes in LHCb detected region, the production cross-section calculated by Pythia is normalised to MCFM prediction.

6.2 Event selection

The $Z \rightarrow \mu^+\mu^-$ candidates are selected based on online (trigger) and offline (Stripping and event selection) selection requirements, which are discussed in this section.

6.2.1 Trigger

Candidate events are required to have at least one muon candidate to be triggered on signal (TOS) with respect to all of the following trigger lines in different stages:

- `L0MuonEW`: Candidate event must contains at least one muon with $p_T > 6$ GeV, a Global Event Cut is required as $N(\text{SPD}) \leq 100000$.
- `Hlt1SingleMuonHighPT`: Candidate event must passes `L0MuonEW`, and has at least one muon with $p_T > 8$ GeV, also satisfies track fit quality requirement as $\chi^2/\text{ndf} < 4$
- `Hlt2EWSingleMuonVHighPtDecision`: Candidate event is required to contain at least one reconstructed muon track with $p_T > 20$ GeV



6.2.2 Stripping

The following stripping lines from the EW stream are used in this analysis:

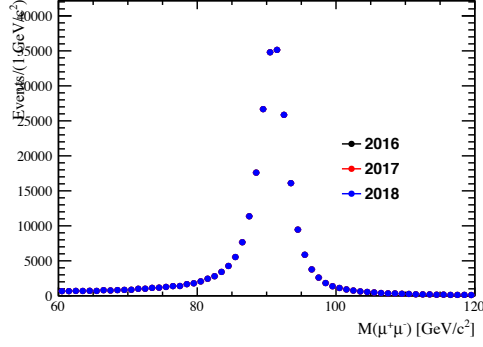
- `StrippingZ02MuMuLine`: This line is used to reconstruct $Z \rightarrow \mu^+\mu^-$ candidates and investigate the contamination from semi-leptonic heavy flavour decays, by requiring two opposite sign `StdAllLooseMuons` particles with $p_T > 3$ GeV and invariant mass of dimuon, $m_{\mu\mu}$, greater than 40 GeV.
- `StrippingMuMuSSLine4`: This line is used to determine contributions from the particle mis-identification background, which requires two same sign `StdAllLooseMuons` candidates with $P > 10$ GeV, $p_T > 3$ GeV, and $m_{\mu\mu} > 40$ GeV.

6.2.3 Offline selection

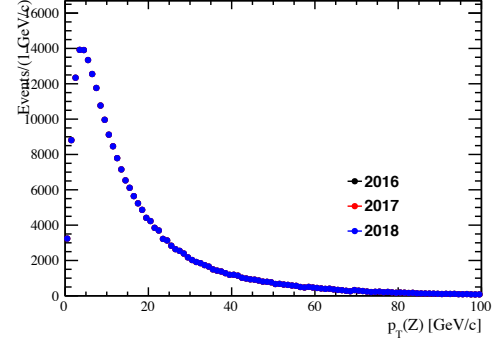
As described in Ref. [45], similar event selection criteria are used in this analysis. The event selection details are listed below:

- At least one muon must pass all three triggers, as shown in Sec. 6.2.1
- Two oppositely charged muons located in the range $2.0 < \eta < 4.5$
- Relative uncertainty in the momentum of the muon track, σ_p/p , must be less than 10%
- Two muons must be isolated, pass isolation requirement ($z > 0.85$). The degree of muon isolation is parameterised as $z = p_T^\mu / p_T^{\mu-cone}$, where $p_T^{\mu-cone}$ is defined to be the sum of p_T of the muon and the tracks within $\delta R < 0.5$. The δR is defined as $\delta R = \sqrt{\delta\eta^2 + \delta\phi^2}$, where $\delta\eta$ and $\delta\phi$ give the separation between the muon track and neighbouring tracks in η and azimuthal angle ϕ .
- Both muons with a transverse momentum greater than 20 GeV, and $50 < m_{\mu\mu} < 150$ GeV
- Two selected muons come from the same vertex (dimuon vertex fit $\chi_{\text{vtx}}^2/\text{ndf} < 9$)

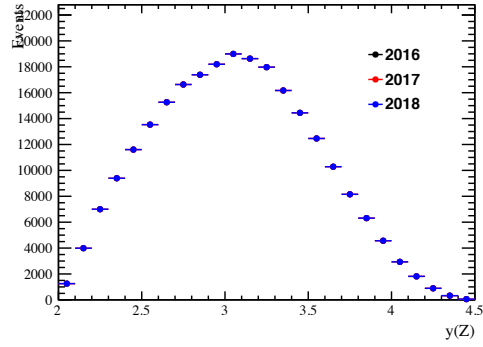
In Section 6.3, we will discuss muon isolation requirement and event vertex requirement with more details. After applying the events selections described above, raw distributions of Z boson mass (a), Z boson p_T (b), Z boson rapidity (y) (c), $\cos\theta$ (d) and ϕ (e) for RunII three years of data sets are shown in Figure 104.



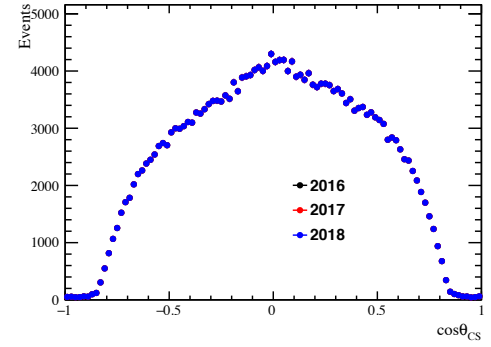
(a)



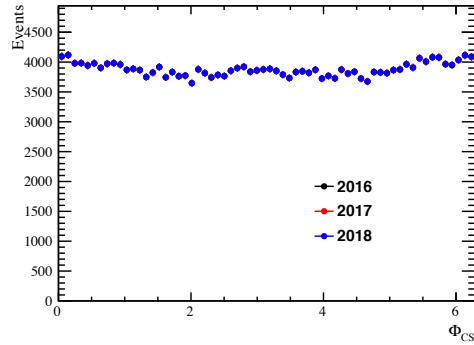
(b)



(c)



(d)



(e)

Figure 104: Comparisons of invariant mass of dimuon (a), Z boson p_T (b), Z boson rapidity (c), $\cos\theta$ (d) and ϕ (e) for RunII data, with event selection applied. All distributions are normalized into 1.



6.3 Backgrounds

The background contribution in the $q\bar{q} \rightarrow \gamma^*/Z \rightarrow \mu^+\mu^-$ candidate events is very small. In this analysis, we considered five different backgrounds, including contributions from heavy flavour (HF) hadrons, hadron mis-identification (mis-ID), $Z \rightarrow \tau^+\tau^-$, $t\bar{t}$, and W^+W^- processes. The HF background is studied in Section 6.3.1, and the mis-ID background is studied in Section 6.3.2, the other background contributions are estimated in Section 6.3.3.

6.3.1 Semileptonic heavy flavour decays

In the LHC, as a hadron collider, production rate of $b\bar{b}$ and $c\bar{c}$ is much higher than that of Z boson. The HF processes can contribute to the dimuon final state, with semi-leptonic decay of two HF hadrons. Although only a small fraction of HF events has two muons in the final state, this background could still makes a significant contribution in the data sample, due to high production rate of $b\bar{b}$ and $c\bar{c}$.

In $Z \rightarrow \mu^+\mu^-$ signal events, two muons in final state are expected to originate from a common vertex. While, for the vertex reconstructed using two muon tracks from decays of b hadrons or c hadrons, is expected to have a large vertex $\chi^2_{\text{vtx}}/\text{ndf}$ value, as the heavy flavour quarks have significantly longer lifetime than that of Z/γ^* , resulting it less likely to contains two muons that originated from the primary vertex, as shown in Figure 105.

To suppress contributions from this background, a requirement on dimuon vertex $\chi^2_{\text{vtx}}/\text{ndf} < 9$ is applied in the event selection, as discussed in Section 6.2.3.

Furthermore, muons from heavy flavour quarks are likely to be surrounded with hadronic activity.

Therefore, the muons in the HF events are expected to be poorly isolated, which is one of characteristics of QCD processes like $b\bar{b}$ and $c\bar{c}$ production. Well-isolated muons have z values close to 1, while poorly isolated muons have value closer to 0. The HF background contribution is highly suppressed by requiring both muons must isolated, as $z > 0.85$.

After applying vertex quality cut and muon isolation cuts, the background contribution from HF is expected to be small, which is negligible in this analysis.

6.3.2 Hadron mis-identification

Events containing pions or kaons can lead to a muon being identified in the final state, as pions and kaons could decay in flight before they reach the muon spectrometer, or if they have sufficient

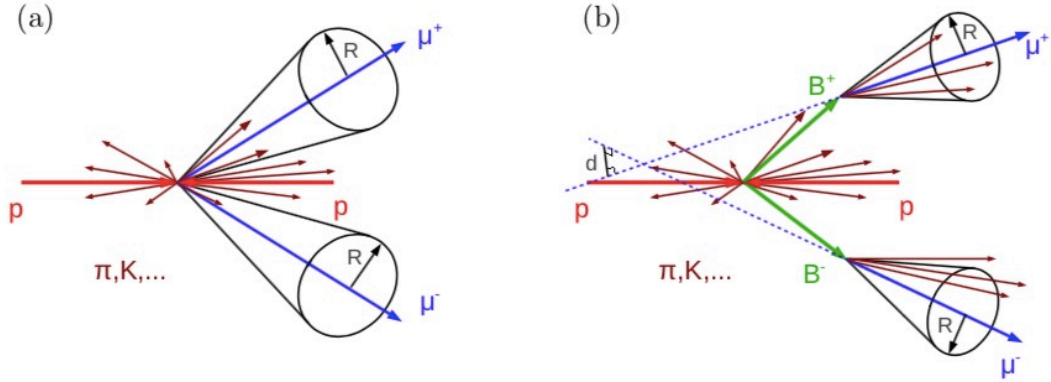


Figure 105: Schematic representation of muons arising from (a) $Z \rightarrow \mu^+\mu^-$ decays and (b) decays of B -hadrons. Due to finite resolution on muon momentum, even muon tracks from signal do not lead back to the exact same point. However, the impact parameter (thin black line d in (b)) is much larger in heavy flavour decays. Decays of B -hadrons also have higher momentum tracks within the $\eta - \phi$ cone around the muon.

energy to punch through the calorimeters and fake as a muon. This background consists of events that contain two mis-identified muons and events with a single mis-identified muon plus a genuine muon. The genuine muon can originate from a $W^\pm \rightarrow \mu^\pm \nu$ decay, and a $Z \rightarrow \mu^+\mu^-$ decay where one muon is outside the LHCb acceptance or in flight decay of a hadron. The normalisation and invariant mass distribution shape for this background is estimated from data, by applying the same selection as the nominal analysis, except running over the `MuMuSSLIne4` stripping line and requiring that the two muons have the same sign. This method takes advantage of the fact that the probability for a kaon or pion to fake a positive or negative muon is same. Therefore, the normalisation is assumed to be equal to the number of same sign candidates remaining, after the event selection has been applied.

6.3.3 Top and EW productions

The top and EW production consists of the single top, $t\bar{t}$, $Z \rightarrow \tau^+\tau^-$, and $W^+W^- \rightarrow \mu^+\nu_\mu\mu^-\bar{\nu}_\mu$ decays, all of which can contain two genuine muons of opposite charge in the final state. The contribution is estimated by using MC events with LHCb detector simulation, where Pythia 8 cross section is scaled to its NLO predictions. The background contributions of different composition for three years are summarized in Table 20.

As shown in Table 20, purity of selected data $Z \rightarrow \mu^+\mu^-$ sample is very high, which is close to



Table 20: Background composition of the candidate samples after event selection has been applied.

Background	Estimation	2016	2017	2018
Hadron mis-ID	Data-driven	0.016%	0.014%	0.016%
$Z \rightarrow \tau^+ \tau^-$	Pythia 8 (ResBos)	0.067%	0.054%	0.064%
$t\bar{t}$	Pythia 8 (MCFM)	0.059%	0.060%	0.060%
$W^+ W^- \rightarrow \mu^+ \nu_\mu \mu^- \bar{\nu}_\mu$	Pythia 8 (MCFM)	0.017%	0.014%	0.016%
Total		0.159%	0.144%	0.159%
Purity		99.841%	99.856%	99.841%

100%. The purity and background contributions of different compositions are consistent within three years of RunII datasets. Comparison of $\cos \theta$ and ϕ between data sample and background could be found at Figure 106, where all of contributions are normalized to 1.

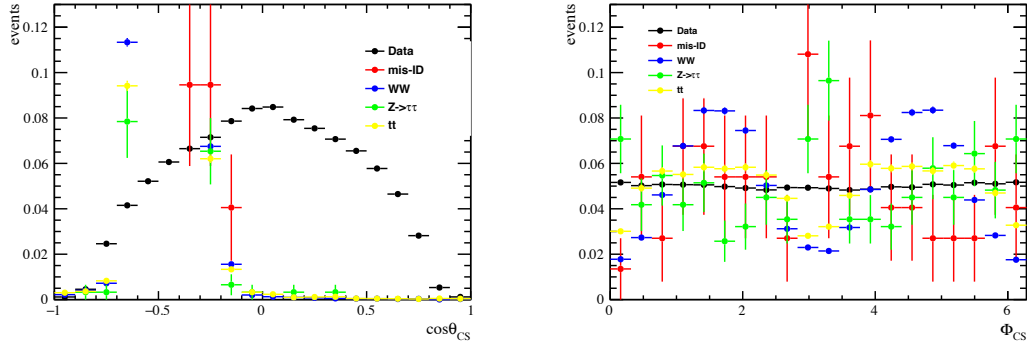


Figure 106: Comparison of $\cos \theta$ (left) and ϕ (right) distributions between data sample and background.

6.4 Corrections

Several corrections are studied and applied to the $Z \rightarrow \mu^+ \mu^-$ data and simulation events, to suppress effects from imperfect detector modelling in MC events, the detector mis-alignment, and selection efficiencies, *etc.* In this section, a correction for detector mis-alignment is presented in Section 6.4.1, the resolution smearing correction is studied in Section 6.4.2, background contamination estimation is discussed in Section 6.4.3, Followed by a discussion on selection efficiency correction in Section 6.4.4, and a data/MC reweight correction in Section 6.4.5, which is necessary for A_i determination.

The corrections used in this analysis are summarized below:



- Muon momentum calibration: it is applied to $Z \rightarrow \mu^+\mu^-$ data and MC events to suppress effects from detector mis-alignments
- MC smearing correction: to ensure MC $Z \rightarrow \mu^+\mu^-$ events have similar detector response as data events
- Background subtraction: it is applied to data sample to remove background contamination, in different Z p_T and rapidity region
- Efficiency correction: a ratio of efficiency of data to MC, and applied to MC events ensure the selection efficiency in MC is agree with that in data.
- Data/MC reweight: to ensure the muon p_T and η distributions of MC $Z \rightarrow \mu^+\mu^-$ events are same as these of data

6.4.1 Muon momentum calibration

During data taking, the LHCb detector alignments are studied and applied in online level, where the alignments are performed by using hadron decays in the low mass region. The online alignment procedure improves charged particle momentum measurement, and therefore benefits most of the LHCb analyses. But for precision EW measurements with muons in the final state, where muons always with very high momentum, are still suffer from remaining detector mis-alignment effects. For instance, the mass resolution of the Z boson data ($Z \rightarrow \mu^+\mu^-$) events is worse than that of Monte Carlo simulation events. Furthermore, in the forward-backward charge asymmetry measurement of the Z/γ^* events, the A_{FB} distributions of the *MagDown* and *MagUp* samples have large differences between each other, which indicates the remaining mis-alignment effects. These effects are understood due to either imperfect detector alignment, or the modelling of magnetic field. In Section 8, a two step offline procedure of muon momentum alignment for the LHCb RunII datasets is performed. In the first step, we applied a track bias correction (muon ϕ dependence) to muons, and refitted muons after correction. Followed by a second-step, which studied the Z mass dependence as a function of muon η and ϕ . As shown in Section 8, after applying these corrections into data, there are significant improvements on the data Z mass resolution, also the A_{FB} differences between *MagDown* and *MagUp* data samples are largely suppressed.

We used same calibration method to correct both $Z \rightarrow \mu^+\mu^-$ data and MC events.

6.4.2 Muon momentum smearing for MC events

In the MC $Z \rightarrow \mu^+\mu^-$ events, the Z mass resolution is different from that of data, due to imperfect modeling of the detector in MC simulation, as shown in left figure of Figure 153. Additional muon momentum smearing is applied to MC $Z \rightarrow \mu^+\mu^-$ events, to achieve good agreement of invariant mass distribution between MC and data. The additional smearing corrections is performed using a formula as:

$$p' = p \times (1 + \gamma \times \text{Gauss}(0, 1)), \quad (75)$$

where γ is a smearing factor, p' (p) is the muon momentum after (before) correction. The smearing parameters are tuned by comparing data and MC invariant mass distributions, and with muon η dependence been considered. After the smearing correction, the $Z \rightarrow \mu^+\mu^-$ invariant mass resolution of MC $Z \rightarrow \mu^+\mu^-$ events has good agreement with that of data events, as shown in right figure of Figure 153.

More details for this study can be found in Section 8.

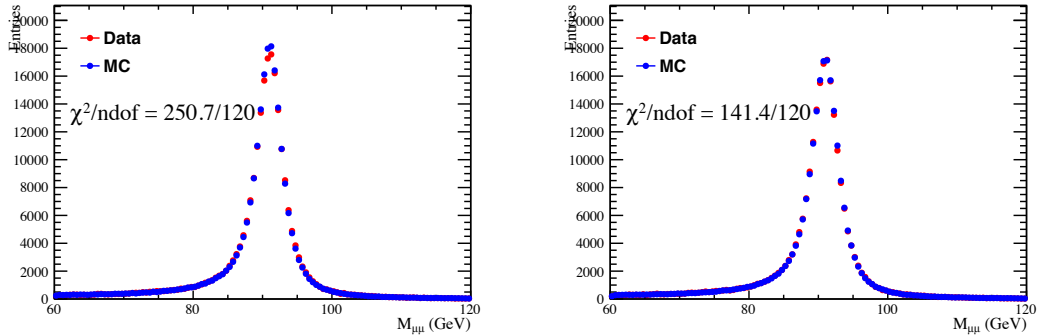


Figure 107: Comparisons of the $\mu\mu$ invariant mass distribution between data and MC sample, before (left) and after (right) MC smearing correction.

6.4.3 Background subtraction

In this analysis, unbinned maximum log-likelihood fit method is used to extract final result as described in Section 6.5, so only a weighted method could be used to subtract the background. The negative-event-weight method [125] is described in Section 6.4.3. In this method, we check the observable angular ($\cos \theta$ and ϕ) distributions, which are obtained from histograms with background component subtracted, and background samples with the negative weights applied. Comparison of these results as Figure 108 shows, top panels of these two figures are the ratio between



these two samples, it could be clearly see that the background angular distribution is consistent between these two samples, which tell us the negative-event-weight method could perform the background subtraction well.

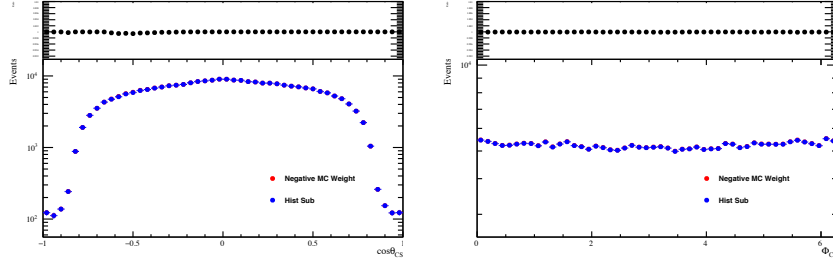


Figure 108: Comparisons of $\cos\theta$ and ϕ between the background subtraction sample obtained by the subtraction of the histogram (blue points) and the negative sample (red points) in 2016 data. Top panels of these two figures are corresponding to the ratio between these two samples. Good agreements are found between these two samples.

6.4.4 Efficiency

In this analysis, there are two final states muons with high p_T . Therefore, a precise determination of the associated muon reconstruction efficiencies is critical to perform this precision EW measurement. The muon reconstruction efficiency, ϵ^{rec} , can be split into three different components, as

$$\epsilon^{rec} = \epsilon^{trg} \times \epsilon^{trk} \times \epsilon^{id}, \quad (76)$$

where ϵ^{trg} is muon trigger efficiency, ϵ^{trk} is muon track reconstruction efficiency, and ϵ^{id} is muon identification efficiency.

Simulation may not model crucial effects like detector occupancy very well, which typically reduce efficiencies. For this reason, these efficiencies are obtained using data itself, from a tag and probe study described in Reference [126]. Muon efficiencies in *MagUp* and *MagDown* data samples are determined, which are consistent with each other for different polarities. Also efficiencies for positive muons as well as negative muons are compared, without any large differences.

The $Z \rightarrow \mu^+ \mu^-$ candidate events are assigned a weight (w) according to η of two muons, as

$$w = \frac{1}{\epsilon_{id}(\eta_{\mu^+})\epsilon_{id}(\eta_{\mu^-})\epsilon_{trk}(\eta_{\mu^+})\epsilon_{trk}(\eta_{\mu^-})[\epsilon_{trig}(\eta_{\mu^+}) + \epsilon_{trig}(\eta_{\mu^-}) - \epsilon_{trig}(\eta_{\mu^+})\epsilon_{trig}(\eta_{\mu^-})]}. \quad (77)$$



More details of the muon efficiency at LHCb RunII can be found in Section 7.

6.4.5 Data/MC reweight

With forward acceptance region of the LHCb detector, the A_i are measured in the fiducial region. However, in generator level, A_i only has physics meaning, only when the cuts are applied on the Z boson variables (*i.e.* Z rapidity > 2 , or Z p_T). In reality, most of event selection cuts that applied to candidate events, are related to the muon properties. Therefore, a acceptance correction is needed in the extraction of A_i , as described in Section 6.5.

In the A_i measurements, the $Z \rightarrow \mu^+ \mu^-$ signal MC sample is used to describe detector acceptance, so a data/MC reweight is applied to MC sample to ensure the muon p_T and η distributions are consistent with these in data. The data distributions after background subtraction are compared to the signal MC distributions efficiency correction (Section 6.4.4) is applied to the MC events.

Comparisons of the muon η and p_T distributions between data and MC are shown in Figure 109. For muon p_T distribution, good agreements between data and MC are seen, so a correction on muon p_T is not necessary. For this correction, only η_μ 2-D reweight is considered, as shown in Figure 110.

6.4.6 Data and MC comparisons

After apply all corrections described in this section, the data and MC comparisons are shown in Figure 111, including the Z boson mass, Z p_T , Z rapidity, muon η , $\cos \theta$ and ϕ distributions in CS frame. Reasonable agreements had been found in all distributions.

6.5 Fitting method

Event distributions as a function of decay observables following from theory in practice get altered by detector acceptance, reconstruction and selection effects. The LHCb detector is a single-arm detector in forward region with unique acceptance, as well as the event selections described in the previous sections, could cause non-uniform efficiencies. There are also effects from detector resolution, and backgrounds modellings. In order to extract physics results from the data, these effects must be taken into account in the A_i determination. In this section, methods are described to implement these effects for all observables that used to determine A_i .

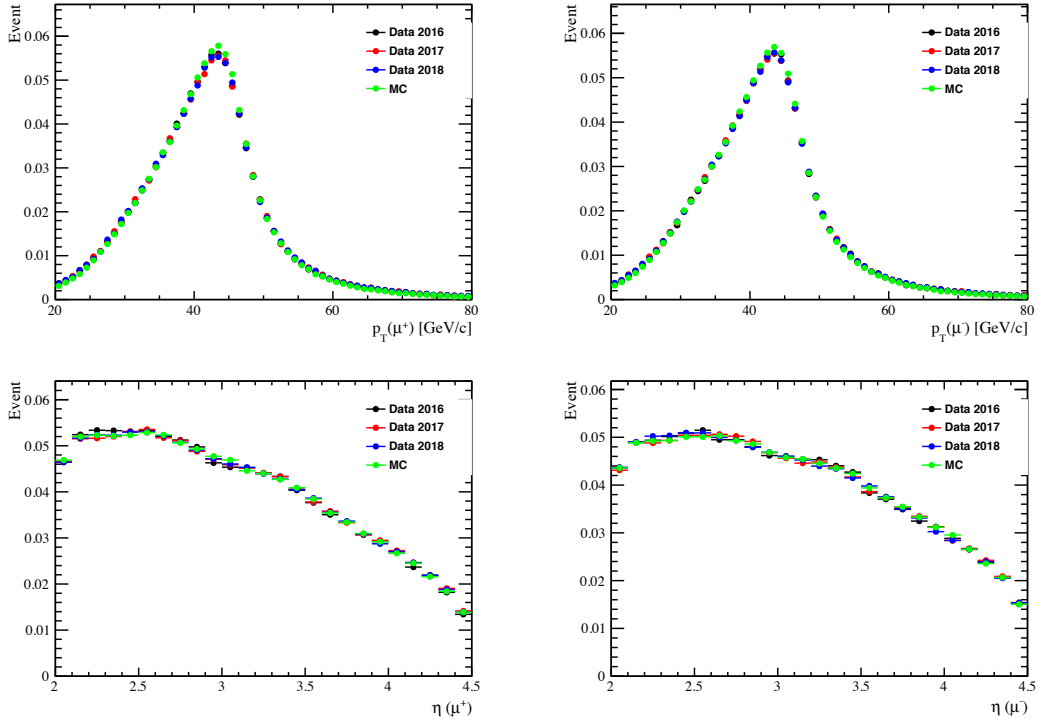


Figure 109: Comparisons of the muon η and p_T distributions between data and MC.

6.5.1 Method introduction

The parameters need to be determined in this analysis are A_0 , A_1 , A_2 , A_3 , and A_4 . The values of these parameters are determined with an unbinned maximum log-likelihood fit to the angular distributions of the selected $Z \rightarrow \mu^+\mu^-$ candidates. As described in Section 6.4.3, to subtract the background component, each event is given a signal weight, W_i^s . Also, the efficiency correction is performed with a efficiency weight, as discussed in Section 6.5.2.

A maximum log likelihood fit is then performed with each candidate weighted by W_i . The fit uses a signal only PDF which is denoted S , obtained from Equation 29.

More details about the fit are discussed in the following sections.

6.5.2 Efficiency correction

In the angular measurement, angular efficiency correction is one of crucial components in the results fitting.

In the MC signal events, an efficiency as functions of two angular observable can be defined as the probability to reconstruct the event, given that it was generated with a certain set of decay

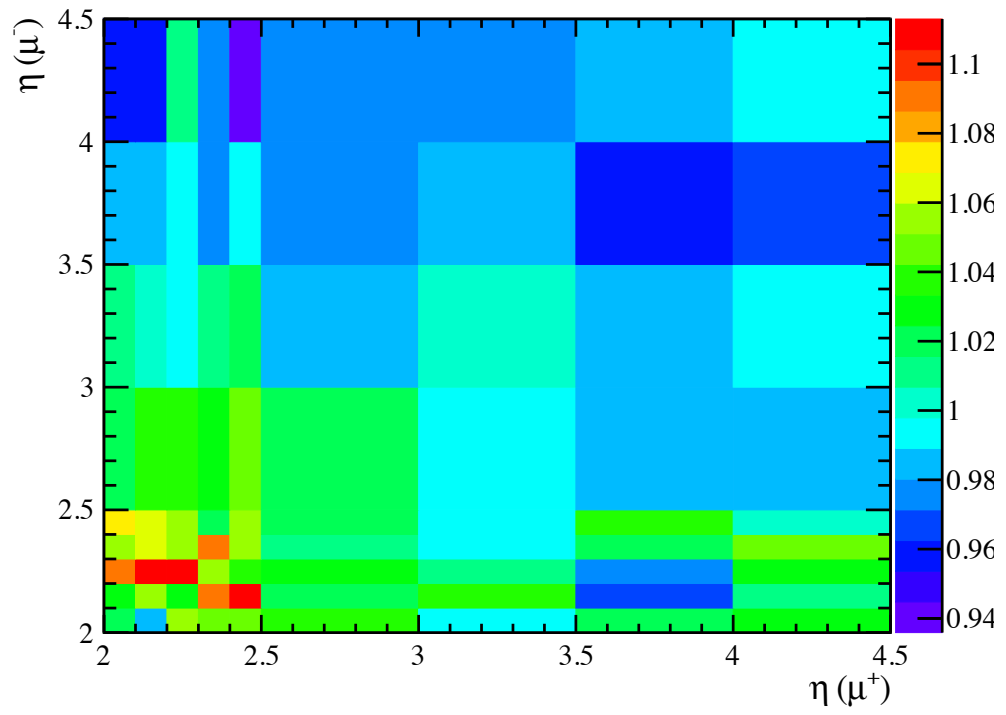


Figure 110: The 2-D data/MC reweight factors, as a function of $\mu^- \eta$ and $\mu^- eta$.

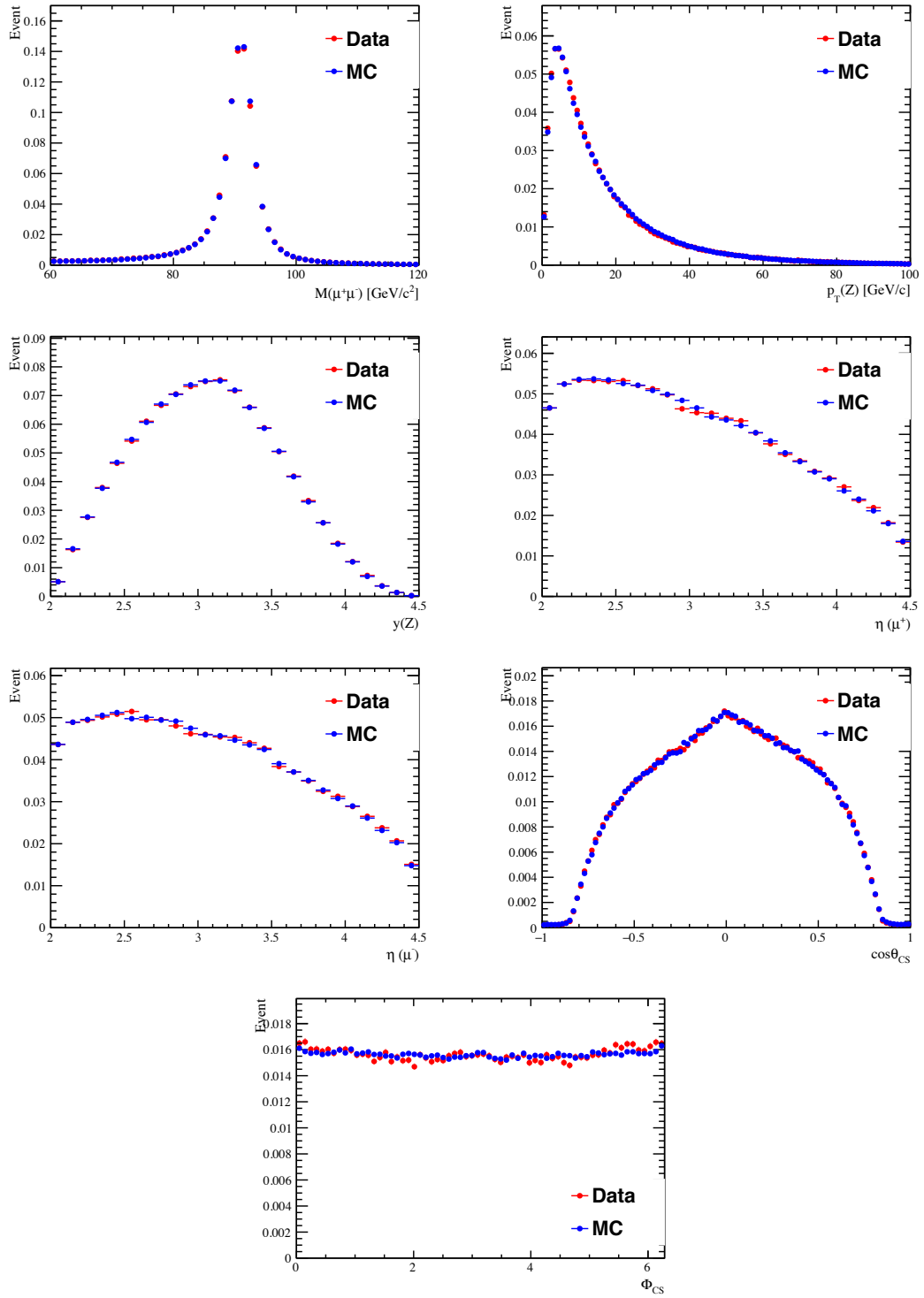


Figure 111: The 2016 data and MC comparisons are shown in this section, including the Z boson mass, Z p_T , Z rapidity, muon η , $\cos\theta$ and ϕ distributions in CS frame.



angles. The efficiency can be determined by dividing the number of reconstructed events in a certain bin by the number of generated events in this bin. If a 2D efficiency is determined in this way several problems can arise. First of all, an unpractically large data sample is required in order to get sufficiently small statistical uncertainties per bin. Secondly, a multi-dimensional function fitted to model such angular efficiency is in general not factorizable into different one-dimensional efficiencies; many terms can be required for a correct parameterization and the fit procedure can become unstable. Furthermore, when multiplying the resulting multi-dimensional function with the probability density function (PDF) of the signal decay, fitting and plotting can become slow, in practice because of the numerical integrations which have to be performed, leading to time-consuming studies. Finally, systematic effects due to any parameterization must be considered.

A method of ‘normalization weights’ avoids the above problems. This method has been introduced and used by many LHCb analyses [127].

Likelihood

Since this analysis uses a likelihood maximization to extract physics results, a brief review of the maximum log-likelihood fitting procedure is given.

The method of maximum likelihood consists of finding, for a set of independently measured quantities, as $\vec{x}$, and a set of values for parameters $\vec{\lambda}$, that maximizes the joint probability density for all the data, given by

$$\mathcal{L}(\vec{\lambda}) = \prod_e S(\vec{x}_e|\vec{\lambda}), \quad (78)$$

where the index e denotes the event. S is the (signal) PDF, which larger than or equal to zero everywhere, and is normalized over the observables. The PDF is written with a capital letter and is implicitly normalized over the variables written to the left of the $|$. The unnormalized signal function, s , is introduced with the following equation applies:

$$S(\vec{x}_e|\vec{\lambda}) = \frac{s(\vec{x}_e|\vec{\lambda})}{\int s(\vec{x}|\vec{\lambda})d\vec{x}}. \quad (79)$$

In the fitting, maximizing $\mathcal{L}$ is equivalent to maximizing $\ln \mathcal{L}$, so the log-likelihood equation can be solved as

$$\frac{d \ln \mathcal{L}}{d \lambda_n} = \frac{d}{d \lambda_n} \sum_e \ln \frac{s(\vec{x}_e|\vec{\lambda})}{\int s(\vec{x}|\vec{\lambda})d\vec{x}} = 0, \quad (80)$$



where n represents the n -th parameter of $\vec{\lambda}$. With a set of measured observables $\vec{x}_e$, and construct a signal PDF $S(\vec{x}|\vec{\lambda})$, the Equation 80 can be used to extract a set of parameters λ , with total probability of all the measurements (which is the product of the individual probabilities of each measurement) is maximal.

Considering effects from the angular efficiency, $\varepsilon(\vec{x})$, the maximum likelihood equation can be written as:

$$\frac{d \ln \mathcal{L}}{d \lambda_n} = \frac{d}{d \lambda_n} \sum_e \ln \frac{s(\vec{x}_e|\vec{\lambda})\varepsilon(\vec{x})}{\int s(\vec{x}|\vec{\lambda})\varepsilon(\vec{x})d\vec{x}} = 0. \quad (81)$$

Since $\ln(AB) = \ln(A) + \ln(B)$, and the efficiency does not depend on the physics parameters $\vec{\lambda}$, the solution of Eq. 81 is independent of the efficiency of numerator and therefore can be ignored.

Efficiencies

A method is discussed here, which describes efficiency in the fit, by determining the integral that appears in the denominator of Equation 81. In this method, the efficiency, and certain components of the PDF, are independent of the parameters λ , and the efficiency factorizes to efficiencies of different observable subsets. Then, the integral is determined for a general angular efficiency by summing over the selected MC events. So, this method is independent of the shape of the efficiency, and the efficiency does not need to be parameterized.

In this analysis, the observed shape of the distribution can be written as

$$s_{obs}(\vec{\Omega}|\vec{\lambda}) = s(\vec{\Omega}|\vec{\lambda})\varepsilon(\vec{\Omega}) = A_i(\vec{\lambda})f_i(\vec{\Omega})\varepsilon(\vec{\Omega}), \quad (82)$$

where A_i is the amplitude term, $f_i(\vec{\Omega})$ is the angular dependent functions for the i -th parameter, and $\varepsilon(\vec{\Omega})$ is a general efficiency. As the efficiency in the numerator of Equation 81 does not influence the estimation of the maximum of the likelihood, and also it does not depend on the fitted parameters, it is irrelevant for the derivative, then Equation 81 can be rewritten as:

$$\frac{d}{d \lambda_n} \sum_e \ln \frac{A_i(\vec{\lambda})f_i(\vec{\Omega}_e)}{\int A_j(\vec{\lambda})f_j(\vec{\Omega})\varepsilon(\vec{\Omega})d\vec{\Omega}} = 0. \quad (83)$$

where i represents the i -th parameter, and j represents the j -th parameter that need to be integrated. From where it can be seen that the integral over the angles is independent of the physics parameters. Furthermore, no description of the efficiency function is needed, but only the normalization integral over the angles has to be determined to include the angular efficiency, and



thus it only has to be done once. While the fitted parameters change value in the likelihood maximization, the value of the angular integral remains constant.

6.5.3 Normalization weights

The integrals over the angles $\vec{\Omega}$, the normalization weights, can be determined as:

$$\xi_j = \int f_j(\vec{\Omega}) \varepsilon(\vec{\Omega}) d(\vec{\Omega}). \quad (84)$$

Whether an event gets accepted or rejected, not only depends on $\vec{\Omega}$, but potentially also depends on all other observable in the event such as momentum, number of tracks, *etc.* Naming all other observable $\vec{z}$, the efficiency equals

$$\varepsilon(\vec{\Omega}) = \frac{\varepsilon(\vec{\Omega}, \vec{z}) S(\vec{\Omega}, \vec{z} | \vec{\lambda}) d\vec{z}}{S(\vec{\Omega} | \vec{\lambda})}. \quad (85)$$

Since the probability to generate an event with certain $\vec{\Omega}$ is independent of $\vec{z}$, it follows that $S(\vec{\Omega} | \vec{\lambda}) = \int S(\vec{\Omega}, \vec{z} | \vec{\lambda}) d\vec{z}$. It should be noted that the probability to generate an event with certain angles, however, does depend on the parameters $\vec{\lambda}$.

Then, the integrals Equation 84 can be written as

$$\xi_j = \int \frac{f_j(\vec{\Omega})}{S(\vec{\Omega} | \vec{\lambda})} \varepsilon(\vec{\Omega}, \vec{z}) S(\vec{\Omega}, \vec{z} | \vec{\lambda}) d\vec{z} d\vec{\Omega}. \quad (86)$$

The $S(\vec{\Omega}, \vec{z} | \vec{\lambda}) d\vec{z} d\vec{\Omega}$ is the probability to generate an event for given $\vec{\lambda}$ with observables between $[\vec{\Omega}, \vec{\Omega} + d\vec{\Omega}]$ and $[\vec{z}, \vec{z} + d\vec{z}]$. In other words, $S(\vec{\Omega}, \vec{z} | \vec{\lambda}) d\vec{z} d\vec{\Omega}$ is a weight for generated MC events, and the integrals can be written as

$$\xi_j \cong \frac{1}{N_{\text{gen}}} \sum_{e \in \text{generated}} \frac{f_j(\vec{\Omega}_e)}{S(\vec{\Omega}_e | \vec{\lambda})} \varepsilon(\vec{\Omega}_e, \vec{z}_e) = \frac{1}{N_{\text{gen}}} \sum_{e \in \text{accepted}} \frac{f_j(\vec{\Omega}_e)}{S(\vec{\Omega}_e | \vec{\lambda})}, \quad (87)$$

where, in the last step, it has been used that for each individual event the efficiency is a boolean (a zero or a one), since an event either gets accepted or not. Note that the overall factor $\frac{1}{N_{\text{gen}}}$ is irrelevant for the likelihood maximization.

In the end, the Equation 83 can be rewritten as:

$$\frac{d \ln \mathcal{L}(\vec{\lambda})}{d\lambda_n} = \frac{d}{d\lambda_n} \sum_e \ln \frac{A_i(\vec{\lambda}) f_i(\vec{\Omega}_e)}{\int A_j(\vec{\lambda}) f_j(\vec{\Omega}) \xi_j}. \quad (88)$$

It can be concluded that there is an expression for the normalization, which can be determined from MC. The integral in which the angular efficiency appeared has become a sum over the accepted MC events.



6.5.4 Validation

Similar to Reference [128], a validation of the method is performed and summarized here. In the validation, a Pythia sample generated in Z rapidity > 2.0 region is divided to two identical and independent sub-samples, labeled as A and B.

The predicted value of A_i is estimated from sample A by using the traditional histogram average method in born level, and the result is marked as "mean". Sample B is used to describe acceptance efficiency (LHCb fiducial region) in bare level, then extract another set of A_i values from the sample A by using unbounded likelihood method, to get the measured A'_i values in bare level and mark results as "fit". The test results are shown in Figure 112, where the results obtained by these two methods are consistent with each other, as expected. This method is good to extract the A_i parameters in real data.

6.6 Systematic uncertainties

Several systematic uncertainties from different sources are considered in this analysis, which play an important role in this precision measurement. In this section, details of systematic uncertainties are discussed, including method used in determination and uncertainty values. In general, for each systematic uncertainty either a 1σ variation, or a range of allowed values is determined for each A_i observable. The total systematic uncertainty is quadratic sum of all systematic uncertainties.

6.6.1 Efficiency

As shows in Section 6.4, the data/MC efficiency correction factor is applied to MC signal events. This analysis is more like a shape measurement, therefore, measured results are not sensitive to any global effect. The systematic uncertainty from tracking efficiencies to cover differences of estimated efficiency between with 'tag-and-probe' and 'Truth method' [103] is not been considered. Two kinds of uncertainties are considered:

- The statistical uncertainties of the efficiency are taken as one systematic uncertainties. The efficiency correction factors shifted by $+1\sigma$ and -1σ uncertainty are used to study the effect on A_i results. The larger deviation on the measured A_i is chosen as systematic uncertainty.
- The default efficiency correction is using the efficiency with muon η dependence. We

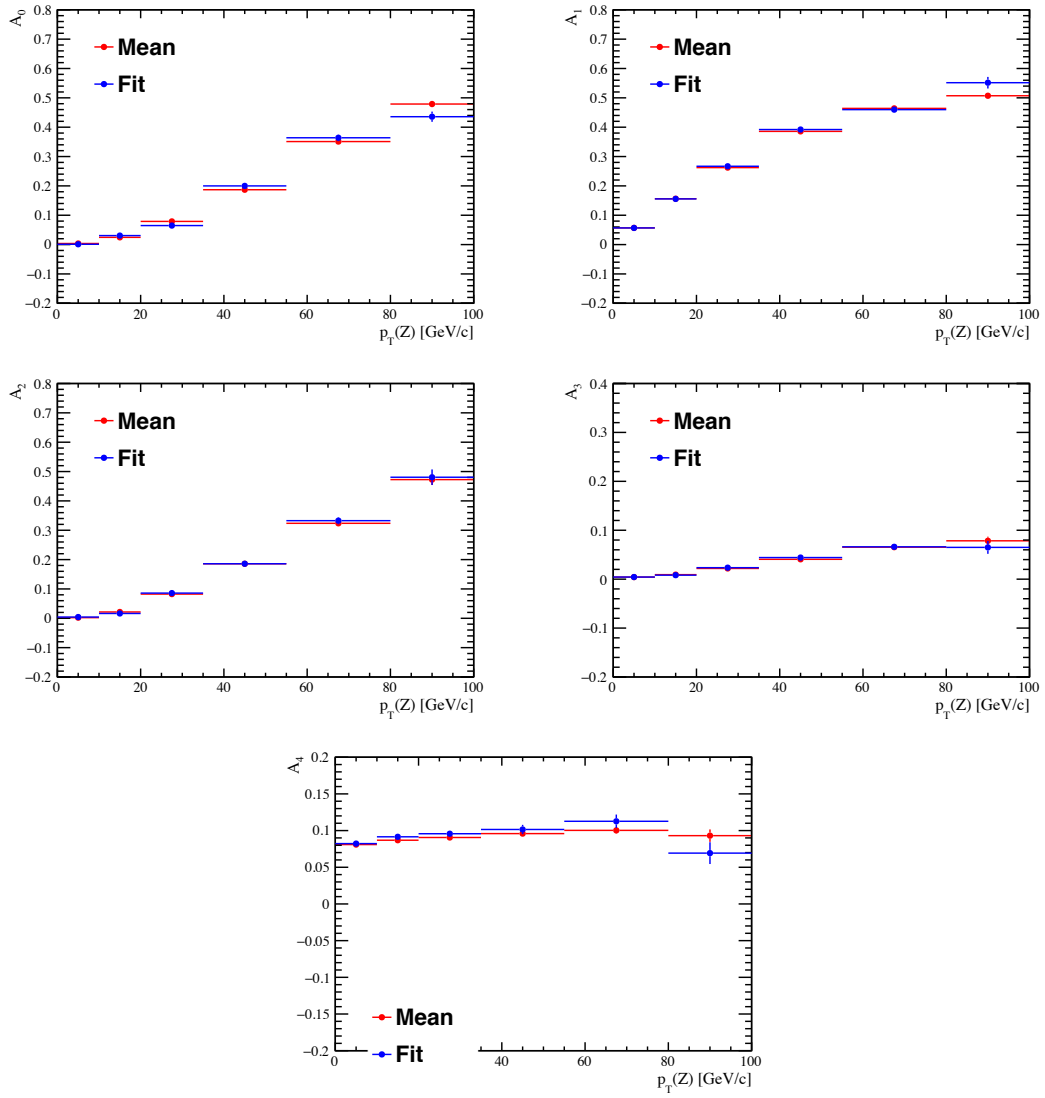


Figure 112: Comparisons of the predicted A_i and measured A'_i using the fitting method, in full phase-space.



replaced the default efficiency with 2-D efficiency with muon p_T and ϕ dependence, and taken differences between these two methods as one of systematic uncertainties.

6.6.2 MC sample size

The detector acceptance is determined using the MC signal sample, which is used in the results fitting process. So a systematic uncertainty from MC sample size is considered for this analysis. The `Bootstrap` method [129] is used to estimate the uncertainty from MC sample size.

6.6.3 Background estimation

To estimate uncertainty from background estimation, the background contribution is modified by $+1\sigma$ and -1σ , and larger uncertainty is taken as systematic uncertainty for the measured A_i . The uncertainties from background estimation is very small, which can be ignored.

6.6.4 PDFs uncertainties

The systematic uncertainty comes from PDF is estimated by reweighting the central PDF set to 56 CT14 error PDF sets. The prescription used in the calculation is:

$$\Delta A^\pm = \sqrt{\sum_{i=1}^{28} (A_i^\pm - A_i^0)^2}, \quad (89)$$

where $A_i^\pm$ is the predicted A_i with i -th eigenvector of PDF sets, and A_i^0 is measured with the central PDF set. Then, asymmetric uncertainties is calculated, but we use only the one with maximal shift from the nominal prediction as systematic uncertainty, either positive or negative value. The default PDFs uncertainty estimated with CT14 PDF is at 90% confidence level (C.L.), a rescaling factor (1.64485) [130] is applied to these uncertainties to obtain the 68% C.L. intervals, as

$$\Delta A^\pm(68\%) = \frac{1}{1.64485} \Delta A^\pm(90\%) \quad (90)$$

6.6.5 Acceptance reweighting

The Pythia signal events are used to study detector acceptance and efficiencies. To decrease the difference between the data and MC distributions, the MC signal events are reweighted to the data distributions as described in Section 6.4.5. In this step, two kinds of uncertainties are considered:



- The statistical uncertainties of the ratio (Data/MC $\mu\eta$ map) are taken as one systematic uncertainties. The ratio central values are varied by $+1\sigma$ and -1σ uncertainty, and the larger deviations on the measured A_i are chosen as systematic uncertainty.
- The different binning schemes for the ratio reweighting map are tested, and deviations of measured A_i are taken as one systematic uncertainties. The default muon η binning is 10 bins in 2.0 to 4.5, two different binning sets are studied, as 5 and 15 bins. The larger deviations on the measured A_i are chosen as systematic uncertainty.

6.6.6 Summary of systematic uncertainty

The determined systematic uncertainties for measured angular coefficient in different Z boson p_T bins in 2016 data, are summarize in Figure 113. Results in 2017 and 2018 could be found at Appendix B.2. The dominated systematic uncertainty in the measurements of the A_i is the MC statistical uncertainty, even in low Z boson p_T region, where with largest statistics. The comparisons of the total, statistical, and systematic uncertainties as a function of Z p_T in 2016 are shown in Figure 114. The similar result could also be seen in 2017 and 2018 datasets as Appendix B.2 shows. Statistical dominated the uncertainties of this analysis.

6.7 Measured A_i results

With method described in Section 6.5, we used a combined data-set of 2016, 2017, and 2018 to perform the angular coefficient measurements. For presenting the measured A_4 results, a ratio of measured values in each bin to the A_4 value in the first Z p_T bin is shown. The measured results are presented and discussed in this section, while the comparisons of data and fitted results in each kinematic bin can be found in Appendix B.1.

The measured results of A_i are compared to different theoretical calculations currently available, as a function of Z boson p_T , rapidity. They probe the dynamics of perturbative QCD, including the presence of higher-order corrections, and explore the effects from the $V - A$ structure of Z boson couplings.

The measurements are compared to various event generators, in particular to probe different parton-shower models and event-generator implementations. For the different predictions, we have Powheg-BOX with Pythia to perform hadronization, followed by different FSR approaches (Pythia and Photos), predictions from Pythia 8 generators (MC using the LHCb default settings),

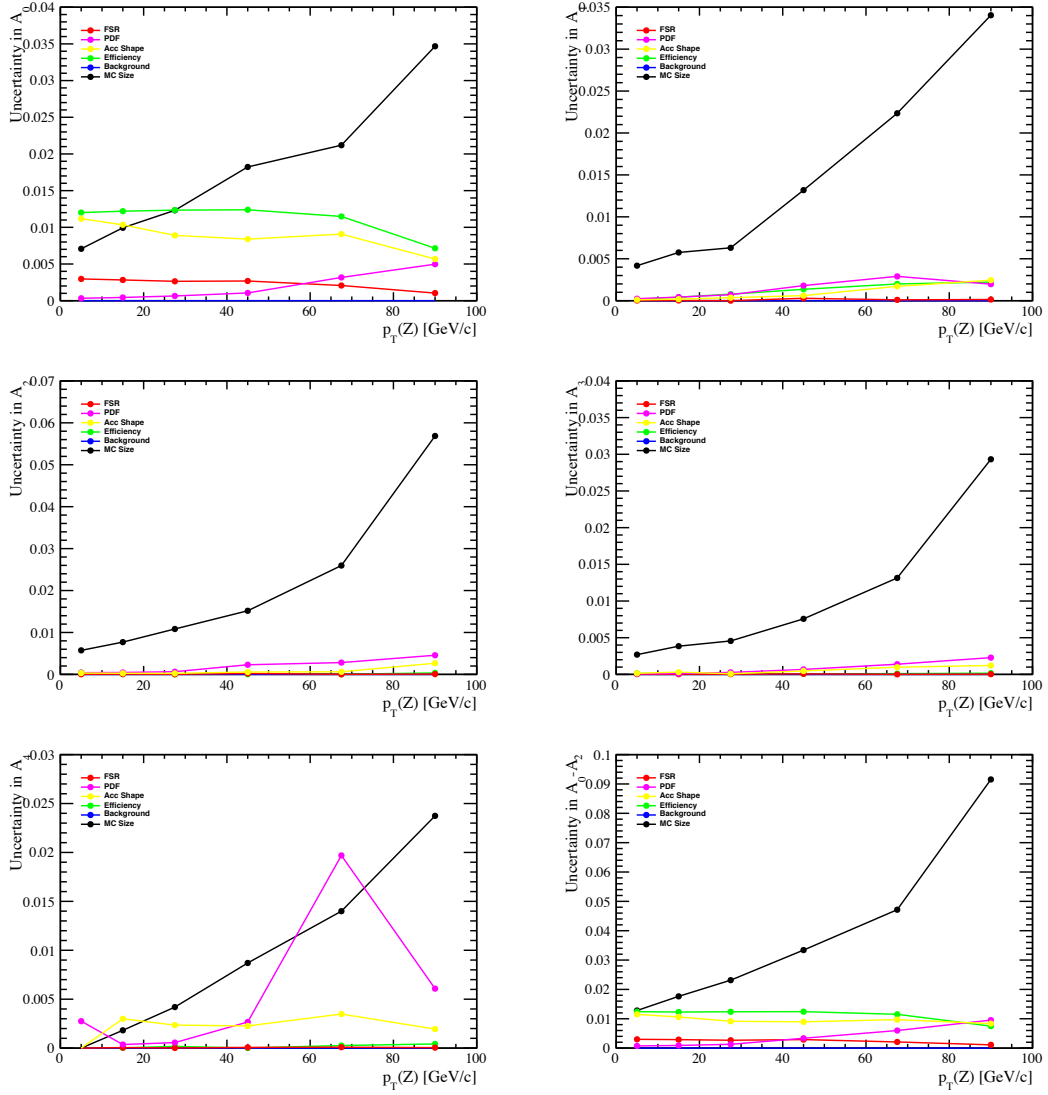


Figure 113: Comparisons of systematic uncertainties of the A_i and $A_0 - A_2$ in 2016 data as a function of $Z p_T$.

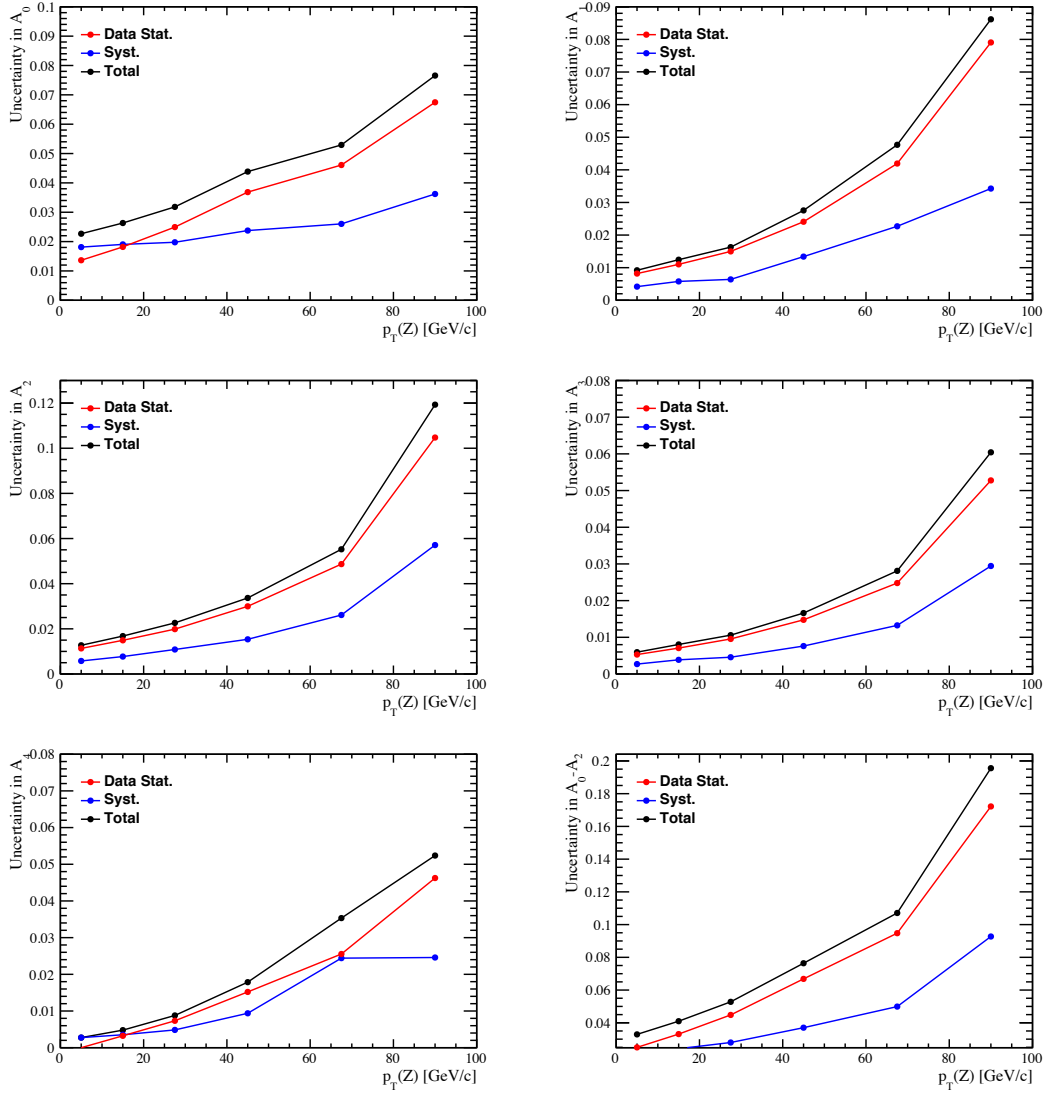


Figure 114: Comparisons of different uncertainties of the A_i and $A_0 - A_2$, as a function of $Z p_T$.



predictions from default ResBos and dyturbo packages without any modifications on them, and prediction from ResBos +zifiter.

6.7.1 Z boson p_T depended results

As shown in Figure 115, the comparisons between the measured result using 2016 dataset and different theory predictions. The measured central values and uncertainties of the coefficients are listed in Table 21, Appendix B.3.1 shows results in 2017 and 2018 dataset.

The measured A_0 is agreed with Powheg-BOX predictions, also has similar trends as all other predictions from Pythia 8, ResBos and dyturbo. While, for the A_1 , the measured result is disagree with Powheg-BOX and ResBos, less than Pythia 8 and dyturbo. For the measured A_2 results, the LHCb results are favored with all theoretical predictions,. The measured A_3 results, as we expected this parameter is small, there are reasonable agreements between measured data and predictions. Finally, for the $A_0 - A_2$ measurement, the LHCb data agree with 0 in the lower Z p_T region, and vary from 0 in the higher p_T region.

Table 21: The measured angular coefficients A_0 to A_4 and $A_0 - A_2$ in bins of Z p_T in 2016 dataset, using Z boson events with $y > 2.0$.

$p_T(Z)$ [GeV]	A_0	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_1	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_2	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-10	0.0105	0.0214	0.0181	0.0328	0.0082	0.0042	0.0110	0.0113	0.0058
10-20	0.0397	0.0242	0.0190	0.0440	0.0110	0.0058	0.0648	0.0149	0.0077
20-35	0.1774	0.0280	0.0198	0.1165	0.0150	0.0064	0.1177	0.0199	0.0109
35-55	0.4008	0.0370	0.0238	0.1119	0.0241	0.0134	0.2450	0.0300	0.0154
55-80	0.5722	0.0499	0.0260	0.1949	0.0419	0.0227	0.4360	0.0487	0.0261
80-100	0.6885	0.0927	0.0362	0.1962	0.0791	0.0343	0.6221	0.1047	0.0571
$p_T(Z)$ [GeV]	A_3	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_4	$\pm\delta_{stat}$	$\pm\delta_{syst}$	$A_0 - A_2$	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-10	0.0342	0.0053	0.0027	1.0000	0.0098	0.0028	-0.0006	0.0177	0.0214
10-20	0.0265	0.0071	0.0039	1.0426	0.0032	0.0035	-0.0251	0.0235	0.0242
20-35	0.0290	0.0096	0.0046	1.0111	0.0073	0.0048	0.0597	0.0319	0.0280
35-55	0.0607	0.0148	0.0076	0.3864	0.0152	0.0094	0.1559	0.0475	0.0370
55-80	0.0977	0.0248	0.0133	0.8090	0.0255	0.0244	0.1361	0.0670	0.0499
80-100	0.0923	0.0528	0.0294	0.4484	0.0462	0.0246	0.0000	0.0000	0.0927

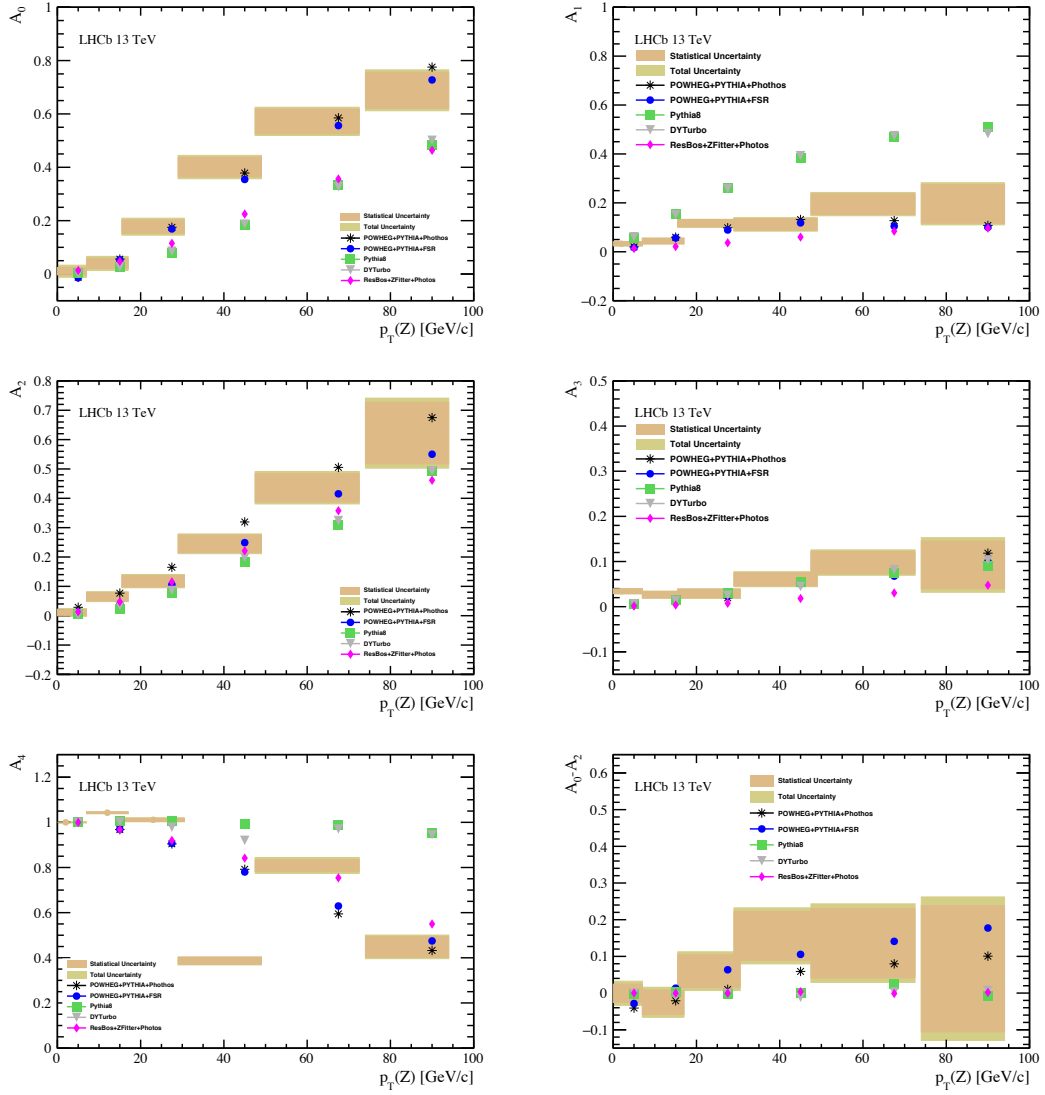


Figure 115: The determined results of the A_i and $A_0 - A_2$, as a function of Z boson p_T , are compared with different theoretical predictions in 2016.



6.7.2 Z boson rapidity depended results

With the unique acceptance of the LHCb detector, it is important to measure the rapidity dependence of angular coefficients, and compared/combined the results from the ATLAS and CMS experiments. The measured rapidity results in 2016 are shown in Figure 116. The measured central values and uncertainties of the coefficients in 2016 are listed in Table 22. Appendix B.3.2 shows results in 2017 and 2018 dataset.

There is no strong Z rapidity dependence in the measured A_i , as expected. Since for the Z rapidity measurement, the QCD effects on the Z boson p_T had been integrated. There are agreements between measured results and predictions for A_0 to A_3 and $A_0 - A_2$. But the measured A_4 are systematically lower than all predictions in high Z rapidity region which indicate a careful study on the A_4 predictions are necessary to make a good understanding of the LHCb results.

Table 22: The measured angular coefficients A_0 to A_4 and $A_0 - A_2$ in bins of Z rapidity in 2016 dataset, using Z boson events with $y > 2.0$.

$y(Z)$	A_0	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_1	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_2	$\pm\delta_{stat}$	$\pm\delta_{syst}$
2.00-2.70	0.1788	0.0530	0.0487	0.0249	0.0155	0.0085	0.1143	0.0144	0.0079
2.70-3.00	0.0400	0.0408	0.0365	0.0857	0.0120	0.0070	0.0880	0.0172	0.0084
3.00-3.25	0.0975	0.0404	0.0355	0.0826	0.0122	0.0075	0.0723	0.0198	0.0111
3.25-3.60	0.0656	0.0324	0.0277	0.1099	0.0117	0.0080	0.0751	0.0184	0.0095
3.60-4.50	0.0141	0.0437	0.0381	0.0750	0.0161	0.0095	0.0898	0.0193	0.0105
$y(Z)$	A_3	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_4	$\pm\delta_{stat}$	$\pm\delta_{syst}$	$A_0 - A_2$	$\pm\delta_{stat}$	$\pm\delta_{syst}$
2.00-2.70	0.0424	0.0071	0.0041	1.0000	0.0187	0.0026	0.0645	0.0363	0.0530
2.70-3.00	0.0587	0.0082	0.0047	1.4324	0.0049	0.0146	-0.0480	0.0272	0.0408
3.00-3.25	0.0303	0.0092	0.0047	1.2129	0.0053	0.0099	0.0251	0.0276	0.0404
3.25-3.60	0.0423	0.0086	0.0046	1.4009	0.0058	0.0083	-0.0094	0.0261	0.0324
3.60-4.50	0.0148	0.0092	0.0052	1.1255	0.0007	0.0039	0.0000	0.0000	0.0437

6.7.3 Results with low Z boson p_T events

As discussed in Section 1.8.4, in this analysis the Boer-Mulders function lower p_T region is also be tested. The measured results in 2016 are shown in Figure 117. The measured central values and uncertainties of the coefficients in 2016 are listed in Table 42. For Z events with lower p_T , the measured $A_0 - A_2$ is agreed with 0, but with large uncertainties due to the limited statistics. Appendix B.3.3 shows results in 2017 and 2018 dataset.

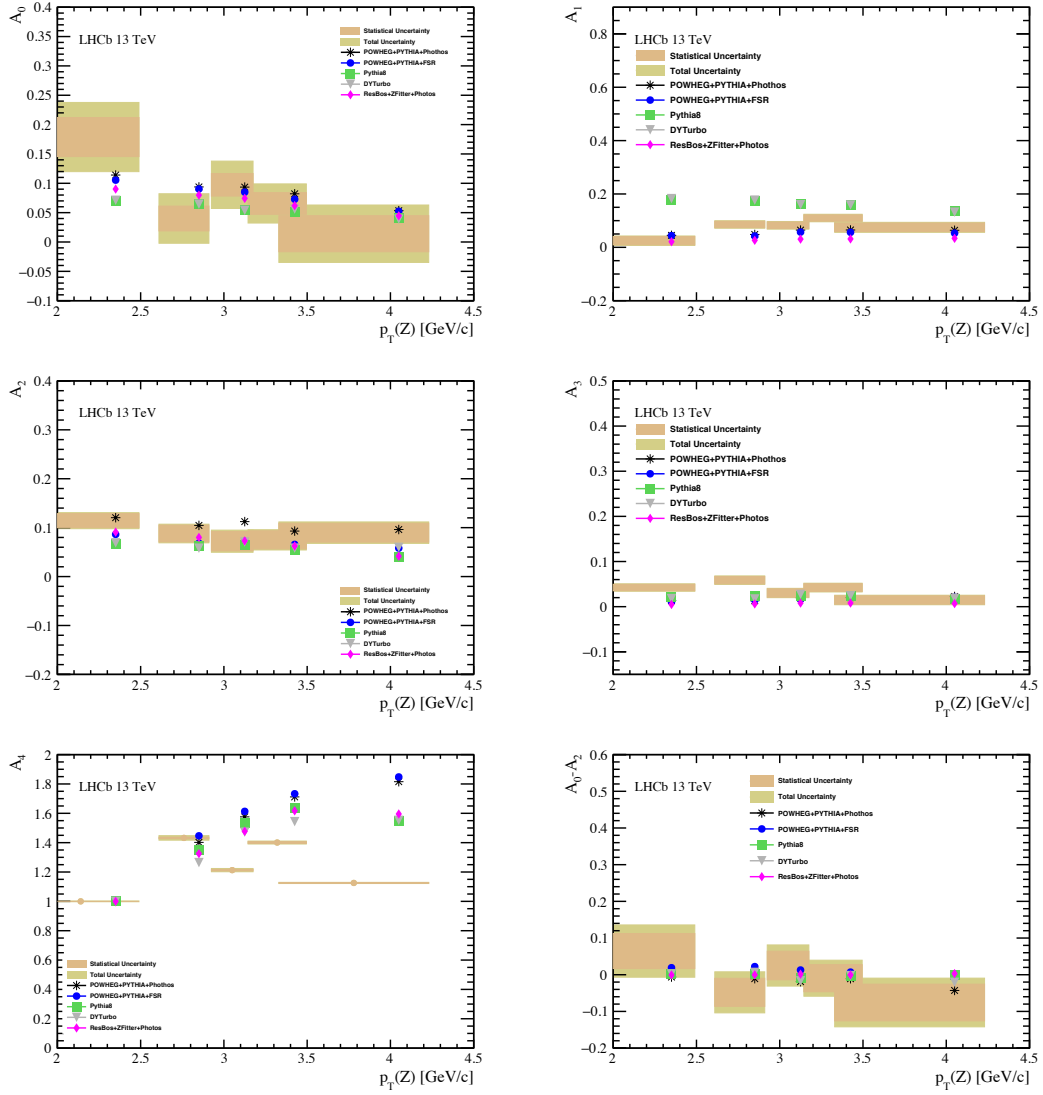


Figure 116: The determined results of the A_i and $A_0 - A_2$ in 2016 dataset, as a function of the Z boson rapidity, are compared with different theoretical predictions.

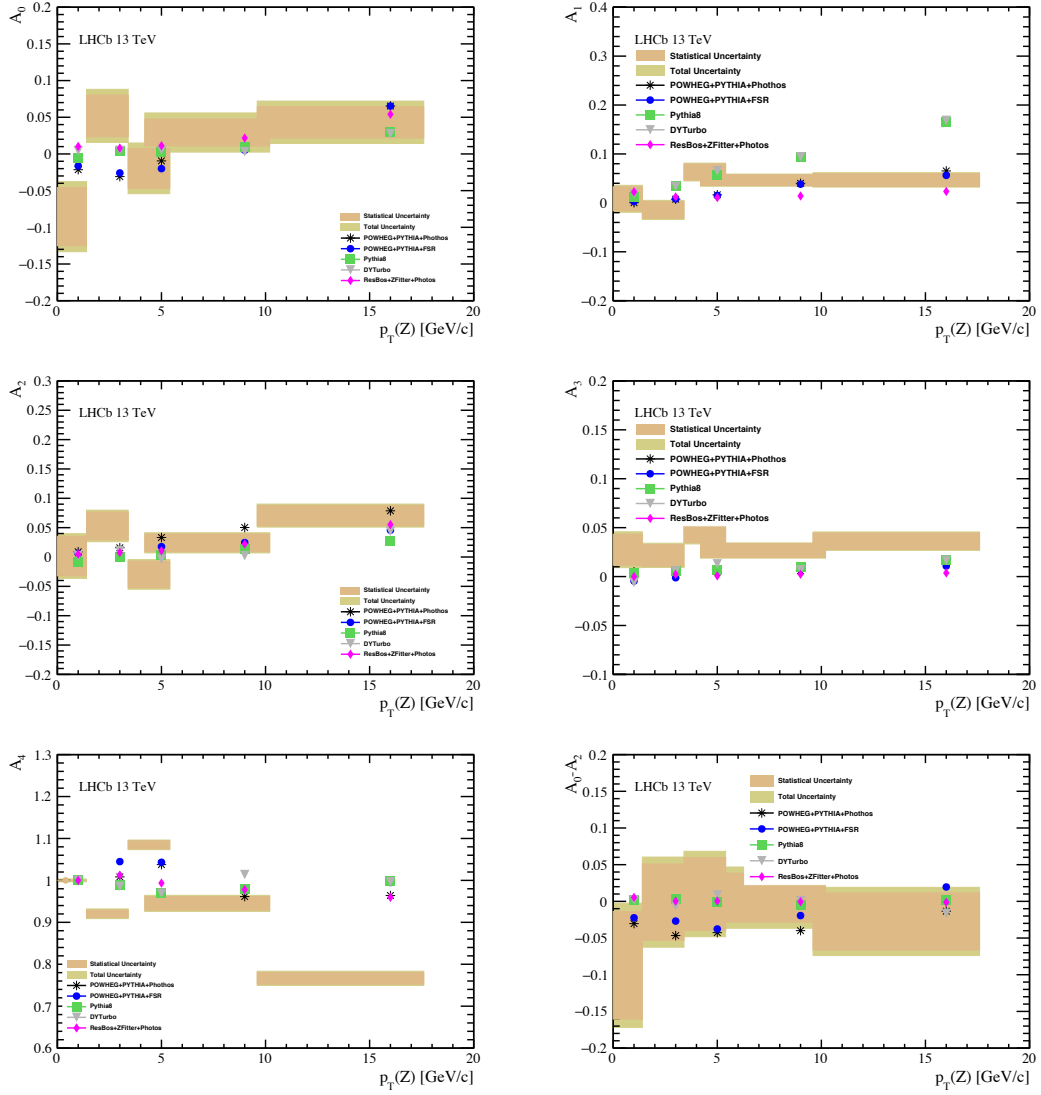


Figure 117: The determined results of the A_i and $A_0 - A_2$ in lower Z p_T region, compared with different theoretical predictions in 2016 data.



Table 23: The measured angular coefficients A_0 to A_4 and $A_0 - A_2$ in bins of low Z p_T region, using Z boson events with $y > 2.0$ in 2016 dataset.

$p_T(Z)$ [GeV]	A_0	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_1	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_2	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-2	-0.0855	0.0424	0.0267	0.0083	0.0244	0.0129	0.0016	0.0337	0.0179
2-4	0.0519	0.0327	0.0224	-0.0145	0.0171	0.0095	0.0529	0.0236	0.0130
4-6	-0.0196	0.0303	0.0214	0.0630	0.0163	0.0081	-0.0297	0.0226	0.0113
6-12	0.0292	0.0250	0.0194	0.0464	0.0110	0.0058	0.0241	0.0151	0.0081
12-20	0.0431	0.0255	0.0194	0.0469	0.0130	0.0069	0.0705	0.0175	0.0089
$p_T(Z)$ [GeV]	A_3	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_4	$\pm\delta_{stat}$	$\pm\delta_{syst}$	$A_0 - A_2$	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-2	0.0274	0.0158	0.0093	1.0000	0.0291	0.0033	-0.0871	0.0520	0.0424
2-4	0.0217	0.0111	0.0055	0.9204	0.0089	0.0073	-0.0010	0.0369	0.0327
4-6	0.0453	0.0105	0.0057	1.0848	0.0095	0.0064	0.0100	0.0353	0.0303
6-12	0.0266	0.0071	0.0032	0.9452	0.0160	0.0106	0.0051	0.0237	0.0250
12-20	0.0362	0.0083	0.0044	0.7664	0.0138	0.0098	0.0000	0.0000	0.0255

6.8 Conclusion

This analysis presents a precise set of measurements of the Z -boson production dynamics in the Z -boson pole region, through the angular distributions of the muons. Data of 2016, 2017 and 2018 data sets, at centre-of-mass energy of $\sqrt{s} = 13$ TeV, have been analysed. By using BLUE method [97], the combined measurements from 2016, 2017 and 2018 are obtained as a function of Z boson p_T as Figure 118 shows, and Figure 119 shows the result as a function of Z boson rapidity. While Figure 120 shows the combined result in low Z boson p_T region. In the process of the combination, the PDF and FSR uncertainties are treated as the correlated uncertainties, the mc size, efficiency and background uncertainties are uncorrelated.

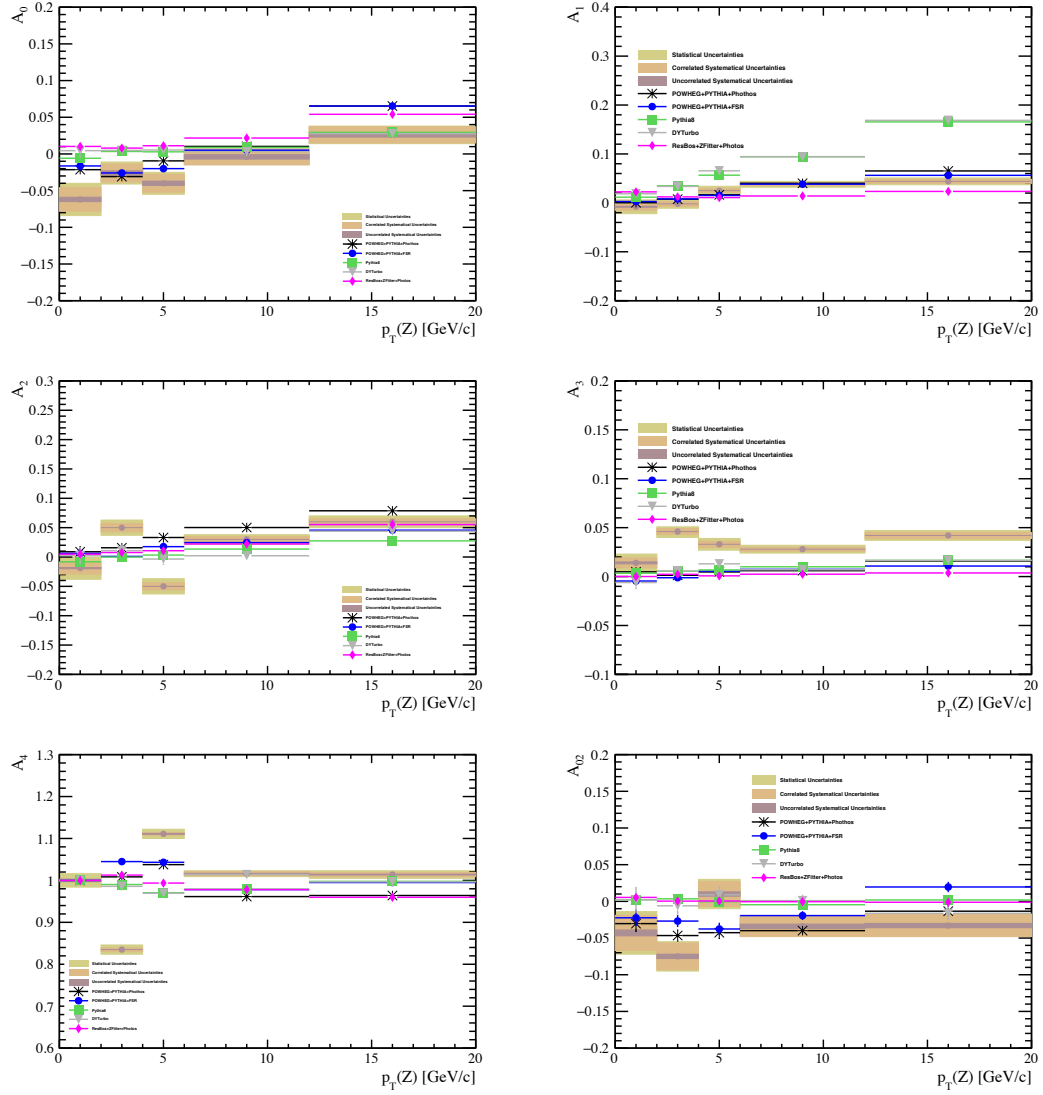


Figure 118: The combined results of the A_i and $A_0 - A_2$ in 2016, 017 and 2018 dataset, as a function of the Z boson rapidity, are compared with different theoretical predictions.

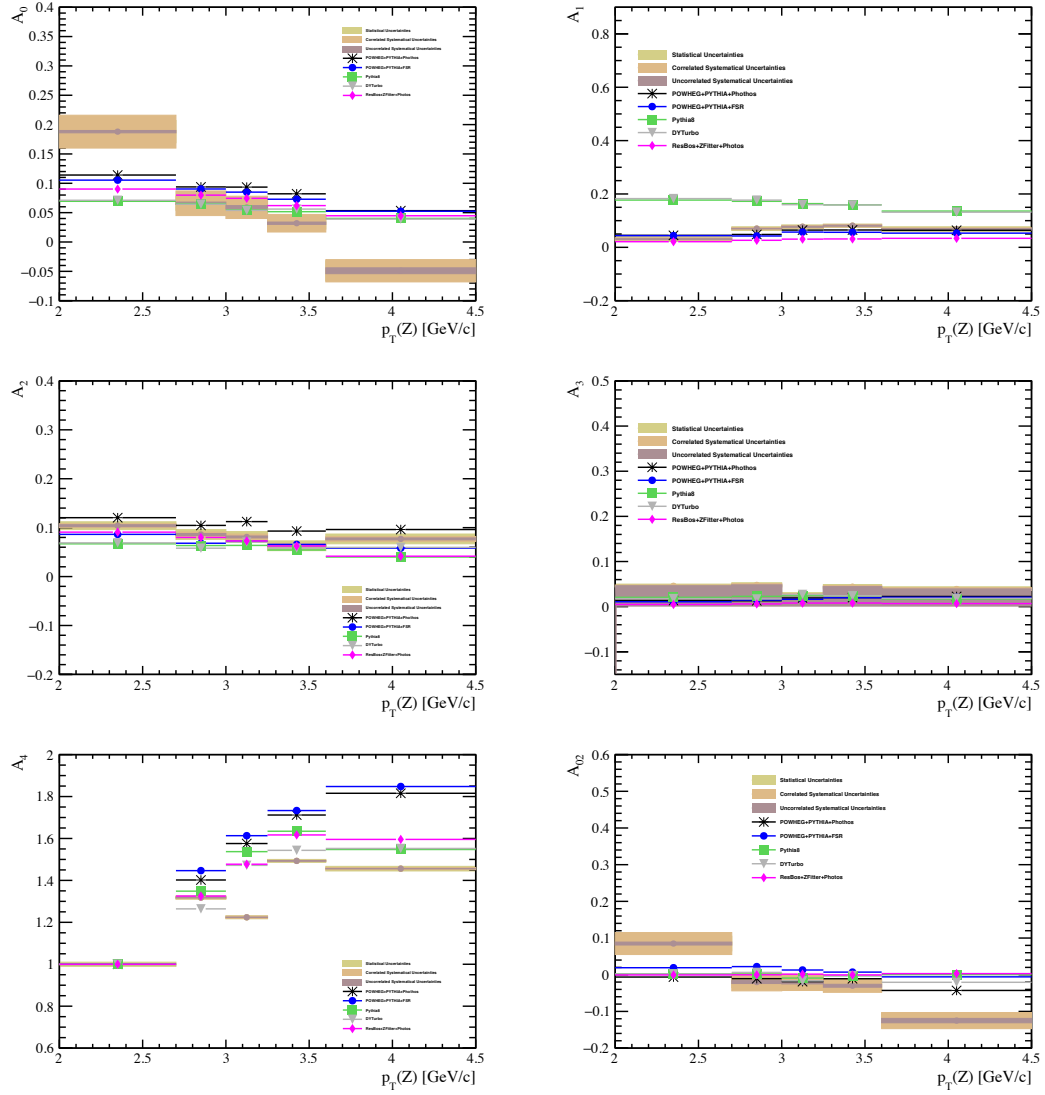


Figure 119: The combined results of the A_i and $A_0 - A_2$ in three years dataset, as a function of the Z boson rapidity, are compared with different theoretical predictions.

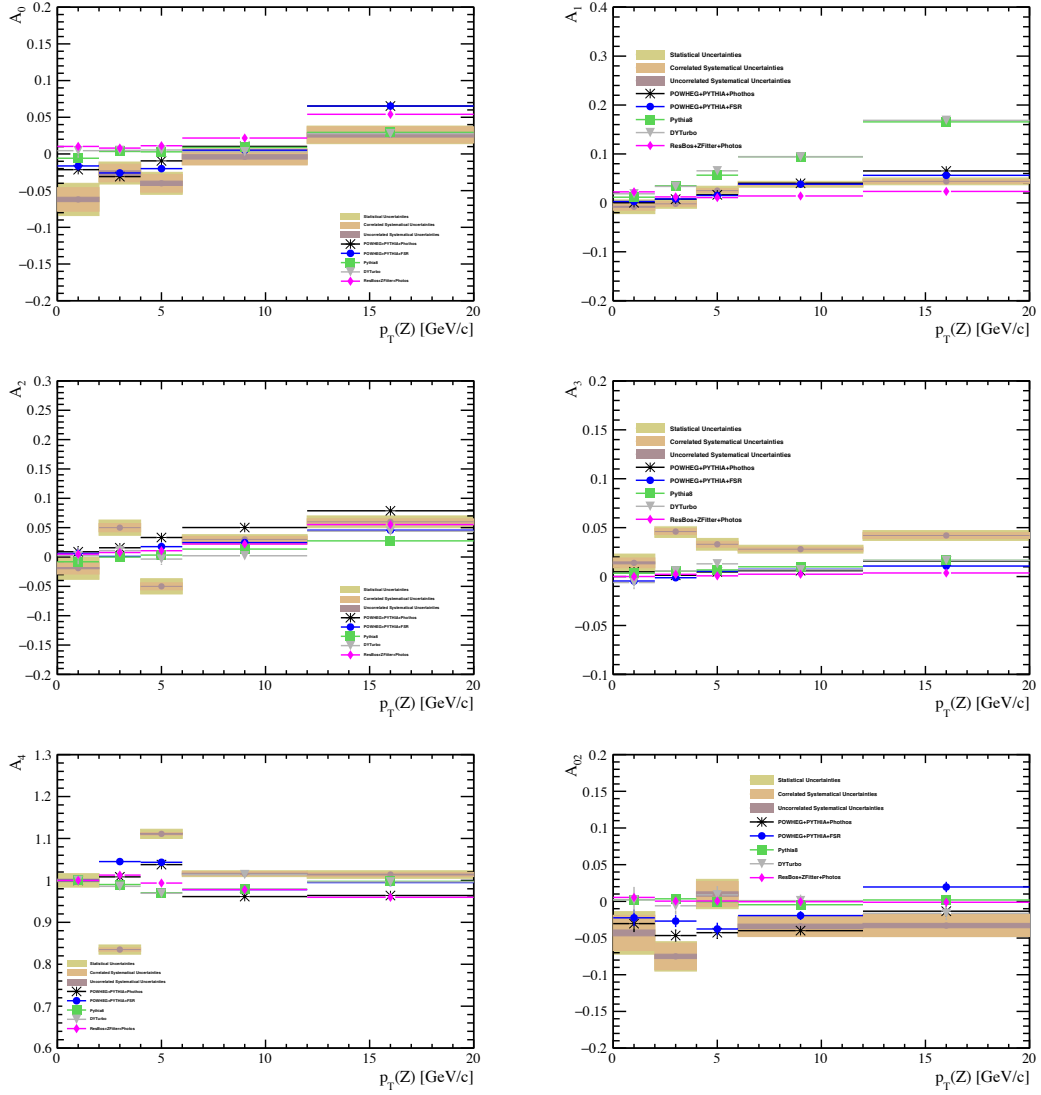


Figure 120: The combined results of the A_i and $A_0 - A_2$ in three years, as in low Z p_T region are compared with different theoretical predictions.



7 Measurements of high- p_T muon reconstruction efficiency for the LHCb RunII data-sets

7.1 Introduction

Precision measurements of the single $W^\pm$ and Z gauge boson production cross section [45, 131–133] at the hadron colliders provide important tests on the Quantum ‘Chromodynamics’ (QCD) and the electroweak (EW) sectors of the Standard Model (SM). The $Z \rightarrow \mu^+\mu^-$ and $W^\pm \rightarrow \mu^\pm\nu$ processes have large production cross-sections, and a clean final state particle (μ), which can be used to perform precise EW measurements. For these studies, the muon efficiency is a crucial element to determining the the production cross section, and an important source of systematic uncertainties. Therefore, a good understanding on the muon efficiency is a important task for almost all of RunII EW measurements⁸. In this note, the high- p_T muon reconstruction efficiency in the LHCb, ε^{rec} , is studied for three independent components, as

$$\varepsilon^{rec} = \varepsilon^{trg} \times \varepsilon^{trk} \times \varepsilon^{id}, \quad (91)$$

where ε^{trg} is the muon trigger efficiency, ε^{trk} is the long track reconstruction efficiency, and ε^{id} is the muon-identification (MuID) efficiency.

The reconstruction efficiency of high- p_T muons cannot be directly determined from the simulated events, as Monte Carlo (MC) events cannot properly model some crucial detector effects (*i.e.*, detector occupancy), resulting in overestimations of the muon efficiency. Therefore, these muon efficiencies are determined with real data, using a tag-and-probe method [134]. The measured efficiencies are further checked with data events collected with different magnet polarities (*MagUp* and *MagDown*), and for positive muons as well as negative muons.

The leptonic decay of Z boson ($Z \rightarrow \ell^+\ell^-$) is a process with high signal purity, with high- p_T lepton pairs in the final state. In the LHCb, $Z \rightarrow \mu^+\mu^-$ events are used to determine the muon efficiencies [126]. In the efficiency determination, one of the muons, required to be triggered by muon triggers and positively identified as a muon at the reconstructed level, is used as a tag. Another reconstructible object (such as a long track or a muon) representing the second muon, is used as the probe muon. The probe muon is used to determine the corresponding efficiency,

⁸In the LHCb W mass measurement and $R_{\tau/\mu}$ measurement, another approach to study the muon efficiency is used, which not be discussed in this note.



ε , with formula as

$$\varepsilon = \frac{N_{pass}}{N_{tot}}, \quad (92)$$

where N_{tot} is the number of events that satisfied the tag-and-probe selection and N_{pass} is the subset of these events, which also satisfy specific ‘pass’ requirement on the probe muon.

The studies are performed with $Z \rightarrow \mu^+\mu^-$ data and simulated events. The stripping version used in this analysis is Reco16-Stripping28r2 for 2016 data-set, Reco17-Stripping29r2 for 2017 data-set, and Reco18-Stripping34 for 2018 data-set. The stripping line Z02MuMuLine and WMuLine are used in this study, where at least one of muons of $Z \rightarrow \mu^+\mu^-$ candidates must be triggered by the L0MuonEW, Hlt1SingleHighPTMuon and Hlt2EWSingleMuonVHighPt trigger lines.

Additionally, the tag-and-probe method is verified using simulated $Z \rightarrow \mu^+\mu^-$ events generated for 2016 data-set. This note is organised as follows: the muon trigger efficiency determination is described in Section 7.2, the muon track reconstruction efficiency determination is described in Section 7.4, followed by a study of muon identification efficiency in Section 7.7.

7.2 Trigger efficiency

7.2.1 Tag-and-Probe selection

For the selected $Z \rightarrow \mu^+\mu^-$ events, the high- p_T muons are required to have been triggered by dedicated lines at the L0, HLT1 and HLT2 stages (L0MuonEW, Hlt1SingleHighPTMuon and Hlt2EWSingleMuonVHighPtDecision) respectively. The trigger efficiency is the fraction of events that have two triggered muons to events that have only have one triggered muon. The requirements placed on the $Z \rightarrow \mu^+\mu^-$ events that are used to determine the muon trigger efficiency are summarized in Table 24.

In the event selection, I_T^{charged} is used to ensure the muon is an isolated particle in the event, which is defined as

$$I_T^{\text{charged}} = \frac{p_T^\mu}{p_T^\mu + p_T^{\mu\text{-cone}}}. \quad (93)$$

It is a ratio of muon transverse momentum to that of all charged tracks within a radius, ΔR , of 0.5 of the muon track. Both tag and probe objects are required to satisfy $I_T^{\text{charged}} > 0.85$.

The tag muon is required to pass all three levels of the trigger, and the trigger efficiency is determined by counting the number of probe muons that passed the trigger requirements.



Table 24: The tag and probe selection used for the muon trigger efficiency study.

Tag	Probe	Event
Long track isMuon Triggered $\sigma_P/P < 0.1$ $p_T > 20 \text{ GeV}$ $2 < \eta < 4.5$ $I_T^{\text{charged}} > 0.85$	Long track isMuon - $\sigma_P/P < 0.1$ $p_T > 20 \text{ GeV}$ $2.0 < \eta < 4.5$ $I_T^{\text{charged}} > 0.85$	$60 < M_{\mu\mu} < 120 \text{ GeV}$ $\chi_{\text{vtx}}^2/\text{ndf} < 5$

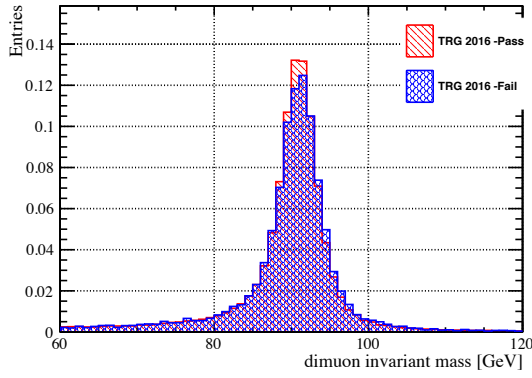
7.2.2 Background estimation

The trigger efficiency may be affected by mis-identification background. This background contribution is estimated from a same-sign data sample, by running over MuMuSSLiNe4 stripping line, with applying all tag-and-probe selections as Table 24 shows, except that the two muons are required to have the same charges. The background contribution is found to be very small, so overall effects from this background contribution to the efficiency determination are considered to be negligible.

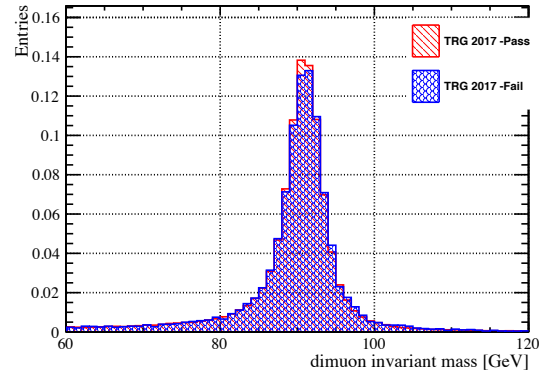
As an additional check, the invariant mass distributions of data sample (after tag-and-probe selection), that pass and fail the trigger requirements are shown in Figure 121, where a good agreement is observed between these two mass distributions, indicating that the muon trigger efficiencies is not affected by the existence of background events.

7.3 MC muon trigger efficiency

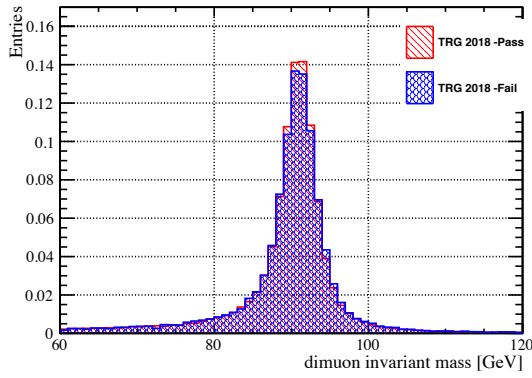
For MC sample, besides the tag-and-probe method, Truth method [103] could also be used to determine the efficiency, by using the particle truth information. In this method, both tag and probe particles are required to match a generator level muon, that come from Z boson. Then, the efficiency is studied using this high purity sample. So the tag-and-probe method could be validated using simulated $Z \rightarrow \mu^+\mu^-$ events, by comparing efficiency estimated with Truth method to that with tag-and-probe method. Comparisons of trigger efficiency as a function of muon η and muon p_T are shown in Figure 122. Good agreements are observed for different variables, indicating that the muon trigger efficiencies calculated using the tag-and-probe method are reliable and robust.



(a)



(b)



(c)

Figure 121: Comparison of the invariant mass distributions for $Z \rightarrow \mu^+\mu^-$ events, which passed and failed the muon trigger efficiency requirements in 2016 (a), 2017 (b) and 2018 (c) data.

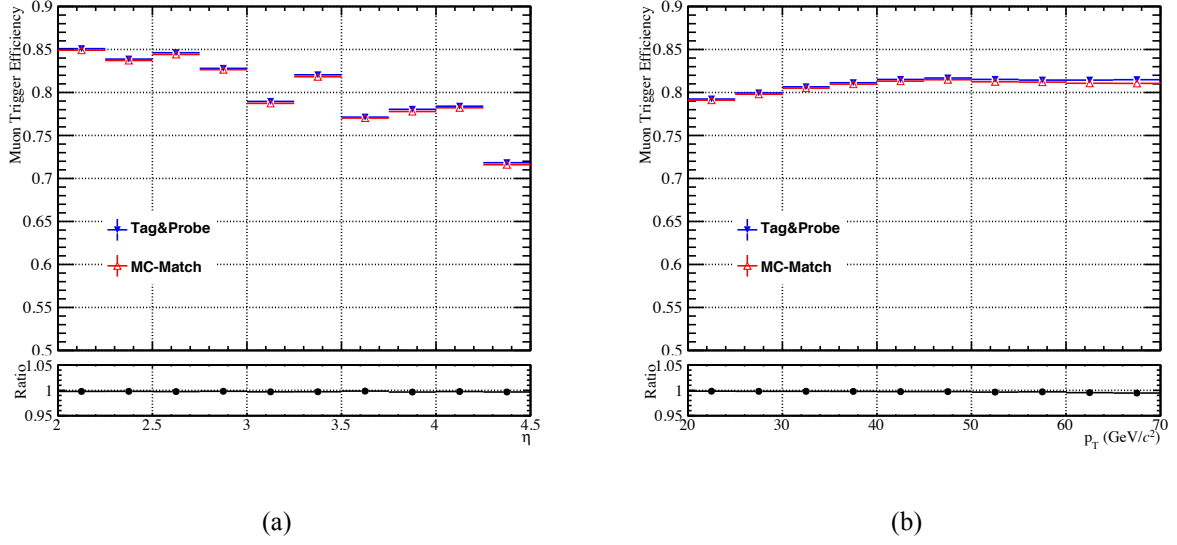


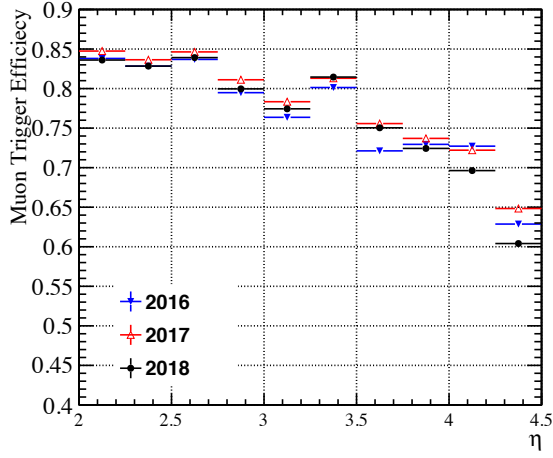
Figure 122: Comparison of muon trigger efficiency calculated using the Truth method and the tag-and-probe method, as a function of muon η (a) and muon p_T (b), estimated with simulated events.

7.3.1 Systematic uncertainties

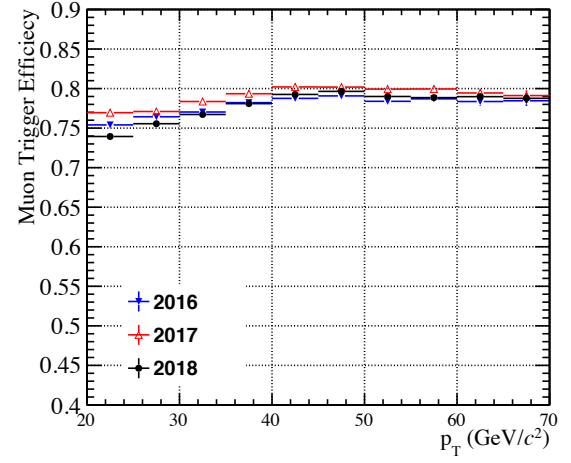
As muon trigger efficiencies measured with different methods are consistent with each other, given this binning scheme and these tag-and-probe selections, these are the muon efficiencies, no additional systematic uncertainty is assigned to the trigger efficiency. The only uncertainty for trigger efficiency is statistical uncertainty, which is used to cover uncertainties due to the finite size of the $Z \rightarrow \mu^+\mu^-$ data sample. This uncertainty in different variable bins varies between 0.002% and 0.004% for 2016 and 2017 data-set, and 0.002% and 0.003% for 2018 data-set.

7.3.2 Results

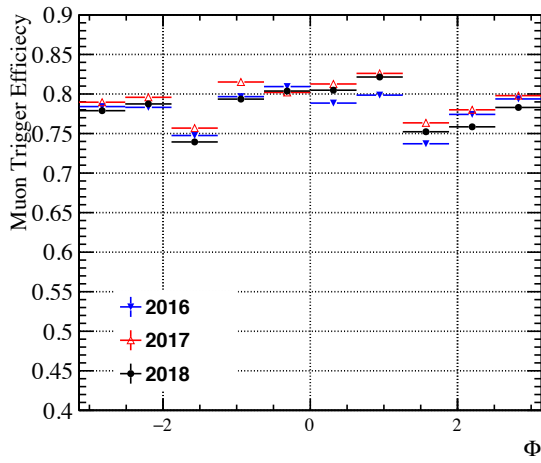
As studied in Appendix C.1 and Figure 124, the muon trigger efficiency has neither muon charge dependence nor event magnet polarity dependence. The muon trigger efficiency is measured for the data-set collected in 2016, 2017 and 2018. The measured trigger efficiency is presented as a function of four kinematic and event variables (muon η , muon p_T , muon ϕ , number of SPD hits in the event) in Figure 123. The efficiency for each trigger stage (L0, HLT1, HLT2) is shown in Appendix C.2.



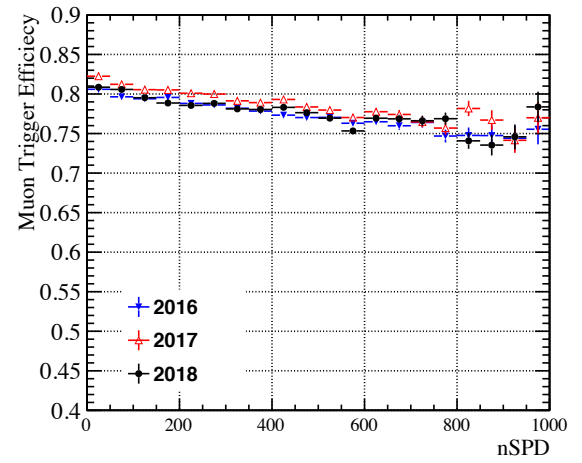
(a)



(b)

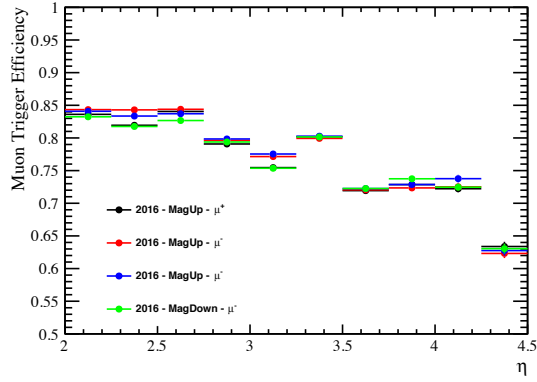


(c)

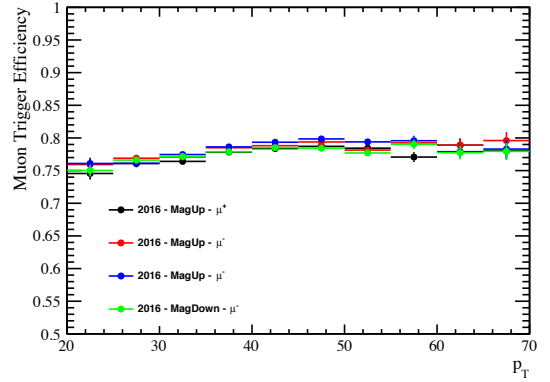


(d)

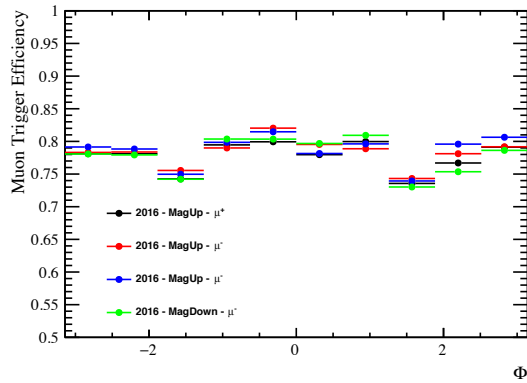
Figure 123: Muon trigger efficiency for 2016, 2017 and 2018 data-set as a function of muon η (a), muon p_T (b), muon ϕ (c) and the SPD multiplicity (d) of events.



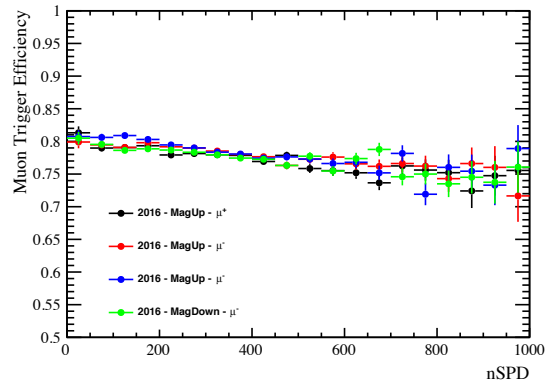
(a)



(b)



(c)



(d)

Figure 124: The measured muon trigger efficiency split by different charge and polarity, in 2016 data, as a function of muon η (a), muon p_T (b), muon ϕ (c), and SPD multiplicity (d).



7.4 Tracking efficiency

7.4.1 Probe track

$Z \rightarrow \mu^+ \mu^-$ events are used to determine the long track reconstruction efficiency (long track of muon particle), with the tag-and-probe method. In the method, the tag muon must be a long track that passing both muon trigger and muon identification requirements. A track reconstructed by combining hits in the muon stations [78] and the Trigger Tracker (TT), known as a MuonTT track, is taken as probe. Long tracks leave hits in the VELO and the T-stations, but not necessarily in TT. Therefore, a MuonTT track is chosen to estimate the long track reconstruction efficiency, as this efficiency is not expected to have any dependence on hits from these particular sub-detectors. [135]

7.4.2 Tag-and-Probe selection

The requirements placed on the $Z \rightarrow \mu^+ \mu^-$ events that are used to determine the muon tracking efficiency are summarized in Table 25.

Compared to the trigger and identification efficiencies studies, a tighter mass window cut is used in this study, due to a larger background contribution and a worse mass resolution of the selected sample. The tag and probe objects are further required to have an azimuthal separation of 0.1 radials, to ensure both tracks do not arise from the same particle (MuonTT track is assigned to a wrong charge).

The ‘track match’ criteria is defined as [126]:

- Shared Muon Hits > 40%,
- Shared TT Hits > 60%,
- $M_{upgrade} > 40 \text{ GeV}$,

where the second condition (Shared TT Hits > 60%) is only applied if the long track has associated TT-hits. The variable $M_{upgrade}$, known as the upgrade mass, refers to the invariant mass of the tag and the long track being tested. By requiring a tight upgrade mass cut, it could suppress contributions from incorrect matching of the MuonTT track with soft tracks from the underlying event.



Table 25: The tag and probe selection used for the muon tracking efficiency study.

Tag	Probe	Event
Long track	Muon TT track	$70 < M_{\mu\mu} < 110 \text{ GeV}$
isMuon	-	$ \Delta\phi > 0.1 \text{ rad}$
Triggered	-	$\chi^2_{\text{vtx}}/\text{ndf} < 5$
$\sigma_P/P < 0.1$		
$\chi^2_{\text{IP}} < 6$	$\chi^2_{\text{IP}} < 6$	
$p_T > 20 \text{ GeV}$	$p_T > 20 \text{ GeV}$	
$2.0 < \eta < 4.5$	$2.0 < \eta < 4.5$	

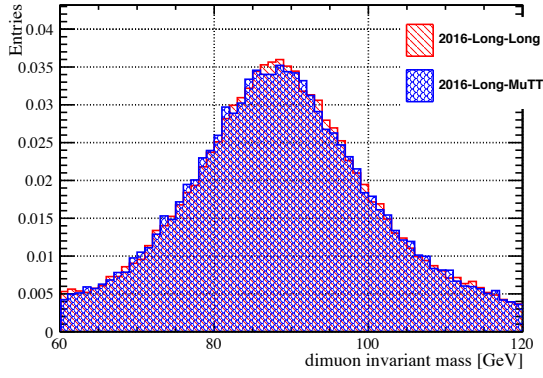
7.4.3 Background estimation

The background contribution in the selected tag-and-probe sample is estimated by comparing the invariant mass distributions of a long track and a Muon TT track in two different tag-and-probe samples, as discussed below:

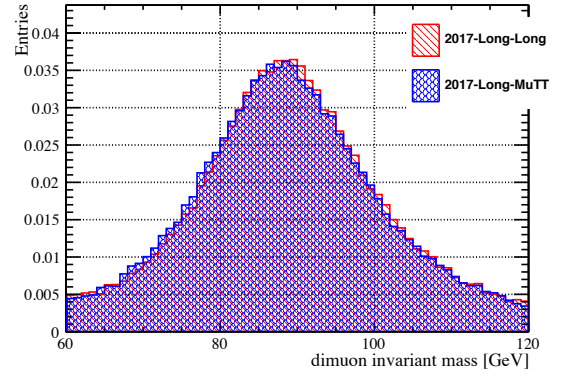
- Long-MuonTT: This sample is a tag-and-probe sample selected with selections as Table 25 described, which is also used to determine the tracking efficiency.
- Long-Long: An ‘inverted’ tag-and-probe selected sample. To get this sample, the standard $Z \rightarrow \mu^+\mu^-$ selection [45] is applied to the data sample, while a MuonTT track is searched within a cone ΔR of 0.1 of the probe muon.

As the Long-Long sample is selected by applying the standard $Z \rightarrow \mu^+\mu^-$ selection, it has a minimal background contribution. Therefore, background contamination in the Long-MuonTT sample can be estimated by comparing the invariant mass distributions of Long-MuonTT and Long-Long samples. The Long-MuonTT sample represents the invariant mass distribution of the tag and probe sample, while the Long-Long sample represents the invariant mass distribution of $Z \rightarrow \mu^+\mu^-$ events, with probe object matched to a long track.

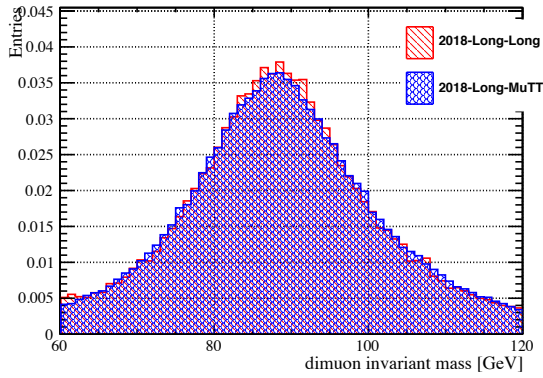
The invariant mass distributions for 2016, 2017 and 2018 data-set are shown in Fig. 125. The mass distributions of Long-Long and Long-MuonTT samples are agreed with each other in all mass region, which indicate the background contribution is small for events in this region. As shown in Fig. 126, there is large background contribution in the lower mass region in the failed events. While in the signal region ($[70,110] \text{ GeV}/c$), the background contribution is small. Therefore, the background contribution is expected to be suppressed with a tight mass window, and is not been considered as a dominated systematic uncertainty in the efficiency study.



(a)

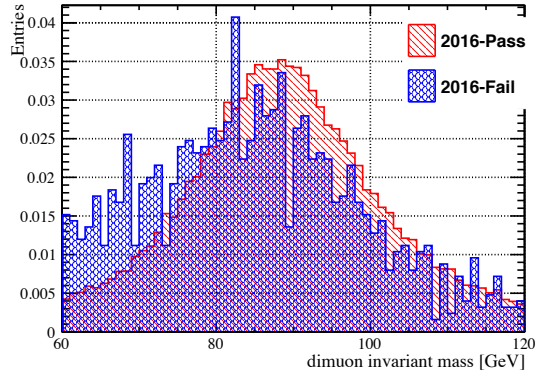


(b)

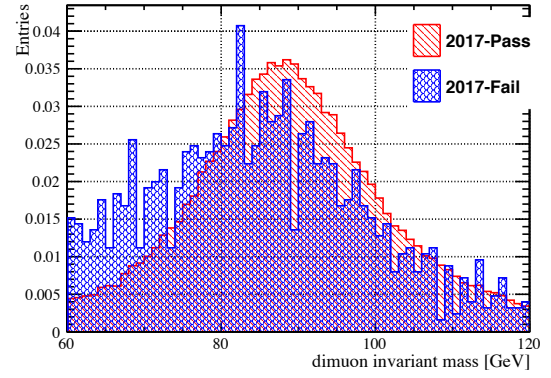


(c)

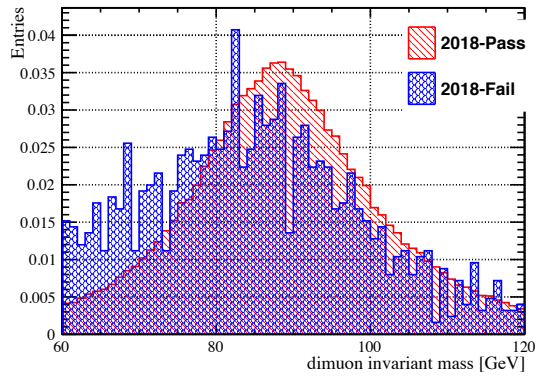
Figure 125: The invariant mass of a long track and a MuonTT track in the background-free Long-Long sample and the tag-and-probe sample, Long-MuonTT, for 2016(a), 2017(b) and 2018(c) data. The good agreement in the region $70 < M < 110$ GeV indicates that no significant background is introduced to the tag-and-probe sample in this mass region.



(a)



(b)



(c)

Figure 126: Comparison of the mass distributions for events which passed and failed the tag-and-probe requirements in 2016(a), 2017(b) and 2018(c) data.



7.4.4 Corrections

In contrast to the determination of the identification and trigger efficiencies, the tracking efficiency determined using the tag-and-probe method is biased by different effects. Therefore, a number of corrections to the track reconstruction efficiency are required, in order to obtain the correct efficiency from the tag-and-probe method. The relevant corrections are discussed below.

7.4.5 Bias Correction

The tag-and-probe method use a MuonTT track as probe particle. However, not all of the long tracks have an associated MuonTT track. The bias on the tag-and-probe track efficiency is investigated using the simulation signal events (MCDecayTree). The track reconstruction efficiency of a truth particle that has an associated MuonTT track is compared to that of all truth particles. The track reconstruction efficiency is calculated as:

$$\varepsilon(\text{MC particle : all}) = \frac{N_{\text{Reconstructed}}}{N_{\text{MC particle}}}, \quad (94)$$

$$\varepsilon(\text{MC particle : With MuonTT}) = \frac{N_{\text{Reconstructed: With MuTT}}}{N_{\text{MC particle: With MuTT}}}, \quad (95)$$

where $N_{\text{Reconstructed}}$ ($N_{\text{Reconstructed: With MuTT}}$) is the number of MC particles that has a reconstructed long track (with an associated MuonTT track), $N_{\text{MC particle}}$ ($N_{\text{MC particle: With MuTT}}$) is the number of MC particles (with an associated MuonTT track).

The bias correction distribution as a function of muon η (a) and muon p_T is shown in Fig. 127, where events has associated MuonTT track are shown to have a higher reconstruction efficiency. The bias correction is calculated as a ratio of these two reconstruction efficiencies, as

$$\mathcal{R}(\text{Bias}) = \frac{\varepsilon(\text{MC particle : all})}{\varepsilon(\text{MC particle : with MuonTT})}. \quad (96)$$

The calculated bias correction for tracking efficiency is shown in Fig. 128, as a function of muon η (a) and muon p_T .

7.4.6 Track Matching Efficiency

The matching conditions outlined in Sec. 7.4.2, are bring inefficient in the track matching, where a MuonTT track is matched to a long track. This inefficiency must be corrected to remove such effects. However, as mentioned in Ref. [103], the matching efficiency is close to 100% for the long track in the LHCb acceptance region. In this study, the track matching efficiency is

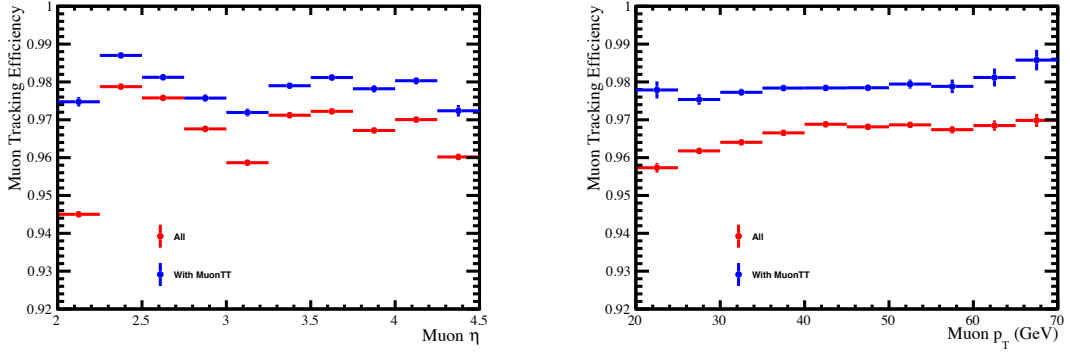


Figure 127: Comparison of the tracking reconstruction efficiencies, estimated using all MC particle and MC particle with an associated MuonTT track, as function of muon η (left) and muon p_T (right).

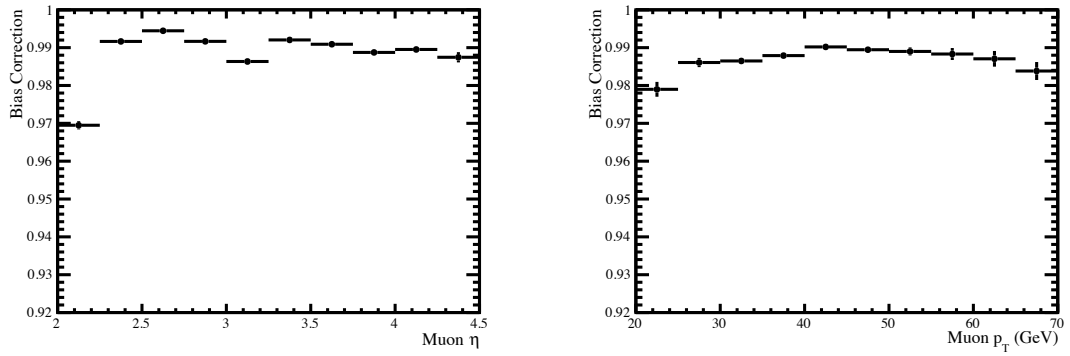


Figure 128: Bias correction as function of muon η (a) and muon p_T (b).



determined by calculating how frequently a MuonTT track is matched to a long track using an ‘inverted’ tag-and-probe method, based on $Z \rightarrow \mu^+\mu^-$ data and simulation events. In this method, as two muon from $Z \rightarrow \mu^+\mu^-$ are selected as two long tracks, the background contribution from Z events is expected to be negligible. However, background contribution cannot be ignored in the searching of MuonTT track, where a random MuonTT track is chosen to matched to the long track. In order to suppress the MuonTT background, we used the χ_{IP}^2 cut, by requiring the muonTT track should point back to a PV. In the study, candidates events are selected with two fully identified muons that satisfying the $Z \rightarrow \mu^+\mu^-$ selection requirements and $\chi_{\text{IP}}^2 < 6$, and a MuonTT track with p_T greater than 20 GeV and $\chi_{\text{IP}}^2 < 6$ is search within an $\eta - \phi$ radius, ΔR , of 0.1 of the long track. If there is such a MuonTT track exists in event, the efficiency is determined by calculating how frequently this MuonTT track is matched to the long track, with the matching conditions described above. The matching efficiency that determined using simulation events is shown in Fig. 129. The determined matching efficiency is $(99.72 \pm 0.02)\%$ in the MC events, which is very close to 100%. Similar as the Ref. [103], the matching efficiency is also assumed to be 100%, and assigned 0.28% as a systematic uncertainty.

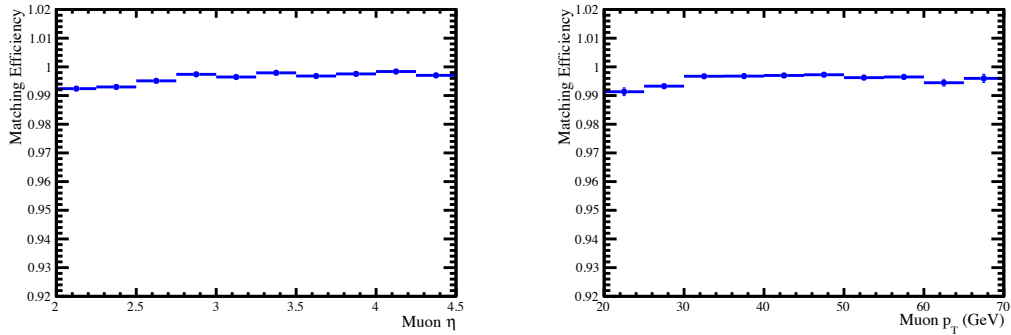


Figure 129: The determined track matching efficiency in MC events, as as a function of muon η (left) and muon p_T (right).

7.4.7 Monte-Carlo Comparison

The tag-and-probe method is validated using the simulated $Z \rightarrow \mu^+\mu^-$ events. As discussed before, the tracking efficiency of MC events estimated using the tag-and-probe method need be corrected for both bias correction and track matching efficiency correction, as

$$\varepsilon^{\text{MC}}(\text{Corrected}) = \varepsilon_{\text{Tag-and-Probe}}^{\text{MC}} \times \mathcal{R}(\text{Bias}) \times \frac{1}{\varepsilon_{\text{Match}}}. \quad (97)$$

In this study, the matching efficiency is assumed to be 100%, so only bias correction is applied to the tag-and-probe tracking efficiency. In principle, with these corrections applied, the tag-and-probe efficiency should be same as MC-Truth efficiency. As shown in Fig. 130, the corrected tag-and-probe tracking efficiency is compared with the MC-Truth efficiency, where good agreements are observed within the uncertainties.

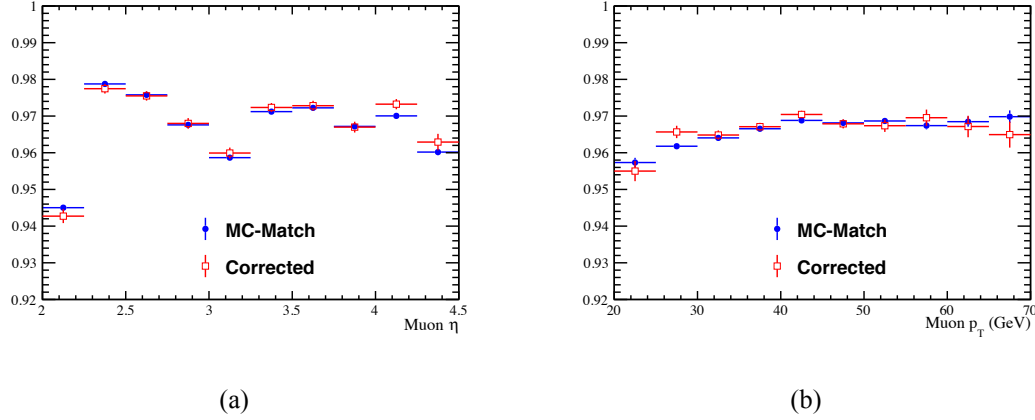


Figure 130: The calculated muon tracking efficiency as a function of (a) muon η , and (b) muon p_T , for the corrected tag-and-probe efficiency and the truth level efficiency.

7.5 The corrected tracking efficiency

As described in Eq. 97, the measured tag-and-probe tracking efficiency of the MC events need further corrections to suppress the bias from the method itself, including the bias correction and track matching correction. With good agreements between the efficiencies measured using the corrected tag-and-probe method and MC-truth method, we could simply use the following formula to correct the measured data tag-and-probe tracking efficiency, as:

$$\varepsilon^{\text{Data}}(\text{Tracking}) = \varepsilon^{\text{Data}}(\text{Tag} - \text{and} - \text{probe}) \times \frac{\varepsilon_{\text{MC-Truth}}^{\text{MC}}}{\varepsilon_{\text{Tag-and-probe}}^{\text{MC}}}. \quad (98)$$

For the systematic uncertainties of the track reconstruction efficiency, the following sources are considered.

- Differences between MC-truth efficiency and the corrected tag-and-probe efficiency of MC events are assigned as the systematic uncertainty. As Fig. 130 shows, good agreements could be seen between the MC-truth efficiency and the corrected tag-and-probe efficiency, the remaining discrepancies are taken as systematic uncertainties.

- The track matching correction estimated using the MC events is not 100%. The difference between the MC track matching efficiency and 100% is 0.28%, and we assign 0.28% as one of systematic uncertainties.
- The track matching efficiency difference between data and MC, which is 0.33%.
- The muonTT finding efficiency difference of between data and MC, which is 0.1%.

7.5.1 Track matching efficiency systematic uncertainty

Using the same method as Sec. 7.4.6 described, the matching efficiency could also be calculated in the real $Z \rightarrow \mu^+\mu^-$ data. In Fig. 131, the comparison of the matching efficiency estimated using the data and MC events are shown, where reasonable agreements between data and MC are seen. The overall difference between data and MC track matching efficiency is assigned as a systematic uncertainty, which is 0.33%.

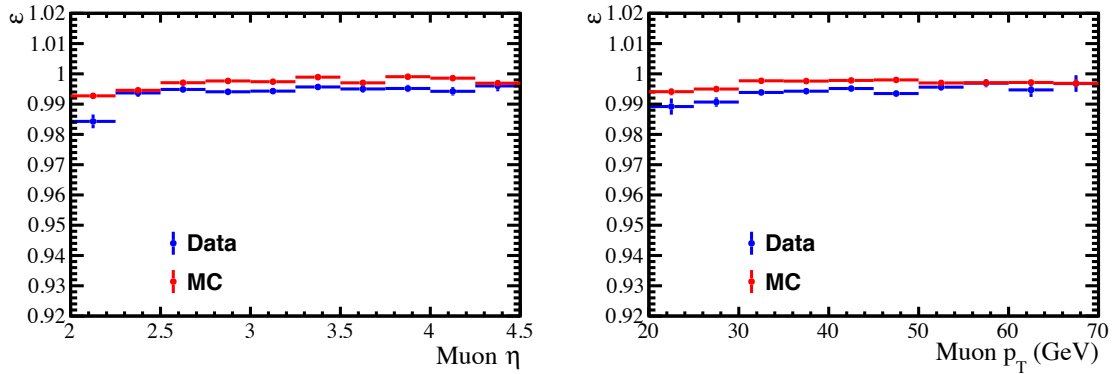


Figure 131: Comparison of track matching efficiency estimated using the data and MC $Z \rightarrow \mu^+\mu^-$ events, as a function of muon η (a) and muon p_T (b).

7.5.2 MuonTT finding systematic uncertainty

In the determination of the bias correction, as shown in Eq. 96, the $\epsilon(\text{MC particle} : \text{with MuonTT})$ is calculated based on the candidates with an associated MuonTT track. Therefore, the differences of MuonTT finding efficiency between data and MC events could affect the bias correction. The MuonTT finding efficiency is defined as a efficiency that finding a MuonTT track around a long track, as:

$$\epsilon(\text{MuonTT Finding}) = \frac{N(\text{Long track, with MuonTT})}{N(\text{Long track})} \quad (99)$$



Table 26: Summary of systematic uncertainties estimated for the tracking reconstruction efficiency.

Sources	Uncertainty
Matching efficiency (data and MC)	0.33%
Matching efficiency correction	0.28%
MuonTT finding efficiency	0.1%
Tag-and-probe Method	-
Total	0.47%

This efficiency is estimated using data and MC $Z \rightarrow \mu^+\mu^-$ events. Fig. 132 shows the comparison of MuonTT finding efficiency estimated using the data and MC events. There is roughly 20% difference between data and MC of MuonTT finding efficiency. To estimated a systematic uncertainty to cover this differences, the MC events are reweighted by a ratio of data and MC MuonTT finding efficiency, and take the differences on the bias correction between with and without this reweight as a systematic uncertainty, which is 0.1%.

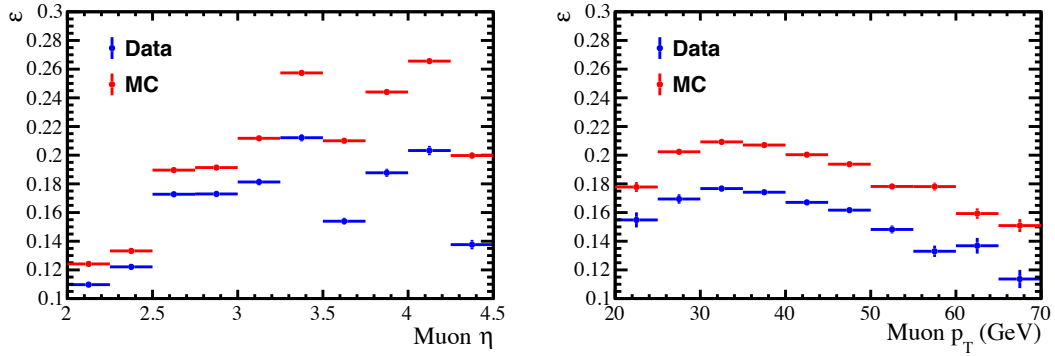


Figure 132: Comparison of MuonTT finding efficiency estimated using the data and MC $Z \rightarrow \mu^+\mu^-$ events, as a function of muon η (a) and muon p_T (b).

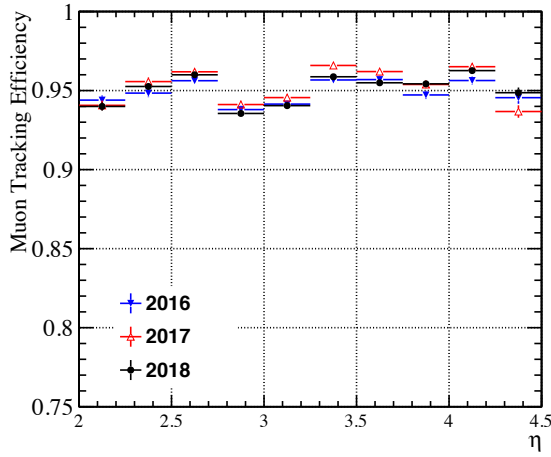
7.5.3 Total systematic uncertainty

Given this binning scheme and these tag-and-probe selections, the systematic uncertainty estimated for the high p_T muon tracking reconstruction efficiency is summarized in Table 26. In summary, the total systematic uncertainty is 0.47% for each muon track.

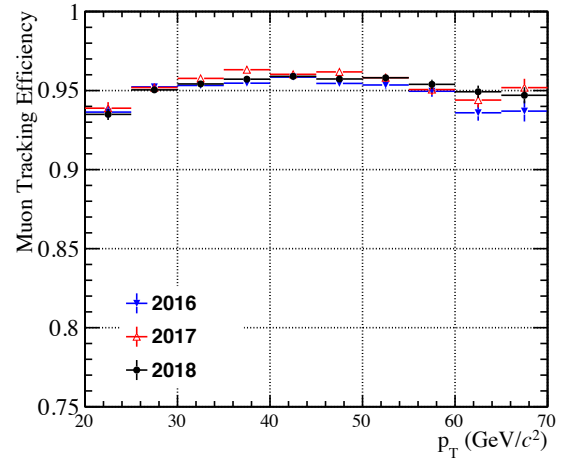


7.6 Results

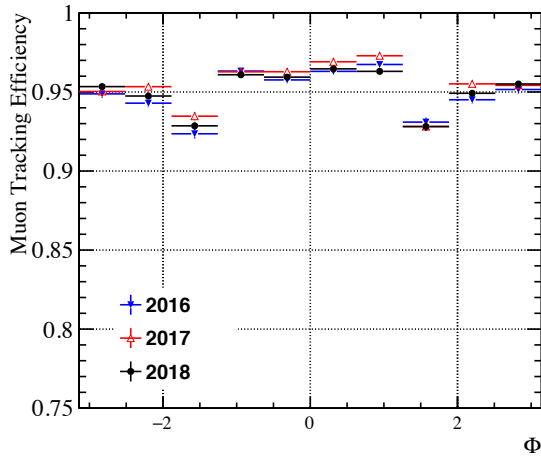
The determined tracking efficiency for 2016, 2017 and 2018 data-sets. As expected, the efficiency has no dependence on lepton199charge or magnet polarity (Appendix A), and the measured tracking efficiency as a function of kinematic and event variables are shown in Fig. 133.



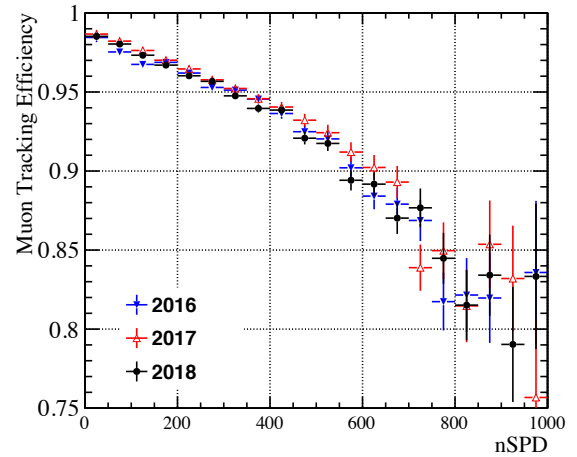
(a)



(b)



(c)



(d)

Figure 133: Muon tracking efficiency for 2016, 2017 and 2018 data-set as a function of muon η (a), muon p_T (b), muon ϕ (c) and the SPD multiplicity (d) of event.



7.7 Identification efficiency

7.7.1 Tag-and-Probe selection

The muon identification efficiency is the efficiency that a real muon of identify a real muon passes the muon quality requirement. In this study, $Z \rightarrow \mu^+\mu^-$ events are used, with the tag-and-probe method. The tag must be a fully reconstructed, identified and triggered muon, and the probe is a long track without any requirement on muon identification. The tag muon is further required to have $p_T > 20$ GeV, $2.0 < \eta < 4.5$, while probe is required to have $p_T > 20$ GeV, $2.0 < \eta < 4.5$. Both tag and probe are required be a long track with relative momentum uncertainty less than 10%. The invariant mass of the tag and probe is required in the mass region of $[60, 120]$ GeV. To select a sample with high purity, additional event requirements are also placed on candidate events, including candidate events must have an azimuthal separation, $|\Delta\phi|$, greater than 2.7 radians. The tag-and-probe selection requirements used in this study are summarized in Table 27.

The muon identification efficiency is calculated by counting the number of probes within the selected sample satisfying the `isMuon` requirement.

Table 27: The tag-and-probe selection used for the muon identification efficiency study.

Tag	Probe	Event
Long track	Long track	$60 < M_{\mu\mu} < 120$ GeV
isMuon	-	$ \Delta\phi > 2.7$
Triggered	-	$\chi^2_{\text{vtx}}/\text{ndf} < 5$
$\sigma_P/P < 0.1$		
$p_T > 20$ GeV	$p_T > 20$ GeV	
$2 < \eta < 4.5$	$2.0 < \eta < 4.5$	

7.7.2 MC muon identification efficiency

The muon identification efficiency obtained with the Truth method is compared with that using the tag-and-probe method, using the simulated $Z \rightarrow \mu^+\mu^-$ events, to vary the method. The results are shown in Figure 134, as a function of muon η and muon p_T . Good agreements are seen in all regions. Therefore, no bias is introduced by the tag-and-probe method, and the tag-and-probe method is stable and robust to determine the muon identification efficiency.

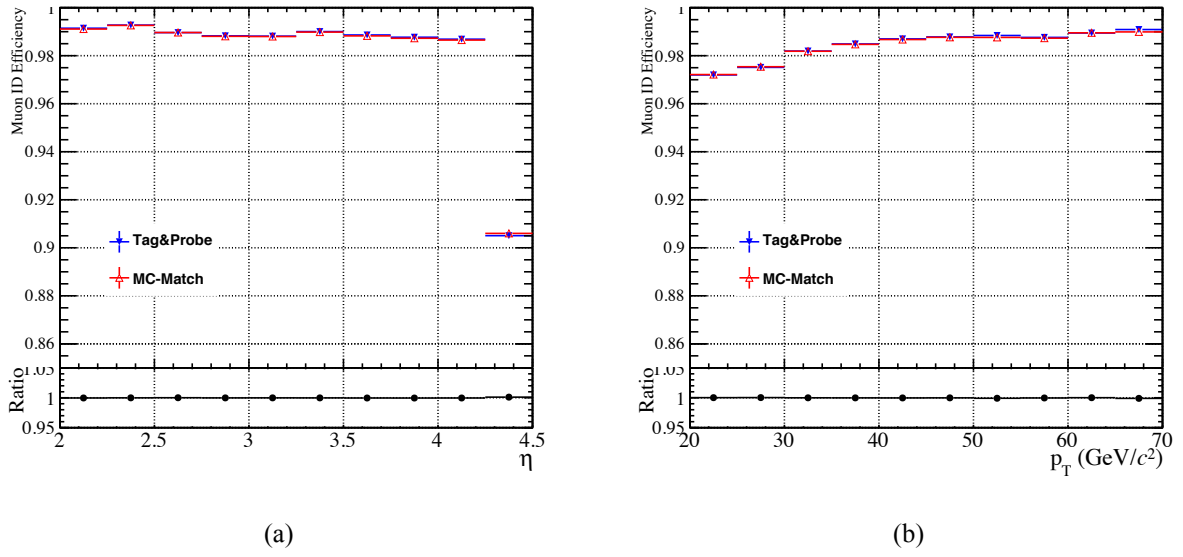
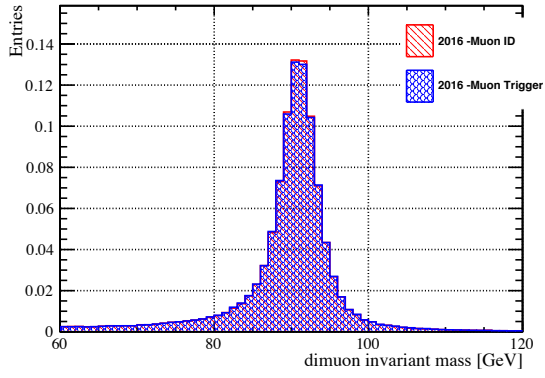


Figure 134: The muon identification efficiency calculated as a function of muon η (a) and p_T (b) in simulated $Z \rightarrow \mu^+\mu^-$ events, using Truth method and the tag-and-probe method.

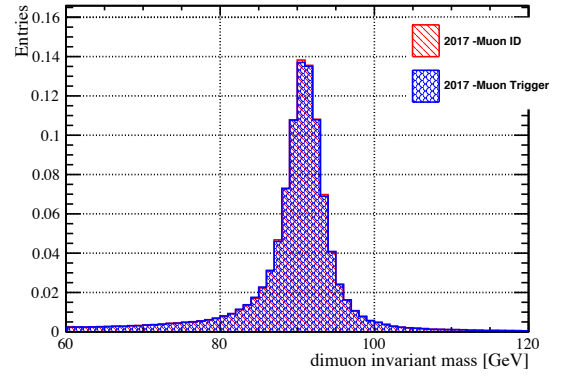
7.7.3 Background estimation

With similar method used in Section 7.2.2, the impacts of background contribution to the muon identification efficiency is studied. Based on previous analysis [45] the dominating background of $Z \rightarrow \mu^+\mu^-$ events is from heavy flavour (HF) processes. However, in this study, as $\chi^2_{\text{vtx}}/\text{ndf} < 5$ selection cut has been applied, which could highly decrease the HF background contribution. Therefore, the background contribution effects to efficiency determination is negligible.

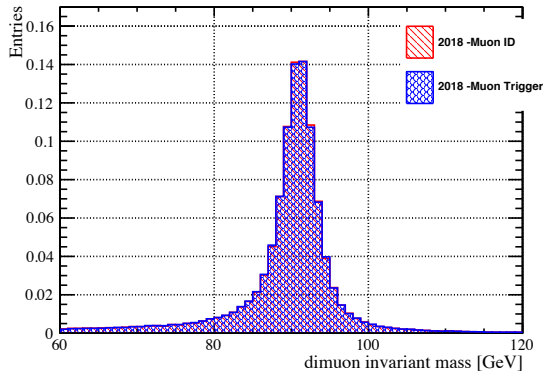
A further cross-check is performed to ensure that there are no potential background effects. The invariant mass distribution of $Z \rightarrow \mu^+\mu^-$ events that passed the muon identification requirement is compared to that of events that passed the muon trigger requirements (candidates used in muon trigger efficiency study). As mentioned before, the selected trigger efficiency candidates have small background contribution. For the sample used in the muon identification efficiency study, if there is any excess in the mass tail region, it will indicate there is an extra background contribution in the sample. The mass distributions for 2016 2017 and 2018 data-sets are shown in Figure 135, where good agreements are found between these two distributions.



(a)

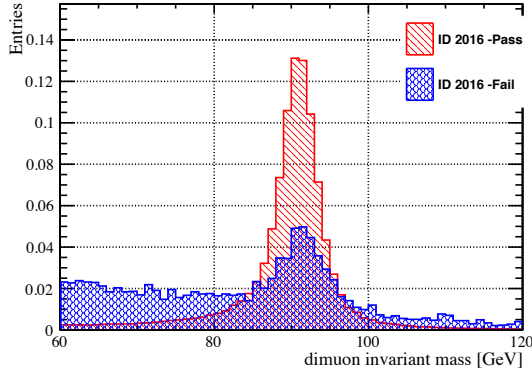


(b)

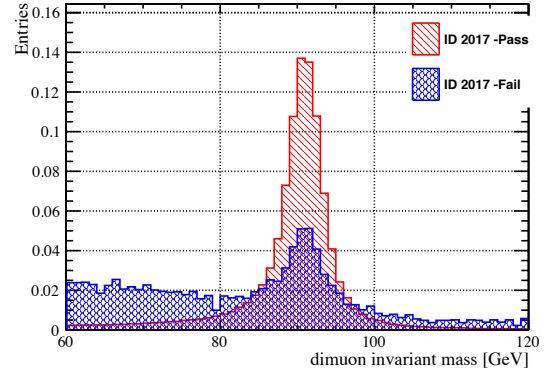


(c)

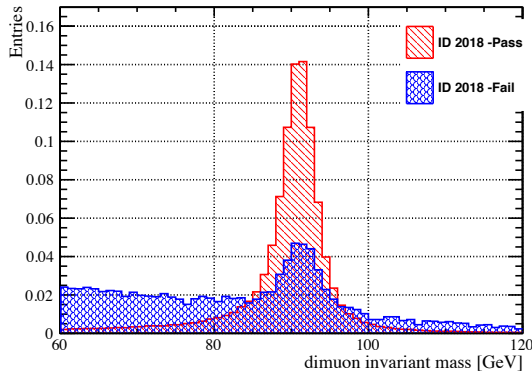
Figure 135: Comparison of the $Z \rightarrow \mu^+\mu^-$ invariant mass distribution of samples obtained for the muon identification and muon trigger efficiency studies, for 2016 (a), 2017 (b), and 2018 (c) data-set. The shadow region represents the mass distribution of muon identification sample, while solid line represents the mass distribution of muon trigger sample.



(a)



(b)



(c)

Figure 136: Comparison of the $Z \rightarrow \mu^+\mu^-$ invariant mass distributions for events passing or failing the muon identification requirement, for the 2016 (a), 2017 (b), and 2018 (c) data-sets.



7.7.4 Systematic uncertainties

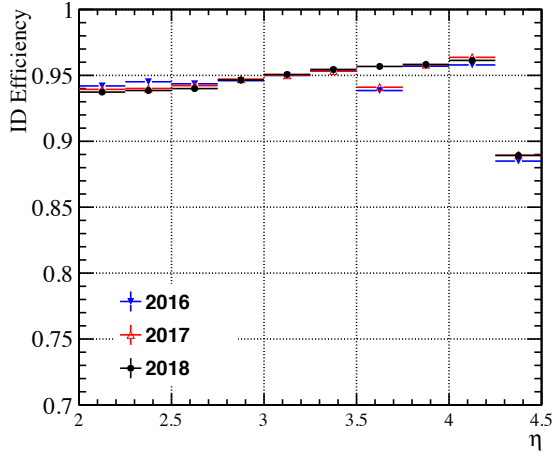
Similar to the systematic uncertainty estimation of the muon trigger efficiency, no systematic uncertainty is assigned to the muon identification efficiency, for both the tag-and-probe method and the background contribution. The only uncertainty in the muon identification efficiency is due to the finite size of the $Z \rightarrow \mu^+\mu^-$ sample. The uncertainty in different bins of phase space varies between 0.001% and 0.003% for the 2016, 2017, and 2018 data-sets.

7.7.5 Results

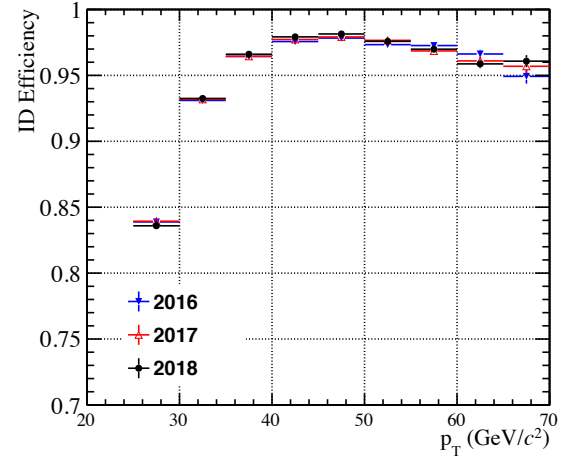
The muon identification efficiency is calculated using the tag-and-probe method, for the 2016, 2017 and 2018 data-sets. As expected, the efficiency has no dependence on lepton charge or magnet polarity (Appendix C.1), and the measured efficiency is shown in Fig. 137, as a function of different event and kinematic variables. Good agreements in efficiency are seen between these three data-sets.

7.8 Conclusion

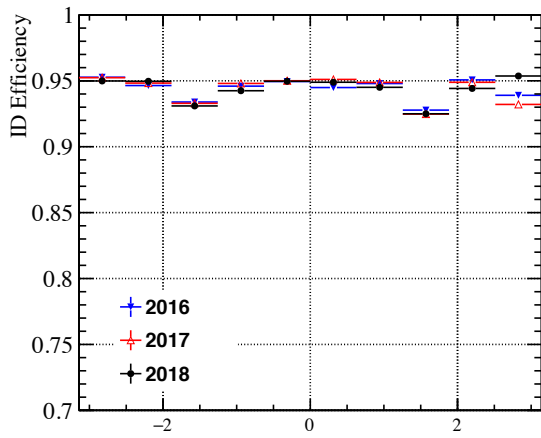
The muon reconstruction efficiencies are determined using the tag-and-probe method with LHCb RunII data-sets, for pp collision data collected in 2016, 2017, and 2018. The measured efficiencies are checked with ‘Truth method’, where good agreements between different methods are seen. The uncertainties of muon efficiencies are studied, which is dominated by the statistics uncertainty. Furthermore, for the muon trigger, tracking and identification efficiencies, there is no dependence on muon charge and magnet polarity.



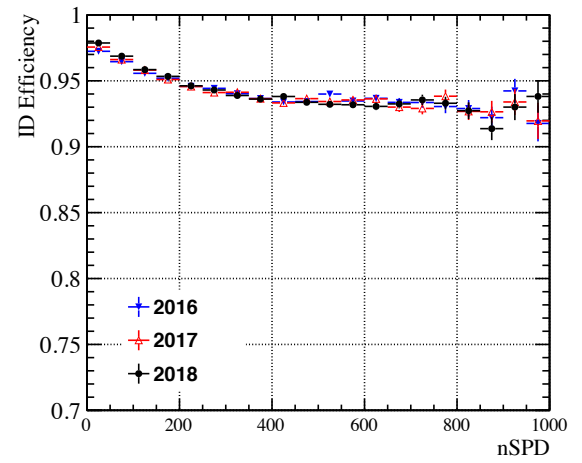
(a)



(b)



(c)



(d)

Figure 137: Muon identification efficiency for 2016, 2017 and 2018 data-set, as a function of muon η (a), muon p_T (b), muon ϕ (c) and the SPD multiplicity (d).



8 Improved-alignment and momentum calibration for physics with high momentum muons in LHCb

8.1 Introduction

The LHCb experiment is a forward spectrometer at the LHC. With unique forward coverage ($2 < \eta < 5$), measurements of $W^\pm$ and Z^0 boson production at LHCb could provide important tests of the theoretical predictions [45]. For instance, the LHCb data could probes a different range of the proton distribution functions, measurement of the Z-boson forward-backward asymmetry, and a planned measurement of the W mass, are sensitive to different theoretical uncertainties than those of the central LHC detectors.

At LHCb the electroweak measurements are outside the main physics program, which is centered around low- p_T flavour physics. As a result detector calibrations have not been optimized for this type of measurements. In particular, the momentum calibration for the high-momentum muons that form the main signature of $W^\pm$ and Z^0 decays in LHCb for has been found to be of relatively poor quality. The systematic uncertainty associated to the momentum measurement affects LHCb's potential in electroweak precision measurements. In this manuscript we present a procedure for the improvement of the momentum calibration for high-momentum muons, using the invariant mass distribution of the $Z \rightarrow \mu^+\mu^-$ decay. Since the start of data taking in 2015, the LHCb collaboration employs a novel prompt alignment procedure [136], with the aim to obtain a stable performance of the detector. The prompt alignment and calibration consists of

- the vertex detector (VELO) alignment, followed by the alignment of the spectrometer tracking stations (TT, IT, OT);
- the alignment of the MUON tracking detector;
- global time alignment offset between the collision time and the LHCb clock that affects the drift time measured in the straw tubes which compose the OT;
- the alignment of primary and secondary mirrors rotation in both RICH detectors;
- RICH gas refractive-index and Hybrid Photon Detectors calibrations;
- ECAL LED (relative) and π^0 (absolute) calibrations.



The detector alignment of the tracking detectors (VELO, TT, IT, OT and MUON) is performed using a global minimum χ^2 algorithm that takes reconstructed tracks and vertices as input [137, 138]. In the online procedure, different types of events are selected. For VELO alignment, minimum bias events enriched by beam collision with residual gas in the VELO region are used. For alignment of the spectrometer, $D^0 \rightarrow K\pi$ candidates are used, where the D^0 mass position provides important information to constrain the curvature bias. For the alignment of the muon detectors, muons from $J/\psi \rightarrow \mu^+\mu^-$ candidates are used. Although the alignment software allows for the simultaneous alignment of all tracking systems, this was not currently exploited for the prompt alignment for LHCb RunII data-taking. Rather the velo, IT/OT/TT and MUON alignments are all run in separate steps. The LHCb tracking detectors are oriented approximately perpendicular to the z -axis. The main component of the dipole magnet is in the y (vertical) direction. Remaining detector mis-alignments lead to a bias in the track curvature, q/p . Since the magnetic field primarily bends tracks in the xz -plane, to first order the curvature bias is directly proportional to mis-alignments of tracking detectors in x . For instance, an displacement Δx of the T station detectors relative to the VELO leads to a curvature bias

$$\Delta \frac{q}{p} = A \Delta x \quad (100)$$

where A represents the field integral, and is approximately 0.3 /GeV /m. As a consequence, the bias in the momentum due to remaining misalignment is proportional p : it grows strongly as a function of momentum. Figure 138 shows the peak position of the $Z \rightarrow \mu^+\mu^-$ invariant mass distribution as a function of the azimuthal angle of the positive muon in run-2 data, using the alignment produced with the prompt alignment procedure. Since Z bosons are produced with small transverse momentum in the LHCb acceptance, the azimuthal angle of the muon is a good proxy for the azimuthal angle of the Z decay plane. A large dependence of the invariant mass on this angle is observed. The fact that the behaviour changes sign with the polarity of the field is in indication that it is due to detector mis-alignment. The largest variations are about 1 GeV, approximately 1% of the Z boson mass. The relative error in the momentum is two orders of magnitude larger than the precision LHCb obtains for the low momentum tracks used for precision mass measurements of charm and B hadrons [95, 139, 140]. As another example Figure 139 shows the average forward-backward charge asymmetry (A_{FB}) as a function of the di-muon invariant mass, which can be used to extract the weak mixing angle [141]. The observed average A_{FB} also shows a large dependence on the magnetic field configuration. This effect is not seen on simulated data, and hence must be the result of a poor momentum calibration.

The prompt alignment used charmed hadrons (D^0 , J/ψ) to fix the curvature bias. The momenta of the final state particles are much smaller than those from $W^\pm$ and Z^0 decays. This explains why the prompt alignment is not sufficiently sensitive to the small misalignments that affect the high-momentum tracks.

In this note we report on a study that exploits $Z \rightarrow \mu^+\mu^-$ events to improve the alignment of the VELO and IT/OT/TT tracking stations. Among others we obtain an improvement of the $Z \rightarrow \mu^+\mu^-$ invariant mass resolution by about 30%. However, as some dependencies of the invariant mass on the kinematics of the decay and the magnetic field orientation remain, we also study additional calibration corrections for muon curvature in bins of azimuthal angle and pseudorapidity. As discussed in Referece [142], the observed muon momentum bias comes

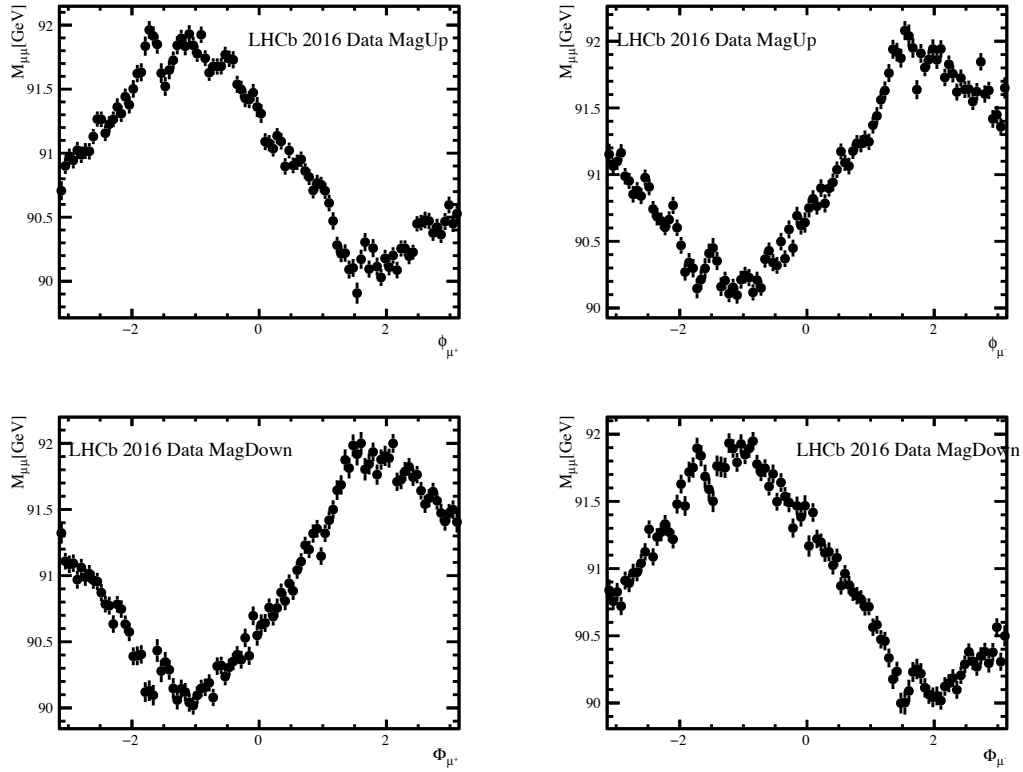


Figure 138: Z^0 mass peak position as a function of muon ϕ . (top-left) is for μ^+ in MagUp sample, (top-right) is for μ^- in MagUp sample, (bottom-left) is for μ^+ in MagDown sample, (bottom-right) is for μ^- in MagDown sample.

from a curvature bias, other than from a momentum scale bias. Momenta are measured by the curvature, which for the purpose of this note we define as q/p with q is the charge of particle.

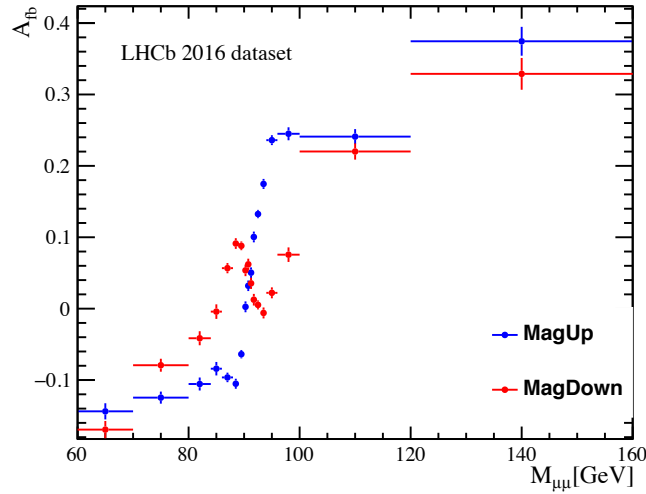


Figure 139: Comparison of A_{FB} distributions measured using MagUp and MagDown events of 2016 data-set.

In LHCb, the curvature of charged track is measured in the xz plane, but as the magnitude of the momentum is dominated by the z component, we should focus on the x direction in this study. To suppress the mis-alignment effects, two alignments are studied and applied, including a detector level alignment (‘Improved-alignment’) and an additional calibration (‘Post-alignment’).

The ‘Improved-alignment’, based on existing detector alignment information, performs offline detector module alignment as described in Reference [143]. With the ‘Improved-alignment’, the detector elements are aligned using the corresponding reconstructed tracks, resulting the mass peak position of reconstructed Z^0 candidates in different regions of phase-space been corrected to its mass of world average value [144].

However, based on our study, the Z^0 mass peak position is varies from its world average value, when different kinematic cuts applied to the final state muons. Therefore, there are Z^0 mass peak position dependencies in different regions of phase-space, which should be considered in the alignment fitting procedure. It is painful to modify the LHCb official detector alignment package (*Alignment*), to implement this constraint. Therefore, we propose an offline muon momentum calibration procedure, named ‘Post-alignment’, to the $Z \rightarrow \mu^+\mu^-$ data. In the ‘Post-alignment’, the $Z \rightarrow \mu^+\mu^-$ candidates are further divided into different sub-samples, according to muon η and ϕ values of the $Z \rightarrow \mu^+\mu^-$ event. An additional correction is applied to muons, to suppress the mass peak differences between MagDown and MagUp samples, also to suppress



differences between data and theoretical prediction. The formula used in this steps is defined as:

$$(q/p)' = (q/p) + \beta, \quad (101)$$

where $(q/p)'$ and (q/p) are curvature of particle before and after alignment, β is a track bias correction, which has dependencies in different muon detection regions. In LHCb, a prompt alignment using $Z \rightarrow \mu^+\mu^-$ events was not feasible in Run-2, as the $Z \rightarrow \mu^+\mu^-$ production rate (~ 100 events per hour) is too small. As LHCb will run with a factor 7 higher instantaneous luminosity in Run-3, the rate may be sufficiently high to provide a meaningful constraint in the prompt alignment in the future. This is another motivation to study the performance of the alignment with tracks from $Z \rightarrow \mu^+\mu^-$ decays. Furthermore, we would like to emphasise importance of a simultaneous alignment at the LHCb. Currently, the prompt alignments of the VELO and spectrometer alignment are run independently. However, based on our study, in order to get an optimal alignment, it is important that at least once the alignments are run simultaneously.

8.2 Samples and event selection

In this study, $Z \rightarrow \mu^+\mu^-$ candidates selected from the 2016 pp collision data-set are used to demonstrate the alignment procedure and improvements from the alignment and calibration. The standard $Z \rightarrow \mu^+\mu^-$ MC events generated by LHCb collaboration are used in this study, which provide important cross-checks. The 2017 and 2018 data-set can be corrected with similar procedure, we will not discuss them in this note.

The $Z \rightarrow \mu^+\mu^-$ data candidates are selected from the `StrippingZ02MuMuLine` stripping line. This stripping line requires two oppositely charged `StdAllLooseMuons` with $p_T > 3$ GeV, and the invariant mass of the dimuon pair, $m(\mu^+\mu^-)$, larger than 40 GeV.

Similar as Reference [45], the standard LHCb $Z \rightarrow \mu^+\mu^-$ selection cuts are used to get a sample with high purity, by requiring both final-state muons must have $p_T > 20$ GeV and pseudorapidity $2.0 < \eta < 4.5$. For the muon candidates, the track probability χ^2 is required to be greater than 1%. At least one of the muon candidates is required to be triggered on signal (TOS) with respect to all three trigger decisions `L0MuonEW`, `Hlt1SingleMuonHighPT` and `Hlt2SingleMuonHighPT`. The $m(\mu^+\mu^-)$ is further required to be in the range $60 < m(\mu^+\mu^-) < 120$ GeV.

During the data taking, the polarity of the LHCb magnet is swapped regularly to cancel detection asymmetries. In this study, the ‘MagDown’ and ‘MagUp’ refer to the data-sets collected with different magnet polarities.



For the VELO alignment, a special set of tracks is used, including `VeloOverlap`, `VeloBackward`, `ITBoxOverlap`, and `GoodLong`. Detailed requirements on each of these track type are summarized in Table 28, and the global requirements are summarized in Table 29.

Table 28: Selection requirements on the tracks used in VELO alignment. `nHits` represents the number of hits in the particular detector region, while `n(VeloHoles)` and `n(THoles)` represents the number of missing VELO/T layers in the track.

Track Type	Inputs	Selections
VeloOverlap	Velo, Backward	$\text{nHits}(A - \text{side}) \geq 3$
		$\text{nHits}(C - \text{side}) \geq 3$
		$\text{nHits}(R) \geq 7$
		$\text{nHits}(\phi) \geq 7$
		$\text{n(VeloHoles)} \leq 1$
VeloBackward	Backward	$\text{nHits}(R) \geq 6$
		$\text{nHits}(\phi) \geq 6$
		$\text{n(VeloHoles)} \leq 0$
ITBoxOverlap	Long	At least two hits from different IT modules $P > 30 \text{ GeV}$
GoodLong	Long	$30 < P < 200 \text{ GeV}$
		$p_T > 0.2 \text{ GeV}$ $\text{n(THoles)} \leq 1$

Table 29: Global selection cuts on the tracks used in VELO alignment.

Variables	Cut values
Track χ^2	≤ 3
Track Match χ^2/ndf	≤ 3
Track VELO χ^2/ndf	≤ 3
n(THoles)	≤ 0



8.3 Detector alignment update

To better understand the source of the misalignment effects seen in the data (c.f. Figure 138 and 139), the update of the detector alignment is performed in two steps. First, the tracking detectors of the spectrometer (TT/IT/OT) are realigned. Subsequently, the VELO detector modules are added to the alignment. In the second step, the spectrometer tracking detectors are still allowed to move, as we have found that the alignments are strongly correlated. This partially explains why the prompt calibration procedure applied during RunII could not reproduce the results: It is not considering sufficiently many alignment degrees of freedom at the same time.

The detector alignment using events with $Z \rightarrow \mu^+\mu^-$ decays takes three kinds of inputs:

1. Di-muon pairs as selecting with the criteria described in Section 6.2.3, but in a narrow mass window $80 < m(\mu^+\mu^-) < 100$ GeV are used as input to the alignment with a Z^0 mass constraint. The mass is applied as part of the vertex fit [138]. The vertex fit changes the track parameters and the vertex. These changes are then propagated to all hit residuals on the track, which is how the detector alignment parameters become sensitive to the mass constraint. The mass constraint in the vertex fit takes the natural width of the Z^0 resonance into account, but it does not account for the detailed shape of the invariant mass distribution.
2. Other high qualities in the selected $Z \rightarrow \mu^+\mu^-$ events are used as input to the alignment as well. The inclusion of medium-high momentum tracks (`GoodLong`) or tracks (`VeloOverlap`, `ITBoxOverlap`) that go through overlap regions in the sub-detectors significantly reduces the correlation between alignment parameters. For the alignment of the VELO detector trans with negative pseudorapidity (`Backward`) are also used. These tracks do not have a momentum estimate: to account for their multiple scattering the track fit uses a fixed transverse momentum of 0.4 GeV.
3. For the internal alignment of the VELO primary vertices are used as input to the alignment as well [138]. The CPU penalty of high multiplicity vertices in the alignment is very large. Therefore, primary vertices are quasi-randomly split in smaller vertices with a maximum multiplicity of 7 tracks before they are included as a constrained in the alignment.

More details on the configuration of the alignment procedure can be found in Appendix ??.



8.3.1 TT/IT/OT alignment

The T-station alignment, includes TT, IT and OT alignments. In the configuration file, the default setting is used, as TTITOTVeloModulesZRyRx. The following detailed settings are used in the alignment:

```
OTFrames("TxRz")
OTModules("TxRz", longmodules)
OTHalfModules("TxRz", shortmodules)

TTLayers("Tz")
TTHalfModules("TxRz")
TTShortModules("TxTzRxRz")

ITBoxs("TxTzRz")
ITLayers("TxTz")
```

After the T-station alignment, there are improvements in Z^0 mass resolution, as shown in left figure of Figure 140. While big improvements in A_{FB} distribution of MagDown and MagUp samples had been seen, the large differences are highly suppressed by this alignment, as shown in right figure of Figure 140. But, there are still large Z^0 mass peak position dependences (as a function of muon ϕ) in the data, as shown in Figure 141, even after this alignment. To further suppress these effects, more TT, IT and OT alignment information (freedom) had been tested, but we cannot get any further improvements, which indicates there are alignment effects from other detector system. More tests for the TTITOT alignment can be found in Appendix D.1.

8.3.2 VELO alignment

To get further improvements, an internal alignment of the VELO is performed, starting from the improved TTITOT alignment. The VELO can be aligned at two levels of granularity simultaneously, namely the VELO half alignment and the VELO module alignment. Due to the movement of the system needed to retract the VELO for beam insertion, the half alignment is normally performed for each run. On the $Z \rightarrow \mu^+\mu^-$ sample this is not possible without significant development of the code. Therefore, it has been decided not to touch the existing half alignment, but only align the VELO modules. In this VELO alignment, the VELO modules are

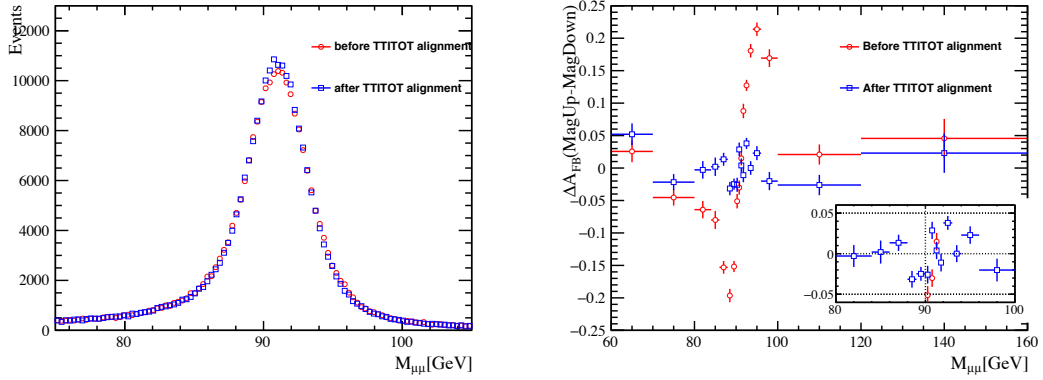


Figure 140: (left) Invariant mass distribution $Z \rightarrow \mu^+\mu^-$ candidates before and after TTITOT alignment. (right) A_{FB} differences between MagUp and MagDown samples, before and after TTITOT alignment. The red points represent A_{FB} differences before TTITOT alignment, and the blue points represent A_{FB} differences after TTITOT alignment.

aligned in xy plane, as ‘TxTyRz’, while the z direction information is used too, as ‘RxRyTz’. In the configuration file, the following setting is used:

```
VeloModules ("TxTyRzTzRyRx")
```

After TTITOT+VELO alignments, the mass distribution of $Z \rightarrow \mu^+\mu^-$ candidates is shown in left figure of Fig. 142. Again, a large improvement in the Z^0 invariant mass resolution is observed, from 3.18 GeV to 2.98 GeV, about 6% improvement. This illustrates how important the VELO internal alignment is, even for resonances with a large opening angle. Comparison of the A_{FB} distribution difference between MagDown and MagUp samples is shown in right figure of Figure 142. Although there is significant improvement on the Z boson mass resolution, the A_{FB} differences are still remaining. The Z^0 mass peak position as a function of the muon azimuthal angle is shown in Figure 143. The dependence of the mass on ϕ is much reduced by adding the VELO alignment.

8.3.3 Summary of ‘Improved-alignment’

Tracker mis-alignment effects in $Z \rightarrow \mu^+\mu^-$ events can be largely suppressed by applying the offline detector alignment. The alignment of the TT, IT and OT systems accounts for most of the difference in A_{FB} between the MagDown and MagUp samples. However, the Z^0 boson mass peak position still shows a large variation as function of the azimuthal angle of the decay plane (a so-called ‘cowboys-versus-sailors’ effects). After adding the internal alignment of the VELO,

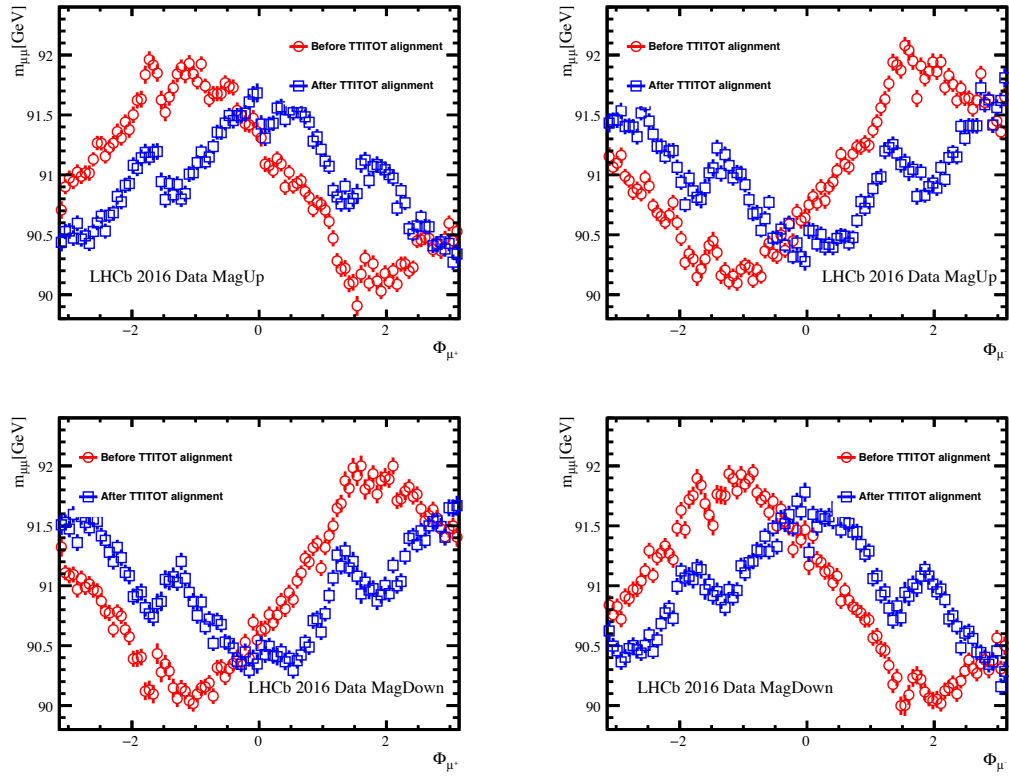


Figure 141: The Z^0 mass peak position as a function of a function of moun ϕ . (top-left) for μ^+ in MagUp sample, (top-right) for μ^- (right) in MagUp sample, (bottom-left) for μ^+ in MagDown sample, and (bottom-right) for μ^- in MagDown sample. The red points represent the peak position dependence before TTITOT alignment, and the blue points represent the dependence after TTITOT alignment.

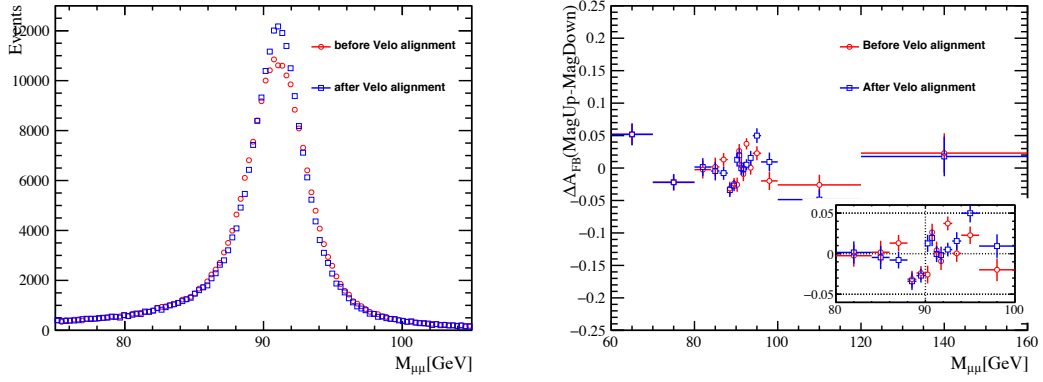


Figure 142: (left) Invariant mass distribution $Z \rightarrow \mu^+\mu^-$ candidates before and after VELO alignment. (right) A_{FB} differences between MagUp and MagDown samples, before and after VELO alignment. The red points represent A_{FB} differences before VELO alignment, and the blue points represent A_{FB} differences after VELO alignment.

the latter effect is largely removed. However, as shown in right figure of Figure 142, there are still large A_{FB} difference between MagDown and MagUp samples, even after TTITOT+VELO alignment. The largest variation between MagDown and MagUp A_{FB} is about 0.05, around Z^0 peak region, which is much larger than its statistical uncertainty, indicates there is still remaining mis-alignment effects in $Z \rightarrow \mu^+\mu^-$ data. The TTITOT and VELO alignments are done with a iterative method. Different number of iterations are tested, we found that four iterations for each alignment is sufficient enough to get stable results. More details can be found in Appendix D.2. To balance fitting speed and reliability of detector alignment, four iterations is used as a default option in this step. As discussed above, with the ‘Improved-alignment’, the Z^0 mass resolution is largely improved, which allow precision electroweak measurement using LHCb Run-2 data. This ‘Improved-alignment’ will benefit many W and Z related measurements. But the A_{FB} differences between MagDown and MagUp samples are still there, which will be discussed and resolved in the coming section.

8.4 Post-alignment

The A_{FB} distribution after ‘Improved-alignment’ is shown in the top-left figure of Figure 144, which indicate an additional muon momentum calibration is needed for the $Z \rightarrow \mu^+\mu^-$ data. The ‘Improved-alignment’ is studied with an assumption that Z^0 mass peak position is stable in different regions of Z^0 decay phase-space. But this assumption is not correct in many special regions

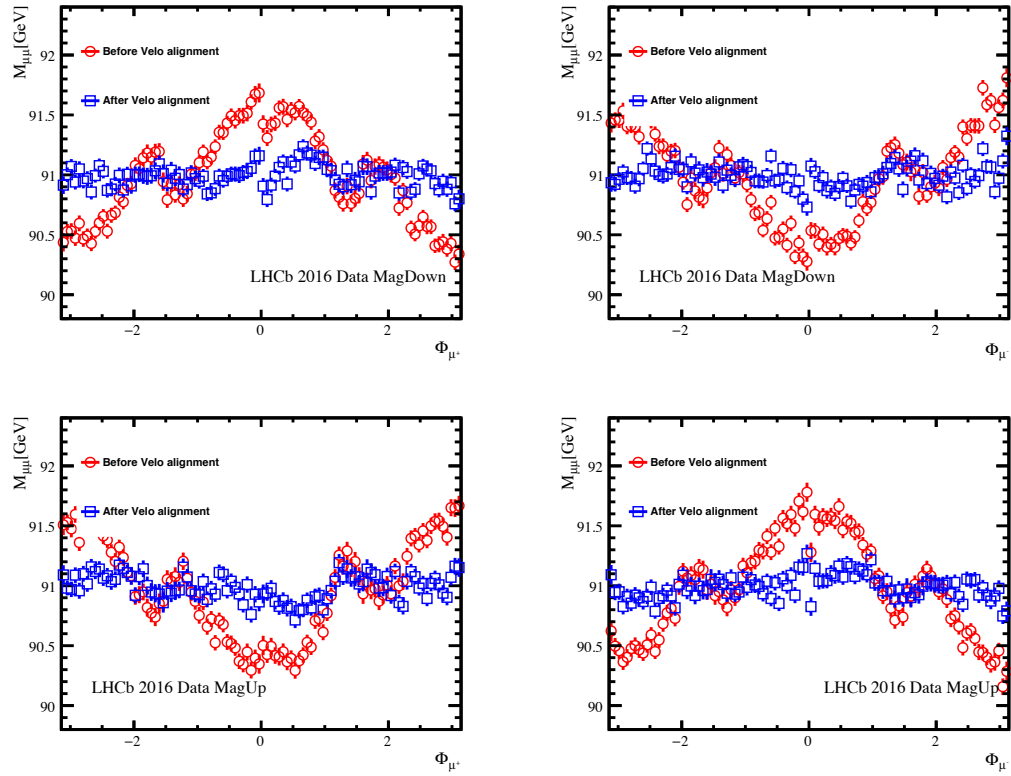


Figure 143: The Z^0 mass peak position as a function of a function of moun ϕ . (top-left) for μ^+ in MagUp sample, (top-right) for μ^- (right) in MagUp sample, (bottom-left) for μ^+ in MagDown sample, and (bottom-right) for μ^- in MagDown sample. The red points represent the peak position dependence before VELO alignment, and the blue points represent the dependence after VELO alignment.

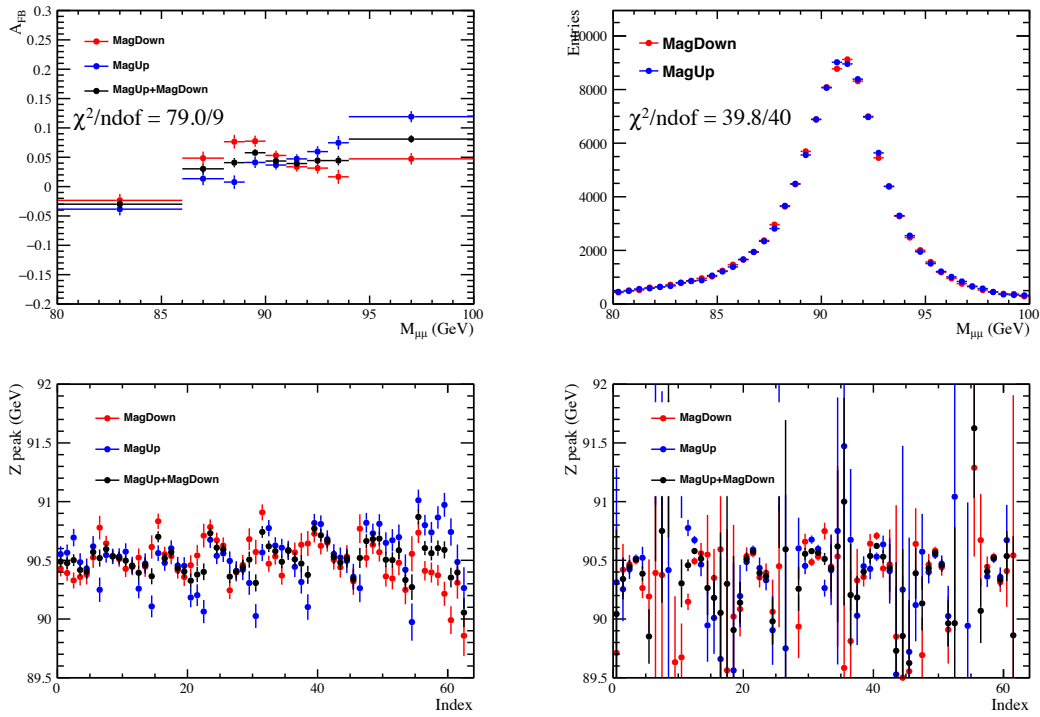


Figure 144: The comparisons between MagDown and MagUp samples, with ‘Improved-alignment’ applied. (top-left) is A_{FB} distribution, (top-right) is $m(\mu^+\mu^-)$ distribution, (bottom-left) is the Z^0 mass peak position in different μ^+ and μ^- η regions, (bottom-right) is the Z^0 mass peak position in different μ^+ and μ^- ϕ regions. In the top two figures, the χ^2/ndof values directly represent the differences between MagUp and MagDown. In the bottom two figures, ‘Index’ is a label of these 64 sub-samples.

of phase-space, the LHCb detector is a single-arm forward detector, only forwardly boosted Z^0 events could be detected, which are located in many unique regions in phase-space. In this section, we checked the Z^0 mass dependence in different regions of phase-space, and a ‘Post-alignment’ is performed to further suppress remaining track bias effects. The ‘Post-alignment’ is developed based on the Z^0 mass peak position information, with an iterative method using TMinuit fitting to get the correction factors. As described in Equation 101, only a track bias correction factor (β) is needed for one type of muon. For a given muon category (for example in a given $\eta(\mu)$ bin), there are four different types of muons, as μ^+ in MagDown sample, μ^- in MagDown sample, μ^+ in MagUp sample, and μ^- in MagUp sample. So in the ‘Post-alignment’, there are four free parameters to be determined by the fitting for a given muon category.



8.4.1 The Z^0 mass dependence in generator level

In LHCb, the $Z \rightarrow \mu^+\mu^-$ simulated events are generated with Pythia [86]. To get a better modelling of Z^0 boson p_T and rapidity, MC-truth and MC reconstruction (MC-reco) events are reweighted to the distribution of a higher order generator, ResBos [114] using CT14NNLO [115]. The ResBos generator has advantage of including most of the electroweak effects with a full simulation of the non-perturbative, at approximate next-to-next-to-leading order (NNLO) plus next-to-next-to-leading-logarithm (NNLL) in QCD interaction. The Pythia events after ResBos reweighting are used to have a better understanding of the Z^0 mass peak position dependence. To correctly modelling kinematic cut effects, the MC events must passed trigger and offline requirements. Then, the MC-truth and MC-reco level Z^0 mass information of selected candidates is used to study the dependence. The Z^0 mass dependence on muon η and ϕ in truth level are shown in Figure 145. In the figure, each bin content in a 2-D histogram means the corresponding Z peak position in a given kinematic region. It is clear that Z peak position has strong dependence in the truth level. The reason is that the event selection cuts only pick up special region of the Z^0 decay phase-space, special in the detector boundary, where the Z^0 boson peak position is no longer same as its world average value. The $\eta(\mu^\pm)$ and CS- $\cos\theta$ dependence is larger than that of others, such as $\phi(\mu^\pm)$ and CS- ϕ dependence, where CS is short for Collins-Soper frame [52]. Considering CS- $\cos\theta$ is 100% correlated with A_{FB} distribution, we should avoid to use it in the muon momentum calibration, so only $\eta(\mu^\pm)$, $\phi(\mu^\pm)$ dependence are considered in the study. The distributions of Z mass dependence for MagUp and MagDown data samples are shown in Figure 146 and Figure 147. While these distributions of MC samples are shown in Figure 148 and Figure 149. From these figures, we can see there are different mass dependence in MagUp and MagDown data samples. While, the mass dependence of MagUp and MagDown MC samples are consistent with each other, which are also consistence with the generator level predictions.

8.4.2 Procedures of ‘Post-alignment’

As discussed above, the Z^0 boson mass peak position has large dependencies on the muon η and ϕ , and therefore affects the A_{FB} measurement. Furthermore, the η and ϕ dependencies are highly correlated. Therefore, two different approaches can be used to decompose these two dependencies, either by making a 2-D global fitting or performing an iterative fitting. For a 2-D global fitting, a $Z \rightarrow \mu^+\mu^-$ sample with large statistics is needed, also a 2-D fitting is a time consuming procedure, which need plenty of CPU resources. Therefore, an iterative fitting

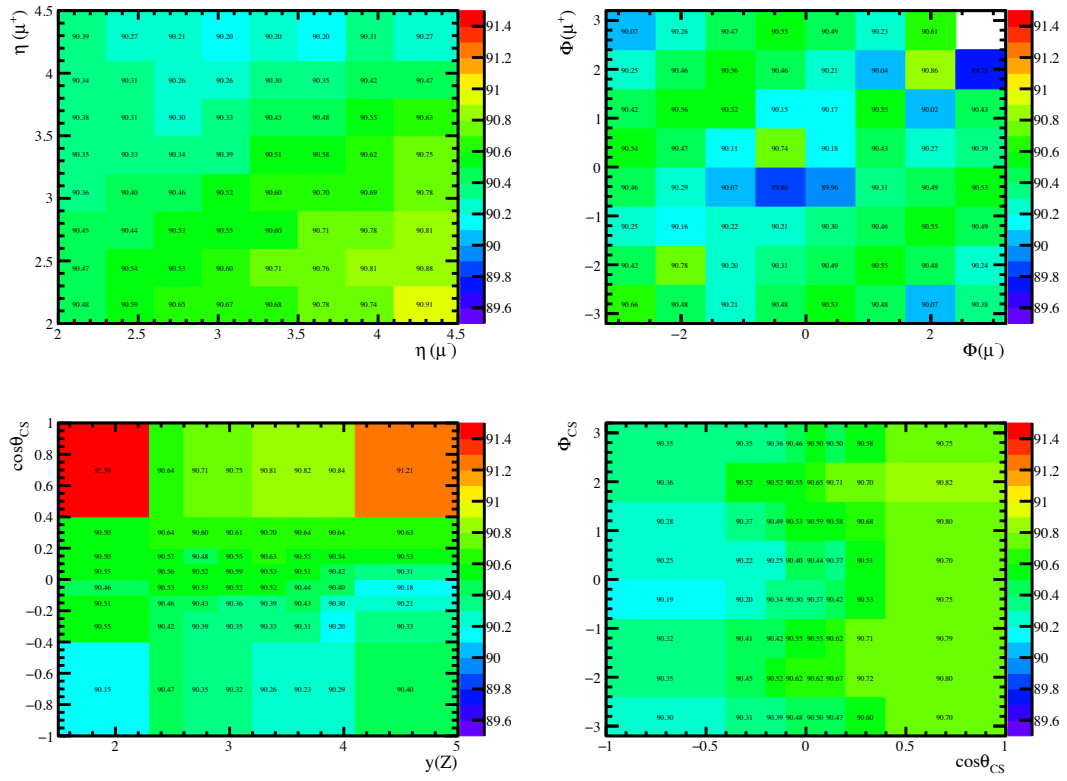


Figure 145: The Z^0 mass peak position dependence, estimated using the ResBos generator. (top-left) is as a function of the $\eta(\mu)$, (top-right) is as a function of $\phi(\mu)$, (bottom-left) is as a function of Z rapidity and $CS\text{-}\cos\theta$, (bottom-right) is as a function of $CS\text{-}\cos\theta$ and $CS\text{-}\phi$.

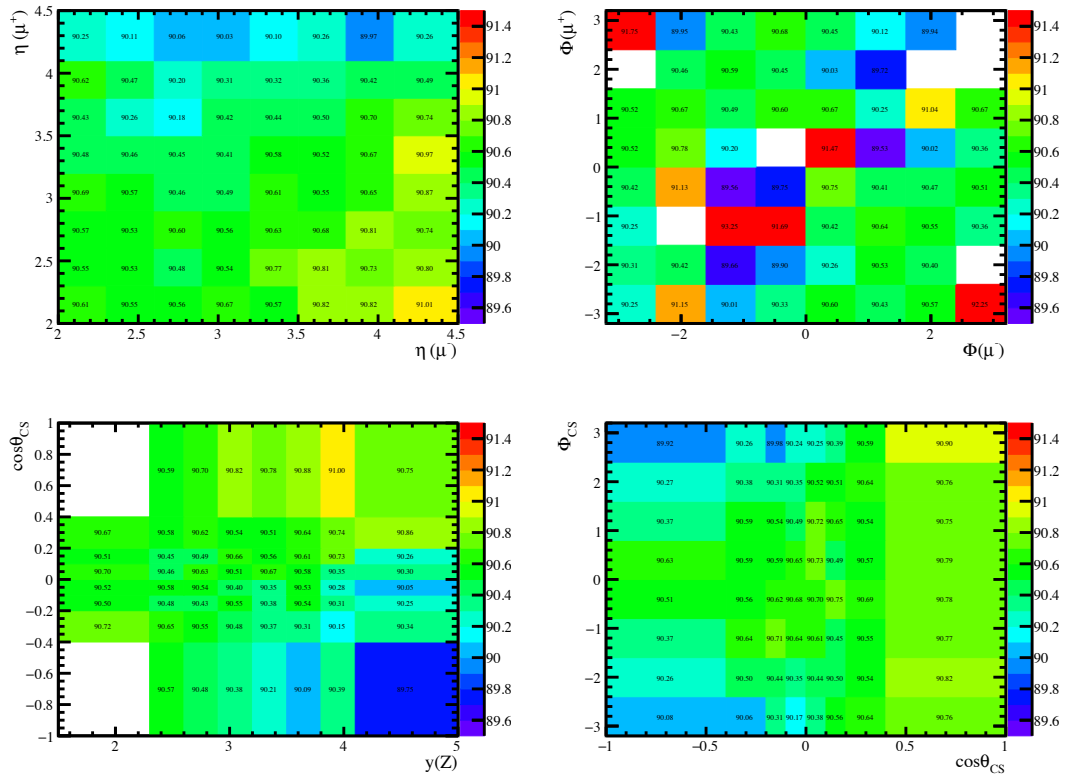


Figure 146: The Z^0 mass peak position dependence of data MagUp sample. (top-left) is as a function of the $\eta(\mu)$, (top-right) is as a function of $\phi(\mu)$, (bottom-left) is as a function of Z rapidity and $CS\text{-}\cos\theta$, (bottom-right) is as a function of $CS\text{-}\cos\theta$ and $CS\text{-}\phi$.

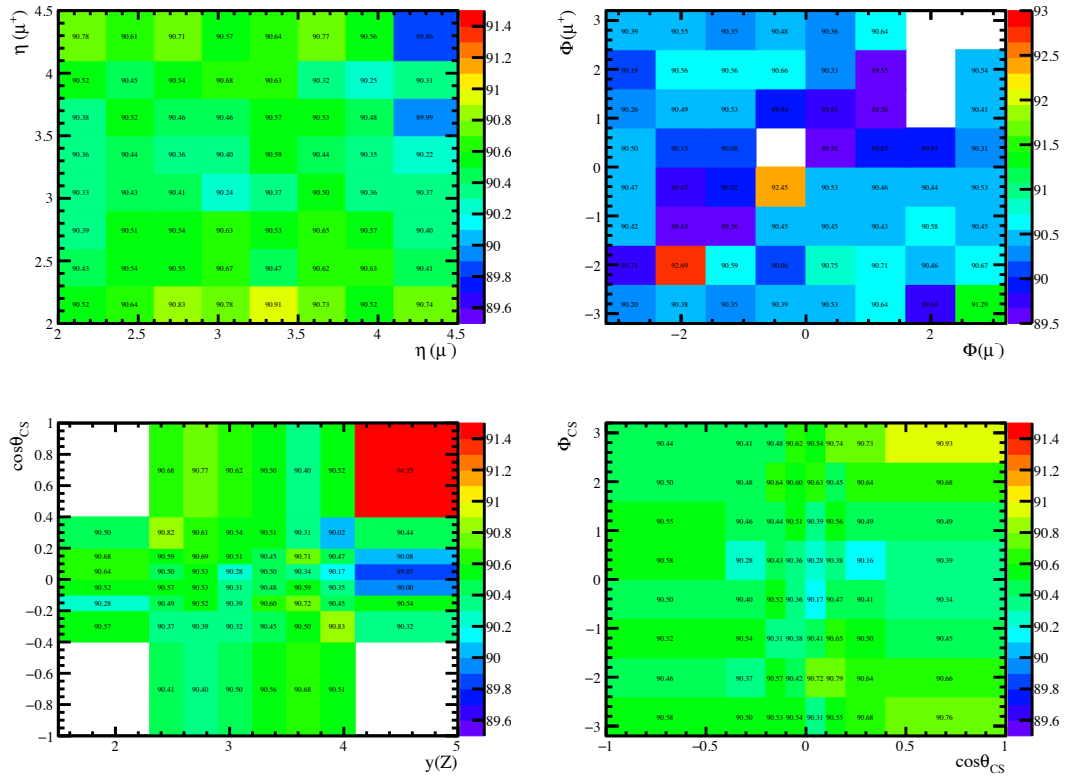


Figure 147: The Z^0 mass peak position dependence of data MagDown sample. (top-left) is as a function of the $\eta(\mu)$, (top-right) is as a function of $\phi(\mu)$, (bottom-left) is as a function of Z rapidity and $CS\text{-}\cos\theta$, (bottom-right) is as a function of $CS\text{-}\cos\theta$ and $CS\text{-}\phi$.

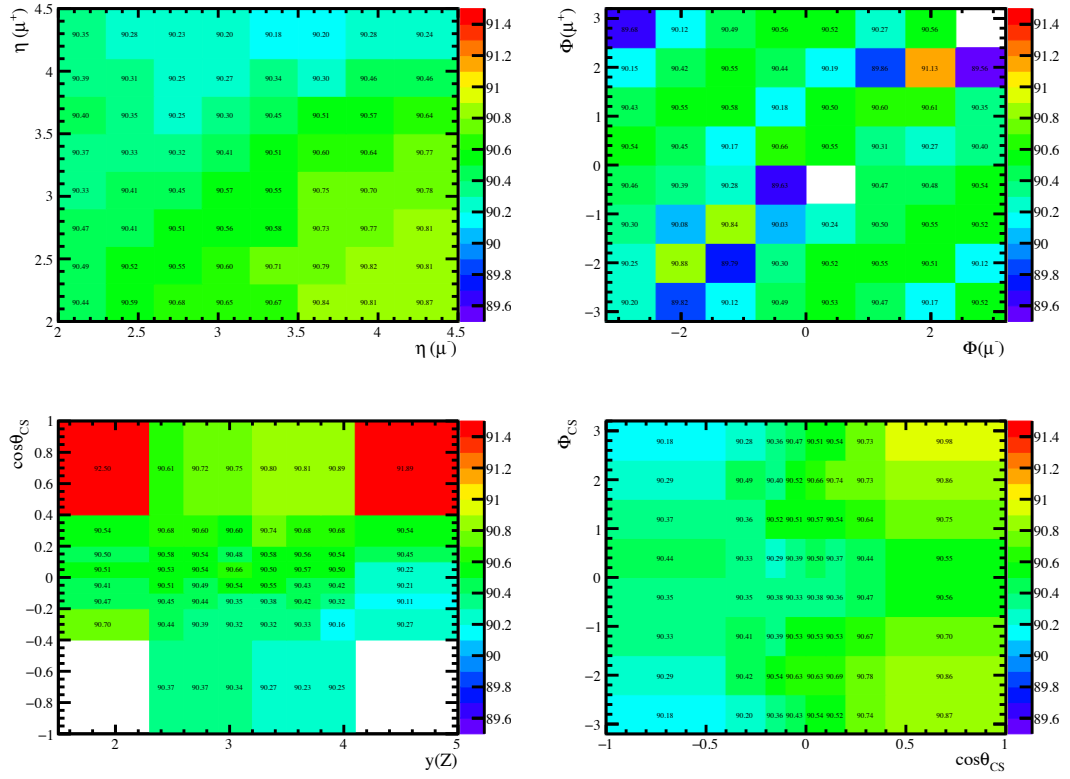


Figure 148: The Z^0 mass peak position dependence of MC MagUp sample. (top-left) is as a function of the $\eta(\mu)$, (top-right) is as a function of $\phi(\mu)$, (bottom-left) is as a function of Z rapidity and $CS\text{-}\cos\theta$, (bottom-right) is as a function of $CS\text{-}\cos\theta$ and $CS\text{-}\phi$.

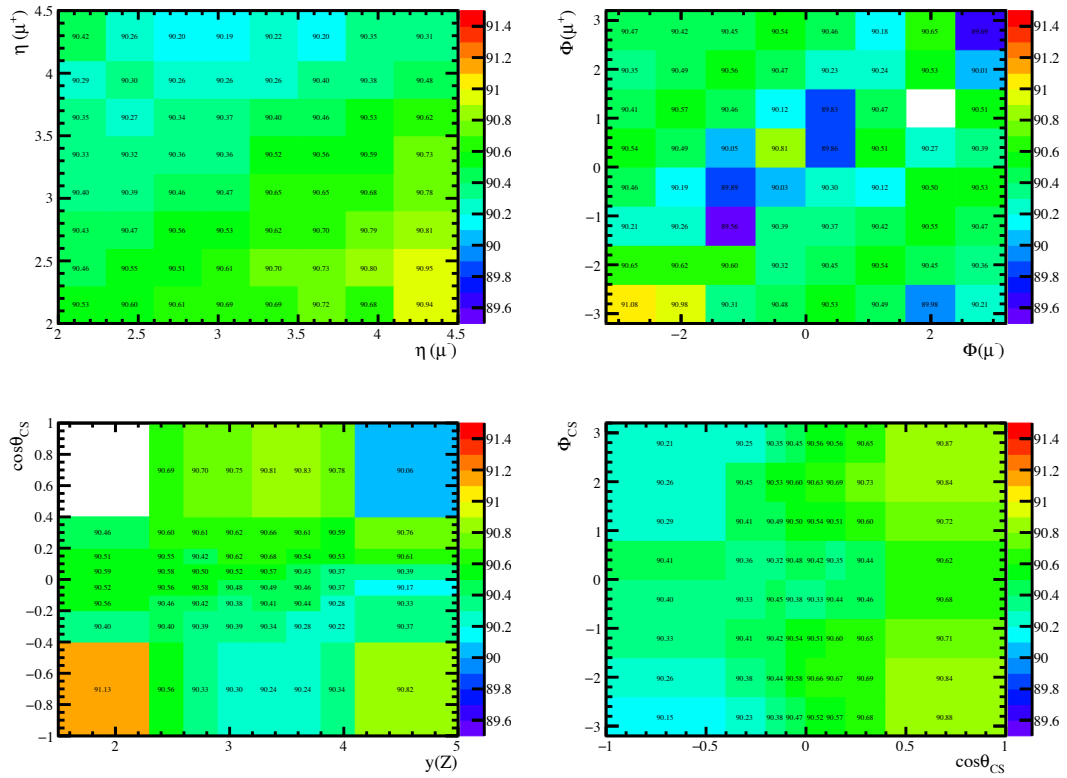


Figure 149: The Z^0 mass peak position dependence of MC MagDown sample. (top-left) is as a function of the $\eta(\mu)$, (top-right) is as a function of $\phi(\mu)$, (bottom-left) is as a function of Z rapidity and $CS\text{-}\cos\theta$, (bottom-right) is as a function of $CS\text{-}\cos\theta$ and $CS\text{-}\phi$.



approach is used to remove all dependencies.

In this iterative procedure, there are three steps calibration are applied to $Z \rightarrow \mu^+\mu^-$ data events. The muon momentum calibration formulas are listed below:

- $\eta(\mu)$ fitting: $(q/p)' = (q/p) + \beta(\eta_i)$
- $\phi(\mu)$ fitting: $(q/p)' = (q/p) + \beta(\eta_i)(\text{fixed}) + \beta(\phi_j)$
- $\eta(\mu)$ fitting: $(q/p)' = (q/p) + \beta(\eta_i) + \beta(\phi_j)(\text{fixed})$

Here, β is the calibration factor, and η_i and ϕ_j are the muon type information. There are two types of parameters to be determined, as $\beta(\eta_i)$ and $\beta(\phi_i)$. In the fitting, the determined parameters will be fixed in the next fitting.

8.4.3 Muon η tuning

For $Z \rightarrow \mu^+\mu^-$ events, there are two muons in each event, and most-likely those two muons are located in different η positions. Thus, there are strong correlations between two $\eta(\mu)$ bins. In order to decouple the Z^0 mass dependence from these $\eta(\mu)$ bins, the entire $Z \rightarrow \mu^+\mu^-$ data sample is divided into 8×8 sub-samples, according to $\eta(\mu^\pm)$ values. The binning scheme (8 bins) for muon η is $\{2.0, 2.3, 2.6, 2.9, 3.2, 3.5, 3.8, 4.1, 4.5\}$, and following observables of each sub-samples are employed in a global fitting, as

- $m(\mu^+\mu^-)$ distribution (Constraint-1): distributions of MagDown and MagUp should be consistent with each other
- $Z \rightarrow \mu^+\mu^-$ mass peak position (Constraint-2): data peak position should be consistent with that of reconstruction level MC, for both MagDown and MagUp samples
- muon p_T distribution (Constraint-3):
 - μ^+ p_T of MagDown sample and μ^+ p_T of MagUp sample should be consistent with each other
 - μ^- p_T of MagDown sample and μ^- p_T of MagUp sample should be consistent with each other
 - μ^+ p_T of MagDown sample and μ^- p_T of MagUp sample should be consistent with each other



The number of constraints used in the fitting, and χ^2 of each distribution before and after fitting are summarized in Table 30. As the same data-set is used for p_T constraints, the statistical uncertainties between the constraint are correlated. To take these correlations into account, the covariance matrix for two p_T distributions are determined and implemented in the χ^2 calculation. With consideration of covariance matrix, the χ^2 from Constraint-3 is changed from 11161 (9410) to 10059 (8232), before (after) ‘Post-alignment’ correction. More discussions on the muon p_T constraint can be found in Appendix D.5.

Table 30: The number of constraints, and comparisons of χ^2 from each histogram before and after fitting, using 2016 data-set.

	Num of constraints	χ^2 (Before fit)	χ^2 (After fit)
Constraint-1	2560	3010	2357
Constraint-2	128	481	155
Constraint-3	9600	10059	8232
Total	12288	13550	10764

To get a better estimation of β , $\beta(\eta_i)$ parameters are studied in a finer binning scheme (10 bins), as $\{2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.5, 3.8, 4.1, 4.5\}$. For each muon η bin, there are four free parameters (μ^+ -MagUp, μ^+ -MagDown, μ^- -MagUp and μ^- -MagDown) need to be determined. Therefore, for the global fitting, there are 40 (10×4) free parameters. In the fitting, muon momentum is modified according Equation 101, and χ^2 values for above observables are calculated and summed together, then the summed χ^2 is minimized by the TMinuit algorithm. The A_{FB} distribution after the first step of ‘Post-alignment’ is shown in Figure 150, where the differences between MagDown and MagUp are highly suppressed. The Z^0 mass peak position of MagDown and MagUp samples in different muon η region are consistent with each other, after this correction, but there are still remaining mass dependence in muon ϕ .

8.4.4 Muon ϕ tuning

Based on the muon η tuning, a similar muon momentum calibration is studied and applied to $Z \rightarrow \mu^+\mu^-$ data to suppress the track bias in muon ϕ direction. The calibration is based on previous step, and $Z \rightarrow \mu^+\mu^-$ sample is divided according to two muons ϕ information. A binning scheme (8 bins) of muon ϕ is used to divide $Z \rightarrow \mu^+\mu^-$ data sample, as $\{-3.2, -2.4, -1.6, -0.8, 0,$

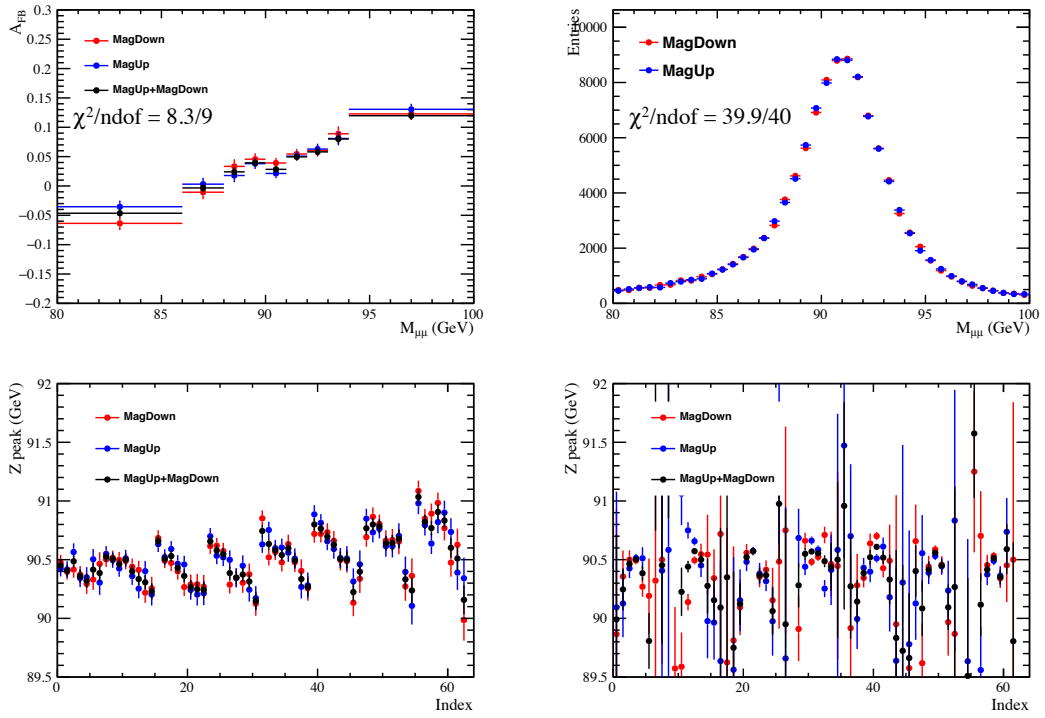


Figure 150: Comparisons between MagDown and MagUp samples, with ‘Improved-alignment’ and first iteration ($\eta(\mu)$) of ‘Post-alignment’ applied. (top-left) is A_{FB} distribution, (top-right) is $m(\mu^+\mu^-)$ distribution, (bottom-left) is the Z^0 mass peak position in different μ^+ and μ^- η regions, (bottom-right) is the Z^0 mass peak position in different μ^+ and μ^- ϕ regions.



0.8, 1.6, 2.4, 3.2}, and $\beta(\phi_j)$ parameters are studied in a finer binning scheme (10 bins), as $\{-3.2, -2.4, -1.8, -1.2, -0.6, 0.0, 0.6, 1.2, 1.8, 2.4, 3.2\}$. Same observables are employed to minimize the χ^2 value, to determine β parameters.

8.4.5 ‘Post-alignment’ results

After ‘Improved-alignment’ and ‘Post-alignment’ correction applied on the muon momentum, the track bias effects are suppressed, and a better μ energy modeling is achieved. The results are shown in Figure 151, where the differences between MagDown A_{FB} and MagUp A_{FB} is suppressed, the A_{FB} distributions are consistent with each other within statistical uncertainty. The Z^0 mass peak position dependences between MagDown and MagUp are also consistent with each other. The invariant mass distributions of Z^0 boson from MagDown and MagUp samples have good agreements.

8.5 MC muon momentum corrections

The LHCb MC events do not expect to have any mis-alignment effects. Therefore, the ‘Improved-alignment’ is not necessary, only ‘Post-alignment’ is applied to the MC events. Also in the MC events, Z^0 peak position does not have ϕ dependence, so only one step muon momentum calibration (muon η) is applied to MC events. The comparison between MagDown A_{FB} and MagUp A_{FB} is shown in Figure. 152. As expected, there is no differences between them. For the MC events, the mass resolution is different from that of data, due to imperfect modeling of the detector in MC sample, as shown in left figure of Figure 153. Additional muon momentum smearing is applied to MC $Z \rightarrow \mu^+\mu^-$ events, to achieve good agreement between invariant mass distribution of MC and that of data. The additional smearing corrections is performed using a formula as:

$$p' = p \times (1 + \gamma \times \text{Gauss}(0, 1)), \quad (102)$$

where γ is the smearing factor. The smearing parameters are tuned by comparing data and MC invariant mass distributions, and smearing factors with muon η dependence is considered. After the smearing correction, the $Z \rightarrow \mu^+\mu^-$ invariant mass resolution of data $Z \rightarrow \mu^+\mu^-$ events has good agreement with that of MC events, as shown in right figure of Figure 153.

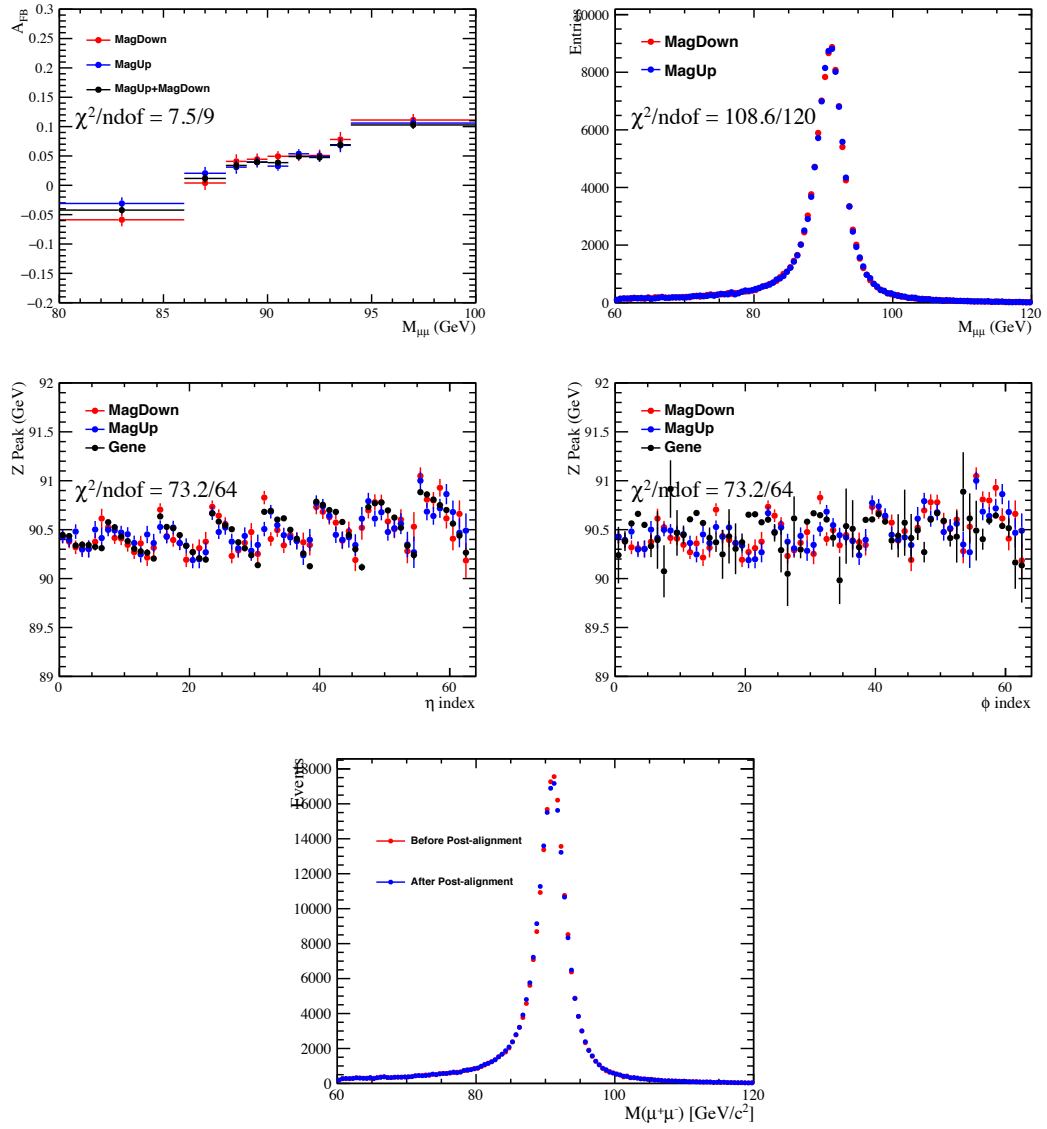


Figure 151: The comparisons between MagDown and MagUp samples, with ‘Improved-alignment’ and ‘Post-alignment’ applied. (top-left) is A_{FB} distribution, (top-right) is $m(\mu^+\mu^-)$ distribution, (middle-left) is the Z^0 mass peak position in different μ^+ and μ^- η regions, (middle-right) is the Z^0 mass peak position in different μ^+ and μ^- ϕ regions, (bottom) is the Z^0 mass distribution.

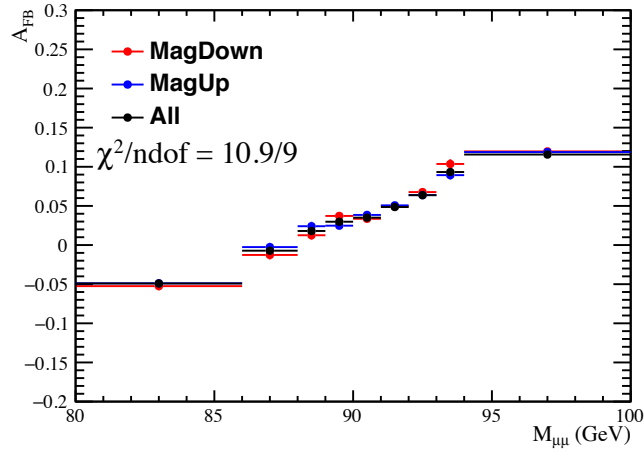


Figure 152: The comparison for A_{FB} distribution of MagDown and MagUp, using the $Z \rightarrow \mu^+\mu^-$ MC sample after ‘Post-alignment’ correction.

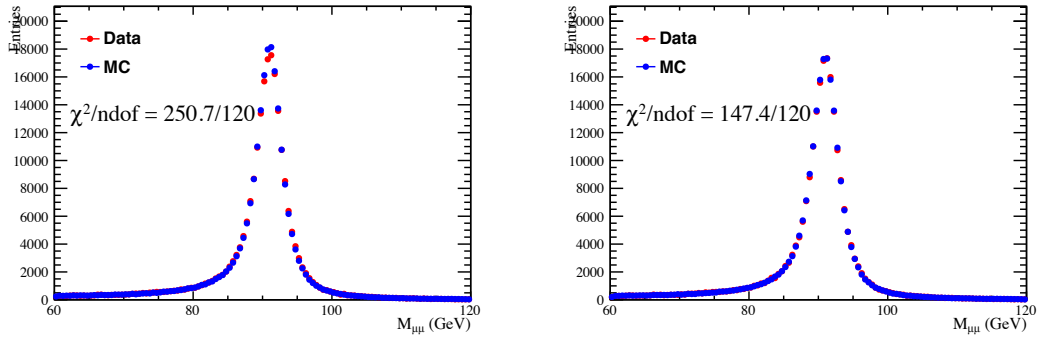


Figure 153: The comparison of the $\mu\mu$ invariant mass distribution between data and MC sample after MC track bias correction

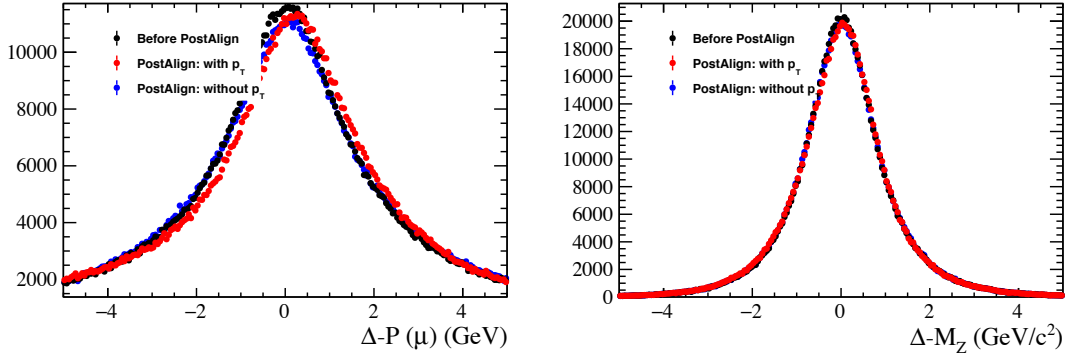


Figure 154: Comparison of the resolution of muon momentum (left) and Z boson mass (right) in MC sample, with and without ‘post-alignment’ corrections applied. Black points represent results of MC signal events without any ‘post-alignment’, red points represent results with ‘post-alignment’ corrections with muon p_T constraint, while blue points represent results with ‘post-alignment’ corrections without muon p_T constraint.

8.6 MC muon momentum resolution check

We checked the difference of the muon momentum and mass resolution in MC sample between with and without these two steps alignment corrections. The result is shown in Figure 154. In the figure, the $P_{\text{Rec}} - P_{\text{True}}$ distributions of μp_T and Z boson mass are shown. After the ‘Post-alignment’, we do see a little worse resolution in MC events, which could be caused by no track refitting is done after the second step correction.

8.7 Systematic uncertainty

To make a cross check, the Magdown and Magup data samples are divided into two independent sub-samples with same statistics. Then, there are four sub-samples, as MagUp sub-sample A (UA), MagUp sub-sample B (UB), MagDown sub-sample A (DA), and MagDown sub-sample B (DB), respectively. The ‘Improved-alignment’ are studied using these sub-samples, as A (UA + DA) and B (UB + DB) sub-samples. Then parameters estimated with A samples are applied to B samples, also for the reversed case. The physics observable (A_{FB}) is checked in both A and B sub-samples after ‘Improved-alignment’. As shown in Figure 155, reasonable agreements between results from these two independent samples are seen, within the statistical uncertainties. We are not planning to take the differences of results obtained from these two samples as a systematic uncertainty, as these differences are dominated by the statistics uncertainty.

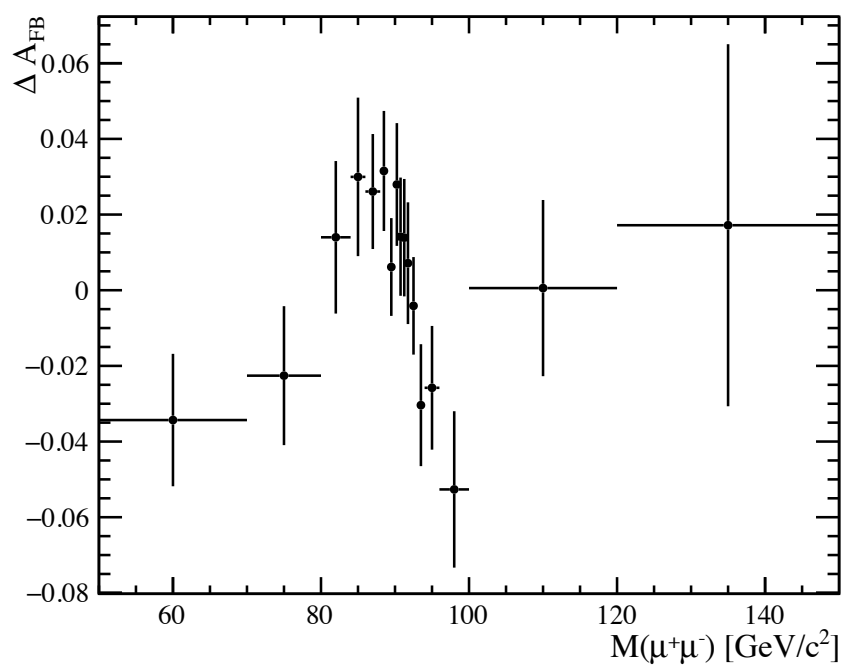


Figure 155: Comparison of the A_{FB} difference distribution between sample A and sample B , with ‘Improved-alignment’ correction applied.



To estimate related systematic uncertainty from this correction, the variations of the MC Z peak position dependencies is considered. In the variation of the MC Z peak position dependencies, the central values of the dependencies are varied within the statistics of the ResBos predictions, and larger deviations of muon momentum calibration are taken as systematic uncertainties. The results of this uncertainty on the A_{FB} measurement as the Figure 156 shows.

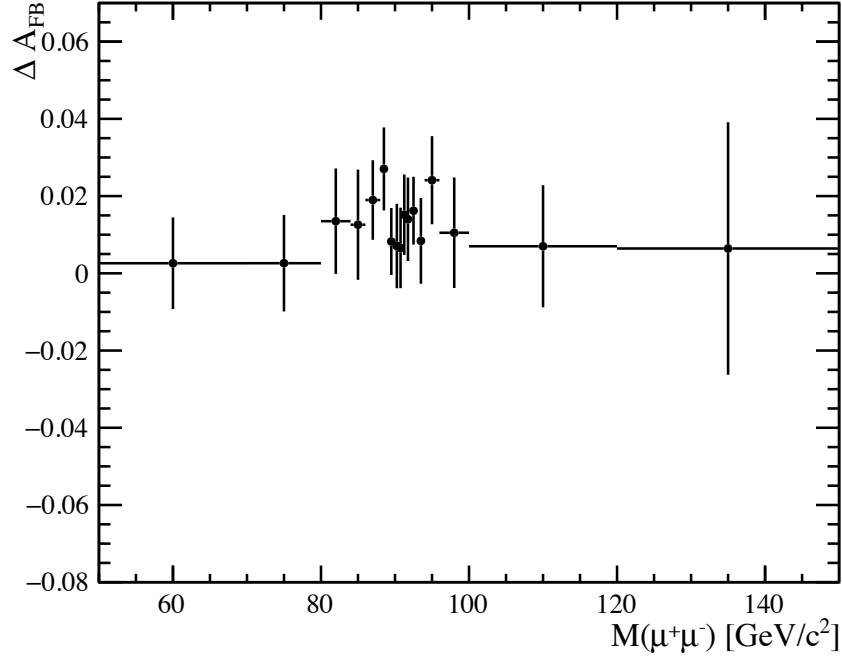


Figure 156: Systematic uncertainties on A_{FB} distribution from the variations of the MC Z peak position dependencies.

8.8 Conclusions

For the LHCb Run-2 data, we applied both ‘Improved-alignment’ and ‘Post-alignment’ to removed detector level mis-alignment effects, resulting a better agreement between MagDown A_{FB} and MagUp A_{FB} , and the Z^0 mass peak position dependence is suppressed. For the $Z \rightarrow \mu^+\mu^-$ simulation events, an additional smearing correction is applied to the muon momentum. A test only with ‘Post-alignment’ applied is studied in Appendix D.3, which shows both ‘Improved-alignment’ and ‘Post-alignment’ are necessary for the muon momentum calibration. Tests of different parameter strategies are shown in Appendix D.4.



For the coming RunIII LHCb data taking, we are planning to merge the ‘Improved-alignment’ and ‘Post-alignment’ into one step correction, which will make the future muon momentum calibration becomes faster and reliable.



攻读博士学位期间完成的工作

- LHCb Collaboration,

First observation of the Doubly Charmed Baryon Decay $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$,

*PHYS. REV. LETT. **43** 121 162002 (2018) [arXiv:1807.01919]*

- LHCb collaboration,

Measurement of the angular coefficients of $\mu^+ \mu^-$ pairs in the Z boson mass region at LHCb

LHCb-ANA-2020-075

- LHCb collaboration,

Improved-alignment and momentum calibration for physics with high momentum muons in

LHCb LHCb-INT-2020-030

- LHCb collaboration,

Measurements of high- p_T muon reconstruction efficiency for the LHCb RunII data-sets

LHCb-INT-2020-031



Appendices

A Appendix-Search for the doubly charmed baryon Ξ_{cc}^{++} with the $\Xi_c^+\pi^+$ decay

A.1 Input Ξ_{cc}^{++} mass in MC

The MC events used in this analysis are generated with $M(\Xi_{cc}^{++}) = 3597.98 \text{ MeV}/c^2$, and the measured value is $M(\Xi_{cc}^{++}) = 3621.40 \text{ MeV}/c^2$, using $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ decay. The difference between input Ξ_{cc}^{++} mass could resulting a potential bias in the efficiency measurement. In this section, we studied the MC p_T distributions of Ξ_{cc}^{++} , Ξ_c^+ , and p, K, π final-state particles, generated with different input Ξ_{cc}^{++} mass hypotheses within LHCb acceptance. The comparisons of p_T distributions with different input mass of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel are shown in Figure 157, and p_T comparisons of $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel are shown in Figure 158. The p_T and y ratio of $M(\Xi_{cc}^{++}) = 3597.98 \text{ MeV}/c^2$ to $M(\Xi_{cc}^{++}) = 3621.40 \text{ MeV}/c^2$ for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ decay channels are shown in Figure 159.

Furthermore, we checked the p_T cut efficiencies on these MC samples. With p_T cuts described in Section ??, the efficiency changed from 47.28% to 47.13% for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ channel, and from 71.87% to 70.73% for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel. The p_T cut efficiency ratio of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ to that of $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ is changes from 0.658 to 0.666. The deviation of ratios ($\sim 1.2\%$) is used as systematic uncertainty.

A.2 PID efficiency

The PID efficiencies (including DLL and ProbNNx) of hadrons are estimated using PID-Calib package, the measured efficiencies as a function of P and η are shown in Figure 160. In Figure 160, as a tighter selection had been applied on the pion from Ξ_{cc}^{++} , the PID efficiency is smaller than that of pion from Ξ_c^+ . Also, for the hadrons with $P > 100 \text{ GeV}/c$, the PID efficiencies is much smaller compared to that in the low P region, special for the kaon. In this analysis, only 10% signal MC event has at least one hadrons with $P > 100 \text{ GeV}/c$. With proper systematic uncertainty assigned in the high P hadrons, the impacts from high P region inefficiency can be ignored. The P and η distribution of Ξ_{cc}^{++} daughter particles (p, K, π) are shown in Figure 161.

The MC Ξ_{cc}^{++} mass with direct PID cut and PID reweight are compared in Figure 162. There

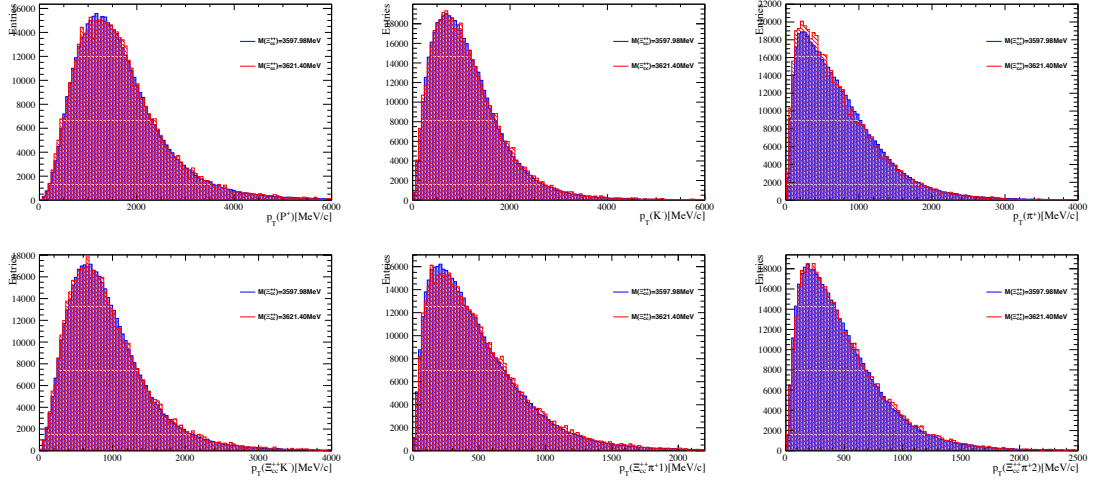


Figure 157: The MC p_T comparisons between $M(\Xi_{cc}^{++}) = 3597.98 \text{ MeV}/c^2$ and $M(\Xi_{cc}^{++}) = 3621.40 \text{ MeV}/c^2$, for $\Lambda_c^+ - p$ (top-left), $\Lambda_c^+ - K$ (top-middle), $\Lambda_c^+ - \pi$ (top-right), $\Xi_{cc}^{++} - K$ (bottom-left), $\Xi_{cc}^{++} - \pi 1$ (bottom-middle), $\Xi_{cc}^{++} - \pi 2$ (bottom-right).

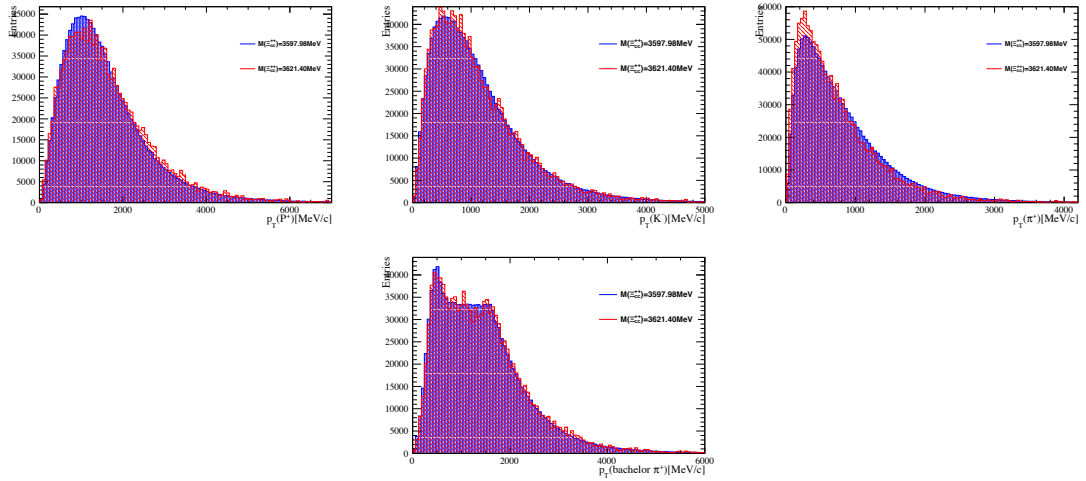


Figure 158: The MC p_T comparisons between $M(\Xi_{cc}^{++}) = 3597.98 \text{ MeV}/c^2$ and $M(\Xi_{cc}^{++}) = 3621.40 \text{ MeV}/c^2$, for $\Xi_c^+ - p$ (top-left), $\Xi_c^+ - K$ (top-middle), $\Xi_c^+ - \pi$ (top-right), $\Xi_{cc}^{++} - \pi$ (bottom).

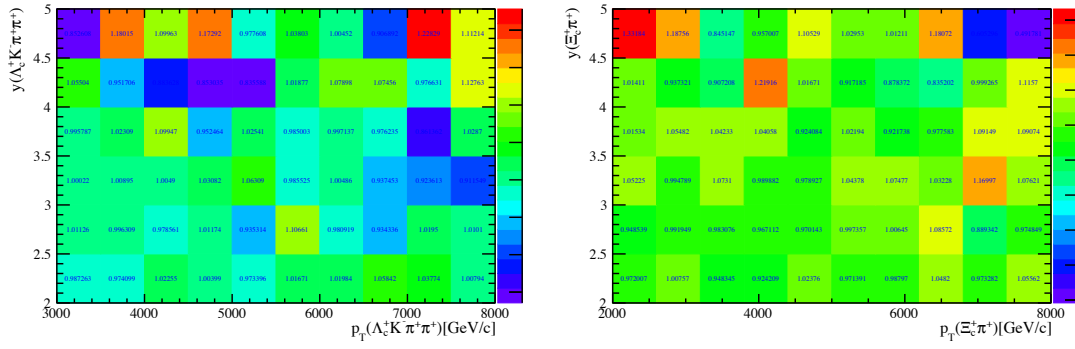


Figure 159: The ratio of p_T and y distribution of $M(\Xi_{cc}^{++}) = 3597.98 \text{ MeV}/c^2$ to $M(\Xi_{cc}^{++}) = 3621.40 \text{ MeV}/c^2$, for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ (left) and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ (right).

are large differences between these procedure, which means we need apply the PID reweight in the MC for this study.

A.3 MVA input variables tests

In this analysis, 19 input variables are used in the MVA training, which could have over-training effects, as some of input variables are calculated with same event information. The signal and background comparisons of 19 input variables are shown in Figure 163 and 164. The input variables ranking with its importance are shown in Table 31. For example, ‘ $\sqrt{\sum \chi_{\text{IP}}^2}$ among the daughters’ is calculated by summing over the daughters χ_{IP}^2 , which is highly correlated with ‘ $\sqrt{\chi_{\text{IP}}^2}$ of Ξ_c^+ daughters’.

In order to check the correlation effects between input variables, we performed three tests, as removing the input variables $> 70\%$ correlated with other variables, $> 80\%$ correlated with other variables, and $> 90\%$ correlated with other variables. The comparisons of trained MVA ROC for these three tests compared with default one is shown in Figure 165, where the default one has best performance. The Punzi FoM distribution are also checked, again, the default one with 19 input variables gives us the best performance. As discussed in Sec. 5.2.4, there are no over-training with 19 input variables, among four different MVA methods. So, the MVA with 19 input variables is used as default one in this analysis.

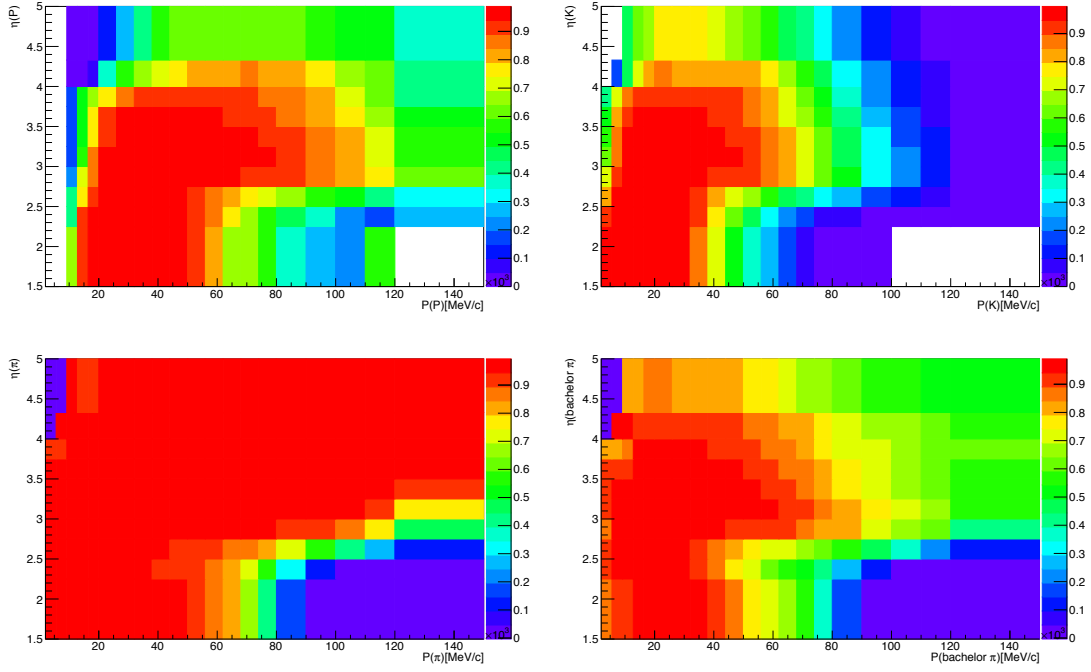


Figure 160: The measured PID efficiency for proton (top-left), kaon (top-bottom), pion from Ξ_c^+ (bottom-left), and pion from Ξ_{cc}^{++} (bottom-right).

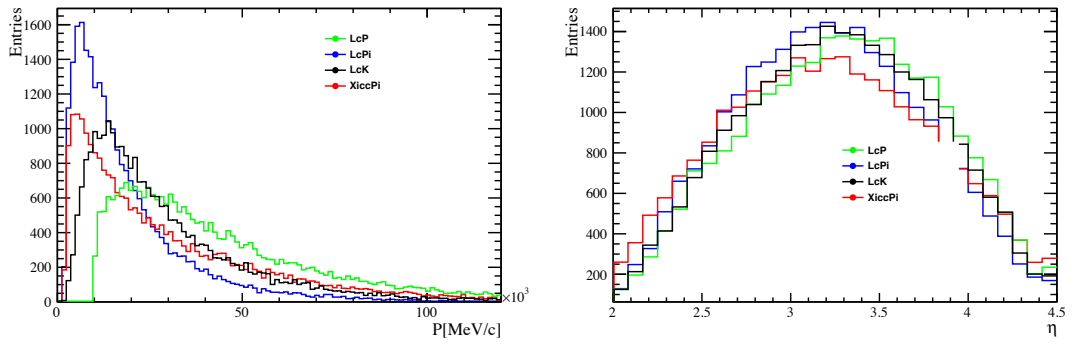


Figure 161: The P and η distribution of Ξ_{cc}^{++} daughter particles in signal MC events, after all the event selection.

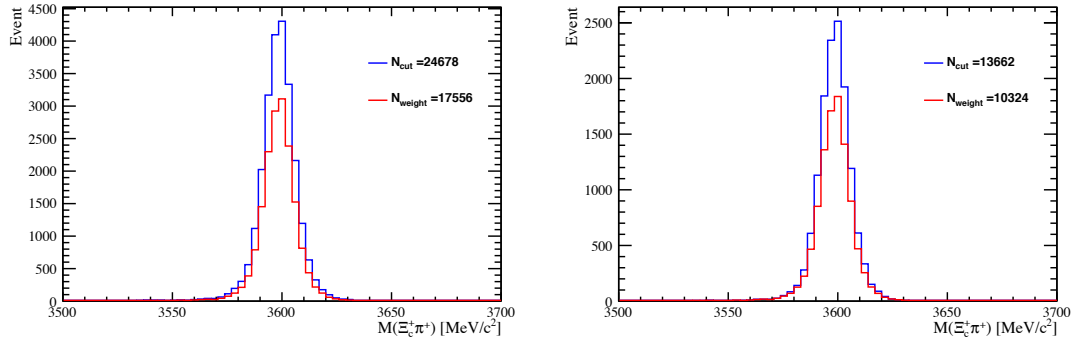


Figure 162: The comparisons of MC E_{cc}^{++} mass distribution with direct PID cut (blue), and PID reweight (red). (left) is the distributions with $\text{ProbNNp} > 0.1$, (right) is the distributions with $\text{ProbNNp} > 0.8$.

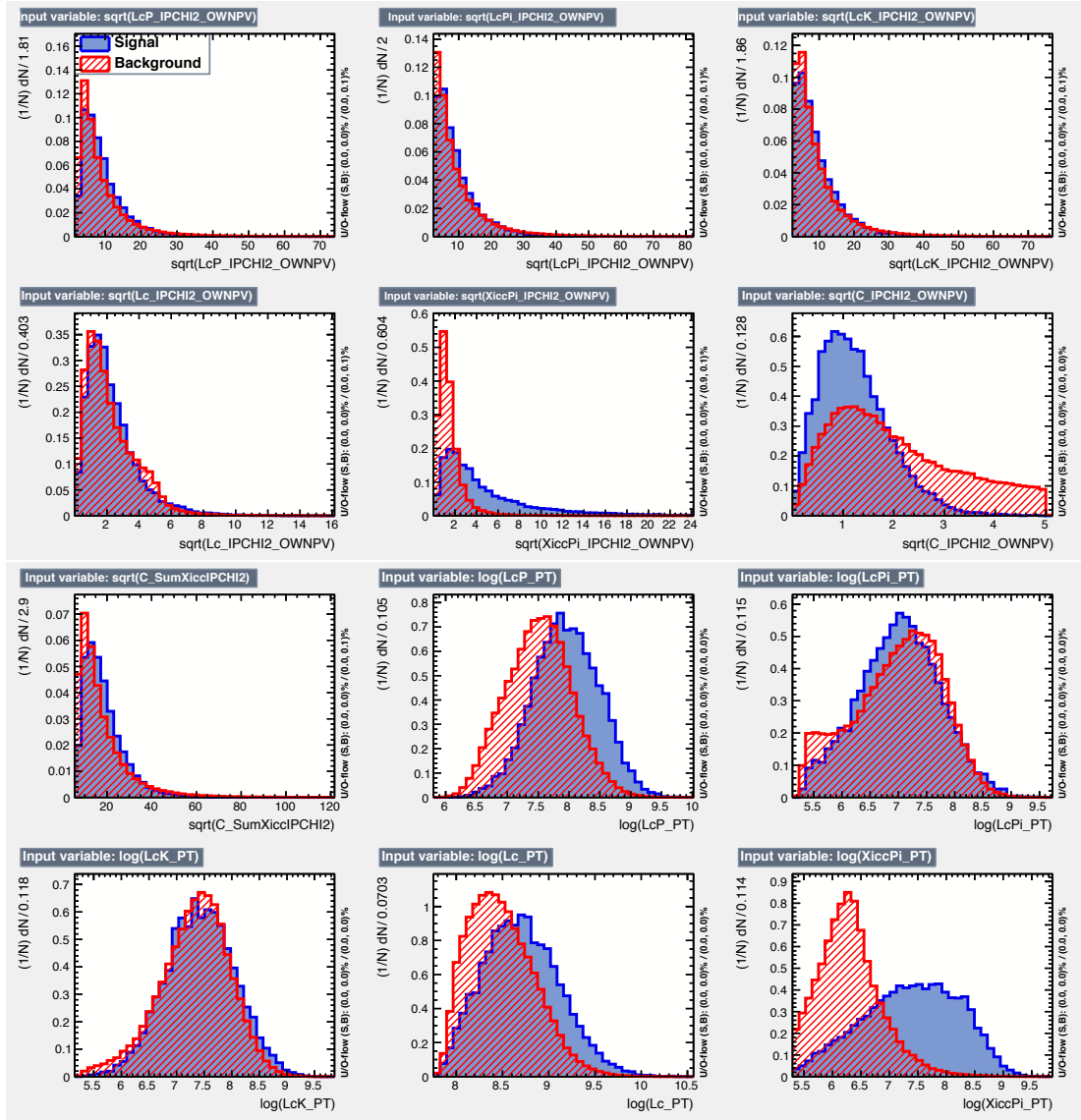


Figure 163: Comparisons of MVA input variables between signal and background events.

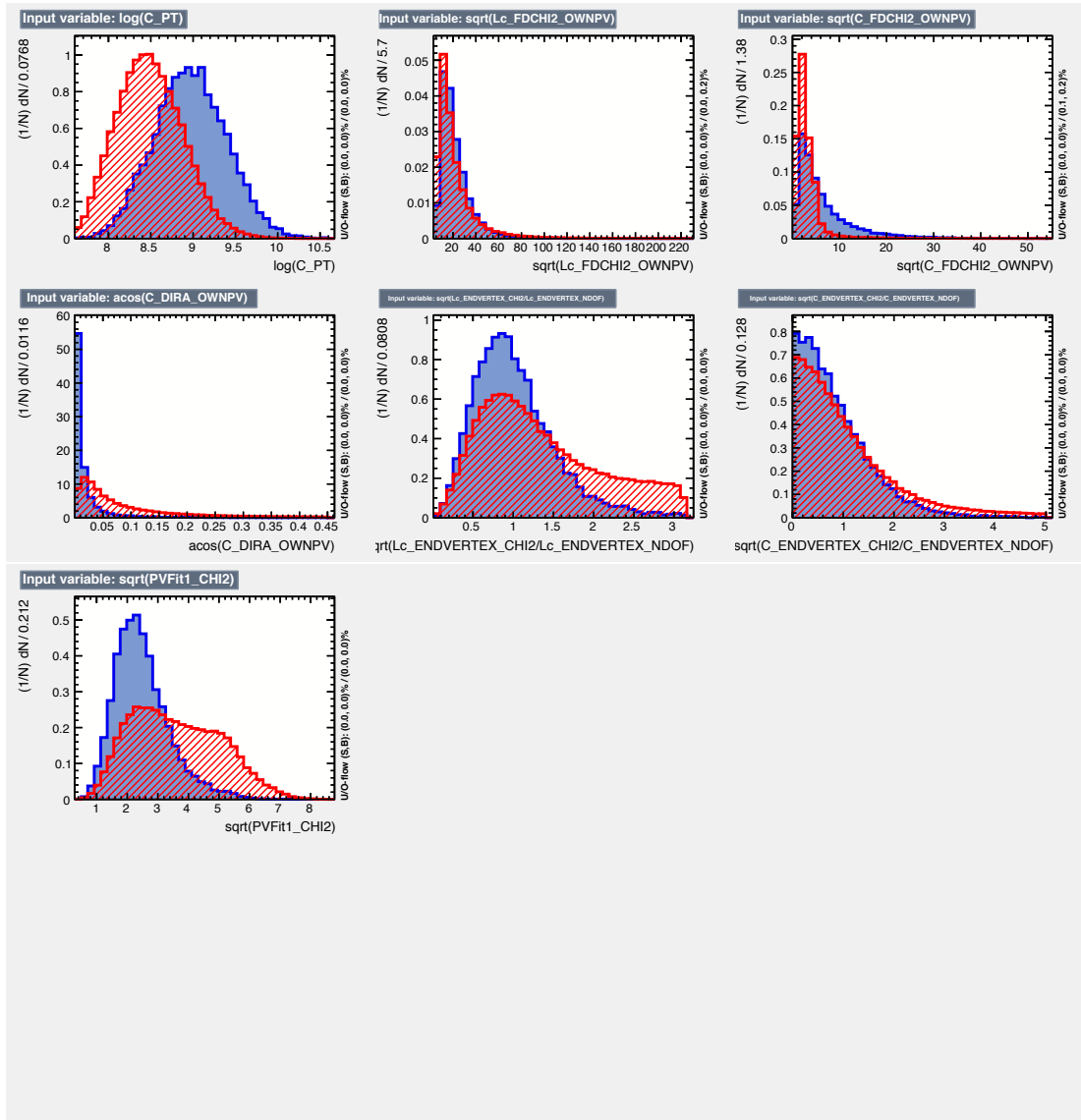


Figure 164: Comparisons of MVA input variables between signal and background events.

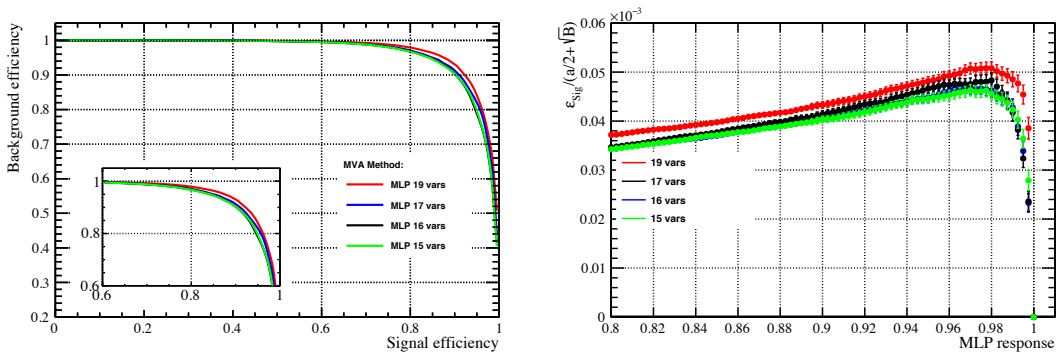


Figure 165: The ROC and FoM distributions with different input variables, the evaluation tests are performed with WS sample.



Table 31: The ranking and importance of 19 variables used in the MLP training.

Rank	Variable	Importance
1	$\sqrt{\chi_{\text{IP}}^2}$ of Ξ_{cc}^{++} daughter π to its PV	1.342×10^3
2	$\sqrt{\chi_{\text{FD}}^2}$ of Ξ_{cc}^{++} from its PV	1.659×10^2
3	$\sqrt{\chi_{\text{IP}}^2}$ of Ξ_c^+ to its PV	1.236×10^2
4	$\cos^{-1}(\text{DIRA})$ of Ξ_{cc}^{++} to its PV	9.786×10^1
5	$\sqrt{\chi_{\text{FD}}^2}$ of Ξ_c from its PV	9.043×10^1
6	$\sqrt{\chi_{\text{IP}}^2}$ of Ξ_c^+ daughters (p) to its PV	8.511×10^1
7	$\sqrt{\chi_{\text{IP}}^2}$ of Ξ_c^+ daughters (π) to its PV	5.726×10^1
8	$\sqrt{\chi_{\text{IP}}^2}$ of Ξ_c^+ daughters (K) to its PV	4.419×10^1
9	$\log(p_T)$ of Ξ_c^+	4.411×10^1
10	$\sqrt{\sum \chi_{\text{IP}}^2}$ among the daughters ($p, K, \pi, \Xi_{cc}^{++} - \pi$) of Ξ_{cc}^{++}	4.275×10^1
11	$\log(p_T)$ of Ξ_{cc}^{++}	2.257×10^1
12	χ^2 of the Ξ_{cc}^{++} vertex fit (DTF, with PV constraint)	1.366×10^1
13	$\log(p_T)$ of Ξ_{cc}^{++} daughter π	1.032×10^1
14	$\chi_{\text{vtx}}^2/\text{ndf}$ of the Ξ_c^+ vertex fit	7.438×10^0
15	$\chi_{\text{vtx}}^2/\text{ndf}$ of the Ξ_{cc}^{++} vertex fit (non-DTF)	6.362×10^0
16	$\sqrt{\chi_{\text{IP}}^2}$ of Ξ_{cc}^{++} to its PV	5.352×10^0
17	$\log(p_T)$ of Ξ_c^+ daughters (p)	3.955×10^0
18	$\log(p_T)$ of Ξ_c^+ daughters (π)	1.573×10^0
19	$\log(p_T)$ of Ξ_c^+ daughters (K)	1.287×10^0



A.4 Particle mis-ID background of Ξ_c^+ and Ξ_{cc}^{++} WS events

With looser PID cuts ($\text{ProbNNx} > 0.1$), there are significant contributions from the particle mis-ID background, which can be estimated by changing the mass hypothesis of final-state hadrons. The candidates used in this section are selected using selection cuts described in Sec. 6.2.3, including the Ξ_c^+ mass window. For the Ξ_c^+ , as there are three final-state hadrons in each candidates, we have 9 different hypothesis distribution, as shown in Figure 166. From the figure, there are two significant peaks (D^+ , D_s^+) in the $M(K\pi\pi)$ and $M(KK\pi)$ hypotheses, which means with looser PID cuts, there will be significant contributions from D mesons. The D meson background are selected with a K or π faked into p , therefore, a tighter PID cut would expected to remove most of these physics backgrounds.

With tighter PID cuts ($\text{ProbNNp} > 0.8$), the mass distribution of $M(K\pi\pi)$ and $M(KK\pi)$ hypotheses are shown in Figure 167, and the contributions from D mesons had been highly suppressed by the tighter proton PID cut.

For the Ξ_{cc}^{++} WS data sample, we also checked the physics background contributions from D meson. With zero charge in the $pK\pi\pi$ system, the background contribution could from neutron D mesons. In Figure 168, the $K\pi\pi\pi$ and $KK\pi\pi$ mass hypotheses are tested, where after applying tighter proton PID cut, the contribution from D meson becomes much smaller. Considering there are potential backgrounds contamination in the WS sample, we decided not use WS sample as default input in the MVA study. In the RS sideband regions, with two charges in the $pK\pi\pi$ system, the physics background contributions are expected to be negligible, as shown in Figure 169.

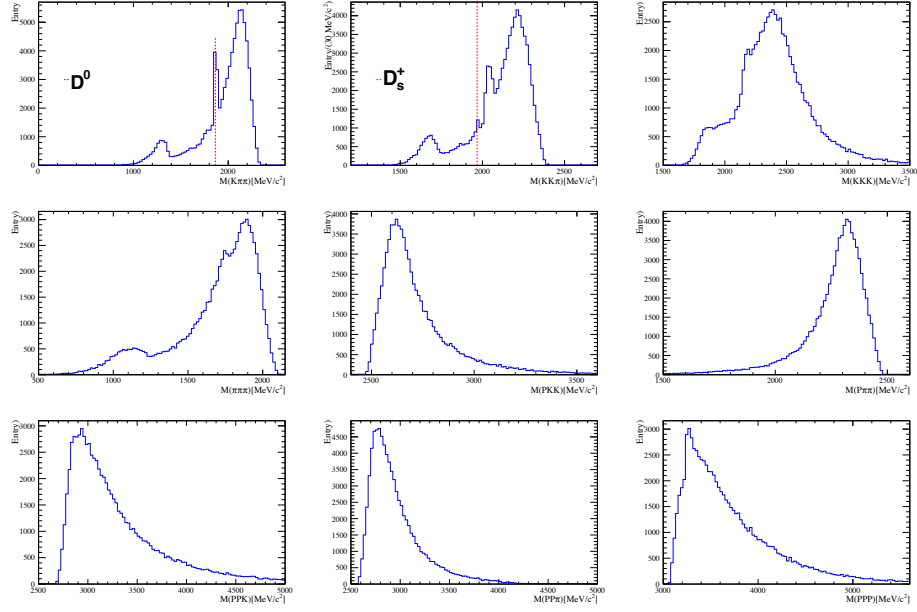


Figure 166: The different mass hypotheses for Ξ_c^+ final-state particles.

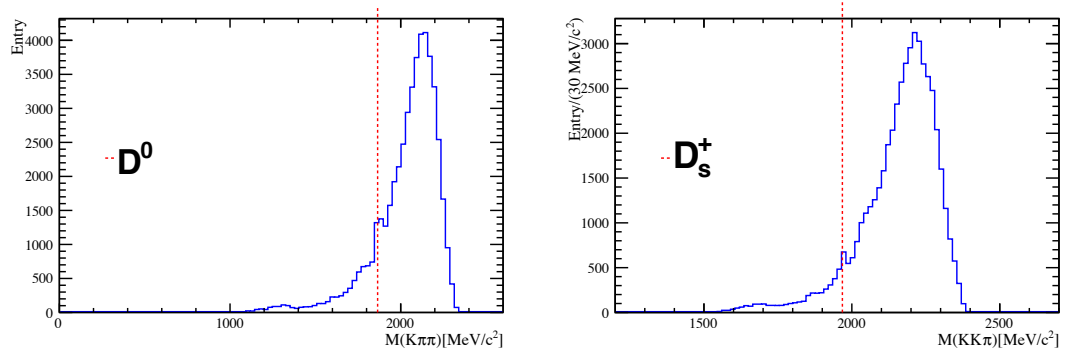


Figure 167: The different mass hypotheses for Ξ_c^+ final-state particles, with tighter proton PID cut applied.

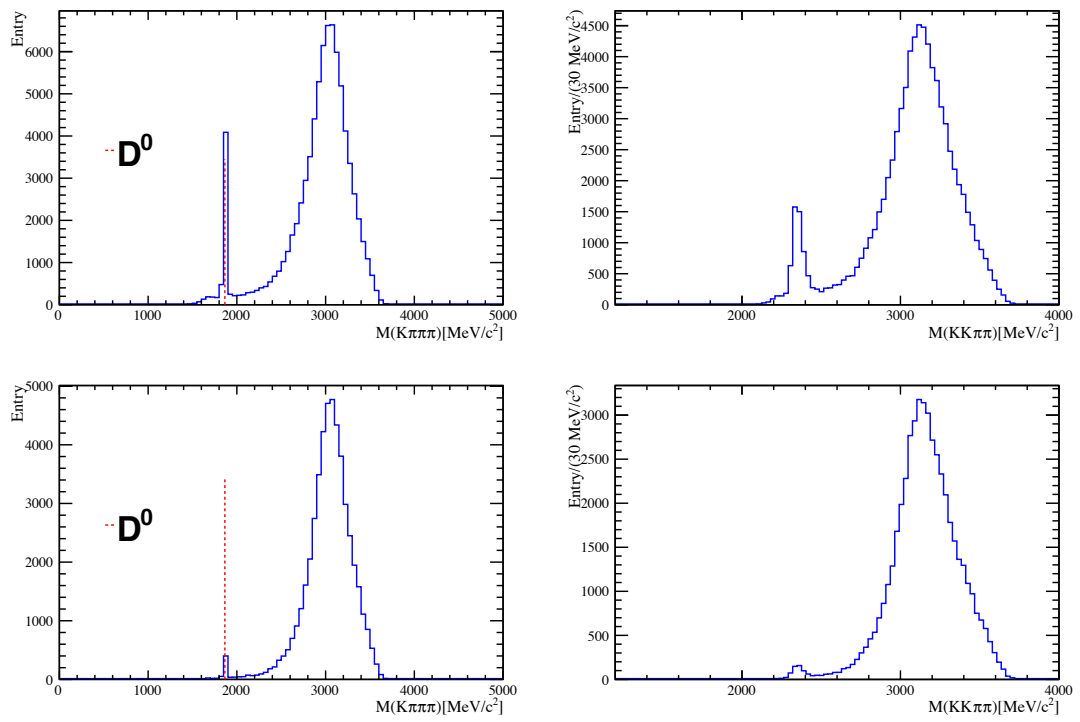


Figure 168: The $K\pi\pi\pi$ (left) and $KK\pi\pi$ (right) mass hypotheses for Ξ_{cc}^{++} WS events, without (top) and without (bottom) tighter proton PID cut applied.

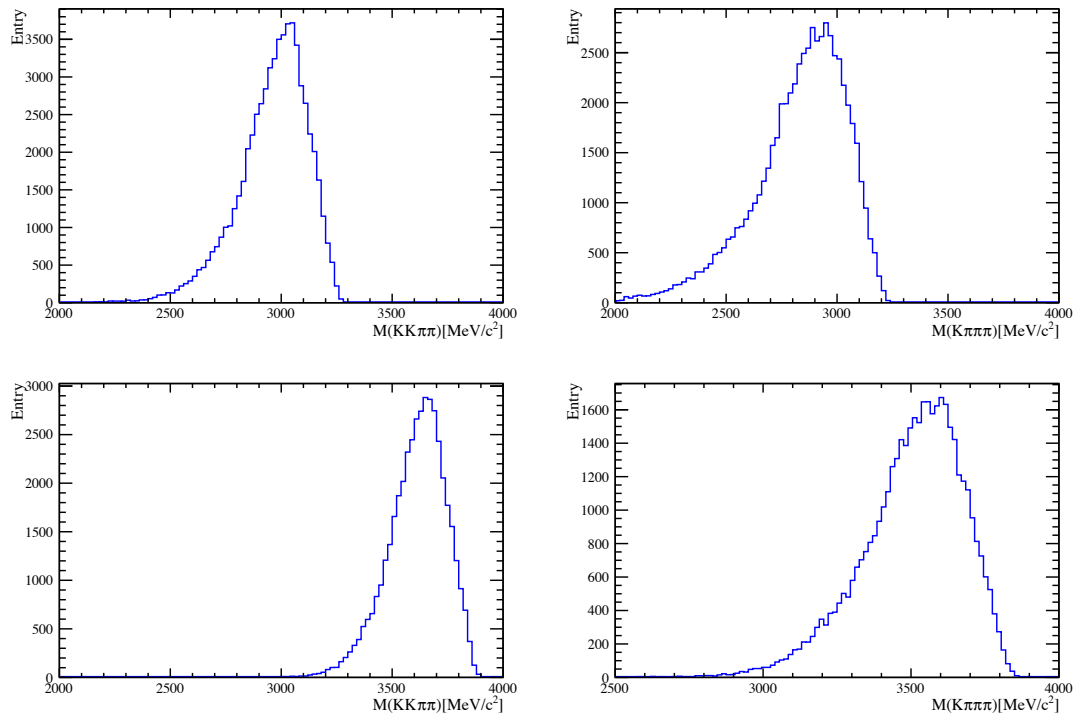


Figure 169: The $K\pi\pi\pi$ (left) and $KK\pi\pi$ (right) mass hypotheses for Ξ_{cc}^{++} RS events, for lower sideband (top) and higher sideband (bottom) events.

A.5 Background types for MVA training

For the input background events in MVA training, we tested the MVA performance with three types of backgrounds, as WS, RS (Upper sideband), and RS (Lower and Upper sideband). In the test, same signal MC events and 19 input variables are used as default, only change the background input, and then evaluated all of them with the WS background sample. For the far upper sideband, the background events are required in the mass region from 3800 to 4000 MeV/c^2 , and the lower sideband, the background events are required in 3200 to 3400 MeV/c^2 .

In this analysis, the default input background are RS (Upper sideband) events, the MVA performance of that sample is shown in Sec. 5.2.4. And the MVA performance of using RS (Lower and Upper sideband) and WS events as background is shown in Figure 170. Unlike the MLP selector has best performance in the MVA training with RS (Upper sideband), the BDTG selector has best performance for RS (Lower and Upper sideband) training. Therefore, ROC comparison and Punzi FoM comparison between RS (Lower and Upper sideband) and RS (Upper sideband) are shown in Figure 171, using MVA selector with best performance. As shown in the figure, the MVA trained using RS (Upper sideband) events has better performance than that of using RS (Lower and Upper sideband) events.

Then, the MVA performance of RS (Upper sideband) is compared to that of WS sample. The Punzi FoM comparison between WS and RS (Upper sideband) are shown in Figure 172. The RS (Upper sideband) has better performance than that of WS events, therefore, we use RS (Upper sideband) sample as MVA training input background.

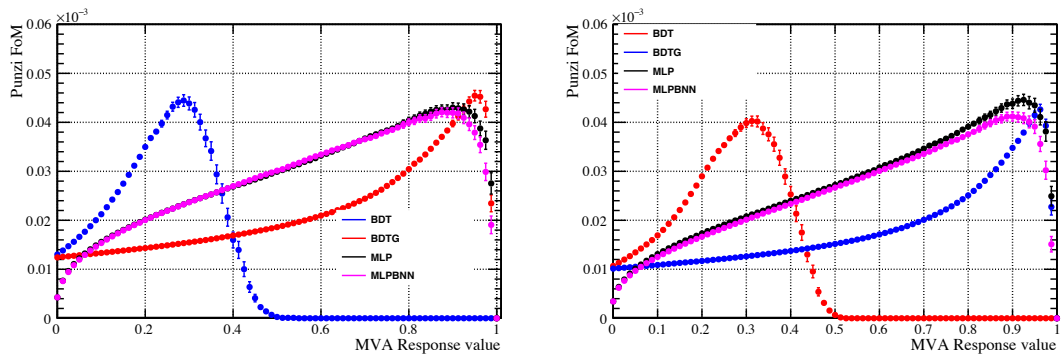


Figure 170: The MVA punzi FoM distribution for different MVA selectors, using (left) RS (Lower and Upper sideband) and (right) WS events as background.

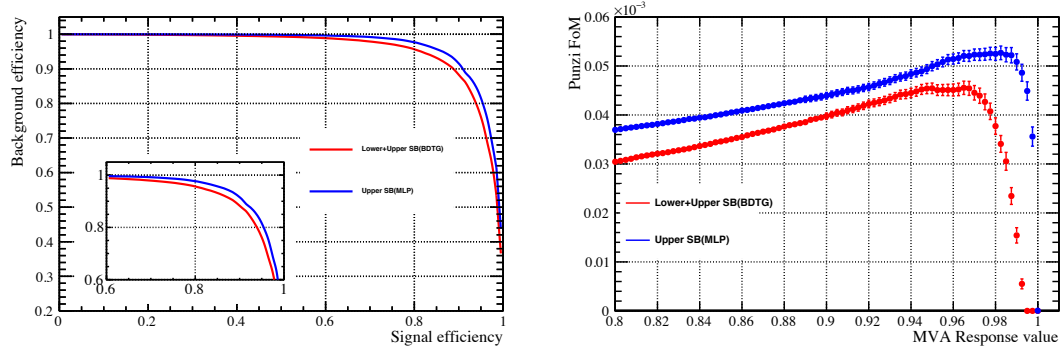


Figure 171: The ROC (left) and punzi FoM (right) comparisons between MVA with RS (Lower and Higher sideband) and RS (Upper sideband) events.

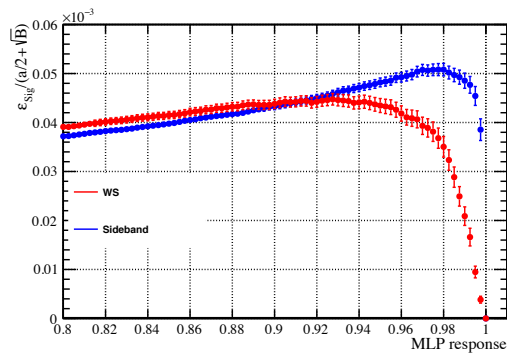


Figure 172: The punzi FoM (right) comparisons between MVA with WS and RS (Upper sideband) events.



A.6 Two-step MVA test

In this analysis, Ξ_{cc}^{++} decays into Ξ_c^+ and a pion, then Ξ_c^+ decays into $pK\pi$. Based on the decay topology, there will be two background sources, as a real Ξ_c^+ randomly combined with a pion, or a faked Ξ_c^+ randomly combined with a pion. To suppress the background contribution, it would be good to reject the second type of background as much as possible. By using the Ξ_c^+ information in the MVA training is a good choice, which is the default solution for this search, but there is another way to do that, which is two-step MVA method.

In the two-step MVA method, the variables from Ξ_c^+ are used to training a MVA at first, which is expected to have a better rejection for Ξ_c^+ background. Then, the calculated MVA variable is used in the second MVA training, combined with other variables related to Ξ_{cc}^{++} decay.

In the one-step and two-step MVA training, the MLP method is used. Then the trained MVAs are optimized with FoM method, The MVA performances of one-step and two-step MVA as a function of cut are shown in Figure 173, where similar performance has been found from both MVA methods, and based on the maximum value of FoM, the one-step MVA has slightly better performance, therefore, we use one-step MVA as default one.

The WS sample is used to evaluate the performances of different MVA. The Ξ_c^+ mass distribution after MVA cuts are shown in Figure 174, where one-step and two-step MVA get similar Ξ_c^+ mass distribution. There is no signal significance improvements by using two-step MVA method.

A.7 Signal MVA efficiency check

The Punzi FoM method is used to optimize the MVA selection, where the MC efficiency is estimated using all of signal events. This could resulting a potential bias of signal efficiency.

In order to study this effect, we calculated the FoM by using half of signal events (Test-Tree in the MVA training), and compared the FoM distribution calculated using all of signal events. For the Punzi FoM calculation of each MVA cut value, with same background events used in the calculation, contribution from background will not be changed, while the measured signal efficiency may vary in different signal samples. As shown in Figure 175, there is a good agreement between these two FoM distributions, in all MVA region, which means there is no over-estimation of the signal efficiency.

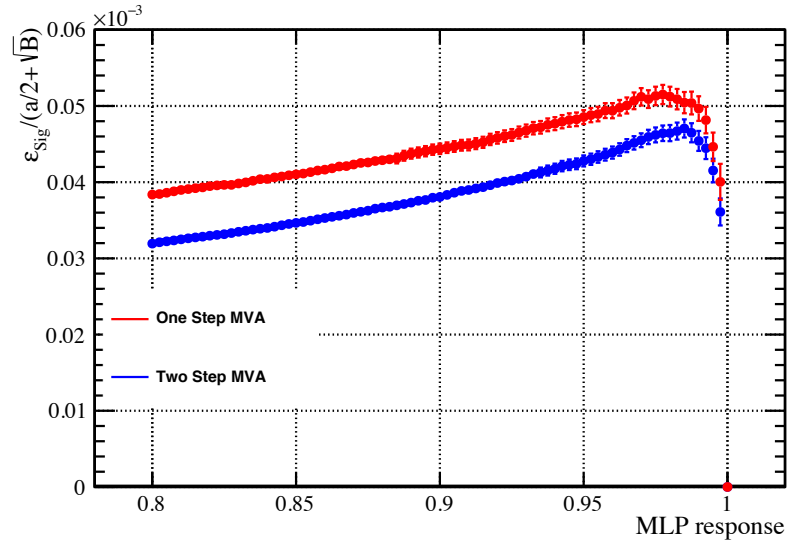


Figure 173: The FoM for one-step and two-step MVA training, the test are done with WS sample.

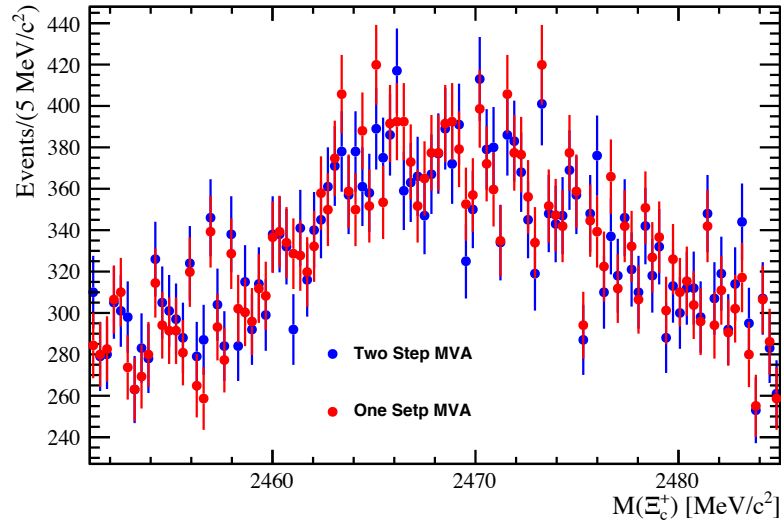


Figure 174: The FoM for one-step and two-step MVA training, the test are done with WS sample.

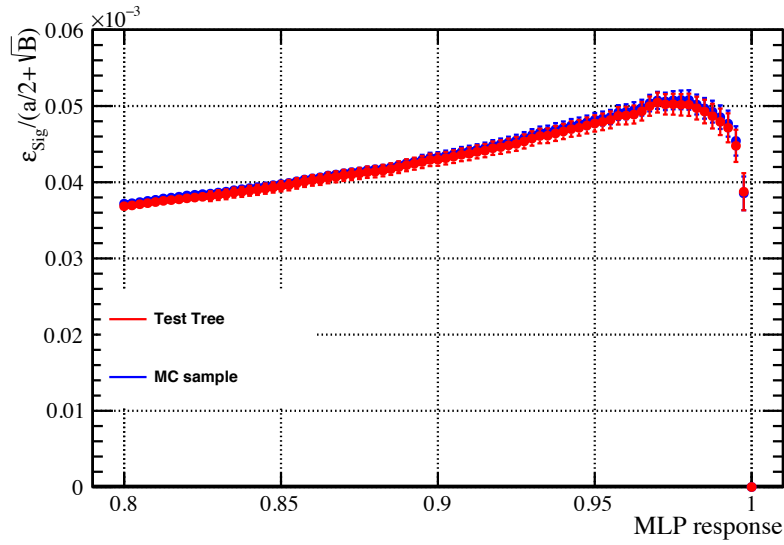


Figure 175: The FoM curve get from half of signal sample compared with that from all signal sample. With exactly same background sample is used in these two tests, the FoM distribution represent the signal efficiencies with different MVA cuts.

A.8 PID cut optimization

The purity of selected Ξ_c^+ data candidates is highly rely on the quality of each daughter particle, a tighter PID cut could reject more Ξ_c^+ background from hadron mis-ID. Then, a dedicated study on the PID cut is necessary in this analysis. The signal purity has been estimated with different PID cuts on kaon and proton. As shown in the Figure 176, a tighter Kaon PID cut cannot give a higher purity of selected Ξ_c^+ . While, with a tighter proton PID selected applied in the data sample could gives us a higher purity of Ξ_c candidates, which means a better control of the background contamination. As discussed in Appendix A.4, the mis-ID background is mainly from the mis-ID proton, not from the mis-ID kaon or pion, therefore, we decided to use tighter PID cut for proton.

Also, with a tighter PID cut ($\text{ProbNNp} > 0.8$) applied in both signal MC (PID reweighting) and data sample, we repeat the whole analysis procedure. As shown in Figure 177, the FoM value has been improved with tighter PID cuts.

Finally, we decided to use a tighter proton PID requirement ($\text{ProbNNp} > 0.8$), to get a better rejection of mis-ID background, and a Ξ_c^+ sample with higher purity.

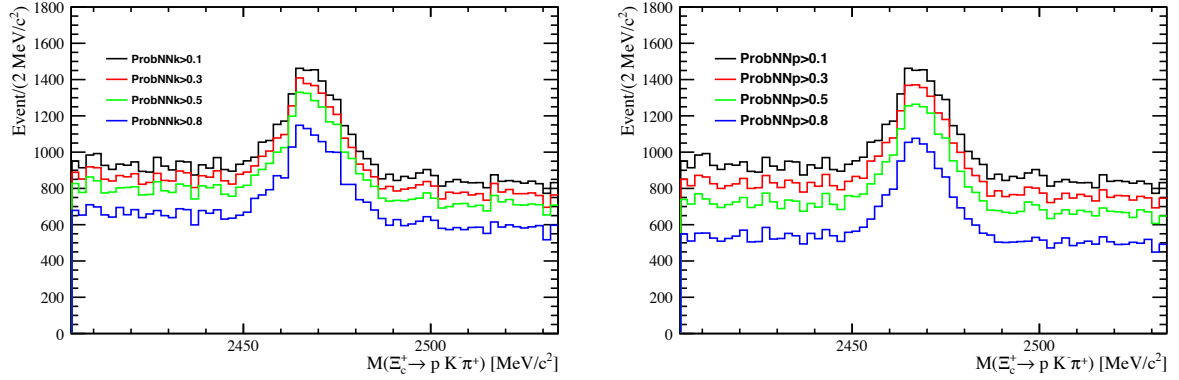


Figure 176: The invariant mass distributions of selected Ξ_c^+ candidates, with different cut values on the Kaon PID cuts (left), and proton PID cut values (right).

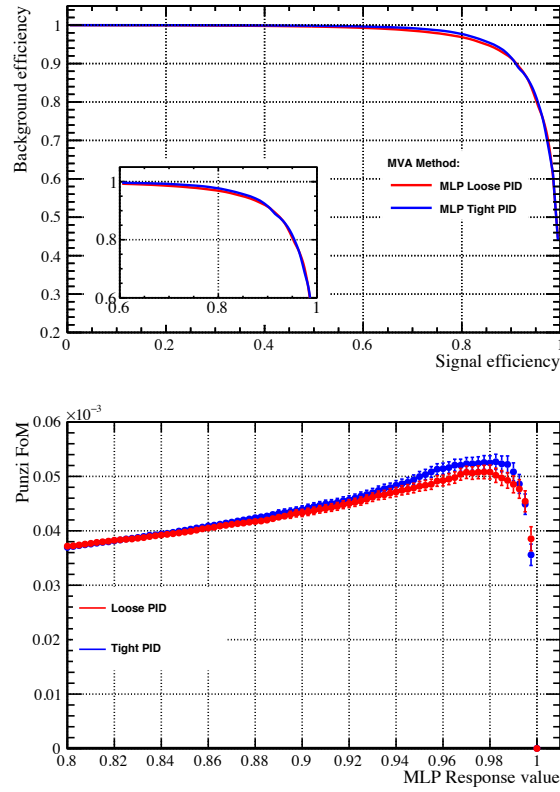


Figure 177: The ROC (left) and punzi FoM (right) comparison between tighter PID cuts and looser PID cuts.



A.9 Comparisons of kinematic distributions of Ξ_{cc}^{++}

Comparisons of Ξ_{cc}^{++} final state particles p_T , η distributions and the input variables of MVA training, are shown in Figure 178 for $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$. With limited statistics, all of variables has a reasonable agreement between data and predictions. The comparisons for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ are shown in Figure 179 for $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$.

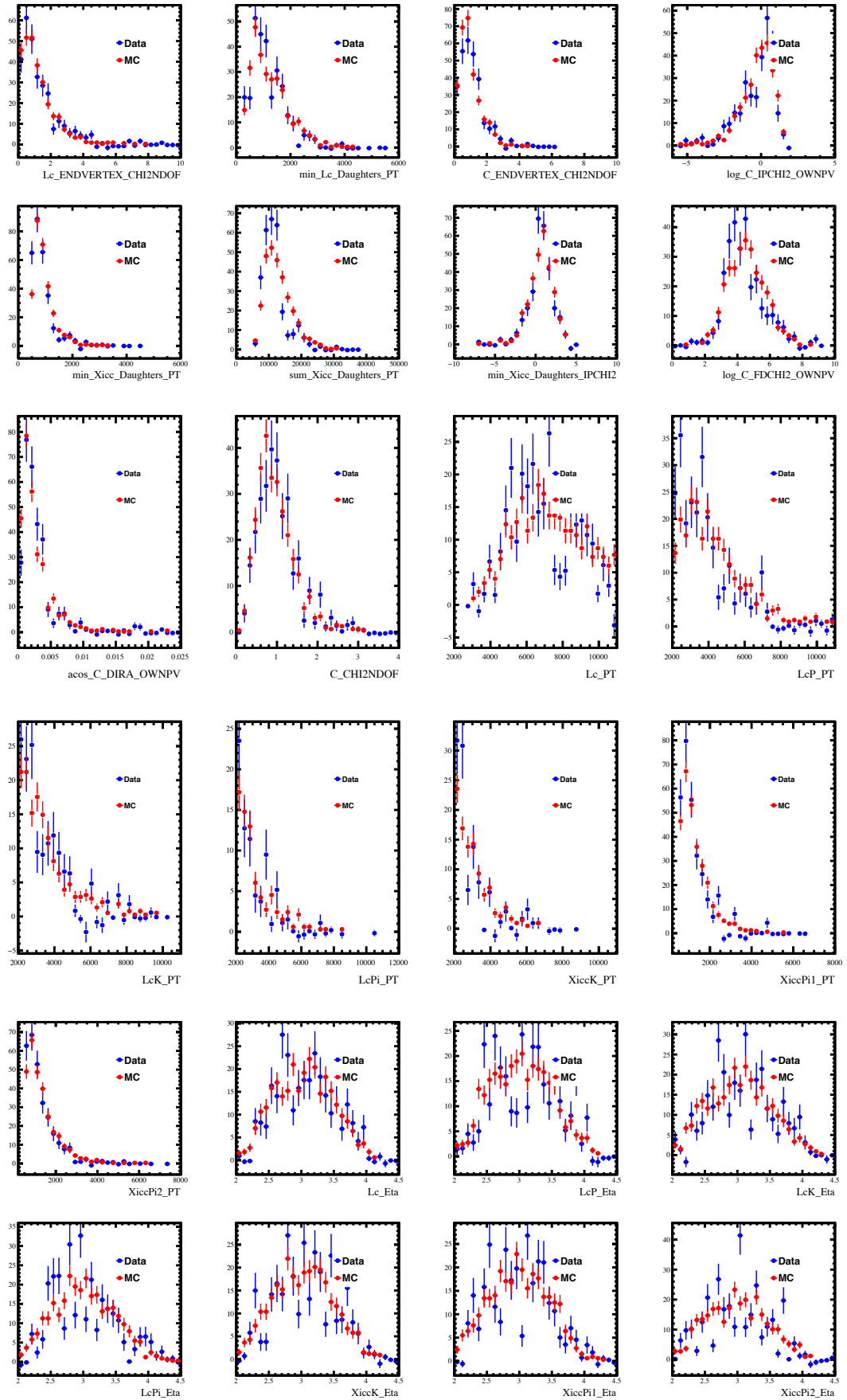


Figure 178: Comparisons of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ final state particle kinematic distribution between s-weighted data and signal after preselection and MVA selection.

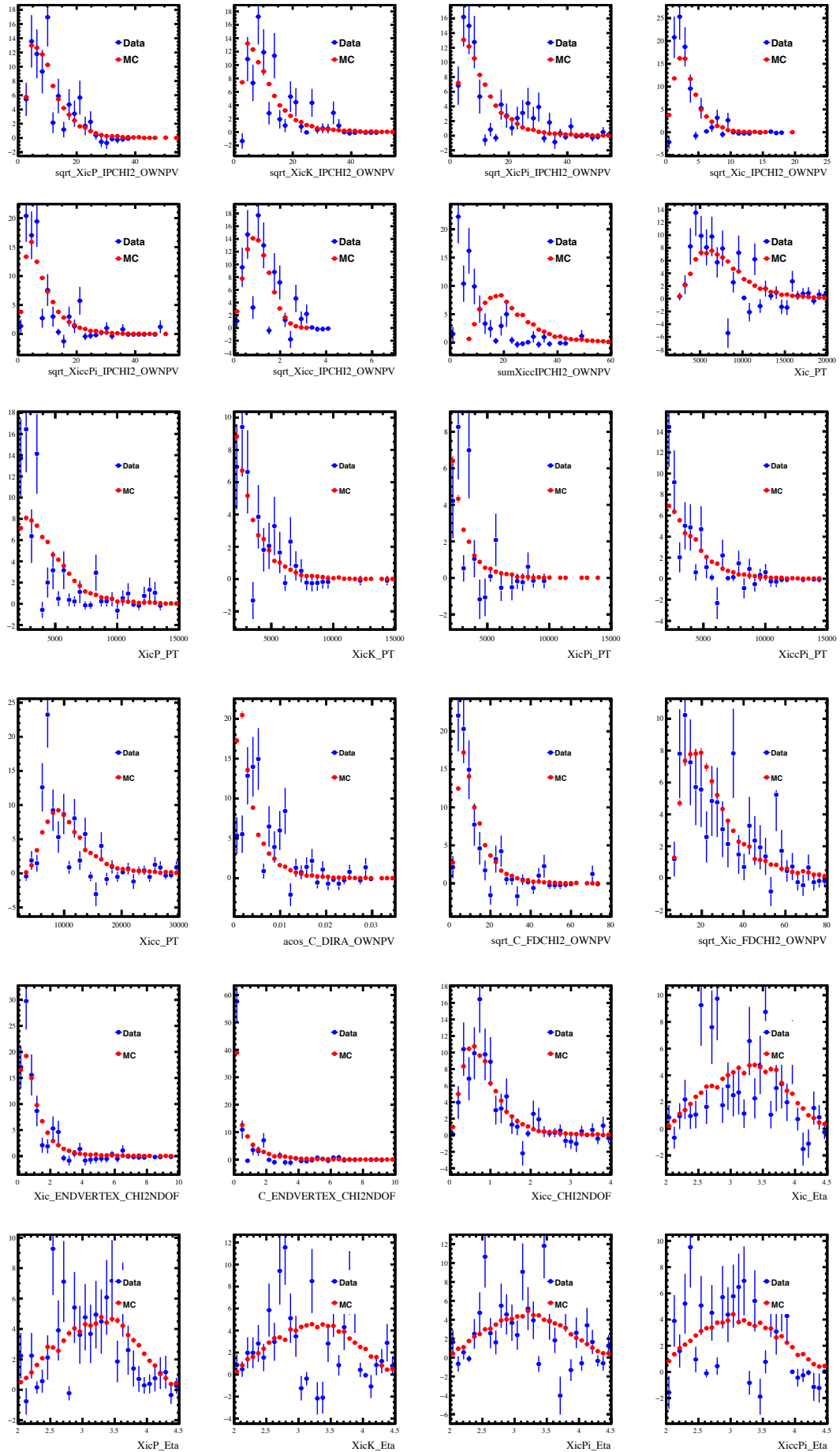


Figure 179: Comparisons of $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ final state particle kinematic distribution between s-weighted data and signal after preselection and MVA selection.



A.10 Λ_b^0 validation

Two Λ_b^0 control channels are used to validate the procedure of branching fraction measurement described in Sec. 5.5.

In this validation, the 2016 stripping data and generated Λ_b^0 MC events are used, with stripping lines *Lb2LcPiPiPiLc2PKPiBeauty2CharmLine* and *Lb2XicPiXic2PKPiBeauty2CharmLine*. The selection criteria for two strippings lines are summarized in Table 32. For the offline selections, we used similar selection cuts as described in Section. 5.2, including PID cuts and mass window cuts, but without MVA selection, as shown in Table 33. Furthermore, for the $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ channel, we also applied the duplicate events remover and clone track remover, as described in the note [91]. For $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$, only the clone track remover selection is applied, as described in Sec. 5.3.3. Also, additional HLT2 trigger requirements are applied, besides the L0 trigger ($\text{Lb_L0Global_TIS} \mid \mid \text{Lc_L0Hadron_TOS}$) and HLT1 trigger ($\text{Hlt1TrackMVA} \mid \mid \text{Hlt1TwoTrackMVA}$), in the HLT2 level, the candidates are required to pass ($\text{Hlt2_Topo2} \mid \mid \text{Hlt2_Topo3} \mid \mid \text{Hlt2_Topo4}$).

For the data, only part of 2016 data sample is used. The integrated luminosity is 951.6 pb^{-1} for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ channel and is 734.6 pb^{-1} for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ channel. In the data mass fitting, two types of background contributions had been considered, one is the combinatorial background and the other one is the background from particle mis-ID and partly reconstructed events. The fitted results for the Λ_b^0 mass is performed to extract the number of signal in different channels after event selections. As shown in Figure 180, the data mass distribution is modelled with a double-side Crystal-Ball function (signal), plus a exponential (combinatorial) and Argus function (mis-ID and partial reconstruction) for backgrounds. Using part of 2016 data, the number of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ L0TOS events is 20387 ± 208 , and L0TIS is 34859 ± 293 . The number of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ L0TOS events is 25525 ± 187 , and L0TIS is 50970 ± 265 .

For the efficiency studies, we followed the same procedures used in the Ξ_{cc}^{++} branching fraction measurement, the total efficiency includes the acceptance (ϵ_{Acc}), reconstruction and selection ($\epsilon_{\text{Reco\&Sel}}$), PID efficiency (ϵ_{PID}), and trigger efficiency ϵ_{Trig} . Again, $\epsilon_{\text{Reco\&Sel}}$ is corrected by the tracking efficiency (ϵ_{Trk}) and MC-matching efficiency ($\epsilon_{\text{MC-Match}}$). The overall efficiency correction for each channel can be written as:

$$\epsilon = \epsilon_{\text{Acc}} \times \epsilon_{\text{Reco\&Sel}} \times \epsilon_{\text{PID}} \times \epsilon_{\text{Trig}} \times \epsilon_{\text{Trk}} / \epsilon_{\text{MC-Match}} \quad (103)$$

The measured efficiencies are summarized in Table 34 and 35, for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ channels, and ratio between them. In the efficiency studies, the MC events are required to



Table 32: Stripping selections for two Λ_b^0 lines.

Particle	Variable	$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$	$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$
Ξ_c^+	Cosine of decay angle (DIRA)	> 0	> 0
	Mass	$\in [2186, 2386] \text{ MeV}/c^2$	$\in [2186, 2386] \text{ MeV}/c^2$
	Arithmetic sum of child p_T	$> 1800 \text{ MeV}/c$	$> 1800 \text{ MeV}/c$
	Vertex quality	$\chi^2_{\text{vtx}}/\text{ndf} < 10$	$\chi^2_{\text{vtx}}/\text{ndf} < 10$
	DOCA	$< 0.5 \text{ mm}$	$< 0.5 \text{ mm}$
	χ^2 from related PV	> 36	> 36
	Maximum child p_T	$> 500 \text{ MeV}/c$	$> 500 \text{ MeV}/c$
	Maximum child P	$> 5000 \text{ MeV}/c$	$> 5000 \text{ MeV}/c$
p, K, π	Transverse momentum	$p_T > 100 \text{ MeV}/c$	$p_T > 100 \text{ MeV}/c$
	Momentum	$p > 1000 \text{ MeV}/c$	$p > 1000 \text{ MeV}/c$
	Impact parameter significance	$\chi^2_{\text{IP}} > 4$	$\chi^2_{\text{IP}} > 4$
	Track quality	$\chi^2/\text{ndf} < 4.0$	$\chi^2/\text{ndf} < 4.0$
	Ghost Prob	$P_{\text{Ghost}} < 0.4$	$P_{\text{Ghost}} < 0.4$
	particle ID (p)	$\text{DLL}_{p\pi} > -10.0$	$\text{DLL}_{p\pi} > -10.0$
	particle ID (K)	$\text{DLL}_{K\pi} > -10$	$\text{DLL}_{K\pi} < 20$
	particle ID (π)	$\text{DLL}_{K\pi} < 20$	$\text{DLL}_{K\pi} < 20$
A_1	Arithmetic sum of child p_T	$> 1250 \text{ MeV}/c$	-
	Vertex quality	$\chi^2_{\text{vtx}}/\text{ndf} < 8$	-
	χ^2 from related PV	> 16	-
	Cosine of decay angle (DIRA)	> 0.98	-
	Impact parameter significance	$\chi^2_{\text{IP}} > 0$	-
	ρ, δ_z distance	$> 0.1, 2.0 \text{ mm}$	-
	Mass	$< 3500 \text{ MeV}/c^2$	-
	Maximum (Second) child p_T	$> 500, 300 \text{ MeV}/c$	-
	Maximum child P	$> 5000 \text{ MeV}/c$	-
	DOCA	$< 0.4 \text{ mm}$	-
$A_1 - \pi(s)$	Transverse momentum	$p_T > 100 \text{ MeV}/c$	$p_T > 500 \text{ MeV}/c$
	Momentum	$p > 2000 \text{ MeV}/c$	$p > 5000 \text{ MeV}/c$
	particle ID	$\text{DLL}_{K\pi} < 10.0$	-
	Track quality	$\chi^2/\text{ndf} < 4.0$	$\chi^2/\text{ndf} < 4.0$
	Ghost Prob	$P_{\text{Ghost}} < 0.4$	$P_{\text{Ghost}} < 0.4$
252 Λ_b^0	Cosine of decay angle (DIRA)	> 0.999	> 0.999
	Mass	$\in [2186, 2386] \text{ MeV}/c^2$	$\in [5200, 9000] \text{ MeV}/c^2$
	Impact parameter significance	$\chi^2_{\text{IP}} < 25$	$\chi^2_{\text{IP}} < 25$
	Decay time	$\tau > 0.2 \text{ ps}$	$\tau > 0.2 \text{ ps}$
	Vertex quality	$\chi^2_{\text{vtx}}/\text{ndf} < 10$	$\chi^2_{\text{vtx}}/\text{ndf} < 10$
	χ^2 from related PV	$\chi^2_{\text{IP}} > 36$	$\chi^2_{\text{IP}} > 36$
	Maximum child p_T	$> 1700 \text{ MeV}/c$	$> 1700 \text{ MeV}/c$
	Maximum child P	$> 10000 \text{ MeV}/c$	$> 10000 \text{ MeV}/c$



Table 33: Offline event selections for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ channels.

Particle	$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$	$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$
all tracks	$2 < p < 150 \text{ GeV}/c$	Same
all tracks	$1.5 < \eta < 5.0$	Same
all tracks	$\text{ProbNNghost} < 0.9$	Same
p	$\text{ProbNNp} > 0.1, \text{DLL}_{p\pi} > 5.0, \text{DLL}_{pK} > 5$	Same
K	$\text{ProbNNk} > 0.1, \text{DLL}_{K\pi} > 5.0$	Same
$\Lambda_c^+ - \pi$	$\text{ProbNNpi} > 0.1, \text{DLL}_{K\pi} < 5.0$	Same
$\Lambda_b^0 - \pi$	$\text{ProbNNpi} > 0.1, \text{DLL}_{K\pi} < 0.0$	Same
Λ_b^0	$5400 < M < 5800 \text{ MeV}/c^2$	Same
Λ_b^0	$p_T > 4 \text{ GeV}/c$	$p_T > 2 \text{ GeV}/c$

match real data, by applying two corrections of n_{SPD} , and $p_T - y$. The corrections are calculated using the s-weighted data and MC, as shown in Figure 181 and 182. The MC-Match correction ($\epsilon_{\text{MC-Match}}$) is determined to be $(81.4 \pm 0.2)\%$ for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ and $(92.7 \pm 0.2)\%$ for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$.

The trigger efficiencies are determined in two steps. First, we determined the L0 trigger efficiency for L0TOS and L0TIS events, using the TISTOS method with selected data and MC events (as described in Sec. 5.5.3). Then, for the HLT trigger efficiency, as there are requirements on HLT2 trigger in the stripping level, as $(\text{HLT_PASS_RE}('Hlt2Topo.*Decision')) | \text{HLT_PASS_RE}('Hlt2.IncPhi.*Decision'))$, where these HLT2 requirements include HLT1 tracking triggers. With this bias in the selected events from stripping, it doesn't make any sense to study the HLT1 and HLT2 trigger efficiency using the TISTOS method. So we decided to use MC events to study the HLT1 and HLT2 trigger efficiency for these two Λ_b^0 channels (as in LHCb-ANA-2011-052 [?]), using the MC events reconstructed from the basic particles from DST files, instead of MC events get from the stripping lines. In the HLT trigger efficiency study, we use the number of MC events that passed all of selection criteria as denominator, and the number of MC events passed the HLT1 ($\text{HLT1TrackMVA} | | \text{HLT1TwoTrackMVA}$) and HLT2 ($\text{Hlt2_Topo2} | | \text{Hlt2_Topo3} | | \text{Hlt2_Topo4}$) requirements as numerator. The measured trigger efficiencies are shown in Table 34 and 35.

The HLT trigger efficiency is very high for these Λ_b^0 channels. To further test the HLT trigger efficiency, we studied the HLT trigger efficiency with different offline selections, as 'Default' (Stripping + Offline cuts in Table 33), 'NoPID' (Stripping + Offline cuts, with PID selections in Table 33) removed, and 'Stripping' (only with the cuts in stripping level), 'MCMatched' (remove



Table 34: Measured efficiencies (L0TOS) for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ channels, and ratio of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ efficiency to that of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$.

ε	$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ (%)	$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ (%)	Ratio (R)
Acc	15.9 ± 0.9	17.4 ± 1.0	0.913 ± 0.074
Reco	3.67 ± 0.01	8.09 ± 0.01	0.454 ± 0.002
Trk	93.6 ± 0.1	96.1 ± 0.1	0.975 ± 0.001
PID	52.2 ± 0.2	58.1 ± 0.2	0.899 ± 0.000
L0 (TOS)	27.6 ± 0.4	23.7 ± 0.4	1.167 ± 0.030
HLT(TOS)	96.8 ± 0.1	94.2 ± 0.1	1.027 ± 0.002

all selection cuts, including the cuts in stripping level). With these three selection scenarios, we use the MC method (reconstruct candidates from the basic particle, with MC-match, but without any other offline selection cuts) to study the HLT trigger efficiency. As shown in Table 36 and 37, with tighter offline selection cuts, the HLT trigger efficiency is higher. Therefore, the high HLT trigger efficiency is mainly due to the tighter selection cuts in the stripping level.

In this Λ_b^0 ratio of branching fraction measurement, we only consider the uncertainty from PID are 100% correlated in two channels, and the other uncertainties are treated as uncorrelated. Also, we only considered systematic uncertainties from the MC/data sample statistics, without any further detailed studied for each uncertainty source. Combined information above, the measured ratio of branching fraction is 0.804 ± 0.069 by using L0TOS events, and 0.851 ± 0.071 by using L0TIS events.

Using Run-I data 35 pb^{-1} 7 TeV data, the ratio of branching fraction of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ to that of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$, which is $1.43 \pm 0.16 \pm 0.13$. By reversing the measured result, we get the ratio of branching fraction of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ to that of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ is 0.699 ± 0.101 .

As expected, there is a good agreement between the measured results using L0TOS and L0TIS events, which are all consistent with the LHCb Run-I published result. We will take the average value of the measured branching fraction results using L0TOS events and L0TIS events as the measured one, and take the deviation as one of systematic uncertainty from L0 trigger, which is determined to be 2.85%. In a sanity check, with published Λ_b^0 numbers and calculated efficiencies, the expected $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ L0TOS events number is $(17 \pm 2.9)\text{k}$, and the number of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ L0TOS events in our data is $(20 \pm 0.2)\text{k}$, where good agreement had been found.

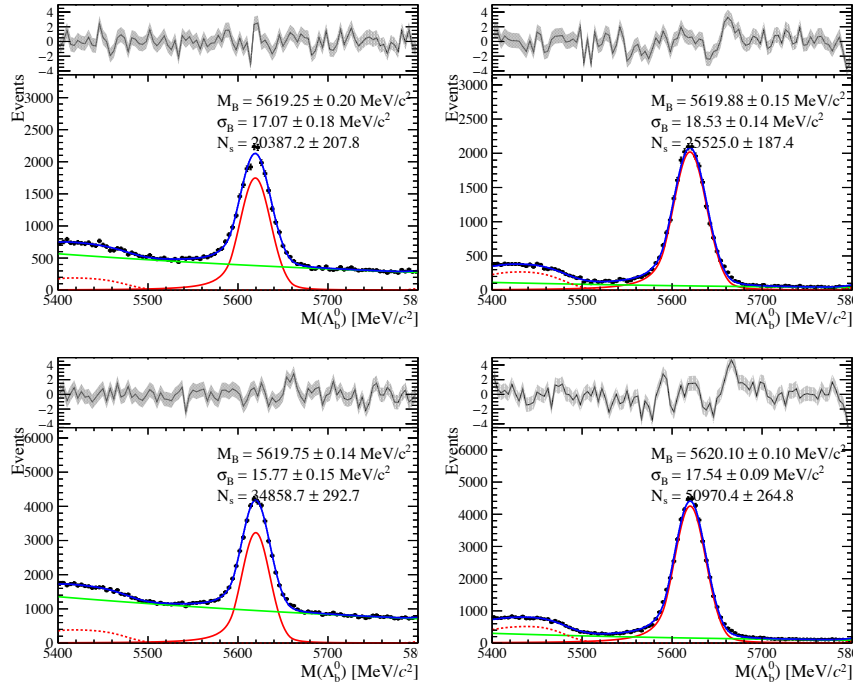


Figure 180: The fitted Λ_b^0 mass distribution, (left) are the mass distributions get from $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ channel, and (right) are mass distributions get from $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ channel. The top two figures for L0TOS events, and bottom two figures for L0TIS events.

Table 35: Measured efficiencies (L0TIS) for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ and $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ channels, and ratio of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ efficiency to that of $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$.

ε	$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ (%)	$\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ (%)	Ratio (R)
Acc	15.9 ± 0.9	17.4 ± 1.0	0.913 ± 0.074
Reco	3.67 ± 0.01	8.09 ± 0.01	0.454 ± 0.002
Trk	93.6 ± 0.1	96.1 ± 0.1	0.975 ± 0.001
PID	52.2 ± 0.2	58.1 ± 0.2	0.899 ± 0.000
L0 (TIS)	38.6 ± 0.3	36.9 ± 0.1	1.048 ± 0.014
HLT(TIS)	95.6 ± 0.1	92.1 ± 0.1	1.038 ± 0.002

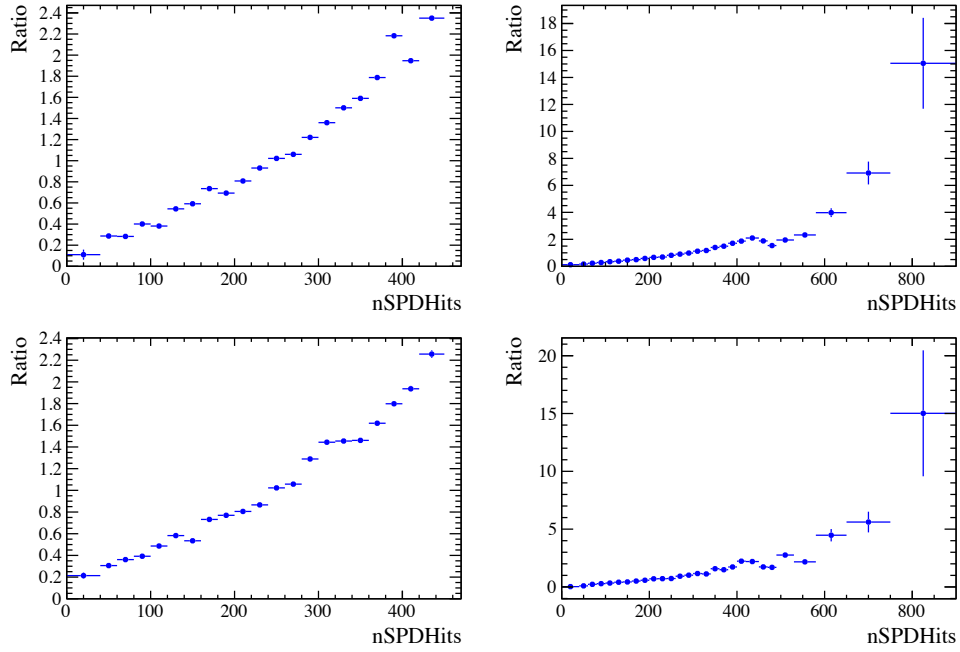


Figure 181: The nSPD correction factors for (top) $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ channel, and (bottom) $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ channel. The left two figures are corrections for L0TOS events, and right two figures are corrections for L0TIS. The nSPD cut is 450 for L0Hadron trigger, and extend to 900 in some of other L0 triggers (L0DiMuon), so the corrections for L0TIS events are calculated upto nSPD=900.

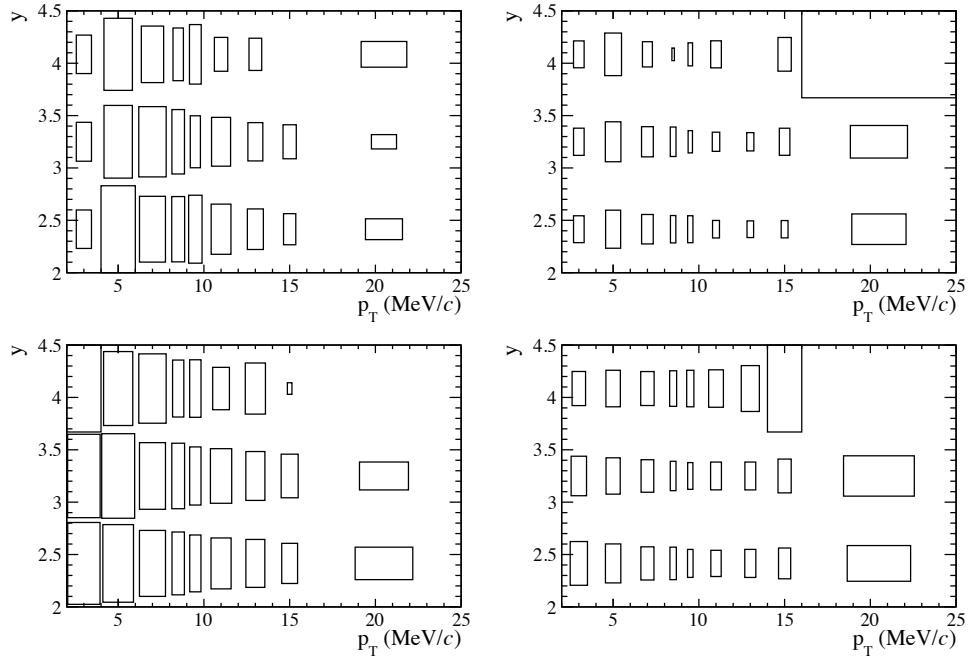


Figure 182: The p_T and y correction factors for (top) $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ channel, and (bottom) $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ channel. The left two figures are corrections for L0TOS events, and right two figures are corrections for L0TIS.



Table 36: Measured HLT trigger efficiencies for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-$ channel, with different offline selections.

$\varepsilon(\text{Trig})$	L0		HLT	
	TOS	TIS	TOS	TIS
MCMatched	24.1 ± 0.2	38.8 ± 0.2	70.4 ± 0.1	65.6 ± 0.1
Stripping	28.1 ± 0.3	39.9 ± 0.3	95.6 ± 0.1	94.2 ± 0.1
NoPID	26.3 ± 0.3	39.6 ± 0.3	95.7 ± 0.1	94.3 ± 0.1
Default	27.6 ± 0.4	38.6 ± 0.3	96.8 ± 0.1	95.6 ± 0.1

Table 37: Measured HLT trigger efficiencies for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ channel, with different offline selections.

$\varepsilon(\text{Trig})$	L0		HLT	
	TOS	TIS	TOS	TIS
MCMatched	20.9 ± 0.2	44.3 ± 0.2	68.1 ± 0.2	62.2 ± 0.2
Stripping	23.4 ± 0.3	38.0 ± 0.3	93.8 ± 0.2	90.7 ± 0.2
NoPID	22.1 ± 0.4	37.6 ± 0.3	93.7 ± 0.2	90.8 ± 0.2
Default	23.7 ± 0.4	36.9 ± 0.3	94.2 ± 0.2	92.1 ± 0.2

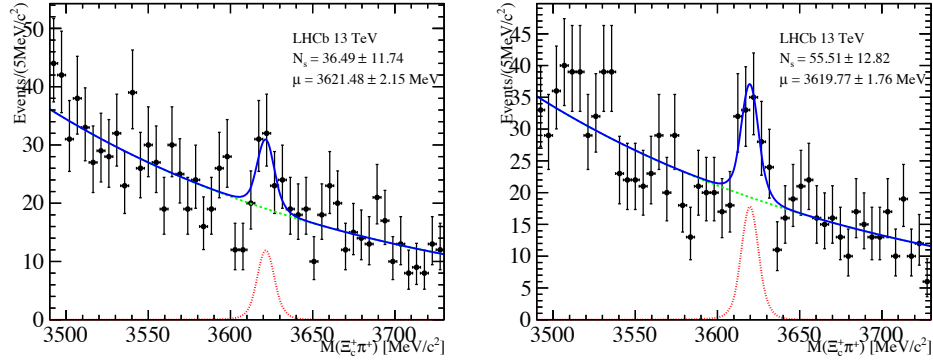


Figure 183: The mass distribution of Ξ_{cc}^{++} and Ξ_{cc}^{--} candidates using $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ channel.

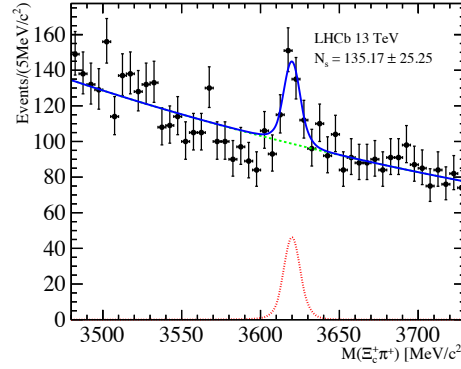


Figure 184: The mass distribution of Ξ_{cc}^{++} candidates using cut-based selections.

A.11 More tests after unblinding

We did two more checks after the $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ unblinded, including the charge conjunction test and cut-based selection test. As shown in Figure 183, there are 36 ± 12 candidates for Ξ_{cc}^{++} and 56 ± 13 candidates for Ξ_{cc}^{--} .

For the cut-base selection, we simply some of pre-selection cuts, including $\Xi_{cc}^{++} - \pi$ $p_T > 500$ MeV/c, Ξ_{cc}^{++} $p_T > 4000$ MeV/c, $\cos(\text{DIRA}, \Xi_{cc}^{++}) > 0.9999$, χ^2 of PV fit < 10 . Without any or cuts optimisation, there is still a mass peak around 3620 MeV/c², with a local significance of 5.9σ , as shown in Figure 184.



B Appendix-Measurement of the angular coefficients of $\mu^+\mu^-$ pairs in the Z boson mass region at LHCb

B.1 Fitting Check

In this analysis, an unbinned maximum log-likelihood fit method is used to extract final result as described in Section 6.5. However, with this method, it cannot directly draw the finally fitting distributions, and make a directly comparison with data. An alternative method can used to check the fitting performance, which produce the fitted PDFs shape by calculating $\frac{PDF_{MC} * PDF_{fitting}}{PDF_{Gene}}$, and then compared with data distributions.

As Figure 185 shows, there are good agreements between data and fitted results in 2016 year, which means the fitting results are reliable. The fitting checks also done for the Z rapidity dependence results and in the low Z p_T region, as Figure 186 and Figure 187 shows.

B.2 Systematic result in 2017 and 2018 datasets

The determined systematic uncertainties for measured angular coefficient in different Z boson p_T bins in 2017 data, are summarize in Figure 188 while Figure 189 shows the results in 2018.

The comparisons of the total, statistical, and systematic uncertainties as a function of Z p_T in 2017 are shown in Figure 190. Figure 191 shows the result in 2018.

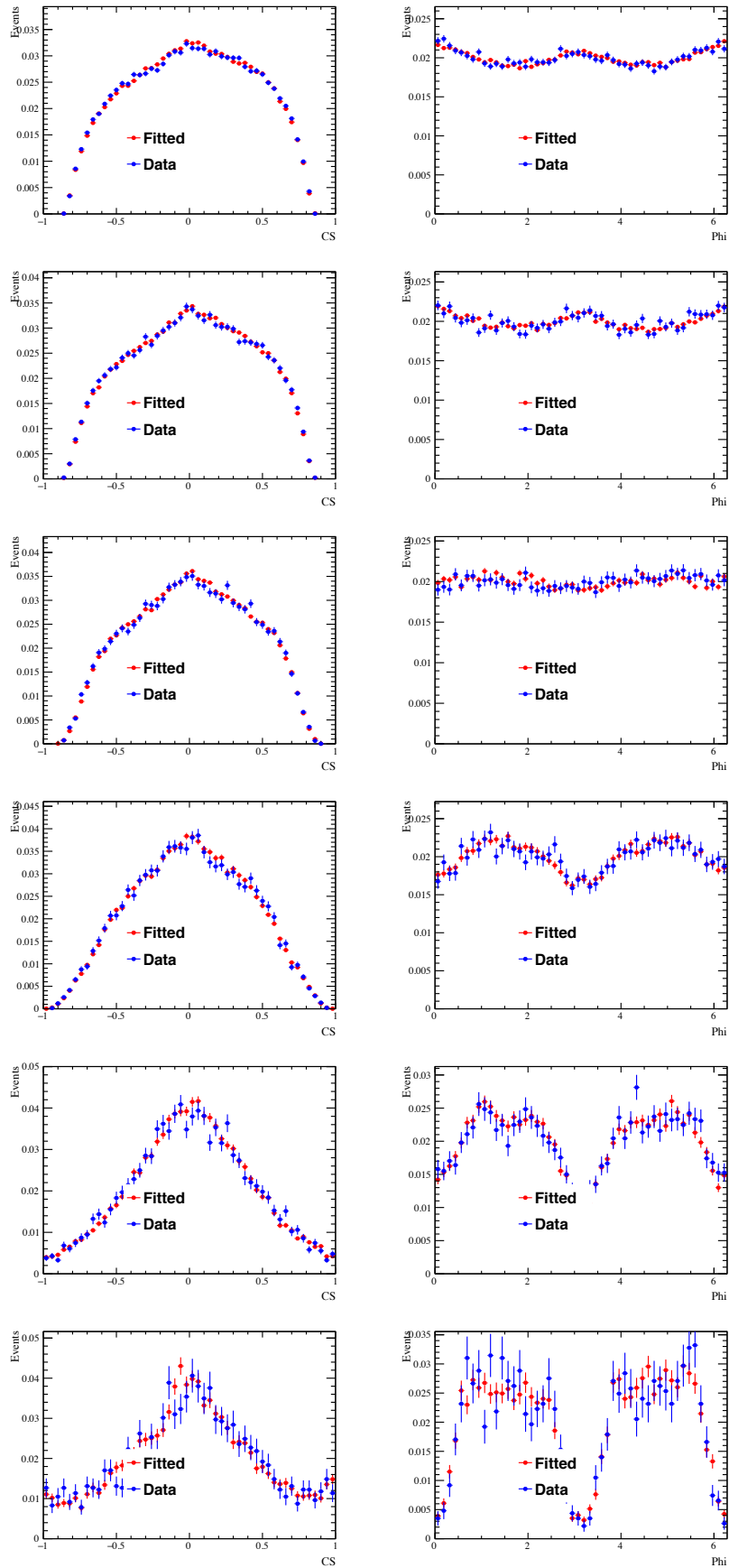
B.3 Final result in 2017 and 2018 datasets

B.3.1 Z boson p_T depended results in 2017 and 2018 datasets

The measured Z boson p_T depended results in 2017 dataset are shown in Figure 192. The measured central values and uncertainties of the coefficients in 2017 are listed in Table 38. While Figure 193 and Table 39 shows the result in 2018 dataset.

B.3.2 Z boson rapidity depended results in 2017 and 2018 datasets

The measured rapidity results in 2017 dataset are shown in Figure 194. The measured central values and uncertainties of the coefficients in 2017 are listed in Table 40. While Figure 194 and Table 40 shows the result in 2018 dataset.



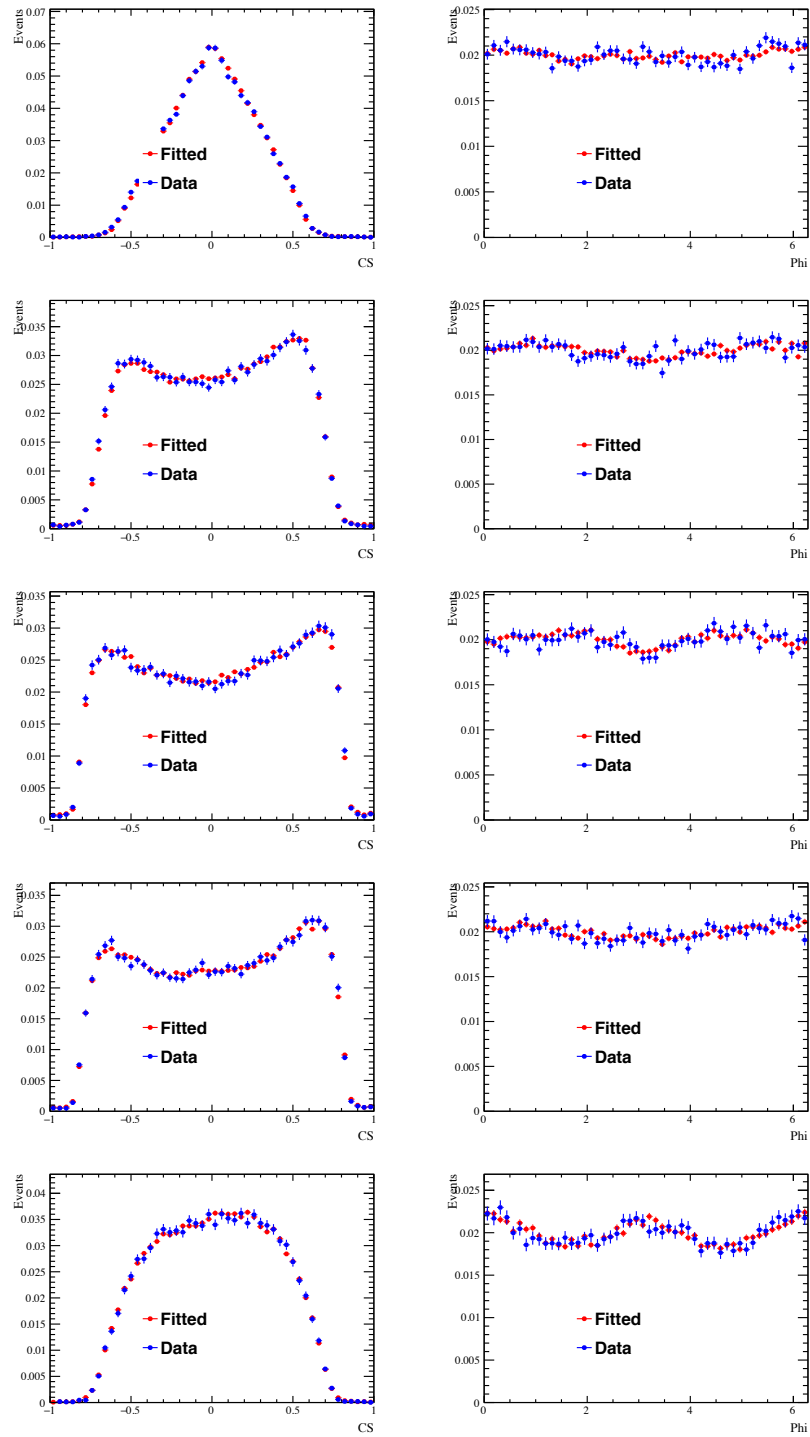


Figure 186: Comparisons of $\cos\theta$ and ϕ between data (blue points) and the fitted results (red points) in different Z boson rapidity bins, as 2.0 - 2.7, 2.7 - 3.0, 3.0 - 3.25, 3.25 - 3.6, and 3.6 - 4.5 (from top to bottom).

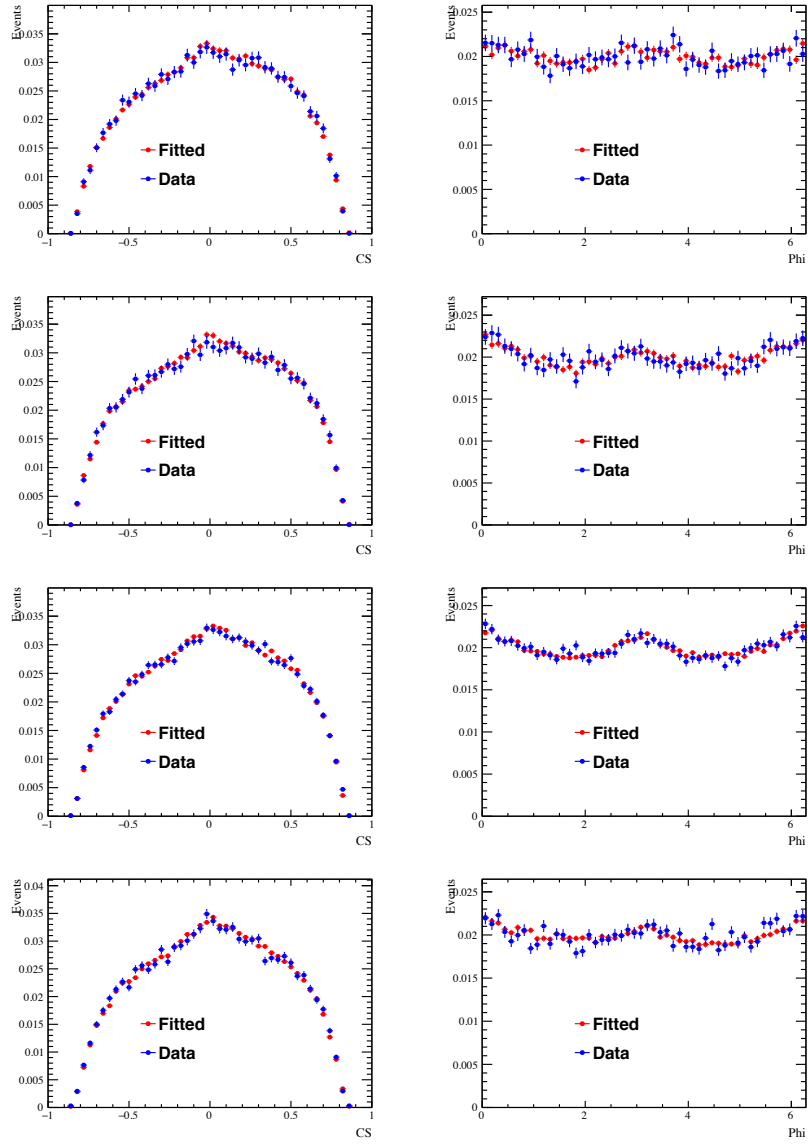


Figure 187: Comparisons of $\cos\theta$ and ϕ between data (blue points) and the fitted results (red points) in different Z boson p_T bins. As $0 - 2$, $2 - 4$, $4 - 6$, $6 - 12$, and $12 - 20$ GeV/c (from top to bottom).

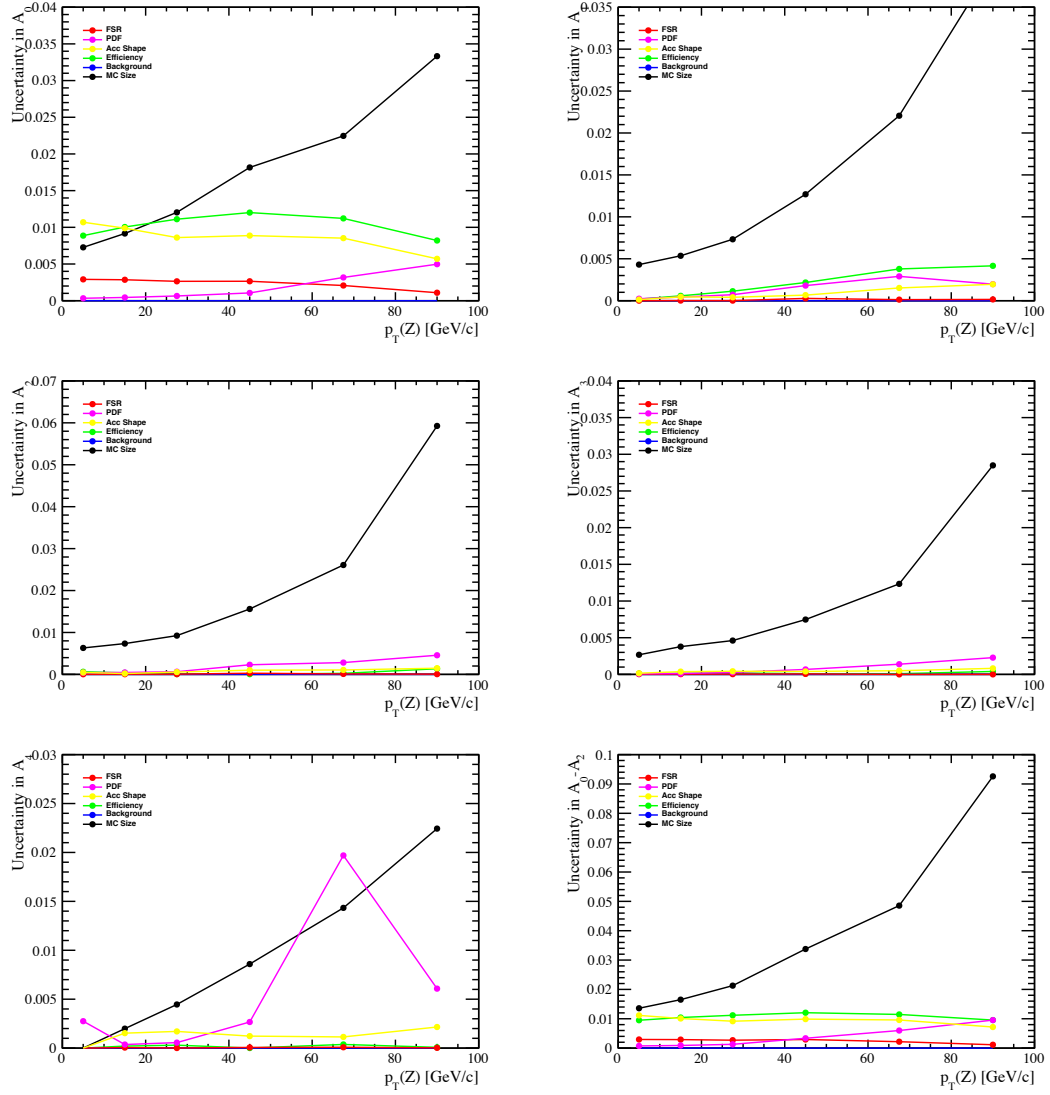


Figure 188: Comparisons of systematic uncertainties of the A_i and $A_0 - A_2$ in 2017 data as a function of $Z p_T$.

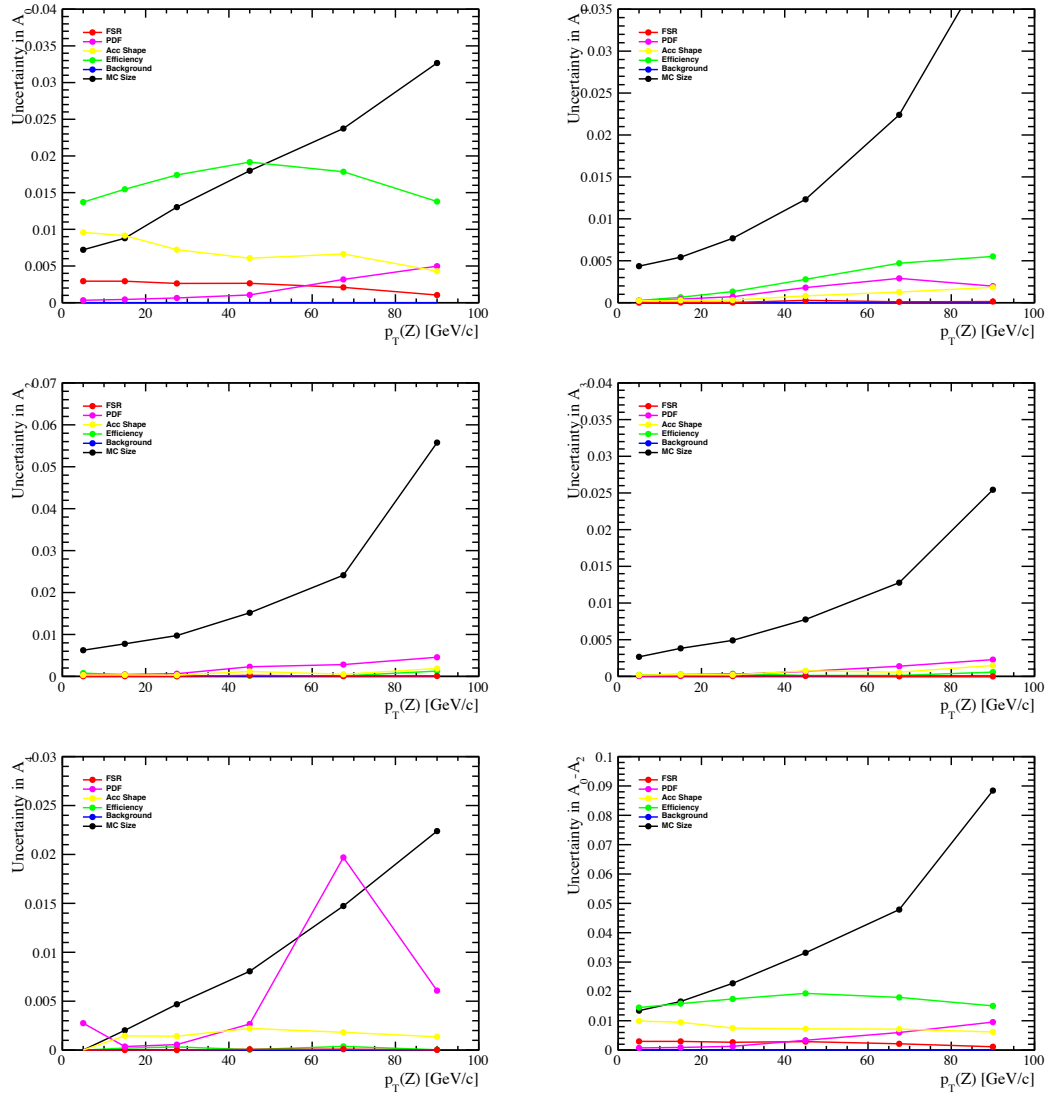


Figure 189: Comparisons of systematic uncertainties of the A_i and $A_0 - A_2$ in 2018 data as a function of $Z p_T$.

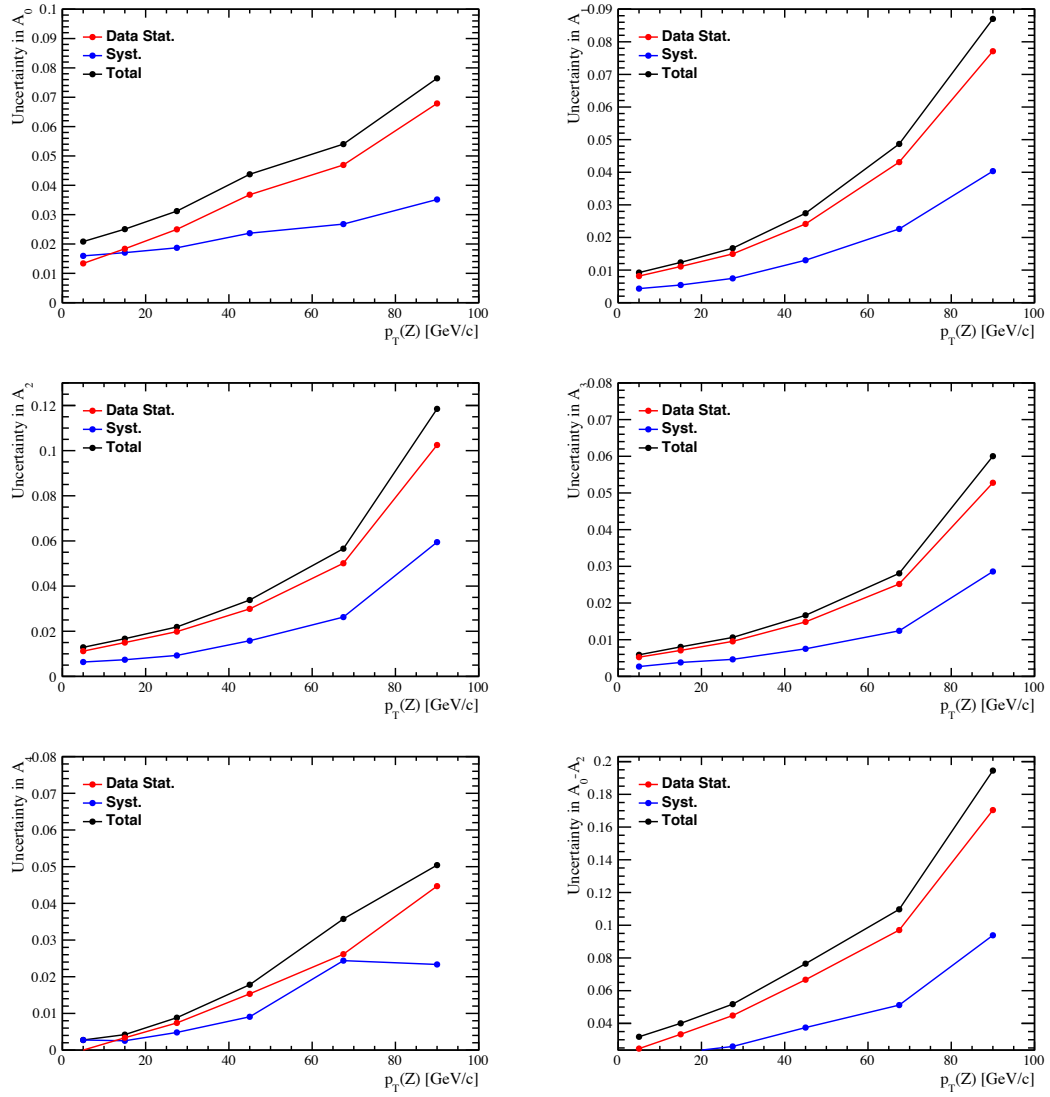


Figure 190: Comparisons of different uncertainties of the A_i and $A_0 - A_2$, as a function of $Z p_T$ in 2017 dataset.

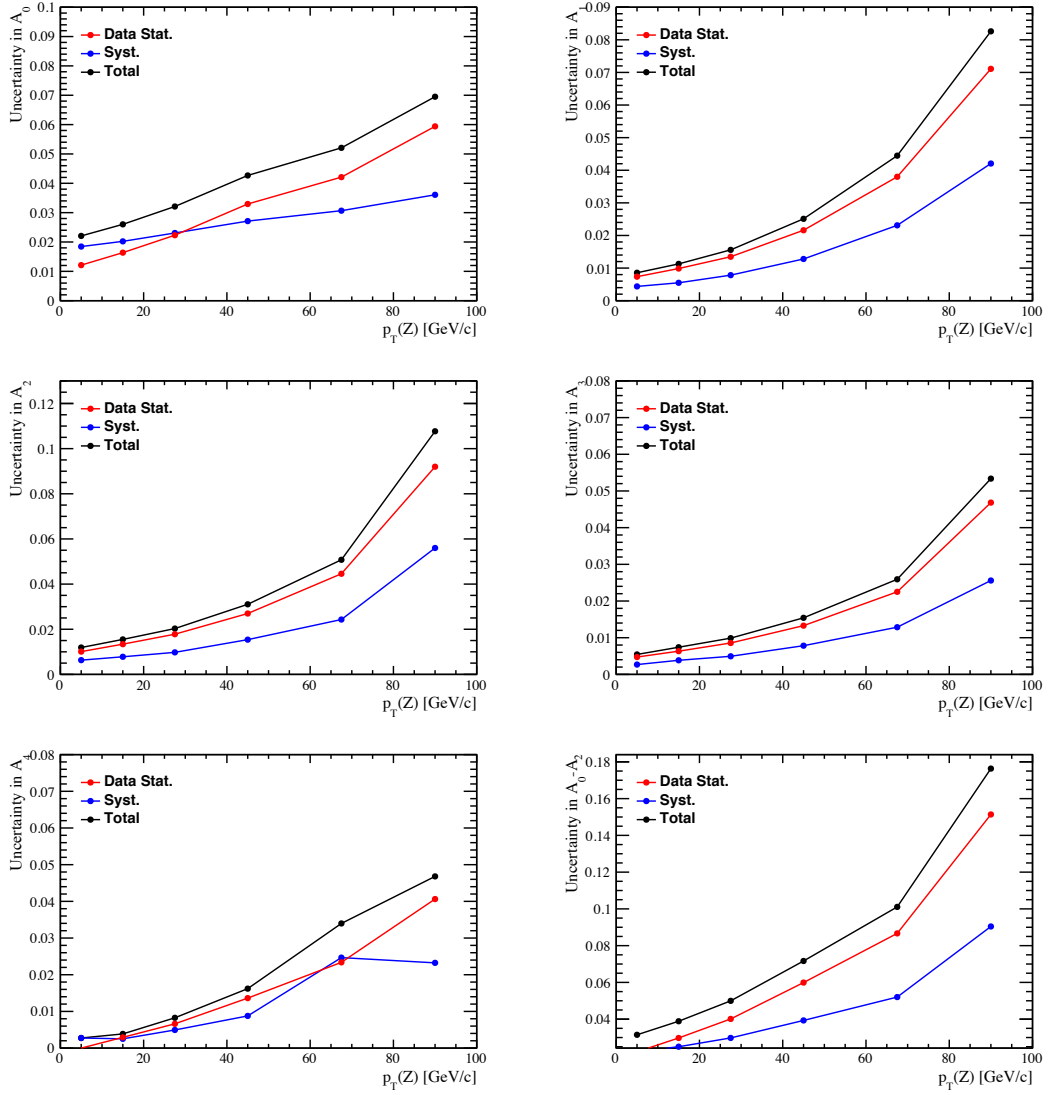


Figure 191: Comparisons of different uncertainties of the A_i and $A_0 - A_2$, as a function of $Z p_T$ in 2018 dataset.



Table 38: The measured angular coefficients A_0 to A_4 and $A_0 - A_2$ in bins of Z p_T in 2017 dataset, using Z boson events with $y > 2.0$.

$p_T(Z)$ [GeV]	A_0	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_1	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_2	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-10	-0.0503	0.0202	0.0159	0.0037	0.0082	0.0043	0.0049	0.0112	0.0064
10-20	0.0157	0.0222	0.0170	0.0325	0.0111	0.0054	0.0537	0.0150	0.0074
20-35	0.1616	0.0259	0.0187	0.1042	0.0150	0.0075	0.1170	0.0198	0.0093
35-55	0.3727	0.0375	0.0237	0.1416	0.0241	0.0130	0.2963	0.0299	0.0158
55-80	0.6596	0.0512	0.0268	0.1412	0.0431	0.0226	0.3021	0.0501	0.0263
80-100	0.7764	0.0938	0.0352	0.1402	0.0771	0.0403	0.7815	0.1025	0.0595
$p_T(Z)$ [GeV]	A_3	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_4	$\pm\delta_{stat}$	$\pm\delta_{syst}$	$A_0 - A_2$	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-10	0.0279	0.0052	0.0027	1.0000	0.0098	0.0028	-0.0552	0.0175	0.0202
10-20	0.0393	0.0071	0.0038	1.0993	0.0034	0.0025	-0.0381	0.0237	0.0222
20-35	0.0360	0.0095	0.0046	1.3994	0.0074	0.0048	0.0447	0.0319	0.0259
35-55	0.0553	0.0149	0.0075	1.5853	0.0153	0.0091	0.0764	0.0474	0.0375
55-80	0.0751	0.0252	0.0124	0.7772	0.0261	0.0244	0.3574	0.0687	0.0512
80-100	0.0619	0.0528	0.0286	-0.7267	0.0447	0.0233	0.0000	0.0000	0.0938

Table 39: The measured angular coefficients A_0 to A_4 and $A_0 - A_2$ in bins of Z p_T in 2018 dataset, using Z boson events with $y > 2.0$.

$p_T(Z)$ [GeV]	A_0	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_1	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_2	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-10	-0.0367	0.0223	0.0184	0.0248	0.0074	0.0044	0.0087	0.0101	0.0063
10-20	0.0158	0.0250	0.0202	0.0452	0.0099	0.0055	0.0458	0.0134	0.0078
20-35	0.1554	0.0298	0.0231	0.0849	0.0135	0.0078	0.1156	0.0178	0.0098
35-55	0.4231	0.0393	0.0271	0.1558	0.0216	0.0128	0.2513	0.0270	0.0154
55-80	0.6146	0.0520	0.0307	0.1623	0.0380	0.0231	0.3491	0.0446	0.0243
80-100	0.7125	0.0904	0.0361	0.2521	0.0711	0.0421	0.5587	0.0920	0.0560
$p_T(Z)$ [GeV]	A_3	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_4	$\pm\delta_{stat}$	$\pm\delta_{syst}$	$A_0 - A_2$	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-10	0.0391	0.0047	0.0027	1.0000	0.0088	0.0028	-0.0454	0.0158	0.0223
10-20	0.0376	0.0063	0.0038	1.0538	0.0029	0.0025	-0.0300	0.0211	0.0250
20-35	0.0446	0.0086	0.0049	1.1718	0.0066	0.0049	0.0398	0.0285	0.0298
35-55	0.0566	0.0133	0.0078	0.5329	0.0136	0.0088	0.1717	0.0426	0.0393
55-80	0.0912	0.0225	0.0129	1.1956	0.0234	0.0247	0.2654	0.0613	0.0520
80-100	0.0000	0.0468	0.0256	-0.7789	0.0406	0.0232	0.0000	0.0000	0.0904

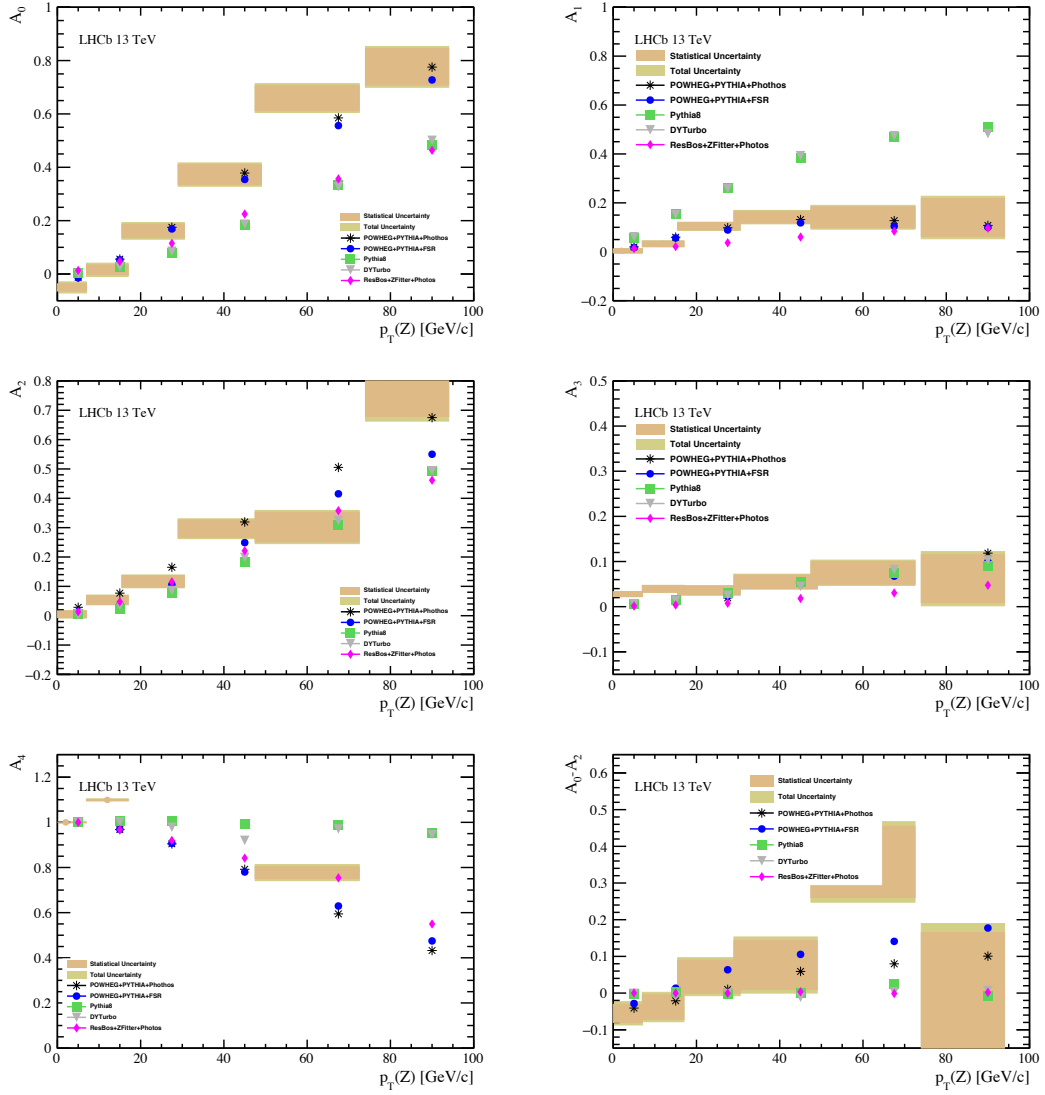


Figure 192: The determined results of the A_i and $A_0 - A_2$, as a function of Z boson p_T , are compared with different theoretical predictions in 2017.

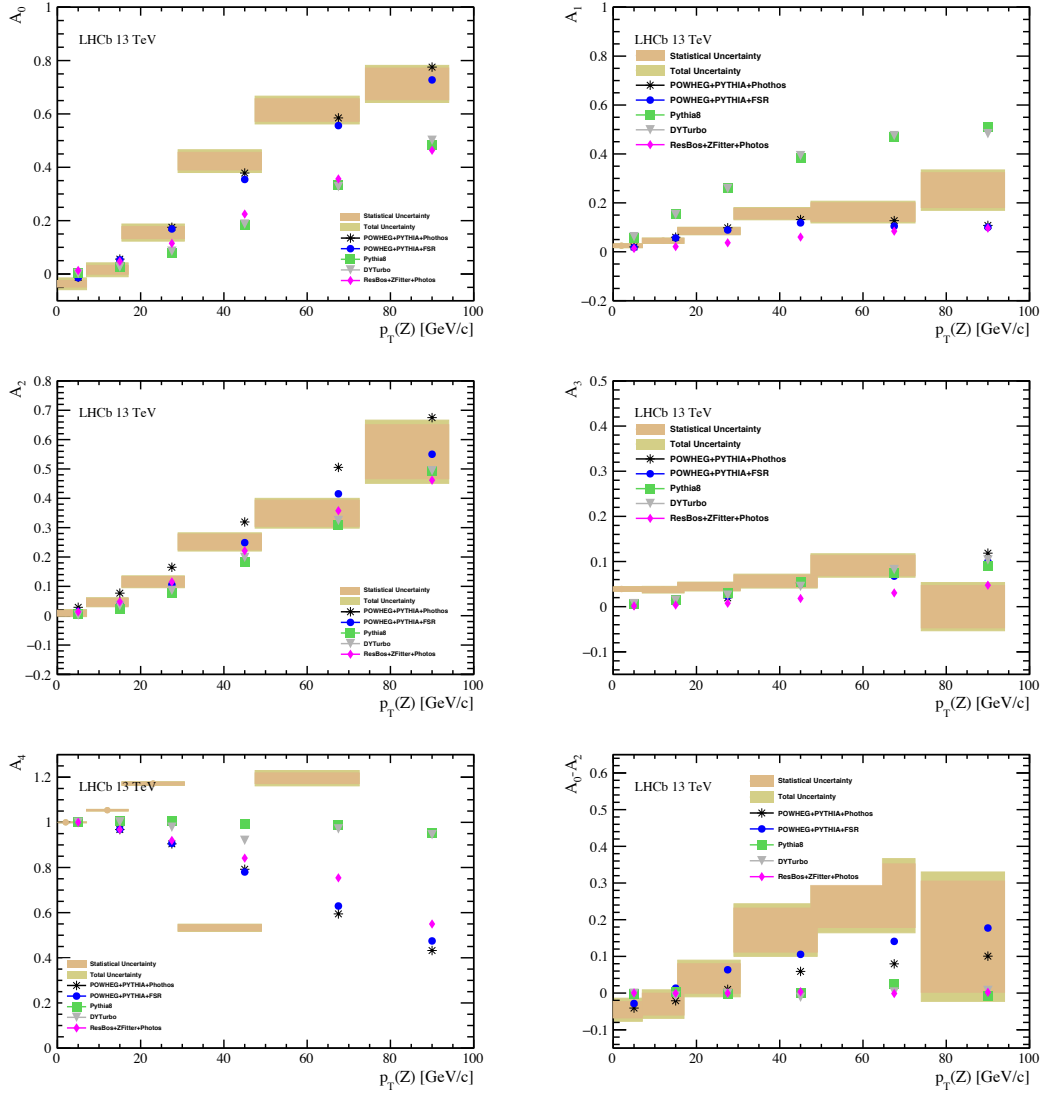


Figure 193: The determined results of the A_i and $A_0 - A_2$, as a function of Z boson p_T , are compared with different theoretical predictions in 2018.

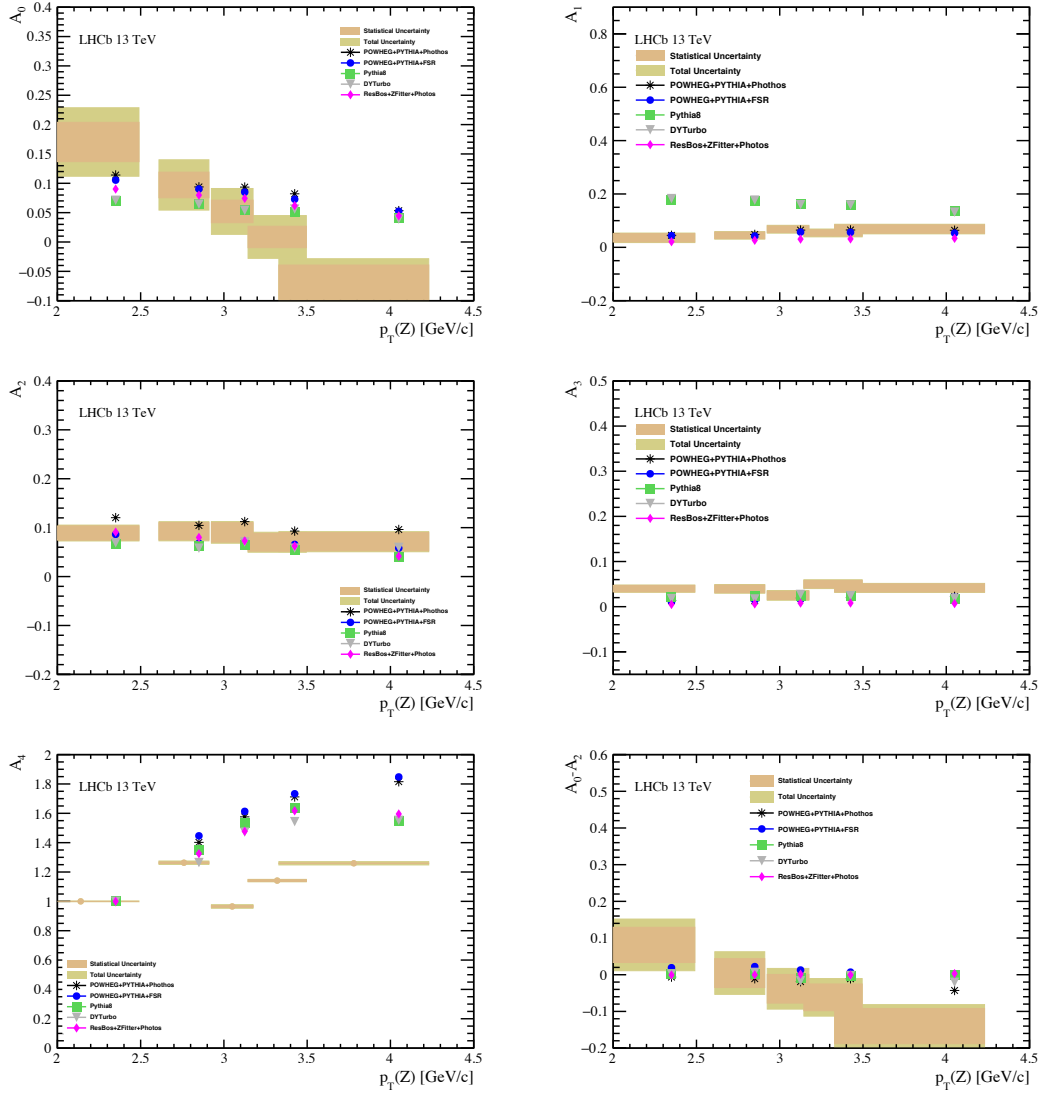


Figure 194: The determined results of the A_i and $A_0 - A_2$ in 2017 dataset, as a function of the Z boson rapidity, are compared with different theoretical predictions.



Table 40: The measured angular coefficients A_0 to A_4 and $A_0 - A_2$ in bins of Z rapidity in 2017 dataset, using Z boson events with $y > 2.0$.

$y(Z)$	A_0	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_1	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_2	$\pm\delta_{stat}$	$\pm\delta_{syst}$
2.00-2.70	0.1704	0.0515	0.0477	0.0357	0.0156	0.0086	0.0890	0.0145	0.0073
2.70-3.00	0.0972	0.0427	0.0369	0.0449	0.0123	0.0068	0.0926	0.0176	0.0087
3.00-3.25	0.0521	0.0394	0.0340	0.0679	0.0123	0.0079	0.0903	0.0198	0.0100
3.25-3.60	0.0086	0.0360	0.0315	0.0539	0.0116	0.0091	0.0702	0.0181	0.0094
3.60-4.50	-0.0687	0.0334	0.0274	0.0685	0.0157	0.0088	0.0713	0.0186	0.0088
$y(Z)$	A_3	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_4	$\pm\delta_{stat}$	$\pm\delta_{syst}$	$A_0 - A_2$	$\pm\delta_{stat}$	$\pm\delta_{syst}$
2.00-2.70	0.0399	0.0072	0.0036	1.0000	0.0188	0.0026	0.0814	0.0365	0.0515
2.70-3.00	0.0394	0.0084	0.0047	1.2634	0.0048	0.0106	0.0046	0.0280	0.0427
3.00-3.25	0.0250	0.0092	0.0055	0.9652	0.0053	0.0110	-0.0383	0.0276	0.0394
3.25-3.60	0.0498	0.0085	0.0048	1.1415	0.0059	0.0059	-0.0616	0.0257	0.0360
3.60-4.50	0.0415	0.0089	0.0045	1.2594	0.0002	0.0113	0.0000	0.0000	0.0334

Table 41: The measured angular coefficients A_0 to A_4 and $A_0 - A_2$ in bins of Z rapidity in 2018 dataset, using Z boson events with $y > 2.0$.

$y(Z)$	A_0	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_1	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_2	$\pm\delta_{stat}$	$\pm\delta_{syst}$
2.00-2.70	0.2141	0.0517	0.0478	0.0319	0.0142	0.0085	0.1073	0.0132	0.0071
2.70-3.00	0.0625	0.0409	0.0370	0.0786	0.0109	0.0075	0.0776	0.0156	0.0083
3.00-3.25	0.0357	0.0360	0.0303	0.0815	0.0111	0.0096	0.0801	0.0177	0.0101
3.25-3.60	0.0224	0.0276	0.0216	0.0759	0.0104	0.0099	0.0477	0.0164	0.0098
3.60-4.50	-0.0758	0.0393	0.0347	0.0629	0.0141	0.0089	0.0712	0.0167	0.0083
$y(Z)$	A_3	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_4	$\pm\delta_{stat}$	$\pm\delta_{syst}$	$A_0 - A_2$	$\pm\delta_{stat}$	$\pm\delta_{syst}$
2.00-2.70	0.0534	0.0065	0.0035	1.0000	0.0171	0.0026	0.1068	0.0333	0.0517
2.70-3.00	0.0463	0.0074	0.0043	1.2989	0.0046	0.0043	-0.0151	0.0248	0.0409
3.00-3.25	0.0217	0.0083	0.0053	1.4350	0.0049	0.0094	-0.0444	0.0247	0.0360
3.25-3.60	0.0414	0.0076	0.0046	1.8310	0.0055	0.0049	-0.0253	0.0232	0.0276
3.60-4.50	0.0549	0.0080	0.0047	1.9353	0.0001	0.0094	0.0000	0.0000	0.0393

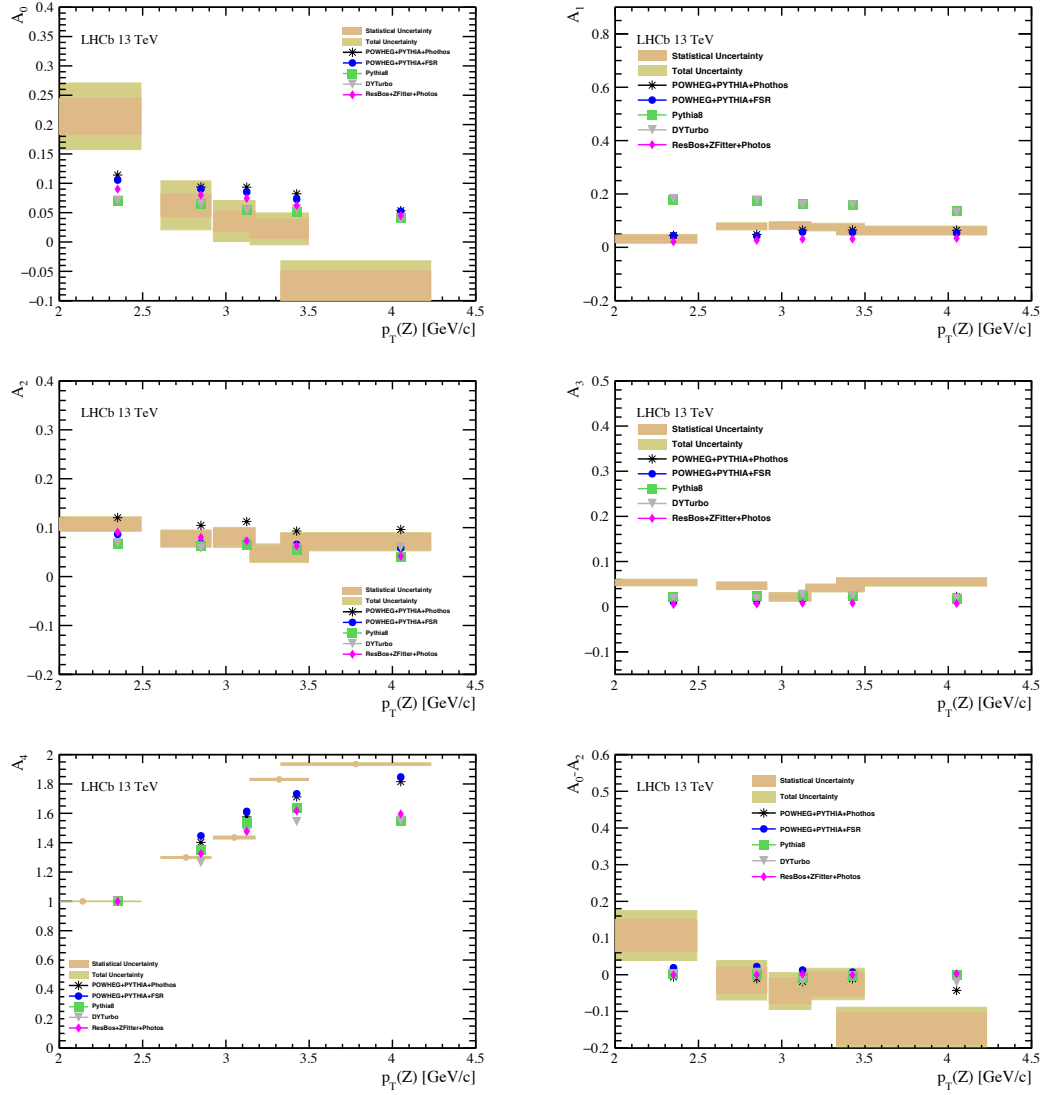


Figure 195: The determined results of the A_i and $A_0 - A_2$ in 1812 dataset, as a function of the Z boson rapidity, are compared with different theoretical predictions.



B.3.3 Results with low Z boson p_T events in 2017 and 2018 datasets

The measured results with low Z boson p_T events in 2017 dataset are shown in Figure 197. The measured central values and uncertainties of the coefficients with low Z boson p_T events in 2017 are listed in Table 43. While Figure 198 and Table 44 shows the result in 2018 dataset.

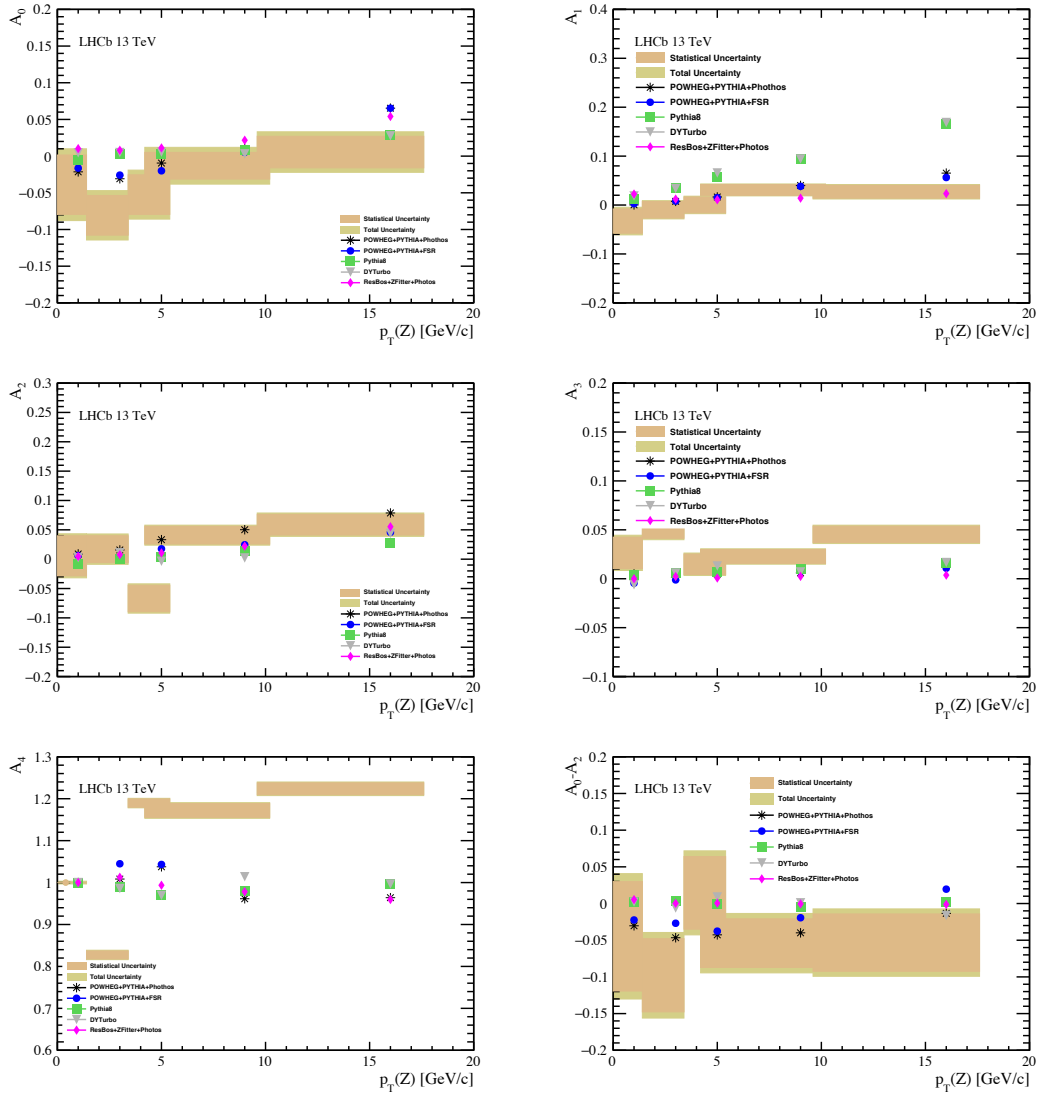


Figure 196: The determined results of the A_i and $A_0 - A_2$ in lower Z p_T region, compared with different theoretical predictions in 2017 data.



Table 42: The measured angular coefficients A_0 to A_4 and $A_0 - A_2$ in bins of low Z p_T region, using Z boson events with $y > 2.0$ in 2017 dataset.

$p_T(Z)$ [GeV]	A_0	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_1	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_2	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-2	-0.0389	0.0418	0.0275	-0.0328	0.0248	0.0135	0.0057	0.0341	0.0157
2-4	-0.0807	0.0303	0.0200	-0.0097	0.0168	0.0081	0.0171	0.0228	0.0122
4-6	-0.0525	0.0289	0.0197	0.0002	0.0162	0.0076	-0.0670	0.0225	0.0108
6-12	-0.0131	0.0233	0.0173	0.0309	0.0110	0.0053	0.0409	0.0150	0.0081
12-20	0.0055	0.0241	0.0173	0.0271	0.0131	0.0070	0.0588	0.0176	0.0094
$p_T(Z)$ [GeV]	A_3	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_4	$\pm\delta_{stat}$	$\pm\delta_{syst}$	$A_0 - A_2$	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-2	0.0264	0.0160	0.0082	1.0000	0.0295	0.0033	-0.0447	0.0529	0.0418
2-4	0.0521	0.0108	0.0057	0.8273	0.0095	0.0062	-0.0978	0.0354	0.0303
4-6	0.0148	0.0104	0.0049	1.1896	0.0099	0.0056	0.0145	0.0351	0.0289
6-12	0.0227	0.0071	0.0035	1.1719	0.0164	0.0090	-0.0540	0.0236	0.0233
12-20	0.0454	0.0083	0.0044	1.2237	0.0141	0.0081	0.0000	0.0000	0.0241

Table 43: The measured angular coefficients A_0 to A_4 and $A_0 - A_2$ in bins of low Z p_T region, using Z boson events with $y > 2.0$ in 2017 dataset.

$p_T(Z)$ [GeV]	A_0	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_1	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_2	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-2	-0.0389	0.0418	0.0275	-0.0328	0.0248	0.0135	0.0057	0.0341	0.0157
2-4	-0.0807	0.0303	0.0200	-0.0097	0.0168	0.0081	0.0171	0.0228	0.0122
4-6	-0.0525	0.0289	0.0197	0.0002	0.0162	0.0076	-0.0670	0.0225	0.0108
6-12	-0.0131	0.0233	0.0173	0.0309	0.0110	0.0053	0.0409	0.0150	0.0081
12-20	0.0055	0.0241	0.0173	0.0271	0.0131	0.0070	0.0588	0.0176	0.0094
$p_T(Z)$ [GeV]	A_3	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_4	$\pm\delta_{stat}$	$\pm\delta_{syst}$	$A_0 - A_2$	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-2	0.0264	0.0160	0.0082	1.0000	0.0295	0.0033	-0.0447	0.0529	0.0418
2-4	0.0521	0.0108	0.0057	0.8273	0.0095	0.0062	-0.0978	0.0354	0.0303
4-6	0.0148	0.0104	0.0049	1.1896	0.0099	0.0056	0.0145	0.0351	0.0289
6-12	0.0227	0.0071	0.0035	1.1719	0.0164	0.0090	-0.0540	0.0236	0.0233
12-20	0.0454	0.0083	0.0044	1.2237	0.0141	0.0081	0.0000	0.0000	0.0241

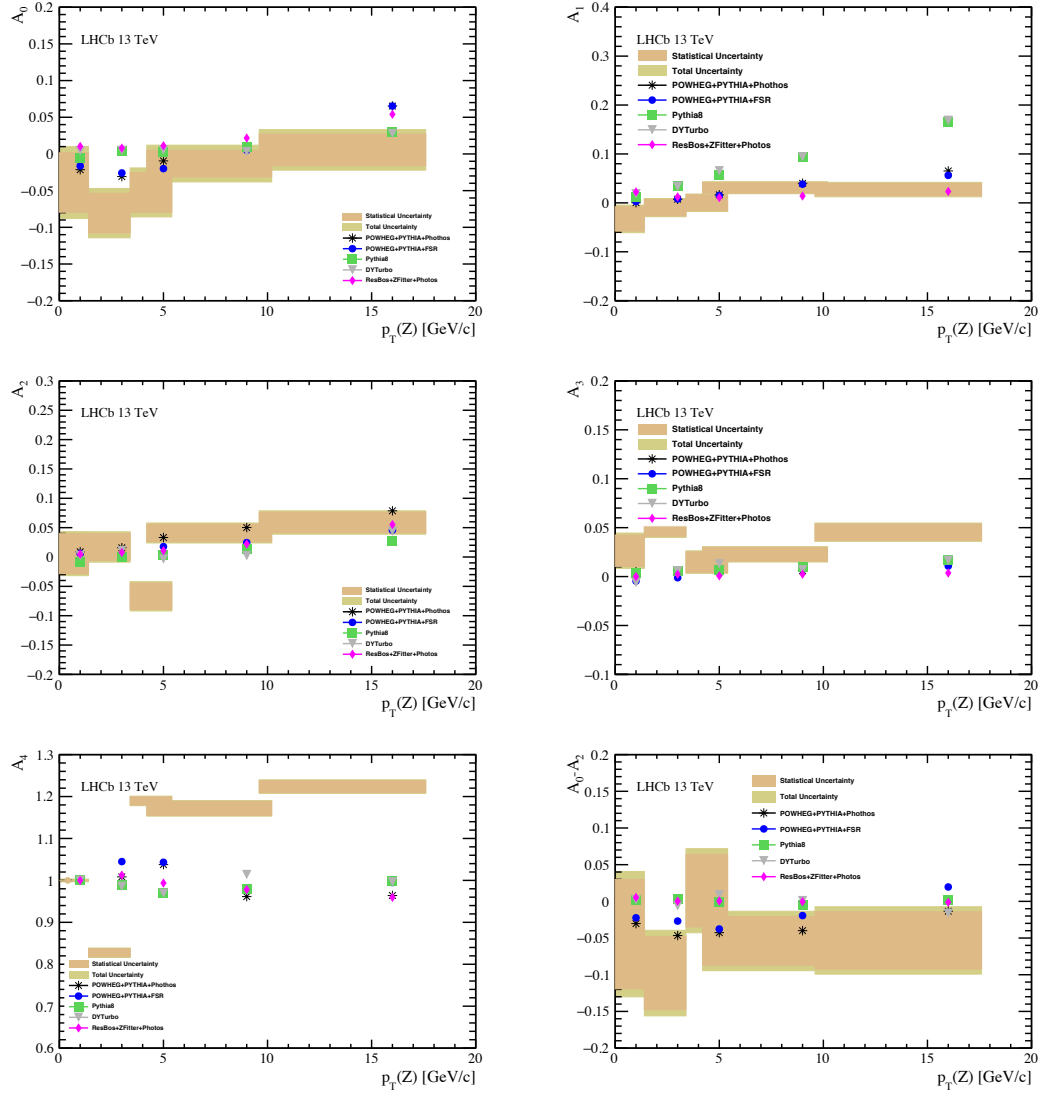


Figure 197: The determined results of the A_i and $A_0 - A_2$ in lower Z p_T region, compared with different theoretical predictions in 2017 data.

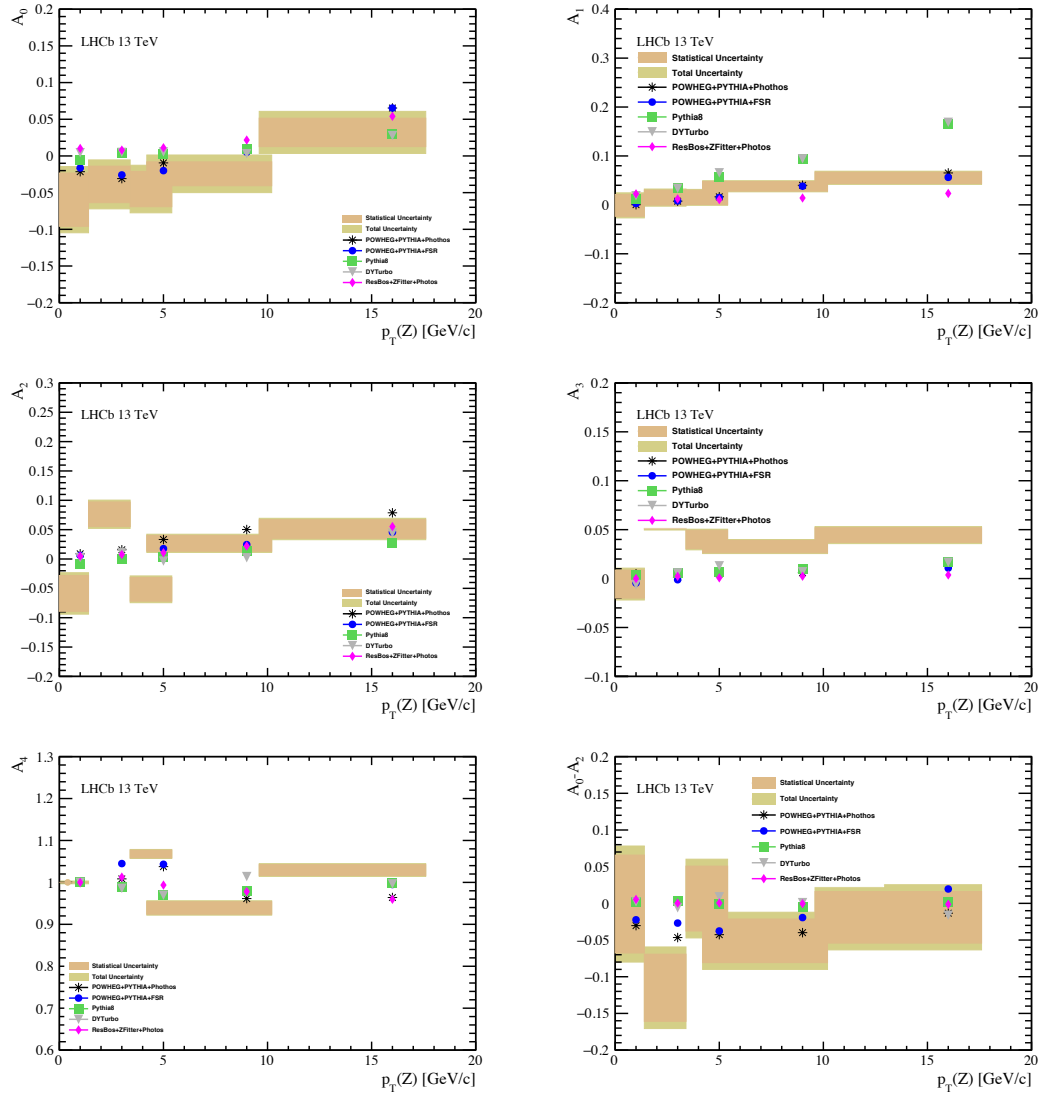


Figure 198: The determined results of the A_i and $A_0 - A_2$ in lower Z p_T region, compared with different theoretical predictions in 2018 data.



Table 44: The measured angular coefficients A_0 to A_4 and $A_0 - A_2$ in bins of low Z p_T region, using Z boson events with $y > 2.0$ in 2018 dataset.

$p_T(Z)$ [GeV]	A_0	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_1	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_2	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-2	-0.0596	0.0425	0.0268	-0.0010	0.0223	0.0126	-0.0587	0.0304	0.0179
2-4	-0.0388	0.0316	0.0222	0.0149	0.0153	0.0086	0.0763	0.0209	0.0120
4-6	-0.0451	0.0304	0.0217	0.0153	0.0146	0.0073	-0.0516	0.0201	0.0107
6-12	-0.0243	0.0252	0.0198	0.0380	0.0098	0.0057	0.0267	0.0135	0.0077
12-20	0.0321	0.0272	0.0211	0.0553	0.0116	0.0068	0.0511	0.0158	0.0092
$p_T(Z)$ [GeV]	A_3	$\pm\delta_{stat}$	$\pm\delta_{syst}$	A_4	$\pm\delta_{stat}$	$\pm\delta_{syst}$	$A_0 - A_2$	$\pm\delta_{stat}$	$\pm\delta_{syst}$
0-2	-0.0056	0.0143	0.0078	1.0000	0.0266	0.0033	-0.0009	0.0474	0.0425
2-4	0.0609	0.0099	0.0054	0.7752	0.0085	0.0058	-0.1150	0.0325	0.0316
4-6	0.0400	0.0093	0.0051	1.0678	0.0090	0.0059	0.0065	0.0314	0.0304
6-12	0.0327	0.0063	0.0034	0.9390	0.0148	0.0086	-0.0511	0.0211	0.0252
12-20	0.0444	0.0075	0.0045	1.0295	0.0128	0.0083	0.0000	0.0000	0.0272



C Appendix-Measurements of high- p_T muon reconstruction efficiency for the LHCb RunII data-sets

C.1 Magnet Polarity and muon charge dependence

The muon efficiencies are studied in two sub-samples, which are collected with different magnet polarities (*MagUp* and *MagDown*). Also, muon probes are split by charge. Comparisons of muon efficiency with different polarities and charges are shown in Figure 199 to Figure 206. For most of bins, within statistical uncertainty, there are no significant differences between them.

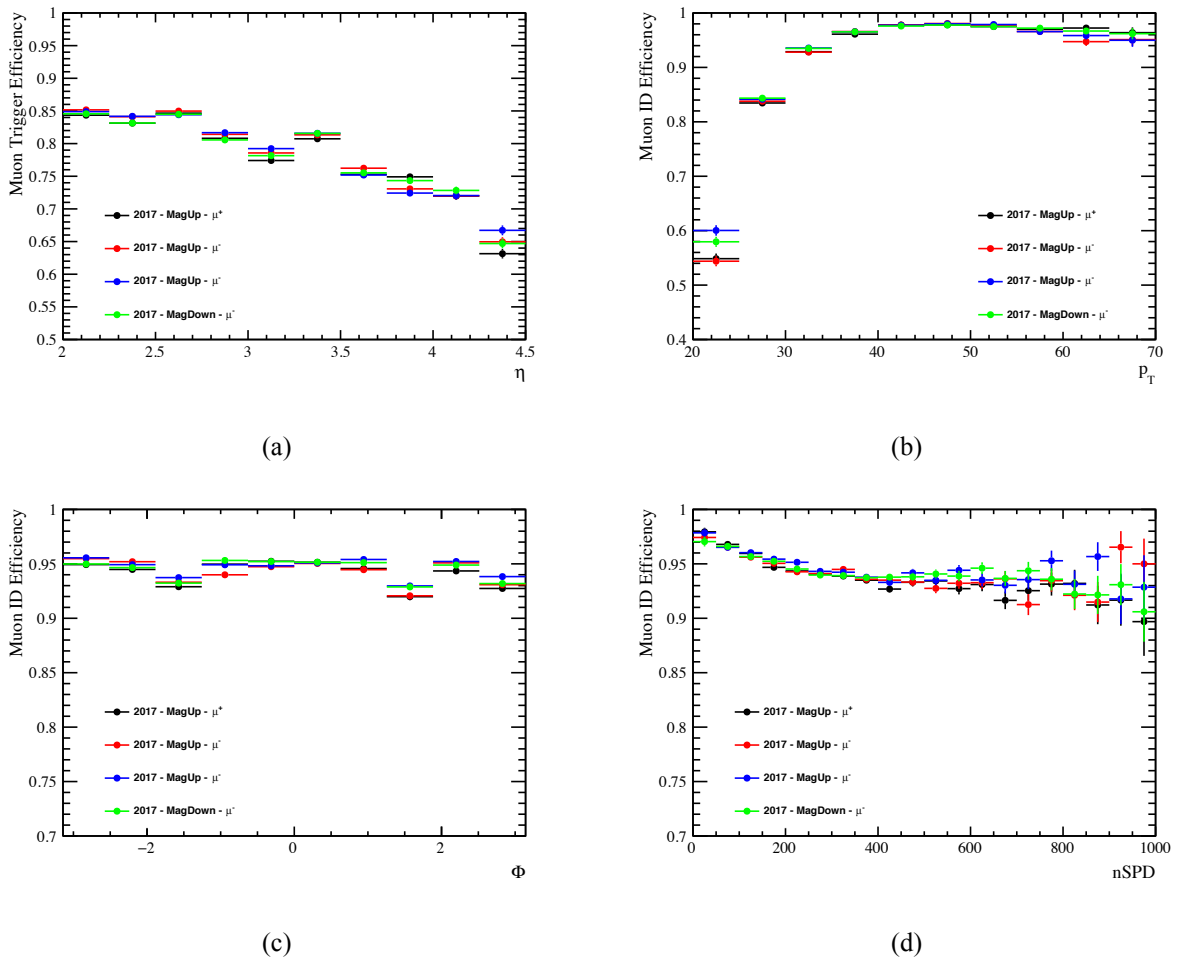
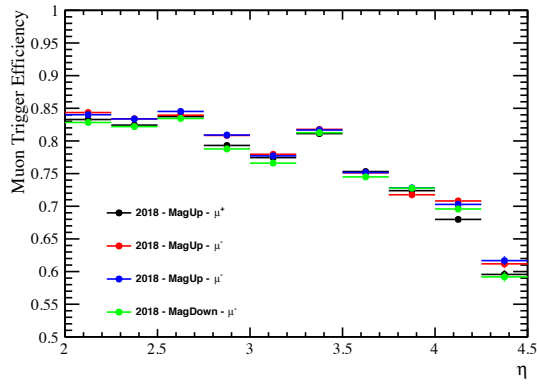
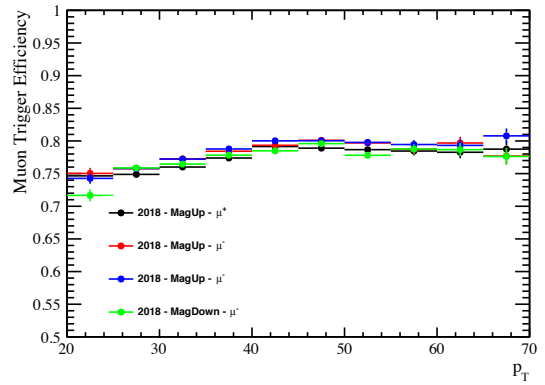


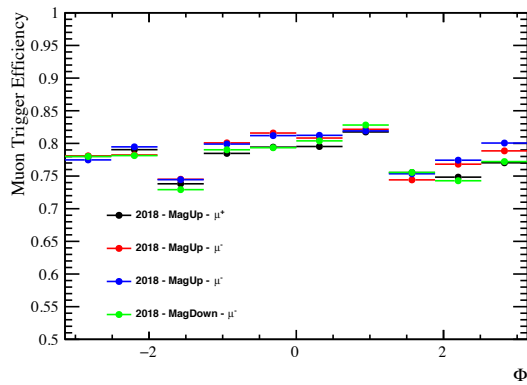
Figure 199: The muon trigger efficiency measured for by different charge and polarity, in 2017 data, as a function of muon η (a), muon p_T (b), muon ϕ (c), and SPD multiplicity (d).



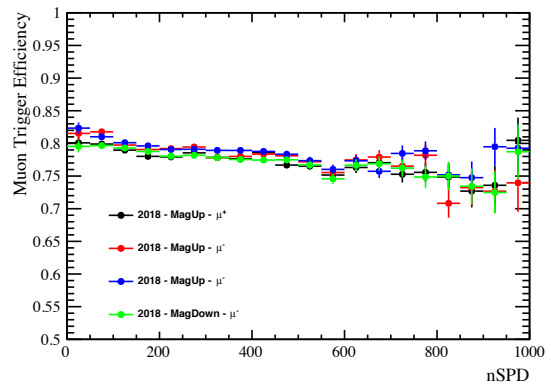
(a)



(b)

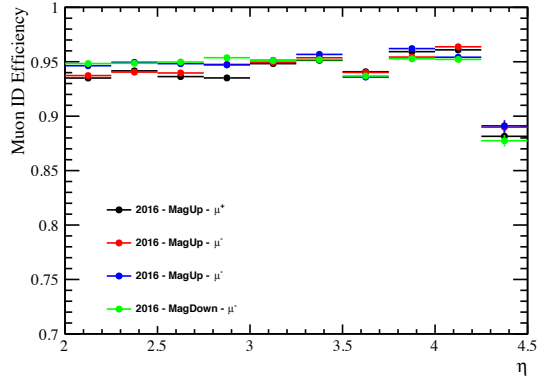


(c)

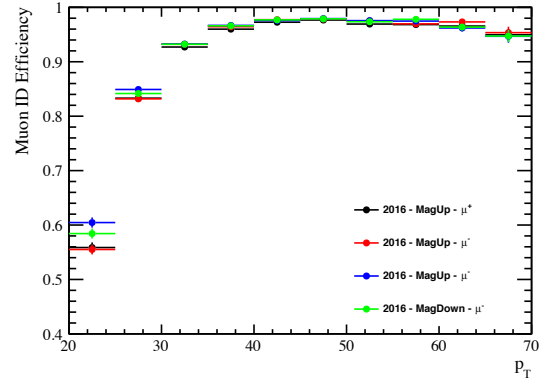


(d)

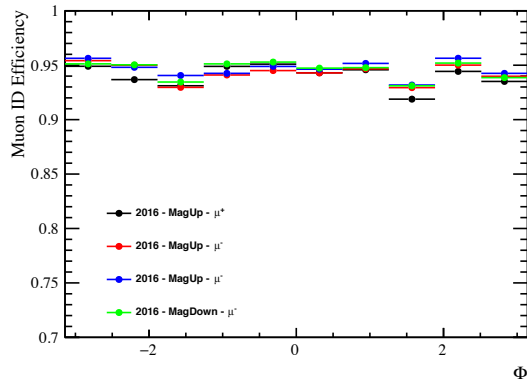
Figure 200: The muon trigger efficiency measured for by different charge and polarity, in 2018 data, as a function of muon η (a), muon p_T (b), muon ϕ (c), and SPD multiplicity (d).



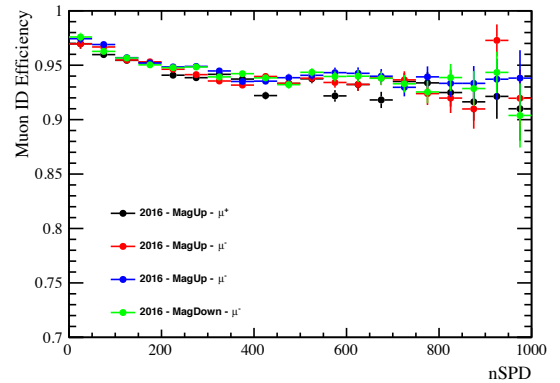
(a)



(b)

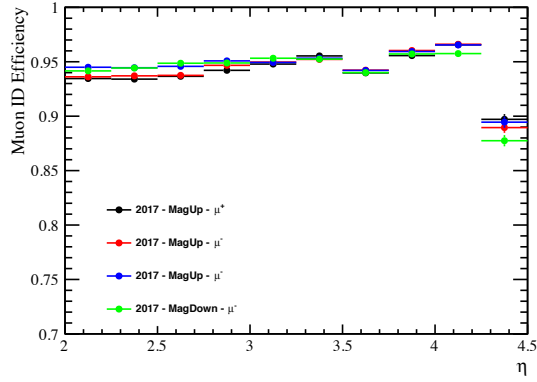


(c)

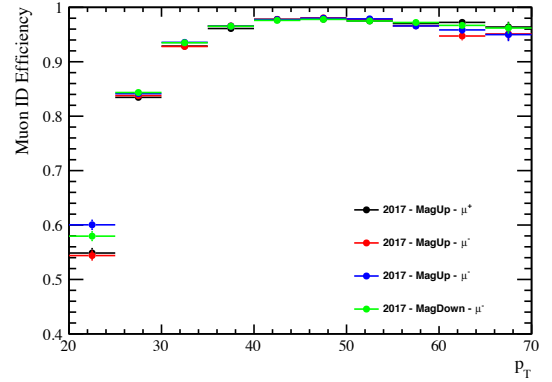


(d)

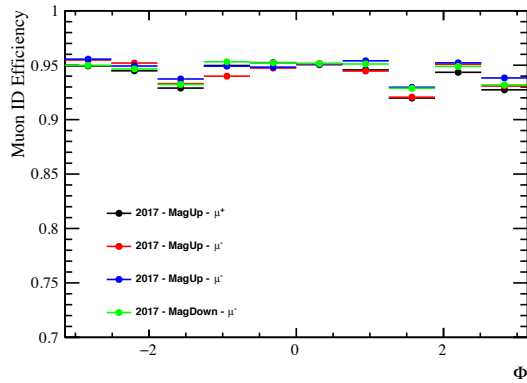
Figure 201: The muon identification efficiency measured for by different charge and polarity, in 2016 data, as a function of muon η (a), muon p_T (b), muon ϕ (c), and SPD multiplicity (d).



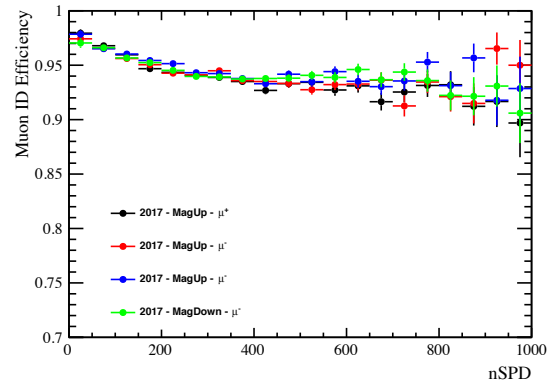
(a)



(b)

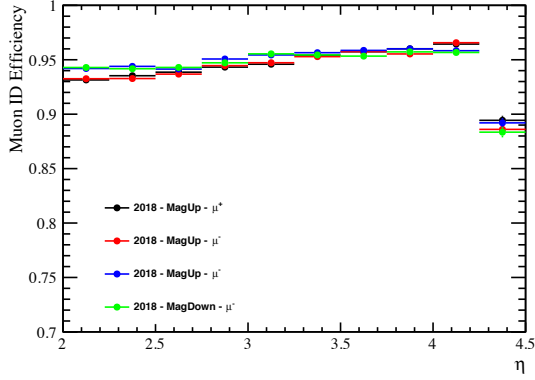


(c)

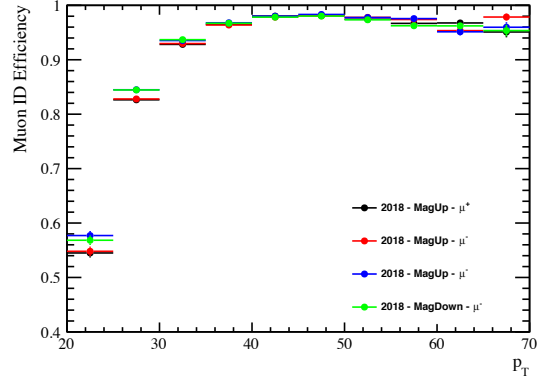


(d)

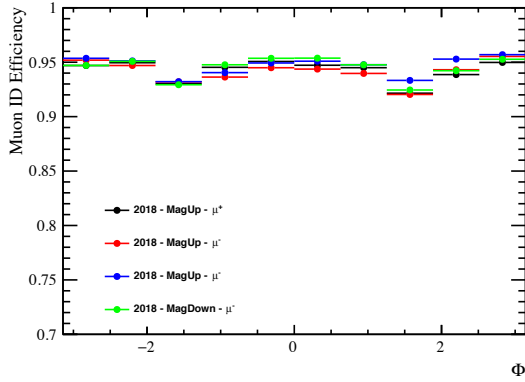
Figure 202: The muon identification efficiency measured for by different charge and polarity, in 2017 data, as a function of muon η (a), muon p_T (b), muon ϕ (c), and SPD multiplicity (d).



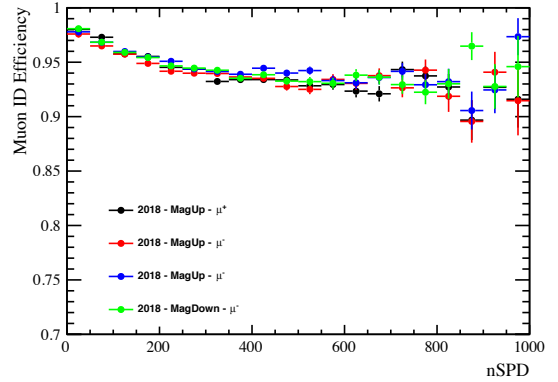
(a)



(b)

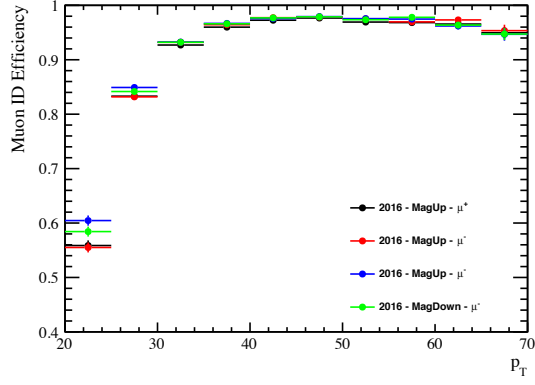


(c)

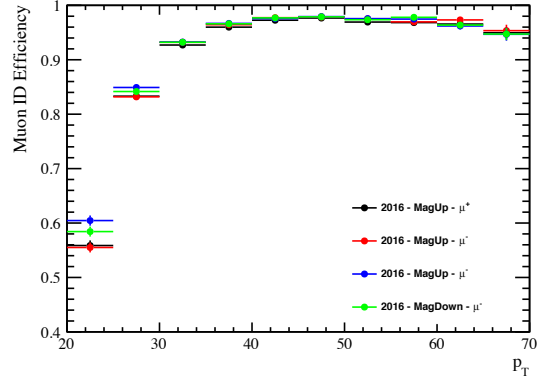


(d)

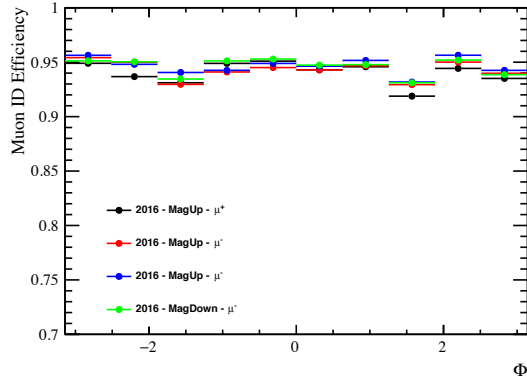
Figure 203: The muon identification efficiency measured for by different charge and polarity, in 2018 data, as a function of muon η (a), muon p_T (b), muon ϕ (c), and SPD multiplicity (d).



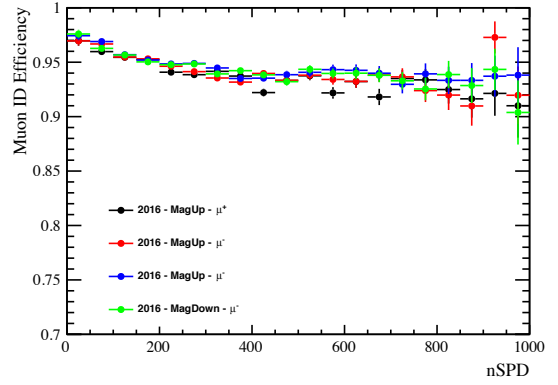
(a)



(b)

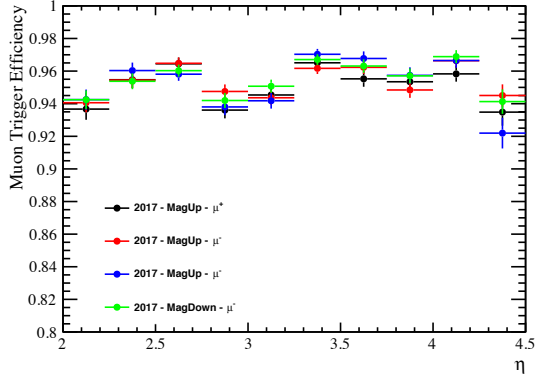


(c)

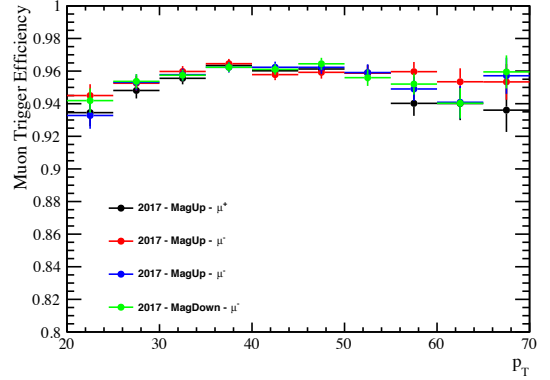


(d)

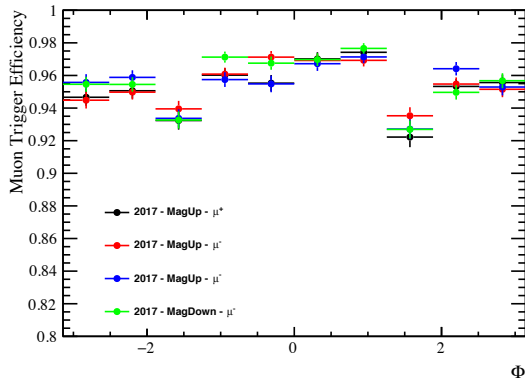
Figure 204: The muon tracking efficiency measured for by different charge and polarity, in 2016 data, as a function of muon η (a), muon p_T (b), muon ϕ (c), and SPD multiplicity (d).



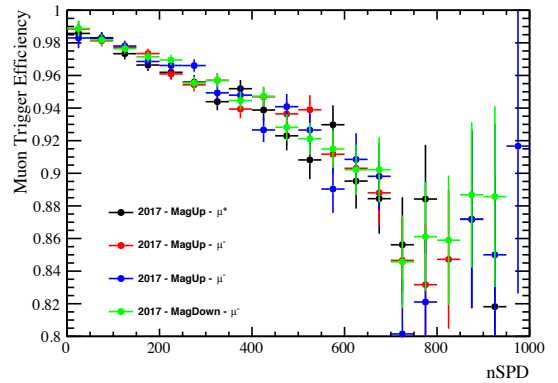
(a)



(b)

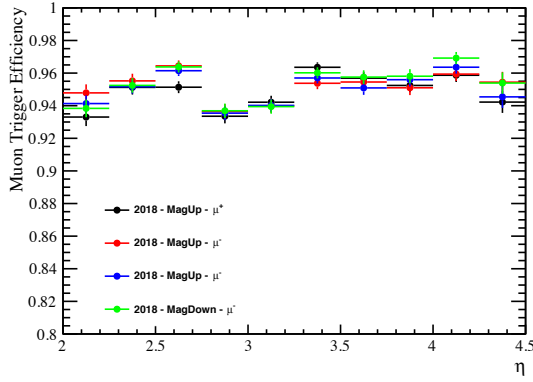


(c)

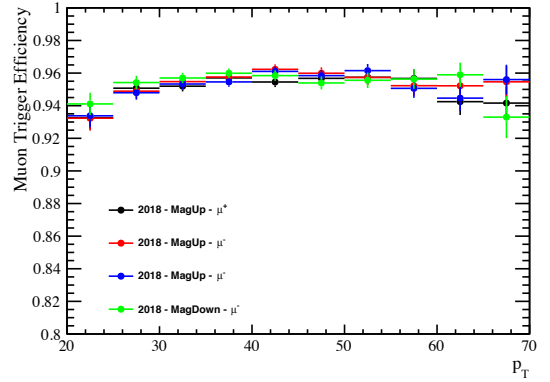


(d)

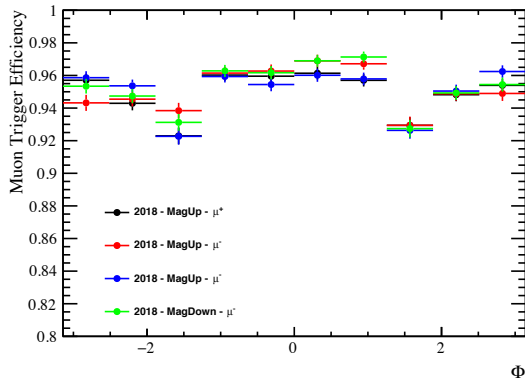
Figure 205: The muon tracking efficiency measured for by different charge and polarity, in 2017 data, as a function of muon η (a), muon p_T (b), muon ϕ (c), and SPD multiplicity (d).



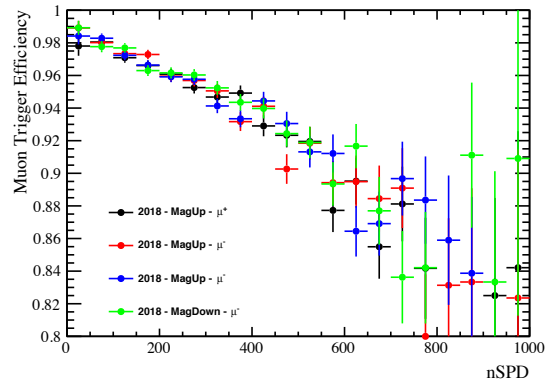
(a)



(b)



(c)



(d)

Figure 206: The muon tracking efficiency measured for by different charge and polarity, in 2018 data, as a function of muon η (a), muon p_T (b), muon ϕ (c), and SPD multiplicity (d).



C.2 Muon trigger efficiencies of each trigger stage

The muon trigger efficiency for a muon to pass all trigger stages was presented in Section 6.2.1. In this section, the trigger efficiency is divided into sub-stage (L0, HLT1 and HLT2). The measured L0 muon trigger efficiency is shown in Figure 207. With respect to L0 trigger selection, the measured HLT1 muon trigger efficiency is shown in Figure 208. Similarly, based on L0 and HLT1 trigger selections, the measured HLT2 muon trigger efficiency is shown in Figure 209. The HLT1 trigger efficiency has an inverse dependence on muon p_T , compared to that of L0.

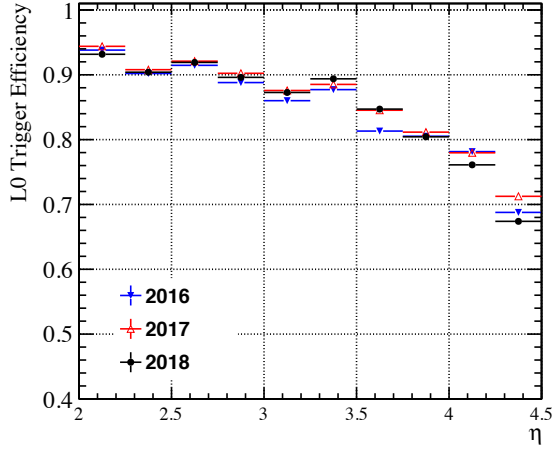
C.3 Isolation efficiency

C.3.1 Tag-and-Probe selection

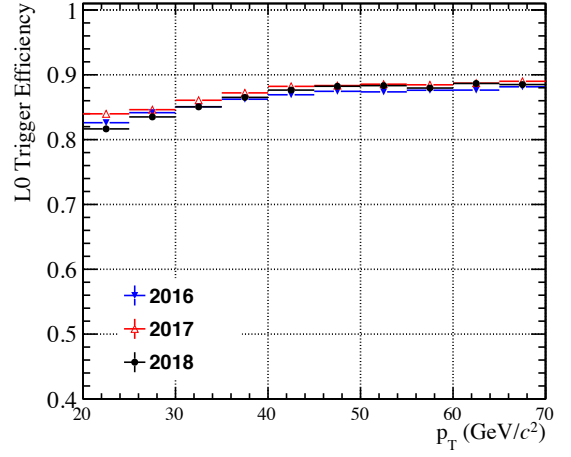
The muon isolation efficiency is an efficiency of identify a real muon to pass muon isolation requirement, as a real muon from Z boson is expected to be isolated in detector, while for a muon from semileptonically decay of heavy flavour hadron, which has additional particles around it. In some precision electroweak measurement, the muon isolation cut is employed to suppress background contribution from heavy flavour. Therefore, we discussed an efficiency study for this cut.

In this study, the $Z \rightarrow \mu^+\mu^-$ events are used, with the tag-and-probe method. The tag must be a fully reconstructed, identified and triggered muon, and the probe is a identified long track, passed muon identification requirement (`isMuon`). The tag muon is further required to have $p_T > 20 \text{ GeV}$, $2.0 < \eta < 4.5$, isolated ($I_T^{\text{charged}} > 0.85$). while probe is required to have $p_T > 20 \text{ GeV}$, $2.0 < \eta < 4.5$. Both tag and probe are required be a long track with relative momentum uncertainty less than 10%. The invariant mass of the tag and probe is required in the mass region of $[60, 120] \text{ GeV}$. To select a sample with high purity, additional event requirements are also placed on candidate events, including candidate events must have an azimuthal separation, $|\Delta\phi|$, greater than 2.7 radians. The tag-and-probe selection requirements used in this study are summarized in Table 45.

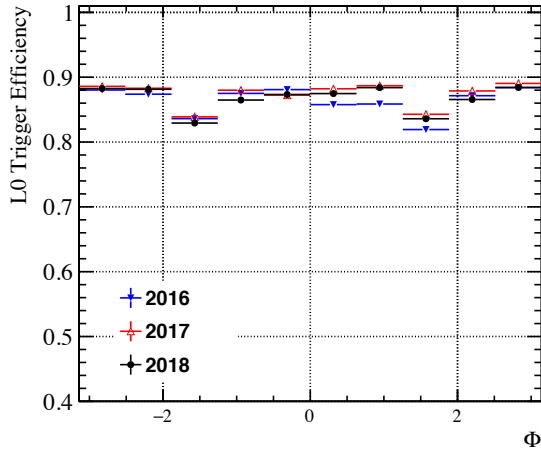
The muon identification efficiency is calculated by counting the number of probes within the selected sample satisfying a isolated ($I_T^{\text{charged}} > 0.85$) requirement.



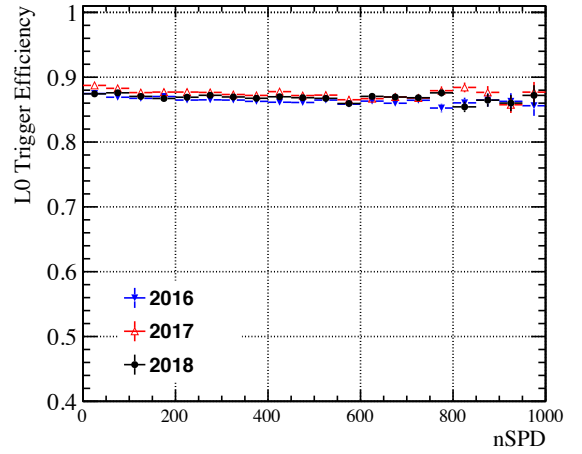
(a)



(b)

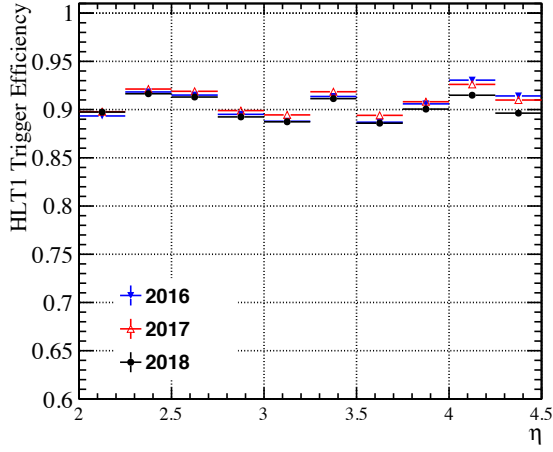


(c)

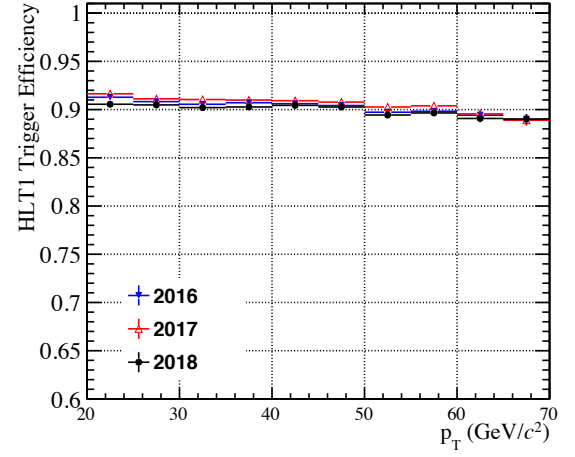


(d)

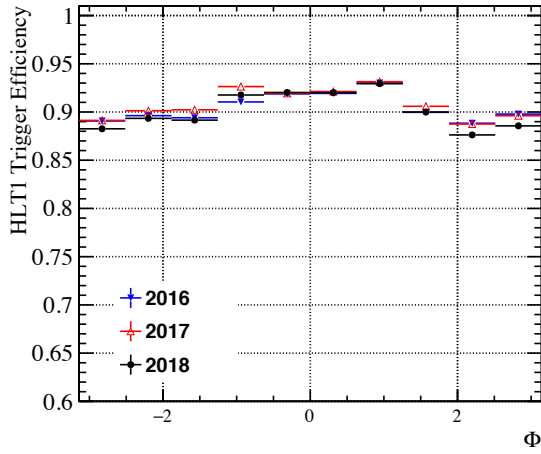
Figure 207: The L0 trigger efficiency in 2016, 2017 and 2018 data-sets, as a function of muon η (a), muon p_T (b), muon ϕ (c) and SPD multiplicity (d).



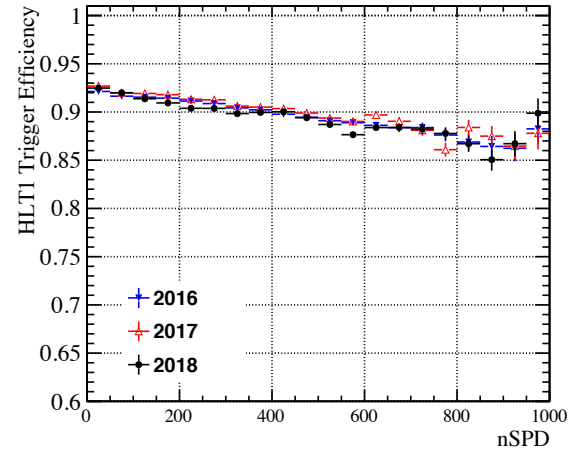
(a)



(b)

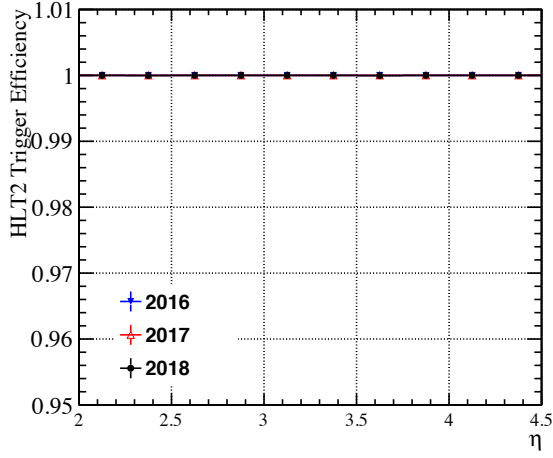


(c)

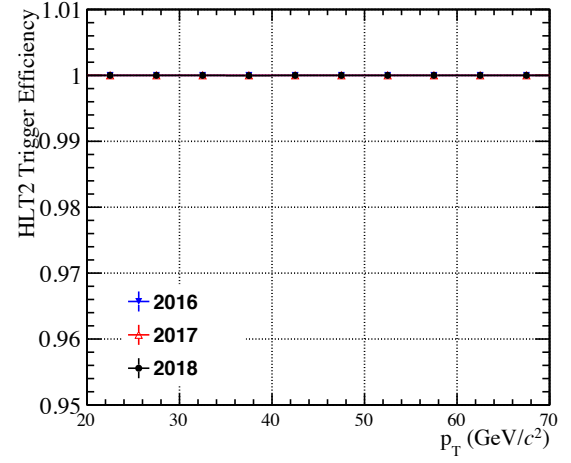


(d)

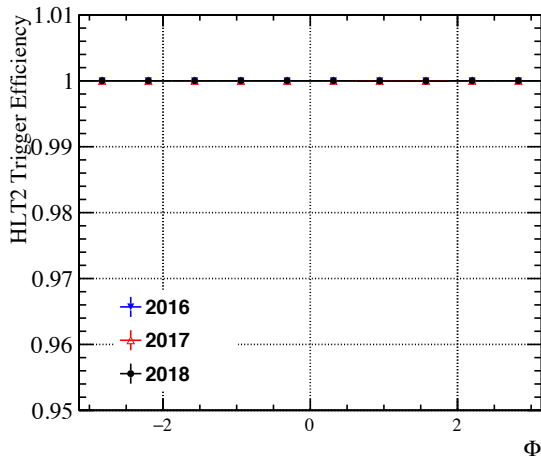
Figure 208: The HLT1 trigger efficiency in 2016, 2017 and 2018 data-sets, as a function of muon η (a), muon p_T (b), muon ϕ (c) and SPD multiplicity (d).



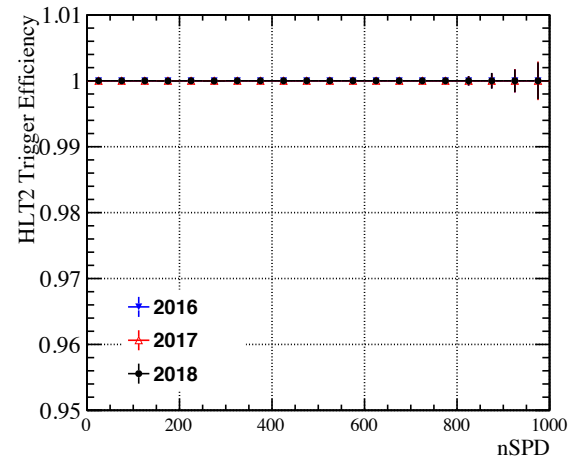
(a)



(b)



(c)



(d)

Figure 209: The HLT2 trigger efficiency in 2016, 2017 and 2018 data-sets, as a function of muon η (a), muon p_T (b), muon ϕ (c) and SPD multiplicity (d).



Table 45: The tag and probe selection used for muon Isolation efficiency study.

Tag	Probe	Event
Long track isMuon Triggered $\sigma_P/P < 0.1$ $p_T > 20 \text{ GeV}$ $2 < \eta < 4.5$ $I_T^{\text{charged}} > 0.85$	Long track isMuon - $p_T > 20 \text{ GeV}$ $2.0 < \eta < 4.5$	$60 < M_{\mu\mu} < 120 \text{ GeV}$ $ \Delta\phi > 2.7$ $\chi^2_{\text{vtx}}/\text{ndf} < 5$

C.3.2 MC muon isolation efficiency

The muon isolation efficiency obtained with Truth method is compared with that of tag-and-probe method, using the simulated $Z \rightarrow \mu^+\mu^-$ events, to vary the method. The results are shown in Figure 210, as a function of muon η and muon p_T . Good agreements are seen in all regions, except in the low p_T region there is a small discrepancy, due to the statistic limitation. Therefore, no bias is introduced by the tag-and-probe method, and the tag-and-probe method is stable and robust to determines the muon isolation efficiency.

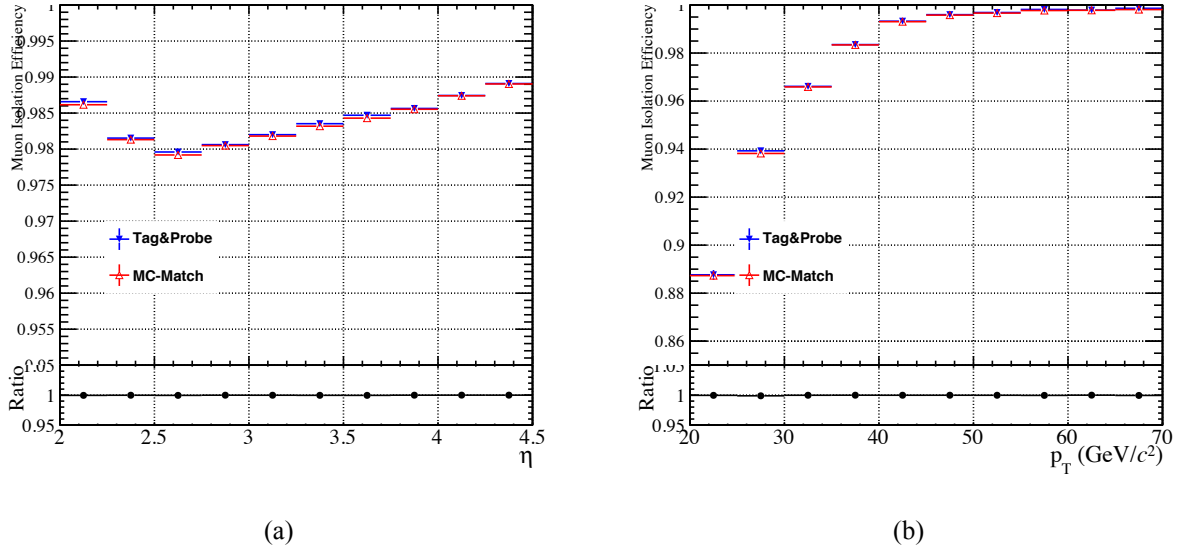


Figure 210: The muon isolation efficiency calculated as a function of muon η (a) and p_T (b) in simulated $Z \rightarrow \mu^+\mu^-$ events, using ‘Truth method’ and the ‘tag-and-probe method’.



C.3.3 Background estimation

As discussed in Sec. 7.7.3, the impacts of background contribution to the muon isolation efficiency could be ignored.

C.3.4 Systematic uncertainties

Similar to systematic uncertainty estimation of muon identification efficiency, no systematic uncertainty is assigned to the muon isolation efficiency, for both the tag-and-probe method and background contribution. The uncertainty of muon isolation efficiency is only from statistical precision of the $Z \rightarrow \mu^+\mu^-$ sample. The uncertainty in different bins of phase space varies between 0.002% and 0.004% for 2016, 2017, and 2018 data-sets.

C.3.5 Results

The muon isolation efficiency is calculated using the tag-and-probe method, for 2016, 2017 and 2018 data-sets, as a function of different variables. The measured efficiency is shown in Figure 211, as a function of different event and kinematic variables. While good agreements of efficiencies amount these three data-sets are seen.

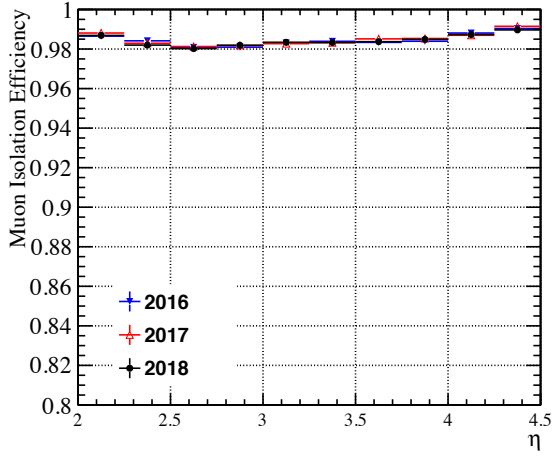
D Appendix-Improved-alignment and momentumcalibration for physics with highmomentum muons in LHCb

D.1 More tests on ‘Improved-alignment’

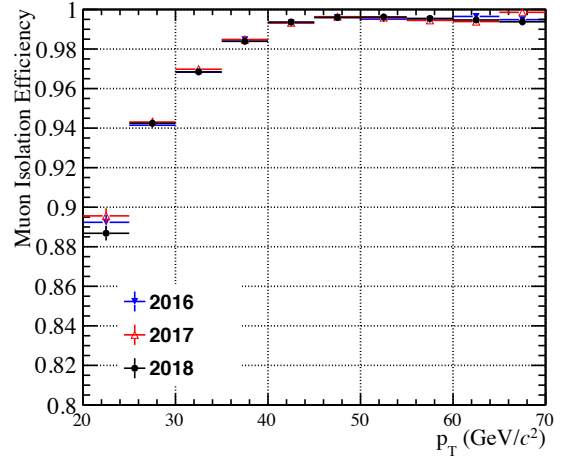
As discussed in Section 8.3.1, the T-station alignment is performed with default setting. Based on that, two additional alignments are studied, which are `TTITOTzCVeloModulesZRyRx` and `TTITOTzVeloModulesZRyRx`. The differences between them are listed below:

- `TTITOTzCVeloModulesZRyRx`: add z alignment for OT, but fixes the T3 station such that the z -scale is not completely free
- `TTITOTzVeloModulesZRyRx`: removes the constraint on T3.

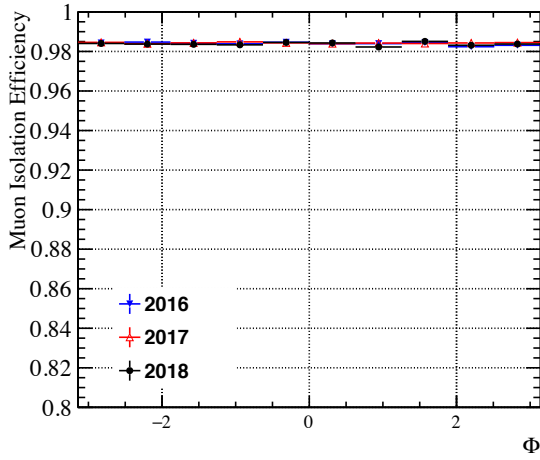
The comparisons of alignment results with different alignment settings, are shown in Figure 212. From where, the default `TTITOTVeloModulesZRyRx` has the best performance.



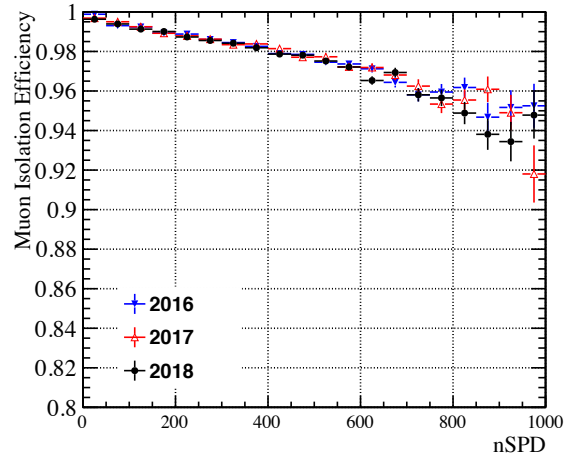
(a)



(b)



(c)



(d)

Figure 211: Muon isolation efficiency for 2016, 2017 and 2018 data-sets, as a function of muon η (a), muon p_T (b), muon ϕ (c) and the SPD multiplicity (d).

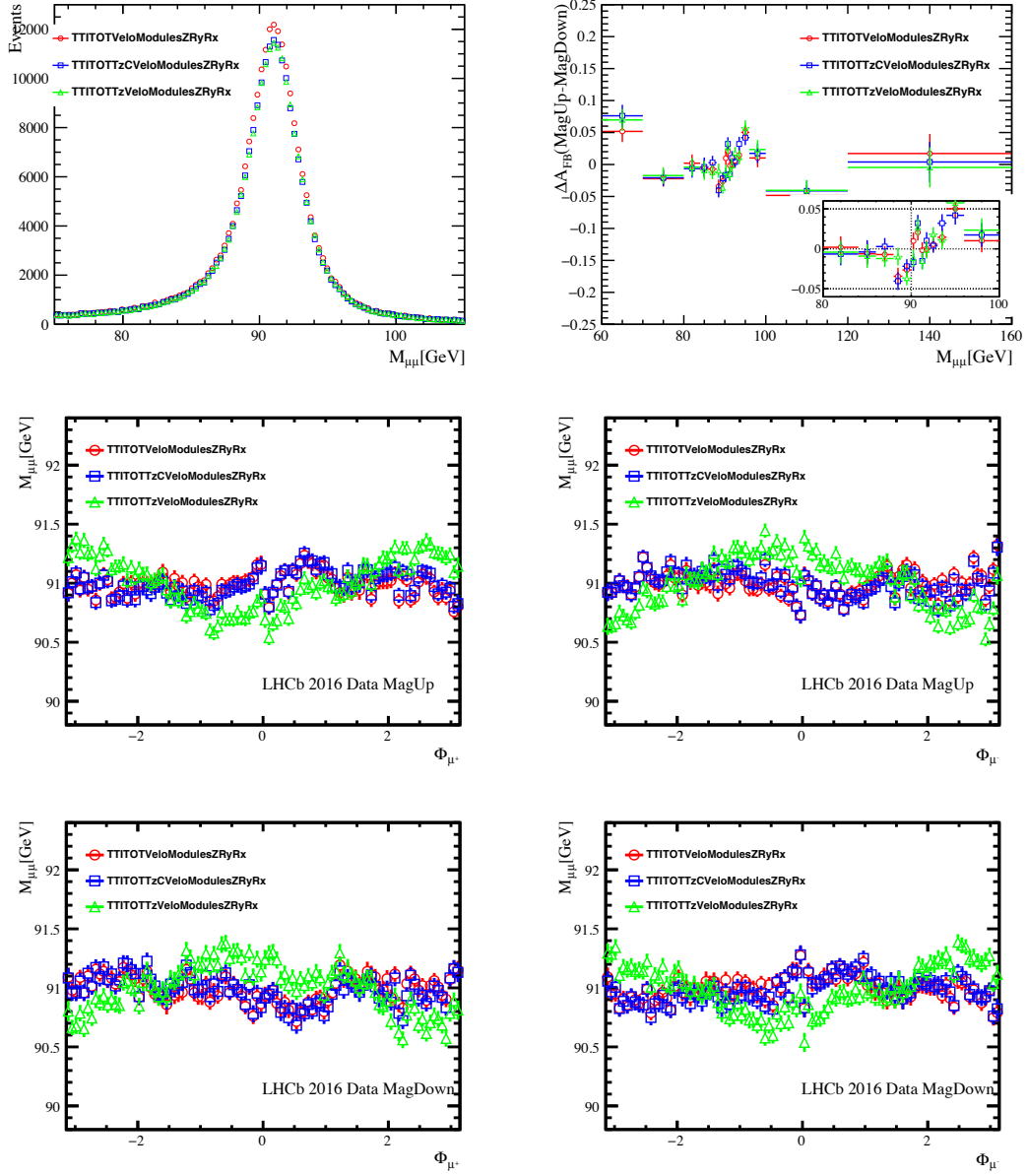


Figure 212: The comparisons between different alignment settings. (top-left) is A_{FB} differences distribution, (top-right) is $m(\mu^+\mu^-)$ distribution, (bottom) is the Z^0 mass peak position in different $\mu^+\mu^- \phi$ regions, of MagUp, MagDown samples.



D.2 Number of iterations in ‘Improved-alignment’

The TTITOT and VELO alignments are done with four iterations. Different number of iterations of alignment have been studied, as shown in Figure 213 and Figure 214. We found that four iterations is sufficient enough for the ‘Improved-alignment’.

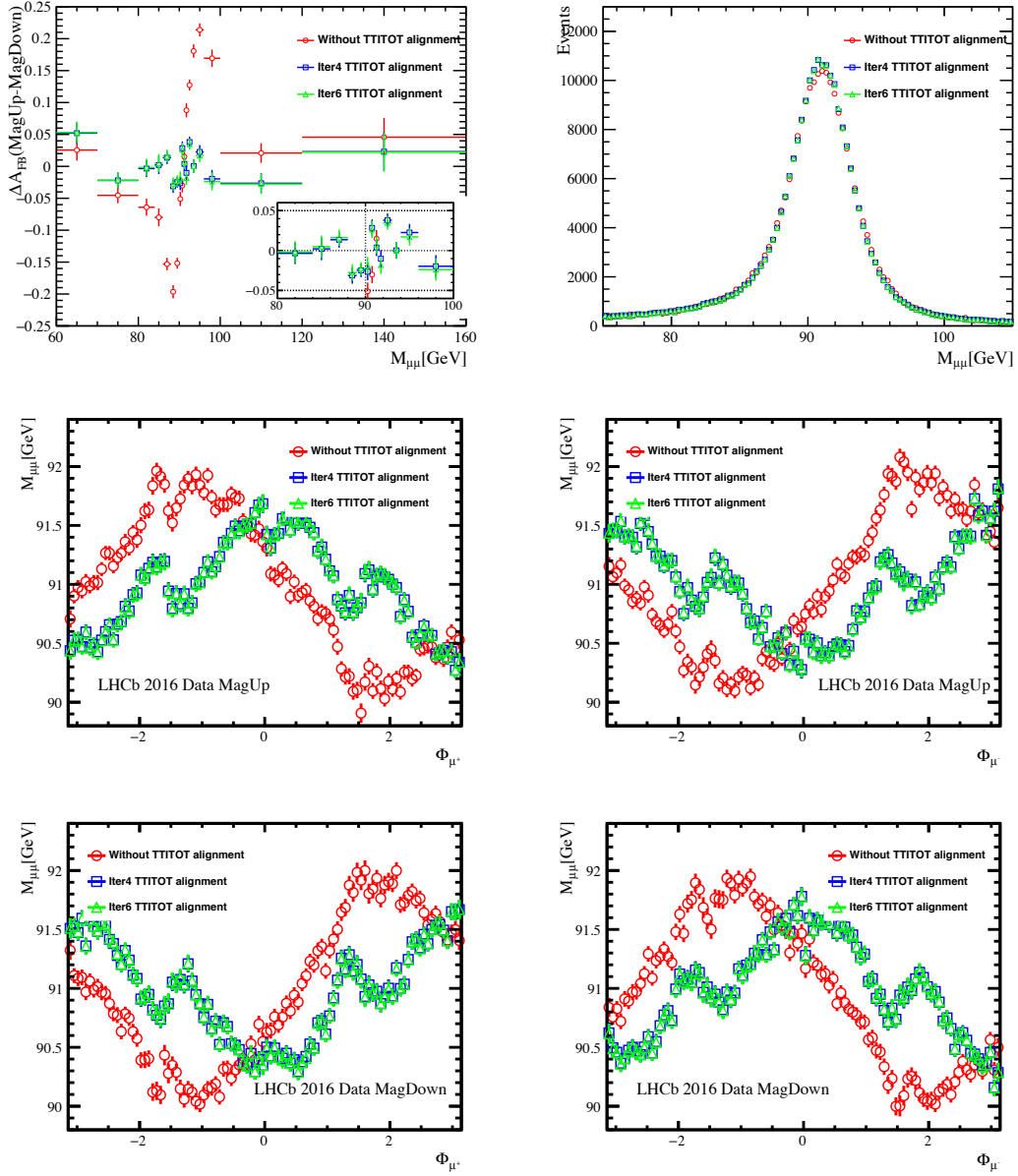


Figure 213: The comparisons for results with different number of iterations for the TTITOT alignment. (top-left) is A_{FB} differences distribution, (top-right) is $m(\mu^+\mu^-)$ distribution, (bottom) four figures are the Z^0 mass peak position in different $\mu^+\mu^- \phi$ regions, of MagUp, MagDown samples.

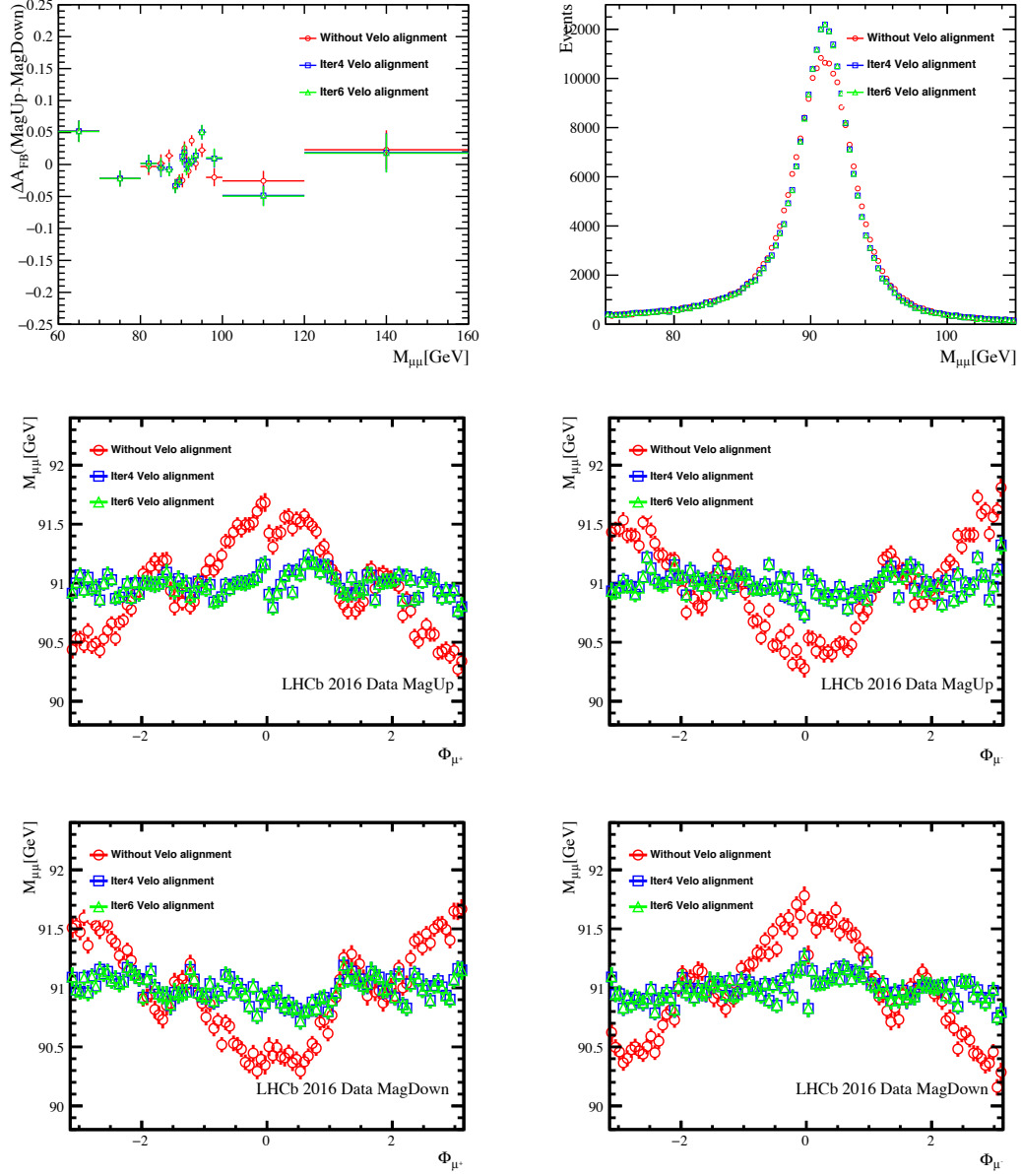


Figure 214: The comparisons for results with different number of iterations for the VELO alignment. (top-left) is A_{FB} differences distribution, (top-right) is $m(\mu^+\mu^-)$ distribution, (bottom) four figures are the Z^0 mass peak position in different $\mu^+\mu^-\phi$ regions, of MagUp, MagDown samples.



D.3 Only with ‘Post-alignment’?

Based on studied in Section 8.4, the ‘Post-alignment’ could largely remove the remaining misalignment effects, and suppress the difference between MagDown A_{FB} and MagUp A_{FB} . So, in this section, we checked the A_{FB} differences between MagDown and MagUp, without ‘Improved-alignment’. By comparing the A_{FB} distributions of these two procedures, we concluded that both ‘Improved-alignment’ and ‘Post-alignment’ are necessary for the muon momentum calibration. The results are shown in Figure 215.

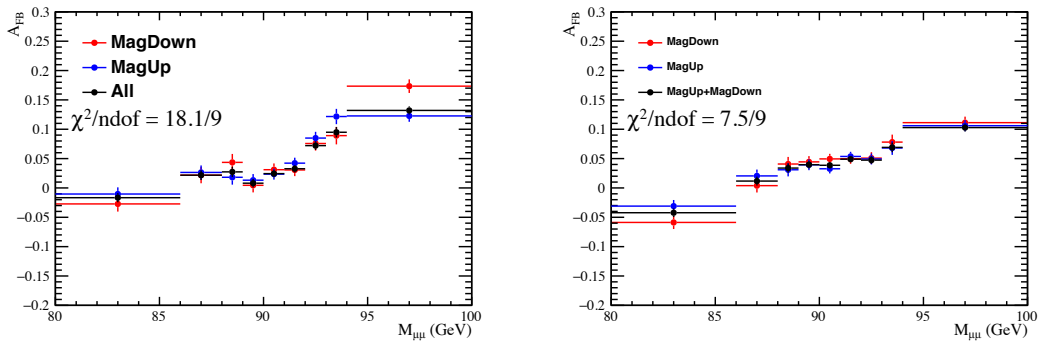


Figure 215: Comparisons of A_{FB} obtained using two different alignment procedures. (left) is A_{FB} distribution obtained only with ‘Post-alignment’ applied, while (right) is A_{FB} distribution obtained with both ‘Improved-alignment’ and ‘Post-alignment’ applied.

D.4 Different strategies for ‘Post-alignment’

In ‘Post-alignment’, if the remaining differences of A_{FB} are from misalignment effects, then we should expect these new track bias correction parameters should be stable for both MagDown and MagUp data sets, but with reversed signs. Figure 216 shows the A_{FB} distribution with three different parameter shared strategies, where ‘Post-alignment’ without any shared parameters has best performance. The other two strategies cannot suppress the differences between MagDown and MagUp A_{FB} . Possible reason for this is that ‘Post-alignment’ does not perform track refit after bias corrections. As we are planning to merge ‘custom alignment’ and ‘Post-alignment’ one detector level alignment for Run-3 data set, which is expected to solve this problem.

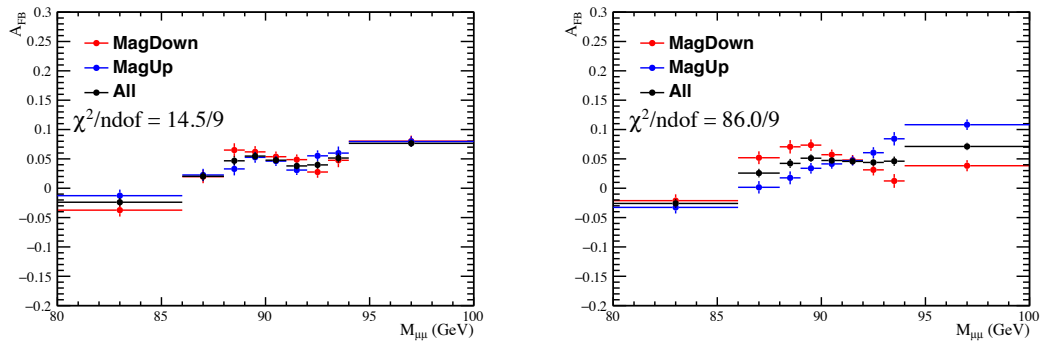


Figure 216: Comparisons of A_{FB} distribution obtained using three different input parameter strategies. (top-left) is A_{FB} distribution obtained with parameters that shared with MagDown, MagUp, for both μ^+ and μ^- . (top-right) is A_{FB} distribution obtained with MagDown- μ^+ , MagUp- μ^- share one bias correction parameter, while MagDown- μ^- , MagUp- μ^+ share other set. (bottom) is A_{FB} distribution obtained with no shared parameters.



D.5 Constraints from muon p_T

In the previous studies, we only used constraints from the Z boson mass, as ‘Constraint-1’ and ‘Constraint-2’ in Section 8.4.3, labelled as ‘Old correction’. However, when we check kinematic distributions after ‘Old correction’ correction, there are unexpected large shifts on the muon p_T , using 2018 data-set, as shown in Figure 217. A comparison of ϕ angle distribution in Collins-Soper frame is shown in Figure 218. It is clear that a fit with mass only constraints does not work for 2018 data-set, which mess up the muon p_T distributions. While for 2016 and 2017 data-sets, everything looks fine. However, we do not expect this method has data sample dependence. If the fitted results of 2018 data-set have problem, there are potential problems may exist in the 2016 and 2017 results, even the fitted results look fine. So we would like to add muon p_T as one of constraints.

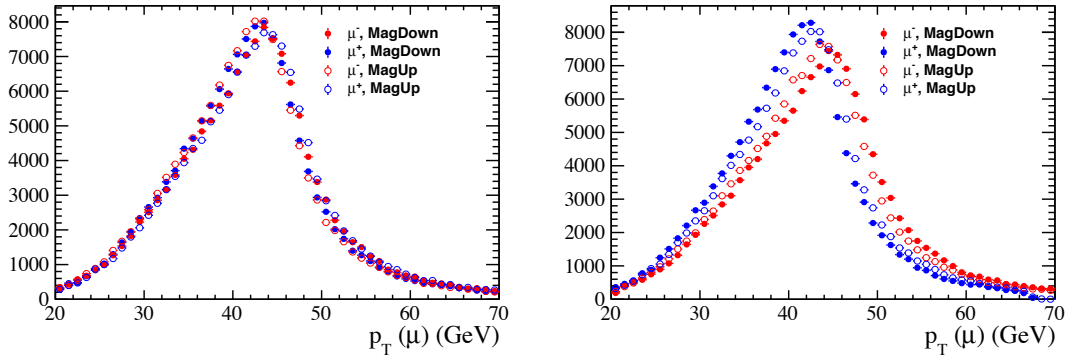


Figure 217: Comparisons of muon p_T distribution before (left) and after (right) the ‘Old correction’.

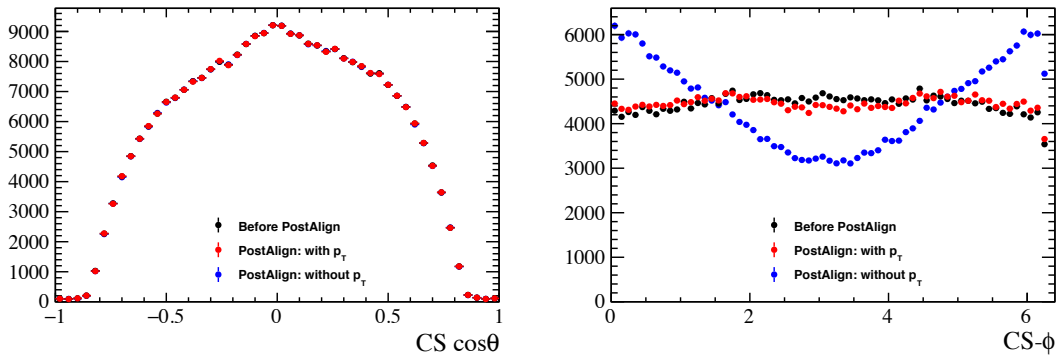


Figure 218: Comparisons of $\cos \theta$ (left) and ϕ (right) angle distribution in Collins-Soper frame, with and without ‘post-alignment’ corrections.



In generator level, there is no difference between μ^- and μ^+ p_T distributions. The prediction from ResBos generator is shown in left figure of Figure 219. Then, the signal events with the LHCb detector simulation also tells us that there is no difference between μ^- and μ^+ distributions, as shown in right figure of Figure 219. Therefore, we decided to include the muon p_T as one of the constraints in the fitting.

There could be a potential bias from the LHCb acceptance, as the muon p_T distributions could be different from each other, due to the crossing angles of the LHC beam and asymmetry of the detector. However, as shown in Figure 219, in the simulated events, there is no difference between them. So we are planning to include the acceptance effects in this momentum calibration model.

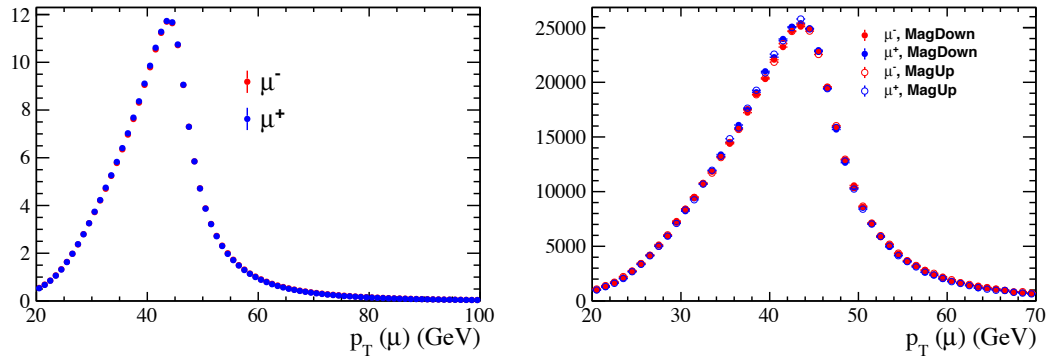


Figure 219: The prediction on μ^- and μ^+ p_T (left), using the ResBos generator, with LHCb fiducial requirement applied. (right) is the muon p_T distributions of the LHCb simulated events, in different magnet polarity.

The kinematic distributions for different data-sets, after ‘post-alignment’ correction are shown from Figure 220 to Figure 222.

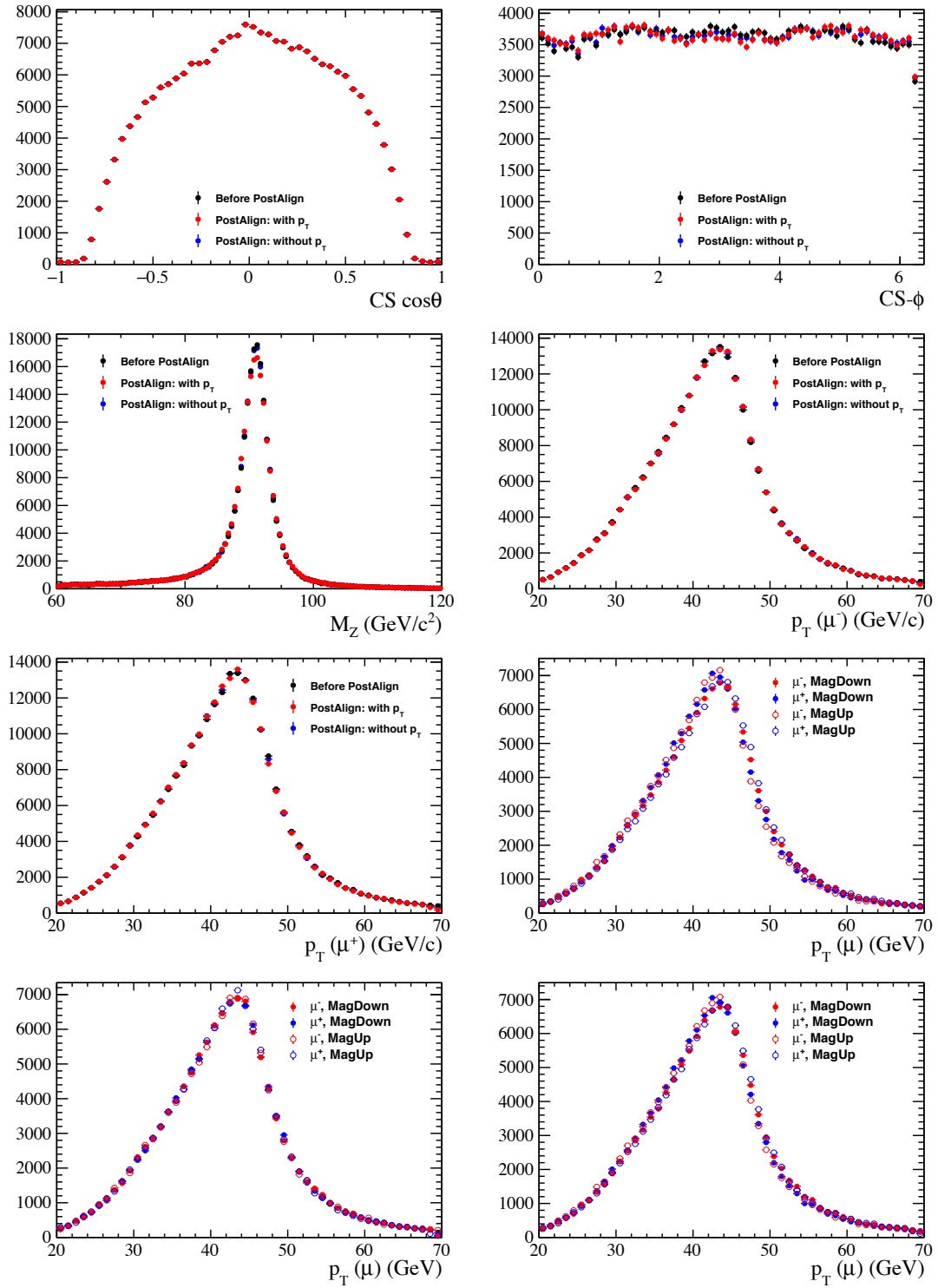


Figure 220: Comparisons of kinematic distribution with/without 'post-alignment' correction, using 2016 data-set. (right figure of third row) is the muon p_T distributions before correction, (left figure of bottom row) is the muon p_T distributions using a correction (with muon- p_T constraint), (right figure of bottom row) is the muon p_T distributions using a correction (without muon- p_T constraint).

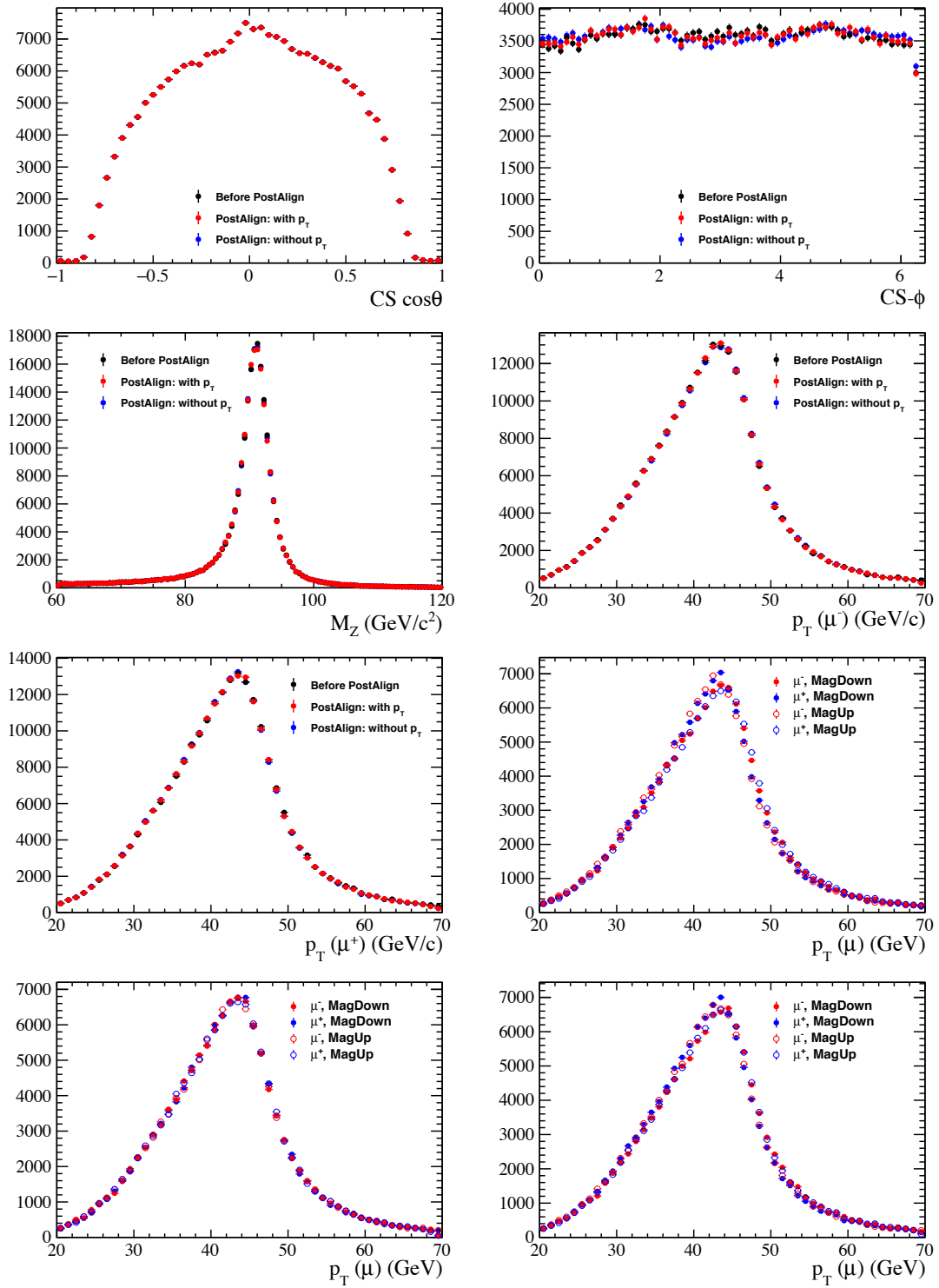
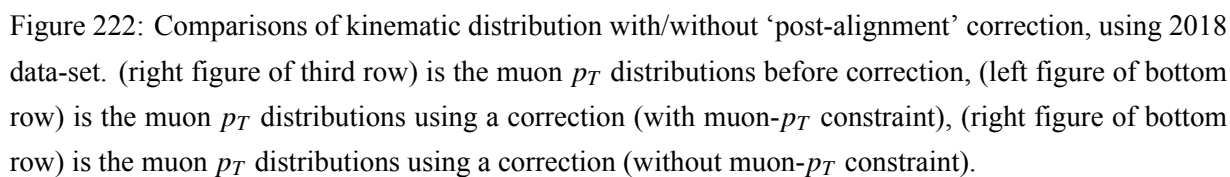


Figure 221: Comparisons of kinematic distribution with/without ‘post-alignment’ correction, using 2017 data-set. (right figure of third row) is the muon p_T distributions before correction, (left figure of bottom row) is the muon p_T distributions using a correction (with muon- p_T constraint), (right figure of bottom row) is the muon p_T distributions using a correction (without muon- p_T constraint).





D.6 ‘Improved-alignment’ output parameters

The ‘Improved-alignment’ output parameters β distribution as a function of muon η and ϕ in 2016, 2017 and 2018 data set can be found in Figure 224.

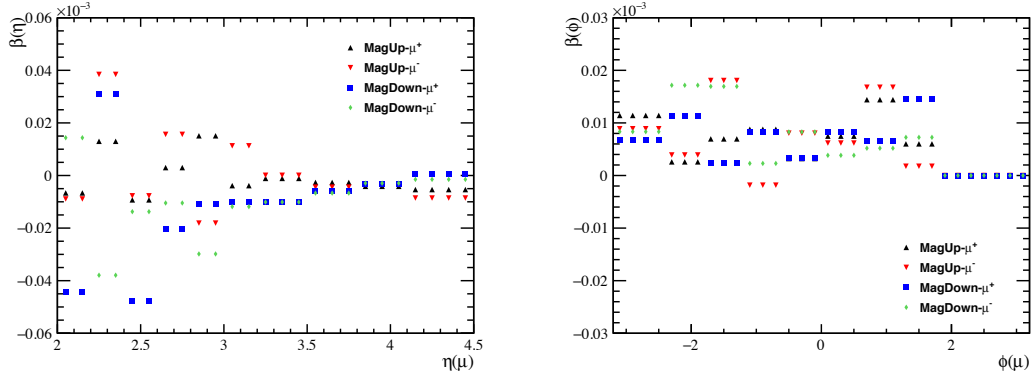


Figure 223: Distribution of ‘Improved-alignment’ output parameters β as a function of muon η (left) and ϕ (right) for different sub-samples in 2016 data.

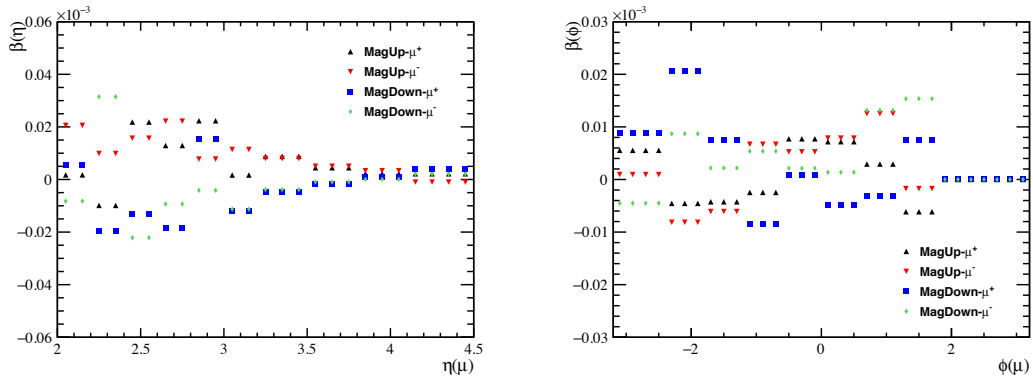


Figure 224: Distribution of ‘Improved-alignment’ output parameters β as a function of muon η (left) and ϕ (right) for different sub-samples in 2017 data.

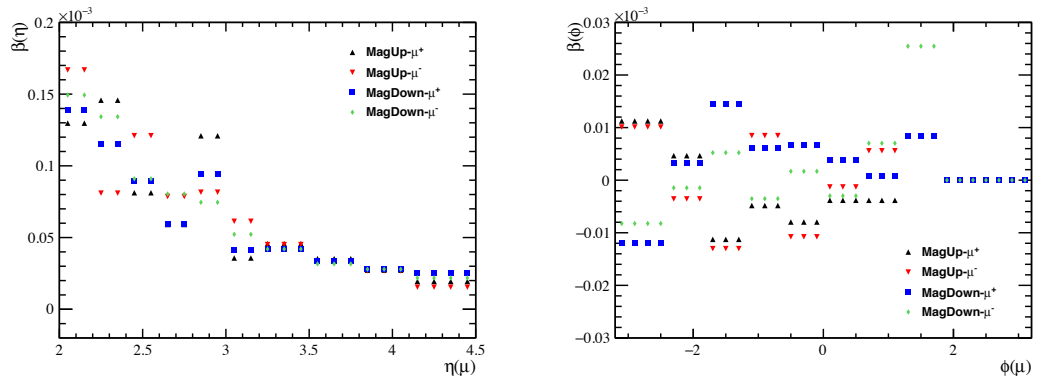


Figure 225: Distribution of ‘Improved-alignment’ output parameters β as a function of muon η (left) and ϕ (right) for different sub-samples in 2018 data.



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