



Università degli Studi di Genova

PhD program in Physics

**Search for  $CP$  violation in the  
charmless decay  $B^0 \rightarrow p\bar{p}K^+\pi^-$  using  
triple product asymmetries at LHCb  
and feasibility studies of a  
SiPM-based readout system for the  
Upgrade II RICH detector**

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**Candidate:**

Matteo Bartolini

**Supervisors:**

Dr. Roberta Cardinale

Prof. Alessandro Petrolini

**Referees:**

Dr. Stephen Wotton

Dr. Jeremy Peter Dalseno



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# Introduction

The Dirac equation [1], the first equation to account fully for special relativity in the context of quantum mechanics, predicts the existence of antiparticles along with the solutions for the corresponding particles. Since its first formulation in 1928, experiments have demonstrated that every known kind of particle has a corresponding antiparticle; under the  $CPT$  theorem, a particle and its antiparticle have the same lifetime, the same mass and opposite charge. Given this symmetry, one would expect the universe to have equal amounts of matter and antimatter. However, the universe that we see today appears to contain only matter with no significant concentrations of antimatter. It is hypothesized that, during the first few instants, the universe was composed of equal amounts of matter and antimatter, and thus contained an equal number of quarks and anti-quarks. Once the universe expanded and cooled to a critical temperature, quarks (anti-quarks) began combining into particles (anti-particles). Once particles and anti-particles formed they started annihilating each other up to a small initial asymmetry of  $\sim$  one part in five billion, until a universe exclusively composed of matter was left. Indeed, as indicated by Sakharov [2], a baryon asymmetry can actually arise dynamically during the evolution of the universe from an initial symmetric state if the following three necessary conditions hold:

1. Baryon number violation
2.  $C$  and  $CP$  violation
3. Departure from thermal equilibrium

The first condition is necessary to produce an excess of baryons over anti-baryons, but  $C$ -symmetry violation is needed as well. In this way the interactions that produce more baryons than anti-baryons will not be counterbalanced by interactions that produce more anti-baryons than baryons. Similarly,  $CP$ -symmetry violation is required, otherwise we would have equal numbers of left-handed baryons and right-handed anti-baryons, as well as equal numbers of left-handed anti-baryons and right-handed baryons. The interactions must also be out of thermal equilibrium, otherwise  $CPT$  symmetry would assure compensation between processes increasing and decreasing the baryon number. In principle all the three Sakharov requirements are present in the Standard Model (SM), but the baryon number conservation is only violated non-perturbatively by a global  $U(1)$  anomaly [3]. This results in extremely suppressed processes that are not sufficient to account for the present baryon asymmetry. The violation of  $C$  and  $CP$  symmetries are incorporated in the SM as well;  $C$  violation was first observed experimentally in the decay of muons [4] whereas  $CP$  violation was first observed in the  $K_L^0 \rightarrow \pi^+ \pi^-$  decays [5].

The subject of  $CP$  symmetry and its violation is often referred to as one of the least understood in particle physics. Indeed,  $CP$  symmetry violation is an expected consequence of the Standard Model with three quark generations, but calculations within this framework show that  $CP$  violation seems to be too small to generate the matter-anti-matter imbalance observed in our universe [6, 7].

So far, direct  $CP$  violation has been established in K, B and D meson decays and the experimental measurements are in good agreement with the Standard Model expectations. However,  $CP$  violation is yet to be confirmed in heavy baryon decays and also in  $B$  decays with half-spin particles in the final state, where sizable asymmetries are predicted as well. In particular, baryonic  $B$ -meson decays mediated dominantly through internal  $W$  emission are believed to be promising processes [8]. In this thesis a search for  $CP$  violation in the charmless baryonic  $B$  meson decay  $B^0 \rightarrow p\bar{p}K^+\pi^-$  using data collected by the LHCb experiment is reported. In order to assign the correct mass to the charged hadrons in the final state and combine them to form the  $B^0 \rightarrow p\bar{p}K^+\pi^-$  candidate, the particle identification informations (PID) provided by the RICH detector are necessary. The two LHCb RICH (Ring Imaging Cherenkov) detectors exploit the Cherenkov light emitted by charged particles traversing a gas to distinguish efficiently  $\pi$ ,  $K$  and  $p$  in the momentum range 1-100 GeV/c. During Run 1 and Run 2 the two RICH detectors operated continuously at the luminosity of  $\sim 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  and provided an excellent PID. In order to be able to operate at the new luminosity of  $\sim 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  from the start of Run3 in 2021 the two RICH detectors must be upgraded; the former HPD (Hybrid Photon Detectors) will be replaced by commercial MaPMTs, the optics of the upstream RICH will be modified and the electronics will be upgraded to cope with the challenges of the 40 MHz readout rate. During the PhD I contributed to the development of the detector control system. The start of the HL-LHC phase in 2027 provides an opportunity to increase the luminosity up to  $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . To be able to operate the RICH detectors in this much harsher environment a further upgrade in the front-end electronics and a new photo-detector system will be mandatory. During my PhD I also investigated the possibility of using SiPMs (Silicon Photomultipliers) in the Upgrade II phase by characterizing a device manufactured by Hamamatsu at low temperatures in the lab. This thesis is divided in six chapters:

- the first chapter provides an introduction on the  $CP$  violation. After a short summary of the Standard Model and the origin of  $CP$  as described by the quantum field theory, the different experimental methods used to search for  $CP$  violation effects and their different sensitivity are listed. The last part of the chapter is devoted to the description of charmless baryonic  $B$  decays and why they could be a good place to search for matter-antimatter asymmetries.
- the second chapter gives a short overview of the LHCb detector during the Run 1 and Run 2 data taking periods, the experimental apparatus used to collect the data used in the analysis described in the third chapter of this thesis.
- the third chapter presents the search for  $CP$  violation in the four-body charmless baryonic  $B^0 \rightarrow p\bar{p}K^+\pi^-$  decay using triple-product correlations. I am the main author of this measurement. The measurement is performed exploiting the full available LHCb dataset, taken during Run 1 and Run 2 data taking periods, corresponding to a total integrated luminosity of  $9 \text{ fb}^{-1}$ . The results presented in this thesis are preliminary and are currently under review of the LHCb collaboration

before submitting the paper for publication.

- the fourth chapter describes the upgraded LHCb detector, which will resume data taking in 2021 with a new trigger architecture; the hardware level 0 (L0) trigger will be removed and only the cpu-based High Level Trigger (HLT) will remain. Particular attention was given to the description of the upgraded RICH detectors which are a fundamental ingredient of the performed data analysis.
- the fifth chapter describes the Detector Control System (DCS) of the upgraded RICH detector, which I contributed developing during the year spent at CERN as a COAS (Cooperative Associate). In particular, I contributed to the commissioning of the hardware and the development of the control software. The first version of the software that controls the RICH 2 side has already been installed in the control room of the LHCb experiment while the part that controls RICH 1 is under development during the writing of this thesis.
- the sixth chapter describes the possibility of using silicon photomultipliers (SiPMs) as photodetectors for a possible phase-2 Upgrade of the RICH detectors during the high luminosity phase of LHC (HL-LHC). After a brief introduction to the main challenges that the new detectors will have to face, the chapter is devoted to the description of the equipment set up in the laboratory for the characterization of the SiPMs and the main results of the analysis. The work described in this chapter was performed entirely by the author and the results obtained represent valuable inputs towards the design of a detector prototype.

# Chapter 1

## $CP$ violation in the Standard Model

The  $CP$  symmetry is minimally violated in nature. Nevertheless, it is not only relevant for the understanding of a small set of rare processes, but it could be the key for understanding the fact that the universe contains only matter and not antimatter, which is one of the most intriguing mysteries of cosmology. In this chapter I will describe how the  $CP$  violation is introduced in the Standard Model through the Cabibbo-Kobayash-Maskawa mechanism (CKM), which requires the presence of at least three families of quarks. Section 1.2.3 describes all the different ways in which  $CP$  violation may arise in neutral mesons while Section 1.2.4 focuses on the description of the triple product asymmetries, which is the method used to search for  $CP$  violation in this thesis. Section 1.3 describes the main features of the multi-body baryonic  $B$  decays.

### 1.1 The Standard Model

The Standard Model is the theory that describes electromagnetic, weak and strong interactions which are responsible for the dynamics of all known subatomic particles. The elementary building blocks of matter in the SM are quarks and leptons, spin  $\frac{1}{2}$  particles organized in three generations. Quarks and leptons are listed in Fig. 1.1. For any of these particle, a respective antiparticle exists, having the same mass, spin and lifetime but with opposite parity and additional quantum numbers

The Standard Model is formulated using the framework of the quantum field theory where it is described by a Lagrangian density that is invariant under a local gauge transformation:  $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ . The Electroweak theory, describing the electromagnetic and the weak interaction, is based on the  $SU(2)_L \otimes U(1)_Y$  symmetry [9]. The subscript  $L$  indicates that the weak interaction acts only on fields having left chirality. The local gauge invariance under this symmetry group leads to the introduction of four spin-1 gauge fields that correspond to the  $W^\pm$  bosons, charged carriers of the weak interaction, the  $Z^0$  boson, neutral carrier of the weak interaction and the photon, neutral carrier of the electromagnetic force. Moreover, the structure of the  $SU(2)$  transformation is non-abelian and this generates additional terms in the SM Lagrangian describing the self-interactions between the gauge bosons. Although the gauge symmetry forbids the writing of a mass

|                |                                                |                                              |                                              |                                      |                                       |
|----------------|------------------------------------------------|----------------------------------------------|----------------------------------------------|--------------------------------------|---------------------------------------|
|                | I                                              | II                                           | III                                          |                                      |                                       |
| mass           | $\approx 2.2 \text{ MeV}/c^2$                  | $\approx 1.28 \text{ GeV}/c^2$               | $\approx 173.1 \text{ GeV}/c^2$              | 0                                    | $\approx 124.97 \text{ GeV}/c^2$      |
| charge         | $\frac{2}{3}$                                  | $\frac{2}{3}$                                | $\frac{2}{3}$                                | 0                                    | 0                                     |
| spin           | $\frac{1}{2}$                                  | $\frac{1}{2}$                                | $\frac{1}{2}$                                | 1                                    | 0                                     |
|                | <b>u</b><br>up                                 | <b>c</b><br>charm                            | <b>t</b><br>top                              | <b>g</b><br>gluon                    | <b>H</b><br>higgs                     |
| <b>QUARKS</b>  | $\approx 4.7 \text{ MeV}/c^2$                  | $\approx 96 \text{ MeV}/c^2$                 | $\approx 4.18 \text{ GeV}/c^2$               | 0                                    |                                       |
|                | $-\frac{1}{3}$                                 | $-\frac{1}{3}$                               | $-\frac{1}{3}$                               | 0                                    |                                       |
|                | $\frac{1}{2}$                                  | $\frac{1}{2}$                                | $\frac{1}{2}$                                | 1                                    |                                       |
|                | <b>d</b><br>down                               | <b>s</b><br>strange                          | <b>b</b><br>bottom                           | <b><math>\gamma</math></b><br>photon |                                       |
| <b>LEPTONS</b> | $\approx 0.511 \text{ MeV}/c^2$                | $\approx 105.66 \text{ MeV}/c^2$             | $\approx 1.7768 \text{ GeV}/c^2$             | $\approx 91.19 \text{ GeV}/c^2$      |                                       |
|                | -1                                             | -1                                           | -1                                           | 0                                    |                                       |
|                | $\frac{1}{2}$                                  | $\frac{1}{2}$                                | $\frac{1}{2}$                                | 1                                    |                                       |
|                | <b>e</b><br>electron                           | <b><math>\mu</math></b><br>muon              | <b><math>\tau</math></b><br>tau              | <b>Z</b><br>Z boson                  |                                       |
|                | $< 1.0 \text{ eV}/c^2$                         | $< 0.17 \text{ MeV}/c^2$                     | $< 18.2 \text{ MeV}/c^2$                     | $\approx 80.39 \text{ GeV}/c^2$      |                                       |
|                | 0                                              | 0                                            | 0                                            | $\pm 1$                              |                                       |
|                | $\frac{1}{2}$                                  | $\frac{1}{2}$                                | $\frac{1}{2}$                                | 1                                    |                                       |
|                | <b><math>\nu_e</math></b><br>electron neutrino | <b><math>\nu_\mu</math></b><br>muon neutrino | <b><math>\nu_\tau</math></b><br>tau neutrino | <b>W</b><br>W boson                  |                                       |
|                |                                                |                                              |                                              |                                      | <b>GAUGE BOSONS<br/>VECTOR BOSONS</b> |
|                |                                                |                                              |                                              |                                      | <b>SCALAR BOSONS</b>                  |

Figure 1.1: Elementary particles in the Standard Model.

term for these bosons, they acquire mass in the SM through the mechanism of spontaneous symmetry breaking [10]: the Lagrangian is fully symmetric under the gauge transformation, but the ground state (or vacuum) is not. With the introduction of the scalar Higgs boson in the theory the  $W^\pm$  and the  $Z^0$  acquire mass. The spontaneous symmetry breaking also generates fermion masses.

The strong interaction is based on the  $SU(3)_C$  symmetry [11]; the local gauge invariance under this symmetry group leads to the introduction of eight massless spin-1 gauge fields that correspond to the gluons. Only quarks can interact through the strong interaction.

## 1.2 The origin of $CP$ violation

The operation of  $CP$  is obtained combining the two discrete transformations of parity  $P$  and charge conjugation  $C$ . Under  $C$ , particles turn into antiparticles, by conjugation of their internal quantum numbers whereas the parity operator,  $P$ , inverts all space coordinates used in the description of a physical process. Parity conservation implies that any physical process is the same when viewed in mirror image.

A more useful way of looking at parity violation in the field of particle physics is by considering helicity,  $h$ , which is the projection of the spin  $\vec{s}$  of a particle onto its direction of motion  $\frac{\vec{p}}{|\vec{p}|}$ :

$$h = \vec{s} \cdot \frac{\vec{p}}{|\vec{p}|} \quad (1.1)$$

As helicity changes sign under  $P$  transformation, finding a process which produces a particle with a preferred helicity also proves that  $P$ -symmetry is violated [12].

During the past decades it has been verified experimentally that only gravitational, electromagnetic and strong interactions respect  $P$  and  $C$  symmetries and also their combination  $CP$ . On the contrary,  $P$  and  $C$  are violated maximally in the weak interaction. Before 1964, it was believed that all of the fundamental interactions had to respect the  $CP$  symmetry, but an experiment by Fitch and Cronin involving neutral kaon decays observed for the first time that also  $CP$  was violated [5]. Since the first discovery of  $CP$  violation in  $K$  mesons, searches for  $CP$  violation effects have been carried out also in decays of  $B_{(s)}^0$  and  $D$  mesons.  $CP$  violation in  $B^0$  mesons was first established in 2001 by the BaBar and Belle Collaborations [13, 14], while the first observation of  $CP$  violation in the  $B_s^0$  system was reported by LHCb in 2013 [15]. In 2019 the LHCb Collaboration measured  $CP$  violation in charm decays [16].

As we will see in Section 1.2.1,  $CP$  violation takes place in the weak charged current interaction when one quark with a given flavour changes into another quark with a different flavour.

### 1.2.1 The CKM Matrix

In the Standard Model  $CP$  symmetry is broken by the presence of a complex phase in the Yukawa term of the full SM Lagrangian  $\mathcal{L}_{SM}$  [17]:

$$\mathcal{L}_{SM} = \mathcal{L}_{kinetic} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} \quad (1.2)$$

where  $\mathcal{L}_{kinetic} = i\bar{\psi}(D^\mu\gamma_\mu)\psi$  term describes the dynamics of the spinor fields  $\psi$  and  $D^\mu$  is the covariant derivative, which is defined as:

$$D^\mu = \partial^\mu + ig_s G_a^\mu L_a + ig W_b^\mu \sigma_b + ig B^\mu Y \quad (1.3)$$

$L_a$  are the  $3 \times 3$  Gell-Mann matrices and  $\sigma_b$  the  $2 \times 2$  Pauli matrices.  $G_a^\mu$ ,  $W_b^\mu$  and  $B^\mu$  are the eight gluon fields, the three weak interaction bosons and the single hypercharge boson, respectively. The fermion fields  $\psi$  inside the  $\mathcal{L}_{kinetic}$  term consist of the following five representations:

$$Q_{Li}^I(3, 2, +1/6), \quad u_{Ri}^I(3, 1, +2/3), \quad d_{Ri}^I(3, 1, -1/3), \quad L_{Li}^I(1, 2, -1/2), \quad l_{Ri}^I(1, 1, -1) \quad (1.4)$$

where the superscript  $I$  indicates that the fermion fields are expressed in the interaction basis and the subscript  $i$  indicates the generation. For example, the  $Q_{Li}^I$  term refers to a  $SU(3)_C$  triplet, left-handed  $SU(2)_L$  doublet field with hypercharge  $Y = 1/6$ .

Following this notation, the charged current interaction between the left-handed quarks can be written as:

$$\begin{aligned} \mathcal{L}_{kinetic,weak} &= i\overline{Q_{Li}^I}\gamma_\mu(\partial^\mu + \frac{i}{2}gW_b^\mu\sigma_b)Q_{Li}^I \\ &= i\overline{u_{iL}^I}\gamma_\mu\partial^\mu u_{iL}^I + i\overline{d_{iL}^I}\gamma_\mu\partial^\mu d_{iL}^I - \frac{g}{\sqrt{2}}\overline{u_{iL}^I}\gamma_\mu W^{-\mu}d_{iL}^I - \frac{g}{\sqrt{2}}\overline{d_{iL}^I}\gamma_\mu W^{+\mu}u_{iL}^I \end{aligned}$$



The  $W^\pm$  and  $Z^0$  bosons are known to acquire their mass through the mechanism of spontaneous symmetry breaking. This requires the addition of the Higgs scalar field  $\mathcal{L}_{Higgs}$  to the Lagrangian:

$$\mathcal{L}_{Higgs} = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2 \quad (1.5)$$

with  $\phi$  being an isospin doublet.

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (1.6)$$

The coupling of the Higgs to the gauge fields is obtained directly from the covariant derivative term  $D^\mu$ .

The last term,  $\mathcal{L}_{Yukawa}$ , represents the interactions between the Higgs and the fermions.

$$\mathcal{L}_{Yukawa} = Y_{ij} \overline{\psi}_{Li} \phi \psi_{Rj} + h.c. = Y_{ij}^d \overline{Q}_{Li}^I \phi d_{Ri}^I + Y_{ij}^u \overline{Q}_{Li}^I \tilde{\phi} u_{Ri}^I + Y_{ij}^l \overline{L}_{Li}^I \phi l_{Rj}^I + h.c. \quad (1.7)$$

The matrices  $Y_{ij}^d$ ,  $Y_{ij}^u$  and  $Y_{ij}^l$  are complex matrices that act in flavour space, giving rise to the couplings between different families. In particular, the first two terms of Eq. 1.7 are related to flavour physics and take the following form after spontaneous symmetry breaking:

$$\mathcal{L}_{Yukawa}^{quarks} = Y_{ij}^d \overline{Q}_{Li}^I \phi d_{Ri}^I + Y_{ij}^u \overline{Q}_{Li}^I \tilde{\phi} u_{Ri}^I + h.c. = M_{ij}^d \overline{d}_{Li}^I d_{Ri}^I + M_{ij}^u \overline{u}_{Li}^I u_{Ri}^I + h.c. + \text{interaction terms} \quad (1.8)$$

To obtain a proper mass term, the matrices  $M^d$  and  $M^u$  are diagonalized by the following transformation:

$$M_{diag}^d = V_L^d M^d V_R^{d\dagger} \quad (1.9)$$

$$M_{diag}^u = V_L^u M^u V_R^{u\dagger} \quad (1.10)$$

where  $V$  are unitary matrices. The matrices  $V$  can be absorbed in the quark states, resulting in the following quark mass eigenstates:

$$d_{Li} = (V_L^d)_{ij} d_{Lj}^I \quad d_{Ri} = (V_R^d)_{ij} d_{Rj}^I \quad (1.11)$$

$$u_{Li} = (V_L^d)_{ij} u_{Lj}^I \quad u_{Ri} = (V_R^d)_{ij} u_{Rj}^I \quad (1.12)$$

If the Lagrangian is expressed in terms of the quark mass eigenstates instead of the weak interaction eigenstates the quark mixing appears directly in the charged current interaction:

$$\begin{aligned} \mathcal{L}_{kinetic,cc}^{quarks} &= -\frac{g}{\sqrt{2}} \overline{u}_{iL}^I \gamma_\mu W^{-\mu} d_{iL}^I - \frac{g}{\sqrt{2}} \overline{d}_{iL}^I \gamma_\mu W^{+\mu} u_{iL}^I \\ &= -\frac{g}{\sqrt{2}} \overline{u}_{iL} (V_L^u V_L^{d\dagger})_{ij} \gamma_\mu W^{-\mu} d_{iL}^I - \frac{g}{\sqrt{2}} \overline{d}_{iL} (V_L^d V_L^{u\dagger})_{ij} \gamma_\mu W^{+\mu} u_{iL}^I \end{aligned}$$

The unitary  $3 \times 3$  matrix

$$V_{CKM} = (V_L^u V_L^{d\dagger})_{ij} \quad (1.13)$$

is known as the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [18].

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (1.14)$$

By convention, the interaction eigenstates and the mass eigenstates are chosen to be equal for the up-type quarks, whereas the down-type quarks are chosen as going from the interaction basis to the mass basis:

$$u_i^I = u_i \quad (1.15)$$

$$d_i^I = V_{CKM} d_j \quad (1.16)$$

The  $V_{CKM}$  matrix contains the couplings of an up-type antiquark and a down-type quark to the charged W bosons. In Section 1.2.2 we will show that the complex nature of the CKM matrix is at the origin of  $CP$  violation in the Standard Model.

### 1.2.2 Properties of the CKM matrix and origin of the $CP$ violation

A general  $n \times n$  matrix has  $n^2$  complex elements and, consequently,  $2n^2$  real parameters. The unitary condition imposed on the matrix determines the number of free parameters:

- $n$  unitary conditions
- $n^2 - n$  orthogonality relations
- $2n - 1$  relative phases can be removed since the phases of the quarks can be freely redefined in the SM and a global phase is irrelevant

Such conditions bring the number of free parameters from  $2n^2$  down to  $(n - 1)^2$ . These remaining parameters can be further divided into Euler angles and phases:

- $\frac{1}{2}n(n - 1)$  angles describing the rotations among the  $n$  dimensions
- $\frac{1}{2}(n - 1)(n - 2)$  phases

The case  $n = 2$  leads to a mixing matrix with only one free parameter and no complex phase. Instead, the case  $n = 3$  leads to a matrix with three mixing angles and one complex phase. It can be shown that, under  $CP$  operation, the Lagrangian remains unchanged only if  $V_{ij} = V_{ij}^*$ , i.e if the elements of the matrix are all real. The complex nature of the CKM matrix is therefore at the origin of  $CP$  violation in the Standard Model.

In the literature there are different parameterizations of the CKM matrix. A convenient representation with the notation  $c_{ij} = \cos \theta_{ij}$  and  $s_{ij} = \sin \theta_{ij}$  was introduced by Chau and Keung [19].

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix} \quad (1.17)$$

Another very popular approximate parameterization of the CKM also exists and was proposed by Wolfenstein [20] by making the following substitutions:

$$\sin \theta_{12} = \lambda \quad (1.18)$$

$$\sin \theta_{23} = A\lambda^2 \quad (1.19)$$

$$\sin \theta_{13} e^{-i\delta_{13}} = A\lambda^3(\rho - i\eta) \quad (1.20)$$

where  $A$ ,  $\rho$  and  $\eta$  are numbers of order unity. The CKM matrix becomes:

$$\begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \quad (1.21)$$

The most up-to-date measured values are  $A = 0.8403^{+0.0056}_{-0.0201}$ ,  $\lambda = 0.224747^{+0.000254}_{-0.000059}$ ,  $\bar{\rho} = \rho(1 - \frac{\lambda^2}{2}) = 0.1577^{+0.0096}_{-0.0074}$ ,  $\bar{\eta} = \eta(1 - \frac{\lambda^2}{2}) = 0.3493^{+0.0095}_{-0.0071}$  [21].

The CKM matrix elements can be most precisely determined using a global fit to all available measurements and imposing the SM constraints (i.e., three generation unitarity). The fit must also make use of theory predictions for hadronic matrix elements.

### 1.2.3 $CP$ violation in neutral mesons

As the work of this thesis deals with search for  $CP$  violation in a  $B^0$  decay channel it is important to show the main features of the  $CP$  violation in neutral meson physics.

The phenomenology of  $CP$  violation in neutral mesons is enriched by the presence of flavour mixing or oscillation. In fact, due to the structure of the weak interaction, a meson that is produced in the flavour eigenstate  $P^0$  oscillates between the states  $P^0$  and  $\bar{P}^0$  before decaying. Four neutral mesons can mix:  $K^0$ ,  $D^0$ ,  $B^0$  and  $B_s^0$ .

A state  $\psi(t_0)$  that is initially a superposition of  $P^0$  and  $\bar{P}^0$  can be written as:

$$\psi(t_0) = a(t_0) |P^0\rangle + b(t_0) |\bar{P}^0\rangle \quad (1.22)$$

will evolve in time according the Schrödinger equation as:

$$i\frac{\partial}{\partial t} \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = \left( M - \frac{i}{2}\Gamma \right) \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} \quad (1.23)$$

The effective Hamiltonian  $H = M - \frac{i}{2}\Gamma$  in the  $(P^0, \bar{P}^0)$  basis governs the time evolution and is a sum of the strong, electromagnetic and weak Hamiltonians  $H = H_{strong} + H_{em} + H_{weak}$ .

$$H = \left( M - \frac{i}{2}\Gamma \right) = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix} \quad (1.24)$$

$M$  and  $\Gamma$  are Hermitian matrices whereas  $H$  is not. This reflects the fact that the probability to observe either  $P$  or  $\bar{P}^0$  is not conserved. The matrix  $M$  is associated with transitions via off-shell intermediate states and provides the mass term, while  $\Gamma$  with on-shell intermediate state and provides the exponential decay. The eigenvectors of  $H$ , called  $|P_L\rangle$  and  $|P_H\rangle$ , have defined masses ( $m_L$  and  $m_H$ ) and decay widths ( $\Gamma_L$  and  $\Gamma_H$ ) and are equal to

$$|P_H\rangle = p|P^0\rangle - q|\bar{P}^0\rangle \quad (1.25)$$

$$|P_L\rangle = p|P^0\rangle + q|\bar{P}^0\rangle \quad (1.26)$$

where  $p$  and  $q$  are complex parameters with  $|p|^2 + |q|^2 = 1$  and

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \quad (1.27)$$

In the neutral meson system  $CP$  violation can be observed as three distinct effects:

- **Direct  $CP$  violation.** It occurs when the decay rate of a neutral meson  $P^0$  to a final state  $f$  differs from the decay rate of a  $\bar{P}^0$  to the  $CP$ -conjugated final state  $\bar{f}$ .<sup>1</sup>
- **$CP$  violation in mixing.** This implies that the oscillation from meson to anti-meson is different from the oscillation from anti-meson to meson
- **$CP$  violation in interference between a decay with and without mixing.** A meson can decay to a  $CP$  final eigenstate directly or changing its flavour (mixing) before decaying.

### 1.2.3.1 Direct $CP$ violation

It occurs when the decay rate  $\Gamma$  of a  $P$  to a final state  $f$  differs from the decay rate of a  $\bar{P}$  to the  $CP$ -conjugated final state  $\bar{f}$ .

$$\Gamma(P \rightarrow f) \neq \Gamma(\bar{P} \rightarrow \bar{f}) \quad (1.28)$$

We now define  $A$  as the decay amplitude of a  $P$  meson to a final state  $f$ :

$$A_f = \langle f | T | P \rangle \quad (1.29)$$

where  $T$  is the transition operator. The  $CP$ -conjugated decay  $\bar{P}$  to  $\bar{f}$  may be similarly expressed as:

$$\bar{A}_{\bar{f}} = \langle \bar{f} | T | \bar{P} \rangle \quad (1.30)$$

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<sup>1</sup>This is the only type of  $CP$  violation that can occur in charged meson decays since there is no mixing.

This is the only kind of  $CP$  violation for charged particles since the mixing process is not present and  $CP$  manifests itself when

$$\frac{|\bar{A}_{\bar{f}}|}{|A_f|} \neq 1 \quad (1.31)$$

The condition expressed in Eq. 1.31 is fulfilled only when there are two or more transition amplitudes contributing to the same decay. The total amplitude is calculated by summing the amplitudes of the several Feynman diagrams that contribute to the process:

$$A_f = \sum_i a_i \quad (1.32)$$

Every amplitude  $a_i$  is a complex number and may contain two different types of phases:

- the strong phase,  $\delta_i$ , typically due to gluon exchange in the final state. This phase is  $CP$ -even because strong interactions are  $CP$ -conserving.
- the weak phase,  $\phi_i$ , due to complex coupling constants of the CKM matrix. This phase is  $CP$ -odd and therefore changes sign under  $CP$  transformation.

We can now write the total amplitude as the sum of the single amplitudes given by product of its magnitude, its weak phase and its strong phase as:

$$A_f = \sum_i |a_i| e^{i(\delta_i + \phi_i)}, \quad \bar{A}_{\bar{f}} = \sum_i |a_i| e^{i(\delta_i - \phi_i)} \quad (1.33)$$

For example, we can consider the case where there are only two different amplitudes,  $a_1$  and  $a_2$ , contributing to the total amplitude,  $A_f$  in Eq. 1.32. Following this, the total amplitude  $A_f$  and its  $CP$ -conjugate  $\bar{A}_{\bar{f}}$  can be written as:

$$A_f = |a_1| e^{i\delta_1} e^{i\phi_1} + |a_2| e^{i\delta_2} e^{i\phi_2} \quad (1.34)$$

$$\bar{A}_{\bar{f}} = |a_1| e^{i\delta_1} e^{-i\phi_1} + |a_2| e^{i\delta_2} e^{-i\phi_2} \quad (1.35)$$

At this point we can define the  $CP$  asymmetry as:

$$A_{CP} = \frac{\Gamma(\bar{P} \rightarrow \bar{f}) - \Gamma(P \rightarrow f)}{\Gamma(\bar{P} \rightarrow \bar{f}) + \Gamma(P \rightarrow f)} = \frac{\bar{A}_{\bar{f}}^2 - A_f^2}{\bar{A}_{\bar{f}}^2 + A_f^2} \quad (1.36)$$

By substituting the two amplitudes of Eq. 1.34 and 1.35 into Eq. 1.36 we get

$$A_{CP} = \frac{2|a_1|a_2| \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)}{|a_1|^2 + |a_2|^2 + 2|a_1|a_2| \cos(\phi_1 - \phi_2) \cos(\delta_1 - \delta_2)} \quad (1.37)$$

Eq. 1.37 shows clearly that, in order for  $CP$  violation to occur, it is necessary to have simultaneously  $\sin(\phi_1 - \phi_2) \neq 0$  and  $\sin(\delta_1 - \delta_2) \neq 0$ , that is different weak phases and different strong phases. Usually the most interesting quantity for the theory is the weak phase difference, but its extraction requires the knowledge of the different amplitudes and the strong phases as well. Both quantities depend on non-perturbative hadronic parameters generally difficult to calculate and their uncertainties affect the measurement of the weak phases.

### 1.2.3.2 $CP$ violation in mixing

As already stated in the introduction, neutral mesons can oscillate between particle and antiparticle states via flavour-changing neutral-current processes since flavour is not conserved in weak interactions. When the probability of oscillation from meson to anti-meson is different from the probability of oscillation from anti-meson to meson we have  $CP$  violation in the mixing:

$$Prob(P^0 \rightarrow \bar{P}^0) \neq Prob(\bar{P}^0 \rightarrow P^0) \quad (1.38)$$

It can be shown that  $CP$  violation can occur in neutral meson mixing if

$$\frac{|q|}{|p|} \neq 1 \quad (1.39)$$

where  $p$  and  $q$  are the complex parameters defined in Eq. 1.27.

In the  $B^0$ - and  $B_s^0$ -system,  $\frac{|q|}{|p|}$  is equal to 1 both within the experimental and the theoretical expectation. On the contrary, this type of  $CP$  violation is active in the  $K$ -system.

### 1.2.3.3 $CP$ violation in interference between a decay with and without mixing

This form of  $CP$  violation is measured in decays to a final state  $f$  that is common for the  $B^0$  and  $\bar{B}^0$  meson. In this case, a meson can decay to a  $CP$  final eigenstate directly or changing its flavour before decaying and  $CP$  symmetry is violated if the following condition is satisfied:

$$\Gamma(P_{(\sim\bar{P}^0)} \rightarrow f)(t) \neq \Gamma(\bar{P}_{(\sim P^0)} \rightarrow f)(t) \quad (1.40)$$

This equation indicates that  $CP$  violation can occur as a result of the interplay between the mixing and the decay amplitudes. For convenience we define the complex ratios

$$\lambda_f = \frac{q}{p} \left( \frac{\bar{A}}{A} \right)_f \quad (1.41)$$

$$\lambda_{\bar{f}} = \frac{q}{p} \left( \frac{\bar{A}}{A} \right)_{\bar{f}} \quad (1.42)$$

where  $\frac{q}{p}$  has already been defined in Eq. 1.27 and  $A$  and  $\bar{A}$  are the amplitudes for  $B^0$  and  $\bar{B}^0$  to decay to the final state  $f$  or  $\bar{f}$ . If we consider the case that  $\frac{|q|}{|p|} = 1$ , a time-dependent  $CP$  asymmetry is defined as:

$$A_{CP}(t) = \frac{\Gamma_{P^0(t) \rightarrow f} - \Gamma_{\bar{P}^0(t) \rightarrow f}}{\Gamma_{P^0(t) \rightarrow f} + \Gamma_{\bar{P}^0(t) \rightarrow f}} = \frac{2C_f \cos \Delta m t - 2S_f \sin \Delta m t}{2 \cosh \frac{1}{2} \Delta \Gamma t + 2D_f \sinh \frac{1}{2} \Delta \Gamma t} \quad (1.43)$$

with

$$D_f = \frac{2\Re\lambda_f}{1 + |\lambda_f|^2}, \quad C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad S_f = \frac{2\Im\lambda_f}{1 + |\lambda_f|^2} \quad (1.44)$$

$CP$  violation can arise if  $|\lambda_f| \neq 1$ . Remembering that  $\frac{|q|}{|p|} = 1$  for the  $B^0$ -system this can happen if  $CP$  is violated in the decay ( $\frac{\bar{A}}{A} \neq 1$ ), but it can also be violated even when neither mixing nor decay  $CP$  violations are present if  $\mathbb{I}\lambda_f \neq 0$

### 1.2.4 $CP$ -violating asymmetries in multi-body differential distributions

In Section 1.2.3, we identified where  $CP$  violation occurs in the general formalism of meson decays, and classified the various categories. Multi-body decays are a good place to search for  $CP$  violation because, due to their rich resonant structures, different amplitudes may interfere and cause local  $CP$  violation effects to appear in regions of the phase space. Experimentally, charge asymmetries are obtained by "counting" the difference between the number of particle and antiparticles. In practice, what is really measured here is the raw asymmetry  $A_{raw}$ , which contains contributions from the true  $CP$  violating asymmetry  $A_{CP}$ , as well as experimental effects such as the collision environment and the interaction of the final state particles with the detector. Assuming that all the asymmetries are small,  $A_{raw}$  can be expressed as

$$A_{raw} = A_D + A_P + A_{CP} \quad (1.45)$$

where the detection asymmetry,  $A_D$ , is the asymmetry in the efficiencies  $\varepsilon$

$$A_D = \frac{\varepsilon(f) - \varepsilon(\bar{f})}{\varepsilon(f) + \varepsilon(\bar{f})} \quad (1.46)$$

production asymmetry,  $A_P$ , is the asymmetry of the  $P^0$  and  $\bar{P}^0$  production cross-sections  $\sigma$ .

$$A_P = \frac{\sigma(P^0) - \sigma(\bar{P}^0)}{\sigma(P^0) + \sigma(\bar{P}^0)} \quad (1.47)$$

The reconstruction asymmetries depend on the kinematics of the decay and, for decays involving more than 2 particles in the final state, they also depend on the phase space itself. In general a very detailed study is needed to properly take into account the effects of  $A_P$  and  $A_D$  when performing searches for  $CP$  violation effects.

A complementary way of searching for  $CP$  violation effects in multi-body decays, which is also much less sensitive to systematic effects as we will see shortly, was presented in [22]. The differential rate of any pair of  $CP$ -conjugate processes can be decomposed into four parts with definite  $CP$  and  $\hat{T}$ <sup>2</sup> transformation properties:

$$\left. \frac{d\Gamma}{d\Phi} \right|_{CP-\frac{even}{odd}}^{\hat{T}-\frac{even}{odd}} = \frac{1 \pm \hat{T}}{2} \frac{1 \pm CP}{2} \frac{d\Gamma}{d\Phi} \quad (1.48)$$

---

<sup>2</sup> $\hat{T}$  is the motion-reversal transformation, reversing both particle helicities and momenta but, contrary to time-reversal  $T$  symmetry, does not exchange initial and final states.

where  $\Phi(\lambda_i, p_i)$  is the phase-space point corresponding to final particle helicities  $\lambda_i$  and momenta  $p_i$ . For simplicity one can assume that the amplitude of our process, which we call  $M(\lambda_i, p_i)$ , consists of three different contributions: two  $\hat{T}$ -even amplitudes and one  $\hat{T}$ -odd amplitude. We can write  $M(\lambda_i, p_i)$  and its  $CP$ -conjugate  $\overline{M}(\lambda_i, \bar{p}_i)$  as:

$$M(\lambda_i, p_i) = a_e^1 e^{i(\delta_e^1 + \varphi_e^1)} + a_e^2 e^{i(\delta_e^2 + \varphi_e^2)} + i a_o^1 e^{i(\delta_o^1 + \varphi_o^1)} \quad (1.49)$$

$$\overline{M}(\lambda_i, \bar{p}_i) = a_e^1 e^{i(\delta_e^1 - \varphi_e^1)} + a_e^2 e^{i(\delta_e^2 - \varphi_e^2)} + i a_o^1 e^{i(\delta_o^1 - \varphi_o^1)} \quad (1.50)$$

where  $\delta_{e,o}^i$  and  $\varphi_{e,o}^i$  are respectively the  $CP$ -even and  $CP$ -odd phases evaluated at the phase-space point  $\Phi(\lambda_i, p_i)$ , whereas  $a_e^i$  and  $a_o^i$  are respectively the  $\hat{T}$ -even and  $\hat{T}$ -odd amplitudes evaluated at the phase-space point  $\Phi(\lambda_i, p_i)$ . Up to a flux factor, the squared modulus of Eq. 1.49 and of its  $CP$  conjugate in Eq. 1.50 provides us with the differential rates that can be decomposed, according to Eq. 1.48, in:

$$\left. \frac{d\Gamma}{d\Phi} \right|_{CP-even}^{\hat{T}-even} \propto a_e^1 a_e^1 + a_e^2 a_e^2 + a_o^1 a_o^1 + 2 a_e^1 a_e^2 \cos(\delta_e^1 - \delta_e^2) \cos(\varphi_e^1 - \varphi_e^2) \quad (1.51)$$

$$\left. \frac{d\Gamma}{d\Phi} \right|_{CP-even}^{\hat{T}-odd} \propto 2 a_e^1 a_o^1 \sin(\delta_e^1 - \delta_o^1) \cos(\varphi_e^1 - \varphi_o^1) + 2 a_e^2 a_o^1 \sin(\delta_e^2 - \delta_o^1) \cos(\varphi_e^2 - \varphi_o^1) \quad (1.52)$$

$$\left. \frac{d\Gamma}{d\Phi} \right|_{CP-odd}^{\hat{T}-even} \propto -2 a_e^1 a_e^2 \sin(\delta_e^1 - \delta_e^2) \sin(\varphi_e^1 - \varphi_e^2) \quad (1.53)$$

$$\left. \frac{d\Gamma}{d\Phi} \right|_{CP-odd}^{\hat{T}-odd} \propto 2 a_e^1 a_o^1 \cos(\delta_e^1 - \delta_o^1) \sin(\varphi_e^1 - \varphi_o^1) + 2 a_e^2 a_o^1 \cos(\delta_e^2 - \delta_o^1) \sin(\varphi_e^2 - \varphi_o^1) \quad (1.54)$$

It is important to note that Eq. 1.53 and Eq. 1.54 vanish in the  $CP$  limit. There are thus two distinct kinds of  $CP$ -violating differential rates: the presence of the  $\hat{T}$ -even one requires non vanishing differences in  $CP$ -even phases while the  $\hat{T}$ -odd- $CP$ -odd does not. Although no phase-space integration of  $CP$ -odd rates is in principle required for testing  $CP$  conservation, practical constraints like the finite available statistics impose the introduction of phase-space integrated observables. Indeed, the total rate asymmetry already defined in Eq. 1.36 is constructed from Eq. 1.53 as:

$$\int d\Phi \left. \frac{d\Gamma}{d\Phi} \right|_{CP-odd}^{\hat{T}-even} \quad (1.55)$$

A second family of  $CP$  observables can be obtained from integrals of its  $\hat{T}$ -odd- $CP$ -odd homologue in Eq. 1.54

$$\int d\Phi f(\Phi) \left. \frac{d\Gamma}{d\Phi} \right|_{CP-odd}^{\hat{T}-odd} \quad (1.56)$$

The function  $f(\Phi)$  must be  $\hat{T}$ -odd, otherwise the integral over the entire phase space would vanish. One of the simpler way to define such a function is to take the asymmetry with respect a  $\hat{T}$ -odd observable  $C_{\hat{T}}(\lambda_i, p_i)$ , that is



$$f(\Phi) = \text{sign}(C_{\hat{T}}(\Phi)) \quad (1.57)$$

One class of such observables are triple products. Triple products can be constructed by using either the momenta or the spins of final state particles in the mother center-of-mass frame:

$$C_{\hat{T}} = \vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) \quad (1.58)$$

where  $\vec{v}_i$  refers either to the momentum or the spin of the final state particle  $i$ .

Four-body decays are particularly suitable for this approach because it is possible to build  $C_{\hat{T}}$  directly in their rest frame by using three of the four momenta of the final state particles. In fact, the condition  $P_1^{\vec{C.o.M}} + P_2^{\vec{C.o.M}} + P_3^{\vec{C.o.M}} + P_4^{\vec{C.o.M}} = \vec{0}$ , where  $P_i^{\vec{C.o.M}}$  refers to the momentum of the daughter particle  $i$  in the mother center-of-mass frame, ensures that there is only one value of  $C_{\hat{T}}$  for the event, up to a sign. By making use of  $C_{\hat{T}}$ , the equations with definite  $CP$  and  $\hat{T}$  transformation properties can be written as:

$$\begin{aligned} \left. \frac{d\Gamma}{d\Phi} \right|_{CP-even}^{\hat{T}-even} &= \frac{d\Gamma(C_{\hat{T}} > 0)}{d\Phi} + \frac{d\Gamma(C_{\hat{T}} < 0)}{d\Phi} + \frac{d\bar{\Gamma}(-\bar{C}_{\hat{T}} > 0)}{d\Phi} + \frac{d\bar{\Gamma}(-\bar{C}_{\hat{T}} < 0)}{d\Phi} \\ \left. \frac{d\Gamma}{d\Phi} \right|_{CP-odd}^{\hat{T}-even} &= \frac{d\Gamma(C_{\hat{T}} > 0)}{d\Phi} + \frac{d\Gamma(C_{\hat{T}} < 0)}{d\Phi} - \frac{d\bar{\Gamma}(-\bar{C}_{\hat{T}} > 0)}{d\Phi} - \frac{d\bar{\Gamma}(-\bar{C}_{\hat{T}} < 0)}{d\Phi} \\ \left. \frac{d\Gamma}{d\Phi} \right|_{CP-even}^{\hat{T}-odd} &= \frac{d\Gamma(C_{\hat{T}} > 0)}{d\Phi} - \frac{d\Gamma(C_{\hat{T}} < 0)}{d\Phi} + \frac{d\bar{\Gamma}(-\bar{C}_{\hat{T}} > 0)}{d\Phi} - \frac{d\bar{\Gamma}(-\bar{C}_{\hat{T}} < 0)}{d\Phi} \\ \left. \frac{d\Gamma}{d\Phi} \right|_{CP-odd}^{\hat{T}-odd} &= \frac{d\Gamma(C_{\hat{T}} > 0)}{d\Phi} - \frac{d\Gamma(C_{\hat{T}} < 0)}{d\Phi} - \frac{d\bar{\Gamma}(-\bar{C}_{\hat{T}} > 0)}{d\Phi} + \frac{d\bar{\Gamma}(-\bar{C}_{\hat{T}} < 0)}{d\Phi} \end{aligned} \quad (1.59)$$

Using Eq. 1.59 we can build the following two **triple product asymmetries** (TPA) [22] [23] [24]:

$$A_{\hat{T}} = \frac{\int d\Phi f(\Phi) \left[ \left. \frac{d\Gamma}{d\Phi} \right|_{CP-even}^{\hat{T}-odd} + \left. \frac{d\Gamma}{d\Phi} \right|_{CP-odd}^{\hat{T}-odd} \right]}{\int d\Phi \left[ \left. \frac{d\Gamma}{d\Phi} \right|_{CP-even}^{\hat{T}-even} + \left. \frac{d\Gamma}{d\Phi} \right|_{CP-odd}^{\hat{T}-even} \right]} \equiv \frac{\Gamma(C_{\hat{T}} > 0) - \Gamma(C_{\hat{T}} < 0)}{\Gamma(C_{\hat{T}} > 0) + \Gamma(C_{\hat{T}} < 0)} \quad (1.60)$$

$$\bar{A}_{\hat{T}} = \frac{\int d\Phi f(\Phi) \left[ \left. \frac{d\Gamma}{d\Phi} \right|_{CP-even}^{\hat{T}-odd} - \left. \frac{d\Gamma}{d\Phi} \right|_{CP-odd}^{\hat{T}-odd} \right]}{\int d\Phi \left[ \left. \frac{d\Gamma}{d\Phi} \right|_{CP-even}^{\hat{T}-even} - \left. \frac{d\Gamma}{d\Phi} \right|_{CP-odd}^{\hat{T}-even} \right]} \equiv \frac{\bar{\Gamma}(-\bar{C}_{\hat{T}} > 0) - \bar{\Gamma}(-\bar{C}_{\hat{T}} < 0)}{\bar{\Gamma}(-\bar{C}_{\hat{T}} > 0) + \bar{\Gamma}(-\bar{C}_{\hat{T}} < 0)} \quad (1.61)$$

By substituting the terms of Eq. 1.51, 1.52, 1.53 and 1.54 into Eq. 1.60 and 1.61 we obtain:

$$A_{\hat{T}} \propto 2a_e^j a_o^k \sin[(\delta_e^j - \delta_e^k) + (\varphi_e^j - \varphi_o^k)] \quad (1.62)$$

$$\bar{A}_{\hat{T}} \propto 2a_e^j a_o^k \sin[(\delta_e^j - \delta_e^k) - (\varphi_e^j - \varphi_o^k)] \quad (1.63)$$

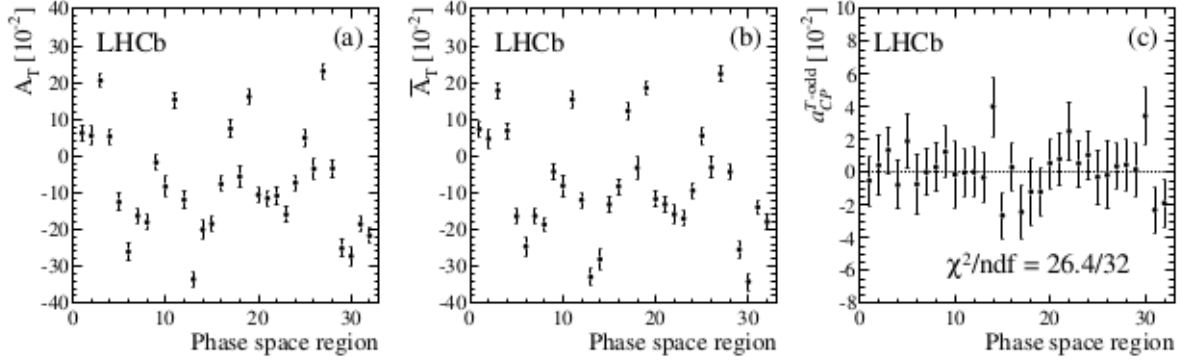


Figure 1.2: Distributions of the asymmetry parameters  $A_T$  (left),  $\bar{A}_T$  (middle) and  $a_{CP}^{T-odd}$  (right) in 32 different regions of the phase space for the decay  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ . FSI effects are clearly visible in  $A_T$  and  $\bar{A}_T$ , but cancel in the difference to give an asymmetry consistent with no  $CP$  violation hypothesis [26].

It is important to note here that  $A_{\hat{T}}$  and  $\bar{A}_{\hat{T}}$  have no definite  $CP$  transformation properties, therefore a non-vanishing value of these observables is not a sign of  $CP$ -violation; their value is influenced by the presence of final-state interactions (FSI) [25]. On the contrary, a  $CP$ -odd observable allowing to unambiguously witness  $CP$ -violation is the difference between the two  $CP$ -conjugated process asymmetries, defined as

$$a_{CP}^{\hat{T}} \equiv \frac{(A_{\hat{T}} - \bar{A}_{\hat{T}})}{2} \propto a_e^j a_o^k \cos(\delta_e^j - \delta_o^k) \sin(\varphi_e^j - \varphi_o^k) \quad (1.64)$$

where the  $CP$ -even final-state contributions cancel out. An example of where FSI effects are clearly visible is the decay  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  [26], as shown in Fig. 1.2. Nonetheless, the sum of  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$  asymmetries is a P-odd observable, defined as

$$a_P^{\hat{T}} \equiv \frac{(A_{\hat{T}} + \bar{A}_{\hat{T}})}{2} \quad (1.65)$$

Contrary to direct  $CP$  asymmetry, a non-zero triple-product asymmetry needs only a weak phase difference to be produced, no strong phases between interfering amplitudes are required. The physics observables  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}}$  and  $a_P^{\hat{T}}$  are, by construction, largely insensitive to the production and detection asymmetries defined in Eq. 1.45.

To avoid dilutions in the integral of Eq. 1.60 and 1.61, the functions chosen should ideally change sign wherever the  $\hat{T}$ -odd  $CP$ -odd piece of the differential decay rate itself changes sign. The bins' boundaries should also be placed there. The question of what set of  $f(\Phi)$  functions would yield the best sensitivity to  $CP$  violation is nontrivial and depends on the process at hand. Actually, when the form of the differential decay rate is known with confidence, one may rely on an unbinned like-likelihood fit to the data for extracting  $CP$ -violating parameters as done in many amplitude analyses. However in many hadronic decays of heavy baryons the decay rate is not known and no amplitude analyses has been carried out. Using tests of  $CP$  violation that have a limited reliance upon the process

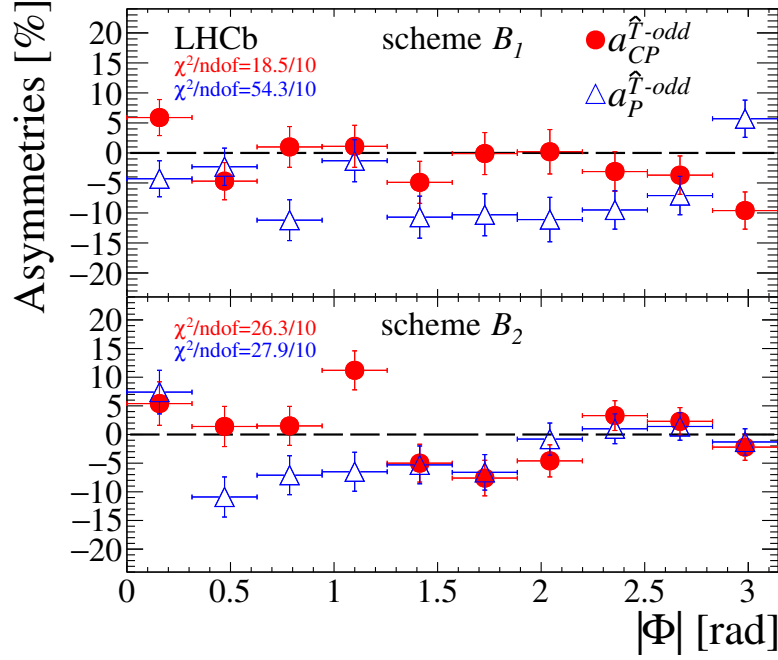


Figure 1.3: Measured  $a_{CP}^{T-odd}$  and  $a_P^{T-odd}$  asymmetries in 10 regions of the phase space. The error bars represent the sum in quadrature of the statistical and systematic uncertainties. The  $\chi^2/ndof$  is calculated with respect to the null hypothesis and includes statistical and systematic uncertainties [29].

dynamics and its parametrization is therefore desirable.

To summarize, the triple-product asymmetries used here is an important tool for the observation and discovery of  $CP$  violation in multi-body decays, while an amplitude analysis would be advantageous to study the origin of  $CP$  violation.

Triple product asymmetries have been already used to search for evidence of  $CP$  violation in b-baryon decays. Using a data sample corresponding to an integrated luminosity of  $1 \text{ fb}^{-1}$  collected in 2011 at a centre-of-mass energy of  $\sqrt{s} = 7 \text{ TeV}$  and  $2 \text{ fb}^{-1}$  collected in 2012 at a centre-of-mass energy of  $\sqrt{s} = 8 \text{ TeV}$ , the LHCb collaboration first measured TPA in three different four-body  $\Lambda_b^0$  baryon decays and one four-body  $\Xi_b^0$  baryon decay:  $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$  [27],  $\Lambda_b^0 \rightarrow pK^-\pi^+\pi^-$ ,  $\Lambda_b^0 \rightarrow pK^-K^+K^-$ ,  $\Xi_b^0 \rightarrow pK^-\pi^+\pi^-$  [28].

Although phase space integrated asymmetries showed no evidence for  $CP$  violation in any of the above mentioned channels, an interesting hint of local  $CP$  violation at the  $3.3\sigma$  level including systematic uncertainties was observed in the  $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$  channel. This result was recently superseded by an updated analysis using a data sample corresponding to an integrated luminosity of  $6.6 \text{ fb}^{-1}$  [29] and collected from 2011 to 2017. No clear evidence of  $CP$  violation was found though a interesting deviation at the  $2.9\sigma$  level was observed also in this case. This channel showed compelling evidence of  $P$  violation with a significance of  $5.5\sigma$ , as shown in Fig. [28].

### 1.3 Multi-body baryonic $B$ decays

Due to large  $B$  meson mass, its decays to baryons are possible. First observations and studies of baryonic  $B$  decays were performed by ARGUS Collaboration and it was found that the inclusive branching fraction for baryonic is roughly 7.5% of the  $B$  total width [30]. Final states containing baryons show an unusual characteristics: three-body decays have substantially larger branching fractions than their two-body counterparts and four-body decays are usually more frequent than the three-body modes. It was also observed that in many three- and four-body decay modes the invariant mass of baryon-antibaryon pair is peaking near threshold and this feature is called threshold enhancement. The theoretical description for the latter phenomenon is very challenging and experimental information is still scarce. In recent years, studies performed by the LHCb Collaboration have increased significantly the knowledge of the decays of  $B$  mesons to final states containing baryons. The first observation of a baryonic  $B_c^+$  was reported in 2014 [31], and also the first observation of a baryonic  $B_s^0$  decay [32] was performed by the LHCb Collaboration. Four-body baryonic  $B$  decays of the topology  $B_{(s)}^0 \rightarrow p\bar{p}h^+h_1^-$ , where  $h$  stands for either a  $K$  or a  $\pi$  meson, have also been observed by LHCb [33]. Besides the hierarchy of the branching fractions, the search for  $CP$  violation in baryonic  $B$  decays is also of great interest. The first evidence of  $CP$  violation in this kind of decays has been reported by the LHCb experiment from an analysis of  $B^+ \rightarrow p\bar{p}K^+$  decays [34]. Similar to the four-body b-baryon decays, the four-body baryonic  $B$  decays can also be a good place to look for  $CP$  violation using the method of TPA described in Section 1.2.4. Four-body decays are particularly suited for this approach since the definition of the TPA do not involve the spins of the final-state particles, unlike the TPA in three-body decays. No theoretical  $CP$  asymmetry expectations are available yet for charmless four-body  $B_{(s)}^0 \rightarrow p\bar{p}h^+h_1^-$  decays using TPA covering all the phase space. However, some angular and direct  $CP$  asymmetries in  $B^{0,\pm} \rightarrow p\bar{p}M_V$  ( $M_V \equiv K^{*,(\pm)}, \rho$ ), have been calculated theoretically [35], [36] and are reported in Table 1.1. Large direct  $CP$  violating (around 20%) asymmetry is expected in  $B^\pm \rightarrow p\bar{p}K^{*\pm}$  and it is indeed confirmed by measurements performed by BaBar [37] and Belle [38] giving an average of  $A_{CP} = 0.21 \pm 0.16$  [39]. Direct  $CP$  asymmetries for the channel  $B^0 \rightarrow p\bar{p}K^{*0}$  are predicted to be a factor smaller instead but, since  $B^0 \rightarrow p\bar{p}K^+\pi^-$  is expected to proceed mainly through intermediate  $K^{*0} \rightarrow K^+\pi^-$  resonances, a complementary search for  $CP$  violation in the same kinematic region used in the theoretical calculation is possible.

| $M_V$      | $\mathcal{B}_{teo}$ | $\mathcal{B}_{exp}$    | $A_\theta^{teo}(M_V)$ | $A_{CP}^{teo}(M_V)$ | $A_{CP}^{exp}(M_V)$ |
|------------|---------------------|------------------------|-----------------------|---------------------|---------------------|
| $K^{*\pm}$ | $6.0 \pm 1.3$       | $3.6^{+0.8}_{-0.7}$    | $0.13 \pm 0.05$       | $0.22 \pm 0.01$     | $0.21 \pm 0.16$     |
| $K^{*0}$   | $0.9 \pm 0.3$       | $1.28^{+0.28}_{-0.25}$ | $-0.27 \pm 0.06$      | $0.013 \pm 0.001$   | $0.05 \pm 0.12$     |
| $\rho^\pm$ | $28.8 \pm 2.1$      | -                      | $0.11 \pm 0.06$       | $-0.029 \pm 0.009$  | -                   |

Table 1.1: Branching ratios (in units of  $10^{-6}$ ) and angular and direct  $CP$  asymmetries in  $B^0 \rightarrow p\bar{p}M_V$ , where the errors are from the experimental data of the three-body baryonic  $B$  decays.

# Chapter 2

## The LHCb experiment at the LHC

The LHCb experiment (Large Hadron Collider beauty) is the experiment dedicated to heavy flavour physics at the LHC at CERN. This chapter describes in details the LHCb detector configuration during the Run 1 and Run 2 data taking periods. The analysis described in Chapter 3 uses data recorded during these two data taking periods where the detector operated at the instantaneous luminosity of  $\mathcal{L} = 4 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$ . This value is nearly two orders of magnitude smaller compared to the nominal instantaneous luminosity of  $10^{34} \text{cm}^{-2} \text{s}^{-1}$  provided by the LHC and exploited by ATLAS and CMS. The primary goal of LHCb was to search for new physics in  $CP$  violation and rare decays of beauty and charm hadrons, but it is now considered a heavy-flavour general purpose experiment thanks to the striking results in different fields such as spectroscopy with the discovery of pentaquarks [40] and hints of tetraquarks [41]. A schematic view of the detector is shown in Fig. 2.2. The LHCb detector was designed as a single arm forward spectrometer with a small angular acceptance with respect to the beam pipe in order to collect the 25% of the  $b\bar{b}$  pairs produced in the collisions at the LHC. The angular distribution of the  $b\bar{b}$  production is peaked in a small region at low polar angles, as shown in Fig. 2.1.

### 2.1 The tracking system and the magnet

The tracking system is used to reconstruct the trajectories of the charged particles and to measure their momenta with the help of the magnetic field created by a dipole magnet. The momentum resolution  $\frac{\sigma_p}{p}$  reached by the tracker can be as low as  $5 \times 10^{-3}$  for a 10 GeV particle [43]. The magnetic field is generated by a warm dipole magnet located between the TT and the T1 tracking station, as shown in Fig. 2.3. The use of a warm magnet allows to quickly ramp-up and down the current to change the polarity. In fact, the polarity of the magnetic field is inverted periodically during the normal data-taking period. Different track types can be reconstructed depending on their paths through the spectrometer (see Fig. 2.3):

- **VELO tracks.** This type of tracks have hits only in the VELO detector and are used for the primary vertex (PV) reconstruction.

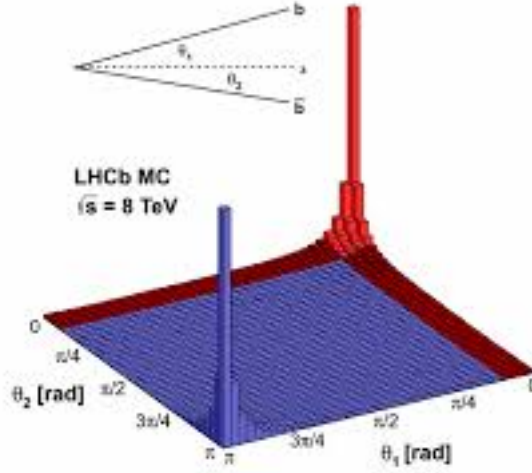


Figure 2.1: Distribution of the angle  $\theta$  between the direction of the  $b\bar{b}$  quarks produced in  $pp$  interactions and the beam axis. This distribution is obtained from the PYTHIA [42] event generator.

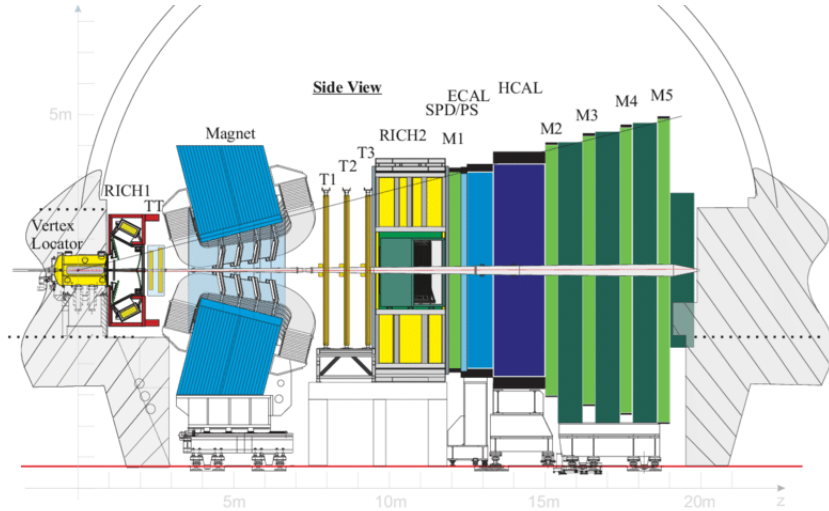


Figure 2.2: View of the LHCb detector in the non-bending vertical plane. The  $z$ -axis runs along the direction of the proton beam.

- **Upstream tracks.** This type of tracks have hits in the VELO and the Tracker Turicensis (TT). These tracks usually belongs to low momentum objects that are deflected outside the acceptance by the magnetic field before reaching the downstream trackers.



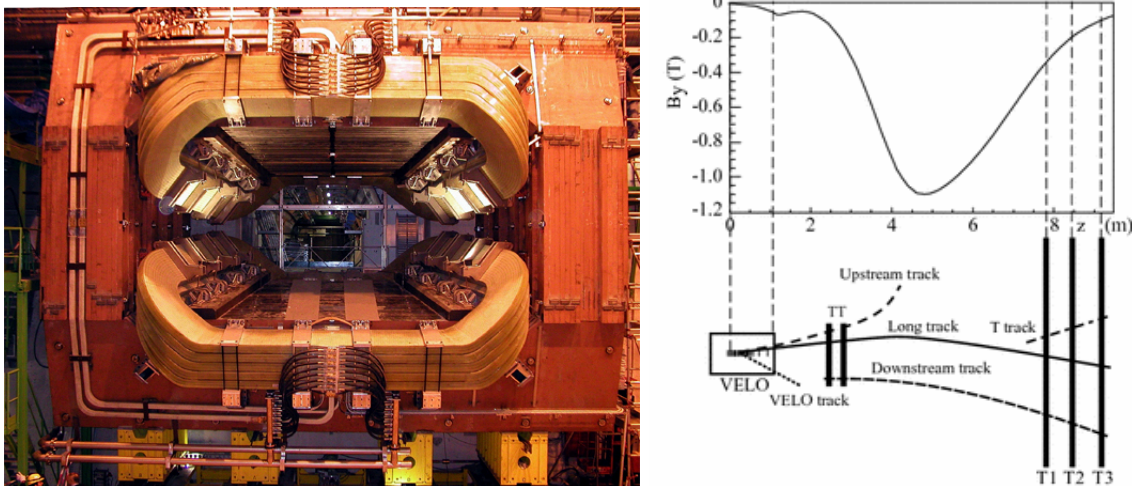


Figure 2.3: Picture of the LHCb magnet (left) and  $B_y$  field component as a function of the  $z$  coordinate with illustration of the various track type (right).

- **Downstream tracks.** This type of tracks have hits only in the TT and T1, T2 and T3. They are mainly used to reconstruct neutral long lived hadrons, such as the  $K_s^0$  meson and the  $\Lambda$  baryon, that decay outside the VELO acceptance.
- **T-tracks.** This type of tracks have hits only in the T1, T2 and T3 stations and are used mainly for calibration purposes and detector studies.
- **Long tracks.** This type of tracks have hits in the VELO, in the tracking stations T1, T2 and T3 and TT (optionally). The momenta of these tracks have the most precise estimate and are, therefore, particularly important for physics analysis.

### 2.1.1 The VELO

The VERtEx LOcator [44] is located close to the  $pp$  interaction point. The main purpose of the VELO is to reconstruct the tracks, assign them to the corresponding primary vertex (PV) and to distinguish displaced secondary vertices (SV), which might be a signature of heavy flavour decays. The VELO consists of 21 silicon tracking stations that are placed perpendicularly to the beam line, as shown in Fig. 2.4. Every station has two separate modules, on the left and on the right side of the beam pipe, which are moved away from the interaction region during the beam injection and are placed back in the nominal position once a stable condition is reached. Every module consists of two silicon strip sensors; one measures the distance from the beam axis and the other measures the azimuthal angle. The resolution on the position of the primary vertex obtained with the VELO varies between  $9\ \mu\text{m}$  and  $35\ \mu\text{m}$  for the  $x$  and  $y$  coordinates and between  $50\ \mu\text{m}$  and  $280\ \mu\text{m}$  for the  $z$  coordinate. In addition, each half contains two Pile-Up VETO stations, which are used at the L0 level trigger, to limit the fraction of multiple events. The fraction of



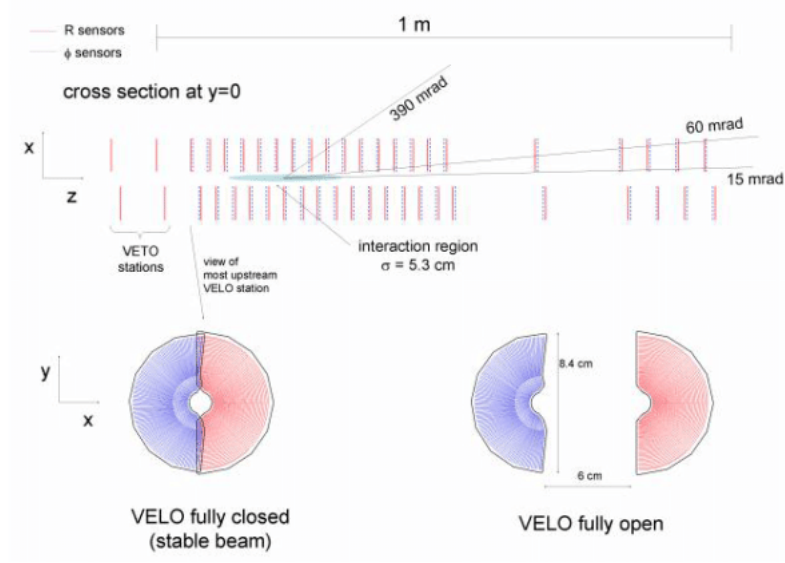


Figure 2.4: Top: The 21 tracking stations of the VELO and the 2 VETO stations as seen from the bending plane. Bottom left: Sketch illustrating the  $r\phi$  geometry of one fully closed VELO tracking station in the  $x$ - $y$  plane. Bottom right: Sketch illustrating the  $r\phi$  geometry of one fully open VELO tracking station in the  $x$ - $y$  plane.

multiple events at LHCb is high and a veto on those events frees bandwidth and allows to lower the thresholds used at the zero-level hadronic triggers.

### 2.1.2 The TT

The Tracker Turicensis (TT) [45] is a silicon strip detector positioned between the Ring Imaging Cherenkov RICH1 detector and the magnet (see Fig 2.2). It is used mainly to reconstruct tracks from the decays of long-lived neutral particles, such as the  $K_s^0$  or the  $\Lambda$  baryon. The two planes in the middle, TTaU and TTbV, are tilted by  $\pm 5^\circ$  with respect to the first and the last plane. The four layers are shown in Fig. 2.5.

### 2.1.3 Inner and Outer Tracker

These tracking stations [46, 47] are located downstream of the magnet (T1, T2 and T3 in Fig. 2.2) and are required to measure the momentum of charged particles deflected by the dipole magnetic field. The three tracking stations use two different technologies because of the different particle flux which they are exposed to. The inner tracker (IT), closer to the beam pipe, is made of silicon sensors, whereas the outer tracker (OT) is made of drift tubes in order to minimize the material budget before the calorimeters. The inner trackers make up only the 2% of the total area of a tracking station, but measure the  $\sim 20\%$  of

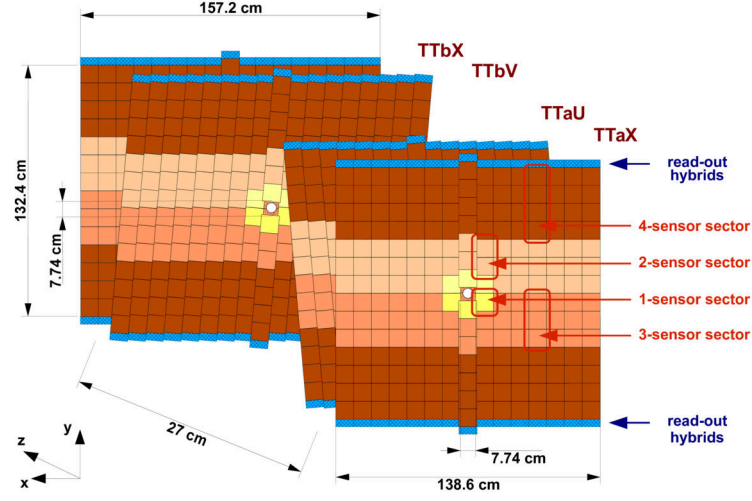


Figure 2.5: The four TT layers

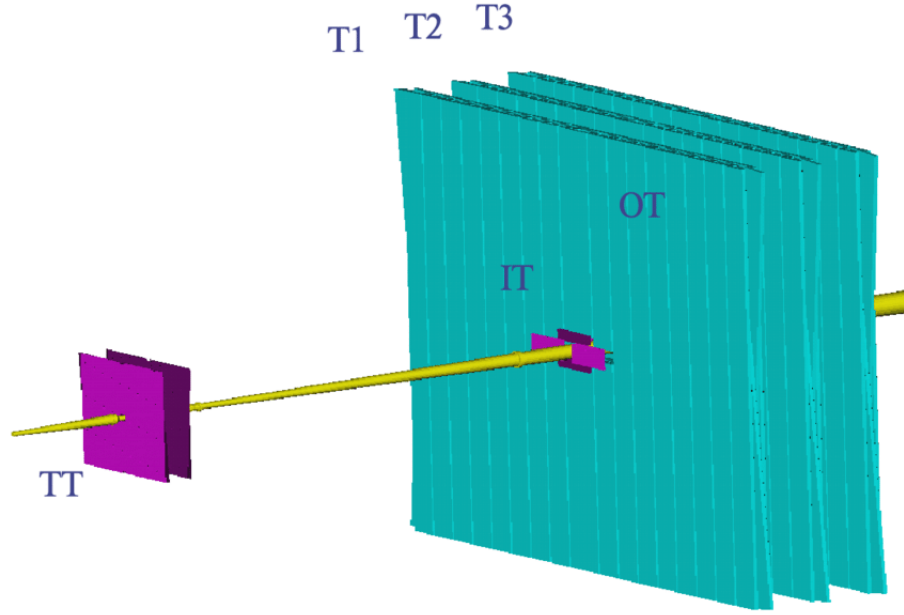


Figure 2.6: Sketch of the T1, T2 and T3 tracking stations. The detectors in purple are made of silicon while those in blue are made of gas.

the total particle flux. The layout of the T1, T2 and T3 stations is shown in Fig. 2.6. The drift tubes are 2.4 m long with 4.9 mm inner diameter and are filled with a gas mixture that guarantees a drift-time below 50 ns. The hit resolution along the x-axis is  $50 \mu\text{m}$  and  $200 \mu\text{m}$  for the inner and outer trackers respectively.

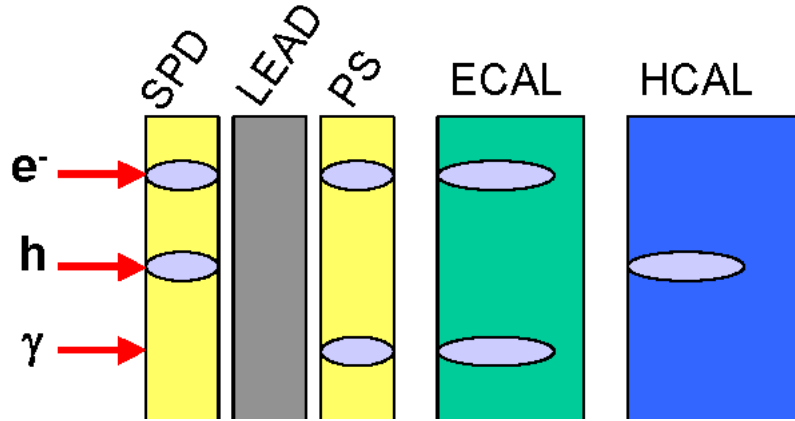


Figure 2.7: Signal deposited in the different layers of the LHCb calorimeter by an electron ( $e^-$ ), a hadron ( $h$ ) and a photon ( $\gamma$ )

## 2.2 The particle identification system

The ability to distinguish different types of particles is essential for many flavour physics analyses. The LHCb experiment uses the combined outputs of the calorimeters, muon chambers and Ring Imaging Cherenkov (RICH) detectors to identify final state particles.

### 2.2.1 Calorimeters

The calorimeters [48] provide particle identification, energy and position measurements for electrons, photons and hadrons. The calorimeters are part of the L0 level trigger where they select electron, photon and hadron candidates with a transverse energy above a certain threshold. They are positioned after the Ring Imaging Cherenkov RICH2 detector and the first muon chamber (see Fig. 2.2). The LHCb calorimeter system is composed of four subdetectors: the Scintillator Pad Detector (SPD), the Pre-Shower detector (PS), the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL). These subdetectors are based on scintillating plastics coupled to photo-multiplier tubes. The function of the SPD/PS is to distinguish electrons from charged hadrons and neutral pions. The SPD identifies charged particles and allows electrons to be separated from photons. Hadrons, instead, pass through the PS detector depositing only a small amount of energy. The ECAL is made of 2 mm layers of thick lead plates interleaved with 4 mm thick scintillator tiles readout by plastic optical fibers. The HCAL, instead, is made of layers of absorbing iron interleaved with scintillator tiles. A sketch of the different layers making up the calorimeter is shown in Fig. 2.7.

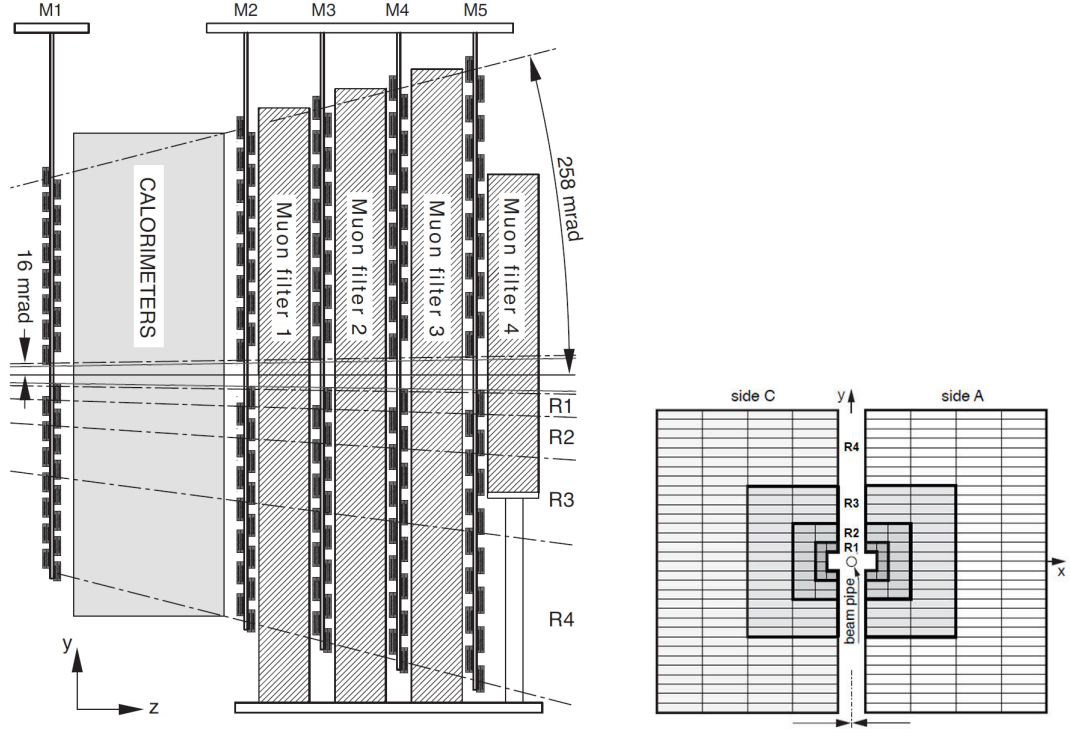


Figure 2.8: Side view of the LHCb muon detector

### 2.2.2 The muon system

The muon system [49] provides muon identification and is the most downstream detector as muons are extremely penetrating particles and is composed of five stations, M1-M5. The M1 station, which is placed upstream of the calorimeters, is used mainly for the measurement of transverse momentum at the L0 level muon trigger. The remaining stations, which are situated downstream of the calorimeters, are used to select high momentum muons ( $P_T > 6$  GeV/c). Stations M1-M3 have high spatial resolution and are able to measure the  $P_T$  of the candidate with a resolution of  $\sim 20\%$ . Station M4 and M5, instead, are used for candidate confirmation as they have a limited spatial resolution. Every muon station is made of concentric regions of increasing pad density towards the beam pipe (see Fig. 2.8). Two types of detector technology are used. The inner region of M1 uses Gas-Electron-Multiplier (GEM) detectors for their radiation-hardness while the rest of M1 and M2-M5 are made of multi-wire proportional chambers (MWPC).

### 2.2.3 The RICH system

The LHCb Ring Imaging Cherenkov (RICH) detector [50] system provides particle identification (PID) of charged hadrons. A large number of b-hadrons show a very similar decay topology, but different final state particles and the informations provided by the

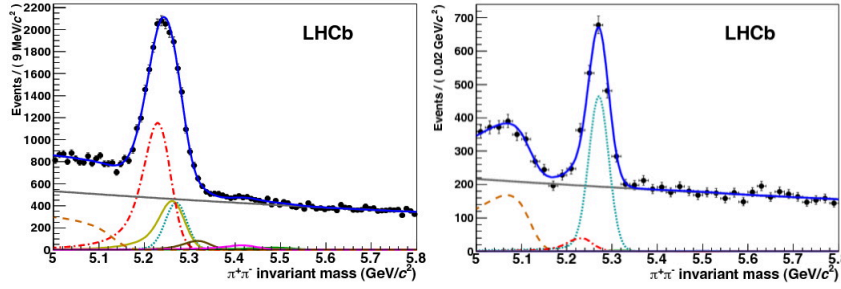


Figure 2.9: The distribution of  $\pi\pi$  masses for decays consistent with the B meson. On the left, the distribution without RICH particle identification (every particle assumed to be  $\pi$ ). The contributions from different b-hadron decay modes ( $B^0 \rightarrow K\pi$  red dashed-dotted line,  $B^0$  to three-body final state orange dashed-dashed line,  $B_s^0 \rightarrow KK$  yellow line,  $B_s^0 \rightarrow K\pi$  brown line,  $\Lambda_b \rightarrow Kp$  purple line,  $\Lambda_b \rightarrow K\pi$  green line), are eliminated by positive identification of pions, kaons and protons and only the signal and two background contributions remain visible in the plot on the right. The grey solid line is the combinatorial background

tracking system is not sufficient to distinguish between pions, kaons and protons. The ability to assign the proper mass to the charged tracks is essential for the LHCb physics program. An example of the importance of having a RICH detector is shown in Fig. 2.9. The operating principle of a RICH detector relies on the properties of the Cherenkov radiation emitted by charged particles passing through a dielectric medium with a speed  $\beta$  greater than the phase velocity of light in that medium. If  $\beta > \frac{1}{n}$ , a coherent wavefront is produced in the form of a cone that moves with a velocity  $1/n$ . The photons are emitted at a constant angle,  $\theta_c$ , with respect to the trajectory of the particle and its cosine is given by

$$\cos \theta_c = \frac{1}{n\beta} \quad (2.1)$$

The RICH uses spherical mirrors to focus the photons that form a ring in the photo-detecting plane. The radius of the ring is related to the velocities of the particle that generated the light cone. When the rings are associated to the track that produced them, a mass can be assigned to the charged particle by using the momentum information provided by the tracking system. The number of Cherenkov photons emitted per unit length in the radiator and per unit of wavelength is given by

$$\frac{d^2 E}{dx d\lambda} = \frac{2\pi z^2 \alpha}{\lambda^2} \left( 1 - \frac{c^2}{v^2 n^2(\lambda)} \right) \quad (2.2)$$

The dependence of the refractive index  $n$  on the wavelength of the emitted Cherenkov photons gives rise to a chromatic uncertainty in the measurement of  $\theta_c$ .

The LHCb RICH detectors, shown in Fig. 2.10, have gas-tight volumes filled with gas radiators. RICH1, which is placed before the magnet and filled with  $C_4F_{10}$ , has a refractive index of  $n = 1.03$  and measures optimally low momentum particles in the range  $\sim 10$ – $60$  GeV/c. RICH2, which is placed after the magnet and filled with  $CF_4$ , has a refractive

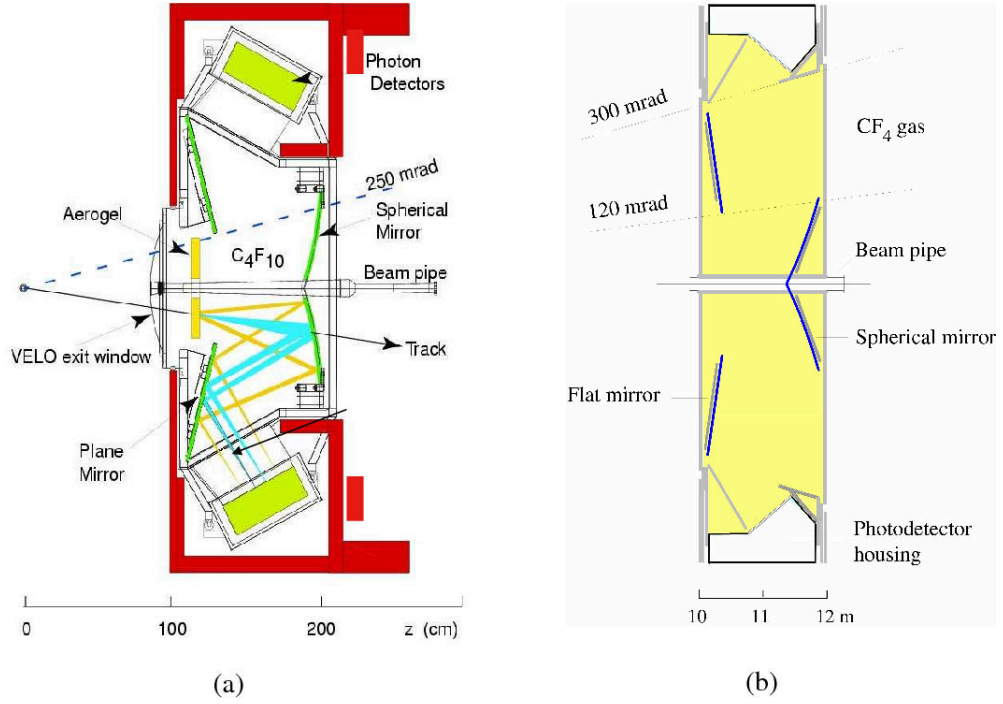


Figure 2.10: Left: Side view of RICH1 during Run1. The Cherenkov photons path is drawn. The Aerogel radiator was removed before the start of Run2. Right: Top view of RICH2

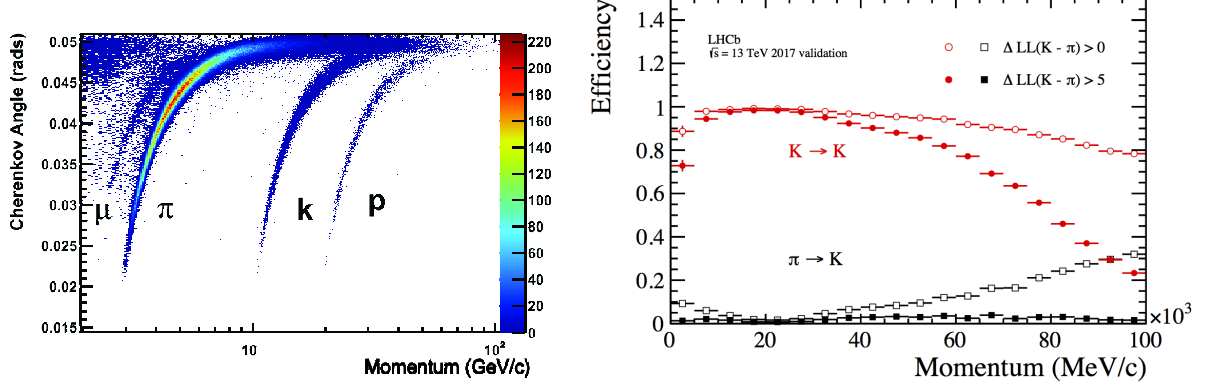


Figure 2.11: Reconstructed Cherenkov angle as a function of track momentum in the  $C_4F_{10}$  radiator (left) and kaon identification efficiency (red) and pion misidentification rate (black) measured on data as a function of track momentum for a loose (open circle) and a tight (full circle) requirement (right).

index of  $n = 1.0005$  and measures the high momentum particles in the range  $\sim 15$ – $100$  GeV/c that remain within the geometrical acceptance after the magnetic deflection.

Hybrid Photon Detectors (HPDs) are used as photo-detectors to detect the Cherenkov light. These photo-detectors are vacuum tubes with a 75 mm active diameter, a quartz



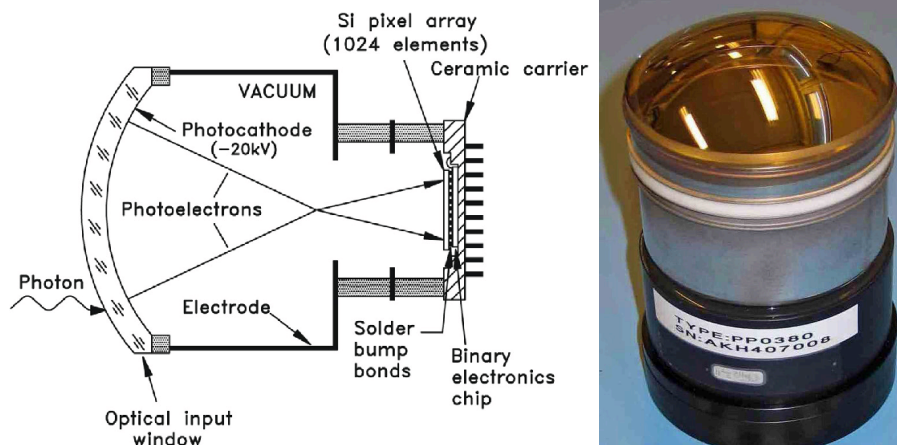


Figure 2.12: Left: Sketch of working principle of an HPD. Right: The HPD developed for the LHCb-RICH detectors.

window and a multialkali photocathode; the photo-electrons emitted by the cathode are focused onto a silicon pixel array, using an accelerating voltage of -16 kV. The silicon detector is segmented into 1024 pixels, each  $500 \mu\text{m} \times 500 \mu\text{m}$  in area and arranged as a matrix of 32 rows and 32 columns. The demagnification factor of the electrostatic focusing system and the internal sides of the vacuum tube is about 5, which translates into an effective granularity of  $2.5 \times 2.5 \text{ mm}^2$  at the photo-cathode. The photodetector planes are kept under a  $\text{CO}_2$  atmosphere. The frontend electronics chip is encapsulated within the HPD tube and bump-bonded to the silicon pixel sensor (see Fig. 2.12), which result in a very low noise. The overall Cherenkov angle resolution determines the performance of the RICH detectors, as it is the fundamental parameter on which the separation of two particle types is based; the limiting factors are the imperfect focusing of the optics, which causes an uncertainty in the emission point of the Cherenkov radiation and the pixel size of the photo-detectors. The overall Cherenkov angle resolution is 1.65 mrad for RICH1 and 0.67 mrad for RICH2. The performances of RICH1 as a function of the momentum of the charged track are shown in Fig. 2.11. The performance of the RICH depends strongly on the detector occupancy, which has to remain under 30% in order to not degrade too much the PID capability of the detector.

## 2.3 The Trigger System

The trigger identifies potentially interesting events to save for offline analysis. The LHCb trigger [51] is structured in two levels, the Level-0 trigger (L0) and the High Level Trigger (HLT). The hardware L0 is implemented in custom electronic boards and reduces the rate from 40 MHz down to 1 MHz, at which point the full LHCb detector can be read out; 1 MHz is the maximum rate imposed by the frontend electronics of the different sub-detectors. The HLT is a software trigger performing a full reconstruction of the events

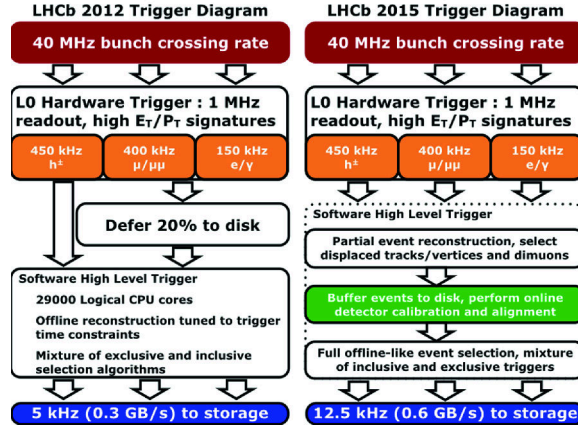


Figure 2.13: Architecture of the trigger system used in Run 1 (left) and in Run 2 (right)

selected by the L0 level in a computer farm consisting of more than 20000 CPU cores in about 1600 physical nodes. All the events selected by the HLT are written to tape. During Run 1, the rate of events to be stored could not exceed  $\sim 5$  kHz due to the constraints imposed by the limited computing resources. This limit was increased to  $\sim 12$  kHz in Run 2 after an increase in computing resources and an improvement in the overall trigger architecture. The trigger architectures used during Run 1 and Run 2 are shown in Fig. 2.13.

### 2.3.1 The L0 trigger

The L0 trigger combines the information from the pile-up VETO system, the calorimeters and the muon detectors and operates synchronously to the 40 MHz LHC bunch crossing clock reducing the acquisition rate to 1 MHz with a fixed latency of  $4 \mu\text{s}$ . It is designed to select events with high transverse energy  $E_T$  and transverse momentum  $P_T$ . In particular, the calorimeters trigger searches for high transverse energy deposits to identify electrons, photon and hadron candidates. The muon trigger system is used to identify one or two penetrating high transverse momentum tracks. The VELO pile-up modules are used to trigger on beam-gas induced events in the backward direction and to reject events with high multiplicity. The L0 trigger creates five independent candidates:

- **L0Hadron** is the highest energy deposit in the HCAL above a certain threshold
- **L0Electron** is the highest energy deposit in the ECAL above a certain threshold with hits both in the SPD and in the PS detector
- **L0Photon** is the highest energy deposit in the ECAL above a certain threshold with no hits in the SPD and hits in the PS detector
- **L0Muon** is the highest  $P_T$  of any muon candidate in the event above a certain threshold



- **L0DiMuon** is the product of the highest and second-highest  $P_T$  above a certain threshold

The total number of hits in the SPD is also used to veto high-multiplicity events that would take too long to process in the HLT. These L0 lines were used in the analysis described in Chapter 3.

### 2.3.2 The High Level Trigger

An event accepted by the L0 trigger is processed by the High Level Trigger, a fully software trigger implemented in C++ that runs asynchronously with respect to the collision rate, on a farm of processors. It reduces the event rate from 1 MHz to 2-5 kHz and all the events selected by the HLT are stored as raw data. The HLT is divided in two stages: HLT1 and HLT2. The first stage, HLT1, performs a partial event reconstruction and an inclusive selection of signal candidates. The most efficient HLT1 selection for hadronic charm and beauty decays used in Run1 is called **Hlt1TrackAllL0**. It selects events with good quality track candidates with high  $P_T$  ( $P_T > 1.6$  GeV) and displaced with respect to the primary vertex. This selection was improved for Run2 and Hlt1TrackAllL0 was replaced by two different selections called **Hlt1TrackMVA** and **Hlt1TwoTrackMVA**. These HLT1 lines were used in the analysis described in Chapter 3.

The HLT1 reduces the rate from 1 MHz down to  $\sim 50$  kHz, low enough that a full event reconstruction can be performed by the HLT2. The HLT2 is composed by a set of exclusive, designed to select specific decays, and inclusive selections, such as the one designed to trigger efficiently on any B decay with at least 2 charged daughter. This line, which is called **Hlt2Topo{2,3,4}BodyBBDTDecision**, was also used in the analysis. HLT2 reduced the rate to 3kHz in 2011, 5kHz in 2012 and 12.5 kHz in Run II, which was then written to permanent storage. The increase from 2011 to 2012 is mainly due to writing 20% of the L0 output directly to disk, as shown in Fig. 2.13, in a process known as “deferred triggering”. These events were then processed between fills when there was less demand on the computing resources. An increase in computing resources from Run II allowed a higher rate to be written to storage. Between Run I and II, the reconstruction used in the trigger changed significantly. In Run I, the reconstruction was a simplified version of the offline reconstruction and the detector calibration and alignment parameters were calculated offline from already triggered data. Starting from Run II, the output from HLT1 was completely deferred. This meant that the alignment and calibration could be performed directly between HLT1 and HLT2.

The events selected by the trigger at LHCb are classified in the following categories:

- **Triggered On Signal (TOS)** when the particles belonging to the signal under study are sufficient to pass the trigger selection
- **Triggered Independent on Signal (TIS)** when particles not belonging to the signal under study pass the trigger selection

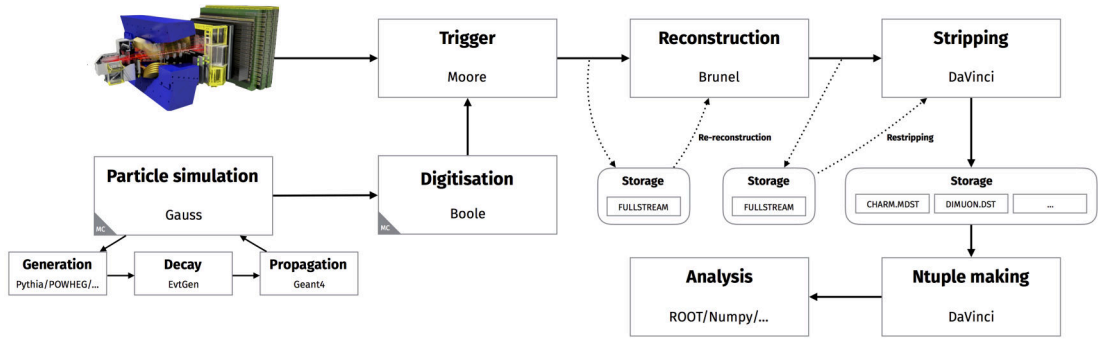


Figure 2.14: The LHCb data-flow and the software applications associated to each step

- **Triggered on Both (TOB)** when both the signal under study and other particles not belonging to the signal pass the trigger selection

### 2.3.3 The LHCb data-flow

The triggered data are stored world wide in large computing centers connected through the LHC Computing Grid (LCG) where the raw detector hits are transformed into objects such as tracks and clusters. PID information is associated to each candidate at this stage. The processing of the raw data is done by the **Brunel** application [52]. The pattern recognition algorithms in Brunel makes use of calibration and alignment constants stored in the Detector Description DataBase (DDDB).

The events fully reconstructed by Brunel can be further filtered through a set of high-level selections, the so-called **Stripping lines**, available in the **DaVinci** application [53]. This tool can be used directly by analysts to select their candidates. The LHCb data-flow and the software applications associated to each step are shown in Fig. 2.14.

## 2.4 The Online System

The Online System provides the infrastructure for the control, configuration, monitoring, operation and running of the entire experiment whose schematic view is shown in Fig. 2.15. The synchronization between all the sub-systems is ensured by the TFC system while the interface between the user and all the equipment is provided by the Experiment Control System (ECS). The ECS was developed within the Joint Control Project (JCOP) [54], a common project between the four LHC experiments and a central group at CERN. JCOP provides tools to "quickly" develop a complex detector control system and is built on top of WinCC-OA [55]. The size and complexity of the LHC experiments control systems have made necessary the adoption of a highly distributed, tree-like structure to represent the behaviour of every sub-detectors, sub-systems and hardware components. This type of architecture allows a high degree of independence between the different components while allowing at the same time an integrated control, both automated and user-driven,

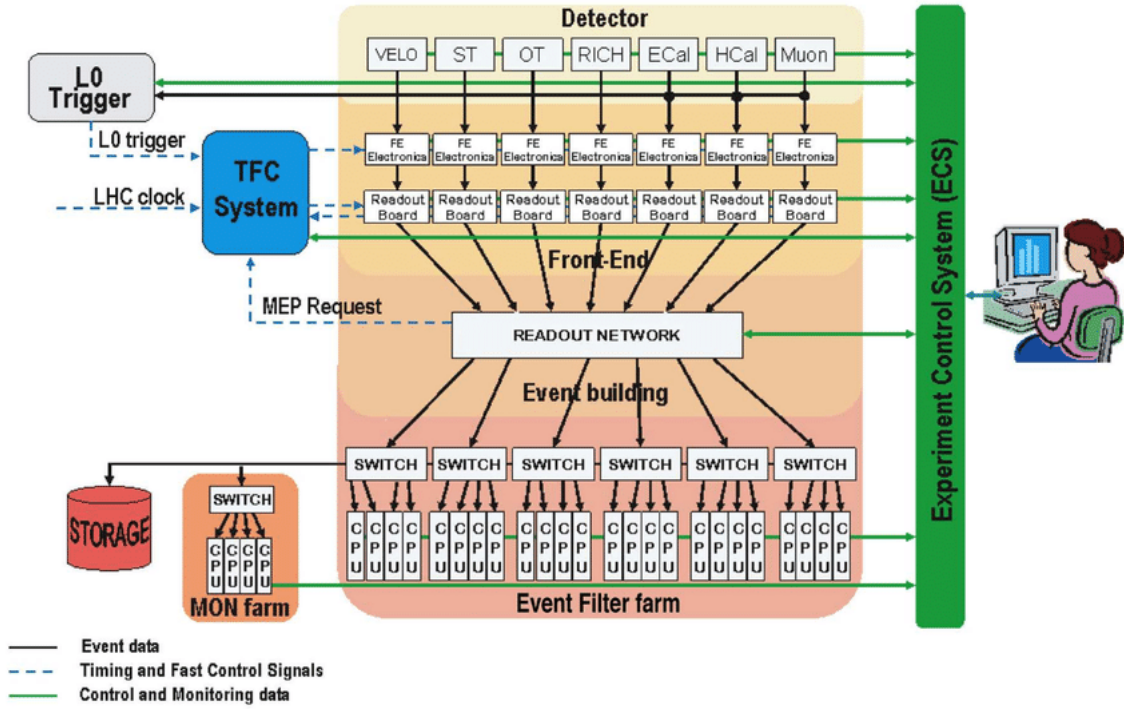


Figure 2.15: Architecture of the Online System

during physics data taking. A more detailed description of the LHCb ECS will be given in Chapter 5 where my contribution to the development of the RICH DCS is also described.

## Chapter 3

# Search for $CP$ violation in the charmless region of $B^0 \rightarrow p\bar{p}K^+\pi^-$ decay

In Section 1.3, it is shown that four-body baryonic  $B$  meson decays can provide a good way of studying and measuring asymmetries by triple product analysis. The decay  $B^0 \rightarrow p\bar{p}K^+\pi^-$  is expected to be dominated by the  $K^{*0}(892) \rightarrow K^+\pi^-$  resonance, with contributions from other  $K^{*0} \rightarrow K^+\pi^-$  resonances and therefore allows to search for  $CP$  violation in the same kinematic region used in the theoretical calculation (see Tab 1.1). In the charmless region of the  $p\bar{p}$  system ( $m_{p\bar{p}} < 2850 \text{ MeV}/c^2$ ), the  $B^0 \rightarrow p\bar{p}K^+\pi^-$  decay can proceed through the Feynman diagram shown in Fig. 3.1.

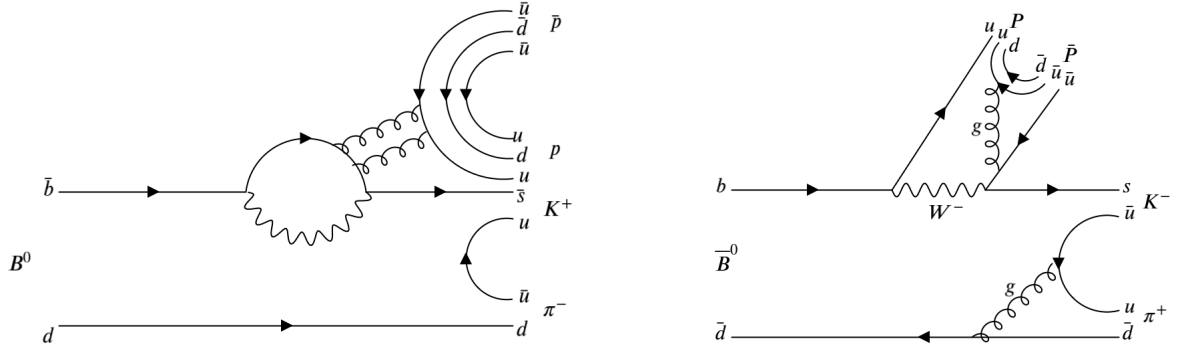


Figure 3.1: Feynman diagrams for the  $B^0 \rightarrow p\bar{p}K^+\pi^-$  in the charmless region: penguin (left) and tree (right).

As it is shown in the picture, the charmless region of this four-body baryonic  $B^0$  decay is mediated by the weak interaction and governed mainly by two amplitudes from different diagrams describing quark-level tree  $b \rightarrow u\bar{u}s$  and penguin  $b \rightarrow s\bar{u}u$ .  $CP$  violation could arise here from the interference of these two amplitudes whose weak phase difference is given by  $\arg(\frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*})$  which in the Standard Model is dominated by the CKM angle  $\gamma$  [56].

Moreover, penguin diagrams are a good place to search for  $CP$  violation effects since new heavy virtual particles might give measurable departures from the Standard Model expectations. The baryon-antibaryon pair can also be produced by a pair of gluons in OZI suppressed penguin diagrams, where gluonic resonances could be formed.

The goal of this analysis is to search for triple-product asymmetries (TPA) which probe  $CP$  violation through differential distributions.

### 3.1 Analysis strategy

The study of triple product correlations is performed in  $B^0 \rightarrow p\bar{p}K^+\pi^-$  decays<sup>1</sup>. The momenta of the final state particles are used to build the triple products which are calculated in the  $B^0$  ( $\bar{B}^0$ ) rest frame,  $C_T$  for  $B^0$  and  $\bar{C}_T$  for  $\bar{B}^0$  defined as:

$$C_{\hat{T}} = \vec{p}_{K^+} \cdot (\vec{p}_{\pi^-} \times \vec{p}_p) \quad (3.1)$$

$$\bar{C}_{\hat{T}} = \vec{p}_{K^-} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\bar{p}}) \quad (3.2)$$

The selected candidates will be split into 4 subsamples depending on the  $B^0$  flavour and the sign of the T-odd variable  $C_T$ . Consequently, the two asymmetries  $A_{\hat{T}}$  and  $\bar{A}_{\hat{T}}$  defined in Eq. 1.60 and Eq. 1.61 will be calculated as:

$$A_{\hat{T}} = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)} \quad \bar{A}_{\hat{T}} = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)} \quad (3.3)$$

where  $N$  is the total number of selected  $B^0$  mesons and  $\bar{N}$  the total number of selected  $\bar{B}^0$  mesons. From these two asymmetries the true  $CP$ -violating asymmetry can be constructed:

$$a_{CP}^{\hat{T}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}}) \quad (3.4)$$

$$a_P^{\hat{T}} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}}) \quad (3.5)$$

A simultaneous unbinned maximum likelihood fit to the  $m_{p\bar{p}K^+\pi^-}$  distribution of the four sub-samples will be used to determine the number of signal and background events. Eq. 3.3 can be inverted to include the asymmetries  $A_T$  and  $\bar{A}_T$  directly in the fit model:

$$\begin{aligned} N_{B^0, C_{\hat{T}} > 0} &= \frac{1}{2}N_{B^0}(1 + A_{\hat{T}}) \\ N_{B^0, C_{\hat{T}} < 0} &= \frac{1}{2}N_{B^0}(1 - A_{\hat{T}}) \\ N_{\bar{B}^0, -\bar{C}_{\hat{T}} > 0} &= \frac{1}{2}N_{\bar{B}^0}(1 + \bar{A}_{\hat{T}}) \\ N_{\bar{B}^0, -\bar{C}_{\hat{T}} < 0} &= \frac{1}{2}N_{\bar{B}^0}(1 - \bar{A}_{\hat{T}}) \end{aligned} \quad (3.6)$$

These relationships are used to extract the asymmetry parameters as floating variables along with the corresponding statistical error directly from the fit procedure.

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<sup>1</sup>Charged conjugated decays are implicitly considered throughout the text

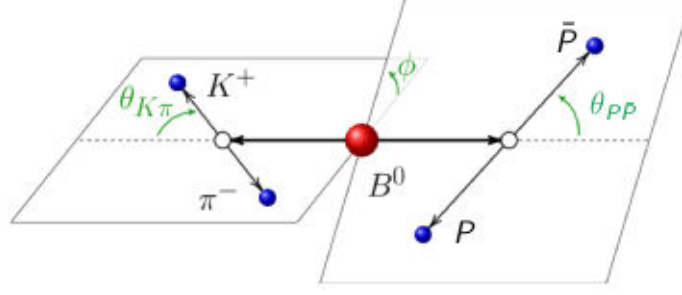


Figure 3.2: Parametrization of the phase space of a  $0 \rightarrow ab \rightarrow (12)(34)$  four-body decay. The momenta of the final-state particle pairs are pictured in their joint rest frames.

### 3.1.1 Search for $CP$ violation in bins of the phase space

In four-body particle decays, the  $CP$  asymmetries may vary over the phase space  $\Phi$  due to resonant contributions or their interference effects, possibly cancelling when integrated over the whole phase space. In order to enhance the sensitivity to  $CP$  violation, measurements in different regions of the phase space have been performed.

The standard Cabibbo-Maksymowicz parametrization [57] of the phase space  $\Phi$  can be used to describe a four-body decay of  $0 \rightarrow ab \rightarrow (12)(34)$  topology. It is based on two invariant masses  $m_a^2$  and  $m_b^2$  and three angles. In the  $a$  and  $b$  subsystems rest frames, the orientations of the final-state particles momenta are respectively characterized by  $\theta_a$  and  $\theta_b$  whereas the relative orientation of the planes formed by the two pairs of momenta is measured by  $\phi$ .

Such a description would likely be the most sensitive to the interferences between the several partial-wave contributions to that topology. On the contrary, the effects of the resonances occurring in other invariant masses would be diluted.

In our analysis the phase-space is described as a function of the variables:  $m_{K^+\pi^-}$  and  $m_{p\bar{p}}$  which are the invariant masses of the  $K^+\pi^-$  and  $p\bar{p}$  combinations,  $\cos\theta_{K^+\pi^-}$  which is the helicity angle of the  $K^+$  in the rest frame of the  $K^+\pi^-$ ,  $\cos\theta_{p\bar{p}}$  which is the helicity angle of the  $p$  in the rest frame of the  $p\bar{p}$  and the angle between the planes defined by the  $K^+\pi^-$  and  $p\bar{p}$  tracks (see Fig. 3.2):

$$\phi = \text{acos}(\hat{n}_{K^+\pi^-} \cdot \hat{n}_{p\bar{p}}) \quad (3.7)$$

where  $\hat{n}_{K^+\pi^-}$  and  $\hat{n}_{p\bar{p}}$  are the normal vectors to the di-baryon and di-meson planes calculated in the  $B^0$  frame. The helicity angles  $\cos\theta_{p\bar{p}}$  and  $\cos\theta_{K^+\pi^-}$  have been calculated as follows:

$$\cos\theta_{p\bar{p}} = -\frac{\vec{Q}_{p\bar{p}} \cdot \vec{P}_{K^+\pi^-}}{|\vec{Q}_{p\bar{p}}||\vec{P}_{K^+\pi^-}|} \quad (3.8)$$

$$\cos\theta_{K^+\pi^-} = -\frac{\vec{P}_{p\bar{p}} \cdot \vec{Q}_{K^+\pi^-}}{|\vec{P}_{p\bar{p}}||\vec{Q}_{K^+\pi^-}|} \quad (3.9)$$

where

$$\vec{P}_{p\bar{p}} = \vec{p}_p + \vec{p}_{\bar{p}} \quad (3.10)$$

$$\vec{Q}_{p\bar{p}} = \vec{p}_p - \vec{p}_{\bar{p}} \quad (3.11)$$

$$\vec{P}_{K^+\pi^-} = \vec{p}_{K^+} + \vec{p}_{\pi^-} \quad (3.12)$$

$$\vec{Q}_{K^+\pi^-} = \vec{p}_{K^+} - \vec{p}_{\pi^-} \quad (3.13)$$

For  $\cos\theta_{p\bar{p}}$  the three-vectors have been calculated in the  $p\bar{p}$  reference frame while they have been calculated in the  $K^+\pi^-$  reference frame for  $\cos\theta_{K^+\pi^-}$ .

## 3.2 Data samples and simulated samples

This analysis uses  $0.98\text{ fb}^{-1}$  of 2011 data collected at a centre-of-mass energy of 7 TeV ( $0.42\text{ fb}^{-1}$  for Magnet Up polarity and  $0.56\text{ fb}^{-1}$  for Magnet Down polarity) and  $1.99\text{ fb}^{-1}$  of 2012 data collected at a centre-of-mass energy of 8 TeV ( $1.00\text{ fb}^{-1}$  for Magnet Up polarity and  $0.99\text{ fb}^{-1}$  for Magnet Down polarity). In addition the analysis uses the data sample corresponding to an integrated luminosity of  $1.67\text{ fb}^{-1}$  and  $1.71\text{ fb}^{-1}$  and  $2.19\text{ fb}^{-1}$  collected during 2016 ( $\sqrt{s} = 13\text{ TeV}$ ) and 2017 ( $\sqrt{s} = 13\text{ TeV}$ ) and 2018 ( $\sqrt{s} = 13\text{ TeV}$ ). Momentum calibration, a factor to correct globally for the momentum scale, is applied to the data samples. Simulated samples have been used to determine and optimize the selection criteria, to study the fit models and also evaluate the shapes of the different sources of background.

Among the simulated samples are :

- $B^0 \rightarrow p\bar{p}K^+\pi^-$
- $B^0 \rightarrow p\bar{p}\pi^+\pi^-$
- $B^0 \rightarrow p\bar{p}K^+K^-$
- $B_s^0 \rightarrow p\bar{p}K^+\pi^-$
- $B_s^0 \rightarrow p\bar{p}\pi^+\pi^-$
- $B_s^0 \rightarrow p\bar{p}K^+K^-$
- $\Lambda_b^0 \rightarrow p\bar{p}pK^-$
- $\Lambda_b^0 \rightarrow p\bar{p}p\pi^-$

The decay modes have been generated with Pythia8 taking into account Run 1 and Run 2 conditions [42]. The PHOTOS option, which includes low energy photons in the final state, was used for every sample and all the samples were generated uniformly in the phase space.



### 3.3 Stripping selection

In order to select four-body B-meson baryonic decays, a specific stripping line was used. This stripping line, called B2pphhKpiLine, reconstructs  $B^0 \rightarrow p\bar{p}h_1^+h_2^-$  decays where  $h_{1,2}^\pm = K^\pm, \pi^\pm$ . The cuts applied at the level of the stripping line are listed in Table 3.1. This line features loose cuts on the momenta  $p$  and transverse momenta  $p_\perp$  of the daughters. A good track quality is ensured by requiring a good track  $\chi^2/\text{ndof}$  and a small ghost probability associated to the track. Ghost tracks are trajectories created from combinations of random hits that together look like a real trajectory. Very loose PID requirements are also applied to each final state particle. In order to reject as much as possible particles coming directly from the primary vertex (PV), requirements on the impact parameter (IP)  $\chi^2$  of the daughters with respect to the PV were placed. Requirements are also applied to combinations of the final state particles: for the  $p\bar{p}$  and  $p\bar{p}K^+$  subsystems, particles are required to come from the same vertex through a requirement on the maximum of the  $\chi^2$  distance among the daughters (DOCA). In addition requirements on the invariant mass of the combinations are applied. Additional kinematical cuts are applied to the  $p\bar{p}$  pair on the sum and on the minimum of the  $p$  and  $p_T$  among the final state particles. The reconstructed  $B^0$  candidates are selected using kinematic and topological requirements such as the cosine of the angle between the momentum of the  $B^0$  and the direction vector connecting the PV to the SV (DIRA), the minimum IP to the PV and the minimum  $P_T$ . In addition a global cut on the maximum number of long tracks reconstructed in the event is applied.

### 3.4 Trigger selection

A combination of cuts at all the three levels of the trigger have been applied to the data. Different sets of cuts were tried and the ones that gave the best performance are listed in Tab 3.2. At L0, the  $B$  candidates are required to satisfy at least one of the L0HadronDecision\_TOS and L0Physics\_TIS conditions on  $B^0$ , where L0Physics\_TIS is the OR of all the five physics lines introduced in Section 2.3.1. The TIS condition on L0Physics is used to trigger on the other  $B$  meson produced from the hadronisation of the  $b\bar{b}$  pair. The decisions of the HLT1 trigger lines rely on the properties of individual tracks and not on information of the complete event. The HLT1 line “Hlt1TrackAllL0Decision” requires at least 9 VELO hits, which are used in the track reconstruction, and less than 3 VELO hits, which were expected from the track extrapolation but not found. The Hlt2Topo{2,3,4}BodyBBDTDecision lines are inclusive trigger lines whereby the trigger candidates for the two-body line are required to have a distance of closest approach between the two particles forming the candidate of less than 0.2 mm. The candidate is then used as input for the three-body line and combined with another particle in the event; the DOCA requirement is imposed on the combination of the two-particle object and the third particle. The same procedure is used to build candidates for the four-body lines.



| Particle         | Run1                                                                                                                                                                                                                                                                            | Run2                                                                                                                                                                                                                                                                             |
|------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $p$              | $P > 1500 \text{ MeV/c}$<br>$P_T > 300 \text{ MeV/c}$<br>Track $\chi^2/\text{ndof} < 3$<br>Track ghost prob $< 0.35$<br>ProbNN $p > 0.05$<br>IP $\chi^2 > 2.0$                                                                                                                  | $P > 1500 \text{ MeV/c}$<br>$P_T > 300 \text{ MeV/c}$<br>Track $\chi^2/\text{ndof} < 4$<br>Track ghost prob $< 0.4$<br>ProbNN $p > 0.05$<br>IP $\chi^2 > 3.0$                                                                                                                    |
| $K^+$            | $P > 1500 \text{ MeV/c}$<br>$P_T > 300 \text{ MeV/c}$<br>Track $\chi^2/\text{ndof} < 3$<br>Track ghost prob $< 0.35$<br>ProbNN $k > 0.05$<br>IP $\chi^2 > 4.0$                                                                                                                  | $P > 1500 \text{ MeV/c}$<br>$P_T > 300 \text{ MeV/c}$<br>Track $\chi^2/\text{ndof} < 4$<br>Track ghost prob $< 0.4$<br>ProbNN $k > 0.05$<br>IP $\chi^2 > 5.0$                                                                                                                    |
| $\pi^-$          | $P > 1500 \text{ MeV/c}$<br>$P_T > 300 \text{ MeV/c}$<br>Track $\chi^2/\text{ndof} < 3$<br>Track ghost prob $< 0.35$<br>ProbNN $\pi > 0.05$<br>IP $\chi^2 > 6.0$                                                                                                                | $P > 1500 \text{ MeV/c}$<br>$P_T > 300 \text{ MeV/c}$<br>Track $\chi^2/\text{ndof} < 4$<br>Track ghost prob $< 0.4$<br>ProbNN $k > 0.05$<br>IP $\chi^2 > 8.0$                                                                                                                    |
| $p\bar{p}$       | $M_{p\bar{p}} < 5000 \text{ MeV/c}^2$<br>$\sum P_T > 750 \text{ MeV/c}$<br>$\sum P > 7000 \text{ MeV/c}$<br>minimum $P_T > 400 \text{ MeV/c}$<br>minimum $P > 4000 \text{ MeV/c}$<br>ProbNN $p \cdot \text{ProbNN}\bar{p} > 0.05$<br>$\chi^2 \text{ DOCA} < 20$                 | $M_{p\bar{p}} < 5000 \text{ MeV/c}^2$<br>$\sum P_T > 750 \text{ MeV/c}$<br>$\sum P > 7000 \text{ MeV/c}$<br>minimum $P_T > 400 \text{ MeV/c}$<br>minimum $P > 4000 \text{ MeV/c}$<br>ProbNN $p \cdot \text{ProbNN}\bar{p} > 0.01$<br>$\chi^2 \text{ DOCA} < 20$                  |
| $p\bar{p}K^+$    | $M_{p\bar{p}K^+} < 5600 \text{ MeV/c}^2$<br>$\chi^2 \text{ DOCA} < 20$                                                                                                                                                                                                          | $M_{p\bar{p}K^+} < 5600 \text{ MeV/c}^2$<br>$\chi^2 \text{ DOCA} < 20$                                                                                                                                                                                                           |
| $B^0$            | Max DOCA $< 0.3 \text{ mm}$<br>$\chi^2 \text{ DOCA} < 20$<br>DIRA $> 0.9999$<br>Vertex $\chi^2 < 30$<br>Min $IP < 0.2 \text{ mm}$<br>$P_T > 1000 \text{ MeV/c}$<br>$\sum P_T^{\text{daughters}} > 3000 \text{ MeV/c}$<br>$m(p\bar{p}K^+\pi^-) \in [5050, 5550] \text{ MeV/c}^2$ | Max DOCA $< 0.25 \text{ mm}$<br>$\chi^2 \text{ DOCA} < 20$<br>DIRA $> 0.9999$<br>Vertex $\chi^2 < 30$<br>Min $IP < 0.2 \text{ mm}$<br>$P_T > 1000 \text{ MeV/c}$<br>$\sum P_T^{\text{daughters}} > 3000 \text{ MeV/c}$<br>$m(p\bar{p}K^+\pi^-) \in [5050, 5550] \text{ MeV/c}^2$ |
| Number of tracks | $< 200$                                                                                                                                                                                                                                                                         | $< 200$                                                                                                                                                                                                                                                                          |

Table 3.1: Requirements of the B2pphhKpiLine stripping line.

| Trigger requirements | Run1                          | Run2                          |
|----------------------|-------------------------------|-------------------------------|
| $L0$                 | L0HadronDecision_TOS          | L0HadronDecision_TOS          |
|                      | L0ElectronDecision_TIS        | L0ElectronDecision_TIS        |
|                      | L0PhotonDecision_TIS          | L0PhotonDecision_TIS          |
|                      | L0MuonDecision_TIS            | L0MuonDecision_TIS            |
|                      | L0DiMuonDecision_TIS          | L0DiMuonDecision_TIS          |
|                      | L0HadronDecision_TIS          | L0HadronDecision_TIS          |
| $HLT1$               | Hlt1TrackAllL0Decision_TOS    | Hlt1TrackMVADecision_TOS      |
|                      |                               | Hlt1TwoTrackMVADecision_TOS   |
| $HLT2$               | Hlt2Topo2BodyBBDTDecision_TOS | Hlt2Topo2BodyBBDTDecision_TOS |
|                      | Hlt2Topo3BodyBBDTDecision_TOS | Hlt2Topo3BodyBBDTDecision_TOS |
|                      | Hlt2Topo4BodyBBDTDecision_TOS | Hlt2Topo4BodyBBDTDecision_TOS |

Table 3.2: Trigger requirements applied to the data in order to increase the signal to background ratio.

### 3.5 Offline selection

The  $m_{p\bar{p}K\pi}$  spectrum for Run1 and Run2 obtained after applying the trigger and stripping line selections to the two data sets separately is shown in Fig. 3.3. One can see that the signal to background ratio is still poor at this level, though a small peak corresponding to the  $B^0$  mass on top of a flat background can be already identified in the data. The offline selection is crucial to obtain an acceptable signal to background ratio in order to proceed further with the analysis. The offline selection used here follows the one that has been optimised, tested and applied to a previous analysis [58].

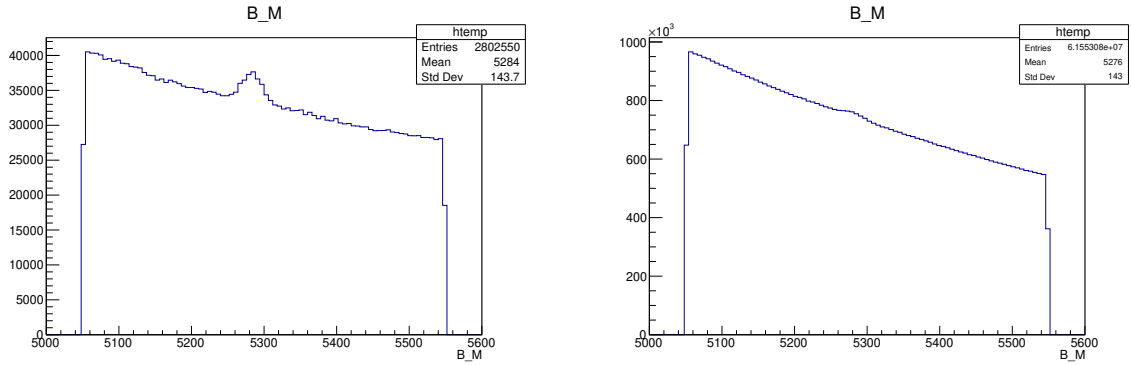


Figure 3.3: The Run1 (left) and Run2 (right)  $m_{p\bar{p}K\pi}$  spectrum after the corresponding stripping and trigger requirements.

Particles are required to be in the RICH acceptance by selecting tracks with pseudo-rapidity  $\eta$  in the range  $2.0 < \eta < 4.9$ . In addition, the proton and anti-proton momenta are required to be  $> 8$  GeV/c in Run 1 and  $> 11$  GeV/c in Run 2. This requirement is used to overcome the limitation of the poor discrimination between kaons and protons at this threshold. The offline selection is based on a multivariate selection (BDT algorithm) including topological and kinematic variables using the toolkit TMVA [59] and PID requirements.

### 3.5.1 Boosted decision tree

A MonteCarlo sample, generated according to the phase space of the decay, of  $B^0 \rightarrow p\bar{p}K^+\pi^-$  candidates is used as signal to train a multivariate algorithm. As background sample, candidates from the right sideband of the reconstructed  $B^0$  invariant mass defined as  $5450 < m_{p\bar{p}K^+\pi^-} < 5550$  GeV/ $c^2$  after trigger and stripping selections, is used. This region of the spectrum is chosen since it is expected not to contain partially reconstructed or  $B_s^0$  events.

The same cuts applied to the real data were also applied to the MC samples. Since no significant differences were found after comparing the 2011 sample to the and 2012 sample, data were merged into a single sample in order to have more statistics. The same holds for 2016, 2017 and 2018 samples, which were also merged into a single sample. The merged background sample for Run1 contains  $\sim 480000$  events in the Run1 data set and  $\sim 9600000$  in the Run2 data set. The merged MC sample contains  $\sim 160000$  events generated according to the detector and beam conditions in Run1 and  $\sim 360000$  events generated according to the detector and beam conditions in Run2. The multivariate algorithm was trained keeping Run1 and Run2 separated and the default option provided by the TMVA tool to randomly split both these samples in two equal parts as training and test samples was used. The variables selected to train the MVA algorithm are the same as the one used in the analysis [58] since they have already proven their ability to discriminate between signal and background events. They are:

- **MINIPCHI2** : minimum IP  $\chi^2$  of the  $B^0$  to the PV
- **B\_AMAXDOCA** : maximum DOCA of the tracks to the  $B^0$  vertex
- **Log(B\_BPVDCCHI2)** : logarithm of the  $\chi^2$  distance of the  $B^0$  vertex from the PV
- **B\_LOKI\_POINTING**: this variable is defined as:

$$\frac{|\vec{p}_B| \sin \theta}{|\vec{p}_B| \sin \theta + \sum_i |\vec{p}_i| \sin \theta_i} \quad (3.14)$$

where  $\vec{p}_B$  is the momentum of the  $B^0$  candidate,  $\theta$  is the angle between the vector  $\vec{p}_B$  and the vector connecting the PV to the SV,  $\vec{p}_i$  is the momentum of daughter  $i$  and  $\theta_i$  is the angle between the vector  $\vec{p}_i$  and the vector connecting the PV to the SV.

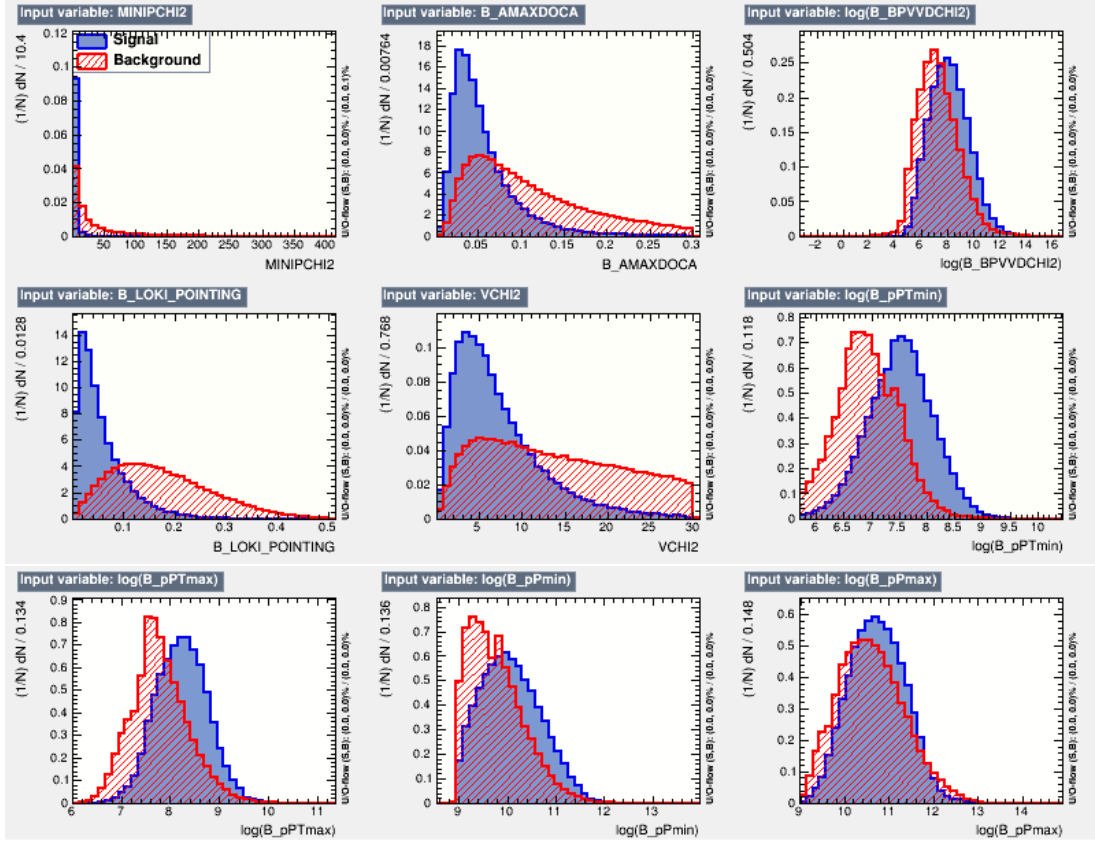


Figure 3.4: Comparison of Run1 signal (blue filled) and background (red dashed) distributions used as MVA discriminating variables.

- **VCHI2** :  $\chi^2$  of the  $B^0$  vertex
- **Log(B\_pPTmin)** : logarithm of the minimum  $p_T$  between the two protons
- **Log(B\_pPTmax)** : logarithm of the maximum  $p_T$  between the two protons
- **Log(B\_pPmin)** : logarithm of the minimum p between the two protons
- **Log(B\_pPmax)** : logarithm of the maximum p between the two protons

The comparison between MC signal and background discriminating variables is shown in Fig. 3.4 and Fig. 3.7 for Run1 and Run2 respectively. The matrices containing the linear correlation coefficients between the discriminating variables are shown in Fig. 3.5 and Fig. 3.8 for Run1 and Run2 respectively. Different types of classifier were tested, namely the BDTD, BDTG, BDT and MLP, but the BDT algorithm was found to have the best performance, as shown in Fig. 3.6 and 3.9. The result of the Kolmogorov-Smirnov test for each classifier is reported in Fig. 3.6 where there is no evidence of over-training.

The BDT variable obtained from the TMVA tool was combined with the PID variables in order to get a better discriminating power. The signal to background ratio was optimised

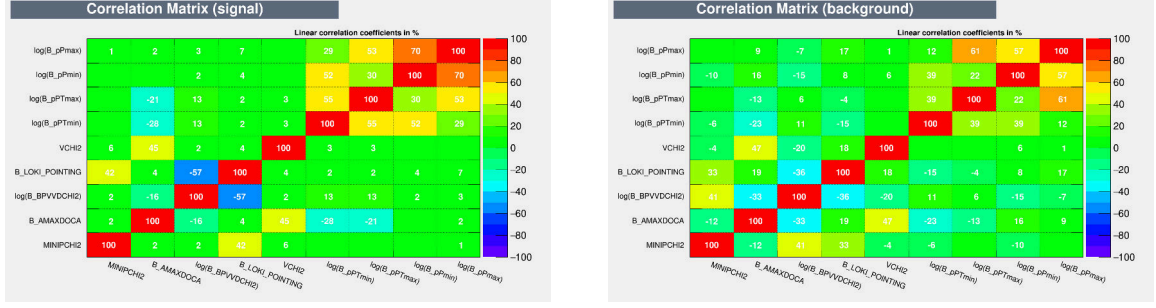


Figure 3.5: Correlation matrices for Run1 signal (left) and background (right) MVA input variables.

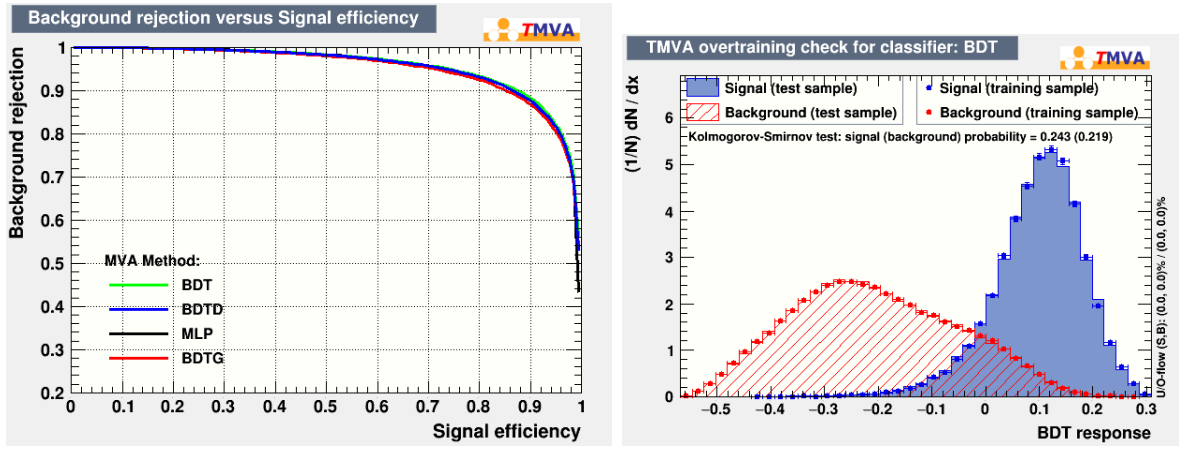


Figure 3.6: ROC curves for the four algorithms which have been investigated for the Run1 MVA analysis.

by maximising the Figure of Merit (FoM) defined as:

$$FoM = \frac{S}{\sqrt{S+B}} \quad (3.15)$$

where  $S$  and  $B$  are respectively the number of signal and background events. The PID cuts used in the optimization process are listed in Tab 3.3. We considered cuts in the  $p, K$  and  $\pi$  ProbNN variables. This quantity is the output of multivariate techniques created by combining tracking and PID information. This results in single probability values for each particle hypothesis. The RICH detectors simulation is challenging because of the variations in the detectors occupancy that can be different from event to event. Consequently, this translates into discrepancies between data and the MC which motivate the decision to avoid merging in the same MVA the topological, kinematical selection from the PID selection

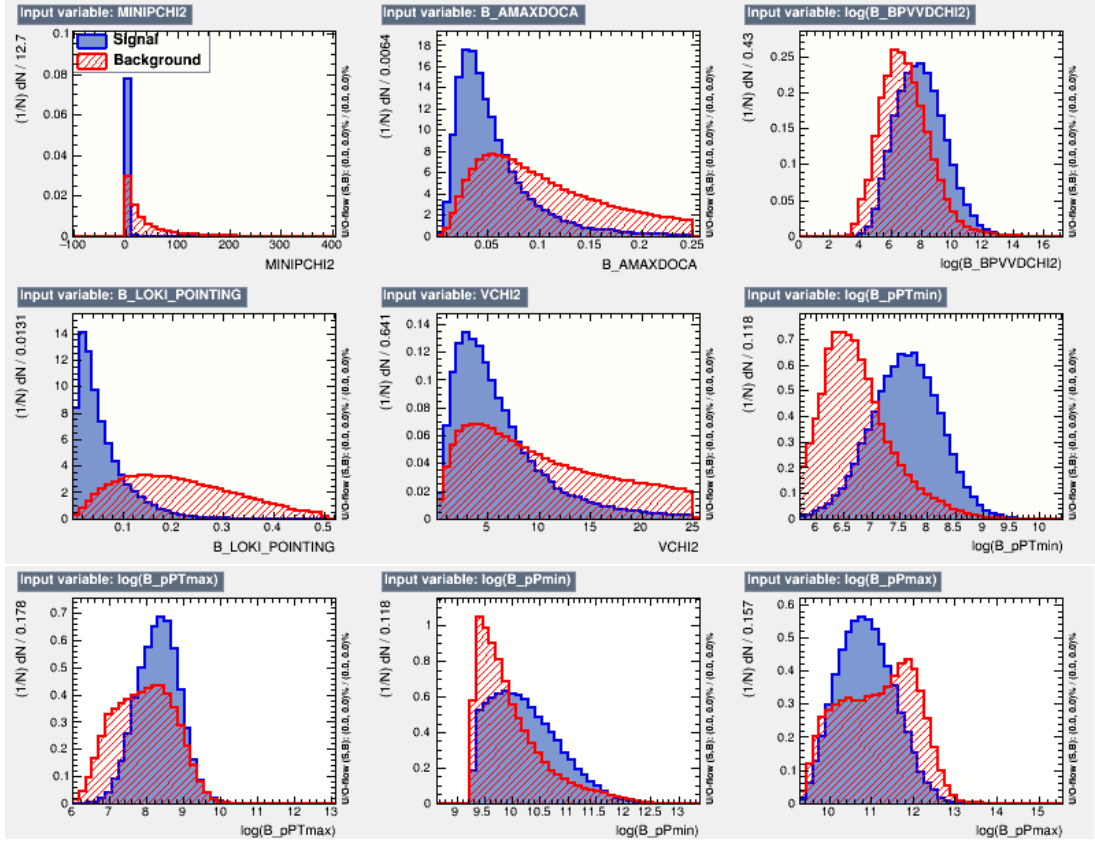


Figure 3.7: Comparison of Run2 signal (blue filled) and background (red dashed) distributions used as MVA discriminating variables.

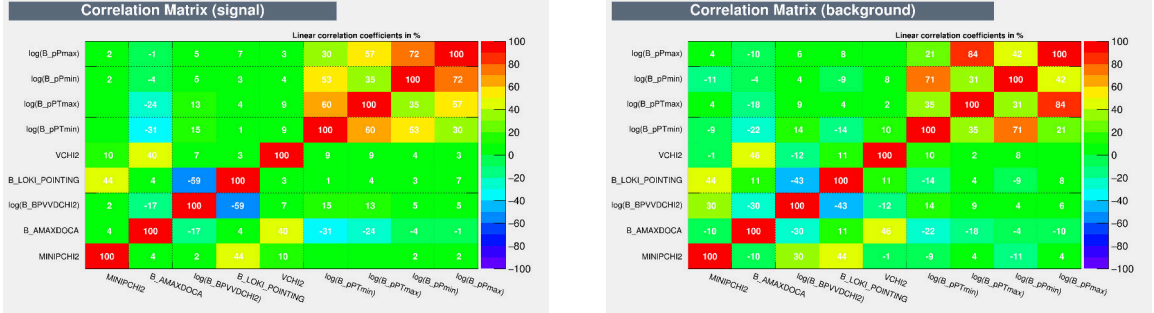


Figure 3.8: Correlation matrices for Run2 signal (left) and background (right) MVA input variables

### 3.5.2 Optimisation of the offline selection for Run 1

As a first step, the PID cut using a combination of the variables listed in Tab. 3.3 is applied to the real data. The  $m_{p\bar{p}K\pi}$  mass distribution is then fitted in the range  $5200 < m_{p\bar{p}K\pi} < 5360$  MeV, which corresponds to a  $\pm 3\sigma$  region around the  $B^0$  peak, in

| variable           | cuts                                      |
|--------------------|-------------------------------------------|
| pProbNNp           | $> 0.15, > 0.175, > 0.225, > 0.25, > 0.3$ |
| kProbNNk           | $> 0, > 0.1, > 0.2, > 0.25$               |
| kProbNNp           | $< 1, < 0.8, < 0.4, < 0.15$               |
| kProbNN $\pi$      | $< 1, < 0.8, < 0.4, < 0.15$               |
| $\pi$ ProbNN $\pi$ | $> 0.125, > 0.15, > 0.2$                  |
| $\pi$ ProbNNk      | $< 1, < 0.8, < 0.4, < 0.15$               |
| $\pi$ ProbNNp      | $< 1, < 0.8, < 0.4, < 0.15$               |

Table 3.3: Cuts on the ProbNN variables used in the optimization process.

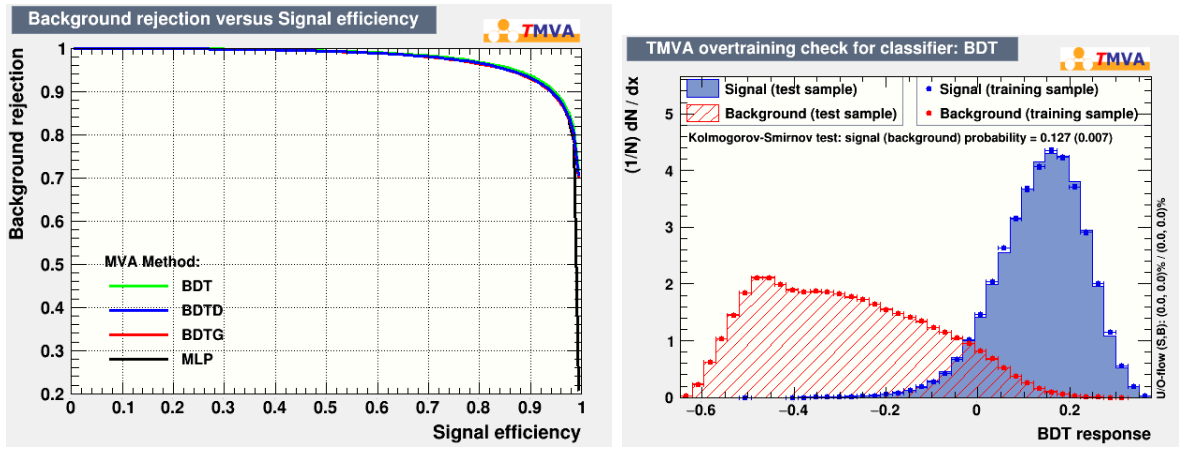


Figure 3.9: ROC curves for the algorithms used in the Run2 MVA analysis

order to get an estimate of the number of event for the signal  $N_{sig}^{data}(PID)$  and for the background  $N_{bkg}^{data}(PID)$  for that particular set of PID requirements. The background was parameterized with a linear PDF, while the signal was parameterized with a two tails Hypatia PDF [60]. The signal PDF was validated using the  $B^0 \rightarrow p\bar{p}K^+\pi^-$  simulated sample and is described in detail in A.1.

In the fit to the  $m_{p\bar{p}K\pi}$  invariant-mass distribution the shape parameters of the Hypatia PDF were fixed. After extracting  $N_{sig}^{data}(PID)$  and  $N_{bkg}^{data}(PID)$ , a cut on the BDT variable is applied and the number of signal events  $S$  to be used in the FoM defined in 3.15 is calculated as:

$$S = N_{sig}^{data}(PID) \cdot \varepsilon^{MC}(BDT) \quad (3.16)$$

where  $\varepsilon^{MC}(BDT)$  is the efficiency of the given BDT cut using the simulated  $B^0 \rightarrow p\bar{p}K^+\pi^-$  sample at the given PID cut. The yield of the background events  $N_{bkg}^{data}(PID, BDT)$  at the given BDT cut was calculated by refitting the data using the same linear model for the background and the Hypathia pdf for the signal. In this way the FoM to be maximised

becomes:

$$FoM = \frac{N_{sig}^{data}(PID) \cdot \varepsilon^{MC}(BDT)}{\sqrt{N_{sig}^{data}(PID) \cdot \varepsilon^{MC}(BDT) + N_{bkg}^{data}(PID, BDT)}} \quad (3.17)$$

BDT cuts from -0.15 to 0.13 in steps of 0.02 were applied. The procedure was repeated for every combination of the ProbNN cuts and the combination of MVA and PID cuts that provided the best performance is

$$\mathbf{BDT > 0.03 \ \& \ pProbNNp > 0.225 \ \& \ kProbNNk > 0.2 \ \& \ \pi ProbNN\pi > 0.125}$$

This set of cuts gives a signal retention of  $(64.8 \pm 0.3)\%$  and background rejection of  $(98.54 \pm 0.02)\%$ .

### 3.5.3 Optimisation of the offline selection for Run 2

The strategy adopted for the optimization of the signal to background ratio for Run2 is similar to the one described for Run1 in Section 3.5.2. The main difference is that, given the evident higher background under the signal window (see Fig. 3.3), a loose BDT cut at -0.3 was applied a priori of the procedure in order to be able to fit the signal component. The same set of PID cuts used for Run1 and listed in Tab 3.3 was used for Run2 as well. The combination of MVA and PID cuts that provided the best performance is:

$$\mathbf{BDT > 0.09 \ \& \ pProbNNp > 0.25 \ \& \ kProbNNk > 0.25 \ \& \ \pi ProbNN\pi > 0.2}$$

This set of cuts gives a signal retention of  $(64.1 \pm 0.2)\%$  and background rejection of  $(99.751 \pm 0.002)\%$ .

## 3.6 Multiple candidates

Even after the full optimized selection a small fraction of the selected  $B^0 \rightarrow p\bar{p}K^+\pi^-$  events still contains two or more candidates. Multiple candidates are mainly due to an ambiguous mass hypothesis assigned to a track. Around 3-4% of multiple candidates was found both in Run1 and Run2 datasets after all the selection cuts. If two consecutive entries in the tuple have the same event ID one of them is retained randomly and the other discarded.

The fraction of multiple candidates for every year is shown in Tab. 3.4. The fraction is calculated for the candidates that fall in the mass window  $m_{p\bar{p}K^+\pi^-} \in [5080, 5480] \text{ MeV}/c^2$ , the same window used for the nominal fit.

## 3.7 Mass fit model

The  $m_{p\bar{p}K^+\pi^-}$  spectra for the Run1 and Run2 data samples after the corresponding selection procedure described are shown in Fig. 3.10. The  $B^0$  mass peak is clearly visible. The small



| Year | Fraction(%) |
|------|-------------|
| 2011 | 4.3         |
| 2012 | 4.4         |
| 2016 | 3.4         |
| 2017 | 3.2         |
| 2018 | 3.3         |

Table 3.4: Fraction of multiple candidates for each year of data taking.

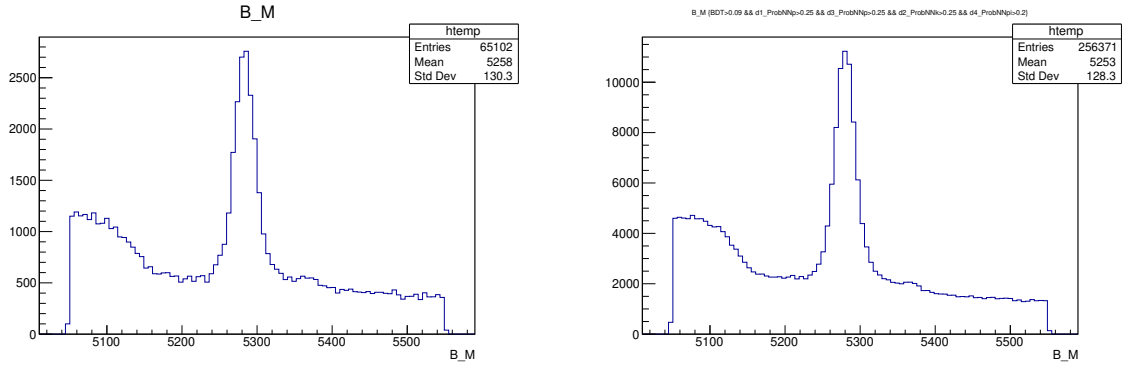


Figure 3.10: The Run1 (left) and Run2 (right)  $m_{p\bar{p}K\pi}$  spectrum after the corresponding stripping and trigger requirements and the offline selection.

peak on the right side of the  $B^0$  peak is due to a contribution from the  $B_s^0 \rightarrow p\bar{p}K^+\pi^-$  decays. The shoulder on the left-side of the mass spectrum is due to partially reconstructed decay instead. Partially reconstructed decays are  $B$  decays where final state particles are not fully reconstructed by the stripping line, such as  $B^0 \rightarrow p\bar{p}K^+\pi^-\pi^0$ ; in this case the  $\pi^0$  is not reconstructed and the invariant mass, obtained by combining the other four particles, is therefore shifted to lower values. Misidentified candidates are also expected to contribute to the spectrum and may potentially form peaking background under the signal region. These are candidates where not all the final state particles have been correctly assigned their mass. In particular misidentified candidates originate from the  $B^0 \rightarrow p\bar{p}\pi^+\pi^-$  decays, where the pion is misidentified as a kaon, or from the  $B_{(s)}^0 \rightarrow p\bar{p}K^+K^-$  decays where the kaon is misidentified as a pion. Due to the lower branching fractions,  $B_s^0 \rightarrow p\bar{p}\pi^+\pi^-$  and  $B^0 \rightarrow p\bar{p}K^+K^-$  contributions are negligible. Possible  $\Lambda_b^0 \rightarrow p\bar{p}pK^-$  contamination, where one of the protons is misidentified as a pion creating possible peaking background in the  $B^0$  mass region, was investigated and found to be negligible. Possible  $\Lambda_b^0 \rightarrow p\bar{p}p\pi^-$  contamination, where one of the protons is misidentified as a kaon was investigated and found not to produce peaking background in the considered invariant mass range. The main identified contributions and the their corresponding PDF are reported in Tab. 3.5

| Component                            | floating parameters          |
|--------------------------------------|------------------------------|
| $B^0 \rightarrow p\bar{p}K^+\pi^-$   | $m_{B^0}, \sigma_{B^0(s)}$   |
| $B_s^0 \rightarrow p\bar{p}K^+\pi^-$ | $m_{B_s^0}, \sigma_{B^0(s)}$ |
| $B^0 \rightarrow p\bar{p}\pi^+\pi^-$ | all fixed                    |
| $B_s^0 \rightarrow p\bar{p}K^+K^-$   | all fixed                    |
| Combinatorial bkg                    | $\lambda$                    |
| Partially reconstructed              | $c, m_0$                     |

Table 3.6: Parameters left floating in the fit for each considered component. The resolution  $\sigma_{B^0(s)}$  is in common for  $B^0$  and  $B_s^0$ . The yields for each component are left free.

| Component                            | PDF model         |
|--------------------------------------|-------------------|
| $B^0 \rightarrow p\bar{p}K^+\pi^-$   | Hypathia          |
| $B_s^0 \rightarrow p\bar{p}K^+\pi^-$ | Hypathia          |
| $B^0 \rightarrow p\bar{p}\pi^+\pi^-$ | Crystal Ball [61] |
| $B_s^0 \rightarrow p\bar{p}K^+K^-$   | Crystal Ball      |
| Combinatorial bkg                    | Exponential       |
| Partially reconstructed              | Fermi             |

Table 3.5: Main components contributing to the  $m(p\bar{p}K^+\pi^-)$  mass spectrum and their corresponding PDF validated on MC samples.

The PDFs used to model the different components were validated on MC samples and the whole process is described in detail in Appendix A.

### 3.8 Fit to the $m_{p\bar{p}K^+\pi^-}$ invariant mass distribution

The fit to the  $CP$ -averaged  $m_{p\bar{p}K^+\pi^-}$  distribution is used to extract the yield of the  $B^0 \rightarrow p\bar{p}K^+\pi^-$  component, to validate the model and to find background contributions coming from intermediate decays containing charmed particles; these contribution must be vetoed. The PDFs listed in Tab 3.5 depend on many nuisance parameters which, if left all floating in the fit, would make the convergence of the fit very difficult. For this reason, the vast majority of these nuisance parameters were fixed in the fit to the values obtained from the validation on MC samples. The parameters that were left floating in the fit are listed in Tab. 3.6. An unbinned extended maximum likelihood fit to  $m_{p\bar{p}K^+\pi^-}$  mass spectrum was performed. The likelihood  $\mathcal{L}$  to be maximised is defined as

$$\mathcal{L}(\vec{\theta}, N_{sig}, \vec{N}_{bkg}) = \prod_{i=0}^N \frac{N_{sig} S_{sig}(m_i, \vec{\theta}) + \sum_j N_{bkg_j} B_{bkg_j}(m_i, \vec{\theta})}{N_{sig} + \sum_j N_{bkg_j}} \times P(N, N_{sig} + \sum_j N_{bkg_j}) \quad (3.18)$$

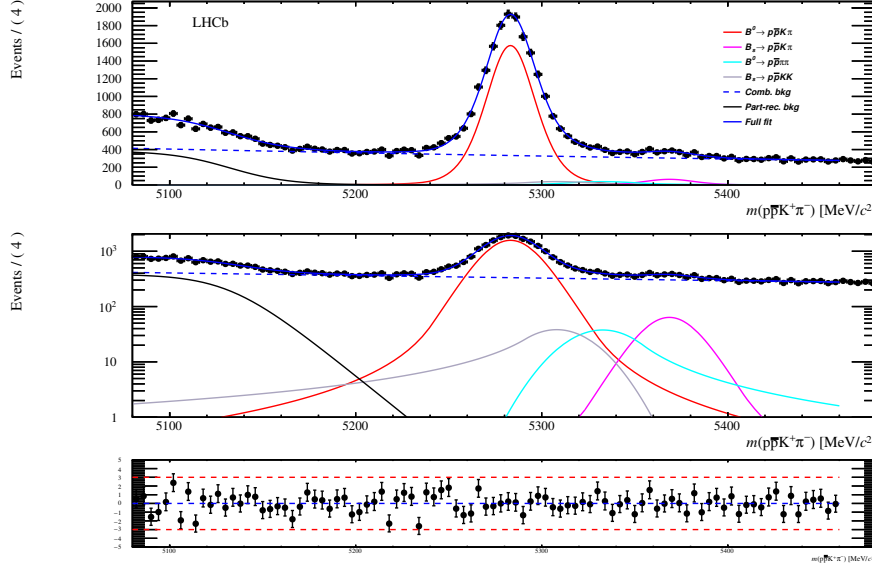


Figure 3.11: Fit to the Run1  $B^0 \rightarrow p\bar{p}K^+\pi^-$  invariant mass distribution shown in linear (top) and logarithmic scale (bottom). The pull distribution is shown under the log scale plot. Data (black points) and fit results (blue solid line) are shown. The legend of the different components is shown on the top plot.

$\mathcal{L}$  depends on some nuisance parameters  $\vec{\theta}$  that define the PDFs of the different components and on the number of signal and background components. The likelihood is extended by allowing Poisson fluctuation on the total number of events  $N$ .

The resolution  $\sigma$  of the reconstructed mass is constrained to be the same for the  $B^0$  and the  $B_s^0$ , according to the compatibility found between the resolutions extracted from the fit to the corresponding MC samples. The same model was used to fit Run1 and Run2 data sets separately. The result of the fit for both Run1 and Run2 is shown in Fig. 3.11 and Fig. 3.12 respectively along with the extracted free parameters in Tab. 3.7 and Tab. 3.8. One can immediately see that the yield of the signal increases by a factor 4 in Run2 with respect to Run1.

The discrepancy between the  $B^0$  mass obtained from the fit to Run1 and the value measured in [39] has already been seen in other Run 1 analyses involving hadrons in the final state [33, 62] and it was found to be consistent with the systematic uncertainty associated to the momentum scale calibration (0.03%). This discrepancy is not observed in the fit to Run2 where the result is consistent with the value reported in [39].

The  $m(p\bar{p}K^+\pi^-)$  distribution is used as discriminant variable to compute the sWeights of the signal component by an sPlot procedure [63]. This allows to study the different intermediate resonant contributions to the  $B^0 \rightarrow p\bar{p}K^+\pi^-$  decay mode, as explained in Sec. 3.8.1, and also to perform a posteriori cross-checks on our selection procedure.

| Variable                                 | Value                   |
|------------------------------------------|-------------------------|
| $c$                                      | $16.0 \pm 4.1$          |
| $m_0$                                    | $5132.4 \pm 2.2$        |
| $m_{B^0}$                                | $5283.19 \pm 0.24$      |
| $m_{B_s^0}$                              | $5368.6 \pm 2.5$        |
| $N_{Comb}$                               | $33656 \pm 421$         |
| $N_{PR}$                                 | $5088 \pm 240$          |
| $N_{B^0}$                                | $14072 \pm 338$         |
| $N_{B_s^0}$                              | $579 \pm 98$            |
| $N_{B^0 \rightarrow p\bar{p}\pi^+\pi^-}$ | $546 \pm 230$           |
| $N_{B_s^0 \rightarrow p\bar{p}K^+K^-}$   | $667 \pm 535$           |
| $\lambda$                                | $-0.001075 \pm 0.00010$ |
| $\sigma_{B^0}$                           | $15.92 \pm 0.33$        |

Table 3.7: Parameters extracted from the fit to the Run1  $B^0 \rightarrow p\bar{p}K^+\pi^-$  invariant mass distribution.

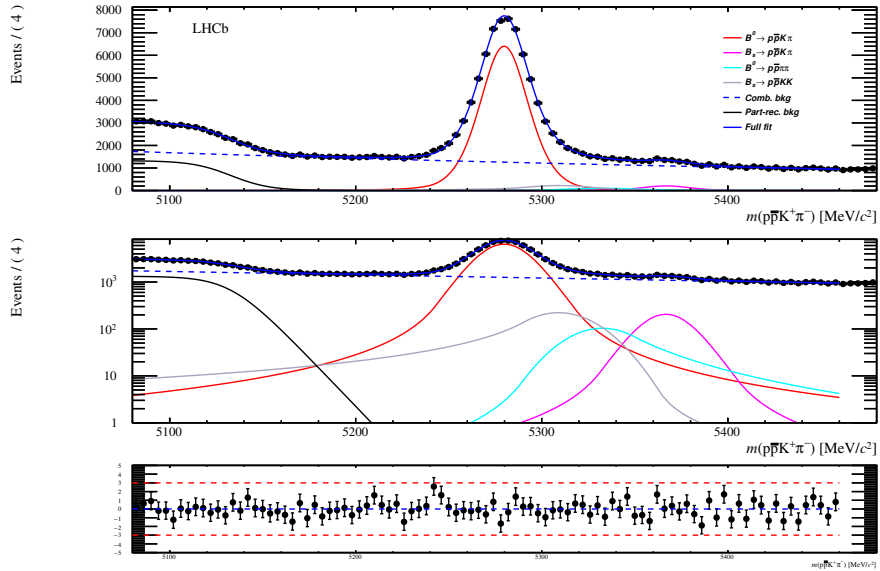


Figure 3.12: Fit to the Run2  $B^0 \rightarrow p\bar{p}K^+\pi^-$  invariant mass distribution shown in linear (top) and logarithmic scale (bottom). The pull distribution is shown under the log scale plot. Data (black points) and fit results (blue solid line) are shown. The legend of the different components is shown on the top plot.

### 3.8.1 Studies of the background-subtracted resonant contributions to the $B^0 \rightarrow p\bar{p}K^+\pi^-$ decay mode

Before measuring the  $CP$  asymmetry, it is important to check which intermediate states contribute to the  $B^0 \rightarrow p\bar{p}K^+\pi^-$  decay as this will guide our choice of the binning scheme

| Variable                                 | Value                     |
|------------------------------------------|---------------------------|
| $c$                                      | $10.50 \pm 0.70$          |
| $m_0$                                    | $5133.01 \pm 0.86$        |
| $m_{B^0}$                                | $5279.79 \pm 0.11$        |
| $m_{B_s^0}$                              | $5366.7 \pm 1.5$          |
| $N_{Comb}$                               | $127922 \pm 748$          |
| $N_{PR}$                                 | $17593 \pm 447$           |
| $N_{B^0}$                                | $56055 \pm 565$           |
| $N_{B_s^0}$                              | $1801 \pm 196$            |
| $N_{B^0 \rightarrow p\bar{p}\pi^+\pi^-}$ | $1524 \pm 527$            |
| $N_{B_s^0 \rightarrow p\bar{p}K^+K^-}$   | $3758 \pm 892$            |
| $\lambda$                                | $-0.0016075 \pm 0.000053$ |
| $\sigma_{B^0}$                           | $15.39 \pm 0.15$          |

Table 3.8: Parameters extracted from the fit to the Run2  $B^0 \rightarrow p\bar{p}K^+\pi^-$  invariant mass distribution.

for the measurement in the different regions of the phase space; in practice this translates into checking any invariant mass combination of the final state particles to see which resonances are present. In order to unfold the signal component from these distributions the sPlot technique was used. Essentially, this technique consists in reweighting the distribution of interest with the so-called sWeights obtained from an unbinned maximum likelihood fit to a discriminating variable. In our case the discriminating variable is the  $m(p\bar{p}K^+\pi^-)$  distribution. By using the covariance matrix returned by the fit to the  $m(p\bar{p}K^+\pi^-)$  distribution it is possible to compute the sWeights as:

$$s_i(\vec{x}_m) = \frac{\sum_j^{N_s} V_{ij} P_j(\vec{x}_m)}{\sum_k^{N_s} N_k P_k(\vec{x}_m)} \quad (3.19)$$

where  $s_i(\vec{x}_m)$  is the sWeight of the  $i$  component for  $m^{th}$  event and  $V_{ij}$  is the covariance matrix. The sum runs over all the signal and background components of Tab 3.5 and  $P_j$  refers to the PDF used to describe that component. In this way the invariant mass spectra of the  $K^+\pi^-$  (Fig. B.1),  $\bar{p}K^+$  (Fig. B.2),  $\bar{p}K^+\pi^-$  (Fig. B.3),  $\bar{p}\pi^-$  (Fig. B.4),  $pK^+$  (Fig. B.5),  $pK^+\pi^-$  (Fig. B.6),  $p\bar{p}$  (Fig. B.7),  $p\bar{p}\pi^-$  (Fig. B.8),  $p\pi^-$  (Fig. B.9),  $p\bar{p}K^+$  (Fig. B.10) systems unfolded using the sWeights corresponding to the  $B^0 \rightarrow p\bar{p}K^+\pi^-$  signal is investigated. In the  $K^+\pi^-$  system two clear peaks corresponding to the known  $K^{*0}(892)$  resonance and to the  $D^0$  meson are visible. Another broad peak is visible around 1400 MeV where several  $K^*$  resonances are expected (Fig. B.1). In the  $p\bar{p}$  system the  $\eta_c(1S)$ , the  $J/\psi$  and the  $\psi(2S)$  resonances are visible (Fig. B.7). In the  $\bar{p}K^+$  invariant mass spectrum, the  $\Lambda(1520)$  baryon already observed at LHCb [34] is clearly visible. Two clear peaks in the  $\bar{p}K^+\pi^-$  and  $K^-\pi^+$  invariant mass distributions corresponding to the  $\Lambda_c^- \rightarrow \bar{p}K^+\pi^-$  and  $D^0 \rightarrow K^-\pi^+$  decays are visible. The 2D scatter plot of two- and three-body masses vs  $m_{p\bar{p}}$  and  $m_{K^+\pi^-}$  are built as a further cross-check and are shown in Fig. B.11, B.12, B.13

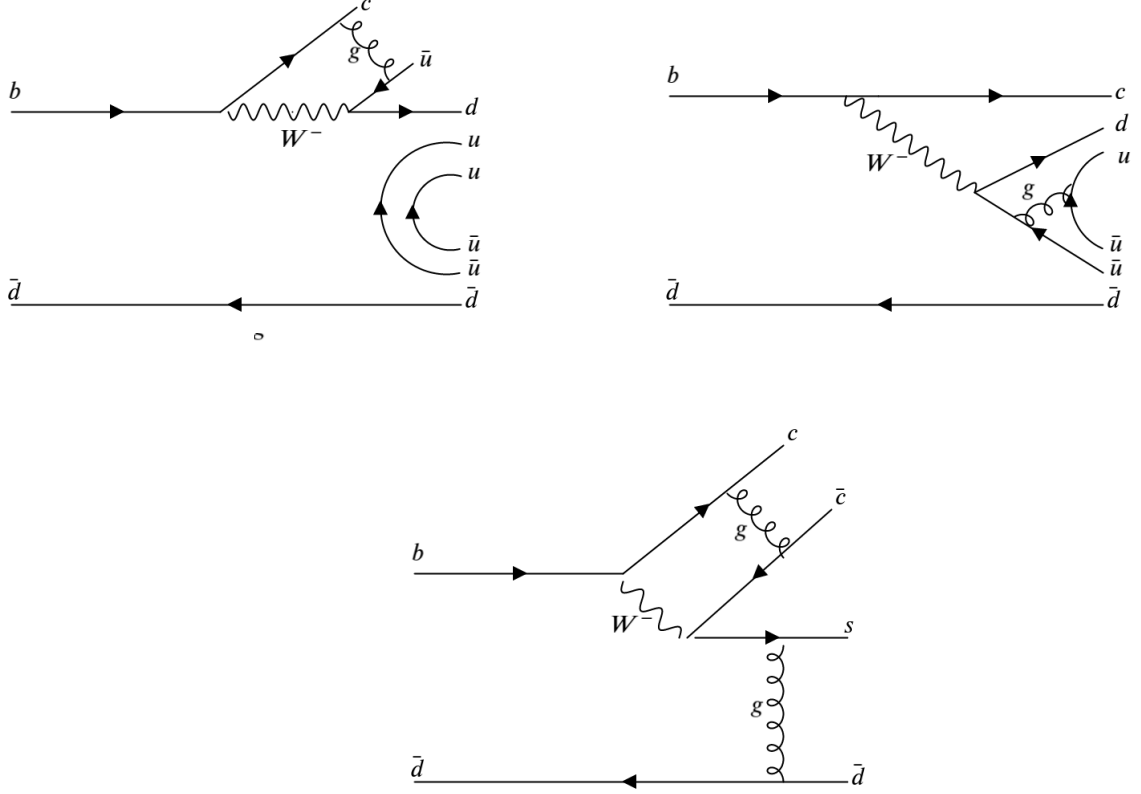


Figure 3.13: Feynman diagrams representing decays of  $B^0$  to charm hadrons via the  $b \rightarrow c$  transition. Top left: Feynman diagram for the decay  $\bar{B}^0 \rightarrow p \bar{p} D^0 (\rightarrow K^- \pi^+)$ . Top right: Feynman diagram for the decay  $\bar{B}^0 \rightarrow \bar{p} \Lambda_c^+ (\rightarrow p K^- \pi^+)$ . Bottom: Feynman diagram for the decay  $\bar{B}^0 \rightarrow c \bar{c} (\rightarrow p \bar{p}) \bar{K}^* (\rightarrow K^- \pi^-)$ . This decay forms charmonium resonances like  $\eta_c(1S)$ ,  $J/\psi$  and the  $\psi(2S)$  before decaying into  $p \bar{p}$ .

and [B.14](#).

### 3.8.1.1 Vetoed regions of the phase space

In the search for  $CP$  violation in the charmless region of the phase space decays of  $B^0$  to charm hadrons represent a source of background that originates from  $b \rightarrow c$  transitions. These processes are shown in Fig. 3.13 and are expected to have negligible  $CP$  violation according to the Standard Model. Such processes are rejected by applying the following cuts to the data.

- Veto the  $\pm 40$  MeV window around the  $D^0$  mass in order to remove  $B^0 \rightarrow p \bar{p} D^0 (\rightarrow K^- \pi^+)$  contribution.

- Veto the  $\pm 25$  MeV window around the  $\Lambda_c^+$  mass,  $2261 \text{ MeV} < m_{\bar{p}K^+\pi^-} < 2311 \text{ MeV}$  in the  $m_{\bar{p}K^+\pi^-}$  mass spectrum
- The region of the  $p\bar{p}$  spectrum containing charmonium resonances is rejected by requiring  $m_{p\bar{p}} < 2850 \text{ MeV}/c^2$

The vetoed channel  $\bar{B}^0 \rightarrow p\bar{p}D^0(\rightarrow K^-\pi^+)$  is used as a control sample to check on real data whether our measurement is affected by any bias or not. This will be explained in details in Section 3.13.1.

### 3.9 Blinding approach

In this thesis the triple-product asymmetries are measured on blinded data. The  $B^0$  flavour is assigned correctly according to the tag provided by the reconstruction, whereas the sign of  $C_{\hat{T}}$  ( $\bar{C}_{\hat{T}}$ ) is assigned randomly. The Y axis of the invariant mass fit plots is also kept blind. The cross-checks with the use of the control channel (see 3.13.1), mainly to exclude the presence of any bias introduced by possible detection asymmetries, are performed on unblinded data instead.

### 3.10 Search for $CP$ violation in the charmless region of the phase space

Two different approaches were followed to exploit the full potential of the data sample: a measurement integrated over the phase space and measurements in bins of phase space. The measurement of the asymmetry integrated over the phase space is performed by fitting the full data sample. Run1 and Run2 samples were first fitted separately to check their agreement, then a combined Run1+Run2 fit was performed. The selected candidates are first split into four subsamples according to the  $B^0(\bar{B}^0)$  flavour and the sign of  $C_{\hat{T}}$  ( $\bar{C}_{\hat{T}}$ ), then a simultaneous maximum likelihood fit to the  $m_{p\bar{p}K^+\pi^-}$  invariant-mass distribution of the four subsamples is used to determine the signal and background yields and the asymmetries  $A_{\hat{T}}$  and  $\bar{A}_{\hat{T}}$ . The fit model is described in Sec. 3.7 and the shape parameters are common to all the 4 subsamples whereas the yields and the  $A_{\hat{T}}$  and  $\bar{A}_{\hat{T}}$  asymmetries are included in the fit model according to equations 3.6. The background-subtracted distribution of  $C_{\hat{T}}$  is shown in Fig. 3.14.

The  $CP$ -violating ( $P$ -violating) asymmetry  $a_{CP}^{\hat{T}}$  ( $a_P^{\hat{T}}$ ) is then calculated from  $A_{\hat{T}}$  and  $\bar{A}_{\hat{T}}$  following Eq. 1.64 and Eq. 1.65. The statistical error assigned to  $a_{CP}^{\hat{T}}$  and  $a_P^{\hat{T}}$  is:

$$\sigma_{a_{CP}^{\hat{T}}} = \frac{\sqrt{\sigma_{A_{\hat{T}}}^2 + \sigma_{\bar{A}_{\hat{T}}}^2 + 2\rho\sigma_{A_{\hat{T}}}\sigma_{\bar{A}_{\hat{T}}}}}{2} \quad (3.20)$$

$$\sigma_{a_P^{\hat{T}}} = \frac{\sqrt{\sigma_{A_{\hat{T}}}^2 + \sigma_{\bar{A}_{\hat{T}}}^2 + 2\rho\sigma_{A_{\hat{T}}}\sigma_{\bar{A}_{\hat{T}}}}}{2} \quad (3.21)$$

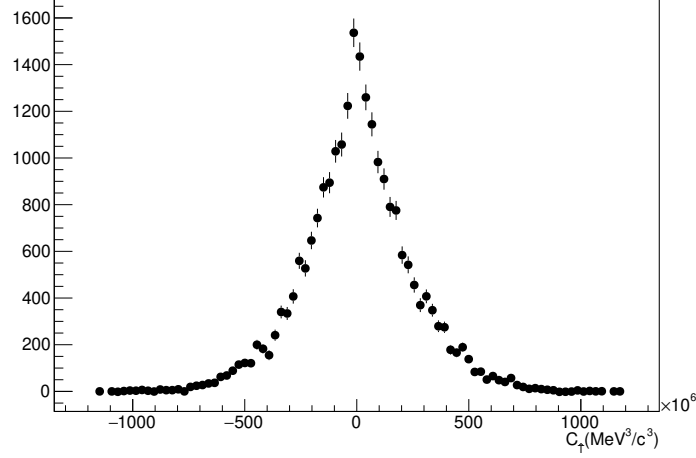


Figure 3.14: Background-subtracted distribution of the  $CP$ -averaged  $C_{\hat{T}}$

Where  $\sigma_{A_{\hat{T}}}^2$  and  $\sigma_{\bar{A}_{\hat{T}}}^2$  are the statistical errors returned by the fitting algorithm and  $\rho$  is the correlation between  $A_{\hat{T}}$  and  $\bar{A}_{\hat{T}}$ , which is also returned by the fit. In the fit the resonances listed in Section 3.8.1.1 have been vetoed.

The combination of Run 1 and Run 2 was obtained by means of a joint maximum-likelihood fit. The likelihood  $\mathcal{L}$  to be maximised is given by the product of likelihoods of the two different datasets:

$$\mathcal{L}(\theta, \theta_{Run1}, \theta_{Run2}) = \mathcal{L}_{Run1}(\theta, \theta_{Run1}) \mathcal{L}_{Run2}(\theta, \theta_{Run2}) \quad (3.22)$$

where  $\theta$  denotes the parameters of interest that are shared by the two datasets and must be simultaneously extracted from both.  $\theta_{Run1}$  and  $\theta_{Run2}$  are parameters that are specific for Run1 and Run2.

The joint fit takes into account the correlations between all fit parameters, not just those of primary interest. The floating parameters specific to Run 1 and Run 2 have already been described in Tab. 3.6 whereas the shared parameters  $\theta$  are: the two asymmetries,  $A_T$  and  $\bar{A}_T$ , and the two resolutions  $\sigma_{B^0}$  and  $\sigma_{B_s^0}$ . Moreover, as it was done for Run1 and Run2 datasets separately,  $\sigma_{B^0}$  and  $\sigma_{B_s^0}$  are constrained to be the same in the fit. The invariant mass  $m(p\bar{p}K^+\pi^-)$  of the Run 1 and Run 2 datasets, split according to the  $B^0$  flavour and the  $C_{\hat{T}}$  ( $\bar{C}_{\hat{T}}$ ) sign, with the projection of the combined fit to the Run1+Run2 data sample overlaid is shown in Fig. 3.15. The parameters extracted from the fit, including the blind result for  $A_T$  and  $A_{\bar{T}}$  are reported in Tab. 3.10. The  $CP$ -violating and  $P$ -violating asymmetries are reported in Tab 3.9.



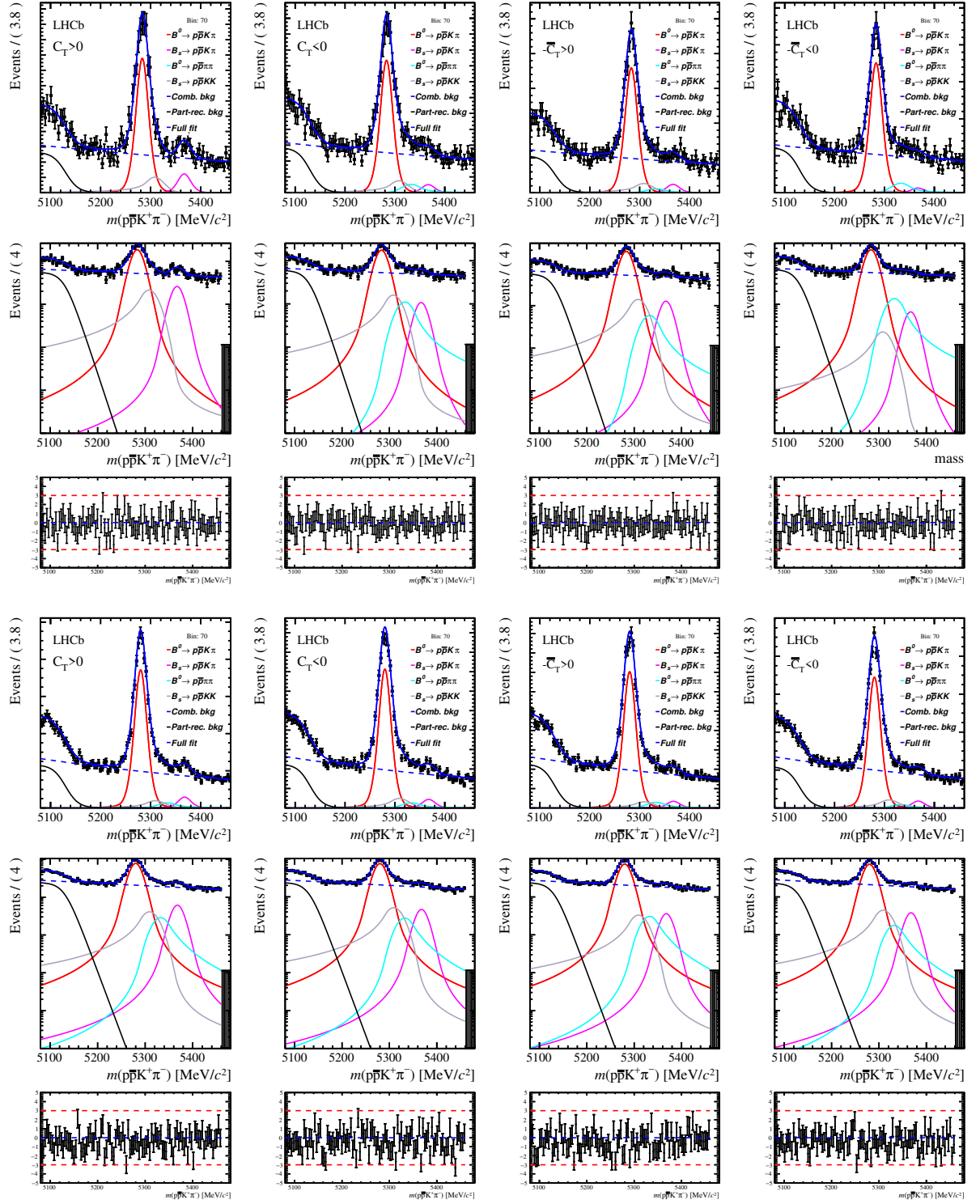


Figure 3.15: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$ . Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.

| Run | $A_T(\%)$       | $\bar{A}_T(\%)$ | $a_{CP}^{T-odd}(\%)$ | $a_P^{T-odd}(\%)$ | $\text{corr}(A_T, \bar{A}_T)$ |
|-----|-----------------|-----------------|----------------------|-------------------|-------------------------------|
| 1   | $-1.2 \pm 3.1$  | $2.0 \pm 2.9$   | $-1.6 \pm 2.1$       | $0.4 \pm 2.1$     | -0.00055                      |
| 2   | $-1.2 \pm 1.4$  | $-0.4 \pm 1.4$  | $-0.4 \pm 0.99$      | $-0.8 \pm 0.99$   | 0.00015                       |
| 1+2 | $0.058 \pm 1.2$ | $0.65 \pm 1.2$  | $-0.3 \pm 0.85$      | $0.35 \pm 0.85$   | -0.000095                     |

Table 3.9: Blinded phase-space integrated asymmetries for the charmless region ( $m_{p\bar{p}} < 2850 \text{ MeV}/c^2$ )

|                                     |                     |                                            |                     |                      |                           |
|-------------------------------------|---------------------|--------------------------------------------|---------------------|----------------------|---------------------------|
| $N_{B_s(C)}$                        | $920 \pm 112$       | $N_{B_s(C)}^{Run1}$                        | $315 \pm 58$        |                      |                           |
| $N_{B_s(\bar{C})}$                  | $630 \pm 108$       | $N_{B_s(\bar{C})}^{Run1}$                  | $163 \pm 56$        |                      |                           |
| $A_{\hat{T}}(B_s)$                  | $-0.048 \pm 0.10$   | $A_{\hat{T}}^{Run1}(B_s)$                  | $0.067 \pm 0.15$    | $A_{\hat{T}}$        | $0.007 \pm 0.013$         |
| $\bar{A}_{\hat{T}}(B_s)$            | $-0.041 \pm 0.14$   | $\bar{A}_{\hat{T}}^{Run1}(B_s)$            | $0.41 \pm 0.31$     | $A_{\hat{T}}$        | $0.001 \pm 0.012$         |
| $N_{comb(C)}$                       | $40962 \pm 395$     | $N_{comb(C)}^{Run1}$                       | $10396 \pm 197$     | $N_{\bar{C}}$        | $12406 \pm 188$           |
| $N_{comb(\bar{C})}$                 | $41123 \pm 394$     | $N_{comb(\bar{C})}^{Run1}$                 | $10465 \pm 197$     | $N_C$                | $12998 \pm 193$           |
| $A_{\hat{T}}(Comb)$                 | $0.0075 \pm 0.0079$ | $A_{\hat{T}}^{Run1}(Comb)$                 | $0.016 \pm 0.015$   | $N_C^{Run1}$         | $3114 \pm 95$             |
| $\bar{A}_{\hat{T}}(Comb)$           | $-0.013 \pm 0.0078$ | $\bar{A}_{\hat{T}}^{Run1}(Comb)$           | $-0.019 \pm 0.015$  | $N_C^{Run1}$         | $3010 \pm 96$             |
| $N_{p\bar{p}\pi\pi(C)}$             | $809 \pm 221$       | $N_{p\bar{p}\pi\pi(C)}^{Run1}$             | $70 \pm 104$        | $\beta$              | $12.92 \pm 0.68$          |
| $N_{p\bar{p}\pi\pi(\bar{C})}$       | $689 \pm 215$       | $N_{p\bar{p}\pi\pi(\bar{C})}^{Run1}$       | $269 \pm 104$       | $cutoff$             | $5130.00 \pm 1.00$        |
| $A_{\hat{T}}(p\bar{p}\pi\pi)$       | $0.54 \pm 0.26$     | $A_{\hat{T}}^{Run1}(p\bar{p}\pi\pi)$       | $0.43 \pm 1.37$     | $\mu_{B^0}^{Run2}$   | $5279.926 \pm 0.089$      |
| $\bar{A}_{\hat{T}}(p\bar{p}\pi\pi)$ | $0.32 \pm 0.27$     | $\bar{A}_{\hat{T}}^{Run1}(p\bar{p}\pi\pi)$ | $-0.25 \pm 0.33$    | $\mu_{B^0}^{Run1}$   | $5283.20 \pm 0.19$        |
| $N_{p\bar{p}KK(C)}$                 | $1531 \pm 322$      | $N_{p\bar{p}KK(C)}^{Run1}$                 | $644 \pm 167$       | $\mu_{B^0}^{Run2}$   | $5367.73 \pm 0.89$        |
| $N_{p\bar{p}KK(\bar{C})}$           | $1286 \pm 314$      | $N_{p\bar{p}KK(\bar{C})}^{Run1}$           | $276 \pm 163$       | $\mu_{B_s^0}^{Run1}$ | $5366.4 \pm 1.9$          |
| $A_{\hat{T}}(p\bar{p}KK)$           | $-0.30 \pm 0.17$    | $A_{\hat{T}}^{Run1}(p\bar{p}KK)$           | $-0.13 \pm 0.19$    | $\lambda_{Run2}$     | $-0.0014900 \pm 0.000060$ |
| $\bar{A}_{\hat{T}}(p\bar{p}KK)$     | $-0.16 \pm 0.18$    | $\bar{A}_{\hat{T}}^{Run1}(p\bar{p}KK)$     | $0.47 \pm 0.50$     | $\lambda_{Run1}$     | $-0.001093 \pm 0.00011$   |
| $N_{preco(C)}$                      | $5915 \pm 201$      | $N_{preco(C)}^{Run1}$                      | $1421 \pm 94$       | $\sigma_{B^0}$       | $15.28 \pm 0.11$          |
| $N_{preco(\bar{C})}$                | $5743 \pm 202$      | $N_{preco(\bar{C})}^{Run1}$                | $1477 \pm 94$       |                      |                           |
| $A_{\hat{T}}(preco)$                | $0.018 \pm 0.022$   | $A_{\hat{T}}^{Run1}(preco)$                | $-0.0091 \pm 0.043$ |                      |                           |
| $\bar{A}_{\hat{T}}(preco)$          | $0.031 \pm 0.023$   | $\bar{A}_{\hat{T}}^{Run1}(preco)$          | $0.021 \pm 0.041$   |                      |                           |

Table 3.10: Results of the simultaneous fit to Run1+Run2 selected candidates invariant mass spectrum.

### 3.11 Search for local $CP$ violation effects in the charmless region of the phase space

Triple-product asymmetries are measured also in bins of the phase space in order to improve the sensitivity to  $CP$  violation. As the study performed in Section 3.8.1 revealed, the description of the decay amplitude over the 4-body phase space of  $B^0 \rightarrow p\bar{p}K^+\pi^-$  is quite complicated and many intermediate resonances can contribute. Like before, we identify the interesting region where possible  $CP$  violation effects could be present in the charmless region of the  $p\bar{p}$  spectrum. In this region very little is known about the underlying resonant structure. Nevertheless, an interesting low-mass baryon-antibaryon enhancement is seen (see Fig. 3.16) and was also observed by BaBar [64] and BES [65]. On the theoretical side this discovery has been discussed by several authors [66], [67] and might be considered either as a gluonic state or as a result of the quark fragmentation process.

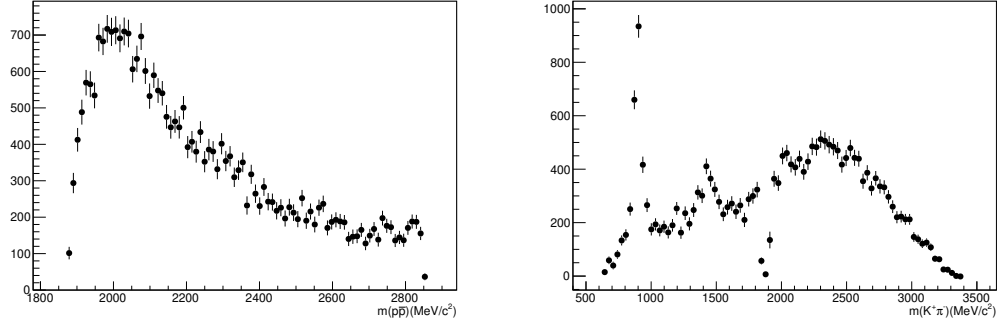


Figure 3.16: Left: Background-subtracted  $m(p\bar{p})$  spectrum in the charmless region. The low mass baryon-antibaryon enhancement is clearly visible. Right: Background-subtracted  $m(K^+\pi^-)$  spectrum in the charmless region. The region corresponding to the  $D^0$  mass is vetoed.

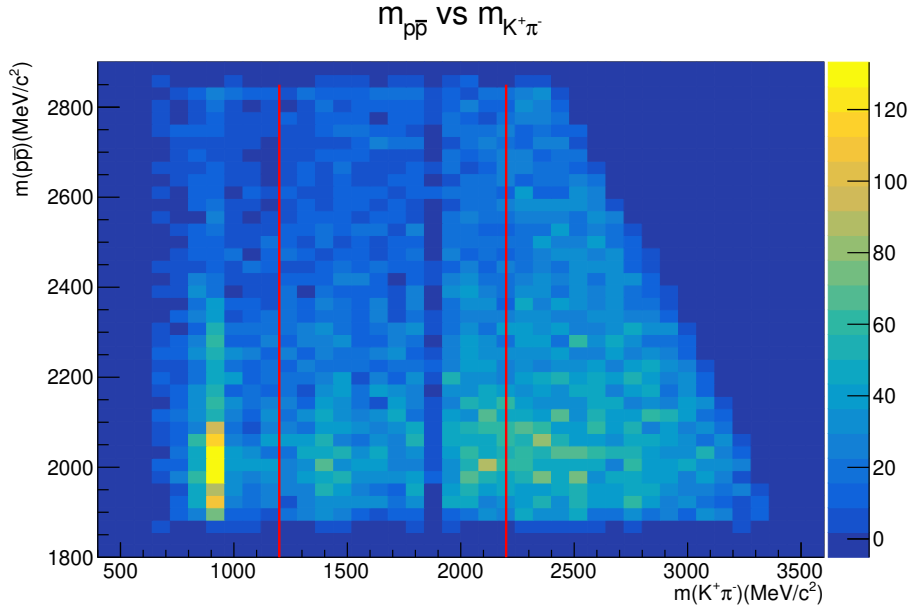


Figure 3.17: Background-subtracted scatter plot of  $m_{p\bar{p}}$  vs  $m_{K^+\pi^-}$ . The scale is in units of  $\text{MeV}/c^2$ . The red vertical lines define the three regions of the phase space where  $CP$  violation is searched for. Every region is further divided in 8 bins: 2 bins for the variable  $\cos\theta_{p\bar{p}}$ , 2 bins in  $\cos\theta_{K^+\pi^-}$ , 2 bins in  $\phi$ .

In the charmless region the invariant mass range of the  $K^+\pi^-$  system is up to  $3.5 \text{ GeV}/c^2$ , as shown in Fig. 3.16. This means that all the neutral  $K^*$  resonances known to decay to  $K^+\pi^-$  could in principle interfere and cause  $CP$  violation effects. They are listed in Table 3.11. Their mass, width and quantum numbers, taken from [39], are reported as well.

In order to optimize the binning scheme to enhance the sensitivity to  $CP$  violation effects we decided to divide the phase space defined by  $m_{K^+\pi^-}$  and  $m_{p\bar{p}}$  in 3 regions:

| State         | Mass (MeV/c <sup>2</sup> ) | Width (MeV/c <sup>2</sup> ) | $J^P$ | $\mathcal{B}(K^* \rightarrow K\pi)$ |
|---------------|----------------------------|-----------------------------|-------|-------------------------------------|
| $K^*(800)$    | $682 \pm 29$               | $547 \pm 24$                | $0^+$ | $\sim 100\%$                        |
| $K^*(892)$    | $895.81 \pm 0.19$          | $47.4 \pm 0.6$              | $1^-$ | $\sim 100\%$                        |
| $K^*(1410)$   | $1414 \pm 15$              | $232 \pm 21$                | $1^-$ | $(6.6 \pm 1.3)\%$                   |
| $K_0^*(1430)$ | $1425 \pm 50$              | $270 \pm 80$                | $0^+$ | $(93 \pm 10)\%$                     |
| $K_2^*(1430)$ | $1432.4 \pm 1.3$           | $109 \pm 5$                 | $2^+$ | $(49.9 \pm 1.2)\%$                  |
| $K^*(1680)$   | $1717 \pm 27$              | $322 \pm 110$               | $1^-$ | $(38.7 \pm 2.5)\%$                  |
| $K_3^*(1780)$ | $1776 \pm 7$               | $159 \pm 21$                | $3^-$ | $(18.8 \pm 1.0)\%$                  |
| $K_0^*(1950)$ | $1945 \pm 22$              | $201 \pm 90$                | $0^+$ | $(52 \pm 14)\%$                     |
| $K_2^*(1980)$ | $1974 \pm 26$              | $376 \pm 70$                | $2^+$ | not seen yet                        |
| $K_4^*(2045)$ | $2045 \pm 9$               | $198 \pm 30$                | $4^+$ | $(9.9 \pm 1.2)\%$                   |
| $K_5^*(2380)$ | $2382 \pm 24$              | $178 \pm 50$                | $5^-$ | $(6.1 \pm 1.2)\%$                   |

Table 3.11: Known neutral  $K^*$  resonances seen in the  $K^+\pi^-$  final state plus the established  $K_2^*(1980)$  resonance not seen yet in the  $K^+\pi^-$  final state

| Bin | $m_{p\bar{p}}$ (MeV/c <sup>2</sup> ) | $K^+\pi^-$ (MeV/c <sup>2</sup> ) | $\cos(\theta_{p\bar{p}})$             | $\cos(\theta_{K\pi})$             | $\Phi$                  |
|-----|--------------------------------------|----------------------------------|---------------------------------------|-----------------------------------|-------------------------|
| 0   | $m_{p\bar{p}} \in [1800, 2850]$      | $m_{K\pi} \in [500, 1200]$       | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [0, \pi/2]$   |
| 1   | $m_{p\bar{p}} \in [1800, 2850]$      | $m_{K\pi} \in [500, 1200]$       | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [\pi/2, \pi]$ |
| 2   | $m_{p\bar{p}} \in [1800, 2850]$      | $m_{K\pi} \in [500, 1200]$       | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [0, \pi/2]$   |
| 3   | $m_{p\bar{p}} \in [1800, 2850]$      | $m_{K\pi} \in [500, 1200]$       | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [\pi/2, \pi]$ |
| 4   | $m_{p\bar{p}} \in [1800, 2850]$      | $m_{K\pi} \in [500, 1200]$       | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [0, \pi/2]$   |
| 5   | $m_{p\bar{p}} \in [1800, 2850]$      | $m_{K\pi} \in [500, 1200]$       | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [\pi/2, \pi]$ |
| 6   | $m_{p\bar{p}} \in [1800, 2850]$      | $m_{K\pi} \in [500, 1200]$       | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [0, \pi/2]$   |
| 7   | $m_{p\bar{p}} \in [1800, 2850]$      | $m_{K\pi} \in [500, 1200]$       | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [\pi/2, \pi]$ |

Table 3.12: Angular binning scheme for the charmless region dominated by the  $K^*(892)$  resonance

- **scheme 1:** Charmless region ( $m_{p\bar{p}} < 2.85 \text{ GeV}/c^2$ ) and dominated by the  $K^*(892)$  resonance in the  $K^+\pi^-$  spectrum ( $m_{K^+\pi^-} < 1200 \text{ GeV}/c^2$ ) (see Tab. 3.12)
- **scheme 2:** Charmless region ( $m_{p\bar{p}} < 2.85 \text{ GeV}/c^2$ ) and region in the  $m_{K^+\pi^-}$  spectrum where many resonances interfere ( $m_{K^+\pi^-} \in [1200, 2200]$ )(see Tab. 3.13)
- **scheme 3:** Charmless region ( $m_{p\bar{p}} < 2.85 \text{ GeV}/c^2$ ) and dominated by the  $K_5^*(2380)$  resonance in the  $K^+\pi^-$  spectrum ( $m_{K^+\pi^-} > 2200 \text{ GeV}/c^2$ )(see Tab. 3.14)

The three regions of the phase space are shown in Fig. 3.17. Following what was anticipated in Section 3.1.1, every scheme  $i$  is further divided in 8 bins: 2 for the variable  $\cos \theta_{p\bar{p}}$ , 2 bins in  $\cos \theta_{K^+\pi^-}$ , 2 bins in  $\phi$  whose distribution is shown in Fig. 3.18. This binning scheme takes into account the main known resonances in the  $m_{p\bar{p}}$  and  $m_{K^+\pi^-}$  invariant mass spectrum, while a binning uniformly distributed between -1 and 1 for  $\cos(\theta_{p\bar{p}})$  and for  $\cos(\theta_{K^+\pi^-})$  and between 0 and  $\pi$  for the  $\Phi$  angle should prevent the dilution of the asymmetries.

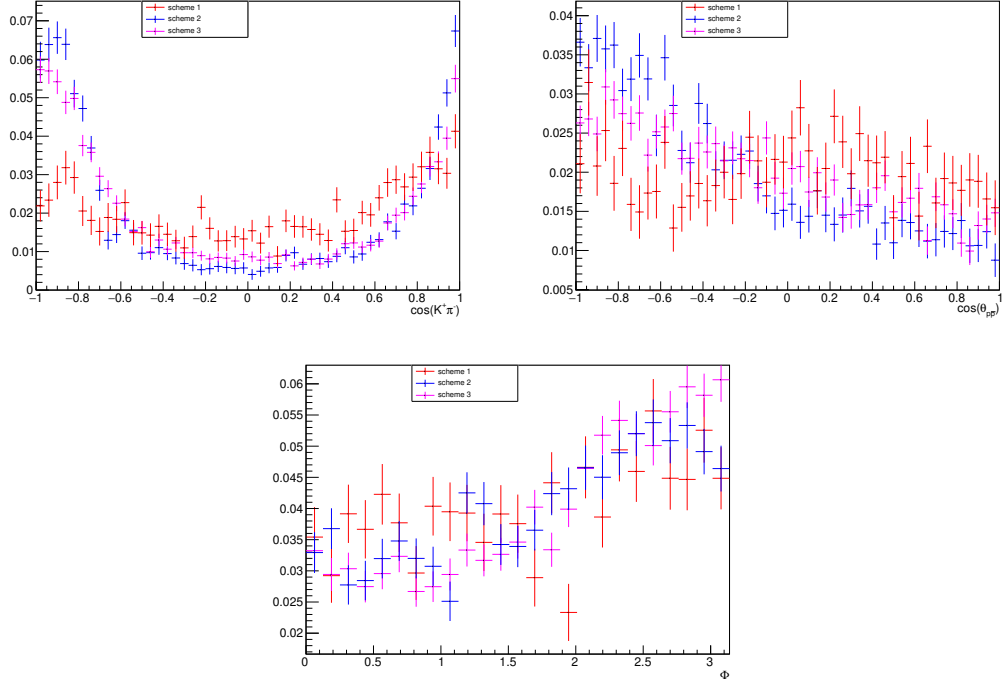


Figure 3.18: Top left: background-subtracted distribution of  $\cos(\theta_{K^+\pi^-})$  for the three different regions. Top right: background-subtracted distribution of  $\cos(\theta_{p\bar{p}})$  for the three different regions. Bottom: background-subtracted distribution of the  $\Phi$  angle for the three different regions

| Bin | $p\bar{p}(\text{MeV}/c^2)$      | $K^+\pi^-(\text{MeV}/c^2)$  | $\cos(\theta_{p\bar{p}})$             | $\cos(\theta_{K\pi})$             | $\Phi$                  |
|-----|---------------------------------|-----------------------------|---------------------------------------|-----------------------------------|-------------------------|
| 8   | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [1200, 2200]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [0, \pi/2]$   |
| 9   | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [1200, 2200]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [\pi/2, \pi]$ |
| 10  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [1200, 2200]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [0, \pi/2]$   |
| 11  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [1200, 2200]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [\pi/2, \pi]$ |
| 12  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [1200, 2200]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [0, \pi/2]$   |
| 13  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [1200, 2200]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [\pi/2, \pi]$ |
| 14  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [1200, 2200]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [0, \pi/2]$   |
| 15  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [1200, 2200]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [\pi/2, \pi]$ |

Table 3.13: Angular binning scheme for the charmless region where many  $K^*$  resonances very close in mass may interfere and cause local  $CP$  violation effects.

## 3.12 Results

In the fits the resonances listed in 3.8.1.1 have been vetoed. The blinded asymmetries  $a_{CP}^T$  and  $a_P^T$  as a function of the bins for the three different regions are shown in Figures 3.19, 3.20, 3.21. The exact asymmetries extracted from the fit are reported in Tab. 3.15, 3.16, 3.17. The results of the combined fits performed in each bin are reported in Appendix D.

| Bin | $p\bar{p}$ (MeV/ $c^2$ )        | $K^+\pi^-$ (MeV/ $c^2$ )    | $\cos(\theta_{p\bar{p}})$             | $\cos(\theta_{K\pi})$             | $\Phi$                  |
|-----|---------------------------------|-----------------------------|---------------------------------------|-----------------------------------|-------------------------|
| 16  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [2200, 3600]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [0, \pi/2]$   |
| 17  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [2200, 3600]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [\pi/2, \pi]$ |
| 18  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [2200, 3600]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [0, \pi/2]$   |
| 19  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [2200, 3600]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [\pi/2, \pi]$ |
| 20  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [2200, 3600]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [0, \pi/2]$   |
| 21  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [2200, 3600]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [\pi/2, \pi]$ |
| 22  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [2200, 3600]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [0, \pi/2]$   |
| 23  | $m_{p\bar{p}} \in [1800, 2850]$ | $m_{K\pi} \in [2200, 3600]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [\pi/2, \pi]$ |

Table 3.14: Angular binning scheme for the charmless region dominated by the  $K_5^*(2380)$  resonance

| Bin | $A_T(\%)$        | $\bar{A}_T(\%)$  | $a_{CP}^{T-odd}(\%)$ | $a_P^{T-odd}(\%)$ | $\text{corr}(A_T, \bar{A}_T)$ |
|-----|------------------|------------------|----------------------|-------------------|-------------------------------|
| 0   | $-13 \pm 10.2$   | $-6.2 \pm 9.8$   | $-3.4 \pm 7$         | $-9.6 \pm 7.1$    | 0.00044                       |
| 1   | $-9.7 \pm 9.4$   | $2.8 \pm 9.9$    | $-6.3 \pm 6.8$       | $-3.4 \pm 6.8$    | -0.00035                      |
| 2   | $-1 \pm 6.7$     | $-10.4 \pm 9.79$ | $4.7 \pm 5.9$        | $-5.7 \pm 5.9$    | 0.0002                        |
| 3   | $-0.18 \pm 7.1$  | $-12.2 \pm 7.92$ | $6 \pm 5.3$          | $-6.2 \pm 5.3$    | -0.00017                      |
| 4   | $-15.4 \pm 11.1$ | $9.3 \pm 9.1$    | $-12.4 \pm 7.1$      | $-3 \pm 7.1$      | 0.00008                       |
| 5   | $-6.4 \pm 8.3$   | $4.5 \pm 8.6$    | $-5.4 \pm 6$         | $-0.95 \pm 6$     | 0.0003                        |
| 6   | $6 \pm 7.5$      | $-2.7 \pm 8.6$   | $4.4 \pm 5.7$        | $1.6 \pm 5.7$     | 0.00051                       |
| 7   | $0.42 \pm 6.8$   | $-7.7 \pm 6.6$   | $4.1 \pm 4.7$        | $-3.6 \pm 4.7$    | 0.00001                       |

Table 3.15: Blinded asymmetries for binning scheme 1 from the combined Run1+Run2 sample

### 3.13 Systematic uncertainties

The following sources of systematic uncertainties have been identified:

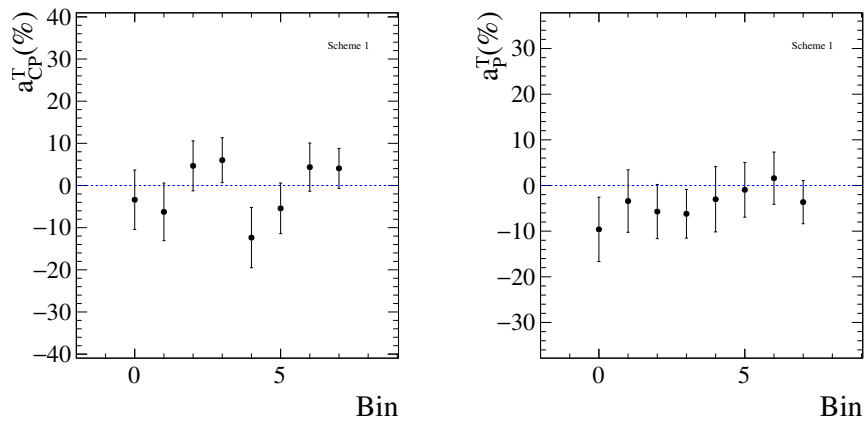


Figure 3.19: Blinded asymmetries  $a_{CP}^T$  and  $a_P^T$  for binning scheme 1 from the combined Run1+Run2 sample.

| Bin | $A_T(\%)$       | $\bar{A}_T(\%)$ | $a_{CP}^{T-odd}(\%)$ | $a_P^{T-odd}(\%)$ | $\text{corr}(A_T, \bar{A}_T)$ |
|-----|-----------------|-----------------|----------------------|-------------------|-------------------------------|
| 8   | $-7 \pm 4.9$    | $7.5 \pm 4.9$   | $-7.2 \pm 3.5$       | $0.26 \pm 3.5$    | -0.00034                      |
| 9   | $-5.8 \pm 8.6$  | $-7.6 \pm 3.2$  | $0.87 \pm 4.6$       | $-6.7 \pm 4.6$    | 0.00034                       |
| 10  | $-1.9 \pm 5.9$  | $8.5 \pm 10$    | $-5.2 \pm 5.9$       | $3.3 \pm 5.9$     | -0.0031                       |
| 11  | $6.8 \pm 5.2$   | $8.1 \pm 5$     | $-0.67 \pm 3.6$      | $7.5 \pm 3.6$     | 0.00065                       |
| 12  | $15.3 \pm 9.27$ | $-3.5 \pm 9.5$  | $9.4 \pm 6.6$        | $5.9 \pm 6.6$     | 0.000024                      |
| 13  | $5.3 \pm 8.7$   | $3.1 \pm 4.8$   | $1.1 \pm 4.9$        | $4.2 \pm 4.9$     | 0.0066                        |
| 14  | $1.9 \pm 9.2$   | $18.5 \pm 8.87$ | $-8.3 \pm 6.4$       | $10.2 \pm 6.4$    | -0.0011                       |
| 15  | $5 \pm 6$       | $5.5 \pm 7.2$   | $-0.22 \pm 4.7$      | $5.3 \pm 4.7$     | -0.00012                      |

Table 3.16: Blinded asymmetries for binning scheme 2 from the combined Run1+Run2 sample

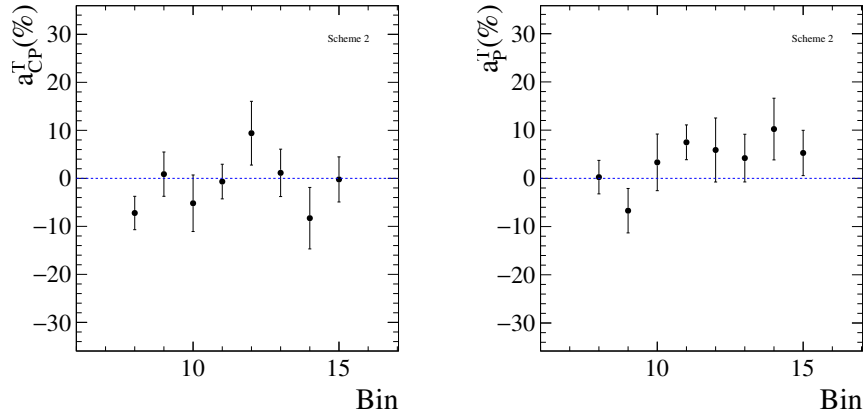


Figure 3.20: Blinded asymmetries  $a_{CP}^T$  and  $a_P^T$  for binning scheme 2 from the combined Run1+Run2 sample.

- **Reconstruction efficiency and selection procedure:** It should not affect the result since  $A_T$  and  $\bar{A}_T$  asymmetries are calculated separately on the same final state. This will be demonstrated by measuring the  $CP$ -odd asymmetries also on the

| Bin | $A_T(\%)$       | $\bar{A}_T(\%)$ | $a_{CP}^{T-odd}(\%)$ | $a_P^{T-odd}(\%)$ | $\text{corr}(A_T, \bar{A}_T)$ |
|-----|-----------------|-----------------|----------------------|-------------------|-------------------------------|
| 16  | $1.8 \pm 4.8$   | $6.4 \pm 4.7$   | $-2.3 \pm 3.4$       | $4.1 \pm 3.4$     | 0.000019                      |
| 17  | $4.8 \pm 7.5$   | $-1.4 \pm 3.3$  | $3.1 \pm 4.1$        | $1.7 \pm 4.1$     | 0.00036                       |
| 18  | $-8.6 \pm 6.7$  | $-14.7 \pm 6.4$ | $3.1 \pm 4.6$        | $-11.6 \pm 4.6$   | 0.00026                       |
| 19  | $-7.4 \pm 5.1$  | $3.2 \pm 5.2$   | $-5.3 \pm 3.6$       | $-2.1 \pm 3.6$    | -0.00026                      |
| 20  | $-1.3 \pm 6.3$  | $-6.8 \pm 7$    | $2.7 \pm 4.7$        | $-4 \pm 4.7$      | 0.0015                        |
| 21  | $-4 \pm 5.7$    | $7.2 \pm 5.8$   | $-5.6 \pm 4.1$       | $1.6 \pm 4.1$     | 0.000054                      |
| 22  | $10.5 \pm 7.06$ | $2.4 \pm 6.7$   | $4.1 \pm 4.9$        | $6.4 \pm 4.9$     | 0.0000092                     |
| 23  | $6 \pm 5$       | $-1 \pm 5.3$    | $3.5 \pm 3.6$        | $2.5 \pm 3.6$     | 0.000047                      |

Table 3.17: Blinded asymmetries for binning scheme 3 from the combined Run1+Run2 sample

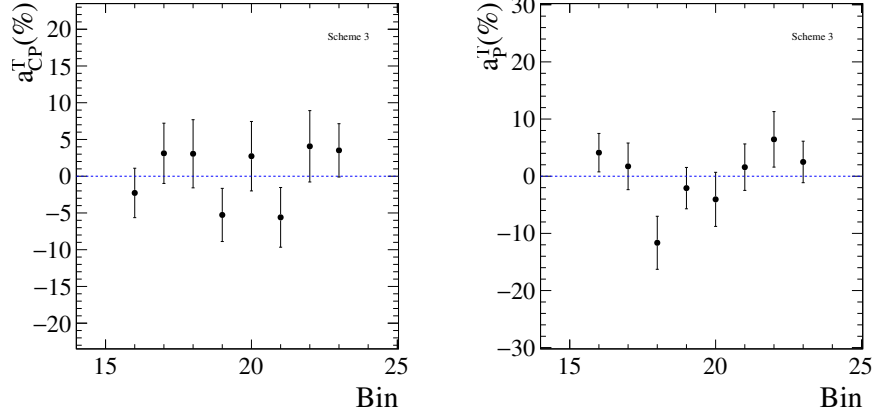


Figure 3.21: Blinded asymmetries  $a_{CP}^T$  and  $a_P^T$  for binning scheme 3 from the combined Run1+Run2 sample.

charmed control channel in order to verify that they are consistent with zero.

- **Effect of the detector resolution on  $C_{\hat{T}}$ :** due to the resolution on the triple product variables  $C_{\hat{T}}$  and  $\bar{C}_{\hat{T}}$ , it is possible to have signal migration between the two categories  $C_{\hat{T}} > 0$  and  $C_{\hat{T}} < 0$ . The effect is expected to be negligible. Nevertheless, it was estimated from the MC sample.
- **Bias of the fit model:** Different models of the signal/background parametrizations may affect the final asymmetry. This will be checked by performing toy MC studies whereby the data generated according to the nominal model will be fit with other pdf models that have comparable fit quality. The maximum likelihood procedure itself may have biases, but this will be evaluated by producing the pull plots and checking if the distributions are consistent with a normal distribution with mean equal to zero and width equal to one.

### 3.13.1 Reconstruction efficiency and selection procedure

The criteria applied for the reconstruction and selection of the signal  $B^0 \rightarrow p\bar{p}K^+\pi^-$  decays and the detector acceptance could in principle introduce an experimental bias on the measurement of the  $\hat{T}$ -odd variables,  $C_T$  and  $\bar{C}_T$ , and hence on  $A_T$  and  $\bar{A}_T$  and finally on  $a_{CP}^T$ . However, we expect the biases from the reconstruction to be very small since  $A_T$  and  $\bar{A}_T$  are calculated separately on the same final state and in principle they do not affect at all the result.

The possible bias introduced by the whole selection procedure was estimated with the  $B^0 \rightarrow p\bar{p}\bar{D}^0(\rightarrow K^+\pi^-)$  control channel. This choice was preferred to the Cabibbo-favoured  $B^0 \rightarrow \bar{\Lambda}_c^-(\rightarrow \bar{p}K^+\pi^-)p$  decay since its kinematic distributions are more similar to our signal.

The  $B^0 \rightarrow p\bar{p}\bar{D}^0(\rightarrow K^+\pi^-)$  channel was selected by requiring the  $K^+\pi^-$  invariant mass to



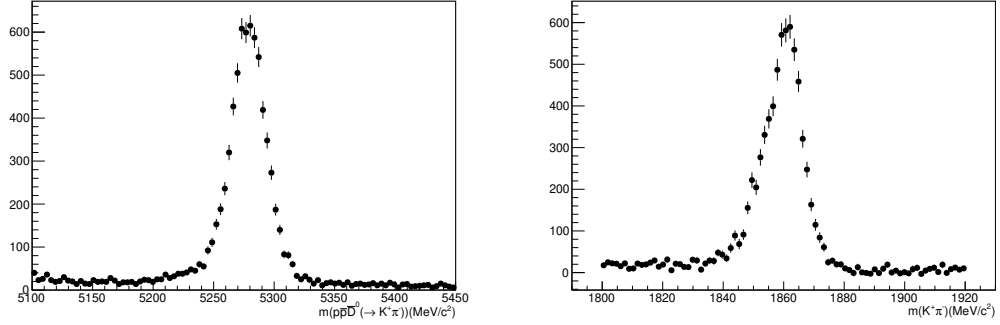


Figure 3.22: Left: The invariant mass distribution of the  $B^0 \rightarrow p\bar{p}K^+\pi^-$  where the  $K^+\pi^-$  subsystem invariant mass was selected in a window  $[1834.84, 1894.84]$   $\text{MeV}/c^2$  around the  $D^0$  mass. Right: The invariant mass distribution of the  $K^+\pi^-$  sub-system around the peak of the  $D^0$ .

be in a window  $\pm 30 \text{ MeV}$  around the nominal  $D^0$  mass. The distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for the selected control channel is shown in Figure 3.22.

### 3.13.1.1 Comparison of the kinematic distributions of $B^0 \rightarrow p\bar{p}K^+\pi^-$ and $B^0 \rightarrow p\bar{p}\bar{D}^0(\rightarrow K^+\pi^-)$

Production and detection asymmetries may depend on the kinematic distributions of the particle in question such as the momenta of the particles or their rapidity. In fact, differences between the interactions of oppositely charged pions, kaons or protons in the material of the spectrometer may induce detection charge asymmetries. This is true in particular when measuring direct  $CP$  asymmetries  $A_{CP}^{dir}$ . As shown in Fig. 3.23, the distributions of the kinematic variables belonging to the region of the control channel  $B^0 \rightarrow p\bar{p}\bar{D}^0(\rightarrow K^+\pi^-)$  are not perfectly equal to those belonging to the signal region defined by the three binning schemes. Moreover, the correlations between the momenta of the final state particles and the three angular variables in which the phase space is divided cause the momentum distributions to change bin to bin. The effect of the different kinematic is expected to be negligible for this measurement, but was checked anyway and will be discussed in details in Section 3.13.1.3.

### 3.13.1.2 Extraction of the asymmetry $a_{CP}^{T-odd}$ for the control channel $B^0 \rightarrow p\bar{p}\bar{D}^0$

The control channel  $B^0 \rightarrow p\bar{p}\bar{D}^0(\rightarrow K^+\pi^-)$  is split into four subsamples according to the  $B^0$  flavour and the sign of  $C_T$  and fit to extract the asymmetries. In this case the fit was unblinded. The  $D^0$  resonance is selected by requiring that  $1834 \text{ MeV}/c^2 < M_{K^+\pi^-} < 1895 \text{ MeV}/c^2$ , corresponding to  $\sim 5 \sigma$  window around the  $D^0$  mass peak. The model of the fit is the same as the one described in 3.8. Fig. 3.24 shows the result of the fit to the data sample.

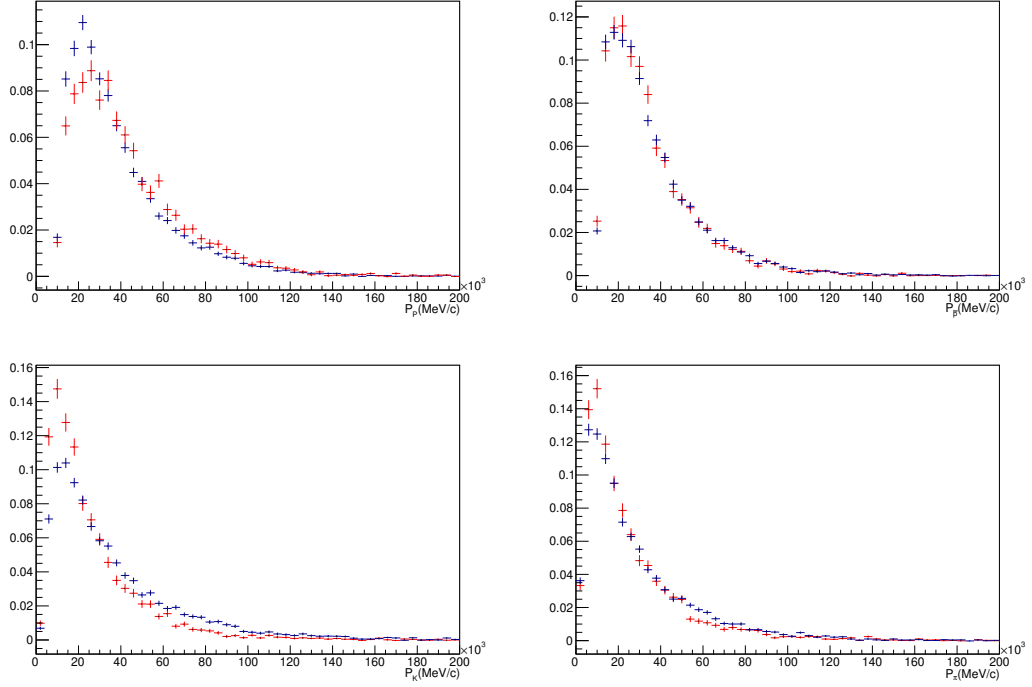


Figure 3.23: Comparison between the background-subtracted momenta of the final state particles in the control channel (red) region  $[1834.84, 1894.84] \text{ MeV}/c^2$  and the background-subtracted momenta of the final state particles in the charmless region  $m_{p\bar{p}} < 2850 \text{ MeV}/c^2$  (blue). Top left: Proton momentum. Top right: Anti-proton momentum. Bottom left: Kaon momentum. Bottom right: Pion momentum.

|                |                 |                      |
|----------------|-----------------|----------------------|
| $A_T(\%)$      | $\bar{A}_T(\%)$ | $a_{CP}^{T-odd}(\%)$ |
| $0.72 \pm 2.1$ | $2.7 \pm 2.0$   | $-1.0 \pm 1.5$       |

Table 3.18: Unblinded asymmetry for the control sample. The fit is performed on the Run2 data sample

The measured asymmetry  $a_{CP}^{T-odd}$  is reported in Tab. 3.18. The asymmetry is consistent with zero.

The asymmetry of the control sample is also measured in bins of the three helicity angles  $\cos(\theta_{p\bar{p}})$ ,  $\cos(\theta_{K\pi})$  and  $\Phi$ . The binning scheme in which the phase space is divided is shown in Tab. 3.19.

The asymmetries extracted by the fit in the different regions of the phase space are reported in Tab. 3.20. In general no significant dependence of the asymmetry on the helicity angles is observed with the only exception represented by a  $2\sigma$  deviation from 0 in bin number 6, but this is probably due to the particular choice made for the angular binning.

As a second cross-check, an adaptive binning scheme to divide the phase space of the

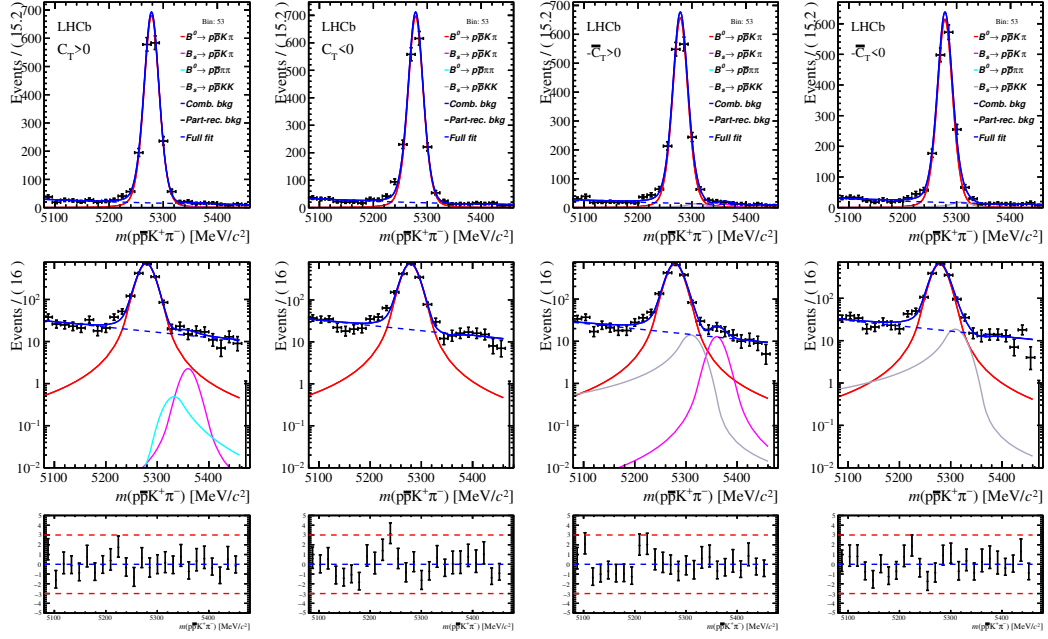


Figure 3.24: Result of the simultaneous fit to the control sample  $B^0 \rightarrow p\bar{p}\bar{D}^0 \rightarrow K^+\pi^-$  after splitting the data according to the  $B^0$  flavour and the sign of  $C_T$ .

| Bin | $K^+\pi^-$ (MeV/ $c^2$ )    | $\cos(\theta_{p\bar{p}})$             | $\cos(\theta_{K\pi})$             | $\Phi$                  |
|-----|-----------------------------|---------------------------------------|-----------------------------------|-------------------------|
| 0   | $m_{K\pi} \in [1834, 1895]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [0, \pi/2]$   |
| 1   | $m_{K\pi} \in [1834, 1895]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [\pi/2, \pi]$ |
| 2   | $m_{K\pi} \in [1834, 1895]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [0, \pi/2]$   |
| 3   | $m_{K\pi} \in [1834, 1895]$ | $\cos(\theta_{p\bar{p}}) \in [-1, 0]$ | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [\pi/2, \pi]$ |
| 4   | $m_{K\pi} \in [1834, 1895]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [0, \pi/2]$   |
| 5   | $m_{K\pi} \in [1834, 1895]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [-1, 0]$ | $\phi \in [\pi/2, \pi]$ |
| 6   | $m_{K\pi} \in [1834, 1895]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [0, \pi/2]$   |
| 7   | $m_{K\pi} \in [1834, 1895]$ | $\cos(\theta_{p\bar{p}}) \in [0, 1]$  | $\cos(\theta_{K\pi}) \in [0, 1]$  | $\phi \in [\pi/2, \pi]$ |

Table 3.19: Nominal binning scheme in which we bin the phase space of the control channel

control channel in a different way was chosen. This second scheme, shown in Tab 3.21, is chosen as to have approximately the same number of entries in every bin. The measured asymmetries are shown in Tab. 3.22

Also in this case we do not observe any significant dependence of the asymmetry on the helicity angles. This result tells us that tracking reconstruction, trigger selection and particle identification requirements did not generate any visible charge asymmetry in our decay. However, this is in principle true only up to the kinematic differences between signal and control channels. The remaining impact was addressed by reweighting the kinematic of the control channel in order to equalize it with that of the three signal region

| Angular bin | $A_T(\%)$        | $\bar{A}_T(\%)$ | $a_{CP}^{T-odd}(\%)$ |
|-------------|------------------|-----------------|----------------------|
| 0           | $0.56 \pm 4.6$   | $2.9 \pm 4.8$   | $-1.2 \pm 3.3$       |
| 1           | $0.0049 \pm 4.5$ | $3.6 \pm 4.9$   | $-1.8 \pm 3.3$       |
| 2           | $5.0 \pm 4.6$    | $0.9 \pm 4.9$   | $2.1 \pm 3.4$        |
| 3           | $2.3 \pm 4.5$    | $-1.8 \pm 4.4$  | $2.1 \pm 3.2$        |
| 4           | $-10.7 \pm 9.9$  | $-1.0 \pm 9.5$  | $-4.8 \pm 6.9$       |
| 5           | $1.5 \pm 8.9$    | $21.1 \pm 10.1$ | $-9.8 \pm 6.9$       |
| 6           | $-18.1 \pm 8.8$  | $12.8 \pm 9.7$  | $-15.5 \pm 6.5$      |
| 7           | $6.1 \pm 7.3$    | $10.3 \pm 7.7$  | $-2.1 \pm 5.3$       |

Table 3.20: Unblinded asymmetries for every bin of the nominal angular binning scheme 3.19. These asymmetries refer to the Run2 data sample

| Bin | $\cos(\theta_{p\bar{p}})$                    | $\cos(\theta_{K\pi})$                    | $\Phi$                  |
|-----|----------------------------------------------|------------------------------------------|-------------------------|
| 0   | $\cos(\theta_{p\bar{p}}) \in [0.025, 0.99]$  | $\cos(\theta_{K\pi}) \in [-0.065, 0.99]$ | $\phi \in [0, 1.99]$    |
| 1   | $\cos(\theta_{p\bar{p}}) \in [-0.99, -0.41]$ | $\cos(\theta_{K\pi}) \in [-1, -0.025]$   | $\phi \in [1.98, 3.14]$ |
| 2   | $\cos(\theta_{p\bar{p}}) \in [-0.41, 1]$     | $\cos(\theta_{K\pi}) \in [-1, -0.025]$   | $\phi \in [1.98, 3.14]$ |
| 3   | $\cos(\theta_{p\bar{p}}) \in [-1, -0.31]$    | $\cos(\theta_{K\pi}) \in [-0.025, 1]$    | $\phi \in [1.98, 3.14]$ |
| 4   | $\cos(\theta_{p\bar{p}}) \in [-0.31, 1]$     | $\cos(\theta_{K\pi}) \in [-0.025, 1]$    | $\phi \in [1.98, 3.14]$ |
| 5   | $\cos(\theta_{p\bar{p}}) \in [-1, -0.025]$   | $\cos(\theta_{K\pi}) \in [-1, -0.075]$   | $\phi \in [0, 0.98]$    |
| 6   | $\cos(\theta_{p\bar{p}}) \in [-1, -0.025]$   | $\cos(\theta_{K\pi}) \in [-1, -0.075]$   | $\phi \in [0.98, 1.98]$ |
| 7   | $\cos(\theta_{p\bar{p}}) \in [-1, -0.025]$   | $\cos(\theta_{K\pi}) \in [-0.075, 1]$    | $\phi \in [0, 0.95]$    |
| 8   | $\cos(\theta_{p\bar{p}}) \in [-1, -0.025]$   | $\cos(\theta_{K\pi}) \in [-0.075, 1]$    | $\phi \in [0.95, 1.98]$ |
| 9   | $\cos(\theta_{p\bar{p}}) \in [-0.025, 1]$    | $\cos(\theta_{K\pi}) \in [-1, -0.065]$   | $\phi \in [0, 1.98]$    |

Table 3.21: Angular binning scheme chosen in order to have the same yields in every bin.

defined in Section 3.11. In this way the true physical asymmetry is not altered, but the detector-induced charge asymmetry is.

### 3.13.1.3 Reweighting of the kinematic distributions for the control channel $B^0 \rightarrow p\bar{p}\bar{D}^0$

The algorithm used to reweight is Gradient Boosted Reweigher from the tool [68]. This algorithm allows to reweight multi-dimensional distributions taking into account correlations between them and without the need of dividing the n-dimensional space into bins. Since we are interested mainly in the charmless region we decided to equalize the kinematics of the control channel to that of the schemes 1, 2 and 3. (see 3.11). The following seven distributions of the control channel have been reweighted:

- the momentum of the proton  $P_p$
- the momentum of the antiproton  $P_{\bar{p}}$

| Bin | $A_T(\%)$       | $\bar{A}_T(\%)$ | $a_{CP}^{T-odd}(\%)$ |
|-----|-----------------|-----------------|----------------------|
| 0   | $-12.8 \pm 6.8$ | $11.0 \pm 8.0$  | $-11.9 \pm 4.8$      |
| 1   | $-6.04 \pm 6.4$ | $3.9 \pm 6.7$   | $-4.9 \pm 4.6$       |
| 2   | $7.2 \pm 6.6$   | $14.6 \pm 8.1$  | $-3.7 \pm 5.2$       |
| 3   | $3.4 \pm 5.9$   | $-5.8 \pm 5.5$  | $4.6 \pm 4.1$        |
| 4   | $9.9 \pm 7.0$   | $5.9 \pm 6.5$   | $2.0 \pm 4.8$        |
| 5   | $-5.3 \pm 5.9$  | $-3.2 \pm 6.1$  | $-1.1 \pm 4.2$       |
| 6   | $10.3 \pm 6.3$  | $4.6 \pm 6.9$   | $2.9 \pm 4.7$        |
| 7   | $8.1 \pm 5.7$   | $-0.6 \pm 6.0$  | $4.3 \pm 4.2$        |
| 8   | $-3.1 \pm 5.7$  | $7.4 \pm 6.8$   | $-5.2 \pm 4.4$       |
| 9   | $-10.8 \pm 8.8$ | $7.5 \pm 8.8$   | $-9.1 \pm 6.2$       |

Table 3.22: Unblinded asymmetries for every bin of the adaptive binning scheme 3.21. These asymmetries refer to the Run2 data sample

- the momentum of the kaon  $P_{K^+}$
- the momentum of the pion  $P_{\pi^-}$
- the helicity angle  $\cos(\theta_{p\bar{p}})$
- the helicity angle  $\cos(\theta_{K^+\pi^-})$
- the helicity angle  $\phi$

The comparison between the seven distributions of the control channel and those of the three signal regions before the reweighting is shown in Fig. 3.25, 3.26 and 3.27. The comparison between the seven distributions of the control channel and those of the three signal regions after the reweighting is shown in Fig. 3.28, Fig. 3.29, Fig. 3.30.

#### 3.13.1.4 Extraction of the asymmetry $a_{CP}^{T-odd}$ for the reweighted control channel $B^0 \rightarrow p\bar{p}\bar{D}^0$

We apply to the control channel the weights that equalize the distribution of its kinematic variables to that of the signal in the three specific regions of the phase space. At this point we fit again the reweighted control channel and measure the asymmetry  $a_{CP}^{T-odd}$ . We expect  $a_{CP}^{T-odd}$  to remain unchanged within the statistical error of the measurement.

Fig 3.31 shows the measured asymmetries as a function of the bins defined in Tab. 3.19 for the nominal case in which no weight is applied to the control sample (black points) and the cases in which weights are applied to the control sample (colored points).

No significant dependence on the bin is observed for all the four cases. Tab 3.23 shows the  $\chi^2/N_{dof}$  with respect to the no  $CP$  violation hypothesis for the case where no weights are applied and for the case where the three different weights are applied.

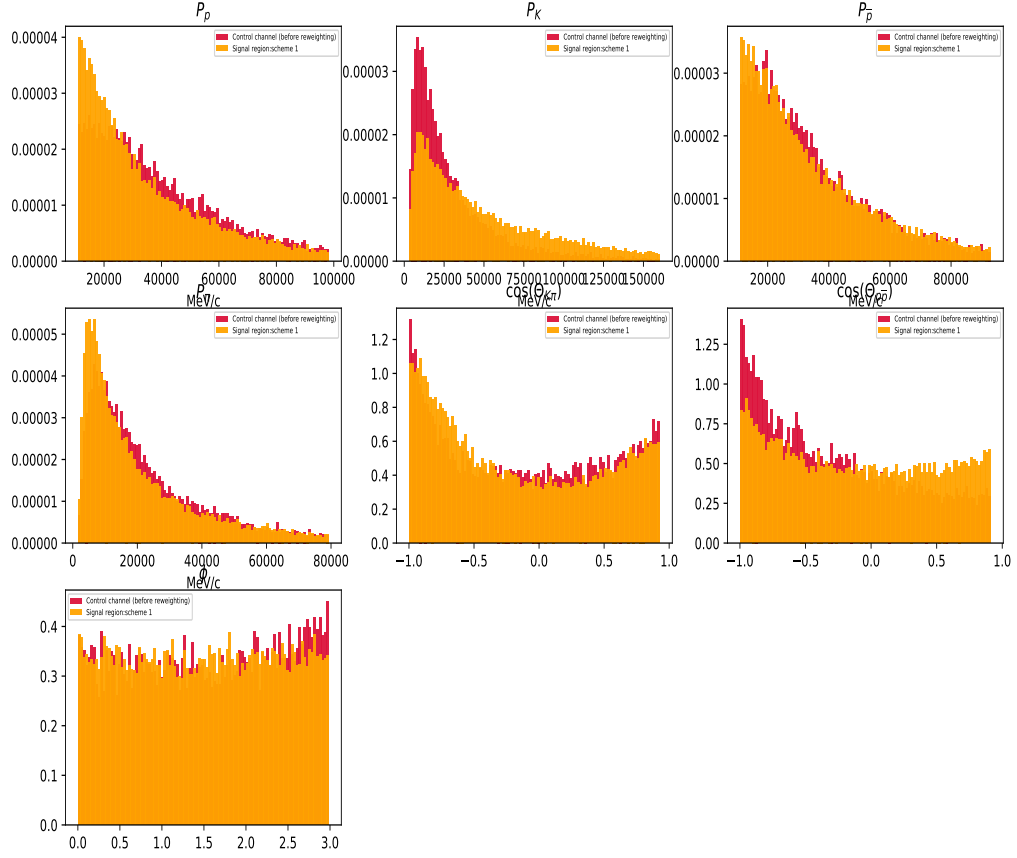


Figure 3.25: Comparison between CP-averaged kinematic distributions of the control channel (crimson) and those of the signal region defined by scheme 1 (see 3.12). The comparison is made between the momenta of the four final state particles and the three helicity angles. Every distribution contains both the signal and the background contributions

Fig 3.32 instead shows the measured asymmetries as a function of the bins defined in Tab. 3.21 for the nominal case in which no weight is applied to the control sample (black points) and the cases in which weights are applied to the control sample (colored points).

No significant dependence on the bin is observed for all the four cases. Tab 3.24 shows the  $\chi^2/N_{dof}$  with respect to the no  $CP$  violation hypothesis for the four different cases. As expected, the asymmetries measured before and after the reweighting procedure are in excellent agreement with a negligible difference compared to the statistical precision indicating that detector-induced charge asymmetries are not sensitive to the kinematic differences between the signal and the control channel at this level of precision.

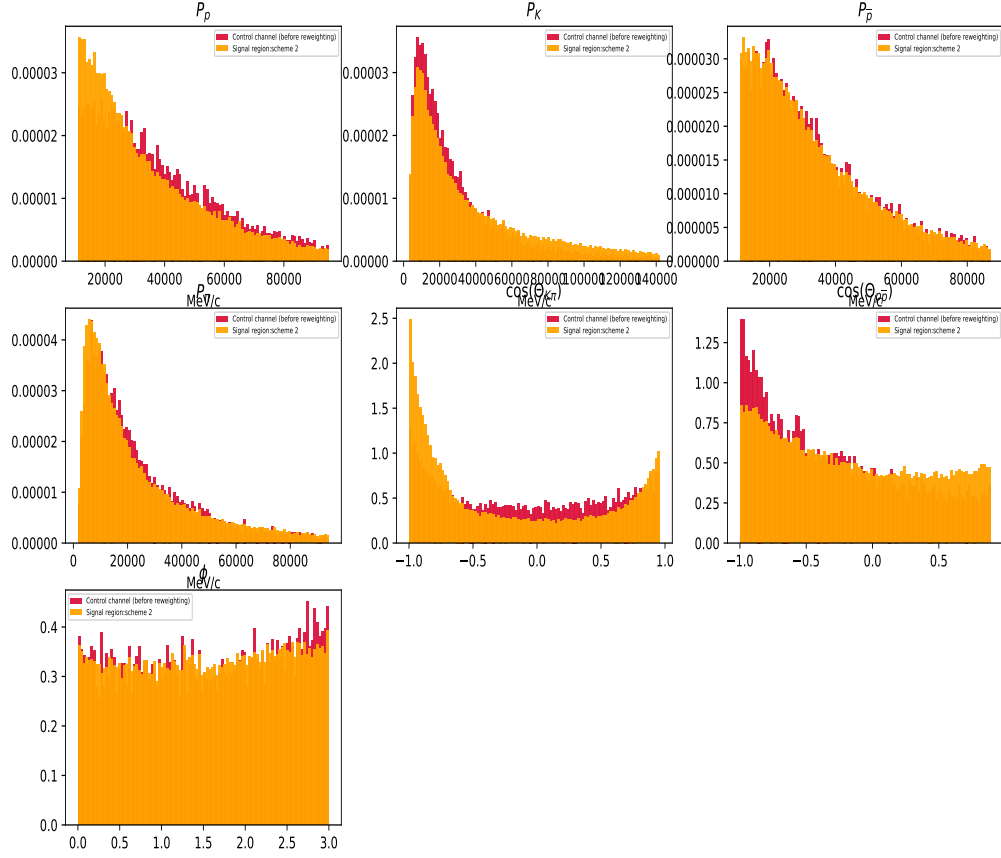


Figure 3.26: Comparison between the CP-averaged kinematic distributions of the control channel (crimson) and those of the signal region defined by scheme 2 (see 3.13). The comparison is made between the momenta of the four final state particles and the three helicity angles. Every distribution contains both the signal and the background contributions

### 3.13.1.5 Asymmetry $a_{CP}^{T-odd}$ for the control channel $B^0 \rightarrow p\bar{p}\bar{D}^0$ for different magnet polarity

We fit again our control sample in bins of the three helicity angles, as it was done in 3.13.1.2, this time splitting the data according to the polarity of the magnet in order to show that the asymmetry does not depend on it. The measured asymmetries as a function of the bin for the two different magnet polarities is shown in Fig. 3.33. No significant dependence on the bin is observed for the two magnet configuration. Tab 3.25 shows the  $\chi^2/N_{dof}$  with respect to the no  $CP$  violation hypothesis for the four different cases.

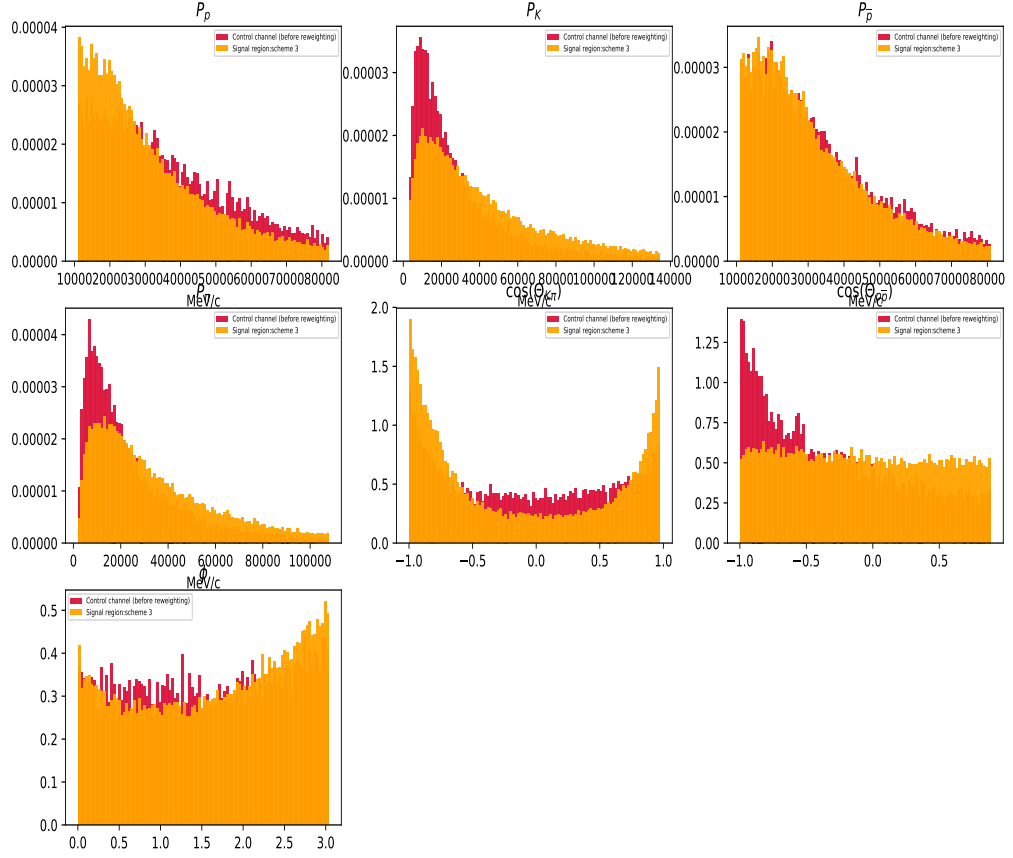


Figure 3.27: Comparison between the CP-averaged kinematic distributions of the control channel (crimson) and those of the signal region defined by scheme 3 (see 3.14). Every distribution contains both the signal and the background contributions

| Weights    | $\chi^2/N_{dof}$ |
|------------|------------------|
| No weights | 9.47/8           |
| Scheme 1   | 11.59/8          |
| Scheme 2   | 13.76/8          |
| Scheme 3   | 18.10/8          |

Table 3.23:  $\chi^2/N_{dof}$  for the control channel calculated with respect to the no CPV hypothesis represented by the blue dashed horizontal line in Fig. 3.31.



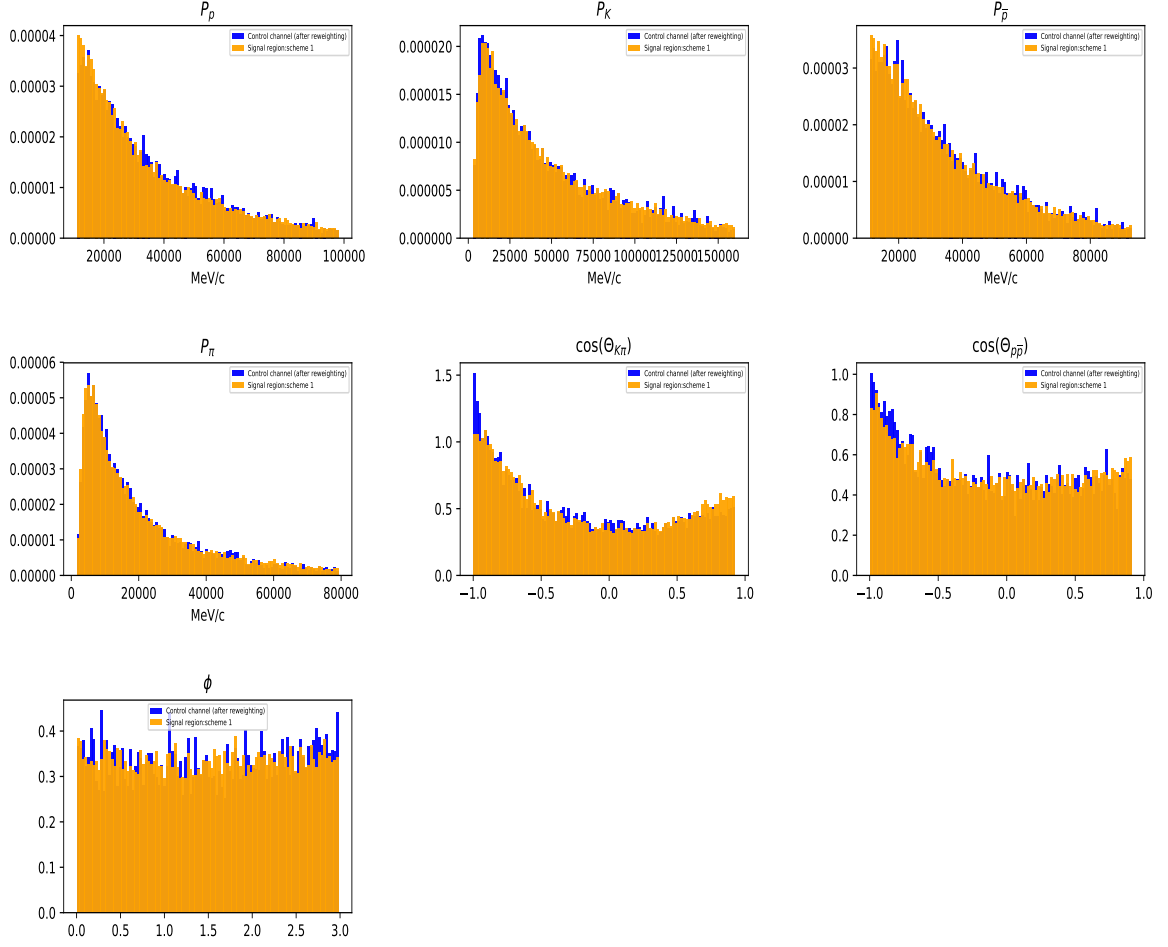


Figure 3.28: Comparison between the CP-averaged kinematic distributions of the control channel after the reweighting (blue) and those of the signal region defined by scheme 1 (orange). Every distribution contains both the signal and the background contributions

### 3.13.2 Effect of the detector resolution on $C_{\hat{T}}$

Because of the finite detector resolution, it is possible to have signal migration between the two categories  $C_{\hat{T}} > 0$  and  $C_{\hat{T}} < 0$  (and similarly for  $-\bar{C}_{\hat{T}} > 0$  and  $-\bar{C}_{\hat{T}} < 0$ ), which

| Weights    | $\chi^2/N_{dof}$ |
|------------|------------------|
| No weights | 13.5/10          |
| Scheme 1   | 14.5/10          |
| Scheme 2   | 11.9/10          |
| Scheme 3   | 12.9/10          |

Table 3.24:  $\chi^2/N_{dof}$  for the control channel calculated with respect to the no CPV hypothesis represented by the blue dashed horizontal line in Fig. 3.32.

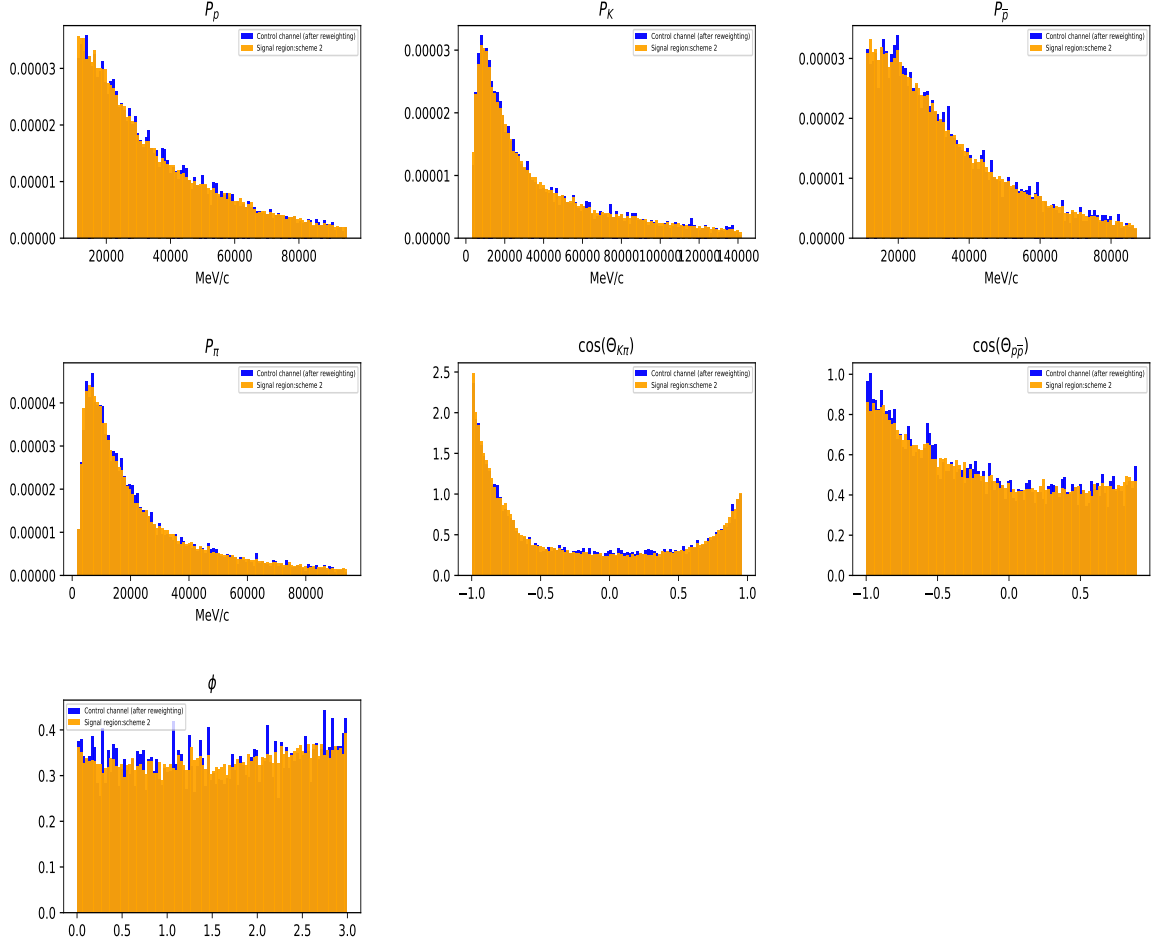


Figure 3.29: Comparison between the CP-averaged kinematic distributions of the control channel after the reweighting (blue) and those of the signal region defined by scheme 2. Every distribution contains both the signal and the background contributions

| Magnet Polarity | $\chi^2/N_{dof}$ |
|-----------------|------------------|
| Up              | 7.7/8            |
| Down            | 8.7/8            |

Table 3.25:  $\chi^2/N_{dof}$  for the control channel calculated with respect to the no CPV hypothesis represented by the blue dashed horizontal line in Fig 3.33.

could bias the measurement. The effect of the  $C_{\hat{T}}$  resolution on  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$  and  $a_{CP}^{\hat{T}-odd}$  is evaluated using Monte Carlo signal events. This is a good approximation since there is indeed a good agreement between MC sample and data for the momentum distribution of charged particle tracks. Using MC candidates, the residual distribution defined as

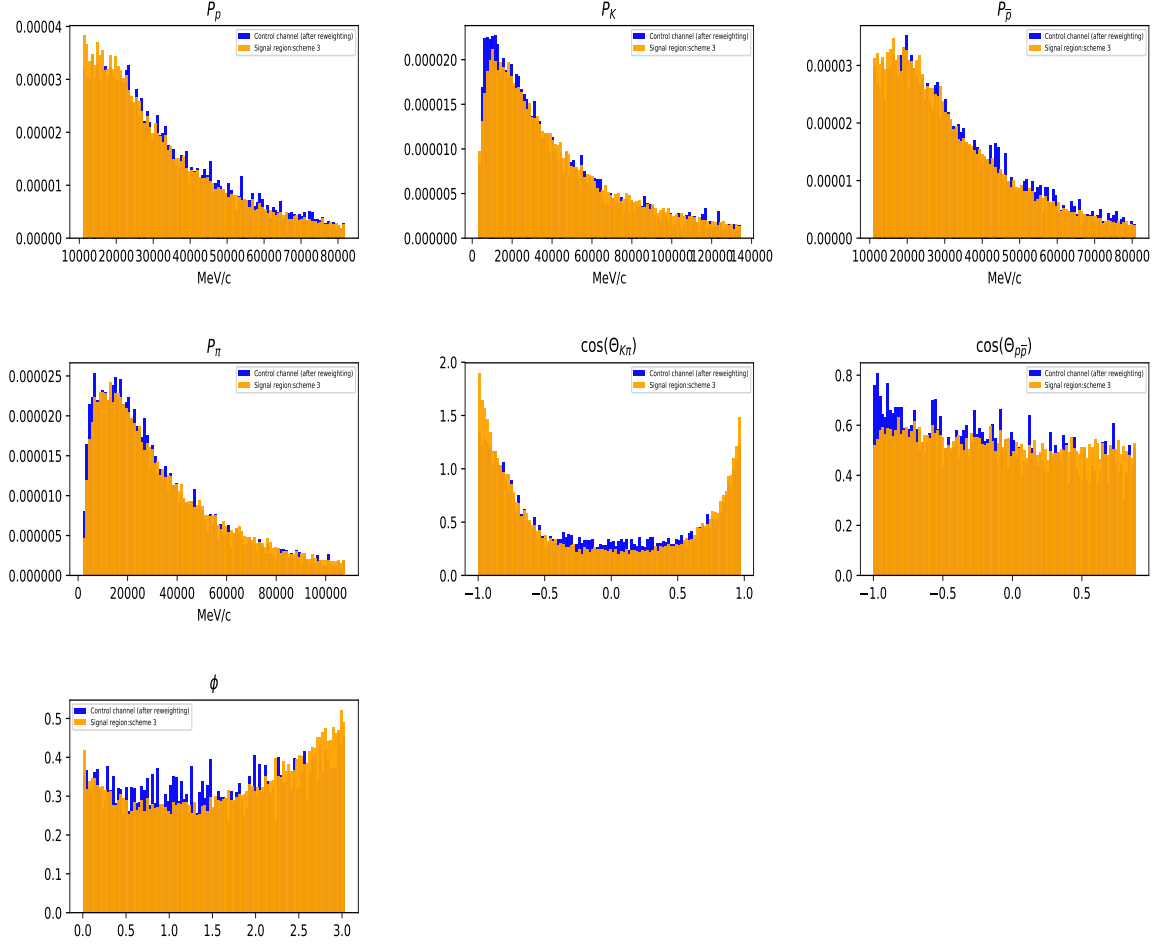


Figure 3.30: Comparison between the CP-averaged kinematic distributions of the control channel after the reweighting (blue) and those of the signal region defined by scheme 3. Every distribution contains both the signal and the background contributions

$C_{\hat{T},meas} - C_{\hat{T},true}$  is calculated, where  $C_{\hat{T},meas}$  is calculated from the momenta of the final state tracks after the reconstruction and  $C_{\hat{T},true}$  is calculated from the true momenta of the final state particles before the reconstruction. The residual distribution for  $C_{\hat{T}}$  and  $\bar{C}_{\hat{T}}$  is shown in Figure 3.34 for Run 1 and in Figure 3.35 for Run 2. Since the mean of both distributions is consistent with 0 within the statistical uncertainties we can conclude that no bias is present. The residual distribution is also plotted in bins of  $C_{\hat{T},true}$  ( $\bar{C}_{\hat{T},true}$ ) and is shown in Figure 3.36 for Run 1 and in Figure 3.37 for Run 2. Although a small bias in the reconstruction as a function of  $C_{\hat{T},true}$  ( $\bar{C}_{\hat{T},true}$ ) is present, the distribution is antisymmetric with respect to 0 and therefore the net effect is a zero bias.

The effect of the finite resolution on  $A_T$ ,  $\bar{A}_T$  and  $a_{CP}^{T-odd}$  is investigated using the MC events where no CP-violating effects are present. The asymmetries  $A_T^{true}$ ,  $\bar{A}_T^{true}$  and  $a_{CP}^{T-odd}$

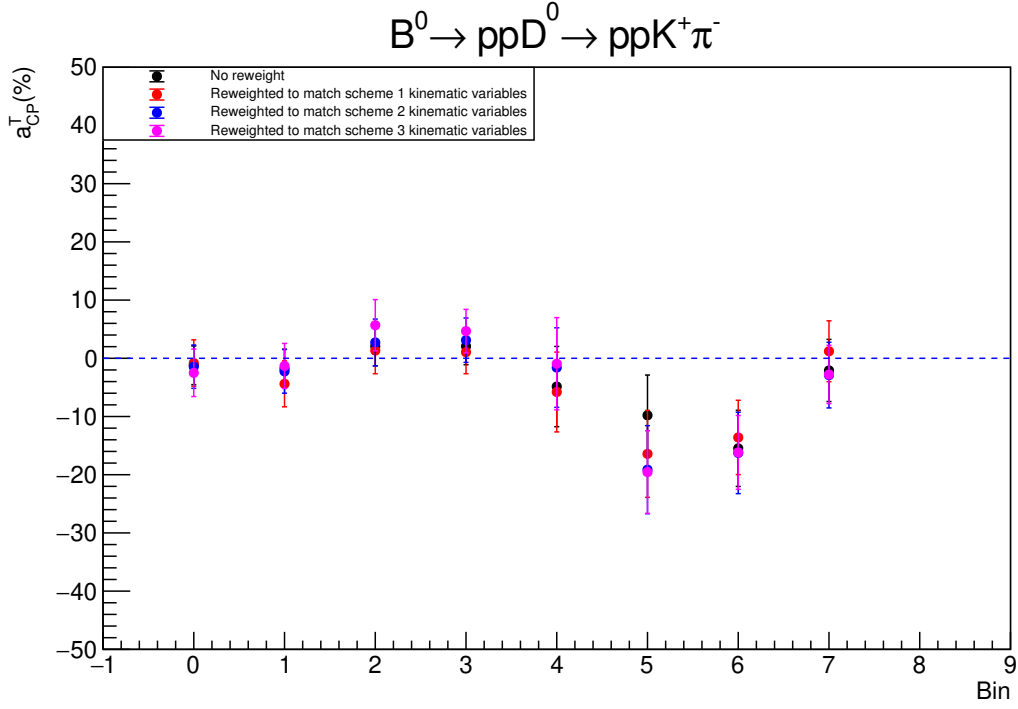


Figure 3.31: Unblinded asymmetries as a function of the nominal angular binning scheme for the control channel. This channel is expected to show negligible CP violation in the SM. The different colors correspond to the different weights applied to the data. Only statistical uncertainty is considered here.

| MC Asymmetry     | Run1                            | Run2                            |
|------------------|---------------------------------|---------------------------------|
| $A_T^{true}$     | $(2.5 \pm 4.3) \times 10^{-3}$  | $(0.04 \pm 2.8) \times 10^{-3}$ |
| $A_T^{true}$     | $(8.9 \pm 4.3) \times 10^{-3}$  | $(-0.6 \pm 2.8) \times 10^{-3}$ |
| $a_{CP}^{T-odd}$ | $(-3.2 \pm 3.1) \times 10^{-3}$ | $(0.3 \pm 2.0) \times 10^{-3}$  |

Table 3.26: Final asymmetries estimated from the MC data by splitting the data sample according to the generated flavour of the  $B^0$  and the generated  $C_T^{gen}$  sign.

are estimated by counting the number of  $B^0$  and  $\bar{B}^0$  events and splitting the two samples according to the true generated values ( $C_{\hat{T},gen}$ ). After applying the same selection of the real data to the MC data the final asymmetries, for both Run 1 and Run 2, are reported in Tab. 3.26. This table is to be compared to Tab. 3.27, where the asymmetries are calculated from the reconstructed tracks and after the whole selection. The differences between the asymmetries in these two tables, albeit negligible, are taken as a systematic uncertainty.

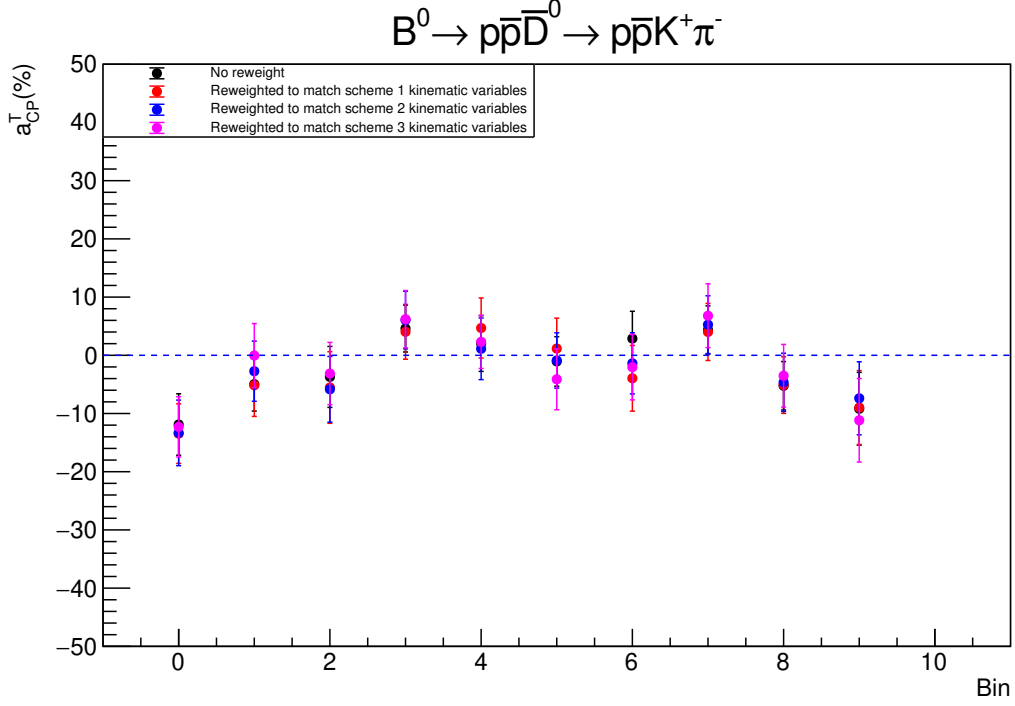


Figure 3.32: Unblinded asymmetries as a function of an angular binning scheme in which the all the bins have the same number of yields. This channel is expected to show negligible  $CP$  violation in the SM. The different colors correspond to the different weights applied to the data. Only statistical uncertainty is considered here.

| MC Asymmetry  | Run1                            | Run2                            |
|---------------|---------------------------------|---------------------------------|
| $A_T$         | $(-1.6 \pm 4.3) \times 10^{-3}$ | $(-0.5 \pm 2.8) \times 10^{-3}$ |
| $A_{\bar{T}}$ | $(5.8 \pm 4.3) \times 10^{-3}$  | $(-1.4 \pm 2.8) \times 10^{-3}$ |
| $a_T^{CP}$    | $(-3.7 \pm 3.1) \times 10^{-3}$ | $(0.4 \pm 2.0) \times 10^{-3}$  |

Table 3.27: Final asymmetries estimated from the MC data by splitting the sample according to the reconstructed  $B^0$  flavour and  $C_T^{reco}$  sign. The same selection applied to the data has been applied to the MC sample

### 3.13.3 Bias of the fit model

We check that the UML procedure using the nominal fit model gives non-biased results. This is done by generating 1500 toy MonteCarlo pseudoexperiment according to the nominal model and computing the pull distribution defined as  $\text{pull}(A) = \frac{A_{rec} - A_{gen}}{\sigma_{rec}}$  where  $A_{rec}$  is the value returned by the fit of the reconstructed asymmetry and  $\sigma_{rec}$  is the error extracted by the fit of the reconstructed asymmetry and  $A_{gen}$  is the blinded asymmetry. The number of generated events is only preliminary and is meant to show that the fit is

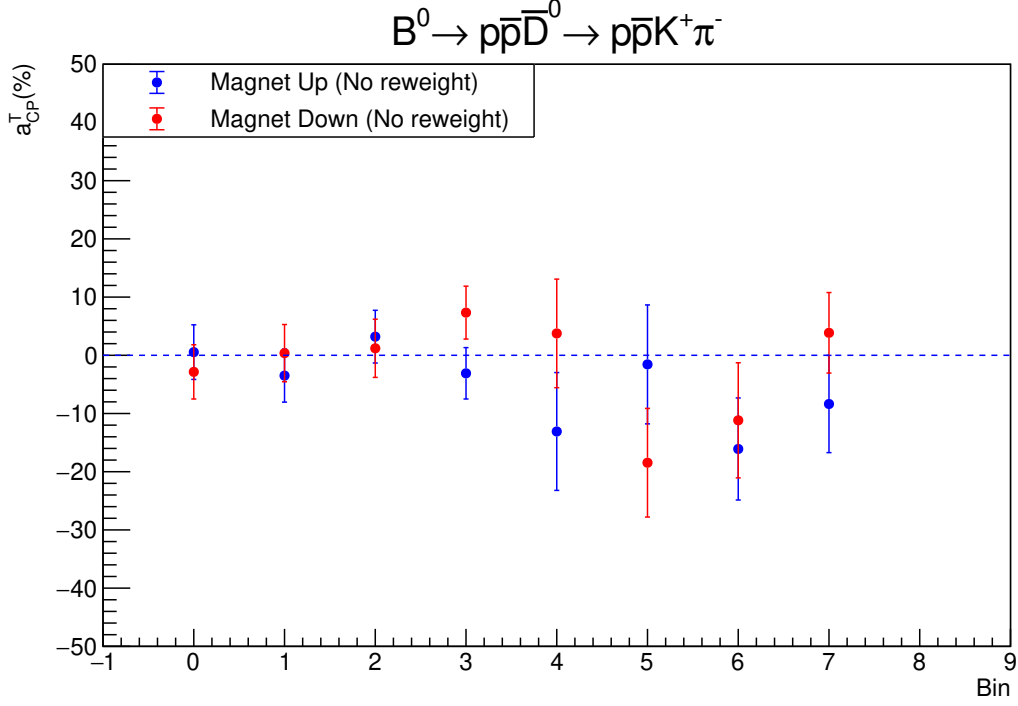


Figure 3.33: Unblinded asymmetries of the control channel as a function of the nominal angular binning scheme and split according to the magnet polarity.

stable. Indeed, the precision reached is only  $\sim 3\%$  which is comparable to the statistical precision of the fit. Once the binning scheme has been fixed, we will calculate the pulls again with a sufficient number of toy experiment. For the combined fit to Run1 and Run2 a summary for the mean and the sigma of the pull distributions are shown in Figures 3.38,3.39,3.40. The pull distributions for all the bins are shown in Appendix C.

Possible biases in the extracted  $a_{CP}^T$  and  $a_P^T$  parameters will be corrected and included in the systematic uncertainties.

## 3.14 Cross-checks

### 3.14.1 Efficiency

The effect of the selection used to enhance the signal over the background on the five variables used to describe the phase space of the decay has been checked using MC samples. The efficiency distributions, which are shown in Fig. 3.41, do not show any significant variation looking indeed flat.

In addition we check that selection efficiency does not depend on the sign of  $C_T$  ( $\bar{C}_T$ ). The ratio  $r$  of the efficiencies for positive and negative  $C_T(\bar{C}_T)$  is evaluated both using MC samples in 3.14.2 and using the control sample, directly on data. Assuming negligible CP

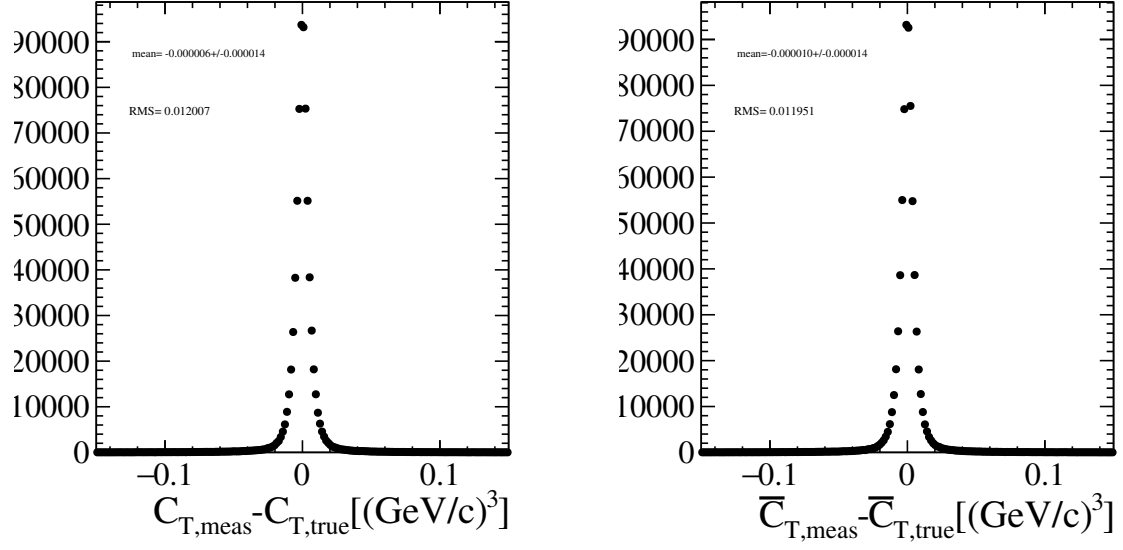


Figure 3.34: Residual distribution,  $C_{T,meas} - C_{T,true}$  and  $\bar{C}_{T,meas} - \bar{C}_{T,true}$  for MonteCarlo truth-matched signal candidates for Run1 sample.

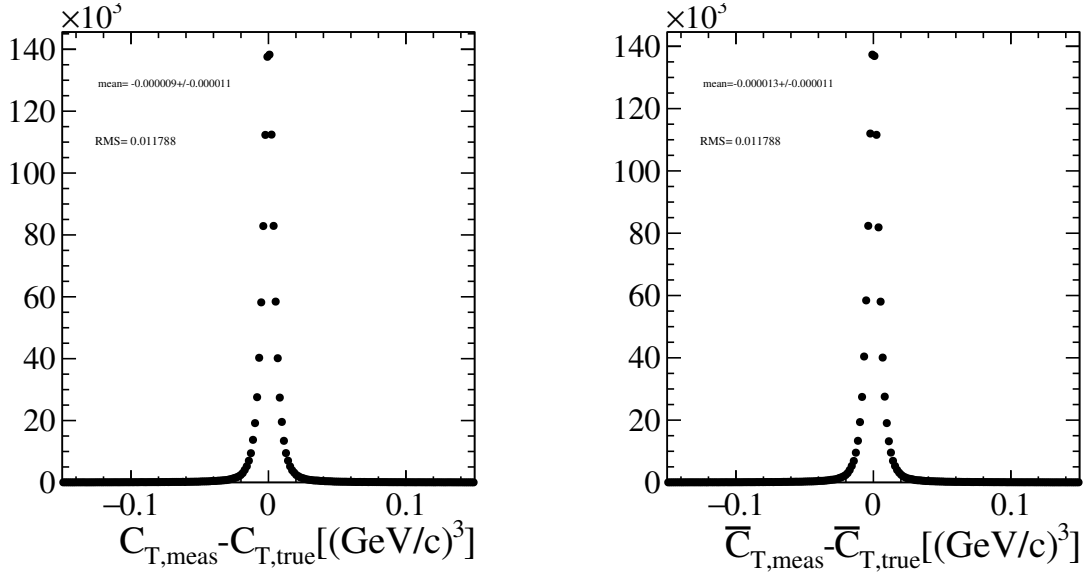


Figure 3.35: Residual distribution,  $C_{T,meas} - C_{T,true}$ , and  $\bar{C}_{T,meas} - \bar{C}_{T,true}$  for MonteCarlo truth-matched signal candidates for Run2 sample.

violation in the control sample, reconstruction efficiencies as a function of  $C_T$  are studied.

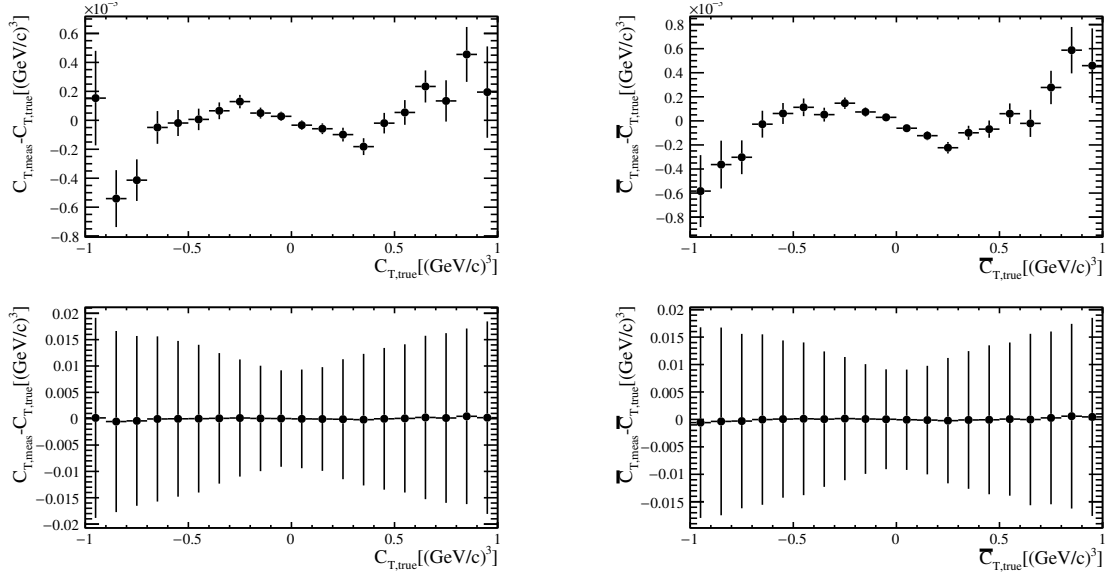


Figure 3.36: Residual distribution  $C_{\hat{T},meas} - C_{\hat{T},true}$  (left), and  $\bar{C}_{\hat{T},meas} - \bar{C}_{\hat{T},true}$  (right), as a function of  $C_{\hat{T},true}$  ( $\bar{C}_{\hat{T},true}$ ) for MC signal events for Run 1 sample. The top (bottom) plots are the mean (RMS) of the residual distribution in each bin.

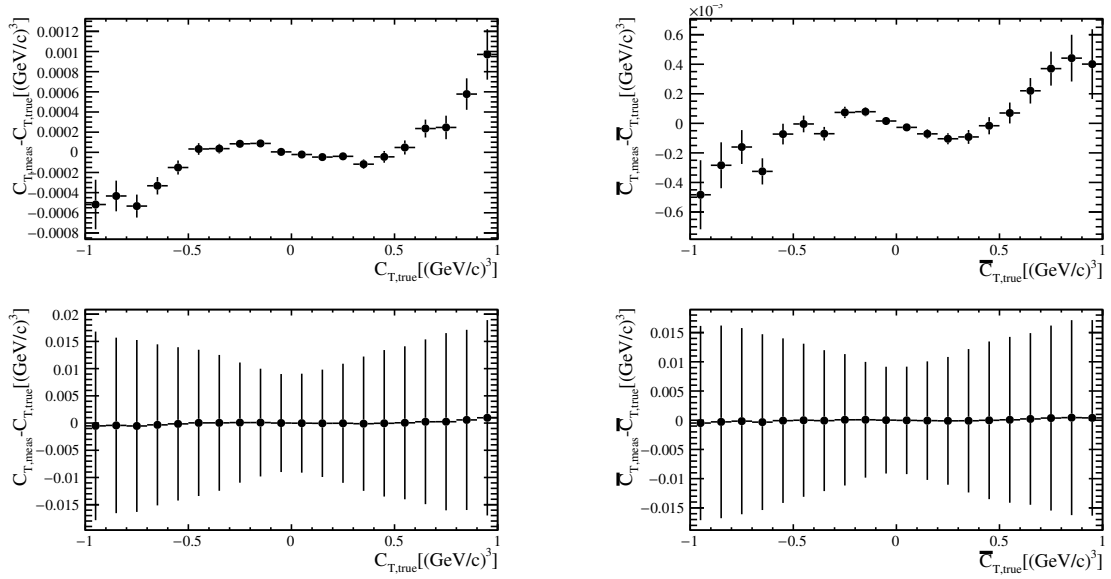


Figure 3.37: Residual distribution  $C_{\hat{T},meas} - C_{\hat{T},true}$  (lef), and  $\bar{C}_{\hat{T},meas} - \bar{C}_{\hat{T},true}$  (right), as a function of  $C_{\hat{T},true}$  ( $\bar{C}_{\hat{T},true}$ ) for MC signal events for Run 2 sample. The top (bottom) plots are the mean (RMS) of the residual distribution in each bin.



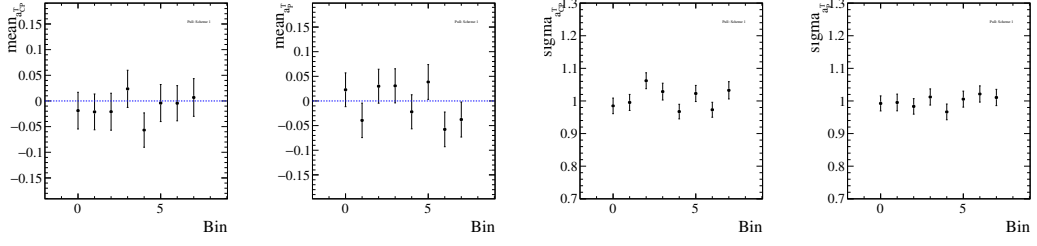


Figure 3.38: Mean and sigma extracted with a Gaussian fit to the pull distributions  $a_{CP}^T$  and  $a_P^T$  for binning scheme 1 using Run1+Run2 sample.

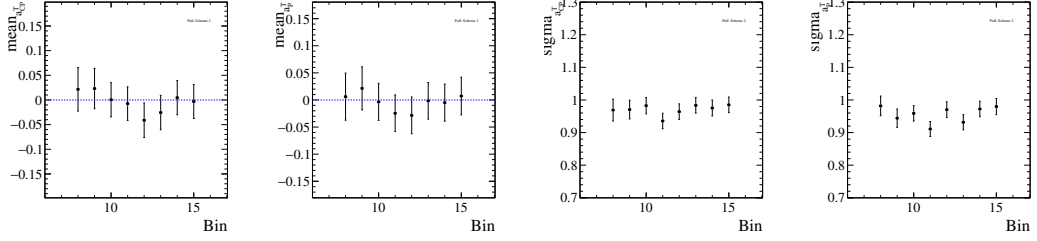


Figure 3.39: Mean and sigma extracted with a Gaussian fit to the pull distributions  $a_{CP}^T$  and  $a_P^T$  for binning scheme 2 using the combined Run1+Run2 sample.

### 3.14.2 Signal reconstruction efficiency vs $C_T$

The reconstruction efficiency as a function of  $C_T$  and  $\bar{C}_T$  is calculated using the MC data sample at three different level of the selection process: after the stripping 3.14.2.1, after the trigger 3.14.2.2 and after the offline cuts 3.14.2.3. This breakdown of efficiency is meant to show that each step of the selection does not alter the  $C_T$  distribution significantly.

#### 3.14.2.1 Stripping efficiency vs $C_T$

In order to calculate the stripping line efficiency, we applied the stripping line requirements to the truth-matched reconstructed MC sample. The resulting histograms for  $\epsilon_{strip|reco}^+$ ,

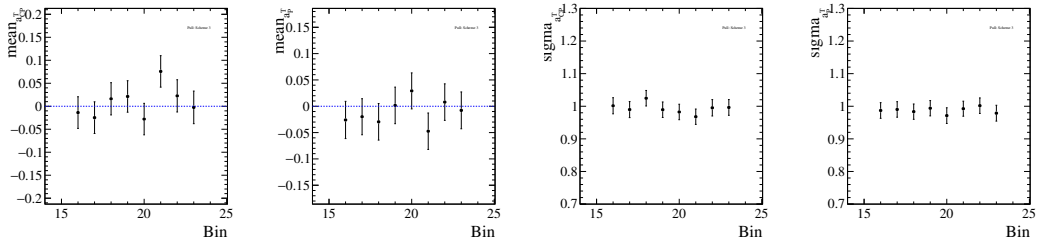


Figure 3.40: Mean and sigma extracted with a Gaussian fit to the pull distributions  $a_{CP}^T$  and  $a_P^T$  for binning scheme 3 using the combined Run1+Run2 sample.

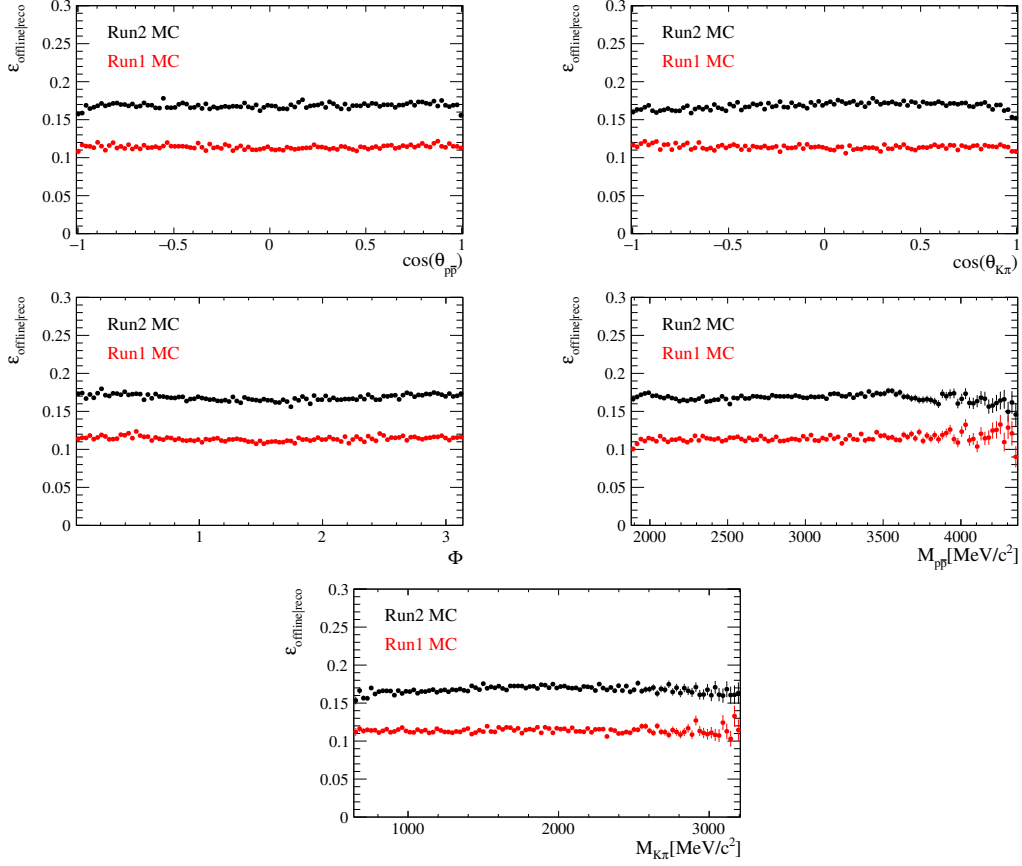


Figure 3.41: The efficiency distribution after the whole selection procedure has been applied to MC data as a function of the  $\cos(\theta_{p\bar{p}})$ ,  $\cos(\theta_{K\pi})$ ,  $\phi$ ,  $M_{p\bar{p}}$  and  $M_{K\pi}$  variables.

| Particle    | $\frac{\epsilon^+}{\epsilon^-}$ (Run1) | $\frac{\epsilon^+}{\epsilon^-}$ (Run2) |
|-------------|----------------------------------------|----------------------------------------|
| $B^0$       | $r = 0.997 \pm 0.003$<br>$Prob = 89\%$ | $r = 0.996 \pm 0.002$<br>$Prob = 71\%$ |
| $\bar{B}^0$ | $r = 0.999 \pm 0.003$<br>$Prob = 2\%$  | $r = 0.998 \pm 0.002$<br>$Prob = 35\%$ |

Table 3.28: This table shows the result of a constant fit to the ratio  $r$  of the efficiencies ( $\frac{\epsilon^+}{\epsilon^-}$ ) after the stripping selection requirements have been applied to MC data and the corresponding probability.

$\epsilon_{strip|reco}^-$  and their ratio is shown in Figure 3.42. The ratio of the efficiencies was fitted with a constant function and the result is shown in Tab. 3.28

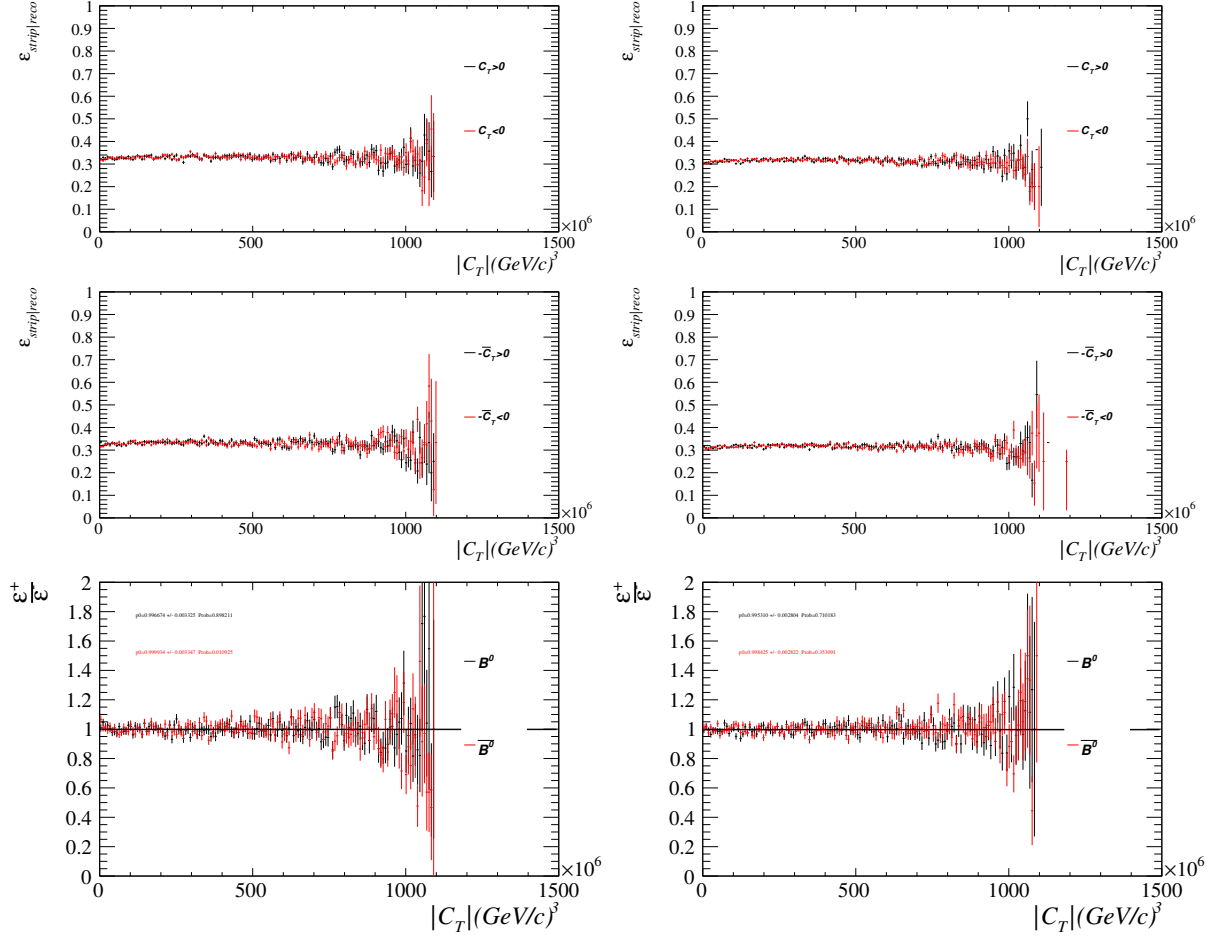


Figure 3.42: Stripping efficiency for  $C_T$  (top) and  $\bar{C}_T$  (middle) and ratio (bottom) as a function of  $C_T$  for Run1 (left) and Run2 (right).

### 3.14.2.2 Trigger efficiency vs $C_T$

The trigger efficiency  $\epsilon_{trig|strip}$  is evaluated by taking the ratio of  $\frac{N_{trig+stripping+reco}}{N_{stripping+reco}}$  i.e the ratio between the truth matched MC that have passed both the trigger and the stripping selections and the truth matched MC that have passed only the stripping selection. The resulting histograms for  $\epsilon_{trig|strip}^+$ ,  $\epsilon_{trig|strip}^-$  and their ratio are shown in Figure 3.43. The ratio of the efficiencies was fitted with a constant function and the result is shown in Tab. 3.29

### 3.14.2.3 Offline efficiency vs $C_T$

The offline cuts include the preselection (cuts on proton momenta and fiducial cuts), the veto placed around the  $\Lambda_c^-$  and  $D^0$  masses, the BDT selection and the PID cuts. The offline efficiency is evaluated by taking the ratio between the truth matched MC that have passed the trigger, the stripping and the offline selections and the truth matched MC that

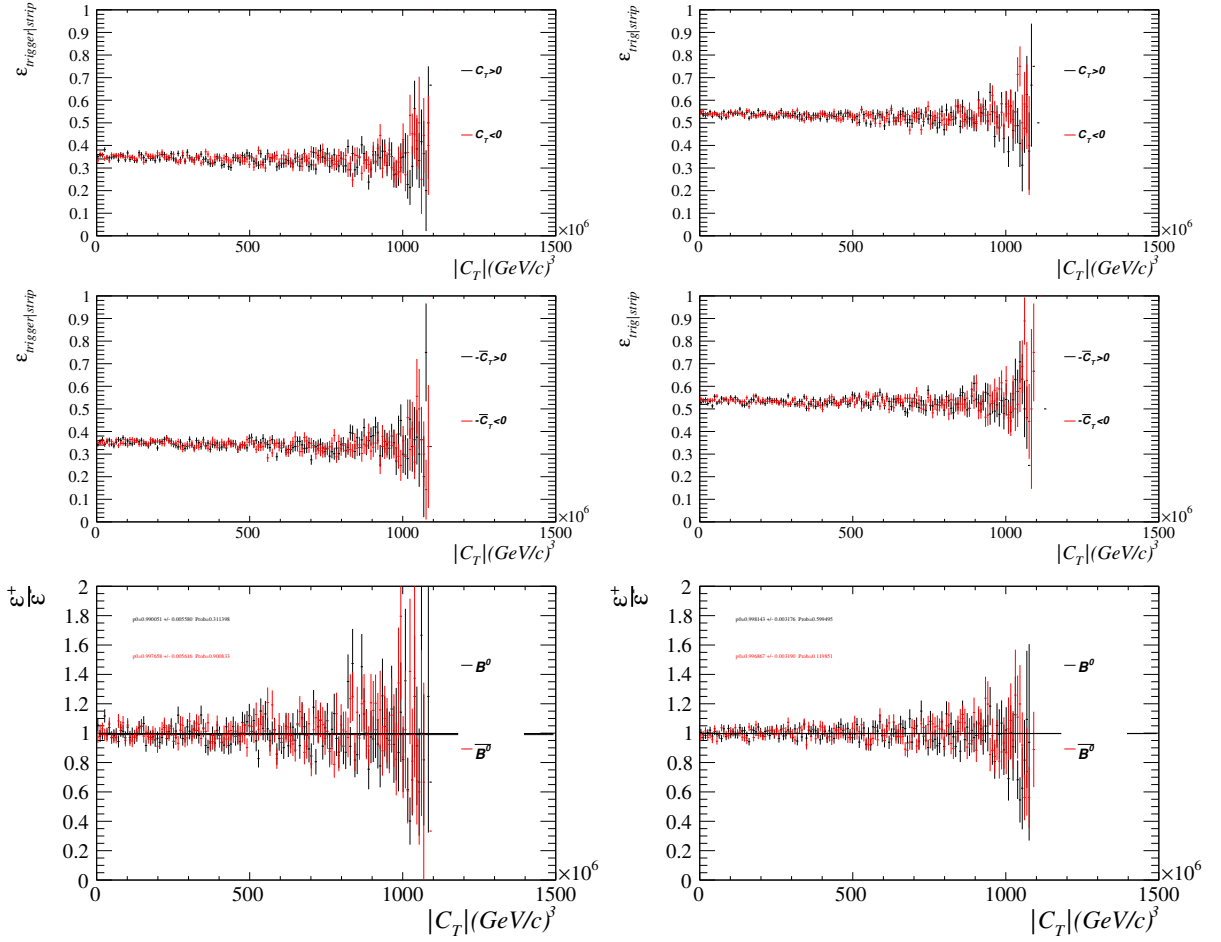


Figure 3.43: Trigger efficiency for  $C_T$  (top) and  $\bar{C}_T$  (middle) and ratio (bottom) as a function of  $C_T$  for Run1 (left) and Run2 (right).

| Particle    | $\frac{\epsilon^+}{\epsilon^-}$ (Run1) | $\frac{\epsilon^+}{\epsilon^-}$ (Run2) |
|-------------|----------------------------------------|----------------------------------------|
| $B^0$       | $r = 0.990 \pm 0.005$<br>$Prob = 31\%$ | $r = 0.998 \pm 0.003$<br>$Prob = 60\%$ |
| $\bar{B}^0$ | $r = 0.997 \pm 0.005$<br>$Prob = 90\%$ | $r = 0.996 \pm 0.003$<br>$Prob = 12\%$ |

Table 3.29: This table shows the result of a constant fit to the ratio  $r$  of the efficiencies ( $\frac{\epsilon^+}{\epsilon^-}$ ) after the trigger selection has been applied to MC data and the corresponding probability.

have passed the trigger and the stripping selection. The resulting histograms for  $\epsilon_{trig|strip}^+$ ,  $\epsilon_{trig|strip}^-$  and their ratio are shown in Figure 3.44. The ratio of the efficiencies was fitted with a constant function and the result is shown in Tab. 3.30

As expected, the efficiency does not depend on the  $C_T$  ( $\bar{C}_T$ ) sign both for particle and

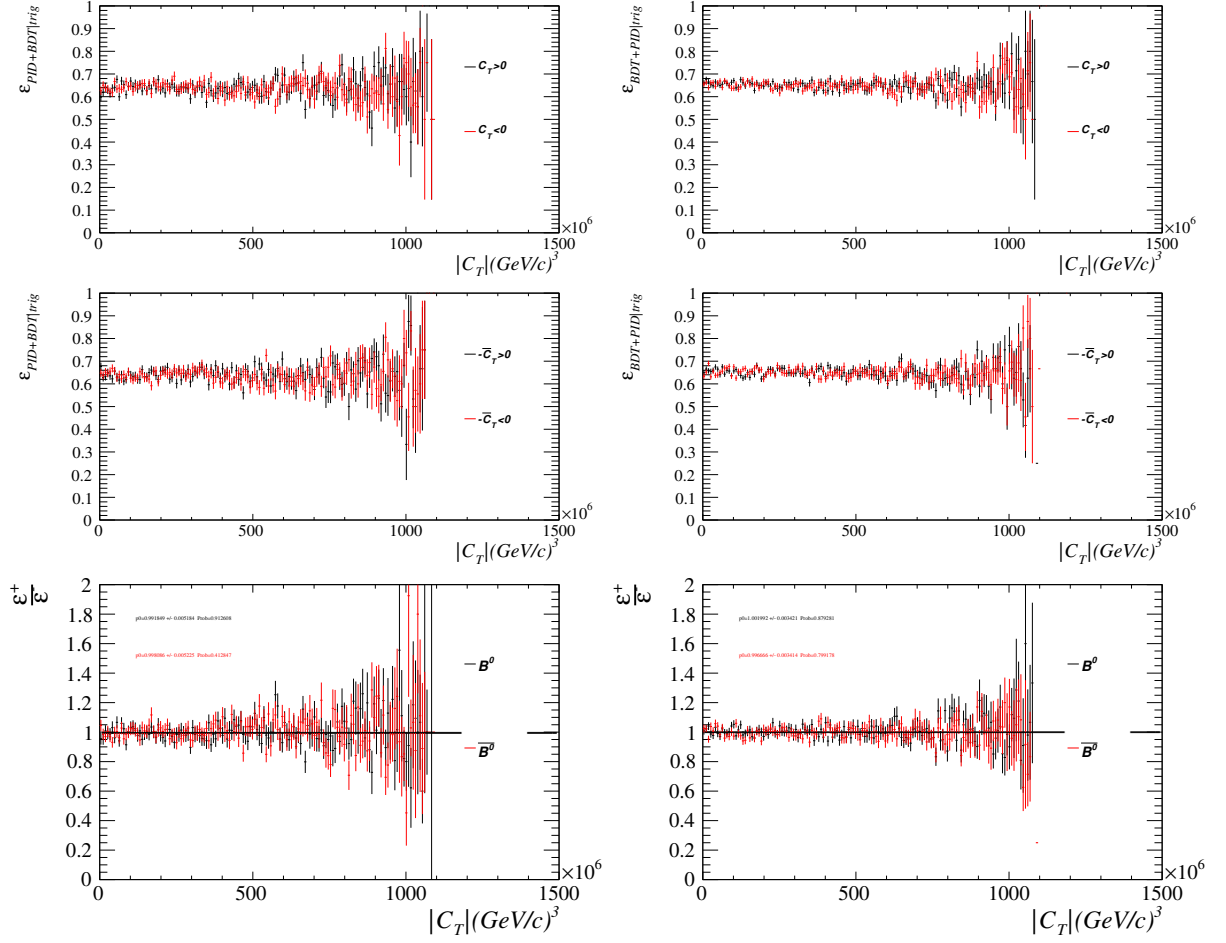


Figure 3.44: Offline efficiency as a function of  $C_T$  for Run1(left) and Run2(right)

| Particle    | $\frac{\varepsilon^+}{\varepsilon^-}$ (Run1) | $\frac{\varepsilon^+}{\varepsilon^-}$ (Run2) |
|-------------|----------------------------------------------|----------------------------------------------|
| $B^0$       | $r = 0.992 \pm 0.005$<br>$Prob = 91\%$       | $r = 1.001 \pm 0.004$<br>$Prob = 87\%$       |
| $\bar{B}^0$ | $r = 0.998 \pm 0.005$<br>$Prob = 41\%$       | $r = 0.997 \pm 0.004$<br>$Prob = 79\%$       |

Table 3.30: This table shows the result of a constant fit to the ratio  $r$  of the efficiencies ( $\frac{\varepsilon^+}{\varepsilon^-}$ ) after the offline selection has been applied to MC data and the corresponding probability.

antiparticle and their ratio is consistent with 1 within the statistical uncertainties.

| Variables                         | Correlation | error       |
|-----------------------------------|-------------|-------------|
| $C_{\hat{T}}$ vs $P_p$            | 0.007       | $\pm 0.009$ |
| $C_{\hat{T}}$ vs $P_K$            | -0.011      | $\pm 0.009$ |
| $C_{\hat{T}}$ vs $P_{\bar{p}}$    | -0.024      | $\pm 0.009$ |
| $C_{\hat{T}}$ vs $P_{\pi}$        | -0.006      | $\pm 0.009$ |
| $C_{\hat{T}}$ vs $\eta_p$         | -0.011      | $\pm 0.009$ |
| $C_{\hat{T}}$ vs $\eta_K$         | 0.003       | $\pm 0.009$ |
| $C_{\hat{T}}$ vs $\eta_{\bar{p}}$ | 0.0006      | $\pm 0.009$ |
| $C_{\hat{T}}$ vs $\eta_{\pi}$     | 0.0068      | $\pm 0.009$ |
| $C_{\hat{T}}$ vs ProbNN $p$       | 0.032       | $\pm 0.009$ |
| $C_{\hat{T}}$ vs ProbNN $K$       | 0.008       | $\pm 0.009$ |
| $C_{\hat{T}}$ vs ProbNN $\bar{p}$ | -0.00015    | $\pm 0.009$ |
| $C_{\hat{T}}$ vs ProbNN $\pi$     | 0.009       | $\pm 0.009$ |
| $C_{\hat{T}}$ vs BDT              | -0.0018     | $\pm 0.009$ |

Table 3.31: Linear correlation between  $C_{\hat{T}}$  and some of the kinematic variables used in the selection.

### 3.14.3 Check of the correlations

Correlations between  $C_T$  and  $\bar{C}_T$  and the relevant variable used for the selection criteria including the BDT output variable are studied. Correlations between  $C_T$  and BDT output variable, daughters momenta, daughters pseudorapidity and ProbNN variables have been checked on the control channel  $B^0 \rightarrow p\bar{p}\bar{D}^0$  and are shown in Figure 3.45. The 2D distributions have been reweighted using the sWeights extracted from the fit to the  $m_{p\bar{p}K^+\pi^-}$  invariant mass distribution. The linear correlations between  $C_{\hat{T}}$  and some kinematic variables are reported in Tab 3.31. The statistical error assigned to the correlation coefficient  $r$  was computed using the Fisher transformation  $F(r)$ :

$$F(r) = \frac{1}{2} \ln \left( \frac{1+r}{1-r} \right) \quad (3.23)$$

$F(r)$  follows approximately a normal distribution with mean  $\mu = \frac{1}{2} \ln \left( \frac{1+r}{1-r} \right)$  and standard deviation  $\sigma = \frac{1}{\sqrt{n-3}}$ , where  $n$  is the number of entries. In our case the control sample  $B^0 \rightarrow p\bar{p}\bar{D}^0$  contains  $\sim 12500$  events. By applying the inverse Fisher transformation to the formula of the standard deviation one obtains the statistical uncertainty for the correlation coefficient  $r$ . As one can see the correlations are consistent with 0 within the statistical uncertainty.

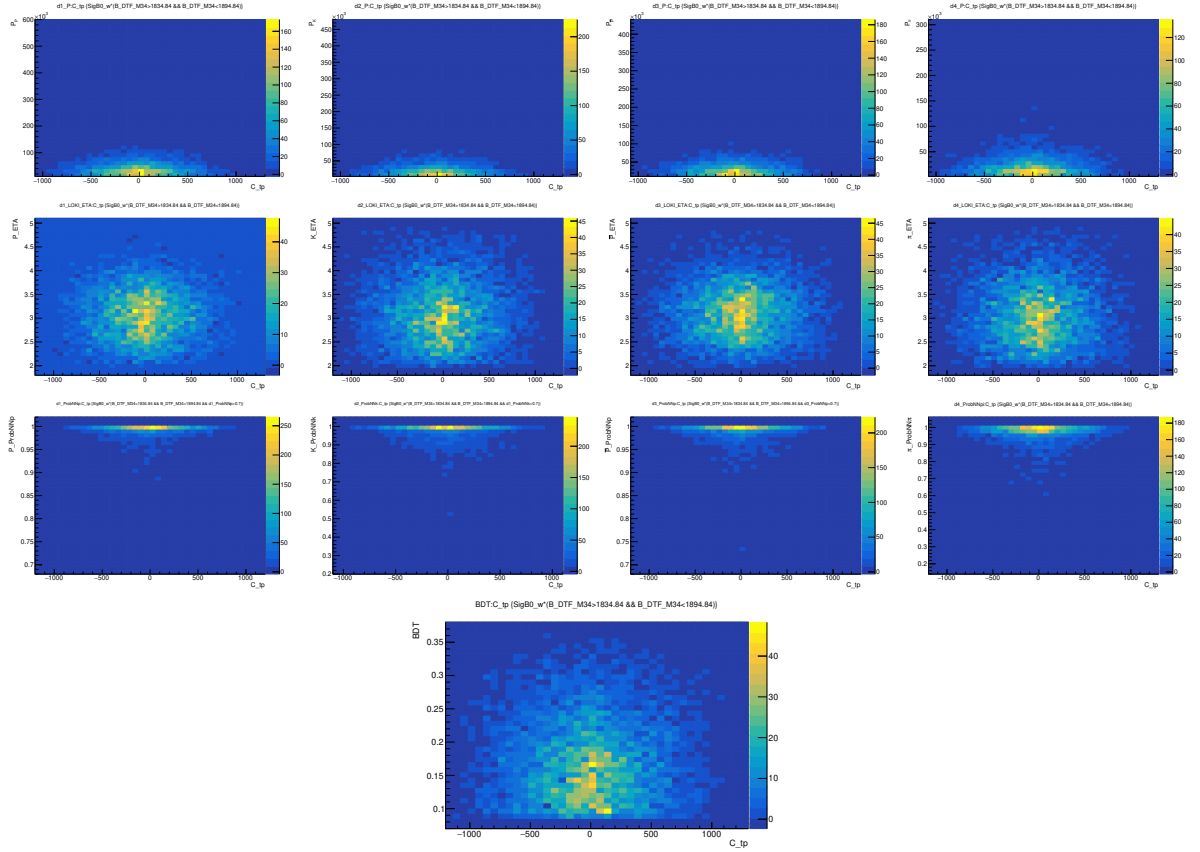


Figure 3.45: Run2 correlations between  $C_T$  and daughters momenta (top), daughters pseudorapidity (middle-top), ProbNN variables (middle-bottom) and BDT output variable (bottom) obtained by applying the sWeights to the data.

### 3.15 Summary of the systematic uncertainties

This section gives a summary of the main contributions to the overall systematic uncertainty. The numbers presented here are still preliminary and some of the contribution have been estimated using MC toys with limited statistics. A bigger statistics will be used once the measurements have been unblinded. Unfortunately the statistical precision of the phase space asymmetry of the control channel, which was used to estimate the experimental bias, is limited and is at the same level of the statistical precision reached in the measurement of the asymmetry integrated over the whole charmless region. The asymmetry of the control channel was also measured in regions of the phase space, using two different binning schemes, to check whether any local departure from the  $CP$  symmetry is present. Moreover, the kinematic of the control channel was reweighted to match that of the three signal region in order to find any deviation due to different kinematics. As expected, the asymmetries measured before and after the reweighting procedure are in excellent agreement with a negligible difference compared to the statistical precision. For this reason we conservatively assign the integrated asymmetry of the control channel as a

systematic uncertainty to the experimental bias. The systematic related to the detector resolution on  $A_{\hat{T}}, A_{\hat{T}}, a_{CP}^{T-odd}$  and  $a_P^{T-odd}$  was estimated with a MC sample, as it reproduces well momentum resolution for charged particle tracks. We measured the asymmetries by counting the number of  $B^0$  and  $\bar{B}^0$  events after splitting them according to generated  $C_{\hat{T}}$  and  $\bar{C}_{\hat{T}}$  and then according to the reconstructed values of  $C_{\hat{T}}$  and  $\bar{C}_{\hat{T}}$  and the difference is assigned as a systematic uncertainty. The difference was found to be  $\sim 0.01\%$  and an error of  $0.01\%$ , albeit negligible, was assigned as a systematic uncertainty. The systematic uncertainty related to the maximization of the likelihood was estimated using 1500 toy MC pseudoexperiment reaching a precision of  $\sim 3\%$ . Once the results have been unblinded a toy MC with at least 10000 will be used to reduce the statistical uncertainty on the pull below 1%. The measured asymmetries will be then corrected with the results of the pulls, if necessary. The systematic uncertainties related to the choice of model for the signal and background components of the fits will be evaluated by using alternative models that have comparable fit quality. The sources of systematic uncertainty and their relative contributions are listed in Tab. 3.32.

| Contribution                        | $a_{CP}^{T-odd}(\%)$ | $a_P^{T-odd}(\%)$ |
|-------------------------------------|----------------------|-------------------|
| Experimental bias (control channel) | 1.5                  | 1.5               |
| $C_T$ resolution                    | 0.01                 | 0.01              |
| Fit model (preliminary)             | $< 0.1$              | $< 0.1$           |
| Pull (preliminary)                  | 3                    | 3                 |

Table 3.32: Sources of systematic uncertainty and their relative contributions to the total uncertainty.

## 3.16 Conclusions

In this thesis a search for  $CP$  violation with the method of triple product asymmetries in the charmless baryonic  $B$  meson decay  $B^0 \rightarrow p\bar{p}K^+\pi^-$  using data collected by the LHCb experiment is reported. Contrary to direct  $CP$  asymmetry, a non-zero triple-product asymmetry needs only a weak phase difference to be produced; no strong phase differences between interfering amplitudes is required, resulting thus in a different sensitivity to  $CP$  effects. The charmless region of this decay is mediated by the weak interaction and governed mainly by two amplitudes describing quark-level tree  $b \rightarrow u\bar{u}s$  and penguin  $b \rightarrow s\bar{u}u$ .  $CP$  violation could arise here from the interference of these two amplitudes whose weak phase difference is given by  $\arg(\frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*})$ , which in the Standard Model is dominated by the CKM angle  $\gamma$ .

This analysis used  $3\text{ fb}^{-1}$  of data collected in 2011 and 2012 at  $\sqrt{s}=7, 8\text{ TeV}$  and  $6\text{ fb}^{-1}$  of data collected during 2016, 2017 and 2018 at  $\sqrt{s}=14\text{ TeV}$ . Thanks to the excellent performance of the LHCb detector and of its PID system this translated into about 14072  $B^0$  in Run 1 and about 56055  $B^0$  in Run 2 after the whole selection procedure. Two different approaches have been followed in order to exploit the full potential of the data



sample: a measurement integrated over the phase space and measurements in bins of phase space to search for local  $CP$  violations. In particular, three regions have been defined:

- **scheme 1:** Charmless region ( $m_{p\bar{p}} < 2.85 \text{ GeV}/c^2$ ) and dominated by the  $K^*(892)$  resonance in the  $K^+\pi^-$  spectrum ( $m_{K^+\pi^-} < 1200 \text{ GeV}/c^2$ )
- **scheme 2:** Charmless region ( $m_{p\bar{p}} < 2.85 \text{ GeV}/c^2$ ) and region in the  $m_{K^+\pi^-}$  spectrum where many resonances interfere ( $m_{K^+\pi^-} \in [1200, 2200]$ )
- **scheme 3:** Charmless region ( $m_{p\bar{p}} < 2.85 \text{ GeV}/c^2$ ) and dominated by the  $K_5^*(2380)$  resonance in the  $K^+\pi^-$  spectrum ( $m_{K^+\pi^-} > 2200 \text{ GeV}/c^2$ )

Each scheme is divided in further divided in 8 bins: 2 for the variable  $\cos\theta_{p\bar{p}}$ , 2 bins in  $\cos\theta_{K^+\pi^-}$ , 2 bins in  $\phi$  to reduce potential dilution of the asymmetry.

Thanks to the increased signal yields in Run 2, about a factor 4 with respect to Run 1, a sensitivity of  $< 1\%$  in  $a_{CP}^{T-odd}$  for the integrated asymmetry when combining  $9 \text{ fb}^{-1}$  of data is reached. On the other hand, the statistical sensitivity reached in the different bins is  $\sim 5\%$  instead. The systematic uncertainty have been estimated to be  $\sim 1.5\%$  using a charmed control channel.

The results presented in this thesis are still blinded as the analysis is currently under review by the LHCb Collaboration.

After the start of Run 3, with the LHCb detector having been upgraded to cope with a five-fold increase in the instantaneous luminosity as described in Section 4, the available statistics will increase considerably. In particular, thanks to the removal of the L0 hardware trigger and the implementation of a new flexible software trigger, decay modes with fully hadronic final state, like  $B^0 \rightarrow p\bar{p}K^+\pi^-$  for instance, will profit considerably of the new strategy. In fact, according to sensitivity studies performed by the LHCb Collaboration [69], channels selected at the hardware level by hadron, photon or electron triggers during Run 1 and Run 2 are expected to have their efficiencies double from Run 3. This, combined with the expected overall improvement in the detector performance, would translate in a factor  $\sim 4 - 5$  increase in the statistical precision expected for the end of Run 4 when  $50 \text{ fb}^{-1}$  of data will have been collected.

## Chapter 4

# The Upgrade I phase of the LHCb detector

During Run 1 and Run 2, the LHCb experiment successfully performed a large number of high precision measurements in heavy flavour physics using up to  $9 \text{ fb}^{-1}$  of data collected at center-of-mass energies of  $\sqrt{s} = 7, 8$  and  $13 \text{ TeV}$ , demonstrating the potential of flavour physics as a place to look for phenomena Beyond Standard Model. Indeed, small tensions with the SM have already appeared in some of the analyzed channels. However, many of the measurements are still limited by statistics and the limit of  $\sim 2 \text{ fb}^{-1}$  of data collected per year cannot be overcome without upgrading the detector. The goal of collecting up to  $\sim 8 \text{ fb}^{-1}$  per year can be reached with the removal of the L0 hardware trigger combined with a highly flexible software-based triggering strategy that will lead to increased efficiencies, especially in decays of particles to hadronic final state. The current limitations caused by the L0 trigger stage are shown in Fig. 4.1. The physics scope after the Upgrade I extends beyond that of flavour, and includes searches for Majorana neutrinos, exotic Higgs decays and precision electroweak measurement [69].

For this reason, the LHCb experiment will undergo in 2020 a major upgrade during the Long Shutdown 2 (LS2) of the LHC, with the aim to collect  $50 \text{ fb}^{-1}$  of data by the end of Run 4 in 2028, as shown in Fig. 4.2. To achieve this goal the LHCb detector readout rate will be upgraded from the current rate of  $1 \text{ MHz}$  to the rate of  $40 \text{ MHz}$  [70], [71]. The instantaneous luminosity delivered to the experiment will increase by a factor five to  $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ . In order to cope with the increased luminosity and readout rate, all the sub-detectors will be upgraded and the selection of events will be uniquely performed by a software trigger, improving the trigger efficiencies. Apart from the changes in the sub-detectors front-end electronics (FE) required by the new trigger strategy described in Section 4.1, the increased luminosity implies that other challenges need to be faced: higher occupancies, an increased pile-up and a harsher radiation environment. This means that detectors with higher granularities and an improved radiation tolerance with respect to the current LHCb detector are needed. The layout of the upgraded LHCb detector is shown in Fig. 4.3.

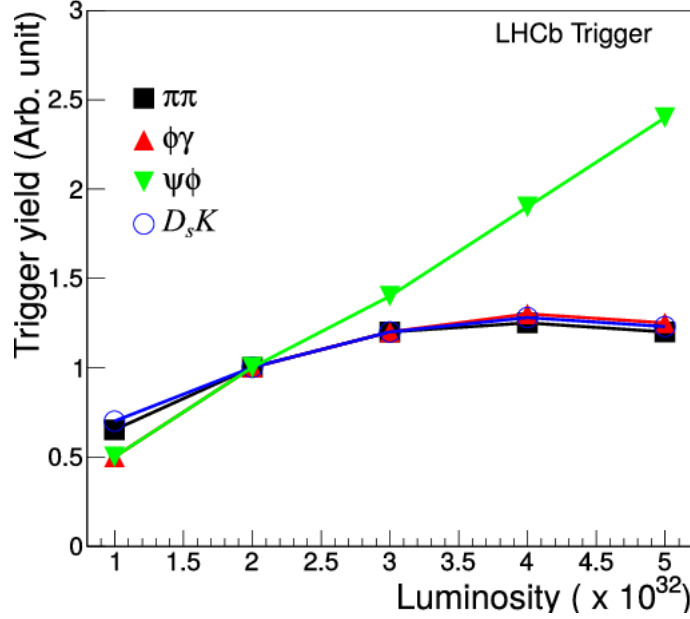


Figure 4.1: Dependence of the L0 trigger yield on the instantaneous luminosity for different types of decays. The green curve represents the trigger yields with muons in the final state whereas the blue, red and black curves represent the trigger yields with hadrons in the final state. One can see that for decays involving muons the trigger yields increases linearly with luminosity while it saturates for decays involving hadrons in the final state.

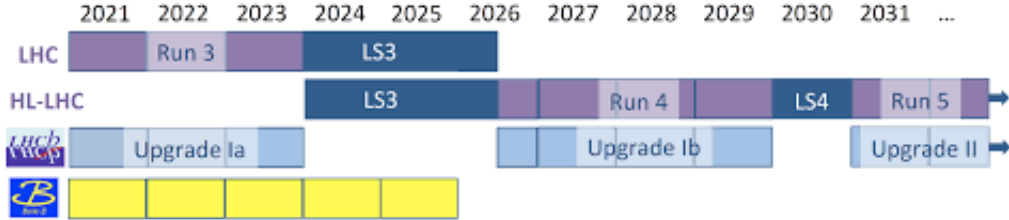


Figure 4.2: The LHCb upgrade time schedule. From the beginning of Run 3 till the end of Run 4 the experiment will run at an instantaneous luminosity of  $2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ . A further jump in luminosity will take place from the start of Run 5.

## 4.1 The new trigger architecture

The old trigger architecture, described in detail in Section 2.3, is the main limiting factor that doesn't allow to take full advantage of the expected increase in luminosity. In the upgraded detector the new readout architecture will be implemented as a trigger-less system, where the full detector information at the inelastic event rate of 30 MHz will be used in a flexible high level software trigger, as shown in Fig. 4.4. In the upgraded readout architecture [72], all Front-End (FE) electronics record and transmit data continuously at 40

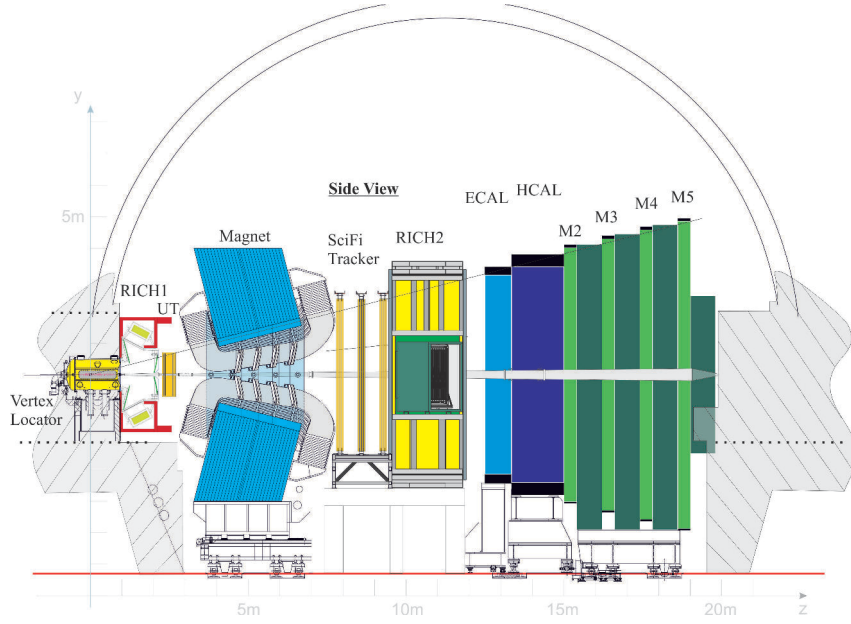


Figure 4.3: Layout of LHCb with the upgraded detectors.

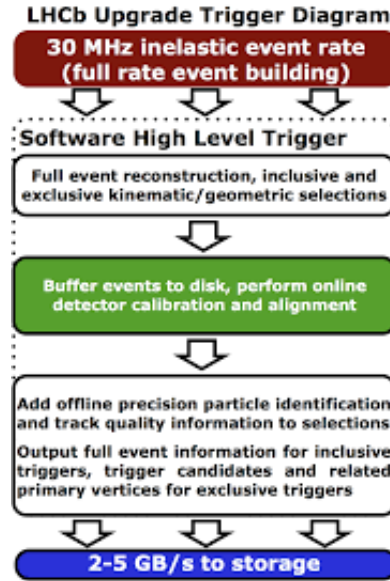


Figure 4.4: The upgraded architecture of the new LHCb trigger system.

MHz to the Readout Boards, called TELL40, with and zero-suppression performed directly at the FE level. Because of zero-suppression the FE data are transmitted asynchronously to the TELL40 and the synchronicity between the two systems is ensured by tagging the event with an identifier, the Bunch Crossing ID (BXID). Once all the fragments with the same BXID are received by the Readout Board, it will create a packet (Multi-Event

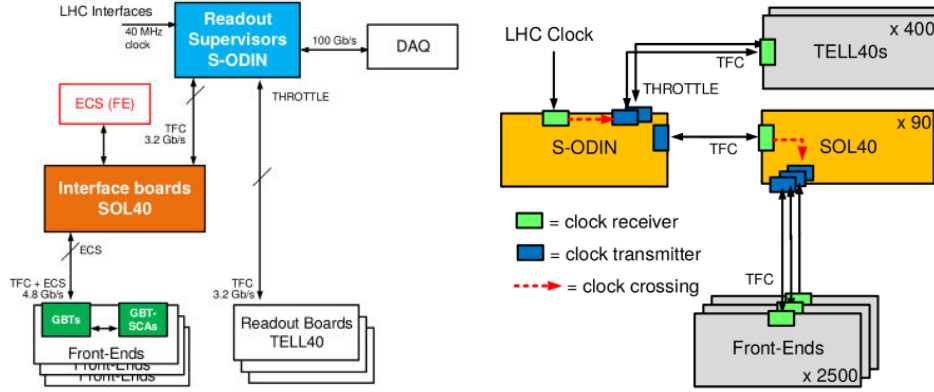


Figure 4.5: Logical architecture of the upgraded TFC system (left) and clock distribution paths in the upgraded LHCb readout architecture (right).

Packet, MEP) and send it to a particular processing node via the event-building network. The synchronicity is ensured by the upgraded Timing and Fast Control System (TFC) [73] shown in Fig. 4.5; this system takes care of distributing timing information, clock and fast commands to the Readout Boards as well as to the FE electronics. At the FE, the synchronous fast control information are decoded and fanned out by a GBT Master chip located in every FE board, which is also responsible for the distribution of the clock. The slow control information is managed by the GBT-SCA chip, which distributes the ECS configurations to the FE. Monitoring data is sent back to the corresponding SOL40 on the same optical link. The hardware backbone of the entire readout architecture is a PCIe card hosted in a commercial PC.

## 4.2 The upgraded tracking system

### 4.2.1 The new VELO

The current VELO detector (described in Section 2.1) will be replaced by new 26 tracking stations based on  $55 \times 55 \mu\text{m}^2$  hybrid pixel sensors [74]. Similar to the current VELO, each tracking station of the new VELO will consist of two modules that can be moved away from the interaction region during beam injection and as close as 5.1 mm from the beam axis when the beam is stable. The material budget will be lowered down to 1.7% radiation lengths from the current 4.6% thus improving the impact parameter resolution by  $\sim 40\%$ . The improved resolution on the position will increase the tracking efficiency of low momentum charged particles and will allow to have a better decay time resolution. In order to limit the radiation damage, an innovative microchannel two-phase  $\text{CO}_2$  cooling technology was designed to keep the sensors at the working temperature of  $-20^\circ\text{C}$ . A sketch of the new VELO is shown in Fig. 4.6.

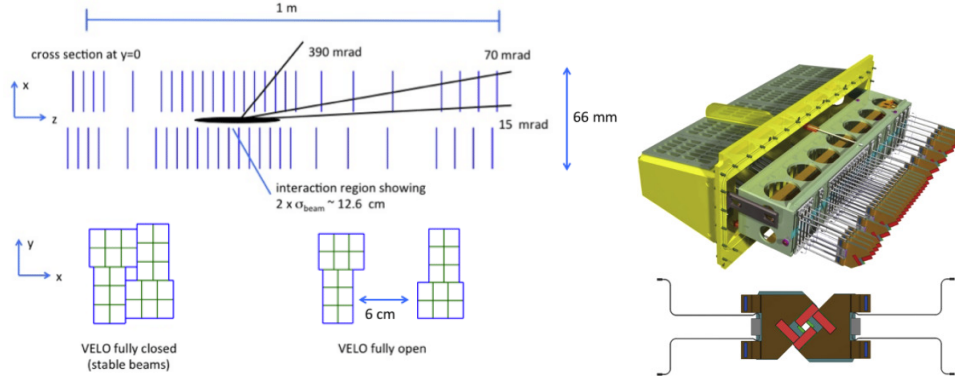


Figure 4.6: Left: The 26 tracking stations of the new VELO as seen from the bending plane. Right: 3D sketch of the upgraded VELO detector.

### 4.2.2 The Upstream Tracker

The new UT detector [75] has four planes (UTaX, UTaU, UTbV, and UTbX) of silicon strip sensors as shown in Fig. 4.7. The silicon sensors will have finer granularity compared to the ones used in the TT. Sensor strips are vertical in order to have precise measurement in the bending direction of the charged tracks. The two planes in the middle, UTaU and UTbV, are tilted by  $\pm 5^\circ$  with respect to the first and the last plane. Every plane is divided into 1317 mm long staves, on top of which the silicon sensors are mounted. The planes UTaX and UTaU are made of 16 staves whereas the planes UTbV and UTbX are made of 18 staves. The UT uses four different types of silicon sensors technology. The sensors closer to the beam pipe will have 49 mm long strips with a  $95 \mu\text{m}$  pitch. The sensors in the central region will have 99.7 mm long strips and  $95 \mu\text{m}$  pitch while those in the outer region will have 99.7 mm long strips with  $190 \mu\text{m}$  pitch. The material budget is reduced with respect to the current TT detector.

### 4.2.3 The SciFi Tracker

The SciFi Tracker detector [75] will be located between the LHCb magnet and RICH2 and will replace both the IT and OT detectors. It will consist of three stations, T1, T2 and T3, each of which is composed of four detection layers with a  $x-u-v-x$  geometry, as shown in Fig. 4.8. This arrangement provides an excellent single hit resolution in the horizontal direction ( $< 100 \mu\text{m}$ ) and information on the vertical hit position. Scintillating fibres with a length of 2.4 m and a diameter of  $250 \mu\text{m}$  will be the active material of this detector and will be read out by arrays of state-of-the-art Silicon Photomultipliers (SiPM) placed at the top and at the bottom of the detector layers. Due to their high dark count rate at ambient temperature and their susceptibility to radiation damage, SiPMs will be cooled at the temperature of  $-40^\circ\text{C}$ .

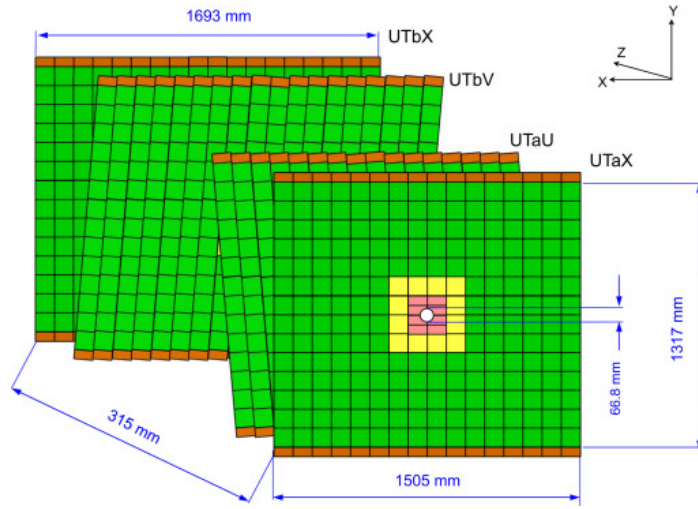


Figure 4.7: Sketch of the four planes of the new Upstream Tracker.

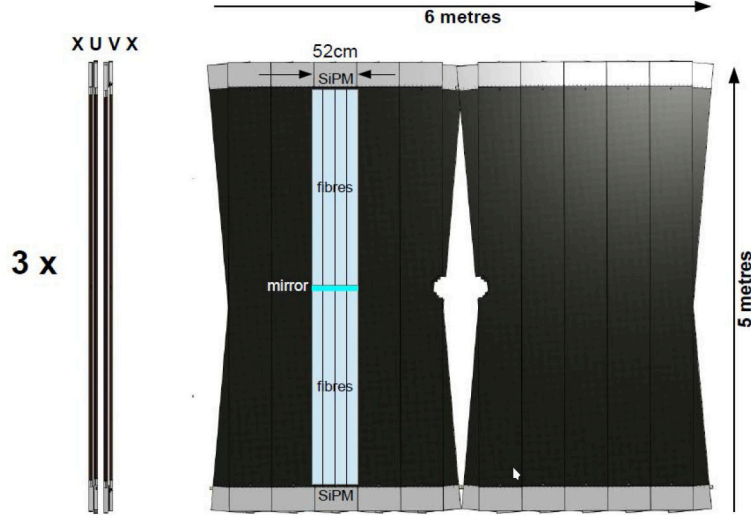


Figure 4.8: Sketch of the new SciFi tracker

### 4.3 The upgraded PID system

The calorimeter and muon systems [76] will undergo minor upgrades with respect to the other subdetectors. The PS, SPD and M1 detectors, used in Run 1 and Run 2 by the L0 level trigger stage, will be removed along with the L0 trigger itself. The FE electronics of the calorimeters will be modified and adapted new readout system and the PMTs will have their gain reduced. The muon system will see the addition of a shielding in front of M2 and the replacement of the entire readout electronics. The RICH detector will undergo significant changes for the upgrades instead [76]; the upgrade comprises the replacement of HPDs with multianode photomultipliers (MaPMTs), a new external frontend electronics



able to work at 40 MHz and a re-arrangement of the focusing optics.

### 4.3.1 The upgrade of the RICH detectors

During the Run1 and Run2 phase some regions of the photon detector array in RICH1 reached occupancies of up to 30%. Occupancy is defined as the fraction of detected photons over the total number of channels; the 30% value for the occupancy is seen as an upper limit beyond which the particle identification performance of the RICH starts to deteriorate. In order to maintain the average occupancy of the old RICH detector in the upgraded configuration where the luminosity increases by a factor five some minimal changes in the optical system are required [77]. This is accomplished by increasing the focal length of the spherical mirror by a factor  $\sqrt{2}$ , from 2710 mm to 3650 mm, and moving the photo detector plane further away from the beam line as shown in Fig. 4.9. Moreover, a slight re-arrangement of the spherical mirror configuration as shown in the same figure allows to decrease the emission point uncertainty and, consequently, improve the overall resolution of the Cherenkov emission angle. The Cherenkov radiators will remain the same:  $C_4F_{10}$  in RICH1 and  $CF_4$  in RICH2. In order to adapt the RICH system to the new trigger system, the HPD detectors with embedded readout electronics limited to 1 MHz will be replaced; Multi-anode Photomultipliers (MaPMTs) with external readout electronics will be used instead. The mechanics housing the photodetectors arrays was also re-designed for both RICH1 and RICH2. The upgraded photodetector system is described in Section 4.3.1.1.

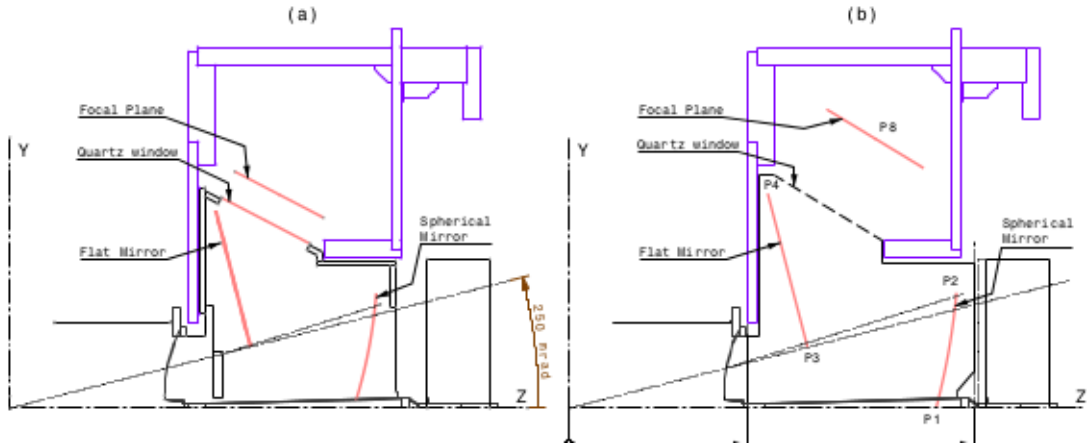


Figure 4.9: Left: The optical geometries of the current RICH1. Right: The optical geometry of the upgraded RICH1. Note that in the upgraded configuration the photodetector plane (focal plane) is moved further away from the beam-line to take advantage of the increased focal length of the spherical mirrors.

#### 4.3.1.1 The upgraded photodetector system

The photodetecting unit used in the upgrade consists of a  $8 \times 8$  pixel MaPMT produced by Hamamatsu Photonics [78]. It features a 12-dynode amplification stage with a nominal



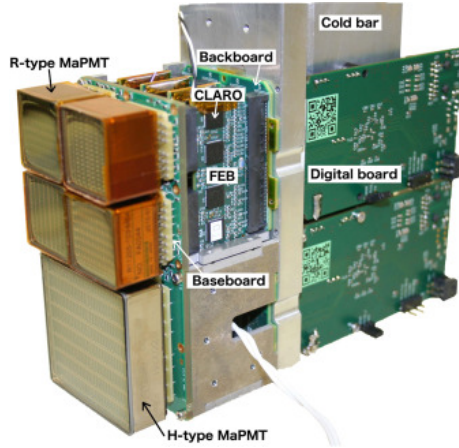


Figure 4.10: EC-R (top) and EC-H (bottom) with the full electronics chain. Note that the digital boards shown in this picture were used in the past for tests in the lab and during testbeams. The final version of the digital board that will be used for the commissioning is shown in Fig. 4.11 instead.

gain factor of  $10^6$  at the working tension of 1kV and a low dark count rate at ambient temperature [79]. The quantum efficiency of the MaPMTs is shifted towards the green wavelength region with respect to the HPDs which has the effect of improving the resolution on the Cherenkov angle by reducing the chromatic error.

Two different types of MaPMTs will be used: the R13742 type and the R13743 type. The R13742 type has an approximate  $2.9 \times 2.9 \text{ mm}^2$  pixel size and will cover the entire RICH1 and the central part of RICH2, whereas the R13743 type has a  $5.6 \times 5.6 \text{ mm}^2$  pixel size and will cover the outer part of RICH2.

The choice of using MaPMTs with bigger pixels in the outer part of RICH2 is motivated by the significant decrease in the photons occupancy with respect to the central part closer to the beam line. This has the benefit of reducing the number of readout channels with negligible impact on the performance.

The analog signal produced by the MaPMTs at the anode is shaped and amplified by the **CLARO** [80], an 8-channel ASIC realized in  $0.35 \mu\text{m}$  AMS CMOS technology, with a recovery time shorter than 25 ns. Each channel features a 6-bit programmable threshold and a 2-bit programmable gain. The MaPMTs and the CLARO chips are assembled in compact structures called **Elementary Cells** (ECs). Two different types of ECs will be installed: the R-type EC, composed of 4 R13742 MaPMTs, and the H-type EC, composed of a single R13743 MaPMT, as shown in Fig. 4.10. 4 ECs are grouped together to form a **Photo Detector Module** (PDM) (see Fig. 4.11). The MaPMTs of an EC are connected to the CLARO via the **BaseBoards**, which provide the interface to the **Front-End boards** (FEBs). The BaseBoard also bring the HV to the MaPMTs and help dissipate the heat produced by the HV power supply. The CLARO chip is housed on the FEBs and the FEBs are directly connected to the **Photon Detector Module Digital Board** (PDMDB) via the the **BackBoards**. An R-type PDM is served by two PDMDBs whereas

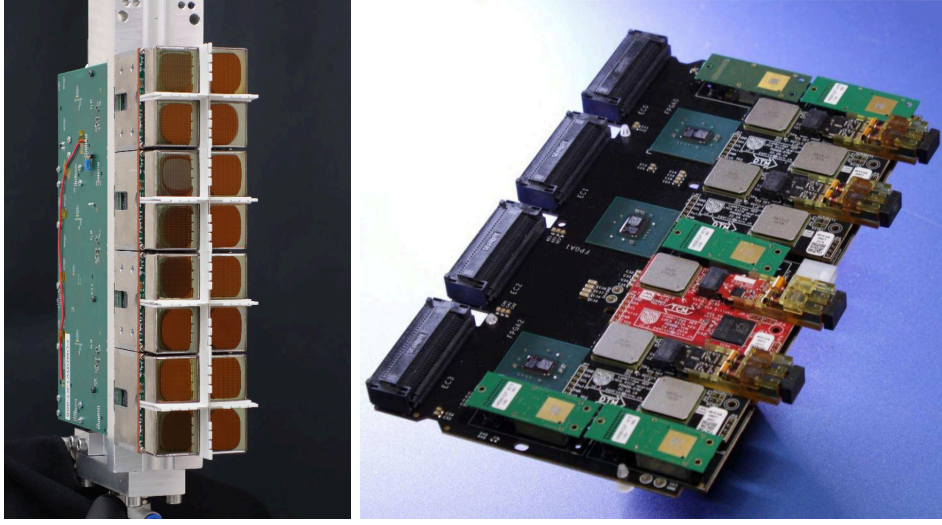


Figure 4.11: Left: The Photo Detector Module (PDM) with the 4 R-type ECs. Right: A PDMDB with the 3 FPGAs and the optical links.

an H-type PDM by only one PDMDB. The PDMDB handles the data packing and sends them via optical links to the TELL40 boards. In the final configuration RICH1 will have 22 columns with 12 PDMDBs each whereas RICH2 will have 24 columns with 8 PDMDBs each. Every column consists of 6 PDMs and forms an independent subsystem with its own mechanical infrastructure, the aluminium cold-bar, inside which a refrigerating fluid circulates in order to prevent the heating of the system. The mechanical infrastructure of the columns was designed in order to provide optimal access when maintenance is needed. In fact, every column can be extracted independently. A sketch of a RICH2 column and of the entire photo-detector plane is shown in Fig. 4.12. At the time of writing this thesis, the commissioning of the RICH2 columns was completed successfully. The columns were ready to be installed in the LHCb detector. The fully assembled photo detector plane is shown in Fig. 4.13.

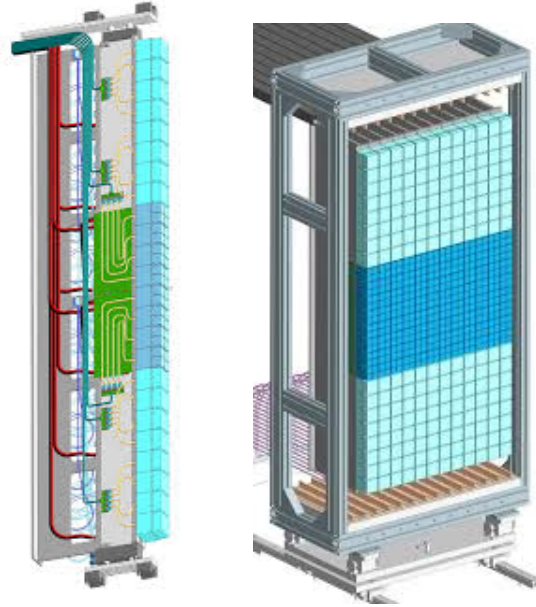


Figure 4.12: Left: A CAD representation of a RICH2 column including the routing of the HV and LV cables and fibres. Right: A CAD representation of an entire photo detector plane.



Figure 4.13: The fully assembled A-side photo detector plane of RICH2.

# Chapter 5

## The RICH Detector Control System

As already introduced in Section 2.4, the Experimental Control System (ECS) is the framework within LHCb in charge of the configuration, control, monitoring, archiving, operation and running of the LHCb experiment. The ECS is a uniform and homogeneous control system developed within the JCOP framework.

The JCOP framework provides tools and guidelines for the development of the LHC control systems and is built on top of the WinCC-OA Supervisory Control And Data Acquisition (SCADA) tool. The use of common hardware components among the experiments at LHC allows the standardisation of solutions for common tasks and, consequently, standard system like the control of power supplies or monitoring of temperatures can be easily configured using the tools provided by the framework. Every subdetector has its own independent ECS interfaced with the central LHCb ECS. Given the complexity of a single detector, its ECS is usually split into different partitions that are in charge of supervising a specific part of the detector. For instance, the RICH ECS summarizes the state of the high voltage system (HV), data acquisition system (DAQ) and the slow control system (DCS). I contributed to the development of the DCS system, which will be discussed in Section 5.3.

### 5.1 WinCC-OA and the JCOP framework

WinCC-OA is a device oriented software designed to develop control systems. The variables can be grouped, allocated in memory and used collectively [55]. The group description is the **Datapoint Type** (DPT) and an instance in memory of a DPT is a **Datapoint** (DP). The individual variables belonging to a given DPT are called **Datapoint elements** (DPEs). Every DPE, apart from the corresponding value, may store other information such as the corresponding hardware address, a range of values outside of which an alarm is raised, whether the values has to be stored in an archive, etc. All this meta information are held in configs. A practical example of a DP is the declaration of a HV channel. The structure of the channel is defined only once as a DPT, which contains different variables (DPEs) used to monitor and control the hardware. Each DP represents a channel and is then declared as an instance of this DPT. Therefore WinCC-OA has capabilities for

device description, through DPs and DPEs, and for archiving, through an archive config appended to the corresponding datapoint element. However, creating from scratch a DPT that completely describes an hardware device can be difficult and may take some time. In order to reduce this effort as much as possible for the developers, CERN has created the **JCOP** framework [54]. This framework is built on top of WinCC and includes, as far as possible, all templates, standard elements and functions required to achieve a homogeneous Control System. These components can be easily installed in any WinCC OA project. For example, if one wishes to create a DPT to control the channels of a CAEN crate, it suffices to install the so called JCOP FwCAEN component inside the WinCCOA project and DPTs suitable for many different types of HV crates are immediately available. Among the many functionalities it provides the possibility to represent a DP as a Finite State Machine (FSM) object; an FSM is a model of behavior composed of states, transitions and actions. As we will see in Sec. 5.2, every piece of hardware of a given detector in LHCb is represented by an FSM object inside a hierarchical tree-like structure.

### 5.1.1 Hardware control within the JCOP framework

In order to follow the LHCb-JCOP guidelines, standard equipments should be used as much as possible and common hardware interfaces, such as Ethernet and CANbuses, should be adopted. Moreover, a hardware manufacturer that provides also an OPC (Open Platform Communications) server embedded in the equipment should be chosen. Since WinCC-OA provides an OPC client this makes the communication with the devices almost trivial. If the equipment manufacturer does not provide an OPC server, the devices can be interfaced using a Distributed Information Management (DIM) client-server architecture provided by the JCOP framework.

DIM is a package for information publishing, data transfer and inter-process communications based on the client/server paradigm. For example, the DIM protocol is currently used for the configuration and monitoring of all DAQ and Trigger electronics, the control of all non-standard equipments, the configuration and monitoring of trigger/monitoring processes, the transportation of data for data quality checks, the interface to the Conditions database, to publish data for the web, etc.

Fig. 5.1 shows a schematic view of how the standard WinCC implements the communication with the hardware and the functionalities added by the JCOP framework. As it is clear from the picture WinCC-OA handles the communication between all the different running processes via the **Event Manager** and the JCOP framework is built on top of that.

The **Device Editor and Navigator** (DEN) is the main user interface to the framework and allows to declare devices in the control system and to configure many channels with alerts, settings, etc. The FSM tool allows to implement an high level view of the control system and to operate the system in a user friendly way.



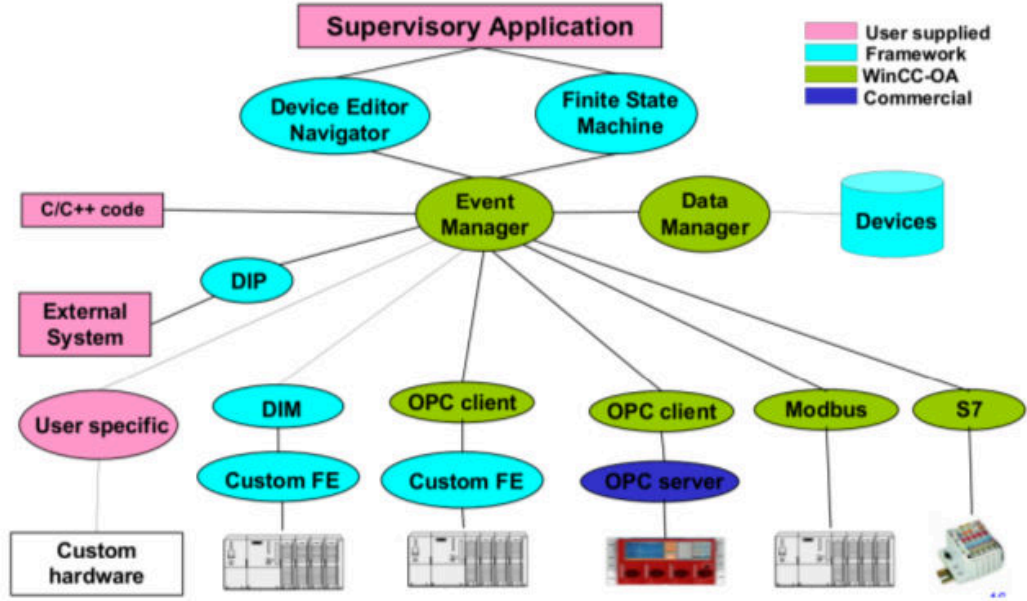


Figure 5.1: A schematic view of how WinCC OA (green) implements communication with the hardware. The functionalities added by the JCOP framework are marked in light blue.

## 5.2 The Architecture of the LHCb Experiment control system

As already anticipated in Section 5.1.1, the structure of LHCb subdetectors, subsystems and hardware components can be represented in a hierarchical, tree-like structure thanks to the functionalities provided by the JCOP framework. This guarantees independence between sub-detectors and sub-systems during calibration or test phases while allowing an integrated control during physics data taking, when all the sub-detectors run together. Every node in the tree behaves as a FSM object and can only be in one state at a time. This object can also receive and react to commands input by an external operator or also by a script running in the background. Commands propagate only downward in the hierarchy whereas states propagate only upward, as shown in Fig. 5.2. This means that a node can send commands only to its children and never to its parent and that its state is determined only by the states of its children and never by the state of its parent.

There are two kinds of nodes in the tree:

- **Device Units (DU)**, the tree leaves, i.e. they have no children, implementing the interface with the lower level components (hardware or software). DU receive commands and act on the device and receive device data translating it into a state. DU do not implement logic behavior.
- **Control Units (CU) and Logical Units (LU)**, the logical decision units able to

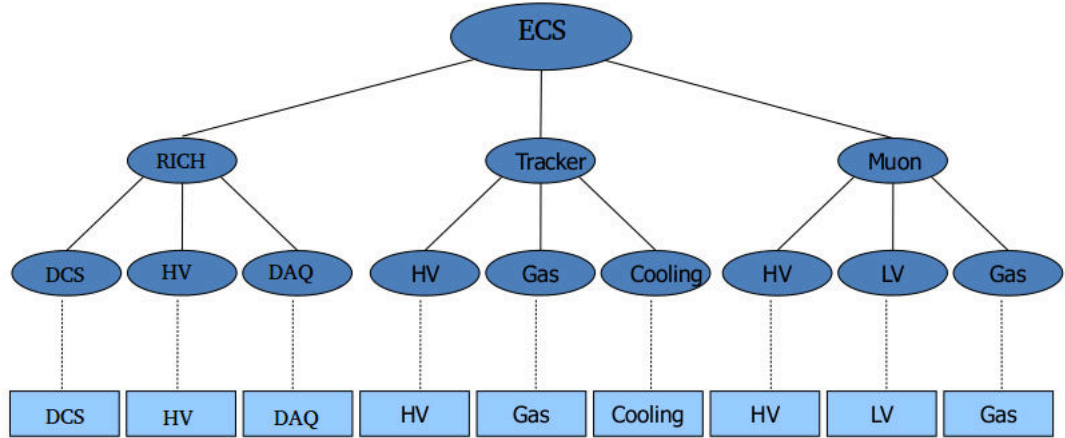


Figure 5.2: Example of a generic control system tree. The Detector Control System (DCS) is the top node. The other nodes are arranged in a tree-like structure and each of them represents a CU/LU. Moving further down in the tree one reaches the DU (yellow). The DUs are the interface with the hardware.

send commands to their children, i.e. a group of DU or CU/LU, depending on their states. The logic behavior is defined in terms of FSMs and the state transitions can be triggered by a command reception, e.g. from an operator or from the CU/LU parent, or by the state changes of the CU/LU children. The evaluation of logical conditions are caused by state transitions. Depending on the state some commands can be sent to the CU children, propagating actions down the tree, allowing for automatic actions and to recover from error situations. A CU differs from a LU for the capability to operate the former independently from the other sub-systems.

The FSM tool incorporated in the JCOP framework is built with the help of SMI++ [81]. Basic concepts of **SMI++** are the decomposition of complex systems in objects instantiated from classes, the behavior modelling for objects through a FSM implementation, the automation and error recovery following user defined rules. The behavioral model is defined in classes; classes instances can be abstract objects (e.g. Vertex sub-detector referring to Fig. 5.2), corresponding to a CU or a LU, or physical objects (e.g. a Vertex HV channel), corresponding to a DU. A collection of one or more abstract objects is called a domain in SMI and corresponds to a CU. Domains have a dedicated user friendly language, State Management Language (SML), implementing the abstract object description as FSMs, having the state as the main attribute. The FSM objects are grouped into SMI domain processes. The individual processes communicate via the DIM protocol and thus can be distributed within a LAN. In order to be able to operate different detector parts independently, individual SMI domains can be separated from the control hierarchy. The partitioning capabilities of the FSM toolkit allow to operate parts of the hierarchy in distinct modes. DU instances can be included in the tree (enabled) or detached from the tree (disabled) such that they neither propagate their state upward nor receive commands,

for example in case of a faulty hardware component. A CU can be included in the control hierarchy, i.e. it receives commands from and send its state to its parent, or excluded from the control tree, i.e. it does not receive commands and its state is not taken into account by its parent. In the latter scenario, the CU could be either faulty or ready to work in stand-alone for calibration or test purposes.

## 5.3 The RICH Upgrade DCS

The RICH ECS is the top domain summarizing the state of the HV, DCS and DAQ domains. In this section I will give a short description of the HV and DAQ domains, which have been developed by other members of the collaboration, whereas in Sec 5.3.1 I will concentrate instead on the description of the DCS domain, of which I am one of the main contributors.

The current version of the RICH upgrade ECS, which will be installed in the LHCb control room, is the evolution of the prototype developed for the control of the setup used during the tests with particle beam and the tests in the laboratory at CERN.

The HV partition controls and monitors the HV power supplies. The DU class implementing the interface of the HV control system with the hardware is such that its state is calculated depending on the status bit received by the considered HV channel. Available states are OFF, RAMPING UP, READY, RAMPING OFF, EMERGENCY OFF (e.g. interlock is active) and ERROR. For example, a typical situation for an HV channel may be the following: when an HV channel is OFF and receives the command GO\_READY, it starts increasing the voltage at a constant speed ending in the state RAMPING UP. Once the desired voltage has been reached the channel will move to state READY. If the channel trips for whatever reason, its state will move to ERROR and only specific actions will be able to recover the channel. Moreover, the HV partition must be able to change its state depending on the LHC state; for example, during injection when particle showers are expected, the HV must be off to prevent serious damages the RICH detectors.

The DAQ partition includes the control of the LHCb readout boards and of the sub-detector back-end (BE) and FE boards. Readout boards are common for all the sub-detectors and physically they are of one board type, named PCIe40, logically separated into the TELL40, SODIN and SOL40 components, having different functionality in the upgraded LHCb readout.

### 5.3.1 The structure of the RICH DCS partition

The DCS partition is the control domain responsible for all the slow control equipment, i.e. control and monitoring of the low voltage (LV), temperature, humidity, pressure etc., with the exception of the HV. Like any other subsystem at LHCb, the DCS features a tree-like structure whose logic is described by Fig. 5.3. The structure of the RICH1 DCS and RICH2 DCS is identical with the exception of the LV where only one channel per



column will be used instead of two.

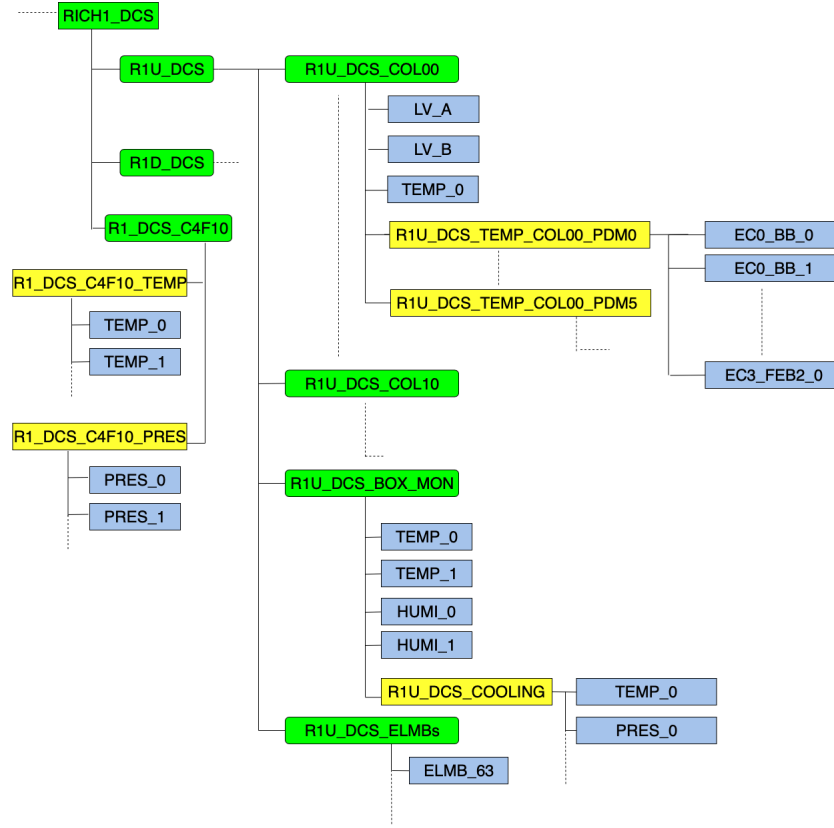


Figure 5.3: Logical view of the DCS project. For RICH2, only one LV channel per column will be used: LVA and LVB will be replaced by the LV label. Source: internal document.

### 5.3.1.1 Low voltage control and monitoring

The low-voltage supply is provided by the Wiener Maraton system [82] and is used to power the PDMDBs. Two LV channels per column will be used in RICH1 mainly for redundancy reasons related to the exposure to an high level of radiation in time. Only one channel per column will be used in RICH2 instead. Four 12-channels power supplies will be used in RICH1 and two 12-channels power supplies will be used in RICH2.

### 5.3.1.2 Monitoring of the front-end electronics temperatures

The monitoring of the temperatures of the frontend devices is achieved with the help of the SCA chip [83] located on the PDMDBs. The monitored devices are:

- the BaseBoards,
- the BackBoards,
- the FEBs,

| SCA-ADC channel | temperature sensor |
|-----------------|--------------------|
| EC0_BB          | Pt1000             |
| EC0_BkB         | Pt1000             |
| EC0_FEB1        | Pt1000             |
| EC0_FEB2        | Pt1000             |
| EC1_BB          | Pt1000             |
| EC1_BkB         | Pt1000             |
| EC1_FEB1        | Pt1000             |
| EC1_FEB2        | Pt1000             |
| EC2_BB          | Pt1000             |
| EC2_BkB         | Pt1000             |
| EC2_FEB1        | Pt1000             |
| EC2_FEB2        | Pt1000             |
| EC3_BB          | Pt1000             |
| EC3_BkB         | Pt1000             |
| EC3_FEB1        | Pt1000             |
| EC3_FEB2        | Pt1000             |

Table 5.1: SCA-ADC sensors that monitor the temperature of a PDM.

Every piece of hardware in a PDM has a Pt1000 sensor that can be readout using the ADC converters of the SCA chip. The list of the SCA-ADC sensors is reported in Tab. 5.1. It is important to remember that an R-type PDM is readout by two PDMDBs while an H-type PDM by only one PDMDB. For this reason the number of SCA-ADC sensors of an R-type PDM is twice that of an H-type PDM. The voltage measured by the SCA-ADC is given by  $V_{\text{ADC}} = R(\text{Pt1000}) \times i_{\text{source}}$ , where  $i_{\text{source}} = 100\mu\text{A}$  is the nominal current source provided by the SCA chip. The hardware registers of these devices in the SCA chip are mapped into datapoint structures inside a WinCC-OA project; by subscribing to the GBT server it is possible to start periodic monitoring of their values. The reading of the temperatures via SCA chip is only possible when the PDMDBs are powered on.

### 5.3.1.3 Monitoring of the columns

One 4-wires Pt100 sensor per column will be used to have a measurement of the temperature independent from the SCA measurements. This temperature sensor, called TESTO, is screwed in the upper part of the cold-bar. Even though a difference of  $\sim 1^\circ\text{C}$  seems to exist between the top and the bottom of the column, as measured during a test in the lab with four temperature sensors, the difference is not dramatic and one sensor for the entire column is sufficient. Moreover, this sensor is also useful to calibrate the SCA-ADC readings, in case the current source provides to be not very stable in the long term. In fact, as shown in Fig. 5.4, the Pt100 appears to be stable over time.

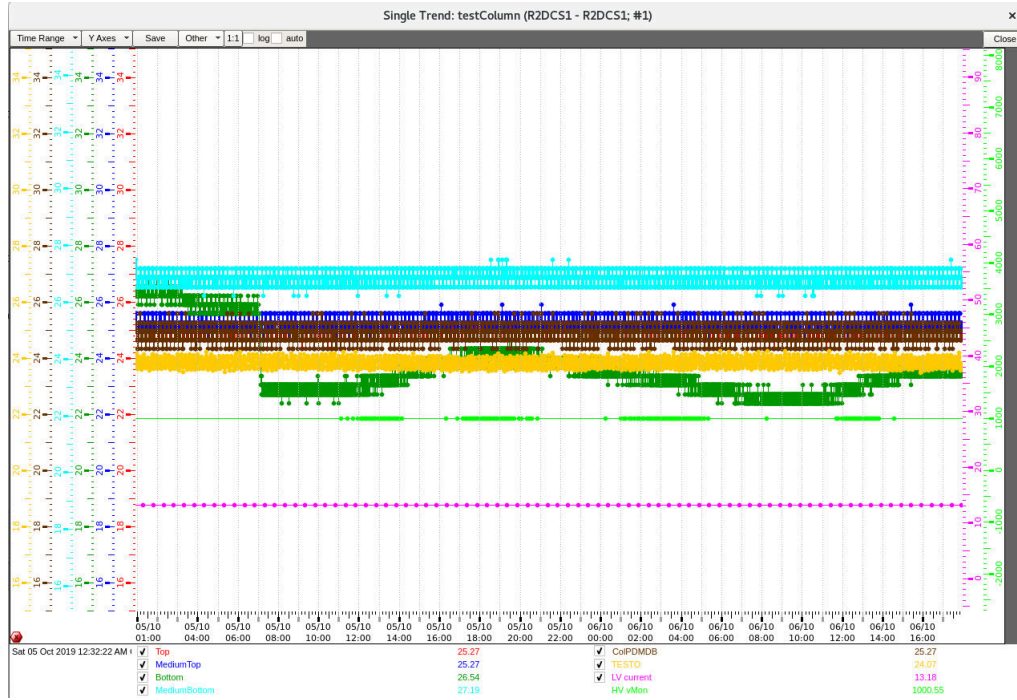


Figure 5.4: Trend of the four Pt100 during the weekend. The four sensors are placed in different positions on the cold-bar: top (red graph), medium-top (blue graph), medium-bottom (light blue) and bottom (green). The yellow graph refers to the nominal Pt100 screwed in the cold-bar. The value appears to be very stable over time for three sensors. The fourth sensor shows an oscillating trend due to the fact that the sensor came off the coldbar.

#### 5.3.1.4 Monitoring at the photo-detector enclosures and at the gas enclosures.

Monitoring of the temperature, pressure and humidity inside the photo-detector box will be present. Two Pt100 will be used to monitor the temperature of the photo-detector enclosure. Two humidity sensors will be used to check that the atmosphere is dry enough to allow the HV ramp-up of MaPMTs. The temperature of the coolant will be monitored by using the same type of T-sensor used for the columns. One T-sensor per cooling manifold will be installed, resulting in two temperature measurements per photo-detector enclosure (coolant input and output). A further check on the circulation of the cooling will be performed by using one pressure sensor per cooling manifold, resulting in two pressure measurements per photo-detector enclosure (coolant input and output). Temperatures and pressures will also be monitored at the gas radiator enclosures, which is used to contain the gas radiator.

### 5.3.2 The ELMB boxes

The output of the sensors monitoring the columns and the two enclosures is fed into the so-called ELMB boards.

The Embedded Local Monitor Board (ELMB) [84] is a general purpose plug-on I/O module for the monitoring and control of subdetector front-end equipment. It was developed by CERN, NIKHEF and the PNPI and it is characterized by a strong radiation hardness. The ELMB is based on the industry standard CANbus and CANopen has been implemented as high-level communication protocol. It can be used to read analog inputs (such as temperature sensors, voltages, etc.) and for digital input and output. The standardized fwELMB component of the JCOP Framework allows to communicate with the OPC server of the ELMB and map the readings to the corresponding WinCC-OA datapoints. The ELMB boards contain adapters on the backside and connectors for the ADC inputs, digital ports, a SPI interface, CAN interface and power connectors on the front side (see Fig 5.5).

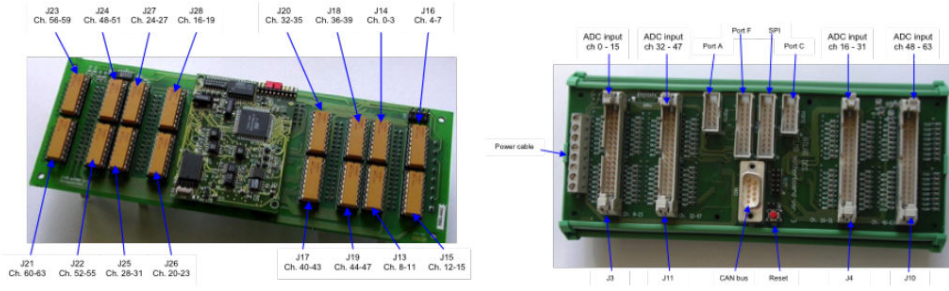


Figure 5.5: Back-side of the ELMB motherboard showing the adapter connectors (left) and front-side of the ELMB motherboard showing the different inputs (right).

The ELMB boards will be placed into four different boxes, one for every RICH side (RICH1Top, RICH1Bottom, RICH2A, RICH2C). The front part of the panel contains the connectors for the different types of cable (see Fig. 5.6). The back part contains the CANBus through which all the ELMB nodes are readout sequentially.

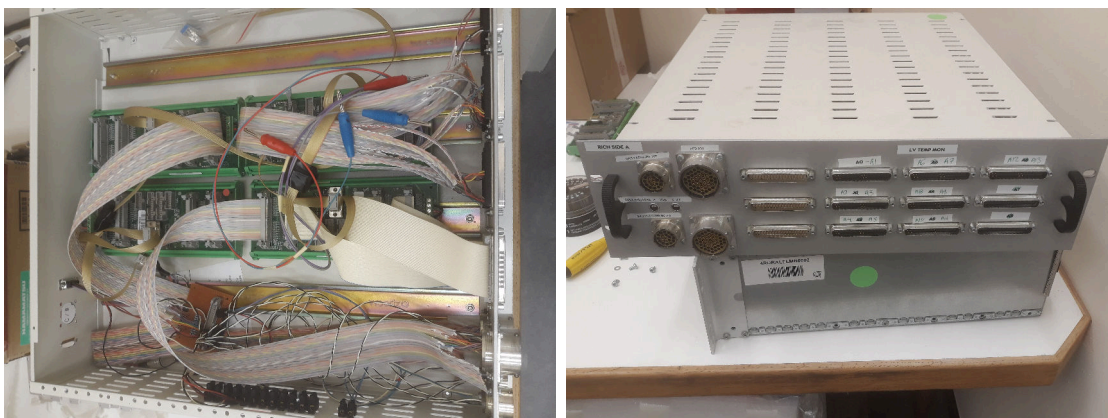


Figure 5.6: Picture of the ELMB box for the RICH2A side. Left: The 4 ELMBs that readout different sensors. Right: The front part of the box containing the connectors for the different types of input signal.

### 5.3.2.1 The configuration panel

I developed from scratch the configuration panel that is used to create the datapoint structure associated to a specific ELMB box; every channel in the box is mapped to a datapoint of the DCS project. Once the datapoints have been created and the OPC server started, the client manager can connect to the server and starts acquiring data. Fig. 5.7 shows the panel that configures both sides, A and C, of RICH2.

The configuration panel also takes care of setting an alias to the corresponding datapoint. In fact, it is much easier to identify a channel by its logical name, instead of by its channel number. As shown in Fig. 5.8, by clicking on any datapoint, it is possible to see its current value and many other operation parameters such as the alert conditions which trigger a warning or to produce a trending plot of the variable. The datapoints for the front-end monitoring are also created by the panel. In order to decouple as much as possible the DCS and DAQ partitions, a script in the DCS project connects to the SCA-ADC datapoints declared in the DAQ project and reads them. The script applies the calibration constant and corrects for the SCA-ADC current source effects.

### 5.3.2.2 Connectivity checks

I also developed a script, which is part of the DCS projects and runs in the background, that check regularly whether SCA-ADC datapoints are updated from GBT server. If these datapoints do not get updated for 10 minutes or more, they will be set to invalid by the script.

### 5.3.2.3 Alarm handling

In the JCOP framework it is possible to easily set alarms message to make the operator aware that standard conditions are not anymore fulfilled. In the case of the temperature





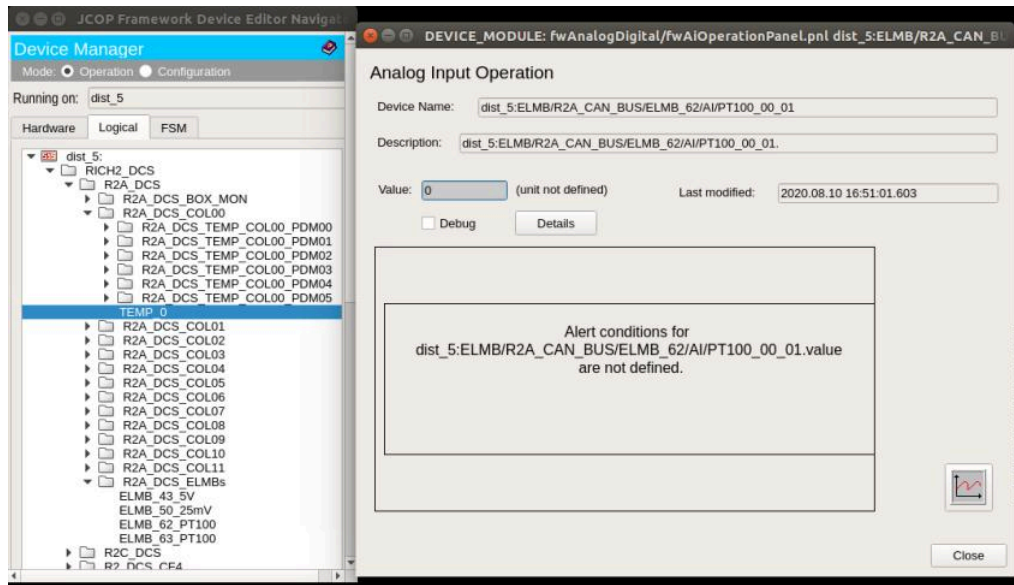


Figure 5.8: Panel showing the operation parameters of the selected datapoint. In this case no alert conditions for the datapoint have been defined.

sensors a set of temperature ranges corresponding to different alert messages have been

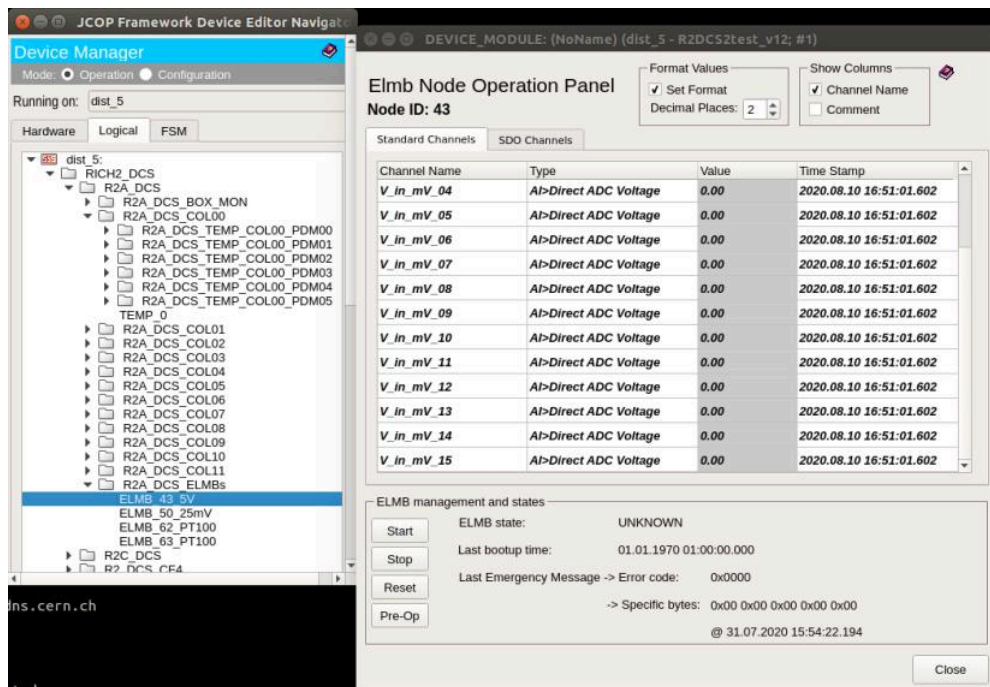


Figure 5.9: ELMB node operation panel. In this panel it is possible to check the general status of the channels and the connectivity status of the board.

defined as shown in Tab. 5.2.

| Temperature range                             | Alert message |
|-----------------------------------------------|---------------|
| $T > 35^{\circ}\text{C}$                      | Too high      |
| $30^{\circ}\text{C} < T < 35^{\circ}\text{C}$ | A bit high    |
| $5^{\circ}\text{C} < T < 30^{\circ}\text{C}$  | OK            |
| $T < 5^{\circ}\text{C}$                       | Too low       |

Table 5.2: Description of the FSM states for the DCS Temperature Device Unit.

### 5.3.3 The DCS FSM

The structure of the RICH DCS FSM partition is shown in Fig. 5.10. Essentially the two sides of the RICH forms an independent CU whose state depends on the states of its columns, on the state of the photo-detector enclosure and on the state of the ELMBs. The state of every column depends on the state of the low voltage channels and on the state of its PDMs.



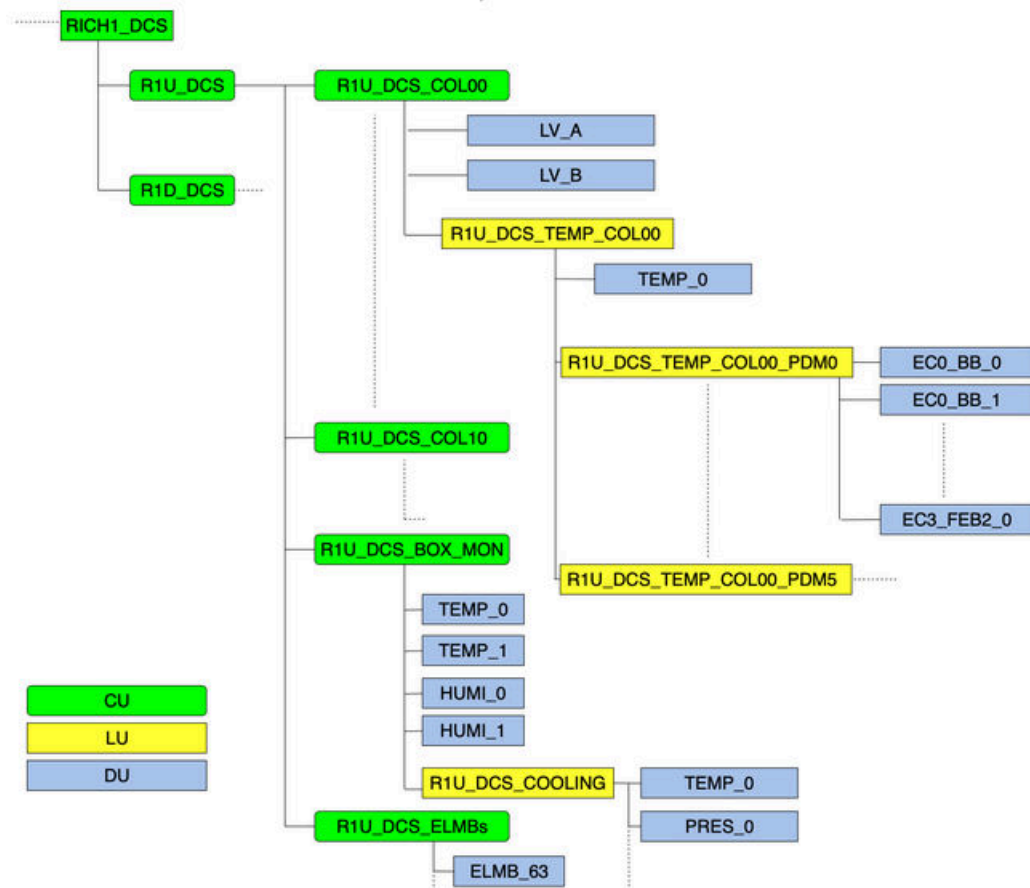


Figure 5.10: Logical structure of the nominal DCS FSM partition. The blue color refers to the Device Unit (DU), the yellow color to the Logical Unit (LU) and the green color refers to the Control Unit (CU). Source: internal document.

### 5.3.3.1 The DCS Device Unit

The FSM component of the JCOP framework allows to configure any DP as a DU (Device Unit). As already described in the introduction, the DU represent the interface between hardware and software and sets the corresponding state for the DP every time the latter receives new data from the server. A state change in the DU can also be triggered by an external action; every state has also a list of commands it responds to which can bring it into another state. The FSM states and actions for the DUs inside the DCS partition are shown in Fig. 5.11.

It should be noted that not all the DUs have the same states; the temperature sensors, the pressure sensors and the humidity sensors are input only devices and therefore the interface with the hardware does not have any available actions. On the contrary the LV channels can react to actions such as SWITCH\_OFF, SWITCH\_ON ecc.

The hardware conditions that bring a DU into a given state are shown in Tab. 5.3 and 5.4.

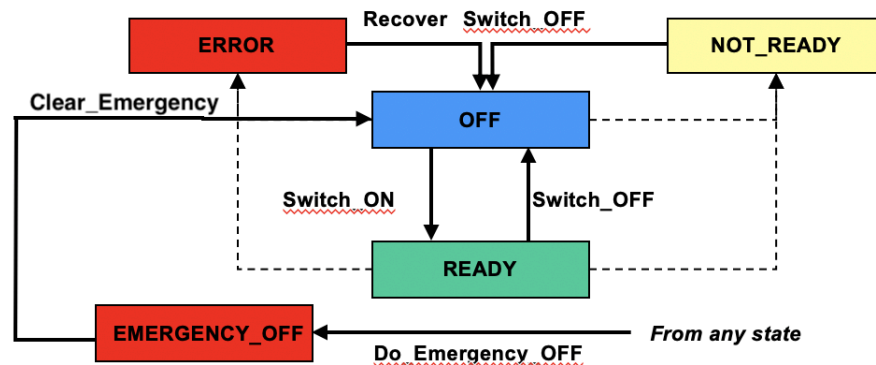


Figure 5.11: This picture shows all the possible states of the DCS DU and the possible actions that can be taken at any time depending on the state of the DU. The description of the state for the temperature DU is given in Tab. 5.3. The description of the state for the LV DU is given in Tab. 5.4. Source: internal document.

| State     | Description                                       |
|-----------|---------------------------------------------------|
| NOT_READY | Temperature too low error or loss of connectivity |
| READY     | The monitored values are OK                       |
| ERROR     | Temperature too high error                        |

Table 5.3: Description of the fsm states for the temperature Device Unit.

| State         | Description                                                     |
|---------------|-----------------------------------------------------------------|
| OFF           | The channel is OFF (only for LV devices)                        |
| READY         | The LV channel is set to the operational voltage                |
| ERROR         | The channel has detected an error, <i>e.g.</i> a voltage trip   |
| EMERGENCY_OFF | The LV channel has been switched off because of external causes |

Table 5.4: Description of the fsm states for the LV Device Unit.

### 5.3.3.2 The DCS Control/Logical Units

The state of a Control/Logical Unit is defined by the combination of its children. As already shown in Fig. 5.10, the DCS partition contains different types of LU and CU whose behaviour depends on their position within the tree-like structure. The description of the fsm

states and actions defined for the R2{A,C}\_DCS Control Unit are reported in Tab. 5.5. The description of the fsm states and actions defined for the R2{A,C}\_DCS\_COL{0..11}, where COL{0..11} refers to the column number, Control Unit are reported in Tab. 5.6. The description of the fsm states and actions defined for the R2{A,C}\_DCS\_TEMP\_COL{0..11} Logical Unit are reported in Tab. 5.7. The description of the fsm states and actions defined for the R2{A,C}\_DCS\_TEMP\_COL{0..11}\_PDM{0..5} Logical Unit are reported in Tab. 5.8.

| State         | Condition                  | Actions                                     |
|---------------|----------------------------|---------------------------------------------|
| OFF           | All children in OFF        | switch on/do emergency off/reset            |
| NOT_READY     | Any child not in READY     | switch on/switch off/do emergency off/reset |
| READY         | All children in READY      | switch off/do emergency off/reset           |
| ERROR         | Any child in ERROR         | recover/do emergency off                    |
| EMERGENCY_OFF | Any child in EMERGENCY_OFF | clear emergency                             |

Table 5.5: Description of the fsm states and actions for the R2{X}\_DCS Control Unit. X can refer either to the A side or the C side.

| State         | Condition                  | Actions                               |
|---------------|----------------------------|---------------------------------------|
| OFF           | All LV channels in OFF     | switch on/do emergency off/reset      |
| NOT_READY     | Any child not in READY     | switch on/switch off/do emergency off |
| READY         | All children in READY      | switch off/do emergency off/reset     |
| ERROR         | Any child in ERROR         | recover/do emergency off              |
| EMERGENCY_OFF | Any child in EMERGENCY_OFF | clear emergency                       |

Table 5.6: Description of the fsm states and actions for the R2{X}\_DCS\_COL{0..11} Control Unit. X can refer either to the A side or the C side while N goes from 0 to 11.

| State     | Condition              |
|-----------|------------------------|
| NOT_READY | Any child in NOT_READY |
| READY     | All children in READY  |
| ERROR     | Any child in ERROR     |

Table 5.7: Description of the fsm states for the R2{X}\_DCS\_TEMP\_COL{0..11} Logical Unit. X can refer either to the A side or the C side while N goes from 0 to 11.

| State     | Condition              |
|-----------|------------------------|
| NOT_READY | Any child in NOT_READY |
| READY     | All children in READY  |
| ERROR     | Any child in ERROR     |

Table 5.8: Description of the fsm states for the R2{X}\_DCS\_TEMP\_COL{0..11}\_PDM Logical Unit. X can refer either to the A side or the C side while N goes from 0 to 11.

### 5.3.4 The DCS control panel

The logic upon which the DCS fsm has been defined in Section 5.3.3 has been implemented in WinCC. The result of this software implementation are user-friendly control panels in which the current state of the fsm units can be easily visualized, as shown in Fig. 5.12. The R2A\_DCS CU shows the global state for the RICH2 side A system as the result of the states of its children according to the rules described in Tab 5.5.

The state of the column R2A\_DCS\_COLXX CU is determined by the conditions of the LV channel DU, which is common to the entire column, and by the condition of the R2A\_DCS\_TEMP\_COLXX LU according to Tab 5.6.

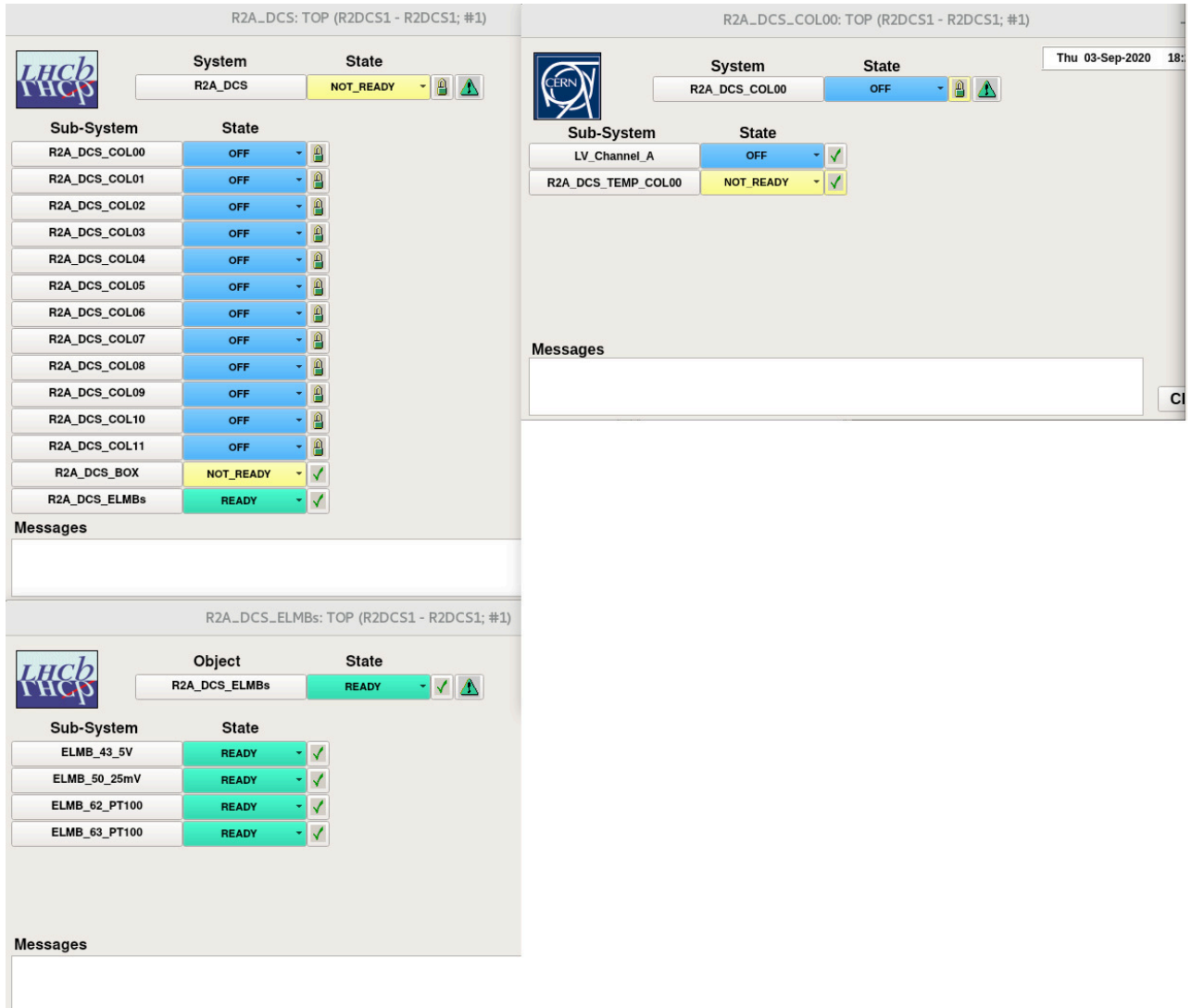
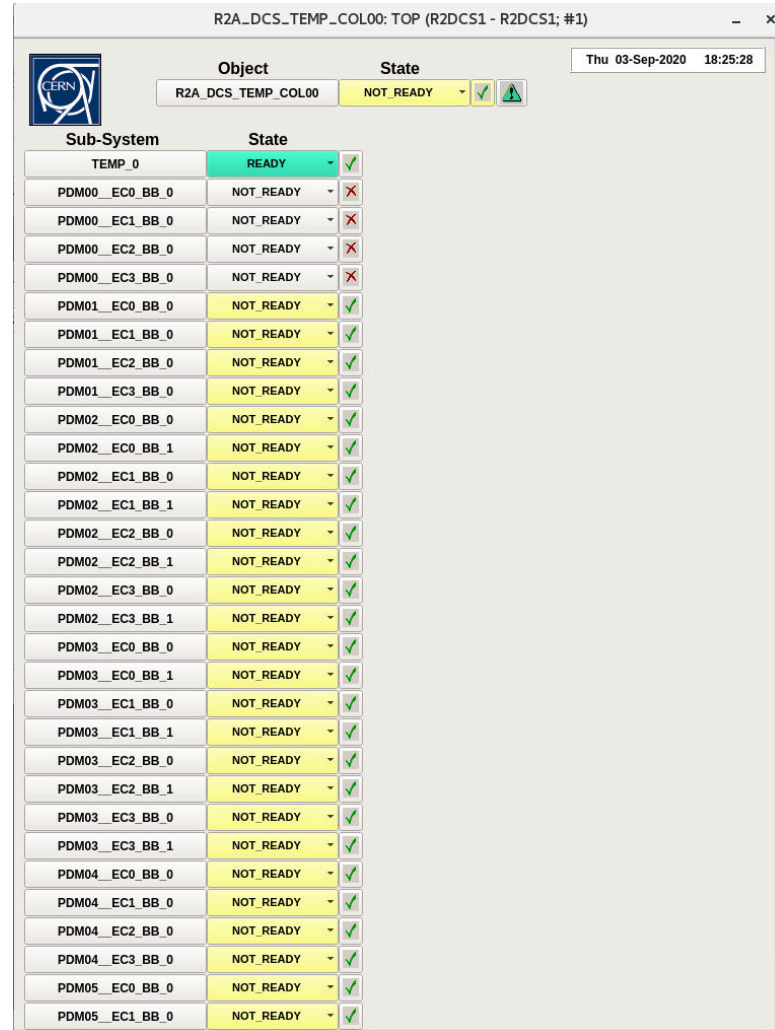


Figure 5.12: The user-friendly control panel of the RICH2 side A showing the current state of every CU/LU and its children. The top-left panel shows the global state of every column, the global state of the RICH2A box and the state of the ELMBs. The top-right panel shows the state of the children belonging to the LU of a particular column while the bottom-left panel shows the state of the children belonging to the R2A ELMBs LU.

Two approaches are currently being investigated to set the state of the R2A\_DCS\_TEMP\_COLXX LU: in the first approach the state of the LU is defined by the conditions of all the temperature sensors of the column and every sensor is a DU (see Fig. 5.13 ). The temperature sensors used in the fsm are:

- One Pt100 TESTO sensor per column mounted on the cold bar
- The Pt1000 of the BaseBoard

BackBoard and FEBs sensors are not used here. The state is therefore determined by the states of its 33 children, 32 BaseBoard DU + 1 Pt100 DU, which are independent of each other. The main advantage of this approach is that the state of the DU depends only on the value of one sensor making the transition from one state to another one very fast. The main disadvantage is that the information of the BackBoard and FEBs temperature sensors are completely neglected here and if something goes wrong no action can be taken.



| Object             | State     |
|--------------------|-----------|
| R2A_DCS_TEMP_COL00 | NOT_READY |

| Sub-System     | State     |
|----------------|-----------|
| TEMP_0         | READY     |
| PDM00_EC0_BB_0 | NOT_READY |
| PDM00_EC1_BB_0 | NOT_READY |
| PDM00_EC2_BB_0 | NOT_READY |
| PDM00_EC3_BB_0 | NOT_READY |
| PDM01_EC0_BB_0 | NOT_READY |
| PDM01_EC1_BB_0 | NOT_READY |
| PDM01_EC2_BB_0 | NOT_READY |
| PDM01_EC3_BB_0 | NOT_READY |
| PDM02_EC0_BB_0 | NOT_READY |
| PDM02_EC0_BB_1 | NOT_READY |
| PDM02_EC1_BB_0 | NOT_READY |
| PDM02_EC1_BB_1 | NOT_READY |
| PDM02_EC2_BB_0 | NOT_READY |
| PDM02_EC2_BB_1 | NOT_READY |
| PDM02_EC3_BB_0 | NOT_READY |
| PDM02_EC3_BB_1 | NOT_READY |
| PDM03_EC0_BB_0 | NOT_READY |
| PDM03_EC0_BB_1 | NOT_READY |
| PDM03_EC1_BB_0 | NOT_READY |
| PDM03_EC1_BB_1 | NOT_READY |
| PDM03_EC2_BB_0 | NOT_READY |
| PDM03_EC2_BB_1 | NOT_READY |
| PDM03_EC3_BB_0 | NOT_READY |
| PDM03_EC3_BB_1 | NOT_READY |
| PDM04_EC0_BB_0 | NOT_READY |
| PDM04_EC1_BB_0 | NOT_READY |
| PDM04_EC2_BB_0 | NOT_READY |
| PDM04_EC3_BB_0 | NOT_READY |
| PDM05_EC0_BB_0 | NOT_READY |
| PDM05_EC1_BB_0 | NOT_READY |

Figure 5.13: Control panel showing the state of the R2A\_DCS\_TEMP\_COLXX LU as determined by the conditions of its children. Every children is an independent DU.

In the second approach the PDM becomes a LU itself (R2{A,C}\_DCS\_TEMP\_COL{0..11}\_PDM) and the entire elementary cell (EC) becomes a DU (PDMX\_ECX) (see Fig. 5.14). The state of this DU is no longer a function of the BaseBoard temperature sensor only, but a function of the BaseBoard, BackBoards and FEBs temperature sensors. The main advantage here is that the

information of all four pt1000 sensors can be combined together making the fsm structure more compact. The main disadvantage is that the DU will go through intermediate states before reaching the final stable state. I concentrated on the development of the second approach to the fsm.

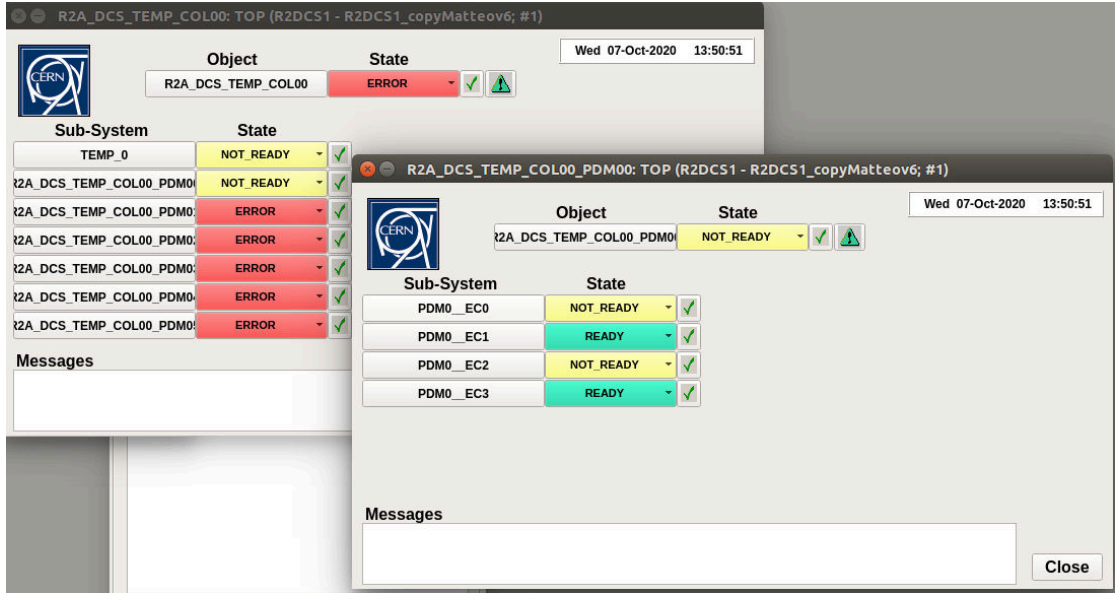


Figure 5.14: Control panel showing the state of the R2A\_DCS\_TEMP\_COLXX LU as determined by the state of its PDMs. The PDM is a LU itself depending on the state of its ECs, which form an independent DU.

The first version of the WinCC project where the temperature sensors form independent DU (see Fig. 5.13) has already been installed on the machines in the LHCb experiment control room. However, since there is still room for optimization before final choices are made, the second option (see Fig. 5.14) remains a viable option and could still be used.

### 5.3.5 Test of the humidity sensors for the photo-detector enclosures

Before making the final choice about which humidity sensors to use in order to monitor the relative humidity (RH) inside the photo detector enclosures, which will be filled with  $N_2$  gas, I tested and compared three different types of sensors:

- HM1500LF [85]
- HIH-4000 [86]
- Rotronic HYGROMER C94 [87]



The HM1500LF sensor is designed for accurate measurements in the range 10 to 95% of relative humidity however, according to the manufacturer, excursion out of this range does not affect the reliability of the measurements. The sensor HIH-4000 has a 3.5% RH accuracy at the temperature of 25 °C in the range 0% RH to 100% RH. The Rotronic has a 2.0 % accuracy in the range 20 to 95 % RH.

The sensors HM1500LF and HIH-4000 were readout via the ELMB (see. 5.3.2) and their output was mapped into a DP after connecting the OPC client of the WinCC-OA project to the CANopen OPC server. Their output voltage was not calibrated and the calibration was performed inside the WinCC-OA project by using the coefficients given in the datasheet provided by the manufacturers. The Rotronic HYGROMER C94 output, instead, was already calibrated and equipped with an embedded readout instead. The sensors were tested simultaneously under three different types of gas:  $N_2$ ,  $CO_2$  and  $CF_4$ . For every type of gas the sensors were tested under both dry and humid atmosphere to check whether they provide an accurate output in the extreme cases of 0% and 100% of humidity. In order to do the measurement the sensors were placed in a plastic bag and gas was inflated in; in this way one can create the 0% humidity condition. The humid environment was created by placing inside the plastic bag a wet towel to let it saturate the gas with water vapor. The entire setup used for the measurement is shown in Fig. 5.15



Figure 5.15: Setup used for the test of the humidity sensors. On the desk you can see the ELMB, which was used to readout the HM1500LF and the HIH-4000 humidity sensors. The three sensors were placed inside the plastic bag and the gas was inject with the help of the bottle on the right.

The measurement took an entire day and the temperature was measured continuously during the test and remained constant throughout the period.



| Sensor   | min value of RH(%) | accuracy(%) |
|----------|--------------------|-------------|
| HM1500LF | -0.18              | $\pm 3$     |
| HIH-4000 | 14.38              | $\pm 3.5$   |
| Rotronic | 1.5                | $\pm 2.0$   |

Table 5.9: Values measured by the three different sensors under dry  $N_2$  atmosphere. The accuracy was taken from the corresponding datasheet.

### 5.3.5.1 Test of the sensors under dry $N_2$ atmosphere

Fig. 5.16 shows the relative humidity as measured by the three sensors as the plastic bag is filled with  $N_2$  gas.

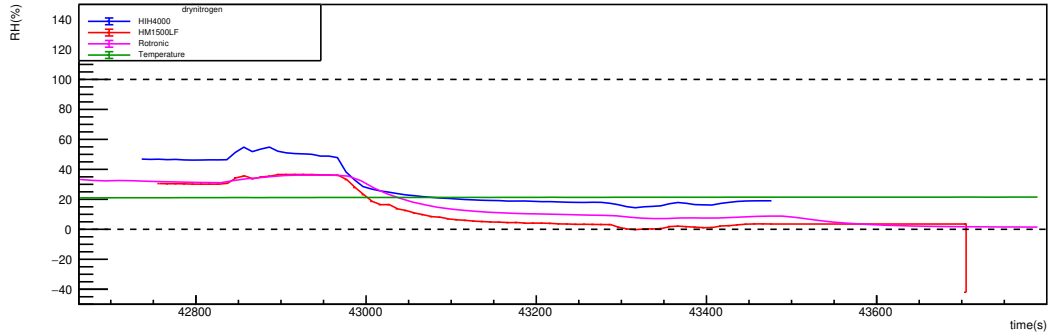


Figure 5.16: Relative humidity measured as a function of time during the injection of the nitrogen gas into the plastic bag. The blue line refers to the HIH-4000 sensor, the red line to the HM1500LF and the purple line to the Rotronic HYGROMER C94. The green line is the temperature measured by a PT1000 sensor placed inside the bag to monitor the stability of the latter in time.

The values readout by the sensors after  $\sim 600$  s under  $N_2$  are shown in Tab. 5.9.

HM1500LF and Rotronic give values consistent with 0 and consistent with each other. This result is very important because it tells us that these two probes are suitable sensors for the monitoring of the photo-detector enclosure in dry conditions. On the contrary, the HIH-4000 probe seems to be affected by an offset since it follows the same downward trend as the one measured by HM1500LF and Rotronic.

### 5.3.5.2 Test of the sensors under humid $N_2$ atmosphere

Fig. 5.17 shows the relative humidity as measured by the three sensors after a wet towel had been inserted into the plastic bag in order to create a humid nitrogen atmosphere.

| Sensor   | max value of RH(%) | accuracy(%) |
|----------|--------------------|-------------|
| HM1500LF | 86.70              | $\pm 3$     |
| HIH-4000 | 119.38             | $\pm 3.5$   |
| Rotronic | 89.31              | $\pm 2.0$   |

Table 5.10: Values measured by the three different sensors under humid  $N_2$  atmosphere. The accuracy was taken from the corresponding datasheet.

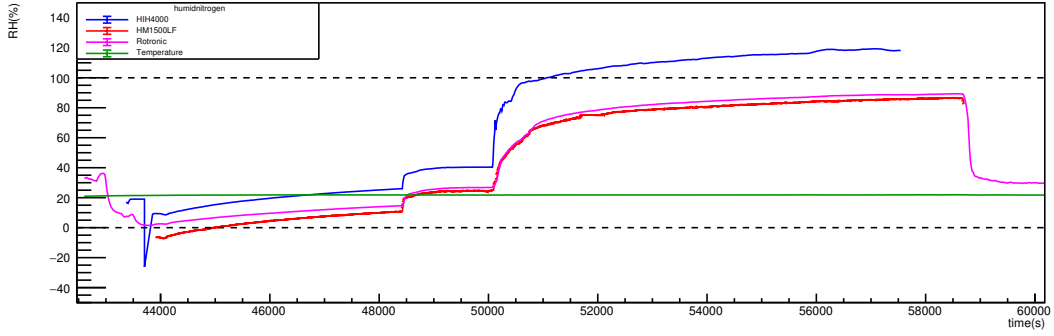


Figure 5.17: RH measured as a function of time after a wet towel had been inserted into the plastic bag in order to create a humid nitrogen atmosphere. The blue line refers to the HIH-4000 sensor, the red line to the HM1500LF and the purple line to the Rotronic HYGROMER C94. The green line is the temperature measured by a PT1000 sensor placed inside the bag to monitor the stability of the latter in time.

The values readout by the sensors after  $\sim 6000$  s under humid  $N_2$  are reported in Tab. 5.10. HM1500LF and Rotronic give consistent values while HIH-4000 reaches non physical values above 100%. The value of  $\sim 90\%$  reached by the HM1500LF and Rotronic is still quite away from the expected value of 100%, but this is probably due to the fact that the saturation of the air was not complete as the upward trend of the two sensors appears not to have stabilized yet.

### 5.3.5.3 Test of the sensors under dry $CO_2$ atmosphere

Fig. 5.18 shows the relative humidity measured by the three sensors during the injection of the  $CO_2$  gas into the plastic bag.

| Sensor   | min value of RH(%) | accuracy(%) |
|----------|--------------------|-------------|
| HM1500LF | -5.68              | $\pm 3$     |
| HIH-4000 | 9.18               | $\pm 3.5$   |
| Rotronic | 4.2                | $\pm 2.0$   |

Table 5.11: Values measured by the three different sensors under dry  $CO_2$  atmosphere. The accuracy was taken from the corresponding datasheet.

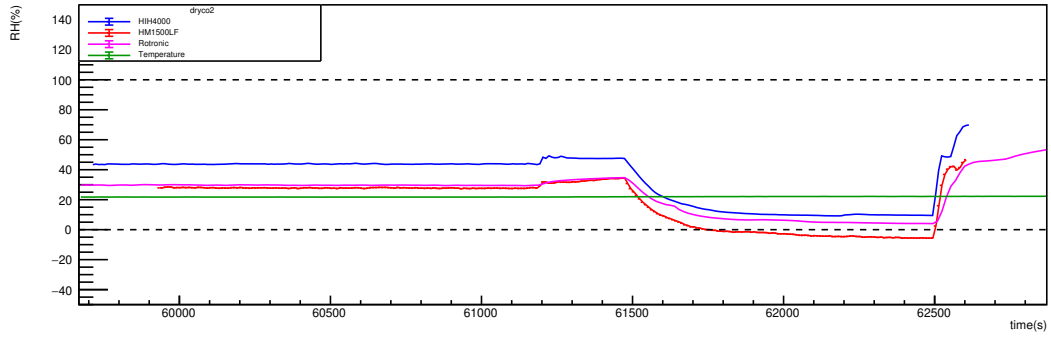


Figure 5.18: RH measured as a function of time during the injection of the  $CO_2$  gas into the plastic bag. The blue line refers to the HIH-4000 sensor, the red line to the HM1500LF and the purple line to the Rotronic HYGROMER C94. The green line is the temperature measured by a PT1000 sensor placed inside the bag to monitor the stability of the latter in time.

The values readout by the sensors after  $\sim 1000$  s under  $CO_2$  are shown in Tab. 5.11. M1500LF and Rotronic give values only partially consistent with 0 and partially consistent with each other. Concerning the HIH-4000 probe, in this case the different with the other two sensors has reduced.

#### 5.3.5.4 Test of the sensors under humid $CO_2$ atmosphere

Fig. 5.19 shows the relative humidity as measured by the three sensors after a wet towel had been inserted into the plastic bag in order to create a humid  $CO_2$  atmosphere.

| Sensor   | max value of RH(%) | accuracy(%) |
|----------|--------------------|-------------|
| HM1500LF | 75.63              | $\pm 3$     |
| HIH-4000 | 98.71              | $\pm 3.5$   |
| Rotronic | 76.38              | $\pm 2.0$   |

Table 5.12: Values measured by the three different sensors under humid  $CO_2$  atmosphere. The accuracy was taken from the corresponding datasheet.

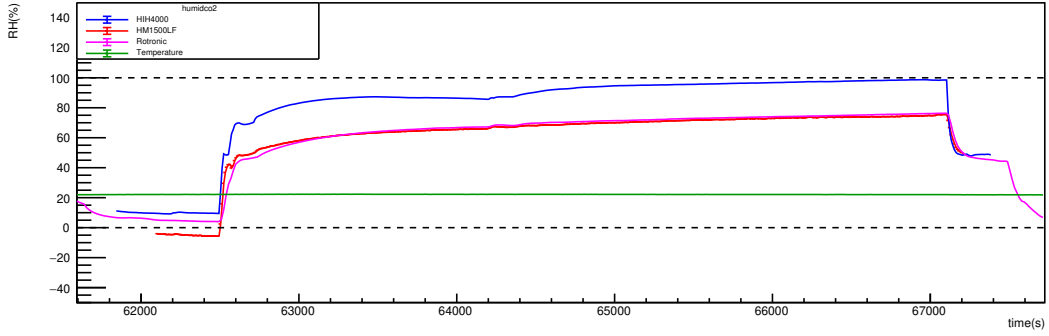


Figure 5.19: RH measured as a function of time after a wet towel had been inserted into the plastic bag in order to create a humid  $CO_2$  atmosphere. The blue line refers to the HIH-4000 sensor, the red line to the HM1500LF and the purple line to the Rotronic HYGROMER C94. The green line is the temperature measured by a PT1000 sensor placed inside the bag to monitor the stability of the latter in time.

The values readout by the sensors after  $\sim 4000$  s under humid  $CO_2$  are shown in Tab. 5.12. In this case the HIH-4000 sensor appears to be more accurate than the other two sensors which, instead, stabilize well under the value of 80%. Also in this case the HM1500LF and the Rotronic give values consistent with each other. The test under  $CO_2$  atmosphere tells us that HIH-4000 sensor behaves better than the other two.

#### 5.3.5.5 Test of the sensors under dry $CF_4$ atmosphere

Fig. 5.20 shows the relative humidity measured by the three sensors during the injection of the  $CF_4$  gas into the plastic bag.

| Sensor   | min value of RH(%) | accuracy(%) |
|----------|--------------------|-------------|
| HM1500LF | -6.85              | $\pm 3$     |
| HIH-4000 | 7.95               | $\pm 3.5$   |
| Rotronic | 1.69               | $\pm 2.0$   |

Table 5.13: Values measured by the three different sensors under dry  $CF_4$  atmosphere. The accuracy was taken from the corresponding datasheet.

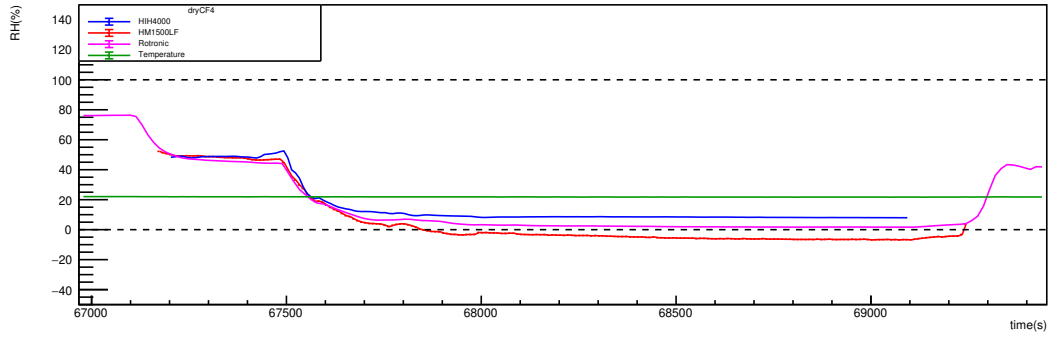


Figure 5.20: RH measured as a function of time during the injection of the  $CF_4$  gas into the plastic bag. The blue line refers to the HIH-4000 sensor, the red line to the HM1500LF and the purple line to the Rotronic HYGROMER C94. The green line is the temperature measured by a PT1000 sensor placed inside the bag to monitor the stability of the latter in time.

The values readout by the sensors after  $\sim 1000$  s under  $CF_4$  are shown in Tab. 5.13. M1500LF, Rotronic and HIH-4000 give values only partially consistent with 0 and partially consistent with each other.

#### 5.3.5.6 Test of the sensors under humid $CF_4$ atmosphere

Fig. 5.21 shows the relative humidity as measured by the three sensors after a wet towel had been inserted into the plastic bag in order to create a humid  $CF_4$  atmosphere.

| Sensor   | max value of RH(%) | accuracy(%) |
|----------|--------------------|-------------|
| HM1500LF | 79.31              | $\pm 3$     |
| HIH-4000 | 115.21             | $\pm 3.5$   |
| Rotronic | 80.94              | $\pm 2.0$   |

Table 5.14: Values measured by the three different sensors under humid  $CF_4$  atmosphere. The accuracy was taken from the corresponding datasheet.

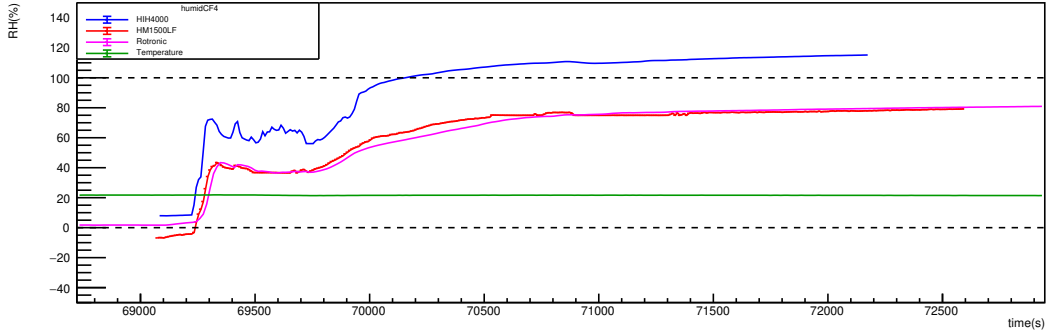


Figure 5.21: RH measured as a function of time after a wet towel had been inserted into the plastic bag in order to create a humid  $CF_4$  atmosphere. The blue line refers to the HIH-4000 sensor, the red line to the HM1500LF and the purple line to the Rotronic HYGROMER C94. The green line is the temperature measured by a PT1000 sensor placed inside the bag to monitor the stability of the latter in time.

The values readout by the sensors after  $\sim 2000$  s under humid  $CF_4$  are shown in Tab. 5.14. The HIH-4000 sensor stabilizes well above 100% while the HM1500LF and the Rotronic give values consistent with each other, but still around 80%. The test under  $CF_4$  atmosphere does not give us a clear indication of which sensor performs better.

To summarize the results of this test we can conclude that all sensors show the same trend following the change in humidity. Sensor HIH4000, however, does not give correct value under  $N_2$  atmosphere 9% in dry  $N_2$  and 119% in humid  $N_2$ . The reason for this could be related to a wrong calibration factor, even if the factor itself was taken from the datasheet of the product. HM1500LF and Rotronic are rather consistent with 0 and with each other. Under dry  $CF_4$  and  $CO_2$  the HM1500LF gives negative values not fully consistent with 0, but it is not obvious to know how sensors should react as they have been designed to be operated in air.

Following the result of this test 8 probes (2 probes per photo-detector enclosure) were purchased: 4 probes of type HM1500LF and 4 of type Rotronic. Using two different sensors will be useful to evaluate the effect of the radiation on the long term.

### 5.3.6 Conclusions

In this chapter I described in details the hardware and software implementation of the RICH DCS of which I have been one of the main contributors. The DCS partition, along with the HV and the DAQ partition, is part of the LHCb RICH ECS. At the time of the writing of this thesis the entire RICH 2 FSM domain of the DCS has been fully developed and successfully tested with the hardware during the commissioning phase in ComLab; the first version of the WinCC project has already been installed on the machines in the LHCb experiment control room. The ELMB box of the A side has been fully cabled and already installed on the detector in the LHCb cavern. The C side box has been fully cabled, but not installed underground yet. The development of the RICH 1 FSM domain of the DCS has already started and will benefit of the work already done for RICH 2.

## Chapter 6

# Characterisation of SiPM photodetectors for the RICH Upgrade phase II

In this chapter, the use of Silicon Photomultipliers (SiPMs) as a possible photo-detector candidate for the Upgrade II phase of the RICH detector is discussed. After an introduction to the challenges faced by the RICH detector with the start of Run 5, the result of my work about the characterization of a SiPM device will be presented. The results obtained here are preliminary and limited by the statistics, but represent useful inputs toward the development of a prototype SiPM BaseBoard. The BaseBoard will serve as the interface between the photo-detector and the front-end electronics and will also have to provide the bias voltage to the SiPMs. The Upgrade II detector is shown in Fig. 6.1. The inner part of the SciFi tracker will be replaced by a silicon tracker in order to better deal with the higher track multiplicity, and the combination of the SciFi and silicon tracker will be renamed as the Mighty Tracker(MT) [88]. A new detector, TORCH, will be added as well. The TORCH (Time of Internally Reflected Cherenkov Light) detector is designed to enhance the charged hadron PID in the momentum range of 2 to 10 GeV/c [89], as shown in Fig 6.3.

### 6.1 The RICH detectors in a HL-LHC scenario

The start of the High Luminosity LHC phase from 2027 (see Fig. 4.2) provides an opportunity for a 10-fold increase in the luminosity at LHCb compared to the present. This would improve significantly the physics reach of LHCb [90], which would profit from an expected integrated luminosity of  $\sim 300 \text{ fb}^{-1}$  by the end of Run 6, as shown in Fig.6.2. Since the RICH detector operates at the single photon level, the main challenge that it will have to face is the harsh radiation environment. In fact, in the high-luminosity environment, a fluence up to  $10^{14} \text{ neq cm}^{-2}$  is expected in the RICH detector. Moreover, the RICH system needs to be redesigned to improve the Cherenkov angular resolution and



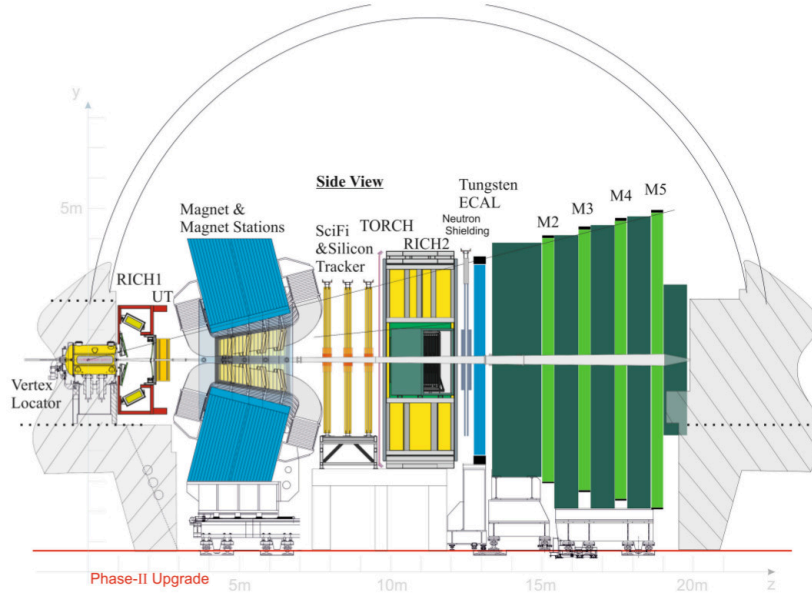


Figure 6.1: Sketch of the Upgrade II LHCb detector

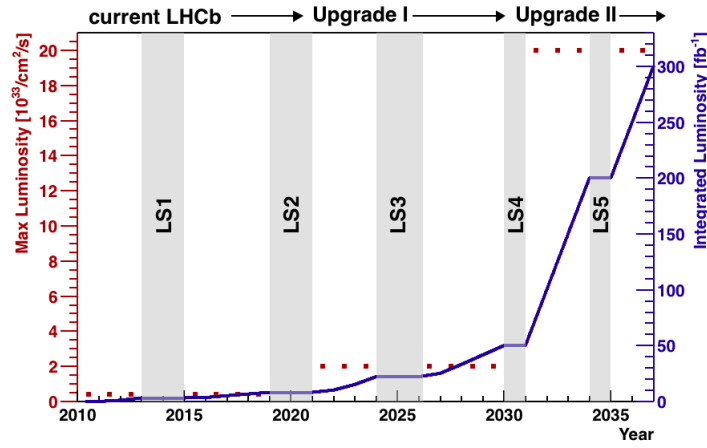


Figure 6.2: Luminosity projections for the original LHCb, Upgrade I, and Upgrade II experiments as a function of time

to reduce the detector occupancy as well. As already discussed in 4.3.1, the entire RICH photo-electronics chain underwent substantial changes for the Upgrade I phase and also the optical system required some adjustments. A further jump in luminosity to  $\sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$  starting from Run 5 would imply for LHCb an increase of the occupancy in the RICH photo-detector planes by a factor 5 if the Upgrade I configuration was maintained. Increasing the detector plane by an other factor 2 with respect to the Upgrade I in order to magnify the image would imply high costs and the need for a larger volume inside LHCb. Instead, a more realistic solution seems to be that of reducing the pixel size of the photo-detectors

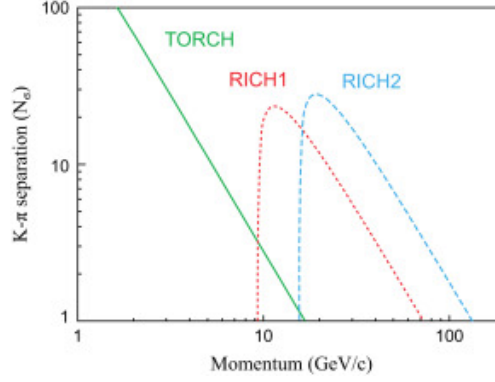


Figure 6.3: Calculated performance (in sigma separation) of the components of the PID system versus momentum for isolated tracks.

down to  $\sim 1 \text{ mm}^2$  [91]. A reduced pixel size must, however, be followed by an improved Cherenkov angle resolution to 0.5 mrad from the current 1.6 mrad in RICH1. This can be easily demonstrated by remembering that, for good pattern recognition, the following condition  $(\sigma_\theta f) < \sqrt{A_p}$  must be met, where  $\sigma_\theta$  is the Cherenkov angle resolution,  $f$  is the focal length of the mirror and  $A_p$  is the pixel area. Chromatic dispersion affects most the near-UV generated photons, reducing the single-photon Cherenkov angle resolution; photon detectors with high quantum efficiency (QE) and a red-shifted spectrum could be employed to limit this effects as the high QE is needed to compensate the lower Cherenkov-photon yield at longer wavelengths (green-red). The emission point error is caused by optical aberrations. The photons emitted by a charged particle along its trajectory take different optical paths to reach the photo-detectors worsening the Cherenkov angle resolution. For the Upgrade II phase, lightweight composite mirrors will be used in order to reduce the overall optical aberrations of the system. The different contributions to the angle resolution are reported in Tab 6.1.

### 6.1.1 Time information for the PID in the HL-LHC

It is also possible to improve the pattern recognition and to improve the ratio of signal photons to background (electronic noise, dark counts and sources of light other than Cherenkov) by using timing information. Indeed, simulation studies show that the prompt Cherenkov photons generated by a particle in the radiator all reach the photon detector planes within 10 ps, even over optical paths of several metres in the RICHes [92]. The Cherenkov photons resulting from particles produced in the proton-proton collisions all arrive at the photon detector plane about 15 ns after the bunch crossing with a  $\sim 1 \text{ ns}$  time spread, as shown in Fig. 6.4. All the other photons, generated by particles directly crossing the photodetectors, curling, spilling over from previous events and generated by radiator scintillation, arrive outside this  $\sim 1 \text{ ns}$  window. Acquiring data only around this peak would exclude all the other background photons thus improving significantly the signal to noise ratio. Indeed, a 3.125 ns hardware time gate in the PDMDB (see Section 4.3.1.1)

| Single photon error (mrad) | RICH 1 Upg 1 | RICH 1 Upg 2 | RICH 2 Upg 1 | RICH 2 Upg 2 |
|----------------------------|--------------|--------------|--------------|--------------|
| Chromatic                  | 0.58         | 0.24         | 0.31         | 0.1          |
| Pixel                      | 0.44         | 0.15         | 0.20         | 0.07         |
| Emission point             | 0.37         | 0.1          | 0.27         | 0.05         |
| Total error                | 0.82         | <b>0.3</b>   | 0.46         | <b>0.13</b>  |

Table 6.1: Preliminary simulated performance and photon yields for the various configurations RICH 1 & RICH 2

will be implemented starting from Run 3 [92]. However, since the width of the signal peaks in the hit time distributions is dominated by the  $PV_s$  time spread, which has a spread  $\sigma_t$  of about 220 ps, Cherenkov rings belonging to different  $PV_s$  will not be resolved with the gated signal only. The beginning of the HL-LHC phase from Run 5 brings a significant increase in the luminosity, which is detrimental to the particle ID performance, as already explained in Section 6.1. This difficulty can be overcome by making use of the timing information of the photon detector itself, i.e. measuring the time at which the Cherenkov photons hit the detector; the PID performance as a function of the sensor time resolution is shown in Fig. 6.5. From simulation it is shown that the same PID performance as the one expected for Run 3 would be met if a time gate of 50 to 100 ps in the high-luminosity environment was used, assuming that time would be the only improvement made during Upgrade II. Although these results are still preliminary, they give a clear indication that photo-detectors with a high intrinsic time resolution will be needed. Among the possible commercial photo-detector candidates with small enough pixel size and sufficiently low time resolution to comply with these requirements are SiPMs (Silicon Photomultipliers) and MCP (Micro Channel Plates). SiPMs would be ideal devices due to their better quantum efficiency spectrum with respect to PMTs, relatively low time resolution of  $\sim 200$  ps [93], comparable high gain at much lower working bias and insensitivity to magnetic fields but are, in turn, more sensitive to radiation damage and have a high dark count rate at room temperature. The MCP combine an excellent time resolution of  $\sim 50$  ps with a low dark-count rate comparable to that of the MaPMTs. The main drawback of the MCP-PMT is its restricted lifetime and its sensitivity to magnetic field. The MCP will be used in the TORCH detector to detect the Cherenkov photons [94]. My work during the PhD focused on the characterization of a SiPM device produced by Hamamatsu Photonics. Section 6.1.2 gives a general description of the SiPM technology whereas the

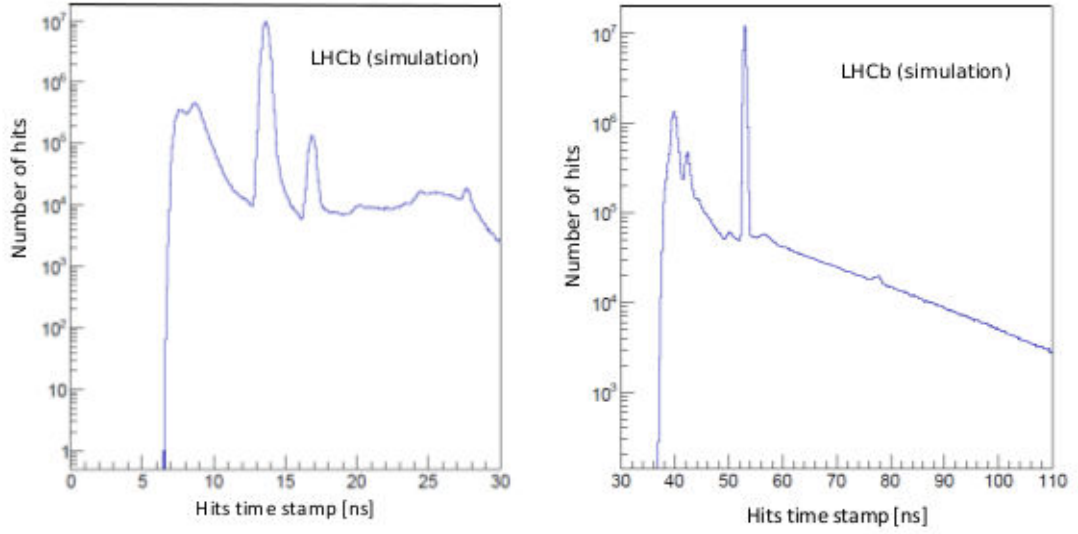


Figure 6.4: Distribution of the simulated time of arrival of Cherenkov photons on RICH1 (left) photo-detector arrays and on RICH2 (right). The main peaks is due to hits from prompt Cherenkov photons generated by a particle in the radiator, while the first peaks in time are due to particles interacting directly with the photo-detectors. Source [92].

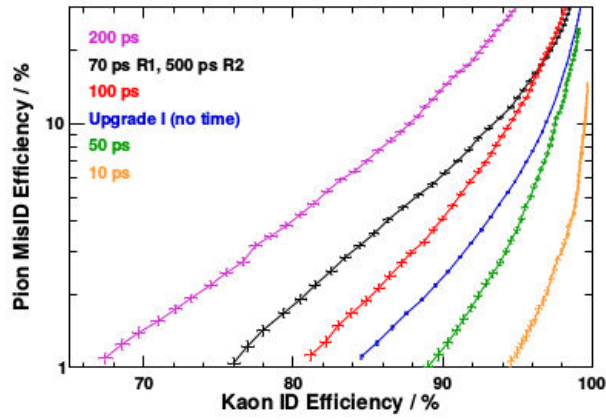


Figure 6.5: Simulated particle ID curves at the HL-LHC Run 5 and Run 6 luminosity. The blue curve corresponds to the PID performance expected for the Upgrade I phase where no photon time of arrival information is available. Source [92]

entire characterization procedure is discussed in 6.2.

### 6.1.2 Silicon Photomultipliers

A photodiode is formed by a silicon p-n junction that creates a depletion region that free of mobile charge carriers. When a photon is absorbed in silicon, it creates an electron-hole pair. By applying a reverse bias to a photodiode the electric field across the depletion region will cause these charge carriers to be accelerated towards the anode (holes), or cathode (electrons).

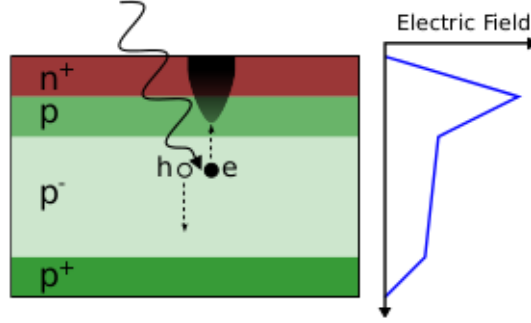


Figure 6.6: Doping structure and electric field of a SiPM pixel. The sharp rise in the electric field at the boundary of the  $p^-$ - $p$  region may cause the avalanche process to start.

Therefore an absorbed photon will result in a net flow of current in a reverse-biased photodiode. When a sufficiently high electric field is present within the depletion region of the silicon, a charge carrier created there will be accelerated to a point where it carries sufficient kinetic energy to create secondary charge pairs through a process called impact ionization. The high electric field can be achieved by doping the silicon according to the structure shown in Fig. 6.6. In this way, a single absorbed photon can trigger a self-perpetuating ionization cascade that will spread throughout the silicon volume subjected to the electric field. The silicon will break down and become conductive, effectively amplifying the original electron-hole pair into a macroscopic current flow. This process is called Geiger discharge, in analogy to the ionization discharge observed in a Geiger-Müller tube. Once a current is flowing, stopping it requires the use of a series quench resistor  $R_q$ , which limits the current drawn by the diode during breakdown. This lowers the reverse voltage seen by the diode to a value below its breakdown voltage  $V_{BD}$ , thus halting the avalanche. The diode then recharges back to the bias voltage, and is available to detect subsequent photons. A SiPM is basically an array of silicon microcells operated in Geiger mode biased a few volts above the breakdown voltage. The difference between the bias voltage  $V_{bias}$  and the breakdown voltage  $V_{BD}$  is referred to as overvoltage  $\Delta V = V_{bias} - V_{BD}$ . Fig. 6.7 shows the equivalent circuit of the SiPM resulting from a large number of Geiger-mode photodiodes connected in parallel. The model of this elementary structure includes the diode capacitance  $C_d$ , the quenching resistor  $R_q$ , a small parasitic capacitance  $C_q$ , placed in parallel to  $R_q$ , and a current source, which models the total charge delivered by the microcell during the Geiger discharge caused by an event.

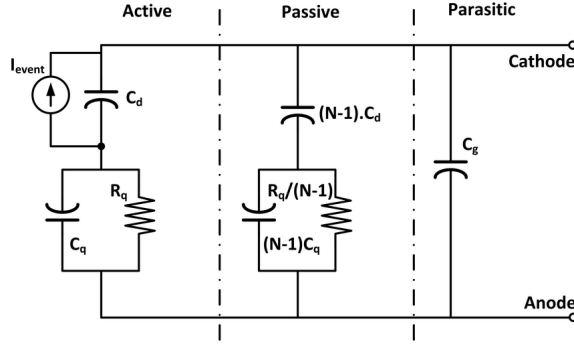


Figure 6.7: Electrical model of a SiPM.

The SiPMs features generally a high photon detection efficiency (PDE), single photon counting capabilities, excellent timing resolution, low bias voltage operation and immunity to magnetic fields. The main drawback of SiPMs is their high dark count rate at room temperatures and their poor tolerance to the radiation, which represent a strong disadvantage if one intends to use them in the LHCb environment. In general the performances of a SiPM depend on different parameters each of which is affected by the temperature and the overvoltage in a different way. In the following a short description of these parameters is presented.

#### 6.1.2.1 Dark count

The main source of noise in a SiPM is the dark count rate (DCR), which is primarily due to thermal electrons generated in the active volume. The DCR is a function of active area, overvoltage and temperature. Each dark count is a result of a thermally generated electron that initiates an avalanche in the high field region. The signals resulting from the breakdown of the microcell, due to either photon-generated or thermally-generated electrons, are identical. Therefore, thermally generated electrons form a source of noise at the single photon level.

#### 6.1.2.2 Optical Cross-Talk

During avalanche, accelerated carriers in the high field region may emit photons that can initiate a secondary avalanche in a neighboring microcells. These secondary photons tend to be in the near infrared region (NIR) and can travel substantial distances through the silicon. Typically  $2 \times 10^{-5}$  NIR photons are emitted per electron crossing the junction. The crosstalk is defined as the probability that an avalanching microcell will cause an avalanche in a second microcell. The process happens instantaneously and as a consequence, single incident photons may occasionally generate signals equivalent to 2 or 3 photons, or even higher. Optical crosstalk is a function of overvoltage and is also affected by the fill factor of the sensor. The fill factor refers to the percentage of the SiPM sensor surface area that is sensitive to light. Due to the structure of the SiPM, each microcell needs to be separated from its neighbor for optical and electrical isolation purposes. In addition, some

surface area is required also for the quench resistor. All of these considerations result in a dead space around the microcell.

#### 6.1.2.3 Afterpulsing

During breakdown, carriers can become trapped in defects in the silicon. After a delay of up to several ns, the trapped carriers are released, potentially initiating an avalanche and creating an afterpulse in the same microcell. Afterpulses with short delay that occur during the recovery time of the microcell tend to have negligible impact as the microcell is not fully charged. However, longer delay afterpulses can impact measurements with the SiPM if the rate is high.

#### 6.1.2.4 Gain

The gain of an SiPM sensor is defined as the amount of charge created for each detected photon, and is a function of overvoltage and microcell size. The gain can be calculated from the overvoltage  $\Delta V$ , the microcell capacitance  $C$ , and the electron charge,  $q$ .

$$G = \frac{C\Delta V}{q} \quad (6.1)$$

#### 6.1.2.5 Cell recovery time

When a microcell in the SiPM is activated, it takes a finite time to quench the avalanche and then reset the diode voltage to its initial bias value. This time is defined as recovery time  $\tau_R$  (or dead time). The recovery time  $\tau_R \propto C_d R_q$  depends on the junction capacitor  $C_d$  and the quenching resistor  $R_q$ . During the recharging period the gain  $G$ , which is proportional to  $\Delta V$  according to Eq. 6.1, is expected to behave like:

$$G(t) = G(1 - e^{-t/\tau_R}) \quad (6.2)$$

The amplitude  $A$  of the signal, which is proportional to the gain, is expected to show the same behavior over time.

#### 6.1.2.6 Radiation hardness

In order to use SiPMs for the next generation RICH detectors, the environment of a high luminosity collider must be considered with a projected neutron fluences of the order of  $10^{14} \text{ cm}^{-2}$ . SiPMs are known to be very sensitive to radiation, in particular to displacement damage, as expected from devices whose operation depends on the properties of bulk silicon [95], [96]. The most evident effect of radiation is an increase of DCR by several orders of magnitude, while the PDE, gain and signal shape are generally unaffected [97–104]. Displacement of silicon atoms from the lattice caused by high energy hadrons creates clusters of defects with energy levels in the band gap that favor the creation and recombination of electron–hole pairs in the depletion region of the device, increasing

|                             | S13360-1375       | Units         |
|-----------------------------|-------------------|---------------|
| Pixel size                  | $1.3 \times 1.3$  | $\text{mm}^2$ |
| Pixel pitch                 | 75                | $\mu\text{m}$ |
| Number of pixels            | 285               |               |
| Fill factor                 | 82                | %             |
| Spectral response range     | 270 - 900         | nm            |
| Peak sensitivity wavelength | 450               | nm            |
| PDE                         | 50                | %             |
| Dark count (typ)            | 90                | kcps          |
| Dark count (max)            | 270               | kcps          |
| Terminal capacitance        | 60                | pF            |
| Gain                        | $4.0 \times 10^6$ |               |
| $V_{\text{BR}}$             | $53 \pm 5$        |               |

Table 6.2: Main characteristics of the SiPM produced by Hamamatsu and tested in the lab

the DCR. High temperature can significantly speed up process of dark current annealing in irradiated silicon devices. It was also demonstrated that single photon detection can be accomplished at cryogenic temperatures about 80 K for SiPMs irradiated up to  $10^{14} \text{ cm}^{-2}$  1 MeV equivalent neutron fluence [105].

## 6.2 Characterization of a SiPM

In this section I will describe the measurements performed in the laboratory and the various steps of the data analysis that allowed to extract the main parameters affecting the performances of a SiPM. The analyzed data were recorded in June 2019. The non-irradiated device under study is the S13360-1375 and its typical characteristics as given by the manufacturer are reported in Table 6.2. A picture of the SiPM under study is shown in Fig. 6.8. These data were acquired in order to study the different contributions to the noise and how these change according to the temperature and the bias voltage. For this reason no measurement using a laser source was performed but only placing the sensor inside a metallic cage to shield it from the background light.

### 6.2.1 Experimental setup

The experimental setup consists of the SiPM under study, an amplifying circuit board, an oscilloscope, two power supply and a PC where a custom daq software acquires the sample from the oscilloscope. One power supply is able to provide output voltage up to 60 V and was used to bias the silicon sensor. The second power supply was used to bias the preamplifier with  $\pm 5$  V. The measurements of the dark count were performed by placing the sensor and the board inside a light-tight metallic shield. The measurements





Figure 6.8: The S13360-137 model tested in the lab

at low temperatures were performed with the help of a climatic chamber; this allowed to characterize the device at temperatures as low as  $-50\text{ }^{\circ}\text{C}$ . The 19 measurements taken under different condition of temperature and  $V_{bias}$  are listed in Tab. 6.3.

|                          | 51V | 52V | 53V | 54V | 55V | 56V |
|--------------------------|-----|-----|-----|-----|-----|-----|
| T [ $^{\circ}\text{C}$ ] | -40 | -20 | -10 | 0   | 0   | 0   |
|                          | -45 | -30 | -20 | -10 | -10 |     |
|                          |     | -40 | -30 | -20 |     |     |
|                          |     | -45 | -40 | -30 |     |     |
|                          |     |     | -45 | -40 |     |     |

Table 6.3: Temperature and  $V_{bias}$  condition under which the measurements were taken.

#### 6.2.1.1 Readout circuit and data acquisition

The readout board used through all the measurement was developed by the Milano Bicocca LHCb group and is shown in Fig. 6.9. Up to four devices can be connected to the board. The input pins are connected via internal routing to the amplifier whose schematic view is shown in Fig. 6.10. The amplifier could in principle be operated both in inverting and non-inverting mode. For the measurement the non-inverting mode was chosen; the resistor R5 and the capacitor C6 were removed and the SiPM was soldered to pins J5 and J6. The gain of the amplifier was  $\sim 100$ , high enough to have a 20 mV single-photon signal on the oscilloscope at room temperature. The only drawback of this amplifier was its limited bandwidth of 50 MHz, resulting in signals with a high rise time of 50 ns and slow decay time of 150 ns. For this reason it was not possible to measure the intrinsic time resolution of the device under study.

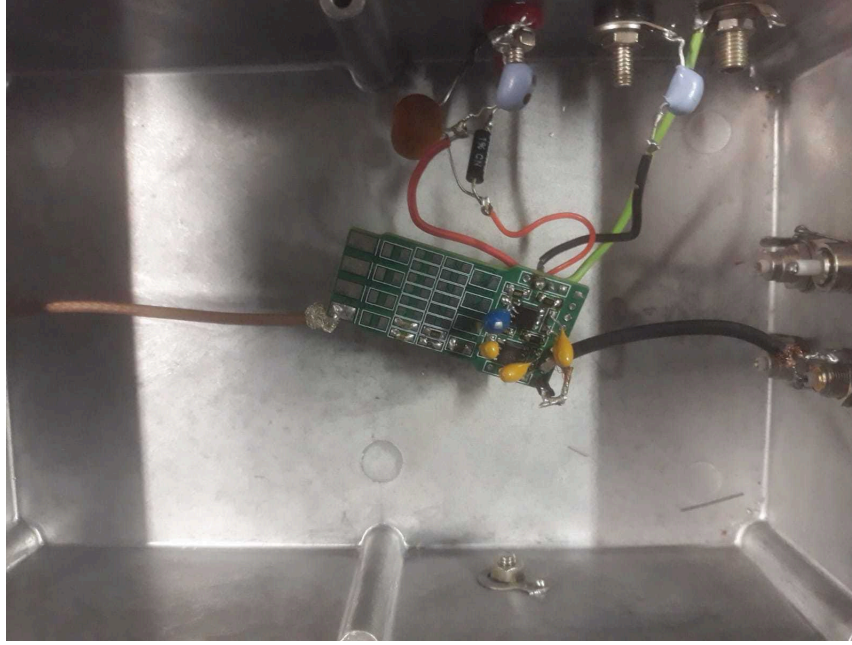


Figure 6.9: The SiPM amplifier board placed inside the aluminium box and the cables used to power the board and to send the amplified signal to the oscilloscope

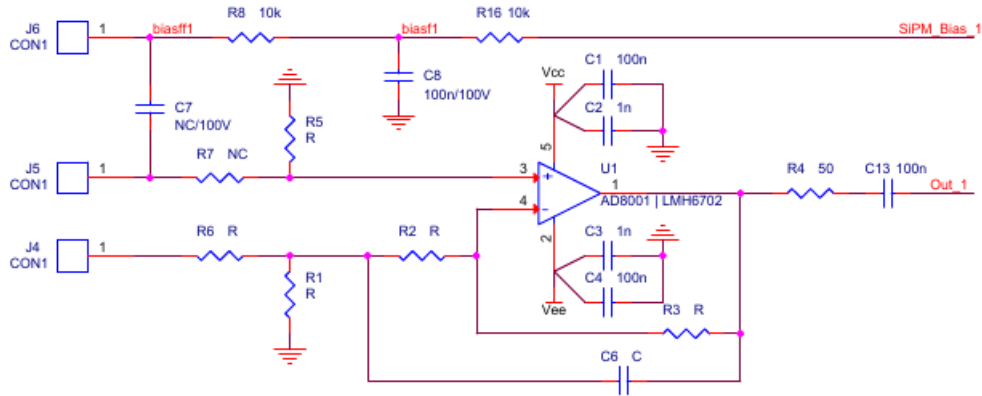


Figure 6.10: Schematic view of the amplifying circuit in the board.

The amplified signal is sent directly to the oscilloscope, which is located outside of the climatic chamber, and is readout via a custom software which I developed specifically for this measurement written in Python. The analog signal produced by the SiPM is shown in Fig. 6.11. Every time the oscilloscope fires a trigger the entire waveform is acquired and saved on a PC disk. The waveform consists of 50000 points sampled at the frequency of 100 MHz: 25000 points before the trigger and 25000 after the trigger for a total of 0.5 ms. Through the data acquisition period the temperatures of the SiPM was constantly monitored by two pt1000 sensors placed close to the sensor and readout by an

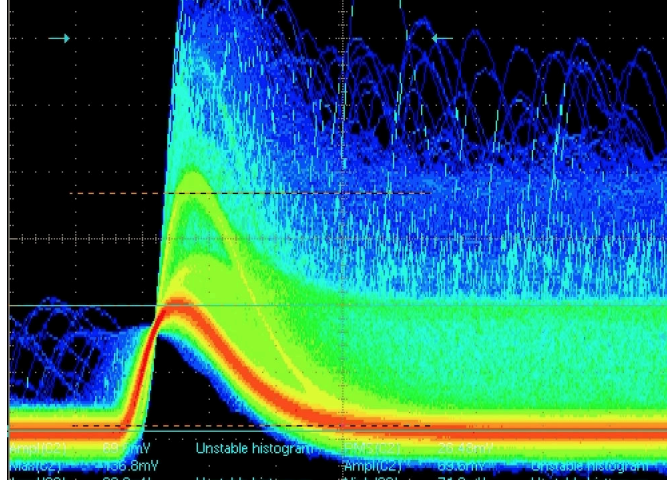


Figure 6.11: SiPM dark count waveforms recorded by the oscilloscope. The colors indicate the intensity. The waveforms correspond to 1 (red), 2(yellow) and 3(blue) fired cells.

Arduino [106].

In the following section I will describe how the data have been analyzed.

## 6.2.2 Data analysis strategy

The main SiPM parameters described in Section 6.1.2 can be measured experimentally using a pulse-shape analysis which calculates the time and amplitude distribution of the SiPM noise in dark condition. From the analysis of the amplitude vs. time-delay scatter plot and of its projections on the two axes, one is able to derive the main characteristics of the device. [107], [108]. Fig. 6.12 shows an illustrative scatter plot of a dark count signal amplitude vs its delay with respect to the preceding pulse. From this picture it is clear that the different noise contributions can be easily resolved.

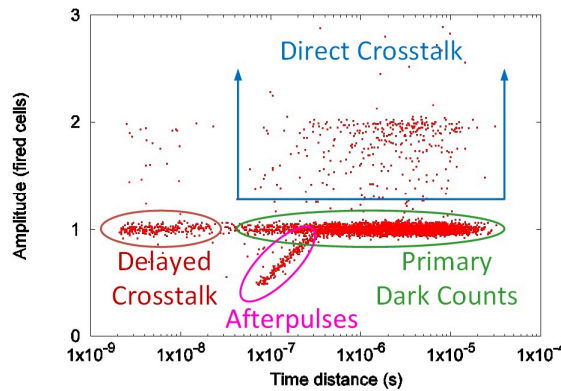


Figure 6.12: Illustrative scatter plot of a noise signal amplitude vs its delay with respect to the preceding pulse. The main components are clearly visible. Source [107]

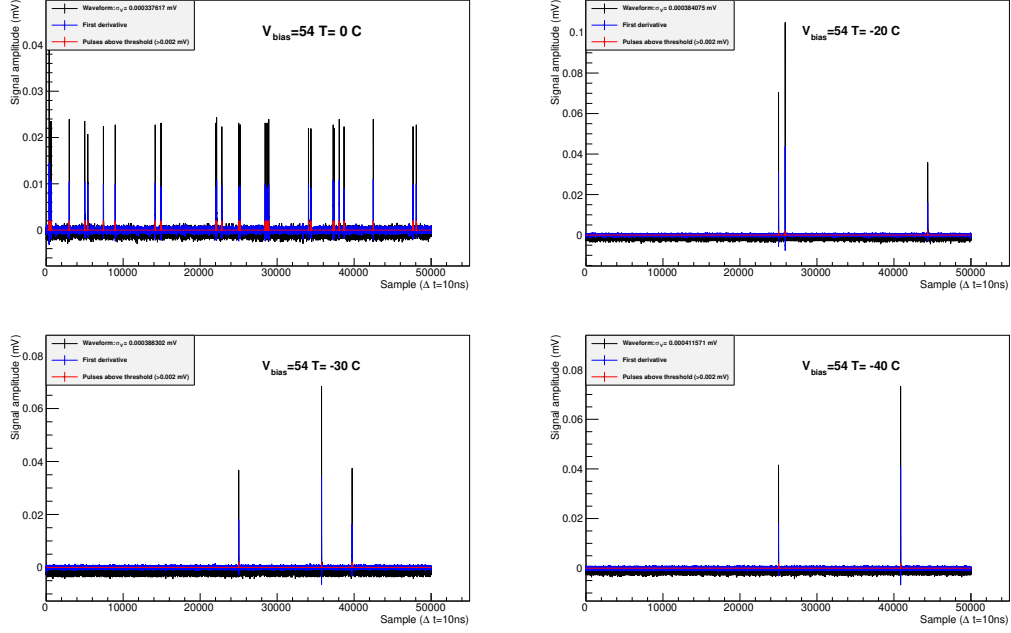


Figure 6.13: Typical dark count waveforms recorded at four different temperatures at  $V_{bias} = 54V$ .

Fig. 6.13 shows a typical waveform recorded at four different temperatures and at  $V_{bias} = 54V$ . Every time the signal in the waveform goes above a given threshold, it is identified as a peak. The threshold is chosen to be  $4\sigma$  over the noise in order to avoid identifying false peaks. As the original waveform has a slow rise time (50 ns) and a even slower decay time (150 ns), it was found that this peak-finding algorithm is very inefficient in separating two consecutive peaks when they happen to be closer in time than the decay time of the pulse. In order to improve the efficiency, the algorithm is applied to the derivative of the pulse instead which, as we can see in Fig. 6.14, turns out to be much faster. As a consequence we are now able to identify two consecutive peaks when they are separated in time by not less than  $\sim 50$  ns.

Once a peak  $i$  has been identified, we can measure its time of arrival  $t^i$  as the point when the threshold signal goes from 0 to high and its amplitude  $A^i$  as the maximum point in the waveform between  $t^i$  and the time of arrival of the next peak  $t^{i+1}$ .

By correlating  $t^i - t^{i-1}$ , the time difference between the pulse and its predecessor, with the amplitude of the signal  $A^i$  we can extract all the relevant parameters of the SiPM such as cross-talk, dark count rate and after-pulse probability as a function of the bias voltage and the temperature. Fig. 6.15 shows the scatter plot of the pulse amplitude  $A^i$  vs  $t^i - t^{i-1}$ .

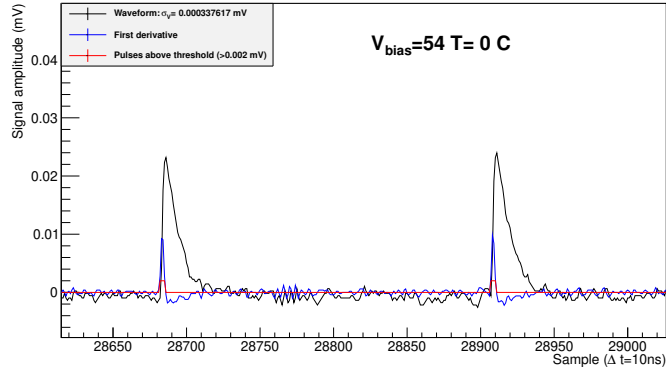


Figure 6.14: Zoom into a particular time window of the waveform. This plot shows clearly the high rise time and the slow decay time of the amplified SiPM pulse. The black waveform is the original signal, the blue one is the first derivative and the red one is the threshold level.

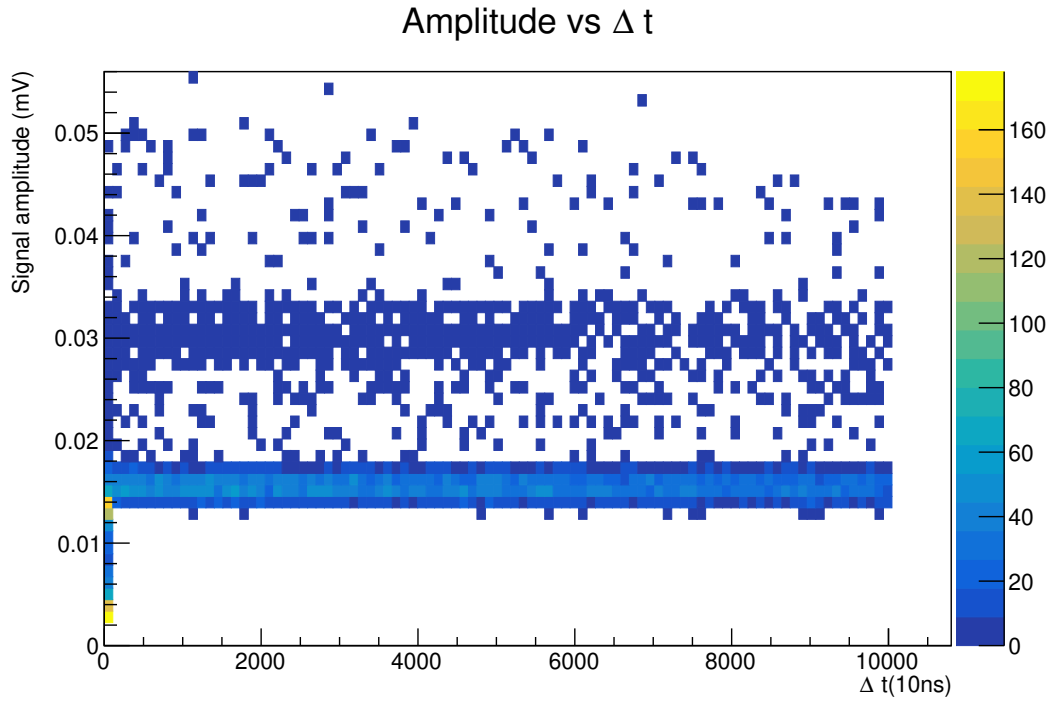


Figure 6.15: Scatter plot of the time difference between a pulse and its predecessor vs the amplitude of the pulse. The two bands corresponding to 1 and 2 thermal photo-electrons respectively are clearly visible. The low amplitude region on the left side of the plot is dominated by the after-pulses instead.

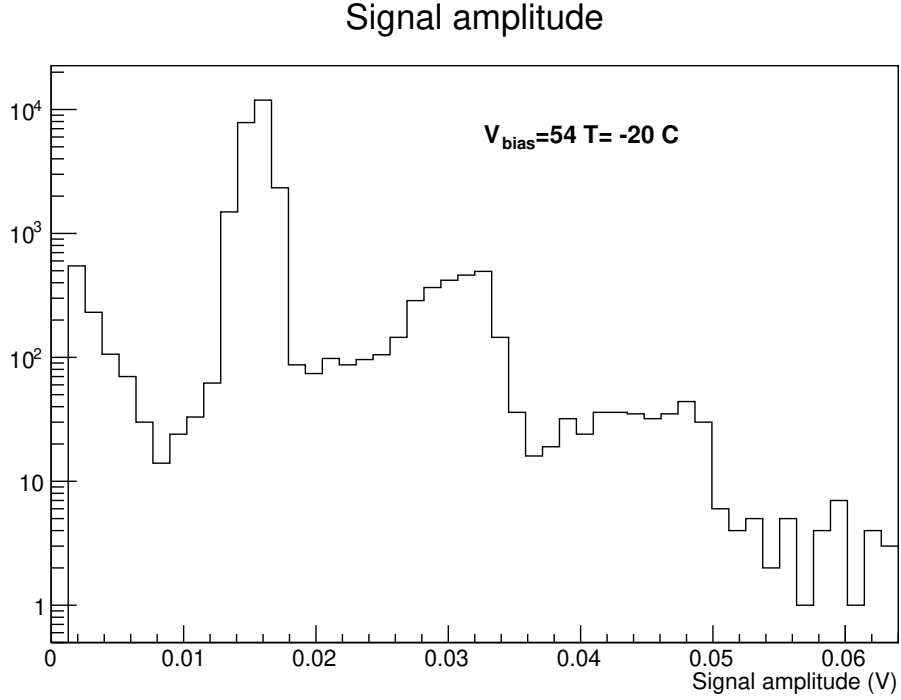


Figure 6.16: Example of the amplitude distribution of signals from the Hamamatsu device. The main peaks correspond to one or more cells fired whereas the small peak to the left of the main peak is due to after-pulsing events.

### 6.2.2.1 Gain

The first information that could be extracted from the recorded waveforms is the signal charge in units of electrons, which is commonly referred to as the gain of an SiPM. The correct determination of the gain would require a detailed calibration of the entire signal chain. However, determining the gain was not possible since the analysis was performed at a later stage and the entire set-up had already been dismantled. In this analysis the signal amplitude, which is taken as a proxy for the gain, is measured as a function of temperature and of  $V_{bias}$  instead. An example of the distribution of the signal amplitudes is shown in Fig. 6.16.

The amplitude of the 1 p.e peak is plotted in Fig. 6.17 as a function of  $V_{bias}$  and the temperature. The points in the graph are fitted with a linear function and the best fit values are listed in Tab. 6.4 and 6.5.

The parameters listed in Tab. 6.5 can also be used to estimate the break-down voltage as a function of the temperature; in fact  $V_{BD}$  can be calculated as the point when the signal amplitude is equal to 0. The break-down voltage  $V_{BD}$  as a function of temperature is shown in Fig. 6.18.

Since the properties of a SiPM depend on the overvoltage  $\Delta V = V_{bias} - V_{BD}$ , it is useful to express the signal amplitude as a function of  $\Delta V$  too. Fig. 6.19 shows the signal

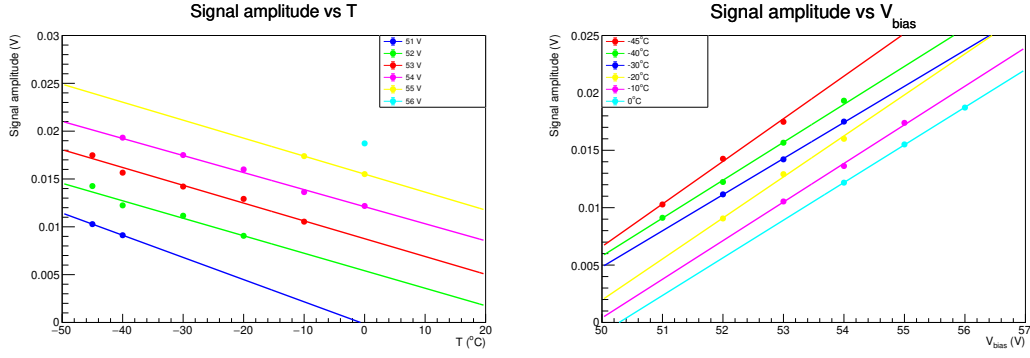


Figure 6.17: Signal amplitude as a function of  $V_{bias}$  and the temperature.

| $V_{bias}$ (V) | $\frac{dG}{dT}$          | Offset                   | T range( $^{\circ}C$ ) |
|----------------|--------------------------|--------------------------|------------------------|
| 51             | $-0.000232 \pm 0.000006$ | $-0.000160 \pm 0.000244$ | $[-45,0]$              |
| 52             | $-0.000183 \pm 0.000001$ | $0.005408 \pm 0.000035$  | $[-45,0]$              |
| 53             | $-0.000186 \pm 0.000001$ | $0.008757 \pm 0.000020$  | $[-45,0]$              |
| 54             | $-0.000178 \pm 0.000001$ | $0.012104 \pm 0.000013$  | $[-45,0]$              |
| 55             | $-0.000178 \pm 0.000001$ | $0.015510 \pm 0.000020$  | $[-45,0]$              |

Table 6.4: Extracted parameters from a linear fit to the SiPM pulse amplitude as a function of temperature for different values of the SiPM bias voltage.  $\frac{dG}{dT}$  is the slope of the line whereas Offset is the intercept. The errors are statistical only

amplitude as a function of the overvoltage.

### 6.2.2.2 After-pulse probability

The time spectrum contains dark-rate events and a contribution from after-pulses (see Fig. 6.20). The shape of the spectrum is related to the probability density for a dark-rate pulse to occur at a time  $t$  with respect to the previous pulse. The probability density for

| T( $^{\circ}C$ ) | $\frac{dG}{dV}$         | Offset                   | $V_{bias}$ range(V) |
|------------------|-------------------------|--------------------------|---------------------|
| 0                | $0.003280 \pm 0.000014$ | $-0.164925 \pm 0.000743$ | $[50,56]$           |
| -10              | $0.003364 \pm 0.000013$ | $-0.167792 \pm 0.000696$ | $[50,56]$           |
| -20              | $0.003573 \pm 0.000017$ | $-0.176709 \pm 0.000887$ | $[50,56]$           |
| -30              | $0.003147 \pm 0.000030$ | $-0.152522 \pm 0.001604$ | $[50,56]$           |
| -40              | $0.003305 \pm 0.000016$ | $-0.159458 \pm 0.000809$ | $[50,56]$           |
| -45              | $0.003712 \pm 0.000030$ | $-0.178995 \pm 0.001530$ | $[50,56]$           |

Table 6.5: Extracted parameters from a linear fit to the SiPM pulse amplitude as a function of the SiPM bias voltage for different values of the temperature.  $\frac{dG}{dV}$  is the slope of the line whereas Offset is the intercept. The errors are statistical only

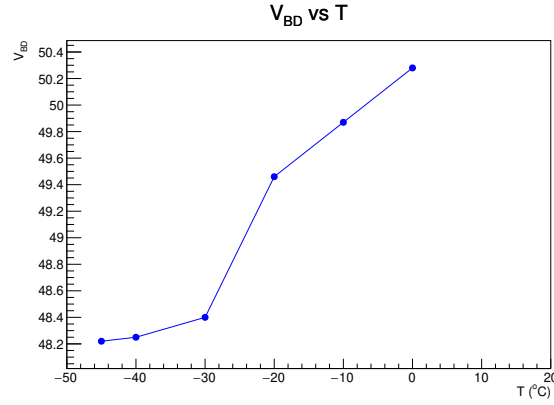


Figure 6.18: Break-down voltage  $V_{BD}$  as a function of the temperature.

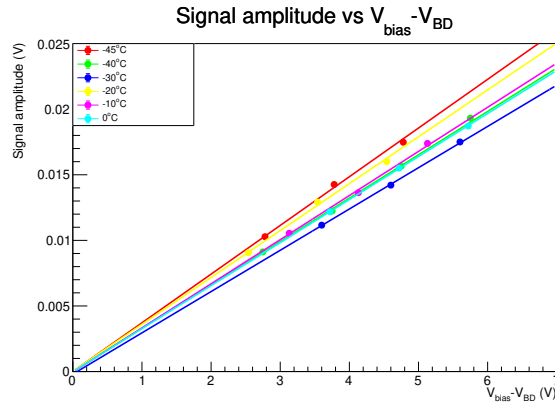


Figure 6.19: Signal amplitude as a function of the overvoltage  $\Delta V = V_{bias} - V_{BD}$  for 6 different values of the temperature.

thermal pulses is given by:

$$p_{DR}(t) = \frac{e^{-t/\tau_{DR}}}{\tau_{DR}} \quad (6.3)$$

For the after-pulse component, this probability density is given by:

$$p_{AP}(t) = P_{AP} \frac{e^{-t/\tau_{AP}}}{\tau_{AP}} \quad (6.4)$$

where  $P_{AP} < 1$  is the after-pulse probability and  $\tau_{AP}$  is the after-pulse time constant.

In general, there can be several after-pulse components with different time constants. If one assumes that the after-pulse probability density can be described by only one time constant the time spectrum  $\Delta t$  can be parametrized by the following equation:

$$N(\Delta t) = N \left( p_{DR}(\Delta t) \left[ 1 - \int_0^{\Delta t} p_{AP}(\Delta t') d\Delta t' \right] + p_{AP}(\Delta t) \left[ 1 - \int_0^{\Delta t} p_{DR}(\Delta t') d\Delta t' \right] \right) \quad (6.5)$$



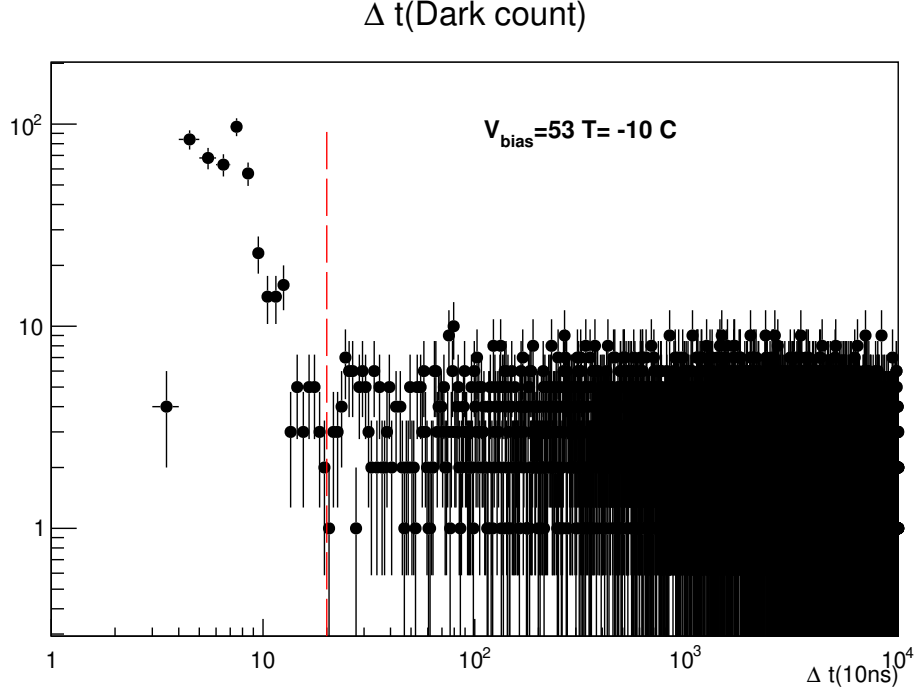


Figure 6.20: Distribution of the time difference  $\Delta t$  between two consecutive pulses. The red vertical dashed line separates the after-pulses dominated region ( $\Delta t < 200\text{ns}$ ) from the thermal dark count region ( $\Delta t > 200\text{ns}$ )

where  $N$  is the total number of entries in the spectrum. The parameters  $P_{AP}$ ,  $\tau_{AP}$ ,  $\tau_{DR}$  can be extracted by fitting the time spectrum.

Since the measurements were taken at low temperature where the dark count rate drops significantly, it follows that  $\tau_{DR} \gg \tau_{AP}$ . Consequently Eq. 6.5 can be simplified into:

$$N(\Delta t) = N \left[ \frac{e^{-\Delta t/\tau_{DR}}}{\tau_{DR}} \cdot (1 - P_{AP}) + \frac{e^{-\Delta t/\tau_{AP}}}{\tau_{AP}} \cdot P_{AP} \right] \quad (6.6)$$

Since  $\tau_{DR} \gg \tau_{AP}$  one can see that the region  $\Delta t > 200\text{ns}$  is virtually after-pulse free and, therefore, we can simply split the time spectrum in two regions, the after-pulse region satisfying  $\Delta t < 200\text{ns}$  and the dark count region satisfying  $\Delta t > 200\text{ns}$ , and count the number of entries in each region to get an estimate of the total number of after-pulses,  $N_{AP}$ , and dark counts,  $N_{DR}$ . The after-pulse probability  $P_{AP}$  is then simply given by:

$$P_{AP} = \frac{N_{AP}}{N_{DR} + N_{AP}} \quad (6.7)$$

As discussed above, the after-pulse candidates were selected by requiring  $60\text{ns} < \Delta t < 200\text{ns}$  and that the signal amplitude be  $< A_{1p.e} - 2\sigma_{A_{1p.e}}$ , where  $\sigma$  is the resolution of the first photo-electron peak and  $A_{1p.e}$  the amplitude of the first photo-electron. As explained at the beginning of Section 6.2.2, the lower cut at  $60\text{ns}$  is motivated by the fact that the

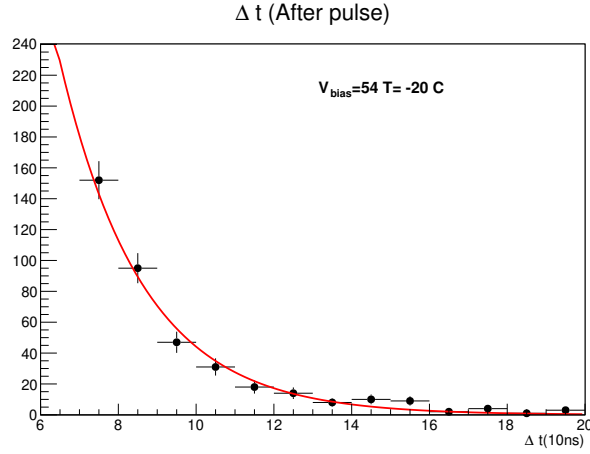


Figure 6.21:  $\Delta t$  distribution in the after-pulse dominated region at  $V_{bias} = 54V$  and  $T = -20^\circ C$  with the exponential function superimposed.

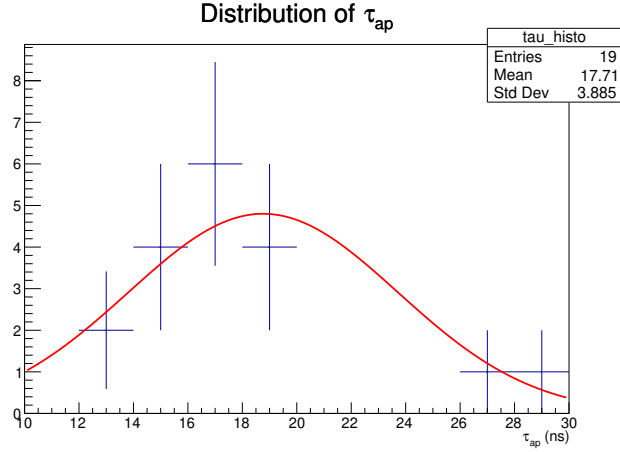


Figure 6.22: Distribution of the extracted  $\tau_{AP}$

high rising time of the waveform does not allow to distinguish two overlapping pulses if they are separated by less than  $50\text{ ns}$  from each other.

Assuming that the after-pulse probability is well modelled by Eq. 6.4, the total number of after-pulses  $N_{AP}$  can be derived from the exponential fit to the data in the after-pulse region. The other parameter obtained from the fit is the after-pulse trapping constant  $\tau_{AP}$ . Fig. 6.21 shows an example of the time distribution in the after-pulse region with the exponential fit on top of it. The distribution of the extracted  $\tau_{AP}$  for all the 19 measurements is shown in Fig. 6.22.

Even though 19 points are not obviously a large statistical sample, one can see that these values are described reasonably well by a Gaussian distribution with a mean of  $\sim 18\text{ ns}$  and a resolution of  $\sim 4\text{ ns}$ . This also suggests that  $\tau_{AP}$  depends neither on the temperature nor on the bias voltage.

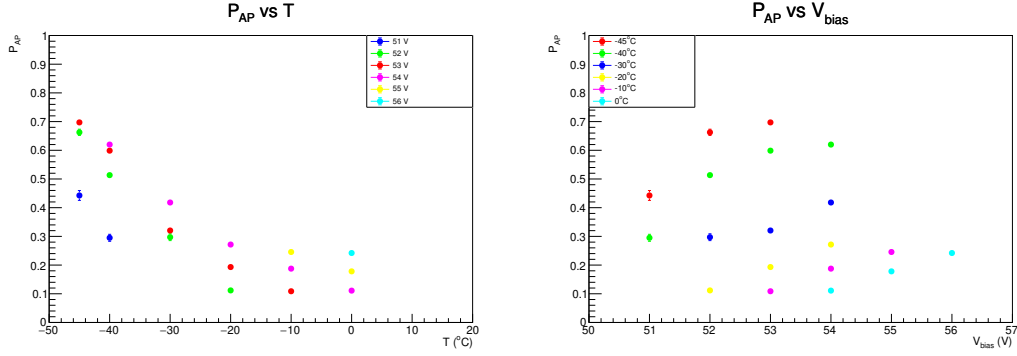


Figure 6.23: (Left) After-pulse probability as a function of the bias voltage. (Right) After-pulse probability as a function of temperature.

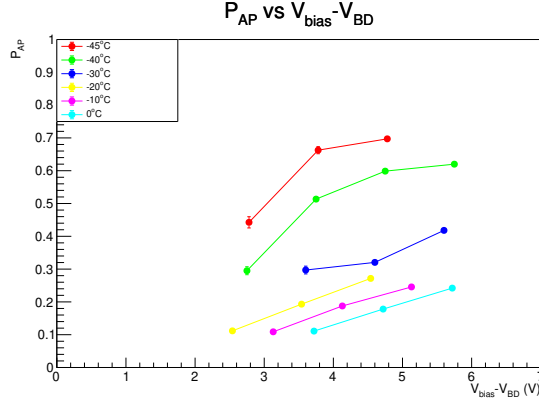


Figure 6.24: After-pulse probability as a function of the overvoltage.

Once  $N_{AP}$  and  $N_{DR}$  have been determined, the after-pulse probability  $P_{AP}$  can be calculated using Eq. 6.7. Fig. 6.23 shows the measured  $P_{AP}$  as a function of the temperature and as a function of the bias voltage.

As expected, the after-pulse probability increases with  $V_{bias}$ ; this can be easily explained with an increase of the avalanche probability when  $V_{bias}$  increases. We also observe an interesting increase of the after-pulsing probability when the temperature decreases and this can be explained by considering that more trapped carriers are released before the cell recovers to a meaningful breakdown probability when the temperature is higher. Using the values of the break-down voltage (see Fig. 6.18), we can also plot  $P_{AP}$  as a function of the overvoltage (see Fig. 6.24).

What is shown in Fig. 6.23 is the true  $P_{AP}$  estimated according to a model that assumes that the recovery time of the pixel is zero. This is why we see very high values for the after-pulse probability. In order to take into account also the finite recovery time of the fired pixel Eq. 6.4 must be modified by multiplying it by the term  $1 - e^{-t/\tau_R}$  so

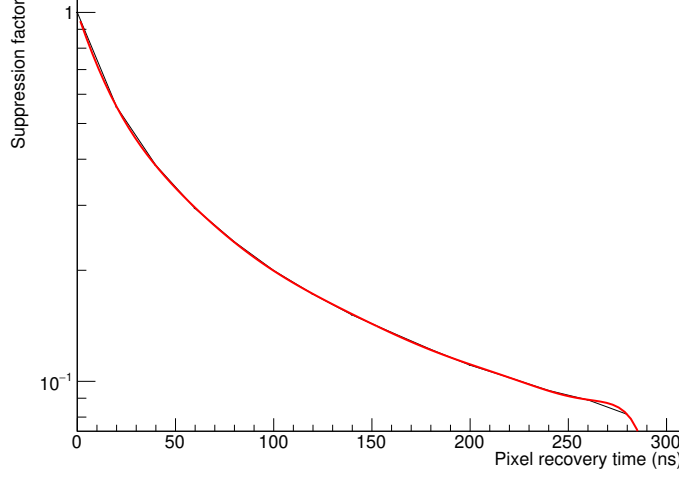


Figure 6.25: Suppression factor as a function of the pixel recovery time obtained from the simulation. The curve was fitted with a ninth order polynomial.

that the term describing the after-pulse probability becomes:

$$p_{AP}(t) = P_{AP} \frac{e^{-t/\tau_{AP}}}{\tau_{AP}} \left(1 - e^{-t/\tau_R}\right) \quad (6.8)$$

Instead of refitting the time distribution of the after-pulses with the modified pdf, I chose to correct for this effect using a simple simulation whereby an event  $t_i$  is generated according to an exponential distribution with time constant  $\tau_{AP} = 18$  ns and then a second number is generated according to a uniform distribution in the range  $[0,1]$ . If the number is  $< 1 - e^{-t_i/\tau_R}$  the event is retained. By counting the ratio between the generated and the retained events, we obtain a correction factor to be applied to  $P_{AP}$ . This correction factor was calculated for different values of the pixel recovery time, as shown in Fig. 6.25. The corrected after-pulse probability as a function of the overvoltage is shown in Fig. 6.26.

### 6.2.2.3 Dark count rate

The dark count candidates are required to have  $\Delta t > 200$  ns and amplitude of  $A = A_{1p.e} \pm 2\sigma_{A_{1p.e}}$ . As one can see in Fig. 6.27, this spectrum is well described by the exponential distribution 6.3. Fitting the distribution of  $\Delta t$  in the dark count region allows us to measure  $\tau_{DR}$ , which is related to the dark count rate  $R_{DR}$  by:

$$R_{DC} = \frac{1}{\tau_{DR}} \quad (6.9)$$

The extracted rates are plotted as a function of the temperature and of the  $V_{bias}$ , as shown in Fig 6.28. The dark count rate as a function of temperature for a fixed bias

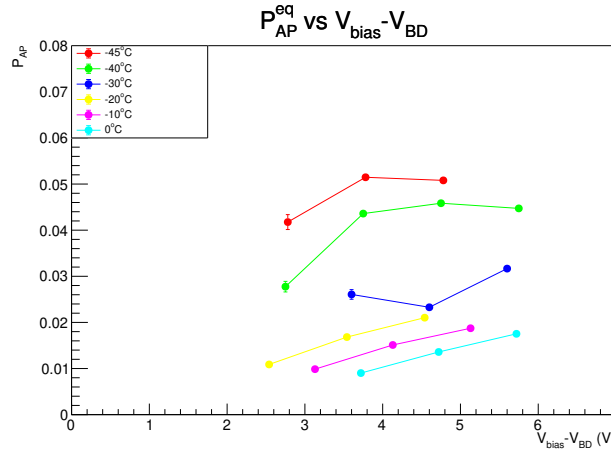


Figure 6.26: Corrected after-pulse probability as a function of the overvoltage.

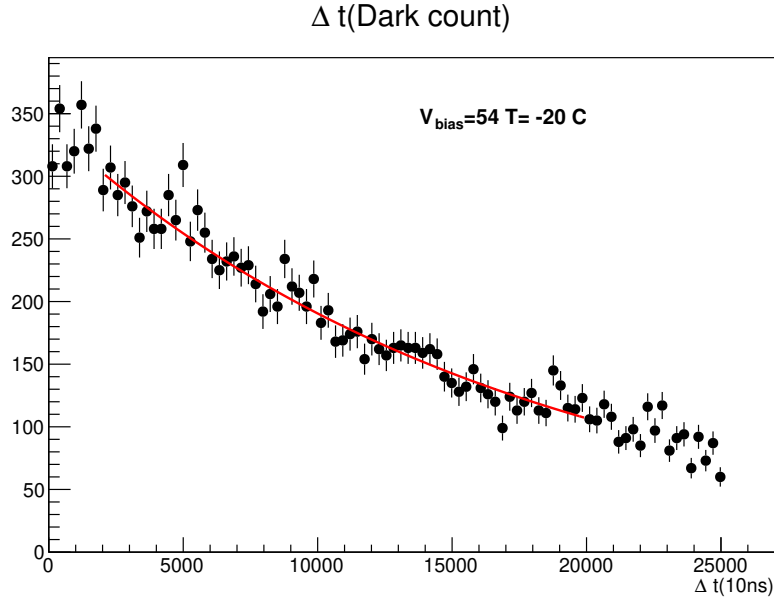


Figure 6.27:  $\Delta t$  distribution in the dark counts dominated region at  $V_{bias} = 54$  V and  $T = -20^\circ\text{C}$  with the exponential function superimposed.

voltage is well described by an exponential function

$$DR(T) = e^{\alpha + \beta T} \quad (6.10)$$

The result of the fit is reported in Tab 6.6. The dark count rate as a function of  $V_{bias}$  for a fixed temperature is well described by a linear function instead. The result of the fit is reported in Tab. 6.7.

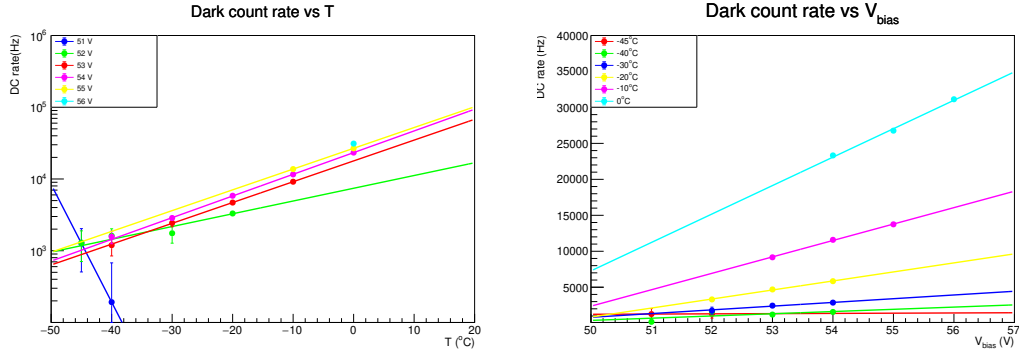


Figure 6.28: Left: Dark count rate in Hz as a function of the temperature with  $V_{bias}$  fixed. Right: Dark count rate in Hz as a function of  $V_{bias}$  at a fixed temperature.

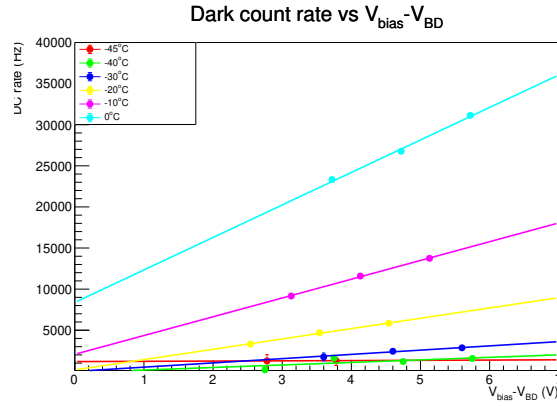


Figure 6.29: Dark count rate in Hz as a function of the overvoltage at a fixed temperature.

#### 6.2.2.4 Cross talk probability

The cross-talk parameter is determined from the amplitude spectrum of dark-rate pulses (see Fig. 6.16). Pulses which occur within a time interval of  $\Delta t < 200$  ns after the preceding pulse are excluded from the spectrum as this rejects the region dominated by the after-pulses. The cross-talk probability is given by counting the number of dark

| $V_{bias}$ (V) | $\alpha$                 | $\beta$                   | T range ( $^{\circ}C$ ) |
|----------------|--------------------------|---------------------------|-------------------------|
| 51 V           | $-0.377655 \pm 0.367180$ | $-9.848525 \pm 16.430044$ | $[-45,0]$               |
| 52 V           | $0.040943 \pm 0.011268$  | $8.912465 \pm 0.257834$   | $[-45,0]$               |
| 53 V           | $0.066781 \pm 0.003303$  | $9.790311 \pm 0.040036$   | $[-45,0]$               |
| 54 V           | $0.069607 \pm 0.000994$  | $10.056461 \pm 0.007853$  | $[-45,0]$               |
| 55 V           | $0.066662 \pm 0.000944$  | $10.195000 \pm 0.005330$  | $[-45,0]$               |

Table 6.6: Extracted parameters from an exponential fit to the SiPM dark count rate as a function of temperature for different values of the SiPM bias voltage. Errors are statistical only.

| T(°C) | $\frac{dDR}{dV}$             | Offset                        | $V_{bias}$ range(V) |
|-------|------------------------------|-------------------------------|---------------------|
| 0     | $3953.328146 \pm 118.253011$ | $8380.123508 \pm 583.431445$  | [50,56]             |
| -10   | $2283.294242 \pm 83.695263$  | $2069.757485 \pm 362.594929$  | [50,56]             |
| -20   | $1255.997644 \pm 136.204855$ | $169.449247 \pm 520.094755$   | [50,56]             |
| -30   | $517.583132 \pm 248.688462$  | $-11.103515 \pm 1243.966256$  | [50,56]             |
| -40   | $308.353651 \pm 174.851647$  | $-152.698197 \pm 826.359017$  | [50,56]             |
| -45   | $30.680000 \pm 966.160908$   | $1183.669600 \pm 3321.278688$ | [50,56]             |

Table 6.7: Extracted parameters from a linear fit to the SiPM dark count rate as a function of the SiPM bias voltage for different values of the temperature

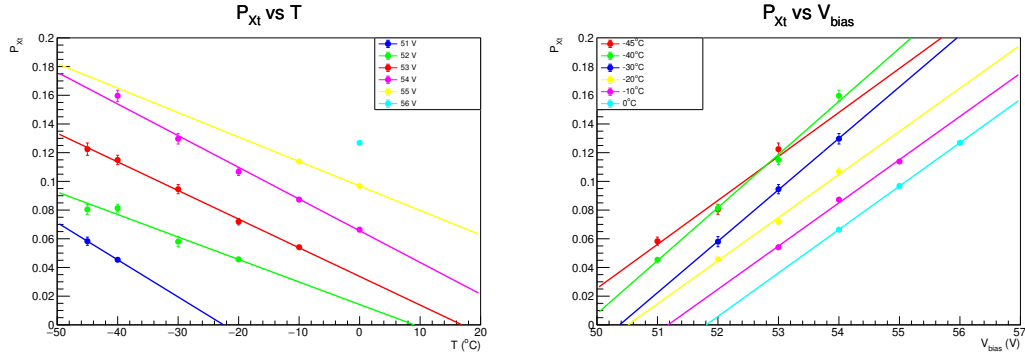


Figure 6.30: Right: Cross-talk probability as a function of temperature. Left: Cross-talk probability as a function of  $V_{bias}$ .

counts with amplitude  $> 1.5p.e$  and dividing this by the total number of dark counts with amplitude  $> 0.5p.e$ . The cross-talk probability  $P_{CT}$  is thus given by:

$$P_{CT} = \frac{N_{A>1.5pe}^{DR}}{N_{A>0.5pe}^{DR}} \quad (6.11)$$

Fig. 6.30 shows the measured cross-talk probabilities at different values of temperatures and  $V_{bias}$ . We can see that  $P_{CT}$  grows linearly at constant  $V_{bias}$  as the temperature decreases. When the temperature is kept constant,  $P_{CT}$  increases linearly with  $V_{bias}$ . The points in the graphs were fitted with linear functions and the extracted parameters are reported in Tab. 6.8 and 6.9.

Using the values of the break-down voltage (see Fig. 6.18) we plot, in Fig. 6.31,  $P_{CT}$  as a function of the overvoltage. We can clearly see that, once the break-down voltage  $V_{BD}$  dependence on the temperature is taken into account, the cross-talk probability is much less influenced by the temperature.

### 6.2.2.5 Pixel recovery time

The recovery time of a pixel usually ranges from  $\sim 10$  ns to few hundreds of ns.

Cell recovery times can be measured by flashing an SiPM with two consecutive pulses

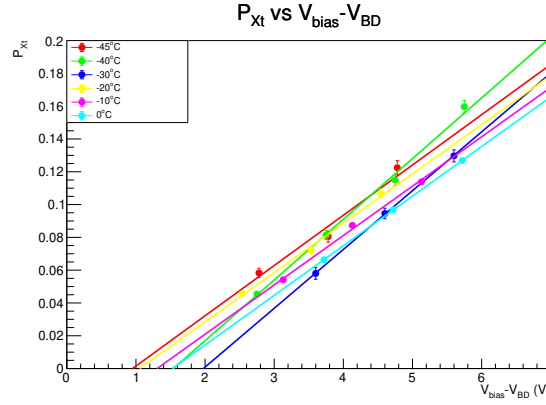


Figure 6.31: Cross-talk probability as a function of the overvoltage.

| $V_{bias}$ (V) | $\frac{dP_{CT}}{dT}$     | Offset                   | T range ( $^{\circ}C$ ) |
|----------------|--------------------------|--------------------------|-------------------------|
| 51 V           | $-0.002590 \pm 0.000694$ | $-0.058230 \pm 0.028954$ | $[-45,0]$               |
| 52 V           | $-0.001568 \pm 0.000128$ | $0.014193 \pm 0.004032$  | $[-45,0]$               |
| 53 V           | $-0.001996 \pm 0.000088$ | $0.033768 \pm 0.001996$  | $[-45,0]$               |
| 54 V           | $-0.002209 \pm 0.000081$ | $0.065600 \pm 0.001241$  | $[-45,0]$               |
| 55 V           | $-0.001705 \pm 0.000244$ | $0.096812 \pm 0.001630$  | $[-45,0]$               |

Table 6.8: Extracted parameters from a linear fit to the cross-talk probability as a function of temperature for different values of the SiPM bias voltage

and recording how the second SiPM signal amplitude changes as a function of the time difference between the two pulses. The recovery time can also be measured by analyzing the amplitude vs. time characteristics of after-pulses. In this analysis the latter procedure has been used.

The after-pulse candidates were selected by requiring  $60ns < \Delta t < 200ns$  and  $A < A_{1p.e} - 2\sigma_{A_{1p.e}}$ , where  $\sigma$  is the resolution of the first photo-electron peak and  $A_{1p.e}$  the amplitude of the first photo-electron. The amplitude of the after-pulse is plotted as

| T ( $^{\circ}C$ ) | $\frac{dP_{CT}}{dV}$    | Offset                   | $V_{bias}$ range (V) |
|-------------------|-------------------------|--------------------------|----------------------|
| 0                 | $0.030258 \pm 0.001120$ | $-1.567541 \pm 0.061472$ | $[50,56]$            |
| -10               | $0.030105 \pm 0.001150$ | $-1.540652 \pm 0.061911$ | $[50,56]$            |
| -20               | $0.030065 \pm 0.001586$ | $-1.518684 \pm 0.083747$ | $[50,56]$            |
| -30               | $0.035861 \pm 0.002550$ | $-1.806500 \pm 0.135131$ | $[50,56]$            |
| -40               | $0.037004 \pm 0.001278$ | $-1.842430 \pm 0.066417$ | $[50,56]$            |
| -45               | $0.030655 \pm 0.002509$ | $-1.507310 \pm 0.129821$ | $[50,56]$            |

Table 6.9: Extracted parameters from a linear fit to the cross-talk probability as a function of the SiPM bias voltage for different values of the temperature



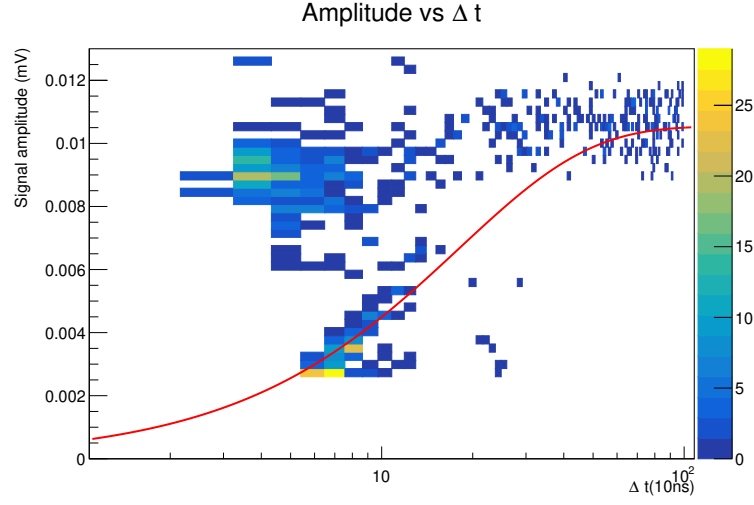


Figure 6.32: Scatter plot of the signal amplitude vs its delay with respect to the preceding pulse with the fitted curve  $A(t) = A_0(1 - e^{-t/\tau_r})$  in red superimposed.

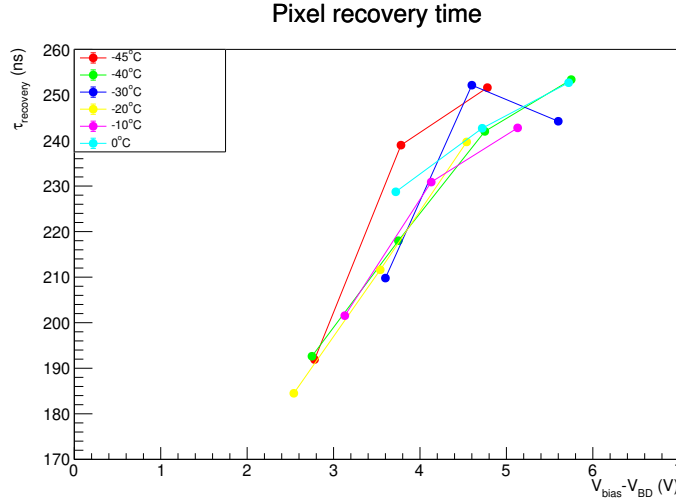


Figure 6.33:  $\tau_{recovery}$  extracted from the fit as a function of the overvoltage  $\Delta V$ .

a function of its delay with respect to the preceding pulse and the curve is fitted with the function  $A(t) = A_0(1 - e^{-t/\tau_r})$ . In the fit,  $\tau_r$  is left floating whereas  $A_0$  is fixed and constrained to be equal to  $A_{1p.e.}$ . An example of a fit is shown in Fig. 6.32.

As  $\tau_r$  is basically determined by the product of the quenching resistor  $R_q$  and the junction capacitance  $C_j$  we expect it to depend in general on the temperature and not on the overvoltage. However, this could be due to the fact that an increase in the overvoltage is followed by an increase in the after-pulsing probability. The increased after-pulses block the recharge of a microcell increasing the recovery time. A further cross-check would be to directly measure  $R_q$  and  $C_j$  and see if  $\tau_r$  is in good agreement with their product.

### 6.3 Simulation studies

As already stated in the introduction, during the Run1 and Run2 phase, some regions of the photon detector array in RICH1 reached occupancies of up to 30%. Occupancy is defined as the fraction of detected photons over the total number of channels. The 30% value for the occupancy is seen as an upper limit beyond which the particle identification performance of the RICH starts to deteriorate. Even if the measurements in the laboratory demonstrate that the tested SiPM from Hamamatsu has small cross-talk probability and a very small after-pulsing probability for different values of the temperature, radiation damage may cause this parameters to change and increase. As discussed in Section 6.1.2, the performances of a SiPM can be significantly affected by the presence of both correlated and uncorrelated noise and their dependence on the temperature and on the bias voltage is not trivial, as has been demonstrated in 6.2. The goal of this preliminary work is therefore to assess the impact of all the excess noise factors that a SiPM has on the average occupancy. In fact, it is expected that both correlated and uncorrelated noise will increase the detector occupancy and their impact was evaluated with the help of a simulation framework. The GosSiP framework [109, 110], is designed to provide a detailed model of the SiPM response. This simulation tool, originally developed for the Mu3e Collaboration [111], can be used for a large variety of applications and essentially allows to model any type of SiPM by specifying the corresponding device parameters. The task of the simulation is to generate the SiPM signal waveform and output charge for a given incident lightpulse. The simulation concept is based on Monte Carlo methods and allows to model all the different noise sources and saturation effects. The input for the simulation comprises the information about the incoming light pulse and the basic parameters describing the SiPM properties: PDE, gain, single pixel amplitude, thermal pulse time constant  $\tau_{DC}$ , after-pulsing probability  $P_{AP}$ , after-pulse time constant  $\tau_{AP}$ , cross-talk probability  $P_{CT}$ , pixel recovery time  $\tau_R$ , electronic noise, the single pixel pulse shape, as well as the number of pixels and the detector size. The default option used to model the single pixel pulse shape is

$$A(t) = A_0(e^{-t/\tau_{rise}} + e^{-t/\tau_{decay}}) \quad (6.12)$$

where  $\tau_{rise}$  and  $\tau_{decay}$  are respectively the rise time and the decay time of the single pixel analog pulse. It is important to note that the simulation software does not simulate the avalanche process itself and therefore does not predict the basic parameters which have to be experimentally measured. As a first test to check whether this simulation tool is able reproduce the experimental data, I compared the distribution of the  $\Delta t$  acquired with the oscilloscope to the corresponding simulated spectrum. The result for two particular measurements is shown in Fig. 6.34. As one can see the data-MC agreement is quite satisfactory for  $\Delta t$  down to 50 ns. The evident difference for  $\Delta t < 50$  ns is due to the reconstruction algorithm used in the data which is not able to identify efficiently two peaks separated by less than 50 ns.

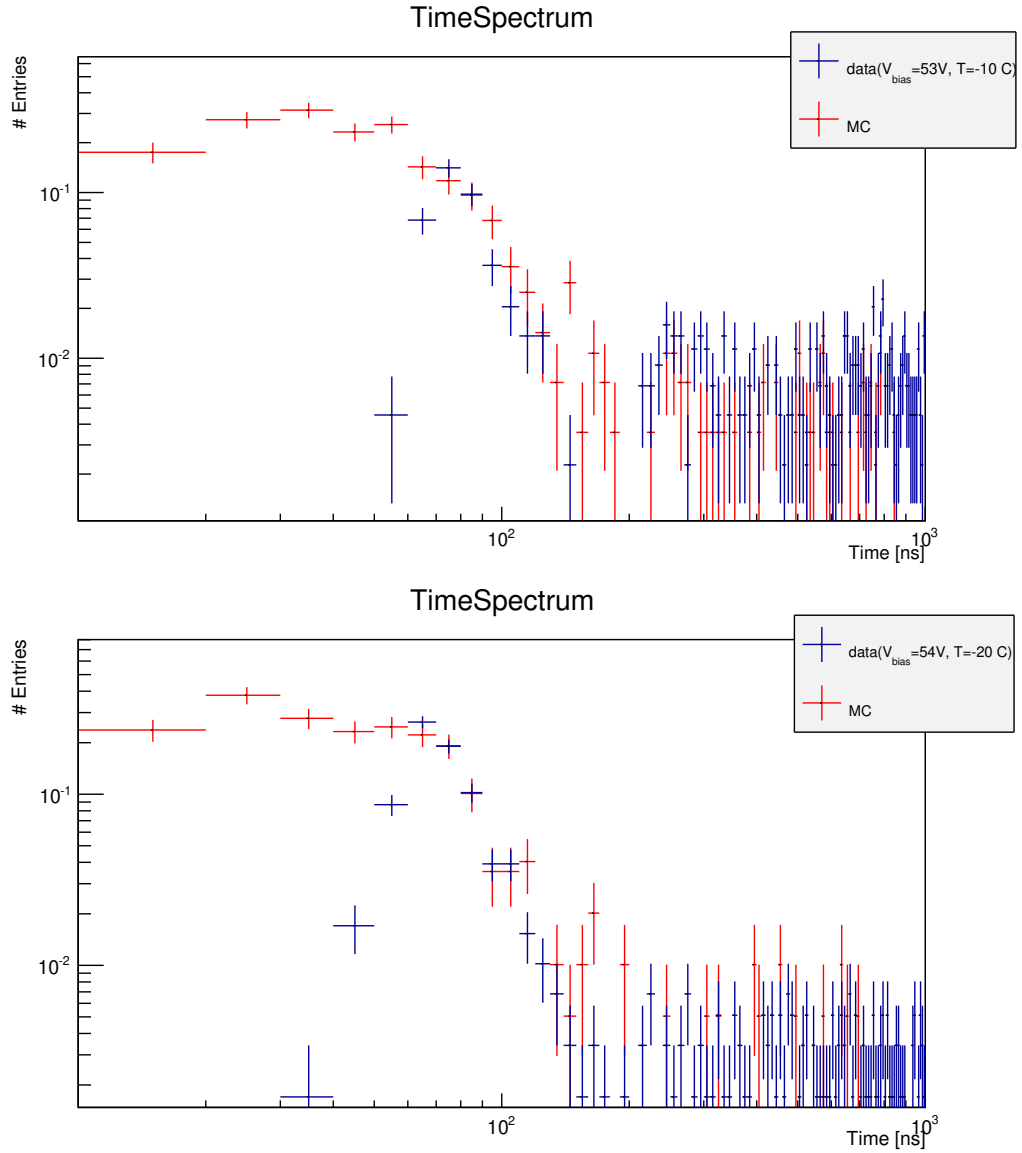


Figure 6.34: Top: Comparison between the  $\Delta t$  distribution measured in the data at  $V_{bias} = 53V$  and  $T = -10^\circ C$  and the one obtained from GosSiP by using the parameters extracted from the data as input to the simulation. Bottom: Comparison between the  $\Delta t$  distribution measured in the data at  $V_{bias} = 54V$  and  $T = -20^\circ C$  and the one obtained from GosSiP by using the parameters extracted from the data as input to the simulation.

### 6.3.1 Evaluation of the effect of the SiPM intrinsic noise on the average occupancy

By design the simulation tool simulates the analog output of a SiPM for a time frame of a given length. If one wishes to simulate more frames the events belonging to one frame are independent from the events belonging to a different frame; this feature is not very

useful one has to take into account spillover events. Spillover is defined as the activity from other bunch crossings that affects the bunch crossing of interest, thus increasing the overall background level. For this reason part of the code was changed and re-arranged in a way that is possible to simulate many frames in a row with spillover effects included. In the simulation the time is divided in frames of 25 ns, corresponding to a bunch crossing event at the LHC and the response of a SiPM is simulated for a total length of 100000 frames. An example of the simulated SiPM output for two consecutive 25 ns frames is shown in Fig. 6.35. In the simulation the number of pixels is  $20 \times 20$  in order to model as close as possible the SiPM (see Tab. 6.2) used during the characterization phase. In order to simulate an average occupancy of 30% a random number between 0 and 10 is generated and, if the number is  $< 3$ , a random pixel of the  $20 \times 20$  matrix is chosen; this simulates the arrival of a Cherenkov photon on the device. The time at which the photon hits the SiPM has a gaussian time profile centered around 10 ns with a time spread of 1 ns. This time structure is chosen as an approximation of the main peak in Fig. 6.4, which shows the time of arrival distribution of Cherenkov photons resulting from particles produced in the proton-proton collisions. The PDE is chosen equal to 1 as its effect is already accounted for in the value of the average occupancy. An example of the result of the simulation showing the time distribution of the signal and of the different source of noise in a SiPM after a period corresponding to 1000000 bunch crossing is shown in Fig. 6.36. As is clear from the picture, the effect of many bunch crossing events increases the level of background.

In Section 6.3.1.1 the results of the simulation with different input parameters are shown.

### 6.3.1.1 Results of the simulation

The simulation was performed for different values of the input parameter in order to show different possible scenarios and they are reported in Tab. 6.10. The time constant of the after-pulse component,  $\tau_{AP}$  and the recovery time of a single pixel cell,  $\tau_R$ , used in the simulation were taken to be similar to those measured experimentally for the device (see 6.2.2). For the dark count rate two values were chosen: 1 MHz and 5 MHz. This is done to simulate a scenario in which the SiPM have already absorbed a significant amount of radiation and, consequently, their dark count rate has increased significantly. According to [105] this would correspond to the value of dark count rate measured at  $-30^\circ C$  after absorbing a dose of about  $10^{11} - 10^{12} n_{eq}/cm^2$ . The single pixel pulse shape used in the simulation is the one provided by default by the tool (see Eq. 6.12). The signal rise time was taken to be  $\tau_{rise} = 1$  ns whereas two different values were tested for the decay time  $\tau_{decay}$ . In this way it is possible to see the effects of the spillover if the pulse decay time is not short compared to the 25 ns of the bunch crossing. In the simulation the effect of the digitization was also taken into account, although in a simplified way; if the output pulse goes above the selected threshold in the time window  $[8 - 12]$  ns the pulse is counted. In the simulation the amplitude of the signal was taken to be 20 mV and the threshold was set to 2.5 mV, corresponding to  $\sim 5\sigma$  above the pedestal noise. This scheme is inspired by the use of a 3.125 ns hardware time gate in the Upgrade Ia PDMDB [92]. This gate was

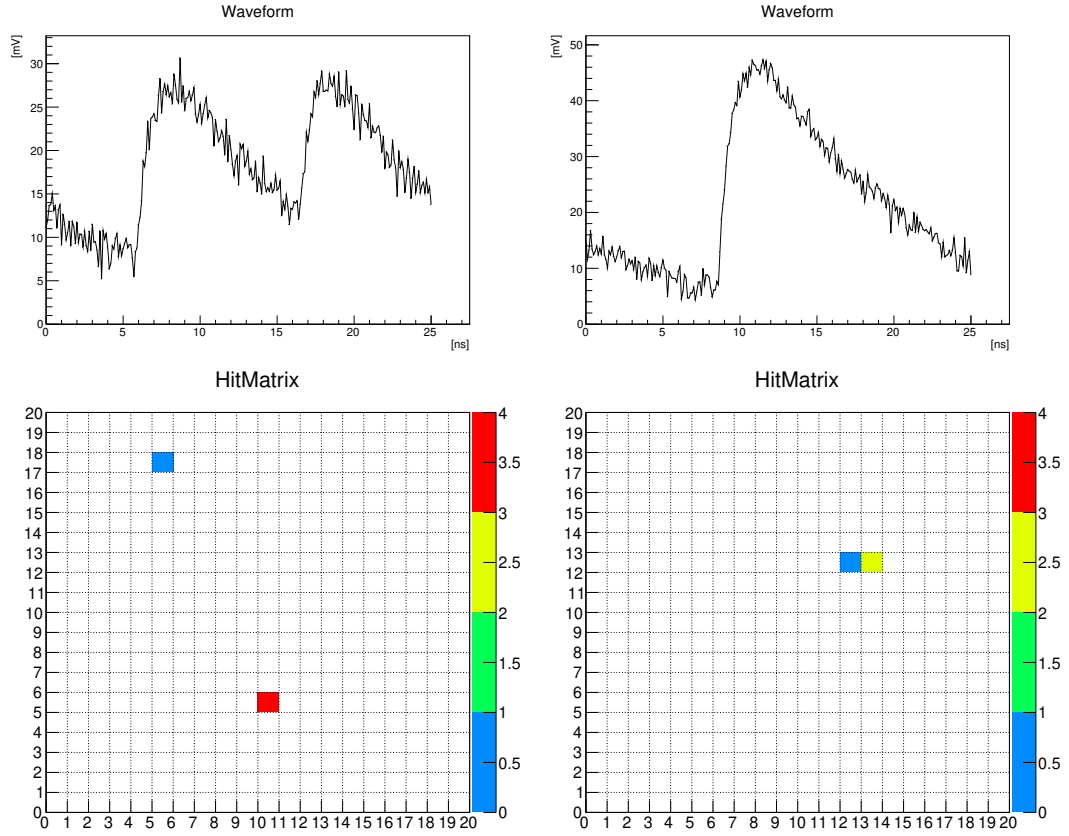


Figure 6.35: Top left: Simulated output of a SiPM within the 25 ns time frame. The first pulse corresponds to the photon whereas the second corresponds to an after-pulse event generated in a previous frame and appearing in this frame. This can be easily visualized in the plot below (bottom-left) where the pixel colored in blue was hit by the photon and the pixel colored in red is the pixel giving an after-pulse. Top right: Simulated output of the SiPM in the next 25 ns time frame. The simulated output pulse is given by the sum of the tail from after-pulse of the previous frame plus an other photon and a correlated cross-talk event happening simultaneously. This can be easily visualized in the plot below (bottom-right) where the pixel colored in blue was hit by the photon and the pixel colored in yellow is the pixel giving a cross-talk.

developed mainly to reduce to an acceptable level the signal-induced noise present in the MaPMTs. The results of the simulation are shown in Fig. 6.37, 6.38, 6.39, 6.40, 6.41, 6.42, 6.43, 6.44.

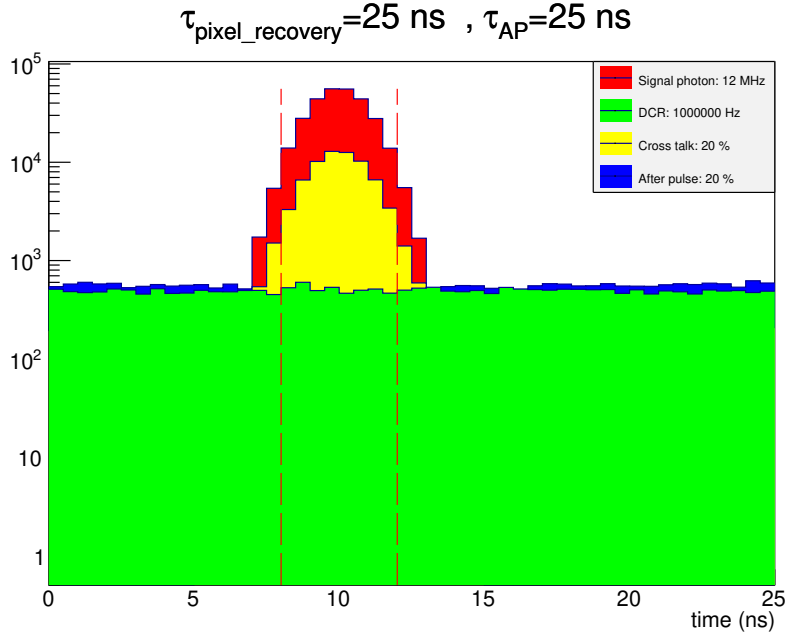


Figure 6.36: Time distribution of the signal and the three different sources of noise inside the 25 ns window frame obtained after simulating 1000000 frames.

| Input parameters    |                        |              |          |          |
|---------------------|------------------------|--------------|----------|----------|
| $\tau_R(\text{ns})$ | $\tau_{AP}(\text{ns})$ | DC rate(MHz) | $P_{xt}$ | $P_{AP}$ |
| 75, 150             | 25                     | 1, 5         | [0..0.8] | [0..1]   |

Table 6.10: Input parameters used in the simulation. [...] indicates that the parameters was chosen in that range in steps of 0.1.

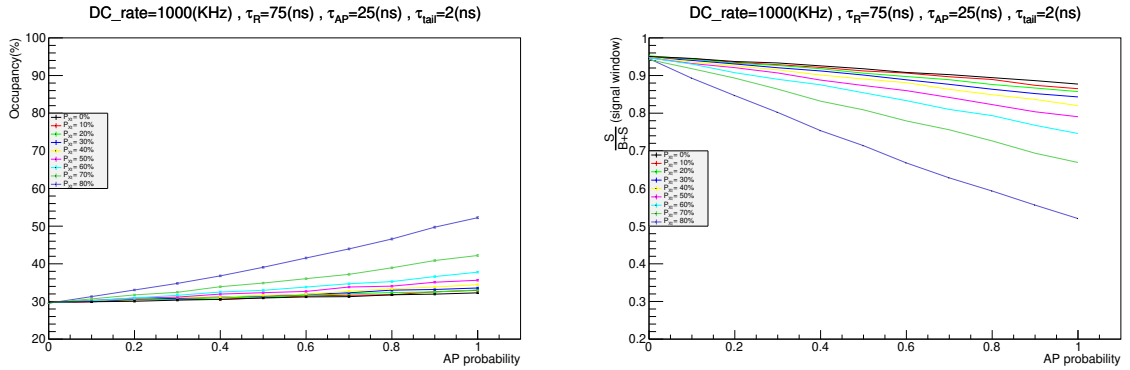


Figure 6.37: Left: Measured occupancy as a function of the after-pulse probability  $P_{AP}$  at different values of the cross-talk probability. In this case the dark count rate is 1 MHz, the pixel recovery time  $\tau_R = 75 \text{ ns}$ , the time constant of the after-pulse  $\tau_{AP} = 25 \text{ ns}$  and the pulse decay time  $\tau_{\text{decay}} = 2 \text{ ns}$ . Right:  $\frac{S}{S+B}$  ratio as a function of the after-pulse probability at different values of the cross-talk probability.

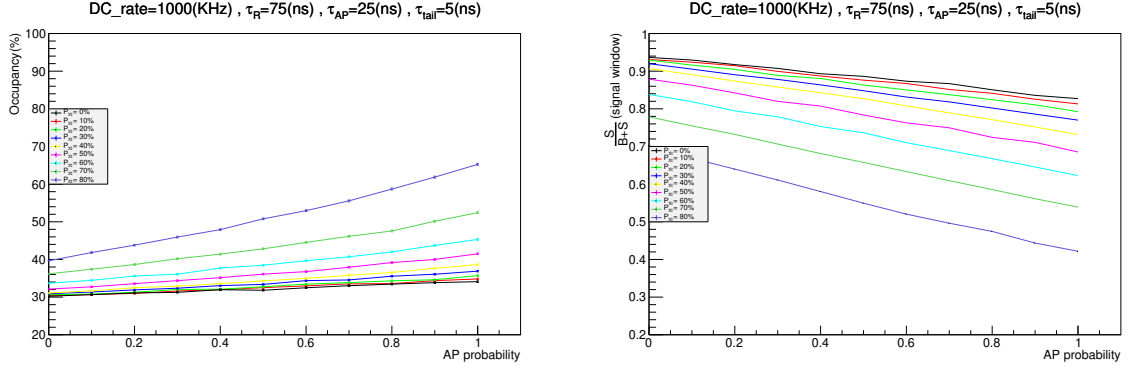


Figure 6.38: Left: Measured occupancy as a function of the after-pulse probability  $P_{AP}$  at different values of the cross-talk probability. In this case the dark count rate is 1 MHz, the pixel recovery time  $\tau_R = 75$  ns, the time constant of the after-pulse  $\tau_{AP} = 25$  ns and the pulse decay time  $\tau_{decay} = 5$  ns. Right:  $\frac{S}{S+B}$  ratio as a function of the after-pulse probability at different values of the cross-talk probability.

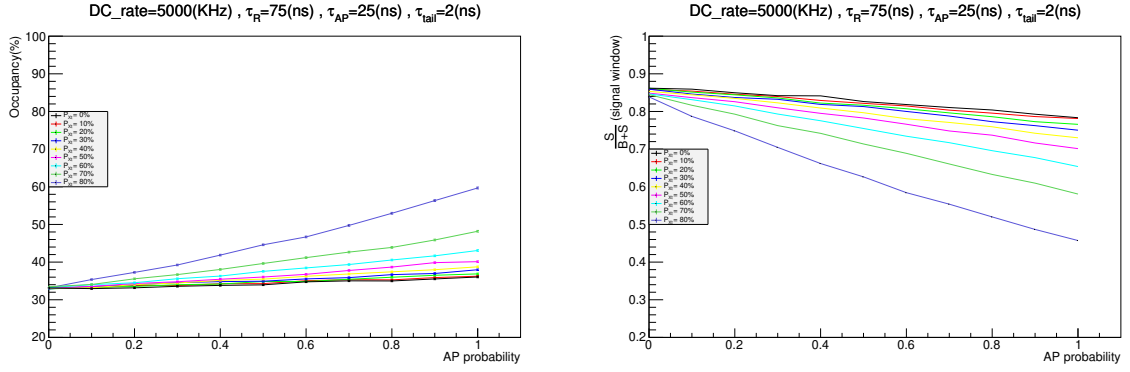


Figure 6.39: Left: Measured occupancy as a function of the after-pulse probability  $P_{AP}$  at different values of the cross-talk probability. In this case the dark count rate is 5 MHz, the pixel recovery time  $\tau_R = 75$  ns, the time constant of the after-pulse  $\tau_{AP} = 25$  ns and the pulse decay time  $\tau_{decay} = 2$  ns. Right:  $\frac{S}{S+B}$  ratio as a function of the after-pulse probability at different values of the cross-talk probability.

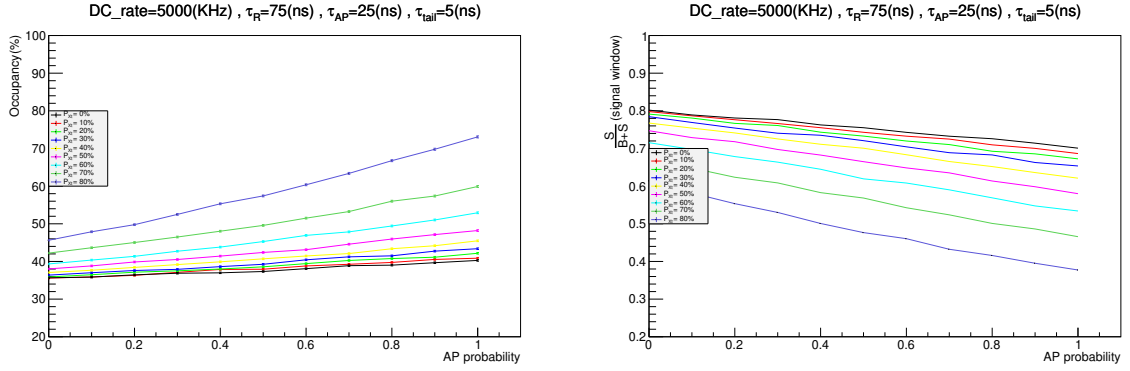


Figure 6.40: Left: Measured occupancy as a function of the after-pulse probability  $P_{AP}$  at different values of the cross-talk probability. In this case the dark count rate is 5 MHz, the pixel recovery time  $\tau_R = 75$  ns, the time constant of the after-pulse  $\tau_{AP} = 25$  ns and the pulse decay time  $\tau_{decay} = 5$  ns. Right:  $\frac{S}{S+B}$  ratio as a function of the after-pulse probability at different values of the cross-talk probability.

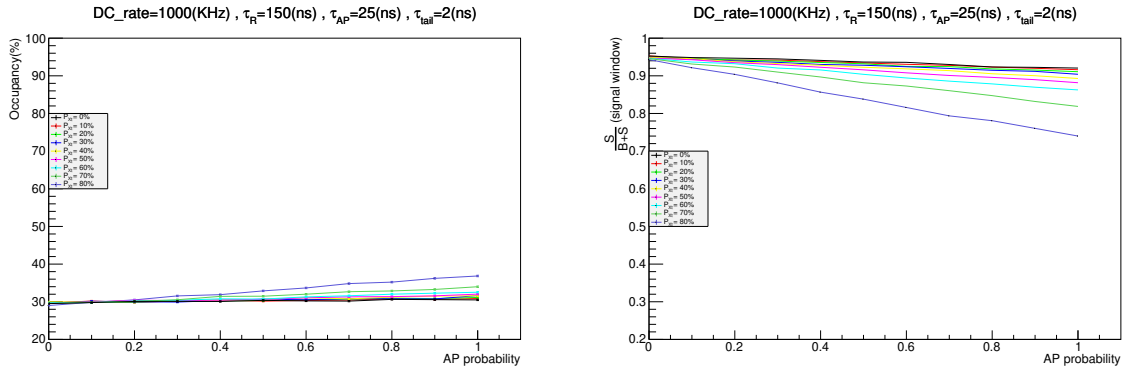


Figure 6.41: Left: Measured occupancy as a function of the after-pulse probability  $P_{AP}$  at different values of the cross-talk probability. In this case the dark count rate is 1 MHz, the pixel recovery time  $\tau_R = 150$  ns, the time constant of the after-pulse  $\tau_{AP} = 25$  ns and the pulse decay time  $\tau_{decay} = 2$  ns. Right:  $\frac{S}{S+B}$  ratio as a function of the after-pulse probability at different values of the cross-talk probability.



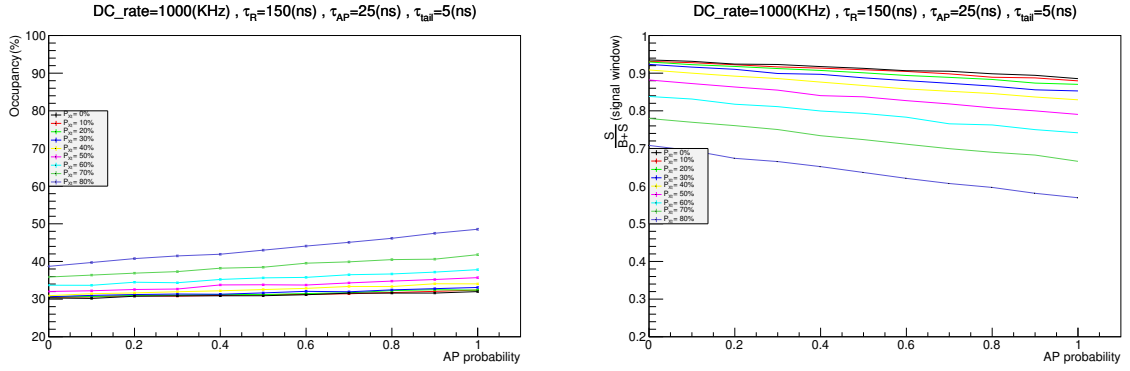


Figure 6.42: Left: Measured occupancy as a function of the after-pulse probability  $P_{AP}$  at different values of the cross-talk probability. In this case the dark count rate is 1 MHz, the pixel recovery time  $\tau_R = 150$  ns, the time constant of the after-pulse  $\tau_{AP} = 25$  ns and the pulse decay time  $\tau_{decay} = 5$  ns. Right:  $\frac{S}{S+B}$  ratio as a function of the after-pulse probability at different values of the cross-talk probability.

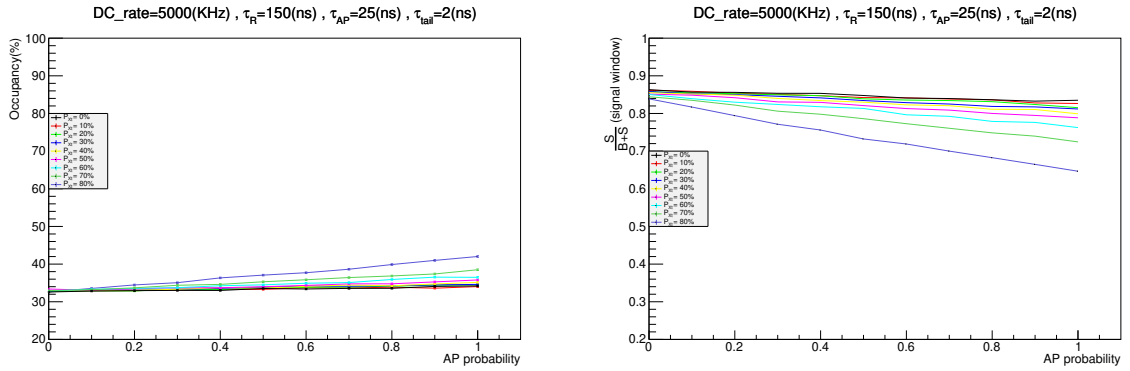


Figure 6.43: Left: Measured occupancy as a function of the after-pulse probability  $P_{AP}$  at different values of the cross-talk probability. In this case the dark count rate is 5 MHz, the pixel recovery time  $\tau_R = 150$  ns, the time constant of the after-pulse  $\tau_{AP} = 25$  ns and the pulse decay time  $\tau_{decay} = 2$  ns. Right:  $\frac{S}{S+B}$  ratio as a function of the after-pulse probability at different values of the cross-talk probability.

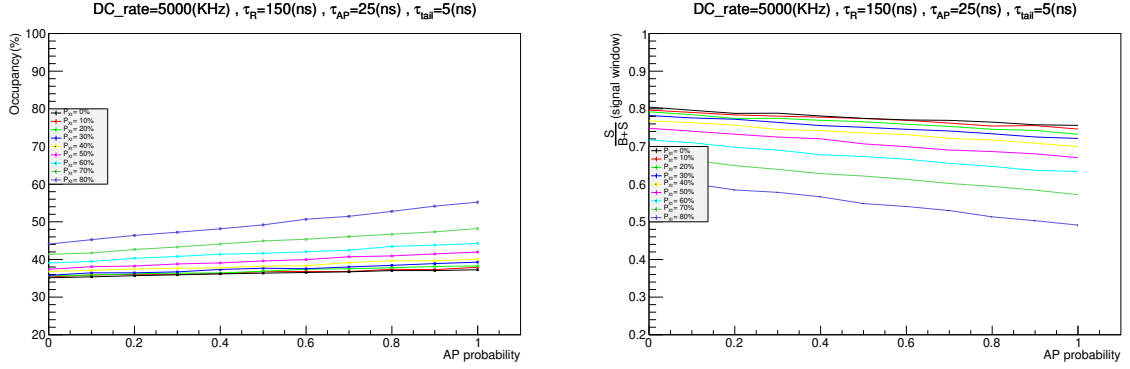


Figure 6.44: Left: Measured occupancy as a function of the after-pulse probability  $P_{AP}$  at different values of the cross-talk probability. In this case the dark count rate is 5 MHz, the pixel recovery time  $\tau_R = 150$  ns, the time constant of the after-pulse  $\tau_{AP} = 25$  ns and the pulse decay time  $\tau_{decay} = 5$  ns. Right:  $\frac{S}{S+B}$  ratio as a function of the after-pulse probability at different values of the cross-talk probability.

### 6.3.2 Summary of the results and future prospect

In this chapter the possibility of using SiPMs as the photo-detector unit for the RICH Upgrade II phase has been discussed. This device offers a number of attractive features: a high, green-shifted quantum efficiency, small pixel size, an excellent photon-counting capability, low bias voltage and low sensitivity to a magnetic field. Furthermore, the silicon technology provides a cost-effective solution. In this chapter, I presented the results of the characterization of a non-irradiated SiPM manufactured by Hamamatsu Photonics at different temperatures and different bias voltage. The results show the good performance of this device in terms of dark count rate when cooled down to low temperatures; in fact the dark count rate is shown to have an exponential dependence on temperature, reaching values as low as  $\sim 1$  KHz at  $-40^\circ\text{C}$ , and a mild dependence on the over-voltage. The cross-talk probability shows a linear dependence on the over-voltage and turns out to be only loosely dependent on the temperature, slightly increasing when the temperature becomes lower. The cross-talk probability can reach values as high as 20% when the overvoltage reaches  $\Delta V = 6\text{V}$ . The after-pulses of this device can be modeled as a single trapping constant of  $\tau_{AP} = 18\text{ns}$ . The after-pulse probability of this device is very low at room temperatures, but increases significantly, up to 70 %, at low temperatures. The effect of the after-pulses is mitigated by the presence of a finite recovery time of the pixel, which was estimated to be  $\sim 200$  ns in our case. In fact, the finite recovery time introduces a dead time in the pixel that suppresses the after pulse probability by a factor 10. It is important to note that these results are limited by the number of measurements taken and also by the low statistics available in every measurement due to the limitation of the DAQ system. Nevertheless, a lot was learned about SiPMs and their behaviour at low temperatures and that finding an optimal operating point for such a device is not trivial as it depends on many parameters.

Comparison of  $IV$  curves of Hamamatsu S13360-1325CS SiPMs at room temperature and after a  $10^{14}$  neq  $\text{cm}^{-2}$  irradiation demonstrate a large increase in current, nearly by a factor  $10^4$  [105]. This tells us that a device cooled down to  $-40$  °C with an initial dark count rate of 1 KHz would reach dark count rates of  $\sim 10$  MHz after exposure, comparable to the photon rate expected for a channel with 30% occupancy at 40 MHz. However, if one starts with a dark count rate of few Hz, a dark count rate of  $\sim 100$  KHz would be reached after exposure thus making the use of SiPM a viable option. In the near future more measurements of this kind are foreseen, this time with an improved acquisition system and a more performant climatic chamber that will allow to characterize the device down to  $-80$  °C, but using the same analysis software developed during the PhD. A multi-channel digitizer readout system was also purchased and it is now present the LHCb lab in Genova; this system integrates functions such as detector bias, pre-amplifier board, readout system and DAQ software. With the new system, it will be also possible to measure the intrinsic time resolution of the device and see how it changes as a function of the temperature and the overvoltage. Beyond Hamamatsu, other manufacturers will be evaluated as well: SensL, FBK, Ketek.

In this chapter I also presented some MC studies to evaluate the impact of the many different sources of noise of a SiPM on the channel occupancy. In fact, cross-talk effects and after-pulses can be the cause of spillover effects and increase significantly the channel occupancy beyond what would be expected from an increase in the thermal dark counts only. Although this studies are still preliminary, a comparison with the analyzed data shows that the simulation works reasonably well and that it could be useful to make the current simulation of the expected RICH performances more realistic by including the effects of a real SiPM.

# Appendix A

## Validation of the fit model

This appendix describes in detail the various PDFs used to model the  $m(p\bar{p}K^+\pi^-)$  mass spectrum. The PDFs were validated on MC samples keeping Run 1 and Run 2 separated. The fit to Run1 and Run2 MC samples was performed using the extended unbinned maximum likelihood (UML) formalism provided by the RooFit package.

### A.1 The $B^0 \rightarrow p\bar{p}K^+\pi^-$ signal component

The  $B^0 \rightarrow p\bar{p}K^+\pi^-$  invariant mass signal shape is determined by using simulated MC decays and it is modeled using an Hypatia PDF. The Hypatia PDF takes the form of:

$$f(m|\mu, \sigma, l, \zeta, \beta, a_1, a_2, n_1, n_2) = \begin{cases} \frac{A}{(B+m-\mu)^{n_1}}, & \text{if } \frac{m-\mu}{\sigma} < -a_1 \\ \frac{C}{(D+m-\mu)^{n_2}}, & \text{if } \frac{m-\mu}{\sigma} > a_2 \\ ((m-\mu)^2 + \delta^2)^{\frac{1}{2}l - \frac{1}{4}} \exp(\beta(x-\mu)) K_{l-\frac{1}{2}}(a\sqrt{(x-\mu)^2 + \delta^2}) & \text{otherwise} \end{cases} \quad (\text{A.1})$$

where  $K_i(z)$  is the modified Bessel function of the second kind,  $\delta := \sigma \sqrt{\frac{\zeta K_l(\zeta)}{\zeta K_{l-1}(\zeta)}}$ ,

$a := \frac{1}{\sigma} \sqrt{\frac{\zeta K_l(\zeta)}{\zeta K_{l-1}(\zeta)}}$  and A, B, C and D are obtained requiring the PDF to be continuous and differentiable. The  $\sigma$  parameter corresponds to the RMS of the distribution if  $\beta = 0$ . The fit was performed using the full Run1 MC sample and the result is shown in Fig. A.1. The measured parameters are listed in Tab. A.1.

The same model was used to fit the full Run 2 MC sample. The result of the fit is shown in Fig. A.2 and the extracted parameters are reported in Tab. A.2.

In the nominal fit to the data, the mean  $\mu$  and the width  $\sigma$  parameters are left floating while the tail parameters ( $a_1, a_2, n_1, n_2$ ) and the  $l$  and the  $\zeta$  parameters are fixed to the values obtained from the fit to the MC signal candidates.

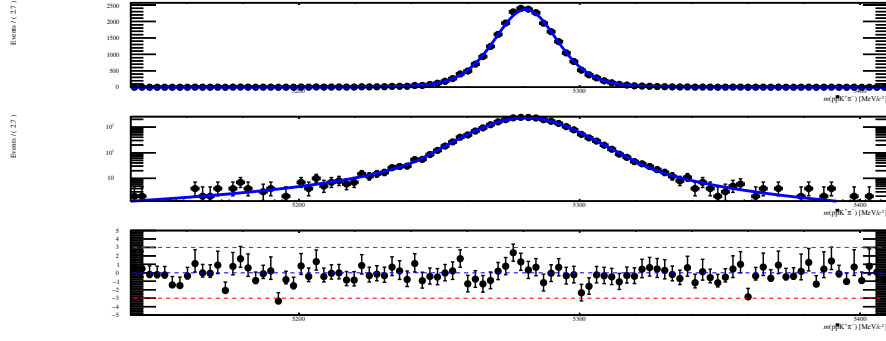


Figure A.1: Fit to Run 1  $B^0 \rightarrow p\bar{p}K^+\pi^-$  MC events shown in linear (top) and logarithmic (middle) scale. The pull distribution is shown under the logarithmic plot (bottom).

|          |                     |
|----------|---------------------|
| $\mu$    | $5280.78 \pm 0.04$  |
| $\sigma$ | $13.45 \pm 0.07$    |
| $a_2$    | $2.90 \pm 0.13$     |
| $a_1$    | $2.65 \pm 0.07$     |
| $l$      | $-3.81 \pm 0.17$    |
| $n_2$    | $2.08 \pm 0.25$     |
| $n_1$    | $1.88 \pm 0.13$     |
| $\zeta$  | $0.0000 \pm 0.0011$ |

Table A.1: Parameters extracted from the fit to the Run 1  $B^0 \rightarrow p\bar{p}K^+\pi^-$  simulated invariant mass distribution.

## A.2 The $B_s^0 \rightarrow p\bar{p}K^+\pi^-$ component

The  $B_s^0 \rightarrow p\bar{p}K^+\pi^-$  has been parametrized using an Hypatia PDF. The fit to the Run1 invariant mass distribution has been performed by chaining together the MC11 and MC12

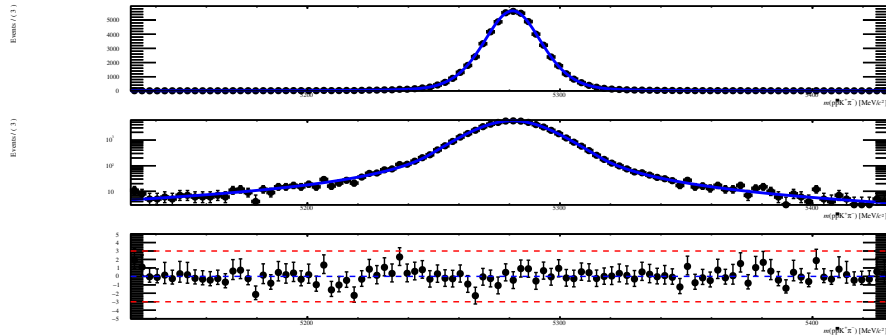


Figure A.2: Fit to Run 2  $B^0 \rightarrow p\bar{p}K^+\pi^-$  MC events shown in linear (top) and logarithmic (middle) scale. The pull distribution is shown under the logarithmic plot (bottom).

|          |                      |
|----------|----------------------|
| $\mu$    | $5281.238 \pm 0.028$ |
| $\sigma$ | $13.64 \pm 0.05$     |
| $a_2$    | $2.550 \pm 0.033$    |
| $a_1$    | $2.392 \pm 0.026$    |
| $l$      | $-3.92 \pm 0.13$     |
| $n_2$    | $1.814 \pm 0.065$    |
| $n_1$    | $1.777 \pm 0.053$    |
| $\zeta$  | $0.0002 \pm 0.0010$  |

Table A.2: Parameters extracted from the fit to the Run 2  $B^0 \rightarrow p\bar{p}K^+\pi^-$  simulated invariant mass distribution.

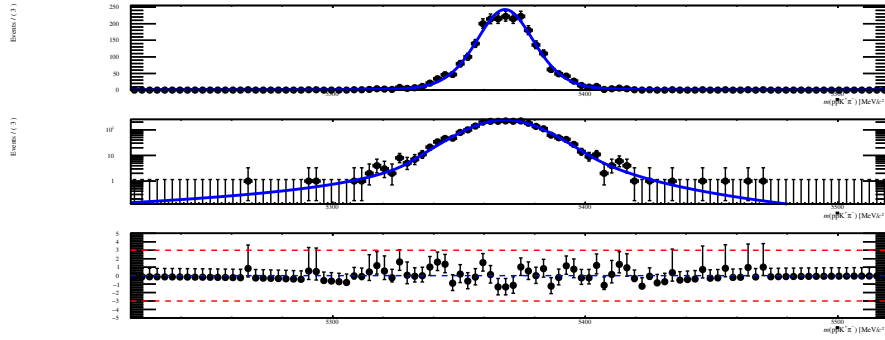


Figure A.3: Fit to Run 1  $B_s^0 \rightarrow p\bar{p}K^+\pi^-$  MC events shown in linear (top) and logarithmic (middle) scale. The pull distribution is shown under the logarithmic plot (bottom).

signal sample and the result of the fit is shown in Fig. A.3 along with the extracted parameters shown in Tab. A.3.

The result of the fit for the Run 2 simulated sample is shown in Fig. A.4 along with the extracted parameters shown in Tab. A.4.

In the fit to the data, the mean is left floating while the tail parameters ( $a_1$ ,  $a_2$ ,  $n_1$ ,

|          |                     |
|----------|---------------------|
| $\mu$    | $5368.25 \pm 0.13$  |
| $\sigma$ | $13.36 \pm 0.29$    |
| $a_2$    | $2.45 \pm 0.29$     |
| $a_1$    | $2.77 \pm 0.27$     |
| $l$      | $-4.24 \pm 0.84$    |
| $n_2$    | $2.78 \pm 0.68$     |
| $n_1$    | $1.56 \pm 0.41$     |
| $\zeta$  | $0.0020 \pm 0.0013$ |

Table A.3: Parameters extracted from the fit to the Run1  $B_s^0 \rightarrow p\bar{p}K^+\pi^-$  simulated invariant mass distribution.

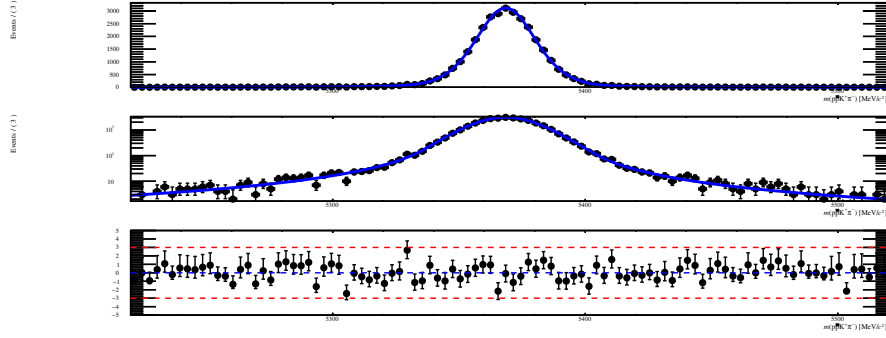


Figure A.4: Fit to Run 2  $B_s^0 \rightarrow p\bar{p}K^+\pi^-$  MC events shown in linear (top) and logarithmic (middle) scale. The pull distribution is shown under the logarithmic plot (bottom).

|          |                       |
|----------|-----------------------|
| $\mu$    | $5368.503 \pm 0.038$  |
| $\sigma$ | $13.903 \pm 0.076$    |
| $a_2$    | $2.533 \pm 0.049$     |
| $a_1$    | $2.315 \pm 0.036$     |
| $n_2$    | $1.837 \pm 0.096$     |
| $n_1$    | $1.865 \pm 0.076$     |
| $l$      | $-4.03 \pm 0.19$      |
| $\zeta$  | $0.00295 \pm 0.00067$ |

Table A.4: Parameters extracted from the fit to the Run 2  $B_s^0 \rightarrow p\bar{p}K^+\pi^-$  simulated invariant mass distribution.

$n_2$ ) and the  $l$  and the  $\zeta$  parameters are fixed to the values obtained from the fit to the MC signal candidates. The resolution parameter,  $\sigma$ , is in common with the  $B^0$  parameter.

### A.3 Background from partially reconstructed decays

A significant low mass background appears in the reconstructed invariant mass spectrum. This contribution could be due to 5-body partially reconstructed decays where one of the final state particles is not reconstructed. This contribution could include for example  $B^0 \rightarrow p\bar{p}K^+\pi^-\pi^0$  decays where the  $\pi^0$  is not reconstructed. In particular  $B^0 \rightarrow p\bar{p}K^+\pi^-\pi^0$  decays where the  $\pi^0$  is produced in for example  $\rho^- \rightarrow \pi^-\pi^0$  or  $K^{*-} \rightarrow K^-\pi^0$  decays or  $B^0 \rightarrow p\bar{p}D^0(\rightarrow K^+\pi^-\pi^0)$  are expected to contribute. Another possible source of partially reconstructed background could be due to charged 5-body  $B^+ \rightarrow p\bar{p}K^+\pi^-\pi^+$  where the charged  $\pi^+$  is not reconstructed. The shape of charged and neutral not reconstructed pion is expected to be similar with a small difference in the end point value which is however smeared by the resolution. Possible contribution to partially reconstructed background due to  $B_s^0 \rightarrow p\bar{p}K^+\pi^-\pi^0$  which can peak under the  $B^0$  signal region is investigated but it has been found to be negligible. Partially reconstructed background mass distribution is

|       |                  |
|-------|------------------|
| $c$   | $9.5 \pm 1.1$    |
| $m_0$ | $5132.1 \pm 2.4$ |

Table A.5: Parameters extracted from the fit to the Run1  $B^0 \rightarrow p\bar{p}K^+\pi^-\pi^0$  simulated invariant mass distribution.

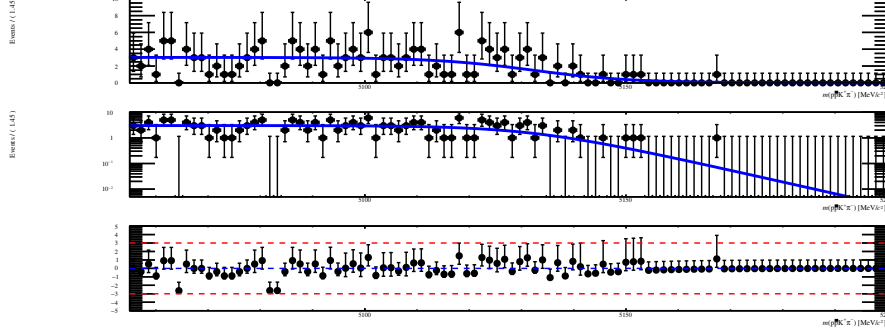


Figure A.5: Fit to Run 1  $B^0 \rightarrow p\bar{p}K^+\pi^-\pi^0$  MC events shown in linear (top) and logarithmic (middle) scale. The pull distribution is shown under the logarithmic plot (bottom).

modeled using a Fermi PDF.

$$f = \frac{1}{e^{c(m-m_0)+1}} \quad (\text{A.2})$$

where  $m$  is the mass,  $m_0$  is the end point and  $c$  controls the slope. The result of the fit is shown in Fig. A.5 and the extracted parameters are reported in Tab. A.5.

Run2 simulated data have not been fitted since in the nominal fit, it has been decided to leave  $m_0$  and  $c$  free to vary in order to take into account the possible different partially reconstructed background decays.

## A.4 Peaking background from misidentified $B_s^0 \rightarrow p\bar{p}K^+K^-$ decays

The  $B_s^0 \rightarrow p\bar{p}K^+K^-$  invariant mass distribution has been modeled using a two tail Crystal Ball PDF (Double Crystal Ball, DCB). The expression for a DCB is

$$f(m|n_1, n_2, a_1, a_2, \mu, \sigma) = \begin{cases} \left(\frac{n_1}{|a_1|}\right)^{n_1} \exp\left(-\frac{|a_1|^2}{2}\right) \left(\frac{n_1}{|a_1|} - |\alpha_1| - \frac{m-\mu}{\sigma}\right)^{-n_1}, & \text{if } \frac{m-\mu}{\sigma} < -a_1 \\ \left(\frac{n_2}{|a_2|}\right)^{n_2} \exp\left(-\frac{|a_2|^2}{2}\right) \left(\frac{n_2}{|a_2|} - |\alpha_2| - \frac{m-\mu}{\sigma}\right)^{-n_2}, & \text{if } \frac{m-\mu}{\sigma} > a_2 \\ \exp\left(-\frac{(m-\mu)^2}{2\sigma^2}\right), & \text{otherwise} \end{cases} \quad (\text{A.3})$$

The result of the fit is shown in Fig. A.6 and Fig. A.7 along with the extracted parameters shown in Tab. A.6 and in Tab. A.7 for Run1 and Run2 respectively.



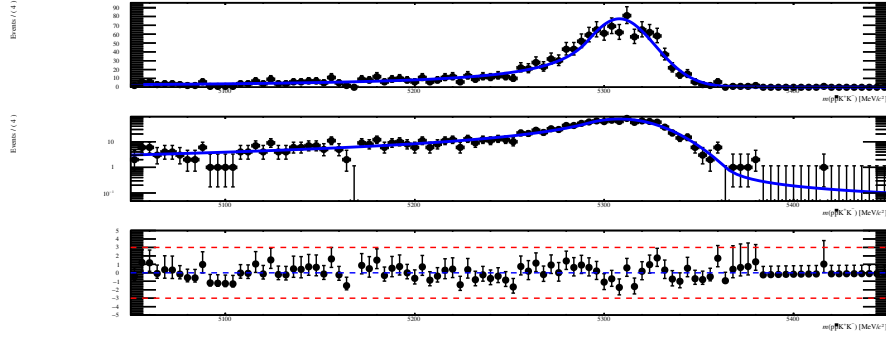


Figure A.6: Fit to Run 1  $B_s^0 \rightarrow p\bar{p}K^+K^-$  MC events shown in linear (top) and logarithmic (middle) scale. The pull distribution is shown under the logarithmic plot (bottom).

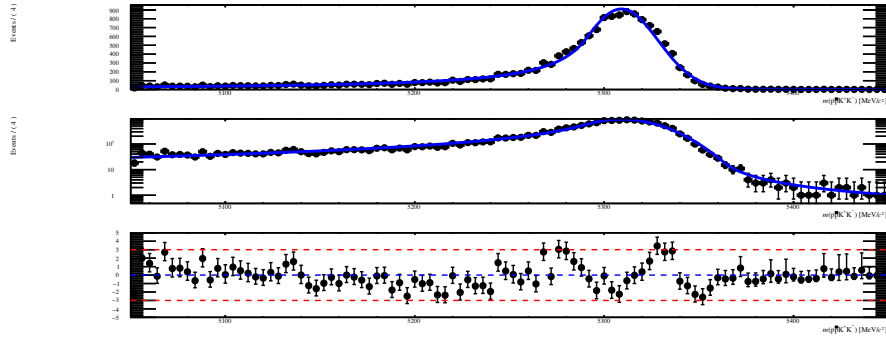


Figure A.7: Fit to Run 2  $B_s^0 \rightarrow p\bar{p}K^+K^-$  MC events shown in linear (top) and logarithmic (middle) scale. The pull distribution is shown under the logarithmic plot (bottom).

## A.5 Peaking background from misidentified $B^0 \rightarrow p\bar{p}\pi^+\pi^-$ decays

The  $B^0 \rightarrow p\bar{p}\pi^+\pi^-$  invariant mass distribution has been modeled using a DCB PDF. The result of the fit is shown in Fig. A.8 and Fig. A.9 along with the extracted parameters shown in Tab. A.8 and in Tab. A.9 for Run1 and Run2 respectively.

|          |                    |
|----------|--------------------|
| $\mu$    | $5308.06 \pm 0.67$ |
| $\sigma$ | $19.00 \pm 0.49$   |
| $a_1$    | $0.883 \pm 0.058$  |
| $a_2$    | $2.96 \pm 0.19$    |
| $n_1$    | $1.23 \pm 0.10$    |
| $n_2$    | $0.78 \pm 0.46$    |

Table A.6: Parameters extracted from the fit to the Run1  $B_s^0 \rightarrow p\bar{p}K^+K^-$  simulated invariant mass distribution.

|          |                    |
|----------|--------------------|
| $\mu$    | $5309.11 \pm 0.19$ |
| $\sigma$ | $19.48 \pm 0.15$   |
| $a_1$    | $0.976 \pm 0.018$  |
| $a_2$    | $2.777 \pm 0.070$  |
| $n_1$    | $1.241 \pm 0.031$  |
| $n_2$    | $1.21 \pm 0.21$    |

Table A.7: Parameters extracted from the fit to the Run2  $B_s^0 \rightarrow p\bar{p}K^+K^-$  simulated invariant mass distribution.

|          |                    |
|----------|--------------------|
| $\mu$    | $5332.77 \pm 0.86$ |
| $\sigma$ | $19.32 \pm 0.70$   |
| $a_1$    | $2.70 \pm 0.43$    |
| $a_2$    | $1.12 \pm 0.12$    |
| $n_1$    | $2.1 \pm 2.0$      |
| $n_2$    | $1.61 \pm 0.25$    |

Table A.8: Parameters extracted from the fit to the Run 1  $B^0 \rightarrow p\bar{p}\pi^+\pi^-$  simulated invariant mass distribution.

## A.6 Combinatorial background

The combinatorial background is modelled with an exponential PDF with a shape parameter,  $\lambda$ , that is left free to vary in the fit.

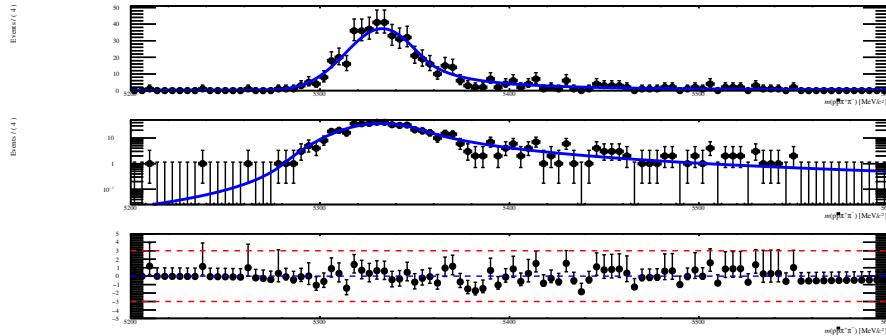


Figure A.8: Fit to Run 1  $B^0 \rightarrow p\bar{p}\pi^+\pi^-$  MC events shown in linear (top) and logarithmic (middle) scale. The pull distribution is shown under the logarithmic plot (bottom).

|          |                    |
|----------|--------------------|
| $\mu$    | $5332.60 \pm 0.29$ |
| $\sigma$ | $18.79 \pm 0.26$   |
| $a_1$    | $2.30 \pm 0.11$    |
| $a_2$    | $0.891 \pm 0.029$  |
| $n_1$    | $2.05 \pm 0.44$    |
| $n_2$    | $2.45 \pm 0.12$    |

Table A.9: Parameters extracted from the fit to the Run 2  $B^0 \rightarrow p\bar{p}\pi^+\pi^-$  simulated invariant mass distribution

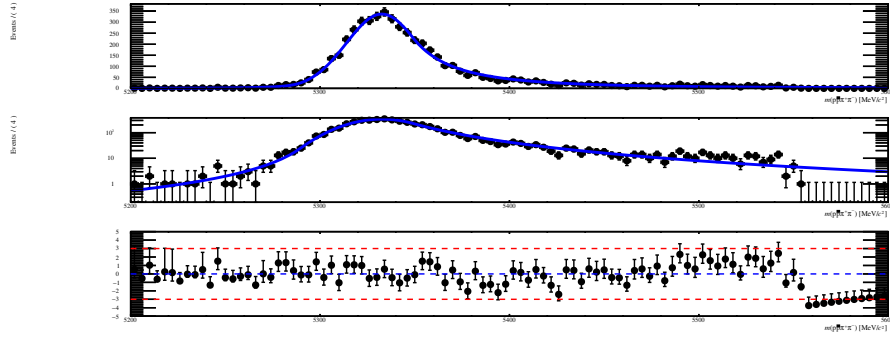


Figure A.9: Fit to Run 2  $B^0 \rightarrow p\bar{p}\pi^+\pi^-$  MC events shown in linear (top) and logarithmic (middle) scale. The pull distribution is shown under the logarithmic plot (bottom).

# Appendix B

## Background studies using sWeights

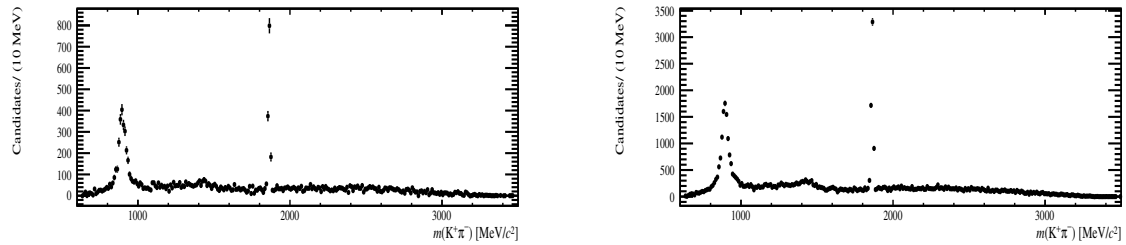


Figure B.1: Background-subtracted  $m_{K^+\pi^-}$  distribution for the Run1 (left) and Run2 (right) dataset. The peak at  $\sim 900$  MeV corresponds to the  $K^{*0}(892)$  resonance. The peak close to  $\sim 1800$  MeV corresponds to the  $D^0$  meson.

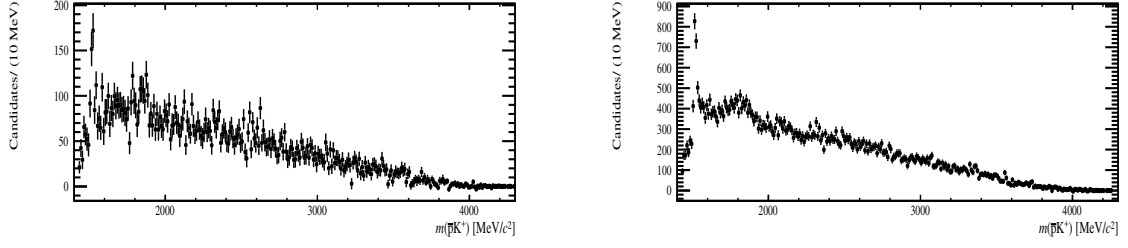


Figure B.2: Background-subtracted  $m_{\bar{p}K^+}$  distribution for the Run1 (left) and Run2 (right) dataset. The peak close to threshold is identified as the  $\Lambda(1520)$  baryon. The broad peak at  $\sim 1800$  MeV could be identified as the  $\Lambda(1800)$  baryon.

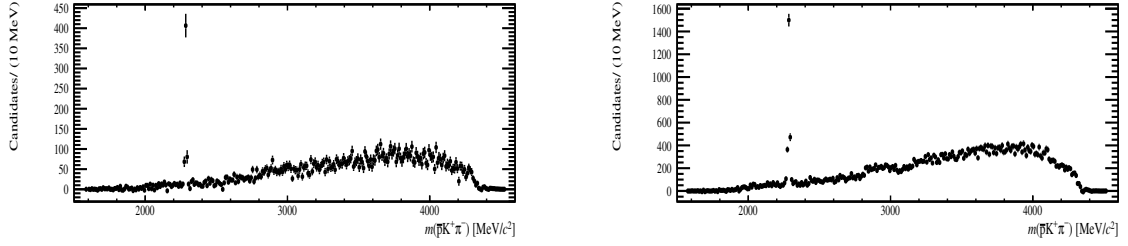


Figure B.3: Background-subtracted  $m_{\bar{p}K^+\pi^-}$  distribution for the Run1 (left) and Run2 (right) dataset. The peak corresponding to  $\Lambda_c^-$  can be clearly identified.

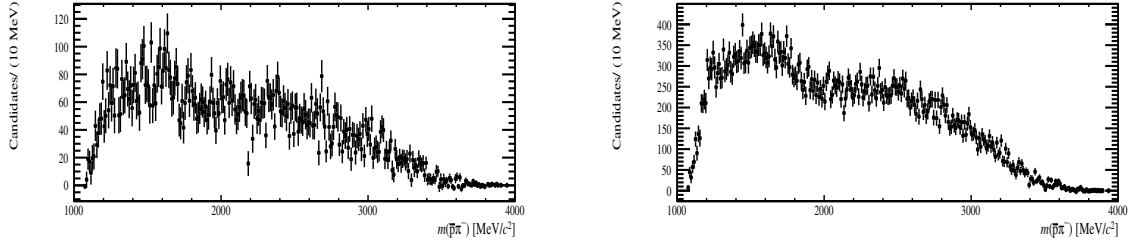


Figure B.4: Background-subtracted  $m_{\bar{p}\pi^-}$  distribution for the Run1 (left) and Run2 (right) dataset. As expected, no resonances can be clearly identified.

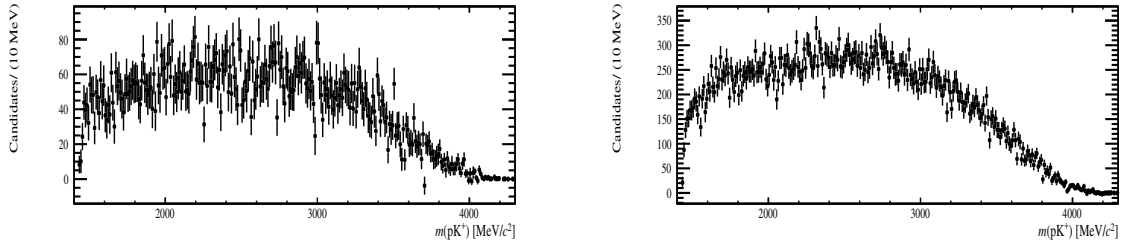


Figure B.5: Background-subtracted  $m_{pK^+}$  distribution for the Run1 (left) and Run2 (right) dataset. As expected, no resonance can be clearly identified.

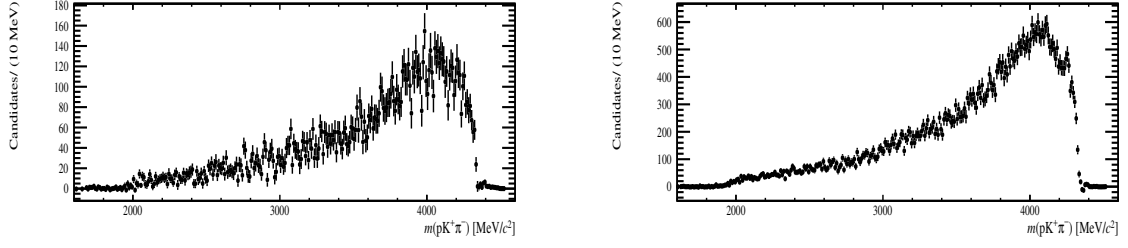


Figure B.6: Background-subtracted  $m_{pK^+\pi^-}$  distribution for the Run1 (left) and Run2 (right) dataset. No resonances can be clearly identified here.

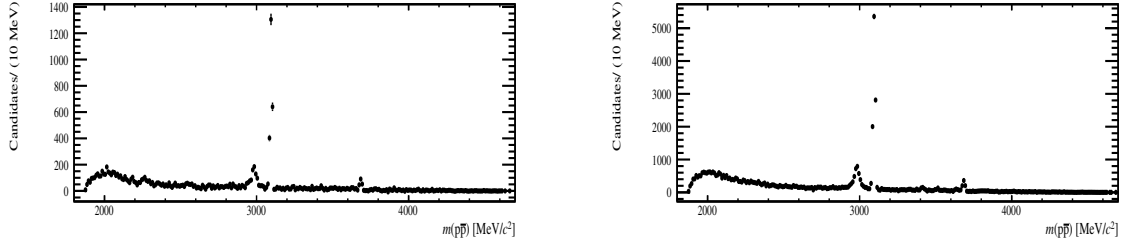


Figure B.7: Background-subtracted  $m_{p\bar{p}}$  distribution for the Run1 (left) and Run2 (right) dataset. Several charmonium resonances are visible ( $\eta_c(1S)$ ,  $J/\psi$ ,  $\psi(2S)$ ). The known threshold enhancement in the charmless region  $m_{p\bar{p}} < 2.85 \text{ GeV}/c^2$  is present.

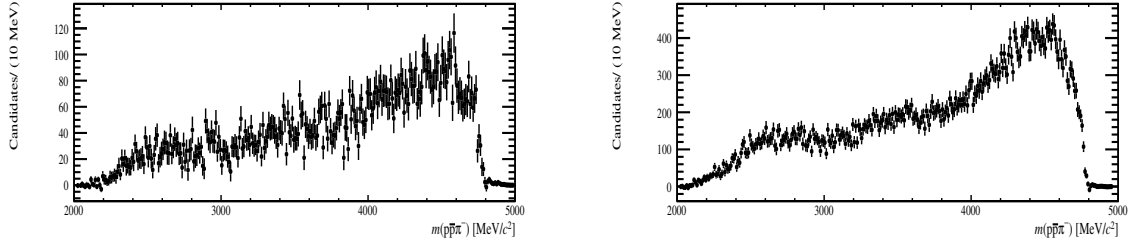


Figure B.8: Background-subtracted  $m_{p\bar{p}\pi^-}$  distribution for the Run1 (left) and Run2 (right) dataset. No resonances can be clearly identified.

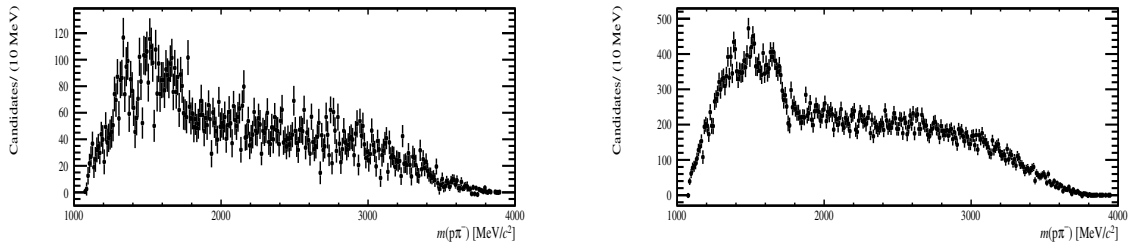


Figure B.9: Background-subtracted  $m_{p\pi^-}$  distribution for the Run1 (left) and Run2 (right) dataset. No resonances can be clearly identified.

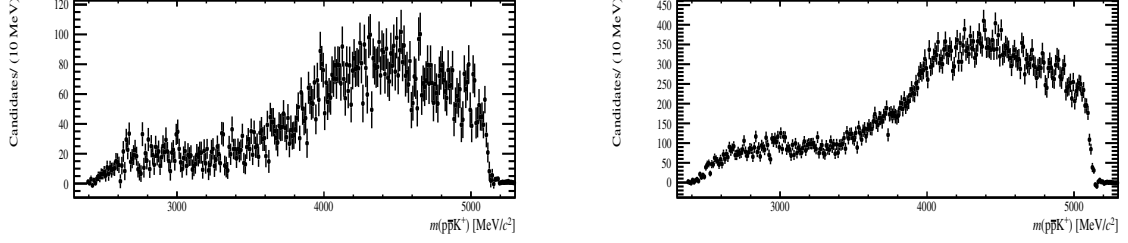


Figure B.10: Background-subtracted  $m_{p\bar{p}K^+}$  distribution for the Run1 (left) and Run2 (right) dataset. No resonances can be clearly identified.

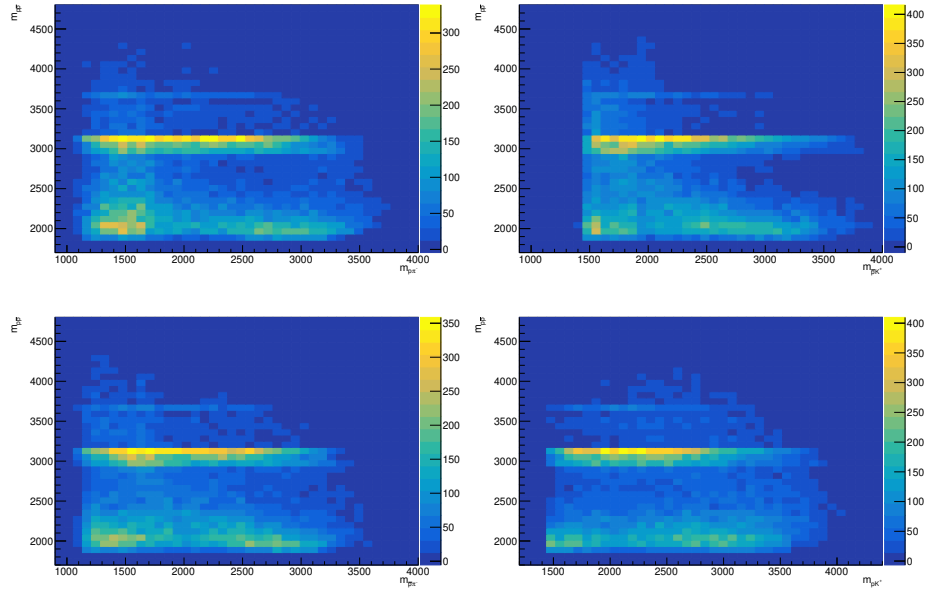


Figure B.11: Scatter plot of background subtracted data:  $m(p\bar{p})$  vs  $m(p\pi^-)$  (top-left), vs  $m(\bar{p}K^+)$  (top-right), vs  $m(\bar{p}\pi^-)$  (bottom-left), vs  $m(pK^+)$  (bottom-right).

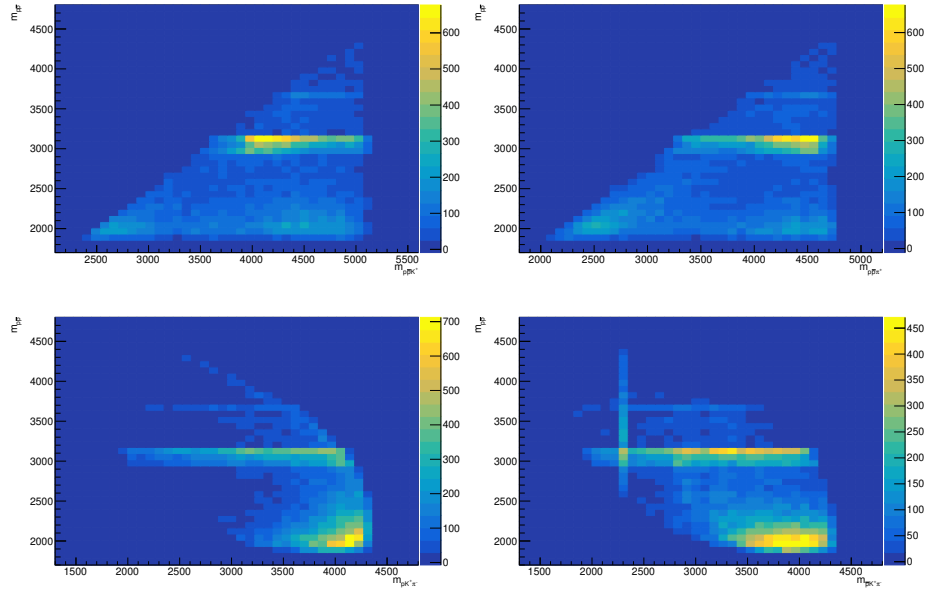


Figure B.12: Scatter plot of background subtracted data:  $m(p\bar{p})$  vs  $m(p\bar{p}K^+)$  (top-left), vs  $m(p\bar{p}\pi^-)$  (top-right), vs  $m(pK^+\pi^-)$  (bottom-left), vs  $m(\bar{p}K^+\pi^-)$  (bottom-right).

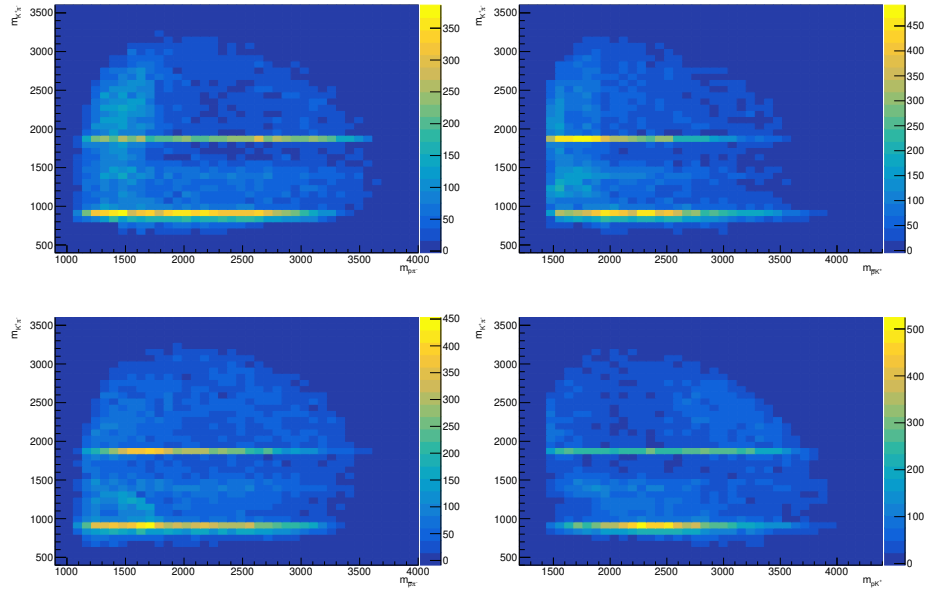


Figure B.13: Scatter plot of background subtracted data:  $m(K^+\pi^-)$  vs  $m(p\pi^-)$  (top-left), vs  $m(\bar{p}K^+)$  (top-right), vs  $m(\bar{p}\pi^-)$  (bottom-left), vs  $m(pK^+)$  (bottom-right).



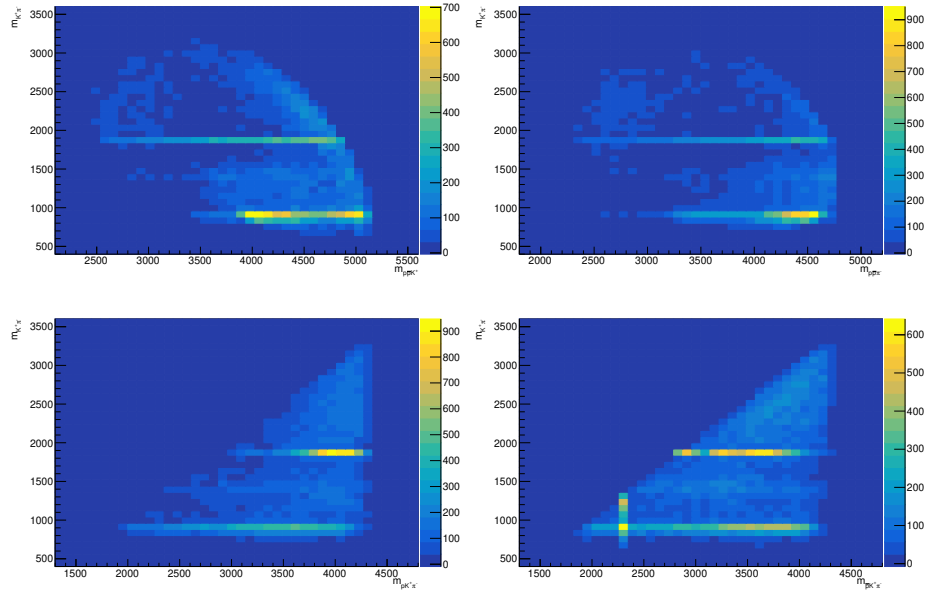


Figure B.14: Scatter plot of background subtracted data:  $m(K^+\pi^-)$  vs  $m(p\bar{p}K^+)$  (top-left), vs  $m(p\bar{p}\pi^-)$  (top-right), vs  $m(pK^+\pi^-)$  (bottom-left), vs  $m(\bar{p}K^+\pi^-)$  (bottom-right).

# Appendix C

## Pull distributions

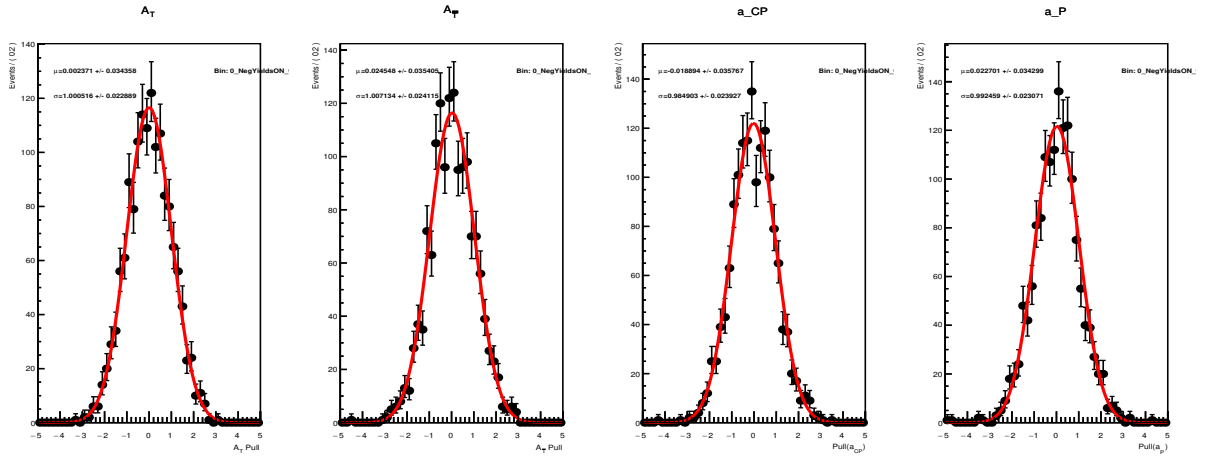


Figure C.1: Pull distributions for the asymmetries in bin 0. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

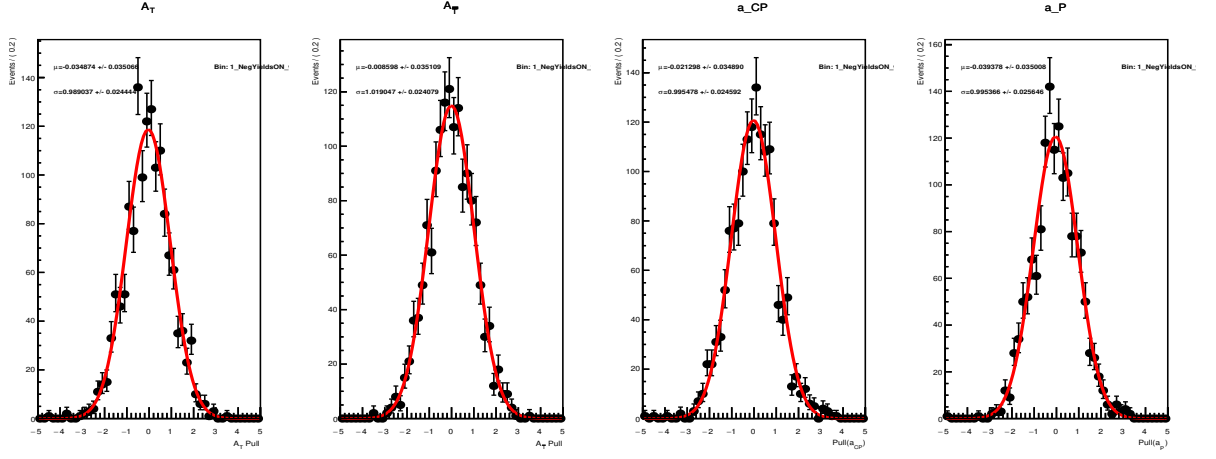


Figure C.2: Pull distributions for the asymmetries in bin 1. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

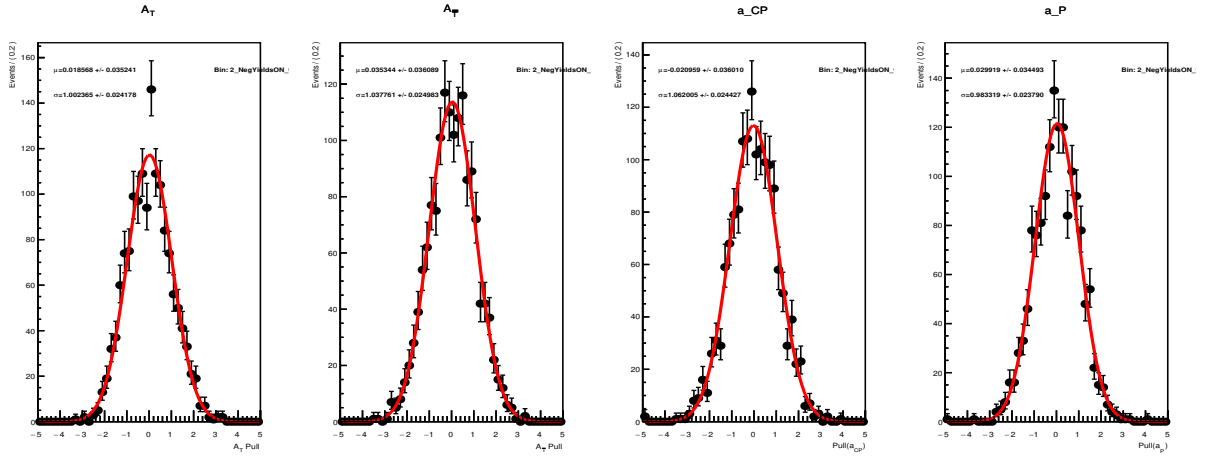


Figure C.3: Pull distributions for the asymmetries in bin 2. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

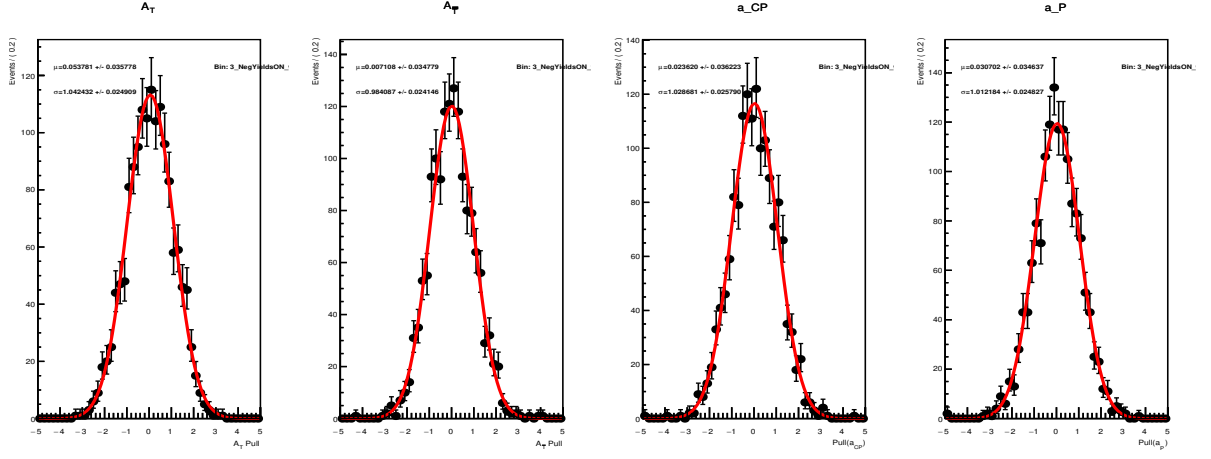


Figure C.4: Pull distributions for the asymmetries in bin 3. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

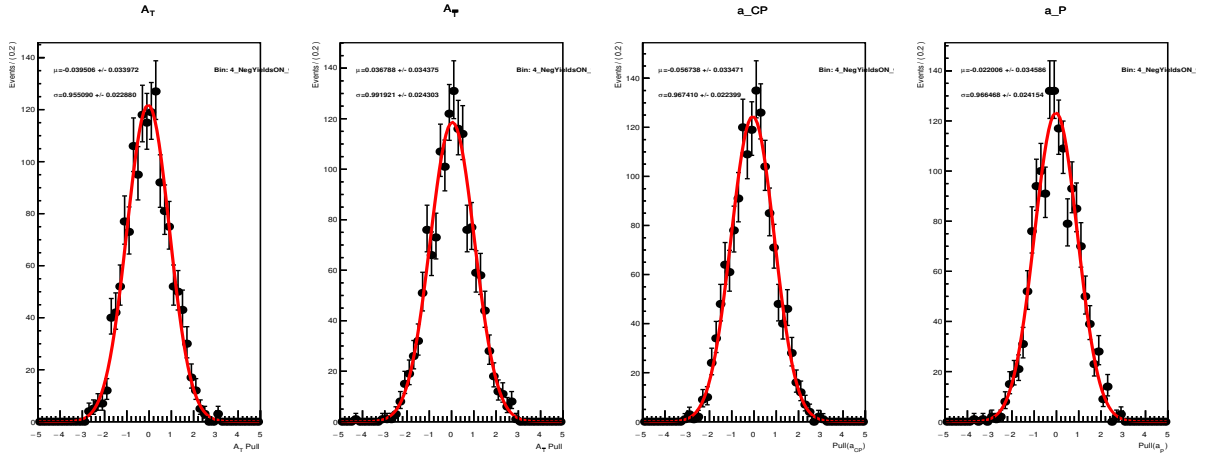


Figure C.5: Pull distributions for the asymmetries in bin 4. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

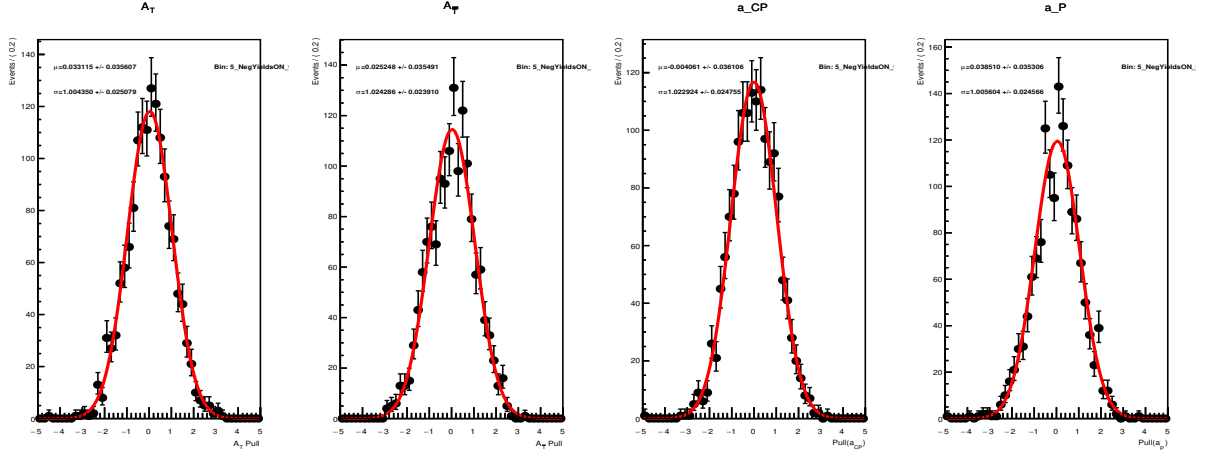


Figure C.6: Pull distributions for the asymmetries in bin 5. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

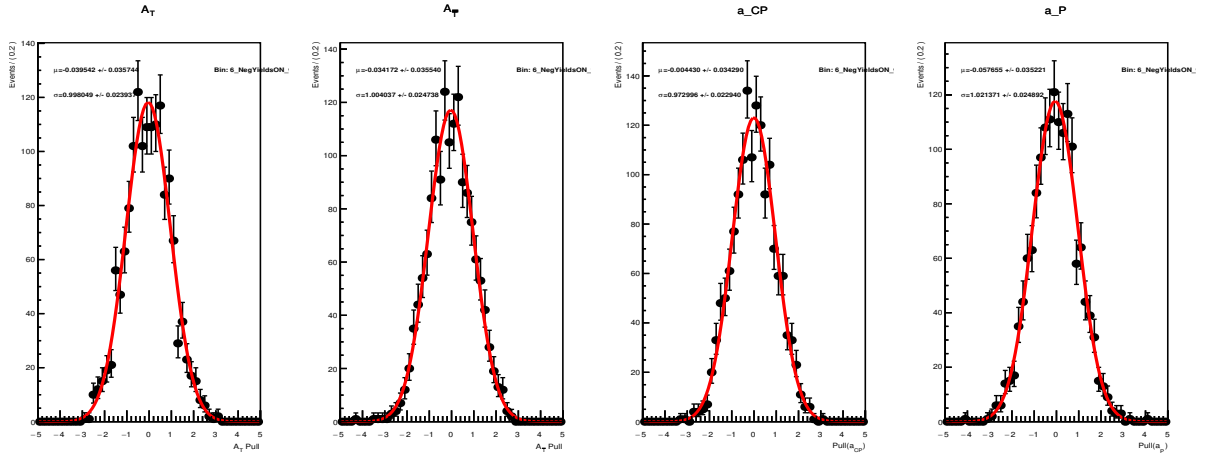


Figure C.7: Pull distributions for the asymmetries in bin 6. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

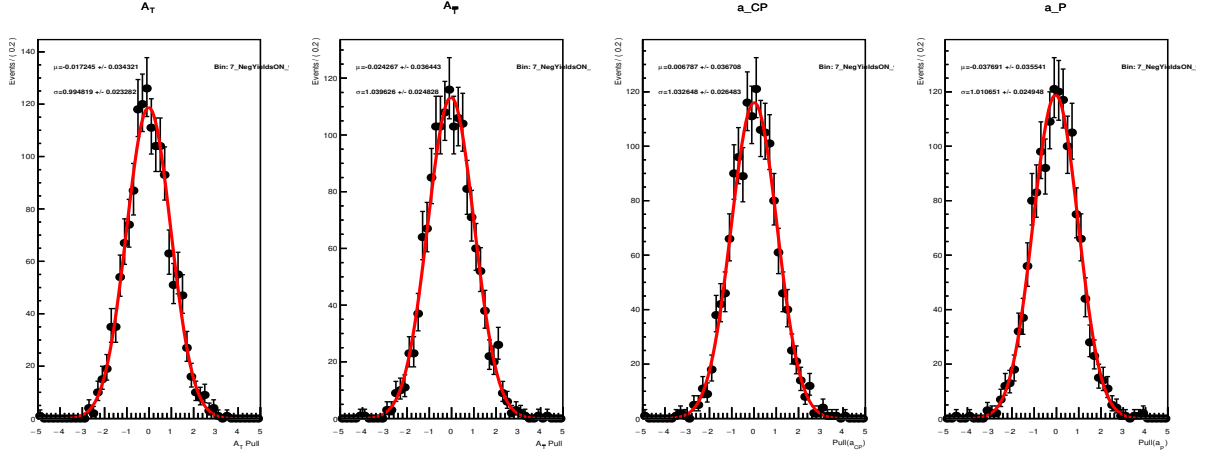


Figure C.8: Pull distributions for the asymmetries in bin 7. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

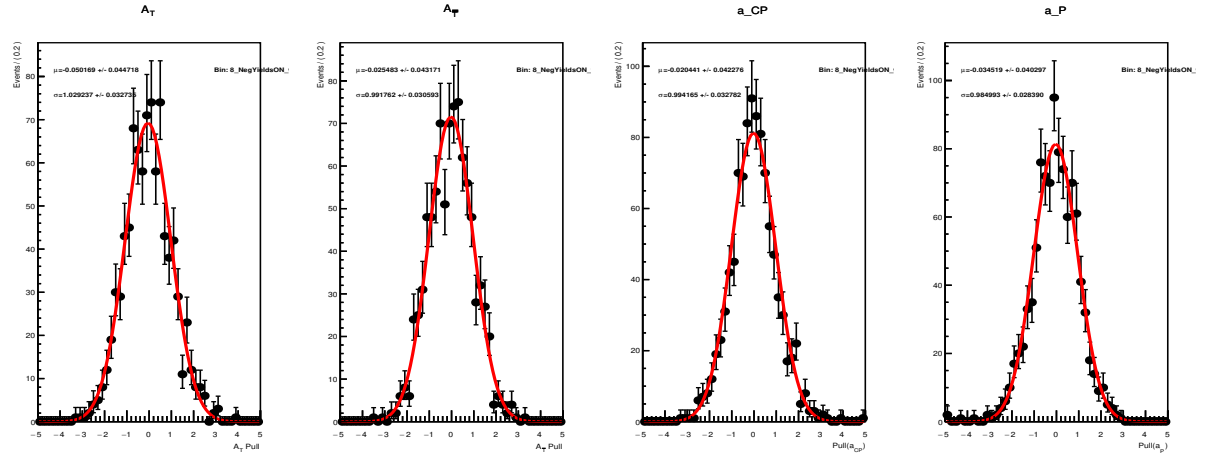


Figure C.9: Pull distributions for the asymmetries in bin 8. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

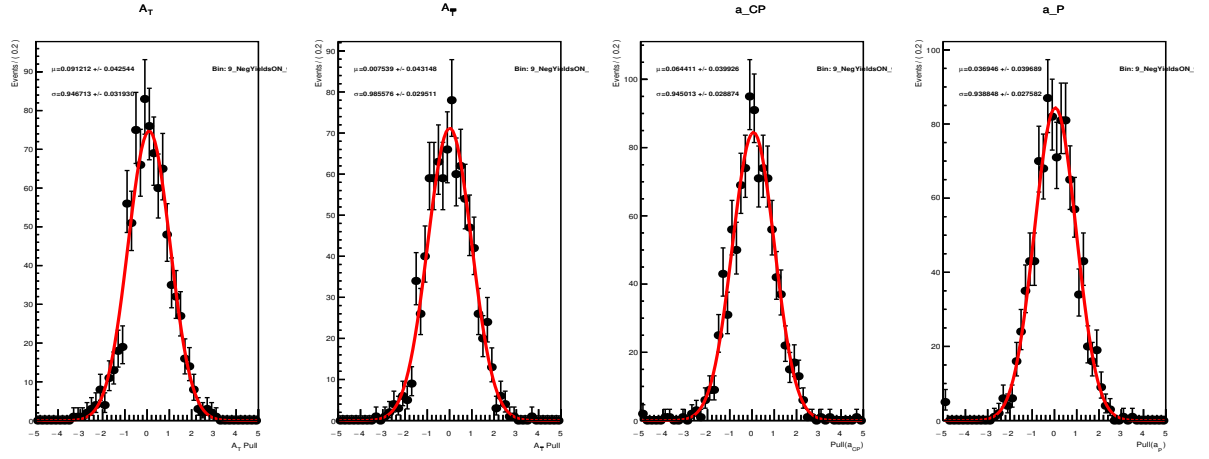


Figure C.10: Pull distributions for the asymmetries in bin 9. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

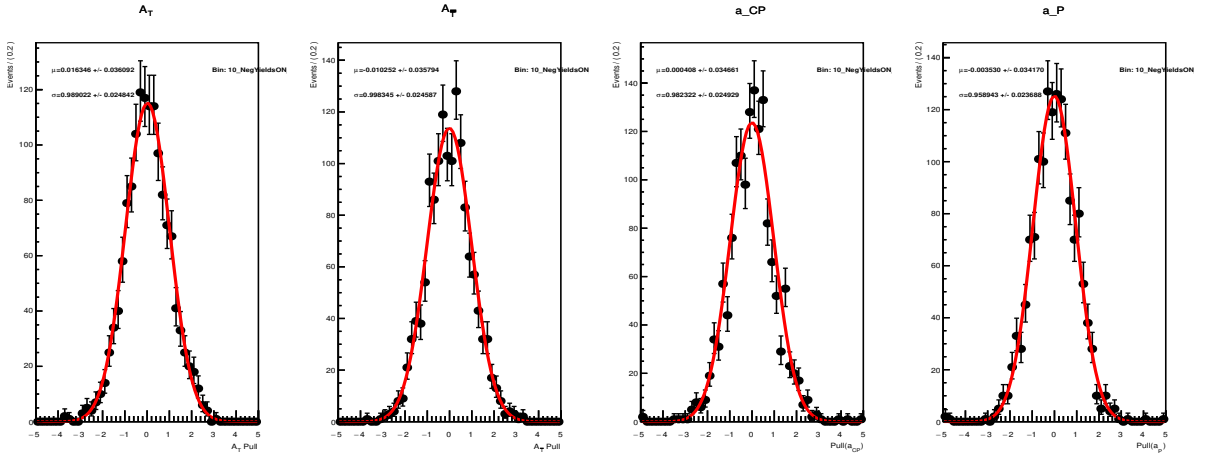


Figure C.11: Pull distributions for the asymmetries in bin 10. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

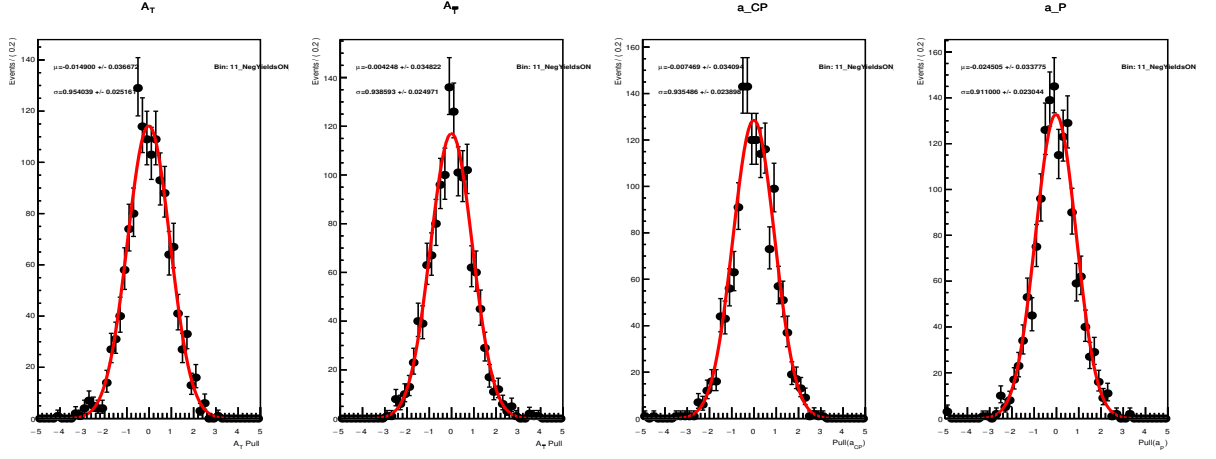


Figure C.12: Pull distributions for the asymmetries in bin 11. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

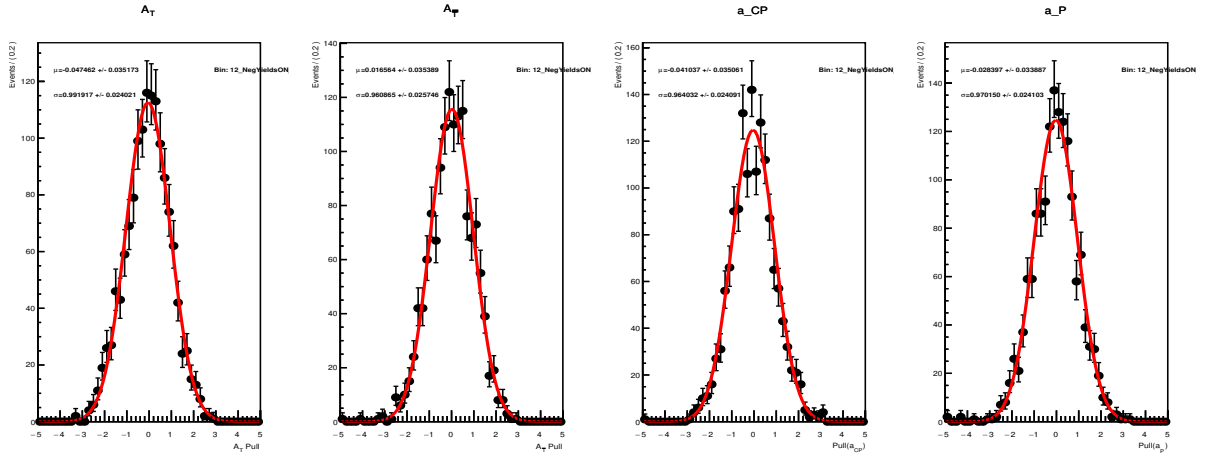


Figure C.13: Pull distributions for the asymmetries in bin 12. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$



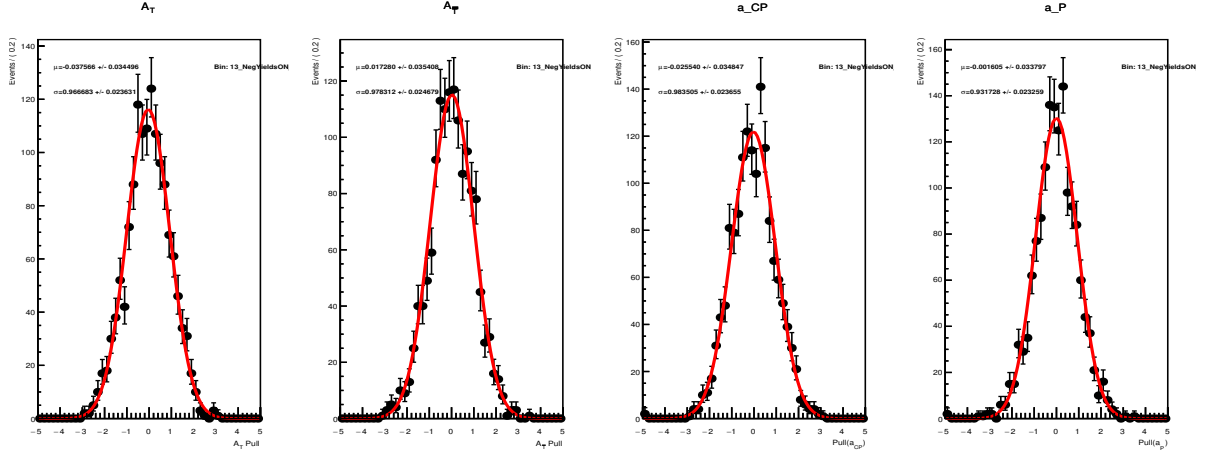


Figure C.14: Pull distributions for the asymmetries in bin 13. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

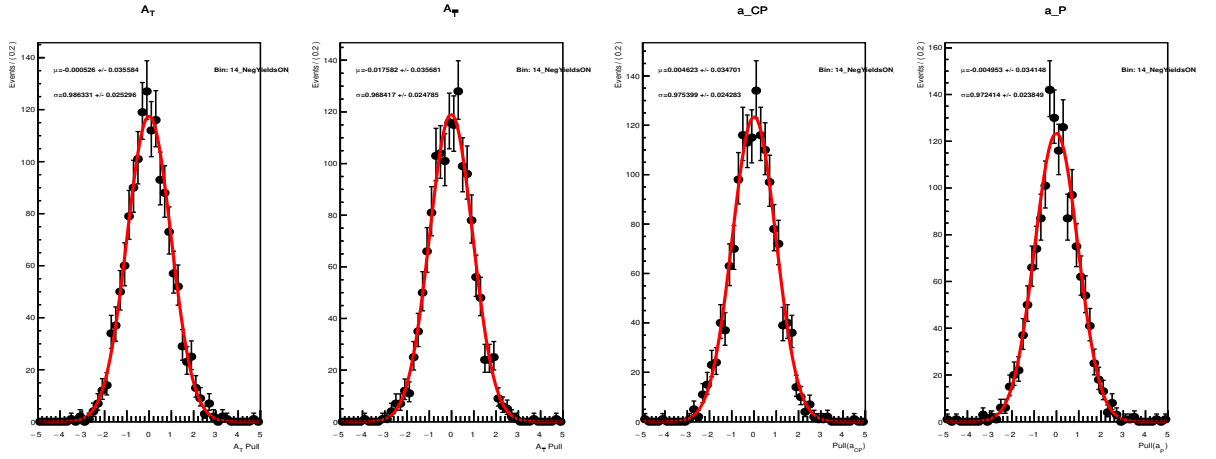


Figure C.15: Pull distributions for the asymmetries in bin 14. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

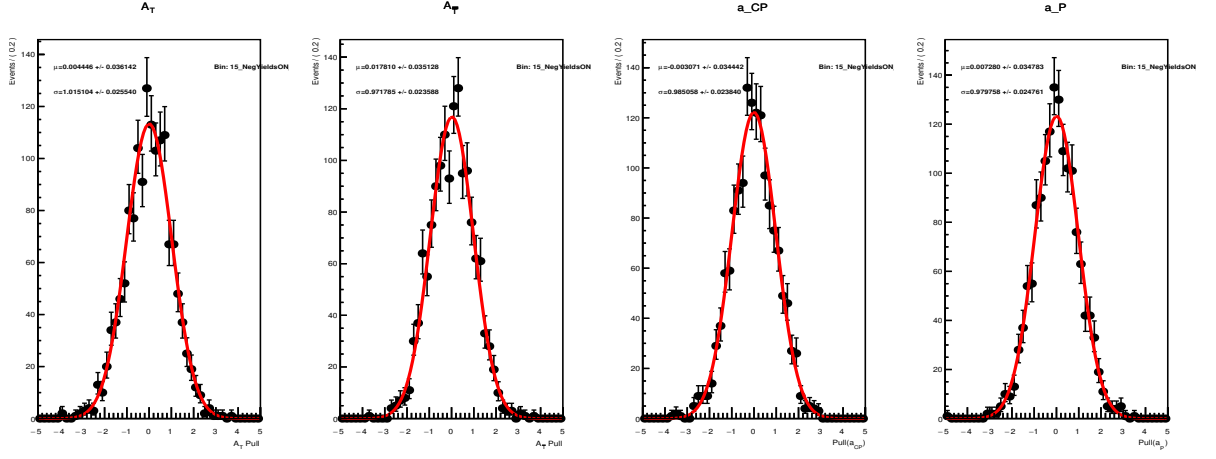


Figure C.16: Pull distributions for the asymmetries in bin 15. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

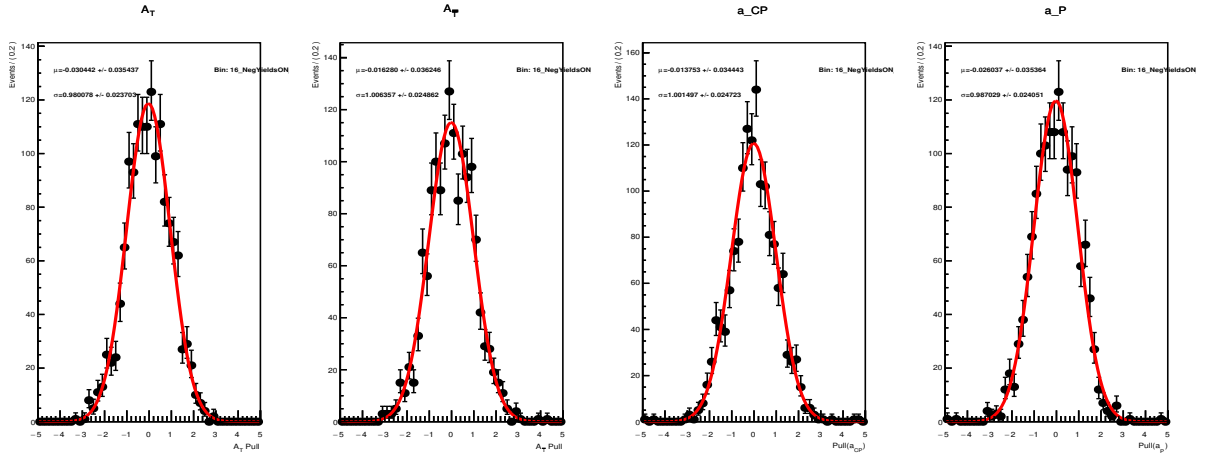


Figure C.17: Pull distributions for the asymmetries in bin 16. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

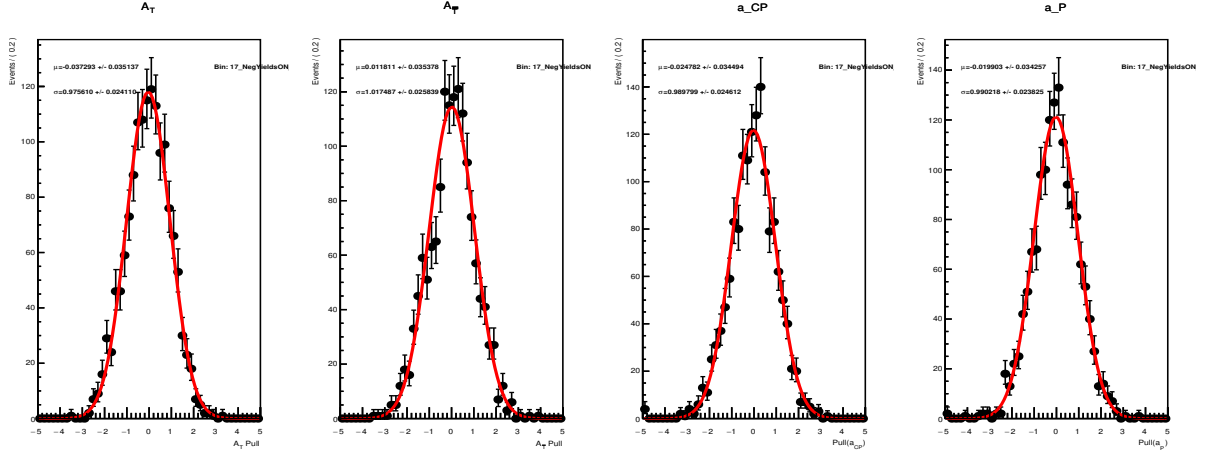


Figure C.18: Pull distributions for the asymmetries in bin 17. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

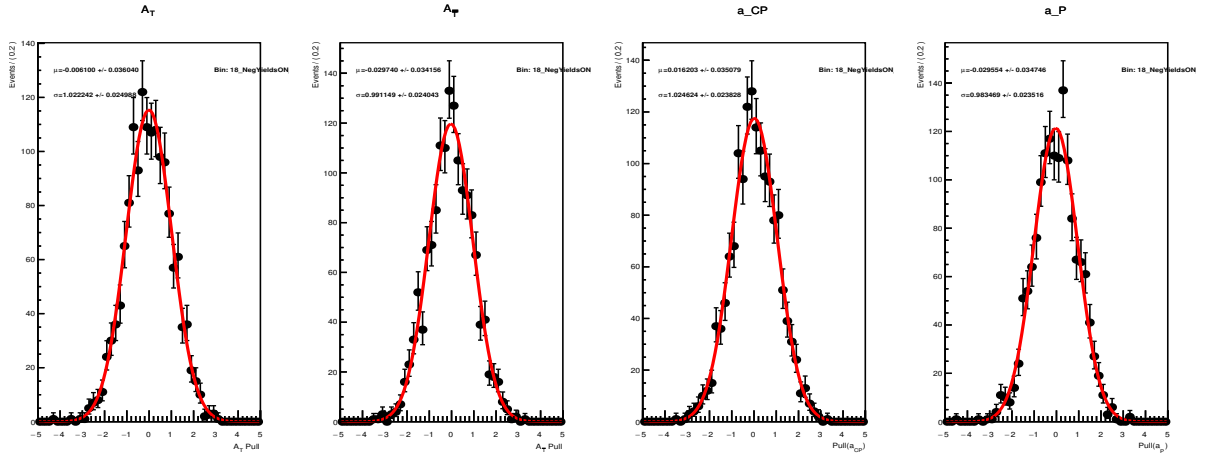


Figure C.19: Pull distributions for the asymmetries in bin 18. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

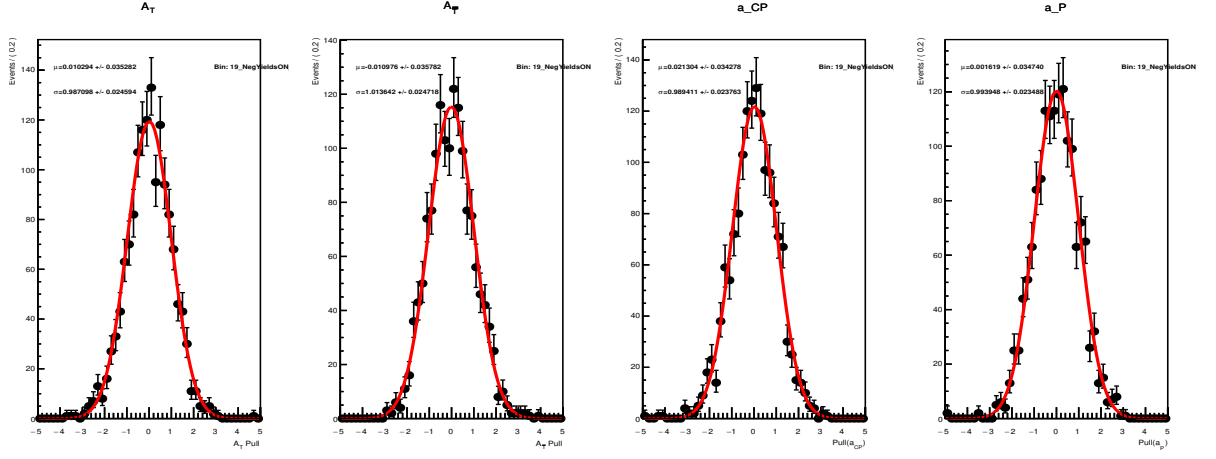


Figure C.20: Pull distributions for the asymmetries in bin 19. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

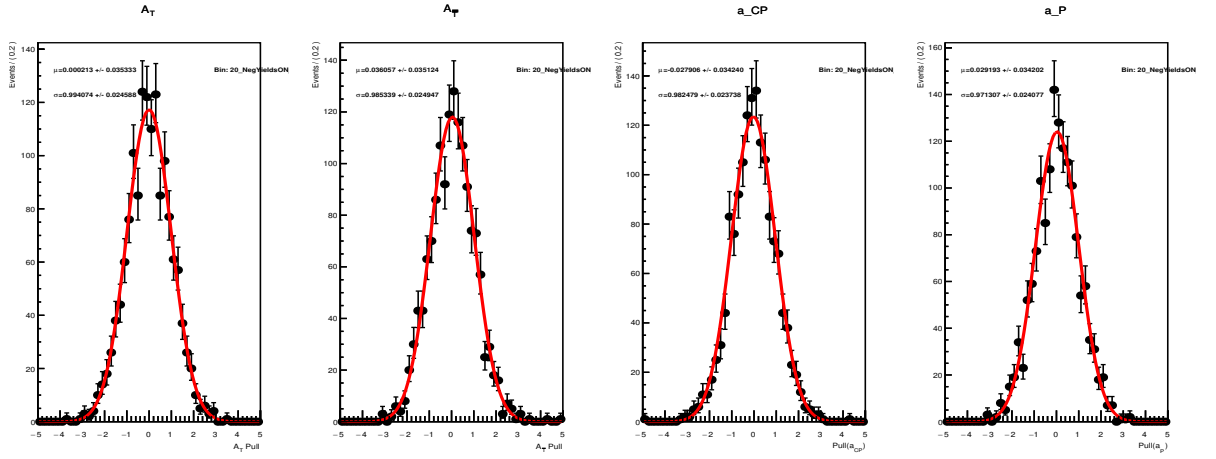


Figure C.21: Pull distributions for the asymmetries in bin 20. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

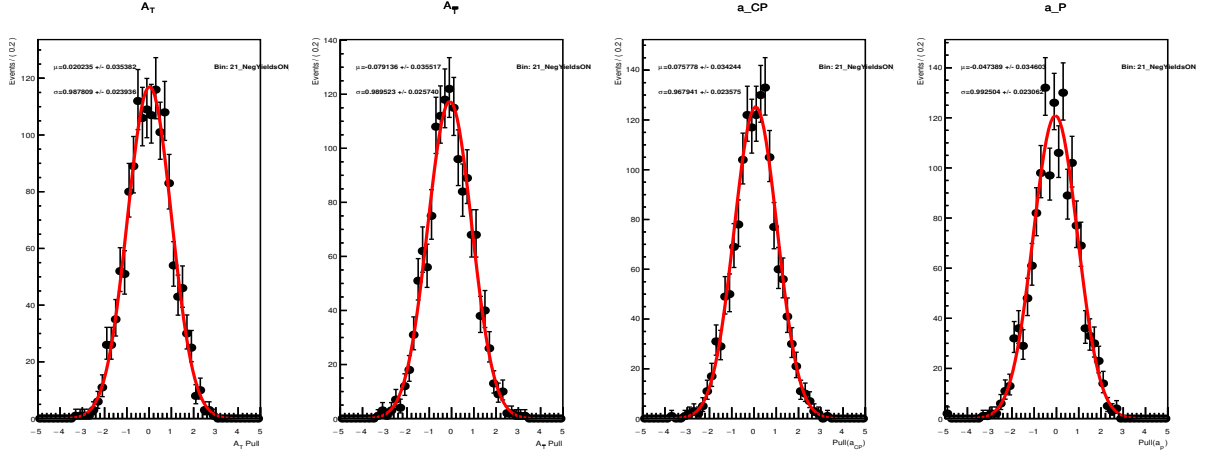


Figure C.22: Pull distributions for the asymmetries in bin 21. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

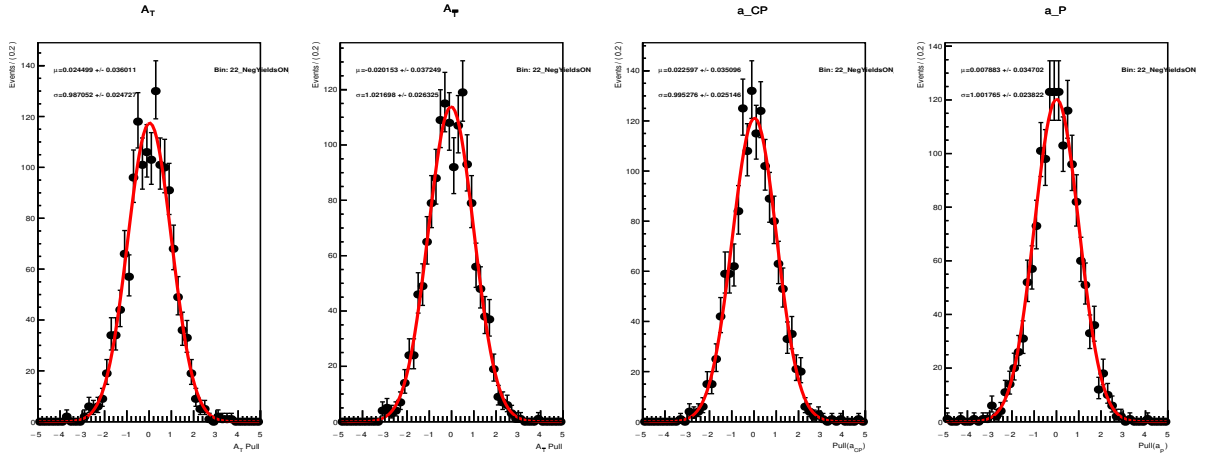


Figure C.23: Pull distributions for the asymmetries in bin 22. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

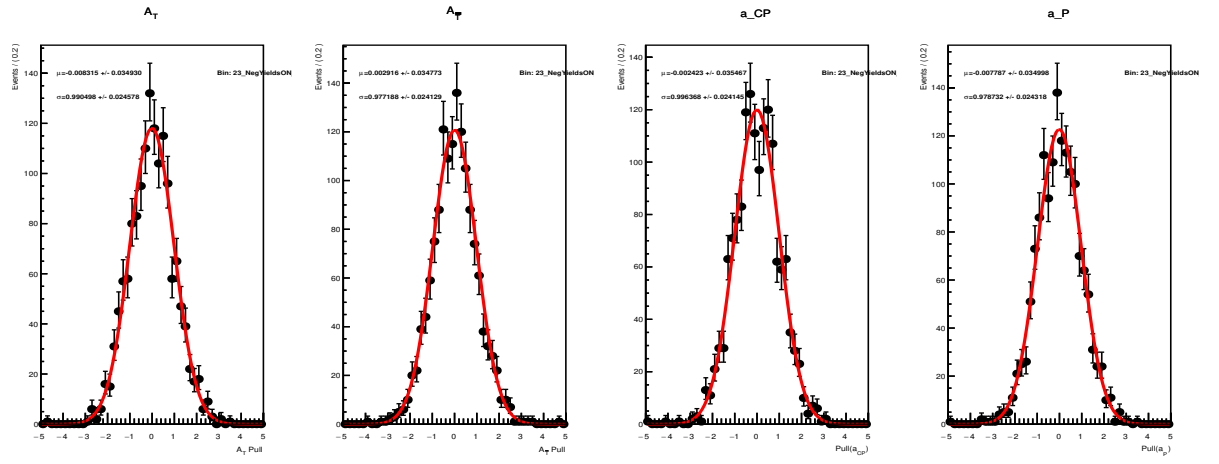


Figure C.24: Pull distributions for the asymmetries in bin 23. From left to right:  $A_{\hat{T}}$ ,  $\bar{A}_{\hat{T}}$ ,  $a_{CP}^{\hat{T}-odd}$ ,  $a_P^{\hat{T}-odd}$

## Appendix D

### Fit result in regions of the phase space





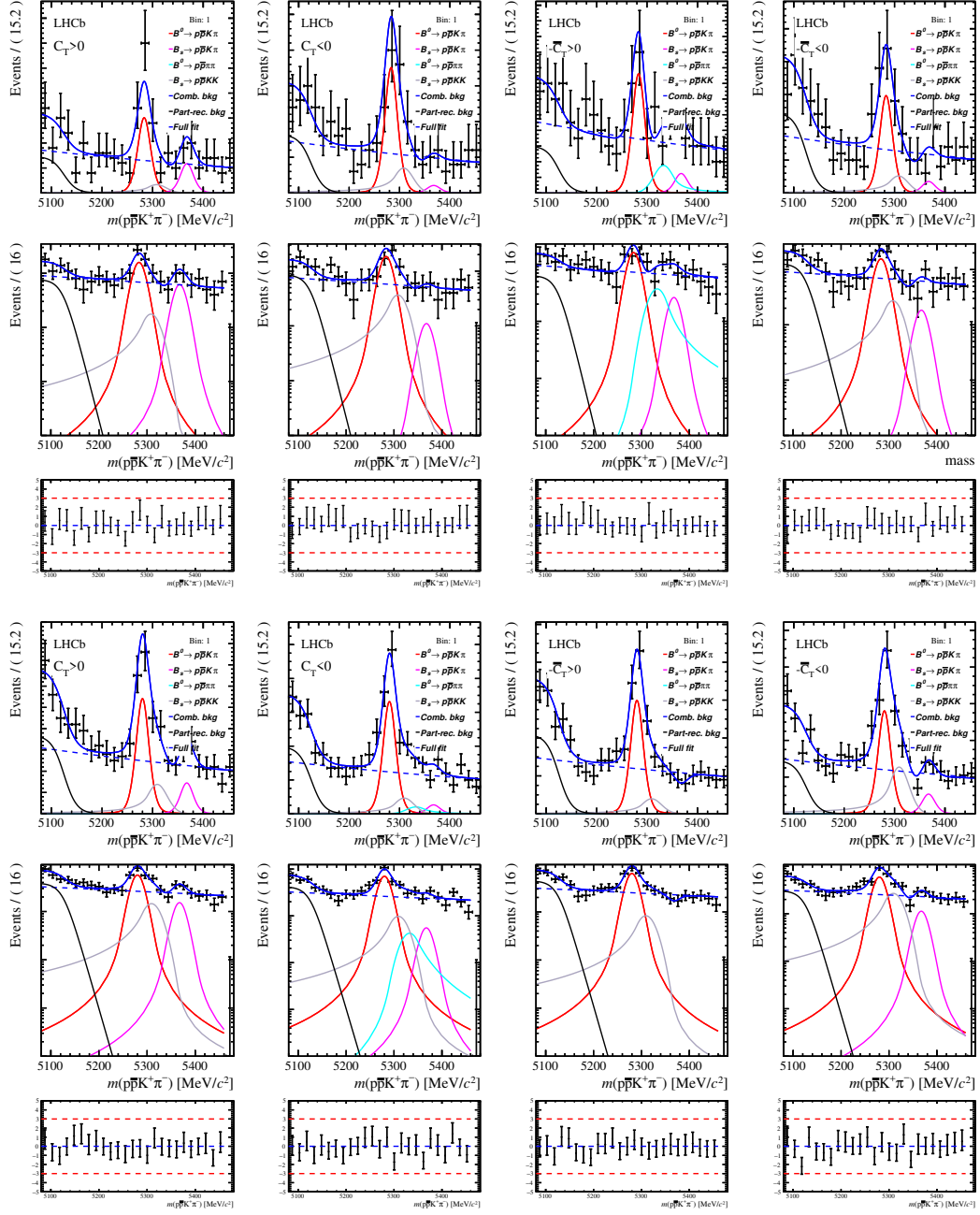


Figure D.2: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 1. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.



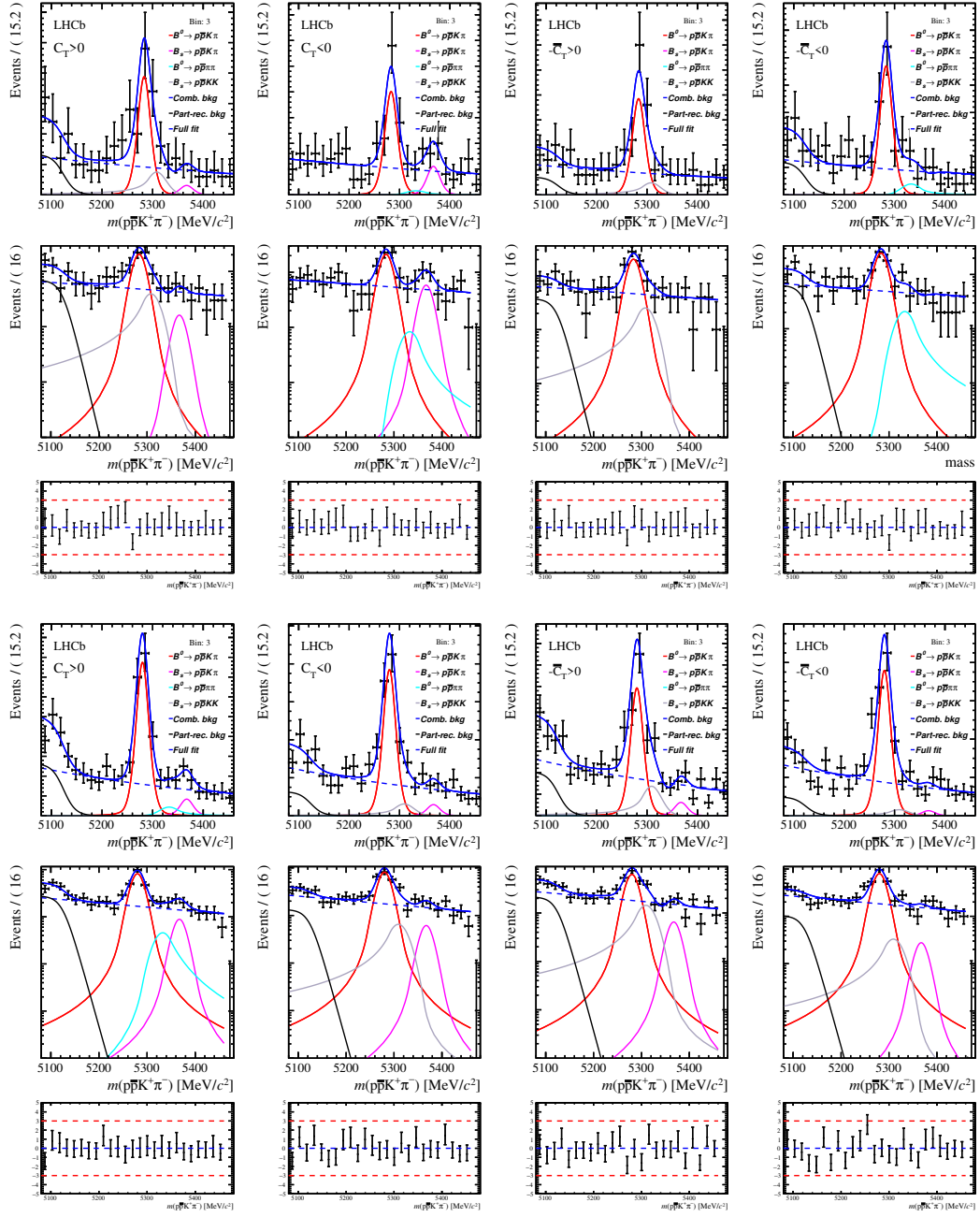


Figure D.4: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 3. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.

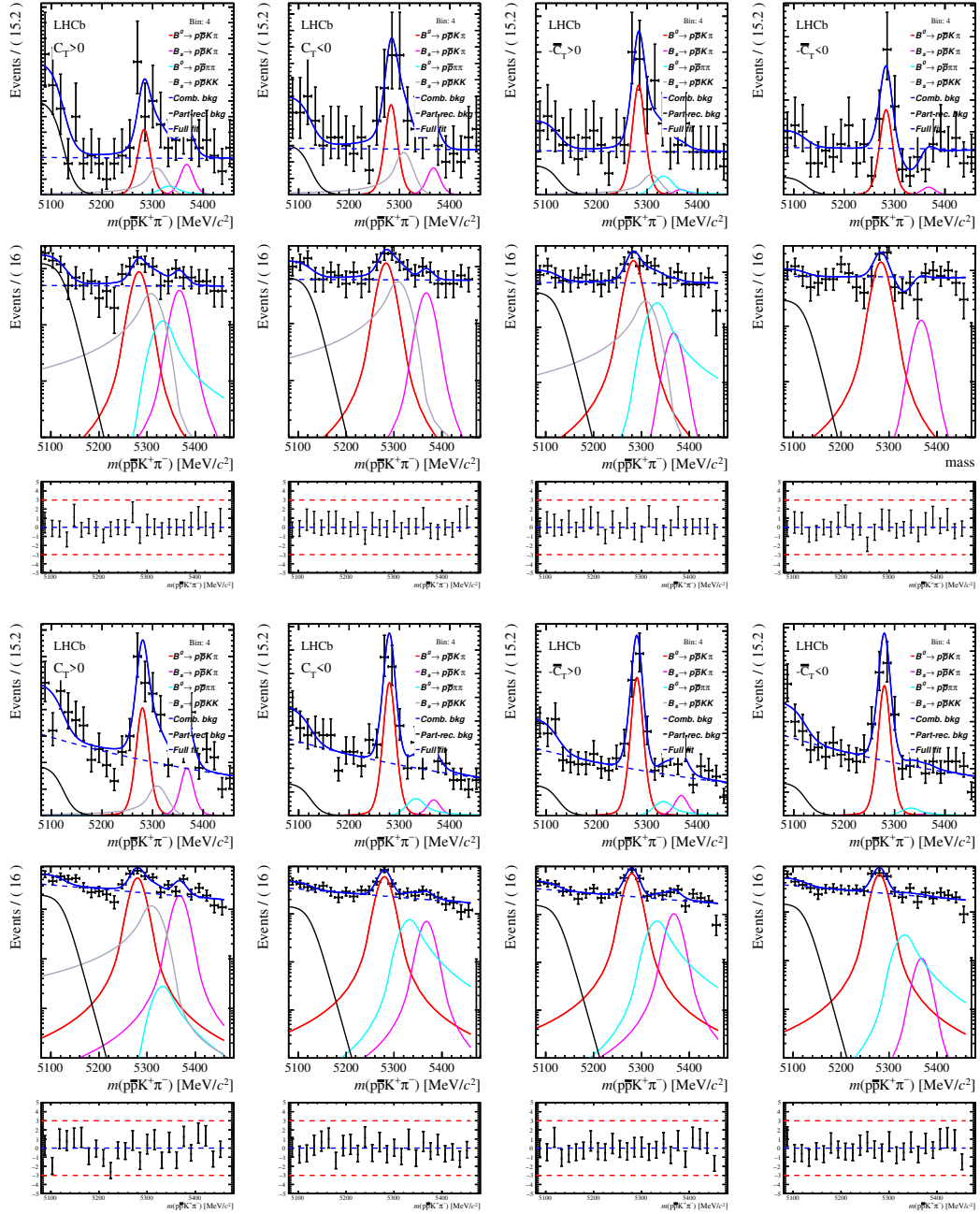


Figure D.5: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 4. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.





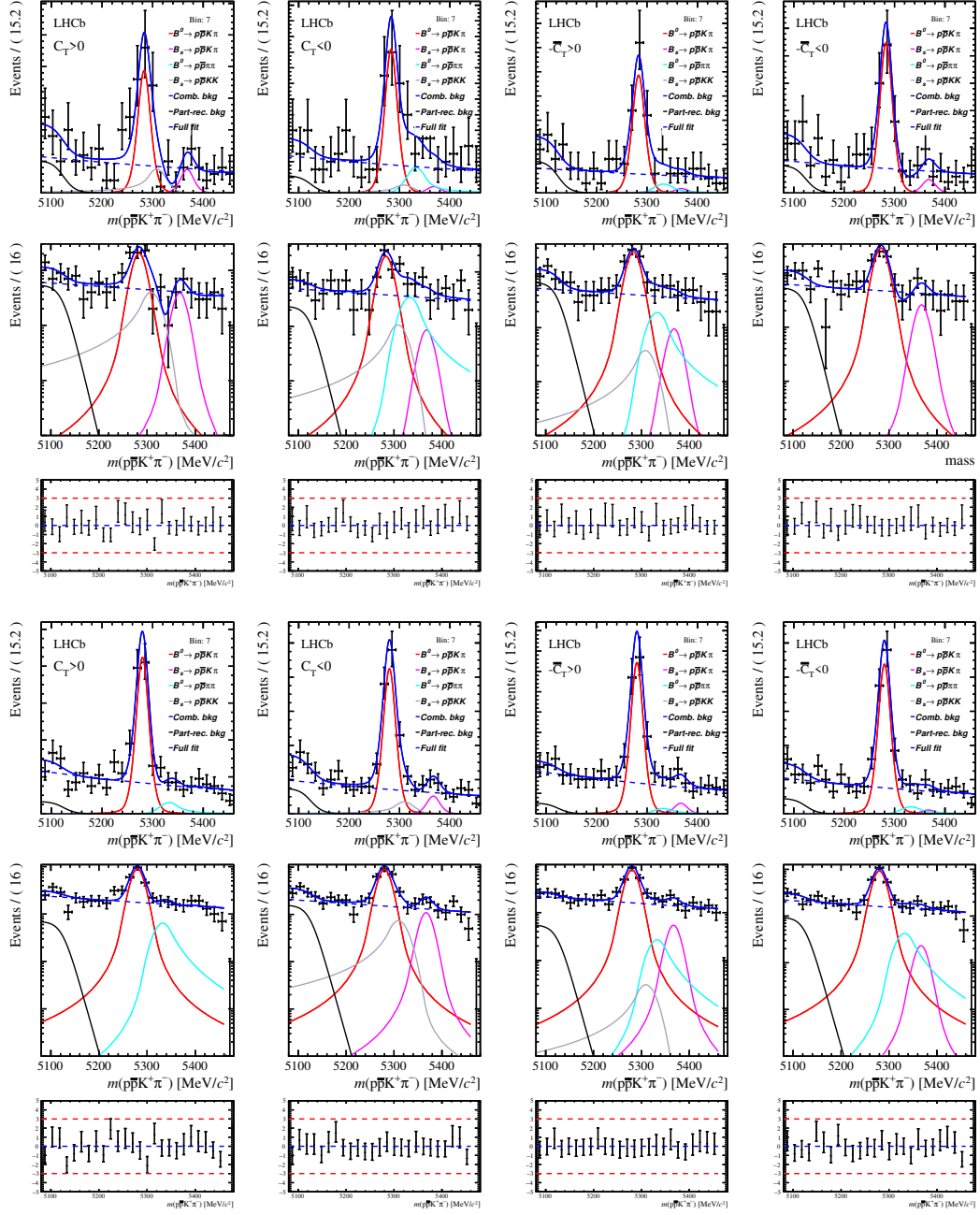


Figure D.8: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 7. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.







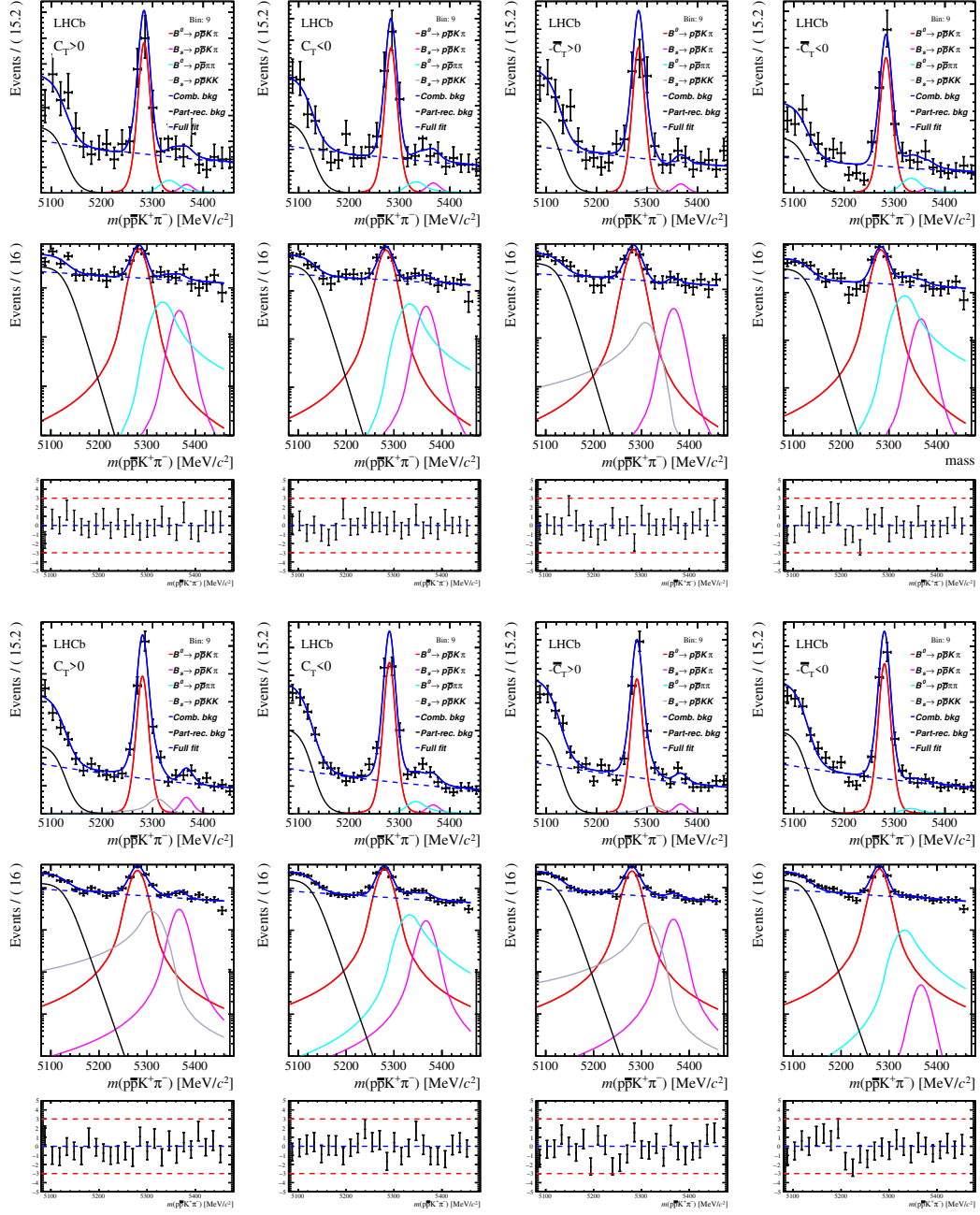


Figure D.10: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 9. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.

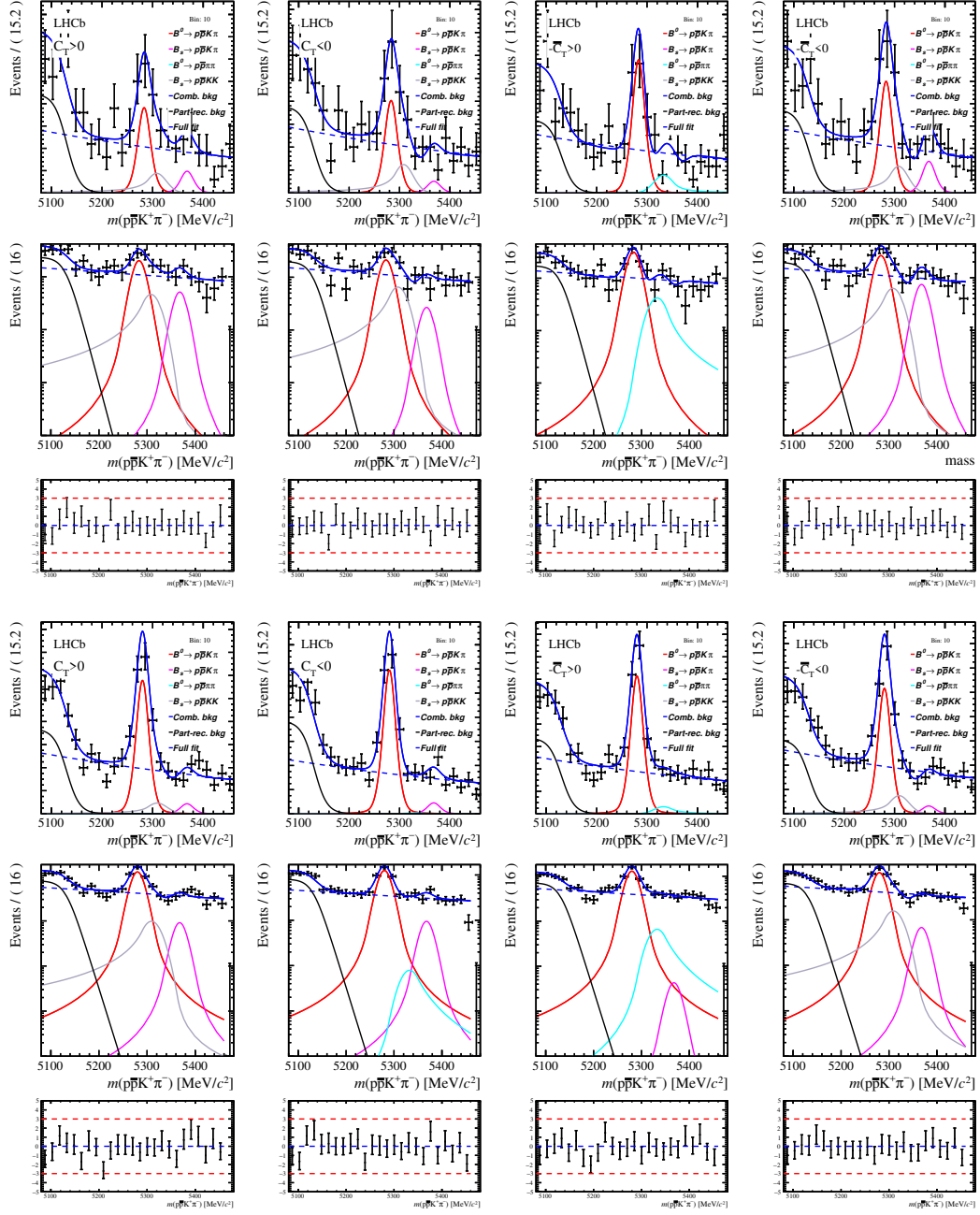


Figure D.11: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 10. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.

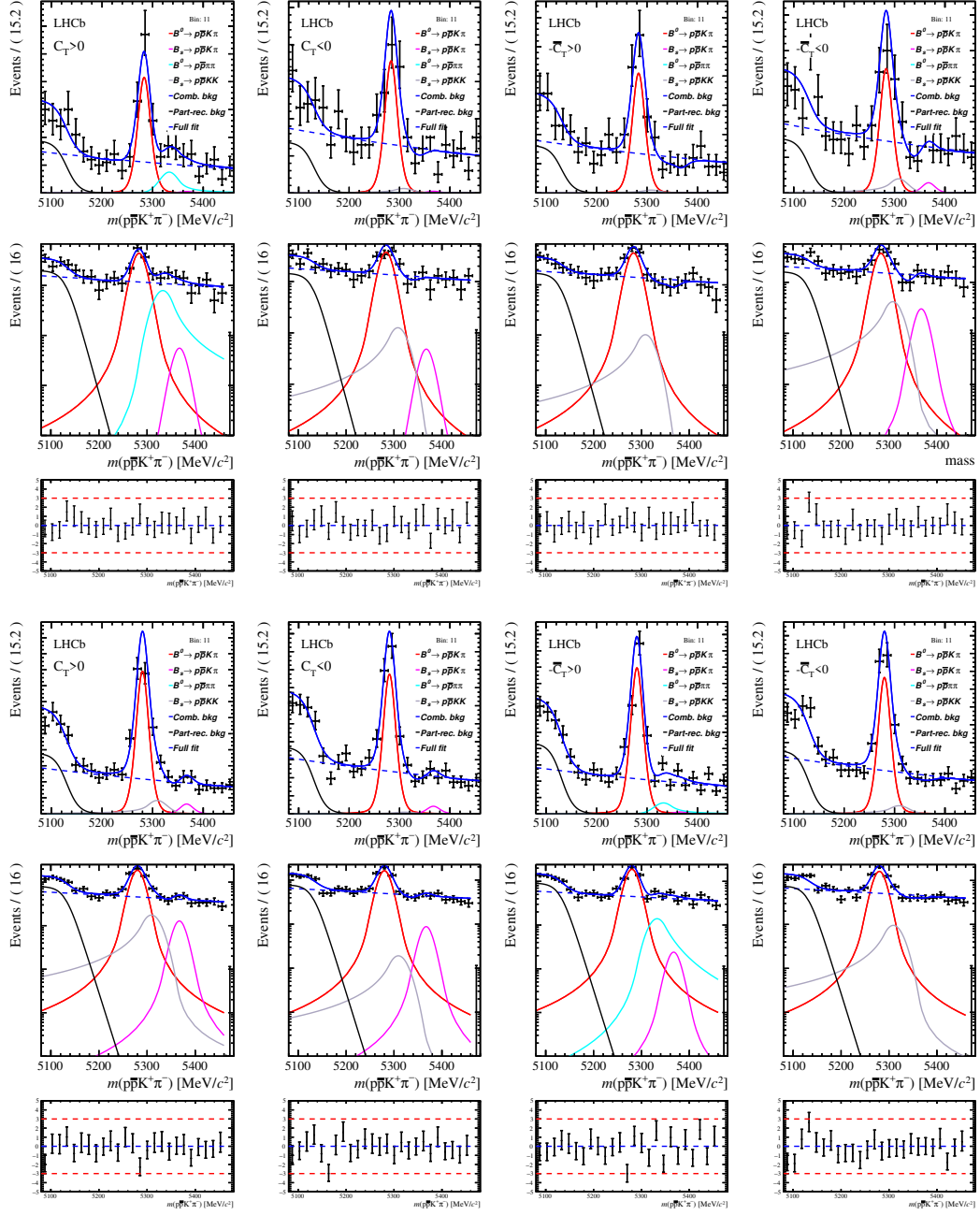


Figure D.12: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 11. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.

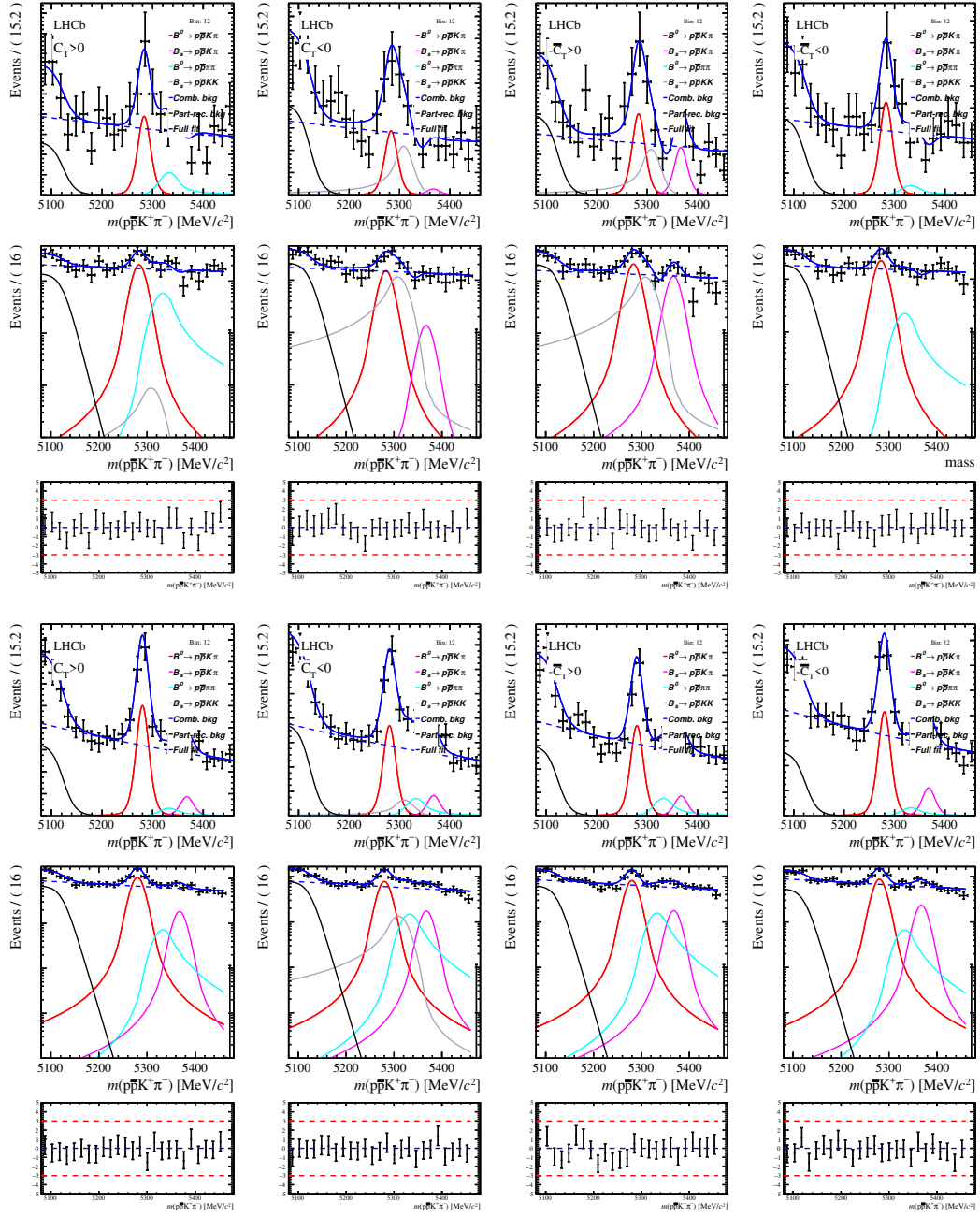


Figure D.13: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 12. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.



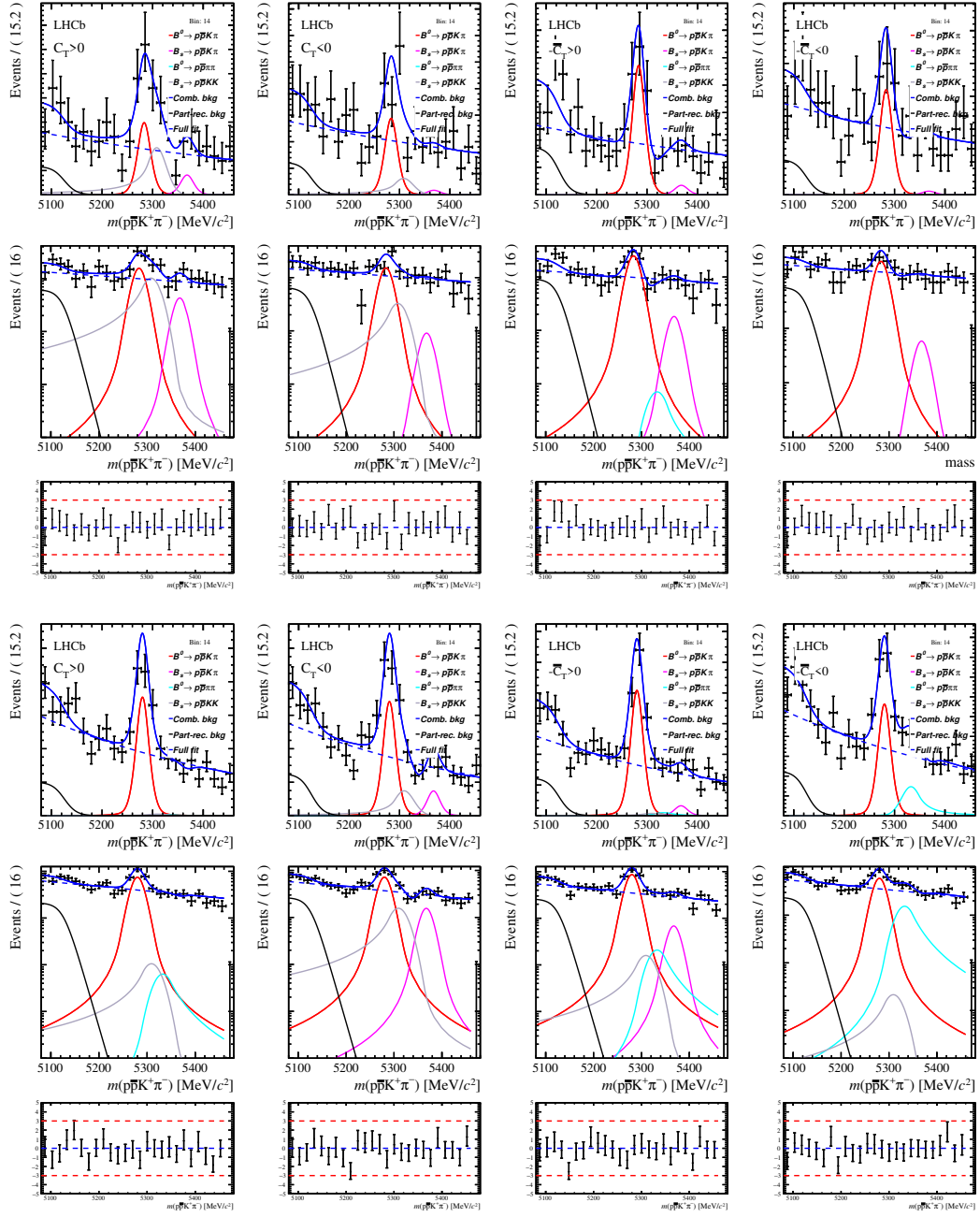


Figure D.15: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 14. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.

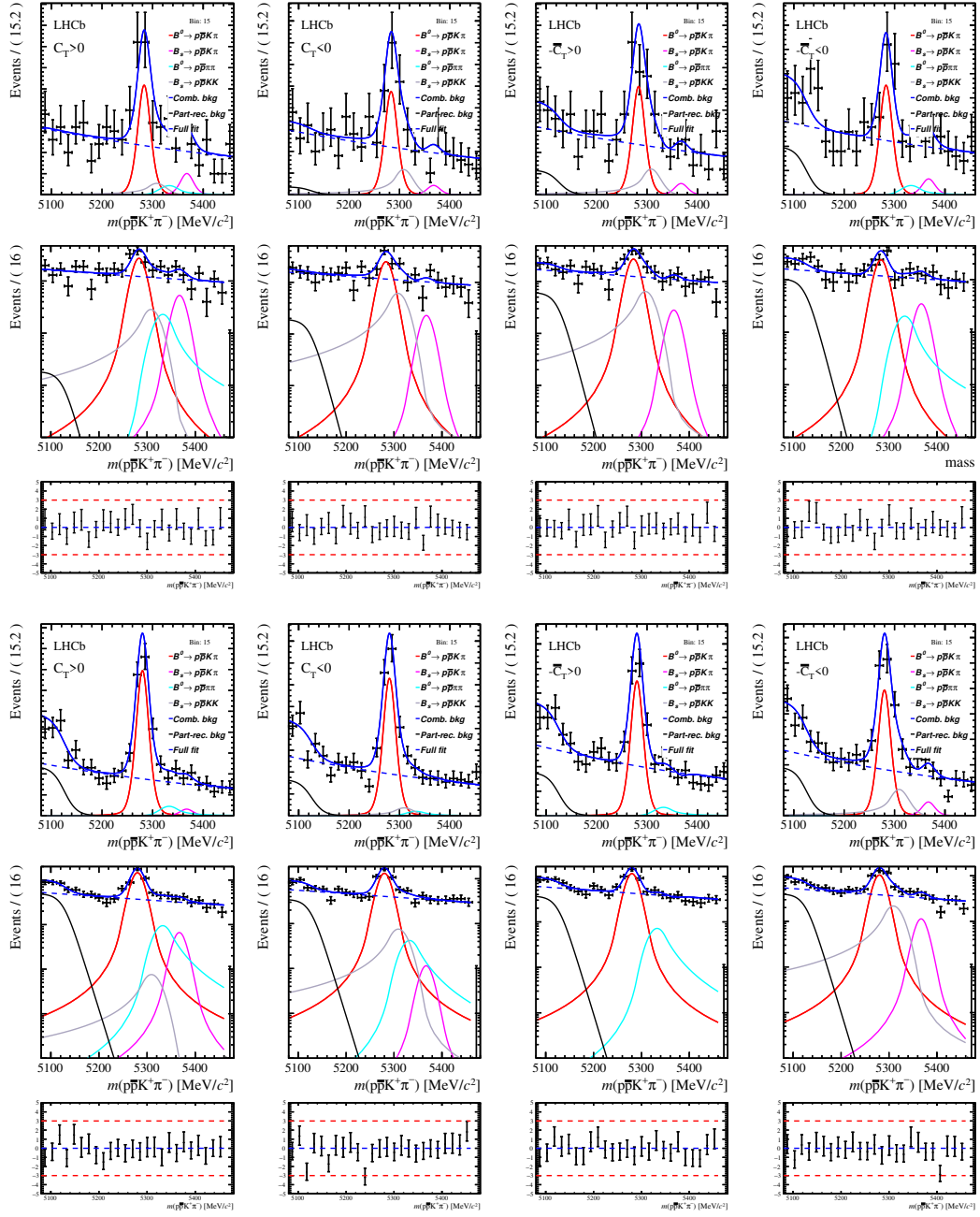


Figure D.16: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 15. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.



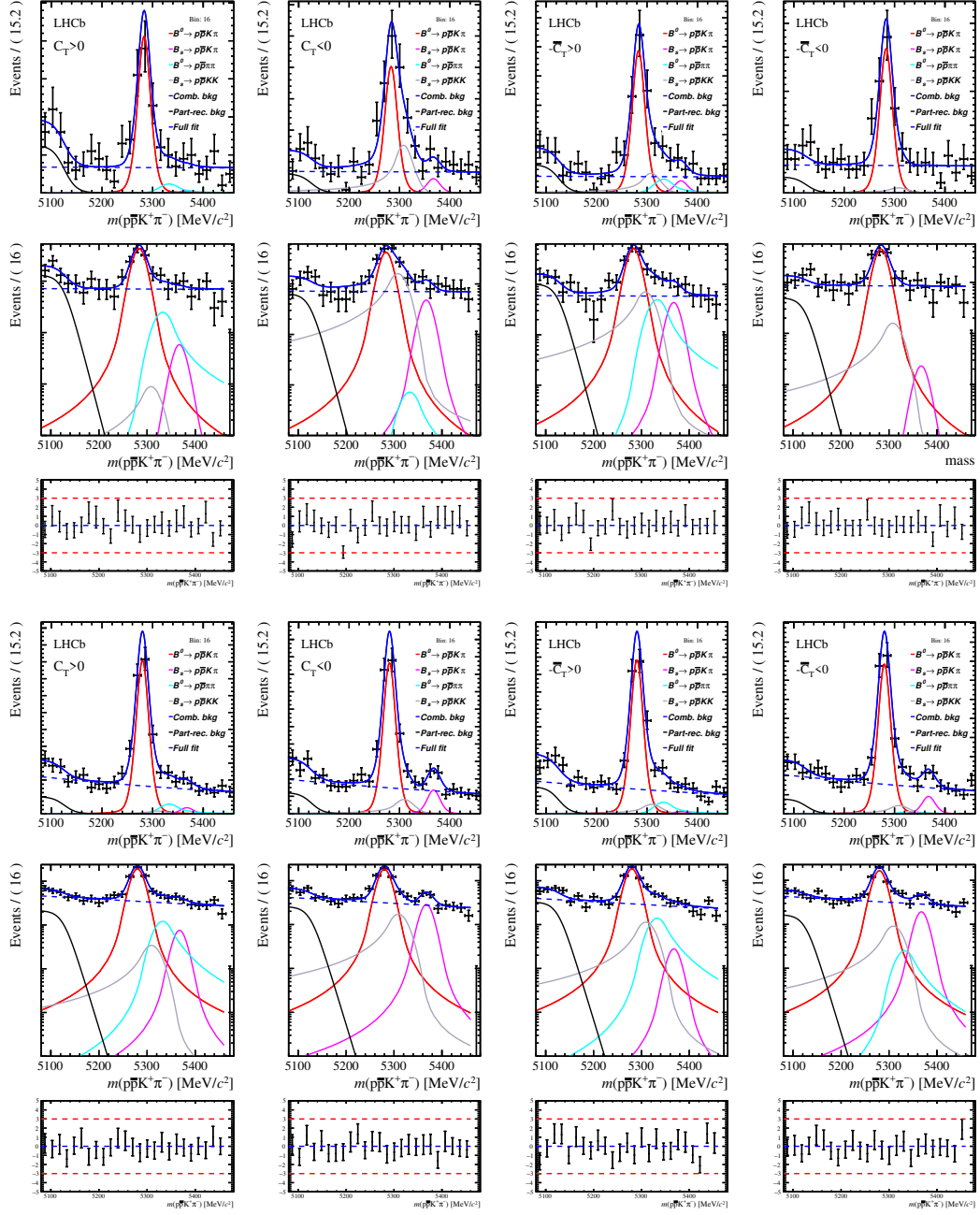


Figure D.17: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 16. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.



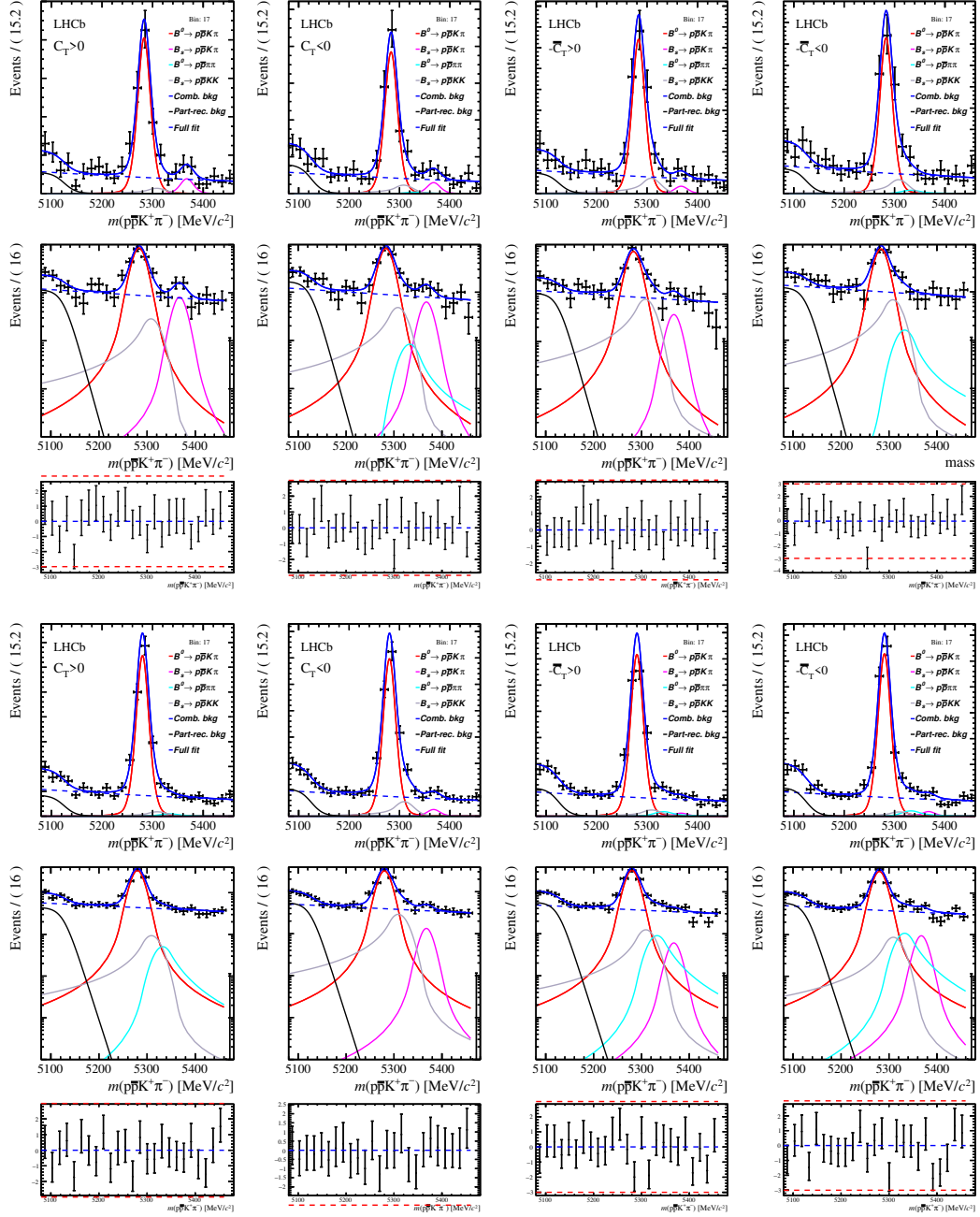


Figure D.18: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 17. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.

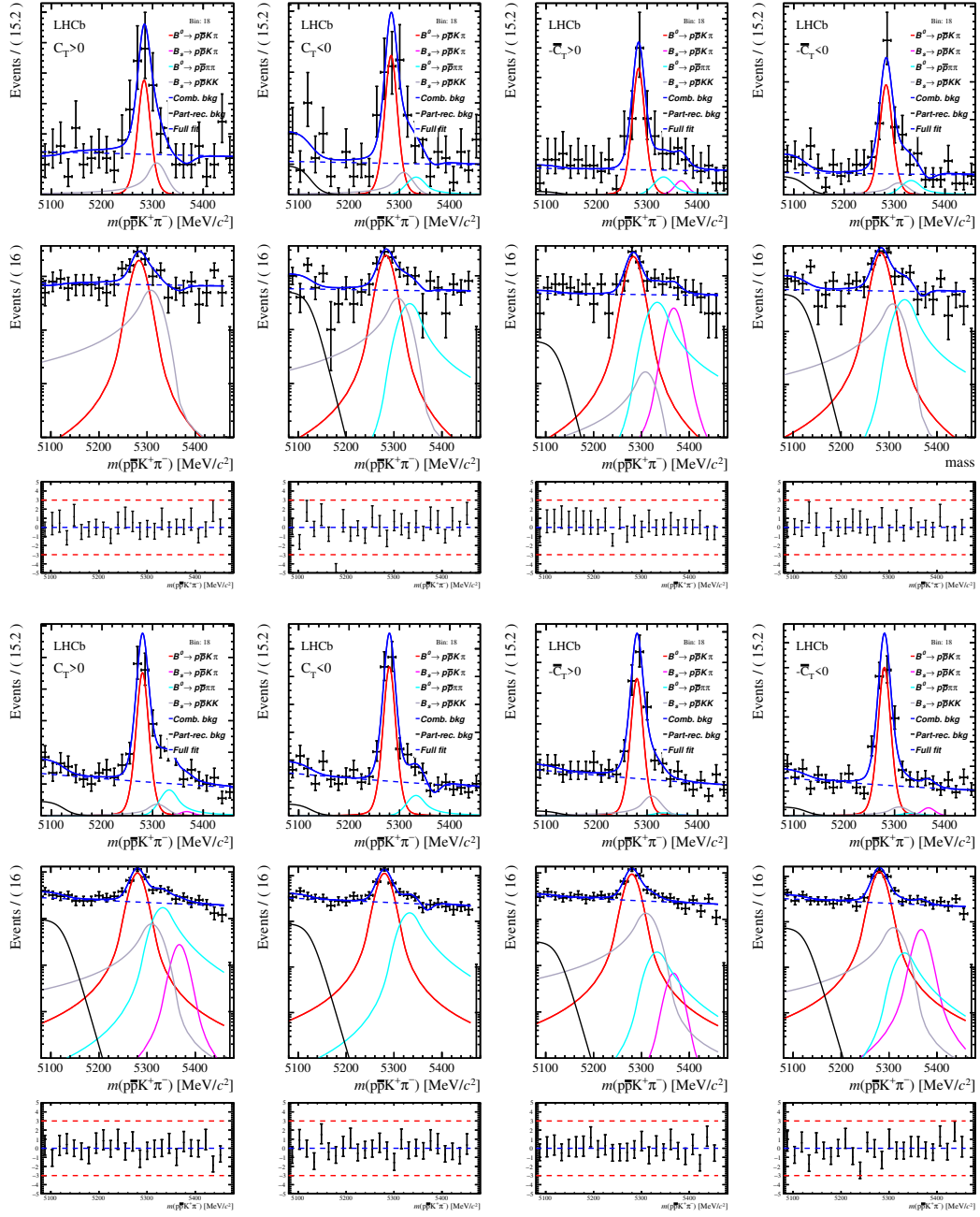


Figure D.19: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 18. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.

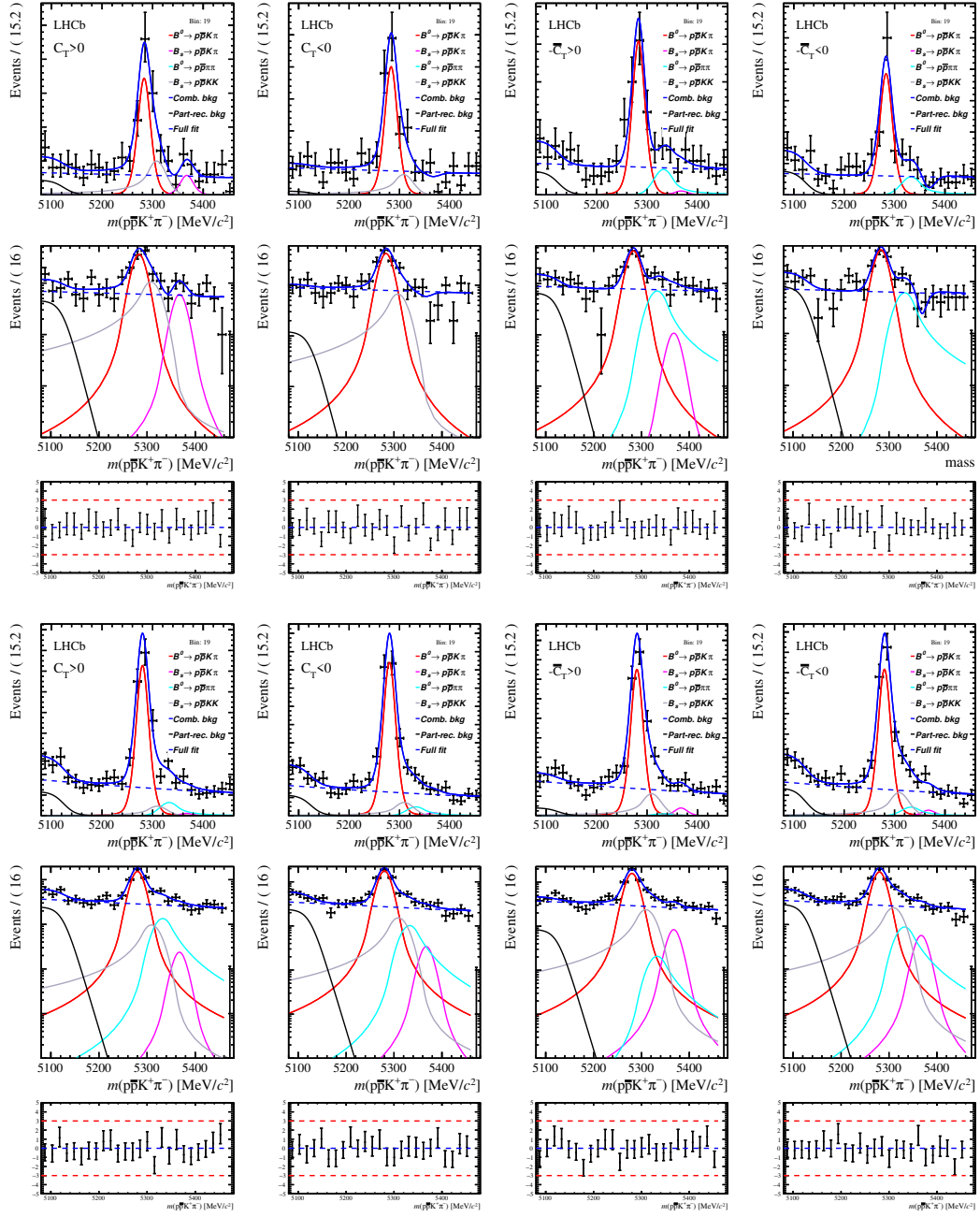


Figure D.20: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 19. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.





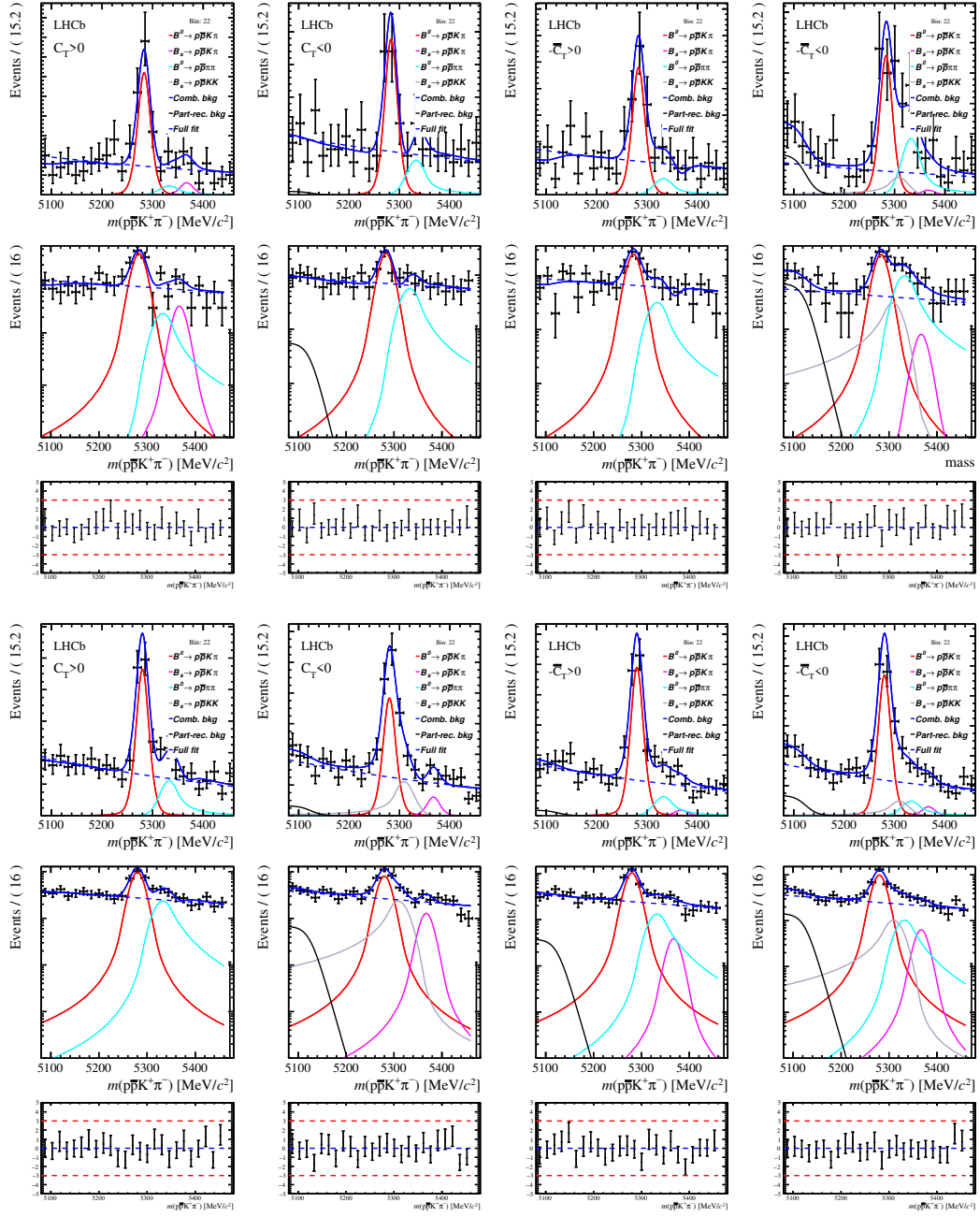


Figure D.23: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 22. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.

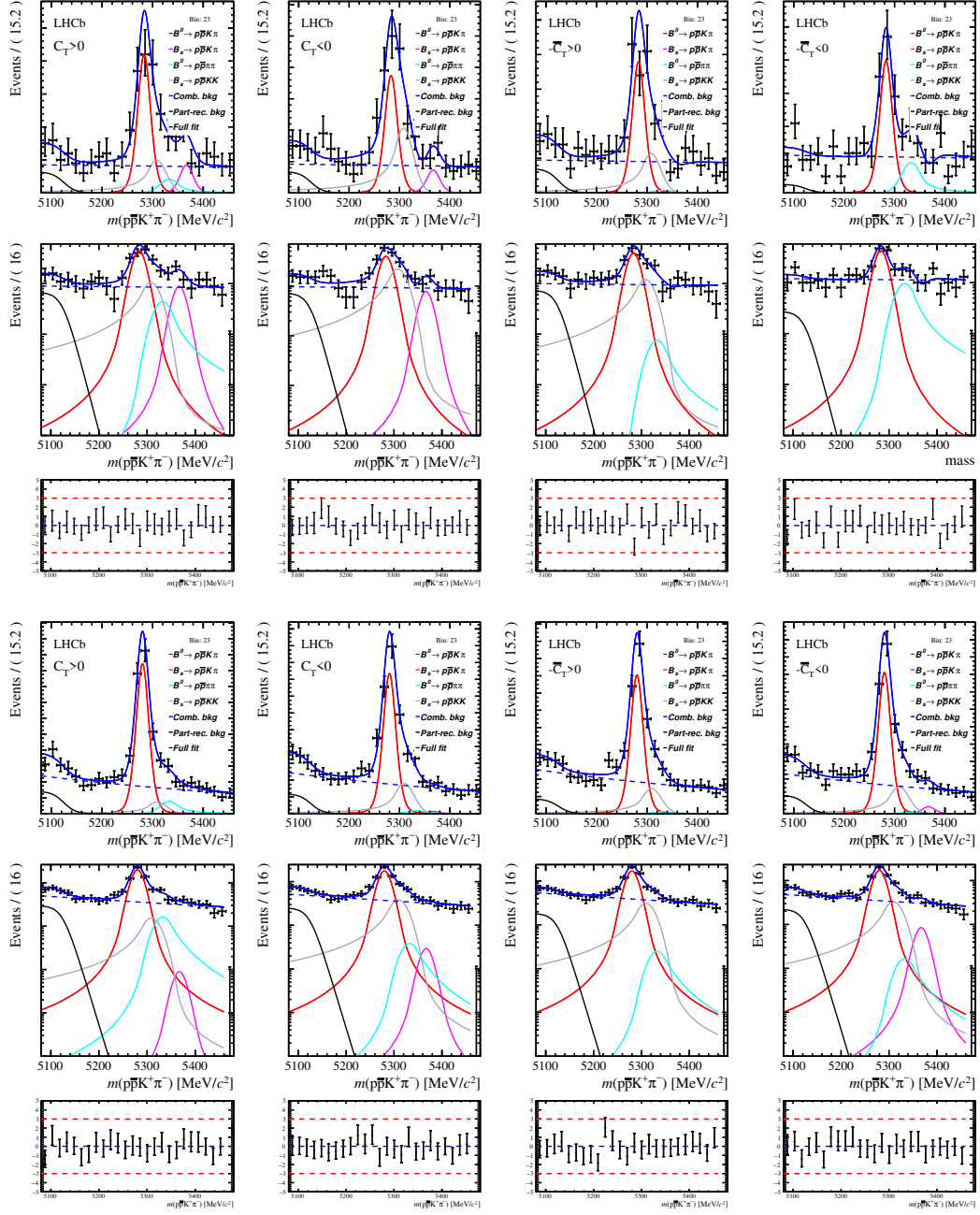


Figure D.24: Distribution of the invariant mass  $m(p\bar{p}K^+\pi^-)$  for bin 23. Top: Run 1 dataset with the projection of the combined fit overlaid. Bottom: Run 2 dataset with the projection of the combined fit overlaid.



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