



DEPARTMENT OF PHYSICS

INDIAN INSTITUTE OF

TECHNOLOGY

MADRAS

CHENNAI-600036

A THESIS

**Measurement of the CP violating weak phase ϕ_s in the
 $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ decay process using the data
collected by CMS in proton-proton collision at $\sqrt{s} = 13 \text{ TeV}$**

to be submitted by

Muhammad Alibordi

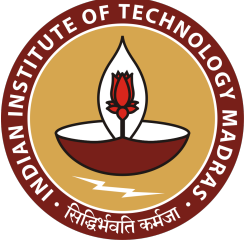
for the award of the degree

of

DOCTOR OF PHILOSOPHY

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THESIS CERTIFICATE

This is to undertake that the Thesis titled, **MEASUREMENT OF THE CP VIOLATING WEAK PHASE ϕ_s IN THE $B_s^0 \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$ DECAY PROCESS USING THE DATA COLLECTED BY CMS IN PROTON-PROTON COLLISION AT $\sqrt{s} = 13\text{ TeV}$** submitted by me to the Indian Institute of Technology Madras, for the award of **Ph.D.** is a bonafide record of the research work done by me under the supervision of **Professor Prafulla Kumar Behera**. The contents of this Thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Date: 30th May 2021

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Research Guide

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- **Journal :**

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- **Conference Proceedings :**

- Measurement of Heavy Flavor Properties at CMS - 16th FPCP 2018: **Springer-SPPHY- 234**.
- Development of CMS silicon strip detector module mechanics for Phase-II upgrade - **PoS-Vertex-2017-048**.

- **CMS internal notes :**

- Measurement of ϕ_s in the $B_s^0 \rightarrow J/\psi \phi$ channel using 2017 and 2018 datasets - **CMS-AN-19-255** .
- $\gamma\gamma \rightarrow \tau\tau$ study with CMS Heavy-Ion data collected at 5.02 TeV - **Restricted - WIP CMS-AN-20-077** .
- Determination of in-time signal profile and calibration of the CMS Zero Degree Calorimeter in the 2018 Pb-Pb Run - **CMS-DN-20-026**.

Abstract

Keywords : CP-violation, Yukawa coupling, CKM matrix, weak phase.

The invariance of the decay rate (the amplitude square) of a decay process $|\mathcal{M}|^2(|\psi_1\rangle \rightarrow |\psi_2\rangle)$ under the simultaneous operation of discrete symmetry operators such as charge conjugation ($\hat{C}$), and parity ($\hat{P}$) is defined as the CP-symmetry i.e., $|\mathcal{M}|^2(|\psi_1\rangle \rightarrow |\psi_2\rangle) = |\bar{\mathcal{M}}|^2(|\bar{\psi}_1\rangle \rightarrow |\bar{\psi}_2\rangle)$. The violation of such invariance $|\mathcal{M}|^2 \neq |\bar{\mathcal{M}}|^2$ is termed as the CP violation (CPV). In the high energy particle physics, the first CP violation was discovered at Brookhaven National Laboratory (1963); the current SM describes the appearance of CP violation in the Yukawa sector via flavor changing transitions of quarks ($q_i \rightarrow W q_j$) as a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Given that the value of the CP-violating phase predicted by the SM is very small, makes it too sensitive toward the new physics. In addition to this, baryogenesis (leptogenesis) can be probed through the window of CP-violation as postulated by Sakharov in 1967. This thesis describes the theory, and the details of the measurement procedure of the CP-violating weak phase using time dependent flavour tagged angular analysis in the $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ decay process. The total data correspond to an integrated luminosity of 96.4 fb^{-1} is used, which is collected during 2017–2018 data taking period in proton-proton collisions at center of mass energy $\sqrt{s} = 13 \text{ TeV}$. This analysis makes the use of robust efficiency estimating algorithms, a DNN based flavour tagger by deploying a dedicated trigger, and an state-of-the-art model building technique toward the extraction of weak phase ϕ_s , decay width difference $\Delta\Gamma_s$. The obtained results are $\phi_s = -11 \pm 50(\text{stat}) \pm 10(\text{syst}) \text{ mrad}$ and $\Delta\Gamma_s = 0.114 \pm 0.014(\text{stat}) \pm 0.007(\text{syst}) \text{ ps}^{-1}$ which are extracted from 48500 reconstructed $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ events. Finally the $\sqrt{s} = 13 \text{ TeV}$ results are combined with the previous 8 TeV results, and the combined results are : $\phi_s = -21 \pm 44(\text{stat}) \pm 10(\text{syst}) \text{ mrad}$, $\Delta\Gamma_s = 0.1032 \pm 0.0095(\text{stat}) \pm 0.0048(\text{syst}) \text{ ps}^{-1}$. The overall improvement is significant when compared to the 8 TeV result.

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Chapter 1

Neutral bottom meson system

...The world is more extraordinary and profound than any of the fables told by our forefathers. I want to go and see it. To accept uncertainty doesn't detract from our sense of mystery...

Reality is Not What it Seems¹

—Carlo Roveli

1.1 The philosophical aspects of particle accelerators in modern physics

The formalism of the quantum electrodynamics (QED) can be considered as the starting point of the modern era of quantum field theory (QFT), and the particle physics as well. There are so much effort has been made through decades by many physicists around the globe to put forward the formalism of QFT until they had the Standard Model (SM)². SM is the low energy effective incomplete QFT based on the invariance of $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ local gauge symmetry. SM posses several drawbacks but still holds a well settled ground since most of the SM predictions are in agreement with the experimental results,

¹ISBN-13: 978-0735213920, Riverhead Books; First American Edition edition (January 24, 2017)

²Standard Model, S.F.Novaes, [arxiv:hep-ph/0001283v1](https://arxiv.org/abs/hep-ph/0001283v1).

even the discovery of the scalar mass generator (Higgs Boson). The analysis of the weak phase measurement projected in this thesis started even after the discovery of the same. Technically, it is very much crucial time for a particle physicist to address the unsolved questions appearing within the formalism of the SM itself and also other questions related to the unification of all the four natural forces and the consequences to those aspects of the unification. A formal approach beyond the SM scenarios is the search of the new physics (NP) which are not described within the SM or appears as a deviation from the SM. Several interesting studies in the low momentum flavour physics sector made by CMS, ATLAS, ALICE and LHCb experiments³ have shown that the collider physics approach may be the best possible scientific procedure in the right direction toward the discovery of new physics. The whole idea of studying physics is to understand the natural resources given by mother nature, utilising those resources to make a scientific and civilised society along the direction of discovering the truth of natural facts or phenomena. In other words it is the study of motion of material universe in terms of the natural forces, interactions and unification between those forces and the consequences of those unifications and interactions since the beginning of the universe called the Big Bang (BB)⁴. The modern techniques of quantisation of the force fields shows a glimpse that what could be the possible operational principles or the governing laws of nature. To do the study of the dynamics and properties of quantised states of the force fields three things are very much obvious: the first one is a high energy probe and the production mechanism which will probe the subatomic world and produce the quantised states of force fields. The next one is a set of complex eyes which will detect those states and the last but not the least is a set of statistical tools, and the methods which will perform the procedure of calculations for various kinematic properties of those states. A particle accelerator evolves when these three techniques are merged together. As a concluding remark of this section a statement can be given that *accelerators are indeed very necessary tools to find the natural truth*. The boost toward the investigation of the Beyond

³CERN public website <https://home.cern/science/experiments>

⁴Baryogenesis, Csaba Balázs, [arxiv:hep-ph/1411.3398v1](https://arxiv.org/abs/hep-ph/1411.3398v1).

the Standard Model (BSM)⁵ is evolving due to the discrepancies comprises in the SM, such as, hierarchy problem, cosmological constant problem, user defined parametric space⁶, inability to explain the existence of the non interacting Dark matter or baryogenesis and so on [13, 14]. The known physics as of today describes the nature with four kind of irreducible

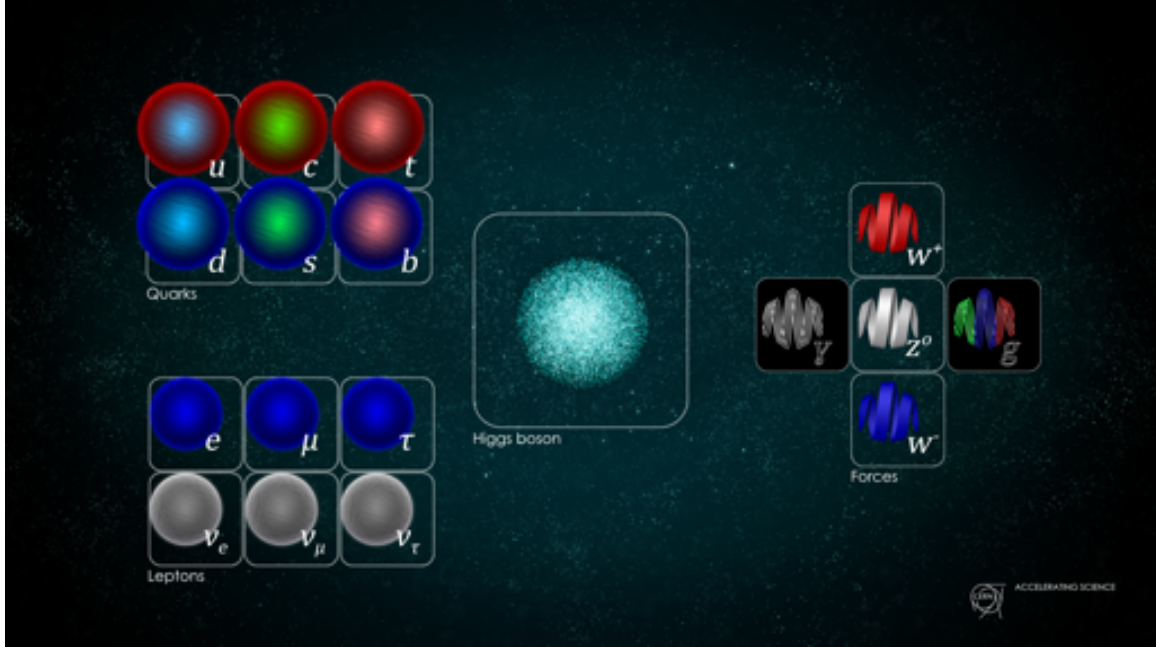


Figure 1.1: The current version of the SM contains three generations of leptons and their corresponding neutrinos, interactions mediators ($\gamma, W^\pm, Z, g$), six quarks and mass generator higgs particle (H). The photons (γ) are the mediator of EM interaction, $W^\pm, Z$ are the mediator of weak interaction, and the gluons are mediating strong force. Spontaneous breaking of electroweak symmetry in gauge theories is achieved by deploying a scalar field; in the electroweak sector this mechanism generates W and Z masses through a complex scalar doublet and also predicts the existence of SM Higgs Boson (H).

natural interactions or fundamental forces. The electromagnetic and the gravitational interactions are long range interactions where as, the strong and the weak interactions are short range forces exist only in the subatomic world. These interactions have different strength and force carriers shown in Figure 1.1⁷.

⁵Beyond Standard Model, B.C.Allanach, [arxiv:hep-ph/1609.02015v2](https://arxiv.org/abs/hep-ph/1609.02015v2).

⁶Free parameters of SM.

⁷CERN posters: CDS: OPEN-PHO-CHART-2015-001-1

1.2 CP violation and $B\bar{B}$ mixing

1.2.1 LHC production of B_s^0

The projected objective of the current thesis is to determine the precise values of the CPV parameters involved in the neutral bottom meson decay process $B_s^0 \rightarrow J/\psi\phi$ by putting main emphasis on the weak phase ϕ_s measurement. The B_s^0 ($\bar{B}_s^0$) meson is a di-quark state $\bar{b}s$ ($b\bar{s}$), produces by strong force, and decaying into $B_s^0 \rightarrow J/\psi\phi$ by exploiting the weak intercation. Given that the current measure of the achievable energy at LHC the production cross section of $b\bar{b}$ is quite large in comparison to the other interesting physics scenarios. There are three elementary $b\bar{b}$ pair production processes are involved in the pp collision, such as,

- **Flavor creation :** This is a Leading Order (LO) process sensitive to α_s ⁸ comprises quark annihilation $q\bar{q} \rightarrow b\bar{b}$, or gluon-gluon fusion mechanism $gg \rightarrow b\bar{b}$.
- **Flavor excitation :** Next-to-Leading Order (NLO) process ($\sigma_{b\bar{b}} \propto \alpha_s^3$), this process defines the interaction of the quark with a gluon and the production of $b\bar{b}$ pair, such as, $g\bar{q} \rightarrow b\bar{b}\bar{q}$.
- **Gluon splitting :** NLO process : pair production of $b\bar{b}$ from a gluon, such as, $g \rightarrow b\bar{b}$.

The CMS ($\sqrt{s} = 7\text{TeV}$) measurement corresponding to B hadron cross section is shown in the Figure 1.2⁹. The uncertainties corresponding to statistical one is depicted by inner error bar, the outer (thinner) error bars shows the quadratic sum of statistical and systematic, and the outermost brackets are describing the total error. The MC@NLO provides the theory predictions at Next to Leading Order.

⁸Coupling of the strong interaction.

⁹CMS public result, measurement of hadron cross section.

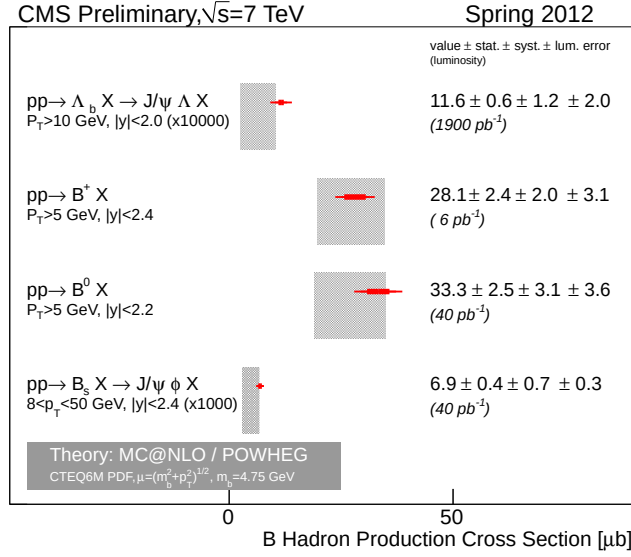


Figure 1.2: The CMS ($\sqrt{s} = 7$ TeV) measurement corresponding to B hadron cross section.

1.2.2 CKM mechanism and the CP-violating phase

The invariance of the decay rate (the amplitude square) of a decay process $|\mathcal{M}|^2(|\psi_1\rangle \rightarrow |\psi_2\rangle)$ under the simultaneous operation of discrete symmetry operators such as charge conjugation ($\hat{C}$), and parity ($\hat{P}$) is defined as the CP-symmetry i.e., $|\mathcal{M}|^2(|\psi_1\rangle \rightarrow |\psi_2\rangle) = |\bar{\mathcal{M}}|^2(|\bar{\psi}_1\rangle \rightarrow |\bar{\psi}_2\rangle)$. The violation of such invariance $|\mathcal{M}|^2 \neq |\bar{\mathcal{M}}|^2$ is termed as the CP violation (CPV). In the high energy particle physics, the first CPV was discovered at Brookhaven National Laboratory (1963) [15]¹⁰; the current SM describes the appearance of CPV in the Yukawa sector via flavor changing transitions of quarks ($q_i \rightarrow W q_j$). Reviews on CPV studies [16] confirms that several measurements on CPV performed in the different experimental environment satisfies the unitarity condition of the Cabibbo-Kobayashi-Maskawa¹¹ (CKM) matrix, and provide a sensible and resourceful comprehensive evidence that the CPV is sourced due to the irreducible complex phase provided by CKM matrix. The research of the flavor changing transitions of quarks $q_i \rightarrow W q_j$ are very

¹⁰It was the first experimental evidence of CP violation when $K_S^0 \rightarrow \pi^+ \pi^-$ decay process has been observed, the K_S^0 were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV proton. The branching ratio $R = K_S^0 \rightarrow \pi^+ \pi^- / (K_S^0 \text{ all modes}) = (2.0 \pm 0.4) \times 10^{-3}$ appeared as a strong evidence of two pion decay mode of K_S^0 , and the very conclusion was that K_S^0 is not a pure CP eigenstate.

¹¹Cabibbo first developed the formalism (1963) of quark mixing matrix for two generation of quarks which further generalized by Kobayashi and Maskawa (1973) for three generation within the context of SM.

prompt in B-physics. The finite measure of the CP-asymmetry ($\mathcal{A}_{CP}$) given in Equation 1.1 describes the unequal decay width between a decay of B to final state f ($\Gamma_{B \rightarrow f}$), and the decay width of CP-conjugate decay ($\Gamma_{\bar{B} \rightarrow \bar{f}}$). This finite CP-asymmetry implies a non-zero irreducible phase of CKM couplings, which is required to generate CP-violating physics processes in the SM. SM accommodates the CPV in the charged weak current interactions between left handed quark fields.

$$\mathcal{A}_{CP} = \frac{\Gamma_{B \rightarrow f} - \Gamma_{\bar{B} \rightarrow \bar{f}}}{\Gamma_{B \rightarrow f} + \Gamma_{\bar{B} \rightarrow \bar{f}}} \quad (1.1)$$

$$\mathcal{L} = \frac{g_w}{\sqrt{2}} J^\mu W_\mu^- + H.C. \quad (1.2)$$

The weak current (J^μ) interaction in the SM given in Equation 1.2 describes that the weak current does not couple to the quark mass eigenstate but with weak isospin eigenstates. The mixing between three generations of isospin doublets are obtained using the CKM matrix (3×3 unitary matrix, $VV^\dagger = \mathbb{1}$). Given that the unitary condition, for three generations of isospin doublets, the CKM matrix comprises 4 irreducible coefficients, 3 real valued mixing angles, and 1 complex weak phase. The mixing coefficients form the CKM matrix at the quark level which is described in the Equation 1.3.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad (1.3)$$

Two Unitarity Triangle (UT) appears for both neutral B mesons $B_d^0 (d\bar{b})$ and $B_s^0 (s\bar{b})$ respectively by imposing the orthonormality condition on the CKM matrix which are described in Equation 1.4 and the graphical description of the UTs are outlined in Figure 1.3.

$$\begin{aligned} B_d^0 : V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* &= 0 \\ B_s^0 : V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* &= 0 \end{aligned} \quad (1.4)$$

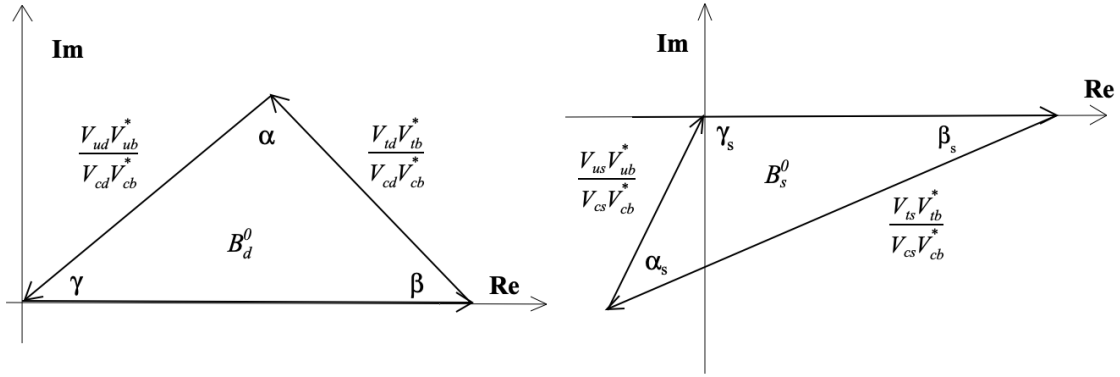


Figure 1.3: The Unitarity Triangles formed by the quark mixing (or transition) coefficients for the B_d^0 system (left) and also for the B_s^0 system (right). The sides are scaled such a way that one of the sides is equal to unity. The scale of the other imaginary axes are arbitrary and different; the directions of the arrows in the complex plane are governed by the measured values of the coefficients of transitions.

Features of the Unitarity Triangles

$$\begin{aligned}\alpha_s &= \arg\left(-\frac{V_{ts}^* V_{tb}}{V_{us}^* V_{ub}}\right) \quad \beta_s = \arg\left(-\frac{V_{cs}^* V_{cb}}{V_{ts}^* V_{tb}}\right) \quad \gamma_s = \arg\left(-\frac{V_{us}^* V_{ub}}{V_{cs}^* V_{cb}}\right) \\ \alpha &= \arg\left(-\frac{V_{td}^* V_{tb}}{V_{ud}^* V_{ub}}\right) \quad \beta = \arg\left(-\frac{V_{cd}^* V_{cb}}{V_{td}^* V_{tb}}\right) \quad \gamma = \arg\left(-\frac{V_{ud}^* V_{ub}}{V_{cd}^* V_{cb}}\right)\end{aligned}\quad (1.5)$$

$$\text{Constraint : } \alpha_s + \beta_s + \gamma_s = \pi, \alpha + \beta + \gamma = \pi$$

β is implying the phase of $B_d^0 - \bar{B}_d^0$ mixing, whereas the β_s is defining the phase of $B_s^0 - \bar{B}_s^0$ mixing. The apex of B_d^0 system is $-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$ and the apex of B_s^0 system is $-\frac{V_{us}V_{ub}^*}{V_{cs}V_{cb}^*}$. The quantitative description of the CPV is proportional to another phase convention independent parameter J , which is called Jarlskog invariant. The quantitative value of the CPV measured by the area of the UT $= |J|/2$ and the definition of the Jarlskog invariant is given in Equation 1.6.

$$\text{Im}[V_{ij}V_{kl}V_{il}^*V_{kj}^*] = J \sum_{m,n} \epsilon_{ikm}\epsilon_{jln} \quad (1.6)$$

For the finite measure of CPV in weak interaction the non-zero area of unitarity triangle is required^a.

^aFor CP-violation to occur in addition the quark masses are required to be non-degenerate.

1.2.3 Wolfenstein parametrization

The coefficients of CKM matrix introduces mixing or the transitions of quarks originated in the Yukawa sector where the fermions are having interactions with scalar particle (Higgs),

$$\mathcal{L}_Y = -Y_{ij}^d \bar{Q}_{Li}^I \Phi d_{Rj}^I - Y_{ij}^u \bar{Q}_{Li}^I \epsilon \Phi^* u_{Rj}^I + h.c. \quad (1.7)$$

In the weak-isospin basis i, j are generation labels, $Y_{ij}^{u,d}$ are 3×3 complex matrix, Φ is scalar¹² field, $\bar{Q}_{(L,R)i}^I$ are left/right handed quark doublet, $(d, u)_{Rj}^I$ are down/up type quark singlet, ϵ is an 2×2 antisymmetric tensor. Physic observables are obtained after diagonalising $Y^{(u,d)}$ at vacuum $(0, v/\sqrt{2})$ of Higgs interact with singlet quark states via $W^\pm$ mediated charged-current interactions and the coupling are involved through the CKM matrix which superposes the rotated flavour states to get the physical states. The most general convention for this matrix in the Yukawa sector is described in Equation 1.8.

$$V_{CKM} = \begin{pmatrix} z_{12}z_{13} & w_{12}z_{13} & w_{13}e^{-i\delta} \\ -w_{12}z_{23} - z_{12}w_{23}w_{13}e^{i\delta} & z_{12}z_{23} - w_{12}w_{23}w_{13}e^{i\delta} & w_{23}z_{13} \\ w_{12}w_{23} - z_{12}z_{23}w_{13}e^{i\delta} & -z_{12}w_{23} - w_{12}z_{23}w_{13}e^{i\delta} & z_{23}z_{13} \end{pmatrix} \quad (1.8)$$

Where $w_{ij} = \sin \theta_{ij}$, $z_{ij} = \cos \theta_{ij}$, θ_{ij} 's are mixing angles between different flavour generation and the KM phase δ is the CPV introducing phase, and $\sum_i V_{ij}V_{ik}^* = \delta_{jk}$ and $\sum_j V_{ij}V_{kj}^* = \delta_{ik}$. The observed values of the mixing angles posses a hierarchy, following that a re-parametrisation was necessary depending upon the hierarchy of the observed magnitude of the couplings which is apparent. In 1983 Wolfenstein [17] re-parametrised the CKM matrix using 4 parameters λ, A, ρ, η ($\lambda = |V_{us}| \sim 0.23$ where, $\lambda = \sin \theta_C$, θ_C is Cabibbo

¹²Higgs.

angle).

$$V_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8}(1 + 4A^2) & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 + \frac{\lambda^4}{2}A(1 - 2\rho - 2i\eta) & 1 - \frac{\lambda^4}{2}A^2 \end{pmatrix} + \mathcal{O}(\lambda^5) \quad (1.9)$$

The parametrised matrix form is described in Equation 1.9, the corresponding coefficients A, ρ, η are real and of the order of unity. More details on the choice of parametrisation can be found in [18] and the references therein. In the Wolfenstein phase convention the CKM matrix takes the form shown in Equation 1.10 implies that the phase of V_{ts} is responsible for the CPV in the decay process $B_s^0 \rightarrow J/\psi\phi$.

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5) \quad (1.10)$$

The constrained CKM matrix phase space updated by *CKM-fitter*¹³ are outlined in Figure 1.4 for B_d^0 and B_s^0 . The estimated values of the constraints are obtained by performing a global fit using both direct and indirect searches are listed in Table 1.1 for Jarlskog invariant J , and UT angle $\beta_s = \arg\left(-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right)$.

Observable	Value ($\pm 3\sigma$)
Jarlskog invariant J	$3.06_{-0.18}^{+0.27} \times 10^{-5}$
β_s	$0.0185_{-0.0013}^{+0.0014}$ (rad)

Table 1.1: Global fit results for Jarlskog invariant J , and UT angle $\beta_s = \arg\left(-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right)$. These results are combined in the summer 2019 ESP conference includes both direct and indirect measurements.

¹³The CKM fitter group.

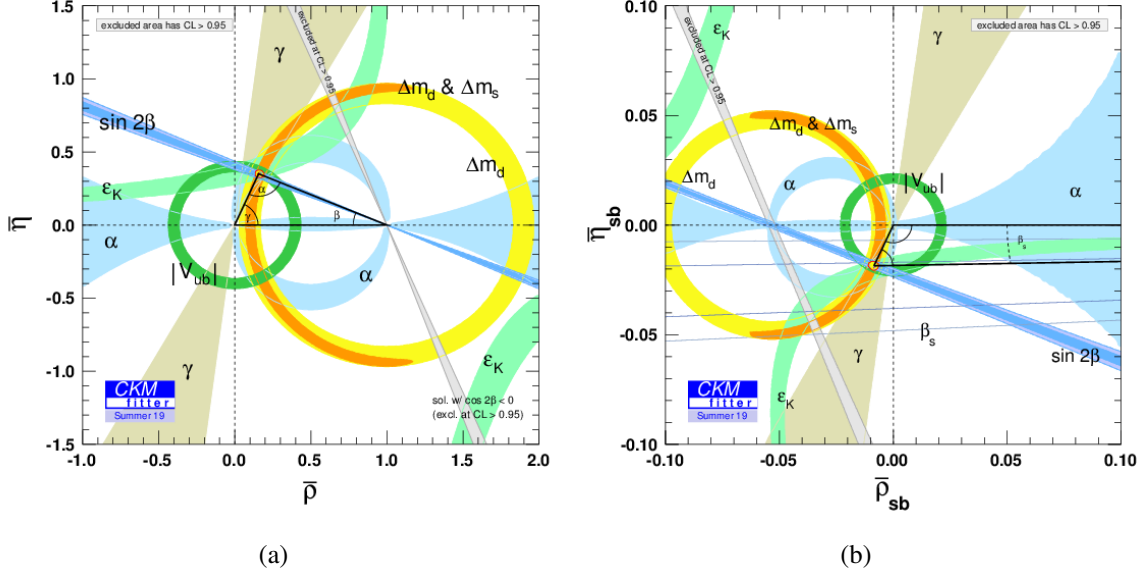


Figure 1.4: The constraints on the Unitarity Triangles obtained from measurements performed by several experiments relevant for the B_d^0 system (left) and the B_s^0 system (right) within the context of Standard Model. The constraints on UTs are multiplied by $V_{us}V_{cd}/V_{ud}V_{cs}$.

1.2.4 $B\bar{B}$ mixing

In the $SU(2)_L \otimes U(1)_Y$ invariant local gauge theory bottom¹⁴ (b) (beauty) quarks are isospin doublet to the top (t) quark in the third generation, and discovered 43 years back in 1977 in E288 experiment at Fermilab [19]. B mesons are two-quark states of which one quark is bottom b quark. B's are important because they are consuming quite heavy quark ($m_b \simeq 5m_p$) interacts most strongly with ultramassive top quarks ($m_t \simeq 175m_p$) but cant decay into top quark. Particularly B_s^0 has long lifetime $\tau_{B_s} \simeq 1.5\text{ps}^{-1}$ ($c\tau_{B_s} = 450\mu\text{m}$) and large mixing frequency¹⁵ and fully mixes in about 4.4 lifetimes, and has a large CP -violation effects (10%-30%) much larger than kaon system (0.1%) which allows sizeable interference effects in decay processes¹⁶. The general particle properties of B_s^0 (B_d^0) meson can be found in Table 1.2. The neutral B mesons, B_d^0 and B_s^0 go through a phenomenon called mixing where a particle state converts to own antiparticle state via oscillation, and vice versa. This

¹⁴ $I(J^P) = 0(1/2)^+$, Charge = $-1/3e$, $m_b = 4.18_{-0.03}^{+0.04}\text{GeV}$

¹⁵ Δm_q , first discovered in ARGUS experiment, ARGUS: hero of Greek mythology having many eyes so that he would see everything (*Alle Richtigen Genies Unter Sich*), H. Albrecht et al., ARGUS, PLB (1987)

¹⁶Which in turn can be used to probe the complex couplings of the CKM parameters

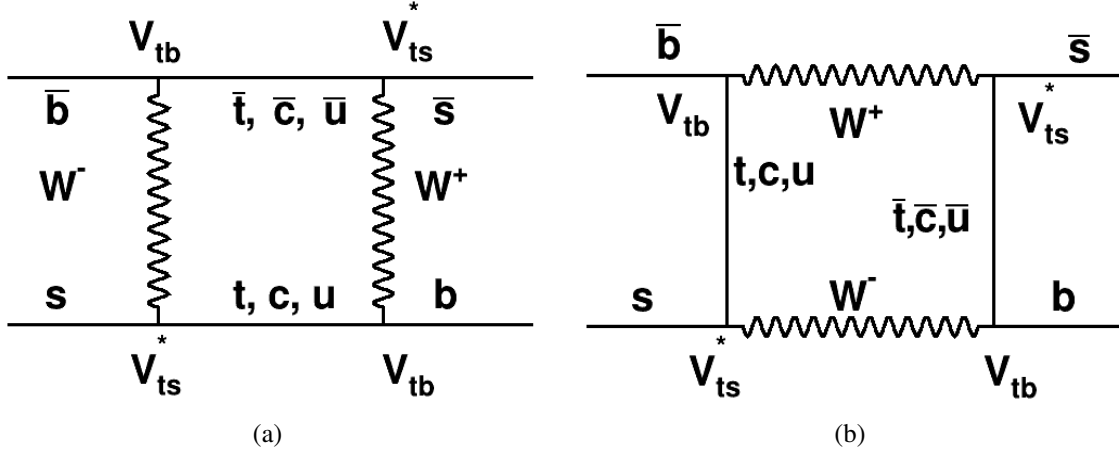


Figure 1.5: SM diagrams for the transition of $\bar{B}_s^0 - B_s^0$ mixing through flavour changing charged current.

fact is described by the box-diagram for B_s^0 , and at the lowest order of the same is outlined in the Figure 1.5. The strange bottom mesons are produced in the strong decay process and decays through weak process. So the $|B_s^0\rangle$ and $|\bar{B}_s^0\rangle$ are strong eigen states while decaying

Properties	B_d^0	B_s^0
Quark content	$d\bar{b}$	$s\bar{b}$
m_q (MeV)	5279.62 ± 0.15	5366.82 ± 0.22
τ_q (ps ⁻¹)	1.520 ± 0.004	1.510 ± 0.005
Δm_q (ps ⁻¹)	0.5096 ± 0.0034	17.757 ± 0.021

Table 1.2: General particle properties of B_d^0 and B_s^0 mesons, the subscript q describes the distinguishability of two different system. Δm_q describes the oscillation frequency of $B\bar{B}$ mixing.

via weak interaction, and evolving with respect to time towards its projection on the mass eigenstate. For the measurement of the time evolution of mixing corresponding physical to B_s^0 system a linear superposition of the flavor eigenstate has to be taken.

$$|\psi(t)\rangle = a(t) |B_s^0\rangle + b(t) |\bar{B}_s^0\rangle \quad (1.11)$$

The generic coefficient $a(t)$, and $b(t)$ multiplied to the particle (anti-particle) time dependent states in Equation 1.11 are the mixing coefficients evolving with time. A simplified non-Hermitian 2×2 Weisskopf-Wigner¹⁷ (WW) Hamiltonian can describe the time evolu-

¹⁷V. Weisskopf and E. P. Wigner, *Zeits.furPhys.* **63**(1930)54.

tion of the oscillating two level system is given in the Equation 1.12,

$$\mathcal{H} = \mathbb{M} - \frac{i}{2}\mathbf{\Gamma} \quad (1.12)$$

Applying the above Hamiltonian, the time evolution differential equation of the two state system is written in the Equation 1.13.

$$i\frac{d}{dt} \begin{pmatrix} |B_s^0\rangle \\ |\bar{B}_s^0\rangle \end{pmatrix} = \left(\mathbb{M} - \frac{i}{2}\mathbf{\Gamma} \right) \begin{pmatrix} |B_s^0\rangle \\ |\bar{B}_s^0\rangle \end{pmatrix} \quad (1.13)$$

The mass and decay width matrices are hermitian, i.e., $\mathbb{M}^\dagger = \mathbb{M}$, $\mathbf{\Gamma}^\dagger = \mathbf{\Gamma}$. The simultaneous invariance of *CPT* further demands that the diagonal elements of the $\mathbb{M}$ and $\mathbf{\Gamma}$ matrices are equal to each other, $M_{11} = M_{22} = M$, $\Gamma_{11} = \Gamma_{22} = \Gamma$, and the off-diagonal elements are satisfying : $M_{12} = M_{21}^*$, $\Gamma_{12} = \Gamma_{21}^*$. With these modification the Hamiltonian further reads as described in the Equation 1.14¹⁸.

$$\mathcal{H} = \mathbb{M} - \frac{i}{2}\mathbf{\Gamma} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix} \quad (1.14)$$

The eigenvalues of the WW Hamiltonian are,

$$\mathcal{E}_\pm = M - \frac{i}{2}\Gamma \pm \sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)}.$$

Considering the heavy and light eigen values $\mathcal{E}_{H,L} = m_{H,L} + \frac{i}{2}\Gamma_{H,L}$ corresponding to the mass eigenstates of the B_s^0 ,

$$|B_{s(H,L)}^0\rangle = p|B_s^0\rangle \pm q|\bar{B}_s^0\rangle; |p|^2 + |q|^2 = 1.$$

¹⁸The contribution of internal on-shell particles (*c*, *t* contribution) is coming from off-diagonal decay width matrix element Γ_{12} . The contribution of internal off-shell (all quarks are involved) is coming from off-diagonal mass matrix element M_{12} .

It is customary to define the heavy eigenstate with larger mass, the explicit forms of the eigenvalues of mass state can be made equate to the flavor state eigenvalues.

$$\begin{aligned}
\mathcal{E}_H &= m_H + \frac{i}{2}\Gamma_H \\
&= M + \Re \left(\sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)} \right) \\
&\quad - \frac{i}{2} \left(\Gamma + \Im \sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)} \right) \\
\mathcal{E}_L &= m_L + \frac{i}{2}\Gamma_L \\
&= M - \Re \left(\sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)} \right) \\
&\quad - \frac{i}{2} \left(\Gamma - \Im \sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)} \right)
\end{aligned} \tag{1.15}$$

Using the Equation 1.15 it is very easy to obtain the oscillation frequency and decay width difference ($\Delta m_s, \Delta \Gamma_s$) [20] in terms of mixing phase ϕ^s .

$$\begin{aligned}
\Delta m_s &= m_H - m_L \\
&= 2\Re \left(\sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)} \right) \\
&= 2|M_{12}| \left[1 + \mathcal{O} \left(1/8 \left| \frac{\sin(\phi^s)\Gamma_{12}}{M_{12}} \right|^2 \right) \right] \\
\Delta \Gamma_s &= \Gamma_L - \Gamma_H \\
&= 4\Im \left(\sqrt{(M_{12} - \frac{i}{2}\Gamma_{12})(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)} \right) \\
&= 2|\Gamma_{12}| \cos(\phi^s) \left[1 + \mathcal{O} \left(1/8 \left| \frac{\sin(\phi^s)\Gamma_{12}}{M_{12}} \right|^2 \right) \right]
\end{aligned} \tag{1.16}$$

The correction factor¹⁹ $1/8|\sin(\phi^s)\Gamma_{12}/M_{12}|^2$ is of the order 6×10^{-11} , and the experimental upper limit is $\ll 5 \times 10^{-5}$, hence a negligible quantity. Diagonalising the mass and decay width ($\mathbb{M}, \mathbf{\Gamma}$) matrices another ratio q/p can be obtained for the superposition

¹⁹Discussion of B_s^0 mixing details :Anikeev, K., et al.,(2001)

coefficients of the mass eigenstate. This ratio is a crucial indicator in the categorisation of CPV which will be discussed later. The mathematical expression of the ratio corresponding to the coefficients is described in the Equation 1.17.

$$\frac{q}{p} = -e^{i\phi_M} \left[1 - \left| \frac{\Gamma_{12}}{2M_{12}} \right| \sin(\phi^s) + \mathcal{O} \left(\left| \frac{\Gamma_{12}}{M_{12}} \right|^2 \right) \right] \quad (1.17)$$

The time evolution of B_s^0 can be denoted by $|B_s^0(t)\rangle$ at t initially started to evolve as $|B_s^0\rangle$ ($t = 0$). Considering CPT is not a good symmetry and using the effective Hamiltonian approximation a more general time dependent state can be written as,

$$\begin{aligned} |B_s^0(t)\rangle &= (g_+(t) + zg_-(t)) |B_s^0\rangle - \sqrt{1-z^2} \frac{q}{p} g_-(t) |\bar{B}_s^0\rangle; (|B_s^0\rangle, t=0) \\ |\bar{B}_s^0(t)\rangle &= (g_+(t) + zg_-(t)) |\bar{B}_s^0\rangle - \sqrt{1-z^2} \frac{q}{p} g_-(t) |B_s^0\rangle; (|\bar{B}_s^0\rangle, t=0) \end{aligned} \quad (1.18)$$

Where

$$g_{\pm} \equiv (e^{-im_H t - \frac{1}{2}\Gamma_H t} \pm e^{-im_H t - \frac{1}{2}\Gamma_L t}) \quad (1.19)$$

Now if CPT is conserved then $z=0$ [21], and the time dependent decay rates,

$$\begin{aligned} \frac{1}{e^{-\Gamma t} \mathcal{N}_f} \frac{d\Gamma[B_s^0(t) \rightarrow f]}{dt} &= (|A_f|^2 + |(q/p)\bar{A}_f|^2) \cosh\left(\frac{\Delta\Gamma}{2\Gamma}\Gamma t\right) + (|A_f|^2 - |(q/p)\bar{A}_f|^2) \cos\left(\frac{\Delta m}{\Gamma}\Gamma t\right) \\ &\quad + 2\Re e((q/p)A_f^* \bar{A}_f) \sinh\left(\frac{\Delta\Gamma}{2\Gamma}\Gamma t\right) - 2\Im m((q/p)A_f^* \bar{A}_f) \sin\left(\frac{\Delta m}{\Gamma}\Gamma t\right) \end{aligned} \quad (1.20)$$

And for anti-particle

$$\begin{aligned} \frac{1}{e^{-\Gamma t} \mathcal{N}_f} \frac{d\Gamma[\bar{B}_s^0(t) \rightarrow f]}{dt} &= (|(p/q)A_f|^2 + |\bar{A}_f|^2) \cosh\left(\frac{\Delta\Gamma}{2\Gamma}\Gamma t\right) + (|(p/q)A_f|^2 - |\bar{A}_f|^2) \cos\left(\frac{\Delta m}{\Gamma}\Gamma t\right) \\ &\quad + 2\Re e((p/q)A_f^* \bar{A}_f) \sinh\left(\frac{\Delta\Gamma}{2\Gamma}\Gamma t\right) - 2\Im m((p/q)A_f^* \bar{A}_f) \sin\left(\frac{\Delta m}{\Gamma}\Gamma t\right) \end{aligned} \quad (1.21)$$

For any final state f ,

$$A_f = \langle f | H | B_s^0 \rangle; \bar{A}_f = \langle f | H | \bar{B}_s^0 \rangle; A_{\bar{f}} = \langle \bar{f} | H | B_s^0 \rangle; \bar{A}_{\bar{f}} = \langle \bar{f} | H | \bar{B}_s^0 \rangle,$$

and $\mathcal{N}_f$ is a time independent normalisation constant within $t \in (0, \infty)$. The $|A_f|^2$ of $|\bar{A}_{\bar{f}}|^2$ terms are describing decays without oscillation where as the $(p/q)|A|^2$ or $|(q/p)\bar{A}_{\bar{f}}|^2$ type terms are describing decay with oscillation. Coefficients of the sinusoidal functions are assigning the interfering amplitude elements between these two decay type. Now having all the necessary cards on the table it is customary to classify the CPV effects in B_s^0 system. For a B_s^0 decaying to an arbitrary state f , the distinct type of CPV can be classified in the following way:

1. CPV in decays without any contribution from mixing effects : differ by decay amplitude from the CP-conjugate counterpart,

$$\left| \frac{\bar{A}_{\bar{f}}}{A_f} \right| \neq 1 \quad (1.22)$$

2. In charged current semi-leptonic neutral meson decay CPV can be found in mixing. The mass eigen states are superposition flavour eigenstate which depends on some complex parameters p, q . CPV occurs if the mass eigen states are not equal to CP-eigen states and it is defined as,

$$\left| \frac{q}{p} \right| \neq 1 \quad (1.23)$$

Also in mixing CPV can be measured for oscillation induced wrong sign [22, 23, 24] decay as,

$$\mathcal{A}_{SL} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \quad (1.24)$$

3. CPV in the interference : contributed by both mixing and decay amplitude components,

$$\lambda_{cp} = \frac{q}{p} \frac{\bar{A}}{A} \neq 1 \quad (1.25)$$

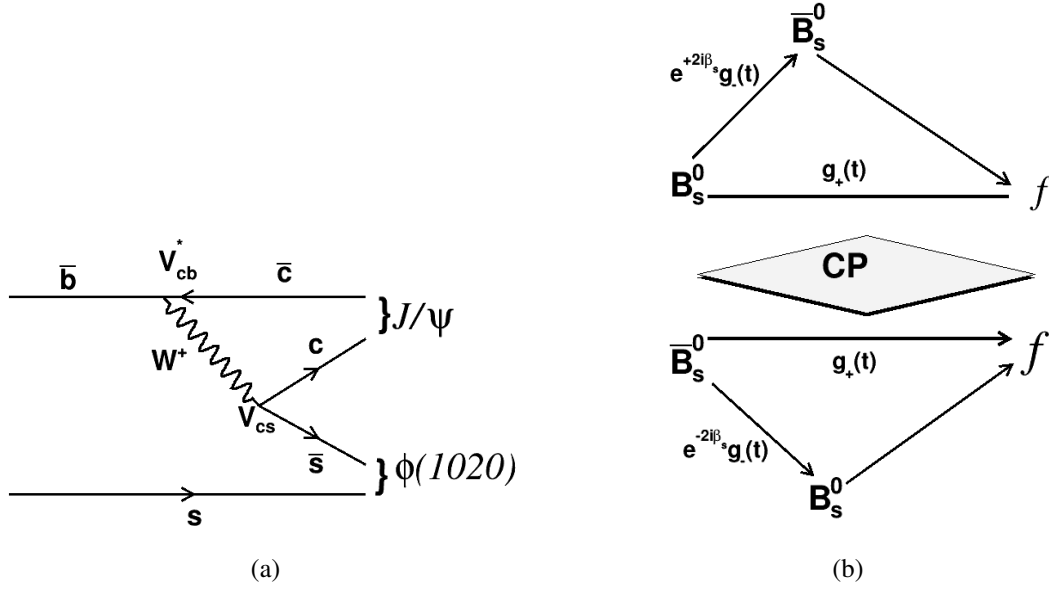


Figure 1.6: (a) The generic Feynman diagram assigned by the quark transitions for the $B_s^0 \rightarrow J/\psi \phi$ decay, and (b) CPV from interference, upper one sketch describes the B_s^0 decays to final CP eigenstate f with a phase of $+2\beta_s$ and in the lower one $\bar{B}_s^0$ decays to final state f with a phase $-2\beta_s$.

1.3 The $b \rightarrow c\bar{c}s$ transition in $B_s^0 \rightarrow J/\psi \phi$ decay

Recalling the box diagram at the lowest level described in the Figure 1.5 of $B_s^0 - \bar{B}_s^0$ mixing it is evident that the off diagonal elements of the $\mathbb{M}$ and $\mathbf{\Gamma}$ matrices are responsible for the oscillation. The Γ_{12} originates from internal on-shell particle contribution such as top t and charm c quark to the final state, and very much CKM favored. The Γ_{12} in general determined by the long-distance physics corresponding to the basis of assumption that it may related to the lower mass scale considered as a sensitive observable toward NP. As for the M_{12} , it is originated by the short-distance physics of internal off-shell (high mass) particles (all quarks are involved) and also sensitive to the new physics in terms virtual particle contribution. The $b \rightarrow c\bar{c}s$ transition involving $B_s^0 \rightarrow J/\psi \phi$ decay is shown in the quark level Feynman diagram of Figure 1.6(a). The convention independent parameter λ_{cp} specific to $B_s^0 \rightarrow J/\psi \phi$ decay can be defined by combining the mixing and tree level

$b \rightarrow c\bar{c}s$ transition,

$$\begin{aligned}\lambda_{J/\psi\phi} &= \left(\frac{p}{q}\right)_{B_s^0} \frac{\bar{A}_{J/\psi\phi}}{A_{J/\psi\phi}} \\ &= \mathcal{E}_{\text{cp}} \left(\frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*} \frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}^*} \right)\end{aligned}\quad (1.26)$$

The $\mathcal{E}_{\text{cp}}$ defines the final state CP eigen value, by exploiting the relation between β_s and CKM coefficients V_{ij} from the Equation 1.5 it is easy to show that²⁰,

$$\lambda_{J/\psi\phi} = \mathcal{E}_{\text{cp}} \frac{e^{-i\beta_s}}{(e^{-i\beta_s})^*} = \mathcal{E}_{\text{cp}} e^{-2i\beta_s}. \quad (1.27)$$

The weak phase β_s does flip sign in the CP conjugate decay originating from mixing and subsequent decay but it does not flip sign when originating from the dynamics of $B_s^0 - \bar{B}_s^0$ oscillation due to the presence of 90° relative phase between $g_+(t)$ and $g_-(t)$. B_s^0 can decay two ways to an arbitrary state f , either directly or first oscillate to $\bar{B}_s^0$ and then decay. The CP mirror imposes exactly the same feature to $\bar{B}_s^0$ which is shown in Figure 1.6(b). Any new physics can contribute in the signal when if all SM contributions both from tree and loop amplitudes (penguin amplitudes) are understood properly. Then the total amplitude turns out to be the sum of the tree amplitude and the penguin amplitude, with their corresponding strong phases. Penguin contributions are expressed in terms of perturbatively calculable Willson co-efficient function and non-perturbative hadronic matrix element [25]. A measurement of Willson co-efficient for $B^0 \rightarrow J/\psi K_s$ is very small that the contribution can be neglected, in the similar way many **PS** $\rightarrow$ **VV** [26, 27, 28] (pseudoscalar to vector-vector)²¹ channels, such as $B_s^0 \rightarrow J/\psi\phi$ are expected to have negligible penguin contribution. However the non-perturbative hadronic matrix elements which appear in penguin amplitudes are associated with large uncertainties. From an analysis of $B^0 \rightarrow J/\psi\pi^0$ decays, penguin uncertainties [29] in $B^0 \rightarrow J/\psi\phi$ as large as $\mathcal{O}(10\%)$

²⁰Here we use $\arg(a) = -i \ln \frac{a}{|a|}$, considering $|a| = \text{unity}$

²¹There are PS $\rightarrow$ VV decay processes with sizeable penguin contribution, such as $B \rightarrow K^* \rho$, and ϕK^* . For the details of the penguin contributions please refer to the cited articles.

can not be ruled out. In this present analysis contribution from penguin diagrams are not considered.

1.4 $B_s^0 \rightarrow J/\psi \phi$ decay kinematics

1.4.1 Present status of ϕ_s measurement and CPV states

The decay of $B_s^0 \rightarrow J/\psi \phi$ ²² process is highly sensitive to NP due to the sensitiveness of the off-diagonal contribution coming from mass and decay width matrix (M_{12}, Γ_{12}) . The ϕ_s induced CPV in $B_s^0 \rightarrow J/\psi \phi$ ²³ decay is the measure of CPV in interference contributed by the direct decays and the decays with mixing. The frequency of the $B_s^0 - \bar{B}_s^0$ oscillation Δm_s turns out to be very sensitive to the tagging performance. The small valued CP violating weak phase ϕ_s is in relation with CKM matrix element via the equation $\phi_s \simeq -2\beta_s$ within the context of SM when penguin diagram contributions are negligible. The smallness of the weak phase ϕ_s is not adequate to describe the baryon asymmetry, though still an important ingredient among the three condition proposed by Shakarov²⁴. The available best value for the parameter $-2\beta_s$ determined by performing an SM global fit using all experimental data [11] is,

$$\phi_s^{c\bar{c}s} = -36.98_{-0.70}^{+0.81} \text{ mrad}. \quad (1.28)$$

BSM physics or the NP is expected to contribute via new particles to the B_s^0 mixing [30] and provides the extra contribution which might modify the phase under question. The precise prediction of the small numeric of ϕ_s in the SM motivates further studies, since a small departure would be the indicator of physics beyond the SM. The predicted²⁵ value of

²² $K^\pm \rightarrow I(J^P) = \frac{1}{2}(0^-)$, $\mu \rightarrow J = \frac{1}{2}$, $B_s^0(s\bar{b}) \rightarrow I(J^P) = 0(0^-)$, $J/\psi(c\bar{c}) \rightarrow I^G(J^{PC}) = 0^-(1^{--})$, $\phi \rightarrow I^G(J^{PC}) = 0^-(1^{--})$, $B_s^0 \rightarrow J/\psi \phi$ at quark level $b \rightarrow sc\bar{c}$, $\phi(1020) \rightarrow K^+K^-$: BF=(48.9±0.5)%, $J/\psi \rightarrow \mu^+\mu^-$: BF=5.961±0.033%.

²³Color suppressed decay channel $B_s^0 \rightarrow J/\psi \phi$ (branching fraction = $1.07 \pm 0.09 \times 10^{-3}$), where B_s^0 decays to $J/\psi(I^G(J^{PC}) = 0^-(1^{--}))$, and $\phi(I^G(J^{PC}) = 0^-(1^{--}))$

²⁴Sakharov A. D, JETP Letters(1967).

²⁵ $1/m_b$ corrections are made to the subleading CKM structure in Γ_{12} and $1/m_b^2$ are made to $\Delta\Gamma_s$

the $\Delta\Gamma_s$ [31] is given by,

$$\Delta\Gamma_s = 0.087 \pm 0.021 \text{ ps}^{-1}. \quad (1.29)$$

The first experimental value of ϕ_s was reported by the Fermilab Tevatron [32, 33, 34, 35, 36], and then Large Hadron Collider (LHC) based LHCb, CMS, and ATLAS [37, 38, 39, 40, 41, 42, 43, 44] experiments. These measurements are performed by making the use of the following channels :

$$\begin{aligned} 1 - B_s^0 &\rightarrow J/\psi \phi \\ 2 - B_s^0 &\rightarrow J/\psi f_0(980) \\ 3 - B_s^0 &\rightarrow J/\psi h^+ h^-, \quad h \in (\pi^\pm, K^\pm) \end{aligned} \quad (1.30)$$

The heavy flavour averaging group²⁶ updates the combine result by using the experimental results from different experiments, which is shown in Figure 1.7. To measure ϕ_s it is indeed

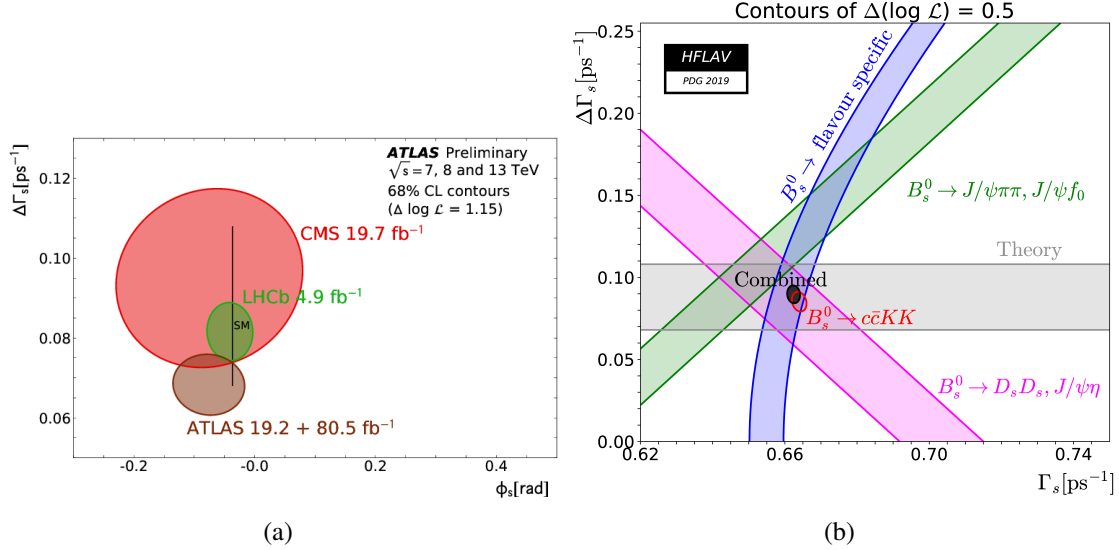


Figure 1.7: (a) 68% confidence level likelihood contour plot of $\phi_s - \Delta\Gamma_s$ (CMS, ATLAS, and LHCb) obtained from $B_s^0 \rightarrow J/\psi \phi$ decay, black rectangle is the SM prediction. (b) Contour plot of Γ_s vs $\Delta\Gamma_s$, the mean of all $B_s^0 \rightarrow J/\psi \phi$, $B_s^0 \rightarrow J/\psi h^+ h^-$ results are depicted in the red contour within the constrains coming from effective lifetime measurement of the specific B_s^0 flavour (blue), the CP-odd (green), and CP-even (purple). The black filled contour is showing the average results taking all constraints in to account, the gray band is the theoretical prediction given by Equation 1.29.

²⁶HFLAV: <https://hflav.web.cern.ch>.

L values	Final state	Amplitude	Relative phase
0	even	A_0	δ_0
1	odd	$A_\perp$	$\delta_\perp$
2	even	$A_\parallel$	$\delta_\parallel$

Table 1.3: Amplitudes and the intermediate phases depending upon the value of the orbital angular momentum of the final state corresponding to $B_s^0 \rightarrow J/\psi \phi$ process.

necessary to specify the two CP components of the final state and study their evolution with varying time and initial flavour. The $B_s^0 \rightarrow J/\psi \phi$ decay process is a $\mathbf{PS} \rightarrow \mathbf{VV}$ type decay where an spin-zero B_s^0 decays into two spin one mesons (J/ψ , ϕ). The conservation of total angular momentum satisfies the relation $\vec{J} = \vec{L} + \vec{S} = 0$ ($\vec{L}$: orbital , and $\vec{S}$: spin), evidently the final state multiplicity of the $\vec{L}$ is $|L| = (0, 1, 2)$.

$$\begin{aligned}
CP|J/\psi\phi\rangle &= \mathcal{E}_{J/\psi\phi}|J/\psi\phi\rangle \\
&= (-1)^L \times (-1) \times (-1) \times (+1)|J/\psi\phi\rangle \\
&= (-1)^L|J/\psi\phi\rangle \\
&= (-1) \times |J/\psi\phi\rangle \quad (L = 1; \text{ odd}) \\
&= (+1) \times |J/\psi\phi\rangle \quad (L = 0, 2; \text{ even})
\end{aligned} \tag{1.31}$$

In Equation 1.31 the $\mathcal{E}_{J/\psi\phi}$ is the CP odd(even) eigenvalue, and at leading order both components contribute with opposite signs to the CP asymmetry, thereby diluting the observable CP asymmetry. The decay distribution comprising CP odd(even) amplitudes ends up with the generic solution as a function of spherical harmonics so as the corresponding angular distributions. The angular distributions determine the relative size of the longitudinal and parallel ($A_0, A_\parallel$) polarisation amplitudes for CP-even case and the transverse perpendicular amplitude ($A_\perp$) for the CP-odd case respectively, and at a glance it can be seen in Table 1.3. In this four track ($\mu^\pm, K^\pm$) decay system the angles $\Theta = (\theta_T, \psi_T, \phi_T)$ are introduced in the transversity²⁷ basis [45] to statistically disentangled the two CP component. As illustrated in the Figure 1.8 the properties of the decay topology are itemised as follows,

²⁷The transversity amplitudes are formed by taking the linear superposition of helicity basis formed in the helicity basis, a very nice description of such details are given in <https://arxiv.org/abs/hep-ex/0103002>.

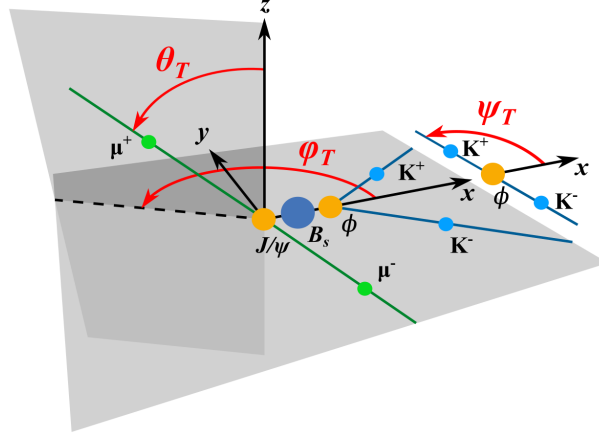


Figure 1.8: The geometrical projection of the decay plane and the corresponding angles ϕ_T , θ_T , ψ_T are defined in the consecutive mother particle rest frame.

- x axis is directing along $\vec{p}_\phi$ of ϕ meson in the B_s^0 rest frame, where the x - y is the $\phi \rightarrow K^+ K^-$ decay plane,
- y axis in the x - y plane is chosen in a way such that $p_y(K^+) > 0$, z axis completes the right-handed coordinate system,
- ψ_T : the helicity angle of K^+ in the $\phi(1020)$ rest frame along the negative flight direction of B_s^0 ,
- θ_T : the polar angle of μ^+ in the rest frame of J/ψ ,
- ϕ_T : the azimuthal angle of μ^+ in the rest frame of J/ψ .

1.4.2 Differential decay rate

The differential distribution of the $B_s^0 \rightarrow J/\psi \phi$ decay rate is projected by a function $\widetilde{\mathcal{F}}(\Theta, ct, \alpha)$, as inspired by the Ref. [46],

$$\frac{d^4 \Gamma(B_s^0(t))}{d\Theta dt} = \widetilde{\mathcal{F}}(\Theta, ct, \alpha) = \sum_{i=1}^{10} \mathcal{O}_i(\alpha, t) \cdot g_i(\Theta). \quad (1.32)$$

Where, g_i are the contribution to the amplitudes from angular functions reported in Table 1.4, α concerns the physics parameters, and $\mathcal{O}_i$ are the time-dependent observables depends

on intermediate phases, oscillation frequency and decay width difference.

$$\mathcal{O}_i = N_i e^{-\Gamma_s t} \left[a_i \cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + b_i \sinh\left(\frac{1}{2}\Delta\Gamma_s t\right) + c_i \cos(\Delta m_s t) + d_i \sin(\Delta m_s t) \right] \quad (1.33)$$

The parameters C , S and D are defined in the Equation 1.34, where, C is the measure

i	$g_i(\theta_T, \psi_T, \varphi_T)$	N_i	a_i	b_i	c_i	d_i
1	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$ A_0(0) ^2$	1	D	C	$-S$
2	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\varphi_T)$	$ A_{\parallel}(0) ^2$	1	D	C	$-S$
3	$\sin^2\psi_T\sin^2\theta_T$	$ A_{\perp}(0) ^2$	1	$-D$	C	S
4	$-\sin^2\psi_T\sin 2\theta_T\sin\varphi_T$	$ A_{\parallel}(0) A_{\perp}(0) $	$C\sin(\delta_{\perp}-\delta_{\parallel})$	$S\cos(\delta_{\perp}-\delta_{\parallel})$	$\sin(\delta_{\perp}-\delta_{\parallel})$	$D\cos(\delta_{\perp}-\delta_{\parallel})$
5	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\varphi_T$	$ A_0(0) A_{\parallel}(0) $	$\cos(\delta_{\parallel}-\delta_0)$	$D\cos(\delta_{\parallel}-\delta_0)$	$C\cos(\delta_{\parallel}-\delta_0)$	$-S\cos(\delta_{\parallel}-\delta_0)$
6	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\varphi_T$	$ A_0(0) A_{\perp}(0) $	$C\sin(\delta_{\perp}-\delta_0)$	$S\cos(\delta_{\perp}-\delta_0)$	$\sin(\delta_{\perp}-\delta_0)$	$D\cos(\delta_{\perp}-\delta_0)$
7	$\frac{1}{3}(1-\sin^2\theta_T\cos^2\varphi_T)$	$ A_S(0) ^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\varphi_T$	$ A_S(0) A_{\parallel}(0) $	$C\cos(\delta_{\parallel}-\delta_S)$	$S\sin(\delta_{\parallel}-\delta_S)$	$\cos(\delta_{\parallel}-\delta_S)$	$D\sin(\delta_{\parallel}-\delta_S)$
9	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\varphi_T$	$ A_S(0) A_{\perp}(0) $	$\sin(\delta_{\perp}-\delta_S)$	$-D\sin(\delta_{\perp}-\delta_S)$	$C\sin(\delta_{\perp}-\delta_S)$	$S\sin(\delta_{\perp}-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\psi_T(1-\sin^2\theta_T\cos^2\varphi_T)$	$ A_S(0) A_0(0) $	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

Table 1.4: The total differential decay distribution model. Angular functions, time-dependent functions, and the coefficients corresponding to P-wave and S-wave amplitudes.

of direct CPV, S measures the mixing induced CPV and D is relevant if the decay-width difference is sizeable.

$$C = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \quad S = -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2}, \quad D = -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2} \quad (1.34)$$

The angular amplitudes terms remain unaltered under the transformations : $\phi_s \leftrightarrow \pi - \phi_s$, $\Delta\Gamma_s \leftrightarrow -\Delta\Gamma_s$, $\delta_{\parallel} \leftrightarrow 2\pi - \delta_{\parallel}$, $\delta_{\perp} \leftrightarrow \pi - \delta_{\perp}$. Equation 1.32 represents the differential decay rate for the B_s^0 ; as for the $\overline{B}_s^0$ decay rate the signature of the coefficients c_i 's and d_i 's terms in Equation 1.33 need to be made negative. This model definitively allows us to measure the following physics observables,

- the amplitudes $A_0, A_{\perp}, A_{\parallel}, A_S$,
- the phases $\delta_0, \delta_{\perp}, \delta_{\parallel}, \delta_S$,
- the B_s^0 lifetime $c\tau, \Delta m_s, \Delta\Gamma_s$
- the CP variables λ and ϕ_s ,

by making the use of the B_s^0 mass, lifetime, initial flavour and the three angles. The significant contribution from S-wave due the $B_s^0 \rightarrow J/\psi K^+ K^-$ (non resonant) decays, and possibly from $B_s^0 \rightarrow J/\psi f_0(\rightarrow K^+ K^-)$, need to be considered, since it has been proved to be non-zero by several measurements by ATLAS²⁸ and LCHb²⁹. The S-wave component is accounted with the last four terms in Table 1.4 ($i = 7, 8, 9, 10$). The contribution from $B_s^0 \rightarrow J/\psi f_0(\rightarrow \pi^+ \pi^-)$ is studied with simulated sample and found negligible³⁰. The model however cannot be fully tested in any MC samples, since the EVTGEN module used simulate only P-Wave. The S-wave contribution is therefore checked to be compatible with zero in the simulated sample and tested with Monte Carlo pseudo experiments where a S-wave contribution has been injected. The proper decay length (often termed as lifetime) of the B_s^0 candidate, the per event decay time uncertainty, and the three angles are the essential observables in this angular analysis. The proper decay time ct is defined as,

$$ct = m_{B_s^0}^{\text{PDG}} \cdot \frac{\mathbf{L}_{\mathbf{xy}}}{p_T} \quad (1.35)$$

where, $m_{B_s^0} = 5.3663$ GeV and $\mathbf{L}_{\mathbf{xy}}$ is the transverse component of decay length in laboratory reference frame. The decay length is the displacement vector of the primary vertex to the secondary vertex obtained from the kinematic fit, while p_T is the transverse momentum of the B_s^0 . Error propagation in the measured lifetime leads to the decay time uncertainty σ_{ct} . The angle definitions in terms of kinematic parameters of corresponding objects are given by,

$$\sin \theta_T \cos \phi_T = \mathbf{p}_{\mu^+} \cdot \mathbf{x} \quad (1.36)$$

$$\sin \theta_T \sin \phi_T = \mathbf{p}_{\mu^+} \cdot \mathbf{y} \quad (1.37)$$

$$\cos \theta_T = \mathbf{p}_{\mu^+} \cdot \mathbf{z} \quad (1.38)$$

$$\cos \psi_T = -\mathbf{p}'_{K^+} \cdot \mathbf{p}'_{J/\psi} \quad (1.39)$$

²⁸<https://arxiv.org/abs/2001.07115>

²⁹[doi:10.1103/PhysRevD.87.072004](https://doi.org/10.1103/PhysRevD.87.072004)

³⁰The expected number of reconstructed $B_s^0 \rightarrow J/\psi f_0(\rightarrow \pi^+ \pi^-)$ decays in data is estimated to be less than ten.

where the axis directions are defined as follows,

$$\mathbf{x} = \frac{\mathbf{p}_{\phi(1020)}}{|\mathbf{p}_{\phi(1020)}|} \quad (1.40)$$

$$\mathbf{y} = \frac{\mathbf{p}_{K^+} - \mathbf{p}_{\phi(1020)}(\mathbf{p}_{\phi(1020)} \cdot \mathbf{p}_{K^+})}{|\mathbf{p}_{K^+} - \mathbf{p}_{\phi(1020)}(\mathbf{p}_{\phi(1020)} \cdot \mathbf{p}_{K^+})|} \quad (1.41)$$

$$\mathbf{z} = \mathbf{x} \times \mathbf{y} \quad (1.42)$$

Bold variables are defined in the J/ψ rest frame where as the primed are in the ϕ rest frame.

Chapter 2

Collider & Experiment

...The soul, fortunately, has an interpreter - often an unconscious but still a faithful interpreter - in the eye....

Jane Eyre¹

—Charlotte Bronte

2.1 LHC at CERN

The European Organization for Nuclear Research (CERN) is a Geneva (Switzerland) based largest HEP laboratory covering research activity ranges from the quark gluon plasma (QGP) to the search of dark matter. Having several other dedicated experimental lab corresponding to particular physics studies, CERN organizes the Large Hadron Collider (LHC) as well. Protons (p), and Lead nuclei (Pb) are mainly used as beam material and are accelerated at very high energy in opposite direction to collide them head-on. Debris of collisions are recorded by the detectors situated at the points of the head-on collisions. A minimal LHC is outlined in the Figure 2.1. Energy of the proton bunches are raised to 50MeV by Linear Accelerator (LINAC2), and then 1.4GeV by Proton Synchrotron Booster (PSB). In the next step the bunches are pushed to much bigger Proton Synchrotron (PS) raising the

¹Smith, Elder, and Co., Cornhill, 1847, OCLC: 3163777

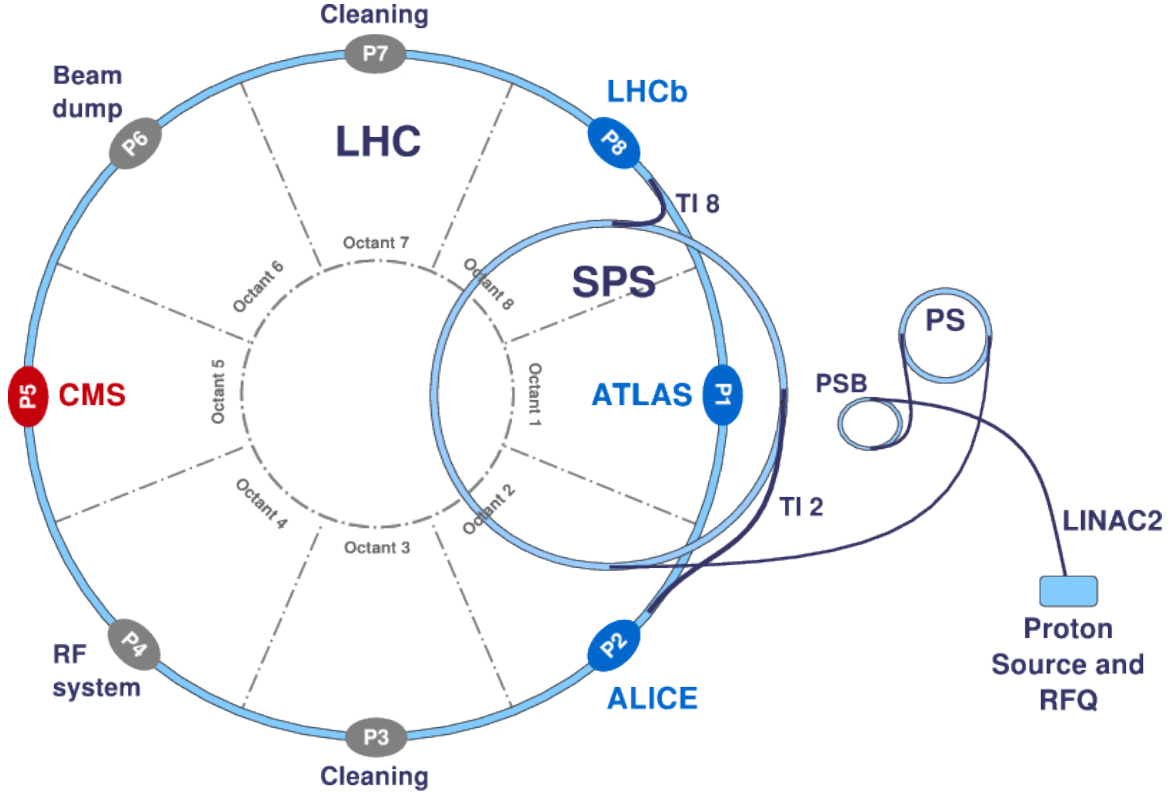


Figure 2.1: Outline of the LHC, before the collision the beam particles are accelerated at various stages, starting from LINAC→PSB→PS→SPS→LHC. CMS is situated at the collision point 5 called as p5 [1].

energy to 26 GeV. A Super Proton Synchrotron (SPS) is involved afterward to accelerate proton bunches to an energy of 450 GeV, and then the bunches are injected into the LHC ring as those are accelerating at a speed of 99.99% of the speed of light. At such a large speed the proton bunches come so close that they look like a beam.

There are eight insertion regions (IRs) at the LHC as depicted in the Figure 2.2. Detectors such as ATLAS [47], ALICE [48, 49], CMS [5]², and LHCb [50] are installed at IR1, IR2, IR5, and at IR8 respectively to record the collision data. Three other small detectors namely LHCf [51], TOTEM [52], and MoEDAL [53] are placed in the cavern similar to ATLAS, CMS, and LHCb respectively. Other IRs are being used to install the collimators, viz., momentum collimator at IR3, betatron at IR7, and RF at IR4. IR6 corresponds to the beam dumping system. Polar magnets (dipole, quadrupole) are installed near the collision points

²A detailed information about this experiment is given in a dedicated section.

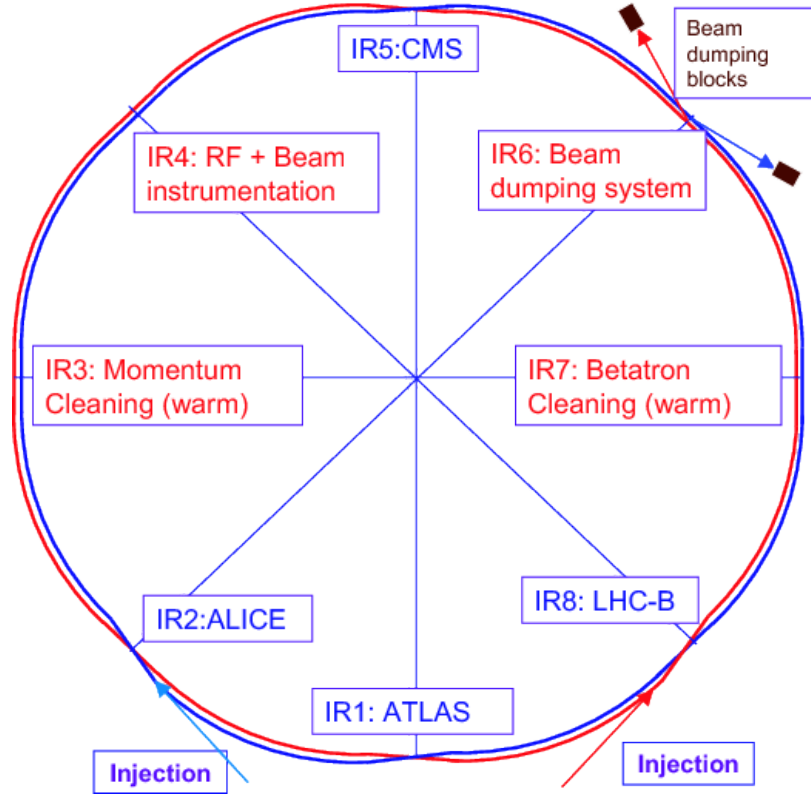


Figure 2.2: The layout of insertion regions (IRs) at the LHC ring does not include the proper scaling of the separation between the two colliding beams. The total circumference of the LHC ring is $2\pi r = 27$ km, oppositely moving beams (Beam **red** and **blue**) are made to collide at four points (1,2,5, and 8) of the ring. Four detectors such as CMS, ALICE, ATLAS, and LHCb are installed at each collision point to record the collision Data. A detail description of beam design and physics behind can be found elsewhere [2] and references there in.

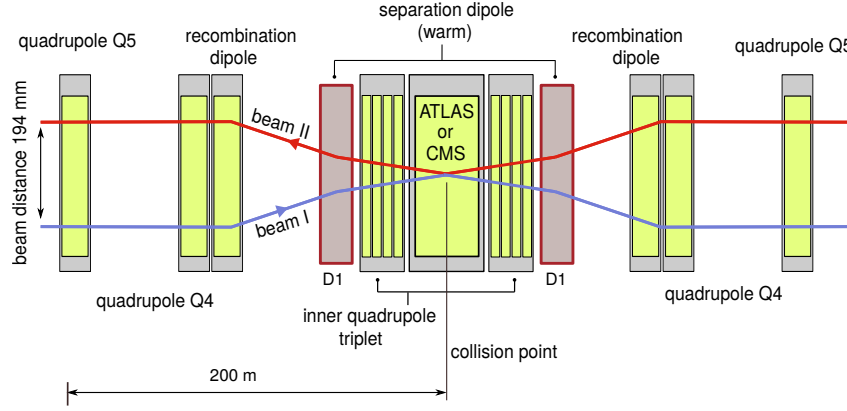


Figure 2.3: Schematic diagram showing quadrupole and dipole magnets for focussing and bending proton beams at the interaction point (IP). The D1 dipole separate beams from both sides of the IP.

to adjust the bending and focus two counter rotating beams and also employed to brought them closer for a head-on collision as shown in Figure 2.3 [54]. The radio frequency (RF) cavities are responsible for the acceleration of beams , and cryogenics are involved for the cooling of the superconducting magnet and the LHC ring. Beam diagnostics are monitoring the beam movement.

2.1.1 Collider parameters

An accurate and updated values of associated parameters corresponding to the colliding proton beams such as the energy of each beam, collision frequency, number of particles in each beam, luminosity etc. are very important inputs during the data taking. The reconstruction of various physics objects, and the detector correction of simulated Monte Carlo samples are also parametrized with these parameters, are being called as non-event data since they only contain information about the hardware configuration. Online master database system (OMDS) is used to monitor these. Among several other parameters it is better to emphasize the usage of few main parameters.

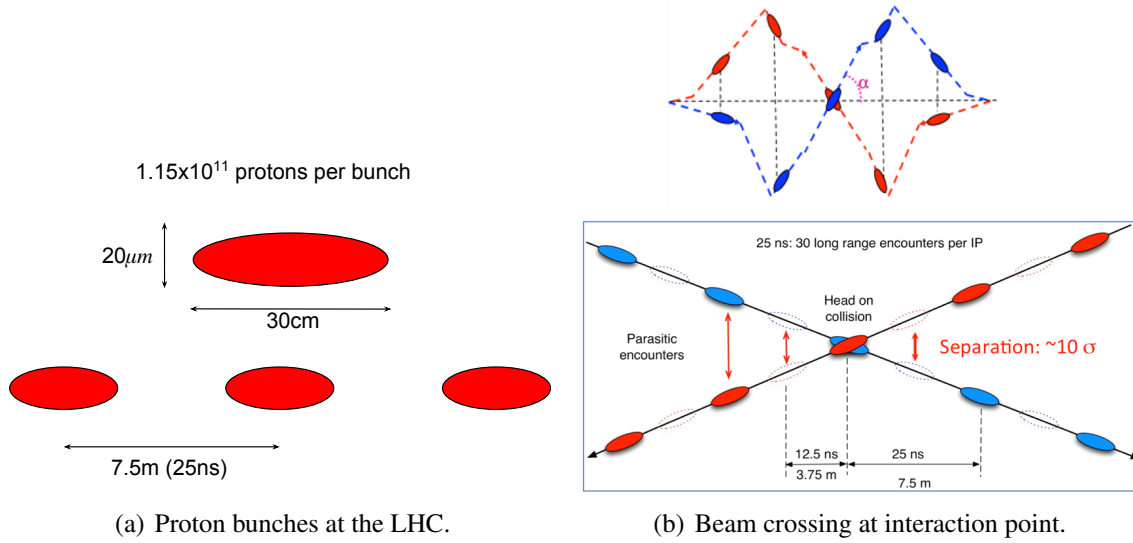


Figure 2.4: The bunch configuration and crossing angle. The bunches are separated by 7.5m. The crossing angle shown is exaggerated for illustration.

The number of particles in each beam

Each proton beam consists of nearly 2556 proton bunches and there are 1.15×10^{11} protons in one bunch. The separation between two consecutive bunch is 7.5m across the LHC ring. The collision frequency is 25ns, that is with a gap of 25ns counter rotating p bunches are enforced to collide at the IP. Bunches filled for each beam is used to discriminate the filled and unfilled bunches out of 2556 bunches during data taking. Assuming that all the bunches of a beam are filled, the number of protons in each beam will be $2556 \times 1.15 \times 10^{11} \approx 10^{14}$. A generic configuration of the bunch is shown in Figure 2.4(a).

α and β^*

The α is the crossing angle³ between two beams cross at the IP lies in the range μrad . The collision multiplicity is very sensitive and inversely proportional to the α ⁴. Figure 2.4(b) outlines the corresponding procedure. The beam sizes is varying throughout the ring and squeezed near the IP by $\mathbf{B}$ applied for the bending of beam using dipole magnets as shown in Figure 2.3. The squeeze parameter β^* is the quantitative measure of the distance between

³<https://home.cern/news/news/accelerators/lhc-report-playing-angles>

⁴<https://indico.cern.ch/event/386181/contributions/1816638/attachments/1143882/1639362/20150825-CMSDAS-LHC-v3.pdf>

the IP and the point where the beam gets double in size, and the mathematical expression is given in Equation 2.1 [55]. The σ_b^2 is bunch cross section, and ε is the emittance. Lying in the mm range smaller value of β^* implies the beam is squeezed near the IP and vice-versa.

$$\beta^* = \frac{\pi\sigma_b^2}{\varepsilon} \quad (2.1)$$

Center-of-mass energy ($\sqrt{s}$)

High energy is required to probe much shorter length⁵. The production of number of particles corresponding to different physics processes is directly proportional to the achievable $\sqrt{s}$. Higher the value of $\sqrt{s}$. Since, the counter rotating proton beams are colliding head-on along the the z-axis, $p_{1z} + p_{2z} = 0$. For two colliding protons with energy E_1 and E_2 , the center-of-mass energy is $\sqrt{s} = E_1 + E_2$. During 2016-18 data taking, the energy of each beam was 6.5 TeV, leading to $\sqrt{s} = 13$ TeV. The momentum in the transverse plane also need to be conserved. The high $\sqrt{s}$ is specially designed for the detection of many BSM particles and to get high statistics for precise measurements.

Luminosity

The production of rare physics processes in the collisions is proportional to the luminosity. The precision of any measurement becomes less uncertain if the number of the events for the particular physics is high, this is where the high luminosity maps to higher statistics. The luminosity and total integrated luminosity is defined in the Equation 2.2, where $\frac{dN}{dt}$ is the number of events/second and σ_p is the cross section⁶. For two counter rotating beams having number of particles N_1 and N_2 in each respectively, and beam density⁷ distribution functions $\rho_1(x, y, s, -s_0)$, and $\rho_2(x, y, s, s_0)$ as shown in Figure 2.5, the definition of luminosity takes the form as described in the first line of Equation 2.3 [3]. The number of

⁵Shorter than the average size of the nucleus $< 10^{-15}$ m.

⁶In the CGS unit, the dimension of L is $(\text{cm}^{-2} \text{s}^{-1})$, however, fb^{-1} (inverse femtobarn) is often used in the collider experiments

⁷The ideal one can be described as Dirac delta distribution, $\rho(x, y, s, -s_0) = \int_4 \delta(x, y, s, -s_0) dx dy ds d(ct)$

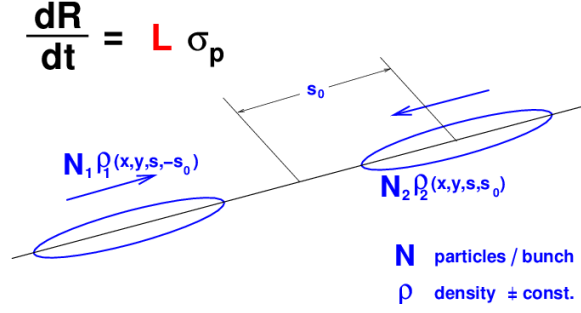


Figure 2.5: Two oppositely moving bunches with the total number of particles N_1 and N_2 , and $\rho(x, y, s, -s_0)$ beam density distribution functions [3].

bunches in the beam (N_b), and the collision frequency (f) are optimized before use.

$$L = \frac{1}{\sigma_p} \frac{dN}{dt}, \quad \mathcal{L} = \int L dt \quad (2.2)$$

$$\begin{aligned} L &= 2N_1 N_2 f N_b \int \int \int \int \rho_1(x, y, s, -s_0) \rho_2(x, y, s, s_0) dx dy ds ds_0; \{s := z, s_0 = ct\} \\ &= 2N_1 N_2 f N_b \int \int \int \int \rho_{1x}(x) \rho_{1y}(y) \rho_{1s}(s - s_0) \rho_{2x}(x) \rho_{2y}(y) \rho_{2s}(s + s_0) dx dy ds ds_0. \end{aligned} \quad (2.3)$$

The second line of Equation 2.3 falls under the assumption that the two bunches collide head-on and the beam density is uncorrelated along all directions, the beam density distribution at the LHC follows a Gaussian distribution as given in Equation 2.4 which implies that the proton density is more in the central region of the beam.

$$\begin{aligned} \rho_{ix}(x) &= \frac{1}{\sigma_{ix} \sqrt{2\pi}} \exp\left(-\frac{(x)^2}{2\sigma_{ix}^2}\right); \{i = 1, 2\} \\ \rho_{iy}(x) &= \frac{1}{\sigma_{iy} \sqrt{2\pi}} \exp\left(-\frac{(y)^2}{2\sigma_{iy}^2}\right); \{i = 1, 2\} \\ \rho_s(s \pm s_0) &= \frac{1}{\sigma_s \sqrt{2\pi}} \exp\left(-\frac{(s \pm s_0)^2}{2\sigma_s^2}\right) \end{aligned} \quad (2.4)$$

where, σ_{ix} and σ_{iy} are the standard deviation of Gaussian distribution of the two beams along the x and y -direction. Using these, for uncorrelated beam profile in all directions the

second line of Equation 2.3 becomes,

$$L = \frac{N_1 N_2 f N_b}{2\pi \sqrt{\sigma_{1x}^2 + \sigma_{2x}^2} \sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}}. \quad (2.5)$$

The final luminosity calculation indeed incorporates other hardware effects such as : non-Gaussian beam profiles, collision offset, nonzero dispersion at the collision point, finite crossing angle, hourglass effect and so on.

Beam modes

LHC first decides which physics is going to be run, given that whether its proton physics or ion physics beams modes are accordingly changes. If everything is fine from accelerator side and detector side as well then LHC changes the beam mode to Setup following Injection warning and Injection probe beam. During the injection LHC continues with the corresponding with which it started, the energy of the beam is creasing through Ramp and finally reaches to collision energy FlatTop. Then it is the time for Squeeze in which the beams are squeezed by betatron towards the target collision⁸, and the separation between the beams are made to collapse, bringing them for collision by Adjust. Finally the Stable beams achieved when it signals that the physics data taking can be started and the beams are dumped after the data taking ends by executing Dump. The normal duration of stable beam mode is few hours, during stable beam mode collisions are recorded by creating a Fill and accordingly all the detector information is updated in the online database. A Fill is divided in Runs and further, a run is divided in lumi sections (LS - each 23 s)⁹. A good LS corresponds to fully working all subdetectors, and the integrated luminosity is obtained by summing over all LS. All the LHC parameters are measured regularly and most of them are fixed during a long period, though small fluctuations are also monitored as shown in Figure 2.6, and in Figure 2.7.

⁸2017-2018 data taking the $\beta^* = 30\text{cm}$

⁹The data taking by a detector has a granularity of 23 s. That is, the detector information is updated/stored after each 23 s

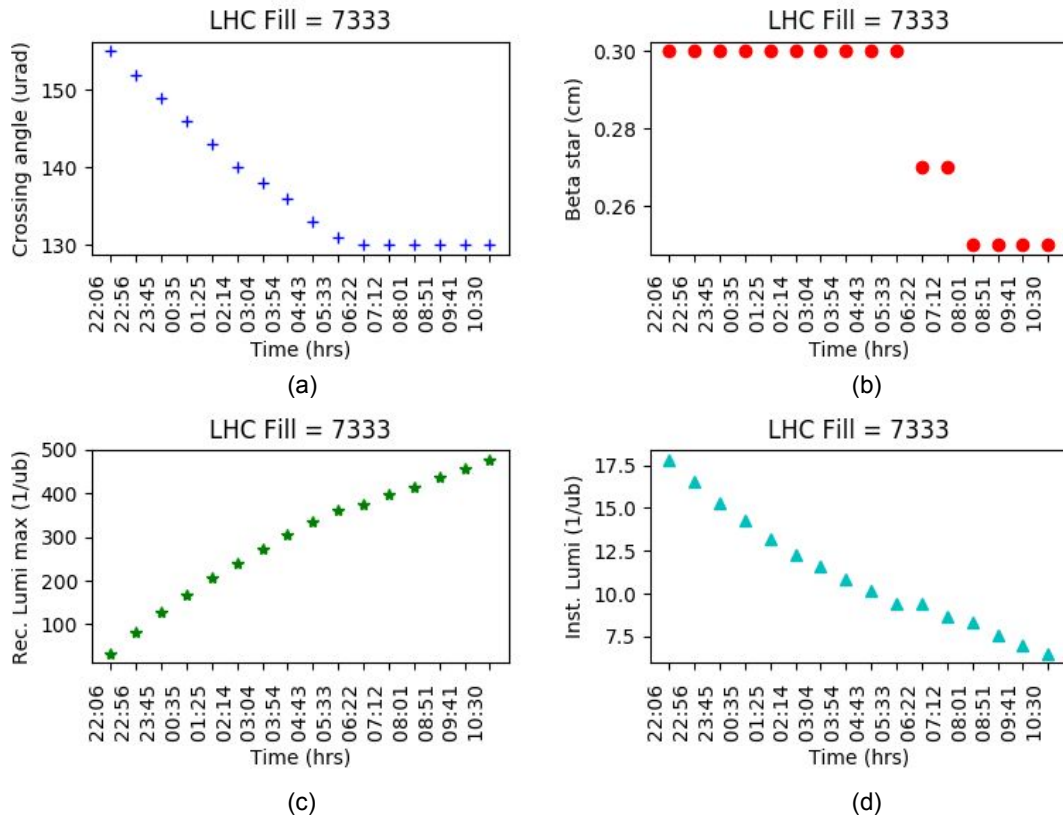


Figure 2.6: Variation of few LHC parameters during the data taking on 22-23rd October 2018 (Fill = 7333). All these parameters change over a different point of time.

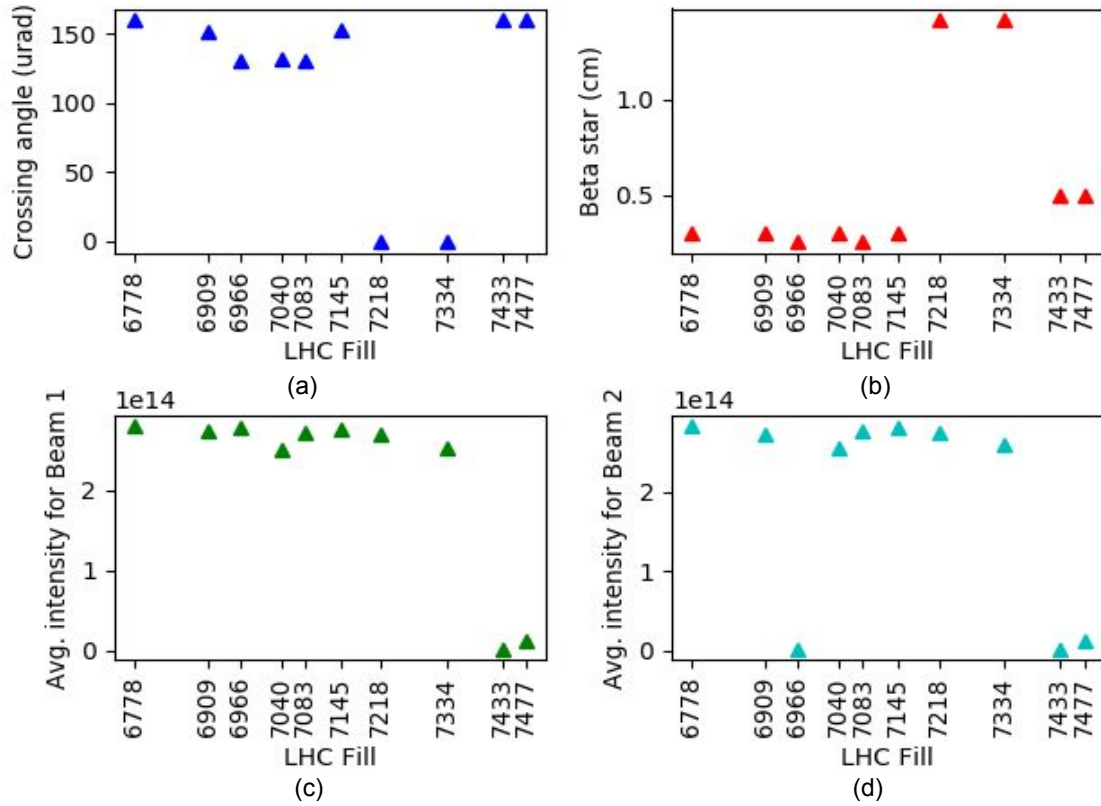


Figure 2.7: Variation of few LHC parameters during the data taking from random days in the period of June-November 2018. Only a few days (Fills) have been chosen for illustration. The last two Fills (7433 and 7477) correspond to Pb-Pb collision, rest are from pp . The average intensity of the beam is the number of particles in each beam. As can be seen, all these parameters change over a different period of time.

2.1.2 Collider kinematics

The LHC kinematic parameters are defined in the reference frame of LHC coordinate system as shown in Figure 2.8(a), where the z -axis is the beam direction. Each detectors are placed at the IRs. The detectors are in general of cylindrical shape and the axis of the cylinder coincides with the beam direction. Each detector consists several sub-detectors placed along ($\parallel$) or perpendicular ($\perp$) to the beam direction. Three main kinematic observables, the transverse momentum, pseudorapidity, and azimuthal angle are considered as the leading kinematic parameter at LHC. The definition of p_T is described in the Equation

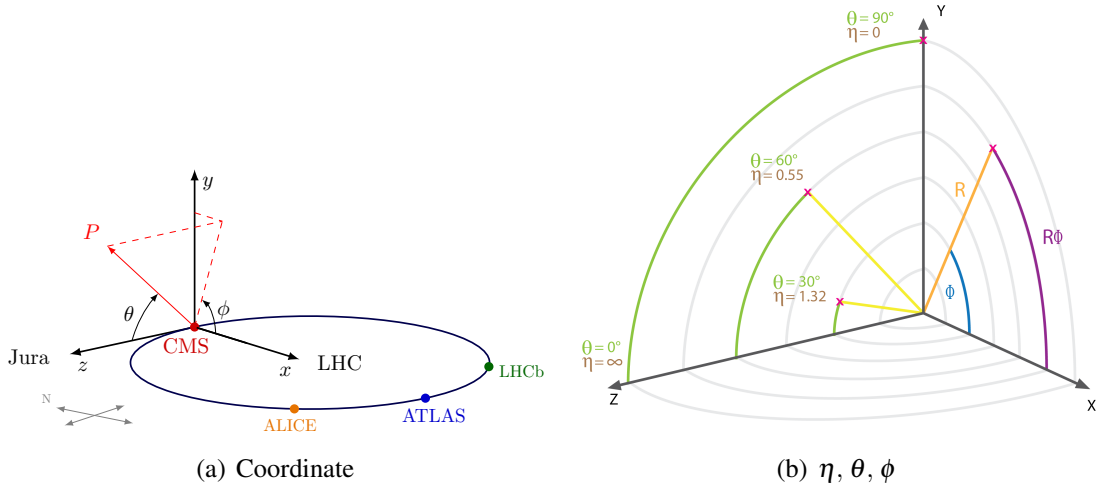


Figure 2.8: (a)The LHC coordinate system, the z -axis is the beam direction. At CMS, the z -axis points towards the mountain Jura in France¹¹. (b)The relationship between θ and η [4]. The value of $\eta = 0$ implies $\theta = \pi/2$.

2.6, where, p_x , and p_y are the momentum components in the x , and y direction respectively. As it is already discussed that the momentum along the beam axis is conserved leading transverse momentum an important quantity for the measurement. The multiplicity of hard collision is about ~ 20 out of 10^{11} numbers of proton. The protons are moving in the forward region, leaving some debris of soft collision while a very few percentage of the protons move along the axis line without any collision. The physics processes are produced

¹¹https://wiki.physik.uzh.ch/cms/latex:example_spherical_coordinates

by hard collisions, and the highest p_T in an event is chosen as actual physics process.

$$p_T = \sqrt{p_x^2 + p_y^2} \quad (2.6)$$

The azimuthal angle ($\phi \in \{\phi :: \hat{p}_x \angle \hat{x}; 0, 2\pi\}$) covers the full barrel region and the polar angle $\theta \in \{\theta :: \vec{p} \angle \hat{z}; 0, \pi\}$ covers both sides of the endcap and a part of which is shown in Figure 2.8(b). To know the value of θ another useful Lorentz invariant¹² quantity called rapidity as described in the Equation 2.7.

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

(2.7)

if $y = 0, E > p_z, \theta = \pi/2 \Rightarrow$ transverse

if $y = \pm 1, E < p_z, \theta = 0 \text{ or } \pi \Rightarrow$ forward

At $p \gg m_0$ the rapidity turns out to be pseudorapidity (η)¹³ as given in Equation 2.8.

$$y = -\ln \tan \left(\frac{\theta}{2} \right) \rightarrow \eta, \quad \text{if } E = \sqrt{p^2 + m_0^2} \approx p \quad (2.8)$$

The η - θ coverage in Figure 2.8(b) shows that higher value of η implies endcap region where the lower value indicates central barrel region.

¹²Under the Lorentz boost, the 4-momentum transforms as $E' = \gamma(E - \beta p_z), \sim p'_x = p_x, \sim p'_y = p_y, \sim p'_z = \gamma(p_z - \beta E)$ implies, $y' = y - \tanh^{-1} \beta$, where $\beta = v$, and $\gamma = \sqrt{1 - \beta^2}$. If an observer measures rapidities of two particles in the boosted frame then difference $y'_1 - y'_2 = y_1 - y_2$.

¹³<https://en.wikipedia.org/wiki/Pseudorapidity>

2.2 Compact Muon Solenoid experiment

The prefix compact is given due to the very high material budget (14ktonnes) within smaller volume ($l = 21.5\text{m}$, $2r = 15.6\text{m}$) compared to other detectors, and is installed at IR5 of the LHC ring. CMS experiment is mainly design to detect muons as they appear as final state particles in both SM and BSM physics processes. Since, the design of the detector is so complex which provides the scope to detect electron, photon, neutral and charged hadrons as well. A gigantic solenoid magnet is placed inside the detector of magnetic field strength 4 T is useful to measure the particles momentum with high resolution. A pictures of CMS detector assembly captured before Run-II installation shown in Figure 2.9, and the schematic layout depicting each sub-detector is shown in Figure 2.10¹⁴. The beam

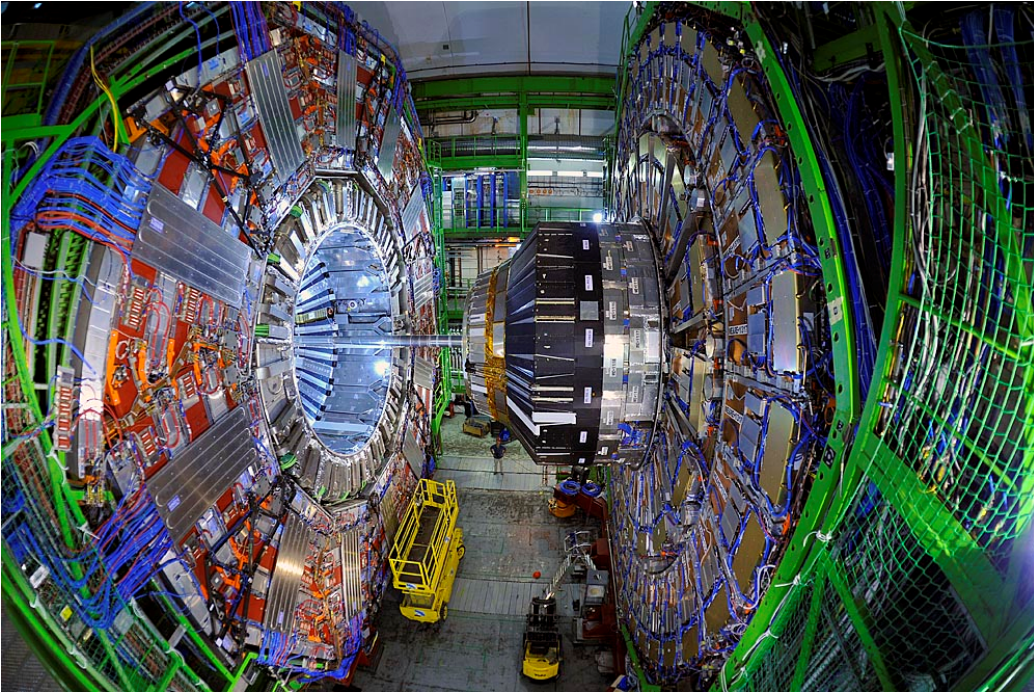


Figure 2.9: The CMS detector installed in IR5 at the LHC [5].

axis coincides with axis of the cylindrical shape detector and surrounded successively by layers of sub-detectors. The innermost detector is the tracking detector comprising pixel and strip surrounded by successively electromagnetic calorimeter (ECAL), and the hadron

¹⁴<https://twiki.cern.ch/twiki/bin/view/CMSPublic/SketchUpCMSGallery>

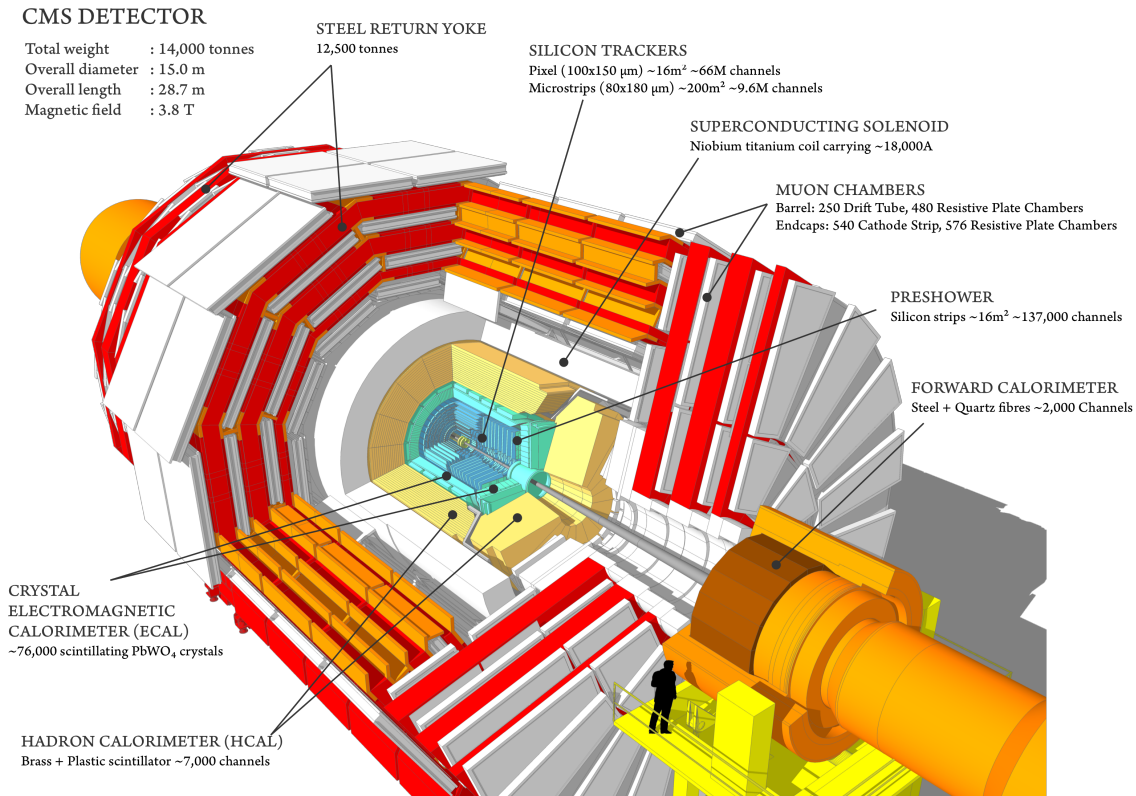


Figure 2.10: Diagram of the CMS detector¹⁶. Various parts of the CMS detector are shown starting from tracker to ECAL to HCAL to magnet to the muon chambers.

calorimeter (HCAL). The magnetic solenoid is placed outside the HCAL followed by the muon chambers. The redundant magnetic field strength outside the solenoid is of $\sim 2\text{T}$ contained by the iron yokes which also provides the stand for the muon chambers. The charged tracks are bend exactly in opposite direction outside the solenoid with respect to the inside one due the opposite direction of magnetic field lines. Needless to say that the neutral particles do not bend at all under $\mathbf{B}$. The particles are produced in the collision point and then pass through several layers of detectors depending on the energy carried by them. The assembly of the subdetectors in CMS are organized to detect muons, electrons, charged hadrons ($\pi^\pm$), neutral hadrons (n), and photons. The trajectories of particles inside the CMS detector are shown in the cross sectional slice Figure 2.11 [6].

¹⁶ <http://physics.stackexchange.com/questions/139540/how-detectors-in-particle-colliders-can-differentiate-neutrons-from-antineutrons>

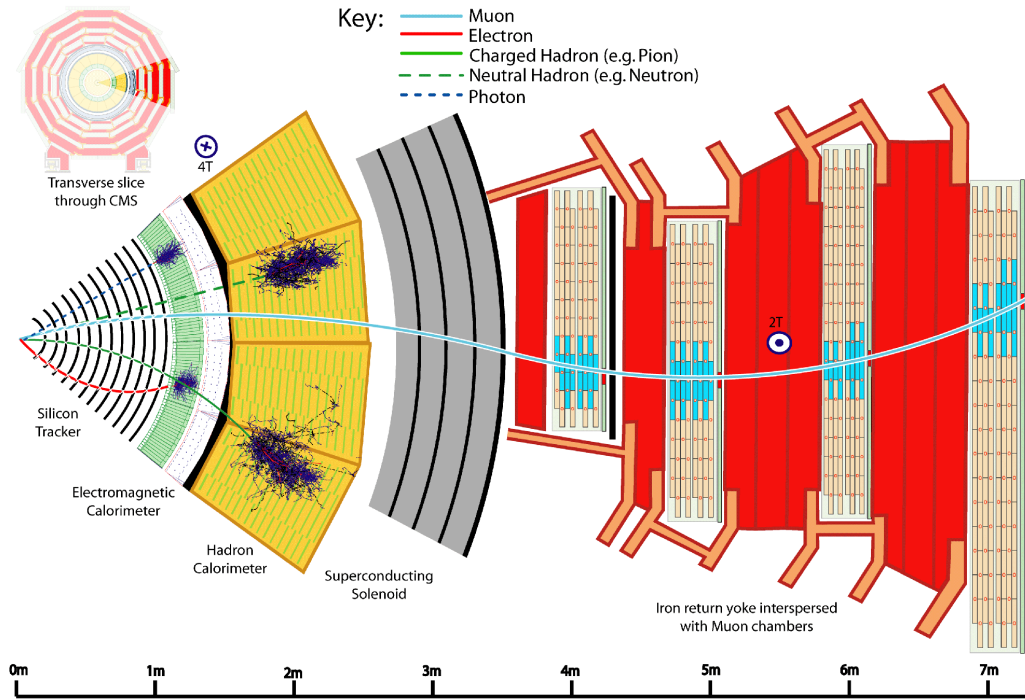


Figure 2.11: Trajectories of various particles inside the CMS detector [6]. The charged particles such as electrons, muons, and charged pions ($\pi^\pm$) are bent inside and outside the solenoid whereas the neutral particles such as photons and neutral pions (π^0) traverse without being bent. The silicon tracker is mainly for measuring the momentum of particles whereas the ECAL and HCAL measure the energy deposits. The e and γ deposits the energy in ECAL, and the hadrons in both ECAL and HCAL. The muons are traversing all the way to the muon chambers.

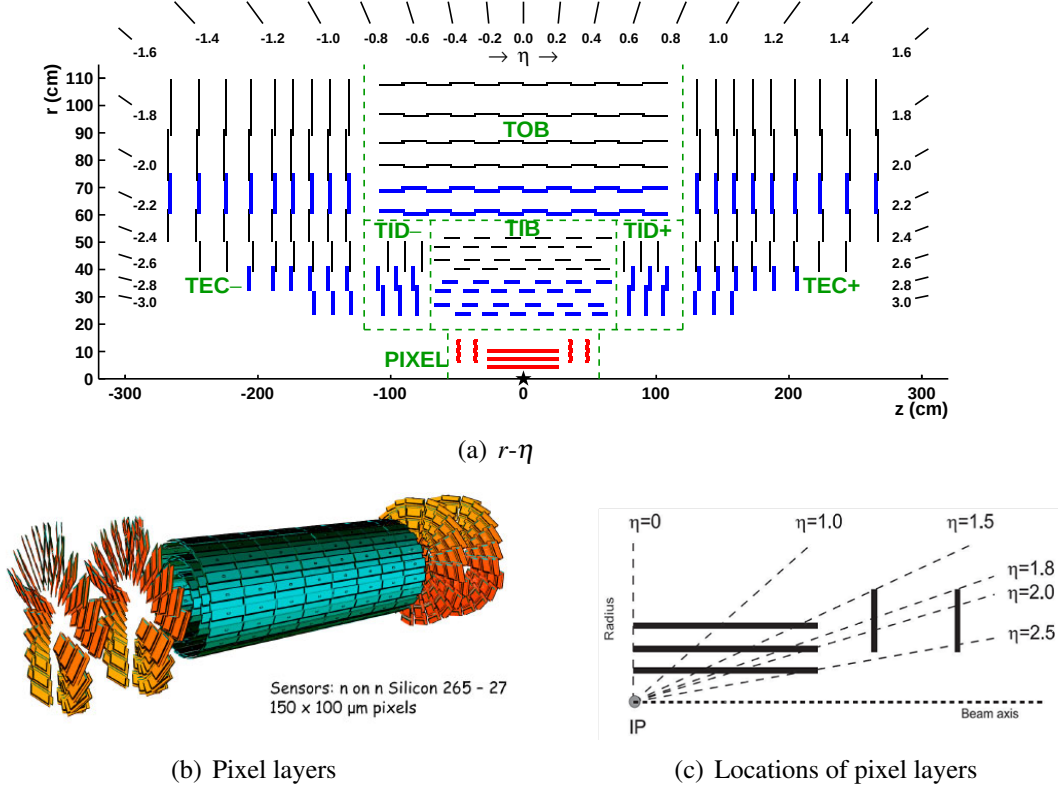


Figure 2.12: (a) The inner part of one of the tracker inner barrels (TIBs) of the CMS experiment. (b) The pixel detector of the tracker [7, 8]. (c) The position of silicon tracker on both sides of the IP ($z = 0$ cm) [9]. The pixel trackers are very close to the IP. For the strip tracker, TIB, TOB are situated in the barrel region, and the TEC, TID in the transition region. The black (blue) lines correspond to single (double) sided silicon strips.

2.3 Silicon tracker

The silicon tracker comprising pixel and strip tracker measures the momentum $\mathbf{p}$ of the particles, and reconstructs the tracks of charged particles including secondary vertex corresponding to given physics processes. There are 48(18) million pixels divided in 3(2) layers in the barrel (endcap) placed near the beam axis, and operating under harsh radiation covering an area of 200m^2 . The length of the pixel detector from IP along the beam axis is 46.5 cm, while two endcaps are placed at $z = 34.5$ and 46.5 cm from both sides of the IP. The 3-layers of the detector are placed at $r = 4.4$ cm, 7.3 cm, 10.2 cm respectively in the barrel apart as shown in Figure 2.12. The strip detectors are situated just outside the pixel, there are 10(9) layers of the strip tracker in the barrel (endcap) covering $0 \leq \eta \leq 2.5$ region. The dimension of the strip detectors is $l \times d \in 5.8\text{m} \times 2.5\text{m}$.

2.3.1 Thickness and resolution

The electrons are losing their energy when traveling through the tracker material in fraction of $1/e$ due to the Bremsstrahlung radiation. This is called the radiation length, the other one is nuclear interaction length which is the average distance traversed by the hadrons before inelastic nuclear interaction. These two characteristic lengths are being used as the thickness unit to characterize the thickness of tracker material. As described in the Figure 2.13(a), and in 2.13(b), the thickness is small ($t/X_0 \approx 0.4$) in the direction $\perp z$ -axis ($\eta = 0$)¹⁷. Resolution is define as resolving parameter for any measurable object during detection, and always expected to be in high granularity. The lower the value of detector resolution, the more precise is the measurement. The absolute (relative) resolution of ϕ (p_T) of the silicon tracker in bins of η is shown in Figures 2.13(c)– 2.13(h) for muons, electrons, and charged pions accordingly [9]. The η and p_T resolution of all particles are better in the barrel region as compared to that in endcap regions. The resolution for muons is better as compared to electrons and charged pions in all regions, and also at the higher p_T resolution is somewhat better for all charged particles.

2.4 ECAL

The electromagnetic calorimeter is largely made with birefringent, tetragonal, and radiation-hard, inorganic lead tungstate (PbWO_4) scintillator crystal, and a small part is made of the Pb absorber¹⁸. A super-module is formed by using each 1.5 kg¹⁹ crystal, and placed in (barrel(61,200 crystal), endcap (14,800 crystal)) the ECAL. When charged particles interacts with PbWO_4 , photons are produced due to de-excitation of the scintillating material. The photons optically guided by the photomultiplier tubes (PMTs) to the avalanche photodiodes (APDs) (barrel), and vacuum phototriodes (VPTs) (endcap), and then photon are converted

¹⁷Normally, an electron produced at collision point can traverse in the $\eta = 0$ direction by losing only 14.7%(0.4/2.718) of its initial energy. The thickness is maximum in the endcap region where drop of energy is more than 40%.

¹⁸Placed in the endcap region primarily to differentiate events coming from $H \rightarrow \gamma\gamma$ and $\pi^0 \rightarrow \gamma\gamma$

¹⁹density 8.3 g cm³

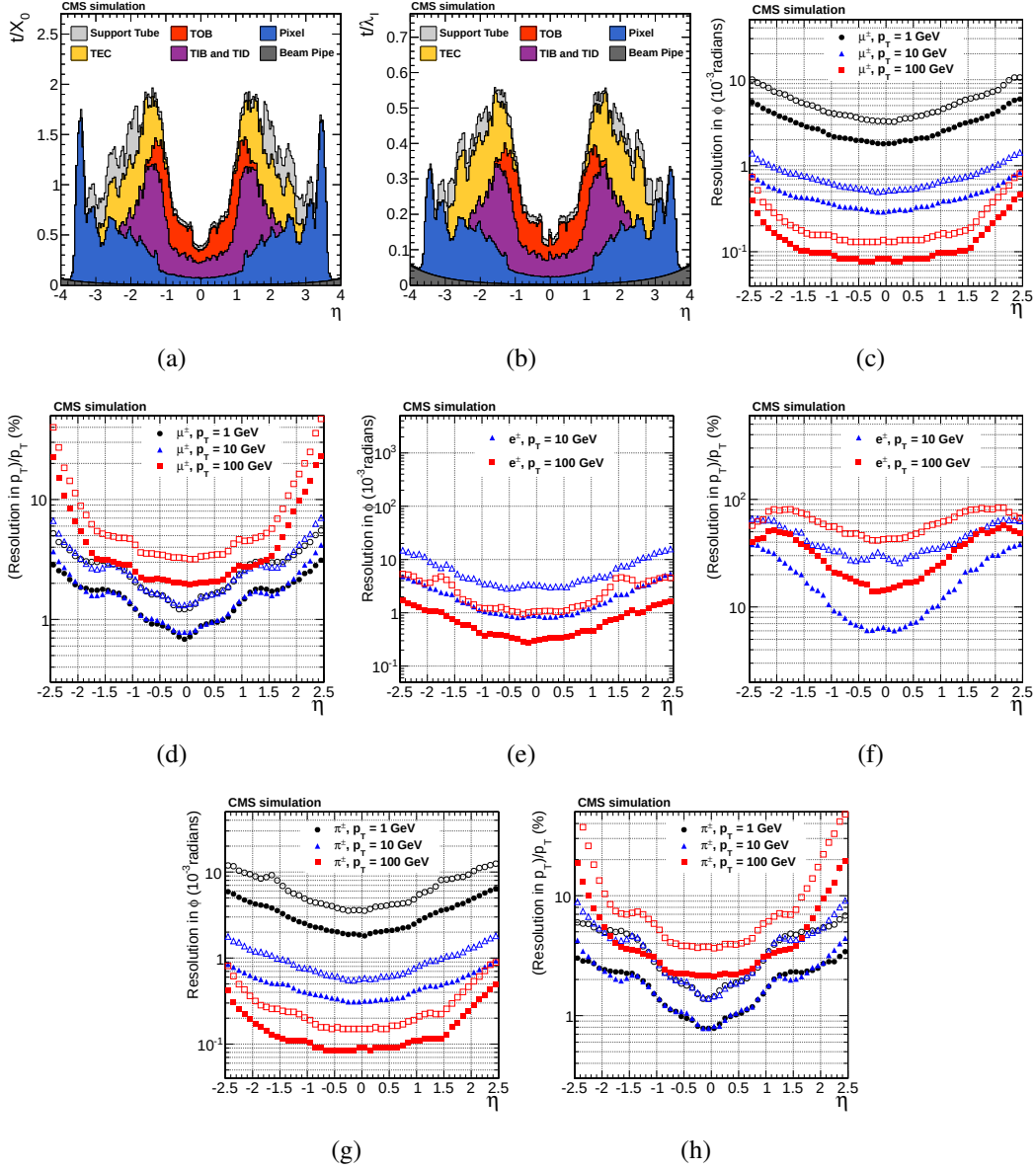


Figure 2.13: Total thickness of the silicon tracker (radiation and interaction length unit) [9]. The thickness of supporting tube and beam pipe is also shown. The absolute resolution of ϕ and relative resolution of p_T measurement of muons, electrons, and charged pions from the silicon tracker as function of η [9]. Other resolution such as d_0 , z_0 , and $\cot \theta$ are given in Reference [9].

into electrical signals, amplified and stored. The working principle of PMT is described in the in Figure 2.14(a). An ECAL preshower placed in the endcap region at $z = 298.5$ cm is designed to distinguish γ 's in the $\pi \rightarrow \gamma\gamma$ from $H \rightarrow \gamma\gamma$ processes. The energy²⁰ resolution

²⁰Energy unit - GeV.

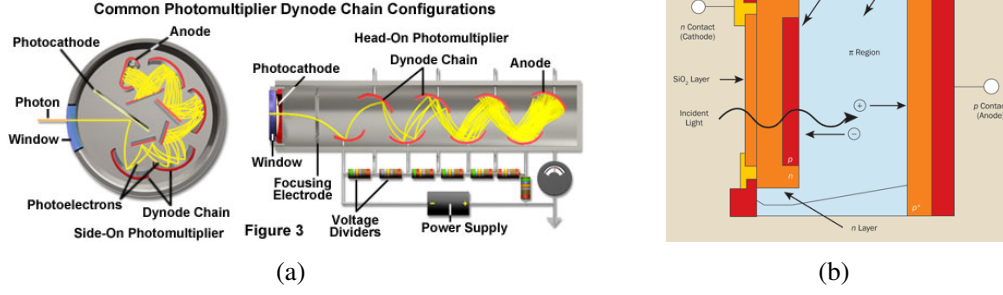


Figure 2.14: (a)The schematic diagram of a circular and cylindrical PMT, and (b) The principle of operation of an APD is shown in [10].

of ECAL is described in the Equation 2.9 [10].

$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{12.8\%}{E} \oplus 0.3\% \quad (2.9)$$

The terms in the quadrature sum correspond to the stochastic correction (preshower energy deposition) and per-event fluctuations, the noise term due to noise in backend electronics, and a constant number relevant to inhomogeneity of the detector and temperature gradient. The relative energy resolution of 3×3 supercluster formed by crystals in bins of η for electron and photon is shown in Figure 2.15. The cluster shape parameter is lying within the range $0.94 < R_9 < 0.94$, and defined as $\max(E_{3 \times 3}/E_{sc})$. The $\max(E_{3 \times 3})$ is the maximum energy deposited in a particular crystal out of 9 crystal, and E_{sc} refers to the energy deposition in the supercluster implying the scalar sum of energy in all 9 crystals [10]. The relative resolution is shown in both barrel and endcap region, which shows it is better in the barrel as compared to the endcap region for both $R_9 < 0.94$, and $R_9 > 0.94$ in case of electron and photon²¹ respectively.

²¹The relative energy resolution from observed data, simulated MC, and smeared MC were determined at $\sqrt{s} = 7 \text{ TeV}$. From data, the minimum (maximum) resolution is about 1% (5%) for both electron and photon.

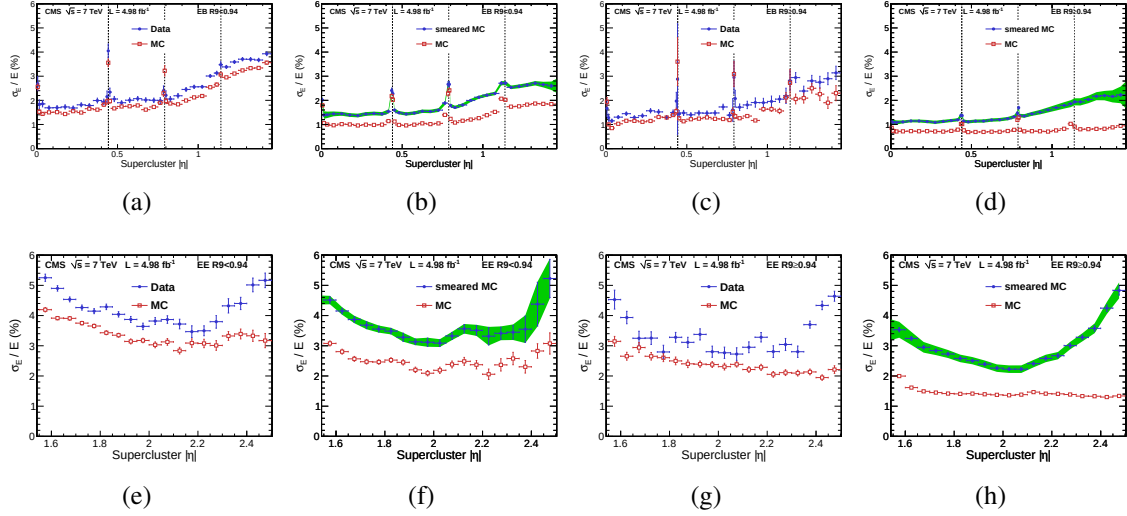


Figure 2.15: The relative energy resolution of electron and photon as a function of supercluster η in the (both in barrel and endcap) ECAL [10].

2.5 HCAL

The hadron calorimeter (HCAL) measures the deposited energy of protons, pions, neutrons, kaons, and so on. It is made of alternating stack of absorbers (brass and steels) and plastic (organic) scintillators (Bicron-BC408 and Kuraray-SCSN81). A secondary cascade of hadronic showers are produced when a particles passes through the absorber, and the produced secondary particles are further producing photon in phosphorescence or fluorescence processes when interacts with scintillating material. The photons are converted into an electronic signal by hybrid photodiodes (HPDs). The HCAL is made up of 36 barrel, 36 endcap wedges , 70000 tiles, and contains over 400 optical decoder units which take light to the HPDs [5]. The hadron calorimeters are placed in the :

HB $\Rightarrow$ Barrel;

HE $\Rightarrow$ Endcap;

HO $\Rightarrow$ Outer;

HF $\Rightarrow$ Forward;

region. The barrel part is of high and uniform granularity in the $\eta - \phi$ plane²², and having high thickness, around 7-11 times of the interaction length, the HB stops almost all the

²² $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$

hadrons passing through it. The outer one is situated outside the magnetic solenoid involved in catching tails, covering $|\eta| = 1.26$ region it measures the energy of the high energetic hadronic showers did not stopped by HB. The HE covers the $1.3 \geq |\eta| \geq 3.0$ region, it has 14 additional calorimeter towers, and overlaps with HB in the $1.305 \geq |\eta| \geq 1.392$ region. As HE is closest to the pipe line of the beam, the response requires a regularly calibration. The HF is used to study jets in the forward region coming from high radiations. The HF covers $1.3 \geq |\eta| \geq 3.0$, and $z = \pm 11.2$ m. The length of the HF is 1.65 m, divided into 900 towers. The hadronization product of the beam remnants and jets with very high η value are detected by the HF. The resolution of energy for the HCAL can be defined as,

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{s}{\sqrt{E}}\right)^2 + c^2, \quad (2.10)$$

where, the constant $s = (0.847) \sqrt{\text{GeV}}$ and $c = 0.074$ for all part of the HCAL except the HF. For the HF, $s = 1.98 \sqrt{\text{GeV}}$ and $c = 0.09$.

2.6 Magnet

The magnet is a superconducting solenoid of length 13 m, and of inner diameter 5.9 m. It is of weight 12,000 ton, providing 4 T magnetic field strength ($\mathbf{B}$)²³, and situated outside of the HCAL. The other parts CMS magnet system consists the magnet yoke (barrel and endcap), a vacuum tank and ancillaries such as cryogenics, power supplies and process controls. The $\mathbf{B}$ bends the trajectories²⁴ of the charged particles moving inside and outside of it. The solenoid is made of an aluminum-stabilized and mechanically reinforced superconducting material NbTi (Niobium Titanium) coils. There are 5 modules placed side-by-side along the z -axis each of length 2.5 m, and 4 internal layer of winding corresponds to 109 turns each. So, the total length $L = 5 \times 2.5 \text{ m} = 12.5 \text{ m}$, and total number

²³The 4 T magnetic field is inside the solenoid where the tracker, ECAL and HCAL are placed, there is 2 T redundant magnetic field outside of the solenoid with opposite field lines provides magnetic field for the muon chamber and iron yoke.

²⁴ $p = |\vec{B}|q|\vec{r}|$.

of turns $N = 5 \times 4 \times 10^9 = 2180$. Having a current $I = 19.14\text{kA}$, relative permeability $k = 0.90$, and permittivity of the free space $\mu_0 = 4\pi \times 10^{-7} \text{ mT/A}$, the obtained magnetic field inside the solenoid is described in the Equation 2.11.

$$|\mathbf{B}| = k\mu_0 \times N \times I/L \sim 4\text{T} \quad (2.11)$$

The requirement of high magnetic field can improve the tracking resolution significantly. The NbTi made superconducting solenoid has very low resistance $R \sim 3.25 \times 10^{-14} \Omega$, and the critical temperature is about 10 K. The Joule heating effect in the coil is $H = I^2 R t$, having a longer period of run and very high current the energy inside the solenoid reaches very high value of about $\sim 2.7\text{GJ}$, which may affect the super conductivity of the coil. To maintain the critical temperature corresponding to the superconductivity of the solenoid a vacuum cooling tank is employed to keep the temperature down to 5 K. The magnetic flux is contained in the gigantic return iron yoke (weight = 10^4 ton), there are 4 sub layers of barrel, and six disks in the endcap. Longitudinal and transverse component of the $\mathbf{B}$ generated by the solenoid is depicted in Figure 2.16. The longitudinal component is the strongest compared to the transverse component. The transverse one is everywhere zero except at the endcap in the region $6\text{ m} < z < 10\text{ m}$.

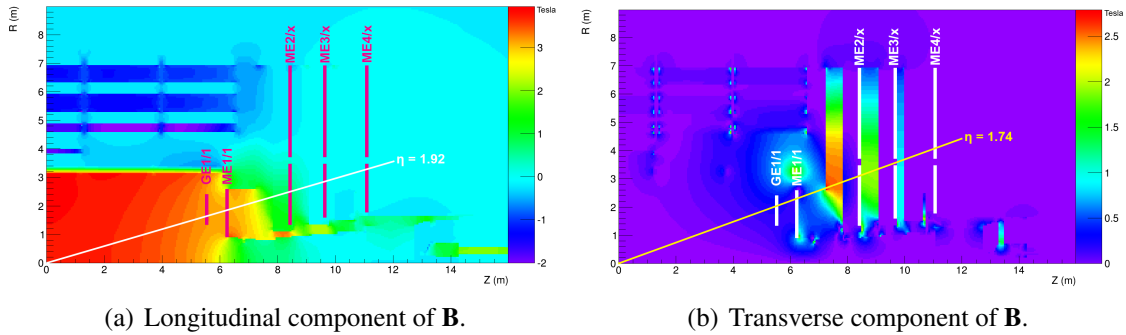


Figure 2.16: Component of the magnetic field inside CMS [?].

2.7 Muon system

The charged muons²⁵ are traverse through the sub-detectors of the CMS cylindrical onion to reach muon chambers [5]. The muon chambers are specially designed to detect the produced muons in the collisions along with the atmospheric muons. The muon chamber consists of three gaseous detector, namely, the drift tube (DT), the resistive plate chamber (RPC), and the cathode strip chamber (CSC), the location of each in the quarter of the geometrical layout is shown in Figure 3.5. The current produced by the resulting atomic electrons due to the interaction between ionized gas and charged muons is amplified and stored using proper electronics. The resolution of the muon chambers varies between 10%-20% in both barrel and endcap region depending upon the momentum of the muons. The DTs are shown in Figure 2.17(a) covers the barrel part influenced by almost uniform $\mathbf{B}$ and relatively low particle multiplicity. The red dots in the schematic diagram are the aluminum wires pointing into the page, the region between the wires are filled 85% with Argon (Ar) and 15% with CO₂ gases. The arrow describes the direction of muon path provides the information of z and ϕ coordinates of the muons. A basic structure of CSC (multiwire proportional chambers) is shown in Figure 2.17(b), the CSC is placed in the endcap region, since, it can operate in the region of inhomogeneous $\mathbf{B}$ and very high multiplicity of the particles. CSCs are perpendicularly oriented to the beam pipe facilitating full geometrical coverage up to $|\eta| < 2.4$. In CSC, the anode of gold-cladded (W/Au) tungsten wire, and cathode strips formed using Cu are placed perpendicular to each other. The space between anode and cathode is filled by a gas mixture is composed of 50% CO₂, 40% Ar, and 10% CF₄. The working principle is similar as the DT except that the CSC can provide the information of 2D coordinates since a strip is involved. A typical CMS RPC is shown in Figure 2.17(c). Having a very high time resolution of about ~ 1 ns RPCs are consist of two resistive plates: an anode and a cathode, and a mixture of gas composed by 95.2% C₂H₂F₄, 4.5% iC₄H₁₀, and 0.3% SF₆. Knocked out electrons from the ionized gas molecules are picked up by the anode strips placed above the anode plate, and

²⁵Apart from the weakly interacting muons.

the momentum of a muon is measured from the hit pattern in the strips²⁶.

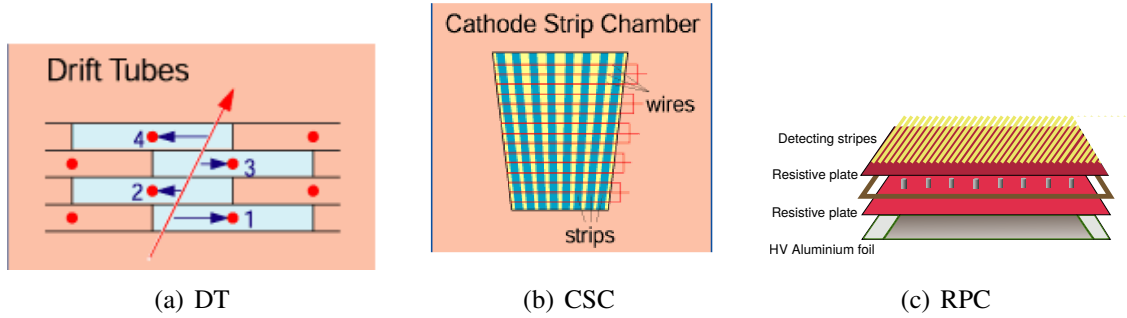


Figure 2.17: (a) Outline of one DT [5], the red dots are the aluminum wires pointing into the page, the red arrow is the direction of an incoming muon, and the horizontal blue lines are the distance traveled by secondary electrons; (b) Sketch of one CSC [5], the wires are red and the CSs are shown in cyan, placed perpendicular to each other; (c) Schematic diagram of one of the RPCs. The cathode (bottom red plate) and anode (top red plate) is separated by a separator (shown in gray). The region between the two plates is filled with gas. The anode is transparent to the secondary electrons. The orange strips (above anode) picks the secondary electrons. The high voltage aluminum foil is placed at the bottom. This figure is adopted from [5].

2.8 Trigger System

In CMS the physics events are accepted by making the use of Level-1 (L1), High Level Trigger (HLT)²⁷. The L1 is hardware based trigger where as the HLT is software algorithm corresponding to particular physics processes. Successive implementation of these triggers boils down the huge event rate of production to 200 Hz (~ 200 MB in PC drive) as described in Table 2.1 [56].

Trigger	Type	Event rate(input)	Event rate(output)
L1	Hardware	40MHz	100kHz
HLT	Software	100 KHz	200 Hz

Table 2.1: Event rate after applying level-1 and high-level triggers.

²⁶CMS Collaboration, JINST 13 (2018) 06, P06015.

²⁷At the LHC, the proton beams are made to collide by keeping an interval of 25 ns of one bunch from other, due to such a high collision rate a huge number of events, roughly 40 million, are produced at every second. Storing all these events would require many *petta bytes* of computer memory makes it practically impossible since the duration of data taking period is very long. Moreover, most of the events are soft collision which does not carry interesting physics process.

2.8.1 L1 trigger

L1 or the level one is a hardware based trigger. It is reducing the event rate frequency from 40MHz to ~ 100 kHz, this is highest readout frequency containing full event information at the FEDs²⁸. Using the informations provided by various sub-detectors, L1 trigger decides the acceptability of an event within 4μ s, this includes also the time that signal takes to propagate from detector to the trigger electronics. To acquire such low latency limit the L1 trigger is devised with FPGAs, ASICs which are capable to run simple hardware based algorithms in parallel. Only if the L1 trigger reaches a positive decision a full detector readout is triggered and the event is further processed by the HLT. The so called trigger primitives are reconstructed locally based on the hits (muon system) and energy deposition (calorimeter). Trigger primitives are then combined into physics objects like muons, electrons or photons, jets and various energy sums and at the global stage, the Global Trigger (GT) decides the acceptability of an event. The identification of local segments built from hits in the CSCs and DTs is made by the front-end-electronics, and, the Track Finder (TF) combines the local segments to form muon track by estimating the corresponding p_T and η using a quality indicator. Parallel to this a pattern matching algorithm is employed in the Pattern Comparator to analyze the RPC hits and optimized track informations are directly sent to the GMT²⁹ along with the information from TF. Eight from TF (4-DT, 4-CSC) and eight from RPC, in total GMT receives 16 track information, and utilizes the different regional trigger systems to improve the p_T resolution and to identify and merge candidates that were found by two subsystems. Finally depending upon reconstruction quality, resolution and transverse momentum GMT propagates only best four candidate to the GT. The Regional Calorimeter Trigger (RCT) meets with the quality flags along with E_T from more than 8k tower of the calorimeters (ECAL, HCAL). After processing parallelly these informations RCT sends the e/γ s along with $\sum E_T$ derived from CAL-towers (4×4) to the GCT³⁰. GCT acquires highest four p_T of isolated (non-isolated) e/γ s, four forward,

²⁸Front end electronics.

²⁹Global Muon Trigger.

³⁰Global Calorimeter Trigger.

central and τ jets of highest p_T^{jets} , the total $\sum E_T$ and the $E_T^{\text{mis-jet}}$. A set of programmable algorithms (L1 seed) are employed in GT to analyze the informations sent by GMT and GCT by keeping thresholds with large enough margins to only minimally affect the offline analysis. An interesting n^{th} event can be accepted by pre-scaling each L1 seed rate with an integer factor n assigned individually to each L1 seed depending upon different instantaneous luminosity range. A complete set of n -factors and L1 seed(algorithms) is defined as L1 menu. All the individual algorithms are combined as final-OR signal toward the final decision made by GT, and if any of the L1 seeds from L1 menu yields a positive boolean output the event is accepted regardless *of the decision of all other seeds*³¹. The decision of the GT is conveyed to the Data Acquisition System (DAQ) which stores data from all sub-detectors.

2.8.2 HLT

HLT runs on a processor farm consisting of commercial CPUs by accessing all full detector data including signals from tracker³². Computing run time consumed by the time intensive HLT reconstruction algorithms is determined completely or partially by the information available from L1. The seed for the HLT is provided by the L1 bits available in the event, the decision to reject or keep an event depends on the presence of the physics objects in the event such as e 's, μ 's, and $jets$ with p_T above particular threshold. For every event, the HLT decision is collected by the so called HLT menu in the form of programming strings also called HLT paths. The HLT paths are providing a set of reconstruction modules interleaved with selection filters, the second module only runs if the logical expression matches with already started first module from one or more L1 seed. Many complex reconstruction steps are run in parallel to immediately determine to keep or abort the reconstruction which is helpful not to waste computing resources. The event is selected and stored if it pass the final selection filter corresponding the particular HLT path. There is another technique

³¹<https://cmsoms.cern.ch>

³²Possible to use during offline reconstruction as well

called the Data Parking where the prompt reconstructions are removed by constraining the HLT event rate and the Parking Data is defined as the processed data recorded at a later time³³.

2.9 PFA

Particle Flow Algorithm³⁴ (PFA) reconstructs physics objects with high precision using the informations provided by all subdetectors. The proper reconstruction and identification of *jets*, p_T^{miss} , isolated e/γ 's, and the very obvious μ 's are the main goal of PFA. It is of great importance though to avoid false identification of tracks as this would consequently result in a false energy measurement. Therefore the particle flow algorithm starts with tracks that were rated as true particle tracks using a criterion with a very small fake rate. Then the quality criteria are gradually loosened, identified tracks are masked after each step thus lowering the risk of misidentification in the further matching. The deposited energy (E) in each part of the ECAL/HCAL is clustered individually. A major challenge here is to divide between the energies of closely passing particles. First, cells with local $E(\text{max})$ are selected. Then a cluster is formed, gradually including directly neighboring cells that pass a certain energy threshold. Proceeding this way until the threshold is not passed any more by any neighbor cells results in so-called topological clusters. The choice of threshold ensures that the clusters are well differentiated from noise. From the last hit in the tracker the tracks are universalized. Typical shower lengths in the ECAL and HCAL were derived from simulations. The tracks are not extrapolated any further than these before determined lengths. If matching calorimeter clusters are found, they are linked to the track. In a last step the hit informations provided by muon system is matched with extrapolated charged tracks. First, individual leptons, and hadrons $^{\pm}$ are reconstructed using the stored data. Each of the identified stable particles is listed and all traces associated with it are removed from the event. If no more of these particles can be identified, the remaining data is assumed to

³³The used HLT path and its description is given in the Section 4.1.2

³⁴<https://arxiv.org/pdf/1706.04965.pdf>

come from photons or neutral hadrons. From the set of stable particles found in this manner, jets can be clustered in the same way as it is done on the particle level in simulations. Use of particle flow algorithm is found to improve the jet resolution up to a factor three, that of missing transverse energy E_T by a factor two. Also the reconstruction of electrons, muons, and photons benefits from its use. The reconstruction of jets exploits the information of calorimeters where as the tagging of jets requires information of tracker since it is evolving from b hadronization and also from hadronic τ decays which are based on the properties of charged particle tracks. The resolution of jet energy is $\sim 15\%$: $p_T^{\text{jet}} \simeq 10\text{ GeV}$, 8% : $p_T^{\text{jet}} \simeq 100\text{ GeV}$, and 4% : $p_T^{\text{jet}} \simeq 1\text{ TeV}$ ³⁵. The μ objects are reconstructed exploiting two algorithms which requires the consistent hit informations provided by tracker, and muon system. The first algorithm matches reconstructed tracker trajectories with the hits obtained in the DT, and CSC, this is called the tracker-based muon reconstruction. The second one performs a global fit inclusively on the consecutive hit outcomes from the muon system and tracker resulting global μ 's. Additionally, a minimal consecutive hit count in tracker and in muon chamber is required to perform the global fit that the associated trajectories with the muons are originating consistently from beam spot³⁶. The reconstruction of isolated e/γ primarily starts with energy deposition (in crystals) clusters comprises a matching flag with tracker hits. This process uses a tracking algorithm including sizeable energy loss (bremsstrahlung) of the e in tracker. The e candidate track should be originating from the beam spot. Shape of the shower and cluster matching flags are defining e candidate identification and reconstruction. Fake electrons produced due to muon bremsstrahlung are removed by utilizing a $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.1$ corresponding to a tracker μ or global μ . In addition to this the e objects originating due to random energy deposits in ECAL or from γ conversion are also rejected³⁷.

³⁵The definition of the missing transverse momentum vector is given by $\vec{p}_T = \sum_{PFO} |\vec{p}_T|$, and $E_T^{\text{miss}} \equiv |\vec{p}_T|$

³⁶<https://cds.cern.ch/record/2232592/files/vol56-issue5-p027-e.pdf>

³⁷<https://indico.in2p3.fr/event/14415/contributions/18288/attachments/15167/18631/PF-CMS.pdf>

2.10 Data distribution system & CMSSW

The collision and simulated data are stored at different tiers located at different places in the world. Being a very large collaboration, where thousands of people from across the world work on the same data, the CMS distributes its data in such a way that any user can access these through the worldwide LHC grid. The data distribution system is divided into various tiers such as tier-0,-1,-2 (T0,T1,T2) depending on the type of operations performed on the data. To analyze the data the CMS software (CMSSW) is employed which is one of the most advanced packages provides thousands of sub-packages needed to analyze data at different steps. The CMSSW exploits C++ and python language. Main design of the CMSSW relies on the event data model (EDM). All the sub-packages (modules) of the CMSSW run on each event separately, that is none of them run on two events at the same time. CMSSW comprises various modules to perform different types of operation. It contains Source, EDProducer, EDFilter, EDAnalyzer, OutputModule.

Chapter 3

Calibration of subdetectors

3.1 Lorentz angle in strip detector

The silicon material has several interesting property such as relatively small band gap 1.12eV, high carrier mobility ($1450\text{ cm}^2/\text{Vs}$), and high specific density 2.33 g/cm^3 . The silicon detector works as reverse biased pn junction. As depicted in the Figure 3.1, when a minimum ionized particle traversing the bulk n-type region under the influence of 80V reverse bias voltage $\sim 24,000$ e -hole pairs are produced in the depletion region. The produced $-e$'s are collected in the p^+ within 10ns and amplified to readout by the backend electronics. The solenoid magnetic field also in effect simultaneously, the non-parallel magnetic field to an electric field will cause a Lorentz force $\mathbf{F}=q(\mathbf{E}+\mathbf{v}\times\mathbf{B})$ may spread the charge carriers to several strips. Since, it is not possible to have a defined coordinate of the distributed charge, the centre of gravity of the charge distribution is considered as the incident and emergent track of a particle, thus, this is playing the crucial toward the determination of the associated trajectories of the particle. At $\mathbf{B}\perp\mathbf{E}$ the angular drift θ_L of the carriers trajectory is the Lorentz angle (LA) with respect to the direction of $\mathbf{E}$. The tangent of the LA is defined in the Equation 3.1.

$$\tan \theta_L = \mu_H |\mathbf{B}|, \quad \mu_H (= r_H \mu, r_H = 0.7(h), 1.15(e)) \text{ drift mobility} \quad (3.1)$$

²http://hep.fi.infn.it/CMS/sensors/Silicon_Detector.gif

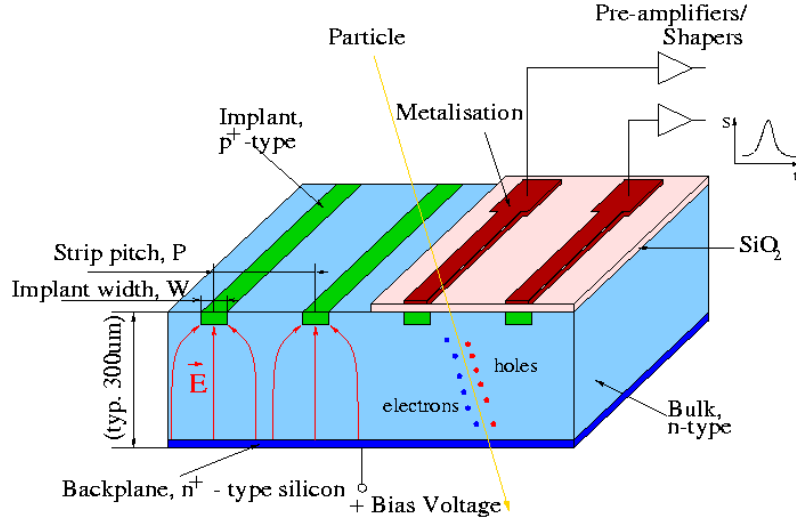


Figure 3.1: The principle of operation of a silicon detector ². The green strips are p⁺-type of semiconductor where the electrons are attracted after being produced in the depletion region when the particle passing the semiconductor. The SiO₂ layer along with metallic surface, on top of the green strips, provides conducting circuits for the electron. The amplifiers/shapers are used to amplify and shape the electron current. The holes are attracted towards the +ve bias voltage.

The pictorial description is given in the Figure 3.2, the x coordinates are set to define the endpoints(junction side) of the hole path which is the distance measured from origin of the local coordinate system corresponding to a silicon strip. The angle between track and the z axis is θ_t , when a hole formed at the depth ($z \leq 0$) the drift in the x -coordinate is,

$$\Delta x(z, \theta_t) = z \tan \theta_t + \delta x(z).$$

The $z \tan \theta_t$ is trajectory projection on the xy plane of the local strip coordinate system and $\delta x(z)$ is the measure of the endpoint distance caused by $\mathbf{F}$. The orange band in the Figure 3.2 describes the size of the cluster formed by the ionization. At $\mathbf{B} = 0$, the hole drifts along the $\mathbf{E}$ which are perpendicular to the strips, to achieve a minimum cluster width with orthogonal tracks to the detector.

$$\Delta x_m = \frac{\Delta x_s}{\cos \alpha}, \quad \alpha = \hat{y} \angle \mathbf{B}, \quad \cos \alpha = \frac{\hat{y} \cdot \mathbf{B}}{B} \quad (3.2)$$

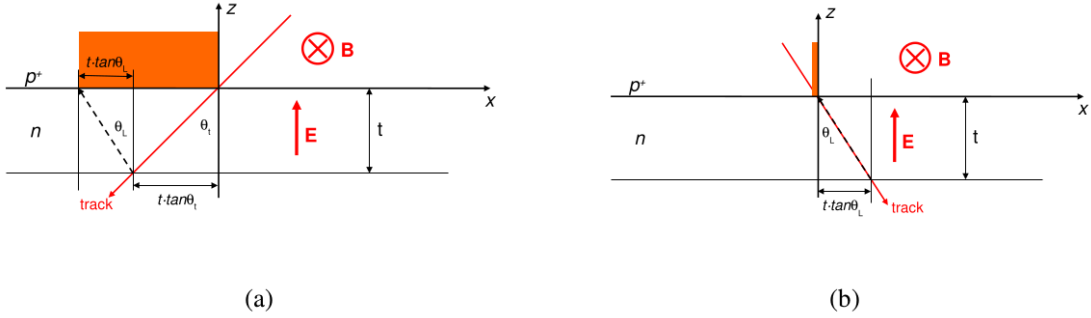


Figure 3.2: Lorentz drift of the hole (Δx) inside the silicon strip due to the influence of the Lorentz force.

$$\sigma^2 = \frac{\sum_{strips=i}^{i+1} x^2 q_i}{\sum_{strips} q_i} - \left(\frac{\sum_{strips=i}^{i+1} x q_i}{\sum_{strips} q_i} \right)^2,$$

$$\Delta x = z \tan \theta_L + \delta x, \quad (3.3)$$

$$x = \frac{1}{t} \int_{-t}^0 \Delta x dz + x_{track}, \quad t = \text{thickness}.$$

Where, θ_L is the angle between $\mathbf{E}$, and the drift axis, the measure of the track angle for which the minimal of cluster size is obtained delivers the direct determination of the LA. In the presence of $\mathbf{B}$, minimal cluster size will be achieved when the three momentum vector of track will be inclined toward the drift lines. Orientation of modules in different layers are different from each other, in local reference frame some modules have y axis parallel to the $\mathbf{B}$ while other antiparallel causing difference in signs of LA. For $\hat{y} \cdot \mathbf{B} > 0$ LA is ve^+ and ve^- otherwise, restricted to the displacement of the cluster centroid which are orthogonal to the module strip³. Stereo (r- ϕ plane) detectors are tilted with respect to the mono (r-z plane) detector by 100 mrad which causes smaller cluster centroid displacement in stereo's than mono's for same incident angle. A correction factor $1/\cos \alpha$ need to be multiplied to track angle $\tan \theta_L$ for stereo's and for mono's $\cos \alpha = \pm 1$, the total definition of the correction factor is given in the Equation 3.2, and the Figure 3.3 illustrates the necessity

³In general measurable by the detector

of the correction factor. There is another variable called cluster variance which can be used in place of cluster width as described in the Equation 3.3. Strip tracker is divided in the four different parts : tracker inner barrel (TIB), tracker outer barrel (TOB), tracker endcap (TEC), and tracker inner disk (TID). The TIB with 4 layers is covering $|z| < 65\text{cm}$ in $\pm z$ direction having $320\mu\text{m}$ thick (t) silicon sensor and strip pitch (sp) in a range $(80-120)\mu\text{m}$. TIB's first two layers (FL2) are stereo and next two layers (NL2) are mono.

Layer wise details of the strip tracker

- **TIB:** 4L, $|z| < 65\text{cm}$, $t = 320\mu\text{m}$, sp- $(80-120)\mu\text{m}$, F2L-stereo(r- ϕ , r-z), N2L-Mono.
- **TOB:** 6L, $|z| < 110\text{cm}$, $t = 500\mu\text{m}$, sp- $(120-180)\mu\text{m}$, F2L-stereo(r- ϕ , r-z), N4L-Mono.
- **TEC:** 9D, modules arranged in Rings, $120\text{cm} < |z| < 280\text{cm}$, 2IM+5th R-stereo(r- ϕ , r-z), $t=3\text{IMR } 320\mu\text{m}$; rest of the modules are of $500\mu\text{m}$.
- **TID:** 3D, F2R-stereo, $t = 320\mu\text{m}$, placed between TIB and TEC.

Total 15400 Detectors (TIB:TOB:TID:TEC $\Leftrightarrow$ 2724:5208:816:6400)

F2R - first two rings, IMR - inner most rings

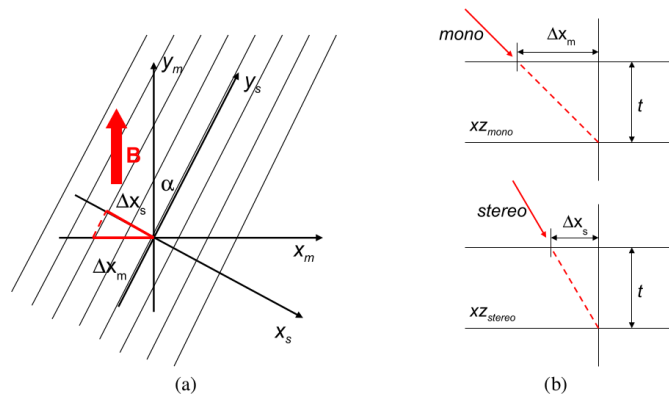


Figure 3.3: The geometric outline of the strips : (a) $\alpha := \hat{y}_s \angle \mathbf{B}$; (b) xz_{mono} , and xz_{stereo} plane view: the drift is defined by the dashed lines xz_{module} plane, track projections are represented by arrows.

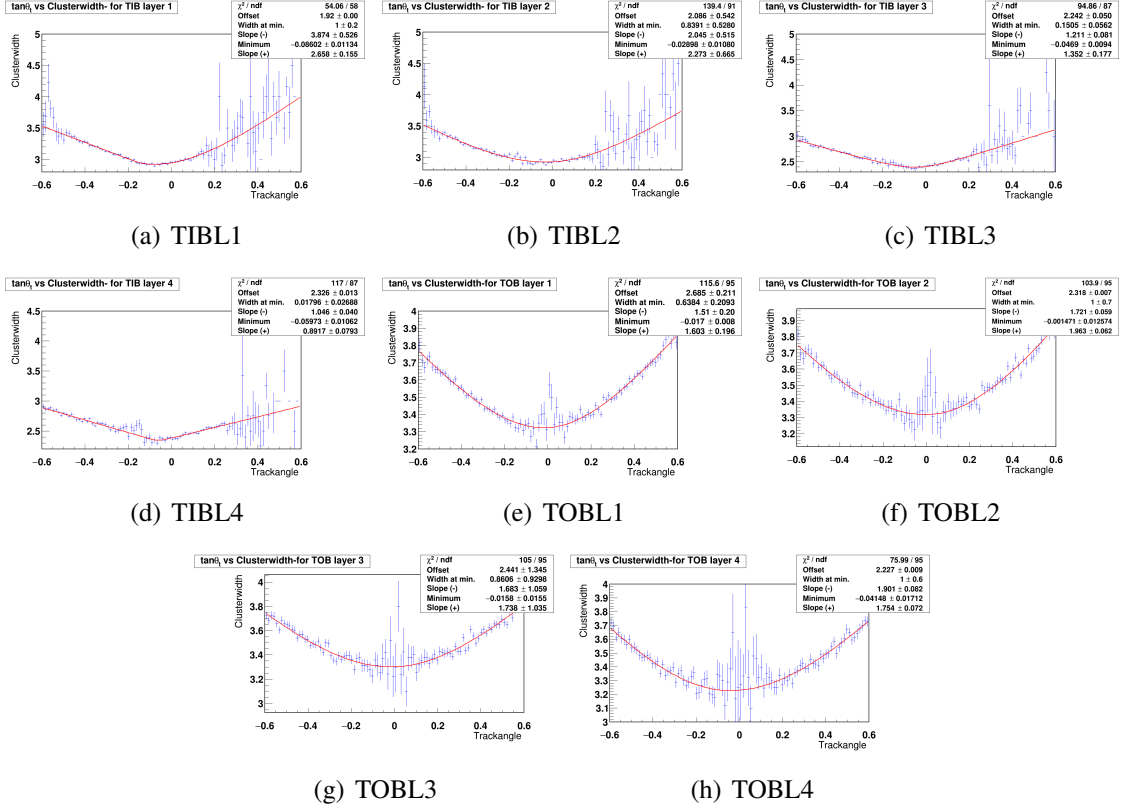


Figure 3.4: Average profile of the cluster width in bins of tangent of the local incident track angle, the blue solid line is the projections of the fit parametrization. Only the tracker inner barrel and outer barrel parts are studies.

The drift in the measurement of the centroid of the cluster width is influenced by the presence of the Lorentz force, the cluster width is plotted as a profile of the incident angle. To determine the minimum of the incident angle the profile is fitted with a function described in the Equation 3.4.

$$f(\Delta x) = a_0 + \sqrt{a_1^2 + a_2^2(\Delta x - a_3)^2} \quad (3.4)$$

The a_i implies fit parameters, $\tan^{-1}(a_3)$ is considered as the shift in the incident angle due to Lorentz force and those values are listed in the Table 3.1.

Detector	Lorentz Angle ($^{\circ}$)	Detector	Lorentz Angle ($^{\circ}$)
TIB-Layer1	$\sim (-4.91 \pm 0.65)^0$	TOB-Layer1	$\sim (-0.97 \pm 0.46)^0$
TIB-Layer2	$\sim (-1.66 \pm 0.62)^0$	TOB-Layer2	$\sim (-0.08 \pm 0.72)^0$
TIB-Layer3	$\sim (-2.68 \pm 0.54)^0$	TOB-Layer3	$\sim (-0.91 \pm 0.89)^0$
TIB-Layer4	$\sim (-3.45 \pm 0.61)^0$	TOB-Layer4	$\sim (-2.37 \pm 0.99)^0$

Table 3.1: The layer wise values of Lorentz Angle are shown in this table, these results are only for the mono detectors, the calculations for the stereo detectors are not performed here. The analysis is performed using the basic 2017 calibration tree centrally produced by the tracker detector performance group (DPG).

3.2 ZDC Calibration

The description of early universe in terms of exact compositions, equation of state, and all possible symmetry breaking effects are unknown. Several theoretical approaches have been made beyond the well-established standard model to investigate these unknowns. In particular, the quark gluon plasma (QGP) is believed to provide the information of the early universe. The study of color neutral QGP scenarios, a subset of QCD, requires measurement of forward neutral spectators by the Zero Degree Calorimeter (ZDC). Useful data requires stable, well calibrated detectors free of pile-up effects. This note describes the study of in-time signal events and calibration of the one neutron peak.

3.2.1 Detector construction

The purpose of the ZDCs are to measure the neutral spectators, such as the neutrons and the very forward photons for the heavy-ion and low-luminosity (up to $10^{33}\text{cm}^{-2}\text{s}^{-1}$) proton-proton (pp) collisions. The ZDCs are capable to deliver reasonable measurements of real-time luminosity, beam tuning, and accelerator monitoring during Pb-Pb, pPb, and pp collisions. The ZDCs are residing in special detector slots in the neutral particle absorber (TAN), which is designed to protect the first superconducting quadrupole magnet from radiation. Inside the TAN, the region corresponding to a very high pseudorapidity ($\eta > 8.3$) provides a large coverage for the detection of neutral particles and photon which are not swept away by bending and focusing of the magnet. Figure 3.5 outlines the acceptance coverage of the trackers, ECAL/HCAL, magnet, and muon chambers in pseudorapidity (η) and radial (θ) directions. As shown in Figure 3.6 the ZDC assembles two sampling Cherenkov heterogeneous quartz based calorimeters with tungsten absorber situated at a distance 140m away from IP. Among the two section of ZDC the electromagnetic (EM) section is used for the optimization of photon detection and energy measurement and the hadronic (HAD) section is used for the measurement of neutron energy. Further the EM section is segmented in to five vertical strip which consists of thirty three 2mm

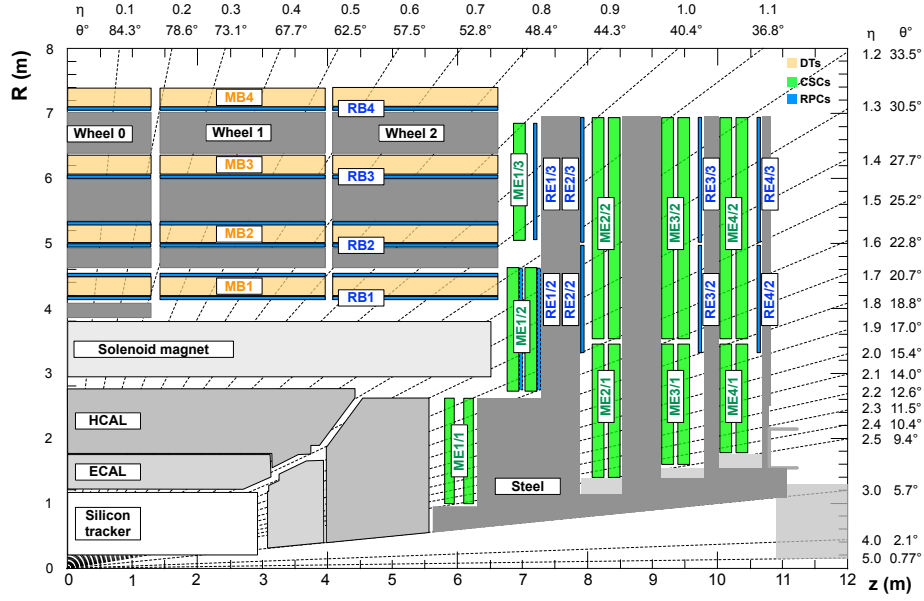


Figure 3.5: Acceptance coverage of the CMS calorimeters, tracking, and muon identification in pseudorapidity (η) and radial (θ) direction. Location of the various sub-detectors of the CMS [5]. The RPCs are placed in both regions. The muon chamber in the barrel region is formed by placing three wheels side-by-side along the z -axis whereas in the endcap regions different segments of RPC and CSC are placed along the radial direction.

Parameters	EM section	HAD section
Sampling ratio	2mmW/0.7 mm	15.5mmW/0.7 mm
Interaction length	$19X_0$	$5.6\lambda_0$
Cell	33	24
Channels	5 horizontal divisions	4 longitudinal segments
Module size ($W \times L \times H$)	$92 \times 116 \times 705 \text{ mm}^3$	$92 \times 711 \times 705 \text{ mm}^3$
Weight	$\sim 65 \text{ Kg}$	$\sim 400 \text{ Kg}$

Table 3.2: The physical characteristic of the ZDC is described here for both EM and HAD section.

thick tungsten plates sandwiching the quartz fibers (QF), the Cherenkov light governed in QED process is passing through the QF, and brought to photomultiplier tubes (PMT). The vertical strips are measuring the coordinate of γ in yz plane. HAD section comprises 24 tungsten layers of plate thickness 15.5 mm, and 24 quartz layers of fibre diameter 0.7 mm. The HAD section is segmented in the longitudinal direction into four readout segments of ~ 1.4 nuclear interaction length each and each segment is tilted 45° to optimise the collection of the Cherenkov light. A readout fibre bundle is formed by collecting together the individual tungsten/quartz fibre cell and those are coupled to four Hamamatsu-R7525

PMT's via long air core light guides. The ZDC in total provides 50 channels, (2×16) for

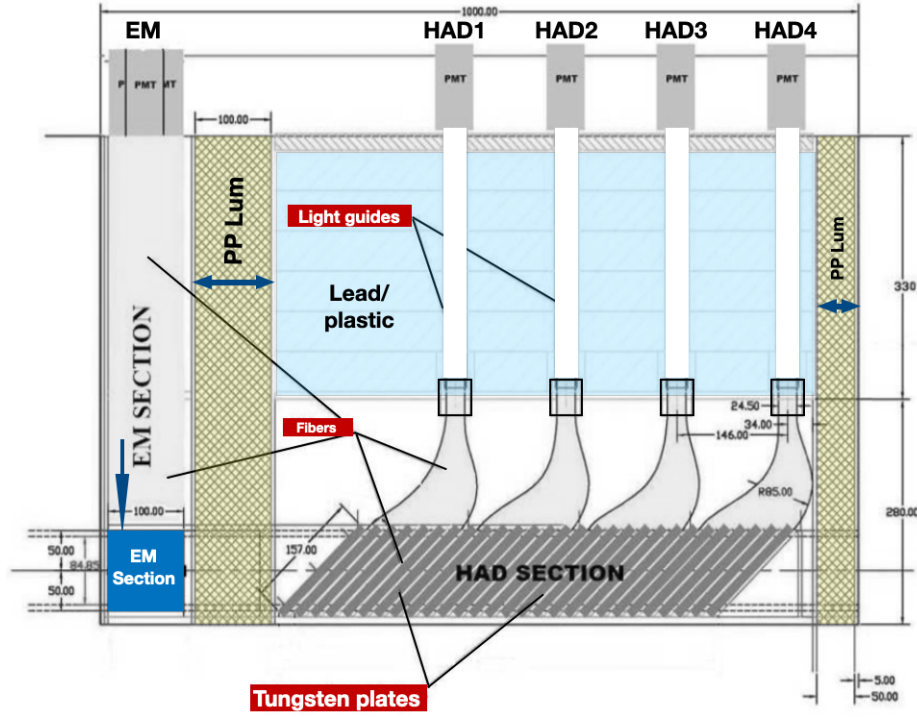


Figure 3.6: Schematic illustration of the TAN slot depicting the placeholder for the pp luminosity monitor and the ZDC (EM & HAD sections). The light brown hatched (pp Lum) segment is the is the slot for the BRAN (Beam RATE for Neutrals) luminosity monitor.

radiation plane detector (RPD), (2×5) for the electromagnetic (EM) section, (2×4) for the hadronic (HAD) sections. The ZDC can be used as a centrality [57] estimator in Pb-Pb and pPb collisions respectively. Table 3.2 describes physical characteristics of the ZDC.

3.2.2 Timing and templates

The signal is collected over 10 time slices (TS) of 25 ns each. The signal pulse expected to be appeared in TS4 and the low gain signal can be obtained by summing over, TS5 and TS6 (for 75 ns, the 2018 run), and a high gain signal by summing over TS4 and TS5. The weighted time averages of timeslices is defined in Equation 3.5.

$$\bar{T}_i = \frac{\sum_t Q_i[t] \cdot t}{\sum_t Q_i[t]} \quad (3.5)$$

where, $Q_i[t]$ is the charge value observed in a certain event in the i^{th} detector segment at timeslice t , and $\bar{T}_i$ refers to normalized time average of the signal in the given channel. The distribution of the weighted time averages of the four channels in the ve^+ HAD side and five channels in the ve^- EM section for 100ns bunch crossing(BX) are shown in Figure 3.7. The weighted time averages distribution is modeled using a single Johnson function.

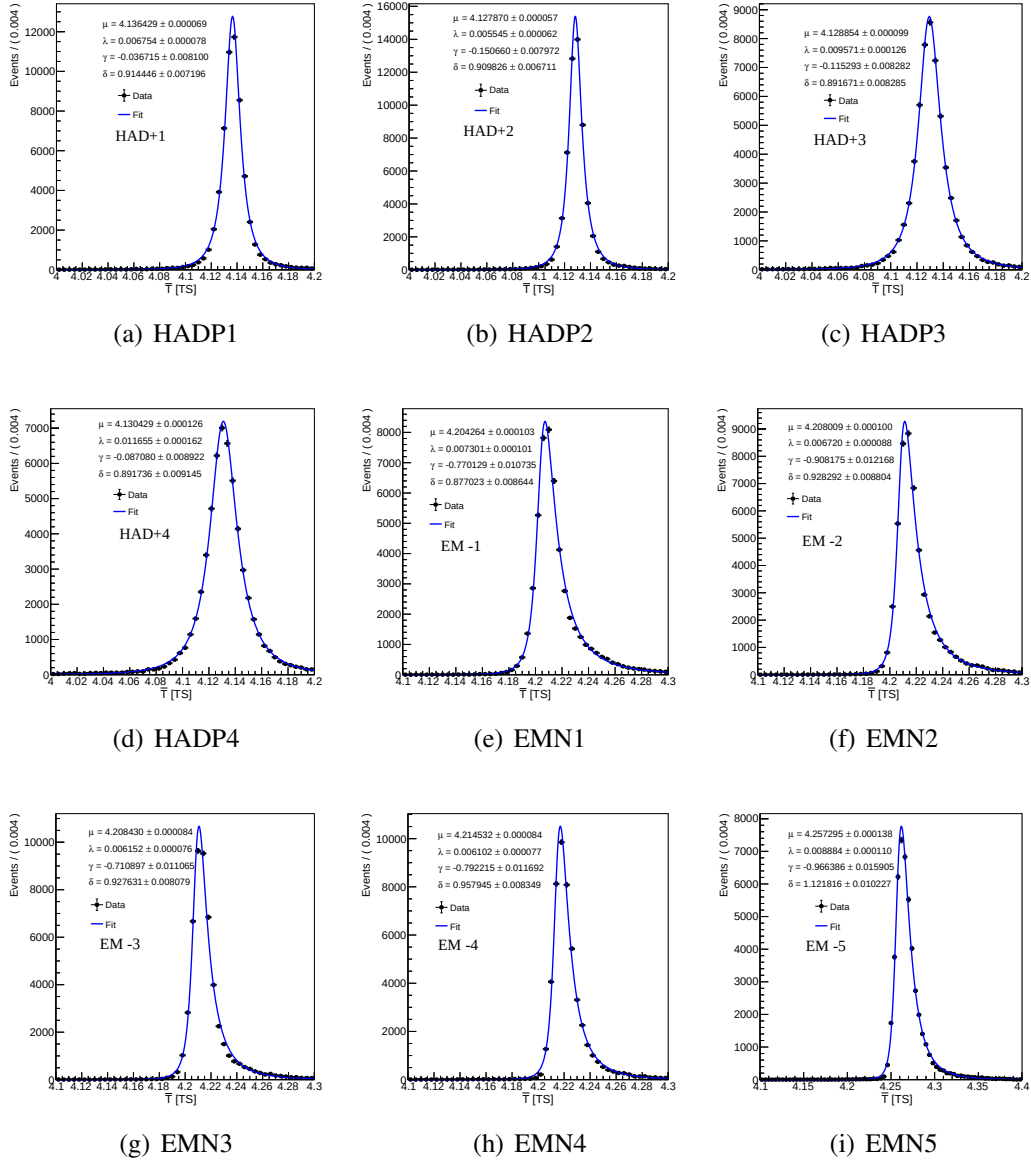


Figure 3.7: Weighted time average distribution of the four channels in the positive z direction of HAD section and negative z direction of the EM section.

This distribution results from transforming a normally distributed variable x to

$$z = \gamma + \delta \sinh^{-1} \left(\frac{x - \mu}{\lambda} \right) \quad (3.6)$$

and the resultant probability distribution function is,

$$\mathcal{P} = \frac{\delta}{\lambda \sqrt{2\pi}} \frac{1}{\sqrt{1 + \left(\frac{\bar{T}_i - \mu}{\lambda} \right)^2}} \cdot \exp \left\{ \left[-\frac{1}{2} \left(\gamma + \delta \sinh^{-1} \left(\frac{\bar{T}_i - \mu}{\lambda} \right) \right)^2 \right] \right\}. \quad (3.7)$$

Uncertainties for these sharp distribution are almost within the range of 5 – 10 ns and these uncertainties related to each distribution can be calculated using the variance 3.8.

$$\sigma = \frac{\lambda^2}{2} (\exp(\delta^{-2}) - 1) \left(\exp(\delta^{-2}) \cosh \left(\frac{2\gamma}{\delta} \right) + 1 \right). \quad (3.8)$$

A more sophisticated method utilizes a general signal template t , where the vector elements belong to different timeslices. The template for a given channel is constructed by averaging over pedestal subtracted signal shapes:

$$\langle \mathbf{T} \rangle = \frac{\sum_n (t_n)_i}{\sum_{i=0}^9 \sum_n (t_n)_i} \quad (3.9)$$

where, $(t_n)_i$ is the signal value in the n^{th} event and i^{th} timeslice. Further an effort is made to find the templates of the out-of-time pile-up effects in timeslice one which is 75 ns earlier than the in-time signal and another one in the timeslice seven which is 75 ns later of the signal. This is also true for 100 ns BX data with the gap of 100 ns between pre- and post-pile up from the signal in TS4. The Pb-Pb collision data collected in 2018 is used in this study, and is given in Table 3.3. Templates corresponding to both EM and HAD sections of 75 ns BX are depicted in the Figure 3.8, and in 3.9 respectively. The x -axis is the time-slice of each 25 ns and y -axis is the charge collection. The estimation of the charge collection in pre-pile-up, post-pile-up and signal events the χ^2 minimization is performed using the TMinuite class of ROOT framework. The general definition of minimized χ^2 when fitted to

Year	Data set
2018(75 ns)	HIRun2018A/HIMinimumBias1/AOD/PromptReco-v2/327219
2018(75 ns)	HIRun2018A/HIMinimumBias1/AOD/PromptReco-v2/327400
2018(75 ns)	HIRun2018A/HIMinimumBias1/AOD/PromptReco-v2/327524
2018(75 ns)	HIRun2018A/HIMinimumBias1/AOD/PromptReco-v2/327525
2018(75 ns)	HIRun2018A/HIMinimumBias1/AOD/PromptReco-v2/327526
2018(100 ns)	HIRun2018A/HIMinimumBias1/AOD/PromptReco-v1/326886

Table 3.3: The Pb-Pb collision data collected in 2018

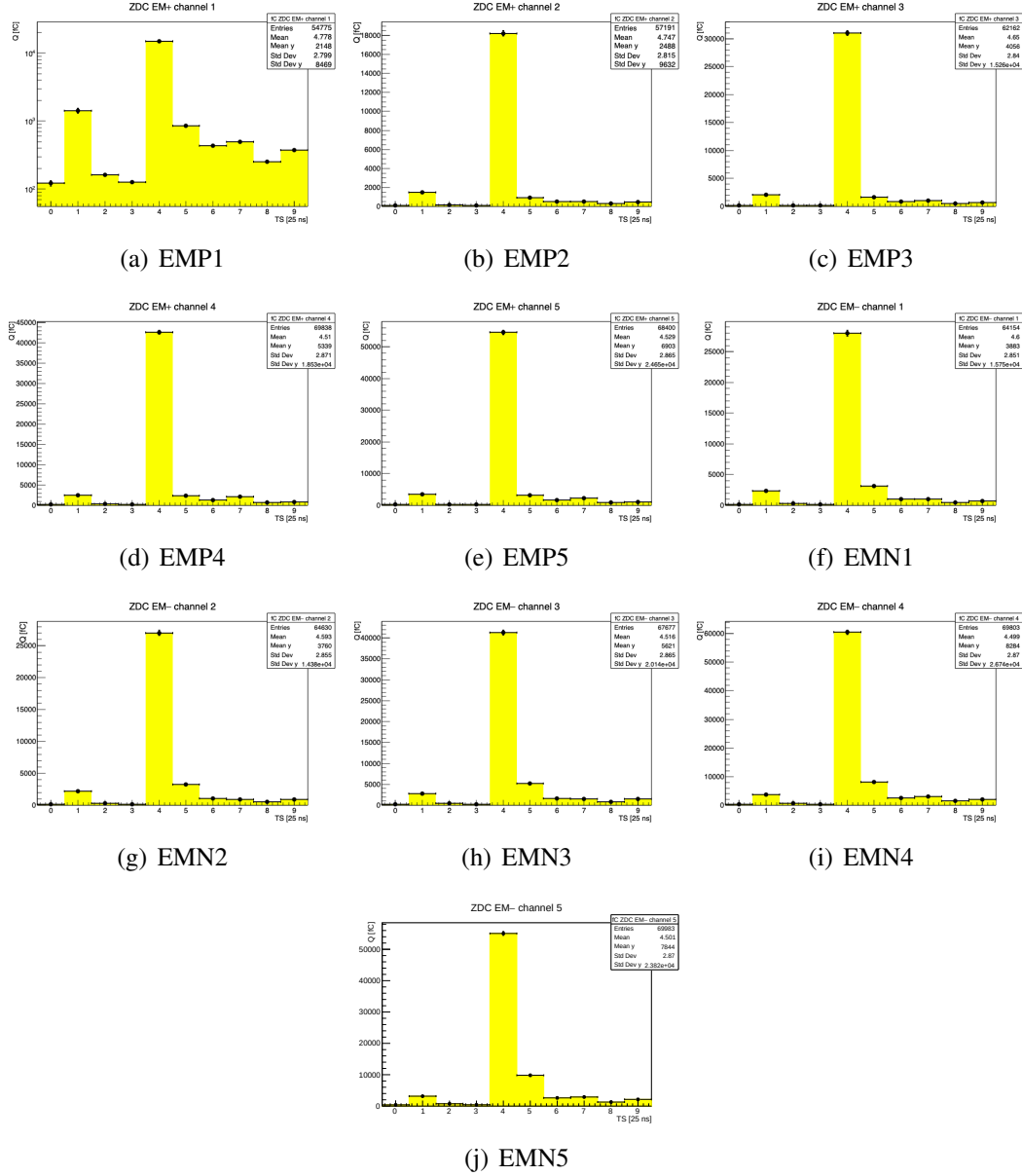


Figure 3.8: Templates corresponding to 75 ns bunch crossing for all channels of EM section.

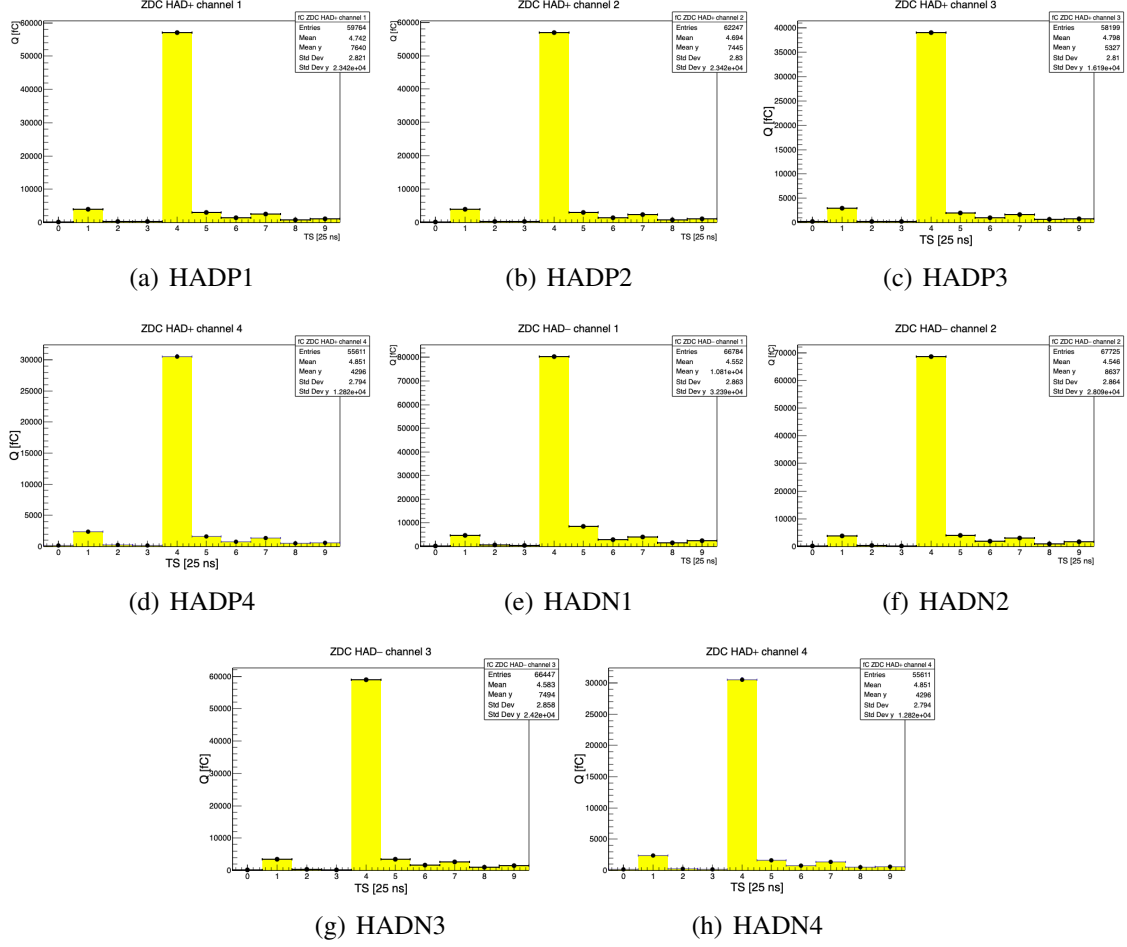


Figure 3.9: Templates corresponding to 75 ns bunch crossing for all channels of HAD section.

data points x_i with a function $f_i(x_i)$ is given by,

$$\chi^2 = \left(\frac{x_i - f_i(x_i)}{\Delta x_i} \right)^2 \quad (3.10)$$

where the $f_i(x_i)$ is given by,

$$f_i(x_i) = a_1 \mathbf{t}_1 + a_2 \mathbf{t} + a_3 \mathbf{t}_2 + a_4 \mathbf{1} \quad (3.11)$$

The t_1, t , and t_2 are assumed templates for pre-pile-up, signal and post-pile-up events. The coefficient a_4 is considered for pedestal coming from simple electronic noise. The presence of electronic noise is being considered a constant factor and a constant vector with unit

entries is assigned to it. To perform the fit a random channel (EM,5) from EM section is chosen in the negative direction of z -axis. The error for template data points in each bin time slice is assumed 5% of the charge collection in the corresponding bin and χ^2 plots are shown in Fig 3.10.

3.2.3 Analytical method of template fitting

To approach the analytical method of matrix calculus the following χ^2 expression is considered,

$$\chi^2 = (\mathbf{x} - a\mathbf{t} - b\mathbf{t}_1 - c\mathbf{t}_2 - d\mathbf{1})^T \mathbf{V}^{-1} (\mathbf{x} - a\mathbf{t} - b\mathbf{t}_1 - c\mathbf{t}_2 - d\mathbf{1}) \quad (3.12)$$

Where, $\mathbf{V}$ recovers covariance property, neglecting the covariance between the templates the covariance matrix is considered $\mathbf{V}$ as unit matrix which leads the χ^2 to be further as,

$$\chi^2 = (\mathbf{x} - a\mathbf{t} - b\mathbf{t}_1 - c\mathbf{t}_2 - d\mathbf{1})^T (\mathbf{x} - a\mathbf{t} - b\mathbf{t}_1 - c\mathbf{t}_2 - d\mathbf{1}) \quad (3.13)$$

Differentiating with respect to each of the coefficients,

$$\frac{d\chi^2}{da} = -2\vec{t}(\vec{x} - a\vec{t} - b\vec{t}_1 - c\vec{t}_2 - d\vec{1}) = 0 \quad (3.14)$$

$$\frac{d\chi^2}{db} = -2\vec{t}_1(\vec{x} - a\vec{t} - b\vec{t}_1 - c\vec{t}_2 - d\vec{1}) = 0 \quad (3.15)$$

$$\frac{d\chi^2}{dc} = -2\vec{t}_2(\vec{x} - a\vec{t} - b\vec{t}_1 - c\vec{t}_2 - d\vec{1}) = 0 \quad (3.16)$$

$$\frac{d\chi^2}{dd} = -2\vec{1}(\vec{x} - a\vec{t} - b\vec{t}_1 - c\vec{t}_2 - d\vec{1}) = 0 \quad (3.17)$$

For a non-trivial solution we end up with a matrix equation which can be written as,

$$\mathbf{A} \cdot \mathbf{v} = \mathbf{D} \quad (3.18)$$

Where the other terms are,

$$\mathbf{A} = \begin{pmatrix} t^T t & t_1^T t & t_2^T t & 1^T t \\ t^T t_1 & t_1^T t_1 & t_2^T t_1 & 1^T t_1 \\ t^T t_2 & t_1^T t_2 & t_2^T t_2 & 1^T t_2 \\ t^T 1 & t_1^T 1 & t_2^T 1 & 1^T 1 \end{pmatrix}, \quad \mathbf{D} = \begin{pmatrix} x^T t \\ x^T t_1 \\ x^T t_2 \\ x^T 1 \end{pmatrix}, \quad \mathbf{v} = \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix} \quad (3.19)$$

The solution for $\mathbf{v}$ from Equation 3.19 is obtained using Gauss-Elimination method. The values extracted by matrix calculus is compatible with the values which one extracted using TMinute class of χ^2 minimization which is shown in Figure 3.11 . To extract a real in-

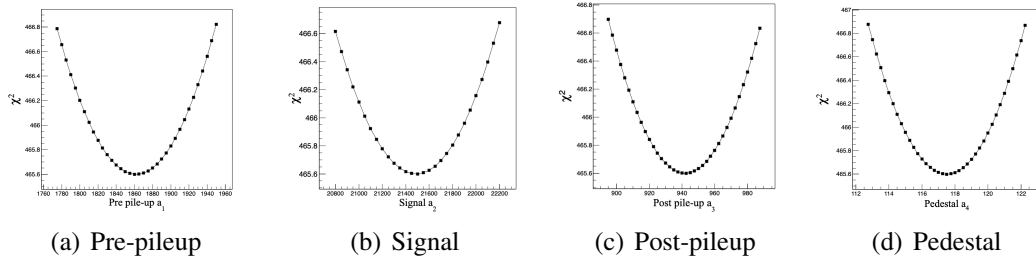


Figure 3.10: Minimized χ^2 of pre-pile-up, signal, post-pile-up and pedestal events for 75 ns BX.

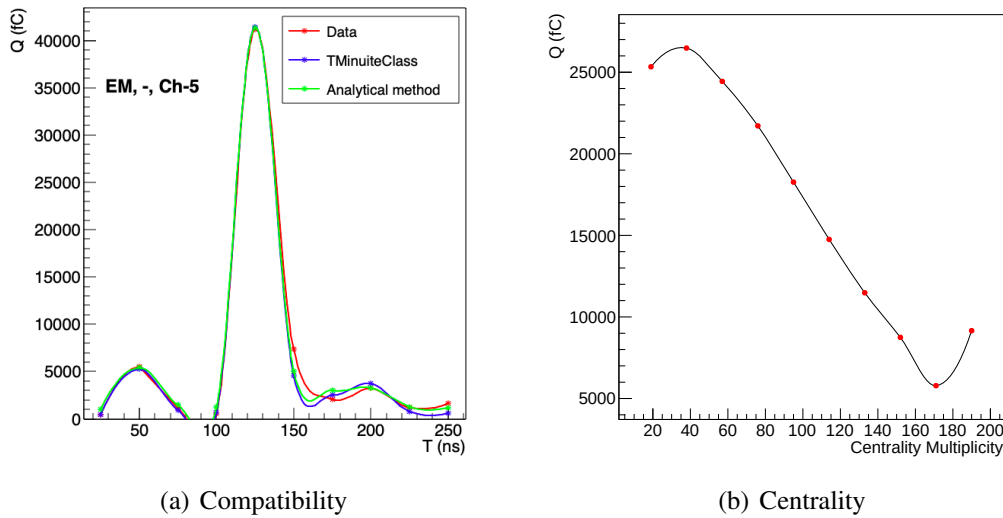


Figure 3.11: The comparison of minimization procedure using TMinute and matrix calculus.

time profile a detector correlation approach is made based upon the sustainability of the

pre-pile (TS1) in the in-time signal time slice (TS4). Also the existence of the very signal tail in the next successive timeslices may interfere with 75 ns later post-pile-up timeslice in TS7. In this regard the estimation of fraction of charge collection in TS5 and TS6 is important. To do that a random study of ratio is made between timeslice five to timeslice four and also for timeslice six to timeslice four. The idea behind this was to understand how much of the charge collection acquired in timeslice four is remaining in the next successive slices. Table 3.4 shows the ratio between time slices of random events and random detector elements by creating the array of 16 detector elements corresponding to any event within 50K events and throw them randomly. It is very much clear from the ratios that obviously

Detector/Events	TS5/TS4	TS6/TS4
EM -3/23446	0.0562	0.03170
EM +4/74	0.1109	0.04200
EM -5/678	0.1780	0.05024
HAD +1/23	0.0525	0.02950

Table 3.4: The ratio calculation between TS4, TS5, TS6 from event by event study.

in TS7 the tail of the signal will not be more that 5% in terms of charge collection. The detector correlation is used to get the signal time profile. These following selections are applied to the templates to get a pile-up free signal profile. To extract the in-time signal profile the HAD +1 detector is chosen by skipping the events collected in the EM section for both positive and negative side. The negative HAD side is also skipped and apply veto of charge selection in TS1 and TS7 if there is pre- and post- pile-up in HAD +1. Apply the same selection in HAD +2 or HAD +3 if the pre- and post- pile-up appeared in HAD +1 still sustains in these channels. For HAD +4 a constant selection is applied of $Q < 150\text{fC}$. The selection of centrality is applied by dividing the centrality in 10 bins and choosing the

Side	Channel	Charge in TS[1]	Charge in TS[7]
Ve^+	1	$Q[TS1] < 120\text{fC}$	$Q[TS7] < 50\text{fC}$
Ve^+	2	$Q[TS1] < 120\text{fC}$	$Q[TS7] < 50\text{fC}$
Ve^+	3	$Q[TS1] < 120\text{fC}$	$Q[TS7] < 50\text{fC}$

Table 3.5: Hadroni channel positive side for 75 ns bunch crossing and the centrality(Cn) ($30 < Cn < 50$).

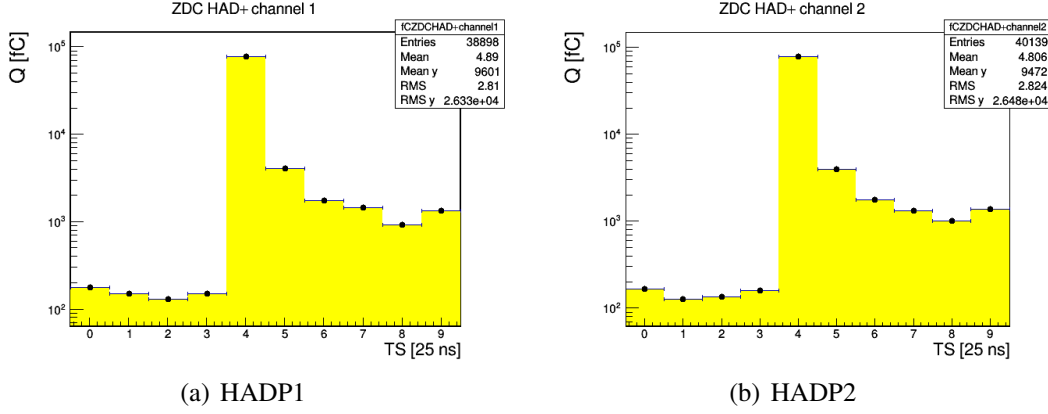


Figure 3.12: Most probable proper time profile HAD section channel one , and two in positive z-axis.

maximum RMS charge collection in the ultra peripheral region. The most probable proper pile-up free time profile of ZDC hadronic section for channel one and two in the positive direction of z-axis are shown in Fig 3.12.

3.2.4 Time profiles of 100 ns bunch crossing data

The extraction of in-time signal profile is performed on 100 ns BX data described in the Table 3.3. All the necessary tests are performed with 100 ns BX data similar to 75 ns BX. Figure 3.14, and 3.15 refers the in-time signal profiles in 100 ns BX Pb-Pb data of 2018. The weighted average of the charge collection in TS4 after applying all selections is,

$$\frac{1}{i} \sum_i^N Q_{TS4}^{Sig} = 1.405 \pm 0.028 \text{ fC}. \quad (3.20)$$

To measure the pre-pile contamination in the signal TS4 the reciprocal selection corresponding to the signal extraction is applied to veto the signal events. Profile description under such selections keeps the events where the pre-pile-up is affecting the in-time signal profile. Profiles of only pre-pile events are shown in Figure 3.13. Though it is more to say that such contamination is very less that one could easily neglect them and a very conclusion can be drawn that the in-time signal profile is unaffected by pre-pile-up. To account such contamination it is found that the contribution of weighted average of pre-pile-up

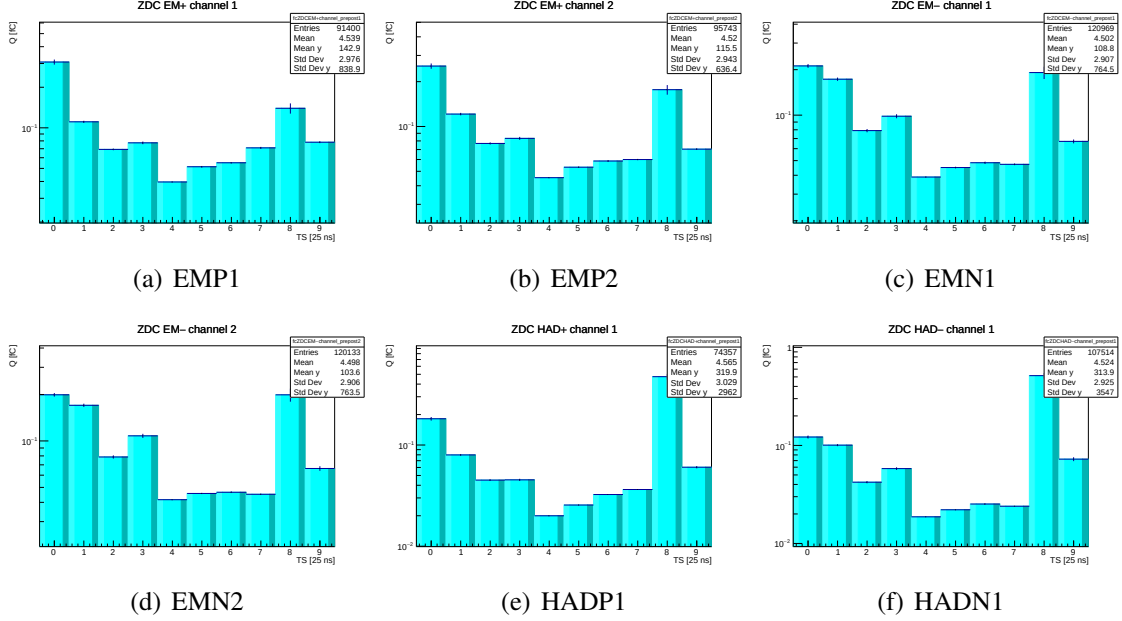


Figure 3.13: Pre-pile-up events without any signal of both EM and HAD section for few channels.

charge in TS4 is,

$$\frac{1}{i} \sum_i^N Q_{TS4}^{PrePU} = 0.000684908 \pm 4.81886 \times 10^{-06} \text{ fC}. \quad (3.21)$$

The corrected charge in TS4 and the charge without any selection (RAW) in TS4 is given as.,

$$\begin{aligned} \frac{1}{i} \sum_i^N Q_{TS4}^{Corrected} &= 1.404 \pm 0.028 \text{ fC} \\ \frac{1}{i} \sum_i^N Q_{TS4}^{RAW} &= 0.7805 \pm 0.0019 \text{ fC}. \end{aligned} \quad (3.22)$$

Finally the relative enhancement of the charge collection in TS4 with respect to the RAW events is found to be,

$$\frac{\frac{1}{i} \sum_i^N Q_{TS4}^{Corrected} - \frac{1}{i} \sum_i^N Q_{TS4}^{RAW}}{\frac{1}{i} \sum_i^N Q_{TS4}^{RAW}} \sim 80\% \quad (3.23)$$

The charge collection in Ts5, TS6 and TS7 for signal-only events are 0.1304 fC, 0.0478 fC and 0.0279 fC respectively.

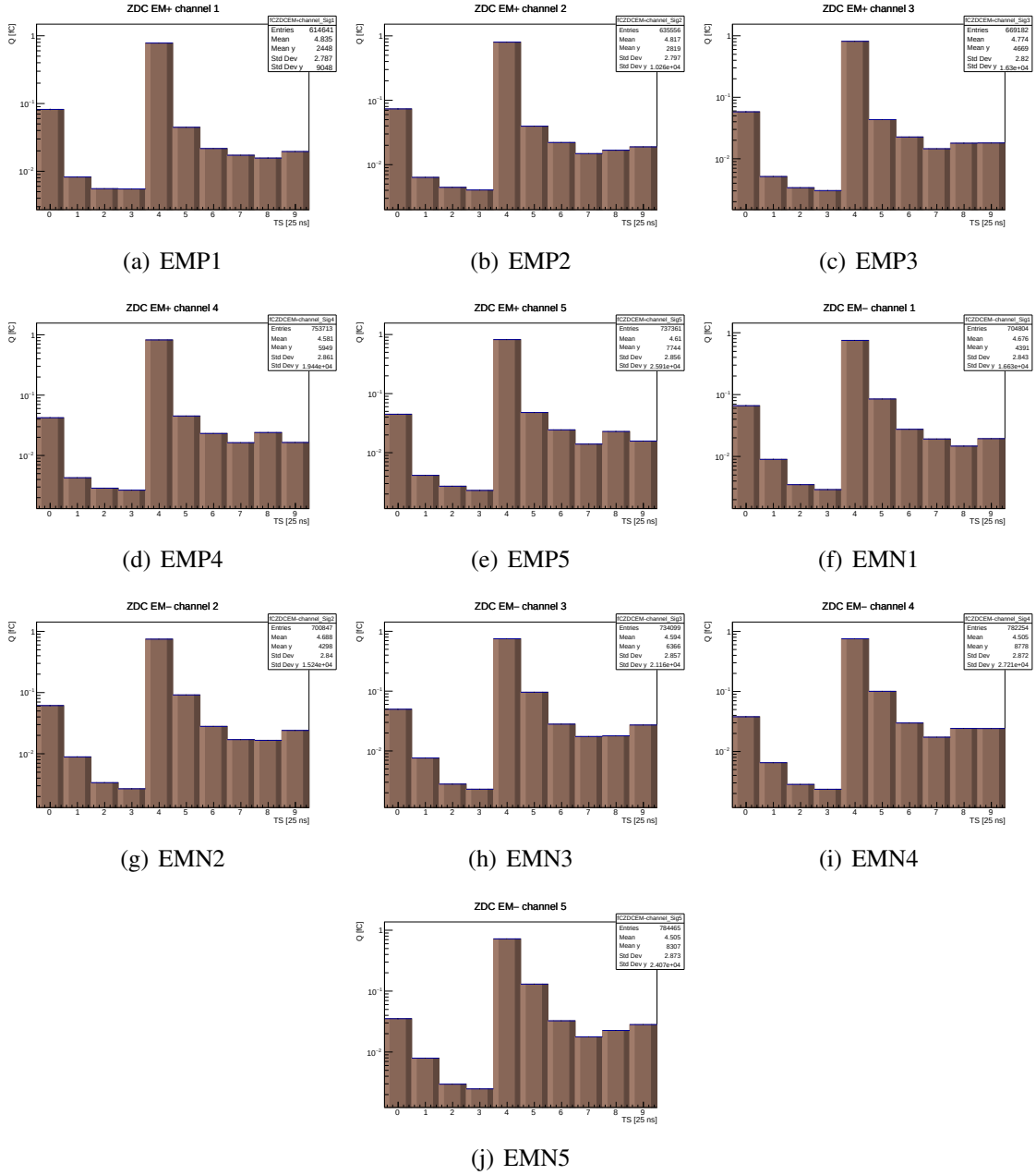


Figure 3.14: Final time-profile corresponding to 100 ns bunch crossing for all channels of EM section.

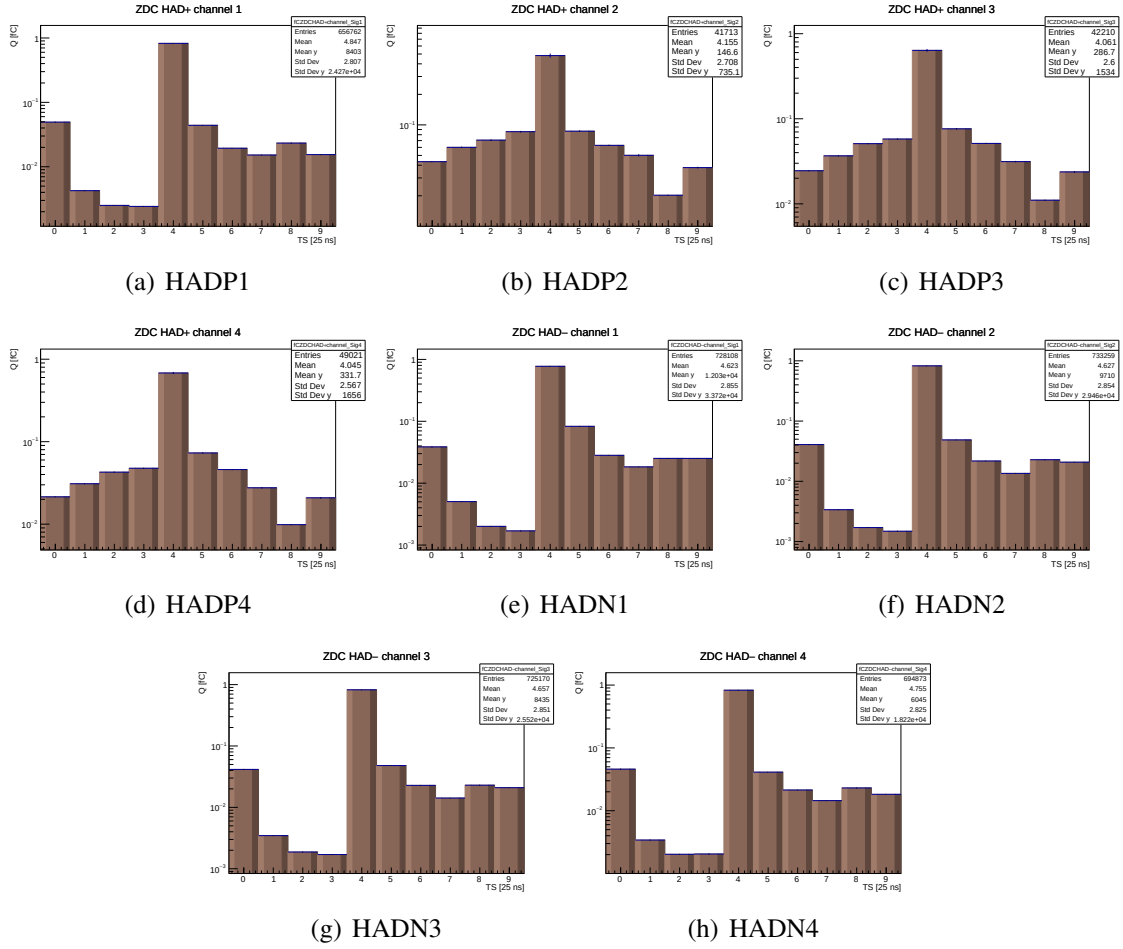


Figure 3.15: Final time-profile corresponding to 100 ns bunch crossing for all channels of HAD section.

3.2.5 Calibration

The weight factor for single neutron events of the HAD section in both positive and negative of z direction are given by,

$$\begin{aligned} ZDC : HAD+ &\in \{1.00, 0.64, 0.30, 0.28\} \\ ZDC : HAD- &\in \{1.00, 0.57, 0.37, 0.42\} \end{aligned} \quad (3.24)$$

The calculation of weight factor requires the reference data of the previous run. The inter calibration of the EM section is not performed because of the different detector parameters used in previous run such as detector alignment, crossing angle and beam divergence. The gain for EM section was extracted from the available HAD gain factors. The neutron signals is plotted in 2D scattering plot EM-HAD+ w_{EM} ·EM in Figure 3.16, the constant w_{EM} need to be adjusted until the bands corresponding to neutrons become perpendicular to x -axis. The w_{EM} is consistently varied from 0.1 to 1.0 and it is found that the difference is not significant in 2D plots that it could provide which value of the w_{EM} should get preference. The total energy distribution shows a difference in resolution and in χ^2/NDF , leads to a conclusive value of w_{EM} to be 0.2. The resolution of the of the ZDC energy is $\sim 22 - 23\%$. The plots of the ZDC total energy distribution is shown in Figure 3.17. The total energy is assumed as the addition of Gaussian distribution. The resultant mean can be written as $\mu = \sum_i \mu_i$ and the variance $\sigma = \sqrt{\sum_i \sigma_i^2}$. The spectrum is fitted with the probability distribution function described in Equation 3.25. The c_i is the amplitude of the i^{th} -neutron peak, $\sigma_1(\sigma)$ and μ_1 are width (resolution) and mean of the single neutron peak and η is the electronic noise, also $\mu_i = i\mu_1$ and $\sigma_i^2 = i\sigma_1^2 + \eta$.

$$\mathcal{P} = \sum_i C_i \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(-\frac{(E - \mu_i)^2}{\sigma_i^2}\right) \quad (3.25)$$

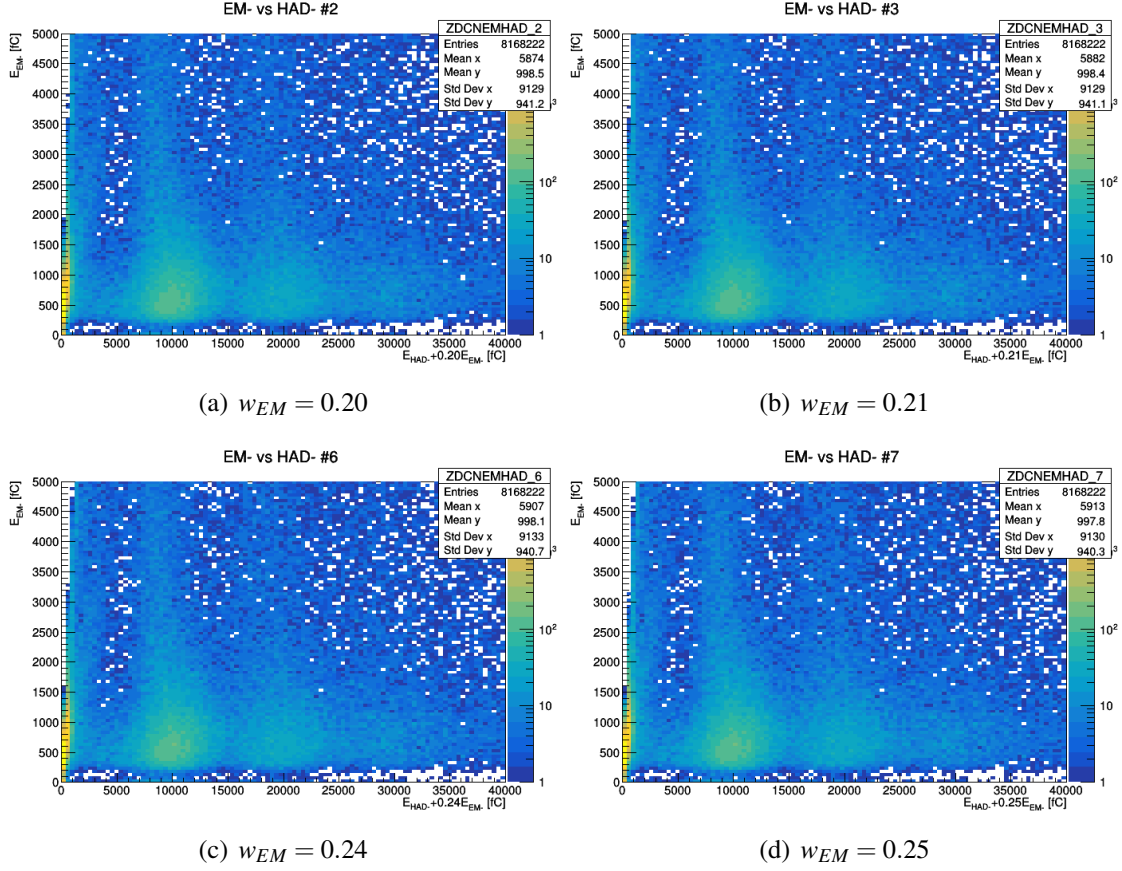


Figure 3.16: EM as function $HAD + w_{EM} \cdot EM$ of for four different values of w_{EM} , every value of w_{EM} shows almost similar properties that bands corresponding to neutron is perpendicular to x -axis in each case.

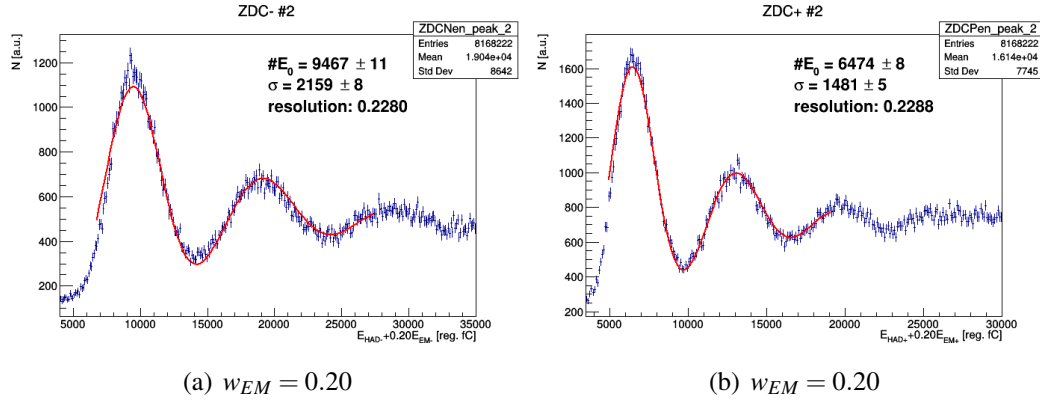


Figure 3.17: The fitted total ZDC energy distribution in both positive and negative direction of ZDC for $w_{EM} = 0.20$, the ZDC energy resolution is $\sim 22 - 23\%$.

The calibration is discussed in detail in the detector note DN-20-026⁴. The shift of total energy peak is observed with respect to luminosity, instantaneous luminosity and bunch

⁴This note is under review, since the calibration results are already presented in the HCAL-DPG and corrected according to their suggestions, we do not expect any change in numbers

trains. The shift one neutron peak and mean are described in Figure 3.18. The compar-

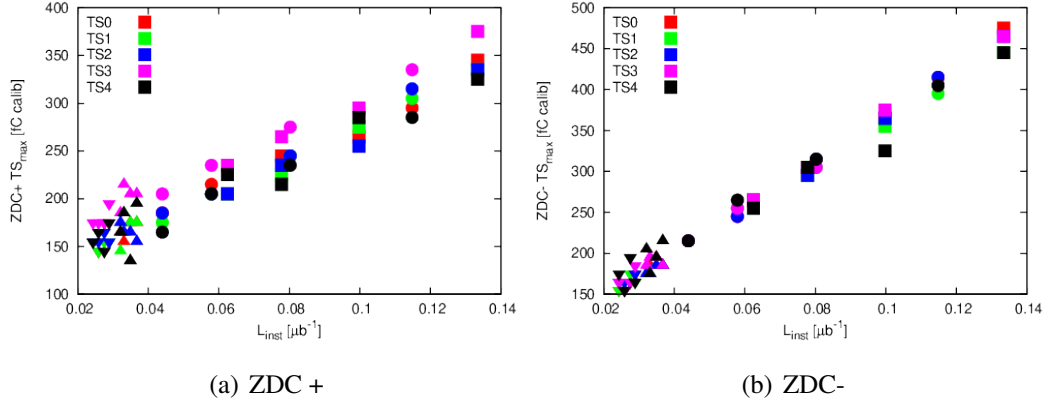


Figure 3.18: Linear departure of one neutron peaks for time slice TS0 to TS4 in case of 150 ns bunch spacing.

ative shift in TS1 is now numerically coincides with TS0, TS2, TS3 and the significantly the multi-neutron peaks are reduced. To measure the shift of TS4 with respect to TS1 the un-triggered one neutron events in TS1 are compared with real one neutron events in TS4. Figure 3.19 describes the fit of the one neutron events with a linear function given in

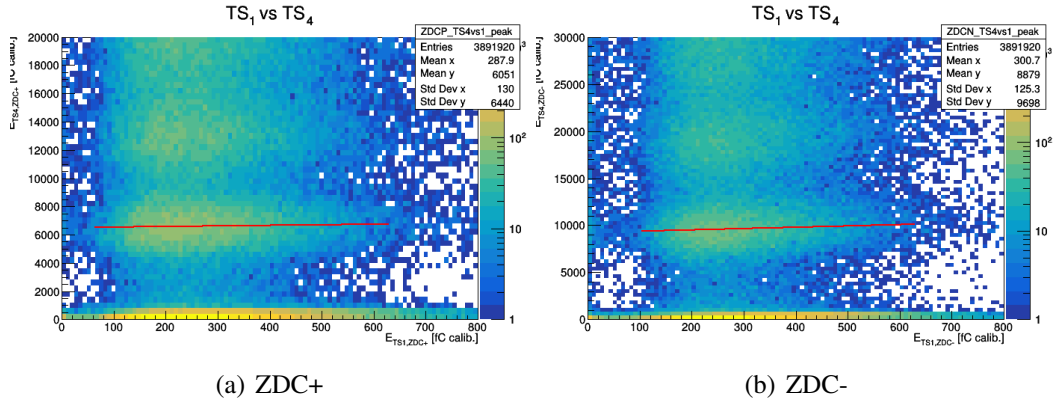


Figure 3.19: The real TS4 one neutron events are plotted as scattered function of un-triggered one neutron events in TS1 and a linear fit is propagated.

Equation 3.27.

$$f(E_{TS4}^{real}) = p_0 + p_1 E_{TS1}^{un-triggered}. \quad (3.26)$$

The extracted Value for both positive and negative side of the ZDC is found to be,

$$\begin{aligned} ZDC+ : E_{TS4}^{real} &= 6500 + 0.4 \cdot E_{TS1}^{un-triggered} . \\ ZDC- : E_{TS4}^{real} &= 9230 + 1.4 \cdot E_{TS1}^{un-triggered} . \end{aligned} \quad (3.27)$$

The parametrization in each side is very much dissimilar to each other and the coefficient is also different which absolutely concludes the different activation timing for ZCC+ and ZDC-.

3.3 Summary and outlook

The extraction of the in-time signal profile and the calibration is performed using Pb-Pb data collected in 2018 LHC run at $\sqrt{s} = 5.02 \text{ GeV}$. The in-time signal profile for both 75 ns and 100 ns are obtained using the detector-detector correlation. An analytical study is performed in parallel using matrix calculus toward the understanding of the selection need to be used for detector-detector correlation. While calibrating the ZDC via the single- and double-neutron peaks, it is observed that the calibration has luminosity dependence. Upon hypothesizing several other possibilities for the shift, such as, activation, in-time/out-of-time pileup; all these have negligible effect on the shift of neutron peaks. Finally it has been shown that the reason for this shift may actually be the broadening of the beam with decreasing luminosity. It is better to end this chapter with two open problems, yet to investigate : the first one is the possible origin of the shifted baseline in the TS3 of the Figure 3.12 and the effect of the neutron multiplicity on the calibration. These open problems can be utilized as the motivation for the future studies.

Chapter 4

Measurement of ϕ_s

The very smallness of the 2π rate, CP-invariance as a near miss, made the news even harder to digest.

CP violation: the first 25 years

—Abraham Pais

4.1 Datasets and triggers

4.1.1 Data and Simulated samples

It is already discussed in the detector part that how the opposite side proton beam are colliding at the interaction point and how the detectors are involved to record the data. This analysis is performed by making the use of data collected in oppositely incoming proton beam colliding at $\sqrt{s} = 13$ TeV, and providing total integrated luminosity $\mathcal{L}_{\text{int}} = 96.4 \text{ fb}^{-1}$, corresponding to the 2017 and 2018 Charmonium Datasets. The luminosity is being calculated using the `Bril` calculator. The detailed list of datasets are reported in Tables 4.1 and 4.3. The luminosity given by Equation (2.5) is what delivered by the LHC. Each detector records the luminosity individually during the collision. Due to the detector effects the recorded luminosity due is always less than the delivered luminosity. Sub-detectors of the CMS experiment are employed to monitor and measure the luminosity. Five detectors

are involved in the process, namely *a.* monitoring system for beam conditions (BCM1f), *b.* the luminosity telescope set in pixel (PLT), *c.* the silicon pixel detector, *d.* the forward hadron calorimeter (HF), and *e.* the drift tubes in the barrel (DT) [58]. The comparison plot between the delivered LHC luminosity and CMS record for 2017-2018 data taking period is shown in the Figure 4.1. During the 2017-2018 data taking period CMS recorded 108.65 fb^{-1} of data, though some amount is rejected by applying the luminosity mask. The reason behind this is that all parts of the CMS detector were not operating in the normal mode. Accordingly the final reduced luminosity equals to 96.4 fb^{-1} on which the present analysis is based on¹. Simulated (Monte Carlo - MC) samples are extensively used to

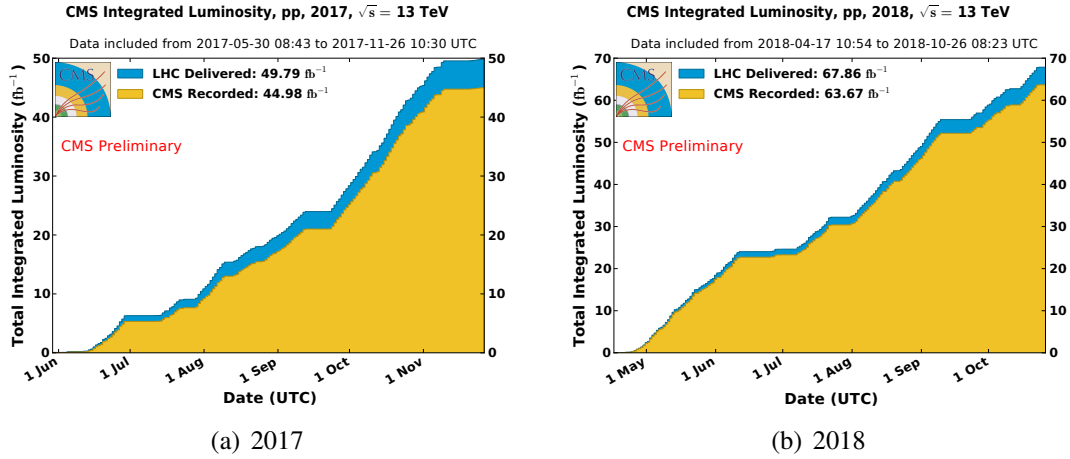


Figure 4.1: As it is discussed that the LHC luminosity will always have the higher values than the value of which is recorded by the CMS detectors assembly - the plots corresponding to the years 2017 and 2018 respectively are advocating the similar scenario for 13 TeV data collection.

estimate the reconstruction efficiency as well as the opposite side muon tagging performance. Toward the production of the MC samples the PYTHIA 8.230 [59] is used as the events generator. The underlying events are tuned using the CP5 [60] while the parton distribution functions are implemented using the NNPDF3.1 [61]. The specific choice of the modelization of the *b* hadron decay is implemented using the 1.6.0 version of EVTGEN package [62]. The final state radiation (FSR) is accounted by interfacing the 215.5 version of PHOTOS [63, 64] with EVTGEN. The GEANT4 [65] includes the detector response to the

¹After applying luminosity mask the good runs are described by officially prescribed JSON files.

generated events. There is the possibility of multiple collisions in the same bunch crossing or in the neighboring BX - this effect is called the pile-up. There are several procedure to account the pile-up effect, for the B_s^0 MC production the effect is included by fusing the min-bias with hard-scattering events. The general CMSSW architecture reconstructs B_s^0 hadron and the corresponding decay kinematics - both for the collision data and simulated events respectively. Events are collected with the trigger described in Section 4.1.2. To develop the analysis and validate the model the simulated MC samples are used as listed in Tables 4.2 and 4.4. A privately produced large ($\sim 10^7$ events) GEN sample is used to evaluate efficiencies and validate the fit method. This dataset will be simply referred to as GEN sample.

Dataset name
Charmonium-MINIAOD-Run2017C-31Mar2018-v1
Charmonium-MINIAOD-Run2017D-31Mar2018-v1
Charmonium-MINIAOD-Run2017E-31Mar2018-v1
Charmonium-MINIAOD-Run2017F-31Mar2018-v1

Table 4.1: Datasets corresponding to the year of 2017.

Dataset name	Description	# evt
BsToJpsiPhi_BMuonFilter_SoftQCDnonD_TuneCP5_13TeV-pythia8-evtgen/ ¹	Signal	$76 \cdot 10^6$
BsToJpsiPhi_MuonFilter_SoftQCDnonD_TuneCP5_13TeV-pythia8-evtgen/ ¹	Signal ($\Delta\Gamma_s = 0$)	$65 \cdot 10^6$
BdToJpsiKstar_BMuonFilter_SoftQCDnonD_TuneCP5_13TeV-pythia8-evtgen/ ²	Control channel	$67 \cdot 10^6$
¹ RunIIFall17MiniAODv2_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM		
² RunIIFall17MiniAODv2_12Apr2018_N1_94X_mc2017_realistic_v14-v1/MINIAODSIM		

Table 4.2: Simulated samples of 2017, number of events implies generated number of events before implementing any physics selection.

Dataset name
Charmonium-MINIAOD-Run2018A-17Sep2018-v1
Charmonium-MINIAOD-Run2018B-17Sep2018-v1
Charmonium-MINIAOD-Run2018C-17Sep2018-v1
Charmonium-MINIAOD-Run2018D-PromptReco-v2

Table 4.3: Datasets corresponding to the year of 2018.

Dataset name	Description	# evt
BsToJpsiPhi_BMuonFilter_SoftQCDnonD_TuneCP5_13TeV-pythia8-evtgen/ ¹	Signal	$73 \cdot 10^6$
BsToJpsiPhi_JpsiPhiFilterDG0_SoftQCDnonD_TuneCP5_13TeV-pythia8-evtgen/ ²	Signal ($\Delta\Gamma_s = 0$)	$107 \cdot 10^6$
BdToJpsiKstar_BMuonFilter_SoftQCDnonD_TuneCP5_13TeV-pythia8-evtgen/ ³	Control channel	$55 \cdot 10^6$

¹ RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v1/MINIAODSIM
² RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM
³ RunIIAutumn18MiniAOD-N1_102X_upgrade2018_realistic_v15-v1/MINIAODSIM

Table 4.4: Simulated samples of 2018, number of events implies generated number of events before implementing any physics selection.

4.1.2 L1 and HLT trigger

The produced b quarks are hadronises to the desire B_s^0 (or $\bar{B}_s^0$) hadron. A high level trigger physics is required to be optimised to detect the corresponding hadronisation process in which one of the intermediate constituent particle would be $J/\psi(c\bar{c})$ vector mesons. This high level trigger has three muons, two of them is used for $J/\psi(c\bar{c})$ vertex reconstruction and the other one is used for the flavour tagging. The minimum transverse momentum p_T requirement at the L1 trigger is following, leading : $\mu_1 - p_T > 5 \text{ GeV}$, and the subleading : $\mu_2 - p_T > 3 \text{ GeV}$ respectively. The third muon present in the event does not require any transverse momentum selection at the L1. An upper bound is set on the invariant mass which is formed by the leading and sub-leading muon is of the value $m_{\mu_1\mu_2} < 9 \text{ GeV}$. The nomenclature of the HLT is assigned by the CMS HLT group - HLT_Dimuon0_Jpsi3p5_Muon2_v, the requirement of the absolute pseudorapidity or the geometrical acceptance for these three muons is $|\eta| < 2.5$. Among three of these muon at least two of opposite charge, $p_T > 3.5 \text{ GeV}$ are expected to form an invariant J/ψ resonance peaking within the range 2.95-3.25 GeV. Both of these muons are required to originate (where the J/ψ is produced) from a common vertex of vertex probability as being originated from a common vertex $> 0.5\%$. The charge of the third muon is used as the tagging variable to determine the B_s^0 production flavour using semileptonic $b \rightarrow \mu^- + X$ decays. This muon is selected with $p_T > 2 \text{ GeV}$. This triple muon trigger both enhance the fraction of events that can be tagged and allows to use events at lower lifetime (0.007 cm).

4.2 Reconstruction & Selection Optimization

The final states of the B_s^0 decay are two muons and two kaons. The J/ψ is constructed with two muon tracks, and ϕ is formed by two kaon tracks. A generic reconstruction code (*PDGeneralNtuple*) serves this purpose. After fitting the four tracks to the same vertex a rectangular selection cuts (offline selections) is applied to get the kinematic observables. A set of variables are chosen to reduce to a minimum the linear correlation. To optimise the physics selection values for a set of variable specific to $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ process, the well know Genetic Algorithm (GA) is used which belongs to the larger class of evolutionary algorithm. The approach is inspired by biological data driven high correlation studies and a step wise construction is based on several correlation operators such as *mutation, crossover and selection*. The very generic optimisation problem can be defined in the following way, the search of an $x_0 \in X$ is getting completed when an arbitrary function f_{merit} converges toward the maximum value at x_0 .

$$\{f_{\text{merit}} \mid \frac{d}{dx_0} f_{\text{merit}} = 0\}, \text{ where } f_{\text{merit}} : X \mapsto \mathbb{R} \mid f_{\text{merit}}(x_0) = \max_{x \in X} f_{\text{merit}}(x) \forall x.$$

To be very precise the above theorem is ill defined, it is not always possible to find a global solution (the maximal of f_{merit} in x_0) for any set of X in real physics constrained environment. Given that the $B_s^0 \rightarrow J/\psi \phi$ physics process it is sufficient to have a local (global) maximum or at least close to such maximum . So the optimum for x is chosen such that the objective function f_{merit} should be maximum. The overall search space X is parametrised with a set of competing individuals

$$x_0 \in \{\text{HLT}, p_T(B_s^0), ct(B_s^0), Vtx_{\text{prob}}, \sigma_c t, p_T(\mu), |\eta(\mu)|, p_T(K), |\eta(K)|\}$$

specific to $B_s^0 \rightarrow J/\psi \phi$ decay. Optimised values of the same competing individuals (defined by set x) is obtained by implementing classical figure of merit (f_{merit}) given in Equation 4.1.

$$f_{\text{merit}} = \frac{S}{\sqrt{S+B}} \quad (4.1)$$

A GA framework, already available as part of the ROOT TMVA [66, 67] package is used for the optimisation of the physics selection. This framework works fairly well defined step wise process such as,

$$\text{Initialisation} \rightarrow \text{Evaluation} \rightarrow \text{Selection} \rightarrow \text{Reproduction} \rightarrow \text{Termination}.$$

The GA uses data side bands of B_s^0 mass peak ($[5.20 - 5.28]$, $[5.45 - 5.65]$ GeV) as background sample (B), and centrally simulated sample as signal sample (S). The yield in MC is reweighed to signal events in the full data, while the background yield has been reweighed by taking into account the expected component under the B_s^0 mass peak. The algorithm starts by assigning initial selection values set by the user, then the selections are changed randomly within a predefined n -dimensional matrix of allowed ranges, also set by the user. In this way the *population* evolves with the goal of maximising the f_{merit} , which in our case is the classical definition of signal significance, though more exotic choices can be adopted. The stability of the selections is checked by changing randomly the starting point within the allowed ranges; no difference in the outcome has been observed. The GA method gives more importance to the selection in p_T compared to the cuts used in 2012. The best configuration of selection cuts is reported in Table 4.5. In the very beginning of

Variable	Cut
Trigger	HLT_Dimuon0_Jpsi3p5_Muon2_v
$p_T(\mu)$	≥ 3.5 GeV
$ \eta(\mu) $	≤ 2.4
$p_T(K)$	≥ 1.2 GeV
$ \eta(K) $	≤ 2.5
$ m(\mu^+\mu^-) - m_{J/\psi}^{\text{PDG}} $	< 150 MeV
$ m(K^+K^-) - m_{\phi(1020)}^{\text{PDG}} $	< 10 MeV
$p_T(B_s^0)$	≥ 11 GeV
$ct(B_s^0)$	$\geq 70 \mu\text{m}$
$B_s^0 \text{ Vtx}_{\text{prob}}$	$\geq 0.1\%$
σ_{ct}	$< 50 \mu\text{m}$
$m(\mu^+\mu^-K^+K^-)$	$[5.24, 5.49]$ GeV

Table 4.5: Optimized physics selections obtained by maximizing the f_{merit} using genetic algorithm optimization corresponding to $B_s^0 \rightarrow J/\psi\phi$ decay.

the reconstruction, J/ψ vector meson candidates are reconstructed using two muon which

are oppositely charged with $p_T > 3.5 \text{ GeV}$ and $|\eta| < 2.4$, and these pairs are required to originate from a common vertex. In this regard for a given set of charge tracks, the job is to determine the best estimate the parametric space related to the vertex parameters such as the *basis coordinates*, *corresponding covariance matrix*, *constrained track parameters and their covariances* by performing a best fit using *total χ^2/NDF* , *track weights* etc. The very reconstructed tracks have only the perigee information, on the other hand the transient tracks are having the trajectory states on surface at any point along its trajectory, it does have information of the magnetic field, also makes the use of the various tracker level geometric propagators. To build the transient tracks of charged muons, tracks are collected in the transverse (xy) plane of the tracker within the vicinity of the magnetic field. Finally the Kalman Vertex Filter [68] algorithm fits the tracks to a common vertex by determining the best χ^2 . If the reconstructed invariant mass of the two muons is in between $\pm 150 \text{ MeV}$ of the world mean of J/ψ resonance [69] then the candidate is accepted as the J/ψ candidate. In the next step the ϕ reconstruction is using pairs of opposite-sign charged tracks by imposing the mass hypothesis that all the tracks are kaon $K^\pm$ track apart from the tracks which are associated with the muons originating from J/ψ . Having $p_T > 1.2 \text{ GeV}$ within the acceptance region $|\eta| < 2.5$ the high-purity [9] kaon tracks are required along with $N_{\text{hit}}^{\text{tracker}} > 5$. The invariant mass formed by the oppositely charged kaon track pair is within the window of $\pm 10 \text{ MeV}$ of the global-average ϕ meson mass [69] is chosen as the ϕ vector meson. Toward the reconstruction of the B_s^0 meson, the J/ψ , and ϕ resonances are combined to form a composite B_s^0 candidate. A B_s^0 vertex is obtained by fitting four track of vertex probability $\geq 0.1\%$. The J/ψ resonance is kinematically constrained to be within the global average of the J/ψ resonance [69] before it is combined with ϕ to obtain the B_s^0 candidates. Since the mass resolution of the ϕ candidate is less than the natural width ϕ mass - thus not constrained. To compute the decay time, it is required to measure the displacement vector between the point of production (PV) and the point of decay (Secondary Vertex - SV) in each selected event. One way to obtain the best PV is by minimising the quantity : $\cos \theta = \frac{(X_{SV} - X_{PV}) \cdot \vec{P}_{B_s}}{L^{P_{B_s}} \cdot L^{PV-SV}}$. The $L^{P_{B_s}}$ is the length of the B_s^0 momentum vector and

Method of ct calculation	Mathematical expression
PV (3D)	$m_{B_s} \frac{(X_i^{vt,xklm} - X_i^{PV}) \cdot \vec{P}_{B_s}}{(\vec{P}_{B_s})^2}$
PV(2D)	$m_{B_s} \frac{(X^{vt,xklm} - X^{PV}) \cdot P_{B_s}^x + (Y^{vt,xklm} - Y^{PV}) \cdot P_{B_s}^y}{(P_{B_s}^x)^2 + (P_{B_s}^y)^2}$
Beam Spot (2D)	$m_{B_s} \frac{(X^{vt,xklm} - X^{bms}) \cdot P_{B_s}^x + (Y^{vt,xklm} - Y^{bms}) \cdot P_{B_s}^y}{(P_{B_s}^x)^2 + (P_{B_s}^y)^2}$
$\cos \theta$ (2D)	$m_{B_s} \frac{(X^{vt,xklm} - X_{costa}^{PV}) \cdot P_{B_s}^x + (Y^{vt,xklm} - Y_{costh}^{PV}) \cdot P_{B_s}^y}{(P_{B_s}^x)^2 + (P_{B_s}^y)^2}$

Table 4.6: Mathematical formulas for the selection of primary vertex of the B_s^0 candidates to get minimum uncertainty of the decay for the reconstructed B_s^0 signal events.

L^{PV-SV} is the distance between the fitted primary vertex and secondary vertex. This is the angle between B_s^0 three momentum and flight direction of B_s^0 . Several other procedures (mathematical expressions of which are listed in Table 4.6 to identify the finest PV have been studied, but found is leading toward higher decay time uncertainty. As Figure 4.2 shows that the optimised physics selections described in the Table 4.5 are effectively reducing the background contributions and enhancing the gain in signal. .

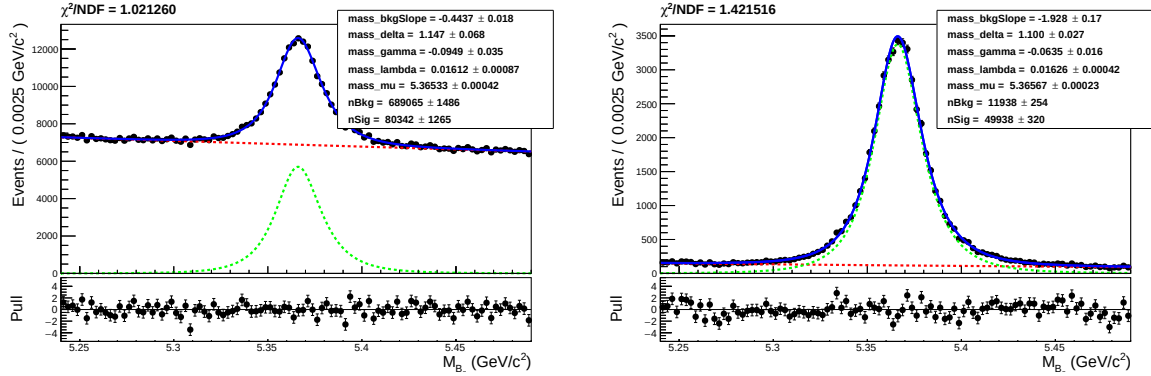


Figure 4.2: Mass of the B_s^0 candidate, here the fit shows the before (left), and after (right) effect of the implementation of the optimised physics selections.

4.2.1 Resolutions

The residuals of the difference between the simulated variables and the reconstructed variables² i.e.,

$$\delta(x) = x_{GEN} - x_{RECO}; x \in \{ct, \cos \theta_T, \cos \psi_T, \phi_T\} \quad (4.2)$$

²GEN: Generator level simulated sample with no detector effect; RECO: Reconstructed events for any variable related to the kinematics of B_s^0 decay with detector effect and optimised selection.

Figure 4.3(a) describes the resolutions of the angular and decay time distributions corresponding to 2017 simulated sample before applying the optimised selections. Figure 4.3(b) depicts the ct resolution as $f(ct, p_T, \eta)$, and reconstructed PV multiplicity of the B_s^0 candidate respectively. The average value of resolution shows bit of fluctuation in the higher region of the ct which is significantly reduced after applying the optimised selections. The transverse momentum dependence shows that the resolution is falling significantly after 15 GeV which also suffice that the optimised selection for p_T of B_s^0 candidate should not be in the higher domain. The dependence of ct on PV is linear and higher in the outer tracker regions. Figure 4.3(c) shows the alignment of the all resolutions corresponding to each observable with respect to B_s^0 transverse momentum p_T near the zero region which is still effective after applying optimised selections on each observable and those resolution for angular observables are shown in Figure 4.4, and for ct resolution in Figure 4.5. To investigate the bias of the ct resolution with respect to the PV multiplicity a rough estimation of the centroid of the ct resolution peak is performed through a Gaussian fit in case without PV selection, $PV > 30$, and $PV < 30$ respectively as shown in Figure 4.6. No such significant bias is observed and the variation of ct resolution as a function of PV multiplicity is almost linear up to $PV < 60$, since the reconstructed PV multiplicity per event is expected to be lying within the range of 25-40 in B-physics regime, so fluctuation in the very high multiplicity does not matter at all. Finally, a general comment, for all the four variables the distribution central value is compatible with zero, suggesting no major bias in the reconstruction of these quantities.

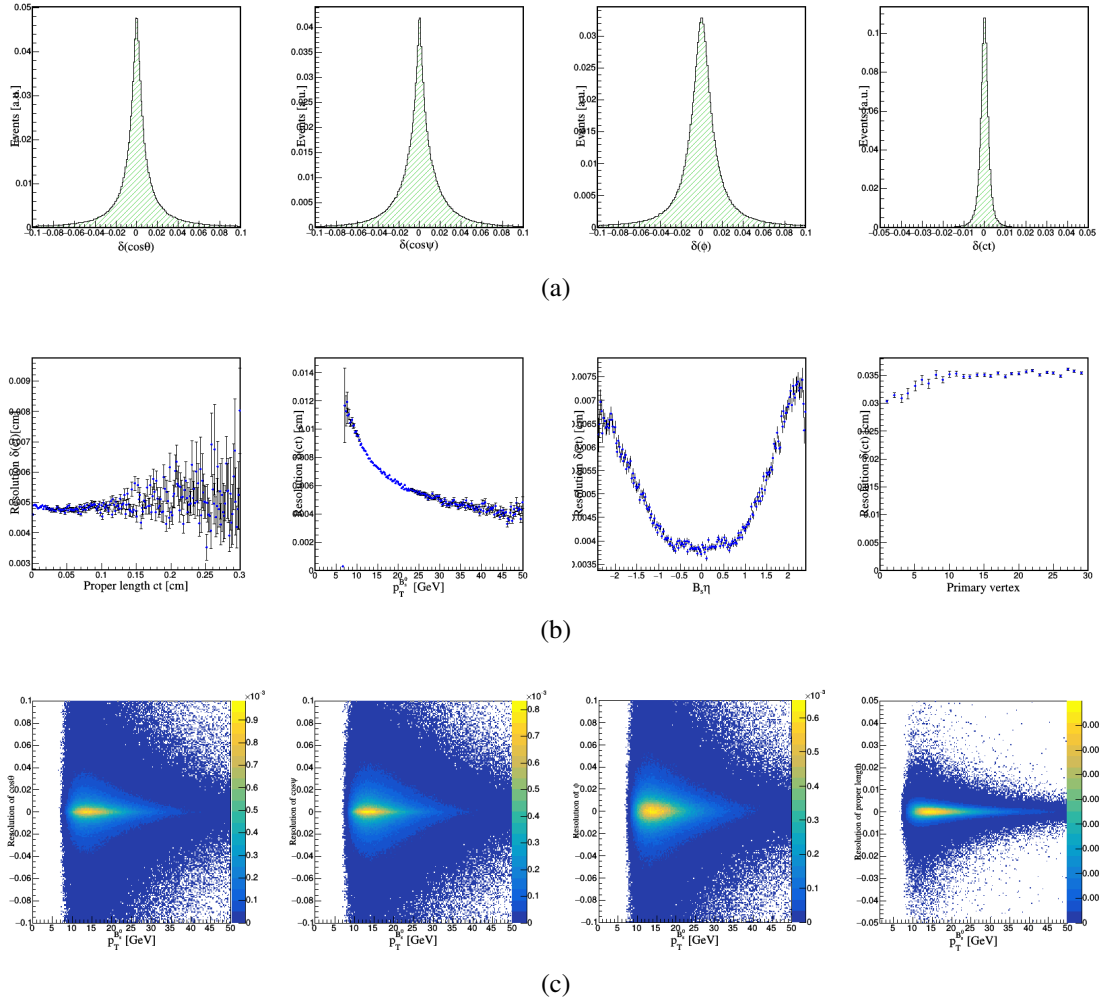


Figure 4.3: Preliminary kinematics of the reconstructed B_s^0 candidates from the 2017 simulated sample without any off-line optimised selection .

4.2.2 Data-Simulation comparisons

The comparison of the kinematic distributions related decay process between MC³, and Data⁴ is performed after applying the all offline optimised selection to all samples. The visualisation of such comparison can be achieved by using *sPlot* [70]. *sPlot* provides an extended $\mathcal{L}$ ikelihood analysis for a given set of data sample, which are in general merged signal events with background species. The source of the signal component is the solely B_s^0 decays and the source of the background components are combinatorial (reconstruction

³Monte Carlo : very generic nomenclature, in CMS it is being used as the centrally produced sample having detector effect embedded within it, often used as the short form of reconstructed sample.

⁴Real pp collision data.

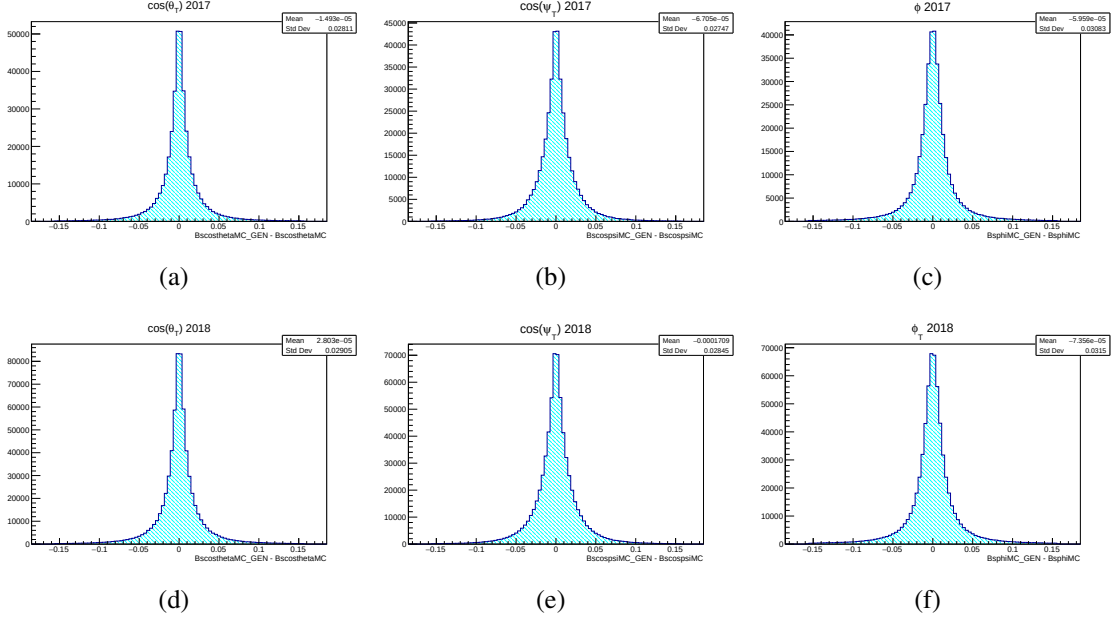


Figure 4.4: Resolution on the angular variables $\cos \theta_T$, $\cos \psi_T$ and ϕ_T used in in simulated 2017 sample (a,b,c) and 2018 sample (d,e,f) respectively.

of misidentified tracks) and peaking background ($B_d^0 \rightarrow J/\psi K^{*0}$). The definition of log likelihood is given in Equation 4.3.

$$\mathcal{L} = \sum_{j=1}^N \ln \left\{ \sum_{i=1}^{N_s} N_i f_i(y_j) \right\} - \sum_{i=1}^{N_s} N_i \quad (4.3)$$

The explanation corresponding to the definition of each parameter can be itemized as follows. N is the total number of merged events originating from two different species, signal events from B_s^0 decay and background events combinatorial and $B_d^0 \rightarrow J/\psi K^{*0}$ decay processes. N_s is the number species, here $N_s = 2$ for signal and background species. N_i is the events refers to i^{th} species, number of signal yields are extracted from area under signal probability distribution function (PDF) where as the background was from the background PDF while fitted to the side-band subtracted data. To compare the signal distributions coming from signal MC samples to the signal distributions coming from the pp collision data after subtracting the background using side-band subtraction, it is necessary to have a model which helps to discriminate the signal of true B_s^0 decays from the background events coming from other sources. In this regard, f_i is the mass PDF for the signal component

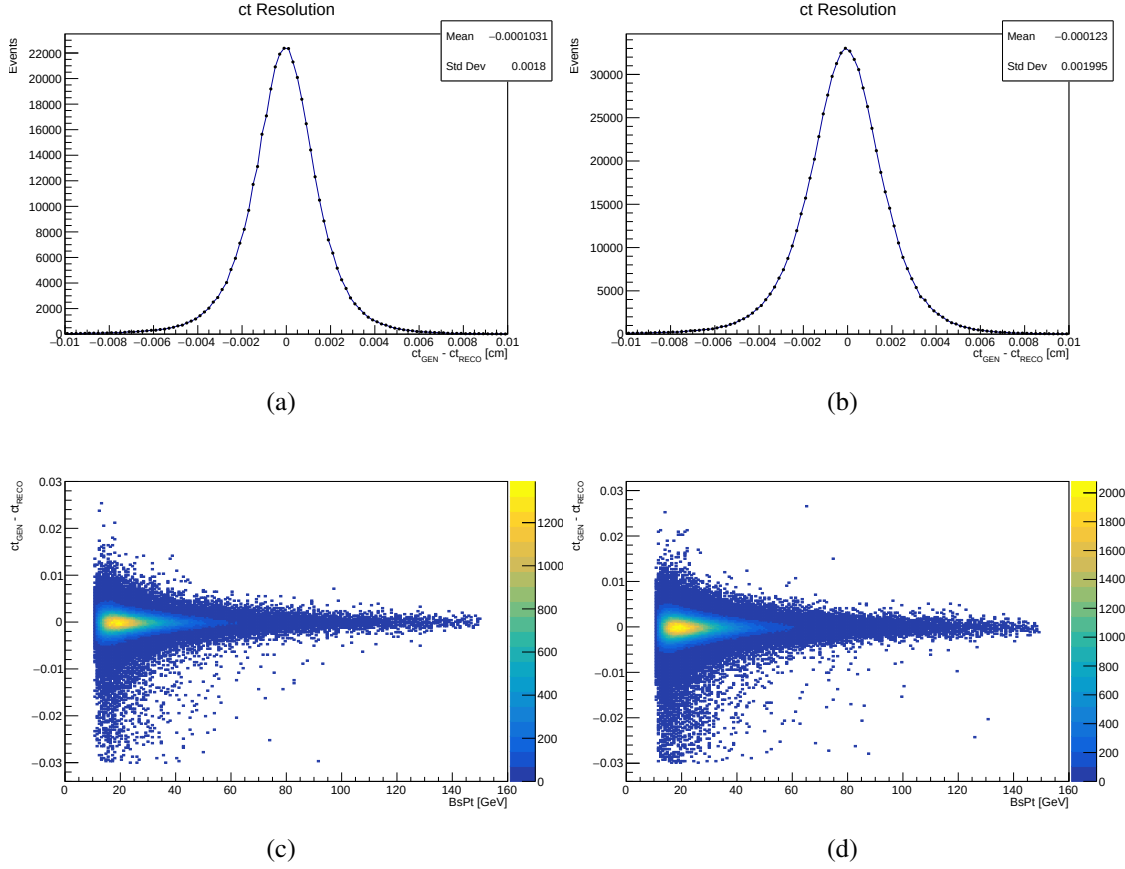


Figure 4.5: B_s^0 ct resolution distribution for 2017 (a) and 2018 (b) and the ct resolution vs p_T for MC samples of 2017 (c) and 2018 (d) respectively.

and the background component respectively, the signal distribution of mass is modeled using a single Johnson function⁵ and as for the background an exponential function is used as described in the Equations 4.5 and in 4.6 respectively. This distribution results from transforming a normally distributed variable x to

$$z = \gamma + \delta \sinh^{-1} \left(\frac{x - \mu}{\lambda} \right), \quad (4.4)$$

resulting in the following PDF,

$$P_{\text{sgn}}(m_{B_s^0}) = \frac{\delta}{\lambda \sqrt{2\pi}} \frac{1}{\sqrt{1 + \left(\frac{m_{B_s^0} - \mu}{\lambda} \right)^2}} \cdot \exp \left\{ \left[-\frac{1}{2} \left(\gamma + \delta \sinh^{-1} \left(\frac{m_{B_s^0} - \mu}{\lambda} \right) \right)^2 \right] \right\}. \quad (4.5)$$

⁵N. L. Johnson, DOI: 10.2307/2332539 <https://www.jstor.com/stable/2332539>

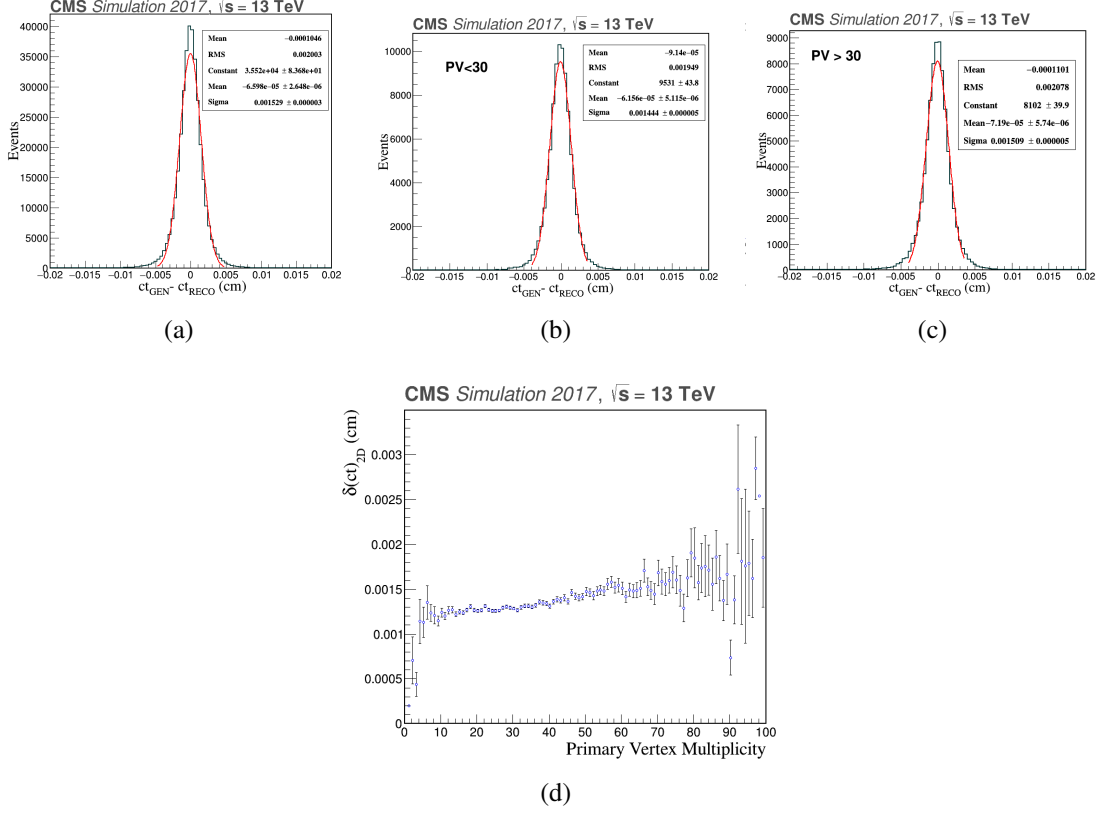


Figure 4.6: Dependency of the ct resolution of reconstructed B_s^0 candidate on the primary vertex multiplicity using 2017 simulated sample.

$$P_{\text{bkg}}(m_{B_s^0}) = A \exp\left(b \cdot m_{B_s^0}\right). \quad (4.6)$$

The parameters $(\delta, \lambda, \mu, \gamma, A, b)$ are left free to float. This technique makes it possible to reconstruct the distribution for a given variable, independently for signal and background, without having any *a priori* knowledge about the decay kinematics. This is achieved by exploiting the available information related to discriminating variable y , the B_s^0 invariant mass, and using it to assign a *weight* as described in Equation 4.7 to each event.

$$\mathcal{P}_i(y) = \frac{N_i f_i}{\sum_{i=1}^{N_s} N_i f_i} \quad (4.7)$$

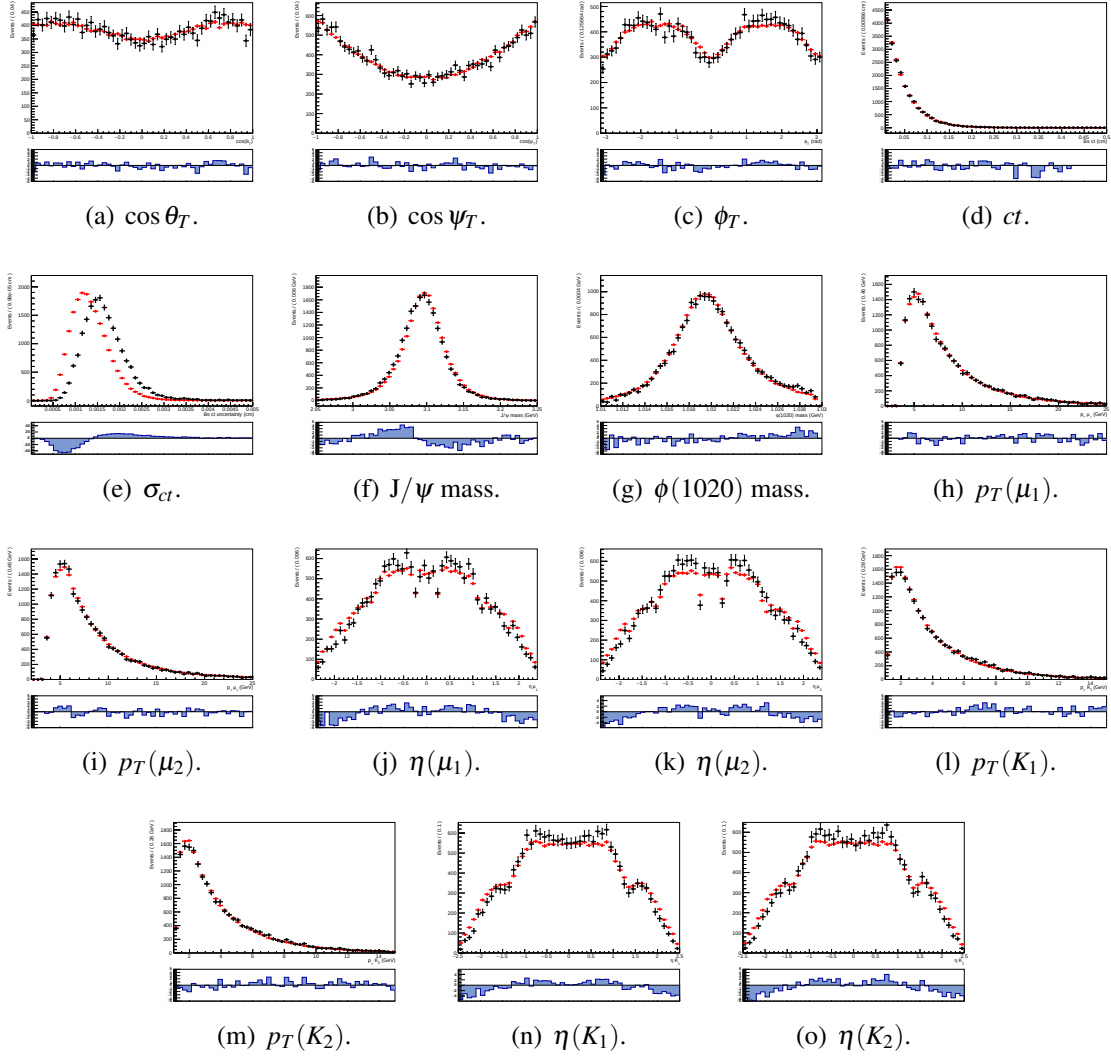


Figure 4.7: Data-MC comparison for 2017 samples. Red markers represent MC, while black markers represent Data.

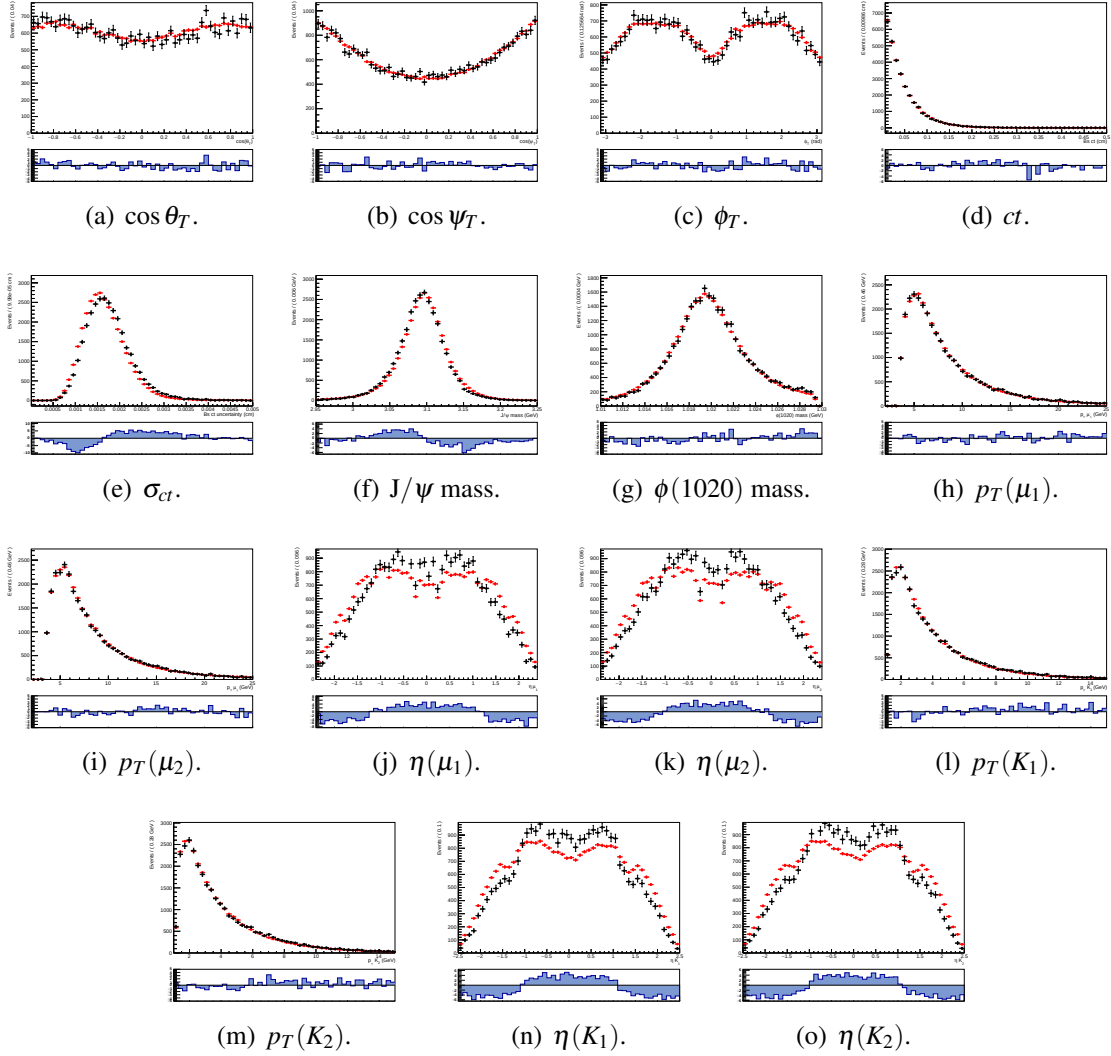


Figure 4.8: Data-MC comparison for 2018 samples. Red markers represent MC, while black markers represent Data.

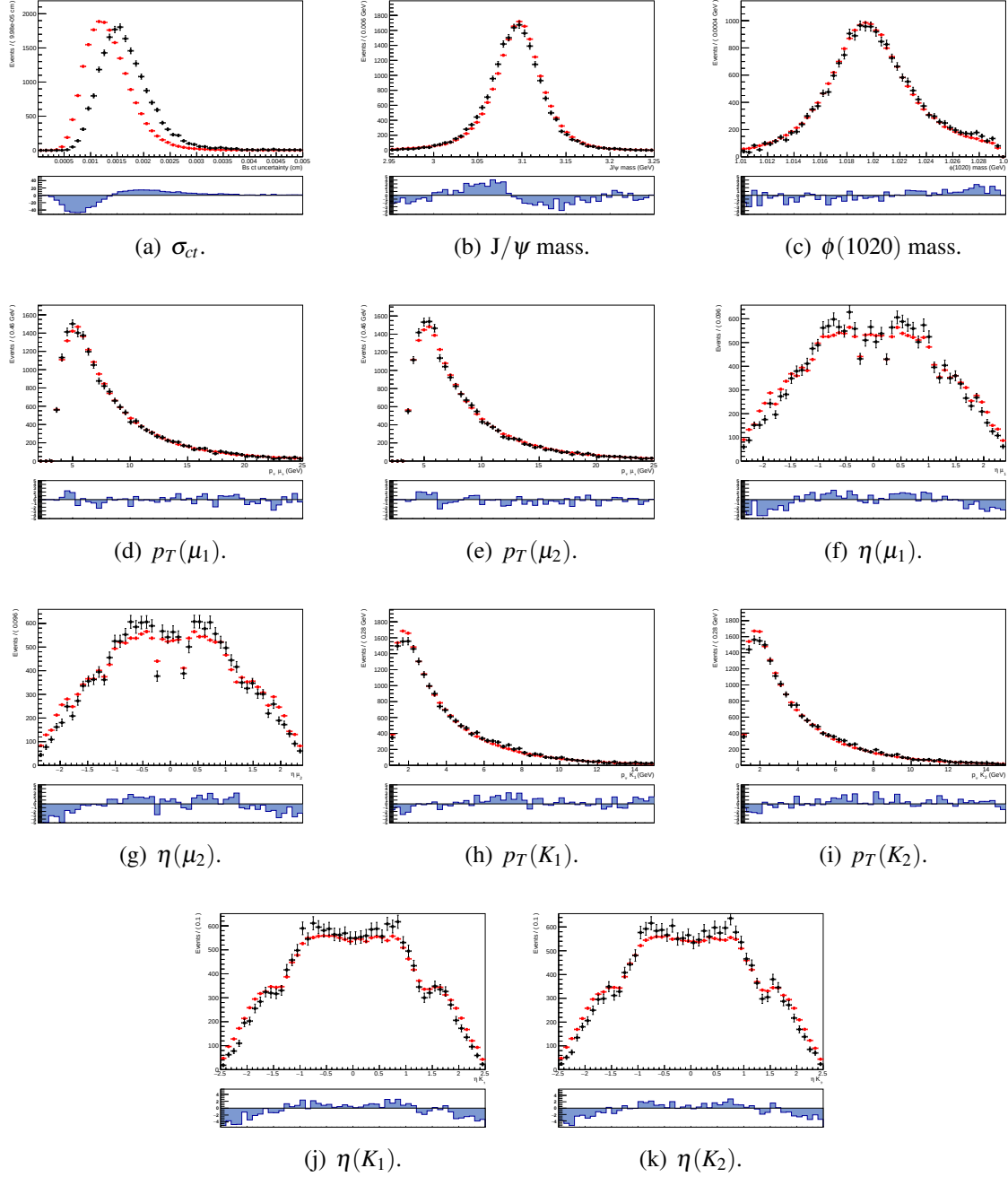


Figure 4.9: Data-MC comparison for 2017 samples, using the simulated sample with $\Delta\Gamma_s = 0$. Red markers represent MC, while black markers represent Data.

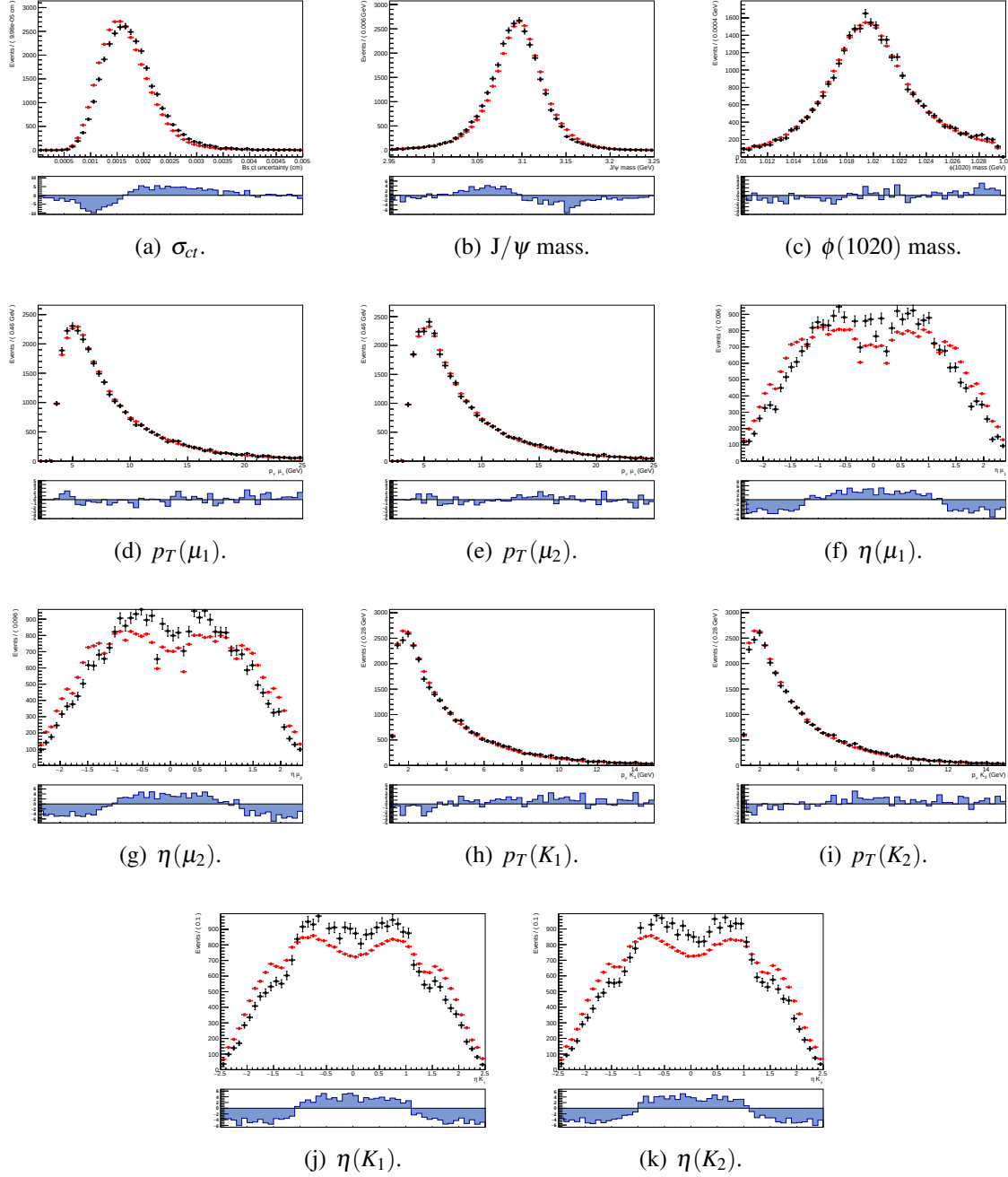


Figure 4.10: Data-MC comparison for 2018 samples, using the simulated sample with $\Delta\Gamma_s = 0$. Red markers represent MC, while black markers represent Data.

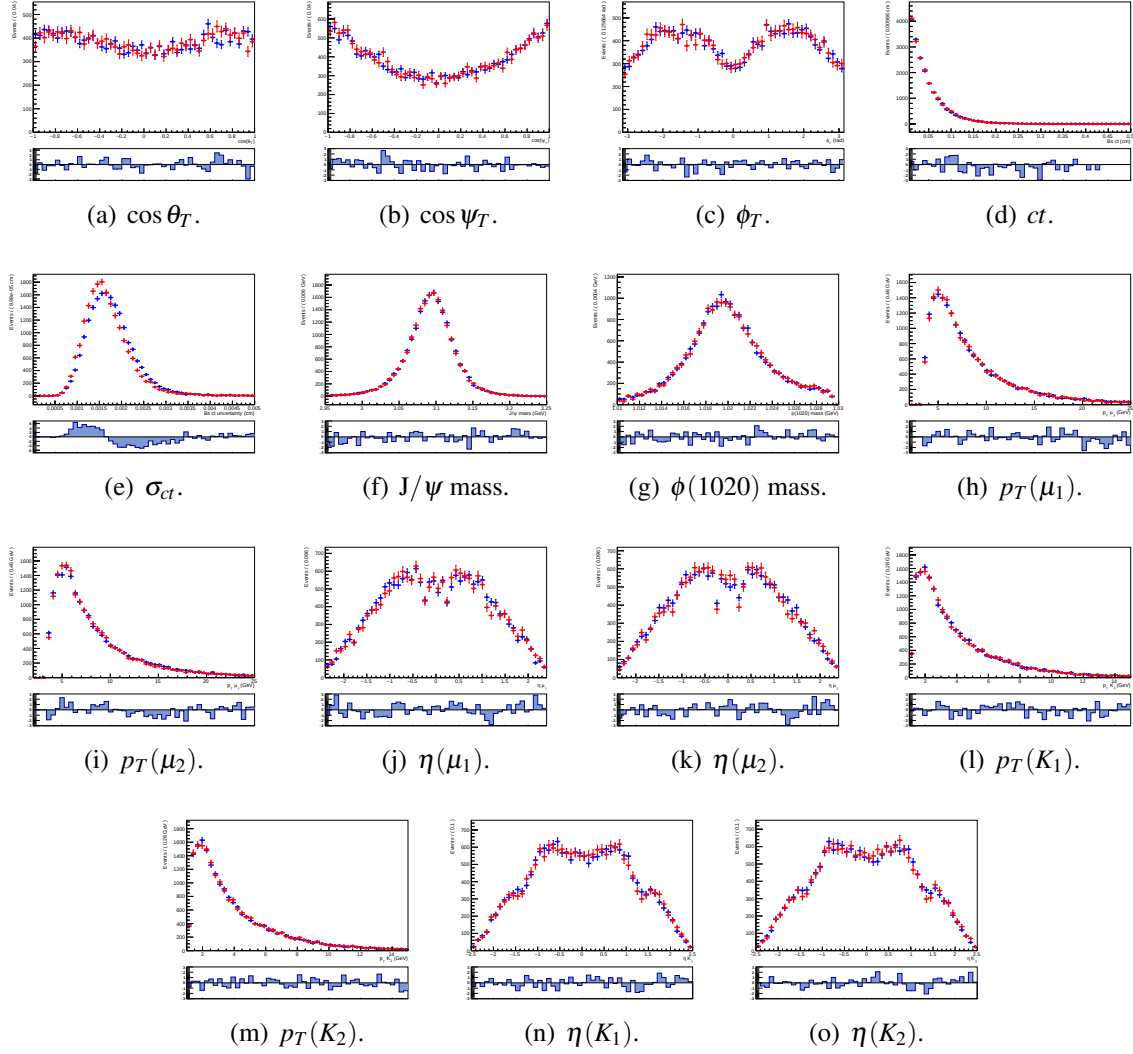


Figure 4.11: Variables distributions comparison between 2017 data (red) and 2018 data (blue).

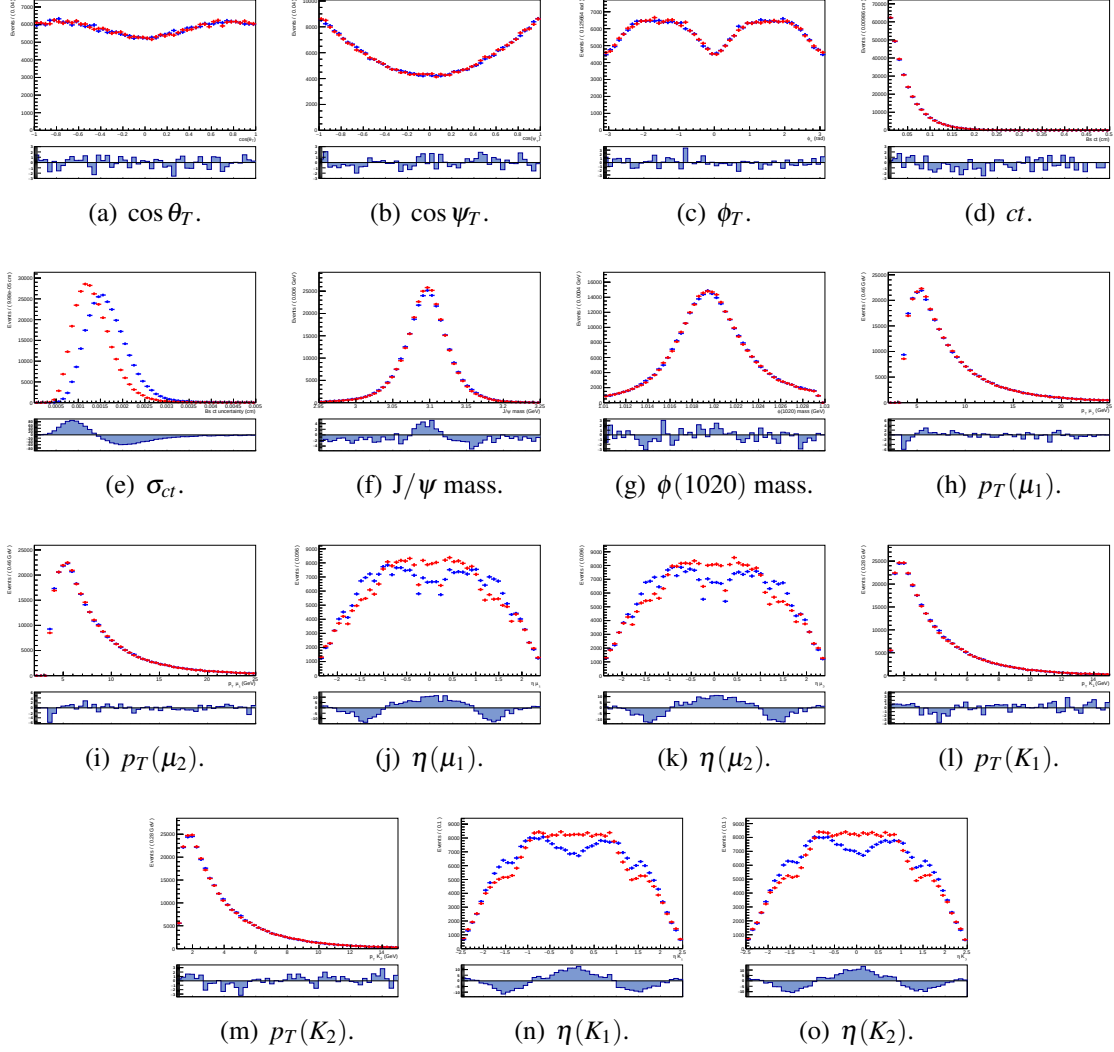


Figure 4.12: Variables distributions comparison between 2017 MC (red) and 2018 MC (blue).

Which simply boils down to the weight factor w_F ,

$$w_F = \frac{N_{\text{Data}}}{N_{\text{MC}}} \times \frac{N_{\text{Sig}}}{N_{\text{Sig}} \times N_{\text{Bkg}}} \quad (4.8)$$

The comparisons are shown in Figure 4.7 for 2017 samples, and Figure 4.8 for 2018 samples. A good overall comparison is observed. Few exceptions such as, the σ_{ct} distribution in MC samples is more skewed towards lower values with respect to data, this is not an issue for the measurement since per-event σ_{ct} obtained from data is used when performing the final fit. The very observation for the pseudorapidity distributions in 2018 samples are having disagreement between MC and collision data. Toward a better understanding the discrepancies observed in the pseudorapidity distribution of the tracks corresponding to final state particles, additional sets of comparison are performed. Figures 4.9 and 4.10 show the data/MC comparisons with the $\Delta\Gamma_s = 0$ sample that are used to compute the angular and lifetime efficiency. The $\Delta\Gamma_s = 0$ requirement in Data distorts the angular variable and lifetime variables that is why those are not shown in those respective figures. Figure 4.11 depicts the comparison plots between the two years of data taking. The total agreement is overall good, with the exception of σ_{ct} where 2017 data show a distribution more skewed towards lower values. Figure 4.12 shows the comparison between the Monte Carlo simulations for the two years of data taking. Discrepancies in σ_{ct} and pseudorapidity distributions are evident. It is also very much evident that the data/MC disagreement is present in both data years of 2017 and 2018, but it's much better in 2018 compared to 2017. The disagreement is similar for both $\Delta\Gamma_s = 0$ and $\Delta\Gamma_s \neq 0$ samples. The data distributions are more similar in two years of data taking period where the simulation is significantly different in 2017 and 2018 respectively. Further studies shows that the data/MC mismatch corresponding to the pseudorapidity between the final state particles, i.e., kaon and muon tracks are depending on the difference of pseudorapidity distributions of the B_s^0 meson. A cross-check is performed by re-weighting the $\eta(B_s^0)$ distribution in MC's to match the same distribution in data for the kaons and muons. For an example the re-wiething studies on 2018 Data and

$\Delta\Gamma_s = 0$ MC is shown in the Figure 4.13, the four plots describes the difference in $\eta(B_s^0)$, the re-weighting factor, difference in final state μ^- , and the reweighted MC for μ^- is compatible with data respectively. The very observation is that the MC is in agreement with data. Though the plot is showing the correction of muon but this is indeed true for kaon tracks as well. Later, after the final fit, a systematic uncertainty related to the disagreement of $\eta(B_s^0)$ in data and MC is going to be estimated and what follows that this mismatch will not affect the final fit results in a major way.

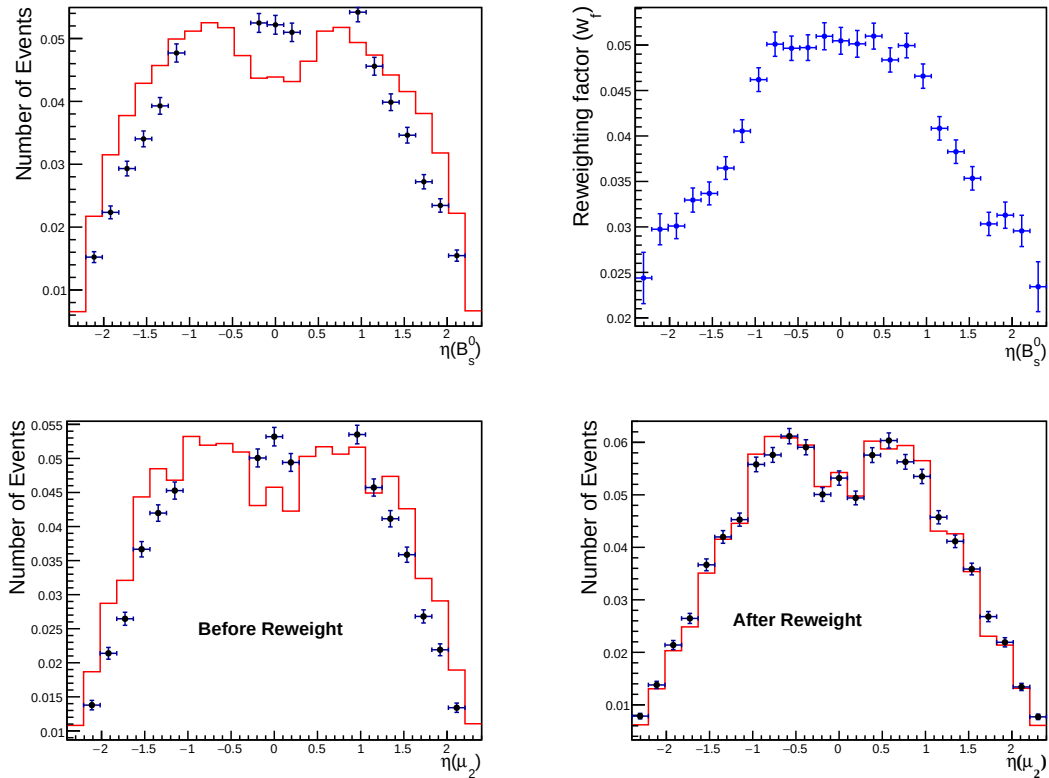


Figure 4.13: Data-MC pseudorapidity distribution comparison for 2018 samples, before and after reweighting the $B_s^0 \Delta\Gamma_s = 0$ MC distribution to match with Data. The solid red lines represent MC, while black markers represent Data.

4.3 Flavour Tagging(FT)

It is always possible that there will be several final state in which the B_s^0 and $\bar{B}_s^0$ can decay. This fact refrains the proper identification of the decaying particle whether it was B_s^0 or

$\bar{B}_s^0$. The constrain on the misidentification can be reduced by looking into the coherent production of the B_s^0 and $\bar{B}_s^0$ from the decay of a known physics process at the production level. If one of these particles decays through a flavor-specific mode at a given time, it is possible to identify the other particle at the same time, and further the time evolution of such decay can be studied. This process is known by an experimental nomenclature - *Tagging*. An opposite side (OS) FT algorithm is employed to identify the initial flavour specific state of the B_s^0 (or $\bar{B}_s^0$) candidate at the production level. This approach works well under the hypothesis that the bottom quarks are dominantly produced in particle-antiparticle ($b\bar{b}$) pairs. The idea is to determine flavour of the b quark on the opposite side present in the same event and use the same information to make an inference about the initial flavour of the B_s^0 at the production level. By exploiting the decays of OS b hadrons through the semileptonic $b \rightarrow \mu^Q + X$ physics processes the flavour of the OS b is identified. Depending upon the charge of the muon the tag side and signal side flavour is determined.

$$\begin{aligned} \text{tag side } \mu^- (\text{OS } b) &\implies \text{signal side } \bar{b} \\ \text{tag side } \mu^+ (\text{OS } \bar{b}) &\implies \text{signal side } b \end{aligned} \quad (4.9)$$

The muons charge sign in the event is the tagging variable which is also used in the final multidimensional fit denoted as ξ ($\xi = +1$ correspond to B_s^0 , $\xi = -1$ to $\bar{B}_s^0$, and $\xi = 0$ for untagged events when OS muon is not found). The predicted flavour by using flavour tagging method under question when matches with the true B_s^0 flavour a correct tag is defined otherwise wrong. The correlation of sign between the tag side muon and the true signal B_s^0 flavour can be diluted by wrong tags. There are several sources of the wrong tags, such as : the cascade decays of $b \rightarrow c \rightarrow \mu^- + X$, muons originating from J/ψ or charged kaon or pion decays, B_d^0 and B_s^0 meson oscillation in the opposite side. The flavour tagging tools is developed by using the simulated $B_s^0 \rightarrow J/\psi \phi$ and $B^\pm \rightarrow J/\psi K^\pm$ samples, and calibrated on data in $B^\pm \rightarrow J/\psi K^\pm$ decay. Figure 4.14⁶ shows the outline how the OS tagging muon is tagging the correct B_s^0 flavor. Characterization of the flavour tagging

⁶<https://cms.cern/news/crack-mirror>

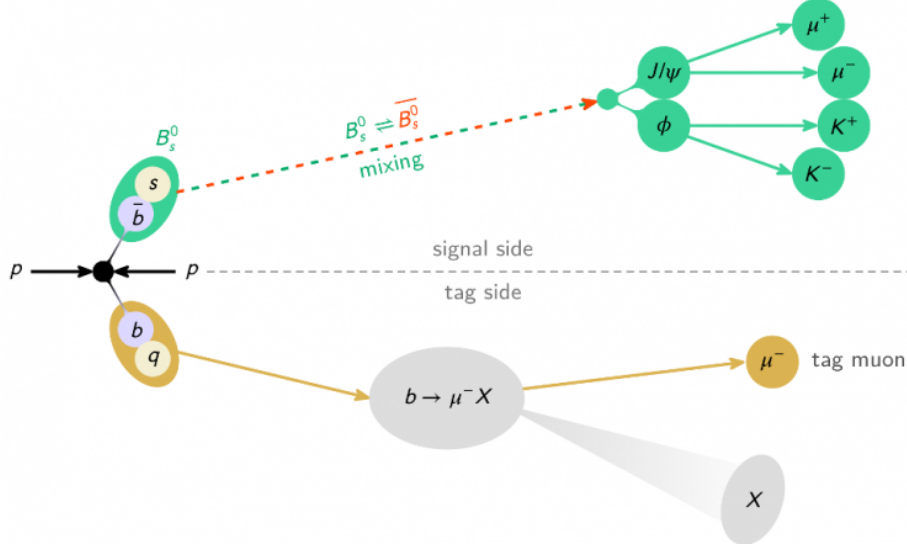


Figure 4.14: Outline of the flavour tagging cartoon, showing the signal side as well as the tag side. The B_s^0 flavour of the in the signal side is determined using OS b quark on the tag side.

performances with some figure of merits, such as,

- The tagging efficiency $\epsilon_{\text{tag}} = N_{\text{tag}}/N_{\text{total}}$, N_{tag} = number of tagged candidates out of total N_{total} number of events.
- $\omega_{\text{evt}} = N_{\text{tag, wrong}}/N_{\text{tag}}$, the per-event mistag fraction.
- The tagging power $P_{\text{tag}} = \epsilon_{\text{tag}}(1 - 2\omega_{\text{tag}})^2$, a re-scaled effective efficiency that takes into consideration mistagged events.

Per-event mistag probability is obtained by training a Deep Neural Network (DNN) on simulated events, and afterwards calibrated on data. This new approach proved to be much more stable and performing than old techniques. The final tagging performances are reported in Table 4.7. The calibration plots from the 2017 and 2018 data samples respectively

Dataset	ϵ_{tag}	ω_{evt}	P_{tag}
Charmonium2017	$(45.7 \pm 0.1) \%$	$(27.1 \pm 0.1) \%$	$(9.6 \pm 0.1) \%$
Charmonium2018	$(50.9 \pm 0.1) \%$	$(27.3 \pm 0.1) \%$	$(10.5 \pm 0.1) \%$

Table 4.7: Results of the OS muon tagging performance studies, based on the $B^\pm \rightarrow J/\psi K^\pm$ events extracted from the Charmonium dataset. The ω_{evt} is the effective mistag rate determined after applying the per-event evaluation.

are shown in Figure 4.15.

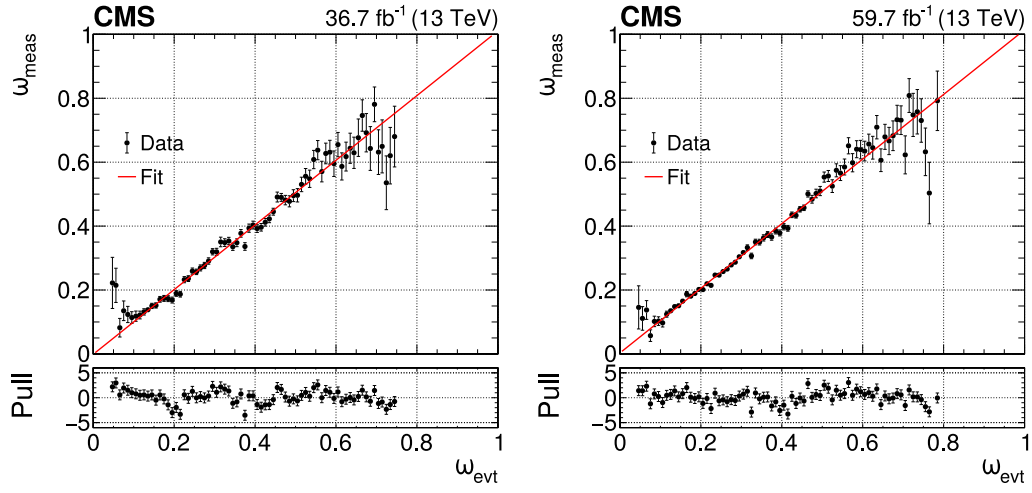


Figure 4.15: The calibration of the ω_{evt} based on $B^\pm \rightarrow J/\psi K^\pm$ process. The left plot is from 2017 data and right plot is from 2018 data, comprises statistical uncertainty and fit to data (red line).

4.4 Fit Methods

4.4.1 Inclusion of efficiencies in maximum likelihood function

In real experiment because of detector acceptance, reconstruction and selection effects the event distributions as function of decay observables following from theory get altered. The CMS experiment and the event selection procedure as well implies toward resolution effects, cause non-uniform efficiencies in addition with the introduction of the backgrounds to the theoretical signal decay distribution of the $B_s^0 \rightarrow J/\psi \phi$ decay. It is obvious that these effects should be considered while fitting data toward the extraction of the desired parameters corresponding to the analysis under question. The efficiencies are estimated using the samples resulting from MC simulations. The efficiency of any variable can be considered as the probability to reconstruct an event : dividing the reconstructed events for some kinematic observable in a particular bin by the generator level events in the same bin. The estimated efficiencies are then applied to retrieve the production values used in simulation. As for the final fit the efficiencies are applied only to the signal probability distribution functions. The method used here is extended version of maximum likelihood estimation to estimate value of ϕ_s . The maximum likelihood is the maximum joint probability for a set of independent outcomes α corresponding to set of β , is defined in the Equation 4.10.

$$\mathcal{L}(\beta) = \prod_i S(\alpha_i|\beta) \quad (4.10)$$

The signal PDF $S \geq 0$ corresponds to the event i , and the unnormalized signal function s satisfies the relation,

$$S(\alpha_i|\beta) = \frac{s(\alpha_i|\beta)}{\int s(\alpha_i|\beta) d\alpha} \quad (4.11)$$

As we know the maximizing $\mathcal{L}$ is directly proportional to the maximization of $\ln \mathcal{L}$, in such case variation of log-likelihood with respect to any set of physics parameter takes the

form as described in Equation 4.12.

$$\frac{d \ln \mathcal{L}}{d \beta_n} = \frac{d}{d \beta_n} \sum_i \ln \frac{s(\alpha_i | \beta)}{\int s(\alpha_i | \beta) d \alpha} = 0 \quad (4.12)$$

The idea is to find a set of β 's for which the product of individual probability in each measurement will be maximal. After the inclusion of efficiency $\varepsilon(\alpha)$, the maximal log-likelihood equation becomes,

$$\frac{d}{d \beta_n} \sum_i \ln \frac{s(\alpha_i | \beta) \varepsilon(\alpha_i)}{\int s(\alpha_i | \beta) \varepsilon(\alpha_i) d \alpha} = 0 \quad (4.13)$$

The signal model of $B_s^0 \rightarrow J/\psi \phi$ decay is described by four observables, the proper decay time ct and the three angular variable defined in transversity basis $\Theta = (\cos \theta_T, \cos \psi_t, \phi_T)$. The $\Delta \Gamma_s \neq 0$ implies that the temporal and angular components can not be decoupled.

$$S(ct, \Theta) \neq \mathcal{P}(ct) \times \mathcal{P}(\Theta) \quad (4.14)$$

In this time dependent flavor tagged angular analysis is it very much evident that the kinematics of B_s^0 in terms of angular variables and proper time distribution need to be analyzed simultaneously. The special feature of the signal PDF may be written as a normalized sum of the products of angular and time dependent functions,

$$S(ct_i, \Theta | \beta) = \frac{\sum_{k=1}^{10} \mathcal{A}_k(ct_i | \beta) f_k(\Theta_i)}{\int \int \sum_{k=1}^{10} \mathcal{A}_k(ct_i | \beta) f_k(\Theta_i) d(ct) d\Theta} \quad (4.15)$$

The angular function $f_k(\Theta_i)$ and time dependent amplitudes $\mathcal{A}_k(ct_i | \beta)$ propagates with index k . The limit 1 – 10 corresponds to each of the amplitudes defines the differential decay rate of the decay process. For constant or ideal angular efficiency the maximization of log-likelihood reads,

$$\frac{d}{d \beta_n} \sum_j \ln \frac{\mathcal{A}_k(ct_i | \beta) f_k(\Theta_i)}{\int \int \mathcal{A}_k(ct_i | \beta) f_k(\Theta_i) d(ct) d\Theta} = 0 \quad (4.16)$$

Since the individual angular dependent functions do not depend on physics parameter β and the integral can be factorized,

$$\int \int \mathcal{A}_k(ct_i|\beta) f_k(\Theta_i) d(ct) d\Theta = \int \mathcal{A}_k(ct_i|\beta) d(ct) \int f_k(\Theta_i) d\Theta \quad (4.17)$$

implies the second integral need to be optimized during likelihood optimization procedure only once. Finally, with the inclusion of efficiency function the maximal equation becomes,

$$\frac{d}{d\beta_n} \sum_j \ln \frac{\mathcal{A}_k(ct_i|\beta) f_k(\Theta_i)}{\int \int \mathcal{A}_k(ct_i|\beta) f_k(\Theta_i) \varepsilon(ct, \Theta) d(ct) d\Theta} = 0. \quad (4.18)$$

In general the inclusion of efficiency is very much customary to test first on simulated samples for this type of time dependent angular analysis and import those efficiencies to the final Data fit.

4.4.2 Lifetime efficiency

The lifetime efficiency is computed separately for 2017 and 2018 MC samples. The generic definition of the lifetime efficiency⁷ can be described by Equation 4.19.

$$\varepsilon(ct) = \frac{ct_{\text{RECO}}}{ct_{\text{GEN}} \otimes \delta(ct)} \quad (4.19)$$

Where, the ct_{RECO} is the distribution obtained from $\Delta\Gamma_s = 0$ simulated samples, ct_{GEN} is the distribution obtained from the GEN sample, and $\delta(ct) = ct_{\text{GEN}} - ct_{\text{RECO}}$ is the lifetime resolution distribution. To fit the lifetime efficiency within the range 0.007 – 0.5 cm with a model as defined in the Equation 4.20, where as the generating function and the form of first class polynomial is described in 4.21.

$$f(\varepsilon(ct)) = \frac{1}{A_{\text{norm}}} \cdot e^{b \cdot ct} \cdot \text{Chebychev4}(ct) \quad (4.20)$$

⁷It is computed in 35 bins, Bins edges in cm: 0.007, 0.009, 0.011, 0.013, 0.015, 0.017, 0.019, 0.021, 0.023, 0.025, 0.030, 0.035, 0.040, 0.045, 0.050, 0.055, 0.060, 0.065, 0.070, 0.075, 0.080, 0.085, 0.090, 0.095, 0.100, 0.125, 0.150, 0.175, 0.200, 0.225, 0.250, 0.275, 0.300, 0.350, 0.400, 0.500.

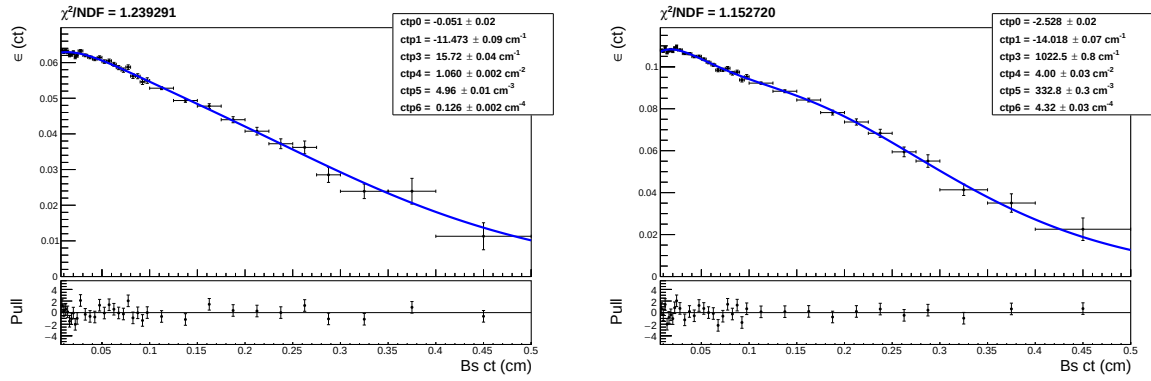


Figure 4.16: Lifetime efficiency distribution measured in 2017 (left) and 2018 (right) samples, after offline selection. The efficiency functions are not normalized in this figure.

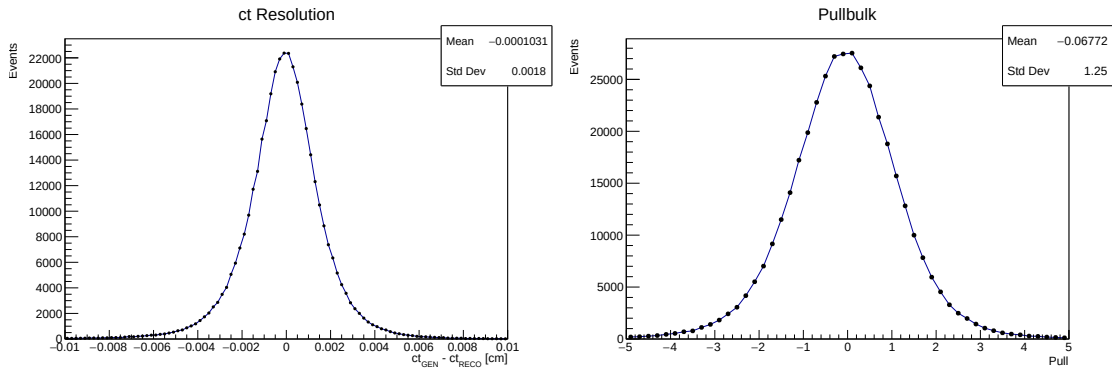


Figure 4.17: ct resolution $\delta(ct) = ct_{GEN} - ct_{RECO}$ distribution (left) and pull (right) in 2017 simulated samples, after offline selection.

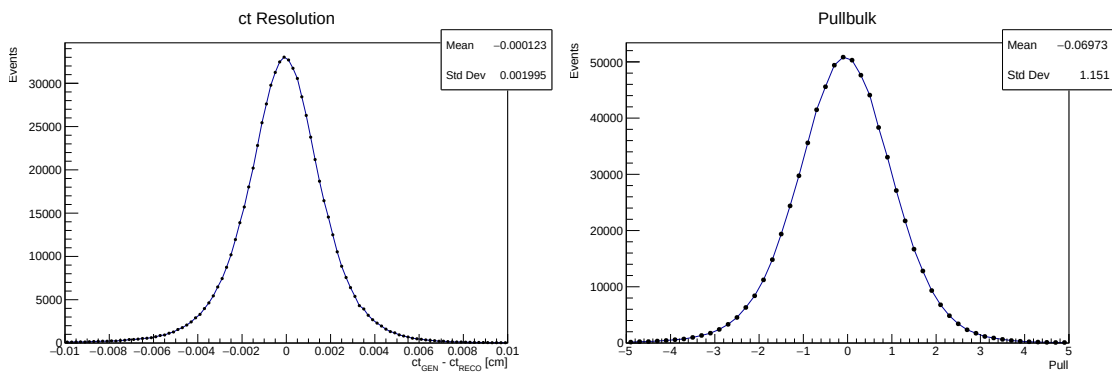


Figure 4.18: ct resolution $\delta(ct) = ct_{GEN} - ct_{RECO}$ distribution (left) and pull (right) in 2018 simulated samples, after offline selection.

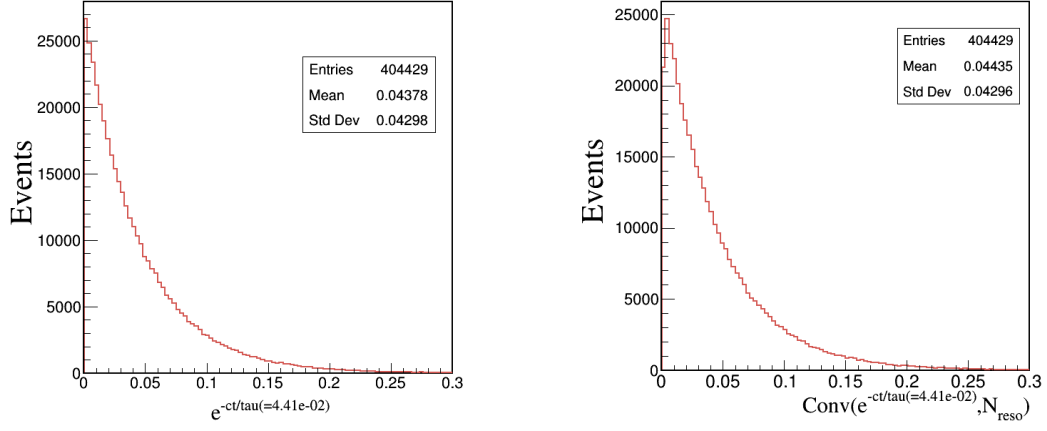


Figure 4.19: $e^{-ct/\tau}$ distribution (left), the same distribution convolved with $\delta(ct)$ (right). ($\tau = 4.41 \times 10^{-2} \mu\text{m}$).

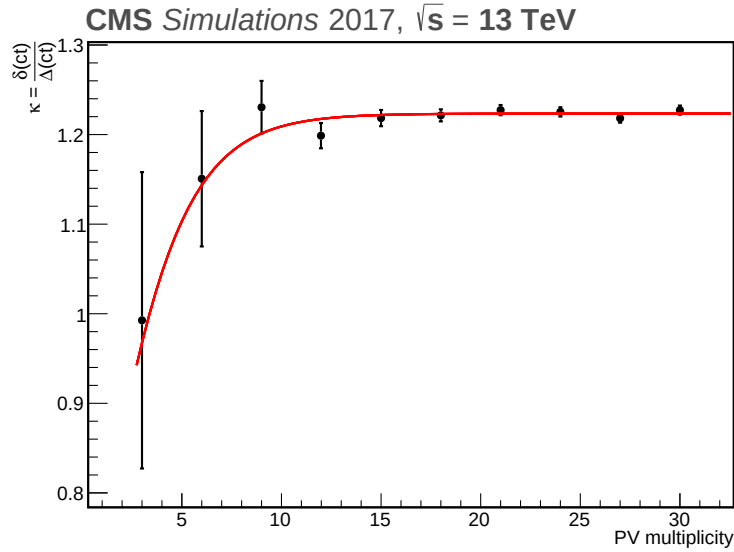


Figure 4.20: Variation of κ in bins of primary vertex from 2017 MC sample. The distributions shows there is no such significant difference of κ values in different bins of primary vertex.

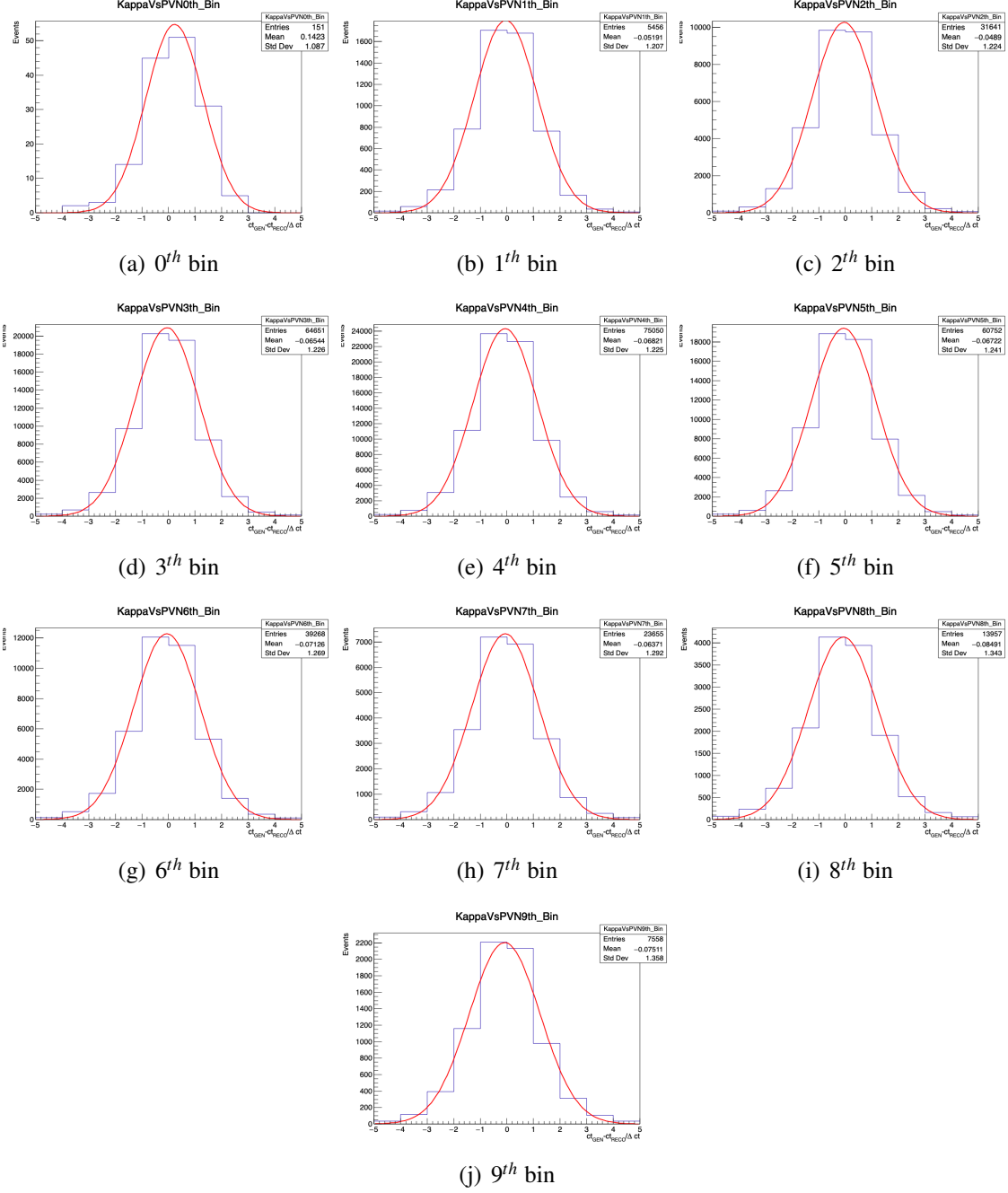


Figure 4.21: The plot of κ factor distributions in bins of primary vertex from 2017 MC sample and fitted with a Gaussian distribution using 2017 $\Delta\Gamma_s = 0$ sample.

$$\sum_{n=0}^{\infty} T_n(x) t^n = \frac{1 - tx}{1 - 2tx + t^2} \quad (4.21)$$

$$T_n(x) = \sum_{k=0}^{n/2} {}^nC_{2k} (x^2 - 1)^k x^{n-2k}$$

where $\text{Chebychev4}(ct)$ is a first class Chebychev polynomial of order four with the constant term fixed to 1, and $1/A_{\text{norm}}$ is a normalization factor. Lifetime efficiencies for 2017 and 2018 MC's are shown in Figure 4.16. Figure 4.17 and 4.18 show the distributions of the ct resolution $\delta(ct)$ and the lifetime pulls $ct_{\text{pull}} = \delta(ct)/\sigma_{ct}$ for 2017 and 2018, respectively. To visualize the effect of resolution in the lifetime a toy is generated using the generic function $e^{-ct/\tau}$ ($\tau = 4.41 \times 10^{-2} \mu m$) by implementing proper lifetime value as similar as the MC production value and convolved it with the resolution distribution as $e^{-ct/\tau} \otimes \delta(ct)$. These two distributions are shown in Figure 4.19.

κ factor

It is observed that there exists small bias at order of few μm in the proper decay time resolution $\delta(ct) = ct_{\text{GEN}} - ct_{\text{RECO}}$ and in the pull distributions of both years (2017, 2018). The idea was to plug-in the measured σ_{ct} in the $\delta(ct)$ PDF that has to be fitted to data in per-event way. When the resolution is dependent on variables involved in the fit, it is assumed that the proper time uncertainty can be used as a replacement of resolution. The first order correction can be done by applying a constant κ factor as defined as in the Equation 4.22 on the proper time uncertainty in order to align it to the resolution value.

$$\kappa = \frac{1}{N} \sum_{i=0}^N \frac{\delta(ct)}{\sigma_{ct}} \quad (4.22)$$

The pile-up effect on the κ value can be mapped to the dependence of the κ on the primary vertex. It is observed that the fitted RMS values of the κ when fitted with the Gaussian distribution in different bins of primary vertex does not differ much from each other as

shown in Figure 4.21. The RMS values extracted from the fit in each bin is plotted using 2017 MC sample in the Figure 4.20 shows that the pile-up is having no effect on the κ factor.

4.4.3 Angular efficiency

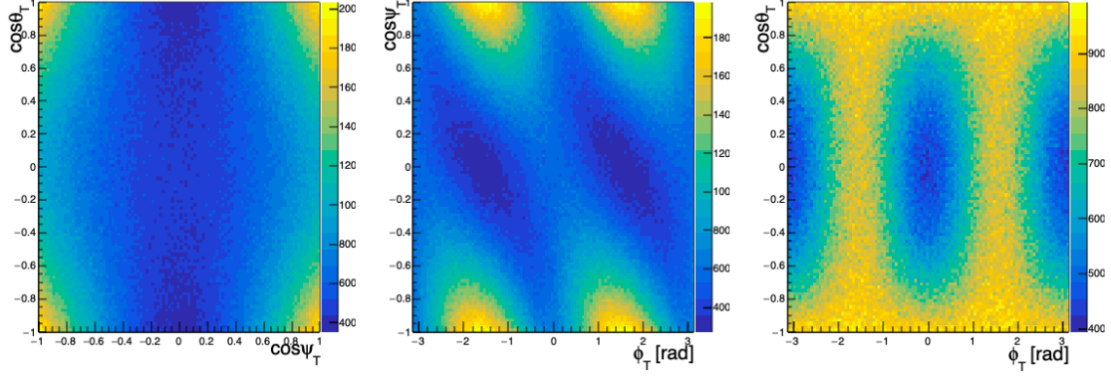
The efficiencies are factorized before implemented in the final fit and this is the reason that the correlation terms are neglected in the efficiency function. In the final the temporal and angular efficiencies are applied explicitly by factorizing them in simple product as given in Equation 4.23.

$$\varepsilon(ct, \cos \theta_T, \cos \psi_T, \phi_T) \cong \varepsilon(ct) \cdot \varepsilon(\cos \theta_T, \cos \psi_T, \phi_T) \quad (4.23)$$

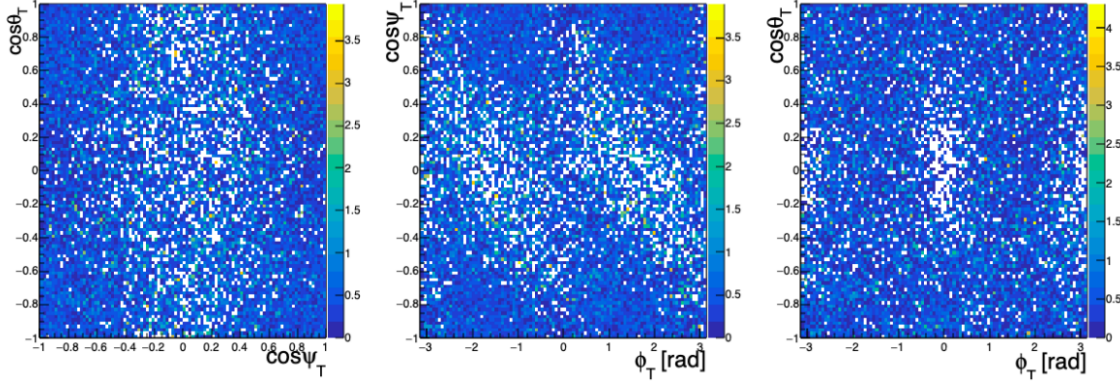
Since the angular efficiency depends on the three angular observable, the correlation among these variables are studied. To visually appreciate the correlations, Figure 4.22 shows the projection of two dimensional histograms of the angular variable pairs one in bins of the other. The top plot is the GEN level projection, the middle one is the reconstructed projection after applying all optimized selections, and the bottom one is the ratio between RECO and GEN level distributions. It is observed that there are no evident correlations between $\cos \psi_T - \cos \theta_T$ and $\phi_T - \cos \theta_T$ variables in all the stages of signal reconstruction (GEN, RECO, Ratio), while a small correlation is observed between $\phi_T - \cos \psi_T$ variables. Not during the efficiency calculation but in also the final fit it is found that the estimation of the correlations between the proper decay time variable and angles are negligible.

Angular efficiencies are computed explicitly for 2017 and 2018 $\Delta\Gamma_s = 0$ samples. *Efficiency histograms* are evaluated as bin-by-bin ratios of the 3D angular RECO histograms to the 3D angular GEN histograms. All the optimized selections are applied the RECO samples where the GEN histograms are from GEN sample. The efficiency histograms are then projected on an orthogonal basis B formed by the elements as given in the Equation 4.24.

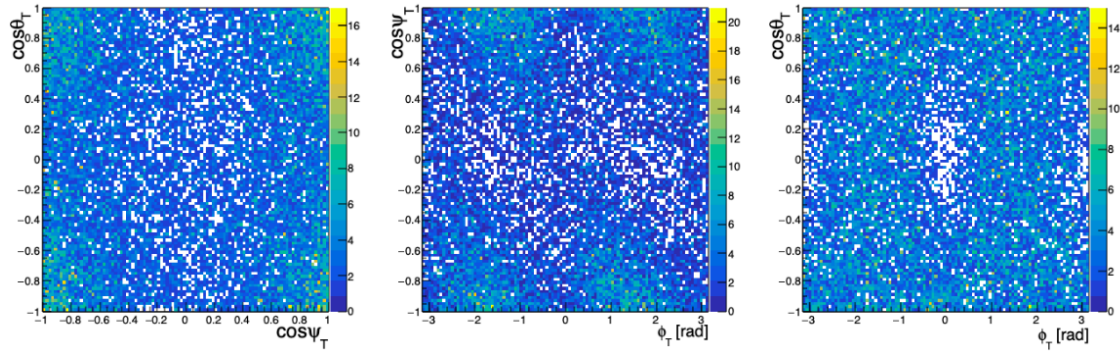
$$b_{l,k,m}(\Theta) = P_l^m(\cos \theta_T) \cdot P_k^m(\cos \psi_T) \cdot \begin{cases} \sin(m \phi_T) & \text{if } m < 0 \\ \cos(m \phi_T) & \text{if } m > 0 \\ 1/2 & \text{if } m = 0 \end{cases} \quad (4.24)$$



(a) Generator



(b) Reconstructed



(c) Ratio

Figure 4.22: In each row, 2D histograms of pairs of angular variables. In the top the GEN level distributions, in the middle the RECO level distributions, and in the bottom ratio between the RECO and GEN level distribution using $\Delta\Gamma_s = 0$ sample of 2018.

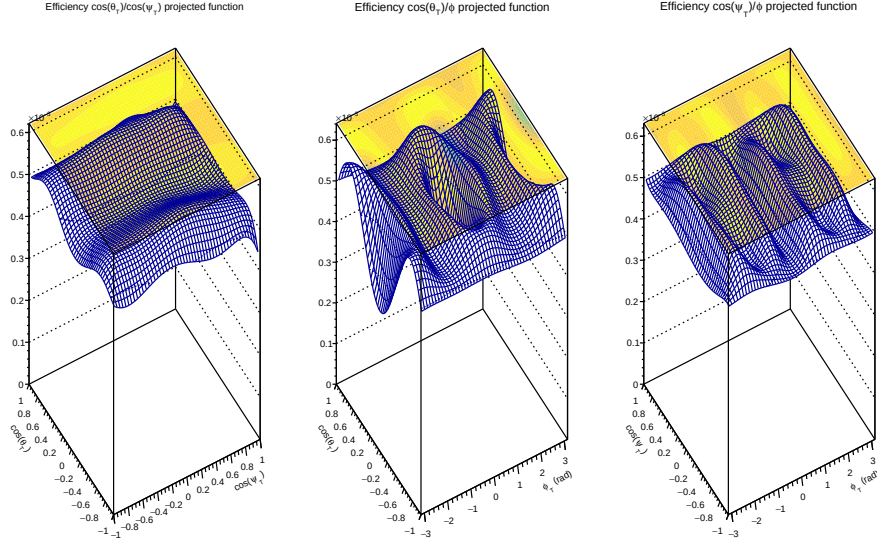


Figure 4.23: Projected efficiency function for $\cos \theta_T$, $\cos \psi_T$ and ϕ_T in 2017 samples.

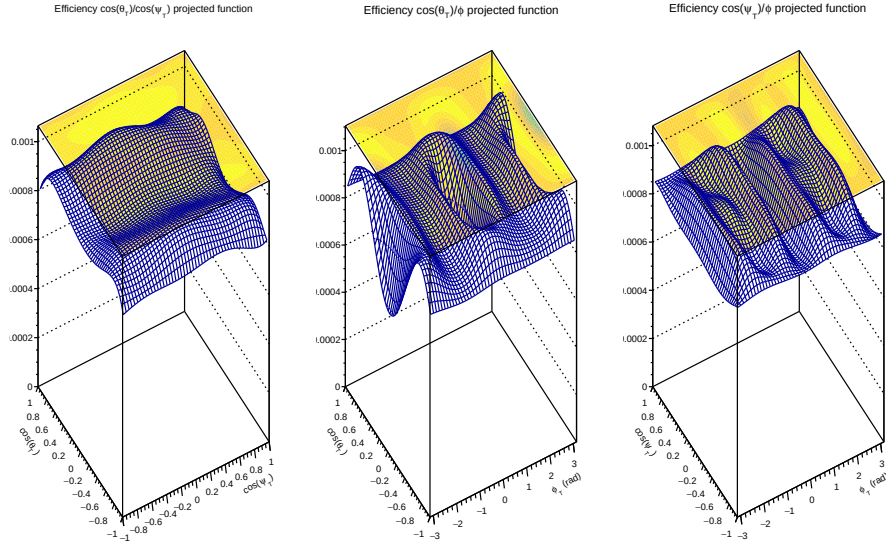


Figure 4.24: Projected efficiency function for $\cos \theta_T$, $\cos \psi_T$ and ϕ_T in 2018 samples.

where, P_i^j are the associated Legendre polynomials of degree i and order j . This basis was chosen because it's the simplest orthogonal basis for functions of three angular variables. The projection coefficients $c_{l,k,m}$ are computed as

$$c_{l,k,m} = \frac{\sum_{\text{bin}} h_{\text{bin}} \cdot b_{l,k,m}(x_{\text{bin}}) / V_{\text{bin}}}{\|P_l^m\|^2 \cdot \|P_k^m\|^2 \cdot \pi} \quad (4.25)$$

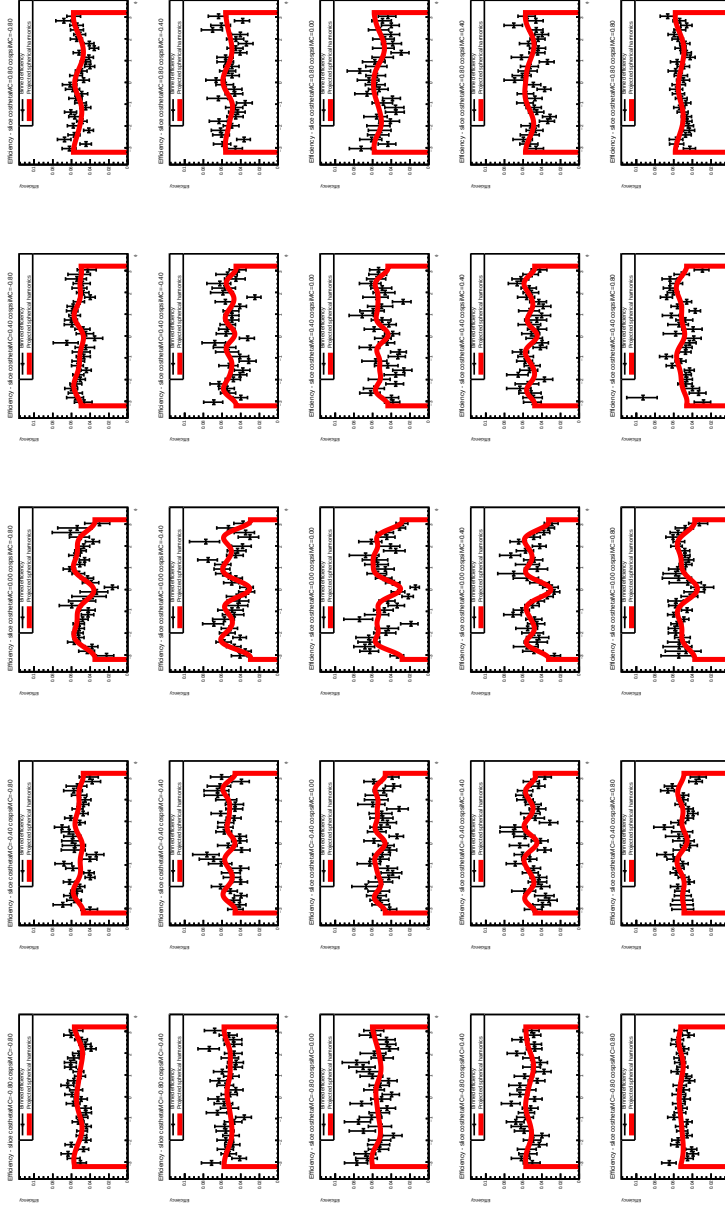


Figure 4.25: One dimensional projection of the fitted efficiency slice of ϕ_T in bins of $\cos \theta_T$, and $\cos \psi_T$ using 2018 samples.

where, $\left\| P_i^j \right\|^2$ is the norm of the associated Legendre polynomial obeying L^2 -type square summable sequence. Having bin height h_{bin} and bin volume V_{bin} the basis elements $b_{l,k,m}(x_{\text{bin}})$ need to be evaluated in the center of each bin. The final mathematical expression of angular efficiencies $\varepsilon(\Theta)$ is given in the Equation 4.26 as a sum of projection coefficients and basis

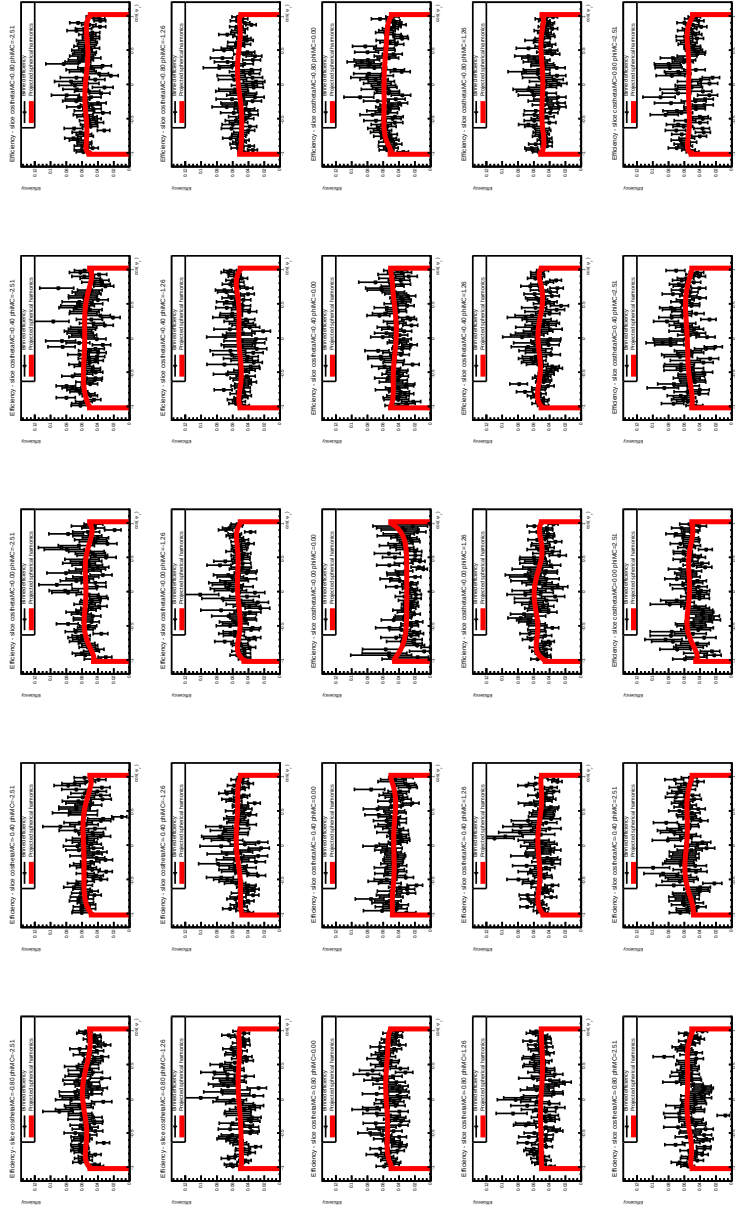


Figure 4.26: One dimensional projection of the fitted efficiency slice of $\cos \psi_T$ in bins of $\cos \theta_T$, and ϕ_T using 2018 samples.

elements.

$$\varepsilon(\Theta) = \sum_{l,k,m} c_{l,k,m} \cdot b_{l,k,m}(\Theta) \quad (4.26)$$

The two dimensional projected efficiency functions are shown in Figure 4.23 and 4.24. The projection of fitted one dimensional sliced histograms are shown in Figure 4.25, 4.26, and 4.27. These are the results obtained by projecting both $\Delta\Gamma_s$ sample and three dimen-

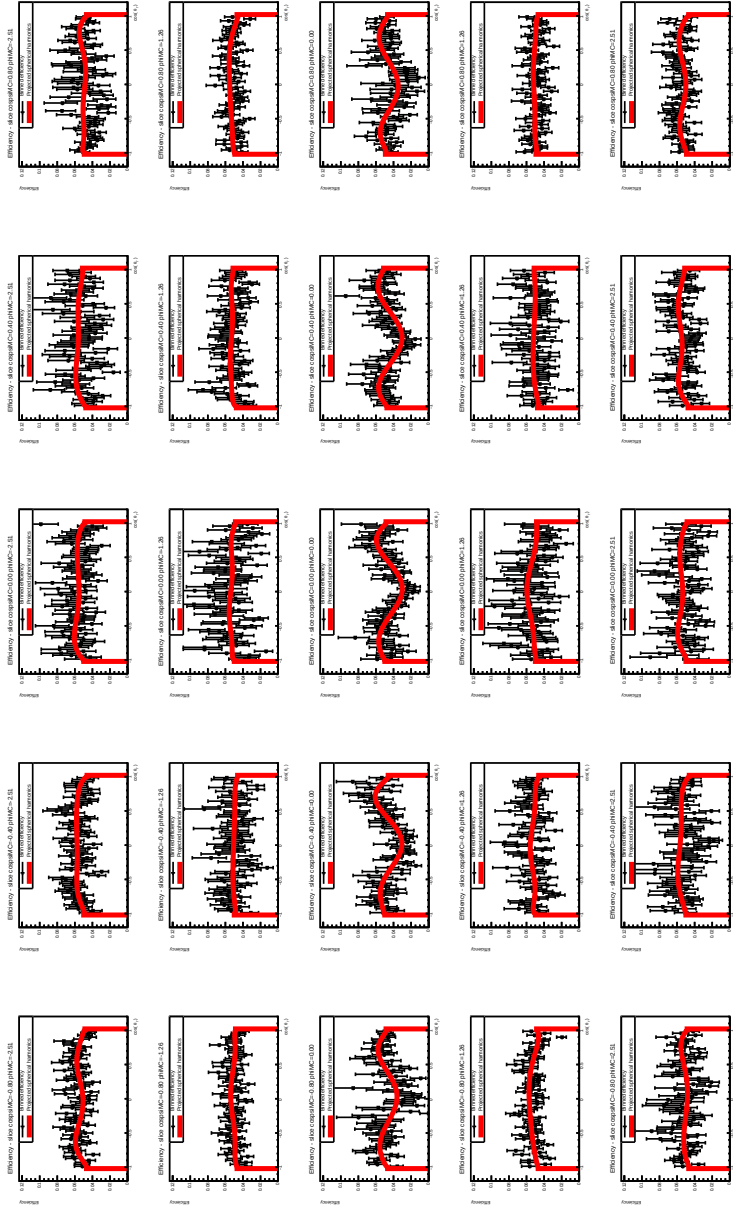


Figure 4.27: One dimensional projection of the fitted efficiency slice of $\cos \theta_T$ in bins of $\cos \psi_T$, and ϕ_T using 2018 samples.

sional efficiency function in a small range in two of the variables and plotting on the third. This procedure of angular efficiency calculation is very fast (the calculation of each coefficient of the base functions is a simple sum). When multiplied with a theoretical angular distribution expressed in 3D spherical harmonics basis, the normalization of PDF fitted to angular variables can be expressed in analytic way, since the properties of the Legendre polynomial is known. This method also speeds up the implementation of the coefficients

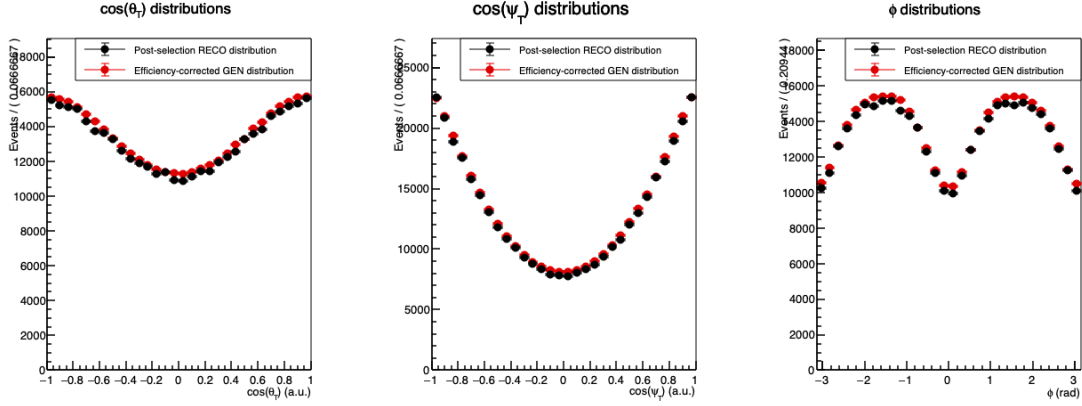


Figure 4.28: Closure test of the three dimensional angular efficiency function. The closure test is performed by iterating several binning configuration, order of the Legendre polynomial, computational time, accuracy in the one dimensional efficiency slices. Both 2017 and 2018 MC samples are used while the plot sis shown here is from 2018 MC.

of the efficiency function in the final fit. Proceeding with testing of several binning configurations, evaluating computational time of the procedure and the accuracy, the optimal, and chosen, configuration is 70 bins for $\cos \theta_T$ and $\cos \psi_T$, and 30 for ϕ_T . For P_i^j , the optimal maximum value of i was found out to be 6, after testing values between 3 and 12. The maximum order to use is determined by the richness of features are rooted in the distribution and the complexity of the function is used in the fit (keeping it stable and not too time-consuming). A closure is approached toward the optimization of the method by overlaying the reconstructed distribution to the efficiency corrected generator level distributions in each iteration. Figure 4.28 shows that the current efficiency modelization is the best among the other binning configuration.

4.4.4 Likelihood fit

The $B_s^0 \rightarrow J/\psi\phi$ differential decay rate forms a multidimensional parametric space including the informations of decaying angle, proper decay time, mass, and tagging information. The generic way to estimate the values of the desired parameters is to maximize the multidimensional parametric space formed by the decay distribution. An extended version of unbinned multidimensional maximum-likelihood fit model is designed, and using the same a fit is performed on pp collision charmonium dataset. Including efficiencies : $\varepsilon(ct)$, and $\varepsilon(\Theta)$ the input parameters to the maximum-likelihood fit model are eight observables, such as :

- The mother neutral meson mass $m_{B_s^0}$,
- The three decay angles $\Theta(\theta_T, \psi_T, \phi_T)$ when the decay is studied in the transversity basis,
- Decay time (ct),
- Per-event uncertainty measured in decay time (σ_{ct}),
- The categorical tagging variable (ξ) and the per-event mistag fraction (ω_{evt}).

The total likelihood function is having contribution from both signal, and background PDF's. RooFit [66, 71] is used to construct the fit model. The definition of the event PDF P is given in the Equation 4.27.

$$P = \frac{N_{\text{sig}}}{N_{\text{tot}}} P_{\text{sig}} + \frac{N_{\text{bkg}}}{N_{\text{tot}}} P_{\text{bkg}} \quad (4.27)$$

The negative log likelihood of the event PDF can be defined as,

$$-\ln \mathcal{L} = -\sum_{i=0}^{N_{\text{evt}}} \ln P_i + N_{\text{tot}} - N_{\text{evt}} \ln N_{\text{tot}}. \quad (4.28)$$

The background has two different source, the combinatorial background is coming from the mis-reconstruction of the tracks and the peaking background is coming from the $B^0 \rightarrow$

$J/\psi K^{*0} \rightarrow \mu^+ \mu^- K^+ \pi^-$ decay. The explicit forms of the components of the event PDFs are described in the Equation 4.29.

$$\begin{aligned}
P_{\text{sgn}} &= \varepsilon(ct) \varepsilon(\Theta) [\widetilde{\mathcal{F}}(\Theta, ct, \alpha) \otimes G(ct, \sigma_{ct})] P_{\text{sgn}}(m_{B_s^0}) P_{\text{sgn}}(\sigma_{ct}) P(\xi)_{\text{sgn}}, \\
P_{\text{comb}} &= P_{\text{comb}}(\cos \theta_T, \phi_T) P_{\text{comb}}(\cos \psi_T) P_{\text{comb}}(ct) P_{\text{comb}}(m_{B_s^0}) P_{\text{comb}}(\sigma_{ct}) P(\xi)_{\text{comb}}, \\
P_{\text{peak}} &= P_{\text{peak}}(\cos \theta_T, \phi_T) P_{\text{peak}}(\cos \psi_T) P_{\text{peak}}(ct) P_{\text{peak}}(m_{B_s^0}) P_{\text{peak}}(\sigma_{ct}) P(\xi)_{\text{peak}},
\end{aligned} \tag{4.29}$$

where,

- $\varepsilon(ct)$, and $\varepsilon(\Theta)$ are the efficiencies.
- $G(ct, \sigma_{ct})$ is the Gaussian resolution function modeling σ_{ct} scaled by the κ factor. The estimated value of κ -factor is equal to 1.25 and 1.15, for 2017 and 2018 MC samples, respectively.
- f_{sgn} is the signal fraction,
- $\widetilde{\mathcal{F}}(\Theta, ct, \alpha)$ is the decay rate PDF, described in Eq. 1.32, where the $\mathcal{O}_i$ terms are modified to include the mistag probability ω_{evt} and the tag information ξ ,

$$\mathcal{O}_i = N_i e^{-\Gamma_s t} \left[a_i \cosh\left(\frac{1}{2} \Delta \Gamma_s t\right) + b_i \sinh\left(\frac{1}{2} \Delta \Gamma_s t\right) + c_i \xi (1 - 2\omega) \cos(\Delta m_s t) + d_i \xi (1 - 2\omega) \sin(\Delta m_s t) \right] \tag{4.30}$$

with $\xi = 0, +1, -1$ for the untagged, $\overline{B}_s^0$, B_s^0 case respectively. The S-wave phase δ_S has also been redefined as $\delta_{S\perp} = \delta_S - \delta_{\perp}$ to reduce correlations. We also use the convention where $\delta_0 = 0$ and $|A_0|^2 + |A_{\parallel}|^2 + |A_{\perp}|^2 = 1$, which allows us to reduce the amplitudes by one redefining $|A_{\parallel}|^2 = 1 - |A_0|^2 - |A_{\perp}|^2$. Table 4.8 presents the time-dependent PDF terms after redefinition⁸.

- $P_{\text{sgn}}(m_{B_s^0})$ is the signal mass PDF defined already in the Section 4.2.2.
- $P_{\text{sgn}}(\sigma_{ct})$ is the signal decay time uncertainty PDF.

⁸The angular and time-dependent terms were already defined in Table 1.4.

- $P(\xi)_{\text{sgn,comb,peak}}$ are the tag PDF.
- $f_{\text{comb}}, P_{\text{comb}}(\cos \theta_T, \phi_T), P_{\text{comb}}(\cos \psi_T), P_{\text{comb}}(ct), P_{\text{comb}}(m_{B_s^0}), P_{\text{comb}}(\sigma_{ct})$ are the respective PDF's modeling the combinatorial background.
- P_{peak} models the peaking background from $B^0 \rightarrow J/\psi K^{*0} \rightarrow \mu^+ \mu^- K^+ \pi^-$ decay process where the pion is misidentified as a kaon.

i	N_i	a_i	b_i	c_i	d_i
1	$ A_0 ^2$	1	D	C	$-S$
2	$1 - A_0 ^2 - A_\perp ^2$	1	D	C	$-S$
3	$ A_\perp ^2$	1	$-D$	C	S
4	$\sqrt{1 - A_0 ^2 - A_\perp ^2} A_\perp $	$C \sin(\delta_\perp - \delta_\parallel)$	$S \cos(\delta_\perp - \delta_\parallel)$	$\sin(\delta_\perp - \delta_\parallel)$	$D \cos(\delta_\perp - \delta_\parallel)$
5	$ A_0 \sqrt{1 - A_0 ^2 - A_\perp ^2}$	$\cos(\delta_\parallel)$	$D \cos(\delta_\parallel)$	$C \cos(\delta_\parallel)$	$-S \cos(\delta_\parallel)$
6	$ A_0 A_\perp $	$C \sin(\delta_\perp)$	$S \cos(\delta_\perp)$	$\sin(\delta_\perp)$	$D \cos(\delta_\perp)$
7	$ A_S ^2$	1	$-D$	C	S
8	$ A_S \sqrt{1 - A_0 ^2 - A_\perp ^2}$	$C \cos(\delta_\parallel - \delta_\perp - \delta_{S\perp})$	$S \sin(\delta_\parallel - \delta_\perp - \delta_{S\perp})$	$\cos(\delta_\parallel - \delta_\perp - \delta_{S\perp})$	$D \sin(\delta_\parallel - \delta_\perp - \delta_{S\perp})$
9	$ A_S A_\perp $	$\sin(\delta_\perp - \delta_\perp - \delta_{S\perp})$	$-D \sin(\delta_\perp - \delta_\perp - \delta_{S\perp})$	$C \sin(\delta_\perp - \delta_\perp - \delta_{S\perp})$	$S \sin(\delta_\perp - \delta_\perp - \delta_{S\perp})$
10	$ A_S A_0 $	$C \cos(-\delta_\perp - \delta_{S\perp})$	$S \sin(-\delta_\perp - \delta_{S\perp})$	$\cos(-\delta_\perp - \delta_{S\perp})$	$D \sin(-\delta_\perp - \delta_{S\perp})$

Table 4.8: Time-dependent coefficients corresponding to the signal model after the following redefinitions: $\delta_{S\perp} = \delta_S - \delta_\perp$, $\delta_0 = 0$, $|A_\parallel|^2 = 1 - |A_0|^2 - |A_\perp|^2$.

4.4.5 Decay time uncertainty

The 3×3 covariance matrix elements corresponding to the **PV**, **SV**, and the total **T** position coordinates $\{x, y, z\}$ are given in the Equation 4.31.

$$\begin{aligned}
\text{cov}[\mathbf{PV}] &= \text{cov}[PV_i, PV_j] = E[(PV_i - E[PV_i])(PV_j - E[PV_j])], \\
\text{cov}[\mathbf{SV}] &= \text{cov}[SV_i, SV_j] = E[(SV_i - E[SV_i])(SV_j - E[SV_j])], \\
\text{cov}[\mathbf{T}] &= \text{cov}[\mathbf{PV}] + \text{cov}[\mathbf{SV}], \\
(i, j &:= 1, 2, 3 \in \{x, y, z\})
\end{aligned} \tag{4.31}$$

The $PV_{i(j)}(SV_{i(j)})$ s are scalar point elements and $E[PV(SV)]$ s are the expectation values or the mean values. The σ_{ct} is estimated by propagating the errors of the vertex position and

the B_s^0 momentum as defined in the Equation 4.32.

$$\sigma_{ct} = \left| \frac{m_{B_s^0}}{|\vec{P}_{B_s^0}|} \sqrt{\frac{\mathbf{X}_{2D}^T \text{cov}[\mathbf{T}] \mathbf{X}_{2D}}{\sum_i |\mathbf{X}_{2D}|^2}} \cos \theta_{\vec{P}_{B_s^0}}^{\mathbf{X}_{2D}} \right|$$

$$\mathbf{X}_{2D} = [\mathbf{PV} - \mathbf{SV}], \quad \theta_{\vec{P}_{B_s^0}}^{\mathbf{X}_{2D}} = \mathbf{X}_{2D} \angle \vec{P}_{B_s^0} \quad (4.32)$$

where, the vector array $\mathbf{X}$ consumes the information of the scalar distance between the PV and SV in each index⁹. The ct uncertainty is modeled separately for 2017 and 2018 datasets with two Gamma PDF's¹⁰ for each year as given in Equation 4.33.

$$P_{\text{sgn}}(\sigma_{ct}) = f \tilde{\Gamma}_1(\sigma_{ct}, \mu_1, \gamma_1, \beta_1) + (1 - f) \tilde{\Gamma}_2(\sigma_{ct}, \mu_2, \gamma_2, \beta_2) \quad (4.33)$$

where, the Gamma distributions can be defined as,

$$\tilde{\Gamma}(\sigma_{ct}, \mu, \gamma, \beta) = \frac{(\sigma_{ct} - \mu)^{\gamma-1} \cdot e^{-(\sigma_{ct} - \mu)/\beta}}{\Gamma(\gamma) \cdot \beta^\gamma} \quad (4.34)$$

The gamma function $\Gamma(\gamma) = (\gamma - 1)!$, μ , γ and β three shape parameters, and f is the probability of occurrence of the first Gamma in the model. Fitted distributions for MC samples are shown in Figure 4.29.

4.4.6 Tag model

The tag decision PDF is defined as

$$P(\xi_{\text{tag}}) = \begin{cases} 1 - \epsilon_{\text{tag}}, & \text{if tag} = 0 \\ \epsilon_{\text{tag}}(1 + A_{\text{tag}})/2, & \text{if tag} = +1 \\ \epsilon_{\text{tag}}(1 - A_{\text{tag}})/2, & \text{if tag} = -1 \end{cases} \quad (4.35)$$

⁹The norm of the $\mathbf{X}$ is the Frobenius norm, and is different from $\mathbf{L}_2$ norm, which is the $\sqrt{\text{largest eigenvalue}}$ of the corresponding matrices involved (although of course they would generate the same topology)

¹⁰<https://root.cern.ch/doc/master/classRooGamma.html>

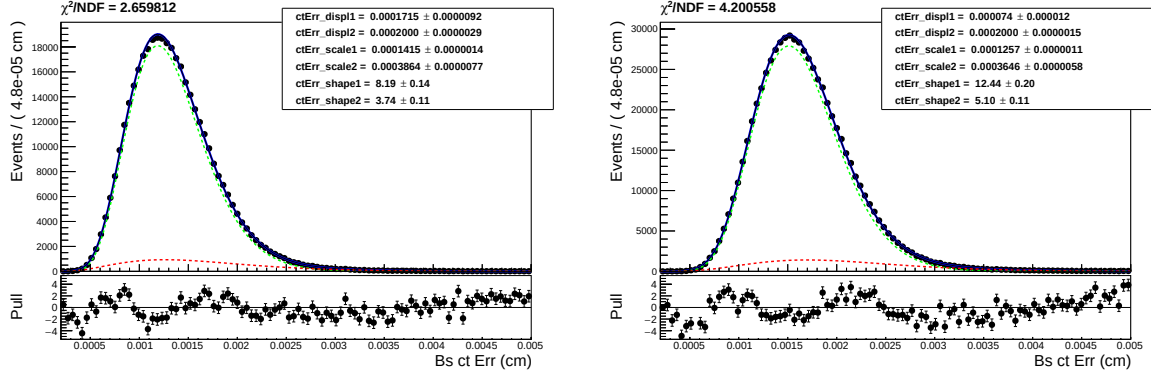


Figure 4.29: Lifetime uncertainty distribution measured in 2017 MC (left) and 2018 MC (right) samples, after offline selection.

which is the algebraic rearrangement of tagging efficiency: ϵ_{tag} , and the tagging asymmetry : A_{tag} defined as,

$$A_{\text{tag}} = \frac{N(\xi_{\text{tag}} = +1) - N(\xi_{\text{tag}} = -1)}{N(\xi_{\text{tag}} = +1) + N(\xi_{\text{tag}} = -1)}.$$

The tagging asymmetry should be very small (ideally zero). In the simulated signal sample the measured value is compatible with zero, $A_{\text{tag}} = (2.3 \pm 1.8) \cdot 10^{-3}$. The backgrounds tag models are defined in a similar way, but with different ϵ_{tag} and A_{tag} .

4.4.7 Background models

$B_d^0 \rightarrow J/\psi K^{*0}$ Veto

For a precise measurements corresponding to each parameter involved in only B_s^0 signal events, an efficiency control on the background events is necessary. The main source of backgrounds which contributes within the reconstructed kinematic region of $B_s^0 \rightarrow J/\psi \phi$ decay are B^0 , B^+ , Λ_b , and the B_c . B_c cross section is expected to be very small that does not contribute significantly and hence neglected. Also the fully reconstructed charmless decays are very small, so that the main source of the background boil downs to the combinatorial one. This background is sourced when one or more particles from the PV misassociated to the SV ($b\bar{b}$, partial B reconstruction), and the decays of Z^0 into lighter quarks. The other source of the background is the peaking background due to $B^0 \rightarrow J/\psi K^{*0} \rightarrow \mu^+ \mu^- K^+ \pi^-$ decays. Topologically equivalent $B_d^0 \rightarrow J/\psi K^{*0}$, and $B_s^0 \rightarrow J/\psi \phi$ decays are impossible

to separate out from each other due to the absence of the particle identification technique in CMS. Within the mass distribution of B_s^0 the background from mis-reconstructed B_d^0 appears to be broad in the peak region. The study of the overlap of mis-reconstructed B_d^0 and K^{*0} mass from both B_s^0 and B_d^0 signal samples are performed and it appears to be fallen on each other as shown in Figure 4.30. These two sources of the background events are modeled with the similar PDFs except mass. The main combinatorial background PDFs are pre-fitted to mass sidebands and the PDFs parameters will be floating freely in the final multidimensional fit. The peaking background PDFs, are modeled in MC samples and fixed in Data.

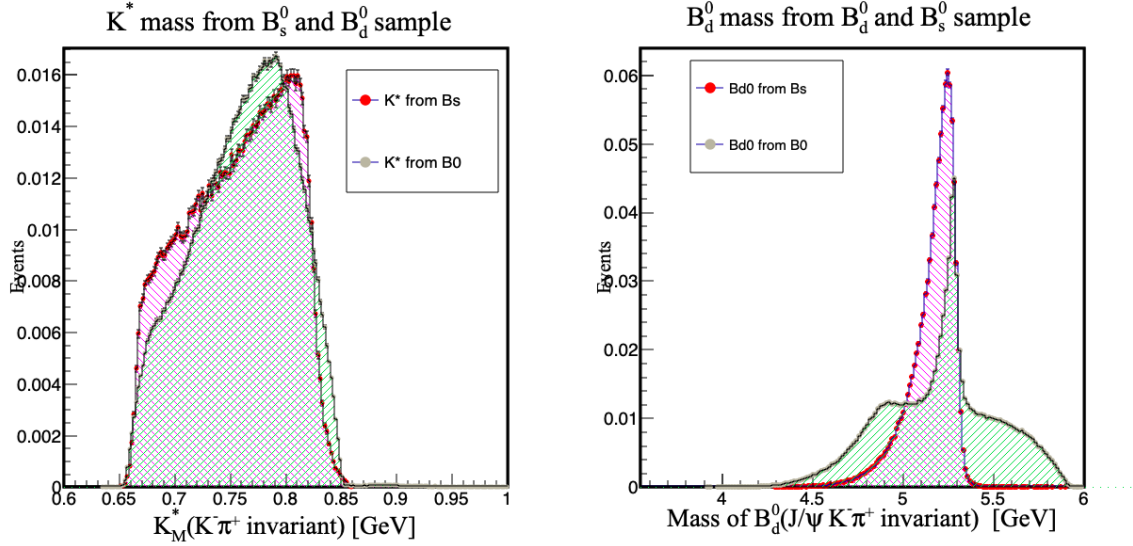


Figure 4.30: Comparison of K^{*0} mass and B_d^0 mass from B_d^0 and B_s^0 MC signal sample.

Main combinatorial background

Re-writing the total combinatorial background PDFs defined in Equation 4.36,

$$P_{\text{comb}} = f_{\text{comb}} P_{\text{comb}}(\cos \theta_T, \phi_T) P_{\text{comb}}(\cos \psi_T) P_{\text{comb}}(ct) P_{\text{comb}}(m_{B_s^0}) P_{\text{comb}}(\sigma_{ct}) P(\xi). \quad (4.36)$$

shows that there are several components contributing to the background PDF corresponding to each kinematic observable present in the B_s^0 decay. The background PDF $P_{\text{bkg}}(\Theta)$ for

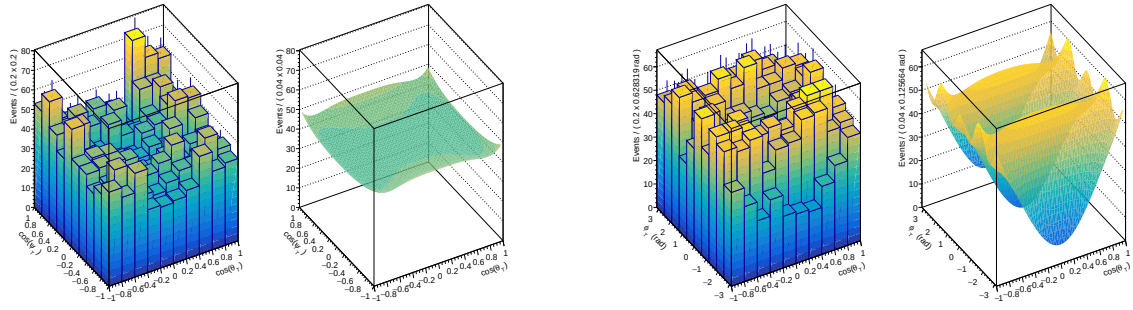
the Angular variables is similar to the old model used in the ϕ_s Run-1 measurement. The factorizing $P_{\text{bkg}}(\Theta)$ and explicit components are shown in the Equation 4.37.

$$\begin{aligned}
P_{\text{comb}}(\Theta) &= P_{\text{comb}}(\cos \theta_T, \phi_T) P_{\text{comb}}(\cos \psi_T) \\
P_{\text{comb}}(\cos \psi_T) &= 1/2 + k_1 P_2(\cos \psi_T) + k_2 P_4(\cos \psi_T) \\
P_{\text{comb}}(\cos \theta_T, \phi_T) &= 1/2 + k_3 P_2(\cos \theta_T) + k_4 P_6(\cos \theta_T) + k_5 \cos(2\phi_T) \\
&\quad + k_6 \cos(4\phi_T) + k_7 \cos(6\phi_T) + k_8 P_2(\cos \theta_T)(\sin^2 \phi_T - 1/2) \\
&\quad + k_9 P_4(\cos \theta_T)(\sin^2 \phi_T - 1/2) + k_{10} P_2(\cos \theta_T)(\sin^4 \phi_T - 3/8).
\end{aligned} \tag{4.37}$$

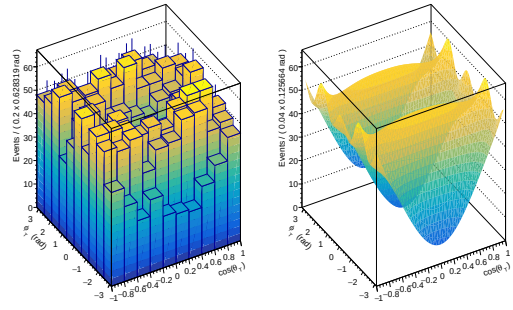
The $P_i(x)$ s are the Legendre polynomials of order i and k_j the PDF parameters. The model is fitted to angular variables extracted from Data in the sideband regions of the mass $\text{SB}_L = [5.24, 5.28] \text{ GeV}$ $\text{SB}_R = [5.45, 5.49] \text{ GeV}$. The two-dimensional projection of the fitted function and the sideband histograms are shown in Figure 4.31. The 3D χ^2 is measured to be $\chi^2/\text{d.o.f.} = 1.29$ using a $(10 \times 10 \times 10)$ 3D binning, by adopting the assumption that $P_{\text{comb}}(\Theta)$ is the same for 2017 and 2018 samples. This assumed hypothesis is tested by measuring the 3D χ^2 explicitly for the 2017 and 2018 Data samples, and it is observed that the $3D \chi^2 \in \{\chi^2/\text{d.o.f.}(2017) = 0.95, \chi^2/\text{d.o.f.}(2018) = 1.21\}$. The normalized χ^2 is close to 1.0 in both years, which leads toward the conclusion that $P_{\text{comb}}(\Theta)$ is the description of the angular functions for both years of data taking. The main combinatorial background proper decay time PDF $P_{\text{bkg}}(ct)$ is modeled with two decreasing exponential distributions,

$$P_{\text{bkg}}(ct) = [p_1 \exp(-p_2 \cdot ct) + (1 - p_1) \exp(-p_3 \cdot ct)]. \tag{4.38}$$

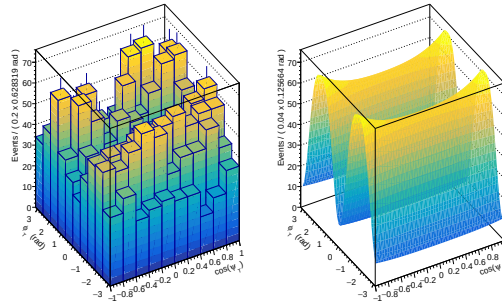
The p_i are the extracted PDF parameters in likelihood fit to the ct obtained by applying sidebands technique. The fit parameters of $P_{\text{comb}}(ct)$ parameters do not differ by more than one standard deviation when fitted to two years of Data. The overall background lifetime PDF is shown in Figure 4.32. The main background mass PDF $P_{\text{bkg}}(m_{B_s^0})$ is a single exponential function as described in the Equation 4.39, where h_i are the PDF parameters.



(a) $\cos \theta_T : \cos \psi_T$ projection.



(b) $\cos \theta_T : \phi_T$ projection.



(c) $\cos \psi_T : \phi_T$ projection.

Figure 4.31: Two-dimensional $P_{\text{bkg}}(\Theta)$ projections (right) and histograms from mass side-bands (left).

$$P_{\text{bkg}}(m_{B_s^0}) = h_1 \exp(h_2 \cdot m_{B_s^0}). \quad (4.39)$$

$$P_{\text{bkg}}(\sigma_{ct}) = f\text{Gamma}_1(\sigma_{ct}, \mu_1, \gamma_1, \beta_1) + (1 - f)\text{Gamma}_2(\sigma_{ct}, \mu_2, \gamma_2, \beta_2). \quad (4.40)$$

The σ_{ct} distribution is fitted with double Gamma PDF, the one dimensional fit to the side-bands is shown in Figure 4.33.

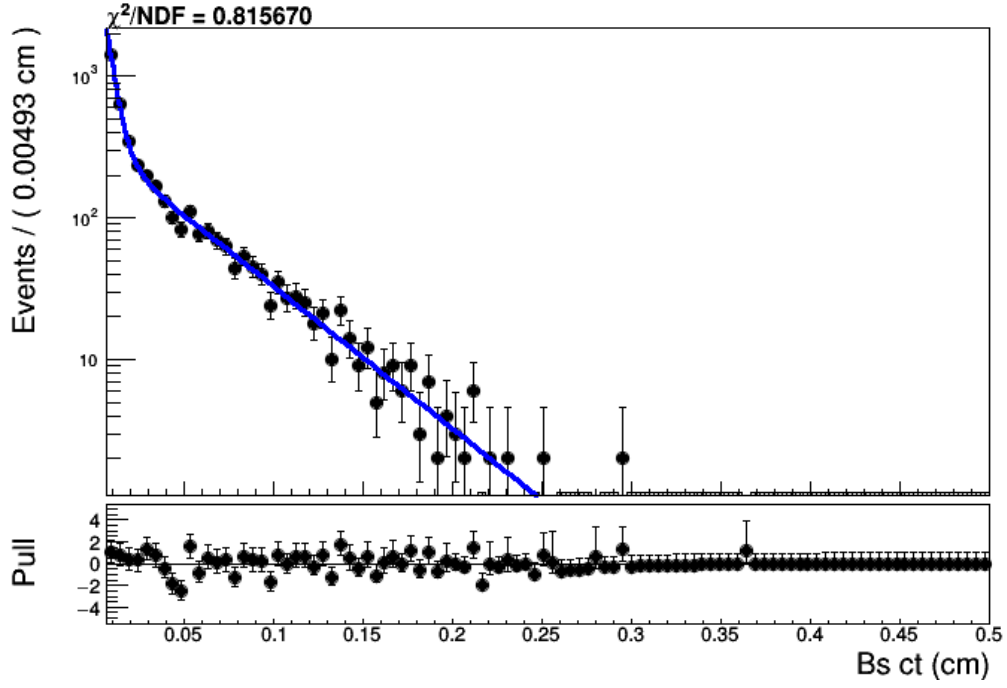


Figure 4.32: Background lifetime PDF $P_{\text{comb}}(ct)$.

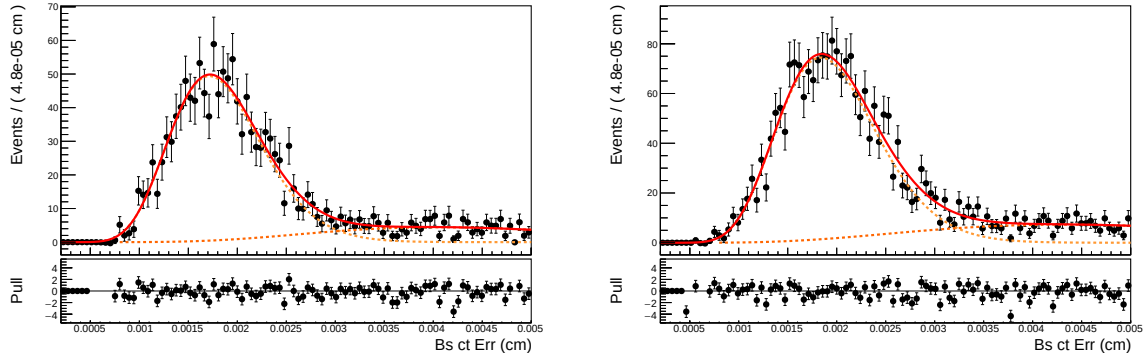


Figure 4.33: Lifetime uncertainty distribution measured in 2017 (left) and 2018 (right) data sidebands. Missing pulls are plotting artefacts due to the signal subtraction procedure which pushes some bins below zero.

Peaking background

The background is sourced by $B^0 \rightarrow J/\psi K^{*0} \rightarrow \mu^+ \mu^- K^+ \pi^-$ decay process, the PDFs are constructed by using the simulated signal $B^0 \rightarrow J/\psi K^{*0}$ samples.

$$P_{\text{peak}} = P_{\text{peak}}(\cos \theta_T, \phi_T) P_{\text{peak}}(\cos \psi_T) P_{\text{peak}}(ct) P_{\text{peak}}(m_{B_s^0}) P_{\text{peak}}(\sigma_{ct}) P(\xi)_{\text{peak}}. \quad (4.41)$$

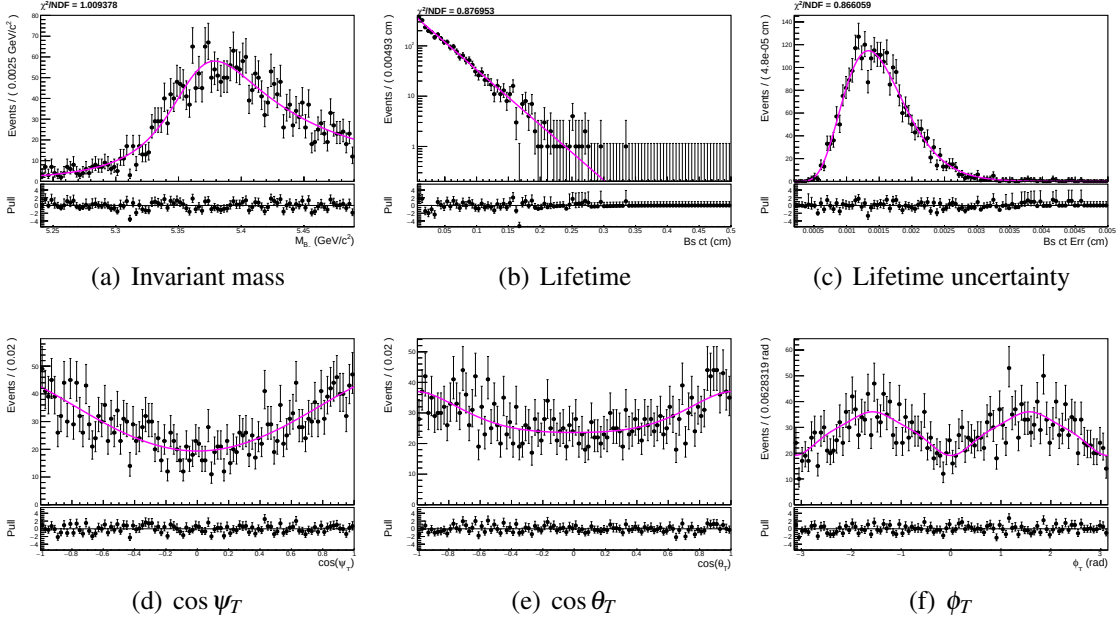


Figure 4.34: Projections of peaking background PDFs on the kinematic observable distributions using simulated $B^0 \rightarrow J/\psi K^{*0} \rightarrow \mu^+ \mu^- K^+ \pi^-$ events.

$$N_{\text{peak}}^{\text{Data}} = N_{\text{peak}}^{\text{MC}} \frac{\mathcal{L}_{\text{int}}^{\text{Data}}}{\mathcal{L}_{\text{int}}^{\text{MC}}} . \quad (4.42)$$

The $P_{\text{peak}}(m_{B_s^0})$ is the single Johnson distribution similar as one of the signal B_s^0 decays, and the angular PDF $P_{\text{peak}}(\Theta)$ is similar as the combinatorial background PDF¹¹. The ct is modelled with $P_{\text{peak}}(ct)$, which is single decreasing exponential distribution, and $P_{\text{peak}}(\sigma_{\text{ct}})$ is assumed to have the same shape as the signal σ_{ct} distribution due to the similarity of the decays. The expected even yield in data is estimated separately for both 2017 and 2018 years, using the MC sample integrated luminosity, as describes in the Equation 4.42 resulting in 1151 and 1640 events, respectively for 2017 and 2018. A six dimensional fit is performed on the $B^0 \rightarrow J/\psi K^{*0} \rightarrow \mu^+ \mu^- K^+ \pi^-$ MC samples and the projections of each PDFs are shown in Figure 4.34.

¹¹Different set of parameter values.

4.5 Fit to simulated samples

4.5.1 Fit to GEN sample

The decay rate is modeled by EVTGEN model file and it is limited to generate the P-wave. The mathematical model for the decay rate is constructed in such a way that it can fit both P-wave and S-wave explicitly and also taking into account both at the same real time. Since, the generator level information is extracted by using the particle identification technique comprises only the P-wave, a fit is performed to validate the P-wave decay rate model by using generator level observables. The P-wave *only* differential decay rate does not include B_s^0 mass, background, mistag, lifetime uncertainty and S-wave¹² PDF's along with lifetime and angular efficiencies. The fit result is reported in Table 4.9. The correlation matrix in the last plot Figure 4.35 shows strong correlation between ct and $\Delta\Gamma_s$, advocated by the numerics reported in Table 4.10. The estimated pulls are large in the strong phases ($\delta_{\parallel}$, $\delta_{\perp}$). This fit is performed on large GEN statistics (~ 8.5 million), and in such type of high precision fit, it is concluded that the fitted values are approximately in agreement with the initial production values used for the event generation¹³.

Parameter	Set value	Fit value	Pull [s.d.]
$ A_0 ^2$	0.600625	0.5999 ± 0.0003	-2.3
$ A_{\perp} ^2$	0.16	0.1600 ± 0.0004	+0.0
ct [μm]	441.2945	441.2 ± 0.3	-0.2
$\Delta\Gamma_s$ [1/cm]	0	-0.03 ± 0.04	-0.6
$\delta_{\parallel}$ [rad]	2.5	2.488 ± 0.002	-6.5
$\delta_{\perp}$ [rad]	-0.17	-0.181 ± 0.003	-4.1
Δm_s [$\hbar/\text{cm}$]	593.74408	593.70 ± 0.04	-1.1
$ \lambda $	1	0.9994 ± 0.0005	-1.1
ϕ_s [rad]	-0.04	-0.0403 ± 0.0007	-0.5

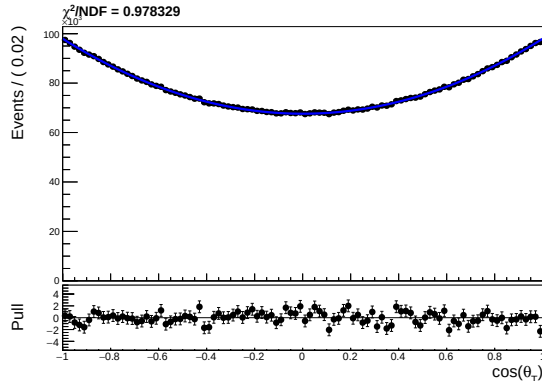
Table 4.9: Results of the maximum likelihood performed using GEN information, the reported uncertainties are statistical estimated by the likelihood function itself.

¹²Since, the S-wave is not simulated in EVTGEN.

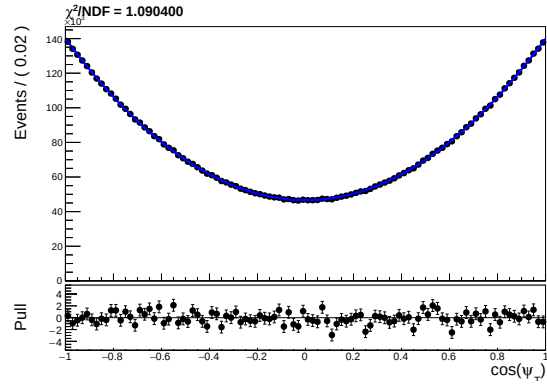
¹³MC set value: The generic nomenclature used in the experimental high energy physics.

	$ A_0 ^2$	$ A_\perp ^2$	ct	$\Delta\Gamma_s$	$\delta_\parallel$	$\delta_\perp$	Δm_s	$ \lambda $	ϕ_s
$ A_0 ^2$	1	-0.588	+0.524	+0.599	+0.015	+0.006	-0.005	+0.002	+0.043
$ A_\perp ^2$		1	-0.564	-0.645	+0.202	+0.095	+0.009	-0.02	-0.059
ct			1	+0.875	+0.000	-0.006	-0.005	+0.003	+0.055
$\Delta\Gamma_s$				1	-0.000	-0.007	-0.006	+0.003	+0.063
$\delta_\parallel$					1	+0.408	+0.009	-0.000	-0.009
$\delta_\perp$						1	+0.647	-0.058	-0.005
Δm_s							1	-0.093	-0.003
$ \lambda $								1	+0.018
ϕ_s									1

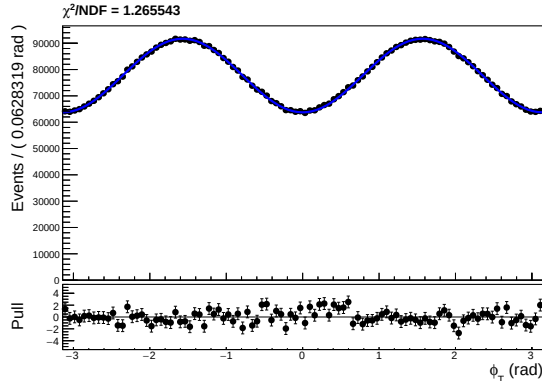
Table 4.10: Statistical correlation matrix of the maximum likelihood performed using GEN information.



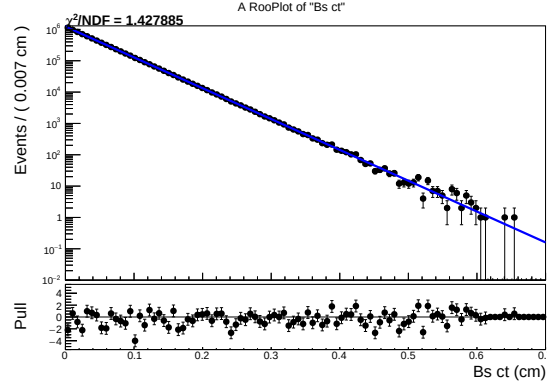
(a) $\cos \theta_T$



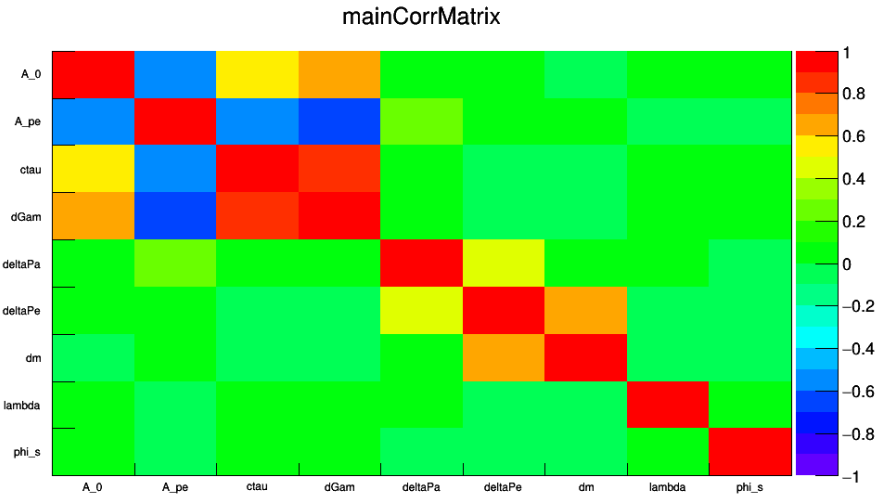
(b) $\cos \psi_T$



(c) ϕ_T



(d) ct



(e) Correlation matrix

Figure 4.35: Fit to generator level events: PDF projection on $\cos \theta_T$, $\cos \psi_T$, ϕ_T , ct , and the pictorial status of the statistical correlation matrix.

4.5.2 Fit to $\Delta\Gamma_s = 0$ samples

The angular efficiencies are estimated by using the 2017 and 2018 $\Delta\Gamma_s = 0$ MC samples respectively, it is assumed that the efficiencies are constant throughout the year. In general the pp collision Data is collected in era basis where the MC samples are produced by applying the average detector condition over the year. The central MC production¹⁴ does not include era by era detector condition, and this is the reason that the angular efficiencies are not calculated in bins of lifetime, hence, those are apparent angular efficiencies so as the ct efficiencies. To validate the lifetime and angular efficiencies simultaneous fit is employed by exploiting the P-wave signal model over the 2017 and 2018 $\Delta\Gamma_s = 0$ MC samples. These are the same MCs which were earlier employed to estimate the efficiencies. The fit is performed on RECO variables with the full signal PDF. The simultaneous fit result is reported in Table 4.11, while the correlation matrix is depicted in Figure 4.36, numerics in Table 4.12. The parameters of interest are reported, the deviation of the fit values with respect to the production values are reasonable considering the very large statistics of the sample. Efficiencies of individual years are validated by performing explicit fit to each year MC samples. The PDF projections on the angular and lifetime variables are shown in Figure 4.37 and 4.38. The agreement is overall very good with χ^2 of the order of 1 for all distribution. The obtained ct value is in agreement with the MC production value.

Parameter	Set value	Fit value	Pull [s.d.]
$ A_0 ^2$	0.600625	0.6072 ± 0.0009	+7.2
$ A_\perp ^2$	0.16	0.156 ± 0.001	-3.4
ct [μm]	441.2945	443 ± 1	+1.7
$\Delta\Gamma_s$ [1/cm]	0	0.3 ± 0.1	+1.9
$\delta_\parallel$ [rad]	2.5	2.519 ± 0.007	+2.6
$\delta_\perp$ [rad]	-0.17	-0.24 ± 0.04	-1.9
Δm_s [$\hbar/\text{cm}$]	593.74408	592.1 ± 0.6	-2.7
$ \lambda $	1	1.018 ± 0.006	+2.9
ϕ_s [rad]	-0.04	-0.053 ± 0.009	-1.5

Table 4.11: Simultaneous fit to $\Delta\Gamma_s = 0$ samples results. Uncertainties are statistical only.

¹⁴CMS Monte Carlo production group produces and validates the required samples for the physics analysis. The sample produced by the CMS MC production group is termed as the central MC production.

	$ A_0 ^2$	$ A_\perp ^2$	ct	$\Delta\Gamma_s$	$\delta_\parallel$	$\delta_\perp$	Δm_s	$ \lambda $	ϕ_s
$ A_0 ^2$	+1	-0.620	+0.604	+0.679	-0.005	+0.007	+0.004	0.000	+0.010
$ A_\perp ^2$		+1	-0.608	-0.681	+0.322	+0.025	-0.002	+0.001	-0.019
ct			+1	+0.888	-0.010	+0.009	+0.005	-0.001	+0.011
$\Delta\Gamma_s$				+1	-0.009	+0.010	+0.006	0.000	+0.011
$\delta_\parallel$					+1	+0.098	+0.004	+0.004	-0.011
$\delta_\perp$						+1	+0.778	-0.191	-0.054
Δm_s							+1	-0.186	-0.068
$ \lambda $								+1	+0.005
ϕ_s									+1

Table 4.12: Simultaneous fit to $\Delta\Gamma_s = 0$ samples statistical correlation matrix.

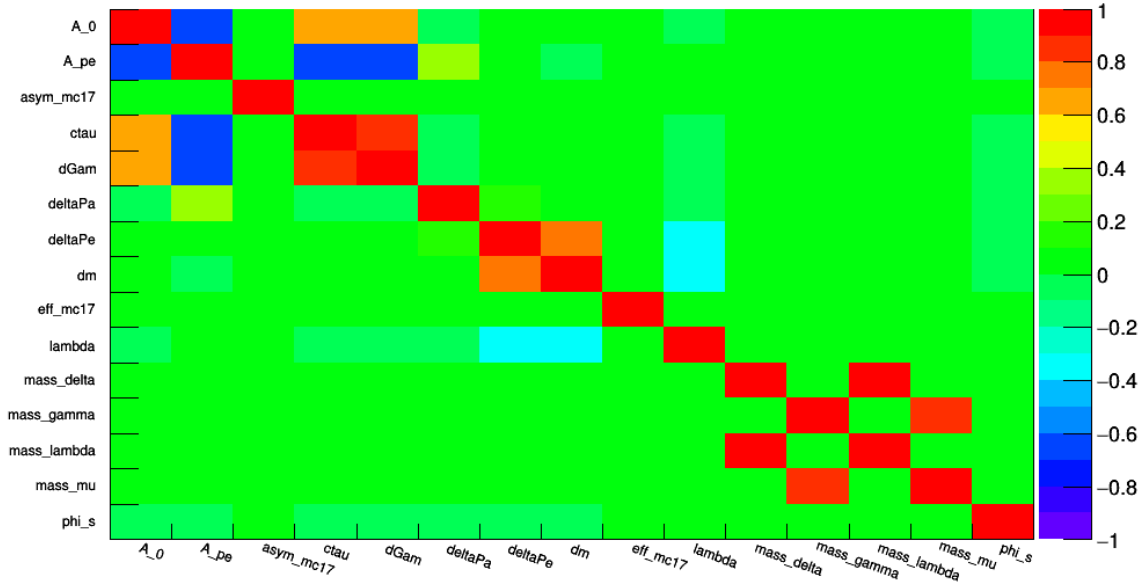


Figure 4.36: Simultaneous fit to $\Delta\Gamma_s = 0$ samples: statistical correlation matrix.

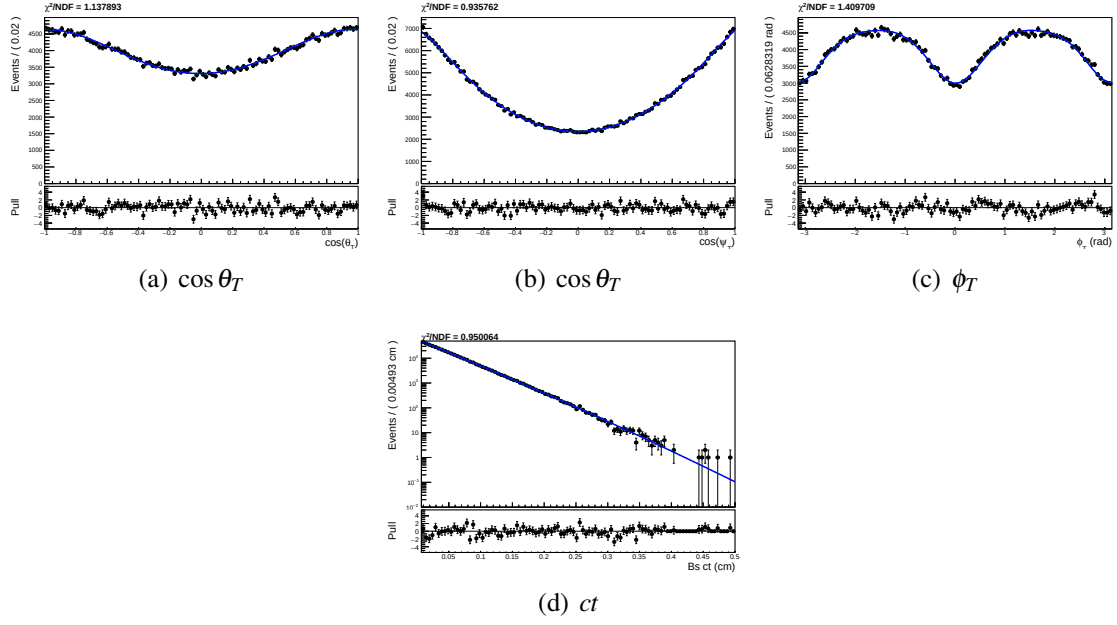


Figure 4.37: Fit to $\Delta\Gamma_s = 0$ 2017 MC sample: PDF projection on $\cos \theta_T$ (a), $\cos \psi_T$ (b), ϕ_T (c), and ct (d).

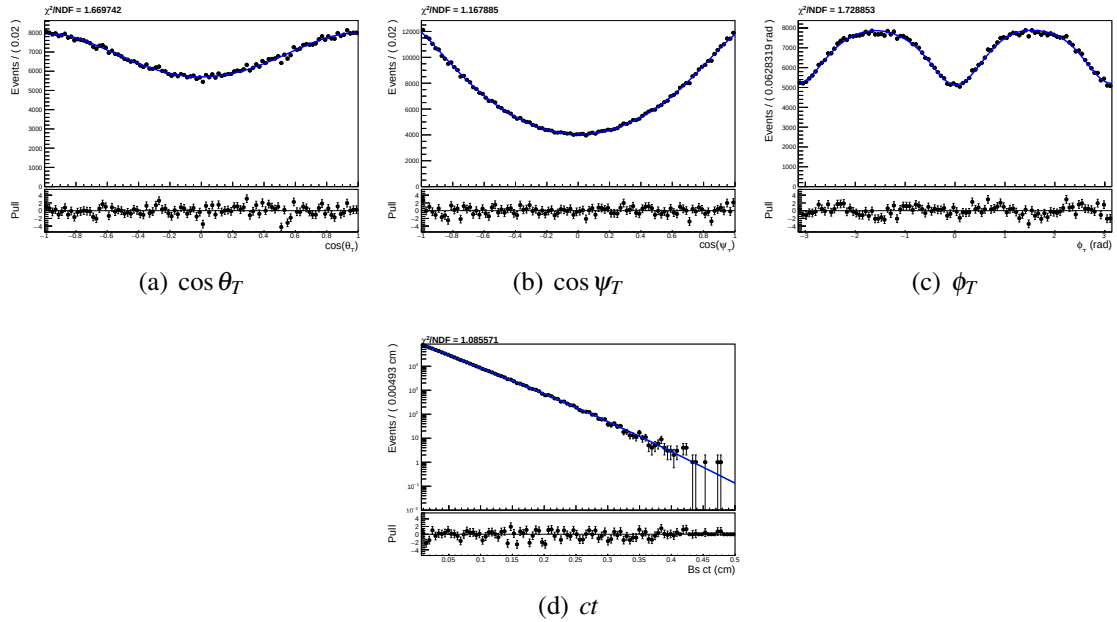


Figure 4.38: Fit to $\Delta\Gamma_s = 0$ 2018 MC sample: PDF projection on $\cos \theta_T$ (a), $\cos \psi_T$ (b), and ϕ_T (c).

4.5.3 Efficiency closure test

P-Wave study

The P-wave simulated signal MC samples for $B_s^0 \rightarrow J/\psi \phi$ decay process are generated with a finite decay width difference, implies $\Delta\Gamma_s \neq 0$, and represents a simulation of the signal events expected in Data. The efficiency closure test is performed on simulated signal samples using the efficiency corrected tagged P-wave model. It is expected that the closure test should return the same numerical values of the physics parameters equal to MC production values as fit results. Two important things need to be mentioned here. One, theoretically the $\Delta\Gamma_s \neq 0$ simulated signal samples do not allow to factorize the angular and ct terms in the model. Since, the angular efficiencies are apparent and no correlation has taken into account between Θ and ct , in the final tagged P-wave model the efficiencies are factorized, $\varepsilon(\Theta, ct) \simeq \varepsilon(\Theta) \cdot \varepsilon(ct)$. Secondly, a successive approach is taken while implementing the tag starting from the GenTag (pure B_s^0 or $\bar{B}_s^0$), RecoTag with fixed mistag fraction, and then optimized per-event mistag ω_{evt} in order to adopt all tag related issues toward the evolution of the final model. A simultaneous fit validates the efficiency closure test using tagged P-wave signal model over the 2017 and 2018 simulated signal samples. The fit results of corresponding physics parameters are reported in Table 4.13, and the correlation matrix in Figure 4.39 of which the numerical values are reported in Table 4.14. It is observed that the overall fit result is in good agreement for all parameters except for $|A_0|^2$. Taking into consideration the very high statistics of the sample, and the fact that systematics are yet to be evaluated, this deviation will not play significant role in the final measurement.

S-Wave study

The simulation of the signal MC sample does not include any S-wave component, and the tagged P-wave model does not include the S-wave component as well. The efficiency closure test including the S-wave is the test of the parametric value of S-wave amplitude $|A_S|^2$ should be zero in the simultaneous fit. The simultaneous fit using P+S-wave tagged

Parameter	Set value	Fit value	Pull [s.d.]
$ A_0 ^2$	0.522729	0.529 ± 0.001	+5.3
$ A_\perp ^2$	0.246016	0.244 ± 0.002	-1.2
ct [μm]	441.2945	441.4 ± 0.8	+0.1
$\Delta\Gamma_s$ [1/cm]	2	2.0 ± 0.1	-0.3
$\delta_\parallel$ [rad]	3.14	3.19 ± 0.05	+1.2
$\delta_\perp$ [rad]	3.14	3.07 ± 0.05	-1.4
Δm_s [$\hbar/\text{cm}$]	593.74408	593.2 ± 0.7	-0.7
$ \lambda $	1	1.004 ± 0.009	-0.7
ϕ_s [rad]	-0.04	-0.05 ± 0.01	-0.5

Table 4.13: Simultaneous fit to simulated signal samples results. Uncertainties are statistical only.

	$ A_0 ^2$	$ A_\perp ^2$	ct	$\Delta\Gamma_s$	$\delta_\parallel$	$\delta_\perp$	Δm_s	$ \lambda $	ϕ_s
$ A_0 ^2$	+1	-0.644	+0.439	+0.663	+0.001	+0.005	+0.006	-0.005	+0.029
$ A_\perp ^2$		+1	-0.498	-0.714	-0.146	-0.075	-0.006	-0.012	-0.034
ct			+1	+0.640	+0.019	+0.014	+0.006	-0.002	+0.029
$\Delta\Gamma_s$				+1	+0.012	+0.012	+0.01	-0.006	+0.032
$\delta_\parallel$					+1	+0.499	+0.014	+0.115	+0.007
$\delta_\perp$						+1	+0.68	+0.15	-0.014
Δm_s							+1	+0.045	-0.023
$ \lambda $								+1	+0.031
ϕ_s									+1

Table 4.14: Simultaneous fit to simulated signal samples statistical correlation matrix.

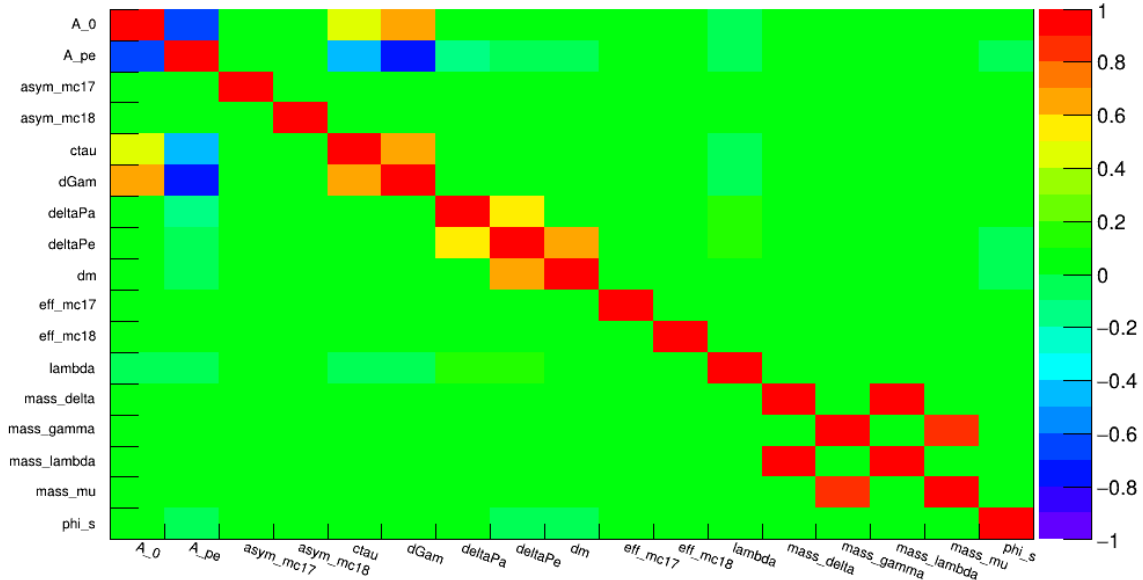


Figure 4.39: Simultaneous fit to signal samples: statistical correlation matrix.

signal model shows it does not *pick up* any non-existent S-wave, and the fit result of $|A_S|^2$ is compatible with zero. The results corresponding other physics parameters are in excellent agreement with those of the P-wave-only fit as reported in the Table 4.15 along with correlation matrix in the Figure 4.40. Adding S-wave component is also a measure of the sensitiveness of the tagged S+P-wave full model toward the non existent S-wave component at the MC production level.

Parameter	Set value	Fit value (P-wave)	Fit value (S+P-wave)
$ A_0 ^2$	0.522729	0.529 ± 0.001	0.5292 ± 0.0009
$ A_\perp ^2$	0.246016	0.244 ± 0.002	0.244 ± 0.001
$ A_S ^2$	—	—	$(0 \pm 1) \cdot 10^{-3}$
ct [μm]	441.2945	441.4 ± 0.8	441.4 ± 0.6
$\Delta\Gamma_s$ [1/cm]	2	2.0 ± 0.1	1.96 ± 0.09
$\delta_\parallel$ [rad]	3.14	3.19 ± 0.05	3.19 ± 0.04
$\delta_\perp$ [rad]	3.14	3.07 ± 0.05	3.07 ± 0.03
$\delta_{S\perp}$ [rad]	—	—	2 ± 9
Δm_s [$\hbar/\text{cm}$]	593.74408	593.2 ± 0.7	593.2 ± 0.5
$ \lambda $	1	1.004 ± 0.009	1.004 ± 0.008
ϕ_s [rad]	-0.04	-0.05 ± 0.01	-0.05 ± 0.01

Table 4.15: Simultaneous S+P wave fit to simulated signal samples results. Uncertainties are statistical only.

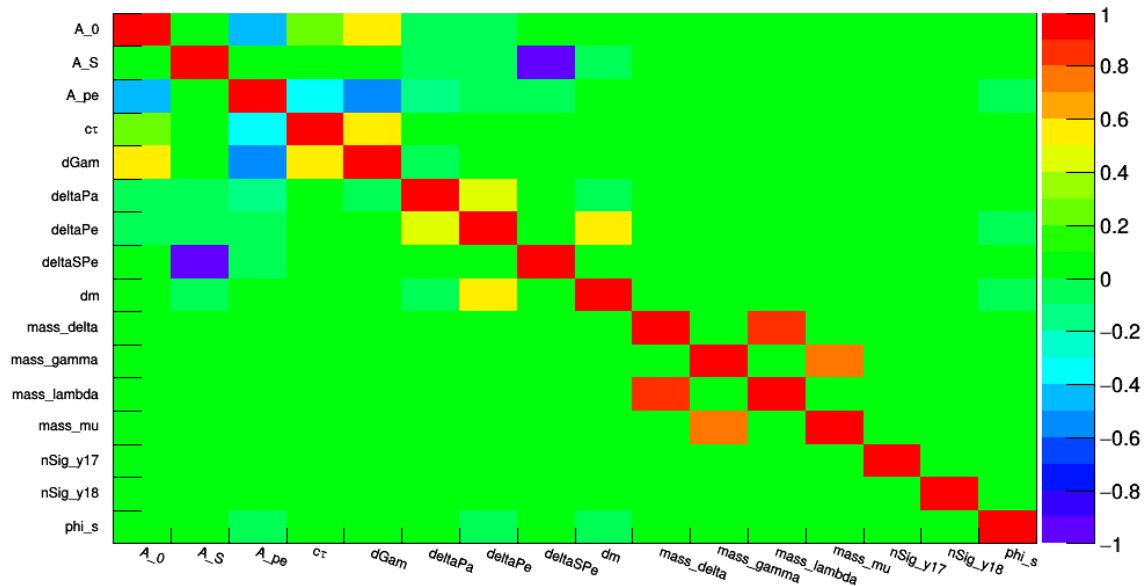


Figure 4.40: Simultaneous fit to signal samples: statistical correlation matrix.

4.5.4 Self consistency of the *tagged* signal model

The sensitivity on ϕ_s need to be enhanced. In order to that the mistag fraction ω_{evt} in included in per-event fashion into the signal model. Apart from this the mass, σ_{ct} PDFs are included to model externally. In such kind multidimensional maximum likelihood fit it is not easy to draw any conclusion regarding the bias of the fit parametric space. To study possible biases in the fitting procedure a MC pseudo-experiments is performed. This method first generates events corresponding to each parameter according to a given model and then fit the generated events using the same base model. Using the fitted B_s^0 signal model in the simulated sample, first, 1000 toy experiments are generated each consistent to 100k events (twice the data signal statistics), and then a fit is employed on the toy samples to study the distribution of the estimated parameters. The S-wave components (terms $i = 7, 8, 9, 10$ of Table 4.8) is also injected. The input parametric space corresponding to pseudo experiments is reported in Table 4.16. Toy generation includes mistag model which does not have a PDF in the fitted distributions. The mistag probability ω_{tag} is modeled with the conditional PDF $P_{\text{tag}}^{\text{KDE}}(\omega_{\text{tag}})$ as shown in Equation 4.43 is evaluated with a KDE¹⁵ method. The RooKeysPdf RooFit class is used with default parameters $\delta(0.5)$, which is a Dirac Delta distribution centered in 0.5. The mistag PDF for tagged events is shown in Figure 4.41. For each fitted parameter V , the pull distribution are plotted.

$$P(\omega_{\text{tag}}) = \begin{cases} P_{\text{tag}}^{\text{KDE}}(\omega_{\text{tag}}), & \text{if tagged event} \\ \delta(0.5), & \text{if untagged event} \end{cases} \quad (4.43)$$

$$\delta V = \text{pull}(V) = \frac{V_{\text{set}} - V_{\text{fit}}}{\sigma_{\text{fit}}}. \quad (4.44)$$

In absence of any bias in the fit model the pull distributions for each variables should converge to a standard normal distribution. Figure 4.42 describes δV distributions. The pull distribution standard deviation is ~ 1 for all the parameters, except for $\delta_{\parallel}$. Slight

¹⁵There will be explicit description of the definition and functionality of the KDE in the Appendix.

Parameter	Set value
$ A_0 ^2$	0.523
$ A_\perp ^2$	0.246
$ A_s ^2$	0.012
$\delta_\parallel$ [rad]	3.14
$\delta_\perp$ [rad]	3.14
$\delta_{s\perp}$ [rad]	0.188
ct [μm]	441.3
$\Delta\Gamma_s$ [cm^{-1}]	2
Δm_s [$\hbar \text{cm}^{-1}$]	593.74
$ \lambda $	1
ϕ_s [rad]	-0.04

Table 4.16: Input parametric space corresponding to signal only MC pseudo-experiment generation.

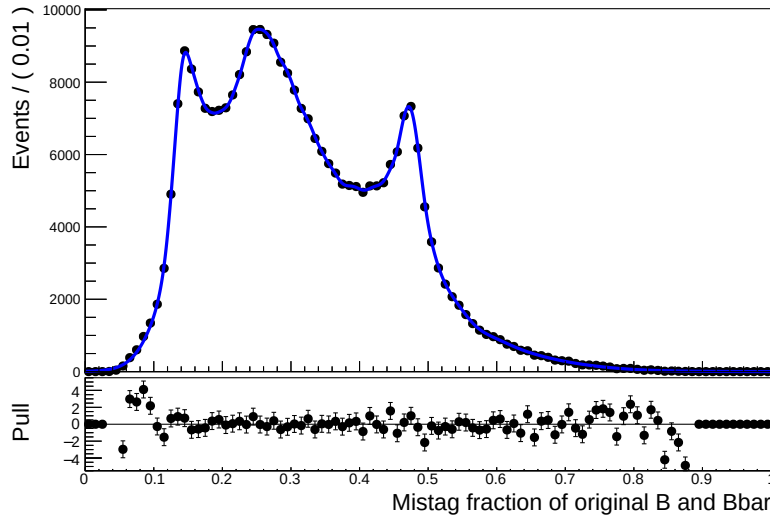


Figure 4.41: Mistag PDF for tagged events, evaluated in simulated signal samples.

biases are also observed in the central values of some parameters, such as, $|A_\perp|^2$, $\delta_\parallel$, $\Delta\Gamma_s$ and ϕ_s .

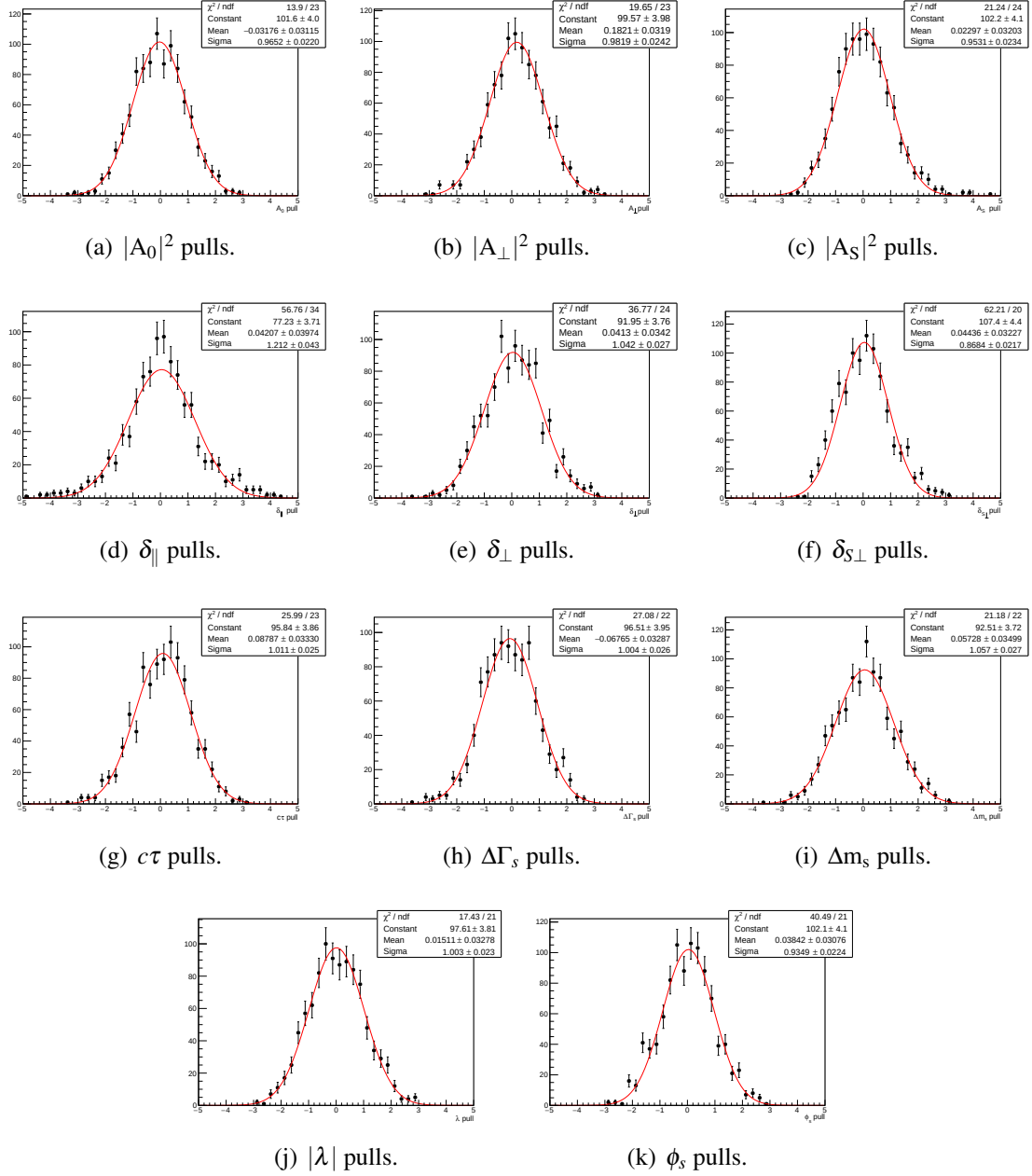


Figure 4.42: Signal-only toy MC pseudo-experiments pull distributions of fitted parameters as defined in Eq. 4.44.

4.6 Fit to Data

4.6.1 Step wise modelling

The data fit is the final step toward the final estimation of the physics parameter, especially the ϕ_s . All the methods discussed so far is the test of model description, its stability, evaluation of computing time and all that. The simultaneous fit on data is performed using the data samples listed in Table 4.1 and Table 4.3 with the model defined in Section 4.4.4. Since, peaking background event yield is fixed to the values obtained with Eq. 4.42, eventually the peaking background PDFs $P_{\text{peak}}(m_{B_s^0})$, $P_{\text{peak}}(\Theta)$, and $P_{\text{peak}}(ct)$ are fitted on MC samples and fixed. Prefits are performed to determine the initial guess values of the distributions parameters for the next steps. Signal distributions are prefitted after background subtraction [72], while background distributions are prefitted to the sidebands after signal and peaking background subtraction. If not stated otherwise, distributions are fitted simultaneously on 2017 and 2018 samples. The prefitted distributions are signal and background mass distribution, angular background distribution and ct background distribution. The σ_{ct} signal and backgrounds are separately prefitted for 2017 and 2018 samples respectively. It is already observed that the data-MC discrepancies in the σ_{ct} distributions, therefore simulated samples cannot be use to model $P_{\text{peak}}(\sigma_{ct})$ accurately. In this regard it is assumed that the peaking background is the same as the signal¹⁶, and finally $P_{\text{peak}}(\sigma_{ct})$ parameters are fixed to the ones of $P_{\text{sgn}}(\sigma_{ct})$. The μ and γ parameters related to mass PDF corresponding to $P_{\text{sgn}}(\sigma_{ct})$ and $P_{\text{comb}}(\sigma_{ct})$ are fixed to the prefit values. The lifetime uncertainty and mass distribution are fitted again with a 2D fit. The lifetime uncertainty is fitted separately for 2017 and 2018 samples, while the mass distribution is shared between years, then finally all $P_{\text{sgn}}(\sigma_{ct})$ and $P_{\text{bkg}}(\sigma_{ct})$ PDF parameter numerics obtained from 2D fit are fixed. Unless otherwise stated, letting all the parameters are left free to float in the final model and a simultaneous fit performed using 2017 and 2018 data. The result is reported in Table 4.17. The uncertainties are first estimated with HESSE and then checked with MINOS¹⁷. The

¹⁶This is verified in simulated sample by performing a separate fit

¹⁷Chapter7, section 7.2 <https://root.cern.ch/download/minuit.pdf>

MINOS results is reported for parameters with asymmetrical uncertainties. The Table 4.18 accounts the numerical values corresponding to the statistical correlation matrix shown in Figure 4.43, and the 1D projections of the PDFs are shown in Figure 4.44.

Parameter	Fit value
$ A_0 ^2$	0.5350 ± 0.0047
$ A_\perp ^2$	0.2337 ± 0.0063
$ A_S ^2$	$0.0224^{+0.0077}_{-0.0072}$
$\delta_\parallel$ [rad]	3.18 ± 0.12
$\delta_\perp$ [rad]	2.77 ± 0.16
$\delta_{S\perp}$ [rad]	$0.221^{+0.083}_{-0.070}$
ct [μm]	459.0 ± 3.0
$\Delta\Gamma_s$ [ps^{-1}]	0.114 ± 0.014
Δm_s [$\hbar \text{ps}^{-1}$]	$17.510^{+0.101}_{-0.089}$
$ \lambda $	0.972 ± 0.026
ϕ_s [rad]	-0.011 ± 0.050

Table 4.17: Final fit results using the full model on 2017 and 2018 Charmonium data, uncertainties are statistical.

	$ A_0 ^2$	$ A_\perp ^2$	$ A_S ^2$	$\delta_\parallel$	$\delta_\perp$	$\delta_{S\perp}$	ct	$\Delta\Gamma_s$	Δm_s	$ \lambda $	ϕ_s
$ A_0 ^2$	+1	-0.614	+0.147	-0.012	-0.008	-0.093	+0.315	+0.633	-0.006	+0.002	-0.010
$ A_\perp ^2$		+1	-0.112	-0.057	-0.001	+0.063	-0.423	-0.713	+0.016	-0.005	+0.009
$ A_S ^2$			+1	-0.070	-0.022	-0.438	-0.149	-0.002	+0.028	-0.033	-0.015
$\delta_\parallel$				+1	+0.271	-0.019	+0.025	+0.012	-0.008	-0.055	-0.017
$\delta_\perp$					+1	-0.098	-0.015	-0.013	+0.680	-0.177	-0.094
$\delta_{S\perp}$						+1	+0.047	-0.043	-0.046	+0.048	+0.026
ct							+1	+0.483	-0.029	+0.016	-0.002
$\Delta\Gamma_s$								+1	-0.020	-0.003	-0.019
Δm_s									+1	-0.142	-0.186
$ \lambda $										+1	+0.217
ϕ_s											+1

Table 4.18: Numerics of correlation matrix showing the correlation between physics parameters obtained in data fit.

4.6.2 Self consistency of *full* model

The full model comprises signal and background together along with S-wave components beside the only P-wave signal components. The full model is validated with MC pseudo-experiments (toys), as is done for the signal model in Section 4.5.4. To do this 1000 toy experiments are generated from the final data fit model. Each toy experiment is statistically identical to the data sample. In the next step each of the pseudo experiment is then fitted with the reference model in order to study the distribution of the estimated parameters. This

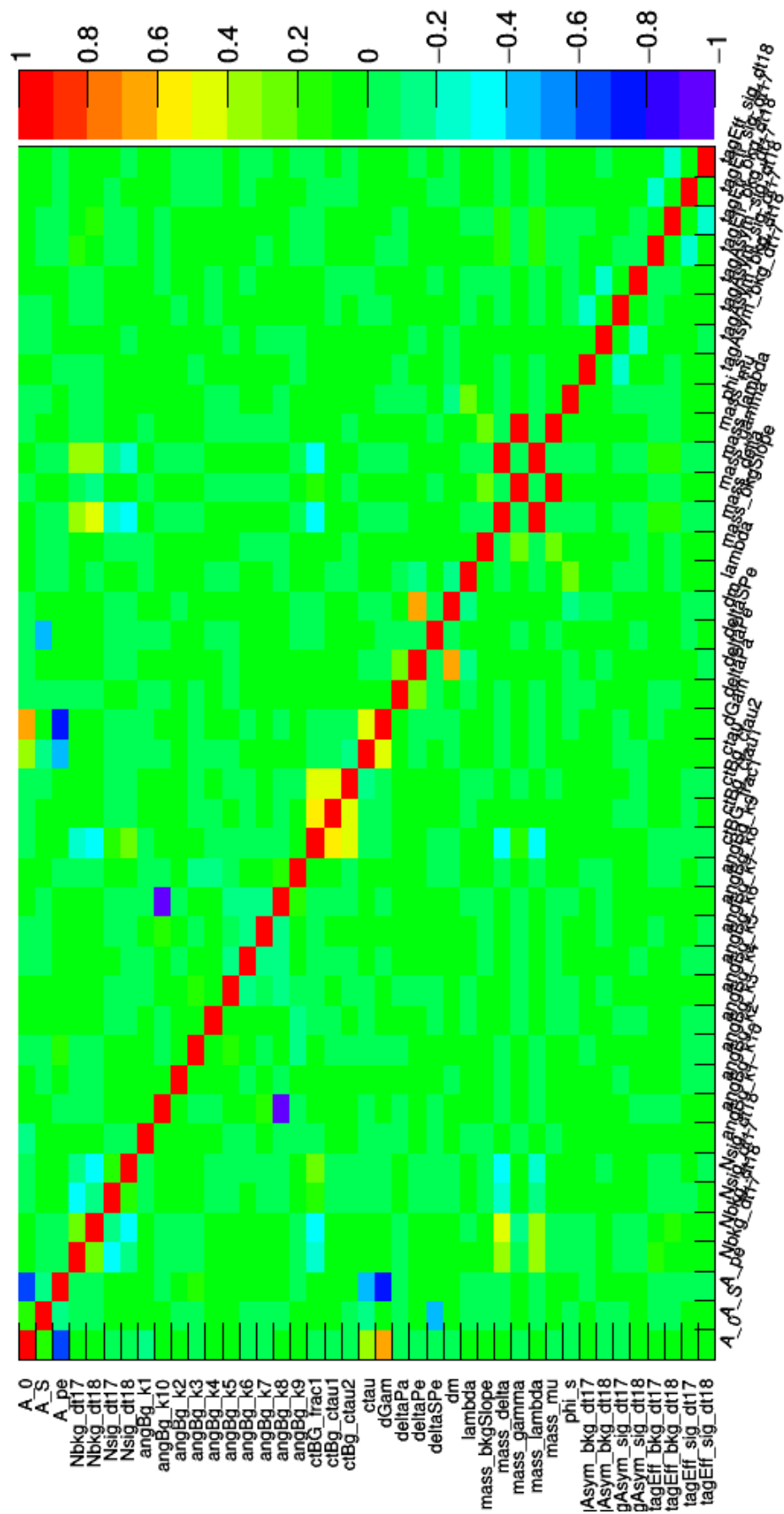
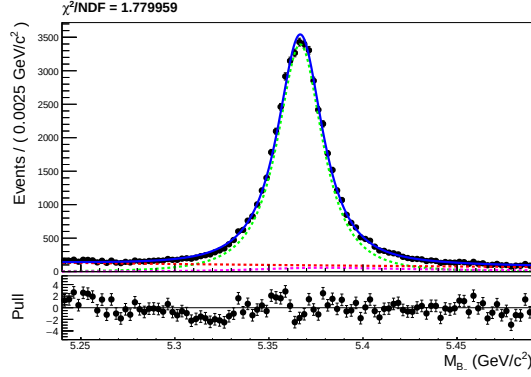


Figure 4.43: Statistical correlation matrix: results corresponding final fit.

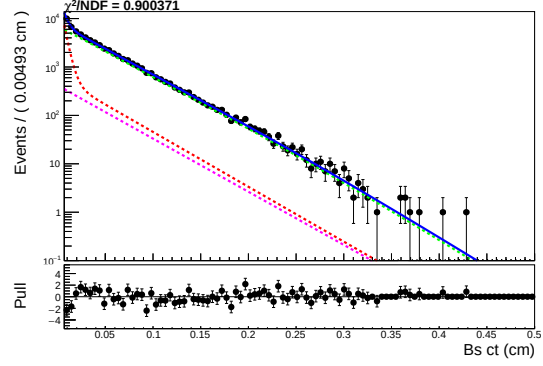
study constitutes a validation of the full fit model and an additional validation of the S-wave component. In the absence of any bias pull distributions corresponding to α 's should be converged toward a standard normal distribution. The pulls are shown in Figure 4.45. The slight bias is observed in the pull central values for several parameters, a related model bias systematics is going to be evaluated in the next step.

Parameter	Set value
$ A_0 ^2$	0.523
$ A_\perp ^2$	0.249
$ A_S ^2$	0.012
$\delta_\parallel$ [rad]	3.19
$\delta_\perp$ [rad]	3.2
$\delta_{S\perp}$ [rad]	0.188
ct [μm]	0.04527
$\Delta\Gamma_s$ [cm^{-1}]	3.00
Δm_s [$\hbar \text{ cm}^{-1}$]	592.3
$ \lambda $	1
ϕ_s [rad]	-0.055

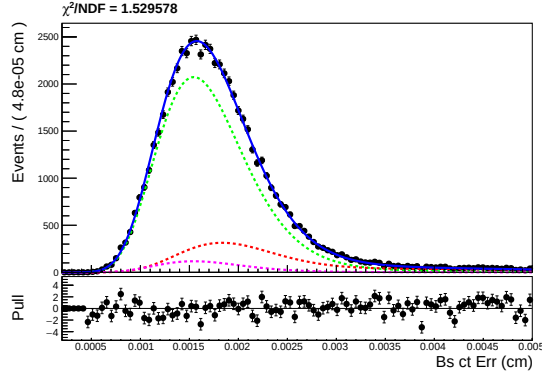
Table 4.19: Parameters used to generate the full model MC pseudo-experiments.



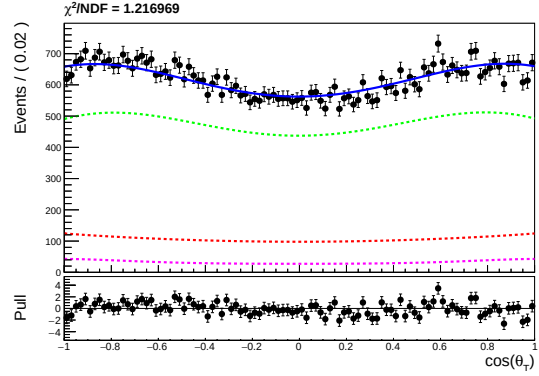
(a) $m_{B_s^0}$ projection.



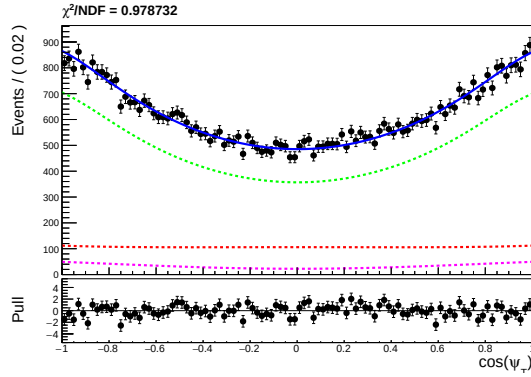
(b) ct projection.



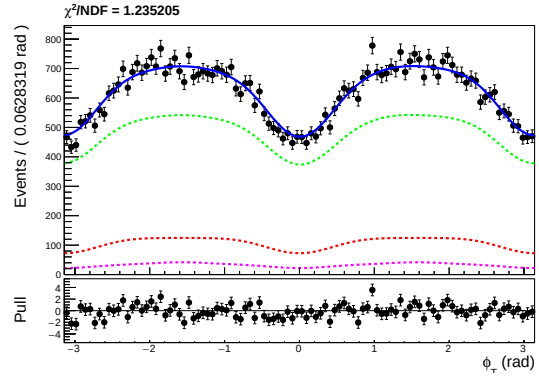
(c) σ_{ct} projection.



(d) $\cos \theta_T$ projection.



(e) $\cos \psi_T$ projection.



(f) ϕ_T projection.

Figure 4.44: Final data fit: one dimensional projections of the PDFs The dashed green line represents the signal, background with red line, and peaking background referred by magenta line. The total PDF projection is drawn with a solid blue line.

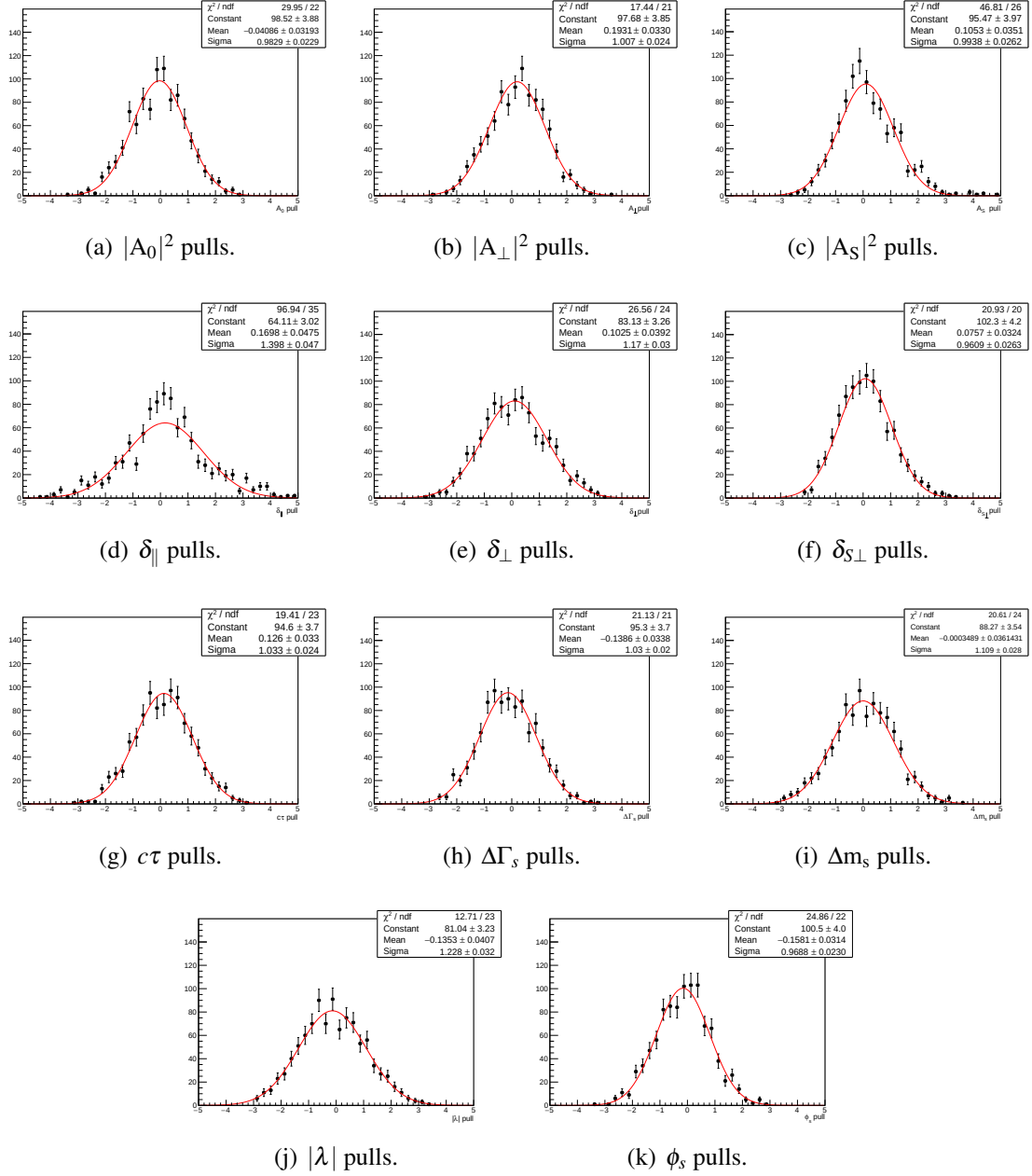


Figure 4.45: Full model toy pseudo-experiments pull distributions of fitted parameters, as defined in Eq. 4.44.

4.7 Systematic uncertainties

4.7.1 Sources of systematic uncertainties

Model bias

The origin of model bias systematic is the the biases found in the self-consistency check described in section 4.6.2 when the bias is more significant than one standard deviation. This systematic is evaluated by multiplying the central value of the pull distributions by the parameters statistical uncertainty obtained with the fit to data.

Angular efficiency

The angular efficiencies are obtained from the simulated sample. In order to calculate the systematics of the angular efficiency 1000 efficiency histograms are generated using efficiency histogram obtained from the MC samples. The three dimensional efficiencies are then injected each time in the full fit. The distributions of the physics parameters of interest are produce with respect to the reference fit value and the RMS is taken as systematics.

Lifetime efficiency and resolution

To assess a systematic in the lifetime efficiencies a cross check is made that if the procedure introduces any significant bias, by measuring the lifetime of the $B^+ \rightarrow J/\psi K^+$ control channel (charge conjugation is implied). The efficiency is evaluate in $B^+ \rightarrow J/\psi K^+$ simulated samples and then a two dimensional fit performed in the MC samples themselves and on the Charmonium dataset. The physics selections are same as $B_s^0 \rightarrow J/\psi \phi$, the results are reported in Table 4.21 and are in overall agreement with global average. Different eras of data taking period do not have similar statistics and what is reflected from the statistical

pull distribution of the 2D fit as shown in Figure 4.46. The likelihood function is :

$$\begin{aligned}
\mathcal{L} &= f_s P_{M,ct}^s + f_{combi} P_{M,ct}^c + f_{prompt} P_{M,ct}^p \\
f_s + f_{combi} + f_{prompt} &= 1 \\
P_{M,ct}^s &= P^s(B^+) \cdot \{\varepsilon(ct) \cdot P^s(ct) \otimes G(\sigma_{ct})\} \\
P_{M,ct}^c &= P^c(B^+) \cdot P^c(ct) \\
P_{M,ct}^p &= P^p(B^+) \cdot P^p(ct).
\end{aligned} \tag{4.45}$$

The 2D fit for the $B^+ \rightarrow J/\psi K^+$ decay process verifies that the efficiency measurement

Sample	$ct_{B^+ \rightarrow J/\psi K^+}$ [μm]	Pull w.r.t PDG/set value [s.d.]
MC 2017	501.0 ± 1.5	$< 10^{-1}$
MC 2018	501.5 ± 1.4	+0.4
Charmonium 2018A	489.3 ± 2.0	-0.4
Charmonium 2018B	495.7 ± 2.7	+1.5
Charmonium 2018C	489.2 ± 1.4	-1.4
Charmonium 2018D	493.2 ± 1.3	+1.2
Charmonium 2018	492.8 ± 0.9	+1.1
Charmonium 2017C	493.8 ± 2.4	+1.0
Charmonium 2017D	494.8 ± 3.5	+1.0
Charmonium 2017E	494.7 ± 2.3	+1.4
Charmonium 2017F	489.5 ± 1.7	-0.8
Charmonium 2017	492.9 ± 1.1	+0.5

Table 4.20: $B^+ \rightarrow J/\psi K^+$ lifetime measurement in different datasets. Reported uncertainties are statistical only. For simulated samples the pull with respect to the set value $ct = 500.95320 \mu m$ is reported, for Data the pull with respect to the PDG 2019 value $ct = (491.1 \pm 1.2) \mu m$ is reported.

Source	$ A_0 ^2$	$ A_\perp ^2$	$ A_S ^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]	ct [μm]	$\Delta\Gamma_s$ [ps $^{-1}$]	Δm_s [$\hbar$ ps $^{-1}$]	$ \lambda $	ϕ_s [rad]
Function stat.	0.0006	0.0009	0.0003	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	1.0	0.0025	0.0009	0.0001	0.0002
Function model	0.0013	0.0022	0.0007	$< 10^{-3}$	0.002	0.002	1.2	0.0057	0.0007	0.0001	0.0003
Total	0.0014	0.0023	0.0007	0.001	0.002	0.002	1.5	0.0062	0.0012	0.0002	0.0003

Table 4.21: Lifetime efficiency systematics. The total systematics is the quadrature sum of the listed uncertainties.

and the modelization of the same not introducing any significant bias. The systematics related to the decay time efficiency is then evaluated in the following way : by varying the coefficients of the ct efficiency fit function within their statistical error. By repeating this

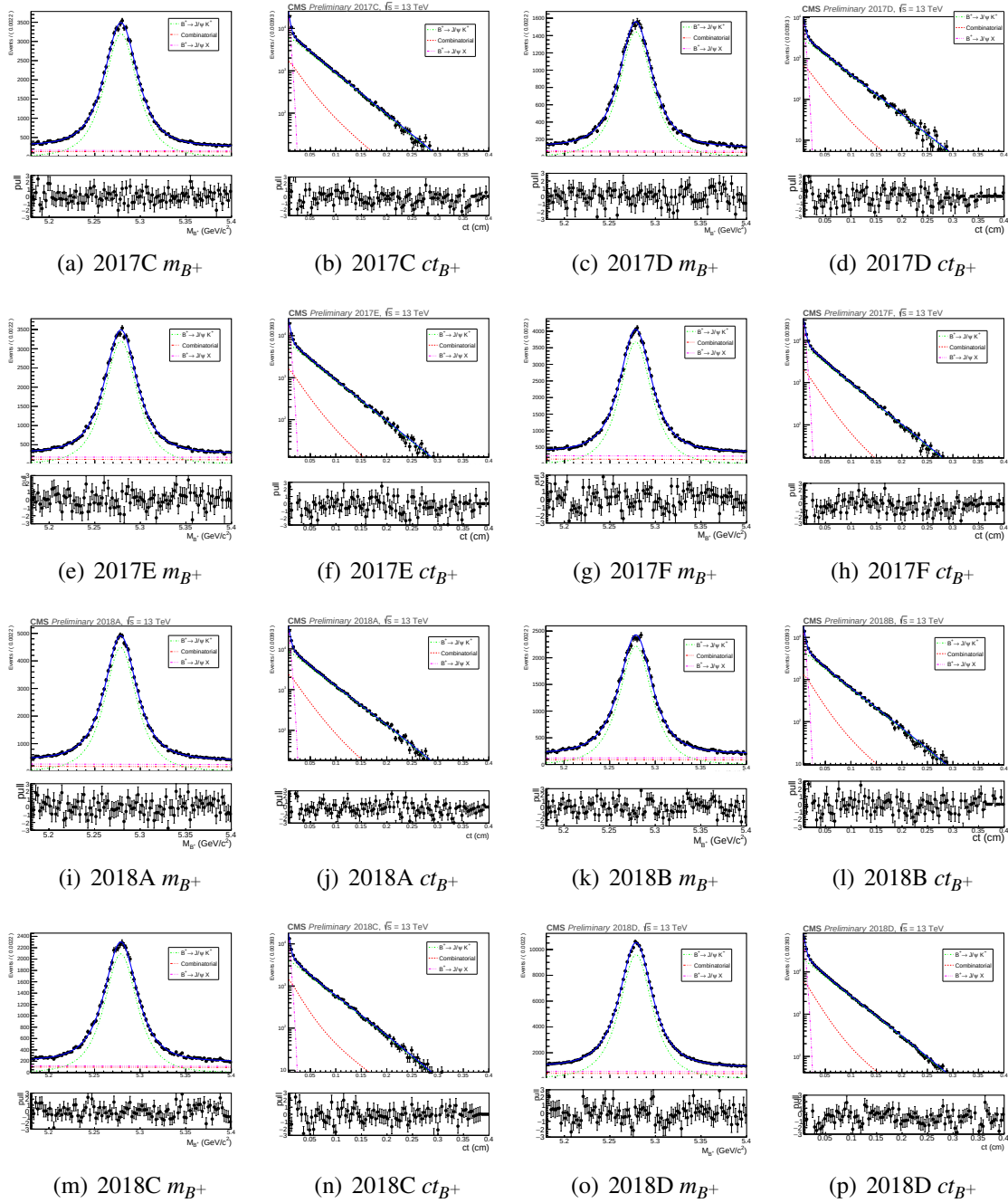


Figure 4.46: 2D fit of mass and decay time of the $B^+ \rightarrow J/\psi K^+$ decay corresponding to different era of 2017 and 2018 data taking period.

procedure 1000 times and inject this new efficiencies into the fit to produce distributions of the physics parameters of interest with respect to the reference fit value. In order to be conservative and account for outliers the RMS is taken as systematics, instead of the standard deviation. Systematics related to the function of efficiency fit model is evaluated

by pushing directly the efficiency histogram in the final fit and obtaining the difference from the reference results as the systematic uncertainty. As for the lifetime resolution the uncertainty is evaluated by redoing the fit changing the κ scaling factor by $\pm 10\%$, and taking the largest difference, from the reference, results as systematics. The $\pm 10\%$ interval is chosen as conservative interval to consider possible data-MC variations of the κ scaling factor.

Data-MC mismatch

The systematic uncertainty concerning the the data-MC mismatch in the final state particles ($\mu^\pm, K^\pm$) transverse momentum p_T and the B_s^0 meson pseudorapidity is evaluated by re-weighting the MC samples to agree with the data. Efficiencies are then evaluated using new rescaled MC distributions and inject them into the fitter. The differences between each physics parameter corresponding to the new fit results and the reference fit is taken as systematics. The results are reported in Table 4.22.

Rewighted variable	$ A_0 ^2$	$ A_\perp ^2$	$ A_S ^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]	ct [μm]	$\Delta\Gamma_s$ [ps $^{-1}$]	Δm_s [$\hbar$ ps $^{-1}$]	$ \lambda $	ϕ_s [rad]
$p_T(K)$	0.0032	0.0020	0.0048	0.006	0.003	0.018	0.15	0.0006	0.0025	0.0003	0.0006
$p_T(\mu)$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-2}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$
$\eta(B_s^0)$	0.0031	0.0021	0.0044	0.002	0.007	0.022	0.14	0.0005	0.0032	0.0031	0.0001
Total	0.0044	0.0029	0.0065	0.007	0.007	0.028	0.20	0.0008	0.0041	0.0031	0.0006

Table 4.22: Data-MC reweight systematics. The total systematics is the quadrature sum of the listed uncertainties.

Flavour tagging

Two different type of systematics assigned corresponding to the flavor tagging. The very first one is related to the calibration ω_{evt} and the second one is related to the transformation of the mistag fraction from $B^\pm$ to B_s^0 . In this case 1000 calibration curves are produced, and then the calibration curve coefficient are varied between their statistical uncertainty range, and using new curves data is refitted. Standard deviation of the fitted parameter distributions is assign as systematic. Another effective assumption exploits the reproduction of correct mistag distribution involved in B_s^0 decays by using the calibration curves mea-

sured on $B^\pm$. The $\omega_{B^\pm}$ curves are corrected by constructing a $\omega_{B^\pm} \rightarrow \omega_{B_s^0}$ transformation, which evaluates on simulated $B^\pm$ and B_s^0 samples. The definition of such transformation is given in Equation 4.46.

$$\omega_{B_s^0, \text{Data}} = f_{B_s, \text{MC}}(f_{B^\pm, \text{MC}}^{-1}(\omega_{B^\pm, \text{Data}})) = f_{B^\pm \rightarrow B_s}(\omega_{B^\pm, \text{Data}}) \quad (4.46)$$

The $f_{\text{Channel, Sample}}$ is the ω_{evt} calibration function for the given decay mode and type of data. Finally a fit is performed to the data with this new calibration and the residual from the nominal fit is assigned as systematics. The effect of both systematic sources, reported in Table 4.23 is found to be negligible for all variables. One of the drawback of this model

Source	$ A_0 ^2$	$ A_\perp ^2$	$ A_S ^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]	ct [μm]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [$\hbar^{-1}$]	$ \lambda $	ϕ_s [rad]
Calibration stat.	0.0003	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-3}$	0.002	0.001	0.02	$< 10^{-4}$	0.0008	0.0001	0.0001
$B_s^0 B^\pm$ diff.	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-3}$	0.003	$< 10^{-3}$	$< 10^{-2}$	$< 10^{-4}$	0.0009	$< 10^{-4}$	$< 10^{-4}$
Total	0.0003	$< 10^{-4}$	$< 10^{-4}$	0.001	0.003	0.001	0.02	$< 10^{-4}$	0.0012	0.0002	0.0001

Table 4.23: Flavour tagging systematics. The total systematics is the quadrature sum of the listed uncertainties.

is that it does not contain the mistag probability (ω_{evt}) distribution, and it is assumed that mistag probability is same for signal and background. To evaluate the systematic related to mistag probability a set of toy experiments are generated with different signal and background ω_{evt} distributions extrapolated from the data samples using the $_s\mathcal{P}$ lot technique. Then both signal and background distributions are explicitly modeled with the Kernel Density Estimation(KDE) method [73, 74] and injected to the final model. The generated samples are fitted with the full model, which does not contain the mistag PDF. The difference of the pull distributions central values from the self-consistency model (Section 4.6.2) is taken as systematic if it exceeds one standard deviation.

Model assumptions

Applying the PDF hypothesis to the mass and ct distribution pseudo samples are generated and fitted using reference fit. The difference in pull distributions central values from the self-consistency model (Section 4.6.2) is taken as systematic if it exceeds one standard

deviation. For example the signal mass PDF changed to three Gaussian, background mass PDF to Chebyshev polynomial of order two, and ct background to an additional Gaussian distribution centered at zero. The results are reported in Table 4.24.

Model	$ A_0 ^2$	$ A_\perp ^2$	$ A_S ^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]	ct [μm]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [$\hbar^{-1}$]	$ \lambda $	ϕ_s [rad]
Signal mass	—	0.0008	—	0.017	0.019	0.011	—	—	—	—	—
Background mass	—	0.0005	0.0006	—	—	—	0.21	—	—	—	—
Background lifetime	—	—	0.0006	—	—	—	—	—	—	0.0023	—
Background angular	—	0.0008	0.0009	—	—	—	—	—	—	0.0040	—
Total	—	0.0013	0.0012	0.017	0.019	0.011	0.21	—	—	0.0046	—

Table 4.24: Model assumptions systematics. The total systematics is the quadrature sum of the listed uncertainties.

Peaking background

The event yield and proper decay time related systematic uncertainties are evaluated for peaking background. A data driven estimation is performed as given in Equation 4.47 to cross check peaking background event yield in data estimated earlier in Equation 4.42 using the MC luminosity information.

$$N_{\text{peak}}^{\text{Data}} = N_{\text{peak}}^{\text{MC}} \frac{N_{B^0 \rightarrow J/\psi K^*}^{\text{Data}}(892)}{N_{B^0 \rightarrow J/\psi K^*}^{\text{MC}}(892)}. \quad (4.47)$$

A systematic on the event yield estimation is evaluated by refitting the data using the data driven yield and reference yield $\pm 2\sigma_{\text{yield}}$. The largest difference of the current fit results from the reference results is taken as systematics. A systematic related to the lifetime distribution is evaluated by changing the lifetime ct by the difference between the $B^0 \rightarrow J/\psi K^{*0}$ simulated samples set value and the current world-average value [69].

Source	$ A_0 ^2$	$ A_\perp ^2$	$ A_S ^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]	ct [μm]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [$\hbar^{-1}$]	$ \lambda $	ϕ_s [rad]
Yield	0.0005	0.0002	0.0025	0.005	0.007	0.011	0.08	0.0008	0.011	$< 10^{-4}$	0.0003
Lifetime	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-3}$	$< 10^{-3}$	$< 10^{-3}$	0.10	$< 10^{-4}$	0.001	$< 10^{-4}$	$< 10^{-4}$
Total	0.0005	0.0002	0.0025	0.005	0.007	0.011	0.13	0.0008	0.011	$< 10^{-4}$	0.0003

Table 4.25: Peaking background model systematics. The total systematics is sum in quadrature of the listed uncertainties.

$P(\sigma_{ct})$ uncertainty

While fitting the data, the parameters of the $P(\sigma_{ct})$ PDF is fixed after performing the pre-fit as described earlier. The $P(\sigma_{ct})$ related systematic is assigned in the following way : resampling the $P(\sigma_{ct})$ parameters between statistical range estimated in the pre-fit 1K times . In each iteration a fit to data is performed. The difference in standard deviation of the pull distribution from base fit model is assigned as the systematic corresponding to each parameter.

	$ A_0 ^2$	$ A_\perp ^2$	$ A_S ^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]	Γ_s [ps ⁻¹]	$\Delta\Gamma_s$ [ps ⁻¹]	Δm_s [ħ ⁻¹]	$ \lambda $	ϕ_s [rad]
$P(\sigma_{ct})$	0.0006	0.0008	0.001	0.001	0.002	0.005	0.0008	0.0019	0.028	0.0004	$<10^{-4}$

Table 4.26: Systematic uncertainty table for the $P(\sigma_{ct})$ or the proper decay length uncertainty.

S - P wave interference: unfitted $m(K^+K^-)$

The P - and S -wave have different m_{KK} dependence and the current fit model is not sensitive to this fact. More specifically the model does not incorporate the difference in the m_{KK} distribution depending on the P -wave from the $B_s^0 \rightarrow J/\psi\phi$ decay when compared to the nonresonant S -wave. The P -wave 0, $\perp$, $\parallel$, and S -wave amplitudes are having different m_{KK} mass dependence, which leads to,

$$A_0(m_{KK}) = A_0 \pi(m_{KK}) \quad A_\perp(m_{KK}) = A_\perp \pi(m_{KK}) \quad (4.48)$$

$$A_\parallel(m_{KK}) = A_\parallel \pi(m_{KK}) \quad A_S(m_{KK}) = A_S \sigma(m_{KK}). \quad (4.49)$$

The $\pi(m_{KK})$ and $\sigma(m_{KK})$ are the mass dependent parametrization of the P -wave, and the S -wave respectively. To properly account this in the fit, the two kaons invariant mass should be modeled in $|\pi(m_{KK})|^2$, $|\sigma(m_{KK})|^2$ (amplitude components) and background components. If m_{KK} is not fitted (as in this analysis), the decay rate terms related to the interference between P -wave, and the S -wave, i.e. the $i = 8, 9, 10^{th}$ amplitudes of the Table 1.4, need to get modified by an effecting coupling factor k_{SP} . This factor can be calculated by

averaging the amplitude combinations over the selected m_{KK} range $[m_1, m_2]$ ¹⁸:

$$\int_{m_1}^{m_2} A_i^* A_S \pi(m_{KK})^* \sigma(m_{KK}) dm_{KK} = |A_i A_S| k_{SP}; (i, j \in \{0, \perp, \parallel\}) \quad (4.50)$$

$|A_i A_j|$ and $|A_S|^2$ terms do not require any corrections, if $\pi(m_{KK})$ and $\sigma(m_{KK})$ are normalized within $[m_1, m_2]$ as described in 4.51.

$$\begin{aligned} \int_{m_1}^{m_2} A_i^* A_j \pi(m_{KK})^* \pi(m_{KK}) dm_{KK} &= |A_i A_j| \\ \int_{m_1}^{m_2} A_S^* A_S \sigma(m_{KK})^* \sigma(m_{KK}) dm_{KK} &= |A_S|^2 \end{aligned} \quad (4.51)$$

An assumption is made that the P-wave can be described by a Briet-Wigner PDF and the S-wave is modeled with a constant distribution¹⁹. Then an effective coupling factor is estimated as,

$$k_{SP} = \frac{\int_{m_1}^{m_2} \pi(m_{KK})^* \sigma(m_{KK}) dm_{KK}}{\sqrt{\int_{m_1}^{m_2} |\pi(m_{KK})|^2 dm_{KK} \int_{m_1}^{m_2} |\sigma(m_{KK})|^2 dm_{KK}}} = 0.538 \quad (4.52)$$

1K toys are generated including k_{SP} in the model, and then fitting each one with the reference fit. Pull distribution of α 's are produced and the difference in central values from the nominal model is taken as systematic. The results are reported in Table 4.27. As expected only the effect on $|A_S|^2$ is large.

	$ A_0 ^2$	$ A_\perp ^2$	$ A_S ^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{S\perp}$ [rad]	$c\tau$ [μm]	$\Delta\Gamma_s$ [ps ⁻¹]	Δm_s [$\hbar^{-1}$]	$ \lambda $	ϕ_s [rad]
Unfitted m_{KK}	0.0005	—	0.013	—	0.02	0.019	0.4	0.0010	0.019	—	—

Table 4.27: Unfitted m_{KK} systematic uncertainties originated by the interference between P-wave and S-wave components.

¹⁸In our case $|m_{KK} - m_{\phi(1020)}^{\text{PDG}}| \leq 10 \text{ MeV}$.

¹⁹Different S-wave distributions lead to very similar k_{SP} values.

4.7.2 Total systematic uncertainties

The source of all systematic uncertainties and the corresponding measures are summarized in the Table 4.28. The dashed (—) lines are suggesting that the systematic related to those parameters are not applicable. In each row the source of systematic uncertainty and systematic uncertainty corresponding to each physics parameter is described.

	ϕ_s [mrad]	$\Delta\Gamma_s$ [ps ⁻¹]	Δm_s [$\hbar ps^{-1}$]	$ \lambda $	Γ_s [ps ⁻¹]	$ A_0 ^2$	$ A_\perp ^2$	$ A_s ^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	$\delta_{s\perp}$ [rad]
Statistical uncertainty	50	0.014	0.10	0.026	0.0042	0.0047	0.0063	0.0077	0.12	0.16	0.083
Model bias	7.9	0.0019	—	0.0035	0.0005	0.0002	0.0012	0.001	0.020	0.016	0.006
Angular efficiency	3.8	0.0006	0.007	0.0057	0.0002	0.0008	0.0010	0.002	0.006	0.015	0.015
Proper decay length efficiency	0.3	0.0062	0.001	0.0002	0.0022	0.0014	0.0023	0.001	0.001	0.002	0.002
Proper decay length resolution	3.5	0.0009	0.021	0.0015	0.0006	0.0007	0.0009	0.007	0.006	0.025	0.022
Data/simulation difference	0.6	0.0008	0.004	0.0003	0.0003	0.0044	0.0029	0.007	0.007	0.007	0.028
Flavor tagging	0.1	$<10^{-4}$	0.001	0.0002	$<10^{-4}$	0.0003	$<10^{-4}$	$<10^{-3}$	0.001	0.003	0.001
Sig./bkg. ω_{vt} difference	3.0	—	—	—	0.0005	—	0.0008	—	—	—	0.006
Model assumptions	—	—	—	0.0046	0.0003	—	0.0013	0.001	0.017	0.019	0.011
Peaking background	0.3	0.0008	0.011	$<10^{-4}$	0.0002	0.0005	0.0002	0.003	0.005	0.007	0.011
S - P wave interference	—	0.0010	0.019	—	0.0005	0.0005	—	0.013	—	0.019	0.019
$P(\sigma_{ct})$ uncertainty	$<10^{-1}$	0.0019	0.028	0.0004	0.0008	0.0006	0.0008	0.001	0.001	0.002	0.005
Total systematic uncertainty	10	0.0070	0.032	0.0083	0.0026	0.0049	0.0045	0.016	0.028	0.045	0.048

Table 4.28: The dashed (—) lines are suggesting that the systematic related to those parameters are not applicable. In each row the source of systematic uncertainty and systematic uncertainty corresponding to each physics parameter is described.

4.8 Summary of $\sqrt{s} = 13 \text{ TeV}$ result

Systematic uncertainties are finally included to the final results in quadrature. The main objective of this thesis was to determine the weak phase ϕ_s , though given that the likelihood fit algorithm constructed for the analysis is very robust and along with weak phase it is capable to extract some other parameters as well. Those parameters are: the decay width $\Delta\Gamma_s$ and the oscillation frequency Δm_s , and the direct CP-violating parameter $|\lambda|$. The number of the reconstructed $B_s^0 \rightarrow J/\psi \phi(1020) \rightarrow \mu^+ \mu^- K^+ K^-$ candidates are 48500, collected at $\sqrt{s} = 13 \text{ TeV}$ with recorded integrated luminosity of 96.4 fb^{-1} . An special trigger and a new DNN based tagging is employed in this analysis. $\sqrt{s} = 13 \text{ TeV}$ results for the weak phase and decay width difference is shown in 4.53.

$$\begin{aligned}\phi_s^{c\bar{c}s} &= -11 \pm 50(\text{stat}) \pm 10(\text{syst}) \text{ mrad} \\ \Delta\Gamma_s &= 0.114 \pm 0.014(\text{stat}) \pm 0.007(\text{syst}) \text{ ps}^{-1}\end{aligned}\tag{4.53}$$

The measured value of the direct CP-violating parameter ($|\lambda|$) is

$$|\lambda| = 0.972 \pm 0.026(\text{stat}) \pm 0.008(\text{syst}).$$

The unit value of $|\lambda| = 1$ concerns no direct violation of CP symmetry. The measured value of the average²⁰ decay width

$$\Gamma_s = 0.6531 \pm 0.0042(\text{stat}) \pm 0.0024(\text{syst}) \text{ ps}^{-1}$$

is also consistent with global $\Gamma_s = 0.6624 \pm 0.0018 \text{ ps}^{-1}$ [69]. The oscillation frequency is determined to be

$$\Delta m_s = 17.51^{+0.10}_{-0.09}(\text{stat}) \pm 0.03(\text{syst}) \hbar \text{ ps}^{-1},$$

aligned with the theoretically predicted value $\Delta m_s = 18.77 \pm 0.86 \hbar \text{ ps}^{-1}$ [12], and a small departure is observed from the world-average of $\Delta m_s = 17.757 \pm 0.021 \hbar \text{ ps}^{-1}$ [69]. This

²⁰ $\Gamma_s = (\Gamma_H + \Gamma_L)/2$.

analysis first time measures the Δm_s and $|\lambda|$ in the $B_s^0 \rightarrow J/\psi \phi(1020) \rightarrow \mu^+ \mu^- K^+ K^-$ decay process. The statistical uncertainties are dominating in all these measured parameters compared to the systematic one. The full results are reported in Table 4.29. The one dimensional projection of all PDFs from the multidimensional fit are shown in Figure 4.47, and in 4.48 respectively.

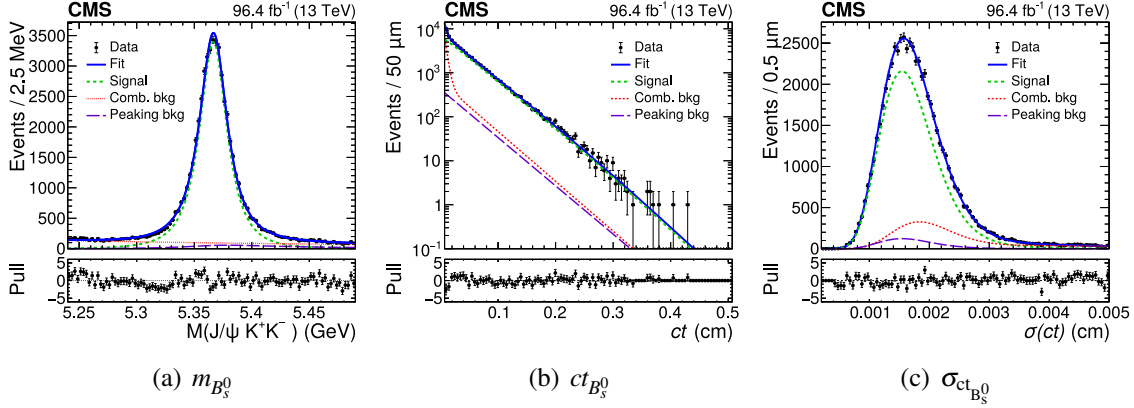


Figure 4.47: The 1D projections of (a) $m_{B_s^0}$, (b) ct , and (c) σ_{ct} . The blue line correspond to the projection of total PDF, dashed green line to B_s^0 signal, red dots to combinatorial background, and long dashed purple to $B^0 \rightarrow J/\psi K^{*0}$. Vertical bars on data points are representing the statistical uncertainties. The lower panels are describing the pull : ratio of the residual of data from the fit to the combined uncertainty.

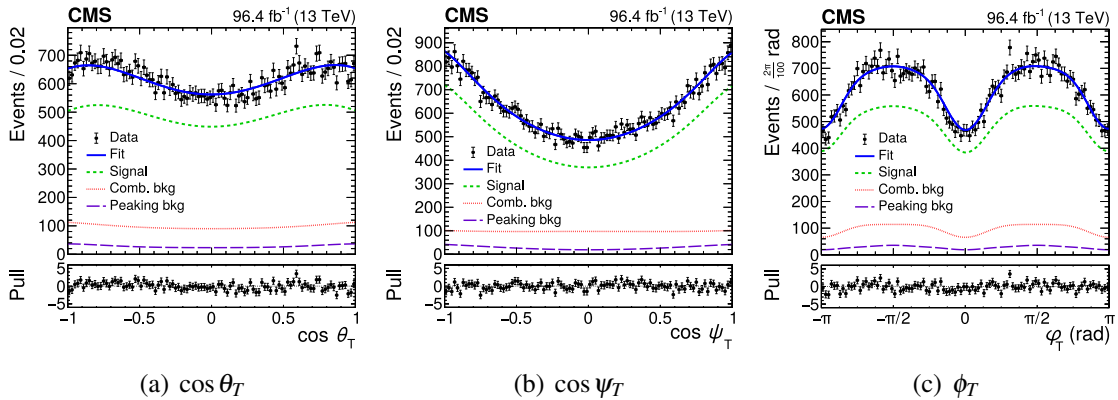


Figure 4.48: One dimensional projections of the angular distributions (a) $\cos \theta_T$, (b) $\cos \psi_T$, and (c) ϕ_T and the fit. The blue line correspond to the projection of total PDF, dashed green line to B_s^0 signal, red dots to combinatorial background, and long dashed purple to $B^0 \rightarrow J/\psi K^{*0}$. Vertical bars on data points are representing the statistical uncertainties. The lower panels are describing the pull : ratio of the residual of data from the fit to the combined uncertainty.

Parameter	Value	Stat. Uncer.	Syst. Uncer.
ϕ_s [rad]	-0.011	± 0.050	± 0.010
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
$ \lambda $	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0026
Δm_s [$\hbar \text{ps}^{-1}$]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$ A_0 ^2$	0.5350	± 0.0047	± 0.0049
$ A_\perp ^2$	0.2337	± 0.0063	± 0.0045
$ A_S ^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.05
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048

Table 4.29: Measured values of parameters obtained in final fit to the 2017, 2018 data at $\sqrt{s} = 13 \text{ TeV}$.

4.9 Combination with $\sqrt{s} = 8 \text{ TeV}$ results

The results reported in Table 4.29 are combined with the 8 TeV results [75] using the BEST LINEAR UNBIASED ESTIMATION (BLUE) method [76]. The approach of the muon tagging, the technicalities related to the efficiency estimation, and partially the fit model are different when measurement of $\sqrt{s} = 13 \text{ TeV}$ compared to $\sqrt{s} = 8 \text{ TeV}$. It is evident that the correlation between the parameters will also be different in two Runs. For simplicity, considering two estimates y_1 and y_2 with variances $\tilde{\sigma}_1$ and $\tilde{\sigma}_2$ originating from two unbiased estimators Y_1 and Y_2 respectively. The true value assignment for the estimate is y_T corresponding to the estimators and $\tilde{\rho}$ is the total correlation between them. The best linear unbiased estimate y of these two estimators given that true value y_T is described in Equation 4.54.

$$y = (1 - \beta^e)y_1 + \beta^e y_2; \quad \text{when} \quad z = \frac{\tilde{\sigma}_2}{\tilde{\sigma}_1} \geq 1$$

$$\beta^e = \frac{1 - \tilde{\rho}z}{1 - 2\tilde{\rho}z + z^2} \quad (4.54)$$

For the combination of 13 TeV results with the results 8 TeV makes the use of the nine estimators²¹ and the corresponding correlations between those. Since the $|\lambda|$ and Δm_s were not measure in the 8 TeV analysis, for the sake of generality those terms are not considered for the combination. An open source algorithm is tuned for the combination under the ROOT constructors. The combined results and their uncertainties are reported in Table 4.30, while the correlation matrix is reported in Table 4.31. The combined result is shown in the Equation 4.55.

$$\phi_s^{c\bar{c}s} = -21 \pm 44 (\text{stat}) \pm 10 (\text{syst}) \text{ mrad}$$

$$\Delta\Gamma_s = 0.1073 \pm 0.0095 (\text{stat}) \pm 0.0048 (\text{syst}) \text{ ps}^{-1} \quad (4.55)$$

²¹ $Y_i = [\phi_s, \Delta\Gamma_s, \Gamma_s, |A_0|^2, |A_\perp|^2, |A_S|^2, \delta_\parallel, \delta_\perp, \delta_{S\perp}]$.

Parameter	Value	Stat. Uncer.	Syst. Uncer.
ϕ_s [rad]	-0.021	± 0.044	± 0.010
$\Delta\Gamma_s$ [ps^{-1}]	0.1032	± 0.0095	± 0.0048
Γ_s [ps^{-1}]	0.6590	± 0.0032	± 0.0023
$ A_0 ^2$	0.5289	± 0.0038	± 0.0041
$ A_\perp ^2$	0.2393	± 0.0050	± 0.0037
$ A_S ^2$	0.016	± 0.006	± 0.013
$\delta_\parallel$ [rad]	3.19	± 0.12	± 0.04
$\delta_\perp$ [rad]	2.78	± 0.15	± 0.06
$\delta_{S\perp}$ [rad]	0.238	± 0.078	± 0.046

Table 4.30: Combined results of the α 's : the results obtained at center of mass energy $\sqrt{s} = 8 \text{ TeV}$ is combined with the results obtained in $\sqrt{s} = 13 \text{ TeV}$.

	ϕ_s	$\Delta\Gamma_s$	Γ_s	$ A_0 ^2$	$ A_\perp ^2$	$ A_S ^2$	$\delta_\parallel$	$\delta_\perp$	$\delta_{S\perp}$
ϕ_s	+1.00	+0.02	-0.03	+0.01	-0.01	+0.01	-0.01	-0.08	+0.03
$\Delta\Gamma_s$		+1.00	-0.45	+0.43	-0.57	+0.01	+0.01	-0.00	-0.01
Γ_s			+1.00	-0.17	+0.30	+0.06	-0.03	-0.00	-0.08
$ A_0 ^2$				+1.00	-0.56	+0.25	-0.03	+0.01	-0.18
$ A_\perp ^2$					+1.00	-0.08	-0.03	+0.01	+0.14
$ A_S ^2$						+1.00	-0.02	+0.02	-0.20
$\delta_\parallel$							+1.00	+0.26	-0.00
$\delta_\perp$								+1.00	-0.05
$\delta_{S\perp}$									+1.00

Table 4.31: Correlations factors between physics parameters are obtained after performing the combination of the from the combination of the CMS 8TeV and 13TeV results. Since the λ and Δm_s were not measured in the 8TeV analysis, these parameters are not used for combination. These are the combined correlations having both statistical and systematic contribution.

4.9.1 Final remark

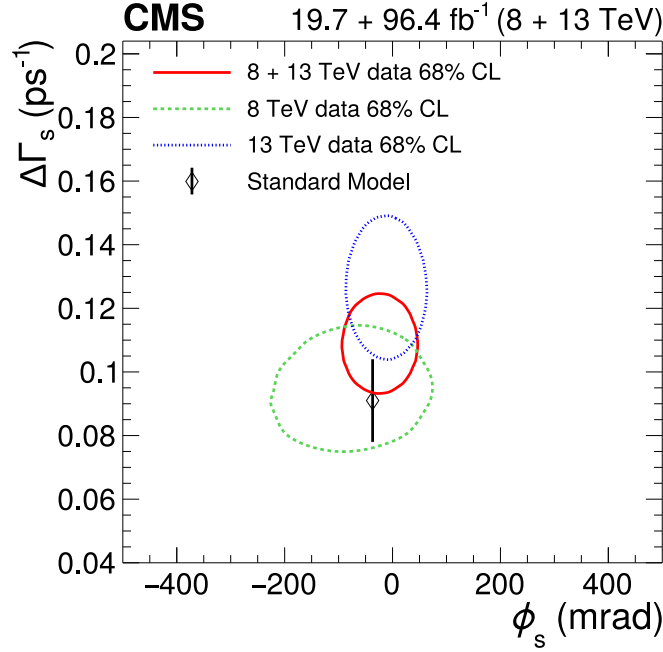


Figure 4.49: The 2D ϕ_s - $\Delta\Gamma_s$ likelihood contours at 68% confidence level. CMS 8 TeV represented by the dashed line, the 13 TeV result by dotted line and the combined result with the solid, and the SM prediction is shown by the diamond marker [11, 12].

This analysis describes the procedure of the estimation of CP-violation parameters in the $B_s^0 \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$ decay process in great detail. The CP violation itself is one of the most celebrated and exciting feature of the flavour physics. Along with this, since the matter-antimatter imbalance of the present universe can be probed through the window of CP-violation - this feature makes the flavour sector studies very unique. This is the first LHC based thesis from Indian Institute of Technology Madras as well. The most important feature of this analysis are : a deep neural network based tagging, robust decay time and angular efficiency estimation tools integrated with the final fit model, and the toy experiments for the validation likelihood recipe and to estimate the systematic uncertainty. The best linear unbiased estimation technique is applied for the combination of the previous result with current one. The two-dimensional likelihood contours at 68% confidence level in the ϕ_s - $\Delta\Gamma_s$ plane for 8 TeV, 13 TeV, and combined results are projected in Figure 4.49. The spread of the SM rectangle is dominating in the $\Delta\Gamma_s$ axis compared to ϕ_s axis given

that the theoretical uncertainties in ϕ_s is very small. The results are dominated by statistical uncertainty and compatible with SM prediction [11, 12].

Appendices

Appendix A

Relevant studies

A.1 Production of $\Delta\Gamma = 0$ sample

The $B_s^0 \rightarrow J/\psi\phi$ decay, in general, possesses the $\Delta\Gamma \neq 0$, implies that the angular observables evolve with respect to decay time. The reason behind this is the different polarization amplitudes have time dependence which leads to different angular distributions corresponding to each. For an approximation $\phi_s \sim 0$, the decay rate for one angle can be written as,

$$\begin{aligned} \frac{d^4\Gamma}{d\Theta dt} &\propto e^{-(\Gamma+\Delta\Gamma/2)t} \{(|A_0|^2 + |A_{\parallel}|^2)(1 + \cos^2\theta)/2\} \\ &\propto e^{-(\Gamma-\Delta\Gamma/2)t} |A_{\perp}|^2 (1 - \cos^2\theta) \end{aligned} \tag{A.1}$$

The evolution of the amplitudes with decay time implies that the amplitudes distributed as $(1 + \cos^2\theta)$ have a lifetime $\tau_L = 1/(\Gamma + \Delta\Gamma/2)$, whereas the amplitude distributed as $(1 - \cos^2\theta)$ has a lifetime $\tau_H = 1/(\Gamma - \Delta\Gamma/2)$. As time evolves, the relative fractions of the different amplitudes therefore changes, and hence it is reflected in the observed angular distributions as well. This fact further refrains to decouple the decay time and angular efficiencies. Technically in a $\Delta\Gamma \neq 0$ MC sample the efficiencies should be evaluated in the decay time bins and plug those in the main maximum likelihood fit as per bin way. To reduce the effect of effective decay on the angular distributions a special MC sample with $\Delta\Gamma = 0$ is produced corresponding each year of Data taking. The angular and decay time

efficiencies are individually estimated in the $\Delta\Gamma = 0$ and tested in $\Delta\Gamma \neq 0$ samples and then finally implemented in Data.

A.2 Theoretical angular analysis

The helicity formalism is used for the derivation of the angular distribution. The helicity operator $\lambda = \vec{S} \cdot \hat{p}$ is invariant under both of the rotation and boost along $\hat{p}$. The matrix element for the decay of $B_s^0 \rightarrow J/\psi \phi$ process, where $J/\psi \rightarrow \mu^+ \mu^-$, and $\phi \rightarrow K^+ K^-$ can be written as,

$$\mathcal{M}(\lambda_{\mu^+}, \lambda_{\mu^-}, \lambda_{K^+}, \lambda_{K^-}) \propto \sum_{\lambda_{\mu}, \lambda_K} \mathcal{A}_{\lambda_{\mu}, \lambda_K}^{B_s^0 \rightarrow J/\psi \phi} \mathcal{A}_{\lambda_{\mu^+}, \lambda_{\mu^-}}^{J/\psi \rightarrow \mu^+ \mu^-} \mathcal{A}_{\lambda_{K^+}, \lambda_{K^-}}^{\phi \rightarrow K^+ K^-} \quad (\text{A.2})$$

Implementing the Jackson convention, the Euler angles of rotations are $(\alpha, \beta, \gamma) \equiv (\varphi, \theta, 0)$, where θ , and ϕ are the polar and the azimuthal angle in the decay plane of each meson respectively. The amplitudes corresponding to B_s^0 meson and subsequent decays of the daughter mesons to the final state particles are,

$$\begin{aligned} \mathcal{A}_{\lambda_{\mu}, \lambda_K}^{B_s^0 \rightarrow J/\psi \phi} &= \sqrt{\frac{2J_{B_s^0} + 1}{4\pi}} \mathcal{D}_{m_{B_s^0}, \lambda_{J/\psi} - \lambda_{\phi}}^{J_{B_s^0}}(\varphi, \theta, 0) \mathcal{H}_{\lambda_{J/\psi}, \lambda_{\phi}}^{B_s^0} \\ \mathcal{A}_{\lambda_{\mu^+}, \lambda_{\mu^-}}^{J/\psi \rightarrow \mu^+ \mu^-} &= \sqrt{\frac{2J_{J/\psi} + 1}{4\pi}} \mathcal{D}_{m_{J/\psi}, \lambda_{\mu^+} - \lambda_{\mu^-}}^{J_{J/\psi}}(\varphi, \theta, 0) \mathcal{H}_{\lambda_{\mu^+}, \lambda_{\mu^-}}^{J/\psi} \\ \mathcal{A}_{\lambda_{K^+}, \lambda_{K^-}}^{\phi \rightarrow K^+ K^-} &= \sqrt{\frac{2J_{\phi} + 1}{4\pi}} \mathcal{D}_{m_{\phi}, \lambda_{K^+} - \lambda_{K^-}}^{J_{\phi}}(\varphi, \theta, 0) \mathcal{H}_{\lambda_{K^+}, \lambda_{K^-}}^{\phi} \end{aligned} \quad (\text{A.3})$$

The Wigner rotation matrices $\mathcal{D}$ are satisfying the general definition, m_i 's are spin projections, and $\mathcal{H}$ is the Hamiltonian. The unpolarized angular distribution is given by averaging over initial spins and summing over final spins,

$$\frac{1}{\Gamma} \frac{d^3\Gamma}{d\Omega_{B_s^0} d\Omega_{J/\psi} d\Omega_{\phi}} \propto \frac{1}{2s_{B_s^0} + 1} \sum_{\lambda_{\mu}, \lambda_K} |\mathcal{M}(\lambda_{\mu^+}, \lambda_{\mu^-}, \lambda_{K^+}, \lambda_{K^-})|^2 \quad (\text{A.4})$$

The initial b -hadron is spinless B_s^0 , $J_{B_s^0} = 0$ and considering $m_{J/\psi} = \lambda$ and $m_\phi = -\lambda$ the matrix element takes the form,

$$\begin{aligned} \mathcal{M}(\lambda_{\mu^+}, \lambda_{\mu^-}, \lambda_{K^+}, \lambda_{K^-}) &\propto \sqrt{\frac{1}{4\pi}} \mathcal{D}_{0,0}^0(\varphi, \theta, 0) \mathcal{H}_\lambda^{B_s^0} \\ &\quad \sqrt{\frac{3}{4\pi}} \mathcal{D}_{\lambda, \lambda_{\mu^+} - \lambda_{\mu^-}}^1(\varphi_\mu, \theta_\mu, 0) \\ &\quad \sqrt{\frac{3}{4\pi}} \mathcal{D}_{-\lambda, \lambda_{K^+} - \lambda_{K^-}}^1(\varphi_K, \theta_K, 0) \end{aligned} \quad (\text{A.5})$$

The $\mathcal{H}$ corresponding to J/ψ and ϕ are neglected since they do not depend on λ and also $\lambda_{K^+} - \lambda_{K^-} = 0$ due to the fact $K^\pm$ spin equal to zero. In addition, in the approximation of massless leptons only opposite helicities couple, hence $\alpha = \lambda_{l^+} - \lambda_{l^-} \neq 0$, the differential decay width can be written as,

$$\begin{aligned} D\Gamma &= \frac{1}{\Gamma} \frac{d^3\Gamma}{d\cos\theta_l d\varphi d\cos\theta_K d\varphi_K} \propto \sum_{\alpha \pm 1} \left| \sum_{\lambda \pm 1, 0} \mathcal{D}_{\lambda, \alpha}^1(\varphi_l, \theta_l, 0) \mathcal{D}_{-\lambda, 0}^1(\varphi_K, \theta_K, 0) \mathcal{H}_\lambda \right|^2 \\ &\propto \sum_{\alpha \pm 1} \left| \sum_{\lambda \pm 1, 0} e^{i\lambda(\varphi_l - \varphi_K)} d_{\lambda, \alpha}^1(\theta_l) d_{-\lambda, 0}^1(\theta_K) \mathcal{H}_\lambda \right|^2. \end{aligned} \quad (\text{A.6})$$

Writing the inner sum explicitly,

$$D\Gamma \propto \sum_{\alpha \pm 1} \left| d_{0, \alpha}^1(\theta_l) d_{0, 0}^1(\theta_K) \mathcal{H}_0 + e^{i\lambda(\varphi_l - \varphi_K)} d_{1, \alpha}^1(\theta_l) d_{-1, 0}^1(\theta_K) \mathcal{H}_+ + e^{-i\lambda(\varphi_l - \varphi_K)} d_{-1, \alpha}^1(\theta_l) d_{1, 0}^1(\theta_K) \mathcal{H}_- \right|^2. \quad (\text{A.7})$$

Where, the $\mathcal{H}_0$ corresponds to the configurations in which the spin is directed perpendicular to the direction of motion of the vector mesons, and $\mathcal{H}_\pm$ terms are originating from configuration in which the spin is directed parallel, anti-parallel respectively. Taking $\varphi \equiv \varphi_l - \varphi_K$, and applying appropriate values of d_{jk}^i matrices one can obtain the differential decay dis-

tribution as,

$$\begin{aligned}
& \frac{1}{\Gamma} \frac{d^3\Gamma}{d \cos \theta_l d \cos \theta_K d \varphi} \\
& \propto |\mathcal{H}_0|^2 \sin^2 \theta_l \cos^2 \theta_K \\
& + \frac{1}{4} |\mathcal{H}_+|^2 \sin^2 \theta_K (1 + \cos^2 \theta_l) \\
& + \frac{1}{4} |\mathcal{H}_-|^2 \sin^2 \theta_K (1 + \cos^2 \theta_l) \\
& - \frac{1}{2} [\text{Re}(\mathcal{H}_+ \mathcal{H}_-^*) \cos 2\varphi - \text{Im}(\mathcal{H}_+ \mathcal{H}_-^*) \sin 2\varphi] \sin^2 \theta_l \cos^2 \theta_K \\
& + \frac{1}{4} [\text{Re}\{\mathcal{H}_0(\mathcal{H}_+ + \mathcal{H}_-^*)\}] \cos \varphi \sin 2\theta_l \sin 2\theta_K \\
& + \frac{1}{4} [\text{Im}\{\mathcal{H}_0(\mathcal{H}_+ - \mathcal{H}_-^*)\}] \sin \varphi \sin 2\theta_l \sin 2\theta_K.
\end{aligned} \tag{A.8}$$

The $\theta_{l,K}$ are helicity angles, a transformation for the amplitudes from helicity basis to transversity basis corresponding to final state angular momentum can be obtained as the following way,

$$\begin{aligned}
\text{CP even : } L=0, 2 \in A_0 = \mathcal{H}_0, A_{\parallel} &= \frac{\mathcal{H}_+ + \mathcal{H}_-}{\sqrt{2}} \\
\text{CP odd : } L=1 \in A_{\perp} &= \frac{\mathcal{H}_+ - \mathcal{H}_-}{\sqrt{2}}
\end{aligned} \tag{A.9}$$

and the transformation of the angles from helicity basis to transversity basis are,

$$\begin{aligned}
\sin \theta_l \sin \varphi &= \cos \theta_{tr} \\
\sin \theta_l \cos \varphi &= -\sin \theta_{tr} \sin \varphi_{tr} \\
\cos \theta_l &= -\sin \theta_{tr} \cos \varphi_{tr} \\
\theta_K &= \psi_{tr}.
\end{aligned} \tag{A.10}$$

In the main maximum likelihood fitter or in the description of the differential decay distribution the subscript X_{tr} is not used throughout the thesis since the whole analysis is performed in the transversity basis.

A.3 Associated studies for the model validation

Signal

- Mass, ct , σ_{ct} pdfs are tested with one dimensional model using MC samples and then on Data after background subtraction.
- Decay time and angular efficiencies are tested in the $\Delta\Gamma = 0$ samples where those were evaluated (first closure test) and then in then $\Delta\Gamma \neq 0$ MC samples of both 2017 and 2018.
- A second efficiency closure test is performed by reweighing the GEN only sample to verify the agreement with the RECO samples.
- The lifetime efficiency evaluation procedure is evaluated by measuring the B^+ lifetime in $B^+ \rightarrow J/\psi K^+$ channel. First, the closure test is performed in the MC samples used to evaluate the efficiency and then in each era of Data taking period.
- The decay rate pdf is tested by performing a fit on the GEN information of a very large GEN only sample.
- The signal pdf is tested in $\Delta\Gamma = 0$ MC samples, PDG samples, and in the PDG samples with statistics equivalent to the Data (this last test is repeated several time on different subsamples (jack knife test)).
- 1000 P-wave signal-only toys are generated and then fitted with the same (self-consistency).
- 1000 S+P-wave signal-only toys are generated and then fitted with the S+P-wave signal model (A_S and δ_S taken from the 8 TeV analysis).

Combinatorial background

- All distributions are studied and tested in a mono dimensional approach for each variable corresponding to data sideband.

- The data sidebands are fitted with the combinatorial background pdf model on all variables (only as a check, the PDFs are floating freely in the main fit).
- 1000 pseudo-experiments is generated taking the signal shape from MC samples and the background shapes from data sidebands, and then fitted with the signal plus background model.

Peaking background

- All the PDF components are modeled on MC sample, except for σ_{ct} to which it was given the same shape and parameters as the signal σ_{ct} distribution. It is checked in MC sample that the σ_{ct} distributions of $B_s \rightarrow J/\psi\phi$ and $B_d \rightarrow J/\psi K^*$ are the same. This is done because MC do not reproduce well the σ_{ct} distribution.
- The peaking background yield has been evaluated with two methods: first with the MC luminosity information, and then with a data driven method: $n(B_d \text{ misreconstructed Data}) = n(B_d \text{ Data})/n(B_d \text{ MC}) \times n(B_d \text{ misreconstructed MC})$. The two methods reproduce results in the same order of magnitude. The most conservative systematic is used by taking the difference in the final result (normalized with respect to MC lumi) with respect to the data driven yield estimation.

Full model

- The full model which incorporates the signal, and the components of combinatorial and the peaking backgrounds which is validated by generating 1000 MC pseudo-experiments and then by performing a fit with the similar model. Pull distributions for each physics parameters is produced. In an ideal case the pull distribution should be gaussian distribution with mean(μ 0) and standard deviation ~ 1 . A systematic is assigned if the distribution central value is more than three standard deviation from zero otherwise not applicable.
- Several systematics is evaluated by generating pseudo-experiment by implementing some changes with respect to the reference fit and then fitting them with the reference

fit model. While these toys are not per se validation of the reference fit, it should be noted that the total amount of pseudo experiment performed on the fit model (albeit with some minor differences) is over 5000.

A.4 Additional fit studies

A.4.1 Separate fit by year

The fit to data is performed separately for the 2017 and 2018 datasets. Results are mostly in agreement, but fit stability and reliability at such reduced statistics has not been studied.

Table A.1: Fit to data by year: results. Uncertainties are statistical only.

Parameter	Fit value 2017	Fit value 2018	Pull [s.d.]
$ A_0 ^2$	0.537 ± 0.007	0.533 ± 0.006	+0.5
$ A_\perp ^2$	0.229 ± 0.010	0.237 ± 0.008	+0.6
$ A_S ^2$	0.02 ± 0.01	0.02 ± 0.1	~ 0
$\delta_\parallel$ [rad]	3.1 ± 0.2	3.2 ± 0.2	+0.4
$\delta_\perp$ [rad]	3.2 ± 0.2	2.5 ± 0.2	+2.5
$\delta_{S\perp}$ [rad]	0.3 ± 0.1	0.2 ± 0.1	+1.1
$c\tau$ [μm]	457 ± 5	460 ± 4	+0.5
$\Delta\Gamma_s$ [ps^{-1}]	0.13 ± 0.02	0.10 ± 0.02	+0.8
Δm_s [$\hbar \text{ps}^{-1}$]	590 ± 4	581 ± 2	+2.0
$ \lambda $	1.06 ± 0.05	0.99 ± 0.02	+1.2
ϕ_s [rad]	-0.00 ± 0.08	0.02 ± 0.07	+0.2

A.4.2 Fit with Δm_s constrained

The fit to data is performed with an additional gaussian constrain around the Δm_s current Wold Average: $\Delta m_s = 17.757 \pm 0.021 \hbar \text{ps}^{-1}$. Results of the other parameters changes according correlation. ϕ_s fit values changes by 0.4 the statistical uncertainty.

A.4.3 Studies on background from $\Lambda_b \rightarrow J/\psi K p$

A possible source of peaking background are $\Lambda_b \rightarrow J/\psi K p$ decay, where, $p := K$ the proton is misidentified as a kaon. The main ambition of this study is to show the possible effect

Table A.2: Fit to data with Δm_s constrained to the WA $\Delta m_s = 17.757 \pm 0.021 \hbar \text{ ps}^{-1}$. Uncertainties are statistical only.

Parameter	Fit value	Reference Value
$ A_0 ^2$	0.5347 ± 0.0047	0.5350 ± 0.0047
$ A_\perp ^2$	0.2342 ± 0.0063	0.2337 ± 0.0063
$ A_S ^2$	0.0234 ± 0.0076	$0.0224^{+0.0077}_{-0.0072}$
$\delta_\parallel [\text{rad}]$	3.18 ± 0.11	3.18 ± 0.12
$\delta_\perp [\text{rad}]$	3.00 ± 0.12	2.77 ± 0.16
$\delta_{S\perp} [\text{rad}]$	0.202 ± 0.072	$0.221^{+0.083}_{-0.070}$
$c\tau [\mu\text{m}]$	458.7 ± 3.0	459.0 ± 3.0
$\Delta\Gamma_s [\text{ps}^{-1}]$	0.112 ± 0.014	0.114 ± 0.014
$\Delta m_s [\hbar \text{ ps}^{-1}]$	17.754 ± 0.021	$17.510^{+0.101}_{-0.089}$
$ \lambda $	0.966 ± 0.033	0.972 ± 0.026
$\phi_s [\text{rad}]$	-0.033 ± 0.050	-0.011 ± 0.050

of the presence of the background $\Lambda_b \rightarrow J/\psi K p$ on the analysis results. On the MC side a sample with very large event is used for this study, implementing the primary vertex reconstruction and physics selection similar to $B_s^0 \rightarrow J/\psi \phi$ 1839 candidates are obtained for the Λ_b . Figure A.1 shows the fitted distribution for the variables used in the ϕ_s measurements. The variables related to Λ_b decay process are modeled with the same distributions used for the $B^0 \rightarrow J/\psi K^{*0}$ peaking background described in Section 4.4.7. The MC sample integrated luminosity is estimated to be $\mathcal{L}_{\text{int}} = 3549 \text{ fb}^{-1}$ using the information listed in Table A.3. Since, the $b \rightarrow \Lambda_b$ fragmentation probability and the $\mathcal{BF}$ are not known, the

Variable	Value	Source
Number of events	73446722	MC sample
Cross section [fb]	$5.48 \cdot 10^{11}$	Gen. information
Filter efficiency	$2 \cdot 10^{-3}$	Gen. information
$\mathcal{BF}(\Lambda_b \rightarrow J/\psi K p)$	$3.17 \cdot 10^{-4}$	PDG ¹
$\mathcal{BF}(J/\psi \rightarrow \mu^+ \mu^-)$	$5.96 \cdot 10^{-2}$	PDG ²

Table A.3: The necessary information of the factors used to estimate the $\Lambda_b \rightarrow J/\psi K p$ MC samples integrated luminosity.

MC sample is generated using a $b \rightarrow b$ -hadron fragmentation probability around $\sim 10\%$ while it is measured to as high as $\sim 20\%$ along with the additional intermediate resonances which could possibly enhance the production cross section. Considering the above facts the estimated integrated luminosity is corrected by a factor of 2, which takes into account twice

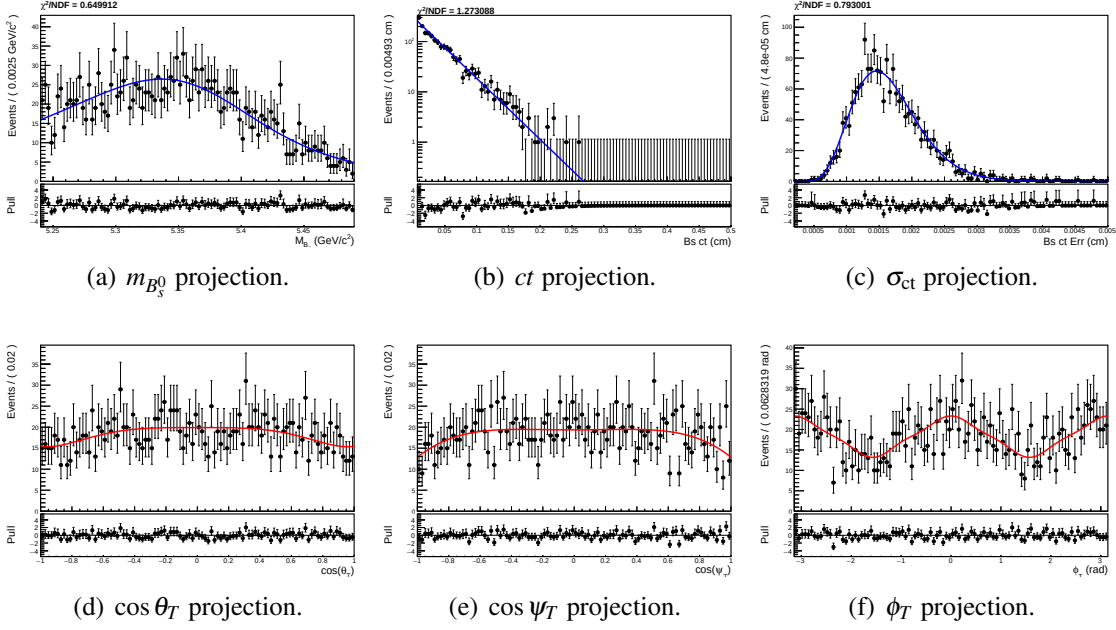


Figure A.1: Variable distributions in the $\Lambda_b \rightarrow J/\psi K p$ MC sample after applying the $B_s^0 \rightarrow J/\psi \phi$ analysis selection and reconstruction. The fit to each variable is drawn with a solid line.

the b-hadron fragmentation probability, and an additional factor of 3, which should cover eventual enhancement from intermediate resonances and the uncertainty on the $\mathcal{BF}$ s.

$$\widetilde{\mathcal{L}}_{\text{int}} = \frac{\mathcal{L}_{\text{int}}}{2 \cdot 3} \sim 590 \text{ fb}^{-1} \quad (\text{A.11})$$

$$N_{\Lambda_b}^{\text{Data}} = N_{\Lambda_b}^{\text{MC}} \frac{\mathcal{L}^{\text{Data}}}{\widehat{\mathcal{L}}^{\text{MC}}} \sim 300 \text{ events} \quad (\text{A.12})$$

Using the number of selected events in MC and the corrected integrated luminosity a conservative expected event yield in data is estimated using the Equation A.12. The very idea is to determine the significant contribution of the $\Lambda_b \rightarrow J/\psi K p$ in data by studying the $J/\psi K p$ invariant mass in both data and MC. The mass distribution of the Λ_b is obtained by introducing the mass hypothesis to one of the two charged kaon tracks, in the MC sample the truth match is performed by exploiting the particle ID and in Data a random track is selected as proton. Using the same physics selection similar to $B_s^0 \rightarrow J/\psi \phi$ decay process a clear mass peak of Λ_b originating from $\Lambda_b \rightarrow J/\psi K p$ decay vertex is observed in MC as

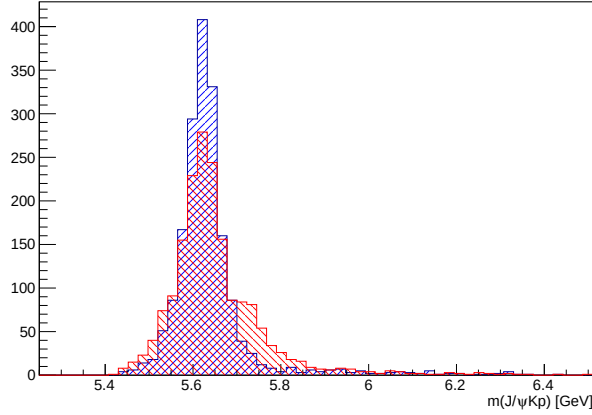


Figure A.2: $J/\psi Kp$ invariant mass distribution in the Λ_b MC sample, after applying the $B_s^0 \rightarrow J/\psi \phi$ selection, when assigning the proton mass using the generation information (blue) and on random basis to one of the two charged tracks (red).

shown in Figure A.2. A large event yield contribution from Λ_b is expected to be observed with a peak at $m(J/\psi Kp) \sim 5.6$ GeV over the reflected B_s^0 mass distribution. Restricting the study only in the left sideband ($5.24 - 5.28$ GeV) of $m(J/\psi KK)$ to increase the ratio of Λ_b events over other sources, the number of Λ_b events is estimated by fitting the $J/\psi Kp$ mass distribution with two Johnson distributions. One left free to float for the B_s^0 mass reflection, and the other with a fixed shape obtained from MC sample, representing the Λ_b peak. In both functions the event yields are left free to float which leads to, $N_{\Lambda_b} = 0_{-0}^{+31}$ and $N_{\text{other}} = 3077 \pm 56$. Thus it is quite unfortunate to argue that in data no Λ_b peak is observed which refrained to estimate the event yield as well. To understand if neglecting the Λ_b peaking background introduces any bias in the measurement a fit is performed including the related terms in the fit model. The Λ_b background is modeled with similar PDFs to the peaking background discussed in the Section 4.6. The parameters are fixed in data with the values obtained by fitting the MC distributions (with the exception of σ_{ct}), so as the event yield is fixed to 300 events (Equation A.12), and splitted between 2017 and 2018 according to the data luminosity. The fit results are reported in Table A.4, the fit projection on the B_s^0 invariant mass and decay time projections are shown in Figure A.4. No evidence of a sizable peaking background related to $\Lambda_b \rightarrow J/\psi Kp$ decay is observed in the Data. Having few hundreds in Data of Using extrapolations from MC samples we estimate that the

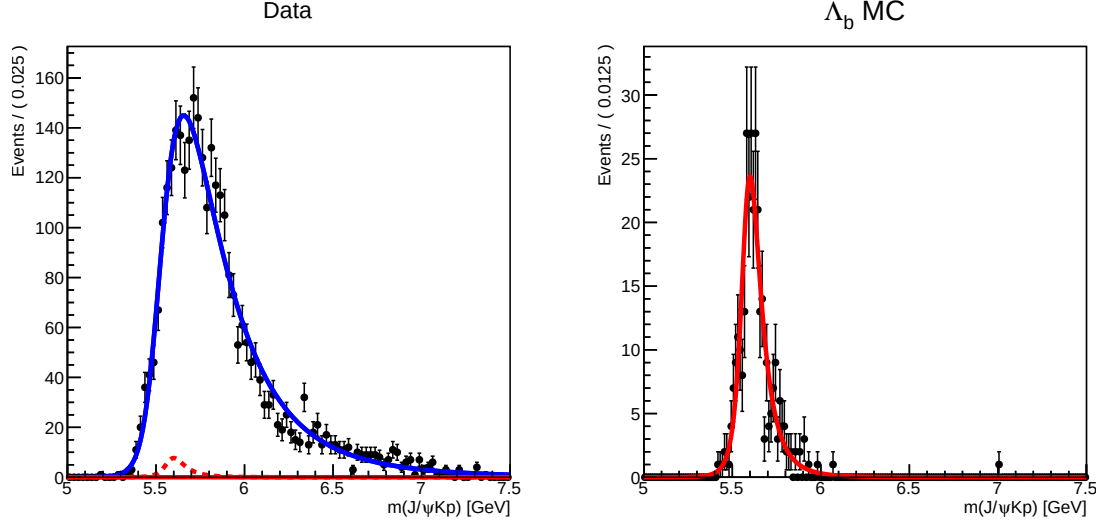


Figure A.3: $J/\psi Kp$ mass distribution in data (left) and in the Λ_b MC sample (right), after applying the $B_s^0 \rightarrow J/\psi \phi$ selection, when assigning the proton mass on random basis to one of the two charged tracks. In the data plot (right) the fit result is drawn with solid blue line, the fitted Λ_b component with a solid red line and the expected Λ_b peak (using the conservative $\mathcal{L} = 590 \text{ fb}^{-1}$ for the MC sample) with a dashed red line.

Parameter	Fit results.	Differences wrt reference
$ A_0 ^2$	0.5360 ± 0.0047	-0.0011
$ A_\perp ^2$	0.2330 ± 0.0063	$+0.0007$
$ A_S ^2$	0.0235 ± 0.0075	-0.0011
$\delta_\parallel$ [rad]	3.18 ± 0.11	$< 10^{-2}$
$\delta_\perp$ [rad]	2.77 ± 0.16	$< 10^{-2}$
$\delta_{S\perp}$ [rad]	0.219 ± 0.073	0.003
ct [μm]	459.0 ± 3.0	0.3
$\Delta\Gamma_s$ [ps^{-1}]	0.114 ± 0.014	$< 10^{-3}$
Δm_s [$\hbar \text{ps}^{-1}$]	17.510 ± 0.095	$< 10^{-3}$
$ \lambda $	0.972 ± 0.026	$< 10^{-3}$
ϕ_s [rad]	-0.012 ± 0.050	$< 10^{-3}$

Table A.4: Fit to data including the Λ_b background. Uncertainties are statistical only. Differences with respect to the reference results (Tab. 4.17) is also presented.

number of events of such background in in data should be of the order of some hundreds of events. Such event yield produce overall a negligible on the fit results, comparable in magnitudes with the smallest systematic uncertainties. We therefore conclude that, in this iteration of the analysis, neglecting the peaking background from $\Lambda_b \rightarrow J/\psi Kp$ does not introduce any bias.

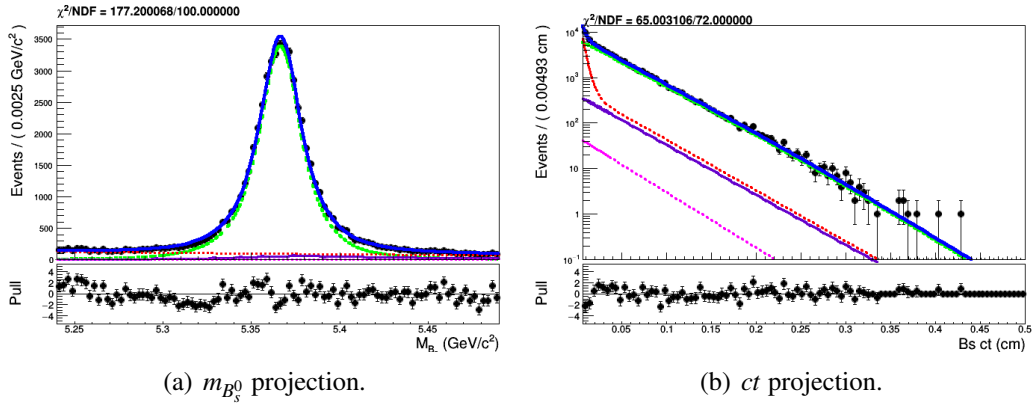


Figure A.4: Fit to data including the Λ_b background: 1D PDF projections. The dashed green line represents the signal, the red line represents the background, the solid dark violet line represents the peaking background from $B^0 \rightarrow J/\psi K^*0$, the dashed magenta line represents the peaking background from $\Lambda_b \rightarrow J/\psi Kp$. The PDF projection is drawn with a solid blue line.

A.5 Effect of the unfitted m_{KK} distribution on the combined results

Parameter	Value	Uncertainty
ϕ_s [rad]	-0.021	± 0.045
$\Delta\Gamma_s$ [ps $^{-1}$]	0.1074	± 0.0097
ct [μ m]	452.9	± 2.3
$ \lambda $	0.970	± 0.027
Δm_s [$\hbar$ ps $^{-1}$]	17.520	± 0.097
$ A_0 ^2$	0.5294	± 0.0058
$ A_\perp ^2$	0.2362	± 0.0064
$ A_S ^2$	0.023	± 0.012
$\delta_\parallel$ [rad]	3.18	± 0.12
$\delta_\perp$ [rad]	2.79	± 0.17
$\delta_{S\perp}$ [rad]	0.229	± 0.083

Table A.5: Combination between 8 and 13 TeV results when including the unfitted m_{KK} distribution systematics. Uncertainties are both statistical and systematic.

	$ A_0 ^2$	$ A_\perp ^2$	$ A_S ^2$	$\delta_\parallel$	$\delta_\perp$	$\delta_{S\perp}$	ct	$\Delta\Gamma_s$	Δm_s	$ \lambda $	ϕ_s
$ A_0 ^2$	+1	-0.60	+0.13	-0.01	-0.01	-0.09	+0.31	+0.61	-0.01	+0.01	+0.02
$ A_\perp ^2$		+1	-0.08	-0.08	-0.01	+0.05	-0.41	-0.71	+0.02	-0.01	-0.02
$ A_S ^2$			+1	-0.07	0.00	-0.52	-0.14	-0.02	+0.02	-0.03	-0.02
$\delta_\parallel$				+1	+0.26	0.00	+0.03	+0.01	-0.01	-0.06	-0.02
$\delta_\perp$					+1	-0.09	-0.02	-0.01	+0.67	-0.17	-0.08
$\delta_{S\perp}$						+1	+0.06	-0.02	-0.04	+0.04	+0.02
ct							+1	+0.48	-0.03	+0.02	+0.03
$\Delta\Gamma_s$								+1	-0.02	+0.01	+0.01
Δm_s									+1	-0.13	-0.17
$ \lambda $										+1	+0.01
ϕ_s											+1

Table A.6: Combination 8+13 TeV results when including the unfitted m_{KK} distribution systematics: correlation matrix.

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