

Probing the Quark Gluon Plasma with B_s^0 and B^+ Mesons
Cross Sections in pp and Nuclear Modification Factors in PbPb Collisions

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Engineering Physics

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Abstract

The quark gluon plasma (QGP) is one of the most exciting frontiers of particle physics. This exotic state of matter forms only under the uttermost conditions, of temperature and density, which are now accessible through relativistic heavy ion collisions. Studying it provides valuable information about its broad underlying theory, quantum chromodynamics. Due to b quarks being long lived particles that can record the QGP medium induced effects, hard probes such as B mesons have been identified as a phenomenological tool to learn about the QGP inner workings. In this thesis, the B_s^0 and B^+ production cross sections are first measured as functions of transverse momentum, p_T , in proton-proton collisions at $\sqrt{s} = 5.02$ TeV. The data was collected with the CMS detector during the 2017 LHC run. The B mesons are exclusively reconstructed through the decay channels $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ and $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$. The production cross sections are compared against the FONLL theoretical prediction and found to be in overall good agreement. To quantify the QGP medium effects on the B meson spectra the nuclear modification factors, R_{AA} , are computed. In PbPb vs pp a high suppression of their production is observed, with B_s^0 mesons being slightly less suppressed than B^+ mesons. At low p_T , B_s^0 R_{AA} is compatible with the hypothesis of quark coalescence.

Keywords: QCD, QGP, LHC, CMS, Heavy Ion Collisions, B Mesons

Resumo

O plasma de quark e glúons (QGP) é uma das mais intrigantes fronteiras da Física de Partículas. Este estado exótico da matéria forma-se apenas em condições extremas, de temperatura e densidade, que agora são recreáveis através de colisões relativistas de íons pesados. O estudo deste fenómeno fornece informações essenciais sobre a sua extensa formulação teórica, a cromodinâmica quântica. Os mesões B têm-se recentemente mostrado extremamente relevantes para sondar o QGP, particularmente devido ao longo tempo de vida dos quarks b permitirem tanto registar os efeitos do meio que atravessaram como uma reconstrução mais clara. Explorando esta última vantagem ao longo desta tese são realizadas medições das secções eficazes dos mesões B_s^0 e B^+ em função do momento transversal, p_T , em colisões próton-próton a $\sqrt{s} = 5.02$ TeV. Os dados analisados foram adquiridos pela experiência CMS, durante a operação do LHC em 2017. O sinal dos dois mesões B foram explorados nos canais de decaimento $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ e $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$. As secções eficazes medidas foram comparadas à previsão teórica FONLL e observou-se uma boa concordância. Para quantificar os efeitos do QGP no espectro de mesões B determina-se os respetivos fatores de modificação nuclear, R_{AA} . Em ambos os mesões observa-se uma elevada supressão da sua produção, sendo os mesões B_s^0 ligeiramente menos suprimidos que os mesões B^+ . A reduzido p_T , o R_{AA} do mesão B_s^0 é compatível com a hipótese de coalescência entre quarks.

Palavras-Chave: QCD, QGP, LHC, CMS, Colisões de Íons Pesados, Mesões B

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Chapter 1

Introduction

1.1 The Standard Model of Particle Physics

Today's knowledge about fundamental particles distinguishes them into two main groups, the Fermions and the Bosons, each respectively obeying Fermi-Dirac or Bose-Einstein statistics. Fermions (spin 1/2) are further divided into quarks and leptons, a separation which has to do with the *color* charge, an additional quantum number that only quarks possess. Both quarks and leptons contain six species of particles labeled by their *flavour* quantum number. Bosons are also further divided into two types, gauge bosons (spin 1) and scalar bosons (spin 0). The former are the actual manifestation of three fundamental forces, the strong, electromagnetic and weak forces, ordered here by decreasing interaction strength. The only elementary scalar boson known, the Higgs boson, arises from a spontaneous symmetry breaking (SSB) of the vacuum and accounts for the particles' mass. The theory describing the fermionic particles, their interactions through gauge bosons and the interactions amongst bosons is called Standard Model (SM). Its respective elementary particle content can be readily organized into a table, Figure 1.1, that summarizes their main properties in a very elegant way.

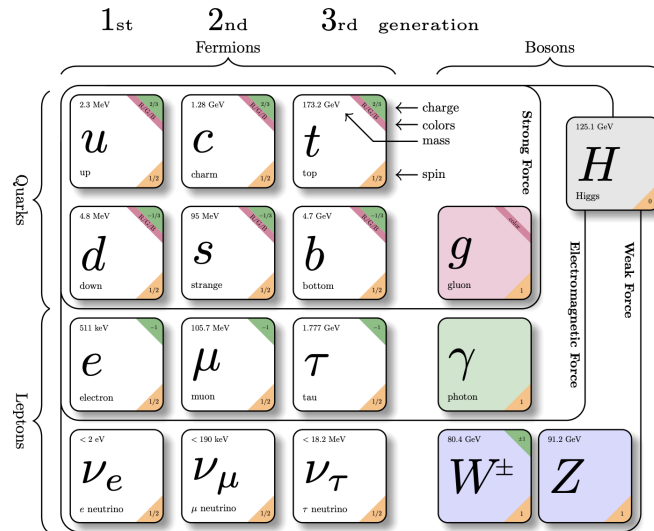


Figure 1.1: All experimentally confirmed fundamental particles and some of their properties.

A key moment of the SM construction was in 1954, when Robert Mills and Chen Ning Yang introduced non-abelian groups to explain the strong interaction between quarks [1]. On that very year, the European Council for Nuclear Research, CERN, was founded, placing the SM construction under solid experimental ground up until today. In fact, by the end of that decade, in 1958, CERN physicists were already providing major insights into weak charged currents by measuring the electron decay mode of pions [2]. Shortly after, in 1961, Sheldon Glashow unified the electromagnetic and the weak force into a single theory, the electroweak theory where, a vital part of it, the Higgs mechanism, would be incorporated in 1967 by Steven Weinberg and Abdus Salam. Such marvelous ideas were lacking experimental confirmation until a breakthrough took place at the Proton Synchrotron, CERN's first synchrotron, in 1973. There, the Gargamelle experiment published the first observation of a processes mediated by a weak neutral current [3], fairy tales about Z bosons whose direct detection would still take another decade. In the mean time, in 1967, CERN turned on the Super Proton Synchrotron, a more robust particle accelerator that made protons collide with anti-protons. The direct observation of the three weak bosons, Z^0, W^+, W^- followed 6 years latter, in 1983 by the UA1 and the UA2 Collaborations [4, 5]. A new experimental step began in 1989, as the large electron-positron collider, LEP, was brought online with the goal of precisely measuring the electroweak theory predictions. Soon the LEP Collaborations had their first major result suggesting that there are only three matter generations as shown in Fig. 1.1. In parallel to these findings, the existence of six quark flavours was also established. The top quark, the most massive one, was the last to be found in 1995 at the Tevatron. By then, the SM was missing a central piece since the physical manifestation of the Brout-Englert-Higgs mechanism, the Higgs boson, had not been observed yet. Its detection followed only after the construction of the Large Hadron Collider (LHC). On the 4th of July 2012 the Compact Muon Solenoid (CMS) and A Toroidal LHC ApparatuS (ATLAS) Collaborations announced the observation of a Higgs-like particle that has been further scrutinised and revealed to be the SM scalar [6, 7].

Ever since its development the SM has made predictions with great success. Among them, the most accurately verified prediction is the magnetic moment of the electron which matches the experimental measurement up to 10 significant figures. Unfortunately, the SM success is limited as it only describes around 5% of the matter and energy of the universe. Among the missing content two very important mechanisms deserve to be highlighted. One to account for neutrino masses, which are known to exist through neutrino oscillation experiments [8], and another to explain the current matter vs anti-matter asymmetry of the universe. Furthermore, although special relativity is incorporated in the theory, general relativity is not, making the Standard Model predictions fail at energies where gravity can no longer be ignored, namely, the Planck scale 10^{19} GeV. As a consequence the SM is seen as an effective field theory, the low energy remnant of a wider theory. Moreover, the observed Higgs mass implies an incredible fine-tuning cancellation between radiative corrections and the bare mass. Solutions to these difficulties require complementing the SM with new physics theories which in turn add a plethora of exciting concepts and predictions. Still, without any experimental evidence such new predictions are doomed regardless of how robust they are. Hence, experimental particle physics serves as a *greatfilter* for ruling out unnatural theories while looking for signatures of unknown particles.

1.1.1 Mathematical Formulation of the Standard Model

The SM is a non-abelian quantum field theory combining quantum chromodynamics (QCD), which has a $SU(3)$ gauge group, with the electroweak theory, which has a $SU(2) \times U(1)$ gauge group. The electroweak part of the theory is chiral since its $SU(2)$ factor, with 3 gauge bosons, W^i , acts only on L -handed fields with a coupling constant g and its $U(1)$ factor, with gauge boson B , couples both to L - and R -handed fields with a coupling constant g' affected by their different weak hypercharges, Y . In contrast, the $SU(3)$ part of the theory is non-chiral. Its gauge bosons, the 8 gluons, G^a , couple only to fields possessing colour charge with a coupling constant g_s unaffected by their chirality. Coupling constants are not physical observables but rather quantities defined in the context of perturbation theory that enter in the prediction of the amplitude of real processes. The particle content of the SM is grouped into $SU(2)$ doublets, containing L -handed fermions and the Higgs, and into $SU(2)$ singlets, containing R -handed fermions (excluding R -handed neutrinos since these have never been observed),

$$SU(2) \text{ doublets : } q_{i\alpha L} = \begin{pmatrix} u_{i\alpha} \\ d_{i\alpha} \end{pmatrix}_L, \quad l_{iL} = \begin{pmatrix} \nu_i \\ e_i \end{pmatrix}_L, \quad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (1.1)$$

$$SU(2) \text{ singlets : } u_{i\alpha R}, \quad d_{i\alpha R}, \quad e_{iR} \quad (1.2)$$

where the i -index refers to the respective up or down quark type of the i -th family and α refers to the three possible colours of a quark, "red" (R), "blue" (B) or "green" (G).

The mathematical formulation of the SM involves a Lagrangian (density), $\mathcal{L}_{SM}$, which, in addition to Lorentz invariance, has the internal symmetry given by the gauge group $SU(3) \times SU(2) \times U(1)$. It is usually divided into four sectors, $\mathcal{L}_{SM} = \mathcal{L}_{gauge} + \mathcal{L}_f + \mathcal{L}_\phi + \mathcal{L}_{Yuk}$, namely the gauge, fermion, scalar and Yukawa sectors. Under global transformations of the above gauge group the action, $S = \int \mathcal{L} d^4x$, remains unaltered, meaning that the equations of motion for fields contained in the Lagrangian are also unaltered. However, for local gauge transformations the kinetic terms for fermionic and scalar sectors ruin the gauge invariance. Thus, derivatives therein must be promoted to covariant derivatives, D_μ . For derivatives acting on quark doublets the covariant version is

$$\partial_\mu \longrightarrow D_{\mu\alpha\beta} = \left(\partial_\mu + ig'YB_\mu + ig \sum_{j=1}^3 \frac{\sigma^j}{2} W_\mu^j \right) \delta_{\alpha\beta} + ig_s \sum_{a=1}^8 \frac{\lambda_{\alpha\beta}^a}{2} G_\mu^a, \quad (1.3)$$

where $\sigma^j/2$ and $\lambda^j/2$ are the fundamental representation of the $su(2)$ and $su(3)$ algebra generators with σ^j the Pauli matrices and λ^j the Gell-Mann matrices divided. The $SU(2)$ and $SU(3)$ factors commute implying conservation of each other charges under the respective interactions. For the Higgs and leptonic fields the $SU(3)$ factor does not enter the covariant derivative since these are colour singlets. Moreover, for R -handed fields the $SU(2)$ factor will also not appear in the covariant derivative since these are flavour singlets. Hence, the SM lagrangian contain the terms

$$\mathcal{L}_{SM} \supset \bar{q}_{iL} i \not{D}_{\alpha\beta} q_{i\beta L} + \bar{u}_{i\alpha R} i \not{D}_{\alpha\beta} u_{i\beta R} + \bar{d}_{i\alpha R} i \not{D}_{\alpha\beta} d_{i\beta R} + \bar{l}_{iL} i \not{D} l_{iL} + \bar{e}_{iR} i \not{D} e_{iR} + (D^\mu \phi)^\dagger D_\mu \phi \quad (1.4)$$

Through the Higgs mechanism, the $SU(2) \times U(1)$ group is spontaneously broken into a single $U(1)$ with generator $Q = Y + \sigma_3/2$ where Q is the electric charge operator. As a consequence, the W_μ^3 and B_μ mix into the massless electromagnetic field A_μ (the photon) and the massive weak neutral field Z_μ^0 while W_μ^1 and W_μ^2 mix into the fields of the two charged massive vector bosons $W^\pm$. These results follow from expanding the last term in Eq. (1.4) around a neutral vacuum given by the second component of the Higgs doublet, $\langle \phi \rangle_{VAC} = (0 \quad \frac{(v+H(x))}{\sqrt{2}})^T$ where v is a constant and $H(x)$ is the Higgs field. A second and equally important consequence of this SSB comes from the Yukawa sector,

$$\mathcal{L}_{Yuk} = - \left[\bar{q}_{iL} \Gamma_{ij}^u \tilde{\phi} u_{jR} + \bar{q}_{iL} \Gamma_{ij}^d \phi d_{jR} + \bar{l}_{iL} \Gamma_{ij}^e \phi e_{jR} + h.c. \right], \quad (1.5)$$

where $\tilde{\phi} = i\sigma^2 \phi^*$ is a conjugate form of the Higgs doublet which gives rise to fermion mass terms after expanding around $\langle \phi \rangle_{VAC}$,

$$\mathcal{L}_{Yuk} \rightarrow \bar{u}_{iL} \Gamma_{ij}^u \frac{(\nu + H)}{\sqrt{2}} u_{jR} + (d, e \text{ terms}) + h.c. = \bar{u}_L M^u (1 + \frac{H}{\nu}) u_R + (d, e \text{ terms}) + h.c. \quad (1.6)$$

where in the second equality $u_{L,R}, d_{L,R}$ and $e_{L,R}$ are family column vectors, $u_{L,R} = (u_{L,R} \quad c_{L,R} \quad t_{L,R})^T$ etc, and $M^{u,d,e} = \frac{\nu}{\sqrt{2}} \Gamma^{u,d,e}$ are mass matrices. These matrices, in the most general case, need not be diagonal. To identify the masses of the physical particles it is necessary to diagonalize them by two separate unitary transformations, A_L and A_R such that $A_L^{u\dagger} M^u A_R^u = \mathcal{M}^u$. Doing so, the physical fields are rotated from the weak basis to the mass basis,

$$(2.6) \rightarrow \bar{u}_L A_L^u A_L^{u\dagger} M^u A_R^u A_R^{u\dagger} u_R + \dots + (d, e \text{ terms}) + h.c. = \bar{u}'_L \mathcal{M}^u u'_R + \bar{d}'_L \mathcal{M}^d d'_R + \bar{e}'_L \mathcal{M}^e e'_R + \dots + h.c.$$

When generalizing this rotation to the rest of $\mathcal{L}_{SM}$ every term remains diagonal in the new basis except the weak charged currents of quarks, J_W^μ , where a unitary quark mixing matrix, the Cabibbo-Kobayashi-Maskawa matrix, V_{CKM} , arises,

$$J_W^{\mu\dagger} = 2\bar{u}_L \gamma^\mu d_L \rightarrow 2\bar{u}_L A_L^u A_L^{u\dagger} \gamma^\mu A_L^d A_L^{d\dagger} d_L = 2\bar{u}'_L \gamma^\mu V_{CKM} d'_L \quad (1.7)$$

since $A_L^{u\dagger} A_L^d = V_{CKM}$ is not equal to the identity in the most general case. The square of the V_{CKM} matrix entries, $|V_{ji}|^2$, give the probability of the flavour transition from a i -quark to a j -quark. Currently, the best determination [9] of the magnitudes of the V_{CKM} matrix elements is

$$|V_{CKM}| := \begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix} \quad (1.8)$$

telling that each quark has a large probability to undergo a flavour transition into a quark of the same generation (diagonal elements are close to unity) but a considerably smaller probability to transit to a quark of other generation (off-diagonal elements are very small).

1.1.2 Quantum Chromodynamics

Inside the SM, quantum chromodynamics is the theory that describes the strong force. Its underlying concept is the unbroken non-chiral $SU(3)$ local gauge symmetry acting on the color indexes of the six flavours of quarks. The kinetic terms for quarks can be read off from Eq. (1.4) and re-written in a form that gets rid of unnecessary chirality indexes. Hence, using $\psi_{q\alpha}$ to denote the Dirac spinor associated with the α -th gauged color and the q -th ungauged quark flavour, the QCD Lagrangian is given by

$$\mathcal{L}_{QCD} = -\frac{1}{4} \sum_a F_{a\mu\nu} F_a^{\mu\nu} + \sum_q \sum_{\alpha,\beta} \bar{\psi}_{q\alpha} (i\not{D}_{\alpha\beta} - m_q \delta_{\alpha\beta}) \psi_{q\beta} \quad (1.9)$$

where the field strength tensor, $F_{\mu\nu}^a = \partial_\mu G_{a\nu} - \partial_\nu G_{a\mu} - g_s f_{abc} G_\mu^b G_\nu^c$, accounts for the gluon field kinematics, f_{abc} are the $SU(3)$ structure constants and m_q is the bare QCD mass of the q -th quark flavour. As a consequence of gauge fixing, a new term giving rise to the Faddeev-Popov ghosts will appear in the Lagrangian. Although nonphysical this new field plays a vital role in QCD. From the Lagrangian the Feynman rules for the tree level correlation functions can be extracted. The associated inverse propagators and vertices are shown in Fig. 1.2.

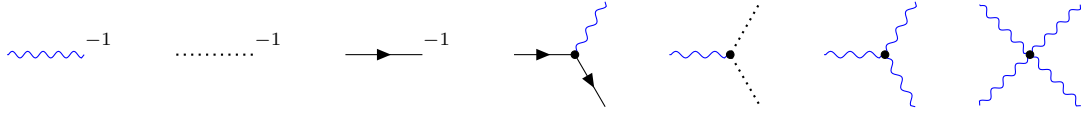


Figure 1.2: Inverse propagators and tree level vertices for QCD.

Higher order corrections to the gluon propagator, ghost propagator and ghost-gluon vertex can always be considered and absorbed into the effective QCD running coupling, $g_s(\mu^2)$ or $\alpha_s = g_s^2/(4\pi)$, depending on the re-normalization scale, μ^2 . At one-loop order the contributing diagrams are shown on Fig. 1.3. These corrections can be safely discarded if the re-normalization scale is comparable to the momentum carried by the gluon.

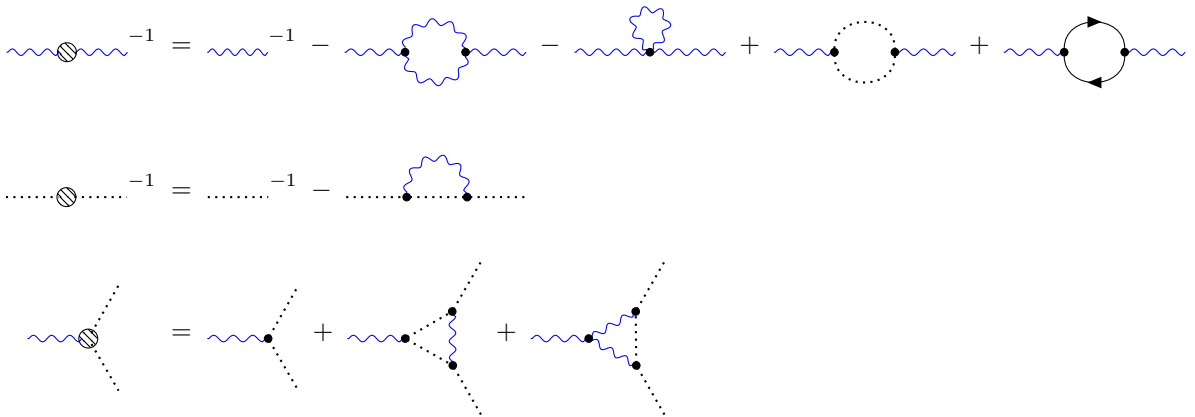


Figure 1.3: One loop corrections to QCD correlation functions. Contributions from quark loops screen the color charge at long distance, making the effective force weaker. In contrast, gluon loops anti-screen. Since these dominate for six flavors the strong force becomes much stronger at long distances and much weaker at short distances.

Employing the dimensional renormalization method the loops of Fig. 1.3 can be evaluated and, using the renormalization group invariant combination, the expression for the running coupling is given by

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi} (33 - 2N_f) \ln(\frac{Q^2}{\mu^2})}, \quad (1.10)$$

where N_f is the number of quark flavours covered by the energy Q . Inspecting Eq. (1.10) follows that the strength of the QCD coupling varies considerably over the range of energies relevant to particle physics. When Q^2 is very small $\alpha_s \rightarrow \infty$ meaning that for small momentum transfers the strong interactions becomes very powerful. As a consequence, if color charges are pushed apart the gluon field between them forms into a string. At zero temperature, the energy stored in the string is given by the Cornell potential [10], $V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + kr$, where the first term accounts for one-gluon repulsive exchanges at short distances and the second term accounts for the gluon self-interactions. From the form of $V(r)$ an immediate conclusion is that color charges can not exist isolated. This hallmark of QCD, known as confinement, implies that color charges must form colorless bound states or *Hadrons*. Depending on the number of valence quarks hadrons are referred to as *Baryons* (qqq) or as *Mesons* ($q\bar{q}$). Further increasing the number of valence quarks leads to exotic hadrons such as the tetraquark, pentaquark and so on. Although it is not possible to isolate quarks or gluons, nature does allow to ever separate them as soon as $V(r) \geq 2m_\pi$. At this point, the confining string splits and gives rise to a new pair of quarks, creating two mesons through a process well establish but poorly understood known as *hadronization*, a second hallmark of QCD. All quarks *hadronize* on a length scale of 10^{-15} m [11] except for the top quark which, due to its large mass, decays instead. On the other hand, when Q^2 takes very high values, $\alpha_s \rightarrow 0$, meaning that if quarks have very big momentum transfers their interactions becomes soft and so, in this limit, quarks can be treated as quasi-free particles. This weakening of the coupling strength is seen as a third hallmark of QCD, known as asymptotic freedom. In Fig. 1.4 a summary of the most precise measurements of α_s are shown.

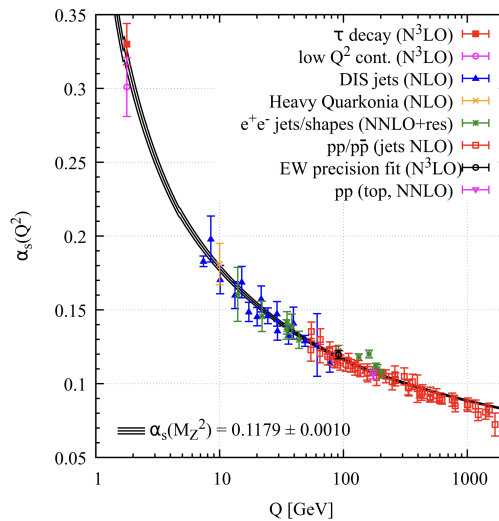


Figure 1.4: Overview of $\alpha(Q^2)$ measurements from the PDG. The barely noticeable kinks in the QCD prediction occur at the thresholds for producing new quarks since these increase the number of flavours, N_f , taking place in the quark loop diagrams.

1.2 The Quark Gluon Plasma

In a bound state of several color charges many-body dynamics becomes relevant as the quanta continuously scatter off each other due to their strong interactions. Naturally, this gives rise to a temperature, T , a variable not accounted in previously introduced Cornell potential, and suggests a description based on thermodynamics. Moreover, in a packed medium of quarks and gluons, Debye color screening effects reduce the radius at which colour charges sense each other and so a more complete potential that embeds the Cornell potential at its $T \rightarrow 0$ limit and accounts for this screening effect is given by

$$V(r, T) = -\frac{4}{3} \frac{\alpha_s}{r} \exp\left(-\frac{r}{r_D(T)}\right) + rr_D(T) \left(1 - \exp\left(-\frac{r}{r_D(T)}\right)\right) \quad (1.11)$$

where the Debye screening radius, $r_D(T)$, is inversely proportional to the system temperature. Consequently, at huge temperatures the screening radius becomes so small when compared to the average charge separation, $r_D \ll r$, that $-\frac{4}{3} \frac{\alpha_s}{r} \exp\left(-\frac{r}{r_D(T)}\right) \rightarrow -\frac{4}{3} \frac{\alpha_s}{r}$, $rr_D(T) \left(1 - \exp\left(-\frac{r}{r_D(T)}\right)\right) \rightarrow 0$. The Coulomb-like term survives and the confining term causing the potential to diverge with increasing r vanishes. Therefore, when Eq. (1.11) simplifies to $V(r, T \rightarrow +\infty) \sim -\frac{4}{3} \frac{\alpha_s}{r}$ a given system of color charges undergo a phase transition into a state where its quarks and gluons become de-confined and compose the relevant degrees of freedom. Thus, when hadrons reach a 'melting' point a very exotic state known as Quark-Gluon Plasma (QGP) emerges.

Thermalized systems of color charges are called quark matter and its study is the scope of hot QCD. A typical temperature of a QGP is of order $T \sim 10^{12}$ K, hundreds of thousands times hotter than the Sun's core, $T_\odot \sim 1.57 \times 10^7$ K. This scorching medium is the closest system to the SM microscopic degrees of freedom, being a direct manifestation of collective behaviour in a fundamental non-abelian quantum field theory. The system is, misleadingly, called a plasma mainly because of the presence of roaming colour charges. Phenomenologically, its behaviour is captured through hydrodynamic models associated to a very small shear viscosity, making the QGP the most perfect liquid undergoing relativistic flow ever reported. The fall of the screening radius with increasing temperature also implies the shortening of the strong force reach and, at extremely high values of T , the very small interaction range throws QCD into its asymptotic freedom behaviour where the QGP medium hosts only soft scatterings. On the other hand, around the aforementioned low temperature the roaming quarks and gluons remain strongly coupled. In addition to temperature, the phase transition that de-confines quarks and gluons depends also on the baryon chemical potential, μ_B , the excess of quarks over anti-quarks. At low μ_B lattice QCD simulations indicate a rapid and continuous increase of the system thermodynamic variables [12]. Accordingly, the phase change must be associated with an ∞ -order transition or, simply put, a crossover. At higher values of μ_B the phase transition becomes first order at a predicted critical point.

Extrapolating the properties of the universe backwards it becomes much hotter, denser and in chemical equilibrium, undergoing the QCD phase transition right after $\sim 10^{-5}$ seconds of the Big Bang at around $T \sim 150$ MeV, the Hagedorn temperature [13]. Hence, shortly after its birth, the universe was permeated by a quark gluon plasma during what is called the quark epoch (10^{-12} s to 10^{-5} s) and so research about the QGP contributes to cosmology by studying the state of the early universe and the same crossover

transition [14] that lead to the formation of all hadrons - the primordial QGP is the source of all protons and neutrons composing the current universe. Moreover, it sheds light into the QCD phase diagram where many features are still poorly understood, like the prediction of a color superconducting phase. Being a rich medium of quarks and gluons, the QGP is a very favourable environment for the formation of exotic bound states like $X(3872)$ [15] or even Glue-Balls [16] whose signatures can be explored by state-of-the-art detectors such as the Compact Muon Solenoid (CMS). Possible beyond SM models are also consistent with the QGP since its liquidness aligns very well with that of other plasmas described by gauge theories close to QCD. Such theories have a dual gravitational description in terms of a $4 + 1$ dimensional Anti-de Sitter space where a black hole horizon encodes the hydrodynamic motion of the QGP [17]. Therefore, studying the QGP also inevitably highlights possible new physics theories.

1.3 Relativistic Heavy Ions Collisions

The crossover transition at the end of the quark epoch can not be detected since it left no signature in the microseconds-old universe that survived to be visible today. However, a quark gluon plasma very similar to the primordial one can be re-created at smaller scales in particle physics accelerators allowing to study both the medium and the phase transition. To achieve the extreme conditions under which this QCD medium forms it is necessary to collide beams of relativistic heavy ions. On Fig. 1.5 the QCD phase diagram with its main features are sketched and some probed regions are highlighted.

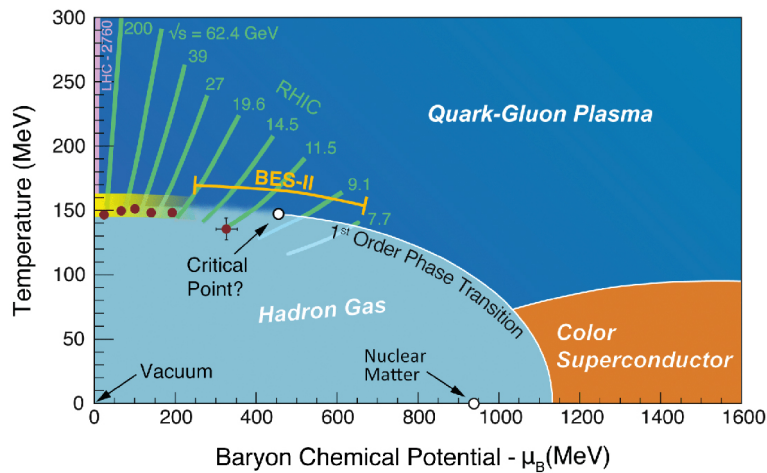


Figure 1.5: The QCD phase diagram [18]. Regions traversed by expanding cooling droplets of QGP formed in heavy ion experiments are sketched. The yellow region has been studied through lattice QCD simulations.

In agreement with Lorentz contraction, at the velocities attained the colliding nuclei are flat disks where each constituent is better described by the parton model [19]. Accordingly, in addition to the three valence quarks, (uud) for the proton and (udd) for the neutron, they are composed by a dense sea of virtual gluons and virtual quark anti-quark pairs. Due to time dilation these quarks and anti-quark should appear real and act, in turn, as sources of transverse colour fields and their respective quanta. This description holds at high energies for any nuclei regardless of its size. At the moment of collision, when

the disks start to overlap the majority of incident partons scatter off with small transverse momentum transfers while a reduced number of them undergo hard scattering, leading to the important production of heavy flavour particles as shall be discussed in Sec. 1.4. As the disks pull away from each other longitudinal color fields fill the space between them and gradually decay into quark anti-quarks pairs and gluons. During the collision a colossal amount of energy is released into a very small region of space. A rough estimate from lead collisions at $\sqrt{s} = 2.76$ TeV [20] indicates the average energy density right after the collision to be $\sim 12 \text{ GeV}/fm^3$, roughly more than twenty times the energy density of a hadron. From lattice QCD this value corresponds to a temperature of approximately 300 MeV. Thus, the newly produced matter is in the state of quark gluon plasma and so a description of the post-collision system in terms of hadrons is not adequate. While the produced QGP is expanding and cooling down more QGP is forming at the wake of each receding disk. This holds until the energy density drops to that within an hadron, $\sim 500 \text{ MeV}/fm^3$, and hadronization takes place. What follows is the end of the quark gluon plasma and the rise of an hadronic gas. These newly formed hadrons eventually scatter off each other and stream away freely.

The QGP formed in heavy ion collisions is a very brief phenomenon, lasting only for an extremely short amount of time, $\sim 10^{-23}$ seconds. Thus, it is too short-lived for external probes to be of any use and so under the framework of modern experimental particle physics its properties are being learned through soft probes emerging from its remnants and through hard probes emerging from the collision. The usual evolution of a QGP formed in a relativistic heavy ion collision is schematically shown in Fig. 1.6.

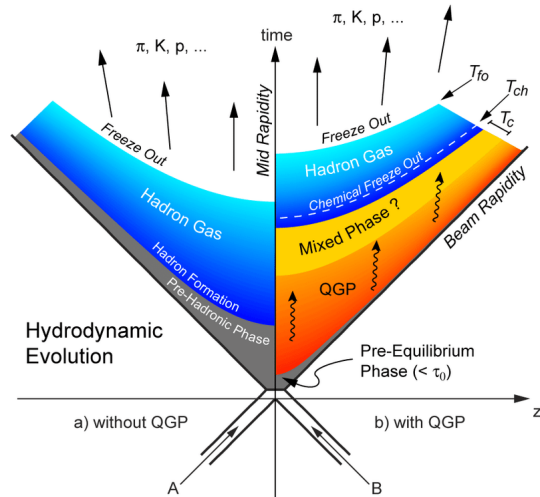


Figure 1.6: Space-time diagram of the evolution of a relativistic heavy ion collision [21]. If following a collision the critical energy density is not reached the system will run into a hydrodynamical evolution as can be seen in the a) region. In that case, right after the impact there is a pre-hadronic phase in which, despite high pressure and temperature, parton deconfinement does not occur. In contrast, if a collision generates the critical energy density a QGP will form and its evolution [22] can be seen in the b) region. In this case, during the first $1 fm/c$ there is an out of equilibrium phase where parton scattering takes place and high transverse momentum particles are created. When the system thermalizes it is in the state of quark gluon plasma. It expands and cools down until the cross-over transition temperature, T_C , is reached. Then, the system hadronizes and a hadron gas emerges. This typically happens after $10 - 15 fm/c$. Shortly after hadronization, when T_{ch} is reached, there is a chemical freeze-out, meaning that no more inelastic scatterings take place. After continuously expanding and cooling down a kinetic freeze-out occurs at T_{fo} . Hence elastic scatterings cease and the hadrons finally stream away.

1.4 B mesons as novel probes of the Quark Gluon Plasma

Heavy flavour quarks are abundantly produced in heavy ion collisions and are very interesting hard probes of the QGP. They are considered “heavy” for two reasons. First, their mass, $m_Q \sim \mathcal{O}(\text{GeV})$, is larger than the typical non-perturbative scale of QCD and so their production [23] can be calculated by perturbation theory, Fig. 1.7. Second, their mass is much larger than the usual temperature, $T \sim \mathcal{O}(\text{MeV})$, of the post collision medium [24]. This implies that any heavy-quark production is essentially restricted to initial nucleon-nucleon hard scatterings since thermal production is impossible. Inspecting the V_{CKM} matrix given in Eq. (1.8) an important observation regarding the b quark mean lifetime can be combined with the previous implication. Since the decay $b \rightarrow t$ is kinetically forbidden ($m_t \gg m_b$) and since both $|V_{cb}|^2$ and $|V_{ub}|^2$ are very small, all decay modes of the b quark are highly suppressed, making them more long lived quarks. As a consequence they shall experience the full evolution of the QGP while being unequivocally produced in the very early stages of the collision.

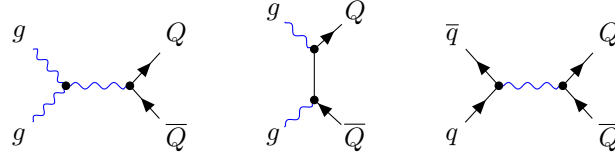


Figure 1.7: Leading order Feynman diagrams for heavy quark pair production in RHICs.

The thermalization of heavy quarks in a QGP medium takes longer than lighter quarks [25] by a factor of m_Q/T . As consequence, b quarks do not thermalize within the reduced lifetime of the QGP and after traversing the medium they hadronize into bound states involving a lighter quark called B mesons, $B^+(\bar{b}u)$, $B^0(\bar{b}d)$, $B_s^0(\bar{b}s)$ and $B_c^+(\bar{b}c)$. These B mesons, whose main properties are summarized in Table (1.1), carry the information about the QGP registered by the b quark. Albeit being bound states of the strong force, B mesons in their ground states decay through the weak interaction only. Thus, they end up being long lived particles since all the possible *beauty* flavour transitions are suppressed. At the energies of modern experiments such lifetime produces a considerable displacement between the collision point and the B meson decay point. This situation can be experimentally exploited since it allows a much cleaner reconstruction of the meson and therefore *beauty* flavoured mesons are outstanding probes of the QGP.

Table 1.1: Main ground state properties of B mesons. The smaller lifetime of B_c^+ steams from the non-suppressed flavour transition of the *charm* quark into a *strange* quark. Moreover, the associated kinematic phase space is bigger than the other B mesons because it is composed by two heavy quarks, further increasing the decay width.

B meson	Invariant Mass [GeV]	Charge	J^P	Lifetime [ps]
$B^+(\bar{b}u)$	5.27931 ± 0.00015	+1	0^-	1.638 ± 0.004
$B^0(\bar{b}d)$	5.27962 ± 0.00015	0	0^-	1.520 ± 0.004
$B_s^0(\bar{b}s)$	5.36682 ± 0.00022	0	0^-	1.511 ± 0.014
$B_c^+(\bar{b}c)$	6.2749 ± 0.0008	+1	0^-	0.507 ± 0.009

The production of the aforementioned B mesons is quantified by their differential cross-section,

$$\frac{d\sigma^B(p_T)}{dp_T} = \frac{1}{\mathcal{B}\mathcal{L}} \frac{1}{\alpha(p_T)\epsilon(p_T)} \frac{dY_s(p_T)}{dp_T}, \quad (1.12)$$

here given as function of the B meson transverse momentum, p_T , and where $\mathcal{L}$ is the integrated luminosity, $\mathcal{B}$ is the decay channel branching fraction, $\alpha(p_T)$ is the detector's acceptance, $\epsilon(p_T)$ is the selection efficiency and Y_s is the total number of detected signal events. Without the presence of a QGP, such as in pp collisions, measurements of this quantity sheds light on the underlying theory, QCD, and allow to test fixed-order plus next-to-leading logarithm (FONLL) [26] predictions by directly comparing the measurements performed with the theoretical expectation. The probability of a b quark hadronizing into a B meson is given by the fragmentation fraction, f_q , where q denotes the flavour of the lighter quark. Knowledge about the production cross section of different B mesons allow in turn to compute the ratio of fragmentation fractions,

$$\frac{f_s}{f_u} = \frac{d\sigma^{B_s^0}(p_T)}{dp_T} \bigg/ \frac{d\sigma^{B^+}(p_T)}{dp_T}, \quad (1.13)$$

which facilitate unique information about hadronization in the vacuum, a critical ingredient for b-hadron branching fraction measurements. Corresponding studies in heavy ion collisions will provide information about the QGP effects on hadronization in particular by computing the ratio of fragmentation fractions measured in the two collision systems, $(f_s/f_u)^{pp}/(f_s/f_u)^{AA}$. The differential cross section of Eq. (1.12) might also be expressed as function of other variables, namely, rapidity, multiplicity and, for RHICs centrality also. Then, new studies can be conducted with complementary goals that highlight more dependencies of the fragmentation fractions. The variable rapidity, y , which is associated with the particle relativistic velocity, facilitates comparisons with heavy-flavour measurements performed by detectors that have different kinematic coverages. Multiplicity, M , which denotes the number of tracks associated with an event, holds direct information about the medium formed and so allows to connect results from different collision systems. Lastly, in heavy ion collisions there is one more variable, centrality, which is related with the number of participant nucleons in the collision and allows to probe the QGP temperature.

As heavy quarks traverse the QGP medium there will be elastic and inelastic medium-induced energy loss mechanisms. The first type is more relevant at low p_T and is due to small momentum transfers between heavy quarks and the medium partons. The second type dominates at higher p_T due to soft gluon emission, whose spectra is given by

$$dP = \frac{\alpha_s C_f}{\pi} \frac{dw}{w} \frac{k_T^2 dk_T^2}{(k_T^2 + \theta^2 w^2)^2}, \quad \theta = \frac{m_q}{E} \quad (1.14)$$

where w is the energy of the radiated gluon, $C_f = 4/3$ for quarks, k_T is the transverse momenta of the radiated gluon and dP is the differential of radiated power in $dwdk^2$. A consequence of Eq. (1.14) is the "dead cone effect" [27], a flavor dependent phenomena that suppresses the radiation in a forward solid angle. Moreover, light quarks will lose a more significant amount of their energy when interacting with the QGP, leading to the hierarchy $\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$. Therefore, the nuclear modification

factor, R_{AA} ,

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \sigma_{AA} / \sigma_{pp}, \quad (1.15)$$

which is the ratio between a cross section measured in heavy ion collisions, σ_{AA} , and pp collisions, σ_{pp} , scaled by the expected number of binary collisions [28], is predicted to be higher for heavy flavoured hadrons, $R_{AA}^{Heavy} > R_{AA}^{Light}$. Any R_{AA} should converge to common values as p_T becomes too big, a region where the flavour dependence of the radiated gluons ceases because the quarks' mass become irrelevant when compared to their energy. Moreover, it should approach unity at even higher p_T , a region where the QGP presence becomes hardly felt by the traversing particles. Contrasting the nuclear modification factor of hadrons of different flavours will provide unique information about the inner workings of the QGP, namely, its scattering power [29]. In turn it relates to the mean free path of the quarks and characterizes how perturbations from equilibrium are transmitted across the medium.

The QGP formed in heavy ion collisions has a temperature much above the *strange* quark mass and so its thermal production is feasible and enriches the medium with s quarks [30] due to the high rate of gluon fusion, $gg \rightarrow s\bar{s}$. For this reason, the presence of a QGP is expected to increment the production of *strange* hadrons like the B_s^0 meson. In addition to fragmentation, low momentum quarks may hadronise through coalescence with other partons roaming in the QGP. Thus, due to the medium-induced energy losses a recombination mechanism [31] is expected to play a significant role on hadronization. This shall further enhance the production of low momentum *strange* hadrons following b quark braking and coalescence with the medium s quarks. To further learn about these possible medium induced effects the double ratio of the nuclear modification factors of different mesons can also be measured.

1.4.1 State of the Art

The highest energies attained at the Large Hadron Collider (LHC) are facilitating tremendous advancements in our understanding of quantum chromodynamics and its implications, particularly the QGP. During the last 55 years, as beams of ultra-relativistic nuclei have become available, heavy ion collisions have been studied in greater and greater detail at ever-increasing collision energies under the experimental framework of the LHC and RHIC Collaborations. The diffusion of heavy flavour in the QGP has been recognised as a promising concept and a phenomenological tool to study this medium and so a comprehensive understanding of the hadronization mechanism is necessary. Nonetheless, although precise heavy flavour data became available at RHIC and the LHC there are still large theoretical uncertainties on the hadronisation of heavy quarks in the presence of a QGP because of the not so clearly understood medium effects affecting their production. To tackle these problems, a plethora of heavy flavour production measurements in pp, pPb and PbPb collisions have been carried out over the past decade allowing to pinpoint QGP effects when compared to each other.

The p_T dependent production cross sections of B_s^0 and B^+ mesons has been measured in PbPb collisions at the LHC by the CMS Collaboration, through the exclusive decay channels, $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ and $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$. The data set, collected in 2015, has a luminosity of $\mathcal{L} = 351 \mu\text{b}^{-1}$, a center of mass energy $\sqrt{s} = 5.02 \text{ TeV}$ and a centrality ranging from 0–100%. The busy

nature of such collision system meant a scarce p_T binning for the B_s^0 meson, namely, $[7, 15, 50]$ GeV/c. For the B^+ meson more bins were possible to consider, $[7, 10, 15, 20, 30, 50]$ GeV/c, however, the $[7, 10]$ GeV/c and $[30, 50]$ GeV/c bins were affected by noticeable statistical uncertainties. Corresponding studies were also conducted in pp collisions. These results can be seen on Fig. 1.8 where both are being compared against the respective FONLL theoretical prediction. The associated data set was also collected in 2015 and featured the same center of mass energy and an integrated luminosity of $\mathcal{L} = 28 \text{ pb}^{-1}$. Due to the low luminosity, the low, $p_T < 10$ GeV/c, and the high, $p_T > 50$ GeV/c, momentum regions of both B mesons were hard to probe since they are respectively characterized by an high amount of background events and by a low amount of data. This restricted both measurements to the $[7, 50]$ GeV/c p_T region and forced the use of three wide p_T bins for the B_s^0 meson, namely, $[7, 15, 20, 50]$ GeV/c, when compared to the B^+ meson case which employed the $[7, 10, 15, 20, 30, 50]$ GeV/c p_T bins. Even so, for the B_s^0 meson the last two bins considered show a somewhat high statistical uncertainty. In contrast, for the B^+ meson this situation did not succeed. The FONLL prediction was found to be very compatible with both measurements, covering the experimental results within its one sigma uncertainty in all bins except for the B_s^0 meson $[15, 20]$ GeV/c p_T bin where the observed value was slightly overpredicted.

Using both collision system results, the nuclear modification factor of both B mesons was then obtained. Although the B_s^0 meson observation was not possible to establish using the 2015 data sample its the R_{AA} was still computed using the only two bins accessible. The lower p_T bin exhibited an exciting hint for strangeness enhancement through quark coalescence as it was found taking R_{AA} values above unity. In the other bin the B_s^0 meson production was found suppressed. On the other hand, the B^+ meson evidenced an overall strong production suppression in the whole p_T region considered. Still, the associated huge uncertainties of most bins leave room for improvement. Moreover, for the B_s^0 meson the possibility of production suppression in the low momentum region can not yet be excluded with certainty and so these studies performed to the 2015 data set await further clarification.

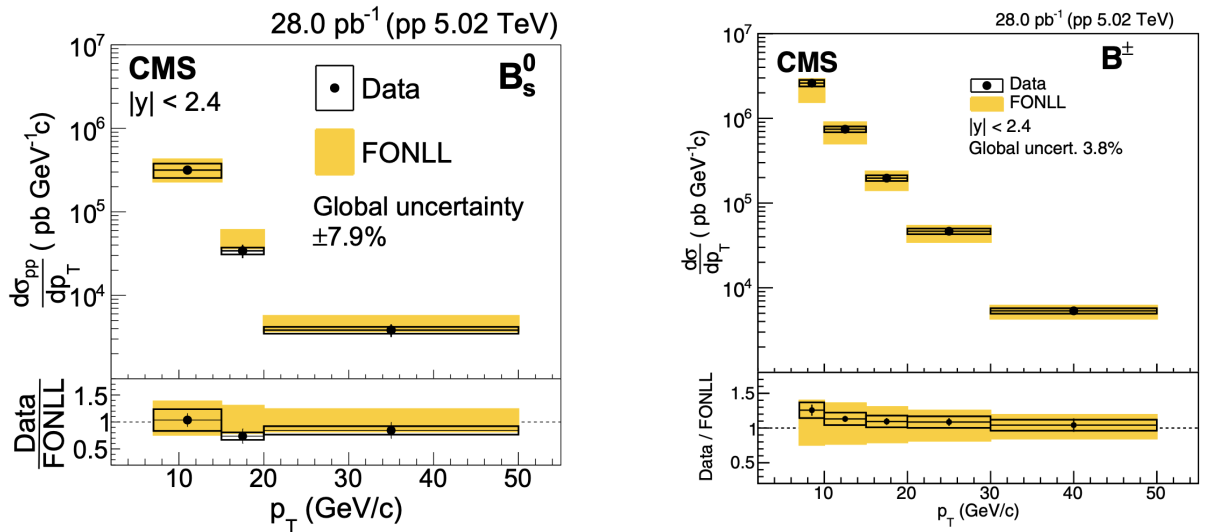


Figure 1.8: The p_T differential production cross section of B_s^0 (left) B^+ (right) mesons in pp collisions at $\sqrt{s} = 5.02$ TeV [32, 33]. The vertical bars (boxes) correspond to statistical (systematic) uncertainties.

The QGP medium effects have been under the scope of several studies by the CMS Collaboration which measured and compared the nuclear modification factors of different hadron species. In Fig. 1.9 the nuclear modification factors, obtained at the same collision energy, $\sqrt{s} = 5.02$ TeV, and in the same centrality range, of prompt D^0 mesons, inclusive charged hadrons, h^+ , featuring mostly light mesons, nonprompt J/ψ mesons and B^+ mesons are shown. In the low p_T region the charged hadron production is found to be more suppressed due to the QGP medium effects than the nonprompt J/ψ and D^0 mesons. In particular, the nuclear modification factor of D^0 mesons remains slightly above that of the inclusive light charged hadrons until $p_T \sim 5$ GeV/c and gradually converges thereafter. It then raises slowly and further merges with the nonprompt J/ψ and B^+ mesons R_{AA} . It should be noticed that at intermediate p_T the nuclear modification factor of nonprompt J/ψ mesons is still higher than that of the D^0 mesons. Then, this supports the foreshadowed bottom-charm hierarchy of the energy losses. All these R_{AA} behaviours are consistent with flavour dependent medium induced energy loss mechanisms and their respective disappearance at higher p_T . As the p_T further increases the D^0 and h^+ R_{AA} are seen to approach unity, indicating that the medium effects cease to noticeably interfere with traversing quarks. Hence, the predictions from Sec. 1.4 hold.

As discussed, the 2015 data samples did not allow to compute the B^+ R_{AA} at $p_T < 7$ GeV/c and so no comparisons with this meson are possible in such region. In the probed $[7, 50]$ GeV/c p_T region its nuclear modification factor is, within the current uncertainties, compatible with the other particles R_{AA} . Still, more studies, particularly towards the low p_T region are desirable to further attest the energy loss hierarchy and reduce the high experimental uncertainties. Moreover, including B_s^0 mesons in these comparisons has the potential of highlighting other QGP medium effects such as strangeness enhancement in the b sector. So far this meson R_{AA} is poorly learned and so its characterization is also very desirable.

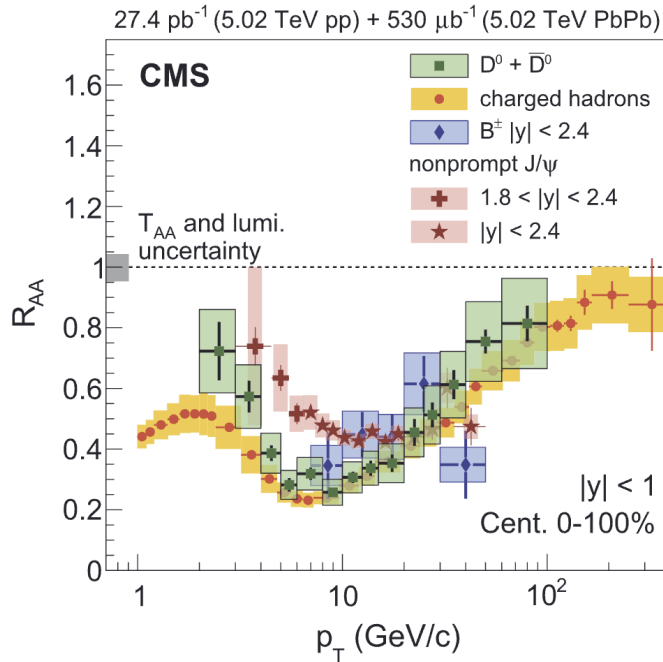


Figure 1.9: Nuclear modification factors of several hadrons [34].

Recently, the production of B_s^0 and B^+ mesons in a PbPb collision system has been revisited [35, 36] by the CMS Collaboration using a new data sample collected in 2018. The associated total luminosity is $\mathcal{L} = 1646 \mu\text{b}^{-1}$, roughly five times higher than its 2015 counterpart, the center of mass energy is $\sqrt{s} = 5.02 \text{ TeV}$ and the centrality region is 0–90%. As a consequence of the luminosity increase two additional bins for the B_s^0 meson were considered in the same p_T range of the 2015 analysis, namely, [7, 10, 15, 20, 50] GeV/c. Furthermore, with a statistical significance exceeding five standard deviations this meson first observation in nucleus-nucleus collisions was established. Because the analysis also aimed to compute the production ratio between the two B mesons the B^+ meson binning had to match the one employed for the B_s^0 meson.

In Fig. 1.10 the resulting p_T dependent production cross sections of both B mesons, measured through the respective exclusive decay channels aforementioned, and the subsequently obtained production ratios can be checked. The B^+ meson cross section is marked by overall low statistical and systematic uncertainties, contrasting with the B_s^0 meson case, where these uncertainties did not go unnoticed. The production ratios are compared against the corresponding measurement performed by the LHCb Collaboration at a similar collision energy, $\sqrt{s} = 7 \text{ GeV}$, but in a pp collision system. Since the discrepancy between the two center of mass energies is small a comparison between the two results is somewhat possible and can hint possible QGP effects. Overall, the production ratios show a huge suppression of B_s^0 meson production when compared to the B^+ meson production. However, this suppression appears to be slightly less in the PbPb system, particularly at the low momentum region where b coalescence with the medium partons is expected to contribute significantly. This constitutes an evidence of strangeness enhancing medium effects in the b sector when a QGP is present. Still, the associated huge uncertainties of the PbPb results prevent a clear conclusion about the significance and strength of such QGP effects.

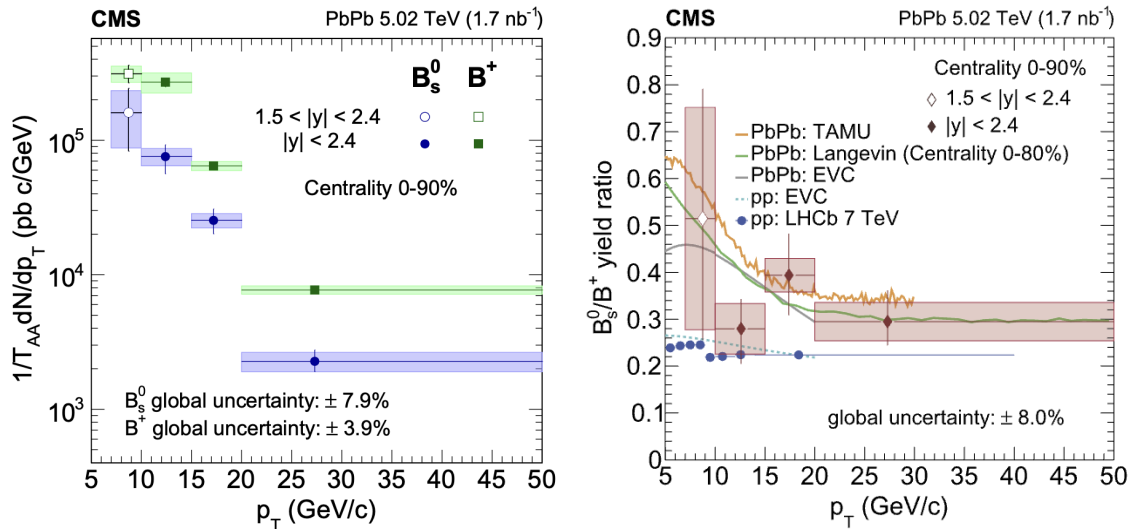


Figure 1.10: On the left plot the p_T dependent production cross sections of the B_s^0 and B^+ meson in PbPb collisions at $\sqrt{s} = 5.02 \text{ TeV}$ are shown. On the right plot, the ratio of their production yields is shown along with the corresponding LHCb measurement in pp [37, 38]. The p_T dependence of the ratio is further compared against three theoretical models that feature quark recombination contributions at low momentum in addition to medium induced energy loss effects.

The *beauty* fragmentation fraction non-universality has also been probed in pp collisions as function of p_T and multiplicity by the LHCb Collaboration. A linear dependence on transverse momentum was observed at low p_T [39] following the precise measurement of the ratio between B_s^0 and B^0 fragmentation fractions. These results were also used to update several B_s^0 branching fractions values which in turn conducted to lower systematic uncertainties in new physics searches. Moreover, a strong and a mild dependence on p_T towards the low momenta region were respectively found for the ratios $f_{\Lambda_b}/(f_u + f_d)$ and $f_s/(f_u + f_d)$. In the same examined region neither ratio showed variations with pseudorapidity. One more relevant finding on the topic of *beauty* hadronization was the increase of the ratio between B_s^0 and B^+ production cross sections with the raise in multiplicity at a transverse momenta below 6 GeV/c as can be seen in the first plot on the left of Fig. 1.11. In contrast, the same ratio but in a higher p_T region, middle plot in 1.11, yielded no significant dependence on the event multiplicity. This suggests a direct observation of the medium influence on the hadronization of b quarks that is most likely related with the coalescence mechanism. Similar studies were performed for the *charm* fragmentation fraction by the ALICE Collaboration in pp collisions at $\sqrt{s} = 5.02$ TeV and 13 TeV. The results, right plot of Fig. 1.11, just like in the case of *beauty*, foreshadow a non-universal behaviour of the fragmentation fractions.

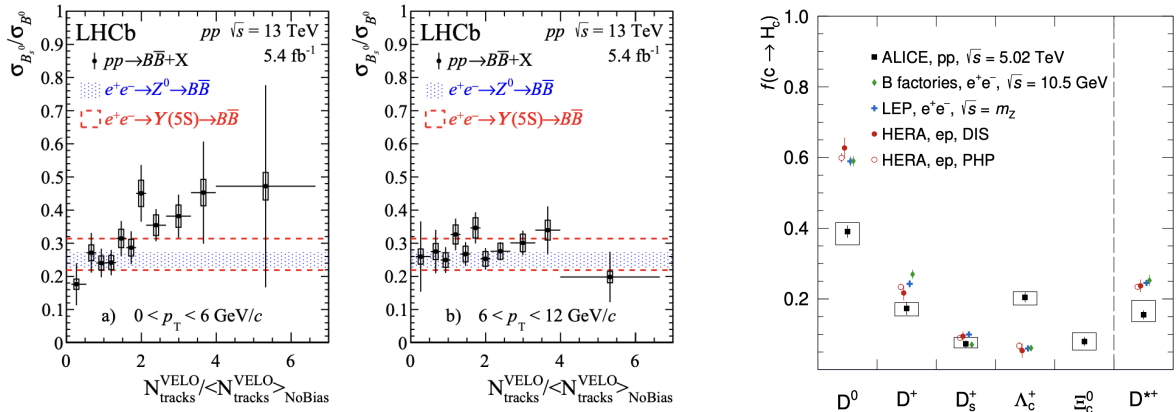


Figure 1.11: On the left the ratio between the multiplicity dependent B_s^0 and B^0 mesons cross sections in two adjacent p_T regions is shown [40]. On the right is shown the hadronization fractions of *charm* into various hadrons are compared to corresponding measurements in e^+e^- and ep collisions [41].

In fact experimental studies employing B physics as a phenomenological tool to explore different scenarios are among the current hot topics of experimental particle physics. An example [42] outside the topic of the QGP where such mesons are also used as probes is for testing violations of lepton flavour universality (LFU). Such processes are interactions whose strength depend on the lepton flavour and thus are associated with physics beyond the SM. One way to pin point their possible effects is through the precise characterization of the branching fraction of the rare beauty decay $B^0 \rightarrow K^{*0} l l$, which occurs only at loop order in the SM, $b \rightarrow s \bar{l} l$, and thus is very sensitive to new physics. In a recent CMS analysis [43] measurements of $\mathcal{B}(B^0 \rightarrow K^{*0} \mu^- \mu^+)$ were performed and evidenced a good compatibility with the SM predictions. Moreover, the result now stands as the most precise determination of this branching fraction. Still, to tackle all the hints appearing over the past years of new physics related phenomena, referred to as flavor anomalies, more studies are necessary.

1.5 Thesis Overview

The study of b flavoured hadrons produced in different collision systems is necessary to learn about *beauty* energy loss and hadronization mechanisms in the vacuum and in the presence of a QGP. This thesis aims to study such effects by first presenting the production cross sections of two B mesons, namely B_s^0 , B^+ , and their charged conjugates, measured with the CMS detector in pp collisions. Then, comparing with previous results obtained in PbPb, the nuclear modification factors are computed and reported along with their double ratio. Moreover, the FONLL theoretical predictions are contrasted against the measured production cross sections.

This work was carried out at Laboratório de Instrumentação e Física Experimental de Partículas (LIP) under the framework of the Portuguese participation in the CMS experiment. The CMS-wide analysis counted with the collaboration of our colleagues from the Massachusetts Institute of Technology Heavy Ion Group.

The aforementioned B mesons are exclusively reconstructed through the decay channels

$$B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^- K^+ \quad (1.16)$$

$$B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+ \quad (1.17)$$

whose total branching fractions are $\mathcal{B}(1.16) = 3.04 \times 10^{-5}$ and $\mathcal{B}(1.17) = 6.08 \times 10^{-5}$. Since the CMS detector has an outstanding muon detection and trigger capability, decay chains involving muons on the final state are much preferred over other decays with higher branching fractions in order to take full advantage of the experimental framework. Hence the chains (1.16) and (1.17) have been chosen. In fact, at tree level, the flavour transition $\bar{b} \rightarrow \bar{c}$ is roughly a hundred times more favoured than $\bar{b} \rightarrow \bar{u}$ while also being the only feasible way of giving rise to flavourless mesons capable of decaying into two muons – the $\pi^0(u\bar{u})$ meson would not have enough mass for instance. Furthermore, the weak W boson involved in the b quark decay is required to decay into a pair of quarks belonging to the 2nd generation, $c\bar{s}$, in order to form the desired J/ψ meson and being at the same time a favoured process, $|V_{cs}|^2 \sim 1$. Although the two decay chains are featuring these two weak vertices, $(\bar{b}W \rightarrow \bar{c})$ and $(W \rightarrow c\bar{s})$, the other meson formed is quite different in both decay cases. For the B^+ meson a $K^+(\bar{s}u)$ meson will appear and propagate towards the detector. In contrast, for B_s^0 a $\phi(\bar{s}s)$ meson appears and quickly decays. Being a flavourless meson, it could also give rise to two muons. However, a muon pair is already ensured by the required charmonium decay and so it is preferred that ϕ undergoes its most frequent decay into a pair of kaons. The Feynman diagrams showing the weak decay of the B_s^0 and B^+ mesons are represented in Fig. 1.12.

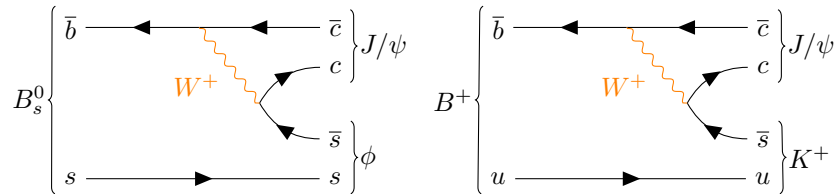


Figure 1.12: Leading order Feynman diagrams of the considered B meson decays.

Each of the following chapters explains the pp analysis from its very beginning. In Chapter 2 a review of the LHC and the CMS detector, including its subsystems, is provided. Then, Chapter 3 details the pp data, $\sqrt{s} = 5.02$ TeV and $\mathcal{L} = 302.3 \text{ pb}^{-1}$, and Monte Carlo (MC) samples used as well as the selection cuts applied. In addition the 2018 PbPb data and MC are introduced since in the end the respective analysis results will be used. The next two chapters describe the key analysis steps where the p_T dependent raw signal yields are obtained, Chapter 4, and the efficiency is estimated, Chapter 5. Because the analysis is employing p_T bins, namely, $[5, 7, 10, 15, 20, 30, 50, 60]$ GeV/c for B^+ and $[7, 10, 15, 20, 50]$ GeV/c for B_s^0 , the differential cross section expression given in Eq. (1.12) should rather be understood as

$$\frac{d\sigma^B(p_T)}{dp_T} = \frac{1}{\mathcal{B}\mathcal{L}} \frac{1}{\alpha(p_T)\epsilon(p_T)} \frac{Y_s(p_T)}{\Delta p_T}, \quad (1.18)$$

where Δp_T is the respective p_T bin width. At this point it is already possible to compute it since all its factors are known. However, the associated systematic uncertainties are not yet characterized and doing so is the scope of Chapter 6. Finally, in Chapter 7, the production cross sections of B_s^0 and B^+ is obtained and contrasted both against the previous 2015 results and the FONLL predictions. Then, the nuclear modification factors of both B mesons are computed according to Eq. (1.15) and compared against the 2015 results, several theoretical curves and to the respective CMS measurement of charged hadrons and D^0 mesons. To further learn about the QGP effects the ratio of the nuclear modification factors, $R_{AA}^{B_s^0}/R_{AA}^{B^+}$, is also obtained.

Experimental Framework

2.1 The Large Hadron Collider

The Large Hadron Collider at the CERN scientific campus lies 100 m underground. Its commissioning started in 1998 and finalized in 2008, decommissioning LEP and becoming the world's largest and most powerful particle accelerator. The LHC is a ring with a circumference of 26.7 km appearing at the end of a succession of smaller accelerators, namely, the Proton Synchrotron Booster, the Proton Synchrotron and the Super Proton Synchrotron. Inside it, proton or lead beams guided by powerful magnetic fields travel at ultra relativistic velocities until they are made to collide, spraying newly formed particles in all directions. The rate at which these collisions occur, $R = L\sigma$, is proportional to the instantaneous luminosity, $L = f \frac{N_1 N_2 n_b}{4\pi\sigma_x\sigma_y}$, where f is the beam frequency, N_1 and N_2 are the number of particles in each bunch, n_b is the number of bunches, and σ_x and σ_y are the transverse dispersion of the beam.

The principal goal of the outstanding scientific and engineering effort behind the LHC was to observe the Higgs boson. With this task achieved in 2012, the LHC now aims to search and explain other aspects of the universe with emphasis on QCD and its phenomenology, the structure of exotic hadrons, the precision measurements of rare physics process, and the predictions from new physics. To achieve these goals there are four main experiments each employing a very unique detector. The Compact Muon Solenoid (CMS) and A Toroidal LHC Apparatus (ATLAS) are two general purposes detectors built to collect data both from pp and PbPb collisions. Their focus is to scrutinize the SM predictions and to conduct searches on physics beyond the Standard Model. Both are optimized to detect high p_T final state particles, a very suitable performance, for instance, when studying the quark-gluon plasma. In particular, CMS excels at this task using heavy flavoured particles as probes of this medium. The Large Hadron Collider beauty (LHCb) is a detector conceived to explore the charge-parity violation arising in beauty flavoured hadron interactions. A much desired outcome of such studies would hint the mechanism that introduced the matter anti-matter asymmetry in the universe. A Large Ion Collider Experiment (ALICE) is a detector dedicated to heavy ion collisions whose objective is to study QCD and its phenomenology. It has the capacity of reaching the low p_T region of interesting observables such as multiplicity. In addition, there are five more ongoing smaller experiments also employing their very own detector. The latest, SND@LHC, has delivered the first observation of collider neutrinos.

2.2 The Compact Muon Solenoid Detector

The CMS apparatus [44] is a multipurpose detector designed to trigger and identify electrons, muons, photons, and both charged and neutral hadrons originating from collisions with a $\sqrt{s}$ on the TeV scale. It has a cylindrical shape with a diameter of 15 m, and a length of 21 m. The CMS detector can be divided into several sub-detectors and components, namely, from the innermost to the outermost, the silicon tracker, the electromagnetic calorimeter, the hadronic calorimeter, the solenoid and, lastly, the muon chambers. In Fig. 2.1 an overview of CMS is shown and in Fig. 2.2 its sub-detectors are sketched. A reconstruction algorithm [45] combines the information provided by the silicon tracker and by both calorimeters with data from the muon chambers. All the particles that CMS was designed to trigger on can be detected and measured with great accuracy.

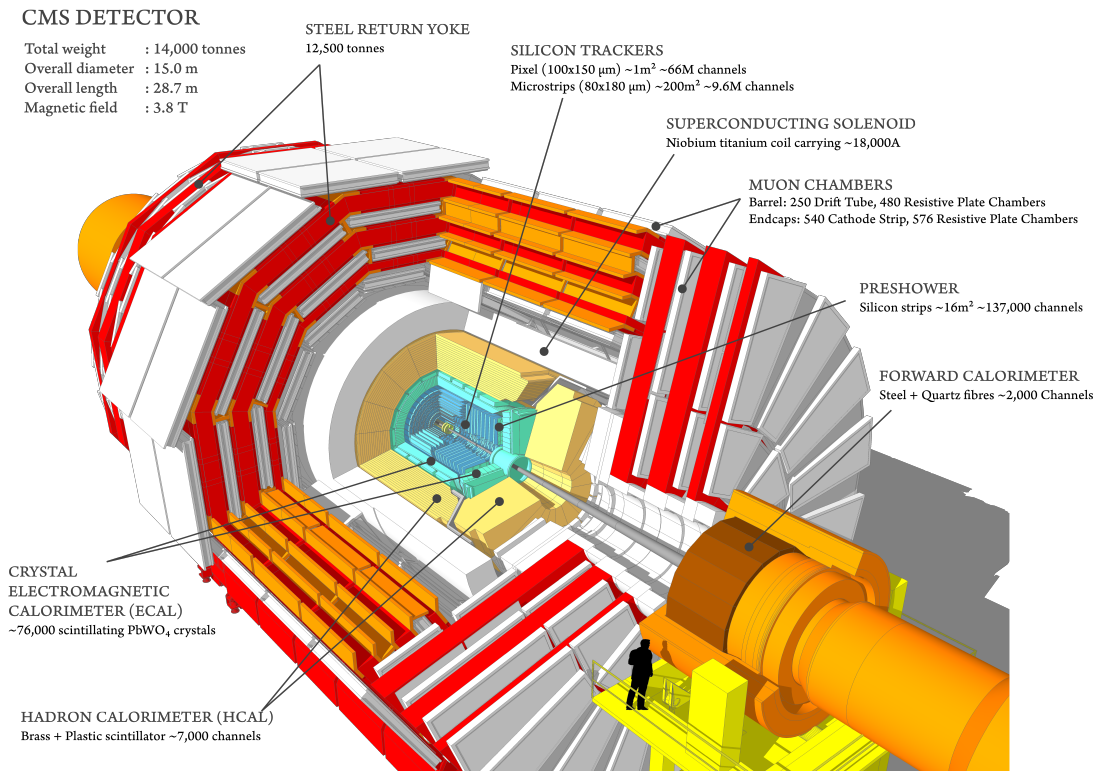


Figure 2.1: Schematic view of the CMS detector.

The silicon tracker can be further divided into two sub-systems, the pixel detector and the microstrip detector, featuring together ~ 135 million electronic readout channels. Since it is located at the hearth of the CMS detector it witness the highest flux of particles. Thus, its materials need to be radiation proof and light enough so that incoming particles are disturbed as little as possible. For this purpose both its sub-systems are entirely made out of silicon and hence the name "silicon" tracker. The pixel and microship detectors were conceived to rigorously measure the trajectories of charged particles. In addition, the pixel detector precisely measures the position of any primary or secondary collision vertexes and for this reason it is often referred to as vertex detector. As particles travel across the silicon tracker they lose energy to the silicon medium through ionization. The electron-hole pairs will give rise to tiny electric currents that can be amplified and detected. This way, "hits" on the silicon atoms can be used

to reconstruct the path of passing charged particles. Moreover, the silicon tracker is submerged in the magnetic field, B , induced by the solenoid and so any charged particle will bend its trajectory according to its positive or negative charge. Hence the particle transverse momentum can be simply learned by equating the Lorentz force to the centripetal force yielding $p_T = qrB$, where q is the electric charge of the particle and r the curvature radius of its trajectory.

Surrounding the silicon tracker is the electromagnetic calorimeter. All incoming photons and electrons interact with this sub-detector crystalline material leading to an electromagnetic shower. Doing so, their initial energy is deposited into the crystals and as a consequence scintillating light is proportionally produced to the particle's energy. Then, photomultipliers allow the deposited energy to be measured by collecting and converting the light into electric signals. The hadronic calorimeter comes next and encapsulates its electromagnetic counterpart. Its goal is to measure the energy and direction of jets and identify the original quarks and gluons. It is made from brass plates interspersed by plastic scintillators and works in a similar manner to its electronic counterpart.

Wrapping around the first three sub-detectors is the most powerful solenoid magnet ever constructed. In fact, after achieving a superconducting state of the coil wires and channeling through an electric current of 20 kA it is capable of generating an axial magnetic field of $B \sim 4$. To put it in perspective this is a hundred thousand times stronger than the Earth's field. Outside the solenoid the steel return yoke controls the magnetic field where it drops to $B \sim 2$ T.

The outermost layer of the CMS detector is composed by the muon stations, a very sophisticated sub-detector that further improves muon detection and reconstruction. To do so, muon tracks from the silicon tracker are combined with the tracks imprinted in the muon stations confirming that they indeed belong to a muon and allowing a more precise momentum measurement. Each muon station consists of four muon chambers that are interspersed by the steel return yoke and made of several layers of drift tubes, cathode strip chambers and complementary resistive plate chambers.

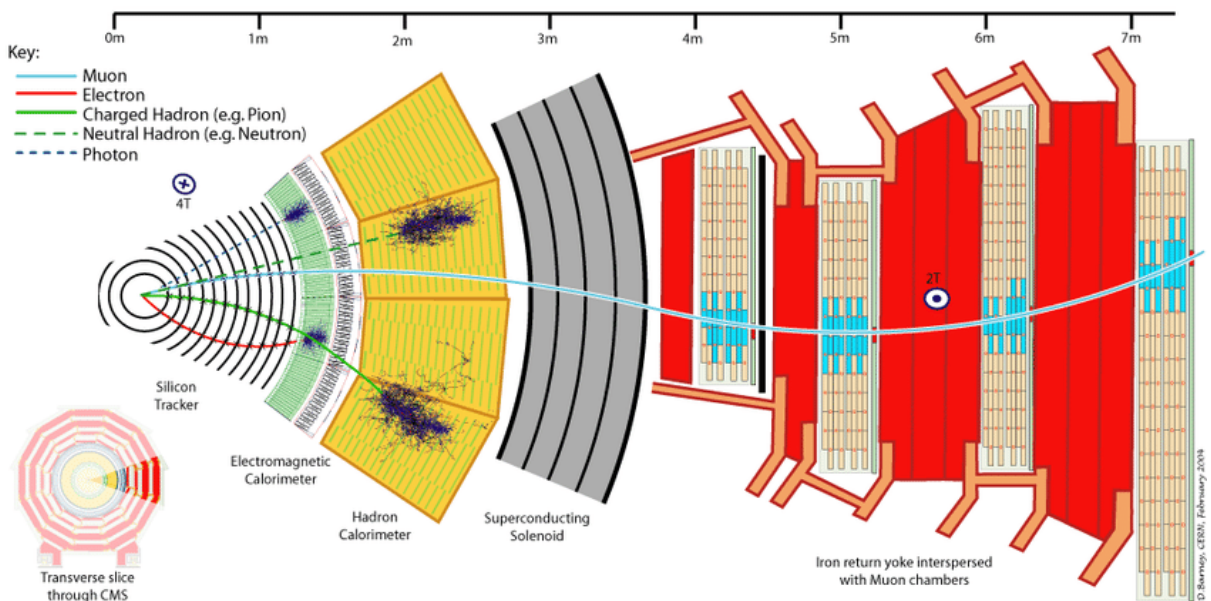


Figure 2.2: Detailed schematic view of CMS sub-detectors.

Among the sub-detectors aforementioned the silicon tracker and the muon stations are the most relevant ones to this analysis. The B mesons measurement and reconstruction is entirely based on the tracks left by the muon and the kaon candidates on these two sub-detectors. Knowing the tracks, the interaction vertices are reconstructed in two steps, namely, vertex finding and vertex fitting. In the first several tracks are grouped into vertex candidates while in the second the best vertex parameters are estimated for a given set of tracks.

2.2.1 Trigger System

The LHC provides particle collisions at very high rates. This deems impossible the storing and processing of the associated large amount of events. An event is essentially a record of a collision outcome. In fact, only a small fraction of them will contain interesting physics going on and should make it into the primary data sets. Thus, a drastic reduction of the data collection rate has to be achieved. This is a task performed by the CMS trigger system which uses two decision levels, namely, the Level-1 (L1) Trigger and the High-Level Trigger (HLT) to filter the events. The total rate reduction capability is designed to be at least a factor of 10^6 for the combined action of these two decision levels.

The L1 trigger is highly programmable and entirely based on hardware, being for this reason also known as hardware trigger. It performs very fast decisions whether to discard or not events containing muons, electrons/photons or jets candidates using information from the calorimeters and from the muon stations. The surviving events are then further processed by the HLT. In contrast, the HLT trigger is entirely based on software running on a processor farm named "Event Filter Farm". It is configured to trigger on events according to a list of algorithms resembling a selection (HLT paths). This is the first stage of the triggering process where information from the silicon tracker is used. Only the events that survive the HLT are saved for future physics analyses.

2.2.2 CMS Coordinate System and Parameters

The CMS experiment uses a Cartesian coordinate system whose origin is located at the collision point. The z axis points along the anti clockwise beam direction, the x axis points to the LHC center and the y axis points perpendicularly to the LHC plane upwards. Some physical variables are rather defined in terms of a polar coordinate system, (r, θ, ϕ) , where the polar angle $\theta \in [0, \pi]$ is measured from the positive z axis, the azimuthal angle $\phi \in [-\pi, \pi]$ is measured from the positive x axis and the radius, $r = \sqrt{x^2 + y^2}$, is measured in the xy plane. In Fig. 2.3 the CMS experiment coordinate systems are sketched.

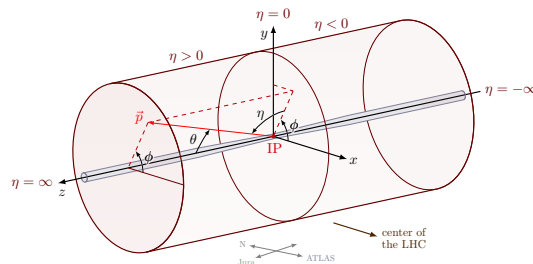


Figure 2.3: The CMS detector portrayed as a red cylinder and its coordinate systems.

Two quantities of particular interest in collider physics are the transverse momentum, p_T , and the transverse energy, E_T . Working with these two variables provides a better framework than their respective total values because it is not possible to know the longitudinal momentum exchanged between the colliding partons. Moreover, from momentum conservation, the total transverse momentum associated with a head on collision should be zero if no neutrinos are expected. Another important quantity is the rapidity, $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ of observed particles. From its expression, the rapidity of a particle moving in the transverse xy plane is $y = 0$ and if it rather moves along the CMS z -axis then $y \rightarrow +\infty$. However, since the longitudinal component of the momentum is hard to measure the pseudorapidity, $\eta = -\ln \left(\frac{\theta}{2} \right)$, can be used as an alternative to rapidity. It is worth to note that in the ultra relativistic limit where $E \sim |p|$ the pseudorapidity and rapidity become equivalent.

In Fig. 2.4 a longitudinal view of the CMS detector is sketched along with increasing pseudorapidity intervals. Inspecting it reveals that in the very forward region for $|\eta| > 2.4$ there are no sub-detectors capable of recording muon candidate tracks.

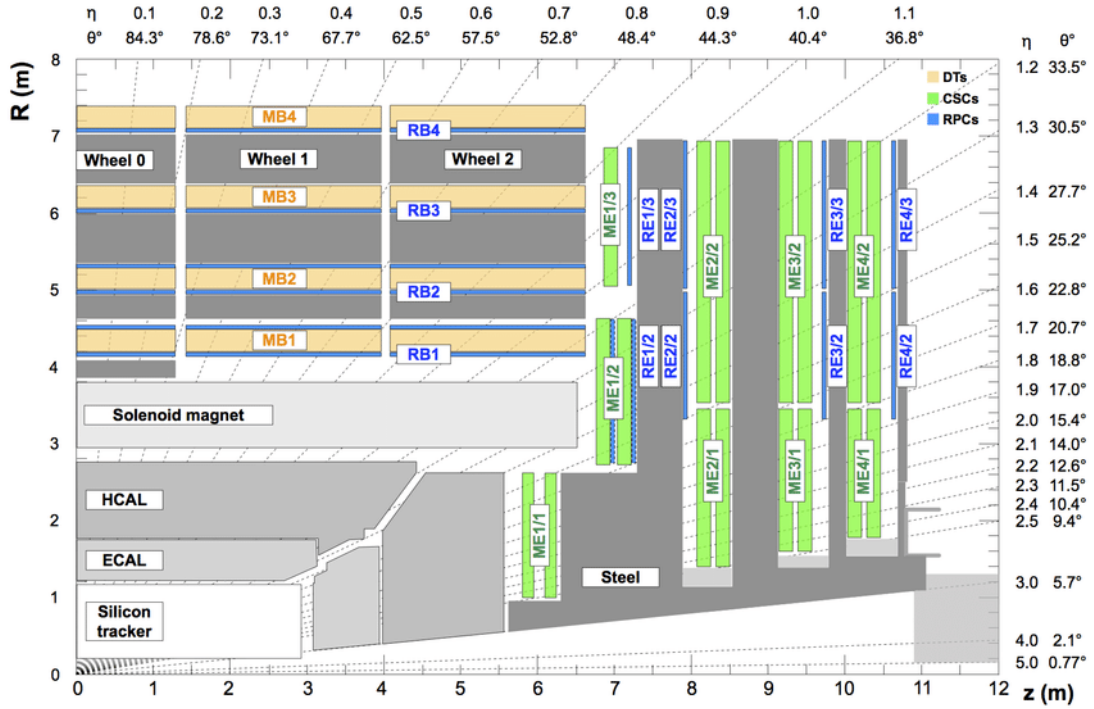


Figure 2.4: Longitudinal cross section view of the CMS with different rapidity intervals marked.

Data, MC and Event Reconstruction

3.1 Data Samples

The analysis is performed to the data collected with the CMS detector during the LHC pp run of 2017 at $\sqrt{s} = 5.02$ TeV. The collision events must feature dimuon candidates to satisfy the HLT condition used and thus make it to the primary data set. An explicit selection is then carried out offline. The results from the 2018 PbPb analysis are used in order to compute the nuclear modification factors of the B_s^0 and B^+ mesons whose primary data followed from a similar trigger condition requiring the presence of two muon candidates in each event in coincidence with lead bunches crossing at the interaction point. Furthermore the results from the 2015 pp and PbPb analysis are quoted for comparisons against this analysis measurements. These two data sets have been acquired under the same double muon trigger condition of the previous samples. The respective collection year of the considered data sets, high level trigger references and total integrated luminosities can be checked in Table 3.1.

Table 3.1: List of pp and PbPb HLT data sets, triggers and their corresponding integrated luminosity.

System	Year	Total Luminosity	HL Trigger
pp	2017	302.3 pb^{-1}	HLT_HIL1DoubleMu0_v1
PbPb	2018	1657 μb^{-1}	HLT_HIL3Mu0NHitQ10_L2Mu0_MAXdR3p5_M1to5_v1
pp	2015	27.7 pb^{-1}	HLT_HIL1DoubleMu0_v1
PbPb	2015	350.7 μb^{-1}	HLT_HIL1DoubleMu0_part_v1

To extract true B meson decay events several offline selections are applied to each event. For any pp and PbPb sample considered, events are required to feature at least one reconstructed primary vertex. The primary vertex (PV) is formed by two or more associated tracks and is required to have a distance from the nominal interaction region of less than 15 cm along the beam axis and less than 0.15 cm in the transverse plane. A beam-background filter is applied to pp events to remove beam-gas and beam-halo events which are essentially collisions with beam remnants. For PbPb, an additional selection of hadronic collisions is applied by requiring a coincidence of at least two forward hadron calorimeter towers, with more than 3 GeV of total energy, from the hadron calorimeters on both sides of the interaction point. In addition a cluster compatibility filter is used in PbPb analysis.

3.1.1 Event Reconstruction

The relatively long mean lifetime of the B mesons, Sec. 1.4, leads to displaced decay vertexes, called secondary vertexes (SV), from the point where the collision occurred. Hence the reconstruction strategy of both B mesons is to identify displaced tracks, imprinted by the muon and kaon candidates of Eqs. (1.16) and (1.17), respectively combine them and learn the most suitable secondary vertex from where they originated. In Fig. 3.1 a diagram of the B^+ meson decay through the channel given in Eq. (1.17) is sketched, for B_s^0 a very similar sketch would follow.

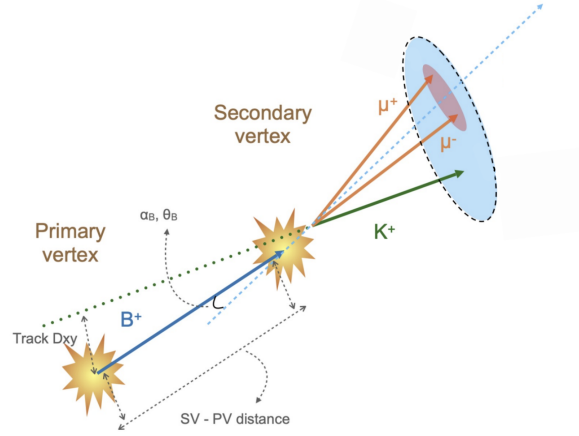


Figure 3.1: A schematic of the B^+ meson decay through the considered channel.

The schematic diagram of the reconstruction workflow is shown in Fig. 3.2. Muon and kaon tracks to be reconstructed are required to pass several quality selection criteria to ensure a high signal to noise ratio. The J/ψ candidates are reconstructed by vertexing pairs of muon tracks with opposite charge. Similarly, the ϕ meson is reconstructed by vertexing pairs of oppositely charged tracks. Then, the respective B meson decay event is built by combining the J/ψ candidates with the K^+ or ϕ meson candidates. A kinematic fit to the systems $J/\psi K^+$ and $J/\psi K^- K^+$ is performed, forcing the mass of dimuon pair to be equal to the nominal J/ψ world average mass.

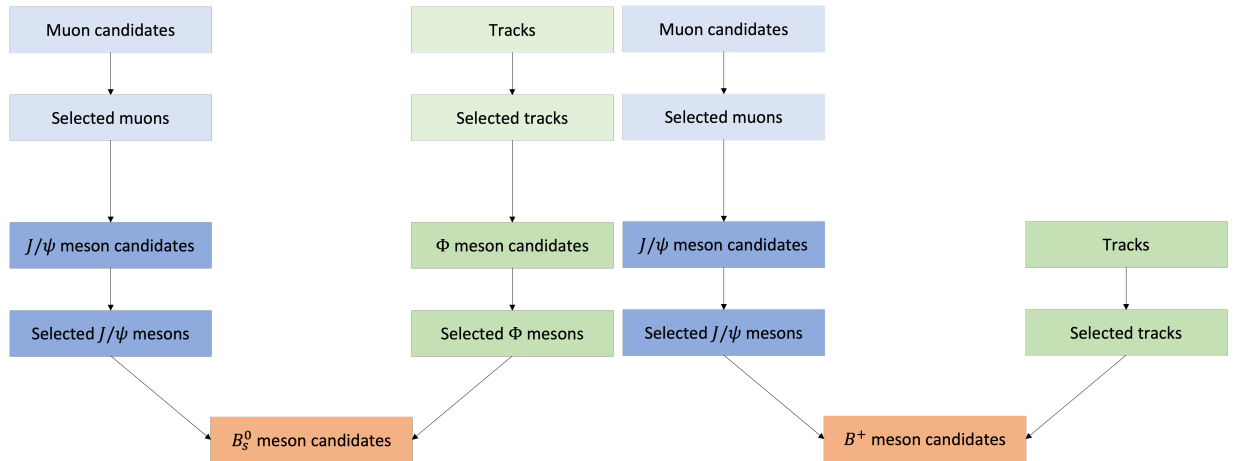


Figure 3.2: Schematic diagrams for the B_s^0 (left) and B^+ (right) mesons reconstruction workflow

The muon quality cuts applied start by requiring each candidate to be simultaneously a global and tracker muon. For the first case this implies matching muon trajectories found on the muon chambers with tracks left in the silicon detector while for the latter it means the reverse approach. The muon tracks are also required to have a transverse impact parameter, D_{xy} , smaller than 0.3 cm and a longitudinal impact parameter, D_z , smaller than 20 cm. Moreover, tracker tracks must match with at least one muon segment in any station. Requirements to the phase space of the muons are also highly needed due to the detector acceptance, the region of phase space within which the final state particles are potentially detectable. Particles with too large pseudorapidities move along the beam axis and escape the CMS detector. Furthermore, they need a minimum p_T in order to be able to traverse a significant portion of the silicon tracker and reach the muon stations in the case of muons. Thus, in order to ensure a reasonable ($> 10\%$) reconstruction and trigger efficiency, muons must also fulfill the following acceptance selections:

$$\begin{aligned} p_T^\mu &> 3.5 \text{ GeV/c} && \text{for } |\eta^\mu| < 1.2, \\ p_T^\mu &> (5.47 - 1.89 \times |\eta^\mu|) \text{ GeV/c} && \text{for } 1.2 \leq |\eta^\mu| < 2.1, \\ p_T^\mu &> 1.5 \text{ GeV/c} && \text{for } 2.1 \leq |\eta^\mu| < 2.4. \end{aligned}$$

In addition, pairs of muons candidates are also required to pass quality selections which require them to have opposite charges, an invariant mass within 0.15 GeV of the J/ψ meson PDG mass and a probability of the two muon tracks to have originated in the same decay vertex bigger than 1%.

The kaon candidate tracks also need to respect a set of criteria. Their pseudorapidity has to be smaller than 2.4 and their transverse momenta, $P_{T, trk}$, has to be higher than 1 GeV/c, with a relative uncertainty, $\frac{\Delta P_{T, trk}}{P_{T, trk}}$, smaller than 10%. The number of valid hits recorded on the silicon tracker must be higher than ten and feature a χ^2/ndf smaller than 18%. For the B_s^0 meson, kaon track pairs are also required to feature an invariant mass within 15 MeV/c² of the ϕ meson PDG mass.

3.1.2 Optimized Selection

Upon reconstruction the data samples will contain information pertaining to events that potentially feature B mesons. These are referred to as B meson candidate events since they are constructed from combinations of muon and hadron tracks without certainty of a common vertex origin. Indeed, some candidates are formed by random combinations of tracks that do not resemble any particle decay at all. Such events constitute the combinatorial background while the ones that actually are associated with the B meson decay are referred to as signal events. Although the selection outlined in Sec. 3.1.1 rejects the reconstruction of many background events it is alone insufficient to fully differentiate signal from background events. Thus the respective B meson data sample does not feature so far any bold mass resonance that can be fitted to extract the number of observed decays. For this purpose, a multivariate analysis (MVA) was carried out in order to improve signal-background separation.

A MVA encompasses a range of techniques that leverage multiple variables simultaneously, resulting in a significantly improved performance when compared to selection criteria based on single variables. In this work, an optimised selection of both B meson data samples is achieved using a Boosted Decision

Tree, BDT, method implemented through ROOT's Toolkit for Multivariate Data Analysis [46]. This is a machine learning algorithm used for classification and regression tasks that work by iteratively training a decision tree on data. Using variables that provide the most discrimination power, in sequential iterations the weights of misclassified events are boosted to improve the algorithm's overall performance. The final BDT score for each event represents the weighted sum of its decision tree output and is used to discriminate between signal and background events. The BDT training is performed employing signal MC samples of the B meson decay and background samples formed from the data sideband regions where B meson candidates with an invariant mass 0.15–0.35 GeV/c away from the B meson nominal mass are featured.

A plethora of kinematic, geometric and other variables were utilized as input for the training processes matching the ones previously employed in PbPb data analysis. These include the χ^2 probability of the decay vertex, the decay length (normalized by its uncertainty), the angle between the line segment connecting the primary and secondary vertices and the momentum vector of the respective B meson, the cosine value of the angle between the B meson displacement and momentum in the transverse plane, the two dimensional distance between the primary and decay vertices of their daughter tracks (again, normalized by their uncertainties) and the p_T of the charged tracks. For the B_s^0 meson two additional variables are considered, namely, the distance along the z -axis between the primary vertex and the secondary vertex (normalized by its uncertainty) and the absolute difference between the reconstructed ϕ meson invariant mass and its nominal value. The selection is optimized separately for each meson and each bin of p_T .

3.2 MC samples

Different MC samples are used with different goals during the analysis, namely, to evaluate the presence of physics backgrounds, to previously characterize fitting models when obtaining signal yields from data, to estimate the selection efficiency and the detector acceptance, to train the BDT and lastly to conduct systematic uncertainty studies. Hence, the employed MC samples include signal simulations of the respective B mesons decay channels, given in Eqs. (1.16) and (1.17), as well as background simulations of their decays through other channels, with a J/ψ meson, that will feed different background structures.

Both the pp and PbPb signal MC samples are generated with PYTHIA 8 [47] and propagated through the CMS detector using the GEANT4 package [48]. The PbPb signal MC was embedded in a PbPb collision background simulated with the HYDJET [49]. Only signal events possessing at least one B meson candidate with $p_T > 5.0$ GeV/c and $|y| < 2.4$ are saved. The decay of these B mesons through the considered channels is modeled with EVTGEN 1.3.0 [50]. Final-state photon radiation is simulated with PHOTOS 2.0 [51]. In addition to the signal MC samples, an inclusive non-prompt J/ψ MC sample, which contains simulations of different B mesons decaying into J/ψ mesons, is also generated. These are used to study and characterize the peaking backgrounds appearing in the final state mass spectra.

3.3 Fiducial Region

Low momentum muons might not reach the outermost layers of the CMS detector where the muon sub-detectors are located. For this reason they don't leave a track there and can not be triggered. This leads to a scarcity of data events in the low p_T and low $|y|$ region. To learn if the production cross section measurement, and consequently the nuclear modification factor computation, should be conducted considering this data region two dimensional histograms, $(|y|, p_T)$, are filled according to the B meson candidates kinematic properties. These are forced to respect a small mass window centered on the respective B meson world average mass in order to reduce the counting of background events in each considered bin. The resulting histograms can be seen in Fig. 3.3 where the counting is projected into a third vertical axis. Based on this rough estimation of signal candidate events a fiducial region will be defined to carry forward the analysis.

For B_s^0 meson candidates in the kinematic region limited by $p_T < 10$ GeV/c and $|y| < 1.5$ very few signal candidate events have been reconstructed. Hence, it is clear that the data events therein are most likely noise and thus should be prevented from disturbing the yields extraction step of the analysis. For B^+ meson candidates in the same kinematic region slightly more signal candidate events are reconstructed, particularly towards this region limits. Still, a single fiducial region to carry out the analysis of both B meson data samples is preferred and given by

$$|y| > 1.5 \wedge p_T < 10 \text{ GeV/c}, \quad |y| < 2.4 \wedge p_T > 10 \text{ GeV/c} \quad (3.1)$$

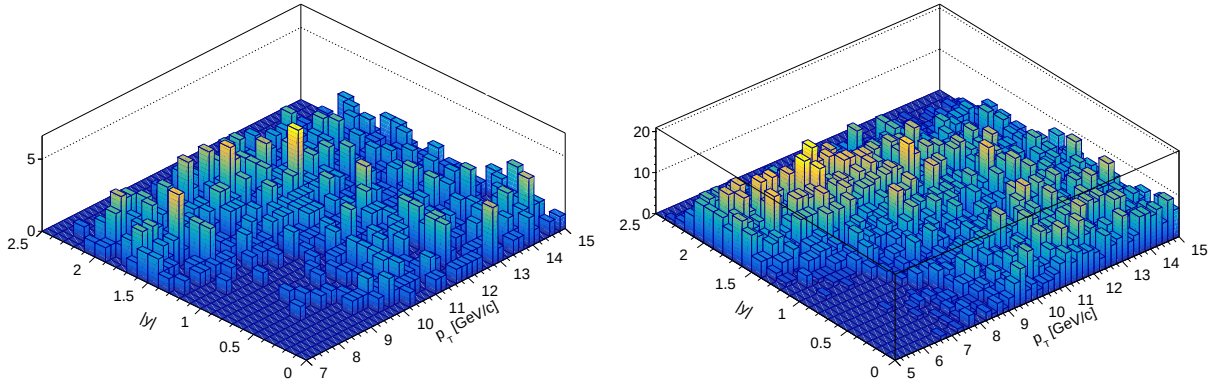


Figure 3.3: Two dimensional distribution of B_s^0 (left) and B^+ (right) meson, signal candidate events in the lower p_T region of the data. The events are required to feature a mass deviation smaller than $\pm 0,015$ GeV/c² when compared to respective B meson world average mass.

Signal Yields

4.1 Extended Unbinned Maximum Likelihood Method

The likelihood function, $\mathcal{L}$, gives the probability of observing a data sample, characterized by a set of n statistically independent quantities, $\vec{x} = (x_1, \dots, x_n)$, knowing the model $l(\vec{Y}, x_i, \vec{\theta})$ composed by a sum of normalized probability density functions (PDFs), $Y_\alpha f_\alpha(x_i, \vec{\lambda}_\alpha)$, whose arguments $\vec{\lambda}_\alpha$ live in a subspace of $\mathbb{R}^p$, with p the number of entries of $\vec{\theta}$. When the normalizing factors, Y_α , are among the parameters of interest, as they are in any event counting experiment, the likelihood function must be extended by adding a multiplicative term corresponding to the Poisson distribution, $\frac{Y^n e^{-Y}}{n!}$ where $Y = \sum_\alpha Y_\alpha$. Therefore, the likelihood function shall be written as

$$\mathcal{L}(Y_1, \dots, Y_\alpha, \vec{x}; \vec{\theta}) = \frac{Y^n e^{-Y}}{n!} \prod_{i=1}^n \left\{ \sum_\alpha Y_\alpha f_\alpha(x_i, \vec{\lambda}_\alpha) \right\}. \quad (4.1)$$

The Extended Unbinned Maximum Likelihood Method (EUML) is a well established approach to estimate the parameters that maximise the likelihood function so that the data distribution at hand is the most probable under the provided model. It requires the likelihood function to be at least twice differentiable in all its θ_i parameters and its shape around the maximum to be normally distributed. For the case of very large data samples, the exponential in Eq. (4.1) will be a very large number. For this reason it is more convenient to consider instead the minimization of the negative logarithm of the likelihood, $-\ln\mathcal{L}$, which will also tame Eq. (4.1) into a more comfortable summation. Even so, a good numerical software is required to workout the minimization of $-\ln\mathcal{L}$. In the case of this analysis the ROOFIT package is used where the minimization is performed by MINUIT [52]. The PDFs chosen to fit the data samples of each B meson are discussed in Sec. 4.2.

Associated with each estimated θ_i parameter there is a statistical uncertainty, $\pm\sigma_i$, obtained by analysing the region around the minimum, $\vec{\theta} = \vec{\theta}'$, of $-\ln\mathcal{L}(\vec{\theta})$. Performing a Taylor expansion,

$$-\ln\mathcal{L}(\vec{\theta}) = -\ln\mathcal{L}|_{\vec{\theta}'} - \underbrace{\sum_i \frac{\partial \ln\mathcal{L}}{\partial \theta_i} \Big|_{\vec{\theta}'}}_{=0} (\theta_i - \theta'_i) - \sum_i \sum_j \frac{1}{2} \frac{\partial^2 \ln\mathcal{L}}{\partial \theta_i \partial \theta_j} \Big|_{\vec{\theta}'} (\theta_i - \theta'_i)(\theta_j - \theta'_j) + \dots \approx \quad (4.2)$$

$$\approx -\ln\mathcal{L}|_{\vec{\theta}'} - \sum_i \sum_j \frac{1}{2} \frac{\partial^2 \ln\mathcal{L}}{\partial \theta_i \partial \theta_j} \Big|_{\vec{\theta}'} (\theta_i - \theta'_i)(\theta_j - \theta'_j) \quad (4.3)$$

the terms involving the partial derivatives on θ_i vanish since $\vec{\theta}'$ corresponds to the minimum of $\mathcal{L}$ and, for a large data set, higher order terms can be neglected. Rewriting Eq. (4.3) as

$$\mathcal{L}(\vec{\theta}) = C e^{\sum_i \sum_j \frac{1}{2} \frac{\partial^2 \ln \mathcal{L}}{\partial \theta_i \partial \theta_j} \Big|_{\vec{\theta}'} (\theta_i - \theta'_i)(\theta_j - \theta'_j)} = C e^{-\sum_i \sum_j \frac{1}{2} V_{ij}^{-1} (\theta_i - \theta'_i)(\theta_j - \theta'_j)} \quad (4.4)$$

the inverse covariant matrix, a square and symmetric matrix whose entries give the covariance between parameters θ_i and θ_j , is identified as $V_{ij}^{-1} = -\frac{\partial^2 \ln \mathcal{L}}{\partial \theta_i \partial \theta_j} \Big|_{\vec{\theta}'}$. The squared statistical uncertainty σ_i^2 correspond to the diagonal elements of the inverse covariance matrix, V_{ii}^{-1} , and so $\sigma_i = \sqrt{V_{ii}^{-1}}$. When moving away from its maximum, the likelihood value changes according to,

$$\Delta \mathcal{L} = \mathcal{L}(\vec{\theta}) - \mathcal{L}(\vec{\theta}') = - \sum_i \sum_j \frac{1}{2} \frac{\partial^2 \ln \mathcal{L}}{\partial \theta_i \partial \theta_j} \Big|_{\vec{\theta}'} (\theta_i - \theta'_i)(\theta_j - \theta'_j) \quad (4.5)$$

indicating that the covariant matrix defines confidence contour maps around the maximum likelihood point [53]. The first confidence region around this point limits a σ_i increase of the respective parameters.

4.2 The Fitting Model

Each event that passed the trigger and the optimized selection described in Sec 3.1 is either reconstructed as a B_s^0 or a B^+ meson and has an invariant mass, m_i , associated to it. These are statistically independent quantities that characterize the data set and so, in this analysis, the quantity $\vec{x}$ is identified with the invariant mass of each B meson candidate event in the data, $\vec{x} = \vec{m} = (m_1, m_2, \dots, m_n)$.

The mass distribution of each B meson event will feature different structures that should be individually addressed when building their respective models. Two such features common to both B meson mass spectra are the signal peak and the combinatorial background. The former is the region where a mass resonance can be observed and the latter is a continuous structure that arises from the wrong combination of particles' tracks. The B_s^0 mass distribution is very simple, involving just these two structures. On the other hand, in the B^+ mass distribution there are potential background feed-down sources coming from other B meson decays that can form peaking structures in the region of interest and thus need to be properly treated in order not to bias the yield extraction procedure. To study these components, the candidates in the inclusive B^+ meson MC sample that are matched to a genuine signal are vetoed. The resulting mass spectrum confirms the existence of two peaking structures, one very robust in the region $< 5.20 \text{ GeV}/c^2$ and one very feeble centred around $\sim 5.34 \text{ GeV}/c^2$. The origin of these two peaking structures is different. The first one arises after missing a track coming from any B meson 4-body decays through similar channels, e.g. $B_s^0 \rightarrow J/\psi K^+ K^-$. For this reason we call it the partially reconstructed background. The second one is formed after misidentifying the pions from $B^+ \rightarrow J/\psi \pi^+$ as kaons. From the V_{CKM} matrix the associated flavour transition is suppressed and so we call it the Cabibbo suppressed decay.

Inevitably, the model considered in the EURL method depends on the B meson. For the decay channel $B_s^0 \rightarrow J/\psi \phi \rightarrow K^+ K^- \mu^+ \mu^-$ the model used to fit the invariant mass distribution of the final

state system, $m_{\mu^+\mu^-K^+K^-}$, is composed by an exponential function, $\mathcal{P}_{exp}(m_i; \lambda_{cb}) = \exp(-m_i \lambda_{cb})$, and a sum of two Gaussians PDFs, $\mathcal{P}_{2G}(m_i; \vec{\lambda}_{2G})$, with $\vec{\lambda}_{2G} = (\sigma_1, \sigma_2, \mu, \alpha)$ and

$$\mathcal{P}_{2G}(m_i; \vec{\lambda}_{2G}) = \frac{\alpha}{\sqrt{2\pi}\sigma_1} \exp\left(-\frac{(m_i - \mu)^2}{2\sigma_1^2}\right) + \frac{(1 - \alpha)}{\sqrt{2\pi}\sigma_2} \exp\left(-\frac{(m_i - \mu)^2}{2\sigma_2^2}\right) \quad (4.6)$$

where σ_1 and σ_2 are the widths of the respective Gaussian functions, α is a parameter relating them and μ its their mean, physically standing for the B meson mass and being for that reason the same in the two Gaussian functions. The $\mathcal{P}_{exp}(m_i; \lambda_{cb})$ PDF accounts for the combinatorial background while $\mathcal{P}_{2G}(m_i; \vec{\lambda}_{2G})$ accounts for the mass resonance. Hence, this model parameters are $\vec{\theta}_{B_s^0} = (\sigma_1, \sigma_2, \mu, \alpha, \lambda_{cb})$ and its full expression is given by

$$l(m_i, \vec{\theta}_{B_s^0}) = Y_s \left[\frac{\alpha}{\sqrt{2\pi}\sigma_1} \exp\left(-\frac{(m_i - \mu)^2}{2\sigma_1^2}\right) + \frac{(1 - \alpha)}{\sqrt{2\pi}\sigma_2} \exp\left(-\frac{(m_i - \mu)^2}{2\sigma_2^2}\right) \right] + Y_{cb} \exp(-\lambda_{cb} m_i) \quad (4.7)$$

where Y_s and Y_{cb} are the signal and background yields.

For the decay channel $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$, the mass resonance and the combinatorial background are also described by a sum of two Gaussians PDF and by an exponential PDF. The partial reconstructed background is modeled through a complementary error function PDF, $\mathcal{P}_{Ec}(m_i, C_{sc}, C_{sh})$,

$$\mathcal{P}_{Ec}(m_i, C_{sc}, C_{sh}) = 1 - \frac{2}{\sqrt{\pi}} \int_0^{\left(\frac{m_i - C_{sh}}{C_{sc}}\right)} e^{t^2} dt, \quad (4.8)$$

where C_{sh} and C_{sc} are, respectively, shifting and scaling parameters that allow a more comprehensive construction of this PDF. The Cabibbo suppressed background is modeled by a PDF, $\mathcal{P}_{2A_G}(m_i, \vec{\lambda}_{2A_G})$, with $\vec{\lambda}_{2A_G} = (\mu_{aG}, \beta, \sigma_{1L}, \sigma_{2L}, \sigma_{1R}, \sigma_{2R})$, that consists in the sum of two asymmetric Gaussians,

$$\mathcal{A}_G(m_i; \mu_{aG}, \sigma_L, \sigma_R) = \frac{2}{(\sigma_L + \sigma_R)\sqrt{2\pi}} \begin{cases} \exp\left(-\frac{(m_i - \mu_{aG})^2}{2\sigma_L^2}\right) & \text{if } m_i < \mu_{aG} \\ \exp\left(-\frac{(m_i - \mu_{aG})^2}{2\sigma_R^2}\right) & \text{otherwise} \end{cases} \quad (4.9)$$

related by the coefficient β according to

$$\mathcal{P}_{2A_G}(m_i, \vec{\lambda}_{2A_G}) = \beta \mathcal{A}_G(m_i, \mu_{aG}, \sigma_{1L}, \sigma_{1R}) + (1 - \beta) \mathcal{A}_G(m_i, \mu_{aG}, \sigma_{2L}, \sigma_{2R}). \quad (4.10)$$

Since this background structure arises from a true physical process its yield, $Y_{J/\psi\pi^+}$, should be proportional to the signal yield instead of a free parameter. Thus, the full model to fit the B^+ meson data has parameters $\vec{\theta}_{B^+} = (Y_s, Y_{cb}, Y_{J/\psi X}, \sigma_1, \sigma_2, \sigma_{1L}, \sigma_{1R}, \sigma_{2L}, \sigma_{2R}, \mu, \mu_{aG}, \alpha, \beta, \lambda_{cb})$, and is given by

$$l(m_i, \vec{\theta}_{B^+}) = Y_s \left[\frac{\alpha}{\sqrt{2\pi}\sigma_1} \exp\left(-\frac{(m_i - \mu)^2}{2\sigma_1^2}\right) + \frac{(1 - \alpha)}{\sqrt{2\pi}\sigma_2} \exp\left(-\frac{(m_i - \mu)^2}{2\sigma_2^2}\right) \right] + Y_{cb} \exp(-\lambda_{cb} m_i) \\ + Y_{J/\psi X} \mathcal{P}_{Ec}\left(\frac{m_i - C_{shift}}{C_{scale}}\right) + Y_{J/\psi\pi^+} \mathcal{P}_{2A_G}(m_i, \mu_{aG}, \sigma_{1L}, \sigma_{1R}, \sigma_{2L}, \sigma_{2R}), \quad (4.11)$$

where $Y_{J/\psi\pi^+} = R_{PDG} \times Y_s$ with $R_{PDG} = \frac{\mathcal{B}(B^+ \rightarrow J/\psi\pi^+)}{\mathcal{B}(B^+ \rightarrow J/\psi K^+)} = 0.038 \pm 0.001$.

4.2.1 PDF Shape Constrains From MC Studies

In principle, the true probability density function that governs the mass distribution of events may never be known. The sole purpose of fitting it is to obtain the number of signal events, Y_s , the very same parameter that enters the cross section expression, Eq. (1.18). To extract it with the most accuracy possible the shape of the two fitting models introduced in Sec. 4.2 shall be constrained through MC studies. This reduces their number of floating parameters, leading to a more reliable adjustment between the individual PDFs and the corresponding data structures.

In order to characterize the shape of the signal PDF of both B meson models, Eq. (4.6), the respective parameters, $\vec{\lambda}_{2G}$, shall be learned by fitting the signal MC sample and then fixed. The two inclusive bin results can be seen in the top row of Fig. 4.1 and the binned results can be checked on Appendix A. Both the partially reconstructed and the Cabibbo suppressed backgrounds PDFs shall also be constrained for the B^+ model. After conducting a binned and an inclusive MC sample study the shape of the Cabibbo suppressed background PDF was found to be consistent across the analysis bins and thus its parameters are fixed once through an inclusive analysis. In contrast, the shape of the partially reconstructed background was found to slightly vary across the bins and so the respective PDF is particularly constrained to each bin, like the signal PDF. However, its last bin, $[50, 60]$ GeV/c^2 , contains very few events making the shape characterization unreliable. To overcome this problem the parameters fixed in the previous bin are considered. The inclusive bin result of these backgrounds can be seen in the bottom row of Fig. 4.1 and the binned results for the partial reconstructed background can be checked on Appendix B.

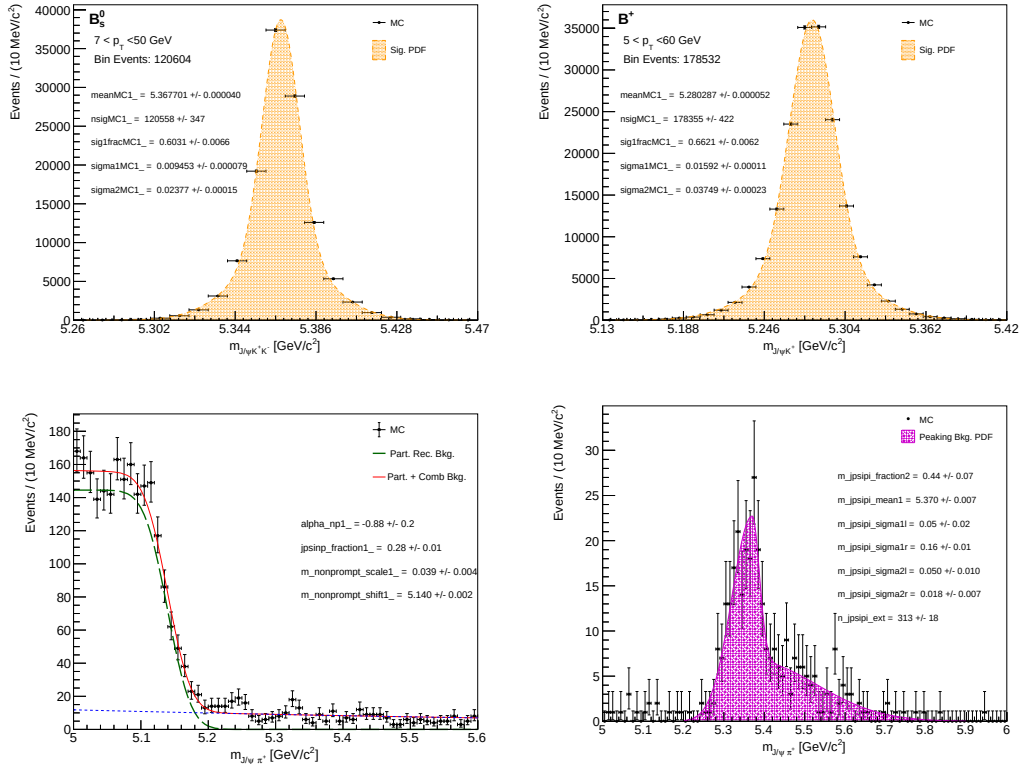


Figure 4.1: On the top row are the fits to the signal MC inclusive bin for the B_s^0 meson (left) and the B^+ meson (right). On the bottom row are the fits to MC inclusive bin for the partial reconstructed background, $B^+ \rightarrow J/\psi X^+$ (left) and for the Cabibbo suppressed background $B^+ \rightarrow J/\psi \pi^+$ (right).

4.3 Invariant Mass Fits

After the studies conducted on Sec. 4.2.1 both B meson models have been left with only one parameter floating, the exponent, λ_{cb} , of the combinatorial background exponential PDF. This leads to a nearly total and unnatural dependence on MC samples. Hence, to make sure that such hard constraints do not end up causing the opposite effect of improving the fit ability to describe the individual data structures the widths of the signal PDFs are allowed to float through the introduction of a common scaling constant, C , so that $\sigma_{1,2} \rightarrow C\sigma_{1,2}$ and thus

$$(4.6) \rightarrow \mathcal{P}_{2G}(m_i; \vec{\lambda}_{2G}) = \frac{\alpha}{\sqrt{2\pi}C\sigma_1} \exp\left(\frac{-(m_i - \mu)^2}{2C\sigma_1^2}\right) + \frac{(1 - \alpha)}{\sqrt{2\pi}C\sigma_2} \exp\left(\frac{-(m_i - \mu)^2}{2C\sigma_2^2}\right). \quad (4.12)$$

This modification specifically accounts for detector resolution effects that can lead to a different width of the data mass resonance. Thus it should allow a better description of the data while still conserving the overall shape of the fitting model. In addition, the mean of the signal PDF is released and a model where it stands fixed is instead considered as a variation to study the systematic uncertainties.

Both B meson data samples are fitted in the mass interval $[5, 6]$ GeV/c^2 . The inclusive bin results are shown in Fig. 4.2 and the respective binned results in Fig. 4.3. The bottom panel of each plot shows the pulls, P_i , quantifying the deviation between the fit result and the data. They are defined as $P_i = \frac{Y_i^{data} - Y_i^{fit}}{\sigma_i^{data}}$, where Y_i^{data} is the total number of data events in the i th-bin, σ_i^{data} its respective uncertainty and Y_i^{fit} is the total number of fit events. A χ^2 test was also performed and the results are visible on the top left part of the upper panel. Thus, for normally distributed data points around the fit result the χ^2 value should match the number of degrees of freedom (ndf) or, equivalently, $\chi^2/ndf \sim 1$. The scaling parameter, C , was found to be consistent with unity with the only exception being the B^+ low data bin, $[50, 60]$ GeV/c^2 . Since the respective MC bin also contains a low number of events the introduction of this parameter indeed prevented a bad signal shape characterization from damaging the yield extraction. The values obtained for the unfixed mean matched the respective B meson mass very well, suggesting the adequate positioning of the PDF components during the fit.

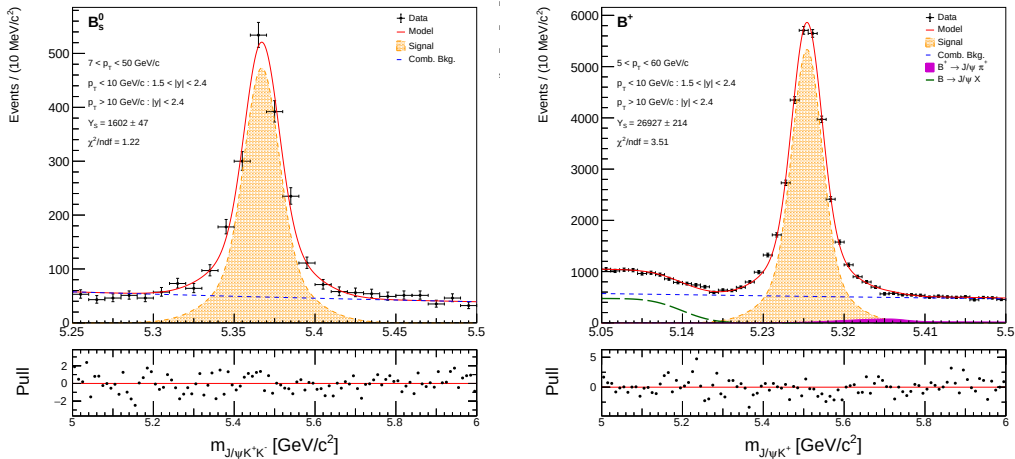


Figure 4.2: Fit to B_s^0 meson (left) and B^+ meson (right) invariant mass distribution.

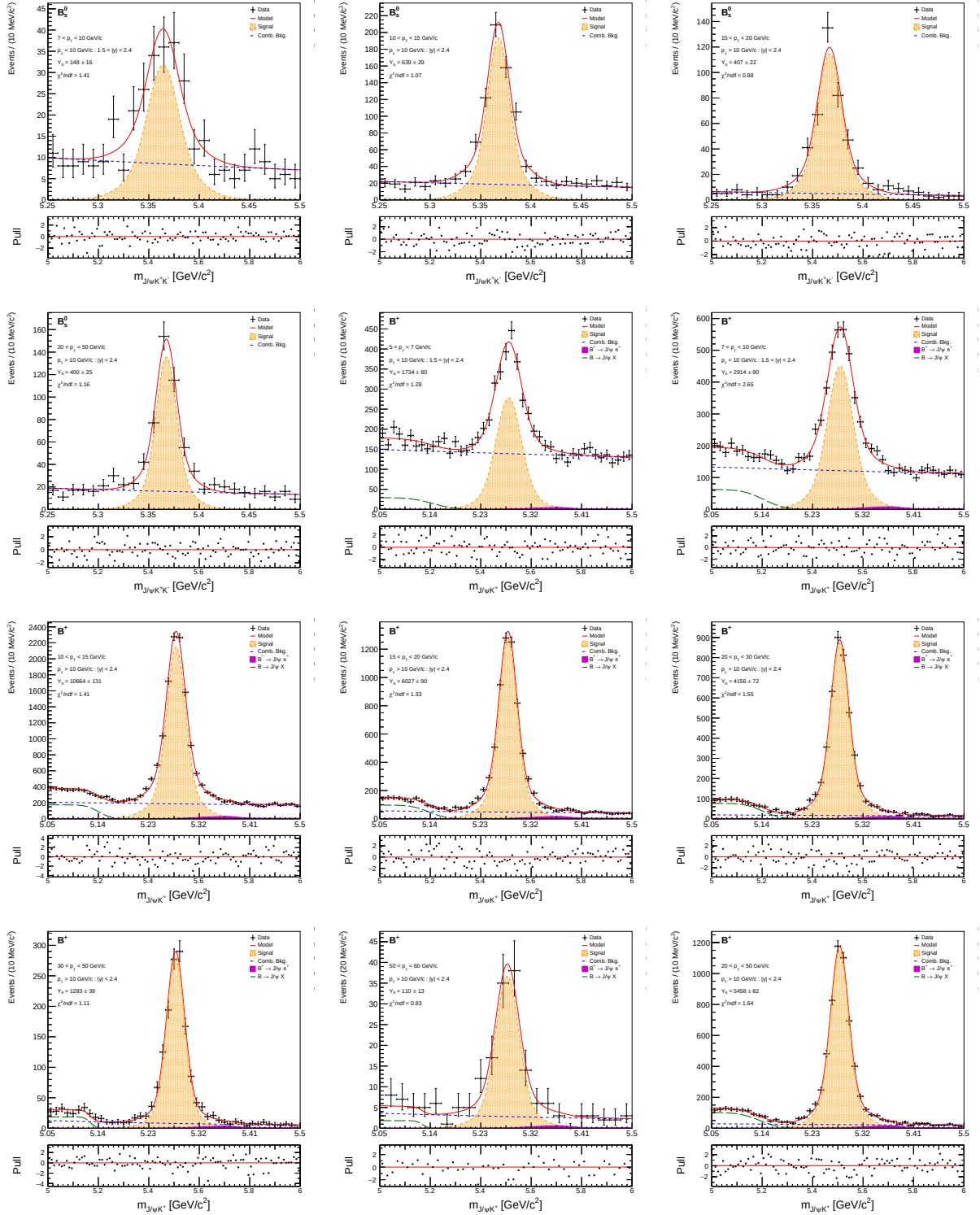


Figure 4.3: The first four plots show the fits to the B_s^0 meson mass distribution. The following eight plots show the fits done to the B^+ case. These are unbinned fits.

In Tables 4.1 and 4.2 the obtained B_s^0 and B^+ meson signal yields normalized by the respective bin widths, $\frac{Y_s}{\Delta p_T}$, are shown along with the associated statistical uncertainties.

Table 4.1: Obtained Y_s normalized by the p_T bin width for the B_s^0 meson.

p_T [GeV/c]	7–10	10–15	15–20	20–50
$\frac{Y_s}{\Delta p_T}$ [c/GeV]	49 ± 5	128 ± 6	81 ± 4	13 ± 1

Table 4.2: Obtained Y_s normalized by the p_T bin width for the B^+ meson.

p_T [GeV/c]	5–7	7–10	10–15	15–20	20–30	30–50	50–60	20–50
$\frac{Y_s}{\Delta p_T}$ [c/GeV]	867 ± 40	971 ± 30	2133 ± 26	1205 ± 18	416 ± 7	64 ± 2	11 ± 1	182 ± 3

4.3.1 Closure Test

In addition to learning the overall fit quality through pulls and χ^2 tests, the obtained signal yields, being a crucial parameter of the analysis, are further submitted to a new test to check if they are unbiased. Thus, using the `RoofitStudy` class, 5000 MC samples are generated and fitted using the respective B meson model. Then, the signal yields obtained from the i -MC toy data, $Y_{s,i}^{toy}$, are compared with the data signal yield, Y_s , according to $P(Y) = \frac{Y_{s,i}^{toy} - Y_s}{\sigma_i^{toy}}$ where σ_i^{toy} is the respective toy data signal yield statistical uncertainty. Doing so generates a pull distribution that, according to the Central Limit Theorem, should follow a Gaussian distribution centered at zero with a unitary standard deviation. Discrepancies from these expected values would reveal, respectively, a fit bias in the former case and a unreliable signal yield statistical uncertainty in the later case. The pull distributions for the inclusive bin of each B meson are shown in Fig. 4.4 where the obtained parameters are seen to be close to the desired values and the small deviation is covered by the uncertainty. Hence, this last test confirms a good performance of the fitting and a very reliable characterization of the signal yields.

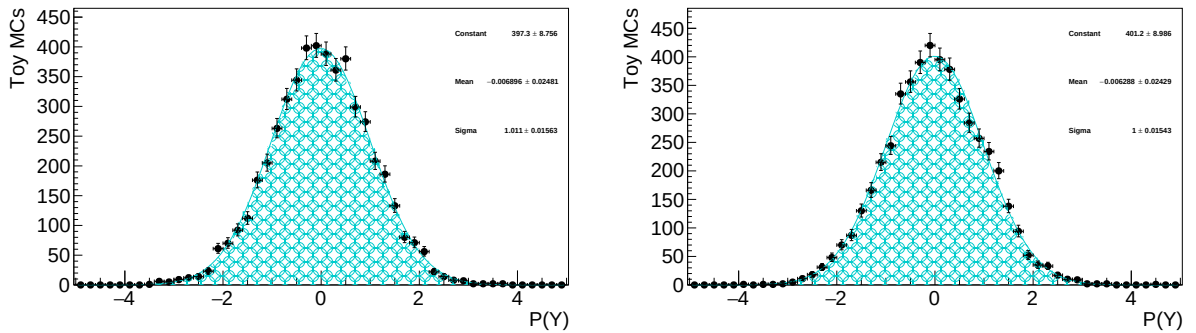


Figure 4.4: Pull distributions obtained from toy MC studies for the B_s^0 (left) and B^+ (right) mesons.

Efficiency

5.1 Detector Acceptance and Selection Efficiency

To arrive at the differential production cross sections of the B mesons, Eq. (1.18), it is necessary to correct the signal yields obtained in Sec. 4.3 considering the selection efficiency, ϵ , and the detector acceptance, α . For this purpose MC samples are used to estimate both factors.

The acceptance, α , corresponds to the ratio between the number of generated events passing the *muon* and *kaon* acceptance thresholds described in Sec. 3, N_{pass} , and the total amount of generated events, N_{GEN} , according to

$$\alpha = \frac{N_{pass}}{N_{GEN}}. \quad (5.1)$$

In turn, the selection efficiency is the fraction of accepted events that pass the all of the analysis selection criteria, N_{ANpass} , according to

$$\epsilon = \frac{N_{ANpass}}{N_{pass}}. \quad (5.2)$$

The total efficiency factor is obtained by multiplying the detector acceptance and the selection efficiency factors. Its inverse,

$$\frac{1}{\alpha \times \epsilon} = \frac{N_{GEN}}{N_{ANpass}}, \quad (5.3)$$

is then used to correct the previously obtained raw signal yields.

The total efficiency factor may have a dependence both on rapidity and transverse momentum. For this reason, considering the analysis' fiducial region the selection efficiency and acceptance formulas, Eq. (5.1) and Eq. (5.2), are employed in different p_T and y ranges leading to two dimensional (2D) maps of $\alpha(p_T, y)$ and $\epsilon(p_T, y)$. Their product $\alpha \times \epsilon(p_T, y)$ forms a new 2D map that shall be used to determine the inverse of the total efficiency factor for each B meson candidate based on its kinematics. The results of the intermediate step where the $\alpha \times \epsilon(p_T, y)$ 2D maps are formed are shown in Sec. 5.1.1 after discussing the improvement made to the $\epsilon(p_T, y)$ 2D map through the application of the *Tag-and-Probe* method. After associating each data event to a $\frac{1}{\alpha \times \epsilon}$ factor, the average,

$$\left\langle \frac{1}{\alpha \times \epsilon(p_T, y)} \right\rangle = \frac{1}{N_{m_B}} \sum_{i=1}^{N_{m_B}} \frac{1}{\alpha \times \epsilon(p_T, y)_i}, \quad (5.4)$$

is obtained for each of the analysis' differential p_T bins considering only the events within a $160 \text{ MeV}/c^2$ window centered on the B meson's mass, N_{m_B} . Although this average should be performed using only the B meson signal candidates the data samples contain both signal and background events. This background contamination can be mitigated by restricting the events entering the average to those with an invariant mass matching the B meson mass. This is achieved through the considered mass window restriction. In Fig. 5.1 the results for $\langle \frac{1}{\alpha \times \epsilon} \rangle$ of each B meson are shown as functions of the analysis' p_T bins and in Tables 5.1 and 5.2 each bin value can be consulted.

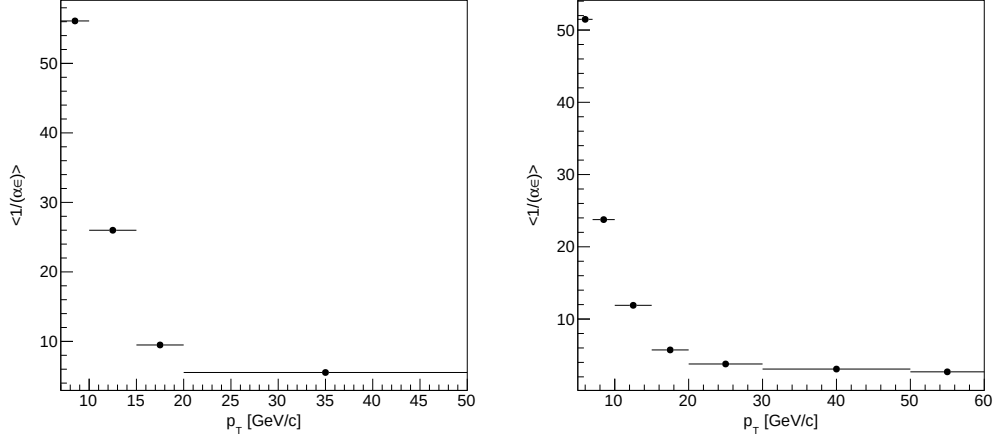


Figure 5.1: The B_s^0 (left) and B^+ (right) average of the inverse total efficiency factor as function of the differential p_T bins used in this analysis.

Table 5.1: Average inverse total efficiency factor for the B_s^0 meson.

p_T [GeV/c]	7–10	10–15	15–20	20–50
$\langle \frac{1}{\epsilon\alpha} \rangle$	55.26 ± 0.49	25.99 ± 0.06	9.49 ± 0.03	5.53 ± 0.04

Table 5.2: Average inverse total efficiency factor for the B^+ meson.

p_T [GeV/c]	5–7	7–10	10–15	15–20	20–30	30–50	50–60
$\langle \frac{1}{\epsilon\alpha} \rangle$	53.95 ± 0.06	24.31 ± 0.03	12.07 ± 0.01	5.72 ± 0.01	3.75 ± 0.01	3.01 ± 0.04	2.62 ± 0.04

5.1.1 Tag-and-Probe Correction

To arrive at the 2D selection efficiency map described in Sec. 5.1, Monte Carlo simulations are used. However, in order to reduce the analysis dependence on simulation it is desirable to obtain the selection efficiency 2D map in a data-driven way. Hence the *Tag-and-Probe* (TnP) method [54] can be used to improve the selection efficiency 2D map using weights obtained from a data comparison against the MC.

The TnP method reconstructs a well-known resonance from its decay into two daughter particles. In the case of this analysis a J/ψ resonance and its di-muon decay is considered. One of the muons is denoted "tag" while the other "probe". The tag muons must meet tight selection criteria to guarantee that they are indeed muons. In contrast the probe muons meet a very loose selection criteria not to induce a bias since these are the ones used to study the efficiency associated with a specific selection criteria. Probe muons are paired with tag muons such that their invariant mass resembles the mass of the J/ψ meson. Two invariant mass distributions are formed according to whether or not the probes meet the selection criteria for which the selection efficiency is being estimated, one for the successful probes and another for the failed probes. Then, both distributions are fitted inside fine transverse momentum and rapidity bins. The resulting signal yields of the mass peaks, $Y_{ok}(p_T^\mu, y^\mu)$ and $Y_{ko}(p_T^\mu, y^\mu)$, are used to calculate the 2D efficiency map of the selection criteria under study, $\epsilon_{TnP}^{sel}(p_T^\mu, y^\mu) = \frac{Y_{ok}(p_T, y)}{Y_{ok}(p_T, y) + Y_{ko}(p_T, y)}$. Then, the ratio between $\epsilon_{TnP}^{sel}(p_T^\mu, y^\mu)$ and the resulting 2D map following the application of the TnP method to the associated MC sample, $\epsilon_{TnP}^{mc}(p_T^\mu, y^\mu)$, is used to form a 2D muon scaling factor map, $SF_\mu(p_T^\mu, y^\mu) = \frac{\epsilon_{TnP}^{sel}(p_T^\mu, y^\mu)}{\epsilon_{TnP}^{mc}(p_T^\mu, y^\mu)}$. Since each event features two muons the product between their scaling factors, $SF_{evt} = SF_{\mu_1} \times SF_{\mu_2}$, gives the final scaling factor for that event.

Considering each event scaled by the associated SF_{evt} value results in a re-weighted MC. From it the TnP weighted 2D selection efficiency map, $\epsilon_{TnP}(p_T, y)$, is obtained and preferred over the 2D map simply obtained from Eq. (5.2). The p_T bin widths used when generating the map are 1/8 GeV/c, 1/4 GeV/c, 1/2 GeV/c, and 1 GeV/c in the respective momentum regions of 5 to 10 GeV/c, 10 to 40 GeV/c, 40 to 50 GeV/c and 50 to 60 GeV/c. The considered rapidity binning is $[0; 0.5; 1; 1.5; 2; 2.4]$. Finally, according to the discussion in Sec. 5.1, multiplying by $\alpha(p_T, y)$ and taking its inverse the TnP weighted $\frac{1}{\alpha(p_T, y) \times \epsilon(p_T, y)}$ 2D map for the B^+ and B_s^0 mesons are obtained and shown in Fig. (5.2).

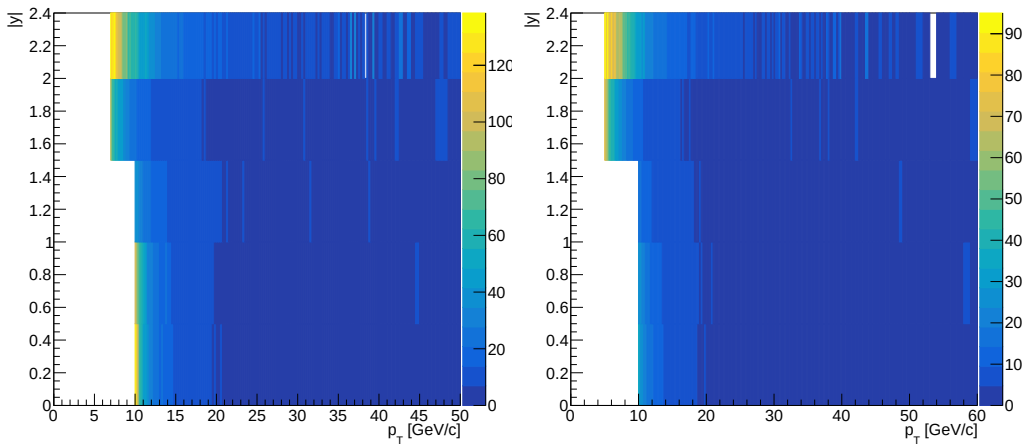


Figure 5.2: TnP weighted 2D maps of $\frac{1}{\alpha \times \epsilon}$ as a function of p_T and $|y|$ for B_s^0 (left) and B^+ (right).

5.2 MC Validation

In this part of the analysis MC samples are used to estimate the selection efficiency and the detector acceptance. However, there is no reason to blindly trust that the MC samples are flawlessly reproducing the data distributions. In fact, many factors like an incorrect modeling of physics processes in the event generation step or unaccounted detector effects in the reconstruction step can cause the MC simulations to deviate from nature and strongly impact the final results. Therefore, a comparison between data and MC is needed. Because there are only signal events in the MC samples such comparison can only be done after separating the signal events from the background events in the data. This is achieved using *sPlot* [55], a technique that has the key advantage of using the full data sample for the comparison.

The *sPlot* is a likelihood-based technique that allows to extract the distributions of relevant variables, for instance p_T , y , etc for the signal or background events in a data sample. These variables must be uncorrelated to the variable entering the likelihood expression, the invariant mass of the final state system. It is used to attribute each event two weights, a probability of being signal, $\mathcal{W}_s(m_i)$, and probability of being background, $\mathcal{W}_b(m_i)$, with $\mathcal{W}_s(m_i) + \mathcal{W}_b(m_i) = 1$ and $\mathcal{W}_n(m_i) = \frac{\sum_j V_{nj} f_j(m_i)}{\sum_k Y_k f_k(m_i)}$, where V_{nj} is the covariance matrix and the sum runs over the j -th and k -th model components, $f_j(m_i)$. Logically, events close to the respective B meson mass will have a considerable signal weight and $\mathcal{W}_b(m_i) \sim 1$ if that is not the case. In this step, all parameters entering the PDFs must be fixed otherwise the covariance matrix is incorrectly determined. Applying the weights to the respective event it is possible to plot each desired variable distribution for the respective data component.

The *sPlot* technique is implemented through the `RooStats::SPlot` class. The distributions are normalised over the range of each variable since it is their shape that should be taken into consideration. The comparisons of a plethora of physical variables from both B mesons against the respective MC ones can be seen on Appendix. C. In the bottom panel of each plot is a bin-by-bin ratio computed using the `TRatioPlot` class. In particular, the comparison between the data signal p_T and BDT distributions against the respective MC distributions are shown in Figs. 5.3 and 5.4. Because the B_s^0 meson has less available data a wider binning had to be used for some BDT variables. Overall, the comparisons are in good agreement for both B mesons and thus the MC samples can be trusted.

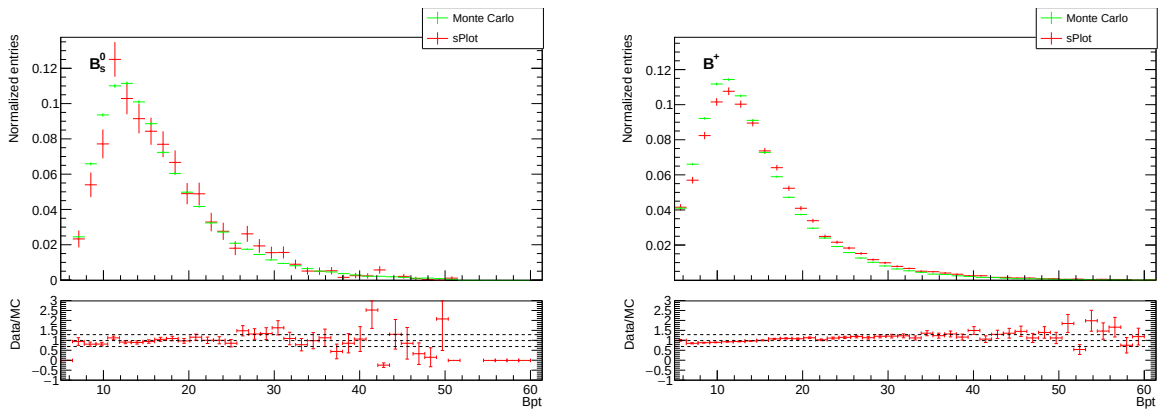


Figure 5.3: Comparison of B_s^0 and B^+ p_T distributions in data and MC using the *sPlot* technique.

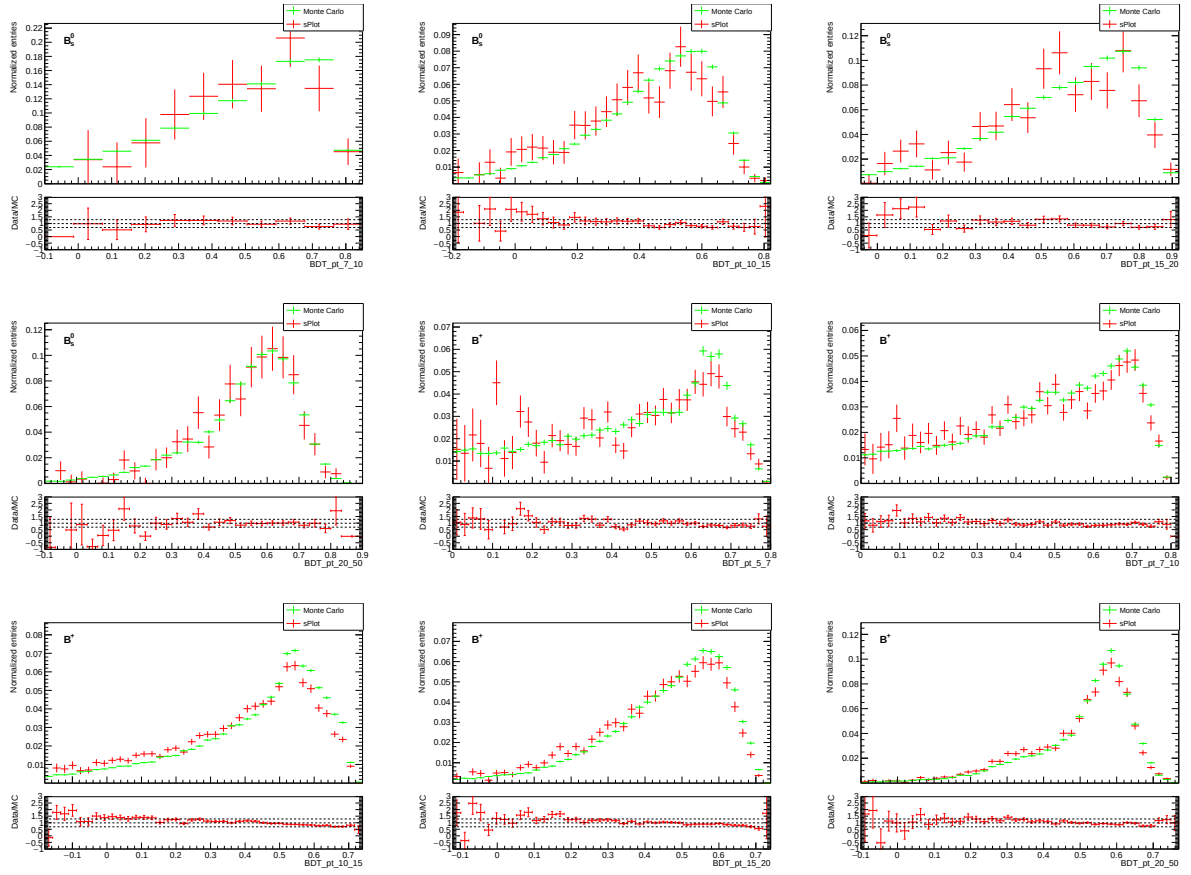


Figure 5.4: Comparison of B_s^0 and B^+ BDT distributions in data and MC using the $sPlot$ technique.

Systematic Uncertainties

6.1 Overview

The B meson differential production cross sections are affected by several systematic uncertainties that arise from the differential signal yields extraction and the total efficiency correction computation steps. In addition, there are two uncertainty sources contributing globally (to all bins simultaneously), namely, the branching fractions and the experiment luminosity. All these uncertainty sources shall be discussed in the following subsections.

The total systematic uncertainties in the pp B_s^0 and B^+ mesons differential production cross-sections are computed as the sum in quadrature of the different contributions, which are respectively summarized in Tables 6.1 and 6.2. In the final results for the cross sections of each B meson the systematic uncertainty from to the branching fraction and the luminosity are presented separately from the rest and for that reason the two Tables also show their sum in separate. The relative systematic uncertainties of the cross sections in pp and PbPb collisions will then be added in quadrature as the systematic uncertainty of the nuclear modification factors. Doing so the uncertainty of branching fractions is canceled, and the uncertainty of track reconstruction efficiency is partially canceled.

Table 6.1: Summary of relative systematic uncertainties, in %, for the B_s^0 cross section vs p_T .

Sources	p_T [GeV/c]			
	7–10	10–15	15–20	20–50
Hadron tracking efficiency	4.800	4.800	4.800	4.800
Track selection	0.646	0.204	2.733	0.780
Data vs MC	4.382	8.080	6.271	3.492
p_T shape	0.045	0.015	0.004	0.002
PDF variation	3.580	2.040	2.856	3.177
TnP	0.457	0.378	0.352	0.449
Sum	7.462	9.627	8.838	6.792
Luminosity $\mathcal{L}$	1.9			
Branching fractions	7.5			
Sum (global systematics)	7.7			

Table 6.2: Summary of relative systematic uncertainties, in %, for B^+ cross section vs p_T .

Sources	p_T [GeV/c]							
	5–7	7–10	10–15	15–20	20–30	30–50	50–60	20–50
Hadron tracking efficiency	2.400	2.400	2.400	2.400	2.400	2.400	2.400	2.400
Track selection	1.794	0.312	0.473	0.258	0.123	0.144	1.826	0.244
Data vs MC	4.442	8.853	2.181	1.822	2.762	1.196	9.192	2.315
p_T shape	0.020	0.005	0.013	0.010	0.005	0.003	0.018	0.003
PDF variation	2.139	1.436	3.160	1.098	0.686	1.839	2.405	0.568
TnP	0.465	0.446	0.372	0.361	0.425	0.637	0.640	0.469
Sum	5.788	9.300	4.568	3.238	3.749	3.316	9.989	3.424
Luminosity $\mathcal{L}$	1.9							
Branching fractions	2.9							
Sum (global systematics)	3.5							

6.1.1 Global Systematics Uncertainties

The uncertainties coming from the branching ratio of the decay channels $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$ and $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$ are calculated by adding in quadrature the uncertainties on each sub-channel, obtained from [56]. The respective resulting values are 7.5% for B_s^0 and 2.9% for B^+ . The 2017 pp data set has a 1.9% luminosity uncertainty.

6.1.2 Signal Yield Systematic Uncertainties

The uncertainty associated with the yield extraction step is evaluated by considering variations of the fitting model components one at a time. Making use of Occam’s razor principle the complexity of the fitting model components shall not be excessively increased and so, for the signal peak, three variations are considered where the PDF is given by (i) a sum of a Gaussian function and a crystal ball function, (ii) a sum of three Gaussian functions and (iii) fixing the mean to its MC simulation value. For the background model, another three variations are considered where the PDF is given by (iv) a first order polynomial function, (v) a second order polynomial function and (vi) varying the mass fitting range from [5, 6] GeV/c² to [5.19, 6] GeV/c² and excluding the partially reconstructed background model if it is the B^+ meson. In addition to these the B^+ meson will see one more variation involving the PDF modeling the Cabibbo suppressed model where $R_{PDG} \rightarrow R_{AN} = 0.0517 \pm 0.0004$. The maximum uncertainty of the signal and background variations are added in quadrature and quoted as systematic uncertainty. The final results for each bin can be checked in Tables 6.3 and 6.4 located at the end of this subsection.

In Fig. 6.1 the B^+ fit results coming from the background variation where the mass range is reduced are shown. Inspecting them reveals that no actual variation of the model used to fit the partial reconstructed background is required since the statistical uncertainties of each bin are always bigger than the respective total systematic uncertainties that see contributions from this background variation. Moreover, the fits properly converged without considering this component of the nominal fitting model. It is worth to note that there are only two bins seeing uncertainty contributions from this variation and one, the bin [50, 60] GeV/c, is characterised by a low number of events. For the B_s^0 meson case only one bin, [10, 15] GeV/c,

saw contributions from this variation to its total systematic uncertainty. However, the associated total systematic uncertainty in that bin is again smaller than the respective statistical uncertainty.

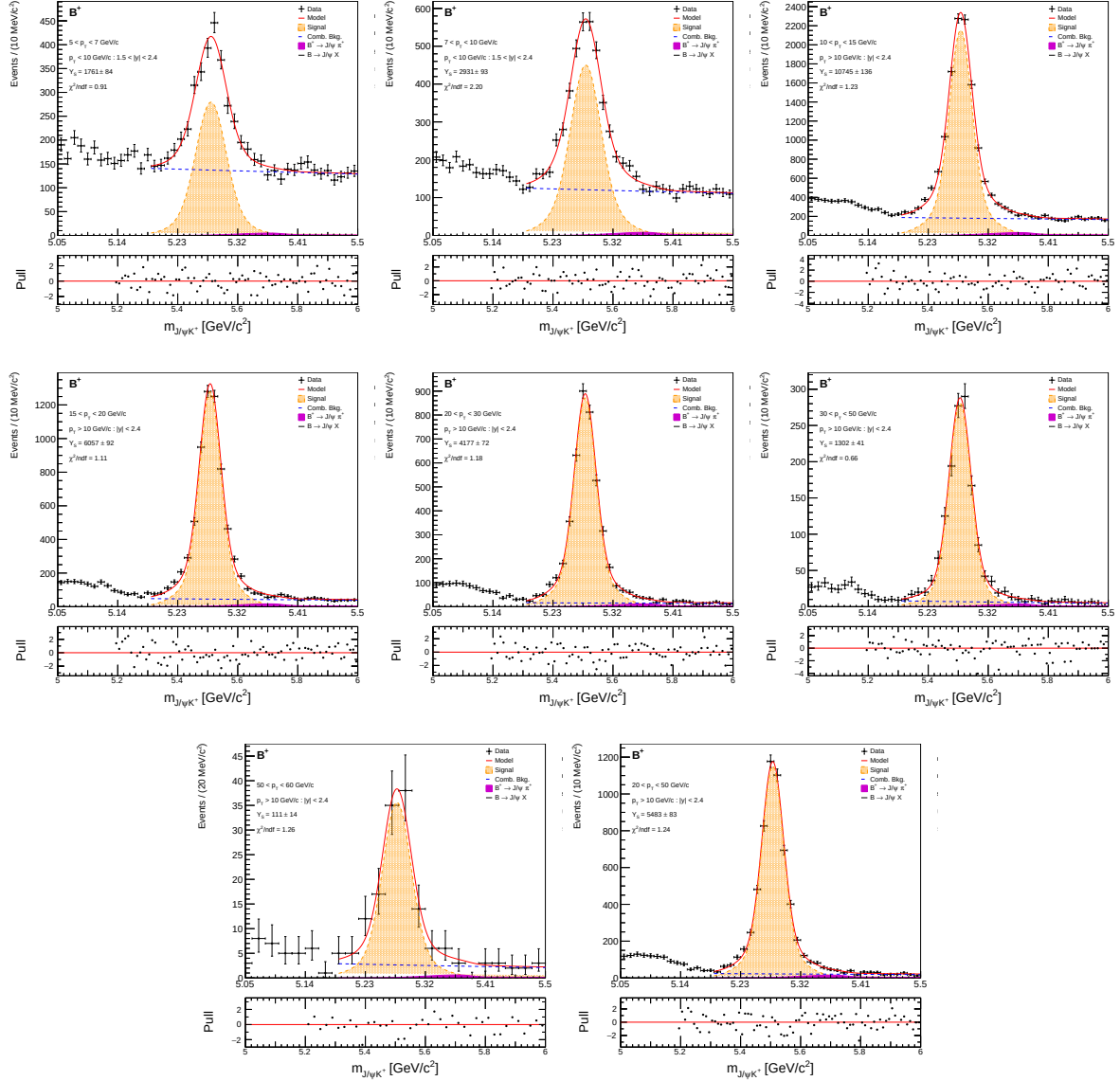


Figure 6.1: Fit to the B^+ meson data distribution using the mass range variation.

To quantify the systematic uncertainty associated with the B^+ meson Cabibbo suppressed background model, R_{PDG} is changed to the uncertainty weighted average value obtained in the differential analysis carried out to the $B^+ \rightarrow J/\psi \pi^+$ MC sample. Although the used MC has a good distribution shape, the branching fraction of the $B^+ \rightarrow J/\psi \pi^+$ in EVTGEN is incorrect, leading to the $\sim 30\%$ different between $R_{AN} = \frac{Y_{J/\psi \pi^+}}{Y_{J/\psi K^+}}$ and the value of R_{PDG} obtained from the PDG. However, standing for a very small data component its impact in the final results is negligible and no further uncertainty studies involving the variation of actual chosen PDF shall be required. The resulting systematic uncertainty arising from each considered signal and background model variation can be inspected in Fig. 6.2 and the mass fit results from the variation of the Cabibbo suppressed model can be seen in Fig. D.1. It indeed follows that using the R_{AN} value yields a very small relative difference between the nominal and the newly extracted signal

yields and no B^+ bin saw contributions to its total systematic uncertainty coming from this variation.

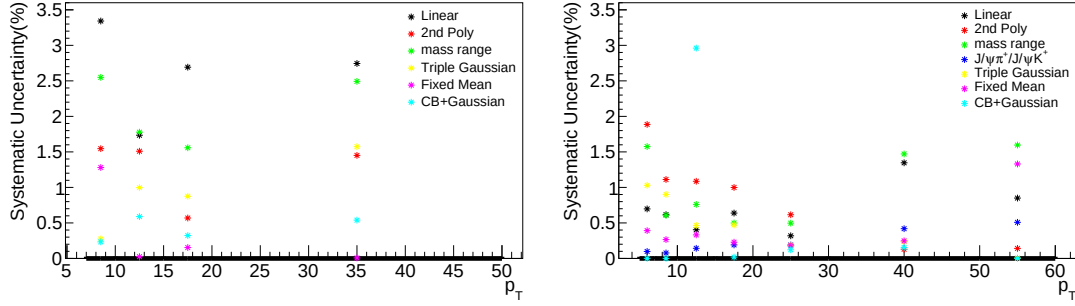


Figure 6.2: Summary of signal and background systematic uncertainties from each model variation for the B_s^0 (left) and B^+ (right) mesons.

Increasing the flexibility of the respective B meson fitting model by using the triple Gaussian maintained the overall good convergence and in some bins the χ^2/ndf values even moved towards unity. From Fig. 6.2 it also follows that this signal variation did not yield huge systematic uncertainties, even in the bins where they stand for the most deviated uncertainty values and thus end up contributing to the final value of the systematic uncertainties. As a conclusion of this particular variation study the remarkably simple model considered to describe the signal peak, a sum of two Gaussian PDFs, is already describing the data very well. In contrast the signal variation involving the sum of a crystal ball and a Gaussian PDF was found contributing to the final systematic uncertainty only in the case of the B^+ [10, 15] GeV/ c^2 bin. In all other B^+ bins it yielded the smallest uncertainties and in the B_s^0 it went as high as 0.6%. A crystal ball PDF consists of a Gaussian PDF and a power-law low-end tail PDF and is commonly used to model processes where the final state particles lose energy through radiation. However, the very low systematic uncertainties found suggest that this scenario did not apply. In this situation the crystal ball PDF reduces to a single Gaussian PDF and summing another Gaussian function ends up reproducing the nominal signal model. The χ^2/ndf values match the nominal ones as if the same model was indeed used. Fitting with this model also proved to be more difficult since associated with the additional freedom are two parameters of no use. The results for these two signal variations can be checked in Figs. D.3 and D.2.

Table 6.3: Summary of relative systematic uncertainties, in %, from the B_s^0 fitting model variations.

p_T [GeV/ c]	7–10	10–15	15–20	20–50
Background Unc.	3.34	1.78	2.72	2.75
Signal Unc.	1.29	0.997	0.87	1.59
PDF variation Unc.	3.58	2.04	2.85	3.17

Table 6.4: Summary of relative systematic uncertainties, in %, from the B^+ fitting model variations.

p_T [GeV/ c]	5–7	7–10	10–15	15–20	20–30	30–50	50–60	20–50
Background Unc.	1.88	1.12	1.08	0.993	0.657	1.82	1.99	0.521
Signal Unc.	1.02	0.899	2.97	0.468	0.198	0.263	1.35	0.227
PDF variation Unc.	2.14	1.43	3.17	1.1	0.687	1.84	2.4	0.568

6.1.3 Data vs MC Comparisons

The efficiency and acceptance determinations are affected by potential disagreements between data and MC. In Sec. 5.2 the signal MC simulation has been validated against data by inspecting the distributions of the variables employed in the selection. In particular, the $sPlot$ -derived signal distributions for the BDT scores were retrieved from the data and the corresponding data/MC ratios formed. These ratios are used to re-weight the MC simulation and repeating the procedure described in Sec. 5.1 a BDT weighted and averaged inverse total efficiency, $\langle 1/(\alpha \times \epsilon) \rangle_w$ is derived. The results for each p_T bin can be seen on Fig. 6.3 where the nominal values obtained in Sec. 5.1 are also shown. The relative deviations between them, $\Delta = \frac{\langle 1/(\alpha \times \epsilon) \rangle_w - \langle 1/(\alpha \times \epsilon) \rangle}{\langle 1/(\alpha \times \epsilon) \rangle}$, are then computed and compared to $\Delta_{pre} = \frac{Y_{lose}^{cor} - Y_s^{cor}}{Y_s^{cor}}$ where Y_s^{cor} are the yields obtained in Sec. 4.3 corrected by the inverse total efficiency obtained in Sec. 5.1 and Y_{lose}^{cor} are the corrected yields obtained from the data sample with a loose pre-selection cut whose only criteria is vertex probability of the secondary vertex being higher than 0.3%. The larger value between the Δ and Δ_{pre} is considered as the systematic uncertainty accounting for the discrepancy between data and MC. These results are shown in the last row of Tables 6.5 and 6.6 for the B_s^0 and B^+ mesons respectively.

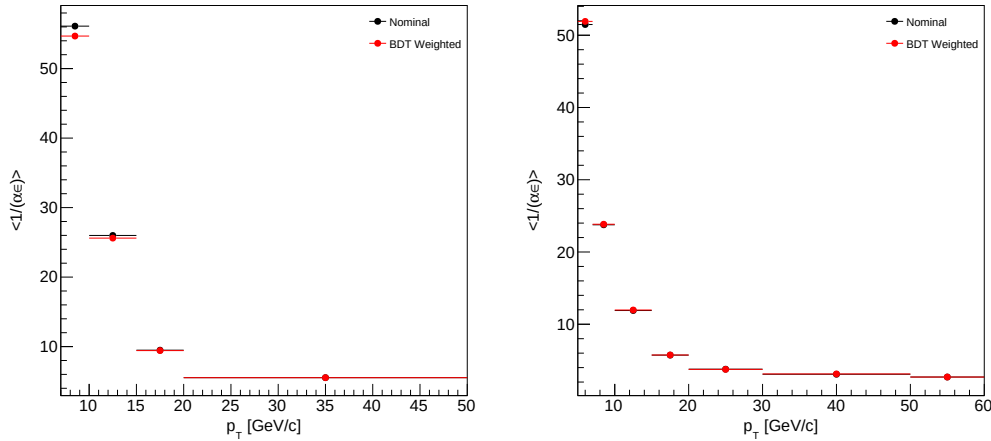


Figure 6.3: The BDT weighted and unweighted total efficiency factors as function of the B_s^0 (left) and B^+ (right) transverse momentum.

Table 6.5: Summary of relative systematic uncertainties, in %, from the data/MC discrepancy in B_s^0 .

p_T [GeV/c]	7–10	10–15	15–20	20–50
BDT Unc.	4.382	0.807	0.734	0.000
Pre-selection Unc.	0.583	8.080	6.271	3.492
Data vs MC Unc.	4.382	8.080	6.271	3.492

Table 6.6: Summary of relative systematic uncertainties, in %, from the data/MC discrepancy in B^+ .

p_T [GeV/c]	5–7	7–10	10–15	15–20	20–30	30–50	50–60	20–50
BDT Unc.	4.442	0.410	0.433	0.527	0.275	0.400	0.000	0.135
Pre-selection Unc.	2.303	8.853	2.181	1.822	2.762	1.196	9.192	2.315
Data vs MC Unc.	4.442	8.853	2.181	1.822	2.762	1.196	9.192	2.315

6.1.4 TnP Systematic Uncertainty

Since the *Tag-and-Probe* weighted total efficiency is used as the nominal factor the systematic uncertainties resulting from the application of the TnP method must be studied as well. A standard approach is to vary the TnP scale factor up and down according to the documented uncertainties. The averaged inverse total efficiency is compared with the up/down TnP weighted inverse total efficiency in Fig. 6.4 for the B^+ and B_s^0 mesons as a function of p_T . The larger difference between them in each of the analysis' bins can be inspected in Tables 6.7 and 6.8 and shall be quoted as the systematic uncertainties associated with the application of the TnP method.

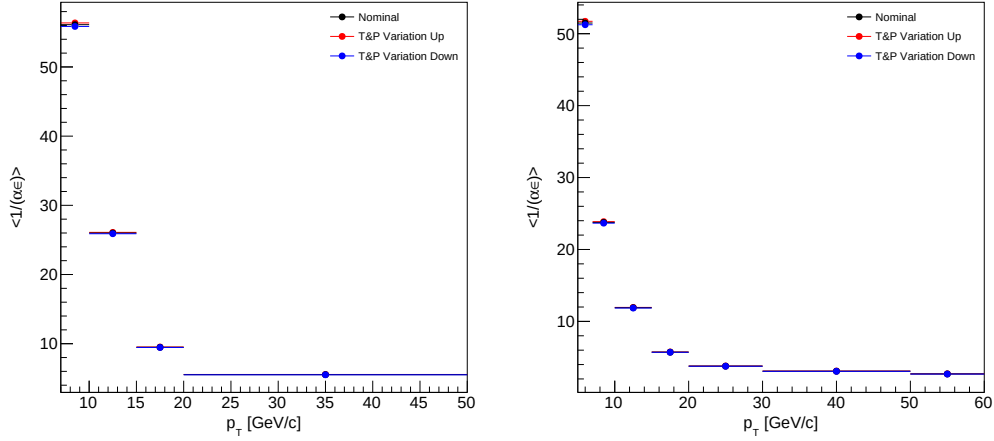


Figure 6.4: The upper and lower TnP weighted total efficiency variations compared to the nominal total efficiency for B_s^0 (left) and B^+ (right).

Table 6.7: Relative systematic uncertainties, in %, from the TnP method for the B_s^0 meson.

p_T [GeV/c]	7–10	10–15	15–20	20–50
Uncertainty	0.457	0.378	0.352	0.449

Table 6.8: Relative systematic uncertainties, in %, from the TnP method for the B^+ meson.

p_T [GeV/c]	5–7	7–10	10–15	15–20	20–30	30–50	50–60	20–50
Uncertainty	0.465	0.446	0.372	0.361	0.425	0.637	0.640	0.469

6.1.5 Track Uncertainty

The difference in the track reconstruction efficiency in data and simulation is estimated by comparing 3-prong and 5-prong D^* decays, $D^* \rightarrow K\pi\pi(\pi\pi)$ [57]. This results in 2.4% uncertainty in the efficiency determination for each hadronic track. Although this value applies globally to all p_T bins it is quoted in separate from the other two global systematic uncertainties since it could have depended on p_T while the luminosity and the branching fraction could not. The systematic uncertainty from the track selection criteria is also computed by comparing the nominal corrected signal yields with those obtained using a tighter selection whose difference is $\frac{\sigma_{p_T}}{p_T} < 0.05$ and $\frac{\chi^2/ndf}{N_{Layers}} < 0.15$.

6.1.6 p_T Shape Discrepancy

In order to account for potential disagreements between data and MC coming from the B meson p_T shape the MC simulation are also re-weighted using the data/MC ratios of the p_T distributions. After computing again the total efficiency factor the difference is assigned as systematic uncertainties. The comparisons between the nominal values of $\langle \frac{1}{\alpha \times \epsilon} \rangle$ and the ones obtained from the p_T re-weighted MC can be seen on Fig. 6.5 for both mesons. Tables 6.9 and 6.10 summarize the B mesons p_T shape systematic uncertainties. This uncertainty source is found to be very small and, indeed, independence from the MC simulation is expected when using the fine-grained 2D maps and the $\frac{1}{\alpha \times \epsilon}$ averaging based on data. Hence, these results attest the robustness of the analysis.

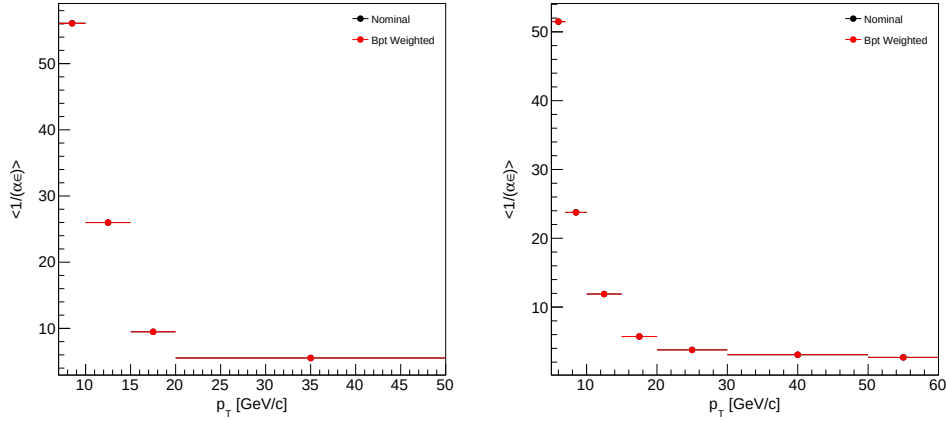


Figure 6.5: The p_T weighted and unweighted total efficiency factors as function of the B_s^0 (left) and B^+ (right) transverse momentum.

Table 6.9: Relative systematic uncertainties, in %, from the p_T shape of the B_s^0 meson candidates.

p_T [GeV/c]	7–10	10–15	15–20	20–50
Uncertainty	0.045	0.015	0.004	0.002

Table 6.10: Relative systematic uncertainties, in %, from the p_T shape of the B^+ meson candidates.

p_T [GeV/c]	5–7	7–10	10–15	15–20	20–30	30–50	50–60	20–50
Uncertainty	0.020	0.005	0.013	0.010	0.005	0.003	0.018	0.003

Results

7.1 Cross Sections in pp

The p_T dependent signal yields, Y_s , were found in Sec. 4.3 and the associated efficiencies, $\langle \frac{1}{\epsilon\alpha} \rangle$, learned in Sec. 5.1. Hence, considering $\mathcal{L}$ and the $\mathcal{B}$ s from Sec. 1.5, the B_s^0 and B^+ production cross sections can now be computed according to Eq. (1.18) employing the bins $[7, 10, 15, 20, 50]$ GeV/c for the B_s^0 meson and $[5, 7, 10, 15, 20, 30, 50, 60]$ GeV/c for the B^+ meson.

In Fig. 7.1 the p_T dependent differential cross sections of the B_s^0 and B^+ mesons are presented in a logarithmic scale. The pp results from the 2015 analysis are also shown to allow a consistency test. The respective 2015 $p_T < 15$ GeV/c and $p_T < 10$ GeV/c regions of the B_s^0 and B^+ mesons can not be directly compared against the corresponding 2017 p_T regions due to the different rapidity range of the considered events and also due to unmatched bins. Nevertheless, in the bins where a direct comparison is possible the obtained results match with an outstanding precision the previous findings. It should also be noted that the B^+ meson cross section results now cover a wider p_T than the earlier analysis, with new bins in the low, $[5, 7]$ GeV/c, and high, $[50, 60]$ GeV/c p_T regions.

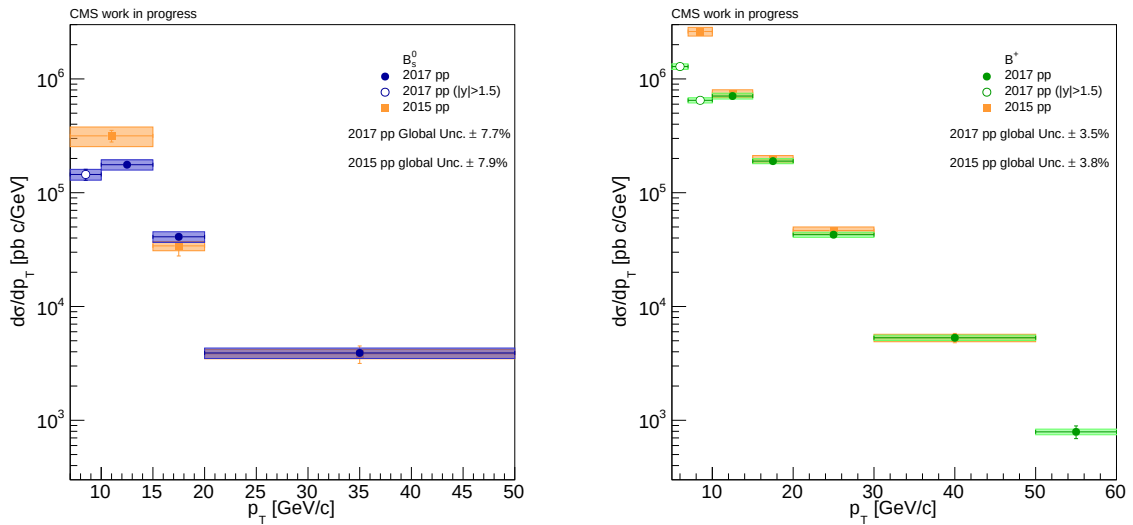


Figure 7.1: The p_T differential cross section of B_s^0 (left) and B^+ (right) mesons in pp collisions at $\sqrt{s} = 5.02$ TeV with $\mathcal{L} = 302.3 \text{ pb}^{-1}$. The vertical bars correspond to statistical uncertainties and the boxes correspond to systematic uncertainties. Global systematic uncertainties are quoted in separate.

In order to test the FONLL theoretical predictions its B_s^0 and B^+ reference production spectra can be seen superimposed in Fig. 7.2 to the respective measured pp spectra. Overall, the one sigma theoretical uncertainty of each bin is covering the corresponding experimental results and their associated statistical and systematic uncertainties very well. The only cases where the experimental uncertainties slightly edge out of the one sigma theoretical uncertainty are the B_s^0 [7, 10] GeV/c and [20, 50] GeV/c bins and the B^+ [50, 60] GeV/c bin. Nonetheless a very good agreement between the FONLL predictions and the latest measurements is found. To further visualize and quantify the compatibility between the measured production cross sections and the theory predictions their ratio is presented in the lower panel of each plot. These results oscillate around unity and so further attest their good agreement. In Tables 7.1 and 7.2 the measured values for the B_s^0 and B^+ differential production cross sections are respectively summarized.

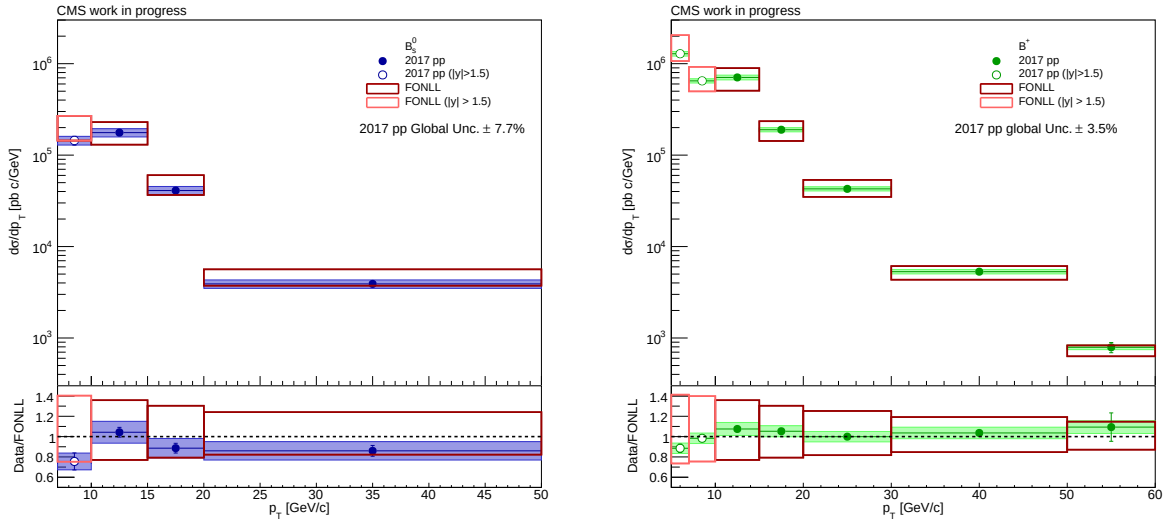


Figure 7.2: The p_T differential cross section of B_s^0 (left) and B^+ (right) mesons in pp collisions at $\sqrt{s} = 5.02$ TeV with $\mathcal{L} = 302.3 \text{ pb}^{-1}$. The FONLL theoretical prediction is superimposed.

Table 7.1: Summary of the measured B^+ p_T differential cross sections.

p_T Bin [GeV/c]	$\frac{d\sigma}{dp_T}$ [pb c/GeV]	Relative Unc. (%)	
		Stat.	Syst.
7–10	144648	11.1	10.9
10–15	176229	4.6	10.3
15–20	40983	5.4	10.8
20–50	3905	6.2	10.5

Table 7.2: Summary of the measured B^+ p_T differential cross sections.

p_T Bin [GeV/c]	$\frac{d\sigma}{dp_T}$ [pb c/GeV]	Relative Unc. (%)	
		Stat.	Syst.
5–7	1284698	4.6	5.8
7–10	648673	3.1	5.2
10–15	707231	1.2	6.0
15–20	189538	1.5	5.2
20–30	42754	1.7	5.1
30–50	5312	3.3	5.5
50–60	791	12.8	5.7

7.2 Nuclear Modification Factors

The measurement of the differential production cross section of B^+ mesons in pp has been presented in Sec. 7.1 using a larger and finer binning than its PbPb measurement counterpart. In the later analysis, due to less available data, only the p_T region between 7 GeV/c and 50 GeV/c could be explored employing the binning [7, 10, 15, 20, 50] GeV/c for both the B mesons. As a consequence the R_{AA} of B^+ must be computed in this range considering a single [20, 50] GeV/c bin.

The nuclear modification factors of B^+ and B_s^0 mesons are determined according to Eq. (1.15) and shown in Fig. 7.3 along with the corresponding 2015 measurement. A first notorious difference in the new measurement is the overall smaller statistical and systematic uncertainties. In general, both mesons R_{AA} shape is found to be similar and compatible with the previous results. Twice as many bins were now employed when computing the B_s^0 meson R_{AA} . This improvement showed that in the [20, 50] GeV/c p_T region its production in PbPb collisions, and hence in the presence of a QGP, is slightly more suppressed than what was previously suggested. Moreover, in this measurement the two p_T bins contained therein are hardly compatible with R_{AA} values higher than unity. This contrasts with the previous findings since the high uncertainties of the bin spanning this region could still mean such values. The finer binning also lead to a better understanding of the region where the coalescence mechanism may be playing a major role in the process of beauty hadronization. Previously the production of B_s^0 mesons was taught to be enhanced in the whole [7, 15] GeV/c p_T region. The latest measurement divided this region in two bins, namely, [7, 10] GeV/c and [10, 15] GeV/c. In the first one, within the associated uncertainties, the coalescence mechanism importance is still hinted since $R_{AA} \sim 1.1$ is higher than unity. Still, the associated high statistical and systematic uncertainties prevent an exact claim about the strength of the medium effects and also do not exclude the possibility of production suppression. For the B^+ meson the obtained R_{AA} values are all way bellow unit, ranging around ~ 0.3 and ~ 0.5 , and meaning a huge suppression of this meson production in the presence of a QGP. This is inline with the 2015 results, which are covering a similar range of R_{AA} values.

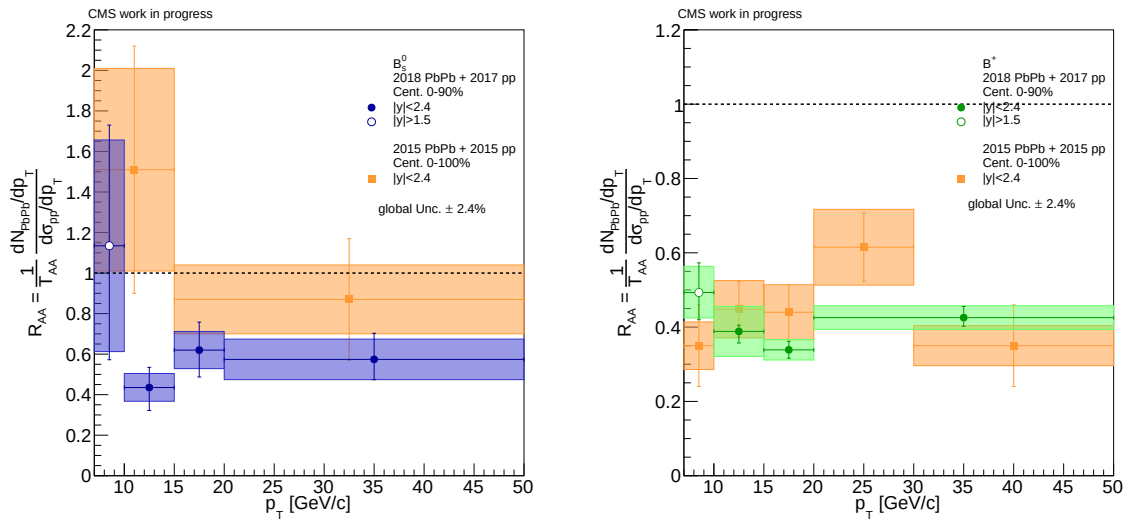


Figure 7.3: The measured B_s^0 and B^+ mesons R_{AA} and respective comparisons against the 2015 values.

The p_T dependence of both B mesons nuclear modification factors was also compared against several theoretical curves obtained from (i) two perturbative QCD models featuring both collisional and radiative medium induced energy losses (Djordjevic [58] and CUJET3.0 [59]), (ii) a model based on the Langevin equation accounting for collisional medium induced energy losses and heavy quark diffusion in the QGP (TAMU [60]) and (iii) a model based on the anti-de-Sitter/conformal field theory duality that includes thermal fluctuations in the energy loss for heavy quarks in a strongly-coupled plasma (AdS/CFT HH [61]). The third model is available for two distinct cases where the diffusion coefficient, D , of the heavy quark propagation through the QGP either exhibits a momentum dependence, $D(p)$, or is independent of it.

In Fig. 7.4 the considered theoretical predictions are superimposed to the B_s^0 and B^+ mesons nuclear modification factors. Within the current uncertainties the AdS/CFT duality calculation using $D(p)$ and the Djordjevic models are found to describe roughly well the B^+ meson R_{AA} . If extrapolated to lower p_T values the later model even suggests a possible good agreement with the $[7, 10]$ GeV/c p_T bin. The TAMU, the AdS/CFT duality without a p_T dependent diffusion coefficient and the CUJET3.0 models predict a rather weaker suppression than the one measured for B^+ mesons production under the QGP medium effects. Nonetheless these three models are still compatible with the latest R_{AA} measurements. Since the experimental uncertainties are smaller than the CUJET3.0 and the two AdS/CFT HH models uncertainties the current results can be used to adjust their parameters and constrain the collisional and radiative medium induced energy loss processes. The B_s^0 R_{AA} result is compared only to the CUJET3.0 and TAMU models. The contrasting behaviour between these two predictions below $p_T < 15$ GeV/c reflects contributions from recombination processes, which are accounted in the TAMU model but not in the CUJET3.0 model. Given the current experimental uncertainties, both model predictions are still compatible with the measurements. However, it should be noted that the TAMU model should be a better candidate if quark coalescence indeed plays a vital role in beauty hadronization.

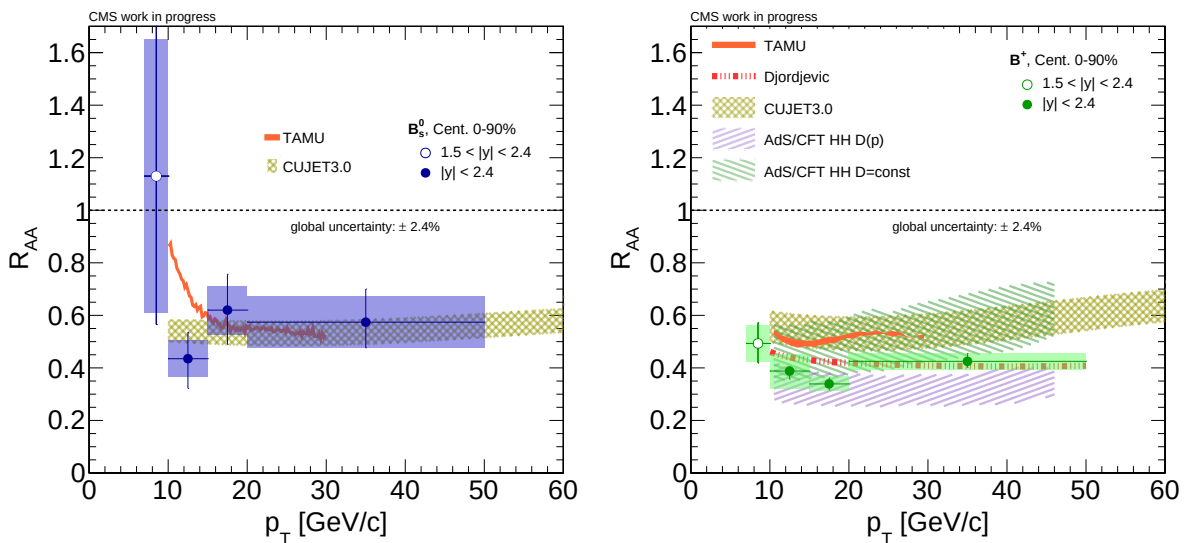


Figure 7.4: Nuclear modification factor of B_s^0 and B^+ mesons compared against several theoretical curves. The rapidity range of all the theoretical predictions is $|y| < 2.4$ and so these have been sketched only in the $[10, 50]$ GeV/c p_T region since a direct comparison against the obtained experimental results is only possible here due to the analysis fiducial region.

In Fig. 7.5 the measured nuclear modification factors of B_s^0 and B^+ are superimposed on the corresponding results using charged hadrons, h^+ , and D^0 mesons. These have been previously achieved using the CMS detector at the same collision energy, $\sqrt{s} = 5.02$ TeV, and in a similar centrality range. The B_s^0 meson, while overall suppressed, is the only particle in this comparison whose R_{AA} is compatible with values above unity in the low momentum region. Thus, so far it is the only open-flavour meson in the comparison whose production could be enhanced in the presence of a QGP. At higher momentum, as discussed in Sec. 1.4, the nuclear modification factor of any particle is expected to converge since the flavour dependence of the medium effects cease. The B_s^0 meson [20, 50] GeV/c bin is characterized by large uncertainties that contains the rising trend of the smaller bins where the h^+ and the D^0 mesons nuclear modification factors are reported. So, this meson R_{AA} is compatible with such prediction. For the B^+ meson, in the [7, 10] GeV/c p_T bin the nuclear modification factor is above that of the charged hadrons and D^0 mesons, indicating a somewhat smaller suppression of its production in PbPb collisions than previously thought. In the p_T region [10, 50] GeV/c the obtained R_{AA} values for this meson are seen catching the upward trend of the particles considered in this comparison. However, possibly due to the large width of the [10, 50] GeV/c p_T bin, the R_{AA} value falls behind those of the considered particles after p_T 30 GeV/c. This overall comparison of B_s^0 and B^+ mesons nuclear modification factors against those of the charged hadrons and D^0 mesons further attests the importance of the QGP effects.

The global shape of the nuclear modification factors of all the particles considered here is also worth to notice. Both B mesons R_{AA} feature a dip followed by an increase whose overall shape seems similar. The only major difference is the B^+ meson downshifted nuclear modification values. Furthermore their shapes also reproduce the dipping structure found for the h^+ , and D^0 mesons R_{AA} in the same p_T interval. Thus, these suggest the existence of at least one common region, around ~ 5 GeV/c to ~ 20 GeV/c, where the medium suppressive effects are more intense.

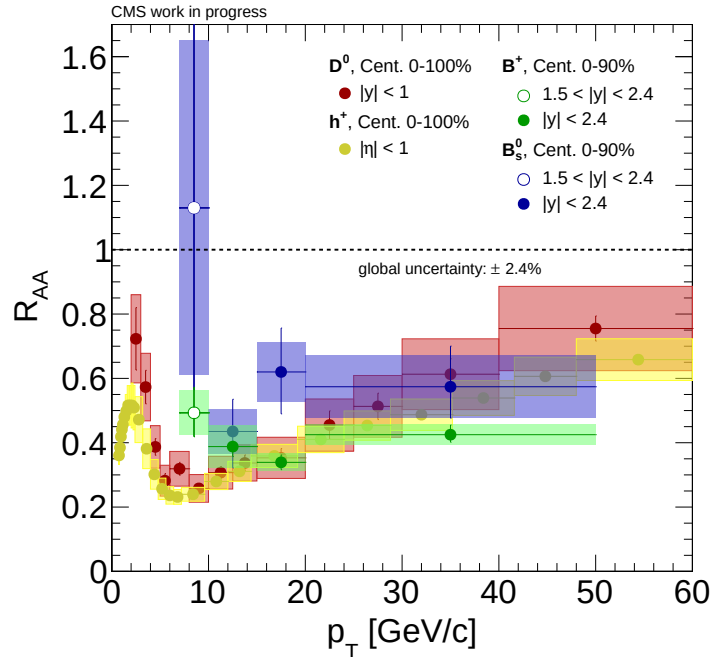


Figure 7.5: Comparison of the B_s^0 and B^+ mesons R_{AA} against those of charged hadrons [62] and D^0 [63].

In order to better characterize the QGP effects on the hadronization of the b quarks the double ratio between the B_s^0 and B^+ mesons nuclear modification factors is now computed. Doing so the common systematic uncertainties sources to both measurements cancel out, namely, the global uncertainties and part of the tracking uncertainty. The result can be seen in Fig. 7.6 where it is compared to the double ratio previously reported in the 2015 analysis. While the latest measurement results are slightly lower than before both analyses are still compatible. The double ratio is found to be systematically above unity, which suggests the relevance of the QGP strangeness enhancing effects. In particular, in the $[7, 10]$ GeV/ c p_T bin and within its current uncertainties such medium effects are notorious and compatible with quark coalescence with the strangeness content of the QGP medium.

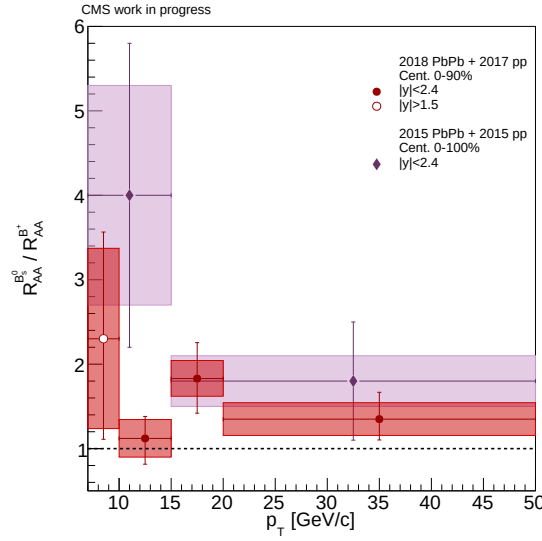


Figure 7.6: Ratio between B_s^0 and B^+ nuclear modification factors.

Conclusions

This thesis studies the production of beauty flavoured mesons in pp and PbPb collisions at the LHC with the CMS experiment. In particular, the B_s^0 and B^+ meson production cross sections are measured in pp and compared to the corresponding published results in PbPb collisions. The differences between their spectra in the two systems owns to the formation of quark gluon plasma droplets in the later.

The B meson nuclear modification factor measurements indicate that the post nuclear collision medium is notoriously interfering with hadronization in the b sector. The B^+ meson production is strongly suppressed in the probed $[7, 50]$ GeV/c p_T region. This new nuclear modification factor measurement is more precise than the one conducted in 2015, allowing to clarify that the high p_T region is in fact compatible with the rising trend of other reported particles R_{AA} . Moreover it shows that the R_{AA} in the low p_T $[7, 10]$ GeV/c bin is higher than previously suggested, being now more compatible with the nonprompt J/ψ meson corresponding measurement. For the B_s^0 meson a slightly less suppression is found up until the low p_T $[7, 10]$ GeV/c bin. There, within the current uncertainties, this meson R_{AA} is compatible with production enhancement. The obtained B_s^0 R_{AA} stands as the first measurement of its kind after this meson observation in PbPb collisions was established. The results from both mesons overall attest the flavour dependence, at low p_T , and then its disappearance, at high p_T , of the QGP medium effects. From the comparison of the nuclear modification factor against the theoretical predictions the experimental uncertainties are seen to be smaller than the CUJET3.0 and the two AdS/CFT HH models uncertainties and so the current results can be used to adjust their parameters. The double ratio of the nuclear modification factors constitutes a robust and sensitive observable whose outcome, being systematically found above unity, show that strangeness enhancement in the b sector can not go unnoticed, particularly at low momentum where the double ratio is compatible with values ranging between ~ 1.2 and ~ 3.5 . Hence this supports the idea of quark coalescence in the QGP. The obtained B mesons cross sections are also used to conduct further studies. The FONLL theoretical predictions is contrasted against them and a very compatible agreement is found.

The results of this work were possible due to the outstanding trigger and tracking capabilities of the CMS detector, capable of identifying the collision vertex from where the B mesons emerges and the secondary vertex where it decays. It allowed their first exclusive and precise reconstruction in PbPb collisions

through the decay channels, $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ and $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$. Nonetheless the conducted measurements are limited by the size of the current data samples and so room for improvement is left towards the lower and upper p_T regions. Fortunately the LHC Run3 has started in the Summer of 2022, with a data taking schedule foreseeing an extended PbPb run in Fall 2023. This stands as an opportunity to further improve and extend the production measurements presented in this work. Moreover, in the future the HL-LHC phase will allow a precision era where rarer processes and observables can be explored, including exotic hadrons.

Bibliography

- [1] C. N. Yang and R. L. Mills. Conservation of isotopic spin and isotopic gauge invariance. *Phys. Rev.*, 96:191, 1954. doi: 10.1103/PhysRev.96.191. URL <https://link.aps.org/doi/10.1103/PhysRev.96.191>.
- [2] T. Fazzini, G. Fidecaro, A. W. Merrison, H. Paul, and A. V. Tollestrup. Electron decay of the pion. *Phys. Rev. Lett.*, 1:247, 1958. doi: 10.1103/PhysRevLett.1.247. URL <https://link.aps.org/doi/10.1103/PhysRevLett.1.247>.
- [3] F. Hasert et al. Search for elastic muon-neutrino electron scattering. *Physics Letters B*, 46:121, 1973. doi: [https://doi.org/10.1016/0370-2693\(73\)90494-2](https://doi.org/10.1016/0370-2693(73)90494-2). URL <https://www.sciencedirect.com/science/article/pii/0370269373904942>.
- [4] UA1 Collaboration. Experimental observation of isolated large transverse energy electrons with associated missing energy at $\sqrt{s} = 540$ GeV. *Physics Letters B*, 122:103, 1983. doi: [https://doi.org/10.1016/0370-2693\(83\)91177-2](https://doi.org/10.1016/0370-2693(83)91177-2). URL <https://www.sciencedirect.com/science/article/pii/0370269383911772>.
- [5] UA2 Collaboration. Observation of single isolated electrons of high transverse momentum in events with missing transverse energy at the CERN pp collider. *Physics Letters B*, 122:476, 1983. doi: [https://doi.org/10.1016/0370-2693\(83\)91605-2](https://doi.org/10.1016/0370-2693(83)91605-2). URL <https://www.sciencedirect.com/science/article/pii/0370269383916052>.
- [6] The CMS Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Physics Letters B*, 716:30, 2012. doi: <https://doi.org/10.1016/j.physletb.2012.08.021>. URL <https://www.sciencedirect.com/science/article/pii/S0370269312008581>.
- [7] ATLAS Collaboration. Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC. *Physics Letters B*, 716:1, 2012. doi: <https://doi.org/10.1016/j.physletb.2012.08.020>. URL <https://www.sciencedirect.com/science/article/pii/S037026931200857X>.
- [8] Y. Fukuda et al. Evidence for oscillation of atmospheric neutrinos. *Phys. Rev. Lett.*, 81:1562, 1998. doi: 10.1103/PhysRevLett.81.1562.

- [9] P.A. Zyla et al. (Particle Data Group). Review of particle physics. Progress of Theoretical and Experimental Physics, 2020, 2020. doi: 10.1093/ptep/ptaa104. URL <https://doi.org/10.1093/ptep/ptaa104>. 083C01.
- [10] R. Vogt. Ultrarelativistic heavy-ion collisions. Elsevier, Amsterdam, 2007. ISBN 978-0-444-52196-5.
- [11] M. Thomson. Modern Particle Physics. Cambridge University Press, New York, 2013. ISBN 978-1-107-03426-6.
- [12] B. Betz. Jet propagation and mach-cone formation in (3+1)-dimensional ideal hydrodynamics, 2009. URL <https://arxiv.org/abs/0910.4114>.
- [13] J. Rafelski. Melting hadrons, boiling quarks. The European Physical Journal A, 51:114, 2015. doi: 10.1140/epja/i2015-15114-0. URL <https://doi.org/10.1140/epja/i2015-15114-0>.
- [14] D. Thomas, D. N. Schramm, K. A. Olive, G. J. Mathews, B. S. Meyer, and B. D. Fields. Production of lithium, beryllium, and boron from baryon inhomogeneous primordial nucleosynthesis. The Astrophysical Journal, 430:291, 1994. doi: 10.1086/174403. URL <https://doi.org/10.1086%2F174403>.
- [15] Belle Collaboration. Observation of a narrow charmoniumlike state in exclusive $B^\pm \rightarrow K^\pm \pi^+ \pi^- J/\psi$ decays. Phys. Rev. Lett., 91:262001, 2003. doi: 10.1103/PhysRevLett.91.262001. URL <https://link.aps.org/doi/10.1103/PhysRevLett.91.262001>.
- [16] V. Mathieu, N. Kochelev, and V. Vento. The physics of glueballs. International Journal of Modern Physics E, 18:1, 2009. doi: 10.1142/s0218301309012124. URL <https://doi.org/10.1142%2Fs0218301309012124>.
- [17] G. Policastro, D. T. Son, and A. O. Starinets. Shear viscosity of strongly coupled $n = 4$ supersymmetric yang-mills plasma. Phys. Rev. Lett., 87:081601, 2001. doi: 10.1103/physrevlett.87.081601. URL <https://doi.org/10.1103%2Fphysrevlett.87.081601>.
- [18] W. Busza, K. Rajagopal, and W. van der Schee. Heavy ion collisions: The big picture and the big questions. Annual Review of Nuclear and Particle Science, 68:339, 2018. doi: 10.1146/annurev-nucl-101917-020852. URL <https://doi.org/10.1146/annurev-nucl-101917-020852>.
- [19] M. E. Noz and Y. S. Kim. Special Relativity and Quantum Theory: a collection of papers on the Poincaré Group. Springer Netherlands, Dordrecht, 1988. ISBN 978-94-009-3051-3.
- [20] ALICE Collaboration. Bulk properties of PbPb collisions at $\sqrt{s} = 2.76$ TeV measured by ALICE. Journal of Physics G, 38:124007, 2011. doi: 10.1088/0954-3899/38/12/124007. URL <https://doi.org/10.1088%2F0954-3899%2F38%2F12%2F124007>.
- [21] Jana Crkovska. Study of the J/ψ production in pp collisions at $\sqrt{s} = 5.02$ TeV and of the J/ψ production multiplicity dependence in pPb collisions at $\sqrt{s} = 8.16$ TeV with ALICE at the LHC. Université Paris-Saclay, 2018 .

- [22] L. Apolinário, Y.-J. Lee, and M. Winn. Heavy quarks and jets as probes of the qgp. *Progress in Particle and Nuclear Physics*, 127:103990, 2022. ISSN 0146-6410. doi: <https://doi.org/10.1016/j.ppnp.2022.103990>. URL <https://www.sciencedirect.com/science/article/pii/S0146641022000485>.
- [23] M. Cacciari, P. Nason, and R. Vogt. QCD predictions for charm and bottom quark production at RHIC. *Phys. Rev. Lett.*, 95:122001, 2005. doi: 10.1103/PhysRevLett.95.122001. URL <https://link.aps.org/doi/10.1103/PhysRevLett.95.122001>.
- [24] X. Dong, Y.-J. Lee, and R. Rapp. Open heavy-flavor production in heavy-ion collisions. *Annual Review of Nuclear and Particle Science*, 69:417, 2019. doi: 10.1146/annurev-nucl-101918-023806. URL <https://doi.org/10.1146/annurev-nucl-101918-023806>.
- [25] R. Rapp et al. Extraction of heavy-flavor transport coefficients in QCD matter. *Nuclear Physics A*, 979:21, 2018. doi: 10.1016/j.nuclphysa.2018.09.002. URL <https://doi.org/10.1016%2Fj.nuclphysa.2018.09.002>.
- [26] M. Cacciari, M. Greco, and P. Nason. The p_T spectrum in heavy-flavour hadroproduction. *Journal of High Energy Physics*, 1998:7, 1998. doi: 10.1088/1126-6708/1998/05/007. URL <https://dx.doi.org/10.1088/1126-6708/1998/05/007>.
- [27] Y. Dokshitzer and D. Kharzeev. Heavy-quark colorimetry of QCD matter. *Physics Letters B*, 519:199, 2001. doi: 10.1016/s0370-2693(01)01130-3. URL <https://doi.org/10.1016%2Fs0370-2693%2801%2901130-3>.
- [28] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg. Glauber modeling in high-energy nuclear collisions. *Annual Review of Nuclear and Particle Science*, 57:205, 2007. doi: 10.1146/annurev.nucl.57.090506.123020. URL <https://doi.org/10.1146%2Fannurev.nucl.57.090506.123020>.
- [29] JET Collaboration. Extracting the jet transport coefficient from jet quenching in high-energy heavy-ion collisions. *Phys. Rev. C*, 90:014909, 2014. doi: 10.1103/PhysRevC.90.014909. URL <https://link.aps.org/doi/10.1103/PhysRevC.90.014909>.
- [30] Rafelski, Johann and Müller, Berndt. Strangeness production in the quark-gluon plasma. *Phys. Rev. Lett.*, 48:1066, 1982. doi: 10.1103/PhysRevLett.48.1066. URL <https://link.aps.org/doi/10.1103/PhysRevLett.48.1066>.
- [31] R. Fries, V. Greco, and P. Sorensen. Coalescence models for hadron formation from quark-gluon plasma. *Annual Review of Nuclear and Particle Science*, 58:177, 2008. doi: 10.1146/annurev.nucl.58.110707.171134. URL <https://doi.org/10.1146%2Fannurev.nucl.58.110707.171134>.
- [32] CMS Collaboration. Measurement of B_s^0 meson production in pp and PbPb collisions at $\sqrt{s} = 5.02$ TeV. *Physics Letters B*, 796:168, 2019. doi: 10.1016/j.physletb.2019.07.014. URL <https://doi.org/10.1016%2Fj.physletb.2019.07.014>.

- [33] CMS Collaboration. Measurement of the $B^\pm$ meson nuclear modification factor in PbPb collisions at $\sqrt{s} = 5.02$ TeV. Phys. Rev. Lett., 119:152301, 2017. doi: 10.1103/PhysRevLett.119.152301. URL <https://link.aps.org/doi/10.1103/PhysRevLett.119.152301>.
- [34] CMS Collaboration. Nuclear modification factor of D^0 mesons in PbPb collisions at $\sqrt{s} = 5.02$ TeV. Physics Letters B, 782:474, 2018. doi: 10.1016/j.physletb.2018.05.074. URL <https://doi.org/10.1016%2Fj.physletb.2018.05.074>.
- [35] Z. Shi. Analysis of Beauty Quark Hadronization in Vacuum and Quark-Gluon Plasma with CMS, CERN-THESIS-2021-123, 2021. URL <https://cds.cern.ch/record/2780359>.
- [36] J. Silva. Probing the quark gluon plasma medium through B meson production measurements in PbPb collisions at the LHC, CERN-THESIS-2019-256, 2019. URL <https://cds.cern.ch/record/2705630>.
- [37] CMS Collaboration. Observation of B_s^0 mesons and measurement of the B_s^0/B^+ yield ratio in PbPb collisions at $\sqrt{s} = 5.02$ TeV. Physics Letters B, 829:137062, 2022. doi: <https://doi.org/10.1016/j.physletb.2022.137062>. URL <https://www.sciencedirect.com/science/article/pii/S0370269322001964>.
- [38] LHCb Collaboration. Measurement of f_s/f_u variation with proton-proton collision energy and b -meson kinematics. Phys. Rev. Lett., 124:122002, 2020. doi: 10.1103/PhysRevLett.124.122002. URL <https://link.aps.org/doi/10.1103/PhysRevLett.124.122002>.
- [39] LHCb Collaboration. Precise measurement of the f_s/f_d ratio of fragmentation fractions and of B_s^0 decay branching fractions. Phys. Rev. D, 104:032005, 2021. doi: 10.1103/PhysRevD.104.032005. URL <https://link.aps.org/doi/10.1103/PhysRevD.104.032005>.
- [40] LHCb Collaboration. Evidence for modification of b quark hadronization in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV, 2022. URL <https://arxiv.org/abs/2204.13042>.
- [41] T. Cheng. Measurements of charm production in pp collisions with ALICE, 2021. URL <https://arxiv.org/abs/2111.12054>.
- [42] A. Boletti. Measurement of angular parameters from the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV, 2018. URL <https://cds.cern.ch/record/2648594>.
- [43] M. C. Feliciano Faria. Investigating the flavour anomalies through the rare beauty decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$, CERN-THESIS-2021-220, 2021. URL <https://cds.cern.ch/record/2791778>.
- [44] CMS Collaboration. The CMS Experiment at the CERN LHC. JINST, 3:8004, 2008. doi: 10.1088/1748-0221/3/08/S08004.
- [45] A. Sirunyan et al. Particle-flow reconstruction and global event description with the CMS detector. Journal of Instrumentation, 12:10003, 2017. doi: 10.1088/1748-0221/12/10/p10003. URL <https://doi.org/10.1088%2F1748-0221%2F12%2F10%2Fp10003>.

- [46] A. Hoecker et al. Tmva - toolkit for multivariate data analysis, 2009. URL <https://arxiv.org/abs/physics/0703039>.
- [47] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands. An introduction to PYTHIA 8.2. Comput. Phys. Commun., 191:159, 2015. doi: 10.1016/j.cpc.2015.01.024.
- [48] J. Allison et al. Recent developments in GEANT. Nucl. Instrum. Meth. A, 835:186, 2016. doi: 10.1016/j.nima.2016.06.125.
- [49] I. P. Lokhtin and A. M. Snigirev. A model of jet quenching in ultrarelativistic heavy ion collisions and high- p_T hadron spectra at RHIC. The European Physical Journal C, 45:211, 2006. doi: 10.1140/epjc/s2005-02426-3. URL <https://doi.org/10.1140%2Fepjc%2Fs2005-02426-3>.
- [50] D. J. Lange. The evtgen particle decay simulation package. Nucl. Instrum. Meth. A, 462:152, 2001. doi: 10.1016/S0168-9002(01)00089-4.
- [51] E. Barberio, B. van Eijk, and Z. Was. PHOTOS: A universal Monte Carlo for QED radiative corrections in decays. Comput. Phys. Commun., 66:115, 1991. doi: 10.1016/0010-4655(91)90012-A.
- [52] F. James. MINUIT: Function Minimization and Error Analysis Reference Manual. 1998. URL <https://cds.cern.ch/record/2296388>. CERN Program Library Long Writeups.
- [53] J. Ocariz. Probability and statistics for particle physicists. 2014. doi: 10.48550/ARXIV.1405.3402. URL <https://arxiv.org/abs/1405.3402>.
- [54] CMS Collaboration. Relative modification of prompt $\psi(2s)$ and J/ψ yields from pp to PbPb collisions at $\sqrt{s} = 5.02$ TeV. Phys. Rev. Lett., 118:162301, 2017. doi: 10.1103/PhysRevLett.118.162301. URL <https://link.aps.org/doi/10.1103/PhysRevLett.118.162301>.
- [55] M. Pivk and F. Le Diberder. $sPlot$: A statistical tool to unfold data distributions. Nuclear Instruments and Methods in Physics Research, 555:356, 2005. doi: <https://doi.org/10.1016/j.nima.2005.08.106>. URL <https://www.sciencedirect.com/science/article/pii/S0168900205018024>.
- [56] M. Tanabashi et al. (Particle Data Group) . Review of particle physics. Phys. Rev. D, 98:030001, 2018. doi: 10.1103/PhysRevD.98.030001. URL <https://link.aps.org/doi/10.1103/PhysRevD.98.030001>.
- [57] CMS Collaboration. Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s} = 5.02$ TeV. Journal of High Energy Physics, 2017:39, 2017. doi: 10.1007/jhep04(2017)039. URL <https://doi.org/10.1007%2Fjhep04%282017%29039>.
- [58] M. Djordjevic, B. Blagojevic, and L. Zivkovic. Mass tomography at different momentum ranges in quark-gluon plasma. Phys. Rev. C, 94:044908, 2016. doi: 10.1103/PhysRevC.94.044908.
- [59] J. Xu, J. Liao, and M. Gyulassy. Bridging soft-hard transport properties of quark-gluon plasmas with CUJET3.0. JHEP, 02:169, 2016. doi: 10.1007/JHEP02(2016)169.

- [60] M. He, R. J. Fries, and R. Rapp. Heavy flavor at the large hadron collider in a strong coupling approach. *Phys. Lett. B*, 735:445, 2014. doi: 10.1016/j.physletb.2014.05.050.
- [61] R. Hambrock and W. A. Horowitz. AdS/CFT predictions for azimuthal and momentum correlations of $b\bar{b}$ pairs in heavy ion collisions. 2017. URL <https://inspirehep.net/record/1518153/files/arXiv:1703.05845.pdf>.
- [62] V. Khachatryan et al. Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s} = 5.02$ TeV. *JHEP*, 04:039, 2017. doi: 10.1007/JHEP04(2017)039.
- [63] CMS Collaboration. Nuclear modification factor of D^0 mesons in PbPb collisions at $\sqrt{s} = 5.02$ TeV. *Physics Letters B*, 782:474, 2018. ISSN 0370-2693. doi: <https://doi.org/10.1016/j.physletb.2018.05.074>. URL <https://www.sciencedirect.com/science/article/pii/S0370269318304386>.

Appendix A

Signal MC Fits

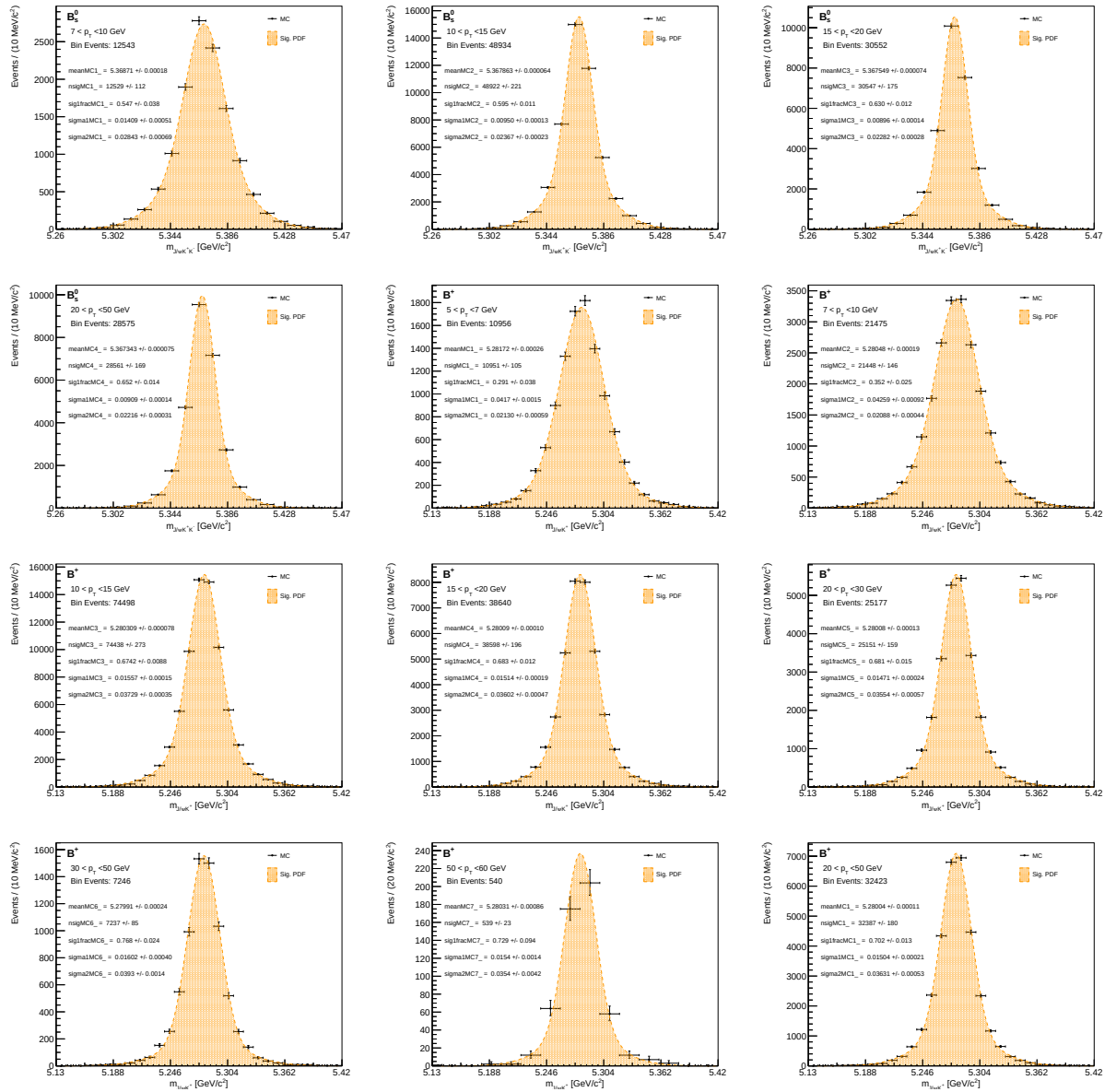


Figure A.1: Fits to the MC mass distribution of both B mesons.

Appendix B

Partially Reconstructed Background MC Fits

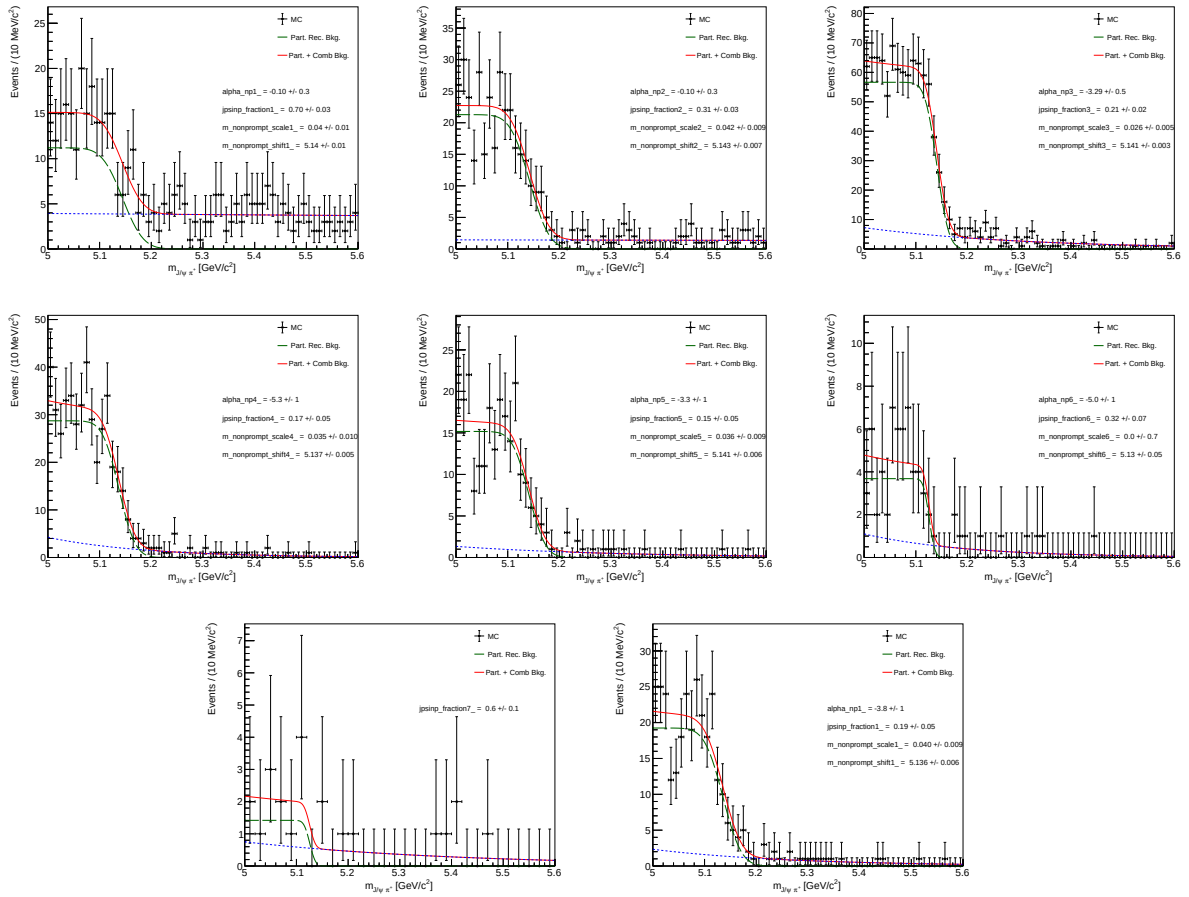


Figure B.1: Fit to the B^+ meson MC mass distribution of the partially reconstructed background.

Comparisons between the $sPlot$ and MC

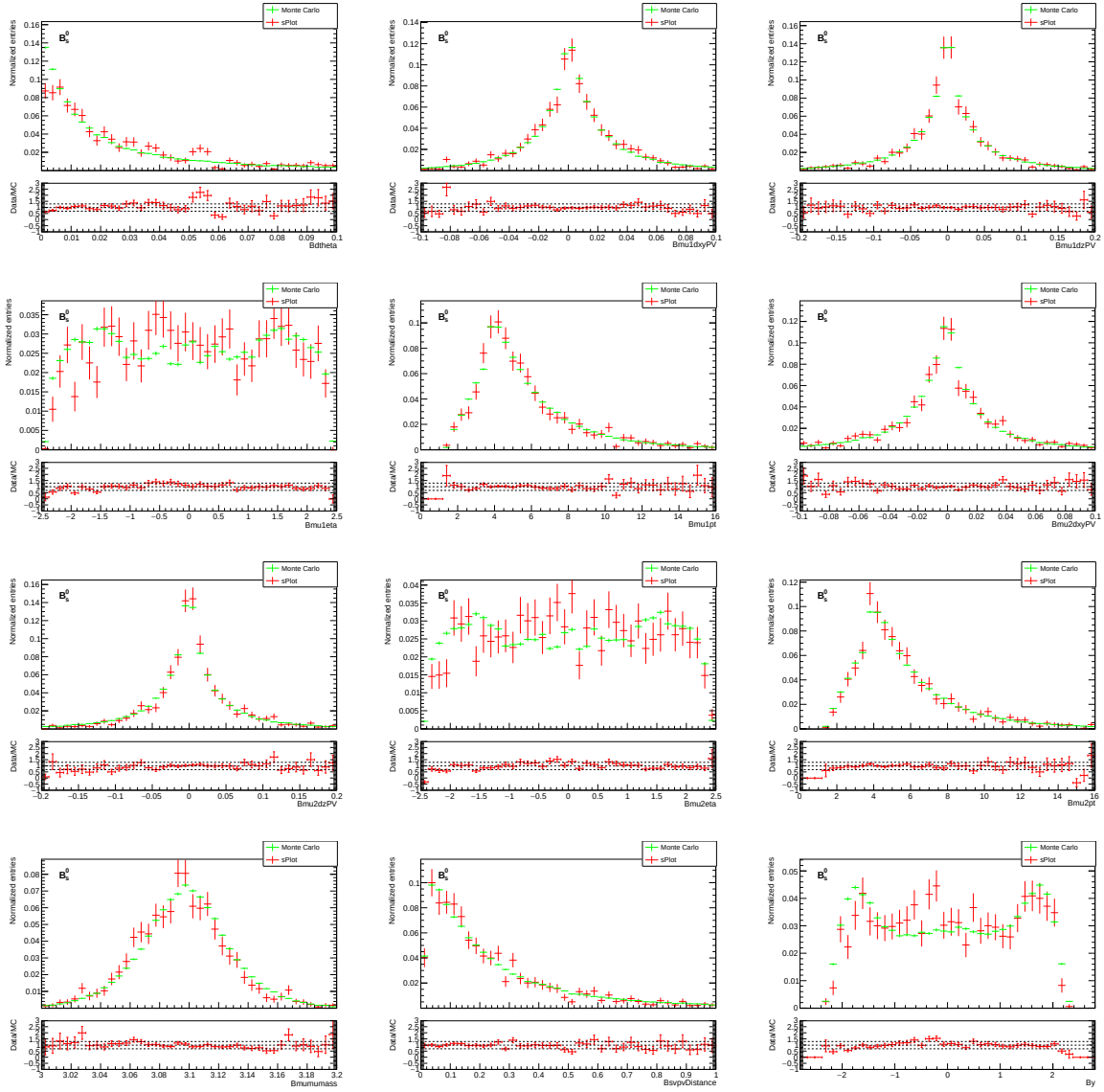


Figure C.1: Signal distributions of several variables of B_s^0 and B^+ mesons compared against the respective MC ones.

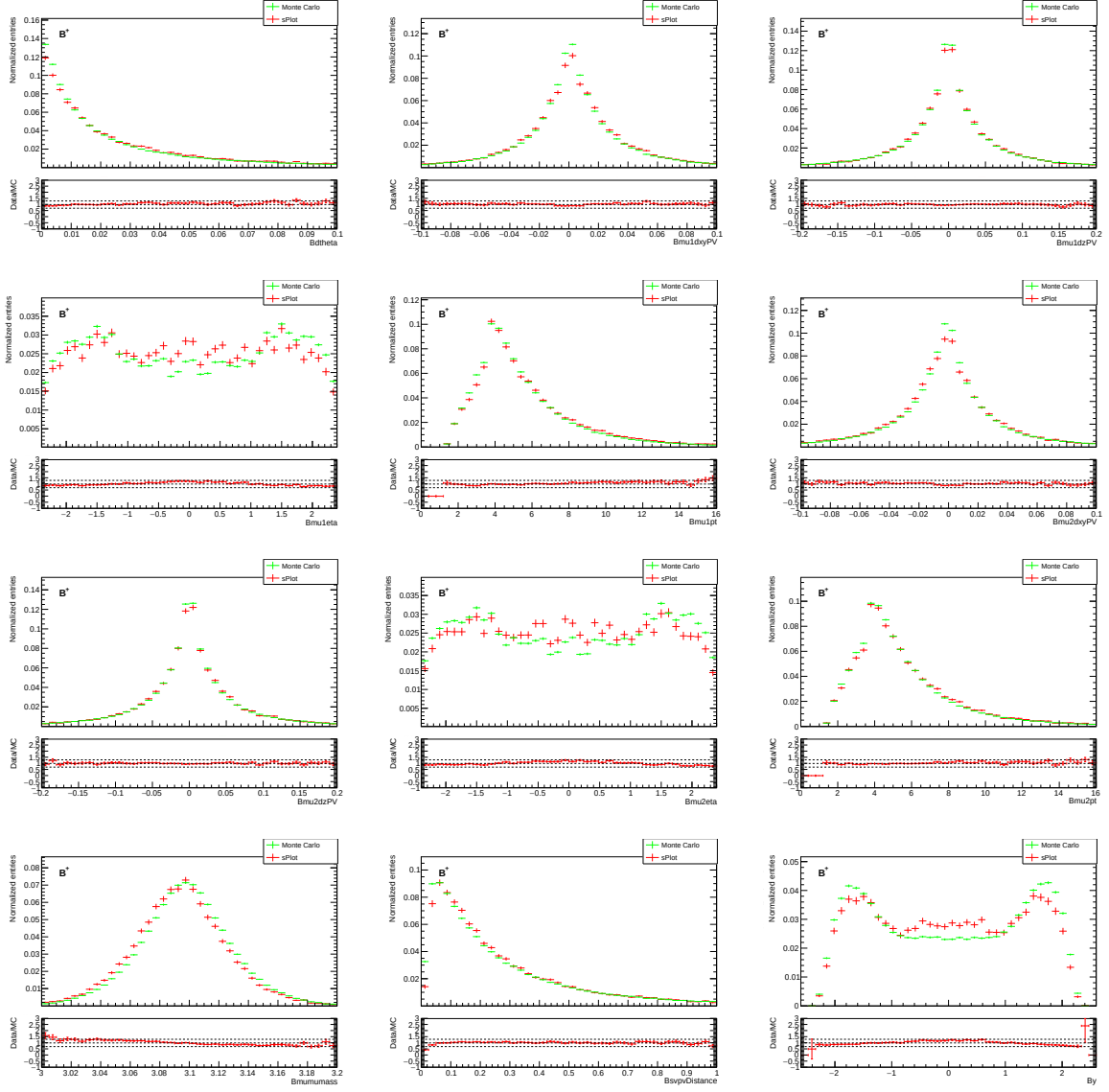


Figure C.2: Signal distributions of several variables of B_s^0 and B^+ mesons compared against the respective MC ones.

Appendix D

Systematic Uncertainties

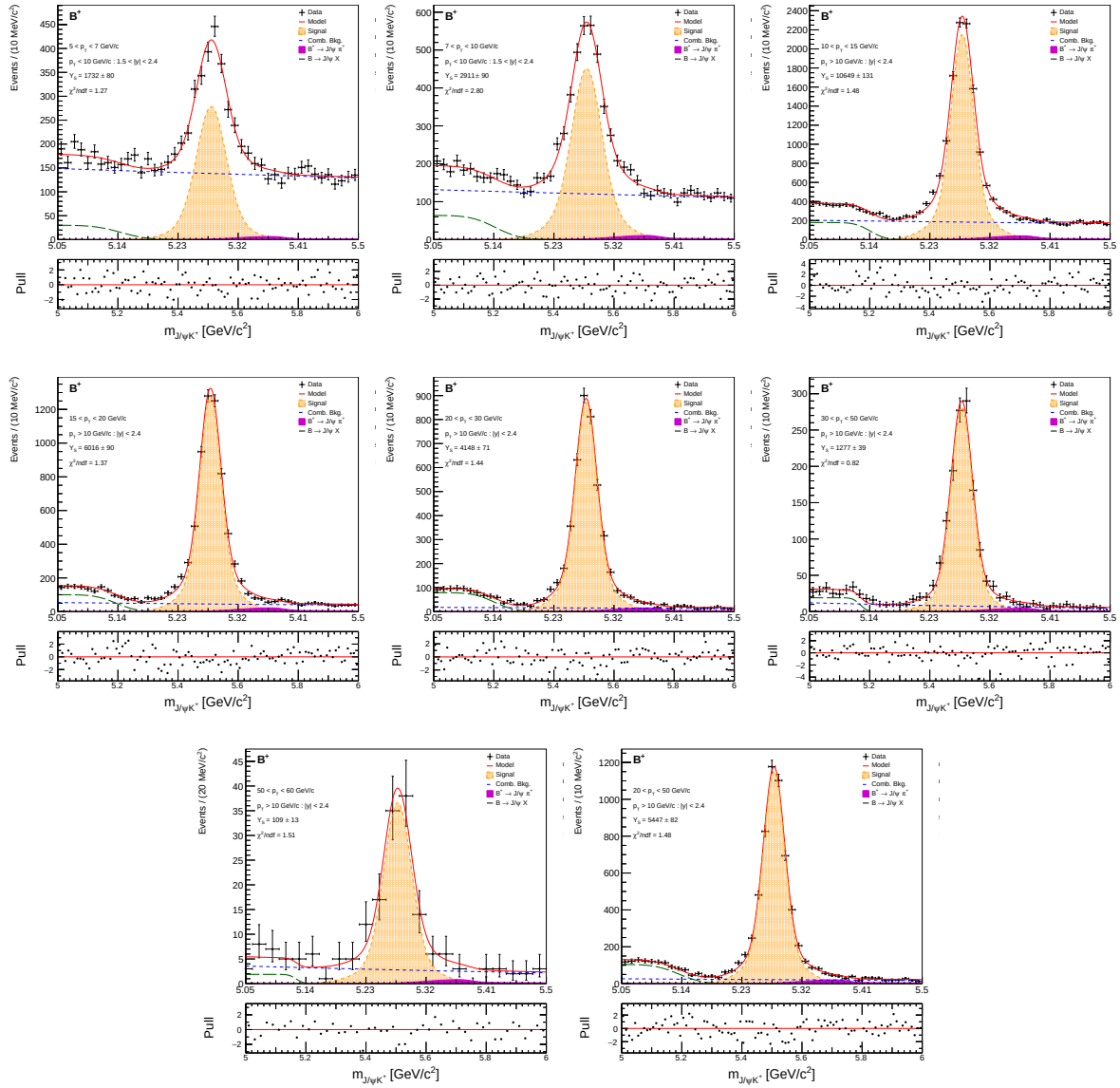


Figure D.1: Fit to the B^+ meson data distribution using the Cabibbo suppressed background variation where $R_{PDG} \rightarrow R_{AN}$.

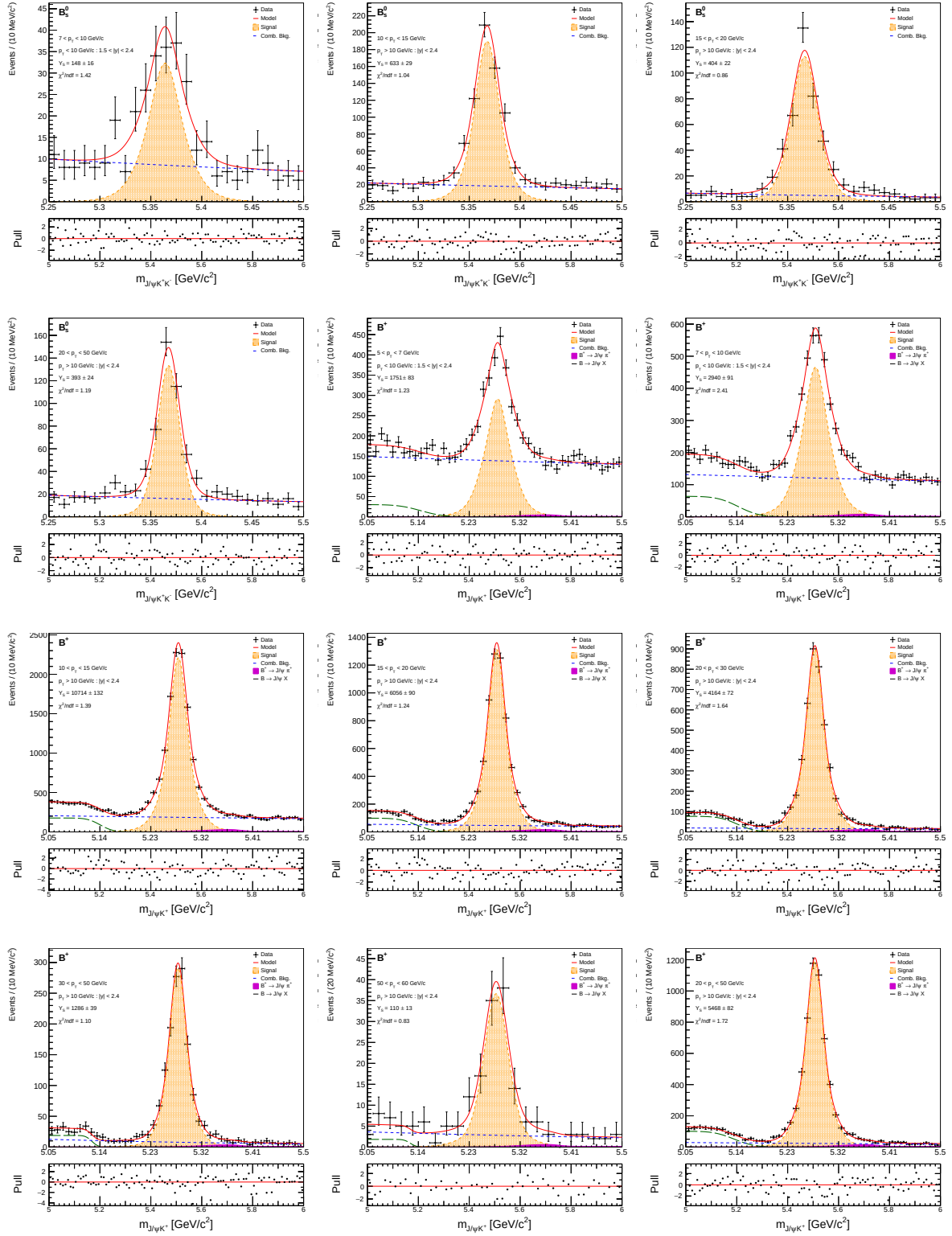


Figure D.2: Fit to the B_s^0 and B^+ mesons data distribution using the signal background variation where a triple gaussian PDF is considered.

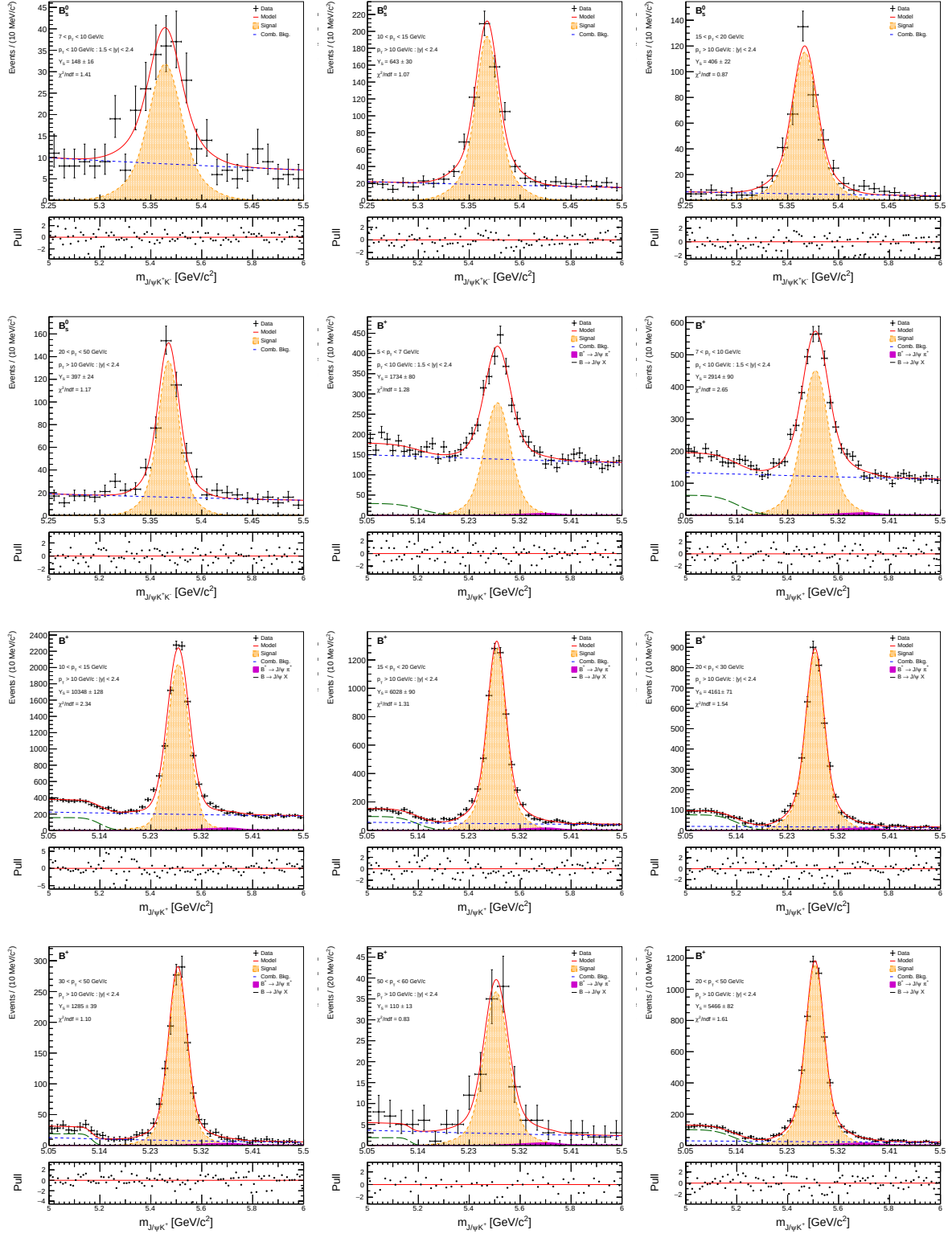


Figure D.3: Fit to the B_s^0 and B^+ mesons data distribution using the signal background variation where the sum of a Gaussian function with a crystal ball function is considered.