

# CMS Draft Analysis Note

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# B meson $R_{AA}$ and Cross Section Ratios in $pp$ and PbPb Collisions at 5.02 TeV

Zhaozhong Shi<sup>1</sup>, Maria Faria<sup>2, 1</sup>, Ran Bi<sup>1</sup>, Nuno Leonardo<sup>2</sup>, and Yen-Jie Lee<sup>1</sup>

<sup>1</sup>Massachusetts Inst. of Technology

<sup>2</sup> Técnico Lisboa

## Abstract

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## 1 Introduction

Relativistic heavy ion collisions allow the study of quantum chromodynamics (QCD) at high energy densities and temperatures. Under such conditions, a state in which quarks and gluons are the relevant degrees of freedom, the quark-gluon plasma (QGP) [? ? ], is formed [? ] as predicted by lattice QCD calculations [? ]. Multiple probes are necessary for characterizing the properties of the QGP medium. Among these, heavy quarks, which are abundantly produced at the CERN LHC, have the potential of providing novel insights into QCD calculations, serving as probes of the QGP [? ? ]. As they traverse the QGP, these hard-scattered partons lose energy by means of elastic collisions and medium-induced gluon radiation [? ? ? ? ]. The study of parton energy loss can provide insights into the energy density and diffusion properties of the QGP. The full reconstruction of beauty and charm gives access to their four-momenta and allows the study of the flavor and mass dependences of such processes.

In particular, beauty quarks are considered as a golden hard probes to study the transport properties of QGP. Beauty quarks are pre produced in the early stage of heavy-ion collisions. They retain their identities and traverse through the QGP before hadronization and decay. They record the entire evolution of the QGP. From the studies of the production cross sections and nuclear modification factor of b hadrons cross section in pp and heavy-ion collisions, we can understand the energy loss mechanism of beauty quarks in the QGP medium. From the ratios of the production yield of  $\Lambda_b$  and  $B_s^0$  to  $B^+$  from low multiplicity pp, to PbPb, we can understand the beauty hadronization mechanism from small to large systems and test the QCD factorization theorem. These, along with the studies of charm and light flavor hadrons, will allow us to understand the flavor dependence of energy loss and probe the microscopic structure of QGP.

In this analysis, we will perform the measurements of  $B_s^0$  and  $B^+$  cross section as functions of transverse momentum, rapidity, and event multiplicity and within the CMS acceptance  $|y| < 2.4$  over a broad range in pp collisions at  $\sqrt{s_{NN}} = 5.02$  TeV with the CMS detector. We will use the 2017 pp datasets corresponding to an integrated luminosity of  $302.3 \text{ pb}^{-1}$ . We will follow the procedures of CADI HIN-17-008 and HIN-19-011 for the analysis. The decay channel we choose for  $B^+$  and  $B_s^0$  measurements are  $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$  and  $B_s^0 \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$ . We will use the 2018 PbPb  $B_s^0$  and  $B^+$  measurements to obtain the nuclear modification factor and  $B_s^0/B^+$  ratios in pp and PbPb collisions. Our results will be important to help interpret other heavy flavor experimental results and constrain theoretical model calculations.

## 2 Datasets, MC samples and event selection

### 2.1 Datasets

This analysis is performed using the **Ultra Legacy** 2017 pp data at  $\sqrt{s_{NN}}=5.02$  TeV, which has an integrated luminosity of  $302.3 \text{ pb}^{-1}$ . The analysis uses the dimuon primary datasets (*DoubleMu* PD). The full name of the used datasets can be found in Table 1.

Table 1: List of pp HLT datasets and triggers with the corresponding integrated luminosities used in the analysis.

System	Primary dataset	Trigger	Luminosity
pp	/DoubleMuon/Run2017G-09Aug2019_UL2017-v1/AOD	HLT_HIL3Mu0NHitQ10_L2Mu0_MAXdR3p5_M1to5_v1	$302.3 \text{ pb}^{-1}$

The pp analysis codes are running under the CMSSW\_9\_4\_10 version, and the global tag (GT) used for processing these samples is 94X\_dataRun2\_ReReco\_EOY17\_v6.

Events used in the measurement are collected with a trigger requiring the presence of two independent muon candidates. No selection is applied on momentum (including transverse momentum) or pseudo-rapidity. A list of the various triggers with the corresponding integrated luminosities can be found in Table Tab. 1. The pp paths had different prescale values in different runs during the data taking period. A complete description of the di-muon datasets and HLT triggers can be found in [? ].

Muon JSON file is applied to filter the pp dataset. It can be found at: Cert306546 – 306826<sub>5</sub>TeV<sub>E</sub>OY2017ReReco

### 2.2 Event Selection

To extract pure collision events, several offline selections are applied to each event:

- `pPAPrimaryVertexFilterNew`: Events are required to have at least one reconstructed primary vertex. The primary vertex 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.
- `HBHENoiseFilterResult`: An additional selection of hadronic collisions is applied by requiring a coincidence of at least 2 HF calorimeter towers, with more than 4 GeV of total energy, from the HF detectors on both sides of the interaction point.
- `pBeamScrapingFilterNew`: In addition to HF coincidence, a cluster compatibility filter is used
- `HLT_HIL1DoubleMu0_v1New`: dimuon triggered events

In addition, we also require the absolute value of the z-component of the primary vertex position to be  $|PV_z| < 15 \text{ cm}$ .

### 2.3 MC samples

The pp sample is reconstructed using the CMSSW version CMSSW\_9\_4\_10 using the **Ultra Legacy** reconstruction procedures. The global tag used for the production is 94X\_mc2017\_realistic\_forpp for pp samples. Dedicated pp  $B_s^0$  samples were generated in order to estimate the acceptance and selection efficiencies, to study the background components, and to evaluate systematic uncertainties. PYTHIA8 Tune CUETPM8 [? ? ], set to generate inclusive (all quark/antiquark, as well as gluon initiated) QCD processes, was used to generate at 5.02 TeV the signal. Several prefilters at the generation steps are applied in order to optimize the generation process

and conserve resources. Only signal events were kept with at least one  $B_s^0$  (forced to decay through the channel  $B_s \rightarrow J/\psi \phi$  by means of the EVTGEN package [? ]), with  $p_T > 5.0 \text{ GeV}/c$ , and  $|\eta| < 2.4$ . In addition, the  $J/\psi$  and  $\phi$  meson, are forced to decay in the two muons and two kaons respectively. Final state radiations (FSR) are generated using PHOTOS [? ]. The selected signal is simulated with PYTHIA 8 pp collisions

Around 2.5 million events were generated in 1  $\hat{p}_T > 5$  bin. The list of  $B_s^0$  and B MC simulation samples used are shown below:

- $B_s^0$ : /BsToJpsiPhi\_pThat-5\_TuneCP5\_5p02TeV\_Pythia8/RunIpp5Spring18DR-94X\_mc2017\_realistic\_forppRef5TeV\_v1-v4/AODSIM
- $B^+$ : /BsToJpsiPhi\_pThat-5\_TuneCP5\_5p02TeV\_Pythia8/RunIpp5Spring18DR-94X\_mc2017\_realistic\_forppRef5TeV\_v1-v4/AODSIM

In addition to the signal samples, inclusive non-prompt  $J/\psi$  samples, which include several different B meson decaying to  $J/\psi$  channels, were also generated. These samples were used to determine the peaking background appearing in the  $\mu \mu K K$  mass spectrum. The following samples were used:

- /Pythia8\_BJpsiMM\_ptJpsi\_00\_03\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_BJpsiMM\_ptJpsi\_03\_06\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_BJpsiMM\_ptJpsi\_03\_06\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13\_ext1-v1/AODSIM
- /Pythia8\_BJpsiMM\_ptJpsi\_06\_09\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_BJpsiMM\_ptJpsi\_06\_09\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13\_ext1-v1/AODSIM
- /Pythia8\_BJpsiMM\_ptJpsi\_09\_12\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_BJpsiMM\_ptJpsi\_12\_15\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_BJpsiMM\_ptJpsi\_15\_30\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_BJpsiMM\_ptJpsi\_30\_inf\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM

The inclusive non-prompt  $J/\psi$  samples are also used in the  $B^+$  analysis to constrain the non-prompt background.

Finally, the following prompt  $J/\psi$  samples were used:

- /Pythia8\_JpsiMM\_ptJpsi\_00\_03\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_JpsiMM\_ptJpsi\_03\_06\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_JpsiMM\_ptJpsi\_03\_06\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13\_ext1-v1/AODSIM
- /Pythia8\_JpsiMM\_ptJpsi\_06\_09\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_JpsiMM\_ptJpsi\_06\_09\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13\_ext1-v1/AODSIM
- /Pythia8\_JpsiMM\_ptJpsi\_09\_12\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_JpsiMM\_ptJpsi\_12\_15\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_JpsiMM\_ptJpsi\_15\_30\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM
- /Pythia8\_JpsiMM\_ptJpsi\_30\_inf\_Hydjet\_MB/HINppWinter16DR-75X\_mcRun2\_HeavyIon\_v13-v1/AODSIM

### 2.3.1 MC reweighting

For our MC reweighting, we reweight our MC directly to our data shape in the RECO level. We extract the data raw yield from the unbinned fit and the MC raw yield by count the total number of MC candidates with  $\hat{p}_T$ ,  $PV_z$ , and centrality reweighting. The  $J/\psi$ ,  $B^+$ , and  $B_s$  Gen  $p_T$  distribution before and after are shown below on Fig 1

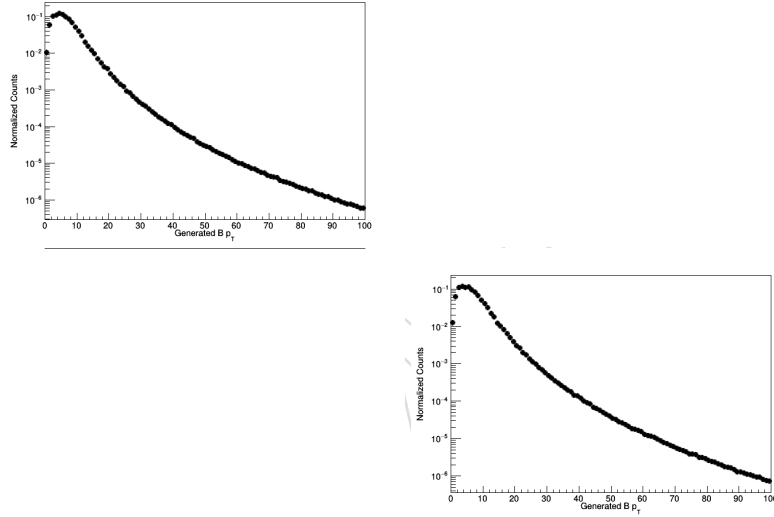


Figure 1: The  $p_T$  distribution of the official MC sample (left) as well as the generated  $J/\psi$  (middle) and B-meson  $p_T$  distribution with  $p_T$  weight applied of  $B^+$  and  $B_s^0$  are shown respectively above.

We can see that after  $\hat{p}_T$  reweighting, the Gen  $p_T$  distributions have become smoother. This validate our  $\hat{p}_T$  reweighting procedures.

Then, we take the ratio of the normalized data raw yield to the normalized MC raw yield and perform a fit with function:  $y = p_0/x^2 + p_1 \log(x) + p_2$ . Our fitting results on spectra ratio are show as follows on Fig 2

The fitting parameters for all functions are shown below on Table 3

Table 2: Summary of fitting parameters for the fitting functions of  $B^+$  and  $B_s^0$  above is shown below.

Particles	$p_0$	$p_1$	$p_2$
$B^+$	8.65	4.26	-1.48
$B_s^0$	1.00	0.436	0.171



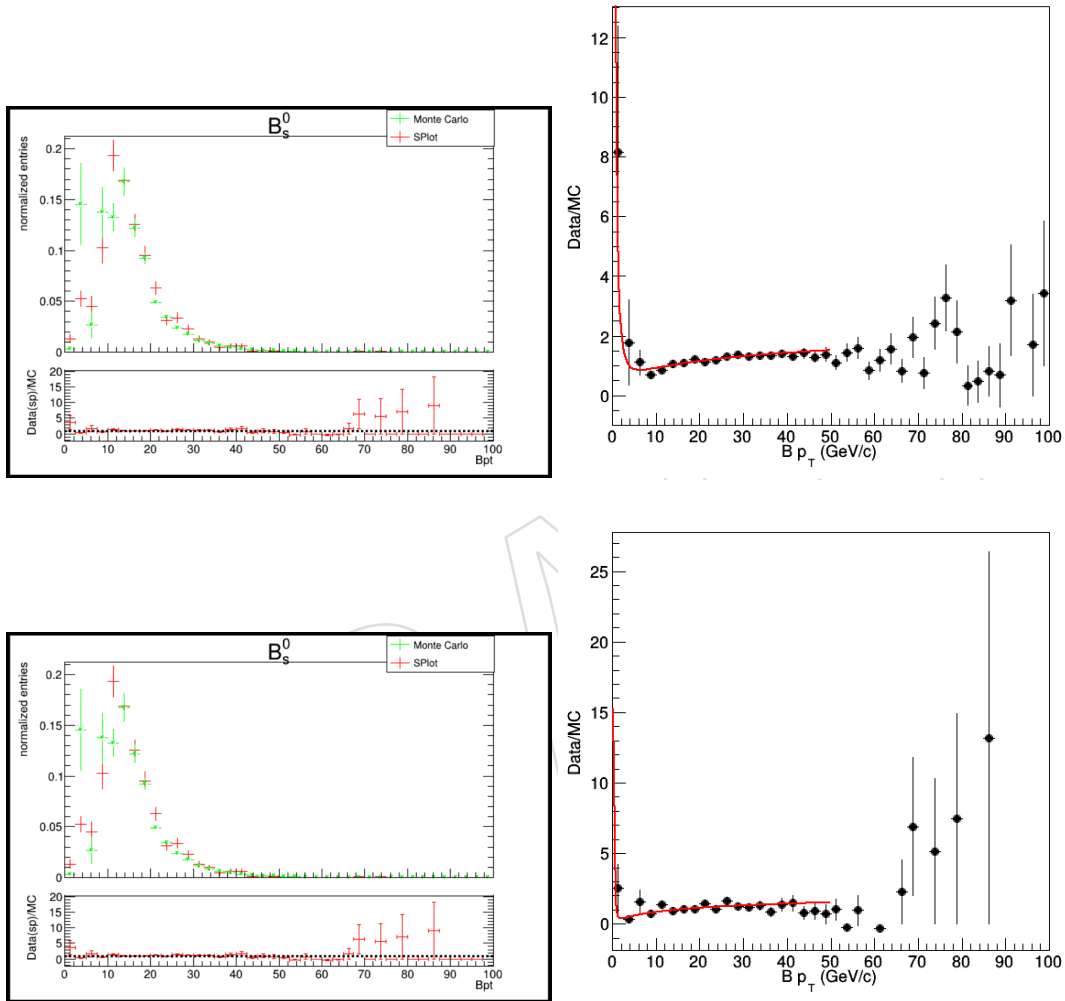


Figure 2: The MC-Data agreement between the signal raw yield in data (red) and MC (green) as a function of B meson  $p_T$  for  $B^+$  (up) and  $B_s^0$  (down). We fit the ratio with the function:  $y = p_0/x^2 + p_1 \log(x) + p_2$ . We will apply this function to the efficiency correct to obtain the systematic uncertainties due to the B  $p_T$  shapes.

In addition to above pt shape and centrality reweighting, there must be a primary vertex z position (PVz) reweighting. It is known there will be some non-trivial disagreement on the primary vertex between data and MC simulated with PYTHIA 8. Also, the offsets between data and MC in the X and Y directions are observed in the 2017 pp collisions. A Gaussian fit is applied to both the data and MC PVz distributions, as showed in Fig. 3. The blue markers represent the distribution points for data (left) and MC (middle), while the red lines represents the Gaussian fit results. Add table with fit results Then, the ratio between the two fit results is taken as the weighting function. Finally, we use the ratio function of reweigh the MC and plot the reweighted MC along with the data on the right window. The result after this weighting can be found in Fig. 3 for  $B^+$  (up) and  $B_s^0$  (down). The Gaussian fit results are given by:

Table 3: Summary of fitting parameters for the Gaussian functions ( $y = Ne^{-\frac{1}{2}\sigma^2}$ ) of  $B^+$  and  $B_s^0$

Gaussian Fitting Parameters	N	$\mu$	$\sigma$
$B^+$ Data	0.0132	0.7538	6.024
$B^+$ MC	0.0137	0.6197	5.813
$B_s^0$ Data	0.0132	0.7539	6.024
$B_s^0$ MC	0.0137	0.6205	5.815

But note that this analysis is not sensitive to the absolute value of the PV position because the reconstruction of the  $B_s^0$  meson rely only on the relative distance between PV and  $B_s^0$  reconstructed vertex which is presented in the following section.

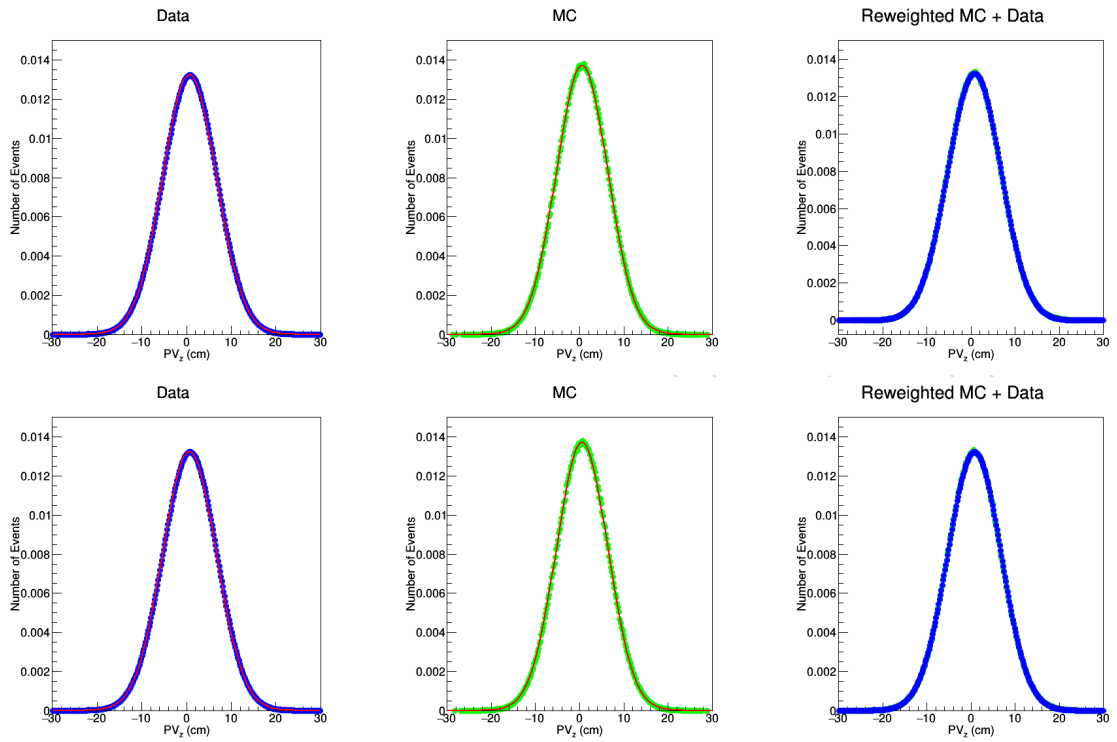


Figure 3: On the left,  $B_s^0$  primary vertex z position (PVz) spectrum obtained in pp data (green marker), fitted with a gaussian function (red line). On the middle, the same but for the MC simulations. On the right is the MC and data after reweighting the MC to data with ratio of data-to-MC Gaussian Fits.

174 In this case, we can see that there is no need to reweight PVz due to the excellent data MC  
175 agreement.

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### 3 $B^+$ meson reconstruction

In this section, the  $B^+$  and  $B_s^0$  mesons reconstruction strategy are presented. The schematic diagram of the workflow is shown in Fig. 4, starting from muons and tracks to  $B^+$  meson candidates. Muon candidates and tracks are required to pass several quality selection criteria as described in Section 3.1 and Section 3.2.  $J/\psi$  candidates are reconstructed by vertexing muon pairs with opposite charge, using KinematicConstrainedVertexFitter. The  $B^+$  candidates are built by combining the  $J/\psi$  candidates with each of the selected tracks. Finally, a kinematic fit to the  $J/\psi$ - $K^+$  system is performed, forcing the mass of dimuon pair to be equal to the nominal  $J/\psi$  mass based on PDG [? ]. The selection criteria of the  $B^+$  candidates are described in Section 4.

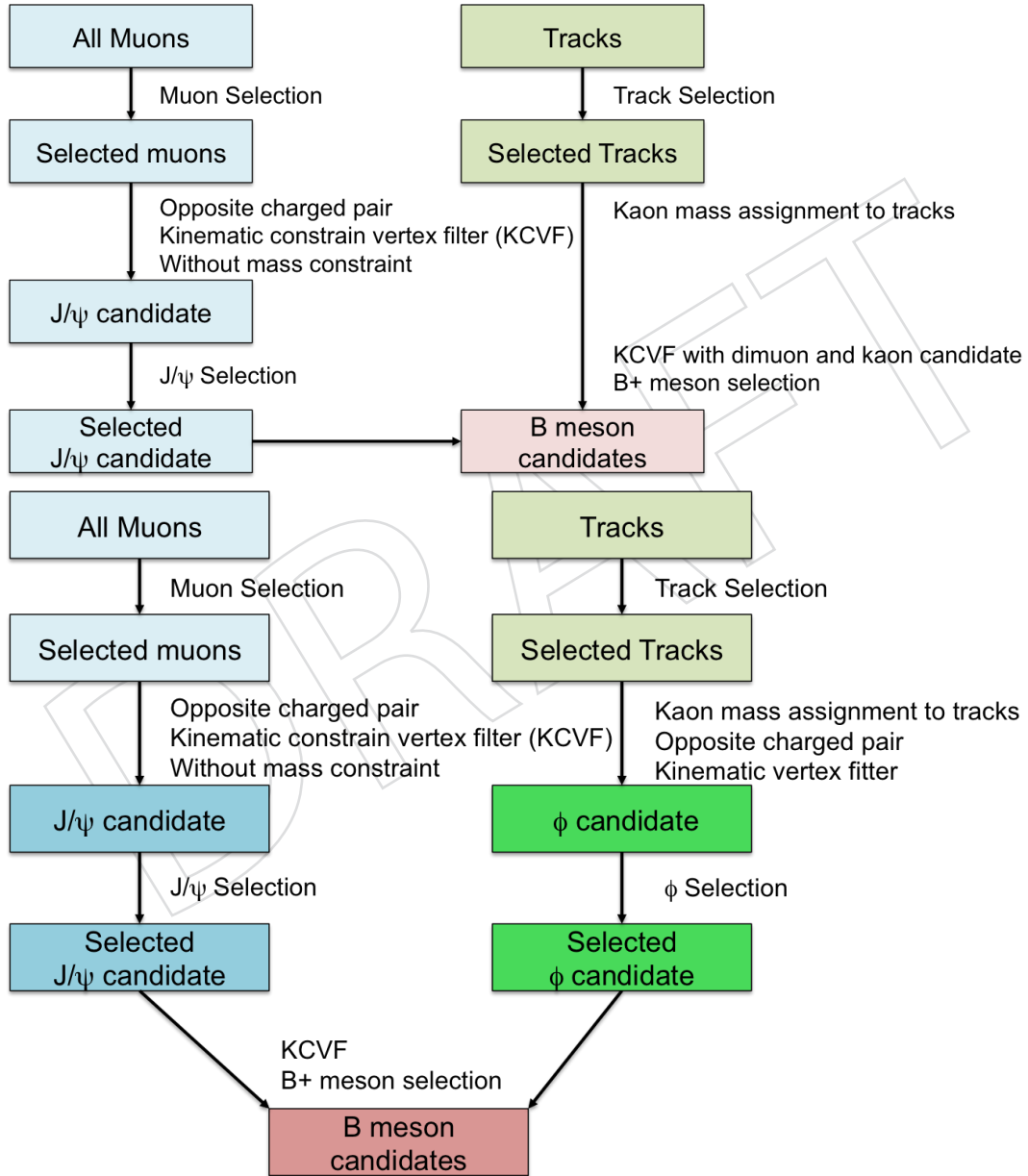


Figure 4: Schematic diagrams of the  $B^+$  meson (top) and  $B_s^0$  reconstruction workflows

### 3.1 Muon and $J/\psi$ selection

The muon candidates are selected according to the *hybrid-soft muon selection*, developed for the muon analyses on the 2017 5.02 TeV data analyses [? ]. It is adapted from the soft-muon ID developed in the BPH group, with two modifications: a) the purity selection is removed, and b) the muon is required to be also global. The *hybrid-soft muon selection* includes the following cuts:

- *isGlobalMuon* and *isTrackerMuon*;
- *isGoodMuon*  $> 0$ ;
- transverse impact parameter  $D_{xy} < 0.3$ ;
- longitudinal impact parameter  $D_z < 20$ ;
- *nPixWMea*  $> 0$  and *nTrkWMea*  $> 5$  (*nPixWMea* and *nTrkWMea* are the number of pixel layers and strips, with valid hits, crossed by a single muon track)

Muons are also requested to fulfill the following acceptance selections:

$$\begin{aligned} p_T^\mu &> 3.5 \text{ GeV}/c && \text{for } |\eta^\mu| < 1.2 \\ p_T^\mu &> (5.77 - 1.89 \times |\eta^\mu|) \text{ GeV}/c && \text{for } 1.2 \leq |\eta^\mu| < 2.1 \\ p_T^\mu &> 1.8 \text{ GeV}/c && \text{for } 2.1 \leq |\eta^\mu| < 2.4 \end{aligned} \quad (1)$$

Muons are required to match specific trigger of the following:

- *Path: HLT\_HLT\_HIL1DoubleMu0\_v1*;
- *Last filter: hltL3f0L3Mu0L2Mu0DR3p5FilteredNHitQ10M1to5 > 0*.

This single muon selection is chosen in order to guarantee a reasonable (above  $\approx 10\%$ ) reconstruction and trigger efficiency for all the selected muons.

In addition to single muon quality selections, for a pair of muon candidates, the following selections are performed:

- the two muons have to have opposite sign;
- dimuon invariant mass has to be within 0.15 GeV from the PDG  $J/\psi$  mass;
- probability of the two muon tracks to originate from the same decay vertex  $> 1\%$ .

### 3.2 Track selection

Tracks were selected according to the following criteria, as recommended by the HIN tracking group:

- transverse momentum  $\text{trkPt} > 0.2$ , pseudorapidity  $|\eta| < 2.4$ ;
- relative uncertainty on the track  $p_T$ ,  $(\text{trkPtError}/\text{trkPt}) < 0.1$ ;
- sum of the numbers of Pixel and Strip hit  $> 10$ ;
- $\chi^2$  probability normalized by number of degrees of freedom and sum of the numbers of Pixel and Strip Layer hit  $> 0.18$ .

### 3.3 $J/\psi$ and $\phi$ selection

Finally, we also apply selections on the dimuon and dikaon tracks (for  $B_s^0$  only):

- $|m_{\mu\mu} - m_{J/\psi}| < 0.15 \text{ GeV}/c^2$

- $|m_{K^+K^-} - m_\phi| < 0.015 \text{ GeV}/c^2$

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## 4 $B^+$ meson selection

The selections described in the previous section (so-called prefilter) are not sufficient to distinguish signal from background, especially at low  $p_T$  range where the entire spectrum is dominated by combinatorial backgrounds which arises from random combination of muons and tracks. In order to see clear signals and reduce the uncertainties, several additional selection on the  $B^+$  decay topology were then applied. A cut optimization procedure was performed to decide the cut values. For more details, see Section 4.1.

### 4.1 Cut optimization

The goal of the optimization procedure is to maximize the statistical significance of the signals while keeping reasonably high signal efficiencies. The optimal cut that minimizes background efficiency for a specific signal efficiency is obtained by the TMVA (Toolkit for Multivariate Data Analysis with ROOT) [? ].

Boosted Decision Tree (BDT) is chosen to be the classification method in TMVA training for  $B^+$ . In addition, for comparison the CutsGA (Genetic algorithm-based rectangular cut decision) is also examined. We found that in the lowest  $p_T$  bin (5-7 GeV), the prefilter itself does not filter out background sufficiently, which limits the performance of BDT method. In order to enhance the performance, we first found the optimal rectangular cuts from CutsGA method in this  $p_T$  bin. After then we used normalized decay length (dls3D) and  $\cos\theta$  (2D angle between  $B^+$  meson displacement and  $B^+$  meson momentum in transverse plane) cuts ( $dls3D > 12.0$   $\cos\theta > 0.95$ ; this is slightly looser than the optimal rectangular cuts, in order not to reject possible signals that BDT can reconstruct but CutsGA cannot) in our prefilter for BDT training. This enhanced the raw yield extraction and reduced the yield error. We also applied this strategy to the  $p_T$  7-10 GeV/c bin with the selection ( $dls3D > 9.0$   $\cos\theta > 0.92$ ) to enhance the performance. For other  $p_T$  bins, we just used the original prefilter for our BDT training.

The reconstructed candidates matched to the generated signal in MC sample are used as signal when training, while the reconstructed candidates in sideband ( $0.15 \text{ GeV}/c^2 < |M_{B^+} - M_{B^+}^{PDG}| < 0.25 \text{ GeV}/c^2$ ) of data sample are used as background.

The kinematic variable distributions of daughter tracks and  $B^+$  mesons before and after applying the prefilter is shown on Figure 5, 6, 7, 8





Figure 5: The normalized  $J/\psi \mu^-$  kinematic variable distributions before and after prefilter for  $p_T = 7 - 10$  GeV/c (left) and  $10 - 50$  GeV/c (right) are shown above.



Figure 6: The normalized  $J/\psi \mu^+$  kinematic variable distributions before and after prefilter for  $p_T = 7 - 10 \text{ GeV}/c$  (left) and  $10 - 50 \text{ GeV}/c$  (right) are shown above.



Figure 7: The normalized  $K^+$  track, muons, and  $K^+$  track kinematic variable distributions before and after prefilter for  $p_T = 7 - 10$  GeV/c (left) and  $10 - 50$  GeV/c (right) are shown above.

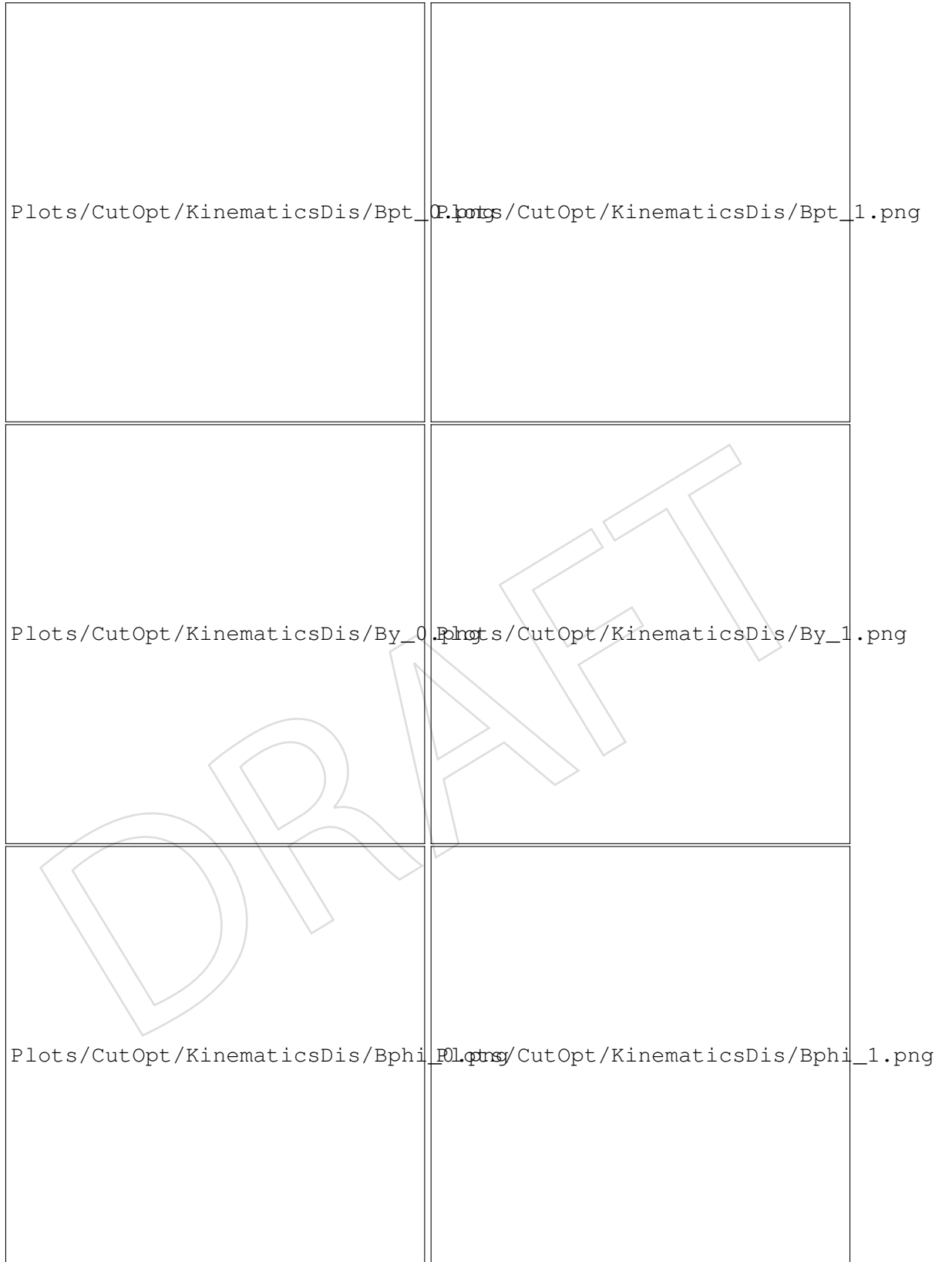


Figure 8: The normalized  $B^+$  kinematic variable distributions before and after prefilter for  $p_T = 7 - 10$  GeV/c (left) and  $10 - 50$  GeV/c (right) are shown above.

We can see that the prefilter cuts do not significantly change the distribution of the kinematic variable shapes and create potential bias. Therefore, these show that our prefilter cut is valid to use.

Then, we use the following six selection variables trained for PbPb:

- dls3D: Normalized decay length (SV PV distance), the distance between primary and  $B^+$  decay (secondary) vertex normalized by its uncertainty
- Balpha: The angle between  $B^+$  meson displacement and  $B^+$  meson momentum in 3D
- Btrk1Pt: Track  $p_T$ , the transverse momentum of the track
- Bchi2cl:  $\chi^2$  probability, the  $\chi^2$  probability of the secondary decay vertex fitting
- Btrk1Eta: The absolute value of the track pseudorapidity
- Btrk1Dxysig: Normalized track Dxy, the transverse distance between track and the primary vertex normalized by its uncertainty

The BDT training setup for all  $p_T$  bins are as follows: NTree = 850, MinNodeSize=2.5%, MaxDepth=3, BoostType=AdaBoost, AdaBoostBeta=0.5, UseBaggedBoost, BaggedSampleFraction=0.5, SeparationType=GiniIndex, nCuts=20

The optimal BDT cut values are defined as the numbers which maximize the figure of merit (statistical significance)  $S / \sqrt{S + B}$ . Here,  $S$  is the number of signal in signal region after applying optimal cuts, while  $B$  is the number of background in signal region after applying optimal cuts. Signal region is defined as  $|M_{B^+} - M_{B^+}^{PDG}| < 0.08 \text{ GeV}/c^2$ . For the lowest  $p_T$  bin, we used a new figure of merit  $S / \sqrt{\gamma_{\text{quantile}}(\alpha/2, S + B, 1)}$  (where,  $\alpha$  is chosen to be 1-0.6827) that is suitable for this low signal/background ratio.

- $S = S' \times (\text{signal optimal cut efficiency})$ , where  $S'$  is the number of signal in signal region before applying optimal cuts.
- $B = B' \times (\text{background optimal cut efficiency})$ , where  $B'$  is the number of background in signal region before applying optimal cuts.

$S'$  and  $B'$  are calculated by fitting the invariant mass plot with prefilter selection, with the same functional form used in the main analysis. However, at the 4 lowest  $p_T$  bins, the prefilter is not sufficient to reveal the signal. In those cases,  $S'$  is calculated by the expected number of signal from FONLL pp cross-section calculation multiplied by pre-filters efficiency, acceptance from MC, and expected  $R_{AA}$  value from previous measurement [? ].

Fig. 9 and Fig. 10 show the correlation matrices of the training, in the lowest and highest  $p_T$  bin, respectively.



Figure 9: TMVA training correlation matrices of PbPb in  $p_T$  5 - 7 GeV/c.



Figure 10: TMVA training correlation matrices of PbPb in  $p_T$  20 - 50 GeV/c.

283 Fig. 11 shows the overtraining check in the lowest and the highest  $p_T$  bin.  
 284



Figure 11: TMVA overtraining check of PbPb in  $p_T$  5-7 and 50 - 100 GeV/c, respectively

285 Fig. 12 shows the variable distribution comparison between signal and background, and the  
 286 statistical significance curve in  $p_T$  15-20GeV. Some variables show prominently distinct distribu-  
 287 tion between signal and background.  
 288

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Figure 12: TMVA training variable distribution of PbPb in  $p_T$  15 - 20 GeV/c.



289 The maximum significance point is selected as our nominal working point, as shown in Fig. 13.  
 290 Tab. 4 shows the summary of the optimal selection criteria in different  $p_T$  intervals.  
 291 All the other TMVA performance plots not listed in this section are on Appendix. ??.

292

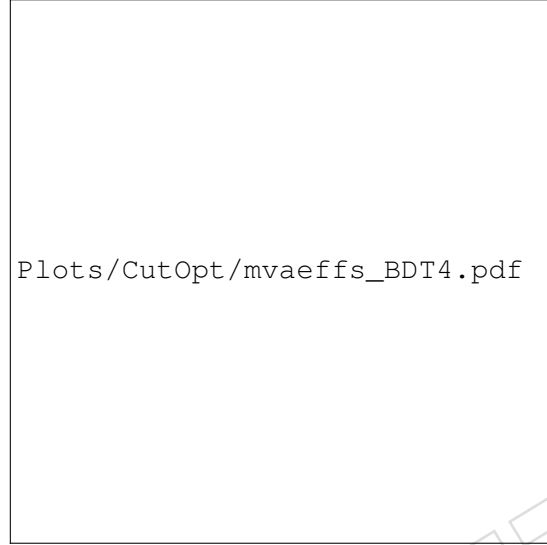


Figure 13: TMVA significance curve of PbPb in  $p_T$  15 - 20 GeV/c.

$p_T$ (GeV/c)	5-7	7-10	10-15	15-20	20-30	30-40	40-50	50-60
BDT	>0.02	>0.03	>0.09	>0.07	>0.10	>0.16	>0.20	>0.27

Table 4: Summary table of selection criteria in different  $p_T$  intervals in PbPb collisions

## 4.2 Fiducial region

As we go to low  $B^+ p_T$  where the daughter particles also have predominantly low  $p_T$ , it becomes improbable to detect muons in low rapidity ranges due to the limited acceptance of the muons. In other words, the signal and background candidates of  $B^+$  are largely confined to forward rapidity region at low  $B^+ p_T$ . Fig 14 shows theoretically possible inverse of acceptance, selection efficiency, and total efficiency vs  $B^+ p_T$  and  $|y|$  2D distribution with only single muon and track selections but without BDT selections.



Figure 14: The two dimensional maps of the inverse of the acceptance efficiency (left), selection efficiency (middle), and total efficiency (right) vs  $B^+ p_T$  and rapidity in MC for the centrality range of 0 - 90% without applying BDT cuts are shown above.

Next, we quantitatively examine the 2D maps of candidate distributions in both data and MC after applying the optimal BDT selections, which are shown in Fig. 15.

It is found that  $B^+$  acceptance is better than  $B_s^0$ , presumably because of less number of tracks needed to reconstruct B meson, which allows broader phase space that the daughter particles can reside. Since this analysis is mainly for the comparison with  $B_s^0$ , we adopted more strict fiducial region ( $5 < p_T < 10\text{GeV}$ ,  $1.5 < |y_{lab}| < 2.4$ ) that is defined using  $B_s^0$  2D map.



Figure 15:  $B^+$   $p_T$  and rapidity two dimensional map of candidates that passed the full analysis cut in data (Left) and MC (right).

## 5 MC-Data Comparison

### 5.1 B candidate properties comparison between data and MC

Potential differences between Data and MC distributions of the variables used for the selection of the  $B^+$  signal, can introduce biases in the efficiency corrections. In this section, the distributions of the  $B^+$  selection variables in PbPb data and MC samples are compared.

The Splot method is used for our analysis. This is a likelihood-based method by which we reweight the data using the unbinned fit result. The weights are added to the dataset based on model and yield extraction variables. Each event has two weights: probability of belonging to the signal given its mass, probability of belonging to the background given its mass. The Splot class gives us the distributions of our variables for a given species (signal or background). The advantage of using this method is that we use the full dataset for the comparison in contrast to the sideband subtraction method where one should select the investigation range of signal and background. Furthermore, we use likelihood to describe events' behavior in contrast to the potential misidentification of signal events in background region which might occur in sideband subtraction method. For more details on general description of Splot method applied to this analysis, please refer to the section 4 and 5 of the analysis note CMS AN-19-219( [? ]).

To show the correlations between the BDT variables to the  $B^+$  invariant mass and validate our Splot techniques approach, we first make the correlation matrices for BDT variables vs  $B^+$  invariant mass Bmass for data and MC as follows in Figure 16:

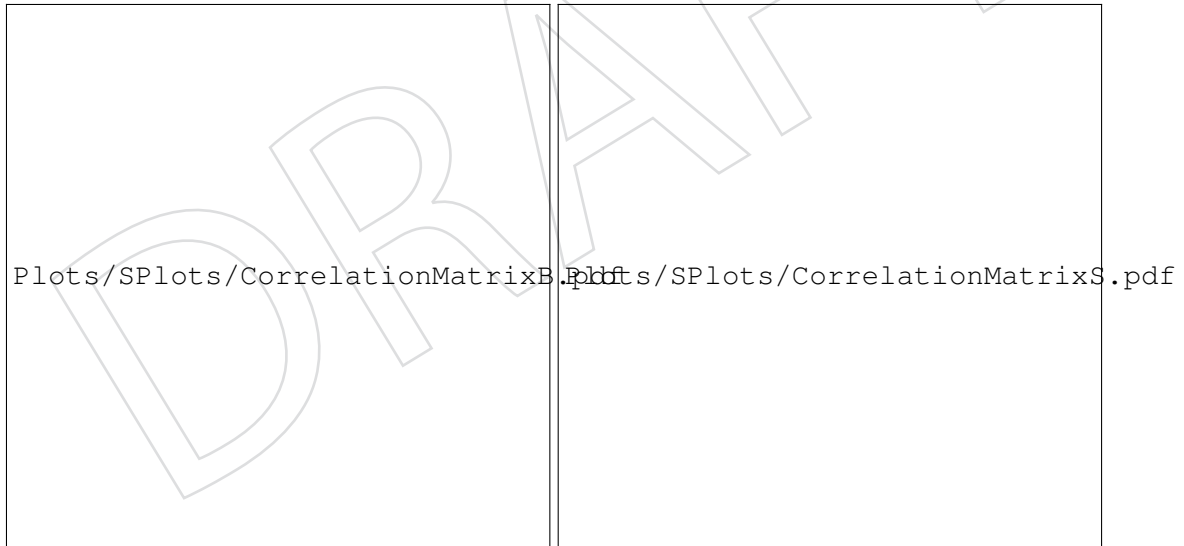
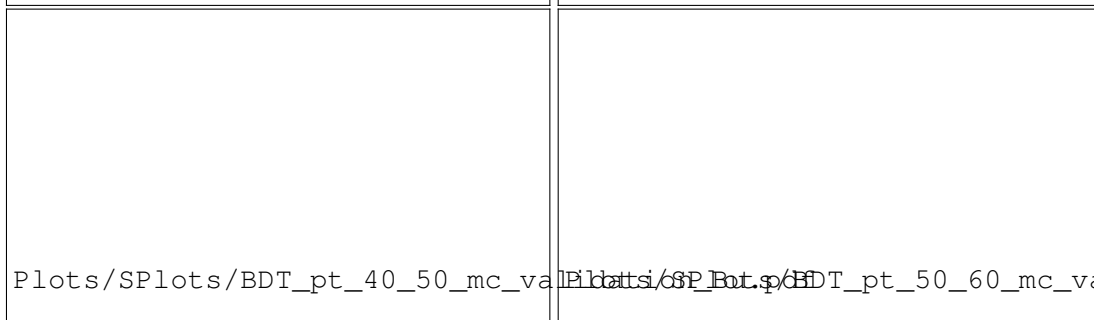
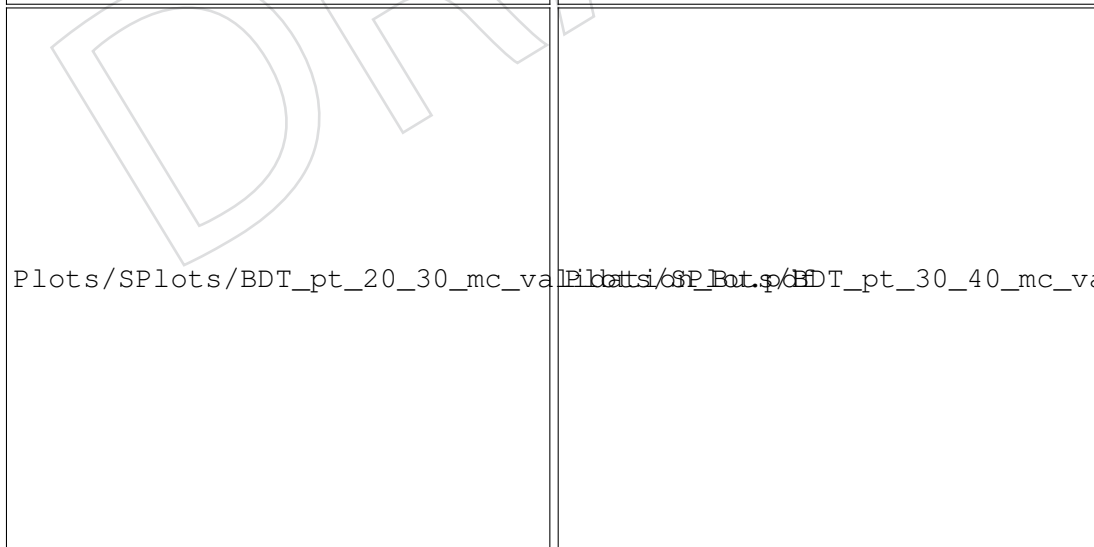
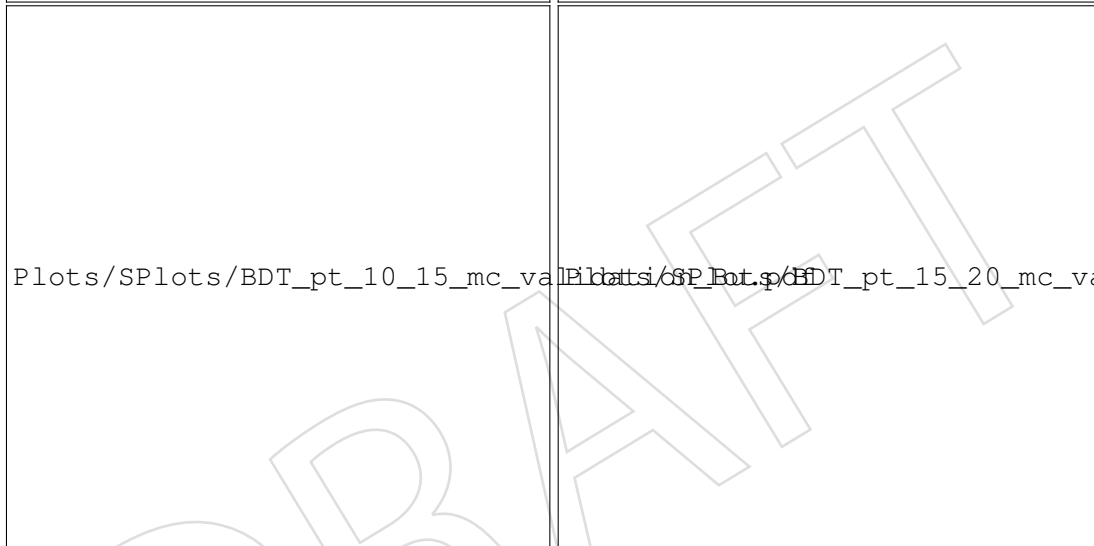
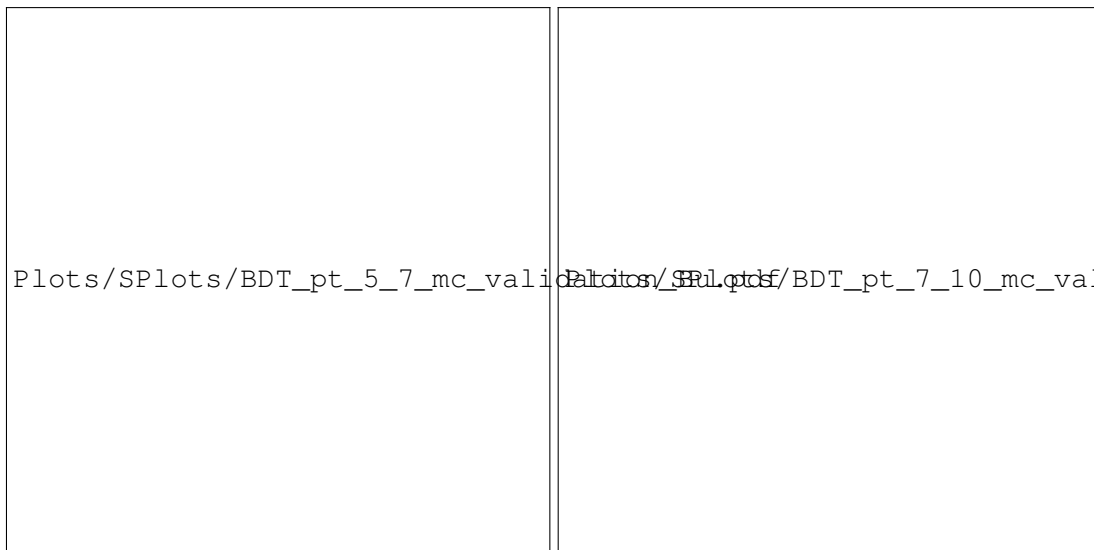


Figure 16: The correlation matrices in data (left) and MC (right) are shown above.

Fig. 17 shows the data and MC comparison results based on Splot method. Here, we focus on BDT values that are directly used in our signal extraction and related to MC distribution validation, rather than the variables themselves used in BDT training. In a wide ranges of BDT, the two distributions show good agreement. We only focus on the region where BDT is greater than the working point and is smaller than the maximum value that candidates have.



## 6 Signal Extraction

The method and the fit model for signal and background we applied are mostly the same with  $B_s$  AN. Please refer to the corresponding section in [? ].

However, there is one major difference between  $B_s$  and  $B^+$  yield extraction. From the inclusive  $J/\psi$  sample study, we have found that there is a clear and sizable contribution from non-prompt  $J/\psi$  candidates that are fed down from the  $B^+$  signal in our region of interest. We model this component with an error function and a Gaussian. The error function component mostly comes from 4-prong B meson decay (e.g.  $B^+ \rightarrow J/\psi K^*(892)^+$ ) that are partially reconstructed as  $B^+ \rightarrow J/\psi K^+$  (one track is lost) and can form peaking structures for values of the invariant mass below  $\approx 5.20 \text{ GeV}/c^2$ . The Gaussian contribution mainly comes from  $B^+ \rightarrow J/\psi \pi^+$  where pion is misidentified as kaon.

The ratio of the height of error function and the Gaussian is fixed by MC simulation. However, the Gaussian component is shown to be relatively negligible compared to the error function, and even more to the signal double Gaussian of our nominal channel. More details on the non-prompt  $J/\psi$  study can be found in Appendix Sec. A.

Note that we do not discriminate  $B^+$  from  $B^-$  in raw yield extraction process. Therefore, the invariant mass plots shown below contains both  $B^+$  and  $B^-$  signal and backgrounds. This double counting is properly canceled in the corrected yield calculation process later.

In Fig. 18 and Fig. 19, the invariant mass spectra and their pull distributions obtained in the  $p_T$  intervals in the PbPb analyses are presented.

We also make the comparison between the symmetric raw yield error and their asymmetric upper and lower yield error using the RooFit framework on the unbinned fit. The table is shown below in Table 5:

Table 5: The comparison between RooFit and unbinned fit framework.

Centrality	$p_T$ (GeV/c)	Raw Yield Error	RawYield Error Up	Raw Yield Error Down
0 - 90%	7 - 10	10.88	11.20	10.66
0 - 90%	10 - 15	20.68	21.05	20.35
0 - 90%	15 - 20	17.86	18.21	17.56
0 - 90%	20 - 50	19.84	20.19	19.55
0 - 30%	10 - 50	27.72	28.01	27.45
30 - 90%	10 - 50	19.53	19.92	19.20
0 - 90%	10 - 50	33.78	34.13	33.47



Figure 18: Invariant mass distribution of  $B^+$  candidates obtained in PbPb collisions in  $p_T$  intervals in the transverse momentum range from 7-50 GeV/c and Centrality 0-90%.



Figure 19: Invariant mass distribution of  $B^+$  candidates obtained in PbPb collisions in centrality intervals 0 - 30%, 30 - 90%, and 0 - 90% in the transverse momentum range from 10 - 50 GeV/c.



## 6.1 Closure test of the fitting procedure

In order to validate the yield extraction procedure, we generate 5000 toy MC for the fit and make the pull distribution. Then we perform the Gaussian fits to the pull distribution to obtain the mean and width. The results are shown in Fig 20 and Fig 21:



Figure 20: The pull distribution and the Gaussian fits for 0 - 90% at 7 - 10, 10 - 15, 15 - 20, 20 - 50 are shown respectfully above.

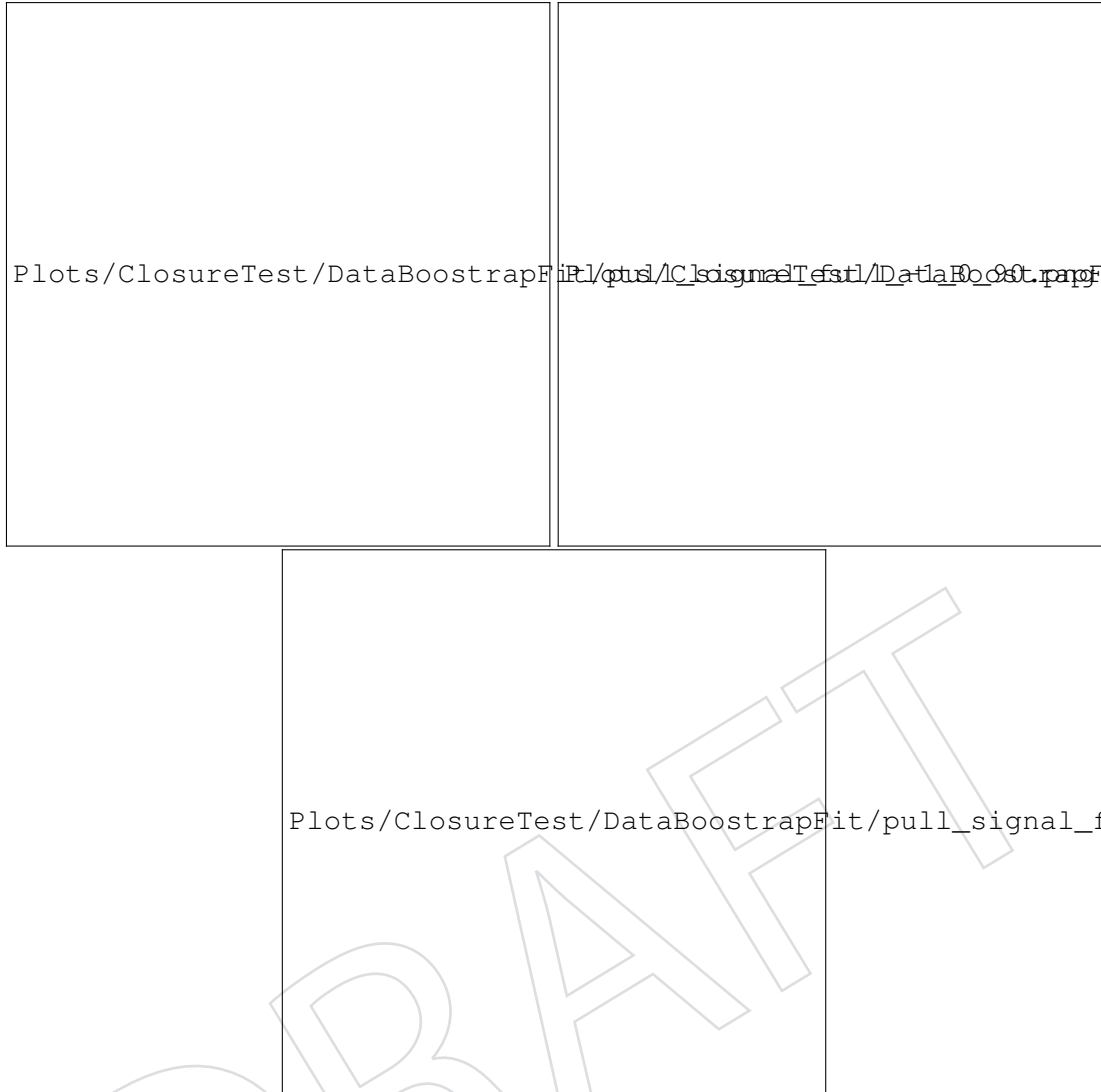


Figure 21: The pull distribution and the Gaussian fits for 0 - 90% at 7 - 10, 10 - 15, 15 - 20, 20 - 50 are shown respectfully above.

361 We can see that all  $p_T$  and centrality bins have zero mean and unit width from the Gaussian fits  
 362 to the pull distribution. This validate the closure of our fits to extract the  $B^+$  raw yield.

## 363 7 Acceptance and Efficiency

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364 **8 Closure Test of the  $B^+$  Corrected Yield**

365 **8.1 Raw Yield Closure**

366 **8.2 Efficiency Closure**

367 **8.3 Corrected Yield Closure**

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## 9 Results

### 9.1 $p_T$ differential corrected yield in pp collisions at 5.02 TeV

The method we applied is the same with  $B_s$  AN [? ].

In Fig. 22, Number of MinBias events-normalized, TAA-normalized, efficiency-corrected and  $p_T$ -width divided yield (let's call this "normalized corrected yield") of  $B^+$  mesons in the centrality 0-90% and rapidity region  $|y_{lab}| < 2.4$  (Caveat: Note the fiducial region  $1.5 < |y_{lab}| < 2.4$  in  $B^+$   $p_T$  7 - 10GeV/c) in PbPb collisions at  $\sqrt{s} = 5.02$  TeV is presented. The boxes around the data points represent the total systematic uncertainties.



Figure 22:  $B^+$  normalized corrected yield vs.  $p_T$  in the inclusive centrality range 0-90%. (Left)  $B^+$  analysis  $p_T$  bin (Right)  $B_s^0$  analysis  $p_T$  bin. Note the fiducial region  $p_T$  5-10GeV and  $1.5 < |y_{lab}| < 2.4$

In addition, we provide the normalized corrected yield for inclusive  $p_T$  10-50 GeV/c in 0 - 30%, 30 - 90%, and 0 -90% centrality bins in Fig. 23.

The normalized corrected yields and their uncertainties for various kinematic ranges are summarized in Table. 6 and Table. 7. For more details on systematic uncertainties, see Section. 10.

Table 6:  $B^+$  normalized corrected yields and the uncertainties in various  $p_T$  ranges within centrality 0-90%. All the corrected yield values are in units of pb\*c/GeV. Note that the global uncertainties are not included here on this table, which are sub 4% level. Note also the fiducial region  $p_T$  5-10GeV and  $1.5 < |y_{lab}| < 2.4$  and the same as the  $B_s$   $p_T$  binning is reported.

$p_T$ (GeV/c)	Center (GeV/c)	Corr. yield (pb GeV <sup>-1</sup> c)	Stat. up	Stat. down	Syst. up	Syst. down
(7,10)	8.73	331984	15.8%	15.1%	13.6%	13.6%
(10,15)	12.4	298062	7.60%	8.77%	19.1%	19.1%
(15,20)	17.2	66567.7	6.54%	6.66%	7.51%	7.51%
(20,50)	27.3	7730.12	6.64%	5.49%	6.02%	6.02%

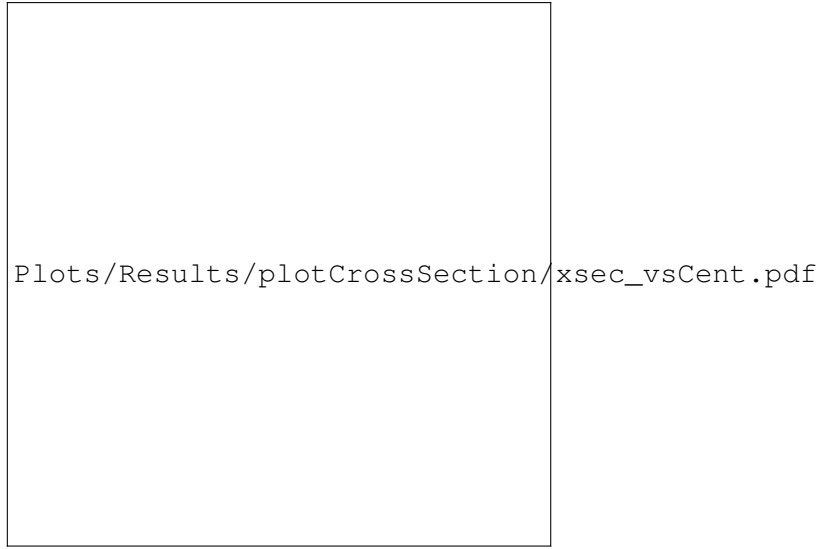


Figure 23:  $B^+$  normalized corrected yield vs.  $\langle N_{part} \rangle$  in inclusive  $p_T$ . 10-50 GeV is shown above.

Table 7: Summary table of  $B^+$  corrected yield for different centrality bins

Centrality	Corr. yield (pb)	stat. up (+)	stat. down (-)	syst. up (+)	syst. down (-)
0% - 30%	1918800	5.81%	5.54%	16.6%	16.6%
30% - 90%	2481820	8.22%	6.97%	13.6%	13.6%
0 - 90%	2092040	5.06%	4.54%	15.2%	15.2%

## 9.2 Rapidity differential corrected yield in pp collisions at 5.02 TeV

## 9.3 Multiplicity differential corrected yield in pp collisions at 5.02 TeV

## 9.4 $B_s^0/B^+$ ratio as a function of $p_T$ in pp collisions at 5.02 TeV

## 9.5 $B_s^0/B^+$ ratio as a function of $y$ in pp collisions at 5.02 TeV

## 9.6 $B_s^0/B^+$ ratio as a function of Multiplicity in pp collisions at 5.02 TeV

## 9.7 B-meson $R_{AA}$ vs $p_T$ at 5.02 TeV

## 9.8 B-meson $R_{AA}$ vs $y$ at 5.02 TeV

## 9.9 B-meson $R_{AA}$ vs Multiplicity at 5.02 TeV

## 10 Systematic uncertainties

### 10.1 Summary table

Below are the summary tables of various systematic uncertainties. For detailed description of each systematics source, please refer to the subsequent subsections.

Table 8: Summary of systematic uncertainties from each factor in  $B^+$  PbPb analysis for corrected yield vs  $p_T$ . All the values are shown in percentage.

Factors	(7,10)	(10,15)	(15,20)	(20,50)
Hadron tracking efficiency	5%	5%	5%	5%
Data-MC Discrepancy	4.17%	15.25%	3.01%	1.65%
$p_T$ shape	0.162%	0.211%	0.010%	0.008%
PDF variation background	4.46%	2.67%	2.74%	2.36%
PDF variation signal	0.117%	0.546%	0.576%	1.03%
TnP Systematics	6.12%	9.36%	3.28%	0.34%
MC stat.	9.22%	3.36%	1.92%	1.35%
Total	13.59%	19.08%	7.51%	6.02%
$N_{MB}$ events	1.26%	1.26%	1.26%	1.26%
$T_{AA}$	2.2%	2.2%	2.2%	2.2%
Branching fractions	2.9%	2.9%	2.9%	2.9%
Global Systematics	3.85%	3.85%	3.85%	3.85%

Table 9: Summary of systematic uncertainties from each factor in  $B^+$  PbPb analysis for corrected yield vs centrality. All the values are shown in percentage.

Factors	0 - 30 %	30 % - 90%	0 - 90 %
Hadron tracking efficiency	5%	5%	5%
Data-MC Discrepancy	13.28%	8.49%	11.51%
$p_T$ shape	0.170%	0.106%	0.154%
PDF variation background	0.412%	1.13%	0.427%
PDF variation signal	2.50%	2.57%	2.60%
TnP Systematics	7.20%	7.85%	7.43%
MC stat.	3.37%	2.26%	2.49%
$T_{AA}$	2.0%	3.6%	2.2%
$N_{MB}$ events	1.26%	1.26%	1.26%
Total	16.63%	13.65%	15.24%
Branching fractions	2.92%	2.92%	2.92%
Global Systematics +)	2.92%	2.92%	2.92%
Global Systematics -)	2.92%	2.92%	2.92%

We also plot the summary plots for the table as follows in Fig 24

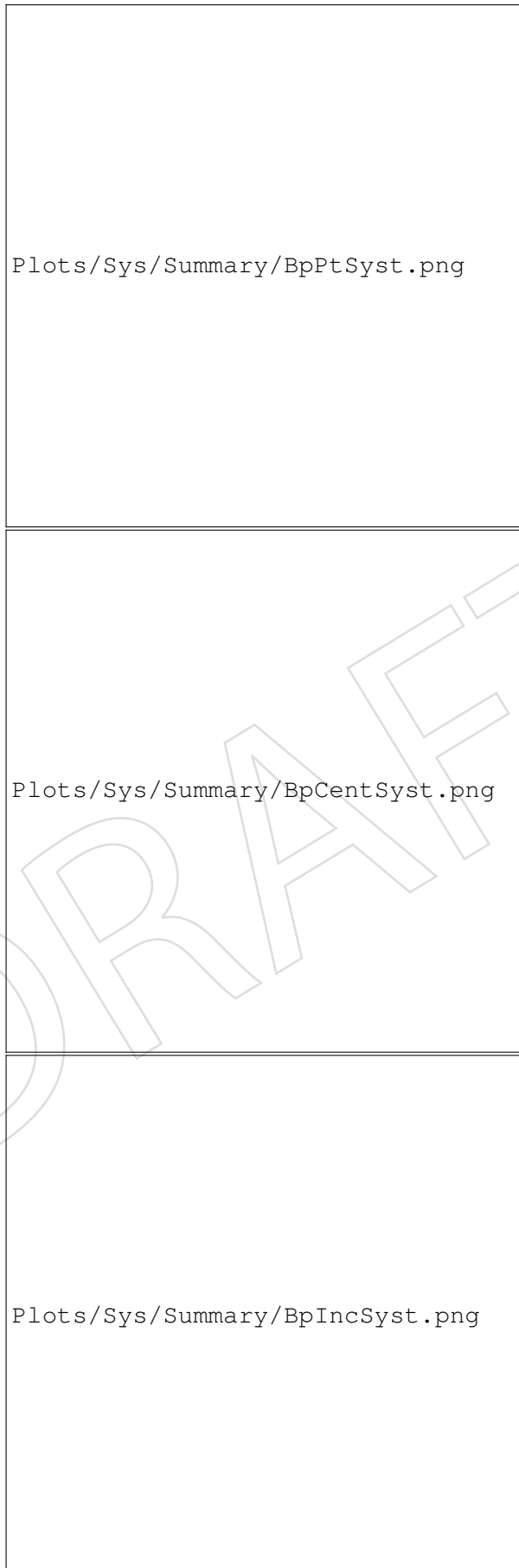


Figure 24: The plots summarizing the systematic uncertainties for  $p_T$  bins and centrality bins are shown above.



## 10.2 $T_{AA}$ and $N_{MB}$

We use the same uncertainties for  $T_{AA}$  (Nuclear overlap function) and  $N_{MB}$  (Number of Min-Bias events) listed on the  $B_s$  AN [? ].

## 10.3 Branching ratio

The systematic uncertainty on the branching ratio of the decay  $B^+ \rightarrow J/\psi K^+$ , with  $J/\psi \rightarrow \mu^+ \mu^-$ , is calculated by adding in quadrature the uncertainties on each sub-channel. The resulting uncertainty for the full decay chain is 2.8% [? ]. This is global to all  $p_T$  and centrality selections in our analysis.

## 10.4 Tracking efficiency

The current standard value of tracking efficiency uncertainty for one track is 5% for now, suggested in the link <https://twiki.cern.ch/twiki/bin/viewauth/CMS/HITracking2018PbPb>. This is global to all  $p_T$  and centrality selections in our analysis. This number may be updated later.

## 10.5 Muon efficiency: Tag and Probe

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408 The difference between the nominal and varied values are quoted as our systematics, and they  
 409 are shown in Figure 25 and Figure 26 and Table. 8 and Table. 9.



Figure 25: The upper bound and lower bound systematic uncertainties in  $\langle \frac{1}{\alpha \times \epsilon} \rangle$  vs  $p_T$  with total tag and probe correction are shown above.



Figure 26: The upper bound and lower bound systematic uncertainties in  $\langle \frac{1}{\alpha \times \epsilon} \rangle$  vs  $p_T$  with total tag and probe correction are shown above.

410 According to the studies, we calculate the systematic uncertainties due to tag and probe scale  
 411 factor. Table ?? and table ?? summarize the tag and probe systematic uncertainties results for  
 412  $p_T$  and centrality from our studies

413 However, according to the Muon POG, due to the issues in the trigger tag and probe scale  
 414 factor, we have also conduct the difference between the efficiencies with and without any tag  
 415 and probe scale factor correction applied. Our results for  $p_T$  and centrality are shown in Figure  
 416 ??:

417 The final summary of tag and probe systematic results are shown on Table ?? and ??.

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418 **10.6 MC-Data Discrepancy**

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## 10.7 $p_T$ shape: Bpt weight

The potential difference in  $p_T$  distributions in data and MC entails difference in calculation of efficiency correction. The  $B^+$   $p_T$  distributions of MC can be modified by Bpt weight (shown in 2.3.1) to have closer distribution with data. The Exponential and Polynomial weight function are given by:

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424 We quote the percentage deviation of B  $p_T$  weighted efficiency correction factor  $\langle 1/(acc \times eff) \rangle$   
 425 from the nominal without B  $p_T$  weight as the systematic uncertainties. Table. ?? and Table. ??  
 426 show the systematics for differential  $p_T$  and inclusive  $p_T$ , respectively. Fig. ?? and Fig. ?? shows  
 427 the comparison plots for differential  $p_T$  and inclusive  $p_T$ , respectively. Note that the systematics  
 428 are very small, thus the differences may not be distinguished prominently on the plots.

429 We can see that the  $p_T$  shape systematic uncertainties on the efficiency correction have been  
 430 reduced to negligible using the  $\langle \frac{1}{a \times e} \rangle$  approach.

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## 10.8 MC stats: Toy MC study

The statistical uncertainties of  $\langle \frac{1}{\alpha \times \epsilon} \rangle$  in MC are examined by toy MC study. From the nominal 2D map, we generated 10000 toy MCs for each rapidity  $p_T$  bin. The toy 2D maps are then propagated to the  $\langle \frac{1}{\alpha \times \epsilon} \rangle$  data-average calculation. The distribution of data-averages are drawn in each analysis  $p_T$  and centrality bin, and the RMS deviation of the distribution (supposedly Gaussian) is compared to the nominal value. The ratio between RMS and the nominal value is quoted as systematics related to MC stats.

Table. ?? and Table. ?? shows the systematics for differential  $p_T$  and inclusive  $p_T$ , respectively. Fig. ?? and Fig. ?? shows the toy MC  $1/(\text{acceptance} \times \text{efficiency})$  distributions for differential  $p_T$  and inclusive  $p_T$ , respectively. The blue markers are toy MC distribution, the red lines are the nominal correction factors in the main analysis.

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## 10.9 Signal extraction: PDF variation

Here we quote the numbers. For plots with more details, see Appendix. ??.

As discussed in detail in Sec. 6, the central value of the raw yields were extracted using a fit function of Double Gaussian signal and exponential combinatorial background. The non-prompt component was modeled with an error function and a Gaussian peak. The systematic uncertainty on the signal extraction was evaluated by varying the functions used to model the various components:

- Model the signal with a triple Gaussian function.
- Release the constraint on the width of the signal double Gaussian (fixed in the default fit to the MC extracted values). In this case, a scaling factor ( $a$ ) between the MC widths is left as a free parameter in order to account for possible differences between the resolution in data and MC.
- Fixed the mean of the signal double Gaussian.
- Consider 1st, 2nd, and 3rd order polynomial for combinatorial background.

The detailed description on the release of the constraints on the widths of the signal double Gaussian is as follows. The full signal model used in the fit to data is:

$$\alpha \frac{1}{a\sigma_1\sqrt{2\pi}} e^{-\frac{1}{2} \frac{(B_{mass}-\mu)^2}{(a\sigma_1)^2}} + (1-\alpha) \frac{1}{a\sigma_2\sqrt{2\pi}} e^{-\frac{1}{2} \frac{(B_{mass}-\mu)^2}{(a\sigma_2)^2}}, \quad (2)$$

where  $a$  is the resolution scaling factor (the same for both gaussians) which describes the possible discrepancy between data and MC fit,  $\alpha$  is the relative proportion between the gaussians,  $\sigma_1$  and  $\sigma_2$  are the Gaussians' widths that are directly derived from MC fit, and  $\mu$  is the mean shared by both Gaussians.

In order to examine the potential systematic difference in data and MC signal fit, we are required to define a moderate variation range of the scaling factor in order not to introduce statistical fluctuations in our estimation. To achieve this, we first performed fit by letting the scaling factor float around in individual  $p_T$  bins and inclusive  $p_T$  bin (Figure ??). The parameter values from the best fit are summarised in Table ??.

We observed that in several individual  $p_T$  bins, the deviations from unity (value for nominal fit) are sizable. In mid  $p_T$  bins (10-15-20-30 GeV) where statistics are comparably large, the deviations are small. Whereas in low  $p_T$  bins (5-7-10 GeV) and high  $p_T$  bins (30-40-50-60 GeV) where statistics are small, the deviations are relatively large. On the other hand, the optimal scaling factors of individual  $p_T$  bins agree with that of inclusive  $p_T$  bin within a significance of  $2\sigma$ . From this observation, the sizable differences can be considered to mainly come from statistical limitation of each small  $p_T$  ranges. In addition, the  $2\sigma$  difference can be considered to be the statistical uncertainties of scaling factors of individual  $p_T$  bins.

To conclude, we can claim that the scaling factor of the inclusive  $p_T$  ( $a = 1.09 \pm 0.04$ ) is a representative of the scaling factor for all  $p_T$  bins. Since that factor is a optimal fit parameter, we can take 10% variation from the nominal value (unity) as our signal PDF variation range where the fits are good enough and has reasonably low statistical uncertainties, which is desirable for systematic uncertainties estimation. Here we used jargons increased and decreased width which refers to  $a = 1.1$  and  $0.9$ , respectively.



## A Non-prompt $J/\psi$ background

In the  $B^+$  invariant mass spectrum, there are potential background feed-down sources coming from other B meson decays that can form peaking structures in the region of interest, and need to be properly subtracted in order not to bias the yield extraction procedure. In order to estimate these components, we processed the inclusive B meson MC sample with the nominal  $B^+$  channel workflow, and vetoed the candidates that are matched to a genuine  $B^+$  signal. The resulting B candidate mass spectrum in the inclusive  $p_T$  range (5-100 GeV/c) is shown in Fig. 27 for PbPb MC samples.

It is clear that these sources create a peaking structure in the region of  $M_{\text{inv}} < 5.20 \text{ GeV}/c^2$ . This structure can be nicely fit with an error function as done previously in B proton-proton analyses [? ]. In addition, there is a minor peak on the right shoulder ( $\approx 5.34 \text{ GeV}/c^2$ ) of the nominal signal ( $\approx 5.28 \text{ GeV}/c^2$ ), and this can be fit with an Gaussian function. There is additional combinatorial background which is fitted with a linear function. This contribution is absorbed in the total combinatorial background of our nominal channel of the main analysis. As described in details in Sec. 6, the shape of the Non-prompt function is used as template in the fit extraction procedure.

Further MC studies were done in order to identify the different channels that give rise to the non-prompt peaking structure in the  $B^+$  invariant mass spectrum. Few main processes were identified:

- 4-body  $B^+$  decays which occur via resonant decay channels e.g.  $B^+ \rightarrow J/\psi K^*(892)^+$ . In these cases, we distinguish the kaons coming from the  $K^*(892)^+$  decays as coming from a signal  $B^+ \rightarrow J/\psi K^+$  decay.
- 4-body  $B^0$  decays channels e.g.  $B^0 \rightarrow J/\psi K^*(892)^0$ .
- $B^+ \rightarrow J/\psi \pi^+$  decays in which we misidentified the  $\pi^+$  as a  $K^+$ .

The different contributions in PbPb are presented in Fig. 28. The contribution from  $B^+ \rightarrow J/\psi \pi$  clearly form a peaking structure on the right shoulder of the nominal decay channel  $B^+ \rightarrow J/\psi K^+$ . However, the overall magnitude of this component is tiny compared to the other two sources, and negligible compared to the nominal signal. As a consequence, we can barely see the contribution of this peaking structure in the invariant mass plot of  $B^+$  nominal channel.



Figure 27:  $B^+$  candidate mass spectrum obtained in inclusive B meson MC production after vetoing the contribution of genuine  $B^+$  signal candidates in PbPb.

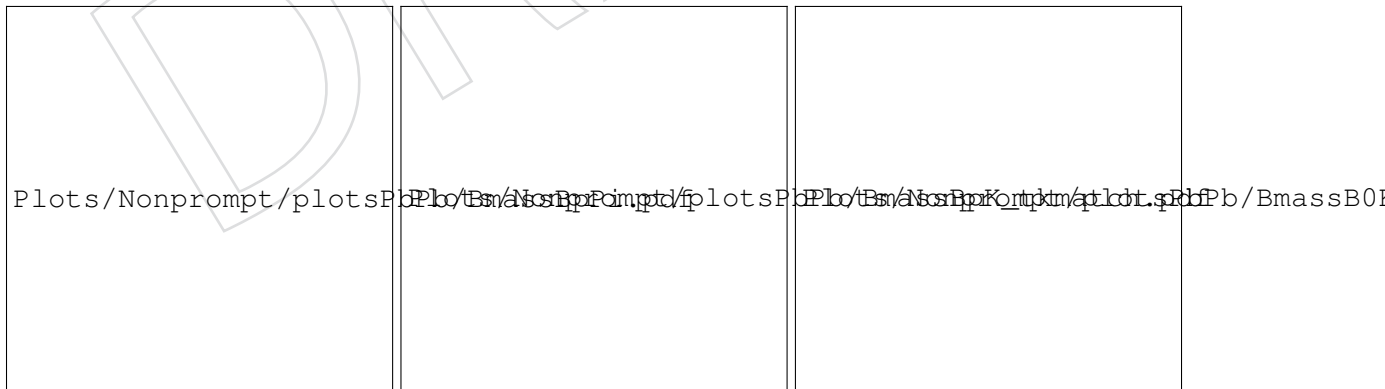


Figure 28: Peaking background contribution from  $B^+ \rightarrow J/\psi \pi$  and from K resonant decay channels of  $B^0$  and  $B^+$  in PbPb MC.

509 **Acknowledgments**

510 **References**

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