Studies of heavy quark dynamics using B mesons with the CMS detector

HP 2023

Tzu-An Sheng
for the CMS Collaboration

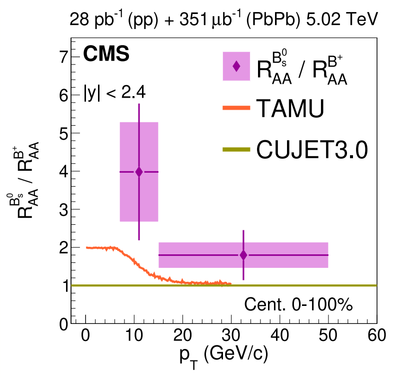
PLB 829 (2022) 137062
PRL 128 (2022) 252301

Mar. 30 2023

Introduction

B_s^0/B^+ ratio: strangeness enhancement

Double ratio, 2015 data



- Enhanced strangeness predicted for $p_T < 15$ GeV in deconfined medium
  [Phys.Lett.B 595 (2004) 202-208, Phys.Lett.B 735 (2014) 445-450]
- Heavy b, c quarks produced at initial hard scattering, recombining with nearby constituent quarks into hadrons
- This talk: 2018 data, 3 times more statistics compared to 2015 B^+ and B_s^0 samples

B^+: PRL 119, 152301
B_s^0: PLB 796 (2019) 168

B_c^+: a bridge between charmonia and bottomonia

- Quarkonia: Recombination of heavy quarks in QGP at low p_T
  - Sequential melting w.r.t binding energies: QGP thermometer Phys.Rev.C 63 (2001) 054905
- Intermediate binding energy of B_c^+
  - 0.64 GeV (J/ψ) < 0.87 GeV (B_c^+) < 1.10 GeV $(\Upsilon(2S))$
  - Sensitive to dissociation + recombination
- Recombination process of b with an uncorrelated c in QGP
  - May be more prominent than J/ψ due to its small cross section

B_s^0/B^+ analysis

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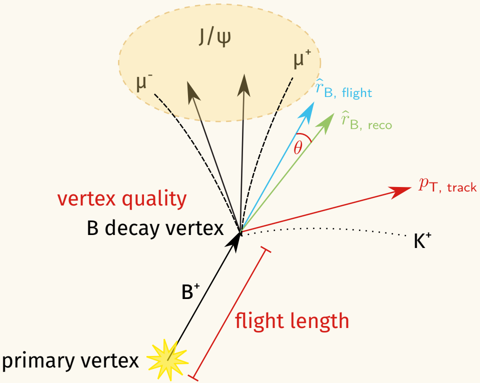
B_s^0 / B^+ event selection



$B^+ \to J/\psi K^+ \to \mu^- \mu^+ K^+$

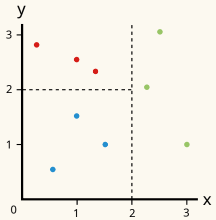
$B_s^0 \to J/\psi \phi(1020) \to \mu^- \mu^+ K^+ K^-$

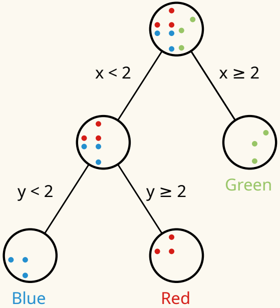
- Long-lived B mesons
  → large flight length
- Angle between B flight direction and PV-SV displacement
  $\cos\theta = \hat{r}_{\text{B, flight}} \cdot \hat{p}_{\text{T, RECO}}$
  Expect $\hat{p}_{\text{T, RECO}} \parallel \hat{r}_{\text{B, flight}}$
- χ^2 Probability of the decay vertex
- p_{T} of the daughter tracks

- Additionally for B_s^0: $m_{K^+K^-} - m_{\phi,\text{PDG}}$

Cut optimization

- Maximize the discriminating power by training a machine learning algorithm in the multi-dimensional parameter space.
- Boosted Decision Tree (BDT):
  - Select on each variable sequentially in a tree structure
  - Train many weak classifiers with subsets of randomly selected samples, emphasizing the misclassified events





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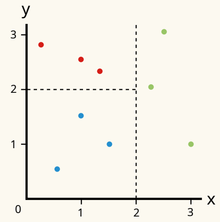
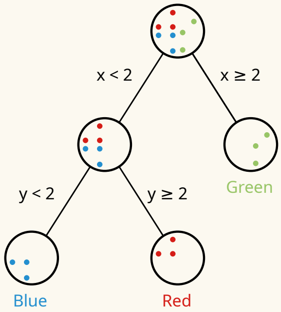
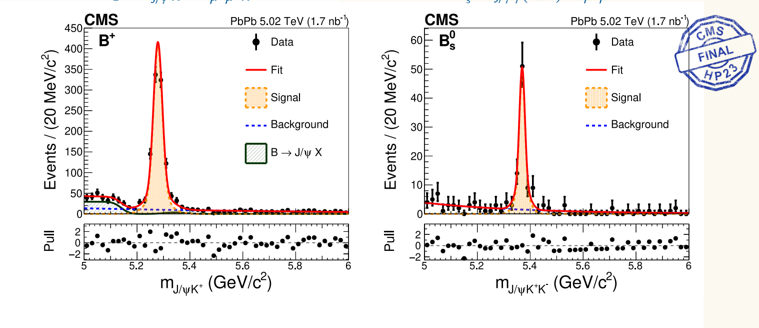




- Training samples: signal MC vs side-band data

B_s^0 / B^+ Yield extraction

$B^+ \to J/\psi K^+ \to \mu^- \mu^+ K^+$ $\quad$ $B_s^0 \to J/\psi \phi(1020) \to \mu^- \mu^+ K^+ K^-$



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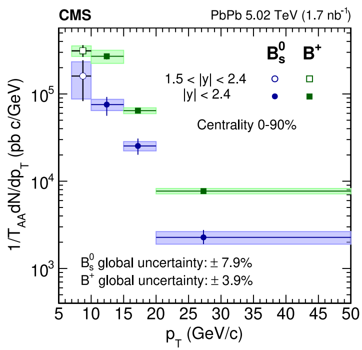
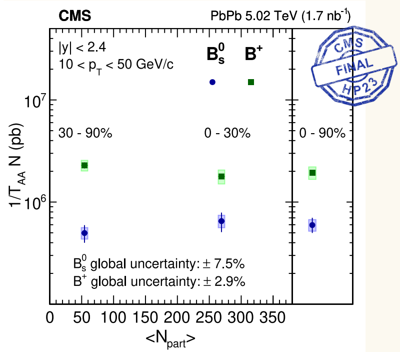
- First 5σ+ observation of B_s^0 in PbPb collision
- B^+ (semi) peaking background:
  - Partially reconstructed B decay (e.g. $B^0 \to J/\psi(K^* \to K^+\pi^-)$)
  - misidentified π in $B^+ \to J/\psi \pi^+$

B_s^0 and B^+ cross sections

yield vs p_T



yield vs centrality



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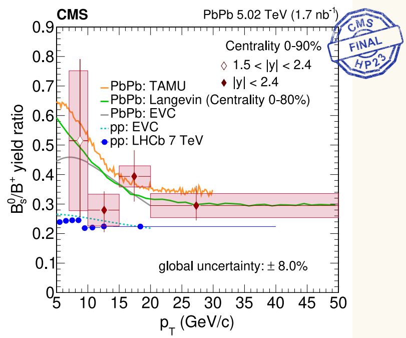
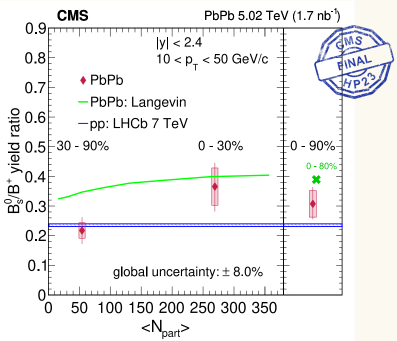
- Enhanced yields in PbPb at low p_T and high centrality
- Dominant uncertainty:
  - Data/MC disagreement on selection variables (BDT score)
  - Tracking efficiency

B_s^0/B^+ yield ratio

B_s^0/B^+ vs p_T



B_s^0/B^+ vs centrality

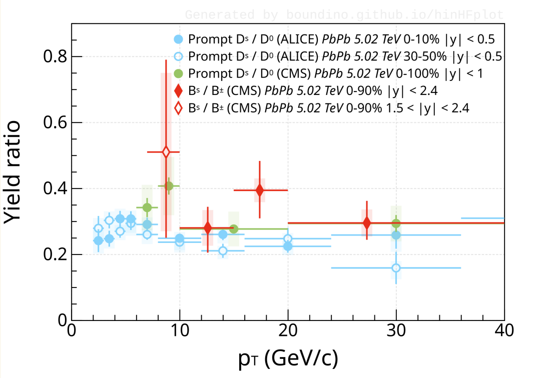


both plots: PLB 829 (2022) 137062

- Compatible with PbPb recombination models
- Compatible with pp data

- Indicate higher B_s^0/B^+ ratio in central events but not significant

B_s^0 / B^+ yield ratio compared with charm



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CMS-PAS-HIN-18-017

PLB 827 (2022) 136986

- Similar magnitudes of D_s / D^0 and B_s^0 / B^+

B_c^+ analysis

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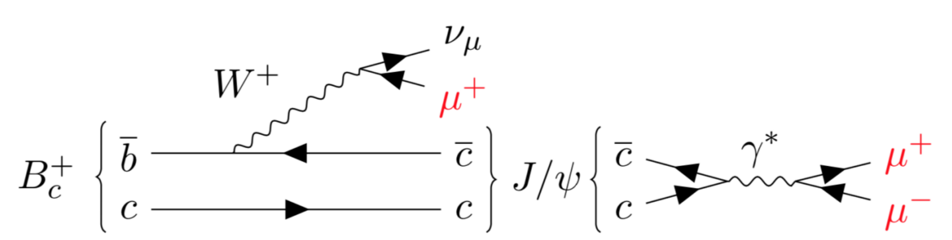
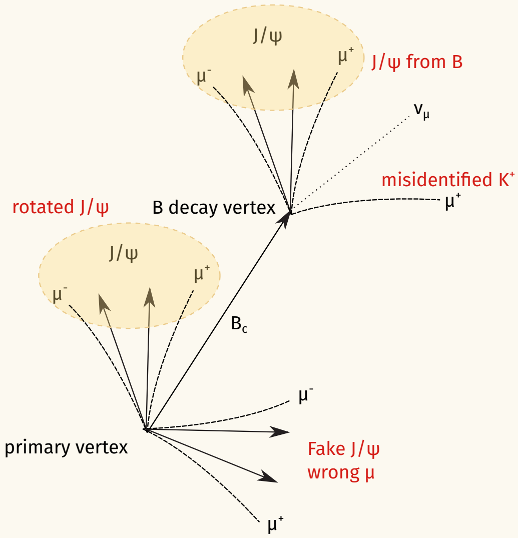
B_c^+ signal: trimuon semi-leptonic decays

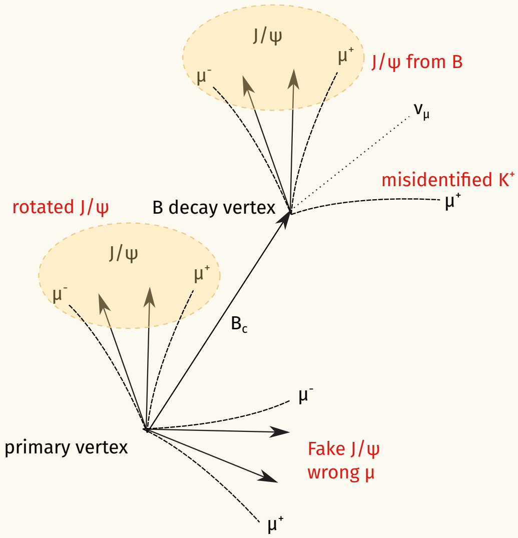


- $m_{J/\psi} + m_\mu \simeq 3.2\,\text{GeV} < m_{3\mu} < 6.3\,\text{GeV} \simeq m_{B_c^+}$
- $\mu^+\ \mu^+\ \mu^-$ final states: 2 J/ψ candidates from opposite-sign (μ^+, μ^-) combinations

3 main backgrounds of $B_c^+ \to J/\psi\, \mu^+ \nu_\mu$



3 main backgrounds of $B_c^+ \to J/\psi\, \mu^+ \nu_\mu$



- rotated J/ψ + X
  - Estimated by rotating J/ψ candidates around the PV
- $B \to J/\psi$ + X
  - Estimated with simulation
- Fake J/ψ + X
  - Estimated from data by interpolating dimuon mass sidebands

B_c^+ event selection with BDT

BDT discriminating variables

- p_T imbalance between J/ψ and the 3rd μ
- Ratio of angular distance ΔR between J/ψ and another 2μ pair
- Significance of the 3rd μ vertex displacement from the PV
- 5 other variables from event selections (see slide 22)

BDT selection: 99.9% signal MC efficiency

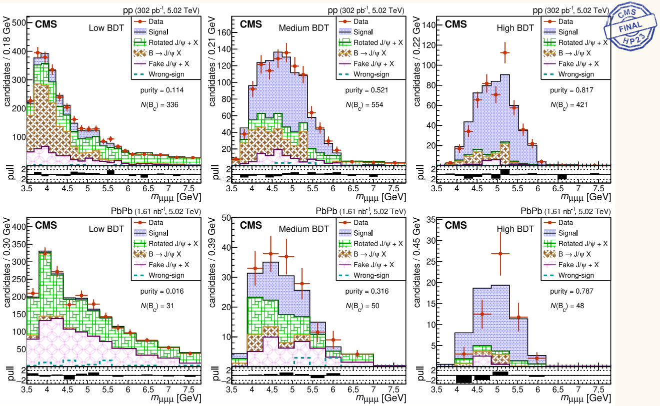
Trimuon template fit

binning:

low BDT score 25% of signal	medium BDT 40%	high BDT 35%

pp

PbPb >5σ



- rotated J/ψ + X: rotating J/ψ candidates around the PV
- $B \to J/\psi$ + X: simulation
- Fake J/ψ + X: interpolating dimuon mass sidebands from data

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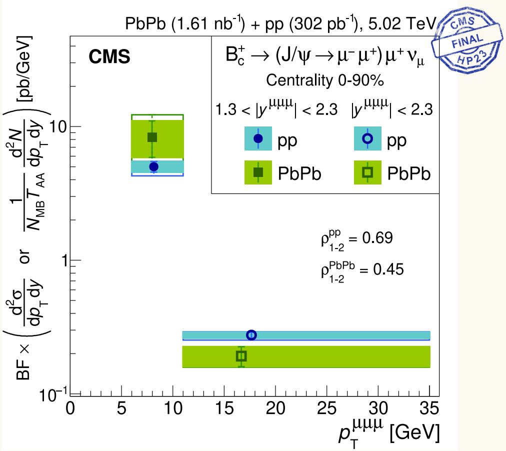
B_c^+ meson production



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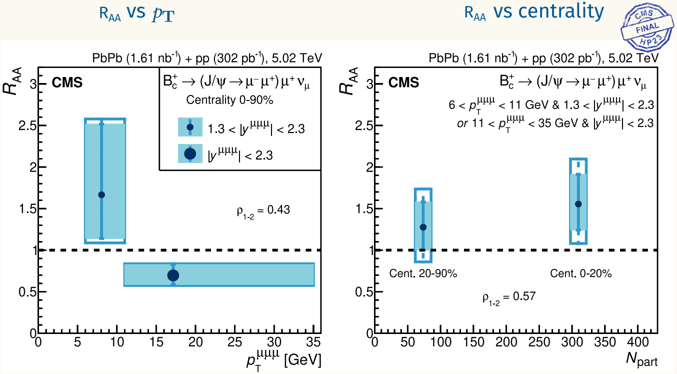
- Enhanced PbPb yield at low p_T, suppressed at high p_T compared to pp result
- Dominant uncertainty: fit, acceptance and efficiency

B_c^+ meson nuclear modification factor

R_{AA} vs p_T | R_{AA} vs centrality



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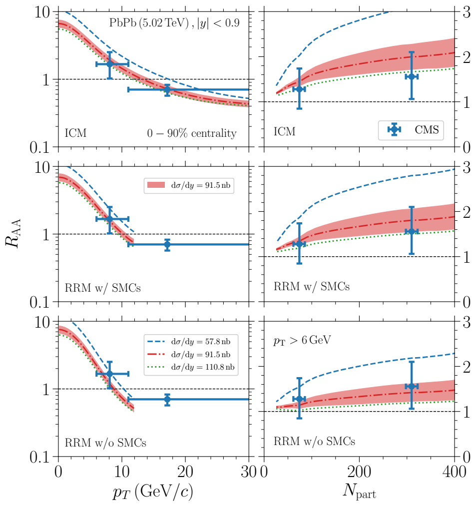
- Moderate suppression at high p_T
- R_{AA} at low p_T higher than unity (1σ) and high p_T (1.6σ)
- Does not significantly depend on centrality

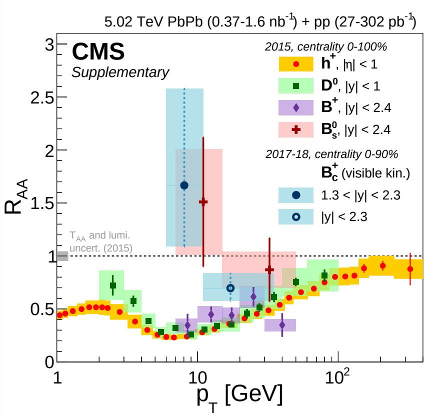
B_c^+ R_{AA} Compared to theory



arXiv:2302.11511

- Compatible with recombination models at different B_c^+ production cross sections in pp
- Top: Instantaneous Coalescence Model
  - Can account for off-equilibrium (non-thermalized) quark spectra
- Middle/Bottom: Resonance Recombination Model
  - conserves 4-momentum, recovers the equilibrium limit for equilibrated HQ input distributions
- Middle: with space momentum correlations between the coalescing quarks
  - Enhanced recombination of fast-moving heavy quarks with high-flow thermal quark

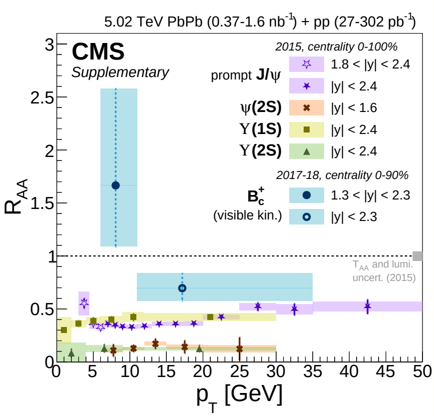
B_c^+ R_{AA} Compared to charged hadron, D^0 and B



arXiv:2201.02659

- Low p_T: R_{AA} higher than charged hadron and B^+
- High p_T: similar suppression
  - Converge at $p_T > 20$ GeV
  - Mass-dependent medium modification (e.g. hadronization, dead cone) reduces at high p_T

B_c^+ R_{AA} Compared to quarkonia



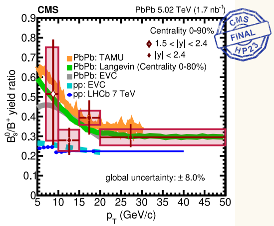
arXiv:2201.02659

- Recombination of c and b could increase R_{AA}
- Need more statistics at low p_T

Summary

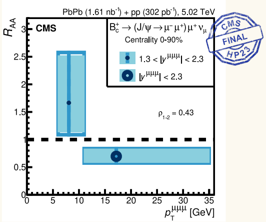
Updated B_s^0/B^+ ratio with the 2018 CMS data

- First observation of $B_s^0 > 5\sigma$ in PbPb collision
- Enhancement at low p_T but not significant with the current precision



B_c^+ measurement

- First observation of $B_c^+ > 5\sigma$ in PbPb collision
- Low-p_T enhancement indicates stronger B_c^+ recombination



Backup

Muon selection for B^+/B^0_s

- $p_T^\mu > 3.5$ for $|\eta^\mu| < 1.2$
- $p_T^\mu > 1.5$ for $2.1 < |\eta^\mu| < 2.4$
- $p_T^\mu > (5.47 - 1.89|\eta^\mu|)$ for $1.2 < |\eta^\mu| < 2.1$
- $m_{\mu^-\mu^+}$ in J/ψ or ϕ range
- Probability of 2μ fitted to a common vertex

Systematic uncertainty for B^+/B_s^0

- Due to fit modeling
  - Signal variation: 3-Gaussian, 10% variation of its width, fixing common mean to MC
  - Background variation: low-order polynomial for combinatorial background
  - Estimated with squared sum of maximum variations
- Due to limited MC sample size
  - 1000 generated $\alpha \times \varepsilon$ 2D maps
  - Estimated with the width of the $1/\langle \alpha \times \varepsilon \rangle$
- Due to data/MC discrepancy
  - Data/MC ratio from sPlot method are used to re-weight the MC distribution

B_s^0/B^+ systematic uncertainty

	B^+				B_s^0			
B meson p_T (GeV/c)	7–10	10–15	15–20	20–50	7–10	10–15	15–20	20–50
Muon efficiency	+7.2 −6.3	+4.3 −3.9	+3.8 −3.5	+3.9 −3.6	+8.9 −7.5	+6.0 −5.2	+3.7 −3.5	+3.9 −3.6
Data/MC agreement	4.2	15	3.0	1.7	35	5.6	4.7	10
MC sample size	9.1	3.2	1.9	1.4	27	6.3	3.1	3.2
Fit modeling	4.5	2.7	2.8	2.6	1.2	3.8	1.8	6.4
Tracking efficiency	5.0	5.0	5.0	5.0	10	10	10	10
T_{AA}	2.2				2.2			
N_{MB}	1.3				1.3			
Branching fraction	2.9				7.5			
Total	+15 −14	+17 −17	+8.7 −8.5	+ 8.2 −8.0	+47 −47	+17 −17	+15 −14	+18 −18

- Data/MC disagreement from reweighted $\alpha \times \varepsilon$ using the sPlot method

B_s^0/B^+ systematic uncertainty

	B^+			B_s^0		
Centrality class	0–30%	30–90%	0–90%	0–30%	30–90%	0–90%
Muon efficiency	$+4.2$ -3.8	$+4.1$ -3.8	$+4.2$ -3.8	$+5.5$ -4.9	$+4.6$ -4.2	$+5.3$ -4.7
Data/MC agreement	13	8.0	12	3.1	3.7	3.2
MC sample size	3.2	2.2	2.4	6.6	2.3	4.4
Fit modeling	2.5	2.8	2.6	2.5	3.2	2.3
Tracking efficiency	5.0	5.0	5.0	10	10	10
T_{AA}	2.0	3.6	2.2	2.0	3.6	2.2
N_{MB}		1.3			1.3	
Branching fraction		2.9			7.5	
Total	$+16$ -15	$+12$ -12	$+15$ -15	$+16$ -16	$+15$ -15	$+15$ -15

B_s^0/B^+ production yield calculation

$$\frac{1}{T_{AA}}\frac{dN}{dp_T} = \frac{1}{2\mathscr{B}N_{MB}T_{AA}}\frac{N_{obs}(p_T)}{\Delta p_T} \times \left\langle \frac{1}{\alpha(p_T, y) \times \varepsilon(p_T, y)} \right\rangle$$

- 1/2: raw yield measured with particles and antiparticles
- $T_{AA} = (5.6 \pm 0.2)\,\text{mb}^{-1}$: nuclear overlapping function [Phys. Rev. C 97 (2018), no.5, 054910]
    - NN-equivalent integrated luminosity per heavy ion collision
- Acceptance and efficiency corrected using a fine (p_T, y) 2D map
- Efficiency map corrected by data/MC scale factors with *tag-and-probe* (with J/ψ)

B_c^+ offline selections

- $m_{\mu^-\mu^+}$ in J/ψ mass range or sideband region (for background estimation)
- Both candidates in the studied mass regions are kept
  - Weighted by the probability of being a true J/ψ
- Probability of the 3μ vertex
- Significance of the vertex displacement from PV
- Angle between $p_{3\mu}$ and B_c^+ flight direction
- Sum of $\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$ between the 3 muon pairs

- Iterative efficiency correction
  - p_T differential analysis with original MC
  - Correct single-μ eff. with tag and probe
  - Corrected yields fitted to correct $p_\mathrm{T}^{3\mu}$ spectrum of the MC
  - Perform a second run of the analysis to correct the $p_\mathrm{T}^{3\mu}$ spectrum again

Acceptance and efficiency correction for B_c^+

- Fraction of signal MC 3μ passing the entire analysis chain
- Single-μ efficiency corrected with *tag-and-probe*, using J/ψ
- Acceptance and efficiency are corrected iteratively
    - p_T differential analysis
    - Corrected yields fitted to correct $p_T^{3\mu}$ spectrum of the MC
    - Perform a second run of the analysis

Systematic uncertainty for B_c^+

uncertainty	pp	PbPb
fit	5%–9%	17%–31%
single-muon efficiency	2%–5%	2%–5%
acceptance and efficiency	10%	25%
bg contamination	4.5%	4.5%