Open beauty production and modifications in PbPb collisions with CMS

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2nd International Workshop on QCD Challenges from pp to AA, Puebla (Mexico)
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Flavor dependence parton energy loss

- Medium induced energy loss ($E_{\text{loss}}$):
  - Collisional
  - Radiative

- Kinematics: "Dead cone effect" [1]: gluon radiation is suppressed at angles smaller than the ratio of quark mass to energy
  - $E_{\text{loss}}$ in light quarks > $E_{\text{loss}}$ in heavy quarks

$$dP = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_\perp^2 dk_\perp^2}{(k_\perp^2 + \omega^2 \theta_0^2)^2}, \quad \theta_0 \equiv \frac{M}{E},$$

- Suppression of induced radiation at low $p_T$ and the disappearance of this effect at high $p_T$

Nuclear modification factor: $R_{AA}$

- $R_{AA} = \text{nuclear modification factor}$

  - $M_b \sim 4.2 \text{ GeV/c}^2 > M_c \sim 1.3 \text{ GeV/c}^2 > M_{\text{light}} \sim O(\text{MeV/c}^2)$

- $R_{AA}^B > R_{AA}^D > R_{AA}^{\text{light}}$?

$$R_{AA} = \frac{N_{PbPb}^{(\text{cent.})}}{N_{Pp}^{Pp}} \times \frac{\mathcal{A}_{Pp} \times \epsilon_{Pp}}{\mathcal{A}_{PbPb} \times \epsilon_{PbPb}^{(\text{cent.})}} \times \frac{\mathcal{L}_{Pp}}{N_{MB} \times \langle T_{AA} \rangle \times (\text{cent. fraction})}$$

- In the following, two CMS 5.02 TeV results will be presented
  - Non-prompt J/ψ
  - Fully reconstructed B meson
Open b flavor in CMS

- $c \tau \approx O(500) \mu m \rightarrow$ secondary vertex

1. Non-prompt $J/\psi$, $B \rightarrow J/\psi \rightarrow \mu\mu$
   Pros:
   - High statistics (0.1% of $b$ xsec)
   - High reconstruction efficiency
   Cons:
   - Convolution of $b$ mesons and $b$ baryons decay

2. Fully reconstructed $B$ mesons decay: $B^+ \rightarrow J/\psi + K^+$
   Pros:
   - Access to the original $B$ hadron kinematics
   - Distinguish $B$ hadrons, e.g. $B^+$ v.s. $B_s$
   Cons:
   - Low Statistic (0.01%)
   - Combinatorial background

- Precise vertexing & tracking
  $\rightarrow$ CMS is a great fit
Signal extraction: $J/\psi$

1. Di-muon triggered events
2. Muon pair fit to a common vertex
3. Fit on invariant mass and decay length spectra
4. Yield extraction in bins of $N_{\text{part}}$, rapidity and $P_T$
5. Extracted yields corrected using simulation and data-driven approach (tag & probe)

**All $J/\psi$**

**prompt $J/\psi$:**
- direct production
- feed down ($\psi'$)

**non-prompt $J/\psi$:**
- from $B$ decays ($ex\ B \rightarrow J/\psi X$)

Muon acceptance:

- $p_T^\mu > 3.5\,\text{GeV/c}$ for $|\eta^\mu| < 1.2$
- $p_T^\mu > (5.77 - 1.89 \times |\eta^\mu|)\,\text{GeV/c}$ for $1.2 \leq |\eta^\mu| < 2.1$
- $p_T^\mu > 1.8\,\text{GeV/c}$ for $2.1 \leq |\eta^\mu| < 2.4$
Non-prompt $J/\psi$ ($B \rightarrow J/\psi \ X$)

- Three component fit for signal extraction
  - Prompt $J/\psi$
  - Non-prompt $J/\psi$ from $B$ hadron
  - Combinatorial background

![Graph showing the CMS-PAS-HIN-16-025 details of the fitting procedure in backup slides](image-url)

PbPb 368 $\mu$b$^{-1}$ (5.02 TeV)

- Data
- Total fit
- Prompt $J/\psi$
- Nonprompt $J/\psi$
- Background

CMS Preliminary

1.8 $\leq |y_{\mu\mu}| < 2.4$
4.5 $\leq p_T^{\mu\mu} < 5.5$ GeV/c
Cent. 0-100%

Events / 0.025 GeV/c$^2$

CMS-PAS-HIN-16-025

- Three component fit for signal extraction
  - Prompt $J/\psi$
  - Non-prompt $J/\psi$ from $B$ hadron
  - Combinatorial background
Signal extraction: \( B^+ \)

- **Signal channel:** \( B^+ \rightarrow J/\psi K^+ \)

  - Similar approach as the non-prompt \( J/\psi \)
  - Charged tracks are assigned a kaon mass
  - Muon pair + track \( \rightarrow \) common vertex fitting

  - fitting for yield extraction \( \rightarrow \) efficiency correction \( \rightarrow R_{AA} \)

  

MVA cut optimization

**Boosted Decision Tree (BDT):**

- track kinematics
- fitting probability
- opening angle
- decay length
**B^+ → J/ψ + K^+**

Phys. Rev. Lett. 119, 152301

- **Signal:** Double Gaussian with same mean

- **Peaking BG:** error function + two sided Gaussian

- **Combinatorial BG:** 1st order polynomial

28.0 pb\(^{-1}\) (pp 5.02 TeV)

10 < p\(_T\) < 15 GeV/c

| y | < 2.4

CMS

B\(^+\)+B\(^-\)

- Data
- Fit
- Signal
- Combinatorial
- B → J/ψ X

**Phys. Rev. Lett. 119, 152301**
Example $B^+$ mass spectra in $p_T = 10-15$ GeV/c in pp and PbPb collision

First fully reconstructed $B$ meson decay in PbPb collision

$B^+ \rightarrow J/\psi X$

Phys. Rev. Lett. 119, 152301
Non-prompt J/ψ
@ pp(PbPb) 5.02 TeV
Non-prompt fraction

- Proportion of measured $J/\psi$ mesons coming from $b$-hadron decays
  - A. $\text{PbPb} > \text{pp} \rightarrow$ indication of $R_{\text{AA}}$ non-prompt $>$ prompt ?
  - B. Strong $p_T$ dependence, non-prompt fraction increases with $p_T$ (20% to 60%)
  - C. No significant dependence on rapidity is observed

![Graph showing non-prompt $J/\psi$ fraction vs $p_T$ and rapidity](image)
• Strong suppression of non-prompt J/ψ production in PbPb v.s. pp

• Increased suppression with event activity is observed in both collision energy

CMS-PAS-HIN-16-025 (5.02 TeV)
EPJC 77 (2017) 252 (2.76 TeV)
\( R_{AA} \) v.s. \( N_{\text{part}} \) and rapidity

- No significant difference in \( R_{AA} \) between the two collision energy
- Interplay between: 1). initial momentum spectrum. 2). increase energy loss ??

\[
R_{AA} \sim \frac{N_{\text{AA}}}{N_{\text{NN}}} = \frac{\frac{\sigma_{\text{AA}}}{\sigma_{\text{NN}}}}{\frac{\sigma_{\text{NN}}}{\sigma_{\text{NN}}}}
\]

\( \sqrt{s_{NN}} = 2.76 \) TeV
\( \sqrt{s_{NN}} = 5.02 \) TeV

\( \frac{\sigma_{\text{AA}}}{\sigma_{\text{NN}}} \)

Preliminary

CMS-PAS-HIN-16-025 (5.02 TeV)
EPJC 77 (2017) 252 (2.76 TeV)

Ta-Wei Wang (MIT), 2nd International Workshop on QCD Challenges from pp to AA
While there was an indication of rapidity dependance of $R_{AA}$ in 2.76 TeV data, no evidence is observed in the current 5.02 TeV result.
- Measurement down to $p_T$ 3 GeV at forward rapidity
- Strong dependence for peripheral events as 2.76 analysis
• Further categorize the result into differentiate rapidity regions
• No evidence of rapidity dependence

@ 5.02 TeV

CMS-PAS-HIN-16-025 (5.02 TeV)
B-meson

@ pp(PbPb) 5.02 TeV
\[ \frac{d\sigma}{dp_T} \bigg|_{|y|<2.4} = \frac{1}{2} \frac{1}{\Delta p_T} \frac{N(p_T)_{|y|<2.4}}{(\text{Acc } e)_{|y|<2.4} \text{BR } \mathcal{L}}. \]

- Result derived in 5 \( B^\pm p_T \) bins, from 7 to 50 GeV in \(|y| < 2.4\)

- Consistent with the upper bound of FONLL predictions [1]

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Compatible with pp 13 and 7 TeV results: upper edge of FONLL @ low $p_T$

Ratios to FONLL

CMS

Data (13 TeV, $|y| < 1.45$)
Data (13 TeV, $|y| < 2.1$)
FONLL (13 TeV)
PYTHIA (13 TeV)
Data (7 TeV, scaled to $|y| < 1.45$)
Data (7 TeV, scaled to $|y| < 2.1$)
FONLL (7 TeV)
PYTHIA (7 TeV)

CMS

Data / FONLL

CMS

B±

Data
FONLL

Global uncert. 3.8%


Phys. Rev. Lett. 119, 152301
Fully reconstructed B meson $R_{AA}$

- Suppression of B meson production rate is observed in PbPb collisions
- B meson $R_{AA} \sim 0.3$ to 0.6 with no obvious trend could be identified within statistical and systematic uncertainty
- Compatible with theory prediction within statistical and systematic uncertainty for $p_T$ 10-50 GeV/c
- Necessity for high $p_T$ measurement: distinguishing pQCD vs AdS/CFT base models

M. He et al., Physics Letters B 735 (2014) 445 – 450
M. Djordjevic, Phys. Rev. C 94 (Oct, 2016) 044908
W. A. Horowitz, Phys. Rev. D 91 (2015) 085019

$28.0 \, \text{pb}^{-1} (pp \, 5.02 \, \text{TeV}) + 351 \, \mu \text{b}^{-1} (\text{PbPb} \, 5.02 \, \text{TeV})$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{CMS $R_{AA}$}
\end{figure}
**$R_{AA}$ zoo: B v.s. D v.s. light**

- Comparisons at 5.02 TeV PbPb:
  - $B^+$ meson
  - $D^0$ meson
  - charge hadron
  - non-prompt $J/\psi$

- $R_{AA}$ of $B$, $D$, and charged hadrons are compatible with each other within uncertainty at mid $p_T$

- Non-prompt $J/\psi$ $R_{AA}$ higher than $D$ and charged hadron at low $p_T$. Merging at high $p_T$

- Compatible results between $B$ meson and non-prompt $J/\psi$ (ex $B$ meson $10\sim15 \approx$ non-prompt $J/\psi 8\sim10$ GeV)

- Note:
  - Probing different kinematic region
  - Rapidity range is different
Cold nuclear matter effect?

- Suppression observed in both non-prompt J/ψ and B meson in PbPb collisions
  - Consequence of CNM effect? e.g.
    Modification of nPDF and potential nuclear absorption

  - No evidence of suppression observed in pPb collisions
  - The suppression seen in PbPb is likely a final state effect.

Summary & Future
Summary

• Non-prompt J/ψ:
  • Great results with unprecedented accuracy!
  • Clear evidence of suppression of production rate ($R_{AA}<1$) in PbPb
  • Smaller suppression than charged particle and D meson at low $p_T$
  • $R_{AA}$ decreasing (more suppression) with centrality and $p_T$
  • No evidence of rapidity dependance is observed in the current analysis

• B meson:
  • First measurement of fully reconstructed B meson in PbPb!
  • A suppression of production rate is observed for B mesons
  • $R_{AA}$ between 0.3 to 0.6 for B meson with no obvious trend observed
  • Open the door for b recombination effect studies!
Future

• An active field of research!
  
  • Non-prompt D meson measurement from B decay:
    
    • Direct: fully reconstructed $B^+$ to $D\pi$ channel
    
    • Indirect: inclusive non-prompt D reconstruction

  • $B_s$ measurement, great probe for strangeness regeneration in QGP

  • Comparison between $B^+$, $B_s$ and $B_0$ at low $p_T$ could unveil more information on flavor recombination
• Future prospect: HL-LHC

• More data available from the HL-LHC will provide more precise measurements and enable us to distinguish different theoretical models.

**B meson $R_{AA}$ in 5.02 TeV**

**Non-prompt $v_2$ in 2.76 TeV**

Future prospect: HL-LHC

- 25 times more statistic expected (factor of 5 reduction in uncertainty)
- Comparison @ low $p_T \rightarrow$ more definite conclusion on flavor dependence energy loss

Stay tuned!!!
Gracias!
Back Up
Why bother?

- Open v.s. Close flavor measurement provides dynamics of parton interactions and hadron formation in the QGP
  - colour-charge and parton-mass differences for the in-medium interactions
  - relative contribution of radiative and collisional energy loss
  - effects of different hadron formation times
- To resolved complicated interplay between:
  - primordial production ($J/\psi$ produced in the initial hard-scattering of the collisions)
  - colour screening and energy loss ($J/\psi$ destroyed or modified by interactions with the surrounding medium)
  - recombination/regeneration mechanisms in a de-confined partonic medium
Quark gluon plasma:

- QCD matter at high temperature and density
- Deconfinement of quarks → color screened (asymptotic freedom)
- Medium effect (momentum stopping, suppression of production...etc)

Relativistic heavy-ion collision at CMS:

- $T = O(10^{12}) \text{ K}, \rho = O(10) \text{ GeV/fm}^3$
- → Creation of QGP
- Understand of the properties of QGP
HF production at pp

**LO process: Flavour Creation (FCR)**
→ gluon fusion or light qq annihilation
→ bb produced back-to-back in azimuthal plane and symmetric in $p_T$

**NLO process: Flavour Excitation (FEX)**
→ excitation of b/b sea quark by gluon or light quark/anti-quark
→ bb pairs produced asymmetric in $p_T$ and with a broad opening angle

**NLO process: Gluon splitting (GSP)**
- gluon splits in a bb pair
→ produced with small opening angles and asymmetric in $p_T$
HF production at pp

EPJC 73 (2013) 2301

ATLAS Simulation
Truth jets, \(\sqrt{s} = 7\) TeV

Gluon splitting
Heavy flavour quark excitation
Quark pair creation

LO \(b\)-\(b\) production (FCR)
sub-dominant at the LHC
Non-prompt J/ψ @ pp(PbPb) 5.02 TeV
Non-prompt J/ψ (B → J/ψ X)

- Fitting procedure: sequential fit on invariant mass and decay length distribution to determine parameterization first. A 2D fitting with parameters either fixed or initialized by the first 1D fit is then performed.
  - **Prompt J/ψ**
    - mass: 2xCrystal Ball (common mean, tail parameter), to account FSR
    - decay length: delta ⊗ resolution function
  - **Non-prompt J/ψ from B meson**
    - mass: 2xCrystal Ball (common mean)
    - decay length: exponential ⊗ resolution function
  - **Combinatorial background**
    - mass: Cheb. Nth (N determined by log-likelihood test which exam when the increase of N to N+1 and N+2 will only result in a < 5% improvement)
    - decay length: 3 exponential function(two 1-sided and one two sided) ⊗ resolution
Non-prompt $J/\psi$ ($B \rightarrow J/\psi X$)

\[ F(\ell_{J/\psi}, m_{\mu\mu}) = N_{\text{Sig}} \cdot F_{\text{Sig}}(\ell_{J/\psi}) \cdot M_{\text{Sig}}(m_{\mu\mu}) + N_{\text{Bkg}} \cdot F_{\text{Bkg}}(\ell_{J/\psi}) \cdot M_{\text{Bkg}}(m_{\mu\mu}), \]

the total 2D fit PDF: invariant mass $X$ decay length

\[ g_{\text{CB}}(m) = \begin{cases} N \sqrt{2\pi} \sigma_{\text{CB}} \exp \left(-\frac{(m-m_0)^2}{2\sigma_{\text{CB}}^2}\right), & \text{for } \frac{m-m_0}{\sigma_{\text{CB}}} > -\alpha; \\ N \sqrt{2\pi} \sigma_{\text{CB}} \left(\frac{n}{|\alpha|}\right)^n \exp \left(-\frac{|\alpha|^2}{2}\right) \left(\frac{n}{|\alpha|} - |\alpha| - \frac{m-m_0}{\sigma_{\text{CB}}^2}\right)^{-n}, & \text{for } \frac{m-m_0}{\sigma_{\text{CB}}} \leq -\alpha. \end{cases} \]

The invariant mass PDF is modeled by Crystall-ball distributions where alpha parameter defines the transition point between Gauss and power law function

\[ F_{\text{Sig,Bkg}}(\ell_{J/\psi},i) = F_{\text{Sig,Bkg}}^{\text{true}}(\ell'_{J/\psi},i) \otimes R(\ell_{J/\psi},i - \ell'_{J/\psi},i \mid \mu, s \cdot \sigma_{\ell,i}). \]

The decay length PDF is a convolution of ‘true’ decay length PDF and resolution

\[ F_{\text{Sig}}^{\text{true}}(\ell'_{J/\psi}) = bF_{\text{NonPrompt}}^{\text{true}}(\ell'_{J/\psi}) + (1-b)F_{\text{Prompt}}^{\text{true}}(\ell'_{J/\psi}). \]

The ‘true’ decay length PDF consists of prompt and non-prompt component
Non-prompt $J/\psi$ ($B \rightarrow J/\psi \ X$)

$$F_{\text{NonPrompt}}^{\text{true}}(\ell'_{J/\psi}) = e^{-|\lambda_{DSS}| \cdot \ell'_{J/\psi}} ,$$

The ‘true’ decay length PDF for non-prompt is model by a (1-sided) decay function

$$F_{\text{Bkg}}^{\text{true}}(\ell'_{J/\psi}) = b_{bkg} \cdot \left[ f_{DLIV} \cdot \left( f_{DFSS} \cdot e^{-|\lambda_{DSS}| \cdot \ell'_{J/\psi}} + (1 - f_{DFSS}) \cdot e^{|\lambda_{DF}| \cdot \ell'_{J/\psi}} \right) + (1 - f_{DLIV}) \cdot e^{-|\lambda_{DSS}| \cdot \ell'_{J/\psi}} \right] + (1 - b_{bkg}) \cdot \delta(\ell'_{J/\psi}) ,$$

The ‘true’ decay length PDF for background is model by a combination of 1-sided decay fn., a flipped 1-sided decay fn. and a 2-sided decay fn.

$$R_i(\ell_{J/\psi}|\mu, s \cdot \sigma_\ell) = [f_{\text{res}} \cdot \text{Gauss}(\ell_{J/\psi}|\mu_1, s_1 \cdot \sigma_\ell) + \left(1 - f_{\text{res}}\right) \cdot [f_{2\text{res}} \cdot \text{Gauss}(\ell_{J/\psi}|\mu_2, s_2 \cdot \sigma_\ell) + \left(1 - f_{2\text{res}}\right) \cdot \text{Gauss}(\ell_{J/\psi}|\mu_3, s_3 \cdot \sigma_\ell)]]$$

Resolution function obtained by utilizing the negative value decay length tail observed in data which originated from prompt component. A Gaus fit on this tail is use to extract the parameter
\[ R_{AA} = \frac{N_{\text{PbPb}}}{(T_{AA} \times \sigma_{pp})} \]

- \( N_{\text{PbPb}} \): number of non-prompt per PbPb collision
- \( T_{AA} \): nuclear overlap function
- \( \sigma_{pp} \): pp cross section, obtained from pp data following the same procedure
- Global systematic = Grey box = pp lumi. + PbPb \( N_{\text{MB}} \) +

- \( T_{AA} \) systematic for results v.s. rapidity and \( P_{T} \)
- all pp statistical and systematic uncertainty for result v.s. \( N_{\text{part}} \)
Global systematic shown as color box at $R_{AA} = 1$

Slow increase of suppression in more central collisions

CMS-PAS-HIN-16-025

$\psi$ Nonprompt $J/\psi$

CMS Preliminary

$R_{AA}$ vs $N_{\text{part}}$

@ 5.02 TeV
• Increase of suppression in the central collision (~35%)
Open vs hidden

- Open beauty vs hidden beauty
- An indication of sequential melting
- Upper bound set on $\Upsilon(3S)$ $R_{AA}$

**Figure:**

- CMS-PAS-HIN-16-023
- CMS Preliminary
- PbPb 368 $\mu$b$^{-1}$, pp 28.0 pb$^{-1}$ (5.02 TeV)

**Graph:**

Open beauty

- Nonprompt $J/\psi$
- $|y| < 2.4$, $6.5 < p_T < 50$ GeV/c

Hidden beauty

- $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$
- $|y| < 2.4$, $p_T < 30$ GeV/c, HIN-16-023

**Cent. 0-100%**

- Open beauty
  - Nonprompt $J/\psi$
  - $1.8 < |y| < 2.4$
  - $|y| < 2.4$, $p_T < 30$ GeV/c, HIN-16-023
The difference in $p_T$ between parent B meson and $J/\psi$
Non-prompt $J/\psi$
@ $pp(PbPb)$ 2.76 TeV
$R_{AA}$ and $v_2$

- $R_{AA}$ = nuclear modification factor
  - $M_b \sim 4.2 \text{ GeV/c}^2 > M_c \sim 1.3 \text{ GeV/c}^2 > M_{\text{light}} \sim \mathcal{O}(\text{MeV/c}^2)$
  - $R_{AA}^B > R_{AA}^D > R_{AA}^{\text{light}}$?

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{dN_{PbPb}^{B^+}}{dp_T} / \frac{d\sigma_{pp}^{B^+}}{dp_T},$$

- $V_n$ = azimuthal anisotropy with respect to the event plane.
  - How does heavy flavor “flow” inside the medium?
  - Collective expansion
  - Path length dependence or independence of energy loss

$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_T dy} \times \left( 1 + \sum_{n=1}^{\infty} 2v_n(p_T, y) \cos \left[ n \left( \varphi - \Psi_R \right) \right] \right)$$
Non-prompt $J/\psi$ $v_2$

- Measurement of azimuthal anisotropy $v_2$
- Event plane method: fit on $|\Delta \Phi|$ 
  - $|\Delta \Phi| = |\phi - \Psi_2|$ 
  - $\Psi_2$ event plane = azimuthal angle of maximum particle density 
- Measured $v_2$ compatible with both zero and positive value

$1 + 2v_2 \cos(|2\Delta \Phi|)$

yields in each $\Delta \Phi$ bin extracted from the 2D fit (mass, $l_{J/\psi}$).

EPJC 77 (2017) 252
Central value of non-prompt $J/\psi$ $v_2$ slightly below $D$ meson and charged hadron at low $p_T$, becoming similar at high $p_T$.

Note: comparison of different collision energy

Statistical uncertainty is still large

Non trivial to disentangle whether:
- Low $p_T$: $b$ quark participates in collective expansion
- High $p_T$: flavor dependent or universal path-length energy loss

Need to take into account their different
- Unmodified vacuum spectra
- Fragmentation functions
• Comparison with pQCD model: MC@sHQ + EPOS
  • collisional only
  • collisional+radiative energy loss
• + recombination components

Experiment meet theory

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

Open beauty: nonprompt J/ψ
- 1.6 < |y| < 2.4
- |y| < 2.4

MC@sHQ + EPOS (Cent. 20-60%, |y| < 1)
- B (K=0.8)
- B (K=1.5)
- NP J/ψ (K=0.8)
- NP J/ψ (K=1.5)

CMS

EPJC 77 (2017) 252
Experiment meet theory

- Collisional $E_{\text{loss}}$: low $p_T$ Radiative $E_{\text{loss}}$: high $p_T$
- Dissociation/Collisional type energy loss important at low $p_T$
- Radiative energy loss important at high $p_T$
- BAMPS under shoots $p_T$ 5-15 GeV/c? single impact para. “b” used for all centralities
- Theories curves shown for B $p_T$(except Mc@sHQ+EPOS): $J/\psi \rightarrow B p_T$ kinematic shift $\sim 2$ GeV/c

CMS

$\sqrt{s_{NN}} = 2.76$ TeV

- Nonprompt $J/\psi$
- $6.5 < p_T < 30$ GeV/c, $|y| < 1.2$
- $MC@sHQ+EPOS$: standard (0-100%, $|y| < 1$)
- $MC@sHQ+EPOS+r$ad+LPM: standard (0-100%, $|y| < 1$)
- TAMU: standard
- Djordjevic et al: standard

CMS

$\sqrt{s_{NN}} = 2.76$ TeV

- Nonprompt $J/\psi$
- $|y| < 1.2$
- $T_{\text{kinematic shift}} \sim 2$ GeV/c

EPJC 77 (2017) 252
• $R_{AA}$ comparison of CMS PbPb 2.76 TeV non-prompt $J/\psi$, D meson, and charged hadron $R_{AA}$ v.s. $N_{part}$

• Comparison is chosen in a similar rapidity range and corresponding D $p_T$ region

• Hint of flavor dependent suppression $\rightarrow R_{AA}^{b} > R_{AA}^{c} \sim R_{AA}^{light}$

• Note: pg
Global systematic at $R_{AA} = 1$

- line box = pp lumi. + PbPb $N_{MB}$ $T_{AA}$ systematic
- color box = all pp statistical and systematic uncertainty

Slow increase of suppression in more central collisions

Low $p_T$ is less suppressed in the forward region

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**Differential $R_{AA}$**

- **CMS**
  - $\sqrt{s_{NN}} = 2.76$ TeV
  - Nonprompt $J/\psi$
    - $3 < p_T < 6.5$ GeV/c
    - $6.5 < p_T < 30$ GeV/c
  - $1.6 < |y| < 2.4$

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**CMS**

- $\sqrt{s_{NN}} = 2.76$ TeV
- Nonprompt $J/\psi$
  - $|y| < 1.2$
  - $1.2 < |y| < 1.6$
  - $1.6 < |y| < 2.4$
  - $6.5 < p_T < 30$ GeV/c
B-meson

\(@\) \text{pp}(\text{PbPb})5.02\ \text{TeV}
To reach high signal to background significance (low production rate of $b$)

→ Multivariate analysis (MVA) for cut value optimization

Five variables are employed

- **track kinematic**: track $p_T$ and pseudorapidity
- **Probability of the vertex fit ($\chi^2$)**: $B^+$ secondary vertex fitting probability
- **Normalized $d_0$**: normalized distance between primary vertex and $B^+$ secondary vertex
- **Cosine($\theta$)**: angle between $B^+$ meson displacement vector and $B^+$ meson momentum

**Maximize** Figure of merit: $S/\sqrt{(S+B)}$

- **$S$**: signals from simulation (normalized to FONLL prediction)
- **$B$**: background from real data (sidebands of the $B^+$ mass spectrum)

Optimization conducted independently for pp and PbPb

![Diagram](https://via.placeholder.com/150?text=Diagram)
Non-prompt contribution

Peaking structure from other types of B meson decay: *two main contributions*

**$B^+ \rightarrow J/\psi + \pi$: Two sided Gaussian**

the pion track is identified as a $K^+$

**$B^+ \rightarrow J/\psi + K^+$ or $B^0 \rightarrow J/\psi + K^0, K^0$: Error function**

tracks coming from the subsequent $K^{*-0}$ decay incorrectly assumed to be from genuine $B^+ \rightarrow J/\psi + K^+$
Systematic: results

**Luminosity & branching ratio**
- BR obtained from PDG

**Signal extraction systematics ~ 3.9%**
- Estimated by varying the modeling PDF and the fitting procedure

**Selection and correction ~ 12.6%**
- Selection variation
- $B$ life-time / $p_T$ modeling
- Tracking efficiency systematic (evaluated by 2 and 4 prongs $D^0$ decays)

**Muon efficiency ~ 16.4%**
- Data-MC single muon efficiency
- Estimate via standard “tag & probe” method by reconstructing $J/\psi$ candidates

**Nuclear modification factor**
- normalization ~ 9%
- total systematic ~ 25%

![Graph showing systematic uncertainty and performance metrics](chart.png)
\[
\left. \frac{d\sigma}{dp_T} \right|_{|y|<2.4} = \frac{1}{2} \frac{N(p_T)|y|<2.4}{\Delta p_T (\text{Acc } \epsilon)|y|<2.4 \text{ BR } \mathcal{L}}.
\]

- \( N \): raw yields of the mass fitting
- \( \text{Acc } \epsilon \): selection efficiency estimated from simulation
- \( \text{BR} \): branching ratio obtained from PDG
- \( \mathcal{L} \): Luminosity of the pp 5 TeV data

**Phys. Rev. Lett. 119, 152301**

28.0 pb\(^{-1}\) (pp 5.02 TeV)

Data

CMS

Data / FONLL

Global uncert. 3.8%
**R_{AA}: B v.s. Non-prompt J/ψ**

- Kinematic consideration: $B^+ p_T \ 10\text{~to~}15 \ \text{GeV} \rightarrow J/\psi \ p_T \ 8\text{~to~}10 \ \text{GeV}$
- Results compatible with each other
Cold nuclear matter effect


CMS

Open beauty

pPb 34.6 nb⁻¹, pp 28.0 pb⁻¹ (5.02 TeV)

|$R_{pPb}$ vs $p_T$ (GeV/c)

- Nonprompt $J/\psi$: $|y_{CM}| < 1.93$
- $B^+$: $-2.86 < y_{CM} < 1.93$

CMS

Open beauty

$pPb$ 34.6 nb⁻¹, pp 28.0 pb⁻¹ (5.02 TeV)

|$R_{pPb}$ vs $y_{CM}$

- Nonprompt $J/\psi$: $10 < p_T < 30$ GeV/c
- $B^+$: $10 < p_T < 60$ GeV/c