Open Heavy Flavor Measurements in Heavy Ion Collisions with CMS

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Outline

- Physics Motivation

- Open Heavy Flavor Measurements in PbPb and pPb

\[ p_T \]

0 \hspace{1cm} 100 \hspace{1cm} \text{GeV/c}

Non-prompt \( J/\psi \)

B meson

Summary
Physics Motivation

- Heavy quarks are primarily produced at the early stages of the collisions

→ Experience the full evolution of the medium

- Flavor dependence energy loss
  - Heavy quarks are expected to lose less energy than light quarks and gluons in medium due to color charge and dead cone effect [1]

\[ \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \rightarrow R_{AA}^B > R_{AA}^D > R_{AA}^{\text{light}} \]

- From light to heavy quark: ratio between radiative and collisional energy loss changes


- Cold nuclear matter effect: Gluon shadowing, Initial state Energy loss, etc
Open beauty measurements in CMS

- **b-jet, B meson and non-prompt J/ψ**
- **Proper decay length ~ 500 µm**

- **Non-prompt J/ψ**
  - O(0.1%) of b cross section

- **B meson**
  - O(0.01%) of b cross section

- **b-jet**
  - O(100%) of total b cross section
Centrality and Nuclear modification factor

- **Centrality**: describes degree of overlap of AA collisions
  - Centrality 0 to 100%, central collision to peripheral collision
  - Normally represented by $N_{\text{part}}$
  - $N_{\text{part}}$: number of participating nucleons
  - $N_{\text{coll}}$: number of the binary nucleon-nucleon collisions

- **Nuclear modification factor**: describes production ratio to pp collision
  \[
  R_{AB} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2 N_{AB}}{dp_T d\eta} / \frac{d^2 N_{pp}}{dp_T d\eta}
  \]
  - $R_{AB} > 1$: enhancement
  - $R_{AB} = 1$: no medium effect
  - $R_{AB} < 1$: suppression
b-jet Measurements in PbPb and pPb
Identifying b-jet

- Primary identification method is using a **Secondary Vertex**
  - Long lifetime of $b = \text{mm or cm vertex displacement}$
- Flight distance ($L_{xyz}$) of the secondary vertex used as a discriminating variable
- Tagging methods independent of secondary vertex reconstruction used as cross-check

B-quark decays are heavily CKM-suppressed → Long lifetimes

Algorithms described in: JINST 8 (2013) P04013
First measurement of heavy flavor jet $R_{AA}$

Clear suppression of b-jet: $R_{AA}$ shows clear trend as a function of centrality

$R_{AA}(\text{b-jet}) \approx R_{AA}(\text{inclusive jet})$: at high pt, no strong indication of flavor dependence within the uncertainties

- Contributions from gluon splitting? Negligible quark mass at these energies?
b-jet in pPb: $R_{pA}^{PYTHIA}$

- pp reference from PYTHIA simulation (no data reference available)
- $R_{pA}$ is consistent with unity within uncertainties
- No suppression observed in pPb collisions at 5.02 TeV
- No significant cold nuclear matter effects are observed within uncertainties. Suppression in PbPb is from medium effect.
Non-prompt J/ψ Measurements in PbPb and pPb
Non-prompt $J/\psi$ reconstruction

- Fit muon pairs to a common vertex
- Simultaneous fit on invariant mass and pseudo-proper decay length for yield extraction

$$\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$

- Yields of non-prompt and prompt $J/\psi$
Non-prompt J/ψ in PbPb: $R_{AA}$

- A slow increase of the suppression is observed with increasing centrality of the collision.
- A hint of less suppression at low $p_T$

(CMS Preliminary PbPb $\sqrt{s_{NN}} = 2.76$ TeV)

1.4
1.2
1
0.8
0.6
0.4
0.2
0

6.5 < $p_T$ < 30 GeV/c

$|y| < 2.4$

Cent. 0-100%

$|y| < 2.4$

CMS PAS HIN-12-014
Why study $R_{FB}$?

At small $x$, partons in nucleus depleted compared to proton
- Characterized by forward/backward asymmetry

Non-prompt $J/\psi$ studied in shadowing range: $10^{-4} < x < 10^{-2}$
- $R_{FB}$ is expected to be smaller than 1.0 in some range

$$R_{FB}(p_T, y) = \frac{d^2\sigma(p_T, y > 0)/dp_Tdy}{d^2\sigma(p_T, y < 0)/dp_Tdy}$$

$$x_{1,2} = \frac{\sqrt{m_{J/\psi}^2 + p_T^{2,J/\psi}}}{\sqrt{s}} \cdot e^{\pm y}$$
Non-prompt J/ψ in pPb: $R_{FB}$

Decreased yields at forward rapidity: consistent with presence CNM effects

$R_{FB}(p_T, y) = \frac{d^2\sigma(p_T, y > 0)/d^2p_Tdy}{d^2\sigma(p_T, y < 0)/d^2p_Tdy}$

CMS Preliminary 34.6 nb$^{-1}$ (pPb 5.02 TeV)

CMS PAS HIN-14-009
B Mesons Measurements in PbPb and pPb
B mesons in pPb

- Fully reconstructed hadronic decays:
  - $B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$
  - $B^0 \rightarrow J/\psi K^0* \rightarrow \mu^+ \mu^- K^+ \pi^-$
  - $B_s^0 \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-$

- B candidate reconstruction
  - $J/\psi \rightarrow \mu^+ \mu^-$ reconstruction
  - Tracks are associated to $J/\psi$ candidate to build $B$-meson candidates

- Candidate selection based on $B$ kinematics

- Mass spectrum fit to get yields of $B$ mesons

CMS PAS HIN-14-004
B mesons in pPb: $R_{pA}^{FONLL}$

- FONLL prediction as pp reference (no data reference available)
- $R_{pA}$ is consistent with unity within uncertainty
- No significant cold nuclear matter effects are observed within uncertainties
- Important reference for PbPb analysis

CMS Preliminary

$34.6 \text{ nb}^{-1} (\text{pPb 5.02 TeV})$

CMS PAS HIN-14-004

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B mesons in PbPb

- Able to reconstruct B meson in PbPb with CMS
- First fully reconstructed B meson signal in PbPb!
- 2015 Run-2: 20x more statistics (Increased luminosity and higher collision energy)
- Potential measurements of $B^+$, $B^0$ and $B_s^0$ in PbPb
Summary

❖ Open beauty measurements with CMS
  ▪ Suppression of b-jet and non-prompt J/ψ in PbPb
  ▪ Cold nuclear matter effects are studied

❖ Perspective analysis
  ▪ D and B meson measurements in PbPb
  ▪ More differential heavy flavor jets measurements
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 in pp

EPJC 73 (2013) 2301

LO b-b production (FCR)
sub-dominant at the LHC
B-Jet reconstruction

jet reconstruction/b-jet identification

SV tagger

b jet purity determination

template (from simulation) fit on SV mass spectrum

Efficiency correction+resolution unfolding

from simulation, cross checked by data-driven method
• Three component fit for signal extraction (Fully reconstructed B meson signal in heavy ion collisions):
  • Signal
  • Combinatorial background from J/ψ + track(s)
  • Non-prompt component from other B-meson decays that form peaking structures (e.g. in B⁺ analysis, bkg from $B^0 \rightarrow J/ψ K^{0*}$)
B meson non-prompt Bkg

**B\(^+\):**
- \(B^+ \to J/\psi \pi\) decays in which \(\pi\) misidentified as \(K\)
- \(B^+\) decays via resonant channels e.g., \(B^+ \to J/\psi K^*(892)^+\). Kaons from \(K^*(892)^+\) are then identified as genuine \(B^+ \to J/\psi K\)
- Similar from \(B^0 \to J/\psi K^*(892)^0\)

**B\(^0\):**
- Peaking BG at high mass from \(B^+ \to J/\psi\) decays
- Peaking BG at intermediate mass from \(B_s \to J/\psi \phi\) where a kaon is misidentified as \(\pi\)
- Peaking BG at low mass is the sum of other contributions such as \(B^0 \to J/\psi K(1270)^0\), \(B^+ \to J/\psi K(1270)^+\) and other \(B^0 \to J/\psi\) tracks decays

**B\(_s\):**
- Potential contribution from \(B^0 \to J/\psi + K^*,\) but not observed in the final spectrum