Open Heavy Flavor Measurements in Heavy Ion Collisions with CMS

Jian Sun
Purdue University
for the CMS Collaboration

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Physics Motivation

- Heavy quarks are produced primarily 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]
    \[ \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \]
  - From light to heavy quark: ratio between radiative and collisional energy loss changes


- Cold nuclear matter effects through heavy flavor study in pPb
Open heavy flavor measurements with CMS

- **c/b-jet, D/B hadron and non-prompt J/ψ**
  - \( c\tau \) (D meson) \( \sim 100 \) to \( 300 \, \mu\text{m} \)
  - \( c\tau \) (B meson) \( \sim 400 \) to \( 500 \, \mu\text{m} \)
c/b-jet identification and fraction determination

- Secondary vertices used to tag heavy flavor jet
  - c-jet: requires secondary vertex with $\geq 3$ tracks
  - b-jet: requires secondary vertex with $\geq 2$ tracks
- c/b-jet purity is obtained through template fit of secondary vertex mass

**Figure**: Diagram showing the primary vertex, secondary vertex, and the Lorentz invariant $L_{xyz}$. The figure illustrates the identification of jets through secondary vertices.

**Graph**: Illustrates the distribution of jets based on secondary vertex mass, showing data and Monte Carlo (MC) comparisons for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The graph shows the number of jets per 0.5 GeV/c$^2$ for $80 < p_T < 90$ GeV/c and $|\eta| < 2$.
b-jet in PbPb and pPb

- b-jet production is suppressed in PbPb. And the suppression has strong centrality dependence.
- \( R_{pA} \) is consistent with unity within uncertainties.
  - No significant cold nuclear matter effects. Suppression in PbPb is from hot medium effect.
c-jet spectrum in pPb and pp

- **c-jet spectrum consistent with PYTHIA for both pPb and pp**
  - Data/Pythia: $1.00 \pm 0.19$ (pPb) and $1.15 \pm 0.27$ (pp)

See poster by Kurt Jung
B meson 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 mesons in pPb: $R_{pA}^{FONLL}$

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

Submitted to PRL arXiv:1508.06678
B mesons in PbPb

- Capable of reconstructing B mesons in PbPb with CMS
- First fully reconstructed B meson signal in PbPb!
- 2015 Run-2: 20x more statistics (Increased luminosity and higher collision energy)
- Measurements of $B^+$, $B^0$ and $B_s^0$ in PbPb

See poster by Kisoo Lee
D⁰ Reconstruction

- D⁰ → Kπ, BR = 3.88±0.05%, cτ(D⁰) = 122.9 μm

- D⁰ candidates reconstructed by combining oppositely charged tracks
  - No PID selection applied: two mass assignments for one track pair → Two candidates for one track pair

- Topological selections:
  - 3D decay length significance (d0/σ(d0))
  - Pointing angle α
  - Vertex χ² fit probability
D⁰ signal extraction: D⁰→Kπ

- Data: 2011 PbPb data with minimum bias trigger ~ 30M events
- Clear D⁰ signal in p_T range 2.5 to 40 GeV
- Misidentification (k-π swapped) D⁰ because of wrong mass assignment
Acceptance and efficiency correction

\[
\frac{dN_{PbPb}}{dp_T} = f_{prompt} \cdot \frac{1}{2} N_{D^0}^{raw} \cdot \frac{1}{\Delta p_T} \cdot \frac{1}{N_{MB} \cdot Br \cdot (\alpha \times \varepsilon)_{prompt}}
\]

- Combined effects of tracking efficiency and cut selection efficiency

- Acceptance and efficiency of non-prompt D^0 (D^0 from B-hadron decay) will be used to estimate the B feed-down correction factor
B feed-down correction

\[
\frac{dN_{PbPb}}{dp_T} = f_{prompt} \cdot \frac{1}{2} N_{D^0}^{raw} \cdot \frac{1}{N_{MB} \cdot Br \cdot (\alpha \times \varepsilon)_{prompt}}
\]

**Non-prompt D^0 subtraction:**

\[
f_{prompt} = 1 - \frac{N_{raw, \text{non-prompt } D^0}}{2 N_{D^0}^{raw}}
\]

**Raw yield of non-prompt D^0**
- Beauty production from FONLL [1]
- Acceptance and efficiency from Pythia embedded Hydjet
- R_{AA} of non-prompt D^0 constrained by non-prompt J/\psi and b-jet R_{AA}
Prompt $D^0$ production is strongly suppressed in PbPb collisions.

→ pp reference:
- $p_T > 16$ GeV, FONLL calculation

Comparison with models

For $p_T > 16$ GeV, the FONLL reference should be taken into account.

**WHDG:** Horowitz et al., arXiv:1104.4958
**T-Matrix:** He, Rapp, private communication
**LANL:** Cao et al., PRC 92 (2015) 2, 024907, PRC 88 (2013) 4, 044907

**BAMPS:** Uphoff et al., arXiv:1408.2964
Comparison with charged particle and non-prompt $J/\psi$ $R_{AA}$

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

- Prompt $D^0 R_{AA}^*$
  - $|y| < 1.0$, Cent. 0-10%

- Charged particle $R_{AA}$
  - $|\eta| < 1.0$, Cent. 0-5%
  - CMS, EPJC 72 (2012) 1945

- Syst. PbPb data

Filled markers: data-extrapolated reference
Open markers: FONLL reference

EPJC 72 (2012) 1945
CMS PAS HIN-15-005
Comparison with charged particle and non-prompt J/ψ $R_{AA}$

- **Prompt D⁰ $R_{AA}^*$**
- **Charged particle $R_{AA}$**
- **Non-prompt J/ψ $R_{AA}$**

- **Hint of $R_{AA}$ (non-prompt J/ψ) > $R_{AA}$ (prompt D⁰) > $R_{AA}$ (h±)**

- The data measurements agree with calculations by Djordjevic et al. within uncertainties

See poster by Yen-Jie Lee
Summary

- **First D meson measurement in heavy ion collisions from CMS**
  - Prompt $D^0$ production is strongly suppressed in PbPb collisions and the suppression is clearly centrality dependent
  - Hint of $R_{AA}$ (non-prompt $J/\psi$) > $R_{AA}$ (prompt $D^0$) > $R_{AA}$ ($h^{\pm}$)

  **See poster by Yen-Jie Lee**

- **First c-jet measurement in heavy ion collisions**
  - c jet spectrum and fraction consistent with PYTHIA in pPb

  **See poster by Kurt Jung**

- Non-prompt $J/\psi$ and b-jet are strongly suppressed in PbPb and the suppression is clearly centrality dependent

- No significant modification due to cold nuclear matter effects are observed within uncertainties through B meson, c-jet and b-jet studies in pPb
Comparison with Alice results

For $p_T > 16$ GeV, differences in pp reference should be taken into account.
Corrected Secondary Vertex Mass

- $M_{\text{corr}} = \text{"Minimum mass of meson decay that’s consistent with direction of flight"}$
- $\text{Attempts to restore } p_{\text{perp}} \text{ balance w.r.t. flight direction from missing energy (e.g. } \nu, \pi^0, \text{ etc.)}$
- $B$ hadrons have higher $p_{\text{perp}}$ components (on average) than do $C$ hadrons
  - $\rightarrow B$’s have statistically larger values of $M_{\text{corr}}$

\[
p_{1,\text{CM}} = p_{v,\text{CM}}
\]
\[
p_{1,\text{lab}} \sin \theta_1 = p_{v,\text{lab}} \sin \theta_2
\]
\[
M_{\text{corr}} = \sqrt{M_1^2 + p_1^2} + \sqrt{M_v^2 + p_v^2}
\]
\[
M_{\text{corr}}(\text{min}) = \sqrt{M_1^2 + p_1^2 \sin^2 \theta_1 + p_1 \sin \theta_1}
\]

LHCb Collaboration 
arXiv: 1504.07670
Mass spectrum fit for centrality 0-10%
<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
<th>$d_0/\sigma(d_0)$</th>
<th>$\alpha$ (radians)</th>
<th>Vertex Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5-3.5</td>
<td>&gt; 5.90</td>
<td>&lt; 0.12</td>
<td>&gt; 0.248</td>
</tr>
<tr>
<td>3.5-4.5</td>
<td>&gt; 5.81</td>
<td>&lt; 0.12</td>
<td>&gt; 0.200</td>
</tr>
<tr>
<td>4.5-5.5</td>
<td>&gt; 5.10</td>
<td>&lt; 0.12</td>
<td>&gt; 0.191</td>
</tr>
<tr>
<td>5.5-7.0</td>
<td>&gt; 4.62</td>
<td>&lt; 0.12</td>
<td>&gt; 0.148</td>
</tr>
<tr>
<td>7.0-9.0</td>
<td>&gt; 4.46</td>
<td>&lt; 0.12</td>
<td>&gt; 0.102</td>
</tr>
<tr>
<td>9.0-11.0</td>
<td>&gt; 4.39</td>
<td>&lt; 0.12</td>
<td>&gt; 0.080</td>
</tr>
<tr>
<td>11.0-13.0</td>
<td>&gt; 4.07</td>
<td>&lt; 0.12</td>
<td>&gt; 0.073</td>
</tr>
<tr>
<td>13.0-16.0</td>
<td>&gt; 3.88</td>
<td>&lt; 0.12</td>
<td>&gt; 0.060</td>
</tr>
<tr>
<td>16.0-20.0</td>
<td>&gt; 3.67</td>
<td>&lt; 0.12</td>
<td>&gt; 0.055</td>
</tr>
<tr>
<td>20.0-28.0</td>
<td>&gt; 3.25</td>
<td>&lt; 0.12</td>
<td>&gt; 0.054</td>
</tr>
<tr>
<td>28.0-40.0</td>
<td>&gt; 2.55</td>
<td>&lt; 0.12</td>
<td>&gt; 0.050</td>
</tr>
</tbody>
</table>

Table 1: Summary table of the selection criteria in different $p_T$ intervals.
• $\alpha \times \varepsilon_{\text{reco}}$: prompt $D^0$ higher than non-prompt $D^0$ (D0 from B-hadron decay)
  ➢ Tracks from non-prompt $D^0$ are more displaced from primary vertex than tracks from prompt $D^0$
  ➢ Hi tracking has lower efficiency on further displaced tracks

• $\varepsilon_{\text{cuts}}$: non-prompt $D^0$ higher than prompt $D^0$
  ➢ Non-prompt $D^0$ are more displaced from primary vertex than prompt $D^0$, thus bigger $d_0/\text{error}_d_0$
To get prompt D0 spectrum, non-prompt D0 should be subtracted

- Rely on FONLL prediction and simulation to calculate expected raw number of non-prompt D0

\[
f_{\text{prompt}} = 1 - \frac{N_{\text{raw}}^{\text{Non-prompt D0}}}{\frac{1}{2} N_{\text{D0}}^{\text{raw}}}.
\]

\[
N_{\text{raw}}^{\text{Non-prompt D0}} = T_{AA} \left( \frac{d\sigma}{dp_T} \right)_{\text{FONLL}} \cdot R_{\text{AA}}^{\text{Non-prompt D0}} \cdot (\alpha \times \varepsilon)_{\text{Non-prompt D0}} \cdot \Delta p_T \cdot Br \cdot N_{\text{evt}}
\]

- Converted from non-prompt J/ψ R_{AA} and hypothesis
- Pythia+EvtGen B→J/ψ and B→D^0 decay kinematics

- FONLL B meson spectrum
- Pythia+EvtGen B→D^0 decay kinematics

CMS PAS HIN-15-012
Non-prompt J/psi R_{AA}

- Intermediate pt (3 to 30 GeV) results from HIN-12-014
- Low pt range (< 3 GeV) assumed to be $1.0 \pm 1.0$ (no available measurements)
- High pt range (> 30 GeV) assumed to be $0.5 \pm 0.5$ based on b-Jet results

Conversion from non-prompt J/psi R_{AA} to non-prompt D^0 R_{AA} relies on

- FONLL B meson spectrum
- Pythia+EvtGen B→Jpsi and B→D^0 decay kinematics
Strong centrality dependence