Jing Wang on behalf of the CMS Collaboration

Probing the Quark Gluon Plasma with Open Heavy Flavor with CMS Detector

LBNL HF/MVTX Workshop
28 February - 3 March 2019
Berkeley, CA (US)
Why study heavy flavors in HI?

Heavy quarks are good probe of QGP!

- Produced mainly via initial hard scatterings ($m_c, m_b \gg T_{QGP}$)
  - Experience the whole evolution of the medium; Number conservation;
- Production cross section calculable with pQCD ($m_c, m_b \gg \Lambda_{QCD}$)
  - Slow “hard probes”
- Strongly interact with the deconfined medium
  - Transport coefficients
Why study heavy flavors in HI?

Heavy quarks are good probe of QGP!
- Produced mainly via initial hard scatterings ($m_c, m_b \gg T_{QGP}$)
  - Experience the whole evolution of the medium; Number conservation;
- Production cross section calculable with pQCD ($m_c, m_b \gg \Lambda_{QCD}$)
  - Slow “hard probes”
- Strongly interact with the deconfined medium
  - Transport coefficients

What information can we get?
- Energy loss in the medium
  - Pictures
    - pQCD: Collisional + Radiative
    - AdS/CFT: drag force
  - Depends on (pQCD)
    - color charge and quark mass (dead cone effect [1])
      - $\Delta E_l > \Delta E_c > \Delta E_b$
  - medium density and path length
- Collective flow
  - Interaction strength
  - Thermalization + Relaxation time

Why study heavy flavors in HI?

Heavy quarks are good probe of QGP!
- Produced mainly via initial hard scatterings \((m_c, m_b \gg T_{QGP})\)
  - Experience the whole evolution of the medium; Number conservation;
- Production cross section calculable with pQCD \((m_c, m_b \gg \Lambda_{QCD})\)
  - Slow “hard probes”
- Strongly interact with the deconfined medium
  - Transport coefficients

What information can we get?
- Energy loss in the medium
  - Pictures
    - pQCD: Collisional + Radiative
    - AdS/CFT: drag force
  - Depends on (pQCD)
    - color charge and quark mass (dead cone effect [1])
      - \(\Delta E_l > \Delta E_c > \Delta E_b\)
      - \(R_{light}^{AA} < R_{D}^{AA} < R_{B}^{AA}\)
    - medium density and path length
- Collective flow
  - Interaction strength
  - Thermalization + Relaxation time

\[
R_{AA} = \frac{1}{T_{AA}} \frac{dN_{AA}}{dp_T} \times \frac{d\sigma_{pp}}{dp_T}
\]

Nuclear modification factor \((R_{AA})\)

\[
\frac{dN}{d\phi} \propto 1 + 2\Sigma_n v_n \cos \left[n(\phi - \Psi_n)\right]
\]

Azimuthal anisotropy \((v_n)\)

Why study heavy flavors in HI?

Heavy quarks are good probe of QGP!
- Produced mainly via initial hard scatterings \((m_c, m_b \gg T_{QGP})\)
  - Experience the whole evolution of the medium; Number conservation;
- Production cross section calculable with pQCD \((m_c, m_b \gg \Lambda_{QCD})\)
  - Slow “hard probes”
- Strongly interact with the deconfined medium
  - Transport coefficients

What information can we get?
- Energy loss in the medium
  - Pictures
    - pQCD: Collisional + Radiative
    - AdS/CFT: drag force
  - Depends on (pQCD)
    - color charge and quark mass (dead cone effect [1])
      - \(\Delta E_l > \Delta E_c > \Delta E_b\)
      - \(R_{\text{light}}^{AA} < R_{\text{D}}^{AA} < R_{\text{B}}^{AA}\)
    - medium density and path length
- Collective flow
  - Interaction strength
  - Thermalization + Relaxation time

\[
R_{AA} = \frac{1}{T_{AA}} \frac{dN_{AA}}{d\mathbf{p}_T} \left/ \frac{d\sigma_{pp}}{d\mathbf{p}_T} \right.
\]

---

### Data collection in CMS

<table>
<thead>
<tr>
<th>Year</th>
<th>System</th>
<th>Energy</th>
<th>LHC Delivered</th>
<th>CMS Recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Pb-Pb</td>
<td>2.76 TeV</td>
<td>184.1 µb(^{-1})</td>
<td>174.3 µb(^{-1})</td>
</tr>
<tr>
<td>2013</td>
<td>p-Pb</td>
<td>5.02 TeV</td>
<td>36.1 nb(^{-1})</td>
<td>35.5 nb(^{-1})</td>
</tr>
<tr>
<td>2015</td>
<td>p-p</td>
<td>5.02 TeV</td>
<td>28.8 pb(^{-1})</td>
<td>28.1 pb(^{-1})</td>
</tr>
<tr>
<td>2015</td>
<td>Pb-Pb</td>
<td>5.02 TeV</td>
<td>0.60 nb(^{-1})</td>
<td>0.55 nb(^{-1})</td>
</tr>
<tr>
<td>2016</td>
<td>p-Pb</td>
<td>8.16 TeV</td>
<td>188.3 nb(^{-1})</td>
<td>180.2 nb(^{-1})</td>
</tr>
<tr>
<td>2017</td>
<td>p-p</td>
<td>5.02 TeV</td>
<td>334.3 pb(^{-1})</td>
<td>316.3 pb(^{-1})</td>
</tr>
<tr>
<td>2018</td>
<td>Pb-Pb</td>
<td>5.02 TeV</td>
<td>1.80 nb(^{-1})</td>
<td>1.71 nb(^{-1})</td>
</tr>
</tbody>
</table>

*New!*
Measuring open charm in CMS

- Relatively long decay length
  - Precise vertexing
- Selection on kinematic variables to suppress combinatorial background
- Cut optimization via ML methods
- No-hadronic PID utilized
- Template fit
  - Double gaussian (Signal)
  - 3rd order polynomial (Combinatorial)
  - Single gaussian (K-π swapped)

- $c \rightarrow D^0$: $O(50\%)$ of $c$ cross-section
- $D^0 \rightarrow K\pi$: $3.93 \pm 0.04\%$
- $c\tau(D^0) = O(100) \mu m$

QGP

Decay

QGP

Hadronization

Primary vertex

Secondary vertex

$D^0$ → $K\pi$

$5 < p_T < 6$ GeV/c

$|y| < 1.0$

Cent. 0-100%

$\times 10^3$

530 $\mu$b$^{-1}$ (5.02 TeV PbPb)

CMS

$D^0 + \bar{D}^0$

$PLB$ 782 (2018) 474
Measuring open beauty in CMS (1/2)

**Exclusive**: fully reconstruct b-hadron decay chain

- \( B^+ \rightarrow J/\psi(\mu\mu)K^+ \)

**Inclusive**: reconstruct daughter resonance of b hadrons

- **non-prompt** \( D^0 \)
  - \( b \text{ quark} \rightarrow \text{B mesons} \)
  - \( \text{Hadronization} \)
  - \( \text{Decay} \)
  - \( K, \pi \rightarrow D^0 \)

- **non-prompt** \( J/\psi \)
  - \( b \text{ quark} \rightarrow \text{B mesons} \)
  - \( \text{Hadronization} \)
  - \( \text{Decay} \)
  - \( \mu, \mu \rightarrow J/\psi \)

- \( b \rightarrow J/\psi + \text{anything}: \sim 1\% \)
- \( b \rightarrow D^0 + \text{anything}: \sim 60\% \)
- \( c\tau(B) = O(500) \mu m \)
Measuring open beauty in CMS (2/2)

**Exclusive:** fully reconstruct b-hadron decay chain

- $B^+ \rightarrow J/\psi(\mu\mu)K^+$
- **non-prompt $D^0$**
- **non-prompt $J/\psi$**

- Long decay length $\rightarrow$ Precise vertexing
- No-hadronic PID utilized
- Selection on kinematic variables to suppress combinatorial background
- Cut optimization via ML methods
- Advantage on $\mu$, $J/\psi$ reconstruction and recognition

**Inclusive:** reconstruct daughter resonance of b hadrons

351 $\mu$b$^{-1}$ (PbPb 5.02 TeV)

<table>
<thead>
<tr>
<th>$m_B$ (GeV/c$^2$)</th>
<th>Events / (20 MeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>5.2</td>
<td>20</td>
</tr>
<tr>
<td>5.4</td>
<td>30</td>
</tr>
<tr>
<td>5.6</td>
<td>50</td>
</tr>
<tr>
<td>5.8</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
</tr>
</tbody>
</table>

$10 < p_T < 15$ GeV/c $|y| < 2.4$

**CMS**

$B^+ + B^-$

- Data
- Fit
- Signal
- Combinatorial
- $B \rightarrow J/\psi X$

[$m_{\psi}$ (GeV/c$^2$)]

$3.0$ $3.1$ $3.2$ $3.3$ $3.4$ $3.5$

$10^7$ $10^6$ $10^5$ $10^4$

$10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$

**PbPb**

- Data total $D^0$
- Prompt
- From b hadrons

**CMS**

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

$1.8 \leq |y| < 2.4$

$4.5 \leq p_T^{\mu\mu} < 5.5$ GeV/c

Cent. 0-100%

- Data
- Total fit
- Prompt $J/\psi$
- $J/\psi$ from b hadrons
- Background

PRL 119 (2017) 152301
arXiv:1810.11102
EPJC 78 (2018) 509
Open HF $R_{AA}$ in PbPb (1/8)

**Centrality 0-100%**

- Strongest suppression at $p_T$ 5-8 GeV/c
- No significant collision energy dependence compared with 2.76 TeV

**Prompt $D^0$**

5.02 TeV pp (27.4 pb$^{-1}$) + PbPb (530 μb$^{-1}$)

PLB 782 (2018) 474
Open HF $R_{AA}$ in PbPb (2/8)

Centrality 0-100%

5.02 TeV pp (27.4 pb$^{-1}$) + PbPb (530/404 μb$^{-1}$)

- **Prompt $D^0$**
  - Strongest suppression at $p_T$ 5-8 GeV/c
  - No significant collision energy dependence compared with 2.76 TeV

- **Charged hadrons vs. Prompt $D^0$**
  - Similar suppression in a wide kinematic range
  - Hint of less suppression of $D^0$ at low $p_T$?

$R_{AA}$ vs. $p_T$ (GeV/c)
Open HF $R_{AA}$ in PbPb (3/8)

Centrality 0-100%

- Strongest suppression at $p_T$ 5-8 GeV/c
- No significant collision energy dependence compared with 2.76 TeV

**Prompt D⁰**
- Similar suppression in a wide kinematic range
- Hint of less suppression of $D^0$ at low $p_T$?

**Charged hadrons vs. Prompt D⁰**
- No significant meson flavor dependence of $R_{AA}$ at high $p_T$ with the current accuracy

---

5.02 TeV pp (27.4 pb⁻¹) + PbPb (530/404/368 μb⁻¹)

**CMS Supplementary**

- Light
  - $h^+$
- Beauty
  - $B^\pm$ $|y| < 2.4$
- Charm
  - $D^0 + \bar{D}^0$

$R_{AA}$ vs $p_T$ (GeV/c)

$|y| < 1$

Centrality 0-100%

---

PRL 119 (2017) 15230
JHEP 04 (2017) 039
PLB 782 (2018) 474
Open HF $R_{AA}$ in PbPb (4/8)

**Centrality 0-100%**

- **Prompt $D^0$**
  - Strongest suppression at $p_T$ 5-8 GeV/c
  - No significant collision energy dependence compared with 2.76 TeV

**Charged hadrons vs. Prompt $D^0$**
- Similar suppression in a wide kinematic range
- Hint of less suppression of $D^0$ at low $p_T$?

**$B^+$ vs. Prompt $D^0$**
- No significant meson flavor dependence of $R_{AA}$ at high $p_T$ with the current accuracy

**Non-prompt $J/\psi$ vs. Prompt $D^0$**
- Hint of flavor hierarchy of $R_{AA}$ at low $p_T$
- Flat Non-prompt $J/\psi$ $R_{AA}$ at high $p_T$
Open HF $R_{AA}$ in PbPb (5/8)

Centrality 0-100%

Prompt $D^0$
- Strongest suppression at $p_T$ 5-8 GeV/c
- No significant collision energy dependence compared with 2.76 TeV

Charged hadrons vs. Prompt $D^0$
- Similar suppression in a wide kinematic range
- Hint of less suppression of $D^0$ at low $p_T$?

$B^+$ vs. Prompt $D^0$
- No significant meson flavor dependence of $R_{AA}$ at high $p_T$ with the current accuracy

Non-prompt $J/\psi$ vs. Prompt $D^0$
- Hint of flavor hierarchy of $R_{AA}$ at low $p_T$
- Flat Non-prompt $J/\psi$ $R_{AA}$ at high $p_T$

Non-prompt $D^0$ vs. Prompt $D^0$
- Stronger suppression for Prompt $D^0$ in intermediate $p_T$
Prompt $D^0$
- Strongest suppression at $p_T$ 5-8 GeV/c
- No significant collision energy dependence compared with 2.76 TeV

Charged hadrons vs. Prompt $D^0$
- Similar suppression in a wide kinematic range
- Hint of less suppression of $D^0$ at low $p_T$?

$B^+$ vs. Prompt $D^0$
- No significant meson flavor dependence of $R_{AA}$ at high $p_T$ with the current accuracy

Non-prompt $J/\psi$ vs. Prompt $D^0$
- Hint of flavor hierarchy of $R_{AA}$ at low $p_T$
- Flat Non-prompt $J/\psi$ $R_{AA}$ at high $p_T$

Non-prompt $D^0$ vs. Prompt $D^0$
- Stronger suppression for Prompt $D^0$ in intermediate $p_T$

Non-prompt $J/\psi$ vs. Non-prompt $D^0$ vs. $B^+$
- Consistent at 10-20 GeV/c
- $B \rightarrow D$ analysis is on-going to reach lower $p_T$
Open HF $R_{AA}$ in PbPb (7/8)

Centrality 0-100%

- **Prompt $D^0$**
  - Strongest suppression at $p_T$ 5-8 GeV/c
  - No significant collision energy dependence compared with 2.76 TeV

- **Charged hadrons vs. Prompt $D^0$**
  - Similar suppression in a wide kinematic range
  - Hint of less suppression of $D^0$ at low $p_T$?

- **$B^+$ vs. Prompt $D^0$**
  - No significant meson flavor dependence of $R_{AA}$ at high $p_T$ with the current accuracy

- **Non-prompt $J/\psi$ vs. Prompt $D^0$**
  - Hint of flavor hierarchy of $R_{AA}$ at low $p_T$
  - Flat Non-prompt $J/\psi$ $R_{AA}$ at high $p_T$

- **Non-prompt $D^0$ vs. Prompt $D^0$**
  - Stronger suppression for Prompt $D^0$ in intermediate $p_T$

- **Non-prompt $J/\psi$ vs. Non-prompt $D^0$ vs. $B^+$**
  - Consistent at 10-20 GeV/c
  - $B \to D$ analysis is on-going to reach lower $p_T$

- **Prompt $J/\psi$ vs. Prompt $D^0$**
  - Consistent over a wide kinematic range

5.02 TeV pp (27.4 pb$^{-1}$) + PbPb (530/368 μb$^{-1}$)

Supplementary CMS

- Open charm
  - $D^0 + \bar{D}^0$

- Hidden charm
  - Prompt $J/\psi$
    - $1.8 < |y| < 2.4$
    - $|y| < 2.4$
  - lyl < 1

- $p_T$ (GeV/c)

- $R_{AA}$

- Cent. 0-100%
Open HF $R_{AA}$ in PbPb (8/8)

Centrality 0-100%

$5.02 \text{ TeV pp (27.4 pb}^{-1}) + \text{PbPb (530/404/368 pb}^{-1})$

**CMS Supplementary**

- **Light**
  - $h^+$

- **Charm**
  - $D^0 + \overline{D^0}$

**Beauty**

- $B^\pm$ $|y| < 2.4$
- $(b \rightarrow) D^0$
- $(b \rightarrow) J/\psi$
- $1.8 < |y| < 2.4$
- $|y| < 2.4$
- $|y| < 1$

$R_{AA}$ vs. $p_T$ (GeV/c)

**Prompt $D^0$**

- Strongest suppression at $p_T$ 5-8 GeV/c
- No significant collision energy dependence compared with 2.76 TeV

**Charged hadrons vs. Prompt $D^0$**

- Similar suppression in a wide kinematic range
- Hint of less suppression of $D^0$ at low $p_T$?

**B vs. Prompt $D^0$**

- No significant meson flavor dependence of $R_{AA}$ at high $p_T$ with the current accuracy

**Non-prompt $J/\psi$ vs. Prompt $D^0$**

- Hint of flavor hierarchy of $R_{AA}$ at low $p_T$
- Flat Non-prompt $J/\psi$ $R_{AA}$ at high $p_T$

**Non-prompt $D^0$ vs. Prompt $D^0$**

- Stronger suppression for Prompt $D^0$ in intermediate $p_T$

**Non-prompt $J/\psi$ vs. Non-prompt $D^0$ vs. $B^+$**

- Consistent at 10-20 GeV/c
- $B \rightarrow D$ analysis is on-going to reach lower $p_T$

**Prompt $J/\psi$ vs. Prompt $D^0$**

- Consistent over a wide kinematic range

---

arXiv:1810.11102
EPJC 78 (2018) 509
PRL 119 (2017) 15230
JHEP 04 (2017) 039
PLB 782 (2018) 474

Jing Wang (MIT), LBNL HF/MVTX Workshop (Berkeley)
Prompt $D^0 v_2$ in PbPb

- Positive prompt $D^0 v_2$ in studied $p_T$ range
  - Low $p_T$: charm quarks take part in the collective motion
  - High $p_T$: indicates path length dependence of energy loss
- Peaks around $p_T$ at 3 GeV/c
- Increase at peripheral events
- Low $p_T$: $v_2$ (prompt $D^0$) < $v_2$ (charged particles)
  - Difference in most central events is smaller
- High $p_T$: $v_2$ (prompt $D^0$) ≈ $v_2$ (charged particles)
  - Consistent with $\Delta E$ (charm) ≈ $\Delta E$ (light quark) observed in $R_{AA}$
- Similar $p_T$ dependence

PLB 776 (2017) 195
PRL 120 (2018) 202301
Prompt $D^0 v_3$ in PbPb

- First measurements of $D^0 v_3$
  - Low $p_T$: $v_3$ (prompt $D^0$) > 0
  - High $p_T$: $v_3$ (prompt $D^0$) ≈ 0
- Peaks around 3 GeV/c
- Little centrality dependence

- Low $p_T$: $v_3$ (prompt $D^0$) < $v_3$ (charged particles)
- High $p_T$: $v_3$ (prompt $D^0$) ≈ $v_3$ (charged particles)
- Similar $p_T$ dependence
- Both have little centrality dependence
# Model Market

<table>
<thead>
<tr>
<th>Models</th>
<th>Transport Impl.</th>
<th>Bulk Evolution</th>
<th>Initial Condition</th>
<th>Starting Time</th>
<th>Final QGP Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>UrQMD</td>
<td>LV</td>
<td>3+1D ideal hydro</td>
<td>Smearred UrQMD string/energy density</td>
<td>0.5 fm</td>
<td>160 MeV</td>
</tr>
<tr>
<td>TAMU</td>
<td>LV</td>
<td>2+1D ideal hydro</td>
<td>Smooth initial conditions</td>
<td>0.4 fm</td>
<td>170 MeV</td>
</tr>
<tr>
<td>Nantes/SUBATECH/MC@sHQ+EPOS2</td>
<td>BM</td>
<td>EPOS2 3+1D ideal hydro</td>
<td>Fluctuating initial conditions</td>
<td>0.3 fm</td>
<td>166 MeV</td>
</tr>
<tr>
<td>Catania</td>
<td>BM</td>
<td>HQ interact with bulk massive quasi-particles, T-dependence of αs is tuned to match the EoS</td>
<td></td>
<td>0.3 fm</td>
<td>170 MeV</td>
</tr>
<tr>
<td>LBL-CCNU</td>
<td>BM</td>
<td>VISHNU 2+1D viscous hydro</td>
<td>Event-by-event fluctuating initial conditions</td>
<td>0.6 fm</td>
<td>165 MeV</td>
</tr>
<tr>
<td>Duke</td>
<td>LV</td>
<td>VISHNU 2+1D viscous hydro</td>
<td>Event-by-event fluctuating initial conditions</td>
<td>0.6 fm</td>
<td>165 MeV</td>
</tr>
<tr>
<td>POWLANG/Torino</td>
<td>LV</td>
<td>ECHO-QGP 3+1D viscous hydro</td>
<td>Event-by-event fluctuating initial conditions</td>
<td>0.6 fm</td>
<td>155 MeV</td>
</tr>
<tr>
<td>PHSD</td>
<td>BM</td>
<td>HQ interact with off-shell light quasi-particles whose masses and widths are determined to match IQCD EoS</td>
<td></td>
<td>0.6 fm</td>
<td>160 MeV</td>
</tr>
<tr>
<td>Djordjevic et al.</td>
<td>DGLV</td>
<td>DGLV: variant of GLV approach including gluon radiation from multiple scattering up to 1st order in opacity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vitev et al.</td>
<td>SCETG</td>
<td>Soft Collinear Effective Theory with Glauber Gluons including quark masses (SCETG)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CUJET3.0</td>
<td>DGLV + VISHNU 2+1D viscous hydro (elastic-only)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AdS/CFT</td>
<td></td>
<td>Model based on the anti-de Sitter/conformal field theory</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Nuclear Physics A 979 (2018) 21–86
arXiv:1809.10734
R_{AA} vs. Theoretical Predictions

- Most models can predict the shape
- (D) Theoretical calculation is below data at high p_{T}
- Shadowing plays an important role at low p_{T}
- $R_{AA}$ is sensitive to evolution models at low p_{T}
- Measurements of $R_{AA} + v_2$ constraint transport coefficients

arXiv:1703.00822
JHEP 02 (2016) 169
Phys. Rev. D 91 (2015) 085019
Phys. Rev. D 93 (2016) 074030
$v_n$ vs. Theoretical Predictions

CMS

PbPb $\sqrt{s_{\text{NN}}} = 5.02$ TeV

Calculations for prompt D
   - LBT
   - PHSD
   - TAMU
   - SUBATECH
   - CUJET 3.0

Prompt $D^0$, $|y| < 1.0$
Syst. from nonprompt $D^0$
Other syst.

Charged particle, $|y| < 1.0$

<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
<th>$v_2$</th>
<th>$v_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>10</td>
<td>0.2</td>
<td>0.25</td>
</tr>
<tr>
<td>15</td>
<td>0.25</td>
<td>0.3</td>
</tr>
<tr>
<td>20</td>
<td>0.3</td>
<td>0.35</td>
</tr>
<tr>
<td>25</td>
<td>0.35</td>
<td>0.4</td>
</tr>
<tr>
<td>30</td>
<td>0.4</td>
<td>0.45</td>
</tr>
<tr>
<td>35</td>
<td>0.45</td>
<td>0.5</td>
</tr>
<tr>
<td>40</td>
<td>0.5</td>
<td>0.55</td>
</tr>
</tbody>
</table>

$|0-10\%|$ $|10-30\%|$ $|30-50\%|$
Strange B mesons

- Proposed enhancement of strangeness in the QGP state compared with hadron gas
- Could heavy quarks be hadronized via recombination with other quarks in the medium in addition to fragmentation? What is the role of coalescence?
- ALICE measurement of $D_s$ production: indicates higher $R_{AA}$ of $D_s$ than $D^0$
- $B_s$ meson: case in beauty, cleaner probe!

arXiv:1804.09083
Bs invariant mass in pp and PbPb

First measurement on combination of beauty and strange in HI collisions!

- Cut optimization via boosted decision tree (BDT) algo plays important role on signal extraction
**B_s R_{AA} in PbPb**

- Hint of higher $R_{AA}$ of $B_s$ compared with non-strange $B$ meson
- Substantial statistical and systematic uncertainty
- Good first try! → CMS’s capability to perform fully reconstructed $B_s$ measurement
- 4-5x more statistics in 2018 data taking

---

**B_s, B^+ R_{AA}**

<table>
<thead>
<tr>
<th>CMS</th>
<th>$B_s^0$</th>
<th>$B_s^+$</th>
<th>TAMU</th>
<th>CUJET3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>y</td>
<td>&lt; 2.4$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**B_s R_{AA} / B^+ R_{AA}**

<table>
<thead>
<tr>
<th>CMS</th>
<th>$R_{AA}^{B_s^0} / R_{AA}^{B_s^+}$</th>
<th>TAMU</th>
<th>CUJET3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>y</td>
<td>&lt; 2.4$</td>
<td></td>
</tr>
</tbody>
</table>

---

Jing Wang (MIT), LBNL HF/MVTX Workshop (Berkeley)

arXiv:1810.03022
Other observables?

CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249

Jet 0, pt: 205.1 GeV
Jet 1, pt: 70.0 GeV

☑️ $R_{AA}$
☑️ Flow $v_n$

Heavy flavor in jets?
Why study D meson production in jets?

- Enhancement of low $p_T$ light hadrons at large angles about jets
  - Light hadron jet shape analysis
Why study D meson production in jets?

- Enhancement of low $p_T$ light hadrons at large angles about jets
  \[ \text{Light hadron jet shape analysis} \]

- **How to explain**
  - medium-induced gluon radiation?
  - medium response?
  - multiple scatterings?
  - ......
Why study D meson production in jets?

- Enhancement of low $p_T$ light hadrons at large angles about jets
  - Light hadron jet shape analysis
- How to explain
  - medium-induced gluon radiation?
  - medium response? $m_c \gg T_{QGP}$
  - multiple scatterings?
  - ……
- Vary mass of the associated hadrons
  - Heavy flavor!

*Why study D meson production in jets?*

*Enhancement of low $p_T$ light hadrons at large angles about jets
  - Light hadron jet shape analysis
  - How to explain
    - medium-induced gluon radiation?
    - medium response? $m_c \gg T_{QGP}$
    - multiple scatterings?
  - Vary mass of the associated hadrons
    - Heavy flavor!*

---


**CMS PbPb, $\sqrt{s_{NN}} = 2.76$ TeV**

\[ L dt = 150 \mu b^{-1} \]

anti-$k_T$ jets: $R = 0.3$

- $p_T^{jet} > 100$ GeV/c
- $0.3 < |n^{jet}| < 2$
- $p_T^{track} > 1$ GeV/c

**JHEP 05 (2018) 006**

pp $27.4 \text{ pb}^{-1}$ (5.02 TeV), PbPb $404 \mu b^{-1}$ (5.02 TeV)

anti-$k_T$, $R=0.4$ jets, $p_T > 120$ GeV, $|\Delta n| < 1.6$

\[ 0.7 < p_T^{track} < 300 \text{ GeV} \]

**PbPb 0-10%**

\[ \rho(\Delta \tau)_{\text{PbPb}} / \rho(\Delta \tau)_{\text{pp}} \]
Why study D meson production in jets?

Even more …

Production mechanism of charm
- The role of gluon splitting
- Recombination in the medium

Heavy quark behavior and interactions in the medium
- Energy loss
  - Inclusive measurements:
    - heavy-flavor hadrons spectra, azimuthal anisotropy, heavy flavor tag jets
  - Details on interaction of heavy quarks about jet directions
- Correlation - More sensitive observable to HQ diffusion coefficients + models
Radial profile of $D^0$ in jets

**Low $D_pT$: $4 < p_{T}^{D} < 20$ GeV/c**

The ratio of PbPb over pp:
- Low $D_pT$: increases as a function of $r$
  - Hint that $D^0$ are further from jet axis in PbPb than pp
- High $D_pT$: consistent with unity
What can we expect by the HL-HLC era? (1/4)

**High-Luminosity LHC!**

CMS Upgrade in Run3/4
- Higher luminosity
- Upgrade inner tracker to cover a large acceptance up to $|\eta| < 4$
- Improve L1 and DAQ rate allowing more sophisticated triggers and recording a larger number of minimum-bias triggered events
- Propose MIP Timing Detector with a good time resolution
What can we expect by the HL-HLC era? (2/4)

**High-Luminosity LHC!**

- A solid conclusion on the flavor dependence of energy loss will be addressed
- Stronger discrimination power on theoretical models
- Low-\(p_T\) exploration: Flow peak

---

arXiv:1812.06772
What can we expect by the HL-HLC era? (3/4)

**High-Luminosity LHC!**

- Stronger constraints on the diffusion coefficients

---

Catania group

Duke group

$\chi^2_{R_{AA}}$ / n.d.f.

$2\pi TD_s$

$p_T = 0 \text{ GeV/c}$

$T/T_c$

arXiv:1812.06772

Jing Wang (MIT), LBNL HF/MVTX Workshop (Berkeley)
What can we expect by the HL-HLC era? (4/4)

**High-Luminosity LHC!**

- High-precision HF correlation measurements
- Strong constraints on CNM effects

**Figure:**
- CMS, 5.02 TeV
  - pp 650 pb$^{-1}$ + PbPb 10 nb$^{-1}$
  - $4 < p_T^D < 20$ GeV/c
  - $|y^D| < 2$

- LHCb, 8.8 TeV
  - pp 104 pb$^{-1}$ + pPb 250 nb$^{-1}$
  - $2.5 < y^* < 3.5$
  - $-3.5 < y^* < -2.5$

- **B$^+$:**
  - POWLANG 0-20%
  - EPS09, no medium
  - HTL, smear=0.2 fm
  - HTL, smear=0.4 fm
  - lQCD, smear=0.2 fm
  - lQCD, smear=0.4 fm
Summary

- $R_{AA}$ of multiple heavy flavor particles are measured over a wide kinematic range
- High precision measurement of $D^0 v_2 v_3$ is performed
- First time probing combination of beauty and strange in HI collisions
- First measurement of the radial profile of $D^0$ mesons in jets in PbPb and pp
- Much more precise measurement of heavy flavors is expected in HL-LHC era

The MIT RHIG’s work was supported by US DOE-NP
Back up

Thanks for your attention!
Prompt D⁰
- Strongest suppression at p_T 5-8 GeV/c
- No significant collision energy dependence compared with 2.76 TeV

Charged hadrons vs. Prompt D⁰
- Similar suppression in a wide kinematic range
- Hint of less suppression of D⁰ at low p_T?

B⁺ vs. Prompt D⁰
- CMS Flavor R_AA Zoo!
- Consistent at 10-20 GeV/c
- B→D analysis is on-going to reach lower p_T

Non-prompt J/ψ vs. Non-prompt D⁰ vs. B⁺
- Consistent over a wide kinematic range

Non-prompt J/ψ vs. Prompt D⁰
- Stronger suppression for Prompt D⁰ in intermediate p_T

Open HF R_AA in PbPb (8/8)

Centrality 0-100%

5.02 TeV pp (27.4 pb⁻¹) + PbPb (530/404/368 μb⁻¹)

CMS Supplementary

Light
- h⁺

Charm
- D⁰ + D̅⁰

Beauty
- B⁺ l_y < 2.4
- (b →) D⁰
- (b →) J/ψ
- 1.8 < l_y < 2.4
- l_y < 2.4

R_AA and lumi. uncert.

|ψ⟩ → (b) D
|ψ⟩ → (b) J/ψ
|y| < 1
|y| < 2.4
±
±

arXiv:1810.11102
EPJC 78 (2018) 509
PRL 119 (2017) 15230
JHEP 04 (2017) 039
PLB 782 (2018) 474

Jing Wang (MIT), LBNL HF/MVTX Workshop (Berkeley)
Observable

- Radial distribution of $D^0$ with respective to the jet axis:
  \[ \frac{1}{N_{JD}} \frac{dN_{JD}}{dr} \]

- Angular distance
  \[ r = \sqrt{\Delta \phi_{JD}^2 + \Delta \eta_{JD}^2} \]

- The final distribution is normalized to unity in $r < 0.3$
- No $p_T$ weight as light-hadron jet shape analysis
Radial profile of $D^0$ in jets (1/3)

Low $D_pT$: $4 < p_T^{D^0} < 20$ GeV/c

- Reach maximum at $0.05 < r < 0.1$

High $D_pT$: $p_T^{D^0} > 20$ GeV/c

- Fall rapidly as a function of $r$

CMS Preliminary

PbPb

pp
Radial profile of $D^0$ in jets (2/3)

**Low $D^0 p_T$: $4 < p_T^{D^0} < 20$ GeV/c**

- Predictions from PYTHIA8
  - Low $D^0 p_T$: produce a wider radial profile than measurements
  - High $D^0 p_T$: agree with measurements

**High $D^0 p_T$: $p_T^{D^0} > 20$ GeV/c**
Comparison among experiments

- Consistent result over experiments and collision energy
- CMS did a good job : )
Beauty $v_2$

![Graph showing $v_2$ vs. $p_T$](image)

- Prompt $D^0$, $|y| < 1.0$
- Charged particle, $|\eta| < 1.0$
- Nonprompt $J/\psi$, 10-60%, 2.76 TeV
- $p_T$ 3-6.5 GeV, 1.6 < $|y|$ < 2.4; $p_T$ 6.5-30 GeV, $|y| < 2.4$

CMS, PbPb $\sqrt{s_{NN}} = 5.02$ TeV

Jing Wang (MIT), LBNL HF/MVTX Workshop (Berkeley)
Extraction of $D^0 \nu_n$

- Simultaneous fit on invariant mass distribution and $\nu_n$ vs mass

\[ \nu_n^{S+B}(m_{\text{inv}}) = \alpha(m_{\text{inv}}) \nu_n^S + (1 - \alpha(m_{\text{inv}})) \nu_n^B(m_{\text{inv}}), \]

- $\nu_n^S$: $\nu_n$ of signal $D^0$
  -> fit parameter
- other terms:
  -> $\nu_n^{S+B}(m_{\text{inv}})$: $\nu_n$ of all $D^0$ candidates
  -> $\nu_n^B(m_{\text{inv}})$: $\nu_n$ of combinatorial background, modeled by a linear function
  -> $\alpha(m_{\text{inv}})$: signal fraction from invariant mass spectra fit

arXiv: 1708.03497
Scalar Product Method

- $v_n$ coefficient can be expressed in terms of Q-vectors as

$$v_n \{SP\} = \frac{\langle Q_{n,D^0} Q_{nA}^* \rangle}{\sqrt{\langle Q_{nA} Q_{nB}^* \rangle \langle Q_{nA} Q_{nC}^* \rangle / \langle Q_{nB} Q_{nC}^* \rangle}}.$$

Scaling factor from 3 sub events

$$Q_n^- = \sum_{k=1}^{M} \omega_k e^{i n \phi_k}.$$
What can we expect by the HL-HLC era?

LHC and CMS schedule

<table>
<thead>
<tr>
<th>LS-2</th>
<th>Run-3</th>
<th>LS-3</th>
<th>HL-LHC (run-4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS Phase I</td>
<td>PbPb: 6-7/nb</td>
<td>CMS Phase II</td>
<td>PbPb: 6-7/nb</td>
</tr>
<tr>
<td>ALICE upgrade</td>
<td>2019-2020</td>
<td>Tracker $</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td>2021-2023</td>
<td>L1: 750kHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2024-2025</td>
<td>DAQ: 60 GB/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2026-2029</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>ITS</td>
<td>TPC readout (50kHz)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
What can we expect by the HL-HLC era?

A Mip Timing Detector at CMS

Design constraints:
- Timing resolution of 30ps
- Radiation tolerance to 4/ab
- MIP sensitivity with time resolution of ~30 ps
- Hermetic coverage for |η|<3

C. Neu, US CMS collaboration meeting, 2018

- Cost effective design over large area
- Manageable data volume and power
- Marginal impact on rest of CMS
- Integration fits within schedule
Prompt $D^0$ cross-section in pp

- $p_T$ range covers from 2 to 100 GeV/c (wide $p_T$ range!)
- Compared with the FONLL [1] and GM-VFNS [2] predictions

$\sigma_{pp} (\text{pb/Gev/c})$

CMS

$|y| < 1.0$

Global uncert. 2.5%

$D^0 + \bar{D}^0$

$27.4 \text{ pb}^{-1}$ (5.02 TeV pp)


arXiv: 1708.04962
Datasets

- LHC Run II PbPb collisions at 5.02 TeV
- Double-muon samples for B mesons
- Large MinBias- and Centrality- triggered samples for low-pT D mesons
- Dedicated **HLT D⁰ filters** to enhance the statistics at very high p_T

**Hardware L1 jet triggers selection**

- Level-1 (L1) jet algorithm with online background subtraction

**Track selection in software triggers**

- Track seed p_T cut applied:
  - p_T > 2 GeV for pp
  - p_T > 8 GeV for PbPb

**D⁰ selection**

- D⁰ online reconstruction
- loose selection based on D⁰ vertex displacement
Extraction of prompt fraction with data

Prompt: $c \rightarrow D^0 \pi K$

Non-prompt: $B \rightarrow D^0 \pi K$

- Prompt: $D^0$ mesons coming from $c$-quark fragmentation
- Extract prompt fraction with data (new method!)
- Different shapes of $DCA$ distributions of prompt and non-prompt $D^0$

Prompt:

- Smaller $D^0$ DCA

Non-prompt:

- Larger $D^0$ DCA
Extraction of prompt fraction with data

- Prompt: $D^0$ mesons coming from c-quark fragmentation
- Extract prompt fraction with data (new method!)
- Different shapes of $DCA$ distributions of prompt and non-prompt $D^0$
- The shapes of the template of DCA distributions from MC

**Prompt fraction**

<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
<th>Prompt fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.8</td>
</tr>
<tr>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>20</td>
<td>0.4</td>
</tr>
<tr>
<td>30</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Syst. uncert.**

27.4 pb$^{-1}$ (5.02 TeV pp)

**CMS Supplementary**

$|y| < 1.0$

$10.0 < p_T < 12.5$ GeV/c
Open HF $R_{AA}$ in PbPb at 5.02 TeV

$|y| < 1$, Centrality 0-100%

5.02 TeV pp (27.4 pb$^{-1}$) + PbPb (530/404/368 μb$^{-1}$)

- **Prompt $D^0$**
  - Strongest suppression at $p_T$ 5-8 GeV/c
  - No significant collision energy dependence compared with 2.76 TeV

- **Charged hadrons vs. Prompt $D^0$**
  - Similar suppression in a wide kinematic range
  - Hint of less suppression of $D^0$ at low $p_T$?

- **$B^+$ vs. Prompt $D^0$**
  - No significant meson flavor dependence of $R_{AA}$ at high $p_T$ with the current accuracy

- **Non-prompt $J/\psi$ vs. Prompt $D^0$**
  - Hint of flavor hierarchy of $R_{AA}$ at low $p_T$
  - Flat Non-prompt $J/\psi$ $R_{AA}$ at high $p_T$

- **Non-prompt $D^0$ vs. Prompt $D^0$**
  - Stronger suppression for Prompt $D^0$ in intermediate $p_T$

- **Non-prompt $J/\psi$ vs. Non-prompt $D^0$ vs. $B^+$**
  - Consistent at 10-20 GeV/c
  - $B \to D$ analysis is on-going to reach lower $p_T$

- **Prompt $J/\psi$ vs. Prompt $D^0$**
  - Consistent over a wide kinematic range
**D^0** reconstruction

- Primary vertex reconstruction *several tracks*
- D^0 candidates (vertex) reconstruction *pairing two tracks + kinematic fitter*
- D^0 candidates selection (TMVA) *decay topology*
  - Pointing angle (\(\alpha\)) < \(~0.12\)
  - 3D decay length (\(d_0\)) normalized by its error > \(~4\)
  - Secondary vertex probability > \(~0.1\)
  - Distance of Closest Approach (DCA) < \(~0.008\ cm\)
- Raw yields extraction *Invariant mass*

Mass distributions fitted by
- Double gaussian (Signal)
- 3rd order polynomial (Combinatorial)
- Single gaussian (K-\(\pi\) swapped)
  - No PID: Candidates with wrong mass assignment

```
Mass distributions fitted by
- Double gaussian (Signal)
- 3rd order polynomial (Combinatorial)
- Single gaussian (K-\(\pi\) swapped)
  - No PID: Candidates with wrong mass assignment
```
CMS detector

- Inner tracker: charged particles
- Muon detectors
- Muon
- HCAL
- ECAL
- Tracker
  - $|\eta| < 2.4$
  - $|\eta| < 5.2$
  - $|\eta| < 3.0$
  - $|\eta| < 2.5$

EM and hadronic calorimeters
  - Photons, Jet

Forward Calorimeter:
  - MB triggers, centrality
High-Level-Trigger (HLT) D⁰ triggers

Triggers performance

CMS Preliminary

pp, \( \sqrt{s} = 5.02 \) TeV

Higgs boson (HVTX) Workshop (Berkeley)

CMS

404 \( \mu \) b⁻¹ (5.02 TeV PbPb)

HLT D meson trigger efficiency vs. \( p_T (D⁰) \) (GeV)

- HLT D meson \( p_T \geq 8 \)
- HLT D meson \( p_T \geq 15 \)
- HLT D meson \( p_T \geq 20 \)
- HLT D meson \( p_T \geq 30 \)

HLT D meson trigger efficiency vs. \( D^0 p_T \) (GeV/c)

- \( D^0 \) trigger \( p_T \geq 20 \)
- \( D^0 \) trigger \( p_T \geq 40 \)
- \( D^0 \) trigger \( p_T \geq 60 \)
Systematic uncertainties from non-prompt $D^0$ are evaluated in a data driven method based on:

- $v_n$ of $D^0$ with all analysis cut and w/o $b_0$ cut
- Fractions of prompt $D^0$ with all analysis cut and w/o $b_0$ cut

**All analysis cut:**

$$v_{n,1}^{\text{sig}} = f_{p,1} v_n^p + (1-f_{p,1}) v_n^{np}$$

**Without $b_0$ cut:**

$$v_{n,2}^{\text{sig}} = f_{p,2} v_n^p + (1-f_{p,2}) v_n^{np}$$

$$v_n^p = v_{n,1}^{\text{sig}} + \frac{1-f_{p,1}}{f_{p,1}-f_{p,2}} (v_{n,1}^{\text{sig}} - v_{n,2}^{\text{sig}})$$

- $D^0$ $v_n$ with all analysis cuts as central value
- As systematics from non-prompt $D^0$
Event mixing technique

- **Signal**: jets and $D^0$ mesons from the same hard scattering
- **Background**: fake jets, jets and $D^0$ mesons in underlying events, …
Event mixing technique

- Correlate $D^0$ mesons and jets in **triggered events (raw)** and **MB events (bkg)**
Event mixing technique

- Correlate $D^0$ mesons and jets in **triggered events (raw)** and **MB events (bkg)**

Raw $D$

\[ \text{Raw D jets} - \text{Raw jets} = \text{raw D signal jet} \]

MB $D$

\[ \text{MB D jets} = \text{MB jets} \]
Event mixing technique

- Correlate $D^0$ mesons and jets in **triggered events (raw)** and **MB events (bkg)**
Event mixing technique

- Correlate $D^0$ mesons and jets in **triggered events (raw)** and **MB events (bkg)**

Raw $D$

MB $D$

Raw jets

MB jets

raw $D$

bkg $D$

signal $D$

signal jet

signal jet

signal jet
D⁰ reconstruction in CMS

CMS
D⁰ + D̅⁰
5 < p_T < 6 GeV/c
|y| < 1.0
Cent. 0-100%

530 µb⁻¹ (5.02 TeV PbPb)

Data
Fit
Signal
Combinatorial
K-π swapped

Primary vertex
Secondary vertex

non-prompt D⁰

Prompt D⁰

Primary vertex
Secondary vertex

Cent. 0-100%
b channel reconstruction in CMS

Inclusive: non-prompt J/ψ

PbPb 368 μb⁻¹ (5.02 TeV)

1.8 ≤ |y| ≤ 2.4
4.5 ≤ p_T^{μμ} < 5.5 GeV/c
Cent. 0-100%

- Data
- Total fit
- Prompt J/ψ
- J/ψ from b hadrons
- Background

CMS

Events / (0.025 GeV/c²)

2.6 2.7 2.8 2.9 3 3.1 3.2 3.3 3.4 3.5
m_{μμ} (GeV/c²)

200 400 600 800 1000 1200 1400

Primary vertex

Secondary vertex

Inclusive: non-prompt D⁰

D⁰

Primary vertex

Secondary vertex

Exclusive: fully reconstructed B

PbPb 351 μb⁻¹ (PbPb 5.02 TeV)

10 < p_T < 15 GeV/c
|y| < 2.4

CMS

Events / (20 MeV/c²)

B⁺+B⁻

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

Jing Wang (MIT), LBNL HF/MVTX Workshop (Berkeley)