Production and Collective Flow of Open Heavy Flavor in PbPb Collisions with CMS

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For the CMS collaboration

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Heavy quarks are ideal probes for the QGP

- Mostly produced early in time, $p_T$ spectra could be calculated with pQCD
- Could be traced (though heavy flavor mesons)

At intermediate to high $p_T$:
- Test our understanding of jet quenching
- Smaller energy loss than gluons (color charge)
- Smaller radiative energy loss than light quarks due to dead-cone effects

At low transverse momentum:
- “Kicked around” by quasi-particles in the QGP
- Probe the temperature and density of the medium

Heavy quarks experience \textbf{drag force} from the QGP

New measurements of Heavy flavor $R_{AA}$ and $v_n$ from CMS

Yen-Jie Lee (MIT)  
Open Heavy Flavor with CMS
2015 pp and PbPb data at 5.02 TeV

- **Non-prompt J/ψ and B meson:**
  - Dimuon trigger which sample the full delivered luminosity by LHC

- **Low $p_T$ $D^0$:** MB and event centrality triggered events
  - pp: 2B MB events
  - PbPb: 170M 0-100% and 270M 30-100% events analyzed

- **High $p_T$ $D^0$:** dedicated $D^0$ triggers for both PbPb and pp
  - Compared to minimum bias triggers, the high $p_T$ $D^0$ statistics are increased by a factor of **800 (30)** in pp (PbPb) collisions

(1) **Hardware level jet trigger**
   (Level 1 filter)

(2) **Online $D^0$ to $K\pi$ analysis** in the high level trigger computing farm (HLT filter)
D⁰ identification in CMS

- No K-π identification for charged tracks used
- D⁰ from pairs of oppositely charged tracks with both Kπ and πK mass assumptions (2 D⁰ candidates per pair)
D^0 identification in CMS

- No K-π identification for charged tracks used
- D^0 from pairs of *oppositely charged tracks* with both Kπ and πK mass assumptions (2 D^0 candidates per pair)
- Secondary vertex reconstruction (SV)
- D^0 identification:
  - Secondary vertex quality

Diagram:
- Secondary vertex
- Primary vertex
D⁰ identification in CMS

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  - 3D decay length significance \( (d_0/\sigma(d_0)) \)
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  - Angle \(\alpha\) between D⁰ momentum \(\vec{P}_{D^0}\) and D⁰ flight direction \(\vec{d}_0\)
**D^0 identification in CMS**

- No K-π identification for charged tracks used
- D^0 from pairs of **oppositely charged tracks** with both Kπ and πK mass assumptions (2 D^0 candidates per pair)
- Secondary vertex reconstruction (SV)
- D^0 identification:
  - Secondary vertex quality
  - 3D decay length significance \( (d_0/\sigma(d_0)) \)
  - Angle \( \alpha \) between D^0 momentum \( \vec{P}_{D^0} \) and D^0 flight direction \( \vec{d}_0 \)
  - D^0 DCA (used in \( v_n \) analysis)
    - DCA < 0.008 cm
    - Suppress non-prompt D^0
Double Gaussian for $D^0 \rightarrow K\pi$ signal

3rd order polynomial for Combinatorial background

Gaussian shape for Swapped mass hypothesis (Wrong $K-\pi$ mass assignment)
Extraction of Prompt $D^0$ with DATA

- Significant contribution of non-prompt $D^0$ from $b$ hadron decays at LHC ($O(10\%)$)
- CMS separates prompt and non-prompt $D^0$ with $D^0$ DCA
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Extraction of Prompt $D^0$ with DATA

- Prompt $D^0$
- Non-prompt $D^0$
- $D^0$ vertex
- Primary vertex
- Smaller $D^0$ DCA
- Larger $D^0$ DCA
Extraction of Prompt D⁰ with DATA

- Significant contribution of non-prompt D⁰ from b hadron decays at LHC (O(10%))
- CMS separates prompt and non-prompt D⁰ with D⁰ DCA
- Prompt fraction extraction from a MC template fit

**PbPb 0-100%**

**PbPb \( s_{NN} = 5.02 \text{ TeV} \)**

CMS Preliminary

![D⁰ DCA (cm) vs. dN / d(D⁰ DCA) (cm⁻¹)]

- Cent. 0-100%
- \( |y| < 1.0 \)
- \( 10.0 < p_T < 12.5 \text{ GeV/c} \)
- Data
- Prompt D⁰
- Non-Prompt D⁰

![D⁰ p_T (GeV/c) vs. Fraction](blue and red graphs)

- \( |y| < 1.0 \)
- Prompt
- Non-prompt
Prompt $D^0 R_{AA}$ in PbPb at 5.02 TeV

- Strongest suppression around $p_T = 5-8$ GeV
- 0-10%: Similar suppression compared to ALICE 2.76 TeV result
D⁰, B⁺ and h± R_{AA} in PbPb at 5.02 TeV

PbPb 5.02 TeV

25.8 pb⁻¹ (5.02 TeV pp) + 404 x⁻¹ (5.02 TeV PbPb)

CMS
Preliminary

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

• New B⁺ R_{AA} data: could constrain the coupling strength between b-quark and the medium in the theoretical models

B⁺ R_{AA} vs. theory

CMS

B⁺ Centrality 0-100%

Charged particle R_{AA} \textbf{JHEP 04 (2017) 039}
B meson R_{AA} \textbf{arXiv:1705.04727} submitted to PRL
**D^0, B^+, b→J/ψ and h^± R_{AA} in PbPb at 5.02 TeV**

**PbPb 5.02 TeV**

25.8 pb\(^{-1}\) (5.02 TeV pp) + 404 \(\mu\)b\(^{-1}\) (5.02 TeV PbPb)

- CMS Preliminary
- charged hadrons \(|y| < 1\)
- \(D^0 + \bar{D}^0\) \(|y| < 1\)
- \(B^\pm\) \(|y| < 2.4\)
- nonprompt J/ψ
- 1.8 < \(|y| < 2.4\)
- \(|y| < 2.4\)

**NEW!**

**CMS**

- \(R_{AA}\)
- Nonprompt J/ψ
- 6.5 < \(p_T\) < 50 GeV/c
- Cent. 0-100%

**New** \(b→J/ψ R_{AA}\) results at 5.02 TeV!

- Significant meson flavor dependence at low \(p_T\)

- \(b→J/ψ R_{AA}\) from 2.76 and 5.02 TeV are compatible to each other.

- No significant \(|y|\) dependence at 5.02 TeV

**Charged particle** \(R_{AA}\) **JHEP 04 (2017) 039**

**B meson** \(R_{AA}\) **arXiv:1705.04727 submitted to PRL**

\(b→J/ψ R_{AA}\) **CMS-PAS-HIN-16-025**
D⁰ Azimuthal Anisotropy: Scalar Product Method

\[ Q_n = \sum_j w_j e^{in_j} \]

Sum over tracks (tracker), or towers (Hadron Forward Calorimeter)

\[ w_j: \text{tower } E_T \text{ for HF, track } p_T \text{ for tracker} \]

- Large \( \eta \) gap applied (\(|\Delta \eta| > 3.0\))
- \( v_n\{\text{SP}\} \), non-ambiguous measure of \( \sqrt{\langle v_n^2 \rangle} \)

\[ v_n \{\text{SP}\} = \sqrt{\frac{\langle Q_n \times Q_{nA}^* \rangle}{\langle Q_{nA} \times Q_{nB}^* \rangle \langle Q_{nA} \times Q_{nC}^* \rangle}} \]

Scaling factor from 3 sub events

\[ \langle \rangle \]

Luzum, Ollitrault PRC87 (2013), 044907
Extract $v_n$ of $D^0$

$D^0$ candidate $v_n$ are first measured as a function of candidate mass

$D^0$ $v_n$ extracted with a simultaneous fit on $D^0$ mass spectra and $v_n$ ($v_2$ or $v_3$) vs. mass:

$$v_n^{Sig+Bkg}(m_{inv}) = \alpha(m_{inv}) v_n^{sig} + (1 - \alpha(m_{inv})) v_n^{Bkg}(m_{inv})$$

$\alpha(m_{inv})$: $D^0$ signal fraction
**Prompt $D^0 v_2$ in PbPb at 5.02 TeV**

- Positive prompt $D^0 v_2$ observed in $p_T$ range studied
  - Low $p_T$: charm quark collective motion
  - High $p_T$: path length dependence of energy loss
- In 30-50%, $D^0 v_2$ peaks around 3 GeV, then decrease vs $p_T$
Prompt $D^0$ $v_2$ vs. Charged Particle $v_2$

- **Low $p_T$:** $v_2$ (prompt $D^0$) < $v_2$ (charged particle)
  - Indication of weaker centrality dependence than charged particles

- **High $p_T$:** $v_2$ (prompt $D^0$) ≈ $v_2$ (charged particle)
  - A consistent picture of $\Delta E$ (charm) ≈ $\Delta E$ (light quark) at high $p_T$
  - from $R_{AA}$ and $v_2$ analyses

- Similar $p_T$ dependence
Prompt $D^0 v_2$ vs. Theoretical Models

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

- **Low $p_T$:** $v_2$ (prompt $D^0) < v_2$ (charged particle)
  - Indication of weaker centrality dependence than charged particles

- **High $p_T$:** $v_2$ (prompt $D^0) \approx v_2$ (charged particle)
  - A consistent picture of (path-length dependent) $\Delta E$ (charm) $\approx \Delta E$ (light quark) at high $p_T$ from $R_{AA}$ and $v_2$ analyses

- Similar $p_T$ dependence

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Yen-Jie Lee (MIT)  
Open Heavy Flavor with CMS
Prompt $D^0 v_3$ in PbPb at 5.02 TeV

- First measurement of $D^0 v_3$
- Low $p_T$: $v_3$ (prompt $D^0$) $> 0$; High $p_T$: $v_3$ (prompt $D^0$) $\approx 0$
- $v_3$ Peaks around 3-5 GeV, then decrease vs. $p_T$
- Little centrality dependence

CMS PAS HIN-16-007
Prompt $D^0 v_3$ vs. Charged Particle $v_3$

- Low $p_T$: $v_3$ (prompt $D^0$) < $v_3$ (charged particle)
- High $p_T$: $v_3$ (prompt $D^0$) ≈ $v_3$ (charged particle)
- Similar $p_T$ dependence
- Both have little centrality dependence
Prompt $D^0 v_3$ vs. Theoretical Models

- Low $p_T$: $v_3$ (prompt $D^0$) $< v_3$ (charged particle)
- High $p_T$: $v_3$ (prompt $D^0$) $\approx v_3$ (charged particle)
- Similar $p_T$ dependence
- Both have little centrality dependence

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

Cent. 0-10%

Cent. 10-30%

Cent. 30-50%

- $D^0$, $|y| < 1.0$
- Charged particle, $|\eta| < 1.0$

CMS PAS HIN-16-007
Summary & Outlook

- **D⁰, B⁺ and b→J/ψ R_{AA} in PbPb at 5.02 TeV**
  - First fully reconstructed B⁺ analysis
  - b→J/ψ R_{AA} (NEW): no significant |y| dependence
  - Strong suppression of D⁰, B⁺ and b→J/ψ, similar to h± at high p_T
  - Significant flavor dependence of R_{AA} at low p_T

- **D⁰ v₂ and v₃ are measured for 3 centrality classes in PbPb at 5.02 TeV**
  - Weaker centrality dependence of D⁰ v₂ than h± v₂
  - First measurement of D⁰ v₃
  - Data consistent with models with charm flow:
    Light flavor azimuthal anisotropy could “transfer” to heavy flavor particles efficiently

- **Provide important inputs for theory models**
  - Many more results from 5 TeV data in the pipeline
  - Expect high precision results with 2018 and Run III data
  … stay tuned!
• Backup slides
The Life of Charm Quark in the Soup

- At low $p_T$: $D^0 v_2$ signal is significantly lower than that of charged particles
- At high $p_T$: $D^0 v_2 \approx$ charged particle $v_2$

Same parton energy loss picture from high $p_T D^0 R_{AA}$ and $v_2$ measurements
• Run I data: 30M MB PbPb events at 2.76 TeV
• $D^0$ $R_{AA}$ both as functions of $p_T$ and centrality
  • pp reference: data-extrapolated and FONLL
• Hint of flavor dependent $R_{AA}$

**Nonprompt J/$\psi$**

- Beauty: nonprompt $J/\psi$, $p_T \in [6.5,30]$ GeV/c, $|y| < 1.2$
- Charm: prompt $D$, $p_T \in [8,16]$ GeV/c
- CMS PAS-HIN-15-005: $|y| < 1$
- Charged hadrons, $p_T \in [7.2,9.6]$ GeV/c
- EPJC 72 (2012): $|y| < 1$

**D meson measurement with CMS in Run-I**

- **Run I data**: 30M MB PbPb events at 2.76 TeV
- **$D^0$ $R_{AA}$**: both as functions of $p_T$ and centrality
  - **pp reference**: data-extrapolated and FONLL
- **Hint of flavor dependent $R_{AA}$**

**CMS Preliminary**

- **PbPb $s_{NN} = 2.76$ TeV**
- **$R_{AA}^{*}$**
- **Filled markers**: data-extrapolated reference
- **Open markers**: FONLL reference
- **Cent. 0-100%**
- **$|y| < 1.0$**

**Nonprompt J/$\psi$**

- **$D^0$ $h^{\pm}$**
- **$<N_{part}>$**
- **CMS PAS HIN-15-005**

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Open Heavy Flavor with CMS
Online $D^0$ triggers

Hardware L1 jet triggers selection

Track selection in software triggers

$D^0$ selection

- Level-1 (L1) jet algorithm with online background subtraction
- Track seed $p_T$ cut applied:
  - $p_T > 2$ GeV for pp
  - $p_T > 8$ GeV for PbPb
- $D^0$ online reconstruction
  - loose selection based on $D^0$ vertex displacement
Comparison between D0 and non-prompt J/ψ

CMS

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

Cent. 10-30% $|y| < 1.0$

$D^0$

Nonprompt J/ψ

$\text{arXiv}:1610.00613$, Cent. 10-60%

$p_T$ 3-6.5 GeV, 1.6<$|y|<$2.4

$p_T$ 6.5-30 GeV, $|y| <$ 2.4

Filled box: syst. from non-prompt $D^0$

Open box: other syst.

Yen-Jie Lee (MIT) Open Heavy Flavor with CMS
Comparison with model calculations

Important inputs and strong constraints on theory:
- Theoretical calculations need to describe $D^0 R_{AA}$ and $v_n$ results simultaneously in a wide kinematic range
- Good progress has been made recently

M. Djordjevic: PRC 92, 024918 (2015)
PHSD: PRC 93, 034906 (2016)
LBT: PRC 94 014909 (2016)
I. Vitev: PRD 93, 074030 (2015)
CUJET3: JHEP 1602 (2016) 169
TAMU: PLB 735 (2014) 445

Open Heavy Flavor with CMS
$D^0 \nu_2$ compared to light hadrons

$D^0 \nu_2$ seems to fall on the trend of light flavor

Xin Dong (QM2017)