D meson nuclear modification factor and azimuthal anisotropy in PbPb at 5.02 TeV with CMS

**Jing Wang** on behalf of the CMS Collaboration

2nd International Workshop on QCD Challenges from pp to AA
31 October - 3 November 2017
Puebla (Mexico)
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
- Production cross section calculable with pQCD ($m_c, m_b \gg \Lambda_{QCD}$)
- Strongly interact with the deconfined medium
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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])
      - $\Delta E_g > \Delta E_c > \Delta E_b$
  - medium density and path length

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      - $\Delta E_g > \Delta E_c > \Delta E_b$
      - $R_{AA}^{light} < R_{AA}^D < R_{AA}^B$
    - medium density and path length
- Collective flow
  - measurement of the interaction strength

D⁰ meson production

- c → D⁰: O(50%) of c cross-section
- D⁰ → Kπ: 3.93 ± 0.04%
- D⁰ cτ = 122.9 µm
Datasets
• LHC Run II at 5.02 TeV in 2015
• Large minbias and centrality triggered samples
• Dedicated **HLT D⁰ filters** to enhance the statistics at very high \( p_T \)

Hardware L1 jet triggers selection

Track selection in software triggers

D⁰ selection

- Level-1 (L1) jet algorithm with online background subtraction
- Track seed \( p_T \) cut applied:
  - \( p_T > 2 \text{ GeV} \) for pp
  - \( p_T > 8 \text{ GeV} \) for PbPb
- D⁰ online reconstruction
  - Loose selection based on D⁰ vertex displacement
**D⁰ reconstruction**

- Primary vertex reconstruction *several tracks*
- D⁰ candidates (vertex) reconstruction *pairing two tracks + kinematic fitter*
- D⁰ candidates selection (TMVA) *decay topology*
  - Pointing angle (α) < ~0.12
  - 3D decay length (d₀) normalized by its error > ~4
  - Secondary vertex probability > ~0.1
  - Distance of Closest Approach (DCA) < ~0.008 cm
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- **Raw yields extraction** *Invariant mass*

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

arXiv: 1708.04962
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 $D^0$

Prompt:

Non-prompt:

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 $D^0$
Extraction of prompt fraction with data

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- 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 $D^0$ $p_T$-differential cross-section

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

Prompt $D^0$ $R_{AA}$ in PbPb at 5.02 TeV

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

- Nuclear modification factor
  \[
  R_{AA} = \frac{1}{T_{AA}} \frac{dN_{PbPb}}{dp_T} / \frac{d\sigma_{pp}}{dp_T}.
  \]
- Strong suppression at $p_T$ 5-8 GeV/c
- No significant collision energy dependence compared with 2.76 TeV

[Graph showing $R_{AA}$ vs. $p_T$]

**arXiv: 1708.04962**
Prompt $D^0 R_{AA}$ in PbPb at 5.02 TeV

**Centrality 0-100%**

$27.4 \text{ pb}^{-1} (5.02 \text{ TeV pp}) + 530 \mu\text{b}^{-1} (5.02 \text{ TeV PbPb})$

CMS Supplementary

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

$R_{AA}$

$|y| < 1$

Centrality 0-100%

$T_{AA}$ and lumi. uncertainty

$|y| < 1$

Cent. 0-100%

$p_T$ (GeV/c)

$R_{AA}$

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arXiv: 1708.04962
Prompt $D^0$ $R_{AA}$ in PbPb at 5.02 TeV

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

- Comparison with charged hadrons
  - Similar suppression in a wide kinematic range
  - Hint of less suppression of $D^0$ at low $p_T$?
  - To be studied with higher statistics data to be taken in 2018 and HLLHC

- Comparison with $B^+ $ meson
  - No significant meson flavor dependence of $R_{AA}$ at high $p_T$ with the current accuracy
  - $B\rightarrow D$ analysis is on going to reach lower $p_T$
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- Comparison with **$B^+$ meson**
  - No significant meson flavor dependence of $R_{AA}$ at high $p_T$ with the current accuracy
  - $B \rightarrow D$ analysis is ongoing to reach lower $p_T$

- Comparison with **nonprompt $J/\psi$**
  - Hint of meson flavor dependence of $R_{AA}$ at low $p_T$

JHEP 04 (2017) 039
arXiv:1705.04727
CMS-PAS-HIN-16-025
arXiv: 1708.04962
Prompt $D^0$ $R_{AA}$ in PbPb at 5.02 TeV

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

Comparison with theoretical predictions

- S. Cao et al. [1] (Improved Langevin eq, Linearized Boltzmann)
- M. Djordjevic [2] (pQCD calculations in a finite size optically thin dynamical QCD medium)
- CUJET 3.0 [3] (jet quenching model based on DGLV opacity expansion theory)
- AdS/CFT [4] (a model based on the anti-de Sitter/conformal field theory)

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arXiv: 1708.04962

Jing Wang (MIT), D meson $R_{AA}$ and $v_n$ in PbPb collisions with CMS, Challenges2017 (Puebla)
Prompt $D^0 R_{AA}$ in PbPb at 5.02 TeV

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  - Vitev et al. [5] (jet propagation in matter, soft-collinear effective theory with Glauber gluons (SCETG))
  - PHSD [6] (Parton-Hadron-String Dynamics transport approach)

$|y| < 1$, Centrality 0-10%

$R_{AA}$

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

CMS

$27.4 \text{ pb}^{-1} (5.02 \text{ TeV pp}) + 530 \mu \text{b}^{-1} (5.02 \text{ TeV PbPb})$

$R_{AA}$ uncertainty

$T_{AA}$ and lumi.

$p_T (\text{GeV/c})$

$D^0 R_{AA}$ in PbPb at 5.02 TeV

Azimuthal anisotropy

- The azimuthal anisotropy can be characterized by the Fourier coefficients $v_n$ in the azimuthal angle ($\phi$) distribution of the hadron yield

$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_t dp_t dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)] \right),$$

- Elliptic flow: $v_2$
- Triangular flow: $v_3$

- Azimuthal anisotropy origins from
  - low $p_T$
    - collective motion in the thermalized medium
    - fluctuation ($v_3$)
  - high $p_T$
    - path length dependence of the energy loss
Scalar Product Method

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

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

$$Q_n = \sum_{k=1}^{M} \omega_k e^{i n \phi_k},$$

Scaling factor from 3 sub events

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<th>B</th>
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<td>$\omega_k$</td>
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Extraction of $D^0$ $v_n$

- Simultaneous fit on invariant mass distribution and $v_n$ vs mass

$$v_{n}^{S+B}(m_{inv}) = \alpha(m_{inv})v_{n}^{S} + [1 - \alpha(m_{inv})]v_{n}^{B}(m_{inv})$$

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

arXiv: 1708.03497
Prompt $D^0 v_2$ in PbPb at 5.02 TeV

- Positive prompt $D^0 v_2$ observed 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, then decreases vs $p_T$

arXiv: 1708.03497
Prompt D⁰ v₂ vs. charged particles v₂

- Low p_T: v₂ (prompt D⁰) < v₂ (charged particles)
  - Difference in most central events is smaller
  - Hint of smaller centrality dependence than charged particles
- High p_T: v₂ (prompt D⁰) ≈ v₂ (charged particles)
  - Consistent with ΔE (charm) ≈ ΔE (light quark) observed in R_{AA}
- Similar p_T dependence

arXiv: 1708.03497
Prompt $D^0 v_2$ vs. theoretical calculations

Models need to describe both $R_{AA}$ and $v_n$ results simultaneously in a wide kinematic range

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

Calculations for prompt $D^0$
- LBT
- SUBATECH
- PHSD
- CUJET 3.0
- TAMU

PRC 94 (2016) 014909
PRC 91 (2015) 014904
PRC 93 (2016) 034906
JHEP 02 (2016) 169
PLB 735 (2014) 445

arXiv: 1708.03497
Prompt $D^0 v_3$ in PbPb at 5.02 TeV

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

arXiv: 1708.03497
Prompt $D^0$ $v_3$ vs. charged particles $v_3$

- Low $p_T$: $v_3$ (prompt $D^0$) < $v_3$ (charged particles)
  - Difference in most central events is smaller
- High $p_T$: $v_3$ (prompt $D^0$) ≈ $v_3$ (charged particles)
- Similar $p_T$ dependence
- Both have little centrality dependence

arXiv: 1708.03497
Prompt $D^0 v_3$ vs. theoretical calculations

- Models need to describe both $R_{AA}$ and $v_n$ results simultaneously in a wide kinematic range

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

- Charged particle, $|y| < 1.0$
- $0-10\%$
- $10-30\%$
- $30-50\%$

Calculations for prompt $D^0$
- LBT
- PHSD
- SUBATECH

arXiv: 1708.03497

PRC 94 (2016) 014909
PRC 91 (2015) 014904
PRC 93 (2016) 034906
What can be expected at the HL-HLC era?

High-Luminosity LHC!

- A more solid conclusion on the flavor dependence of energy loss will be addressed
- Stronger constraints on the theory models

CMS Projection

CMS-FTR-17-002
Summary

- $D^0 R_{AA}$ in PbPb at 5.02 TeV
  - Strong suppression
  - No significant flavor dependence at high $p_T$
  - Hint of flavor dependence at low $p_T$
  - $B \to D$ analysis is on going to reach lower $p_T$

- $D^0 v_2$ and $v_3$ measured in 3 centrality ranges in PbPb at 5.02 TeV
  - First measurement of $D^0 v_3$
  - Low $p_T$: $v_n$ (prompt $D^0$) < $v_n$ (charged particle)
  - High $p_T$: $v_n$ (prompt $D^0$) ≈ $v_n$ (charged particle)

- Results provide important inputs for theoretical models

- We can expect much more precise measurements in Run 3 and HL-LHC
Thanks for your attention!
D⁰ measurements with CMS in Run I

Run I 2.76 TeV
- Dataset: MB events
- $p_T$: 2-40 GeV/c
- pp reference: data-extrapolated and FONLL

Run II 5.02 TeV
- Dataset: MB + D trigger events
- $p_T$: 2-100 GeV/c
- pp reference: direct data

Measurements reaching very high $p_T$ for the first time!

CMS-PAS-HIN-15-005
Systematic uncertainties summary

**Signal extraction systematics ~5%**
- Varying signal and background fit functions

**D meson selection ~13%**
- Comparing data and MC driven efficiencies of the different cut selections
- Systematics on trigger efficiency
- Tracking efficiency systematic (evaluated by 2 and 4 prongs D⁰ decays)

**B-feed down uncertainty ~8%**
- Obtained by comparing f_{prompt} estimation with alternative method based on decay length and FONLL predictions

**PbPb, Centrality 0-100%**

- 25.8 pb⁻¹ (5.02 TeV pp) + 404 μ b⁻¹ (5.02 TeV PbPb)
- CMS **D⁰ R_{AA}, |y| < 1**
- Overall Normalization (N_{MB}, Lumi)
- Total Systematics
- Signal Extraction
- D Meson Selection and Correction
- B feed down subtraction
High-Level-Trigger (HLT) $D^0$ triggers

- Level-1 (L1) jet algorithm with online background subtraction
  - $p_T > 2$ GeV for pp
  - $p_T > 8$ GeV for PbPb

$D^0$ selection

- $5.02$ TeV pp collisions
- Extend to $D^0$ high $p_T$ to $200$ GeV/c

- $D^0$ online reconstruction
- Loose selection based on $D^0$ vertex displacement
Heavy flavor measurements with CMS

LHC Run I
2.76 PbPb + 5.02 pPb

1. b-jet $R_{AA}$ in PbPb
2. $J/\psi$ $R_{AA}$ in PbPb
3. $D^0$ meson $R_{AA}$ in PbPb
4. B meson $R_{pPb}$ in pPb

[2] CMS-PAS-HIN-12-014
CMS detector

Inner tracker: charged particles

Muon detectors

EM and hadronic calorimeters
Photons, Jet

Forward Calorimeter:
MB triggers, centrality

Muon | $|\eta| < 2.4$
---|---
HCAL | $|\eta| < 5.2$
ECAL | $|\eta| < 3.0$
Tracker | $|\eta| < 2.5$
High-Level-Trigger (HLT) $D^0$ triggers

Triggers performance

CMS Preliminary

HLT D meson trigger efficiency

- $\sqrt{s}=5.02$ TeV pp
- $404 \mu b^{-1}$ (5.02 TeV PbPb)

- $D^0$ trigger $p_T \geq 8$
- $D^0$ trigger $p_T \geq 15$
- $D^0$ trigger $p_T \geq 20$
- $D^0$ trigger $p_T \geq 30$

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Systematics

**pp**

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

**PbPb 0-10%**

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

**CMS Performance**

- \(D^0 d\sigma / dp_T\), \(|y| < 1\)

**Systematical Uncertainty**

- Overall Normalization (Lumi + BR)
- Total Systematics
- Signal Extraction
- D Meson Selection and Correction
- B feed down subtraction

**Luminosity**

Overall Normalization (Lumi + BR)
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:**

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

**Without $b_0$ cut:**

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

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

$D^0$ $v_n$ with all analysis cuts as central value

As systematics from non-prompt $D^0$