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

Jing Wang on behalf of the CMS Collaboration

The 8th International Conference on Hard and Electromagnetic Probes of High-energy Nuclear Collisions
23 - 27 September 2016
Wuhan (China)
Why studying heavy flavors in HI?

Heavy quarks are produced via initial hard scatterings
- Carry information about the system at early stage \(\rightarrow\) **Good probe of QGP**

the probe heavy quarks interact with the medium

In-medium energy loss
- Two energy loss mechanisms: **Collisional + Radiative**
- **Flavor-dependent**
  - Dead cone effect \([1]\)
  - (kinematic: **Radiative energy loss is suppressed at small angles**)

\[
dP = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k^2_1 dk^2_1}{(k^2_1 + \omega^2 \theta_0^2)^2}, \quad \theta_0 \equiv \frac{M}{E}
\]

- Expect: \(\Delta E^\text{light} > \Delta E^c > \Delta E^b\)
- Nuclear modification factor:
  - \(R^\text{light}_{AA} < R^D_{AA} < R^B_{AA}\) \(?\)
- Dead cone effect is expected to be important at low \(p_T\)

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

CMS-PAS-HIN-15-005
**D^0 measurements with CMS in Run II**

**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!
D⁰ meson production at 5.02 TeV

CMS-PAS-HIN-16-001
First Run II heavy flavor analysis
D^0 meson production

- c → D^0: O(50%) of c cross-section
- D^0 → K\pi: 3.93 ± 0.04%
- D^0 cτ = 122.9 µm
D^0 \rightarrow K\pi in pp and PbPb collisions at 5.02 TeV, Centrality 0-10% and 0-100%, |y|<1

Datasets

- **Low p_T** ( < 20 GeV/c)
  
  **MinBias** Events (pp: 2 billions events; PbPb: 150 million events)

- **High p_T** ( > 20 GeV/c)
  
  Events triggered by dedicated **HLT D^0 filters** to enhance the statistics at very high p_T

![HLT D meson trigger efficiency](image)
High-Level-Trigger (HLT) $D^0$ triggers

**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

**$D^0$ selection**

- $D^0$ online reconstruction
- Loose selection based on $D^0$ vertex displacement

$D^0$ decay vertex

Primary vertex
D⁰ → Kπ in pp and PbPb collisions at 5.02 TeV, Centrality 0-10% and 0-100%, |y|<1

Analysis strategy

- 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
- Raw yields extraction *Invariant mass*
- Cross-sections
Invariant mass spectra in pp (5.02 TeV)

Raw yields extraction

Mass distributions fitted by
- Double gaussian (Signal)
- 3rd order polynomial (Combinatorial)
- Single gaussian (K-π swapped)
  - No PID: Candidates with wrong mass assignment
Obtain cross-section from raw yields

Raw yields $\rightarrow$ Cross-sections

$$\left. \frac{d\sigma^{D^0}}{dp_T} \right|_{|y|<1.0} = \frac{1}{2} \frac{f_{prompt}}{\Delta p_T} \left( Acc \times \epsilon \right)_{prompt} \cdot BR \cdot \alpha_{prescale} \cdot \epsilon_{trigger} \cdot \mathcal{L}$$

Prompt $D^0$ Cross-section

Raw yields

[Graph showing $m_{D^0}$ distribution withCMS Preliminary pp $\sqrt{s_{NN}} = 5.02$ TeV, data points, fit, signal, K-$\pi$ swapped, and combinatorial background.]
Obtain cross-section from raw yields

Raw yields $\rightarrow$ Cross-sections

$$\left. \frac{d\sigma^{D^0}}{dp_T} \right|_{|y|<1.0} = \frac{1}{2} \frac{f_{\text{prompt}}}{\Delta p_T} (\text{Acc} \times \epsilon)_{\text{prompt}}$$

Acceptance & efficiency

from MC simulation

Trigger efficiency

fit turn on curve
Obtain cross-section from raw yields

Raw yields $\rightarrow$ Cross-sections

$$\frac{d\sigma^{D^0}}{dp_T} \bigg|_{|y|<1.0} = \frac{1}{2} \Delta p_T \left( \text{Acc} \times \epsilon \right)_{\text{prompt}} \cdot \text{BR} \cdot \alpha_{\text{prescale}} \cdot \epsilon_{\text{trigger}} \cdot \mathcal{L}$$

Fraction of prompt $D^0$

Branching fraction

Luminosity

Prompt: $D^0$ mesons coming from c-quark fragmentation

Non-prompt:
**$f_{prompt}$: Fraction of prompt $D^0$**

$$\frac{d\sigma^{D^0}}{dp_T} \bigg|_{|y|<1.0} = \frac{1}{2} f_{prompt} \frac{N^{D^0}}{\Delta p_T} (Acc \times \epsilon)_{prompt} \cdot BR \cdot \alpha_{prescale} \cdot \epsilon_{trigger} \cdot \mathcal{L}$$

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

- Different shapes of distance of closest approach ($DCA$) distributions of prompt and non-prompt $D^0$
- The shapes of DCA distributions come from MC
- Fit DCA distributions of data

![Graph showing DCA distributions for prompt and non-prompt $D^0$](image)

$D^0$ DCA = flight distance $\times \sin(\alpha)$

Promt frac. = 76.7 ± 2.4 %

- $10.0 < p_T < 12.5$ GeV/c  
- $|y| < 1.0$
- Data
- Prompt $D^0$
- Non-Prompt $D^0$
\[ \frac{d\sigma^{D^0}}{dp_T} \bigg|_{|y|<1.0} = \frac{1}{2} \frac{f_{\text{prompt}}}{\Delta p_T} \frac{N^{D^0}}{\text{Acc} \times \text{BR} \times \alpha_{\text{prescale}} \times \epsilon_{\text{trigger}} \times \mathcal{L}} \]

- Consistent with that from FONLL convoluted with MC efficiency

CMS Preliminary

**Prompt frac. = 76.7 ± 2.4 %**

- Data
- Prompt D^0
- Non-Prompt D^0

**Prompt** vs. D^0 p_T

CMS Preliminary

**pp \sqrt{s_{NN}} = 5.02 TeV**

10.0 < p_T < 12.5 GeV/c   |y| < 1.0
The first measurement of $D^0$ cross-section in pp collisions at 5.02 TeV

- $p_T$ range covers from 2 to 100 GeV/c in $|y| < 1$
- Consistent with the upper bound of FONLL predictions [1]

Invariant mass spectra in PbPb

Raw yields extraction

5.02 TeV, 0-100%

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

<table>
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<tr>
<th>$m_{\pi K}$ (GeV/c$^2$)</th>
<th>Entries / (5 MeV/c$^2$)</th>
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<tr>
<td>1.7</td>
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<td>1.95</td>
<td>25000</td>
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Data, Fit, $D^0 + \overline{D^0}$ Signal, K-$\pi$ swapped, Combinatorial

Centrality 0-100%

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

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Data, Fit, $D^0 + \overline{D^0}$ Signal, K-$\pi$ swapped, Combinatorial

Centrality 0-100%
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 D\(^0\) decays)

**B-feed down uncertainty ~8%**
- Obtained by comparing f\(_{\text{prompt}}\) estimation with alternative method based on decay length and FONLL predictions

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**PbPb, Centrality 0-100%**

![Diagram](image)

- CMS
- D\(^0\) \(R_{AA}\), \(|y| < 1\)
- Centrality 0-100%

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

- Overall Normalization (\(N_{MB}, \text{Lumi}\))
- Total Systematics
- Signal Extraction
- D Meson Selection and Correction
- B feed down subtraction
$D^0$ $R_{AA}$ in PbPb collisions at 5.02 TeV

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

- Strong suppression at $p_T$ 5-8 GeV/c
- Less suppression for low and high $p_T$
- Similar suppression with 2.76 TeV

CMS-PAS-HIN-16-001
D$^0 R_{AA}$ in PbPb collisions at 5.02 TeV

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

- Comparison with charged hadrons [1]
- Similar suppression in a wide kinematic range

CMS-PAS-HIN-15-015

[1] CMS-PAS-HIN-16-001
D⁰ Rₐₐ in PbPb collisions at 5.02 TeV

|y| < 1, Centrality 0-100%

- Comparison with charged hadrons [1]
- Similar suppression in a wide kinematic range
- Comparison with B⁺ meson [2]

CMS-PAS-HIN-16-001

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

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

- Comparison with **charged hadrons** [1]
  - Similar suppression in a wide kinematic range
- Comparison with **theoretical predictions**
  - S. Cao et al. [2] (Improved Langevin eq, Linearized Boltzmann)
  - M. Djordjevic [3] ($pQCD$ calculations in a finite size optically thin dynamical QCD medium)

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

CMS-PAS-HIN-16-001

D⁰ \textit{R}_{AA} \text{ in } \text{PbPb collisions at 5.02 TeV}

**Centrality 0-100%**

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

**Centrality 0-10%**

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

CMS-PAS-HIN-16-001
$D^0 R_{AA}$ in PbPb collisions at 5.02 TeV

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

- Comparison with charged hadrons [1]
- Similar behavior with 0-100%

CMS-PAS-HIN-16-001

D⁰ Rₐa in PbPb collisions at 5.02 TeV

|y| < 1, Centrality 0-10%

- Comparison with charged hadrons [1]
  - Similar behavior with 0-100%
- Comparison with theoretical predictions
  - S. Cao et al. [2] (Improved Langevin eq, Linearized Boltzmann)
  - M. Djordjevic [3] (pQCD calculations in a finite size optically thin dynamical QCD medium)
  - CUJET3.0 [4] (jet quenching model based on DGLV opacity expansion theory)
  - I. Vitev [6] (jet propagation in matter, soft-collinear effective theory with Glauber gluons (SCETG))

CMS-PAS-HIN-16-001

Summary
Summary

Conclusions

Strong constraints on theoretical calculations

- Require theoretical calculations to describe $D^0 R_{AA}$ and $v_n$ measurement results simultaneously in a wide kinematic range

Jian’s talk (24 Sep. 8:50)
Summary

Conclusions

Strong constraints on theoretical calculations
• Require theoretical calculations to describe $D^0 R_{AA}$ and $v_n$ measurement results simultaneously in a wide kinematic range

Outlook

$D$ meson at very low $p_T$
• Down to $\sim 1 \text{ GeV/c}$
Thanks for your attention!
D^0 R_{AA} in PbPb collisions at 5.02 TeV

|y| < 1, Centrality 0-10%

- Comparison with charged hadrons [1]
- Similar behavior with 0-100%
- Comparison with theoretical predictions
  - M. Djordjevic [3] (pQCD calculations in a finite size optically thin dynamical QCD medium)
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CMS-PAS-HIN-16-001

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

|y| < 1, Centrality 0-10%

- Comparison with charged hadrons [1]
- Similar behavior with 0-100%
- Comparison with theoretical predictions
  - S. Cao et al. [2] (*Improved Langevin eq, Linearized Boltzmann*)

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CMS-PAS-HIN-16-001

High-Level-Trigger (HLT) $D^0$ triggers

CMS Preliminary

- $p_T > 2$ GeV for $pp$
- $p_T > 8$ GeV for PbPb

- $D^0$ online reconstruction
- loose selection based on $D^0$ vertex displacement

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

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

- $|y| < 1.0$
- $100.0 < p_T < 200.0$ GeV/c

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

$K-\pi$ swapped

Combinatorial

Data

Fit

Entries / (5 MeV/c^2)

$m_{\pi K}$ (GeV/c^2)
D⁰ measurements with CMS in Run I

PbPb @ 2.76 TeV

CMS-PAS-HIN-15-005

Run II: pp + PbPb @ 5.02 TeV

- Measurements reaching very high p_T (>100GeV/c) for the first time!
- PP reference directly from data
Comparison with CMS 2.76 TeV

PbPb 0-100%

Comparison with CMS 2.76 TeV

PbPb 0-100%
Comparison with ALICE 5.02 TeV

PbPb 0-10%

![Graph showing comparison between CMS and ALICE for D meson R_AA in PbPb collisions. The graph displays D^0 R_AA as a function of p_T (GeV/c) with CMS Preliminary data for 5.02 TeV PbPb collisions (25.8 pb^{-1}) and ALICE 5.02 TeV pp collisions (+ 404 μ b^{-1}). The CMS data is shown with CMS, 5.02 TeV, |y|<1 and the ALICE data with ALICE, 2.76 TeV, |y|<0.5. The graph includes T_{AA} and luminosity uncertainty.]

CMS: 0-10%, ALICE: 0-7.5%
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 detectors

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Mass spectra

CMS Preliminary

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

| $|y| < 1.0$ | $5.0 < p_T < 6.0$ GeV/c |
|-----------|-------------------------|
| Data      | Fit                     |
| $D^0 + \overline{D^0}$ Signal | K-$\pi$ swapped |
| Combinatorial |                      |

Entries / (5 MeV/c$^2$)

$|y| < 1.0$

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

| $|y| < 1.0$ | $25.0 < p_T < 30.0$ GeV/c |
|-----------|-------------------------|
| Data      | Fit                     |
| $D^0 + \overline{D^0}$ Signal | K-$\pi$ swapped |
| Combinatorial |                      |

Entries / (5 MeV/c$^2$)
Mass spectra

PbPb 0-100%

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

Centrality 0-100%

$|y| < 1.0$

$5.0 < p_T < 6.0$ GeV/c

Entries / (5 MeV/c²)

$m_{\pi K}$ (GeV/c²)

Data

Fit

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

K-π swapped

Combinatorial

Preliminary CMS

= 5.02 TeV

$\sqrt{s_{NN}}$

PbPb

Centrality 0-100%

$|y| < 1.0$

$25.0 < p_T < 30.0$ GeV/c

Entries / (5 MeV/c²)

$m_{\pi K}$ (GeV/c²)

Data

Fit

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

K-π swapped

Combinatorial

Jing Wang (MIT), D meson $R_{AA}$ in PbPb collisions with CMS, HP2016 (Wuhan)
Mass spectra

PbPb 0-10%

CMS Preliminary

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

l|l < 1.0
5.0 < $p_T$ < 6.0 GeV/c
Centrality 0-10%

Centrality 0-10%

|$y|$ < 1.0

Data

Fit

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

K-π swapped

Combinatorial

CMS Preliminary

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

l|l < 1.0
25.0 < $p_T$ < 30.0 GeV/c
Centrality 0-10%

Centrality 0-10%

|$y|$ < 1.0

Data

Fit

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

K-π swapped

Combinatorial
High-Level-Trigger (HLT) D^0 triggers

- 5.02 TeV pp collisions
- Extend to D^0 high pT to 200 GeV/c
High-Level-Trigger (HLT) D\(^0\) triggers

Triggers performance

**CMS Preliminary**

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

**CMS Performance**

- D\(^0\) trigger \(p_T > 20\)
- D\(^0\) trigger \(p_T > 40\)
- D\(^0\) trigger \(p_T > 60\)
**$f_{\text{prompt}}$: Fraction of prompt D$^0$**

**PbPb**

**CMS Preliminary**

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

10.0 < $p_T$ < 12.5 GeV/c  lyl < 1.0

Prompt frac. = 81.6 ± 1.1 %

- Data
- Prompt D$^0$
- Non-Prompt D$^0$

**CMS Preliminary**

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

lyl < 1.0

- Prompt
- Non-prompt

Jing Wang (MIT), D meson R$^{AA}$ in PbPb collisions with CMS, HP2016 (Wuhan)
Systematics

**CMS Performance**

**pp**

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

**PbPb 0-10%**

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

**Systematical Uncertainty**

<table>
<thead>
<tr>
<th>5.02 TeV pp</th>
<th>5.02 TeV PbPb</th>
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<tr>
<td>-0.4</td>
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- Overall Normalization (Lumi + BR)
- Total Systematics
- Signal Extraction
- D Meson Selection and Correction
- B feed down subtraction

Jing Wang (MIT), D meson R$_{AA}$ in PbPb collisions with CMS, HP2016 (Wuhan)
Heavy flavor measurements with CMS

LHC Run I (2.76 PbPb + 5.02 pPb)

- b-jet $R_{AA}$ in PbPb
- B meson $R_{pPb}$ in pPb
- J/ψ $R_{AA}$ in PbPb


CMS-PAS-HIN-12-014

Jing Wang (MIT), D meson $R_{AA}$ in PbPb collisions with CMS, HP2016 (Wuhan)