Open charm production in PbPb and pPb collisions at LHC with CMS

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QCD@LHC 2016
22-26 August 2016,
Zurich (Switzerland)
Heavy quarks produced in hard scatterings (described by pQCD) at the early stages of the collisions **interact with medium and lose energy!**

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**Why studying heavy flavours in HI?**

Heavy quarks produced in hard scatterings (described by pQCD) at the early stages of the collisions **interact with medium and lose energy!**

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**Does energy loss depends on the flavour?**

Expected $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ due to:

- **Casimir factor** $\propto C_R$
- **Dead cone effect** (radiation suppressed at small angles)
How to measure beauty with CMS

Leptons from heavy quarks

Non-prompt $J/\psi$

Primary vertex

Secondary vertex

$\mu^+$

$\mu^-$

$J/\psi$

$K^+$

Exclusive B meson decays

$b$-jet reconstruction

$b$-tagged jet sample $\mathcal{O}(100\%)$ of $b$ cross-section
and $\sim 70$-$90\%$ of the $b$ quark energy
How to measure charm with CMS

D^0 → Kπ decay channels sample $O(0.01\%)$ of c cross-section
Run I heavy flavour analysis
non-prompt $J/\psi$ measurements

Getting closer to the $b$-quark kinematics!

Charged particle

Non prompt $J/\psi$

D mesons

Hints of different suppression for D mesons and non-prompt $J/\psi$ at low $p_T$!
b-jet nuclear modification in PbPb at 2.76 TeV

b-jets tagged by selecting displaced secondary vertices (SV) in the jet cone

CMS *PRELIMINARY PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
$\int L \, dt = 7$-150 $\mu b^{-1}$

*Inclusive jet (0-5%) $|\eta| < 2$
*b-jet (0-10%) $|\eta| < 2$

b-jets $R_{AA}$ shows strong suppression (factor~3) observed in central PbPb collisions (0-5%)

Same suppression observed for b-jets and inclusive jets in the same centrality

Are we measuring the energy loss of gluons in both cases (gluon splitting)?

Exclusive B meson measurements

PRL 116 (2016) 032301

• $J/\psi \rightarrow \mu^+\mu^-$ reconstruction
• Tracks are associated to $J/\psi$ candidate to build B-meson candidates

Measured in pPb collisions only:
• $R_{pA}^{\text{FONLL}}$ consistent to unity

PbPb measurement coming soon!
First Run II heavy flavour analysis!

CMS-PAS-HIN-16-001
$D^0 \rightarrow K^-\pi^+$ in pp and PbPb collisions
(0-10% and 0-100%) at 5.02 TeV in $|y|<1.0$

**Analysis strategy:**
- Primary and $D^0$ vertex reconstruction
- $D^0$ candidate reconstruction
- $D$ meson selection:
  - pointing angle ($\alpha$)
  - decay length normalised to its error ($d_0$)
  - $D^0$ vertex probability

**Invariant mass analysis**

**Data samples:**
- **2 billion pp MB events** in pp and 150 million PbPb MB for low $p_T$ analysis ($<20$ GeV/c)
- **Triggered sample selected with dedicated HLT $D^0$ filters** to enhance the statistics up to very high $p_T$ ($p_T>20$ GeV/c)
proton-proton spectra at 5.02 TeV

- Invariant mass spectra of $D^0$ mesons in pp collisions at 5.02 TeV

**5<p_T<6 GeV/c**

Mass distributions fitted with:
- 3rd order polynomial fit for **combinatorial background**
- Double gaussian to **model the signal**
- Gaussian shape to model the candidates with swapped mass hypothesis
b-feed subtraction in pp collisions

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

CMS Preliminary \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

10.0 < p_T < 12.5 GeV/c \( |y| < 1.0 \)

Prompt frac. = 76.7 ± 2.4 %

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

\( f_{\text{prompt}} \) = fraction of D^0 mesons coming from c-quark fragmentation

\( f_{\text{prompt}} \) estimated **fully data driven** by exploiting the different shapes of distance of closest approach (DCA) distributions of prompt and non prompt D^0 mesons
$f_{\text{prompt}}$ fraction in pp collisions

CMS Preliminary

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

$|y| < 1.0$

- Red: Prompt
- Blue: Non-prompt

$D^0 p_T$ (GeV/c)

Fraction
- First measurement of pp D⁰ cross section at 5.02 TeV
- p_T coverage from 2 to 100 GeV/c in |y|<1.0
- Consistent with upper bound of FONLL calculations!
PbPb analysis at 5.02 TeV in 0-100% centrality

Centrality 0-100%

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

- Data
- Fit

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

K-π swapped

Combinatorial

5<p$_T$<6 GeV/c

$-1.0 < y < 1.0$

60<p$_T$<100 GeV/c

$-1.0 < y < 1.0$
强分离力也存在于PbPb！
首次数据驱动的重离子碰撞提取！

$f_{\text{prompt}}$ 是 $p_T$ 的函数作为平的！
→ 保守系统不确定性
D^0 R_{AA} in PbPb collisions at 5.02 TeV in 0-100%

Centrality 0-100% \(|y| < 1\)

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

CMS Preliminary

Centrality 0-100%

Strong suppression (~4-5) at 5-8 GeV/c

R_{AA} \approx 0.7-0.8 at very high \(p_T\)
Comparison with charged particle $R_{AA}$ in 0-100%

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

CMS Preliminary

$R_{AA}$ $D^0$

$R_{AA}$ charged hadrons

$T_{AA}$ and lumi. uncertainty

Centrality 0-100%

$y| < 1$

similar suppression observed up to very high $p_T$

CMS-PAS-HIN-15-015
Comparison with theoretical calculations

- S. Cao et al. (Linearized Boltzmann transport model + hydro [1])
- M. Djordjevic (QCD medium of finite size with dynamical scattering centers with collisional and radiative energy loss [2])

CMS Preliminary

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

Comparison with charged particle $R_{AA}$ in 0-10%

- Similar behaviour observed in central collisions 0-10%
- No indication of sizeable difference between $D^0$ and charged particle $R_{AA}$

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

CMS Preliminary

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

$T_{AA}$ and lumi.

uncertainty

→ Similar behaviour observed in central collisions 0-10%
→ No indication of sizeable difference between $D^0$ and charged particle $R_{AA}$
Comparison with charged particle $R_{AA}$ in 0-10% 

$D^0 R_{AA}$ vs $p_T$ (GeV/c) 

CMS Preliminary 

- $T_{AA}$ and lumi. uncertainty 
- Centrality 0-10% $|y| < 1$ 

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

- **CUJET3.0** (jet quenching model based on DGLV opacity expansion theory [1]) 
- **M. Djordjevic** (QCD medium of finite size with dynamical scattering centers with collisional and radiative energy loss [2]) 
- **I. Vitev** jet propagation in matter, soft-collinear effective theory with Glauber gluons (SCETG)[3] 

Comparison with theoretical calculations

- S.Cao et al. (Linearized Boltzmann transport model + hydro [1])
- PHSD (Parton-Hadron-String Dynamics model[2])

\[ p_T (\text{GeV/c}) \]

Conclusions

- Hints of different suppression of J/\psi \leftrightarrow B and D mesons at low p_T

- At higher p_T (>100 GeV/c) inclusive jets and b-jets are well in agreement

- D and charged particle RAA agree up to very high p_T!
  - putting stronger constraints on theoretical calculations
  - forcing theoretical to describe HF measurements in a much wider kinematic range where different processes (e.g. radiative vs collisional) have a different relevance
BACKUP
Outlook

• More precise measurements of B production are getting urgent:
  • with Run2 data, CMS can measure with good precision the b-production via \( J/\psi \leftarrow B \), b-jets and exclusive B measurements
  → complete picture of the HF energy loss

• D-meson production at low \( p_T \)
  • measure D meson production in PbPb (and pPb) down to \( \sim 1 \) GeV to further constrain the mechanisms of productions (e.g. recombination) and relevance of cold nuclear effects

• D and B \( v_n \) measurements
  • fundamental to understand collective behaviour of HF quarks and to constraint theoretical calculations

• Gluon splitting?
  • the relevance of soft and hard gluon splitting processes still needs to be addressed. Are we always measuring gluon energy loss?
  • More differential measurement (HF/photon, D-hadron correlations) are needed
CMS detector

- Muon detectors
- EM and hadronic calorimeters: Photons, Jet
- Forward Calorimeter: MB triggers, centrality
- Inner tracker: charged particles

Diagram showing the CMS detector with layers labeled as:
- Tracker: |η| < 2.5
- ECAL: |η| < 3.0
- HCAL: |η| < 5.2
- Muon: |η| < 2.4
How to measure beauty with CMS

Leptons from heavy quarks:
- $\mu^+$
- $\mu^-$
- $K^+$

Secondary vertex:
- $b$

Primary vertex:
- Sample $O(10\%)$ of $b$ cross-section
How to measure beauty with CMS

Leptons from heavy quarks

Secondary vertex

Primary vertex

Non-prompt J/ψ

μ⁺

μ⁻

J/ψ

K⁺

Dileptons channel sample $O(0.1\%)$ of b cross-section
How to measure beauty with CMS

Leptons from heavy quarks

Non-prompt J/ψ

Primary vertex

Secondary vertex

J/ψ+1(2) tracks decay channels sample O(0.01%) of b cross-section

Exclusive B meson decays
D⁰ triggers at High-Level-Trigger

CMS Preliminary

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

l_\gamma l < 1.0
100.0 < p_T < 200.0 \text{ GeV/c}

Data
Fit
D⁰ + \overline{D⁰} Signal
K-π swapped
Combinatorial

Entries / (5 MeV/c²)

\begin{align*}
1.7 & \quad 1.75 & \quad 1.8 & \quad 1.85 & \quad 1.9 & \quad 1.95 & \quad 2 \\
0 & \quad 10 & \quad 20 & \quad 30 & \quad 40 & \quad 50 & \quad 60 \\
\end{align*}

pp collisions at 5.02 \text{ TeV}

extending the high \( p_T \) reach of D⁰ analysis up to 200 \text{ GeV}!
Events firing hardware jet triggers (Level-1) are selected

- L1 jet algorithm with online background subtraction

Tracks are reconstructed in software trigger system (HLT) for selected events

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

$D^0$ meson are reconstructed

- Online $D^0$ reconstruction
- Loose selection to reduce the rates based on $D^0$ vertex displacement
Performances of $D^0$ triggers

$\rightarrow$ pp efficiency reaches 100% right above its $D^0$ $p_T$ threshold

$\rightarrow$ PbPb efficiency goes from ~90 to 100% depending on $p_T$
PbPb analysis at 5.02 TeV in 0-10% Centrality

Centrality 0-10%

CMS Preliminary

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

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

5<p_T<6 GeV/c

60<p_T<100 GeV/c
Acceptance x efficiency in pp collisions

CMS Preliminary

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

- Prompt
- Non-prompt

$\alpha \times \xi_{\text{reco}} \times \xi_{\text{sel}}$

$p_T$ (GeV/c)

0 20 40 60 80 100

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
From raw yields to cross sections

\[ \frac{d\sigma^{D^0}}{dp_T} \big|_{|y|<1.0} = \frac{1}{2} \frac{f_{\text{prompt}}}{\Delta p_T} \left( \text{Acc} \times \varepsilon \right)_{\text{prompt}} \cdot \text{BR} \cdot \alpha_{\text{prescale}} \cdot \varepsilon_{\text{trigger}} \cdot \mathcal{L} \]

fraction of prompt $D^0$: fully data driven for the first time in heavy ions

For triggered data:
- Needs to correct for trigger selection efficiency

raw yields extracted via fits to invariant mass distributions

G.M. Innocenti, QCD@LHC, Zurich (Switzerland), 22-26 August 2016
Drop in the efficiency is due to the tracking selection applied in the HLT tracking that requires a tight selection in the offline analysis.
Summary of systematic uncertainties

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

- **Signal extraction systematics**
  - Varying signal and background fit functions

- **D meson selection:**
  - Comparing data and MC data driven efficiencies of the different cut selections
  - Systematic on trigger efficiency
  - Tracking efficiency systematic: (evaluated data driven with 2 and 4 prongs D⁰ decays!)

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

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![Graph showing CMS Performance](image-url)
Heavy-Flavour production in pPb

B\(^+\) production in pPb → compatible with predictions from FONLL scaled by \(A=208\)

tagged c and b-jet production → compatible with predictions from PYTHIA scaled by \(A=208\)

HF pPb production not significantly modified by cold nuclear matter effects (e.g. PDF modification in nuclei)

D^0 R_{AA} comparison with ALICE

![Graph showing D^0 R_{AA} comparison with ALICE](image-url)

- CMS Preliminary
- CMS, 5.02 TeV, |y|<1
- ALICE, 2.76 TeV, |y|<0.5

25.8 pb\(^{-1}\) (5.02 TeV pp) + 404 \(\mu\) b\(^{-1}\) (5.02 TeV PbPb)
$D^0 R_{AA}$ comparison with CMS 2.76 TeV

2.76 TeV pp reference was done by extrapolating ALICE measurement via FONLL
HF production mechanisms in pp

LO production mechanisms are not dominant at the LHC energies
Background subtraction

1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

Estimate background for each tower ring of constant $\eta$

estimated background = $\langle p_T \rangle + \sigma(p_T)$

- Captures $dN/d\eta$ of background
- Misses $\phi$ modulation – to be improved
1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

Background level
Background subtraction

1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

2) Run anti $k_T$ algorithm on background subtracted towers

Background level
Background subtraction

1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

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Background subtraction

1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

2) Run anti $k_T$ algorithm on background subtracted towers

3) Exclude reconstructed jets
Background subtraction

1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

2) Run anti $k_T$ algorithm on background subtracted towers

3) Exclude reconstructed jets. Recalculate the background energy
Background subtraction

1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

2) Run anti $k_T$ algorithm on background subtracted towers

3) Exclude reconstructed jets. Recalculate the background energy

4) Run anti $k_T$ algorithm on background subtracted towers to get final jets

Background level
Jet analysis workflow

1. Raw jet energy
2. Background subtraction
3. Jet energy correction
4. Jet energy

Remove underlying events contribution

MC Simulation PYTHIA
Gluon splitting matters!

- A non negligible fraction of b-jets at the LHC come from gluon splitting
- Even more important for charm than for bottom at LHC energy!

Plots from Matthew Nguyen
Double differential cross section ($y$ and $p_T$)

- MC@NLO agreement at the edge of uncertainties
- Pythia overshoots at low $p_T$, agrees well at high $p_T$
b-jet to inclusive jet ratio

b-jet fraction = # of tagged jets * purity / efficiency

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

Centrality 0-100%

$\int L \, dt = 150 \mu b^{-1}$

PbPb Data
Pythia+Hydjet
Syst. uncertainty

• b-jet fraction consistent within pp and PbPb within uncertainty
• Both measurements consistent with MC predictions
Tracking in heavy-ion collisions

“Standard” HI Tracking (2011)

Tracking performance

Efficiency

Fake track rate

$\text{CMS-PAS-HIN-12-013}$
b-jet efficiency vs misidentification

![Graph showing b-jet efficiency vs misidentification probability for CMS Simulation and Pythia (+Hydjet). The graph compares tagging efficiency for SV udsg jets, PbPb, SV charm jets, PbPb, SV udsg jets, pp, and SV charm jets, pp. The data is presented for √s_{NN} = 2.76 TeV.]
jet probability tagger

- Alternative tagger used as a cross-check on SSV
- Each track assigned a probability to be from primary vertex
- Determined separately for Data and MC using negative IP tracks
- JP = probability that all tracks originate from primary vertex

\[ P_N = \Pi \cdot \sum_{j=0}^{N-1} \frac{\log \Pi}{j!} \]

with \[ \Pi = \prod_{i=1}^{N} P(S^i) \]
Excellent pixel spatial resolution
• ≈100 μm at 1 GeV/c, 20 μm at 20 GeV/c
• well described by MC simulations based on GEANT