What have we learnt with CMS on flavour dependence?

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How to measure beauty with CMS

Leptons from heavy quarks

Secondary vertex

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 $J/\psi$

Dileptons channel sample $O(0.1\%)$ of $b$ cross-section
Leptons from heavy quarks

Primary vertex

Secondary vertex

b

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

Non-prompt J/ψ

Exclusive B meson decays

µ⁺ µ⁻ K⁺ J/ψ
Leptons from heavy quarks

Non-prompt J/ψ

Primary vertex

Secondary vertex

b-jet reconstruction

b-tagged jet sample $O(100\%)$ of b cross-section and ~70-90% of the b quark energy

Exclusive B meson decays

How to measure beauty with CMS
How to measure charm with CMS

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

Getting closer to the b-quark kinematics!

Hints of different suppression for D mesons and non-prompt J/ψ at low pT!
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 $\int L \, dt = 7-150 \mu b^{-1}$

$R_{AA}$ 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

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

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)
D⁰ triggers at High-Level-Trigger (HLT)

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

D⁰ meson are reconstructed

- Online D⁰ reconstruction
- loose selection to reduce the rates based on D⁰ vertex displacement
Performances of $D^0$ triggers

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

→ $PbPb$ efficiency goes from ~90 to 100% depending on $p_T$
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

60<p_T<100$ 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**
From raw yields to cross sections

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

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
b-feed subtraction in pp collisions

- $f_{\text{prompt}}$ = 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

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

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

$10.0 < p_T < 12.5 \text{ GeV/c} \quad |y| < 1.0$

Prompt frac. = 76.7 ± 2.4 %

- Data
- Prompt $D^0$
- Non-Prompt $D^0$
Fraction of prompt $f_{\text{prompt}}$ in pp collisions

CMS Preliminary

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

$|y| < 1.0$

- Red: Prompt
- Blue: Non-prompt

$D^0 p_T$ (GeV/c)

**p_T-differential cross section in pp**

- First measurement of pp D^0 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%

CMS Preliminary

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

Centrality 0-100%

1.7 1.75 1.8 1.85 1.9 1.95 2

$5<p_T<6$ GeV/c

$m_{\pi K}$ (GeV/c$^2$)

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

Data

Fit

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

$K-\pi$ swapped

Combinatorial

Centrality 0-100%

$m_{\pi K}$ (GeV/c$^2$)

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

Data

Fit

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

$K-\pi$ swapped

Combinatorial

$60<p_T<100$ GeV/c

|y| < 1.0

5.0 < p_T < 6.0 GeV/c

60.0 < p_T < 100.0 GeV/c
b-feed subtraction in PbPb collisions

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

$10.0 < p_T < 12.5$ GeV/c  $|y| < 1.0$

Prompt frac. = 81.6 $\pm$ 1.1 %

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

strong separation power also in PbPb!
first data-driven extraction in heavy-ion collision!

$f_{\text{prompt}}$ is $\sim$ flat as a function of $p_T$
$\rightarrow$ conservative systematic uncertainties
• **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 $D^0$ decays!)

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

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![Graph showing systematic uncertainty](image)
D^0 R_{AA} in PbPb collisions at 5.02 TeV in 0-100%

Centrality 0-100%
|y| < 1

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

R_{AA} \approx 0.7-0.8 at very high p_T

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

T_{AA} and lumi. uncertainty

Comparison with charged particle $R_{AA}$ in 0-100%

CMS

Preliminary

$R_{AA}$ D$^0$

$R_{AA}$ charged hadrons

Centrality 0-100%

$|y| < 1$

Uncertainty

Similar suppression observed up to very high $p_T$

CMS-PAS-HIN-15-015

See Austin Baty’s talk

25.8 pb$^{-1}$ (5.02 TeV pp) + 404 μb$^{-1}$ (5.02 TeV PbPb)
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])
Comparison with charged particle $R_{AA}$ in 0-10%

$R_{AA}^{D^0}$ vs. $p_T$ (GeV/c) for CMS Preliminary data.

- 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%

CMS Preliminary

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])

Conclusions

- Hints of different suppression of $J/\psi \rightarrow B$ 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
Outlook

• **More precise measurements of B production are getting urgent:**
  • with Run2 data, CMS can measure with good precision the b-production via $J/\psi \rightarrow B$, 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 ~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
BACKUP
**D⁰ triggers at High-Level-Trigger**

CMS Preliminary

- Data
- Fit
- D⁰+D⁰ Signal
- K-π swapped
- Combinatorial

**pp collisions at 5.02 TeV**

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

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

Extending the high p_T reach of D⁰ analysis up to 200 GeV!
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!

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 = $\langle \Delta E \rangle \propto C_R$
- Dead cone effect (radiation suppressed at small angles)
CMS detector

Inner tracker: charged particles

Muon detectors

EM and hadronic calorimeters
Photons, Jet

Forward Calorimeter:
MB triggers, centrality

|η|< 2.4

|η|< 5.2

|η|< 3.0

|η|< 2.5
PbPb analysis at 5.02 TeV in 0-10%

CMS Preliminary

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

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

Centrality 0-10%

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

$m_{\pi K}$ (GeV/c$^2$)

5<p$_T$<6 GeV/c

60<p$_T$<100 GeV/c

Acceptance x efficiency in pp collisions

\[ \alpha \times \xi_{\text{reco}} \times \xi_{\text{sel}} \]

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

CMS Preliminary

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

- Prompt
- Non-prompt
Acceptance x efficiency in PbPb collisions

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

CMS Performance

D⁰ dσ / dp_T, |y| < 1

Systematical Uncertainty

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

pp 5.02 TeV

PbPb 5.02 TeV Centrality 0-10%
Heavy-Flavour production in pPb

B⁺ production in pPb
→ compatible with predictions from FONLL 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

CMS Preliminary

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

T_{AA} and lumi. uncertainty

25.8 pb^{-1} (5.02 TeV pp) + 404 μ 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
LO production mechanisms are not dominant at the LHC energies.
1) Background energy per tower calculated in strips of $\eta$. Pedestal subtraction

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

estimated background = $<p_T> + \sigma(p_T)$

- Captures $dN/d\eta$ of background
- Misses $\phi$ modulation – to be improved
Background subtraction

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

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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 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

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
Jet analysis workflow

Raw jet energy → Background subtraction → Jet energy correction → 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

- b-jet fraction consistent within pp and PbPb within uncertainty
- Both measurements consistent with MC predictions
b-jet efficiency vs misidentification

![Graph showing b-jet efficiency vs misidentification probability for CMS Simulation at \(\sqrt{s_{NN}} = 2.76\) TeV. The graph compares tagging efficiency for SV udsg jets and SV charm jets in lead-lead (PbPb) and proton-proton (pp) collisions using Pythia (+Hydjet).]
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

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

with \[
\Pi = \prod_{i=1}^{N} P(S^i)
\]
Excellent pixel spacial resolution
- $\approx 100 \, \mu m$ at 1 GeV/c, 20 $\mu m$ at 20 GeV/c
- well described by MC simulations based on GEANT
Charged particle $R_{AA}$ at 5.02 TeV

CMS-PAS-HIN-15-015, See Austin Baty’s talk