Heavy flavour measurements in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE experiment

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1 Introduction
- Motivations
- ALICE layout

2 Analysis
- $D \rightarrow$ hadrons (mid-rapidity)
- $B, D \rightarrow$ electrons (mid-rapidity)
- $B, D \rightarrow$ muons (forward-rapidity)

3 Results: nuclear modification factors
- Prompt $D$ mesons
- Single electrons from $B, D$ decay
- Single muons from $B, D$ decay

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Motivations

• Charm and beauty: hard probes of the hot and dense matter formed in heavy-ion collisions:
  • produced at the beginning of the collision (large $Q^2$)
  • experience the evolution of the “fireball” (large $c\tau$)
  • interact strongly with the medium (parton energy-loss)

• QCD models describing collisional and radiative energy-loss in the medium depend on:
  • medium density and size
  • color charge (Casimir factor)
  • parton mass (dead-cone effect*)

\[ \begin{align*}
\Delta E_g &> \Delta E_{q/c} > \Delta E_b \\
R_{AA}^h &< R_{AA}^D < R_{AA}^B
\end{align*} \]


• New ratios available at the LHC:

\[ R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_t}{d\sigma_{pp}/dp_t} \]

\[ \Delta E_g > \Delta E_{q/c} > \Delta E_b \]

\[ R_{AA}^h < R_{AA}^D < R_{AA}^B \]

LHC, Pb-Pb 0-10%, $\sqrt{s_{NN}} = 5.5$ TeV

- dashed: $q = 25$ GeV$^2$/fm
- solid: $q = 100$ GeV$^2$/fm
- thin: $m_c = 0$
- thick: $m_c = 1.2$ GeV

\[ R_{AA}^D / R_{AA}^h: \text{isolating color charge dep.} \]

\[ R_{AA}^B / R_{AA}^D: \text{isolating mass dep.} \]


Centrality selection based on a geometrical Glauber model fit of the V0 scintillators amplitude
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- Minimum-Bias (MB) triggers from the coincidence of V0 & SPD (Silicon Pixel Detector)
- Muon triggers ($p_t^\mu \gtrsim 0.5$ GeV/c) in pp

<table>
<thead>
<tr>
<th>$N_{MB}$</th>
<th>pp @ 7 TeV</th>
<th>pp @ 2.76 TeV</th>
<th>PbPb @ 2.76 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-180 M</td>
<td>65 M</td>
<td>17M</td>
<td></td>
</tr>
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**D meson analysis**

**Example:** $D^0 \rightarrow K^- \pi^+$

- Main selection: displaced-vertex topology (for $D^0 \rightarrow K^- \pi^+$ large impact parameters of opposite-sign pairs & good pointing of reconstructed $D$ to primary vertex)

- Kaon ID in TPC+TOF to reduce background at low $p_t$

**TPC:** $p/K$ separation for $p \lesssim 1.1$ GeV/c

**TOF:** $\pi/K$ separation for $p \lesssim 1.5$ GeV/c
In ~ 3M central collisions (0-20%) 
- $D^0$: 5 bins in $2 < p_t < 12 \text{ GeV/c}$
- $D^+$: 3 bins in $5 < p_t < 12 \text{ GeV/c}$
Heavy-flavour electrons analysis

Electron identification:
- TOF: reject kaons ($p_t \lesssim 1.5$ GeV/$c$) and protons ($p_t \lesssim 3$ GeV/$c$)
- TPC dE/dx: asymmetric cut around the electron Bethe-Bloch line
- TRD (pp only): reject pions ($p_t \lesssim 10$ GeV/$c$) via TR + energy deposit

Background subtraction:
1. Cocktail of background electrons:
   - Dalitz decays using as inputs the measured distributions of
     - $\pi^0$ (pp collisions)
     - $\pi^\pm$ (PbPb collisions)
     - heavier mesons by $m_t$ scaling
     - prompt $\gamma$ from pQCD
2. Heavy-flavour electrons $= \text{data} - \text{background cocktail}$
Heavy-flavour muons analysis

- Remove hadrons and low-$p_t$ secondary $\mu \Rightarrow$ matching tracks with tracklets in the trigger chambers
- Remove decay $\mu \Rightarrow$ MC normalized to data
- Correct for acceptance/efficiency
- Estimate the cross-section

In PbPb:
- No decay $\mu$ subtraction but restrict data to high-$p_t$ region where bkg. contribution is small

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$p_t \geq 4$ GeV/c</th>
<th>$p_t \geq 6$ GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>0.15 ± 0.02</td>
<td>0.09 ± 0.03</td>
</tr>
<tr>
<td>20-40%</td>
<td>0.11 ± 0.02</td>
<td>0.05 ± 0.02</td>
</tr>
<tr>
<td>40-80%</td>
<td>0.06 ± 0.02</td>
<td>0.02 ± 0.02</td>
</tr>
</tbody>
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Proton-proton data at $\sqrt{s} = 7$ TeV scaled to $\sqrt{s} = 2.76$ TeV with FONLL
- full theoretical uncertainty used
- assume no dependence of quark mass and scales with $\sqrt{s}$
- Relative scaling uncertainty: $25\% \rightarrow 10\%$ in $p_t$ $2 \rightarrow 10$ GeV/c
- Cross-check with 3-days pp data at $\sqrt{s} = 2.76$ TeV

Heavy flavours results in pp collisions: talk by Y. C. Pachmayer
Strong suppression observed in central collisions (0-20%)

Significant suppression also in semi-peripheral collisions (40-80%)

Large suppression factor for \( p_t \gtrsim 5 \text{ GeV/c} \)

Little contribution from initial state effects expected

The suppression is a hot medium effect!
Charm suppression compatible with pions $R_{AA}$ (slightly higher for $p_t \lesssim 4 - 5 \text{ GeV}/c$)
Heavy-flavour electrons (inclusive - cocktail)

- Large systematic uncertainties at low-$p_t$ (also in pp collisions)
- Heavy-flavour decay dominant for $p_t \gtrsim 3 - 4$ GeV/c
- Suppression in most central collision (factor 1.5 – 4)
- Suppression factor of $\sim 3$ for $p_t > 6 \text{ GeV/c} \Rightarrow$ region dominated by beauty according to FONLL
- Small $p_t$ dependence

$$R_{CP}(p_t) = \frac{\langle 1/T_{AA} \rangle \times dN/dp_t \rangle_{\text{central}}}{\langle 1/T_{AA} \rangle \times dN/dp_t \rangle_{\text{peripheral}}}$$

- Suppression increases with centrality
Data comparison

Electrons + Muons

- Consistent within errors

Forward muons vs. mid-rapidity electrons:

D⁰ mesons vs muons:

- Consistent centrality dependence
- Higher $R_{AA}$ for muons $\Rightarrow$ beauty contribution?
Energy loss

CAVEAT: Most of the theoretical predictions are for PbPb @ 5.5 TeV: qualitative comparison only

- **Radiative energy loss** for $\hat{q} = 25$ GeV/fm$^3$ in qualitative agreement with both D mesons and muons $R_{AA}$
- **Light-cone wave function approach with dissociation** in agreement with muon but a bit high for D mesons
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3. **Results: nuclear modification factors**
   - Prompt $D$ mesons
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   - Single muons from $B, D$ decay

4. **Summary**
The nuclear modification factors for heavy flavour in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV have been measured in ALICE:

- in the hadronic channel at mid-rapidity
- in the semi-leptonic channel at mid and forward rapidities

Strong suppression measured in $R_{AA}$ and $R_{CP}$ variables:

- increasing with centrality (down to 0.2 for D mesons)
- persisting in a $p_t$ region where initial state effects are expected to be small

Outlooks:

- Study of heavy flavour’s flow (measuring event plane)
- Extract beauty contribution
5 Backup slides
Centrality selection

- Minimum-bias triggers from the coincidence of SPD & V0A & V0C

- Centrality selection based on a geometrical Glauber model fit of the V0 amplitude
D mesons analysis: feed down subtraction

- Prompt D yields obtained after subtracting secondary D mesons from B decay
- Rely on FONLL predictions (as in pp)
- Additional hypothesis on B mesons $R_{AA}$ required

$$\frac{dN_{D\rightarrow B}^{uncorrected}}{dp_t} = \epsilon_{D\rightarrow B}^{MC} \times \frac{d\sigma_{theory}}{dp_t} \times T_{AA} \times R_{AA}^{D\rightarrow B}$$

- Choice for systematic computation on $R_{AA}^D$: $1/3 < R_{AA}^D/R_{AA}^B < 3$
D mesons analysis: systematics

\[ \text{Relative Error} \]

\[ \text{Total (excl. norm.)} \]

\[ \text{Tracking efficiency} \]

\[ \text{Branching ratio} \]

\[ \text{Yield extraction} \]

\[ \text{Cuts efficiency} \]

\[ \text{PID efficiency} \]

\[ \text{MC } p_t \text{ shape} \]

\[ D = \bar{D} \]

\[ D^0 \rightarrow K^+ \pi^- \]

Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

0-20\% Centrality

ALICE Performance

13/05/2011

\[ p_t \text{ [GeV/c]} \]

\[ D^+ \]

\[ 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10 \quad 11 \quad 12 \]

\[ p_t \text{ [GeV/c]} \]

\[ D^0 \rightarrow K^+ \pi^- \]

Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

40-80\% Centrality

ALICE Performance

13/05/2011

\[ p_t \text{ [GeV/c]} \]

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Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

0-20\% Centrality

ALICE Performance

12/05/2011

\[ p_t \text{ [GeV/c]} \]
Heavy-flavour electron analysis: PID (I)

Electron identification:

- **TOF**: reject kaons ($p_t \lesssim 1.5 \text{ GeV}/c$) and protons ($p_t \lesssim 3 \text{ GeV}/c$).

- **TPC dE/dx**: asymmetric cut around the electron Bethe-Bloch line.

![Graph showing electron identification criteria in TOF and TPC dE/dx](image)

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**TPC + TOF (3\sigma electron compatibility cut)**

![Graph showing TPC + TOF (3\sigma electron compatibility cut)](image)
Electron identification with TRD (in pp):

- Energy deposit + transition radiation
- Electron likelihood cut fixed at 80% electron efficiency
- Strong $\pi$ suppression when combining TOF+TRD+TPC cuts:

![Graph showing normalized yield vs. TRD signal with p = 2.0 GeV/c]

![Graph showing TRD tracking efficiency x acceptance vs. p (GeV/c) with 7 supermodules and number of tracklets $\geq 5$]

![Graph showing TRD signal (a.u.) vs. TRD Signal (a. u.) with pp, $\sqrt{s} = 7$ TeV]

![Graph showing number of tracklets vs. TRD tracking efficiency x acceptance with ALICE Performance 19/05/2011 and pp, $\sqrt{s} = 7$ TeV]
Heavy-flavour electron analysis: systematics

Data

![Data Graph]

Cocktail

![Cocktail Graph]
- Hint for an electron excess at low $p_T$
- Increase with centrality

**Thermal photons?**
Two ways of extracting heavy flavour contribution:

1. Subtract “background” electrons from cocktail:
   - input from measured distributions of
     - $\pi^0$ (pp collisions)
     - $\pi^\pm$ (PbPb collisions)
   - Dalitz decays based on $\pi$ inputs
   - heavier mesons by $m_t$ scaling
   - prompt $\gamma$ from pQCD

2. Isolate beauty decay by the large impact parameter of the electron (beauty $c\tau \sim 500 \mu m$)
Data sample:
- **Minimum-bias** events

Track selection:
- Acceptance cut: $-4 < \eta < -2.5$
- Cut on the angle of the track at the exit point of the front absorber ($171^\circ < \theta_{abs} < 178^\circ$).
- **Rejection of beam-gas** background events.
- Reject events with no **reconstructed vertex** in the two pixel layers
- Matching tracks with trigger (see next slide)
- Remove **fake tracks** and improve **beam-gas** rejection: cut on $p \times DCA$ variable:
Heavy-flavour muons analysis: trigger selection

Hadrons rejected by requiring the matching of tracks with trigger

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**Graphs:**

- **MC**
- **Data**

**Graph Descriptions:**

- **MC** graphs show distributions of DCA with different categories of particles (e.g., charm, beauty, decay, secondary, hadrons, fakes).
- **Data** graph illustrates the distribution of DCA for events with different angular constraints (e.g., $-4 < \eta < -2.5$, $171^\circ < \theta_{abs} < 178^\circ$).

**Legend:**

- **Pythia Perugia0**
- **pp @ $\sqrt{s} = 7$ TeV**
- **$4 < \eta < 2.5$**
- **$171^\circ < \theta_{abs} < 178^\circ$**
- **Reconstructed vertex**
- **w/ trigger matching**
Systematics in pp collisions at 7 TeV:
- background subtraction: \(\sim 20\%\)
- alignment: \(1\% \times p_t\)
- detector response: \(5\%\)
- Minimum-Bias pp cross section from van der Meer scan: \(7\%\) (not shown)
Heavy-flavour muons: disentangle charm and beauty

• **CAVEAT:** assuming perfect combinatorial bkg. subtraction.

• Statistical [ ] and systematic [ ] errors in 1 month of pp collisions @ 14 TeV, assuming $\mathcal{L} = 10^{30}$.

• Systematic error (taking into account combinatorial bkg. subtraction):
  $\sim 20\%$ for $B$ and $\sim 20\%$ for $D$

L. Manceau et al., ALICE-INT-2010-004