Heavy-flavour production in Pb-Pb collisions at the LHC, measured with the ALICE detector

Andrea Dainese
(INFN Padova, Italy)
on behalf of the ALICE Collaboration
Outline of the Talk

- Introduction: probing Quark Matter at LHC with HQs
- ALICE apparatus and datasets
- Open heavy flavour measurements in ALICE
  - D mesons at central rapidity
  - electrons at central rapidity
  - muons at forward rapidity
- Calibrating the probe: pp results at $\sqrt{s} = 7$ (and 2.76) TeV
- pp reference at 2.76 TeV: $\sqrt{s}$-scaling
- Nuclear modification factors of D mesons and leptons in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV
- Summary
Related Parallel Talks (3) and Posters (15)

- **Andrea Rossi**: D meson $R_{AA} \rightarrow$ Fri parallel
- **Silvia Masciocchi**: Electrons $R_{AA} \rightarrow$ Mon parallel
- **Xiaoming Zhang**: Muons $R_{AA} \rightarrow$ Mon parallel
- **Posters**:
  - D mesons: Renu Bala, Chiara Bianchin, Davide Caffarri, Zaida Conesa del Valle, Sadhana Dash, Robert Grajcarek, Alessandro Grelli, Gian Michele Innocenti, Giacomo Ortona, Rosa Romita, Xianbao Yuan
  - Electrons: Markus Fasel, MinJung Kweon, Yvonne Pachmayer, Shingo Sakai
  - Muons: Matthieu Lenhardt
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Heavy quarks as medium probes: Energy Loss

Parton Energy Loss by
- medium-induced gluon radiation
- collisions with medium gluons

\[ \Delta E(\varepsilon_{\text{medium}}; C_R, m, L) \]

pred: \( \Delta E_g > \Delta E_{c=q} > \Delta E_b \)

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

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

HQs $R_{AA}$: some expectations ...

- Energy loss based predictions: factor 3-5 suppression for D mesons
- Significantly smaller suppression for B

$$R_{AA}^D(p_t) \text{ and } R_{AA}^B(p_t)$$
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**ALICE apparatus and datasets**

- **Two main parts:**
  - barrel ($|\eta|<0.9$), $B = 0.5$ Tesla
  - forward muon spectrometer, $-4<\eta<-2.5$

- **Crucial for HF:**
  - vertexing, tracking
  - hadron and lepton ID

- **Collected data for 4 combinations of system/energy, fully exploiting the superb LHC performance**

- **Datasets used here:**

<table>
<thead>
<tr>
<th>system, $\sqrt{s_{NN}}$ (TeV)</th>
<th>pp 7</th>
<th>pp 2.76</th>
<th>Pb-Pb 2.76</th>
</tr>
</thead>
<tbody>
<tr>
<td>when</td>
<td>10/apr-aug</td>
<td>11/mar</td>
<td>10/nov</td>
</tr>
<tr>
<td>$N_{MB}$</td>
<td>100-180M</td>
<td>65 M</td>
<td>17 M</td>
</tr>
</tbody>
</table>

- **Pb-Pb centrality:** Glauber model analysis of large-$\eta$ V0 scintillator amplitudes (centrality from many other detectors as well: ZDC, Pixel, TPC)

\[ \rightarrow J.\text{Schukraft, Mon plenary} \]

\[ \rightarrow A.\text{Toia, Tue plenary} \]
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ALICE Heavy Flavour Program: D mesons, |y|<0.8

TPC (tracking, p/K/π id)

TOF (p/K/π id)

K

π

TPC (tracking, p/K/π id)

ITS (tracking & vertexing)

D^0 → Kπ
D^+ → Kππ
D_s → KKπ
D^* → D^0π
D^0 → Kπππ
Λ_c → πKp

Strip  Drift  Pixel
D meson reconstruction in ALICE

- Main selection: displaced-vertex topology
- Example: $D^0 \rightarrow K^- \pi^+$
  - good **pointing** of reconstructed $D$ momentum to the primary vertex
  - pair of opposite-charge tracks with large impact parameters
- $K$ ID in TPC+TOF helps in rejecting background at low $p_t$

![Diagram showing D meson reconstruction](image)

- TPC dE/dx vs $p$
- TOF $\beta$ vs $p$
D meson reconstruction in ALICE

- Main selection: displaced-vertex topology
- Tracking and vertexing precision is crucial here
- Inner Tracking System (ITS) with 6 Si layers
  - two pixel layers at 3.9 cm (closest barrel layer at LHC!) and 7 cm
- The ITS was aligned using cosmics and collisions
  - current resolution for pixels: 14 µm (nominal: ≈11 µm)

Same tracking precision in pp and Pb-Pb, described in MC, incl. mass dep.
ALICE Heavy Flavour Program: electrons, |y|<0.8

TPC/TOF/TRD/EMCAL (e/π id)

TPC (tracking e/π id)

ITS (tracking & vertexing)

D0 → Kπ
D+ → Kππ
D_s → KKπ
D* → D^0π
D^0 → Kπππ
(Λ_c → πKp)

D,B → e+X
(B → J/ψ→ee, tagged b-jets)
Heavy flavour decay electrons: e-ID

- High quality tracks in TPC and ITS
  - Hit in innermost Si layer to reduce $\gamma$-conv.
    (beam pipe + $\sim$1/3 inner pixel = 0.5% $X_0$)

- Electron identification:
  - Pb-Pb: TOF + TPC-dE/dx
    - TOF to reject K and p
    - TPC: asymmetric cut around the electron
      Bethe-Bloch line
  - pp: TOF + TPC-dE/dx + TRD (+EMCAL)
  - hadron contamination measured with a 2-component fit to the TPC dE/dx in p slices

- Two procedures to get heavy flavour:
  1. subtract cocktail of “photonic” electron sources, à la PHENIX
  2. select electrons with large displacement to interaction vertex $\rightarrow$ beauty dominance
    (only in pp for now)

$\rightarrow$ S. Masciocchi, Mon parallel
ALICE Heavy Flavour Program: muons, -4<y<-2.5

- $D^0 \rightarrow K\pi$
- $D^+ \rightarrow K\pi\pi$
- $D_s \rightarrow KK\pi$
- $D^* \rightarrow D^0\pi$
- $D^0 \rightarrow K\pi\pi\pi$
- ($\Lambda_c \rightarrow \pi\Lambda\pi$)
- $D,B \rightarrow e^+X$
- ($B \rightarrow J/\psi \rightarrow ee$)
- tagged b-jets
- $D,B \rightarrow \mu(\mu)+X$
Heavy flavour from forward single muons

Muon sources:

- Analysis strategy:
  - remove hadrons and low $p_t$ secondary muons by requiring a muon trigger signal
  - remove decay muons by subtracting MC $dN/dp_t$ normalized to data at low $p_t$
  - what is left are muons from charm and beauty

- In Pb-Pb, we don’t subtract the decay muons for now, but restrict the analysis to a high-$p_t$ region, where this background is small

→ X.Zhang, Mon parallel
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D mesons cross sections:
pp 7 TeV, |y|<0.5

- $2 < p_t < 12$ GeV/c, with 1.6 nb$^{-1}$ (~20% of 2010 statistics)
- $y$ acceptance is $p_t$-dep ($\Delta y\sim1.0\rightarrow1.6$): data scaled to $|y|<0.5$
- pQCD predictions (FONLL and GM-VFNS) compatible with our data
Charm in pp 7 TeV: Outlook

- Extend $p_t$ range with full 2010 statistics: 1—20 GeV/c (e.g. $D^*$ shown)
- The shy charming: $D_s$ and $\Lambda_c$

**ALICE Performance**

**10/05/2011**

**ALICE performance**

**13/05/2011**
D mesons cross sections:

\[ \text{pp } 2.76 \text{ TeV, } |y|<0.5 \]

- 2 < \( p_T \) < 8 GeV/c, with 1.1 nb\(^{-1}\) (3 days of data 3 months ago!)
- \( y \) acceptance is \( p_T \)-dep (\( \Delta y \sim 1.0 \rightarrow 1.6 \)): data scaled to \( |y|<0.5 \)
- pQCD predictions (FONLL) compatible with our data

FONLL: Cacciari et al., private comm.
The Total Charm Cross Section in pp

Extrapolation from $p_t = 2$ GeV/c to 0 (about $\times 2$) and full $y$ using FONLL

Consistent comparison with NLO over 3 orders of magnitude
Heavy flavour decay electrons: pp 7 TeV, |y|<0.8

- Cocktail of “photonic” backgrounds based on measured $\pi^0$ cross section
- Inclusive – Cocktail: electrons from c and b decays
- Agrees with measured-D decay electron spectrum at low $p_T$
- Well described by FONLL

+ Select electrons displaced from interaction vertex

Electrons from beauty decays!
Agrees with difference: $\square = \blacklozenge - \blacksquare$
Well described by FONLL

$\Rightarrow$ S. Masciocchi, Mon parallel
Heavy flavour decay muons:
pp 7 TeV, -4<\(\eta\)<-2.5

- Measured d\(\sigma/dp_t\) in 2-10 GeV/c and d\(\sigma/d\eta\) in -4 to -2.5
- Well described by FONLL predictions
  - FONLL indicates beauty dominance above 6 GeV/c

→ X.Zhang, Mon parallel
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pp reference at 2.76 TeV via pQCD-driven $\sqrt{s}$-scaling

- Scale the 7 TeV cross sections by the 2.76/7 factor from FONLL, with full theoretical uncertainty
  - assume that pQCD scales and quark masses don’t change with $\sqrt{s}$
  - relative scaling uncertainty: 25% $\rightarrow$ 10% in $p_t = 2 \rightarrow 10$ GeV/c
The D meson reference was checked against

- ALICE data at 2.76 TeV, $p_t < 8$ GeV/c (only 3 days... limited $p_t$ cov., large uncertainties)
- CDF data, $p_t > 6$ GeV/c (using a scaling to 1.96 TeV)

Comparison with CDF at 1.96 TeV
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D⁰ and D⁺ reconstruction in Pb-Pb

- In ~3M central collisions (0-20%):
  - D⁰: 5 \( p_t \) bins in 2-12 GeV/c
  - D⁺: 3 \( p_t \) bins in 5-12 GeV/c

- Reconstruction efficiency ~1-10%
  - evaluated from MC simulation
    - detector status and performance described by the MC to few % level
    - no centrality dependence found

- Feed-down from B decays ~10-15% after cuts
  - subtracted based on FONLL with hypothesis on \( R_{AA}^B \) (\( \rightarrow \) more later)

→ A.Rossi, Fri parallel
$D^0 \rightarrow K\pi$ in central Pb-Pb (0-20%)
**D⁰ and D⁺ **ₚₜ **distributions in Pb-Pb**

- Strong suppression observed in central collisions (0-20%) wrt T_{AA}-scaled pp reference
- Significant suppression also in semiperipheral (40-80%) wrt T_{AA}-scaled pp reference
The $D$ meson $R_{AA}$ (0-20%)

- Suppression for charm is a factor 4-5 above 5 GeV/c

ALICE Preliminary
B feed-down: effect on \( R_{AA}^D \)

- Correction for \( B \rightarrow D \):
  \[ -\langle T_{AA} \rangle \times \epsilon_{MC}^{D_{fromB}} \times \frac{d\sigma_{FONLL}^{D_{fromB}}}{dp_t} \times R_{AA}^B \]

- from FONLL, using ALICE efficiencies for these D's: ~10-15%
  - systematic uncertainty from FONLL, partly cancels in \( R_{AA}^D \)
  - + need to make hypothesis on \( R_{AA}^B \)
    - conservative: \( 1/3 < R_{AA}^D/R_{AA}^B < 3 \) → systematic uncert. on \( R_{AA}^D \)

\[ D^0, \text{ Pb-Pb } \sqrt{s_{NN}}=2.76 \text{ TeV} \]

- ALICE Preliminary

\[ R_{AA} \text{ prompt } D^0 \]

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

\[ \text{max unc. } \sim 15\% \]
The $D^0$ meson $R_{CP}$ (0-20%/40-80%)

- Suppression clearly seen also in $R_{CP}$ (no pp reference)
- Factor 2-3 above 5 GeV/c
Inclusive electron $p_t$ spectra in six centrality bins
- hadron cont. $<10\%$ up to 6 GeV/$c$, measured from TPC dE/dx fits

Background electron cocktail, based on $\pi^\pm$ spectra + $m_t$-scaling + pQCD direct photons
- Compare inclusive spectra to cocktail ...

→ S. Masciocchi, Mon parallel
Electron spectrum in Pb-Pb vs. cocktail

- Hint of an **electron excess** at low $p_t$ (beyond our systematic errors, mainly from e ID)
- Increases with centrality
- Might be explained by thermal photons (cfr. PHENIX, PRL104 and QM2011)
Consider (inclusive electrons – cocktail) spectrum

- low $p_t$: large systematic uncertainties (also from pp reference)
- above 3-4 GeV/c: dominated by charm and beauty decays

Suppression in central collisions: factor 1.5-4
Muons at forward rapidity in Pb-Pb

- $-4 < \eta < -2.5$, $p > 4$ GeV/c
- Pointing to interaction vertex to remove fake tracks (don’t point)
- Efficiency from MC simulation, validated by $J/\psi$ embedding

- The low-\(p_t\) background of muons from $\pi/K$ decays is not subtracted (will be done based on ALICE data)
- We provide the inclusive muon $R_{AA}$
- We estimate from Hijing simulations that this background is about 15% (10%) at $p_t = 4 (6)$ GeV/c
  \(\rightarrow\) heavy flavour decay dominance

\(\rightarrow\) X.Zhang, Mon parallel
Muon $R_{AA}$ at forward rapidity

- Suppression is of about a factor 3 above 6 GeV/$c$
- According to FONLL, beauty dominant in this region
Data Comparison: Leptons $y \sim 0$, $y \sim 3$

- Consistent with the large uncertainties of electron PID
Consistent centrality dependence

Muons ~ Electrons ~ CMS J/ψ from B (QM2011)

D mesons clearly lower (charm vs beauty?)
Data Comparisons: D and $\pi^\pm$

- Suppression for charm is a factor 4-5 above 5 GeV/c
- Compatible with pions $R_{AA}$ (slightly larger below 5 GeV/c)
  - maybe hint for $R_{AA}^{D} > R_{AA}^{\pi}$? stay tuned for 2011 Pb-Pb run results
Model Comparisons: Shadowing

- Suppression for charm is a factor 4-5 above 5 GeV/c
- This is a hot medium effect (little shadowing at these $p_t$'s)
- $p$-Pb run at LHC crucial to understand the low-$p_t$ rise
Model Comparisons: Energy Loss

- Published calculations are mostly for 5.5 TeV
- Radiative E loss (BDMPS—ASW)
  - data lie on same curve, both D and muons
- Radiative+collisional E loss (WHDG, 2.76 TeV)
  - fair description
- Light-cone wave function approach with dissociation (Vitev)
  - a bit high for D mesons, OK for muons (~beauty)
The nuclear modification factors in Pb-Pb for heavy flavour have been measured by ALICE.

The D meson and high-\(p_t\) lepton \(R_{AA}\) exhibit a strong suppression in central collisions (down to \(\sim 0.2\) for D’s)
- The suppression tends to vanish towards peripheral collisions
- It persists in a momentum range where very small initial state effects are expected

These analyses can be performed vs. event plane → Flow

The cross section of electrons from B decays can be measured, as done in pp
EXTRA SLIDES
Tu sais ?
ALICE rapporte la suppression des quarks lourds !

Oh la la !
Bravo les physiciens !

...t'inquiète pas...
... nous, on est également supprimés ...

Mais... ce sont qui ces quarks lourds ?

Ils sont comme nous, mais avec du charme ou de la beauté

... moi, je m’en fous du charme ...

(not on behalf of the ALICE Collaboration)
LHC: heavy quarks factory!

◆ NLO predictions (charm & beauty)

➢ ~ factor 2 uncertainty from NLO and shadowing (Pb-Pb)

<table>
<thead>
<tr>
<th>system : ( \sqrt{s_{\text{NN}}} )</th>
<th>Pb-Pb (0-5%) 5.5 TeV</th>
<th>Pb-Pb (0-5%) 2.76 TeV</th>
<th>pp 14 TeV</th>
<th>pp 7 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{\text{NN}}^{\bar{Q}Q} ) [mb]</td>
<td>3.4 / 0.14</td>
<td>2.1 / 0.075</td>
<td>11.2 / 0.5</td>
<td>6.9 / 0.23</td>
</tr>
<tr>
<td>( N_{\text{tot}}^{\bar{Q}Q} )</td>
<td>90 / 3.7</td>
<td>56 / 2</td>
<td>0.16 / 0.007</td>
<td>0.10 / 0.003</td>
</tr>
<tr>
<td>( C_{\text{EKS98/ESP08, shadowing}} )</td>
<td>0.58 / 0.77</td>
<td>0.60 / 0.85</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

HQs $R_{AA}$: some expectations …

**Heavy-to-light ratios**: parton colour charge and mass dependence

\[ R_{D/h}(p_t) = \frac{R_{AA}^D(p_t)}{R_{AA}^h(p_t)} \]

\[ R_{B/D}(p_t) = \frac{R_{AA}^B(p_t)}{R_{AA}^D(p_t)} \]

- dashed: $\bar{q} = 25 \text{ GeV}^2/\text{fm}$
- solid: $\bar{q} = 100 \text{ GeV}^2/\text{fm}$
- thin: $m_c = 0$
- thick: $m_c = 1.2 \text{ GeV}$

massive

massless

\[ \frac{R_{B/D}(p_t)}{R_{D/h}(p_t)} = \frac{R_{AA}^B(p_t)}{R_{AA}^D(p_t)} \]

… and, quite a different picture from AdS/CFT

\[ 1/R_{B/D}(p_t) = \frac{R_{AA}^D(p_t)}{R_{AA}^B(p_t)} \]

$\times 2$ difference already at 10-20 GeV

AdS/CFT $\Rightarrow$ D. Mateos, Fri plenary


Horowitz, Gyulassy, PLB666 (2008)
Signals: $D^0 \rightarrow K^- \pi^+$

$10^8$ events; 1-12 GeV in 7 bins
Signals: $D^+ \rightarrow K^- \pi^+ \pi^+$

$10^8$ events; 2-12 GeV in 6 bins

Quark Matter 2011, Annecy, 27.05.11
Andrea Dainese
D mesons pp 7 TeV:
from signals to cross sections

- Corrections: 1) efficiency
  - 1% → 10% from low to high $p_T$
  - factor 2 larger for B feed-down D mesons

- Corrections: 2) feed-down B→D
  - ~20-25%
  - will be corrected based on data (D displacement to vertex, à la CDF)
  - for now, subtract using FONLL predictions
D mesons: from signals to cross sections

\[
\frac{d\sigma}{dp_t}_{|y|<0.5} = \frac{1}{2} \frac{1}{\Delta y(p_t)} \frac{1}{B.R.} \varepsilon_c \left[ f_c(p_t) \right] \frac{N^D_{raw}(p_t)_{|y|<\Delta y(p_t)}}{\Delta p_t} \left( \frac{\sigma^{CINT1B}}{\sigma^{V0AND}} \right) \frac{\sigma^{V0AND}}{N_{CINT1B}}
\]

- Corrections: feed-down B\(\rightarrow\)D: \(\sim 10\text{-}15\%\)
  - main method ("Nb-subtraction"): FONLL input is only the DfromB cross section
    \[
    f_c(p_t) \cdot N^D_{raw}(p_t)_{|y|<\Delta y(p_t)} = N^D_{raw}(p_t)_{|y|<\Delta y(p_t)} - N^{DfromB}_{FONLL}(p_t)_{|y|<\Delta y(p_t)}
    \]
    where:
    \[
    N^{DfromB}_{FONLL}(p_t)_{|y|<\Delta y(p_t)} = \sigma^{DfromB}_{FONLL}(p_t) \varepsilon^{DfromB} \Delta y \Delta p_t \cdot 2 \cdot BR \cdot L_{int}
    \]
  - second method ("prompt fraction fc"): FONLL input is the ratio of prompt to total D meson cross sections
  - use the total envelope of the error bands (from FONLL) of two methods as a systematic error
FONLL vs. data, beauty production 2-7 TeV

CDF, B

|y(J/ψ)| < 0.6

Points: CDF
Curves: FONLL

$\sigma(p_T(J/ψ)>1.25 \text{ GeV}) \text{ BR:}$

$19.9^{+3.8}_{-3.2} \text{ nb (CDF)}$

$18.3^{+3.9}_{-5.9} \text{ nb (FONLL)}$

Solid histogram: MC@NLO, 17.2 nb,
Dashed histogram: MC@NLO, 16.4 nb

FONLL, MC@NLO:
Cacciari, Frixione, Mangano, Nason and Ridolfi, JHEP0407 (2004) 033

CMS, arXiv:1011.4193

$|y_{J/\psi}| < 1.2$

$1.2 < |y_{J/\psi}| < 2.4$

CMS, $\sqrt{s} = 7 \text{ TeV}$
$L = 314 \text{ nb}^{-1}$

$B \times d^2\sigma/dp_T^2 (\text{nb/GeV/c})$

CMS, $\sqrt{s} = 7 \text{ TeV}$
$L = 314 \text{ nb}^{-1}$

$B \times d^2\sigma/dp_T^2 (\text{nb/GeV/c})$
Systematic Uncertainties: D pp 7

- Total systematic 20-40% $p_t$-dep. + 7% on $\sigma_{MB}$ (VdM scan)
- Main systematic error: B feed-down from FONLL + ALICE-MC
  - conservative estimate of error
    - FONLL uncertainty (small for B) +
    - two methods considered (subtr. of D from B, fraction of prompt D)
  - to be reduced using data-driven method with full 2010 statistics

**Figures**

- $D^0 \rightarrow K^- \pi^+$
  - $pp, \sqrt{s} = 7$ TeV, 1.4 nb$^{-1}$
  - ALICE Performance 30/11/2010

- $D^+ \rightarrow K^- \pi^+ \pi^+$
  - $pp, \sqrt{s} = 7$ TeV, 1.4 nb$^{-1}$
  - ALICE Performance 30/11/2010
Mass Plots $D^+ \text{ Pb-Pb} 0$-20%
Systematic uncertainties D Pb-Pb
D mesons Pb-Pb: data vs MC
Systematic unc. Muons Pb-Pb

-4 < η < -2.5
Systematic unc. Electrons Pb-Pb

from cocktail: 25%

Pb-Pb, \( \sqrt{s_{NN}} = 2.76 \) TeV
0-10% central

ALICE Performance
19/05/2011

from electron reco/ID: 35%

ALICE Performance
20/05/2011
**B-decay muon $R_{AA}^{\mu}$, ASW**

- Z. Conesa del Valle et al, PLB663 (2008)