Heavy Flavour and Quarkonia production measurement in Pb-Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV with the ALICE detector

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Road Map

Introduction

✦ Physics Motivation
✦ Detector Layout

Open Heavy Flavour measurement in ALICE

✦ D-mesons at central rapidity
✦ electrons at central rapidity
✦ muons at forward rapidity

Quarkonium measurement in ALICE

✦ J/ψ at both central and forward rapidity

Summary and outlook
Heavy quarks as probes of the QGP

Probes the properties of the medium created in the initial hard scatterings → experience the whole collision evolution

Possible comparison heavy quarks/light partons
Parton Energy loss:

$$\Delta E_g > \Delta E_u,d,s > \Delta E_c > \Delta E_b$$

dead cone effect* and Color Charge (Color coupling factor, 4/3 for quarks and 3 for gluons)

Nuclear Modification Factor:

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

The heavy flavour $R_{AA}$ at RHIC also shows high $p_t$ suppression.
However suppression is as large as for pions → contradicting the prediction(?)

In addition, measurement of heavy quarks elliptic flow is sensitive to degree of thermalization of QGP medium


Quarkonia as probes of QGP

Quarkonia formed at the early stage of the collision
- Quarkonium suppression* by Debye screening
- Different bound states → different binding energies
  → sequential suppression

Significant $J/\psi$ suppression observed
- NA38, NA50, NA60 at SPS
- PHENIX, STAR at RHIC

Still many open questions:
  Suppression @ SPS ~ @RHIC while energy density is larger at RHIC
  Larger suppression at forward rapidities

Unique opportunity at LHC to answer these questions
- Large charm quark multiplicity
  $\sigma_{cc^-}(LHC) = 10 \times \sigma_{cc^-}(RHIC)$
- Large statistics for $J/\psi$ and $Y$ family

$J/\psi$ (re)generation by statistical hadronization* from a deconfined medium?

Central barrel (|η|<0.9)
- Open heavy flavour
- charm hadronic channels
- semi-leptonic decays (e)
- Quarkonia
- $e^+e^-$

- Muon spectrometer (-4.0<η<-2.5)
  -- Open heavy flavour
  -- Quarkonia
  -- $\mu^+\mu^-$

**ALICE @LHC**

- **TPC**: full length tracks for |η| < 0.8
- **EMCAL**: electrons, $\gamma$, $\pi^0$
- **ITS**: tracking, vertex, PID
- **TRD**: electron ID, tracking
- **TOF**: PID
- **V0**: trigger, centrality
- **forward muon arm**
- **magnet B = 0.5T**
- **ZDC**: centrality
- **forward muon arm**
### Data Set and Trigger Description

**Analyzed data sample for the present analysis**

<table>
<thead>
<tr>
<th>System</th>
<th>Energy (TeV)</th>
<th>Trigger</th>
<th>Analyzed events</th>
<th>∫ L dt</th>
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<tr>
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<td>MB</td>
<td>300 M</td>
<td>5 nb⁻¹</td>
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<tr>
<td></td>
<td></td>
<td>Muon</td>
<td>130 M</td>
<td>16 nb⁻¹</td>
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<td>MB</td>
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<td>2.9 µb⁻¹</td>
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<tr>
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<td>2.76</td>
<td>MB</td>
<td>~75 M</td>
<td>1.35 nb⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Muon</td>
<td>~9 M</td>
<td>20 nb⁻¹</td>
</tr>
</tbody>
</table>

**P-P**
- Minimum bias (MB) trigger
  - V0-A or V0-C or SPD
  - Single-muon trigger
  - forward muon in coincidence with MB trigger

**V0**: Array of scintillators  
**SPD**: Silicon Pixel Detector

**Pb-Pb**
- Minimum bias trigger (MB)
- Centrality from Glauber model fit to V0 signal
**Heavy flavour Production measurement**

**Hadronic decay channels at central rapidity**

\[ D^0 \rightarrow K\pi, \ D^+ \rightarrow K\pi\pi, \ D^* \rightarrow D^0\pi, \ D_s \rightarrow KK\pi, \ D^0 \rightarrow K\pi\pi\pi, \ \Lambda_c \rightarrow \pi Kp \]

**Selection strategy: displaced vertices**

- Main topological cuts:
  - Impact parameter of the tracks,
  - Angle between the meson flight line and particle momentum.

**Particle identification: TOF and TPC to reduce the background at low \( p_t \)**

- Invariant Mass Analysis to extract raw yield
Semi-leptonic decays

- **Electrons at central rapidity** (|y|<0.8)
  - PID: TPC+TOF+(TRD only in pp for now)
  - Background estimation from cocktail

- **Muons at forward rapidity** (2.5<y<4.0)
  - “PID”
  - MUON trigger matching
  - Background estimation from MC

**Pb-Pb, TPC dE/dx**

**MC pp 7 TeV Pythia Perugia-0**

- Remove hadrons and low pt secondary muons by requiring a muon trigger signal plus a cut on the DCA
- Subtract decay muons by subtracting MC dN/dp normalized to data at low pt
- In Pb-Pb, we don’t subtract the decay muons for now, but restrict the analysis to the high pt region where the background is small.

**Analysis Strategy:**
- Remove hadrons and low pt secondary muons by requiring a muon trigger signal plus a cut on the DCA
- Subtract decay muons by subtracting MC dN/dp normalized to data at low pt
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Heavy flavour: Measurement in pp @7 TeV

D mesons in $|y|<0.5$

- $p < p_t < 24$ GeV/c, with 5 nb$^{-1}$ (2010 statistics)
- pQCD predictions (FONLL and GM-VFNS) are compatible with our data

Good agreement with pQCD(FONLL) over the full $p_t$ range

FONLL suggests that beauty predominate above 6 GeV/c


$\mu$ in $2.5<y<4$

- Good agreement with pQCD(FONLL) over the full $p_t$ range
- FONLL suggests that beauty predominate above 6 GeV/c

FONLL: M. Cacciari et al., JHEP 0103 006 (2001)
D mesons in |y|<0.5

- Reference pp spectra at 2.76 TeV from an extrapolation of the 7 TeV measurements (R. Averbeck et al, arXiv:1107.3243)

- Scaling was cross checked with our own measurement at 2.76 TeV for 2<p_t<8 GeV/c (only 3 days of data taking, limited pt coverage, large uncertainties)

e in |y|<0.8

μ in 2.5<y<4


Hot and dense QCD at LHC, Santiago, 08.02.12                          Andrea Dainese

Rencontres de Moriond Renu Bala (INFN, Torino) 13/03/2012
D-meson reconstruction in Pb-Pb 2010

~3M central collisions (0-20%):

Reconstruction efficiency ~1-10%  
* evaluated from MC simulation  
* no centrality dependence found

Feed-down from B decays ~10-15% after cuts  
* evaluated considering B-FONLL-predictions, and an hypothesis on the R_{AA} of D-mesons from B feeddown (included in the systematic uncertainty)

arXiv:1203.2160v1
\( R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}}{dp_t} \frac{d\sigma_{pp}}{dp_t} \)

- **R\(_{AA}\) (0-20\%)** shows a suppression of about a factor of 3-4 for \( p_t > 5 \text{ GeV/c} \)

- **D\(^0\)**, **D\(^+\)** and **D\(^{**+\)** R\(_{AA}\) are in agreement with in statistical uncertainties
Comparison with charged hadron $R_{AA}$:

- Very close at high $p_t$
- Hints of $R_{AA}^{D}>R_{AA}^{charged}$
- Non prompt $J/\psi$ mesons (from B-decays) with $p_t>6.5$ GeV/c measured by CMS coll. (arXiv:1201.5069) show clearly less suppression than charged hadron
- Comparison with D-mesons requires precise measurement, extended to low $p_t$
Little shadowing is expected for $p_t > 6$ GeV/c \(\Rightarrow\) final state effect

$p$-$Pb$ run at LHC crucial to understand the low-$p_t$ rise


**arXiv:1203.2160v1**
**First measurement of D⁰ elliptic flow**

- Indication of charm flow at low \( p_t \)
- Measurement is statistically limited with 2010 data
- Will be improved with 2011 PbPb run
**Electron $R_{AA}$ at central rapidity**

**Consider:** Inclusive electrons - cocktail

- Large systematics from the PID, cocktail and the reference spectrum
- Spectra dominated by charm and beauty decays above 3-4 GeV/c

**Suppression in central collisions** by a factor about 1.5-4
**Muons R\textsubscript{CP} at Forward Rapidity**

Consider: inclusive muon spectrum

- Restrict to tracks pointing to the vertex (remove background)
- Background from hadronic decays contribution not subtracted

\[ R_{\text{CP}}^i = \frac{(dN / dp_t)^i / \langle T_{\text{AA}}^i \rangle}{(dN / dp_t)^{40-80\%} / \langle T_{\text{AA}}^{40-80\%} \rangle} \]

0-10%/40-80% suppression \(\sim 2.5\) above 6 GeV/c

Background subtraction and R\textsubscript{AA} measurement is in progress
**Quarkonium Analysis**

**J/ψ → e^+e^- (central rapidity)**
- Like-sign background subtraction, scaled to opposite sign (match integral for M_{inv}>3.2)
- Signal extraction by bin-counting in a narrow mass window (2.90-3.15 GeV/c^2)

**J/ψ → μ^+μ^- (forward rapidity)**
- Crystal ball fit for signal & two exponential fits for continuum
- Event-mixing technique & fit of background subtracted distribution

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**0-40%**

![Graph showing quarkonium analysis results for 0-40% centrality.]

- **TPC only**
  - Centrality: 0 - 40%
  - Number of events: 6 × 10^6
- **TPC and TRD combined**
  - Centrality: 0 - 40%
  - Number of events: 6 × 10^6

**Pb-Pb √s_NN = 2.76 TeV**

- **Same event**
  - Number of events: 1427 ± 262
  - Signal: 1427 ± 262
  - S/B: 0.021 ± 0.004
  - Signif.: 5.45 ± 0.14
- **Mixed event**
  - Number of events: 2000 ± 400
  - MC shape

- **Event-mixing technique & fit of background subtracted distribution**
Results are in good agreement with NLO NRQCD calculations

pp@ 2.76 TeV results are used as a reference to compute $R_{AA}$
J/ψ suppression observed with no centrality dependence

J/ψ $R_{AA}$ is larger with respect to PHENIX results at forward rapidity and is closer at mid-rapidity.

...but Cold Nuclear Matter (CNM) effects are expected to be different at the two energies

Trend in data as predicted with statistical hadronization scenario

Indication of J/ψ (re)generation(?)

Needs a precise charm cross-section

Needs better knowledge of gluon shadowing (pA collisions)
SUMMARY AND OUTLOOK

Heavy flavour nuclear modification factors in Pb-Pb collisions at 2.76 TeV have been measured.

- Data exhibit a clear centrality dependence
- $D$ mesons $R_{AA}$ is suppressed by about a factor of 3-4 in the 0-20% CC
- Hint of following the hierarchical pattern i.e $R_{AA}^D > R_{AA}^{charged}$
- Inclusive-cocktail electrons ($|\eta| < 0.8$) show a suppression of about a factor of 3 in the most central collisions (0-10%)
- Muon $R_{cp} (0-10%/40-80%)$ shows a suppression of about a factor of 2.5 for $p_t>6$ GeV/c

First measurement of $D$ meson elliptic flow has been performed: indication of charm flow at low $p_t$

$J/\psi$ $R_{AA}$ measured at forward rapidity down to $p_t=0$

- No significant dependence on centrality
- Less suppression than at RHIC at forward rapidity
- $p$-$Pb$ needed for further understanding

**Improved precision and extended $p_t$ reach with 2011 PbPb data**
Heavy flavour zoo in Pb-Pb 2011

D^0 → K^+π^+ + c.c.
Pb-Pb √s_{NN} = 2.76 TeV
2011 run
0-7.5% central collisions
5.4×10^6 events

Centrality: 0-7.5%

Mean = 1.865 ± 0.001
Sigma = 0.016 ± 0.001
Significance (3σ) 21.4 ± 1.1
S (3σ) 3976 ± 205
S/B (3σ) 0.130 ± 0.007

D^+ → K^+π^+π^+ + c.c.
Pb-Pb √s_{NN} = 2.76 TeV
4.0 × 10^6 events, p_T^D > 3 GeV/c

Centrality: 0-7.5%

Mean = 1.873 ± 0.003
Sigma = 0.017 ± 0.003
Significance (3σ) 5.8 ± 1.1
S (3σ) 281 ± 53
S/B (3σ) 0.14 ± 0.03

D_{s}^{*+} → K^+K^-π^+ + c.c.
Pb-Pb √s_{NN} = 2.76 TeV
3.15 × 10^6 events, p_T^{D_s} > 5 GeV/c

Centrality 20-40%

Mean = 1.983 ± 0.004
Sigma = 0.014 ± 0.005
Significance (3σ) 4.1 ± 1.2
S (3σ) 130 ± 39
S/B (3σ) 0.15 ± 0.04

J/ψ

ALICE Performance
4/03/2012
Pb-Pb, √s_{NN} = 2.76 TeV
N_{J/ψ} = 39249 ± 718
σ_{J/ψ} = 78.0 ± 1.5 MeV/c^2
S/B (3σ) = 0.208 ± 0.004

Invariant Mass (Kππ) (GeV/c^2)

Events/(50 MeV/c^2)

Heavy flavour at LHC with ALICE
Andrea Dainese (INFN Padova, Italy)
on behalf of the ALICE Collaboration

Hot and dense QCD at LHC, Santiago, 08.02.12
Andrea Dainese
RENCONTRES DE MORIOND

RENOTES DE MORIOND

Renu Bala (INFN, Torino)
13/03/2012

HEAVY FLAVOUR ZOO IN Pb-Pb 2011

THANK YOU FOR YOUR KIND ATTENTION !!!!!
Backup
Scale the 7 TeV measurements with the pQCD (FONLL) 2.76/7 factor

- Consider that the calculation scales and quark masses doesn’t change with $\sqrt{s}$
- Uncertainties range from 25% (low-pt) to 10% (high-pt)

Scaling procedure validation:
- Compare different calculations (MNR, GM-VFNS,...)
- CDF measurements at 1.96 TeV
- ALICE data at 2.76 TeV for 2 < $p_t$ < 8 GeV/c (only 3 days... limited $p_t$ cov., large uncertainties)
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
Many models give reasonable prediction for charm $R_{AA}$, but only a few models also give predictions for charged hadrons $R_{AA}$. Among those some (rad+collisional energy loss – GLV/WHDG/CUJET 1.0) describe fairly well both charged hadrons and D meson $R_{AA}$.
• Inclusive electron pt 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
• Subtract cocktail from inclusive spectra
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)

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 → beauty dominance (only in pp for now)
**Open Heavy flavour : Single muons at forward rapidity**

**Analysis Strategy:**
- Remove *hadrons* and low *pt* secondary muons by requiring a muon trigger signal plus a cut on the impact parameter.
- Subtract *decay* muons by subtracting MC \( \text{d}N/\text{d}p_T \) normalized to data at low \( p_T \).
- In Pb-Pb, we don’t subtract the decay muons for now, but restrict the analysis to the high \( p_T \) region where the background is small.
D mesons cross sections in pp@ 7 TeV

\( D^0 \rightarrow K^- \pi^+ \)

\( D^+ \rightarrow K^- \pi^+ \pi^+ \)

\( D^{**} \rightarrow D^0 + \pi^+ \)

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**Open Heavy Flavour: D mesons at Central Rapidity**

**Hadronic decay Channels**

\[ D^0 \rightarrow K\pi, \quad D^+ \rightarrow K\pi\pi, \quad D^* \rightarrow D^0\pi, \quad D_s \rightarrow KK\pi, \quad D^0 \rightarrow K\pi\pi\pi, \quad \Lambda_c \rightarrow \pi Kp \]

Selection strategy: displaced vertices

Main topological cuts:

- Impact parameter of the tracks,
- Angle between the meson flight line and particle momentum.

Particle identification: to reject background at low \( p_t \)

- TPC allows \( K/\pi \) separation up to \( \sim 0.6 \) GeV/c,
- TOF allows \( K/\pi \) separation up to \( \sim 2 \) GeV/c.

Invariant Mass Analysis to extract Raw Yield
J/ψ $R_{AA}$ comparison with CMS results

Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

- ALICE (arXiv:1202.1383), $2.5 < y < 4, p_T (\text{GeV/c}) > 0$  
  global sys. = ± 12.5%

- CMS (arXiv:1201.5069), $|y| < 2.4, 6.5 < p_T (\text{GeV/c}) < 30$  
  global sys. = ± 6%
More charm in pp (2010): D_s and \Lambda_c

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Renu Bala (INFN, Torino) 13/03/2012

ALICE Preliminary, pp, \sqrt{s} = 7 TeV
- ALICE Prelim. (tot. unc.)
  \text{p}_{t}>2 \text{ GeV/c}, |y|<0.5
- LHCb Prelim. (tot. unc.)
  \text{p}_{t}>0, 2<y<4.5
- e^+e^- (tot. unc.)
  \text{p}_{t}>0, \text{ mid-y}
- H1 (tot. unc.)
  \text{p}_{t}>2.5 \text{ GeV/c}, \text{ mid-y}