Heavy Flavour Production in Pb-Pb collisions at LHC with ALICE

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- Motivation
- Analysis strategy
- Nuclear modification factor $R_{AA}$
- Azimuthal anisotropy $v_2$
- Summary and outlook
Heavy Flavour (Charm & Beauty) Production

- **Heavy-flavour quarks (c, b)**
  - $m_c \sim 1.3 \text{ GeV/c}^2$, $m_b \sim 4.7 \text{ GeV/c}^2$
  - Originate from initial scattering processes
  - Produced on a very short time scale ($\approx 1/(2m_q) \leq 0.1 \text{ fm/c}$)
  
    → Sensitive to the full history of the collision
  
    → Excellent probes to study the de-confined medium produced in nucleus nucleus collisions
    
      - Study flow and energy loss of heavy quark
        
          → Independent way to extract properties of the medium
Energy Loss in the Medium

- **Energy loss depends on**
  - Properties of the medium (gluon densities, size)
  - Properties of the probe (color charge, mass)

- **Dead cone effect**
  - Gluon radiation is suppressed for angles \( \theta < \frac{M_q}{E_q} \)

\[ \langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2 \]

**Color Charge**
- \( C_R = 3 \) for gluons, \( C_R = 4/3 \) for quarks

**Transport coefficient** related to medium characteristics and gluon density

- Heavy flavour energy loss should be smaller than the one of light hadrons:
  - \( \Delta E_g > \Delta E_{\text{charm}} > \Delta E_{\text{beauty}} \)
  - \( R_{AA} \) (light hadrons) < \( R_{AA} \) (D) < \( R_{AA} \) (B)


**Possible other mechanisms for the interaction with the medium**
- Collisional energy loss, in-medium dissociation, resonance scattering

**Proton-proton collisions** provide an important test of pQCD in a new energy domain and heavy ion reference

\[ R_{AA} (p_T) = \frac{1}{< T_{AA} >} \times \frac{dN_{AA}}{dp_T} / \frac{d\sigma_{pp}}{dp_T} \]

**Proton-nucleus collisions** disentangle initial and final state effects
A Large Ion Collider Experiment

Central Barrel ($|\eta| \leq 0.9$)
- Open Heavy Flavour
  - Hadronic decays
  - Semi-electronic decays

Forward Muon Arm ($4 \leq \eta \leq 2.5$)
- Open Heavy Flavour
  - Semi-muonic decays

Reconstruction of Electrons from Semi-electronic c/b Decays

**Analysis Strategy**

- **Electron Identification** with Time Of Flight system, Time-Projection Chamber
- Remaining hadron contamination determined via fits of dE/dx in momentum slices
- Requirement of a hit in the innermost layer of the Inner Tracking System (r = 3.9 cm) to reduce bkg from photon conversion
- Subtraction of the background via data-tuned MC cocktail

Semi-electronic decays:
c, b → e + anything
Cocktail-subtracted Electron $R_{AA}$

$\rightarrow$ $p_T$ region 3.5-6 GeV/c: charm and beauty decays dominate

$\rightarrow$ Suppression in central collisions: factor 1.5-4

$\rightarrow$ Ongoing:
- Reduction of systematic uncertainty
- High-$p_T$ extension with TRD and EMCAL particle identification

pp reference at 2.76 TeV: measured 7 TeV spectrum scaled with FONLL
R. Averbeck et al, arXiv:1107.3243

$R_{AA}(p_T) = \frac{1}{<T_{AA}>} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$

60-80%

0-10%
Disentangle Contributions from c and b Decays

**pp \( \sqrt{s} = 7 \) TeV**

- Large b mass and c\( \tau \) of 500 \( \mu m \)
- → Analysis Strategy: selection of electrons from displaced vertex

**pp, \( \sqrt{s} = 7 \) TeV**

\[ \int L dt = 1.3 \text{ nb}^{-1} \]

- \( \text{ALICE Preliminary} \)
- \( 7\% \) normalization error

**FONLL in agreement with data**
**Available as reference for Pb-Pb**
**Pb-Pb work in progress**

FONLL: Cacciari, Greco, Nason, JHEP05(1998)007
and M. Cacciari private communication
Open Heavy Flavour from Forward Muons

$2.5 < y < 4$

**Analysis Strategy**

- Muon identification with muon arm
- Removal of hadrons and low $p_T$ secondary muons via requirement of a muon trigger signal, $p_T$ cut-off and DCA cut
- Subtract muons from pion and kaon decays by subtracting
  - in pp: MC $dN/dp_T$ normalized to data at low $p_T$
  - in PbPb: extrapolated $K^\pm$ and $\pi^\pm$ spectra, measured at mid-rapidity, to forward rapidities and applying decay kinematics

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Semi-muonic decays:

$c, b \rightarrow \mu + $ anything

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**Graphs:**

1. $pp \sqrt{s}=2.76$ TeV, PYTHIA Perugia-0
2. ALICE $pp \sqrt{s}=2.76$ TeV, $\mu^\pm$-HF in $2.5<y<4$

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ArXiv:1205.6443
Heavy Flavour Decay Muon $R_{AA}$

→ Suppression in central collisions: factor 3, no significant $p_T$ dependence
→ $p_T$ region 6-10 GeV/c: FONLL - beauty decays dominate
D Meson Decay Reconstruction

Hadronic decays:
- $D^0 \rightarrow K\pi^+$
- $D^* \rightarrow K\pi^+$
- $D^0 \rightarrow K\pi^+$
- $D^0 \rightarrow K\pi^+$
- $D^* \rightarrow D^0 \pi^+$
- $D^0 \rightarrow K^+\pi^-\pi^+$ and charge conj.

### Analysis Strategy

- **Main Selection:** displaced-vertices topology
- **Charged Kaon ID** in Time-Projection Chamber and Time of Flight system to reduce bkg at low $p_T$
- Invariant mass analysis
- **Feed-down from B meson** decays corrected with FONLL

arXiv:1203.2160

Pb-Pb run 2010

Pb-Pb run 2011
D Meson $R_{AA}$

- pp reference at 2.76 TeV: measured 7 TeV spectrum scaled with FONLL

- Cross-checked against measured result at 2.76 TeV
  (large errors and limited $p_T$-coverage due to short data taking period)

R. Averbeck et al, arXiv:1107.3243

pp reference → P. Antonioli (4C)
D Meson $R_{AA}$

- **pp reference at 2.76 TeV:** measured 7 TeV spectrum scaled with FONLL
- **Cross-checked against measured result at 2.76 TeV**
  (large errors and limited $p_t$-coverage due to short data taking period)

→ **Suppression in central collisions:** factor 3–4 for $p_t > 5$ GeV/c
→ **Suppression for 40–80% CC:** factor 1.5 for $p_t > 5$ GeV/c
→ **Reduce errors with Pb–Pb data from 2011 run:**
  ~factor 6–7 more statistics in 0–7.5% CC

R. Averbeck et al, arXiv:1107.3243
D Meson $R_{AA}$

Initial State Effects

- Comparison to NLO + shadowing (EPS09 parametrization)

- Strong suppression likely to be a final state effect
- $p$-Pb measurement end of 2012 will give decisive answer

$R_{AA}^{(\pi)} < R_{AA}^{(D)} < R_{AA}^{(B)}$ ?

- Preliminary charged $\pi$ $R_{AA}$ coincides with charged hadron $R_{AA}$ for $p_t > 5$ GeV/c

- Hint of $R_{AA}^{(\pi)} < R_{AA}^{(D)}$
- $R_{AA}^{(D)} < R_{AA}^{(B)}$ ? not conclusive - different $p_t$ range
- Reduce errors (2011 Pb-Pb run)
Collective Effects - Elliptic Flow $v_2$

\[ \frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos(n(\varphi - \Psi_{RP})) \]

\[ v_2 = \langle \cos(2(\varphi - \Psi_{RP})) \rangle \]

- **Anisotropic particle production in-plane and out-of-plane**
- **Evaluation via 2nd Fourier coefficient “$v_2$”**
- **Charm flow sensitive to**
  - Degree of thermalization of massive quarks in the medium (low $p_T$)
  - Path length dependence of energy loss (high $p_T$)

**Reaction plane**

**Collective interaction pressure**

**Momentum space: final asymmetry**
Signal Extraction for D Meson $v_2$

- Event plane determination from Q-vector

$$Q_2 = \frac{1}{n} \sum_{i=1}^{n} w_i \cos(2 \phi_i)$$

- Using tracks in TPC at central rapidity
- $\phi_i$-weights to improve EP flatness
- Signal extraction in-plane and out-of-plane
- Calculate $v_2$

$$v_2 = \frac{\pi}{4} \frac{N_{inp} - N_{outp}}{N_{inp} + N_{outp}}$$

- Correct for EP resolution
\[ D^0 \text{ and } D^+ \text{ Meson } v_2 \]
in 30-50\% Collision Centrality

→ Indication of non zero \( v_2 \)
→ 3\( \sigma \) effect in 2-6 GeV/c for \( D^0 \)
→ \( D \) meson \( v_2 \) comparable with \( v_2 \) of charged hadrons measured with ALICE in the same rapidity region
→ Models based on charm transport in the medium predict a non-zero \( v_2 \) of up to 0.15-0.20

Indication of non-zero $v_2$

- 3σ effect in 2-6 GeV/c for $D^0$
- $D$ meson $v_2$ comparable with $v_2$ of charged hadrons measured with ALICE in the same rapidity region
- Models based on charm transport in the medium predict a non-zero $v_2$ of up to 0.15-0.20, but do not describe well the $R_{AA}$.$\,$

\[ D^0 \text{ and } D^+ \text{ Meson } v_2 \text{ in 30-50% Collision Centrality} \]

Summary and Outlook

- ALICE has excellent particle identification and vertexing capabilities
  → Rich harvest of heavy flavour results

- Nuclear modification factors $R_{AA}$
  - Measured in several channels, which all show a strong suppression in central collisions
  - Comparison with theoretical models suggests final state effect
  - Possible hint of lower suppression for D than for pions

- D meson azimuthal anisotropy
  - Indication of non zero $v_2$
  - Comparable with charged hadron $v_2$

Outlook

- Separate charm and beauty contribution
- Reduction of systematic uncertainties and increase of $p_T$ reach
- Disentangle initial and final state effects (p-Pb run end of 2012)