Measurements of the suppression and anisotropy of heavy-flavour particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE

- D mesons via hadronic decay channels
- Electrons from heavy-flavour hadron decays
- Muons from heavy-flavour hadron decays

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Physics motivation

→ Charm and beauty quarks are produced in hard scattering processes (large $Q^2$) in the early stage of the collision.

→ They experience the full evolution of the system → sensitive probes of the properties of the hot and dense QCD matter (QGP).

→ Expected to lose energy while traversing the medium.

→ Do heavy quarks participate in the collective expansion of the medium?

→ Hadronization: fragmentation vs coalescence.

→ Need reference measurements in pp and p-Pb collisions.
  → Perturbative QCD describes the cross sections measured in pp collisions.

(talk Grazia Luparello: Saturday 24th – 8:30)
ALICE detector

**EMCal**: trigger, electron ID

**V0**: trigger, centrality and event plane determination

**ITS**: tracking, vertexing and PID via $dE/dx$

**TRD**: tracking, electron ID

**TOF**: PID via time of flight

**TPC**: tracking, PID via $dE/dx$, event plane determination

**Forward** muon spectrometer
D mesons via hadronic decay channels

- Analysis based on reconstruction of decay vertex topologies displaced from the primary vertex
- TPC and TOF are used to identify π and K and to reduce the combinatorial background
- Signal extraction through invariant mass analysis

$$5 < p_T < 8 \text{ GeV/c}$$

$$8 < p_T < 16 \text{ GeV/c}$$

- **$D^0$**
  - $D^0 \rightarrow K^-\pi^+$
  - $c\tau \sim 123 \mu m$
  - BR$\sim 3.88\%$

- **$D^+$**
  - $D^+ \rightarrow K^-\pi^+\pi^+$
  - $c\tau \sim 312 \mu m$
  - BR$\sim 9.13\%$

- **$D^{*+}$**
  - $D^{*+} \rightarrow D^0\pi^+$
  - BR$\sim 67.7\%$

- **$D^0 \rightarrow K^-\pi^+\pi^+$**
  - $c\tau \sim 312 \mu m$
  - BR$\sim 9.13\%$

- **$D^{*+} \rightarrow D^0\pi^+$**
  - BR$\sim 67.7\%$

- **$D_s^+ \rightarrow \phi \pi^+ \rightarrow K^-K^+\pi^+$**
  - $c\tau \sim 150 \mu m$
  - BR$\sim 2.28\%$

${|y| < 0.8}$

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Electrons from heavy-flavour hadron decays

- **Low-**\(p_T\) electrons (\(p_T < 3 \text{ GeV/c}\)): PID via TPC dE/dx complemented with TOF and ITS
- **High-**\(p_T\) electrons (\(p_T > 3 \text{ GeV/c}\)): PID using TPC, EMCal

Main background sources:
- direct and decay \(\gamma\) conversions
- \(\pi^0\) and \(\eta\) Dalitz decays

**Background subtraction:**
- Measured: invariant mass method (e\(^+\)e\(^-\) pairs)
- Calculated: cocktail method based on data.
Muons from heavy-flavour hadron decays

-4 < $\eta$ < -2.5

**Track selection:**
- Acceptance and geometrical cuts
- Muon trigger matching:
  - reject the hadrons that cross the absorber
- **Select tracks pointing back to the vertex:**
  - Remove tracks from beam-gas interactions

**Remaining main background:**
- $\mu$ from primary $\pi$ and K decays
  - (subtracted with MC-tuned cocktail)
- $\mu$ from $W/Z/\gamma^*$ decays at high $p_T$
Study in-medium energy loss

- Production of hard probes (heavy quarks, jets...) in A-A collisions is expected to scale with the number of nucleon-nucleon collisions $N_{\text{coll}}$ (binary scaling).

- Observable: nuclear modification factor

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA} \rangle d\sigma_{pp}/dp_T} \sim \frac{\text{QCD medium}}{\text{QCD vacuum}}$$

- If no nuclear effects are present $\rightarrow R_{AA} = 1$ (binary scaling).

- In-medium parton energy loss via radiative (gluon emission) and collisional processes depending on:
  \begin{align*}
  &\rightarrow \text{color charge} \\
  &\rightarrow \text{quark mass (dead cone effect)} \\
  &\rightarrow \text{path length and medium density}
  \end{align*}

$\Rightarrow \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
Need to compare $R_{AA}^{n}$, $R_{AA}^{D}$, $R_{AA}^{B}$

Dokshitzer and Kharzeev, PLB 519 (2001) 199
New high $p_T R_{AA}$ measurements in several Pb-Pb centrality classes show stronger suppression in the 10% most central collisions respect to semi-central collisions. Stronger energy loss in central collisions due to the increase of medium density.
New $R_{AA}$ measurements in 0-10% central Pb-Pb collisions are extended down to $p_T = 0.5$ GeV/c → low-$p_T$ measurements crucial in all systems to test binary scaling of total $c\bar{c}$ cross section
→ systematic uncertainty dominated by the pp reference at the same collision energy (Phys. Rev. D 91 (2015) 012001)
→ Suppression compatible with the one observed in the muon decay channel (talk Zuman Zhang: Sunday 25th – 10:40)
Heavy-flavour decay electron nuclear modification factor

- $R_{\text{pPb}}$ consistent with unity (PLB 754 (2016) 81) $\rightarrow$ no strong modification of heavy-flavour decay electron spectra in p-Pb collisions relative to pp collisions
- Large suppression at high $p_T$ in Pb-Pb collisions
  $\rightarrow$ final-state effect due to heavy quarks in-medium energy loss
Heavy-flavour decay electron nuclear modification factor

- $R_{pPb}$ consistent with unity (PLB 754 (2016) 81) → no strong modification of heavy-flavour decay electron spectra in p-Pb collisions relative to pp collisions
- Large suppression at high $p_T$ in Pb-Pb collisions
  → final-state effect due to heavy quarks in-medium energy loss
- $R_{AA}$ compatible within uncertainties with PHENIX (PRL 98, (2007) 172) at low $p_T$
D-meson and pion nuclear modification factor

- Expected hierarchy in the energy loss:
  \( \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \) \( \Rightarrow \) \( R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B) \)
- D-meson and \( \pi \) \( R_{AA} \) as a function of \( p_T \) and \( <N_{\text{part}}\) are compatible within uncertainties
- Consistency between \( R_{AA}(D) \) and \( R_{AA}(\pi) \) described by models taking into account:
  \( \rightarrow \Delta E_g > \Delta E_{u,d,s} > \Delta E_c \)
  \( \rightarrow \) different shape of the parton \( p_T \) spectra
  \( \rightarrow \) different parton fragmentation functions
D-meson and $J/\psi \leftrightarrow B$ $R_{AA}$ vs centrality

- Similar $\langle p_T \rangle$ (~10 GeV/c) for D and B mesons ($J/\psi \leftrightarrow B$) from CMS
- Rapidity range slightly different
- Indication of $R_{AA}(D) < R_{AA}(J/\psi \leftrightarrow B)$ in central events at high $p_T$

✔ Djordjevic: non-prompt $J/\psi$ $R_{AA}$ considering for energy loss

✔ Djordjevic: D-meson $R_{AA}$

\[ R_{AA} = \frac{\text{signal in AA collision}}{\text{signal in pp reference}} \]

- $p_{QCD}$ model including mass-dependent radiative and collisional energy loss predicts a difference between the D-meson and non-prompt $J/\psi$ $R_{AA}$ similar to that observed
- Similar pattern from other calculations (e.g. BAMPS, WHDG, Vitev et al.)
Beauty-decay electron $R_{AA}$

- Analysis based on the electron impact parameter distribution.

- First $R_{AA}$ measurement of beauty-decay electron:
  \[ R_{AA} < 1 \text{ for } p_T > 3 \text{ GeV/c} \]
  \[ \rightarrow \text{consistent with the picture of mass-dependent radiative and collisional energy loss} \]

\[ b (\rightarrow c) \rightarrow e \]
\[ b, c \rightarrow e \]

**Figures:**
- Left: ALICE, 0–20% Pb–Pb, $\sqrt{s_{NN}} = 2.76$ TeV
  - $1.5 < p_T < 2.0$ GeV/c
  - Data, Conversion electrons, Dalitz electrons

- Right: ALICE, 0–20% Pb–Pb, $\sqrt{s_{NN}} = 2.76$ TeV
  - $b (\rightarrow c) \rightarrow e$, $|y_{cms}| < 0.8$
  - $b, c \rightarrow e$, $|y_{cms}| < 0.6$

**ArXiv:** 1609.03898
Re-scatterings among produced particles convert the initial geometrical anisotropy into an observable momentum anisotropy.

In addition, path-length dependent energy loss induces an asymmetry in momentum space.

**Observable**: elliptic flow $v_2 = 2^{\text{nd}}$ Fourier coefficient of the particle azimuthal distribution.

**Heavy-flavour $v_2$ measurements probe:**

- **Low/intermediate $p_T$**: collective motion, degree of thermalization of heavy quarks and hadronization mechanism (recombination).

- **High $p_T$**: path-length dependence of heavy-quark energy loss.
Leptons from heavy-flavour hadron decays

HF-decay muons
-4 < η < -2.5
PLB 753, (2016) 41

HF-decay electrons
|y| < 0.7
arXiv:1606.00321

$v_2$ of heavy-flavour decay electrons (at mid-rapidity) and muons (at forward rapidity) are similar in the different centrality classes. Positive $v_2$ observed $\rightarrow$ 5.9σ effect for $2 < p_T < 2.5$ GeV/c in 20-40% centrality class for the heavy-flavour decay electrons.

Hint for an increase of $v_2$ from central to semi-central collisions as observed for D mesons
Suggests collective motion of low-$p_T$ charm quarks in the expanding fireball
D-meson elliptic flow

Positive $v_2(D)$ observed (5σ effect for $2 < p_T < 6$ GeV/c in 30-50% centrality class)

**D-meson $v_2$ similar to charged-particle $v_2$**
Confirms significant interaction of charm quarks with the medium

$\Delta v_2 = \frac{1}{R^2} \left( \frac{2 N_{in-plane} - N_{out-of-plane}}{4 N_{in-plane} + N_{out-of-plane}} \right)$

**PRL 111, 102301 (2013)**
**PRC 90 (2014) 034904**
Model predictions: $R_{AA}$ and $\nu_2$

- $\nu_2$ and $R_{AA}$ measurements for different heavy-flavour decay channels together start to provide constraints for models
Strong suppression of heavy-flavour yields at high $p_T \rightarrow$ final-state effect
- D mesons at central rapidity
- Semi-leptonic decays at central and forward rapidity

Larger suppression for D mesons with respect to B mesons (non-prompt J/ψ by CMS) at high $p_T$
- Described by theoretical models implementing mass-dependent energy loss

Hint for $R_{AA} < 1$ for beauty decay electrons at high $p_T$

A non-zero elliptic flow of heavy flavours was measured in semi-central collisions

Hint for an increase of heavy-flavour $v_2$ from central to semi-central collisions
- D-meson elliptic flow similar to charged-particle $v_2$
- 5.9σ effect in 20-40% centrality class for the heavy-flavour decay electrons

Suggests collective motion of low-$p_T$ heavy quarks (mainly charm)

Comparison of different observables ($R_{AA}$, $v_2$) with theory starts to constrain the energy-loss and hadronization models
BACKUP
Model predictions: \( R_{AA} \) and \( v_2 \)

\[ R_{AA} \] and \( v_2 \) measurements for different heavy-flavour decay channels together start to provide constraints for models.

→ Both collisional and radiative energy loss mechanisms and an expanding medium seem to be needed to describe \( v_2 \) and \( R_{AA} \) for most of the model.

→ Role of recombination of heavy quark in the medium seems to help in describing \( v_2 \)
Nuclear modification factor: $D_S^+$

- Measurement of $D_S^+$ production in Pb-Pb collisions
- Expectation: enhancement of the strange over non-strange D-meson yield at intermediate $p_T$ if charm hadronizes via recombination in the medium, due to enhanced strangeness abundance

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- Strong $D_S^+$ suppression in central collisions (similar to other D-meson) for $8 < p_T < 12$ GeV/c
- Hint of less suppression for $p_T < 8$ GeV/c

TAMU: PRL 110 (2013) 112301
Andronic et al. PLB 659 (2008) 149
Kuznetsova, Rafelski EPJ C51 (2007) 113
D-meson nuclear modification factor

- **$R_{pPb}$ consistent with unity** *(PRL 113 (2014) 232301)* → no strong modification of D-meson spectra in p-Pb collisions relative to pp collisions

- **Large suppression** of D-mesons at high $p_T$ in Pb-Pb collisions → larger suppression in the 10% most central collisions → **final-state effect** due to charm quark in-medium energy loss

- D-meson $R_{AA}$ compatible within uncertainties with $D^0 R_{AA}$ by STAR for $p_T > 2$ GeV/c → **low$p_T$** measurements crucial in all systems to test binary scaling of total $c\bar{c}$ cross section
**$R_{AA}$ of beauty decay electrons and $J/\psi \leftarrow B$**

- Indication of suppression $R_{AA}(J/\Psi \leftarrow B)$ in central events at high $p_T$

- $R_{AA}$ measurement of beauty:
  $\rightarrow$ Hint for $R_{AA} < 1$ for beauty-decay electrons in $p_T > 3$ GeV/c

- models including in-medium energy loss can describe qualitatively the measured suppression

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**Graphs:**

1. Graph showing $R_{AA}$ vs. $p_T (\text{GeV}/c)$ for non-prompt $J/\Psi$
   - Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
   - 0-20% and 20-100% CMS ($|y| < 2.4$)
   - 0-50% ALICE ($|y| < 0.8$)
   - Models: HTL, ALQCD, WHDG, AdS/CFT
2. Graph showing $R_{PbPb}$ vs. $p_T (\text{GeV}/c)$ for $b(\rightarrow c) \rightarrow e$
   - Models: 0-20% Pb-Pb, FONLL + EPS09NLO shad., MC@sHQ+EPPOS2, Coll+Rad(LPM), BAMPS, $\kappa=1$, BAMPS, $\kappa=0.2$, WHDG, TAMU, POWLANG-IQCD ($T_{dec}=155$ MeV), POWLANG-HTL ($T_{dec}=155$ MeV), AdS/CFT

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*References:*

- A. Dubla
- JHEP 1507 (2015) 051
- JHEP 1205 (2012) 063
- arXiv:1609.03898
Model predictions: \( R_{AA} \) and \( v_2 \)

\( v_2 \) and \( R_{AA} \) measurements together start to provide constraints for models.
Model predictions: D-meson $R_{AA}$ and $v_2$

- models including in-medium energy loss can describe qualitatively the measured strong suppression ($R_{AA} < 1$) of the yield at high $p_T$ and the anisotropy ($v_2 > 0$)
- $v_2^D$ and $R_{AA}^D$ measurements together start to provide constraints for models
Model predictions: HFM $R_{AA}$ and $v_2$

Models of in-medium parton energy loss can describe reasonably well heavy-flavour decay muons at forward rapidity.

- Similar picture from the comparison of $R_{AA}$ and $v_2$ to models as for other heavy-flavour measurements.
  → Models of in-medium parton energy loss can describe reasonably well heavy-flavour decay muons at forward rapidity.

- $v_2^{HFM}$ and $R_{AA}^{HFM}$ measurements together start to provide constraints for models.
Expected hierarchy in the energy loss:
\[ \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \Rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B) \]

- D meson and π $R_{AA}$ as a function of $p_T$ and $N_{\text{part}}$ are compatible within uncertainties.
D-meson and pion $R_{AA}$

Centrality 0-10%

arXiv:1509.06888

→ low-$p_T$ measurements better described by model including nuclear shadowing (EPS09)

→ low-$p_T$ measurements crucial in all systems to test binary scaling of total $c\bar{c}$ cross section
$D$ meson and $J/\psi \leftrightarrow B$

$R_{AA}$ vs centrality

$\text{MC@sHQ+EPOS2: PRC 89 (2014) 014905}$

$\text{TAMU: PLB 735 (2014) 445}$

$Pb-Pb, \ s_{NN} = 2.76 \text{ TeV}$

- $D$ mesons (ALICE) $8<p_{T}<16 \text{ GeV/c, } |y|<0.5$
- Non-prompt $J/\psi$ (CMS Preliminary)
  - $6.5<p_{T}<30 \text{ GeV/c, } |y|<1.2 \text{ CMS-PAS-HIN-12-014}$
  - (empty) filled boxes: (un)correlated syst. uncert.

$\text{MC@sHQ+EPOS2 Phys.Rev.C 89 (2014) 014905}$

$\text{D mesons}$
$\text{MC@sHQ+EPOS2}$
$\text{Non-prompt } J/\psi$
$\text{Non-prompt } J/\psi \text{ with c quark energy loss}$

$\langle N_{\text{part}} \rangle$

$\text{50-80\%}$
$\text{40-50\%}$
$\text{30-40\%}$
$\text{20-30\%}$
$\text{10-20\%}$
$\text{0-10\%}$

$\text{TAMU elastic Phys.Lett.B 735 (2014) 445}$

$\text{D mesons}$
$\text{MC@sHQ+EPOS2}$
$\text{Non-prompt } J/\psi$
$\text{Non-prompt } J/\psi \text{ with c quark energy loss}$

$\langle N_{\text{part}} \rangle$

$\text{50-80\%}$
$\text{40-50\%}$
$\text{30-40\%}$
$\text{20-30\%}$
$\text{10-20\%}$
$\text{0-10\%}$

$\rightarrow$ Models including mass dependence energy loss predict a difference between $D$-meson and non-promt $J/\psi$ similar to that observed.
$c, b \rightarrow (e^+ + e^-)/2$

- ITS+TOF+TPC eID, $|y| < 0.8$
- ALICE Preliminary
- TPC+EMCal eID, $|y| < 0.6$
- arXiv:1609.07104

ALICE

Pb-Pb, $s_{NN} = 2.76$ TeV
0-10% Centrality Class

$1/(2\pi p_T) \cdot 1/N_{ev} \cdot d^2 N/dp_T dy$ (GeV/c)$^{-2}$

$p_T$ (GeV/c)
$p_T$-differential cross section

Heavy-flavour $p_T$-differential cross sections well described by pQCD calculations at both energies (7 and 2.76 TeV)

FONLL: JHEP 9805 (1998) 007
$k_T$ Fact: PRD 62 (2000) 071502

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ALICE, JHEP 1201 (2012)

ALICE, PRL 109 (2012) 112301


ATLAS PLB 707 (2012) 438


Data: ECE 2016, GSI
Model predictions: D meson $R_{AA}$ and $v_2$

$R_{AA}$ measured in-plane and out-of-plane, sensitive to
- path length dependence of parton energy loss at high $p_T$
- collectivity at low $p_T$
D-Meson elliptic flow:

- Event plane method (TPC 0<η<0.8 or VZERO event plane)
- Extraction of the D-meson yield in- and out-of-plane

\[ v_2\{\text{EP}\} = \frac{1}{R_2} \frac{\pi N_{\text{in-plane}} - N_{\text{out-of-plane}}}{4 N_{\text{in-plane}} + N_{\text{out-of-plane}}} \]

Consistent between the three D-meson species

Positive D-meson \( v_2 \) (\( v_2^0 \)) observed

5.7σ effect for \( D^0, D^+, D^{*+} \) averaged for \( 2 < p_T < 6 \text{ GeV/c} \) in 30-50% centrality

ALICE collaboration, PRL 111, 102301 (2013)