Measurements of D-meson production in p-Pb and Pb-Pb collisions with the ALICE detector at the LHC

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OUTLINE

- Physics motivation
- The ALICE detector
- D-meson reconstruction with ALICE
- Results in p-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV
  - Nuclear modification factor
  - Production vs event multiplicity
- Results in Pb-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV
  - Nuclear modification factor
  - Azimuthal anisotropy ($v_2$)
- Conclusions
Physics Motivation

- Heavy quarks are produced in hard scattering processes in the initial stages of the collision
  - production time: $\Delta t$ charm $\sim 0.1$ fm/c, beauty $\sim 0.04$ fm/c
  - QGP: $\sim 0.3$ fm/c
    

- They experience the whole evolution of the system
  - sensitive probe to study the QGP formation in Pb-Pb collisions

- Study of p-Pb collisions to disentangle cold nuclear matter effects and possible collective effects in high-multiplicity events
Physical observables

- **Nuclear modification factor**

  Modification in p-Pb or Pb-Pb with respect to pp collisions

  In Pb-Pb collisions allows to study:
  - In-medium **parton energy loss** occurring via collisional and radiative processes
    - color-charge and quark-mass dependence \( \Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b \)
  - Modification of **hadronisation mechanism** in presence of a medium: possible coalescence of charm with medium quarks

\[
R_{AA} = \frac{1}{\left<T_{AA}\right> \frac{d\sigma_{pp}}{dp_T}} \frac{dN_{AA}}{dp_T}
\]
Physical observables

- **Nuclear modification factor**
  Modification in p-Pb or Pb-Pb with respect to pp collisions

  In Pb-Pb collisions allows to study:
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- **Azimuthal anisotropy**

  \[
  E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left\{ 1 + \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_{RP})] \right\}
  \]

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

  \( v_2 > 0 \)

  - **at low** \( p_T \): thermalization/
collective motion of heavy quarks in the medium
  - **at high** \( p_T \): path length
dependence of energy loss
The ALICE detector

Data samples:
- p-Pb collisions (Run2): 600 M minimum bias events
- Pb-Pb collisions (Run2): 10 M events in the centrality class 0-10%, 20 M events in 30-50% and 20 M events in 60-80%
D-meson reconstruction

Reconstruction of hadronic decay channels

<table>
<thead>
<tr>
<th>meson</th>
<th>$M$ (GeV/$c^2$)</th>
<th>$c\tau$ (µm)</th>
<th>decay</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D$^0$ (c$\bar{u}$)</td>
<td>1.865</td>
<td>123</td>
<td>K$^-$π$^+$</td>
<td>3.93</td>
</tr>
<tr>
<td>D$^+$ (c$\bar{d}$)</td>
<td>1.870</td>
<td>312</td>
<td>K$^-$π$^+\pi^+$</td>
<td>9.46</td>
</tr>
<tr>
<td>D$^{*+}$ (c$\bar{d}$)</td>
<td>2.010</td>
<td>$\Gamma = 83.3$ KeV</td>
<td>D$^0$(K$^-\pi^+\pi^+$)</td>
<td>67.7 x 3.93</td>
</tr>
<tr>
<td>D$^{*+}_s$ (c$\bar{s}$)</td>
<td>1.968</td>
<td>150</td>
<td>$\Phi$(K$^-K^+\pi^+$)</td>
<td>2.27</td>
</tr>
</tbody>
</table>

- Signal extracted from invariant-mass distributions

**Standard method:**
- Identification of secondary vertices displaced few hundred µm from the primary vertices
- Topological selections and PID to reduce background
D-meson reconstruction

Background-subtraction method (D⁰ only)

- Without vertex reconstruction
- PID selection only
- Combinatorial background subtraction via: event mixing, like sign, track rotation, side-band fit
- Method effective for low \( p_T < 1 \) GeV/c, that decay very close to the primary vertex
D-meson reconstruction

- Signal extracted corrected using Monte Carlo simulations for the acceptance of the detector and the selection efficiencies.

- Higher efficiency by a factor of 20 without vertex reconstruction for $1 < p_T < 2$ GeV/c
- Better S/B and significance with the “standard method” for $p_T > 1$ GeV/c
D-meson reconstruction

- Feed-down from b-hadrons subtracted with a FONLL-based method

Alternative data-driven method exploits the different shape of prompt and feed-down impact parameter distributions

Agreement between data driven and FONLL-based methods
p-Pb collisions
D-meson cross section

- **Prompt D⁰** $p_T$-differential cross section with and w/o vertexing method down to $p_T=0$, consistent results for $p_T>1$ GeV/$c$
- Prompt D-meson cross section **consistent between Run1 and Run2**: reduced uncertainties and extended $p_T$ coverage with Run2 data
D-meson $R_{pPb}$

Nuclear modification factor of $D^0$, $D^+$ and $D^*$ mesons compatible within uncertainties

**Non-strange D-meson $R_{pPb}$ compatible with unity**

$D_s$ $R_{pPb}$ compatible with non-strange D mesons within uncertainties
Models including QGP formation in p-Pb collisions

Models including CNM effects and incoherent multiple scattering

- Data described by models including CNM effects, as well as effects deriving from the formation of QGP in p-Pb collisions
- Disfavour QGP models that predict suppression >10-15% at high $p_T$
**D**-meson production vs centrality

- Centrality classes obtained from the energy deposited in the neutron calorimeter on Pb-going side (ZNA)
- \( Q_{pPb} \) in most central and peripheral centrality ranges are compatible within uncertainties

\[
Q_{pPb} = \frac{\left( \frac{dN^0}{dp_T} \right)_{pPb}}{T_{pPb} \times \left( \frac{d\sigma^0}{dp_T} \right)_{pp}}
\]

\[
\langle T_{pPb} \rangle = \frac{\langle N_{coll} \rangle}{\sigma_{NN}}
\]

- **\( D^0 Q_{pPb} \) in agreement with charge-particles \( Q_{pPb} \)**
  - caveat: slightly different centrality ranges
Centrality classes obtained from the energy deposited in the neutron calorimeter on Pb-going side (ZNA)

$Q_p\text{Pb}$ in most central and peripheral centrality ranges are compatible within uncertainties

**Hint of $Q_{CP} > 1$ in 3-8 GeV/c with 1.7σ**

- Initial or final state effect?
- Possible influence of radial flow on heavy-flavour hadrons in p-Pb collisions
Pb-Pb collisions
Increasing suppression from peripheral (60-80%) to central (0-10%) collisions

Similar D-meson $R_{AA}$ at $\sqrt{s_{NN}}=5.02$ TeV and $\sqrt{s_{NN}}=2.76$ TeV, consistent with theoretical predictions

Improved precision in Run2
\(D_s\) and non-strange D-meson \(R_{AA}\)

- **Hint of higher \(D_s\) with respect to non-strange D-meson \(R_{AA}\)**
- **Still large uncertainties to conclude**

**Elliptic Flow**

**Event plane method**: estimation of the Reaction Plane
(using **V0** detector: $-3.7 < \eta < -1.7 \ U 2.8 < \eta < 5.1$)

D-meson candidates divided in 2 categories: **in-plane and out-of-plane** particles

\[ \nu_2 = \frac{1}{R_2} \frac{\pi N_{\text{in-plane}} - N_{\text{out-of-plane}}}{4 N_{\text{in-plane}} + N_{\text{out-of-plane}}} \]

$R_2$=resolution term

[Graph showing elliptic flow analysis]
D-meson $v_2$

- **Non strange D-meson $v_2$ larger than 0** for $2<p_T<10$ GeV/c
- **$D^+_s$ $v_2$ compatible with non strange D-meson $v_2$**

**ALICE**

30–50% Pb–Pb, $|S_N| = 5.02$ TeV, $|y|<0.8$

Prompt $D^0$

Prompt $D^+$

Prompt $D^{*+}$

Prompt $D^+_s$

$D^0$, $D^+$, $D^{*+}$ average

**arXiv:1707.01005**

Cristina Bedda
D-meson $v_2$

- **Non strange D-meson $v_2$ larger than 0 for** $2<p_T<10$ GeV/c
- **$D^+_s$ $v_2$ compatible with non strange D-meson $v_2$**
- **D-meson $v_2$ compatible at $\sqrt{s_{NN}}=5.02$ TeV and $\sqrt{s_{NN}}=2.76$ TeV**
- **D-meson $v_2$ similar to $\pi^\pm v_2$**
  - hint of difference at low $p_T$ but more statistics needed to conclude

$\nu_2$ vs $p_T$ (GeV/c)

**arXiv:1707.01005**
Comparison with models

Heavy-quark transport models

pQCD energy loss based models

Measurement of D-meson $R_{AA}$ and $v_2$ provide important constraints to theoretical predictions thanks to the improved precision.
D-meson $v_2$ (Event-shape engineering)

The second-harmonic reduced flow vector $q_2$ can be used to quantify the eccentricity (average $v_2$) of the events.

$$q_2 = \frac{|Q_2|}{\sqrt{M}}$$

- $M$: multiplicity
- $|Q_2| = \sqrt{Q_{2,x}^2 + Q_{2,y}^2}$

$$Q_{2,x} = \sum_{i=1}^{M} \cos 2\varphi_i, \quad Q_{2,y} = \sum_{i=1}^{M} \sin 2\varphi_i$$

$$\langle q_2^2 \rangle \approx 1 + \langle (M - 1) \rangle \langle (v_2^2 + \delta_2) \rangle$$

S. A. Voloshin, A. M. Poskanzer, and R. Snellings, Relativistic Heavy Ion Physics, Vol. 1/23 (Springer-Verlag, 2010), pp. 5–54

- Opportunity to study the coupling of $c$ quarks to the bulk of light quarks from the underlying medium by measuring the D-meson $v_2$ for different values of $q_2$

60% with smaller $q_2$
20% with larger $q_2$
Larger D-meson $v_2$ for events with larger $q_2$ and smaller D-meson $v_2$ for events with smaller $q_2$

- Auto-correlations between $q_2$ and D mesons $v_2$ present
- Sensitivity of D mesons to the light quarks collectivity and event-by-event fluctuations
Conclusions

Large collection of new ALICE results on D-meson production in p-Pb and Pb-Pb collisions from Run2 at $\sqrt{s_{NN}}=5.02$ TeV

- Compatible results with Run1 analyses but better precision and extended $p_T$ range

- p-Pb collisions
  - $R_{pPb}$ of D mesons consistent with unity
  - central/peripheral: $Q_{CP} > 1$ in 3-8 GeV/c with $1.7\sigma$, radial flow? initial- or final-state effects?

- Pb-Pb collisions
  - Increasing suppression from peripheral to central collisions for D-meson $R_{AA}$
  - Hint of coalescence+strangeness enhancement comparing strange and non-strange D mesons
  - D-meson elliptic flow in semi-peripheral Pb-Pb collisions larger than 0 (even for $D_s$)
    - strong coupling of charm quark with the medium
  - Event-Shape Engineering for the D-meson elliptic flow
    - sensitivity of charm quark to the light-quark collectivity and to the event-by-event initial fluctuations
Backup
Theoretical models

**BAMPS**: Boltzmann equation with collisional energy loss in expanding QGP

**TAMU**: HQ transport with coll. e.loss only, resonant scattering and coalescence + hydro

**POWLANG HTL**: HQ transport with Langevin equation with collisional energy loss and, recombination, viscous hydrodynamic expansion. Transport coeff. dependence on quark momentum

**Djordjevic**: energy loss due to both radiative and collisional, processes in a finite size dynamical QCD medium

**Ads/CFT**: energy loss fluctuations included in a realistic strong coupling energy loss model from AdS/CFT

**SCET\textsubscript{M,G NLO}**: in-medium formation and dissociation of D and B, ideal fluid with Bjorken expansion
[JHEP 03, 146 (2017)]

**Xu, Cao, Bass**: Langevin with coll. and rad. term and recombination + hydro

**PHSD**: Parton-Hadron-String Dynamics transport approach, coalescence

**MC@sHQ+EPOS**: coll. and rad. e.loss in expanding medium based on EPOS model, recombination
Reference obtained scaling 7 TeV pp collisions, reduced uncertainties

arXiv:1702.0766
D-meson $R_{AA}$

\[ R_{AA} = \frac{1}{<T_{AA}>} \frac{dN_{AA}}{d\rho_T} / \frac{d\sigma_{pp}}{d\rho_T} \]

- Non-strange D-meson $R_{AA}$ compatible within uncertainties
- Increasing suppression from peripheral (60-80%) to central (0-10%) collisions
D-meson $R_{AA}$ comparison with models

Peripheral centrality class

**ALICE Preliminary**
60-80% Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
$|y| < 0.5$

- Average $D^0$, $D^+$, $D^{**}$

- **POWLANG HTL**
- **PHSD**
- **LBT**
- **TAMU**

- **Djordjevic**
- **CUJET3.0**
- **SCET_{T,M0} g=1.9-2.0**


**Pb–Pb COLLISIONS: EVENT SHAPE**

**Charged particles**

![Graphs showing $v_2$ for different Pb–Pb collisions]

**D meson**

![Graph showing $v_2$ for D meson]

ALICE

Pb–Pb $\sqrt{s_{NN}} = 2.76$ TeV

0.5 < |η| < 0.8

90-100% 0-10%

60% small $q_T^{TPC}$

20% large $q_T^{TPC}$

Prompt $D^0$, $D^+$ average

Syst. data

[ALICE Preliminary]

AL–PUB–95335

prompt fraction of D mesons

signal extracted from invariant mass distributions

\[
\frac{dN^{D^+}}{dp_T} \bigg|_{|y|<0.5} = \frac{1}{2} \frac{1}{\Delta y \Delta p_T} \left[ f_{\text{prompt}} \cdot \frac{N^{D^+_{\text{raw}}}}{|y|<y_{\text{fid}}} \right]
\]

Acceptance times efficiency

- \( N_{\text{ev}} = \) number of events
- \( \Delta y = \) rapidity interval
- \( \Delta p_T = \) transverse momentum interval
- \( \text{BR} = \) branching ratio
CENTRALITY RANGES
DEFINITION

Pb-Pb collisions

\[
P_{p,k} \times \left[ (1-f) N_{\text{coll}} + f N_{\text{part}} \right]
\]

p-Pb collisions

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

Events (a.u.)

Peripheral collisions (b = R)

Central collisions (b=0)

\( f = 0.801; \mu = 29.3; k = 1.6 \)

\( 50-60\% \)
\( 40-50\% \)
\( 30-40\% \)
\( 20-30\% \)
\( 10-20\% \)
\( 0-5\% \)

L.U.

Events (a.u.)

ALICE p-Pb | \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

Data

SNM-Glauber

E_{ZN} (TeV)

80-100 \%
60-80 \%
40-60 \%
20-40 \%
10-20 \%
0-5 \%