Measurement of D-meson production and flow in Pb-Pb collisions with ALICE at the LHC

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Quantum chromodynamics (QCD) calculations predict a phase transition of nuclear matter to a colour-deconfined medium, the quark–gluon plasma (QGP), under extreme conditions of temperature and/or density.

▶ The QGP can be created in the laboratory by ultra-relativistic heavy-ion collisions.
Heavy flavours in Pb-Pb collisions

Large masses ($m_c \approx 1.3 \text{ GeV}/c^2$, $m_b \approx 4.5 \text{ GeV}/c^2$) of charm and beauty quarks → produced in hard-scattering processes in the early stages of the collision

- They experience the full evolution of the Quark-Gluon Plasma
- Negligible thermal production and annihilation in the medium
- Strongly interacting with the QGP

Heavy flavours are unique probes of the deconfined medium
Heavy flavours in Pb-Pb collisions — Observables

Heavy flavours propagate through the QGP and interact with the medium constituents

- **Energy loss via elastic scatterings and gluon radiation**, depending on
  - colour charge (Casimir factor)
  - quark mass (Dead-cone effect)
  - path length

Observable: Nuclear Modification Factor ($R_{AA}$)

\[
R_{AA} (p_T) = \frac{1}{\langle N_{AA}^{coll} \rangle} \frac{dN_{AA}/p_T}{dN_{pp}/p_T}
\]

\(\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b\)
Heavy flavours in Pb-Pb collisions — Observables

Heavy flavours propagate through the QGP and interact with the medium constituents

▶ Energy loss via elastic scatterings and gluon radiation

▶ Participation in the **collective motion** of the fireball
  – possible thermalisation of heavy quarks in the medium

**Observable:** *azimuthal anisotropy* of produced particle momenta

Fourier decomposition of particle-momenta azimuthal distribution

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

\[ v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle \]

\textit{2}nd harmonic coefficient elliptic flow
Heavy flavours propagate through the QGP and interact with the medium constituents

- Energy loss via elastic scatterings and gluon radiation
- Participation in the collective motion of the fireball
- **Modification of the hadronisation mechanism**
  - recombination with quarks from the medium

**Observable:** $p_T$-dependent yield ratios and $R_{AA}$ of different hadron species
A Large Ion Collider Experiment

- Inner Tracking System
  - Track reconstruction
  - Reconstruction of primary and decay vertices
- Time Projection Chamber
  - Tracking
  - Particle identification via specific energy loss
- Time of Flight detector
  - Particle identification with time-of-flight measurement
- V0 detectors
  - Trigger
  - Centrality determination
  - Event-plane estimation
A Large Ion Collider Experiment

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**Time Projection Chamber**
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- Particle identification via specific energy loss

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**V0 detectors**
- Trigger
- Centrality determination
- Event-plane estimation
D-meson reconstruction

<table>
<thead>
<tr>
<th>Meson</th>
<th>$M$ (GeV/$c^2$)</th>
<th>Decay</th>
<th>$c\tau$ ($\mu$m)</th>
<th>BR (%)</th>
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</thead>
<tbody>
<tr>
<td>$D^0 (c\bar{u})$</td>
<td>$\sim 1.865$</td>
<td>$K^- \pi^+$</td>
<td>$\sim 123$</td>
<td>$\sim 3.89$</td>
</tr>
<tr>
<td>$D^+ (c\bar{d})$</td>
<td>$\sim 1.870$</td>
<td>$K^- \pi^+ \pi^+$</td>
<td>$\sim 312$</td>
<td>$\sim 8.98$</td>
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<tr>
<td>$D^{*+} (c\bar{d})$</td>
<td>$\sim 2.010$</td>
<td>$D^0 (\rightarrow K^- \pi^+)\pi^+$</td>
<td>strong decay</td>
<td>$\sim 2.66$</td>
</tr>
<tr>
<td>$D_s^+ (c\bar{s})$</td>
<td>$\sim 1.968$</td>
<td>$\phi (\rightarrow K^- K^+)\pi^+$</td>
<td>$\sim 151$</td>
<td>$\sim 2.25$</td>
</tr>
</tbody>
</table>

Candidates built from pairs/triplets of tracks reconstructed at mid-rapidity ($|\eta| < 0.8$) with proper charge combination

To reduce the background:

- particle identification of decay tracks
- geometrical and kinematical selections of displaced decay-vertex topology
Non-strange D-meson $R_{AA}$

- D-meson $R_{AA} < 1$ observed $\rightarrow$ expected in presence of the QGP medium

- Hierarchy in the suppression: increasing from peripheral to semi-central and central Pb-Pb collisions

- Strong suppression of $R_{AA}$ in 0 – 10% centrality class (factor $\sim 5$ in magnitude at 8 – 12 GeV/c)
Non-strange D-meson $R_{AA}$ — Flavour dependence

- $R_{AA}(D) > R_{AA}(\pi^\pm)$ for $p_T$ below 8 GeV/$c$, many factors play a role:
  - pion production scaling with $N_{part}$ at low $p_T$
  - different initial $p_T$ shape and fragmentation functions
  - possible mass and color-charge effects
  - different effects of coalescence and radial flow on $\pi^\pm$ and D

- $R_{AA}(D) \simeq R_{AA}(\pi^\pm) \simeq R_{AA}(ch.\ part.)$ for $p_T > 8$ GeV/$c$

- Similar behaviour observed in semi-central collisions

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Non-strange D-meson $R_{AA} —$ Model comparison

- Low $p_T$ D-meson $R_{AA}$ described by transport models
- TAMU, BAMPS el., POWLANG do not include radiative energy loss
  - data suggest that radiative energy loss is relevant at $p_T > 6 - 8 \text{ GeV/c}$
- BAMPS predictions, not including recombination, diverge from data at low $p_T$

BAMPS: JPG 42, 115106 (2015)
POWLANG: EPJC 75, 121 (2015)
LIDO: PRC 98, 064901 (2018)
TAMU: PLB 735, 445-450 (2014)

PHSD: PRC 92, 014910 (2015)
Catania: EPJC 78, 348 (2018)
MC@sHQ+EPOS: PRC 89, 014905 (2014)
Non-strange D-meson $R_{AA}$ — Model comparison

- High $p_T$ D-meson $R_{AA}$ described by pQCD-based energy-loss models

- Low $p_T$ D-meson $R_{AA}$ described by transport models

ALICE Preliminary
$0-10\%$ Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
Prompt $D^0$, $D^+$, $D^{*+}$ average, $|y|<0.5$

Filled markers: pp measured reference
Open markers: pp $p_T$-extrapolated reference

Djordjevic: PRC 92, 024918 (2015)
CUJET3.0: JHEP 02 (2016) 169
SCET: JHEP 03 (2017) 146

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Strange and non-strange D-meson $R_{AA}$ show a similar $p_T$ dependence.

- Hint of smaller suppression of $D_{s}^{+}$ mesons w.r.t. non-strange D mesons at $p_T < 8 \text{ GeV}/c$, both in 0 – 10% and 30 – 50%.
Strange and non-strange D-meson $R_{AA}$

▶ $D_s^+$ and non-strange D-meson $R_{AA}$ show a similar $p_T$ dependence

▶ Hint of smaller suppression of $D_s^+$ mesons w.r.t. non-strange D mesons at $p_T < 8$ GeV/c, both in $0 – 10\%$ and $30 – 50\%$

▶ Models including coalescence describe the hierarchy $R_{AA}(D_s^+) > R_{AA}(D)$
Non-strange D-meson relative abundances: no modification is observed from pp to Pb-Pb collisions

Compatible ratios between 0 – 10% and 30 – 50% centrality classes
**Indication of an higher $D_s^+/D^0$ ratio in Pb-Pb collisions than in pp at $p_T < 8$ GeV/$c$, both for central and semi-central collisions**

**$p_T$-trend of double ratio qualitatively described by transport models including hadronisation via recombination**
**Non-strange D-meson elliptic flow in Pb-Pb collisions**

Positive D-meson $v_2$ in semi-central Pb-Pb collisions → participation of charm quark in the collective motion of the system

- **Hint of** $v_2(D) < v_2(\pi^{\pm})$ for $p_T < 4$ GeV/c
- $v_2(D) \simeq v_2(\pi^{\pm}) \simeq v_2(\text{ch. part.})$ for $p_T > 4$ GeV/c
- $v_2(D) > v_2(J/\Psi)$ for $p_T < 6$ GeV/c

- coalescence of charm quarks with flowing light-flavour quarks
Non-strange D-meson elliptic flow — Model comparison

- Non-strange D-meson $v_2$ reproduced by theoretical models based on charm-quark transport
- Simultaneous prediction of D-meson $R_{AA}$ and $v_2$:
  - important constraints on models
  - estimation of QGP transport coefficients

![Graph showing $v_2$ vs. $p_T$ for different models with TAME, PHSD, BAMPS, and POWLANG data]

PHSD: PRC 92, 014910 (2015)
POWLANG: EPJC 75, 121 (2015)

MC@sHQ+EPOS: PRC 89, 014905 (2014)
LIDO: PRC 98, 064901 (2018)
BAMPS: JPG 42, 115106 (2015)
DAB-MOD: PRC 96, 064903 (2016)
Strange and non-strange D-meson elliptic flow

- Similar elliptic flow for strange and non-strange D mesons, within the large uncertainties
Strange and non-strange D-meson elliptic flow

Similar elliptic flow for strange and non-strange D mesons, within the large uncertainties.

\( v_2 \) of \( D_s^+ \) and non-strange D mesons predicted to be similar by models (TAMU and PHSD) including hadronisation via quark recombination.
Event-shape engineering for D-meson $v_2$

- Event-shape engineering (ESE) → event classification according to their eccentricity
- Magnitude of the second-harmonic reduced flow vector* used
  \[ q_2 = \frac{\vec{Q}_2}{\sqrt{M}} \]

20% smallest $q_2$  \[ \langle v_2 \rangle_{small-q_2} < \langle v_2 \rangle_{unb.} \]
20% largest $q_2$  \[ \langle v_2 \rangle_{large-q_2} > \langle v_2 \rangle_{unb.} \]

- Measurement of D-meson $v_2$ in ESE-selected samples → charm sensitive to collectivity of light-hadron bulk and event-by-event fluctuations

*more details in the backup
ESE for D-meson $v_2$ — Model comparison

- Models based on charm-quark transport in an hydrodynamically expanding medium → describe $q_2$ dependence of elliptic flow
- Variation of D-meson $v_2$ in ESE-selected samples w.r.t. unbiased sample similar for different transport parameters (e.g. POWLANG HLT vs. IQCD)
Conclusion

- **Suppression of non-strange D-meson** $R_{AA}$ **in Pb-Pb collisions at** $\sqrt{s_{NN}} = 5.02$ **TeV** → **charm-quark energy loss in the QGP**

- $R_{AA}(D) > R_{AA}(\text{light hadron})$ at $p_T < 8$ GeV/c observed

- Indication of $R_{AA}(D_s^+) > R_{AA}(D)$ and increase of the $D_s^+/D^0$ ratio in central and semi-central collisions

- **Positive D-meson elliptic flow and similar $v_2$ between strange and non-strange D mesons** → **participation of charm quark in the medium collective motions**

- **Correlation between D mesons and light-hadron $v_2$** measured with ESE technique
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- Indication of $R_{AA}(D_\text{S}^+) > R_{AA}(D)$ and increase of the $D_\text{S}^+/D^0$ ratio in central and semi-central collisions

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- Correlation between D mesons and light-hadron $v_2$ measured with ESE technique
Backup
The two measurements are compatible within their uncertainties

Higher $p_T$ granularity in 2018 w.r.t. 2015
Non-strange D-meson $R_{AA}$ in Pb-Pb collisions

$\bullet$ $D^0$, $D^+$ and $D^{*+}$ $R_{AA}$ are compatible within their uncertainties

$\bullet$ Maximum of the $R_{AA}$ suppression (factor $\sim 5$ and $\sim 2.5$) at $8 - 12$ GeV/$c$ in $0 - 10\%$ and $30 - 50\%$ centrality classes
Non-strange D-meson $R_{AA}$ — Model comparison

Transport models based on Boltzmann/Fokker-Plank/Langevin equations

<table>
<thead>
<tr>
<th>Transport Models</th>
<th>Collisional en. loss</th>
<th>Radiative en. loss</th>
<th>Coalescence</th>
<th>Hydro</th>
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<td>BAMPS</td>
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</table>

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Non-strange D-meson $R_{AA}$ — Model comparison

High $p_T$ D-meson $R_{AA}$ described by pQCD-based models

<table>
<thead>
<tr>
<th>pQCD e-loss</th>
<th>Collisional en. loss</th>
<th>Radiative en. loss</th>
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<td>x</td>
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</tr>
<tr>
<td>MC@sHQ+EPOS</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

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D-meson elliptic flow in Pb-Pb collisions

- D-meson $v_2$ measured at mid-rapidity ($|y| < 0.8$) with the scalar-product (SP) method

$$v_2\{SP\} = \frac{\langle u_2 \cdot Q_2^A / M^A \rangle}{\sqrt{\frac{\langle Q_2^A / M^A \cdot Q_2^B / M^B \rangle}{\langle Q_2^B / M^B \cdot Q_2^C / M^C \rangle}}$$

where $Q_2 = \sum_{j=0}^{M} w_j e^{i2\varphi_j}$ and $u_{2,D} = e^{i2\varphi_D}$

- Sub-events:
  - A: V0C ($-3.7 < \eta < -1.7$)
  - B: V0A ($2.8 < \eta < 5.1$)
  - C: TPC ($|\eta| < 0.8$)

- $v_2$ of the signal extracted from a $v_2$ vs mass fit

$$v_2(M) = \frac{S}{S + B} v^{sig}_2 + \frac{B}{S + B} v^{bkg}_2$$
The two measurements are compatible within their uncertainties

Statistical uncertainty reduced by a factor \( \sim 2 \) in 2018

Extended \( p_T \) coverage up to 36 GeV/c
Effect of detector resolution in ESE selection

- Small effect from detector resolution in case of $q_{TPC}^2$, while significant smearing of $q_{2}^2$ distribution in case of $q_{2}^{V0A}$ due to resolution in azimuthal angle.
Hint of higher (lower) $p_T$-differential yields in large-$q_2$ (small-$q_2$) samples compared to the unbiased one at intermediate $p_T$ — consistent with correlation between radial and elliptic flow

Measurement quantitatively in agreement with the POWLANG prediction in the small-$q_2$ sample, while smaller effect observed in large-$q_2$ sample
Further studies

Very nice preliminary results! Still room for improvements:

▶ Candidate selection based on machine learning techniques
  - $D_s^+$ measurement at lower $p_T$ to better constrain the models
  - reduce the $R_{AA}$ statistical uncertainty for the $D_s^+$ and $D^0$ (at low $p_T$) mesons

▶ $D^0$ analysis without topological cuts → to reach lower transverse momenta

\[ M(KK\pi) \text{ (GeV/c}^2) \]

**ALICE Preliminary**

0-10% Pb–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
88 × 10^6 events

$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$
and charge conj.
2 < $p_T$ < 3 GeV/c

Counts per 6 MeV/c^2

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