Open-heavy-flavour production and elliptic flow in p-Pb collisions at the LHC with ALICE

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Aix-Les-Bains
Open heavy flavour in p-Pb collisions

Heavy quarks effective probes of the Quark-Gluon Plasma in Pb-Pb collisions

Interpretation of Pb-Pb measurements
- understanding of **cold nuclear matter (CNM) effects** in initial and final state
- constrain them by studying p-Pb collisions
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p-Pb collisions not only reference for CNM effects:
in high multiplicity p-Pb collisions, effects typically observed in A-A collisions
• ex. in the light flavour sector: long-range $v_2$-like angular correlations, enhancement of baryon production

open questions:
• collective effects in high-multiplicity p-Pb events?
• final-state effects also in p-Pb collisions?
• small-size QGP?

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**similar observations in the heavy-flavour sector?**

**News:** more differential measurements to investigate high multiplicity p-Pb collisions
Open heavy-flavour reconstruction in ALICE

TPC: tracking, PID $|\eta|<0.9$

TRD: eID $|\eta|<0.9$

TOF: PID $|\eta|<0.9$

V0, ZDC: trigger and event characterization

EMCal: eID, trigger $|\eta|<0.7$

ITS: vertexing, tracking and PID $|\eta|<0.9$

Muon Spectrometer: $-4<\eta<-2.5$
Tracking, Trigger, $\mu$ID

Fully reconstructed D mesons and $\Lambda_c$ hadronic decays:
- **ITS, TPC, TOF**
  - $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^{*+} \rightarrow D^0 \pi^+$, $D_s^+ \rightarrow \Phi \pi^+ \rightarrow K^- K^+ \pi^+$,
  - $\Lambda_{c^+} \rightarrow \pi^+ K^- p$, $\Lambda_{c^+} \rightarrow p K^0_s$

Partially reconstructed semi-leptonic decays
- **Muons**: Forward Muon Spectrometer. $D, B \rightarrow \mu^\pm + X$
- **Electrons**: ITS, TPC, TOF, EMCal, TRD. $D, B \rightarrow e^\pm + X$
Nuclear modifications in p-Pb collisions
Nuclear Modification Factor: D-meson $R_{pPb}$

$$R_{pPb} = \frac{1}{A} \frac{d^2 \sigma_{pPb}^{\text{prompt}D}}{d p_T dy} \bigg/ \frac{d^2 \sigma_{pp}^{\text{prompt}D}}{d p_T dy}$$

**ALICE-PUBLIC-2017-008**

- $D_s$ $R_{pPb}$ compatible with unity within uncertainties
- $D^0$ measured down to $p_T = 0$:
  - improved precision due to new reference
- $D_s$ $R_{pPb}$ compatible with averaged non-strange $D$ mesons

**ALICE-PUBLIC-2018-006**

pp reference measured at 5.02 TeV (NEW!)

C.Terrevoli
Nuclear Modification Factor: D-meson, $\Lambda_c$ $R_{p\text{Pb}}$

$$R_{p\text{Pb}} = \frac{1}{A} \frac{d^2\sigma_{p\text{Pb}}^{\text{prompt D}}}{dp_Tdy} / \frac{d^2\sigma_{pp}^{\text{prompt D}}}{dp_Tdy}$$

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- $D_s R_{p\text{Pb}}$ compatible with averaged non-strange D mesons

$R_{p\text{Pb}}$ compatible with unity within uncertainties

**D, $D_s$**

ALICE Preliminary  $p$-$\text{Pb}$, $\sqrt{s_{NN}} = 5.02$ TeV
Prompt D mesons, $-0.96 < y_{cms} < 0.04$

ALICE-PUBLIC-2017-008

ALICE-PUBLIC-2018-006

**pp reference measured at 5.02 TeV (NEW!)**

D, $D_s$

**pp reference scaled from 7 TeV**


- $\Lambda_c^+$ JHEP 04 (2018) 108
- $D$ mesons (average $D^0$, $D^+$, $D^*$)
- $D^0$ meson

ALICE-PUBLIC-2015-008

Baryon measurements: E.Meninno’s Talk
Nuclear Modification Factor: D-meson $R_{pPb}$ vs models

$$R_{pPb} = \frac{1}{A} \frac{d^2 \sigma_{pPb}^{\text{prompt}D}}{dp_T dy}$$

- **Models** including **CNM effects only** are compatible with data
- a model including **incoherent multiple scattering** describes data within uncertainties for $p_T > 5$ GeV/c
Nuclear Modification Factor: D-meson $R_{pPb}$ vs models

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**Models** including **QGP formation** in p-Pb collisions can describe data up to $p_T \sim 6$ GeV/c

Data do not favour a suppression larger than 10-15% for $5 < p_T < 12$ GeV/c
Nuclear Modification Factor: $R_{pPb}$ vs $R_{AA}$

$$R_{pPb} = \frac{1}{A} \frac{d^2\sigma_{pPb}^{\text{prompt D}}}{dp_Tdy}$$

ALICE Preliminary p–Pb, $\sqrt{s_{NN}} = 5.02$ TeV
Prompt D mesons, $0.96 < y_{\text{cm}} < 0.04$

Pb–Pb results: F. Grosa's Talk

Suppression observed at intermediate-high $p_T$ in Pb–Pb collisions is due to final-state effects.
Heavy-flavour hadron decay electron $R_{pPb}$

- Beauty and beauty+charm electron results are compatible within uncertainties
- $R_{pPb}$ described by models that include CNM

Heavy-flavour hadron decay electron (HF-e) $R_{pPb}$ compatible with unity
Nuclear modification factor in centrality classes: $Q_{pPb}$

Centrality classes: slicing the distribution of the energy deposited in the neutron calorimeter in the Pb-going side (ZNA).

\[ Q_{pPb}^{\text{cent}} = \frac{(d^2N_{\text{prompt}}/dp_Tdy)_{pPb}^{\text{cent}}}{\langle T_{pPb} \rangle_{\text{cent}} \times (d^2\sigma_{pp}^{\text{prompt}}/dp_Tdy)} \]

ALICE Preliminary

$p$–$Pb$, $\sqrt{s_{NN}} = 5.02$ TeV

- Average $D^0$, $D^+$, $D^{**}$, 0–10% ZN energy
- Charged particles, 0–5% ZN energy

D, charged particles

Similar charged-particle $Q_{cp}$

ALICE-PUBLIC 2017-008

- $Q_{pPb}$ in most central (0–10%) and peripheral (60–100%) centrality classes are compatible within uncertainties and consistent with unity.
- Hint of $Q_{pPb}>1$ in central 0–10% in $3<p_T<8$ GeV/c

Centrality determination in p–Pb


C. Terrevoli
Nuclear modification factor in centrality classes: $Q_{cp}$

\[ Q_{CP} = \frac{(d^2N^{promptD}/dp_Tdy)_{pPb}^{0-10}}{(d^2N^{promptD}/dp_Tdy)_{pPb}^{60-100}} / \frac{10}{(T_{pPb})^{0-10}} / (T_{pPb})^{60-100} \]

Central/peripheral ratio

$Q_{cp}$ more precise measurement than $Q_{pPb}$
- independent from pp reference
- some sources of systematic uncertainties cancel in the ratio

Hint of $Q_{cp} > 1$ in $3 < p_T < 8$ GeV/c for D mesons with $1.5 \sigma$ significance
- Radial flow?
- Initial or final-state effect?

ALICE Preliminary

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

Charged particles

D, charged particles

Central: 0–10% ZN energy
Peripheral: 60–100% ZN energy

ALICE-PUBLIC 2017-008


ALICE-PUBLIC 2017-008

investigating the high multiplicity p-Pb collisions
Charm-hadron ratios in small systems
Charm-hadron ratios

Relative abundances of $D^{*+}/D^0$ and $D_s^{+}/D^0$ compatible in pp and p-Pb collisions
• and also consistent with measurements in $e^+e^-$ collisions at LEP (Gladilin, EPJ C75 (2015) 19)

Hint of a enhanced production of $D_s$ w.r.t. non-strange D meson ($D^0$) in Pb-Pb collisions
**Charm-hadron ratio: strange/no-strange**

- **Light flavour sector:** strangeness enhancement with multiplicity in small systems. **Heavy-flavour?**

D$_s$/D$^+$ measured as a function of multiplicity in different $p_T$ ranges

- compatible ratios in pp and p-Pb collisions
- no dependency vs multiplicity with the current uncertainties

**ALICE Preliminary**

- pp Minimum Bias, $\sqrt{s} = 5.02$ TeV
- p-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- SPD multiplicity classes

$\pm 4.3\%$ BR uncertainty not shown
collectivity in high-multiplicity p-Pb collisions?
Angular correlations between heavy-flavour decay electrons and charged particles at mid-rapidity 0-20% and 60-100%:
- multiplicity selected via V0A at forward rapidity $2.8 < \eta < 5.1$
- hint of an enhancement of near- and away-side peaks distribution in central 0-20% p-Pb

High-multiplicity - low-multiplicity events

$$
\left( \frac{1}{N_a} \frac{dN^{ab}_{\text{HM}}}{d(\Delta \phi)} \right)_{\text{sub}} - \left( \frac{1}{N_a} \frac{dN^{ab}_{\text{LM}}}{d(\Delta \phi)} \right)_{\text{sub}} = P \left( 1 + \sum_{n=1}^{\infty} 2 \times v_n^a v_n^b \times \cos[n\Delta \phi] \right)
$$

Azimuthal modulation remains!
**HF-decay lepton $\nu_2$ in p-Pb**

$\nu_2$: second-order coefficient of the Fourier expansion of the azimuthal distributions of particles

\[ \nu_2 \]

\[ ALICE = 5.02 \text{ TeV} \]

\[ p-Pb, \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ (0-20\%) - (60-100\%) \]

- **HF-e $\nu_2 > 0$** in $1.5 < p_T < 4$ GeV/c in high multiplicity events with significance $> 5 \sigma$
- Sizeable effect, possibly lower than charged-particles maximum, and similar to inclusive muons at large rapidities

\[ arXiv:1805.04367 \]
**HF-decay lepton $v_2$ in p-Pb**

$v_2$: second-order coefficient of the Fourier expansion of the azimuthal distributions of particles

- **NEW!** $\mu v_2$ measured in different collision energy $\sqrt{s_{NN}} = 8.16$ TeV, in an extended $p_T$ range
  - where HF-$\mu$ components dominate
- **Analysis Strategy:** Q-cumulants with 2-particle correlations
- 0-10% high-multiplicity class: CL1, $N_{\text{tracklets}} = $ # track segments in the two innermost layers of the ITS
- similar values at forward and backward rapidities
- $\mu v_2 > 0$ in $2 < p_T < 6$ GeV/c in high multiplicity events with significance $> 3 \sigma$
- compatible with HF-e and inclusive $\mu$ in p-Pb collisions at 5.02 TeV

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**Figure:**

- ALICE Preliminary
- p-Pb $\sqrt{s_{NN}} = 8.16$ TeV
-Multiplicity class CL1: 0-10%
-Pb-going: $-4.46 < y_{CMS} < -2.96$

**Legend:**

- Systematic Uncertainty
- p-going
- Pb-going
Conclusions

• $R_{pPb}$ of heavy-flavour hadrons compatible with unity and described by models including CNM effects
• Measured D-meson $R_{pPb}$ at high $p_T$ disfavours QGP models that predict a significant suppression at high $p_T$ in p-Pb collisions

• suppression in Pb-Pb collisions at intermediate $p_T$ is due to final-state effects

• Investigation of high-multiplicity p-Pb collisions:
  • D-meson $Q_{pPb}$ compatible with unity
  • Hint of D-meson $Q_{CP} > 1$ at low-intermediate $p_T$
  • No modification in the ratios of strange/non-strange mesons in different systems and vs multiplicity
  • Non-zero $v_2$ for HF-decay leptons in high multiplicity events
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Charm Baryons-to-meson ratios in E. Meninno’s Talk
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Collective effects in p-Pb: origin? Initial- or final-state effects
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**Collective effects in p-Pb: origin? Initial- or final-state effects?**

- More in HF-jets, D-h correlation results in p-Pb

**Upgrades of ALICE** in LHC Run 3-4
- improved precision and extended $p_T$ reach for HF measurements

S. Aiola Talk

Upgrade prospects: C. Bedda’s Talk
backup
Data Samples

p-Pb collisions, data samples:

**Min. bias** $\sqrt{s_{NN}} = 5.02$ TeV min.bias
- **Run1** 2013 100 M $L_{\text{int}} = 47.8 \, \mu\text{b}^{-1}$
- **Run2** 2016 600 M $L_{\text{int}} = 292 \, \mu\text{b}^{-1}$

**electrons (2016)** $\sqrt{s_{NN}} = 8.16$ TeV min. bias
- Trig.1 ($p_T > 10 \, \text{GeV/c}$) $L_{\text{int}} = 599 \, \mu\text{b}^{-1}$
- Trig.2 ($p_T > 5 \, \text{GeV/c}$) $L_{\text{int}} = 34.6 \, \mu\text{b}^{-1}$
- $\approx 20\text{M MB events} \, L_{\text{int}} = 10.1 \, \mu\text{b}^{-1}$

**Muons (2013)** $\sqrt{s_{NN}} = 5.02$ TeV min. bias
- Trigger MSL ($p_T > 0.5 \, \text{GeV/c}$) p-Pb $L_{\text{int}} = 196 \, \mu\text{b}^{-1}$, Pb-p $L_{\text{int}} = 254 \, \mu\text{b}^{-1}$
- Trigger MSH ($p_T > 4.2 \, \text{GeV/c}$) p-Pb $L_{\text{int}} = 4.9 \cdot 10^3 \, \mu\text{b}^{-1}$, Pb-p $L_{\text{int}} = 5.8 \cdot 10^3 \, \mu\text{b}^{-1}$

**Muons (2016)** $\sqrt{s_{NN}} = 8.16$ TeV min. bias
- Trigger MSL ($p_T > 0.5 \, \text{GeV/c}$) p-Pb $L_{\text{int}} = 22 \, \text{M}$, Pb-p $L_{\text{int}} = 3.4\text{M}$
- Trigger MSH ($p_T > 4.2 \, \text{GeV/c}$) p-Pb $L_{\text{int}} = 17\text{M}$, Pb-p $L_{\text{int}} = 34\text{M}$
Different rapidity ranges allow access to different Bjorken-$x$ regimes
- central and forward production consistent with no nuclear modification
- hint of enhancement at backward rapidity at low $p_T$
- described by models including CNM effects
charm hadrons: Family Portrait in p-Pb and Pb-Pb

![Graph showing nuclear modification factor vs. pseudorapidity for charm hadrons in p-Pb and Pb-Pb collisions.](image)

### Graph Descriptions
- **p-Pb, \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
  - \(-0.96 < y < 0.04\)
- **R_{AA}**
  - \( \Lambda_c^+ \), \( \bar{y} < 0.5 \), 0–80%
  - p–Pb reference from JHEP 04 (2018) 108
  - Average D^0, D^+, D^{*-} \( \bar{y} < 0.5 \), 0–10% (arXiv:1804.09083)
  - D^0, \( \bar{y} < 0.5 \), 0–10% (arXiv:1804.09083)
  - Charged particles, \( \bar{y} < 0.8 \), 0–10% (arXiv:1802.09145)
- **Pb–Pb, \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
  - Average D^0, D^+, D^{*-} \( \bar{y} < 0.5 \), 0–10% (arXiv:1804.09083)
  - Charged particles, \( \bar{y} < 0.8 \), 0–10% (arXiv:1802.09145)
Azimuthal Flow

• Signature of collective motion in heavy-ion collisions, due to presence of QGP
• Provide experimental information on the equation of state and the transport properties of the created QGP

Initial spatial anisotropy of peripheral collisions

• “almond shaped” of the overlap region:
  • larger pressure gradient in x-z plane than in y direction
  • particle re-scattering: convert the initial spatial anisotropy into a momentum anisotropy

Observable: elliptic flow $v_2$

Second coefficient of the Fourier expansion of the azimuthal distributions of particles

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

low $p_T$: multiple interactions between partons (collectivity)

positive $v_2$ for HF hadrons $\rightarrow$ charm participates to the collective effects in the QGP
D-hadron and e-hadron azimuthal correlations

Azimuthal correlations of D mesons and HF decay electrons with charged particles: $\Delta \phi = \phi_{e/D} - \phi_{\text{ch}}$ distributions access charm fragmentation and jet properties.

D-h correlation in minimum bias pp and p-Pb collisions

E-h correlation: different centrality classes in p-Pb

- No evidence of modification of charm quark production and fragmentation in different collisions systems.
- references for future Pb-Pb measurements.

hint of a enhanced of near and away side peaks distribution in central 0-20% p-Pb collisions than in 60-100%
2-particle correlation


Cumulants are directly related to the Fourier coefficients

\[ v_n \{2\} = \sqrt{c_n \{2\}} \]

- Rapidity gap between **Particle of interests (F)**
  - **Particles**: muons (forward rapidity)

**v_2 calculation:**
- reference flow \( v_{2}^{\text{ref}} = \sqrt{c_n \{2\}} \)
- \( d_2 \{2\} \): differential cumulants (POI correlated with 1 reference particle)

- Non-flow subtracted: few particle correlations not associated to the common symmetry plane
  - Correlations between particles in jets, or from resonance decays, etc.

- **Non-flow subtraction**: estimated in pp at 13 TeV

\[
v_2^{\text{PPb,sub}}(p_T) = \frac{d_2^{\text{PPb}}(p_T) - k \cdot d_2^{\text{PP}}(p_T)}{\sqrt{c_2^{\text{PPb}} - k \cdot c_2^{\text{PP}}}} \quad k = \frac{<M>^{\text{PP}}(0-100\%)}{<M>^{\text{PPb}}(\text{cent})}
\]

- Non-Uniform-Acceptance corrections
muon $v_2$

**ALICE**

ALICE Preliminary

p-Pb $\sqrt{s_{NN}} = 8.16$ TeV

Multiplicity class CL1: 0-10%

Inclusive $\mu^\pm$

$p$-going: $2.03 < y_{CMS} < 3.53$

Pb-going: $-4.46 < y_{CMS} < -2.96$

**ATLAS**

https://cds.cern.ch/record/2244808

ATLAS Preliminary

$p+$Pb $\sqrt{s_{NN}} = 8.16$ TeV, 171 nb$^{-1}$

0.5 < $p_T^\mu$ < 5 GeV

$N_{ch}^{rec} \geq 100$

$h-\mu$ Correlations

muon $v_2$

azimuthal correlation with charged particles and muons

$|\eta| < 2.5$
investigating the high multiplicity pp and p-Pb collisions

**Charm hadron ratio: strange/no-strange**

\[ \frac{D_s}{D^+} \text{ measured as a function of multiplicity in different } p_T \text{ ranges} \]
- ratios compatible in pp and p-Pb collisions
- no dependency with the current uncertainties
Charm hadron ratio: strange/no-strange

- Investigating the high multiplicity pp and p-Pb collisions

Ds/D⁺ measured as a function of multiplicity in different p_T ranges
- Ratios compatible in pp and p-Pb collisions
- No dependency with the current uncertainties
New pp reference: better precision at low pt

**Graph Description:**
- **Title:** ALICE Preliminary
- **Legend:**
  - Average $D^0, D^+, D^{*+}$
  - o scaled reference from pp at $\sqrt{s} = 7$ TeV
  - • measured reference at $\sqrt{s} = 5.02$ TeV

**Figure Details:**
- $R_{pPb}$ vs. $p_T$ (GeV/c)
- $p$-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- Prompt $D$ mesons, $-0.96 < y_{cm} < 0.04$

**Note:** ALI-PREL-150535
HF hadron $v_2$ in Pb-Pb

ALICE Preliminary

30-50% Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV

- ALICE, e$^+$ - HF, $|\eta| < 0.7$
- BAMPS el.+rad.
- BAMPS el.
- PHSD
- POWLANG, HLT transp. coeff.
- MC@e$^+$HQ+EPOS2
- TAMU elastic
- CUJET 3.0

ALICE

$\pi^+$, $|\eta| < 0.5$, $\sqrt{s_{NN}} = 2.76$ TeV
- $v_2$ [EP, $|\Delta\eta| > 0.9$, $\sqrt{s_{NN}} = 5.02$ TeV]
- $v_2$ [EP, $|\Delta\eta| > 0$, $\sqrt{s_{NN}} = 2.76$ TeV]

PRL 111 (2013) 102301

$D^0$, $D^+$, $D^*$ average, $|\eta| < 0.8$
- $v_2$ [SP, $|\Delta\eta| > 0.9$, JHEP 06 (2015) 190
- $v_2$ [EP, $|\Delta\eta| > 2$, PLB 719 (2013) 18

Phys. Rev. Lett. 120, 102301
**$R_{pPb}$ models**

- **CGC**: arXiv:1706.06728