Measurements of heavy-flavour production in p-Pb collisions with ALICE

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Motivation: Why open heavy flavour in p-Pb?

- Heavy-flavour (charm & beauty) production offers a unique probe into the properties of the **Quark-Gluon Plasma (QGP)** formed in heavy-ion collisions

- Due to their large masses, charm and beauty quarks are produced in the **early stages** of the collision.  
  → Experience the **full evolution** of the system.  
  → Described well by pQCD calculations in pp collisions

- p-Pb: moderate number of binary collisions ($\langle N_{\text{coll}} \rangle \approx 7$); **no medium formed**
  → Comparisons of results (such as nuclear modification factors) in p-Pb and Pb-Pb disentangle in-medium effects from cold nuclear matter effects (e.g. transverse momentum broadening, initial-state energy loss, nuclear shadowing)

- Production measured in ALICE in three ways:  
  → Hadronic decays of D mesons at mid-rapidity  
  → Semileptonic decays at mid-rapidity  
    \(D \rightarrow e^{\pm} + X, \ B \rightarrow e^{\pm} + X\)  
  → Semileptonic decays at forward/backward rapidity  
    \(D/B \rightarrow \mu^{\pm} + X\) (to probe different Bjorken-\(x\) regions)

ALICE: A Large Ion Collider Experiment (D mesons)

Time Projection Chamber (TPC):
- PID via $dE/dx$, tracking
- $D^0 \rightarrow K^-\pi^+$ (BR = 3.88 ± 0.05%; $\Delta t \approx 123 \mu$m)
- $D^+ \rightarrow K^-\pi^+\pi^+$ (BR = 9.13 ± 0.19%, $\Delta t \approx 312 \mu$m)
- $D^{*+} \rightarrow D^0\pi^+$ (BR = 67.7 ± 0.5%)
- $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$ (BR = 2.28 ± 0.12%, $\Delta t \approx 150 \mu$m)
  (and respective charge conjugates)

Prompt D selected via decay topology (e.g. decay length, pointing angle) and PID of decay products

Inner Tracking System (ITS):
- Vertexing, tracking

Zero-Degree Calorimeter (ZDC / ZN):
- Centrality determination

V0 detector:
- Centrality, multiplicity

Time-of-Flight (TOF):
- PID via time of flight

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Nuclear modification factor $R_{pPb}$: $D^0$, $D^+$, $D^{**}$, $D_s^+$ (top-left), average of $D^0$, $D^+$, $D^{**}$ (bottom-left)

$$R_{pPb} = \frac{d\sigma_{pPb}}{dp_T} \times A \times \frac{d\sigma_{pp}}{dp_T}$$

$R_{pPb}$ of all species consistent with unity & each other within uncertainties

Described within uncertainties by models that include initial-state effects

**CGC**: H. Fujii & K. Watanabe, arXiv:1308.1258

**pQCD NLO (MNR)**: M. Mangano et al., Nucl. Phys. B 373 (1992) 295

**EPS09**: K. J. Eskola et al., JHEP 04 (2009) 065


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\(R_{\text{pPb}}\) of D mesons

- **Nuclear modification factor** \(R_{\text{pPb}}\): \(D^0, D^+, D^{**}, D_s^+\) (top-left), average of \(D^0, D^+, D^{**}\) (bottom-left)

\[
R_{\text{pPb}} = \frac{\frac{d\sigma_{\text{pPb}}}{dp_T}}{\frac{d\sigma_{\text{pp}}}{dp_T}}
\]

- \(R_{\text{pPb}}\) of all species **consistent with unity** & each other within uncertainties

- Described within uncertainties by models that include initial-state effects

- \(R_{\text{AA}}\) **significantly** < 1 for \(p_T > 3\) GeV/c; \(R_{\text{pPb}}\) consistent with unity
  - No suppression at intermediate-high \(p_T\) in p-Pb collisions
  - Suppression of yield in Pb-Pb collisions in this momentum region is due to in-medium effects

- See poster by Jasper van der Maarel (p-Pb) and talk by Andrea Dubla (Pb-Pb) for more details

Multiplicity dependence of D-meson production

- Studies vs multiplicity **probe interplay of hard & soft processes** in charm production
- “Self-normalised yield” as a function of charged-particle multiplicity from two estimators:
  - **Multiplicity at mid-rapidity** via tracklets (track segments) reconstructed in Silicon Pixel Detector within $|\eta| < 1.0$ (left)
  - **Multiplicity at backward rapidity** (Pb-going direction) measured in **V0A detector** (right)
- Results **independent of $p_T$** for both estimators
- Slightly faster-than-linear increase at high multiplicity in the mid-rapidity region
- Linear increase in measured multiplicity interval for V0A estimator; **consistent with mid-rapidity result in measured interval** within uncertainties
Comparison of result vs. $dN_{ch}/d\eta$ with pp results & models

- Multiplicity at mid-rapidity: trend for average D-meson result is **similar in pp and p-Pb collisions**
  - Behaviour at high multiplicities consistent between collision systems at mid-rapidity
- Results compared with **EPOS 3 event generator** → slightly closer consistency with calculations that **include viscous hydro** at high multiplicity
- **See talk by Fabio Colamaria (next) for more on multiplicity dependence in pp and p-Pb**


*ALICE Collaboration (pp results)*: arXiv:1505.00664
Multiplicity dependence of D-meson production \( (Q_{pPb}) \)

- **Centrality-dependent nuclear modification factor** \( Q_{pPb} \): alternative approach to studying multiplicity dependence of D-meson production in p-Pb collisions
  - Collision centrality expressed in terms of nuclear overlap function \( T_{pPb} \)
  - Determined using Zero-Degree Neutron Calorimeter (ZN); based on energy deposited by neutrons at forward rapidity
  - \( T_{pPb} \) & \( N_{coll} \) determination relies on the assumption that charged-particle multiplicity at mid-rapidity scales linearly with \( N_{part} \)
  - **No centrality dependence** of nuclear modification seen, nor any significant \( p_T \) dependence in any centrality class.
  - **See poster by Riccardo Russo for further details on multiplicity analysis & \( Q_{pPb} \) results**
ALICE: A Large Ion Collider Experiment (Electrons)

- **Time Projection Chamber (TPC):**
  - PID via $dE/dx$, tracking

- **Inner Tracking System (ITS):**
  - Vertexing, tracking

- **Transition Radiation Detector (TRD):**
  - $e^\pm$ trigger, PID via $dE/dx + TR$

- **Electromagnetic Calorimeter (EMCal):**
  - $e^\pm$ trigger, PID via $E/\rho$ at high $p_T$

- **Time-of-Flight (TOF):**
  - PID via time of flight

**D \rightarrow e^\pm + X (BR \sim 10\%)**

**B \rightarrow e^\pm + X (BR \sim 11\%)**

Subtraction of background from:
- $\gamma$ conversions
- neutral-meson Dalitz decays
- $J/\psi$ decays
$R_{pPb}$ of inclusive heavy-flavour decay electrons

- **Left:** $p_T$-differential cross section measured in minimum-bias p-Pb collisions for inclusive electrons from heavy-flavour decays in $0.5 < p_T < 12$ GeV/c, compared with rescaled pp results. Right: $R_{pPb}$ results compared with model calculations.

- $R_{pPb}$ is consistent with unity & described by various models, as seen for D mesons


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Heavy-flavour decay electrons at high $p_T$ using EMCal

- Additional analysis of inclusive heavy-flavour decay electrons using trigger from EMCal (Electromagnetic Calorimeter), with trigger on deposited energy > 11 GeV

- Results consistent with minimum-bias analysis, extending $R_{pPb}$ above $p_T = 12 \text{ GeV}/c$, consistent with unity over entire momentum range
  → See poster by Cristiane Jahnke for further details
Nuclear modification factor of beauty-decay electrons measured in p-Pb collisions

Beauty-decay electrons are separated from inclusive heavy-flavour decay electrons via their impact parameter distributions

$R_{pPb}$ of beauty-decay electrons is consistent with that of inclusive heavy-flavour decay electrons & with unity

ALICE Collaboration (b,c → e): arXiv:1509.07491
ALICE: A Large Ion Collider Experiment (Muons)

D → μ± + X (BR ~10%)
B → μ± + X (BR ~11%)
Background mainly from π + K decays

Dipole magnet
Front absorber
Trigger chambers
Muon filter
Tracking chambers
$R_{p\text{Pb}}$ of heavy-flavour decay muons

- **Consistent with unity** at backward (Pb-going, left) and forward (p-going, right) rapidity at high $p_T$
  - Backward rapidity: slightly larger than unity in $2 < p_T < 4 \text{ GeV/c}$
- Data described within uncertainties by model calculations that include cold nuclear matter effects

Summary

- **Nuclear modification factor** $R_{ppb}$ measured for prompt D mesons & semileptonic heavy-flavour decays at mid-, forward and backward rapidity
  → All channels (D mesons, electrons, muons) show charm $R_{ppb}$ consistent with unity; yield suppression seen at high $p_T$ in Pb-Pb collisions is due to in-medium effects
  → **Beauty** $R_{ppb}$ measured via electron decays; consistent with $R_{ppb}$ of heavy-flavour decay electrons and with unity

- **Centrality-dependent** $Q_{ppb}$ measured for D mesons
  → Results consistent with unity for all $p_T$ and centrality
  → **Consistent with binary scaling**

- Measurement of relative D-meson yields as a function of multiplicity:
  → Slightly faster-than-linear increase seen for D mesons with respect to charged particles at high multiplicity at mid-rapidity; roughly linear for V0A multiplicity over measured interval. Estimators consistent within uncertainties.
  → Multiplicity dependence comparable with that measured in pp for charged-particle multiplicity at mid-rapidity
  → Results in this region described more closely by EPOS 3 calculations that include viscous hydrodynamics
Future prospects – what's next?

- Run I
  - $D^0$ under study at ultra-low $p_T (< 1 \text{ GeV/c})$ in pp & p-Pb collisions
  - Greatly reduced uncertainties on open-charm cross section; $R_{pPb}$ down to $p_T = 0 \text{ GeV/c}$
  - Centrality-dependent $Q_{pPb}$ of heavy-flavour decay muons also being studied
Future prospects – what's next?

- **Run I**
  - *D⁰* under study at ultra-low $p_T$ (< 1 GeV/c) in pp & p-Pb collisions
    - Greatly reduced uncertainties on open-charm cross section; $R_{pPb}$ down to $p_T = 0$ GeV/c
    - Centrality-dependent $Q_{pPb}$ of heavy-flavour decay muons also being studied

  - Higher $\sqrt{s}$ + increased luminosity in all systems
  - Transition Radiation Detector (TRD) completed, with full azimuthal coverage
    - Enhanced electron triggering + identification at intermediate & high $p_T$
  - Further p-Pb run planned at higher $\sqrt{s_{NN}}$ towards end of Run II
Future prospects – what’s next?

**Run I**
- D⁰ under study at ultra-low $p_T$ (< 1 GeV/c) in pp & p-Pb collisions
  - Greatly reduced uncertainties on open-charm cross section; $R_{pPb}$ down to $p_T = 0$ GeV/c
  - Centrality-dependent $Q_{pPb}$ of heavy-flavour decay muons also being studied

**Run II (2015-2017)**
- Higher $\sqrt{s}$ + increased luminosity in all systems
- Transition Radiation Detector (TRD) completed, with full azimuthal coverage
  - Enhanced electron triggering + identification at intermediate & high $p_T$
- Further p-Pb run planned at higher $\sqrt{s_{NN}}$ towards end of Run II
- First look at Run II data in pp collisions at $\sqrt{s} = 13$ TeV: already high statistical significance for D⁰, D⁺ and D*⁺ for $p_T > 2$ GeV/c in first 48M events
Further talks & posters on HF in p-Pb in ALICE

- **Fabio Colamaria**, Heavy-flavour correlations and multiplicity dependence in pp and p-Pb collisions with ALICE *(Next talk in this session)*

**Posters:**
- **Yasser Corrales Morales**, MC performance studies of beauty-jet tagging in p-Pb collisions
- **Cristiane Jahnke**, High-$p_T$ heavy-flavour decay electron measurements in p-Pb collisions with the ALICE EMCal
- **Jasper van der Maarel**, $D^{*+}$-meson production in p-Pb collisions in ALICE
- **Riccardo Russo**, $D^+$-meson production as a function of charged-particle multiplicity in p-Pb collisions
- **Sonia Rajput**, Measurement of D meson-charged particle azimuthal angular correlations in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE
– Backup slides –
Reconstruction of D mesons

- Strategy: full reconstruction of hadronic decays of D mesons
  → Retains full kinematic information of original particle

\[ D^0 \rightarrow K^-\pi^+ \text{ (BR = 3.88 ± 0.05%; } c\tau \approx 123 \text{ μm}) \]
\[ D^0 \rightarrow K^-\pi^+\pi^+ \text{ (BR = 9.13 ± 0.19%, } c\tau \approx 312 \text{ μm}) \]
\[ D^{*+} \rightarrow D^0\pi^+ \text{ (BR = 67.7 ± 0.5%) } \]
\[ D_s^+ \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+ \text{ (BR = 2.28 ± 0.12%, } c\tau \approx 150 \text{ μm}) \]

(and respective charge conjugates)

- Standard reconstruction relies on topological + PID selections to reduce combinatorial background

- Example (left): D^0 meson: non-zero lifetime; decay vertex of mesons displaced from interaction point (primary vertex)
  → Decay length, impact parameter, pointing angle (for example) can be used to select candidates

- For D^{*+}, D^0 candidate paired with soft π^+ at primary vertex

- Standard PID at mid-rapidity uses TOF (where available) + TPC, with 'nσ' PID
  → Strong separation of pions, kaons and protons at wide range of momenta

D-meson measurements in pp

- Results at $\sqrt{s} = 7$ TeV used as reference for p-Pb and Pb-Pb collisions
  - Energy scaled using FONLL\textsuperscript{[1]} where necessary for other systems
- Provides constraint on model calculations
  - Results well described by FONLL and GM-VFNS\textsuperscript{[2]} pQCD frameworks (right: results for D$^{*+}$)
- Results for all D-meson species at $\sqrt{s} = 2.76$ and 7 TeV extrapolated to full phase space using FONLL to extract total cc cross section (below, latest STAR result)
  - Good agreement with NLO\textsuperscript{[3]} predictions & trend from other experiments at wide range of energies

\[ \text{References:} \]
\[ \text{[1] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007} \]
\[ \text{[4] B. Abelev et al. (ALICE collaboration), JHEP 1201 (2012) 128} \]
D mesons vs V0A multiplicity: comparison with pp

- pp results show faster-than-linear increase at high multiplicity
- p-Pb: consistent with linear increase with respect to backward multiplicity
- Caveat: multiplicity in different rapidity intervals in two measurements (due to coverage of detector & rapidity of p-Pb centre-of-mass system with respect to lab frame)
  → Requires model calculations with multiplicity at backward rapidity to fully understand difference between collision systems
Heavy-flavour decay electron identification

- PID at low $p_T$: TPC, TOF, TRD
  - PID at high $p_T$: TPC + EMCal

- Background subtraction:
  - Cocktail method: MC generator for variety of hadronic sources
  - Invariant mass method for $e^+e^-$ to remove photon conversions and Dalitz decays
Impact parameter distributions for electrons from b, c

- Maximum-likelihood fit to impact parameter distribution used to extract fraction of electrons from beauty-hadron decays
- Template impact parameter distributions for electrons from beauty, charm, conversions, Dalitz decays via PYTHIA generator & DPMJET
- Impact parameter distribution from beauty-decay electrons broad due to large decay length ($c\tau \approx 490 \mu$m)
$R_{AA}$ & $R_{pPb}$ of heavy-flavour decay electrons

- $R_{pPb}$: consistent with unity & models that include initial-state effects
- $R_{AA}$: significantly less than unity above $p_T = 3$ GeV/c, consistent with models that include final-state effects

→ Yield suppression at high $p_T$ in Pb-Pb collisions is due to in-medium effects


**FONLL**: M. Cacciari et al., JHEP 9805 (1998) 007; **EPS09**: K. J. Eskola et al., JHEP 04 (2009) 065

**ALICE Collaboration (p-Pb)**: arXiv:1509.07491
Identification of heavy-flavour decay muons

- Track selection:
  - Acceptance: $-4 < \eta_{\text{lab}} < -2.5$
  - Punch-through hadrons removed by muon trigger matching
  - Beam-gas & secondary muons removed using muon trigger signal & cut on $p_x \times \text{DCA}$

- Background subtraction:
  - Main source: muons from decays of pions and kaons; subtracted using MC $dN/dp_T$ normalised to data at low $p_T$
  - Background decreases with increasing $p_T$
$R_{pPb}$ & $R_{AA}$ of heavy-flavour decay muons

- $R_{pPb}$: consistent with unity at both forward and backward rapidity
- $R_{AA}$: significantly smaller than unity for $4 < p_T < 10$ GeV/c

→ Suppression is due to in-medium effects