Recent open heavy-flavour results from ALICE at the LHC

Jeremy Wilkinson (Universität Heidelberg, Germany)
on behalf of the ALICE Collaboration
Motivation: Why open heavy flavour?

- 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 large mass, charm and beauty quarks are produced in the **early stages** of the collision. → Experience the **full evolution** of the system.
- Expected hierarchy: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$ due to colour charge & mass dependence of in-medium energy loss\(^1\)
- Production measured in ALICE in three ways:
  → Hadronic decays of D mesons at mid-rapidity
  → Semileptonic decays at mid-rapidity ($D/B \to e^\pm + X$)
  → Semileptonic decays at forward/backward rapidity ($D/B \to \mu^- + X$); probes different Bjorken-$x$ region

ALICE: A Large Ion Collider Experiment (D mesons)

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

Inner Tracking System (ITS): Vertexing, tracking

Zero-Degree Calorimeter (ZDC): Event activity (p-Pb)

VZERO detector: Centrality, event plane

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

$D^0 \rightarrow K^- \pi^+$ (BR = $3.88 \pm 0.05\%$; $c\tau = 123 \mu m$)

$D^+ \rightarrow K^- \pi^+ \pi^+ \pi^+$ (BR $9.13 \pm 0.19\%$, $c\tau \approx 312 \mu m$)

$D^{*+} \rightarrow D^0 \pi^+$ (BR $67.7 \pm 0.5\%$) $\rightarrow K^- \pi^+ \pi^+$

$D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$ (BR $2.28 \pm 0.12\%$, $c\tau \approx 150 \mu m$)

(and respective charge conjugates)

Selected via decay topology (e.g. decay length, pointing angle) and PID of decay products
Measured $R_{AA}$ of D mesons

- Nuclear modification in Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV measured for all four species using:

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

- Results in most-central collisions consistent between $D^0$, $D^+$ and $D^{**}$ at all $p_T$

- Significant suppression at high $p_T$, due to substantial energy loss of charm quarks in medium

- Not yet possible to draw firm conclusions on predicted enhancement of $D_s^+$ yield relative to non-strange D mesons at low $p_T$ due to recombination$^{[1,2]}$

→ More statistics needed to reduce uncertainties

$R_{AA}$ compared with CMS non-prompt J/$\psi$

- D-meson results compared with non-prompt J/$\psi$ (i.e. from B decays) measured by CMS collaboration as function of centrality
  - Different rapidity & $p_T$ ranges, but similar kinematic region

- Indicates $R_{AA}(D) < R_{AA}(B)$ in central Pb-Pb collisions
  - Observed difference is described by models including mass-dependent energy loss

\[ \langle N_{\text{part}} \rangle \text{ weighted with } N_{\text{coll}} \]

\[ s_{NN} = 2.76 \text{ TeV} \]

CMS Preliminary Non-prompt J/$\psi$
6.5 < $p_T$ < 30 GeV/c, $|y|<1.2$

\(R_{\text{AA}}\) of D mesons in 30-50% centrality

- New measurements in the 30-50% centrality interval in Pb-Pb
- Simultaneous comparison in two centrality classes → provides constraints on model predictions


Measured $v_2$ of D mesons

- Elliptic flow $v_2$ measured using event-plane method:

$$v_2 = \frac{1}{R_2^\text{ch}} \frac{\pi}{4} \frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$

- Definition: $N_{\text{in-plane}}$ = particles within $\Delta \phi = [-\pi/4, \pi/4] \& [3\pi/4, 5\pi/4]$ relative to reaction plane; $N_{\text{out-of-plane}}$ = particles within $\Delta \phi = [\pi/4, 3\pi/4] \& [5\pi/4, 7\pi/4]$.

- Above: results for $D^0$, $D^+$, $D^{*+}$; below: $D^0$ compared with charged-particle measurement (dominated by pions)

  - Results for species consistent with one another
  - Significantly $> 0$ at low $p_T$

  compatible with light-flavour measurements $\rightarrow$ suggests collective motion of charm quarks in medium

Comparison of $R_{AA}$ and $v_2$ with models

- Simultaneous description of $R_{AA}$ and $v_2$ by models remains challenging → considering both observables together provides useful constraint for theory


**$R_{pPb}$ of D mesons**

- Measured similarly to $R_{AA}$: $D^0$, $D^+$, $D^{*+}$ & $D_s^+$ (above), average of $D^0$, $D^+$, $D^{*+}$ (below)

- All meson species in agreement within uncertainties

- $R_{pPb}$ consistent with unity
  - No significant suppression of D mesons in p-Pb at higher $p_T$
  - Suppression in Pb-Pb is hot medium effect rather than initial-state effect

- Described by models including initial-state effects within uncertainties

---

**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


**B. Abelev et al. (ALICE Collaboration)**: arXiv:1405.3452
Multiplicity dependence of D-meson production (vs. $N_{\text{ch}}$)

- Measured in pp & p-Pb to probe role of multi-parton interactions in charm production
- “Self-normalised yield” as function of charged-particle multiplicity $N_{\text{ch}}$ (left: $D^0$, $D^+$, $D^{*+}$ in pp; right: average of species in p-Pb)
  - Multiplicity estimator: tracklets (track segments) reconstructed in Silicon Pixel Detector within $|\eta| < 1.0$
- Increase of D-meson yield as function of multiplicity consistent between pp and p-Pb
- Self-normalised yield independent of $p_T$. 

New @ QM 2014
Multiplicity dependence of D-meson production ($Q_{pPb}$)

- Multiplicity-dependent nuclear modification $Q_{pPb}$ ($D^0$, $D^{**}$ in $p$-$Pb$) to study $p_T$ dependence in multiplicity classes.
  - $N_{\text{coll} \text{ mult}}$ determined assuming that charged-particle multiplicity at mid-rapidity is proportional to number of participants ($N_{\text{part}}$).
  - No multiplicity dependence of nuclear modification seen.

$$Q_{pPb}^{\text{mult}} = \left( \frac{dN_{pPb}^{Z\text{N}}}{d\rho_T} \right) \frac{\langle N_{\text{coll} \text{ mult}}^{\text{mult}} \rangle}{\langle dN_{pp}^{\text{mult}} \rangle}$$
ALICE: A Large Ion Collider Experiment (Electrons)

**Electromagnetic Calorimeter (EMCal):**
- $e^{\pm}$ trigger, PID via $E/p$

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

**VZERO detector:**
- Centrality, event plane

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

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

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

D $\rightarrow e^{\pm} + X$ (BR ~10%)
B $\rightarrow e^{\pm} + X$ (BR ~11%)

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

- Significant suppression of heavy-flavour decay electrons observed in \( 3 < p_T < 18 \text{ GeV}/c \)
- Theoretical models give different predictions for \( R_{AA} \) of electrons from b and c decays
- Electrons dominated by \( b \to e \) at high pT

**Cao, Qin, Bass:** *Phys. Rev. C 88 (2013) 044907*
Electrons from beauty decays in Pb-Pb

- Analysis based on impact parameter distribution of electrons
- Preliminary measurements in 0-20% most-central events suggest $R_{AA}(e \leftarrow b) < 1$ for $p_T > 3$ GeV/c
$p_T$-differential cross section of $e^\pm$ in p-Pb collisions

- $p_T$-differential cross sections measured in minimum-bias p-Pb collisions for:
  - inclusive electrons from heavy-flavour decays in $0.5 < p_T < 12$ GeV/c
  - electrons from beauty-hadron decays in $1.2 < p_T < 7$ GeV/c

**New @ QM 2014**
$R_{pPb}$ of heavy-flavour decay electrons

- $R_{pPb}$ of both heavy-flavour-decay and beauty-decay electrons consistent with unity within uncertainties

ALICE Preliminary

p-Pb, $s_{NN} = 5.02$ TeV, min. bias, $-1.06 < y_{CMS} < 0.14$
Comparison of $R_{pPb}$ with $R_{AA}$, models

- $R_{pPb}$ described within uncertainties by pQCD using EPS09 shadowing
- $R_{pPb}$ compatible with unity (similar to result for D mesons)

→ Suppression in Pb-Pb due to hot medium effects rather than cold nuclear matter effects


Elliptic flow of heavy-flavour decay electrons

- Measured via event-plane method using VZERO detector
- Confirms significant interaction of heavy quarks with medium
  → Hints at collective motion of low-$p_T$ heavy quarks in expanding fireball
- Increase of elliptic flow of electrons when going from central to semi-central events
Elliptic flow and $R_{AA}$ of heavy-flavour decay electrons

$R_{AA}$ and $v_2$ results consistent with picture from D mesons (significant suppression); help to provide further constraints to model calculations when compared side-by-side.


ALICE: A Large Ion Collider Experiment (Muons)

- Dipole magnet
- Front absorber
- Tracking chambers
- Trigger chambers
Heavy-flavour decay muon $R_{AA}$

- Suppression of muons at forward rapidity (green, $2.5 < y < 4.0$) compatible with that of electrons at mid-rapidity (red, $|y| < 0.6$)

**Graphical Elements**

- **Axes**: $p_T$ (GeV/c) on the x-axis and $R_{AA}$ on the y-axis.
- **Data Points**:
  - Green triangles: Heavy flavour decay $\mu^\pm$ 0-10% central, $2.5 < y < 4.0$.
  - Red circles: Heavy flavour decay $e^\pm$ 0-10% central, $|y| < 0.6$.
  - Red stars: With pp ref. from scaled cross section at $\sqrt{s} = 7$ TeV.
  - Green squares: With pp ref. from FONLL calculation at $\sqrt{s} = 2.76$ TeV.

**Graph Title**: Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV
Cross section of heavy-flavour decay muons in p-Pb

- Measured in backward (Pb-going, left) and forward (p-going, right) rapidity in $2 < p_T < 16$ GeV/c
$R_{ppb}$ of heavy-flavour decay muons

- Compatible with unity at forward and backward rapidity at high $p_T$
  - Backward rapidity: slightly larger than unity in $2 < p_T < 4$ GeV/c
- Data described by pQCD calculations with EPS09 shadowing within uncertainties

Summary

- **Pb-Pb results:**
  - Significant **suppression** of D mesons, electrons, muons at high $p_T$ when compared with pp at both forward and mid-rapidity
  - D-meson $R_{AA}$ compared with CMS non-prompt J/$\psi$
    - $R_{AA}(D) < R_{AA}(J/\psi \rightarrow B)$, as expected from energy-loss hierarchy
  - Elliptic flow $v_2$ measured for D mesons, electrons and muons; compatible with measurement for charged particles
  - Suggests **collective motion of charm quarks in medium**

- **p-Pb results:**
  - Mid-rapidity: D-meson & electron $R_{pPb}$ compatible with unity; **suppression in Pb-Pb is due to hot medium effects**
  - $R_{pPb}$ of electrons from beauty decays compatible with that from heavy flavour decays
  - Muons: $R_{pPb}$ also compatible with unity; slight enhancement over pp result at low $p_T$ in backward rapidity region
  - Multiplicity dependence of D-meson production compatible with that in pp
Future prospects

- **Λ_c being measured** in two channels (Λ_c → pK_S^0 & Λ_c → pKπ)

- **D^0 at low p_T** (< 1 GeV/c) also under study
  - Resolution limits effectiveness of topological selections
  - Controlling background using track rotation, reflections

  - Higher √s + increased luminosity in all systems
  - Transition Radiation Detector (TRD) at full coverage
    - Enhanced electron triggering + identification at high p_T

- **LS2 in 2017, Run III**: Further upgrade in luminosity, + upgrades to ITS and other detectors will allow for many refinements
  - Full reconstruction of B mesons via hadronic decays
  - Precision measurements of Λ_c and D_s R_{AA}, higher precision on D-meson ν_2...
    - Will allow (among other things) measurement of baryon-to-meson ratio in charm sector

Many interesting results so far, but **still plenty more on the way!**
– Backup slides –
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 $c\bar{c}$ cross section (below, latest STAR result)
  - Good agreement with NLO\textsuperscript{[3]} predictions & trend from other experiments at wide range of energies

\[1\] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007
\[4\] B. Abelev et al. (ALICE collaboration), Phys.Rev. D86 (2012) 112007
• D-meson $R_{AA}$ compatible with pion $R_{AA}$ within uncertainties

• Consistency described by models that take into account:
  → $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$
  → Different shapes of $p_T$ distributions
  → Differing fragmentation functions
Heavy-flavour decay muon $v_2$

- Measured using $Q\{2\}$ cumulant method

$$v_2^{\mu \leftarrow HF} = \frac{v_2^{incl \mu} - f_{\text{decay } \mu} v_2^{\text{decay } \mu}}{1 - f_{\text{decay } \mu}}$$

- $f_{\text{decay}} \sim 15 \,(5\%)$ at $p_T = 3 \,(10) \text{ GeV/c}$, based on extrapolation of $\pi/K$ spectra at mid-rapidity

- $v_2^{\text{decay}}$ determined using cocktail method based on data

- $v_2$ significantly greater than 0 ($3\sigma$ effect for $3 < p_T < 5 \text{ GeV/c}$)

- Comparison with $e^\pm$: $v_2^{\mu \leftarrow c,b\mid_{\text{forward}}} \sim v_2^{e \leftarrow c,b\mid_{\text{mid-rapidity}}}$