Study of open heavy-flavour hadron production in pp and p-Pb collisions with ALICE

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Open heavy flavour in pp and p-Pb collisions

Heavy quarks (charm and beauty), have a large mass: $m_c \sim 1.3$ GeV/$c^2$, $m_b \sim 4.2$ GeV/$c^2$.

- Produced via initial hard scatterings at the early stages of the collision.
- Production cross-section calculable perturbatively down to low $p_T$.

In pp collisions:
- Important test of perturbative QCD calculations

In p-Pb collisions:
- Studies provide access to cold nuclear matter (CNM) effects. HF yield can be modified by
  - Nuclear modification of the PDFs
  - $k_T$ broadening: Multiple elastic scattering of the parton before the hard scattering. Modifies the $p_T$ distribution.
  - Energy loss in cold nuclear matter (in the initial or final state)
- Address possible collective effects and effects related to the (possible) formation of a QGP in p-Pb collisions

\[
d\sigma_{AB \rightarrow C}^{\text{hard}} = \sum_{a,b} f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes d\sigma_{ab \rightarrow c}^{\text{hard}}(x_a, x_b, q^2) \otimes D_{c \rightarrow C}(z, Q^2)
\]

Parton Distribution Function (PDF) Partonic hard scattering cross-section Fragmentation function
Open heavy flavour in pp and p-Pb collisions

Particle production as a function of multiplicity \( \rightarrow \) More differential measurement

Multiplicity is defined as the number of charged particles per event.

High multiplicity pp and p-Pb collisions have shown similar features reminiscent of those observed in Pb-Pb
Azimuthal correlations (ridge formation) and mass dependent hardening of \( p_T \) distributions.

High multiplicity pp collisions reach similar number of charged particles as in peripheral Pb-Pb collisions

- Investigate the possible influence of **multiple partonic interactions (MPI)** to the particle production.
- Study the interplay between soft and hard process.
- Understand the collective behaviour in small system.
Open heavy-flavour reconstruction in ALICE

Electromagnetic calorimeter (ePID and trigger) $|\eta| < 0.7$

Time of Flight (PID) $|\eta| < 0.9$

Time Projection Chamber (tracking and PID) $|\eta| < 0.9$

Inner Tracking system (tracking, Vertexing and PID) $|\eta| < 0.9$

Muon Arm (tracking and trigger for $\mu$) $-4 < \eta < -2.5$

V0
V0A: $2.8 < \eta < 5.1$
V0C: $-3.7 < \eta < -1.7$
(trigger and multiplicity)

Fully reconstructed $D$ meson and $Λ_c$ hadronic decays:

**ITS, TPC, TOF**

$D^0 \rightarrow K^- \pi^+,$ $D^+ \rightarrow K^- \pi^+ \pi^+,$ $D^{*+} \rightarrow D^0 \pi^+,$

$D_s^+ \rightarrow \Phi \pi^+ \rightarrow K^- K^+ \pi^+,$ $Λ_c^+ \rightarrow \pi^+ K^- p,$ $Λ_c^+ \rightarrow p K_0^s$

Partially reconstructed semi-leptonic decays:

Electrons: **ITS, TPC, TOF, EMCal.** $D, B \rightarrow e^\pm + X$

Muons: **Forward Muon Spectrometer.** $D, B \rightarrow \mu^\pm + X$

$Λ_c$ and $Ξ_c$: **ITS, TPC, TOF.** $Λ_c^+ \rightarrow e^+ \Lambda \nu_e,$ $Ξ_c^0 \rightarrow e^+ Ξ^- \nu_e$

SQM 2019 / P. Dhankher
Results in pp collisions
Heavy flavour production cross-sections in pp

D meson ($D^0$, $D^{*+}$, $D^+$, $D_{s}^+$) production cross section in pp at $\sqrt{s} = 5$ TeV at mid-rapidity.

- Precise pp reference measurement down to low $p_T$ ($\sim 0$ with $D^0$).

Comparison with models:

Data described well by pQCD model
- **FONLL (Fixed order with Next-to-Leading Log resummation):** Data lies within uncertainty, central value of predictions lies below the data\(^{(\text{JHEP 10} \ (2012))\ 137}\)
- **GM-VFNS (General- Mass Variable Flavour Number Scheme):** Data lies within uncertainty\(^{(\text{Eur. Phys. J. C72} \ (2012))\ 2082}\)
- **GM-VFNS SACOT-\(m_T\)** good agreement with data\(^{(\text{JHEP05(2018))196}\ )\)
- **\(k_T\)-factorisation** describes the data at low and intermediate $p_T$, but overestimates for $p_T > 7$ GeV/c.\(^{(\text{PRD 87 (2013) 094022})}\).
Heavy flavour production cross sections in pp

Ratios of the $p_T$-differential cross sections of $D^0$, $D^{*+}$, $D^+$, $D_s^+$ mesons and $\Lambda_c$ at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 7$ TeV.

- No significant $p_T$ dependence within the experimental uncertainties.
- Small difference between the fragmentation functions of the different species.
- Compatible within uncertainties with the ratios measured in pp collisions at $\sqrt{s} = 7$ TeV.

\begin{itemize}
  \item $\Lambda_c^+/D^0$ production is underestimated by theoretical predictions.
  \item Tensions in $\Lambda_c^+$ sector. More details in C. Zampoli’s talk.
\end{itemize}

Lucas Anne Vermunt’s Poster

ALICE Preliminary

| $p_T$ (GeV/c) | $\Lambda_c^+/D^0$ |
|--------------|--|}

- $\sqrt{s} = 5.02$ TeV
- $\sqrt{s} = 7$ TeV

Data (JHEP 04 (2018) 108)

PYTHIA8 (Monash)

PYTHIA8 (CPU Mode1)

DIPSY (ropes)

HERWIG7
Heavy flavour production cross sections in pp

Heavy-flavour hadron decay electron (mid-rapidity, $|y| < 0.8$) and muon (forward rapidity, $2.5 < y < 4$) cross section at $\sqrt{s} = 5.02$ TeV.

- Data lies on the upper edge of the theoretical (FONLL) uncertainty band for both electrons and muons
- Insight about relative abundance of beauty and charm quarks from the muon cross section
  - At low $p_T$ charm decay is dominant.
  - Beauty is the main component for $p_T > \sim 5$ GeV/c.
Heavy flavour production cross sections in pp

– HFE at 13 TeV: Data lies on the upper edge of the theoretical (FONLL) uncertainty band.

– Contributing more precise charm measurements in pp collisions at different energies.
Heavy flavour production vs multiplicity in pp

Self-normalized yield of heavy-flavour decay electrons ($\sqrt{s} = 13$ TeV, mid-rapidity) and muons ($\sqrt{s} = 8$ TeV, forward rapidity) versus multiplicity compared with model predictions with $p_T$ dependence:

- The self-normalized yields show a faster than linearly increasing trend.
- In the high $p_T$ range, hint for steeper increase.

Comparison with model prediction:

- $c,b \rightarrow \mu$ data compared to EPOS3.210 prediction without hydrodynamics (Phys. Rev. C 89 (2014) 064903). EPOS3.210 underestimates data at higher multiplicities for all $p_T$ ranges

Results in p-Pb collisions
Self-normalized yield of average D mesons ($\sqrt{s_{\text{NN}}}=5.02$ TeV) and electrons ($\sqrt{s_{\text{NN}}}=8.16$ TeV) versus multiplicity at mid-rapidity:

- Similar trend in both pp and p-Pb collisions.
- High-multiplicity p-Pb collisions: MPI (like pp) but also have higher number of binary nucleon-nucleon collisions.
- The trend of HF-decay electrons is compatible with the average D mesons.
D-meson nuclear modification factor in p-Pb

- Nuclear modification factor provides access to cold nuclear matter (CNM) effects and the effects related to the (possible) formation of a QGP in p-Pb collisions

\[ R_{pPb} = \frac{1}{A} \frac{d\sigma_{pA}/dp_T}{d\sigma_{pp}/dp_T} \]

arXiv:1906.03425

- Left: Data described well by the models including the CNM effects.
- Right: Data compared with the model which predicts the production of a QGP in p-Pb.
  - Tend to predict a suppression on the D mesons \( R_{pPb} \) at high \( p_T \). At present results tend to disfavour suppressions larger than 10-20%.

\[ \text{ALICE} \quad \text{p-Pb, } \sqrt{s_{NN}}=5.02 \text{ TeV} \]
D-meson nuclear modification factor in p-Pb

- \( Q_{pPb} \): centrality-dependent nuclear modification factor. \( \rightarrow \) centrality-dependent CNM effects.

\[
Q_{pPb}^{\text{cent}} = \frac{1}{< T_{pPb}^{\text{cent}} >} \frac{dN_{pPb}^{\text{cent}}}{dp_T} \frac{d\sigma_{pp}}{dp_T}
\]

- Central and peripheral results are compatible with each other and with unity for D mesons.
- D-meson \( Q_{pPb} \) similar to charged particles within uncertainties.

- \( Q_{cp} \): Ratio of most central collisions to the most peripheral collisions spectra.
  
  Central : 0-10%  Peripheral : 60 - 100%

- \( Q_{cp} > 1 \) by \( \sim 3\sigma \) in \( 3 < p_T < 7 \text{ GeV/c} \) in 20-40%.
  
  \( \rightarrow \) similar trend as charged particles.
  
  Origin: CGC like Initial or QGP for final state effects? Need models for interpretation.
Collectivity in small systems?

- **Anisotropic flow:** Initial spatial anisotropy translates into final momentum anisotropy (pressure gradients).

\[
E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T d\eta} \left[ 1 + 2 \sum_{n=1}^{\infty} \nu_n \cos[n(\phi - \psi_n)] \right] \\
\nu_n = \langle \cos[n(\phi - \psi_n)] \rangle, \ n = 1, 2, 3, \ldots
\]

- Also observed in the small systems.
- Study to understand better the collective behaviour in small system in the HF sector.

Positive $v_2$ observed for HF-decay electrons and inclusive muons.

- Heavy flavour decay **electron** (mid-rapidity).
  - Effect observed is qualitatively similar to inclusive muons.
  - Significance: $> 5\sigma$ for $1.5 < p_T < 4$ GeV/c.
  - Origin: CGC like Initial or QGP for final state effects.

- Heavy flavour decay **muon** (forward rapidity).
  - Effect observed is qualitatively similar to HFE
Conclusions

- **D mesons and heavy-flavour decay lepton production** cross-section is measured with good precision. Compared with pQCD calculation. Described well within uncertainty.

- **Heavy flavour production vs multiplicity.**
  - **Self-normalised yield**
    - Results show **stronger than linear enhancement** as a function charged-particle multiplicity.
    - pp collisions: **Higher \( p_T \) ranges** hint of steeper increase.
    - Particle yield and multiplicity measured at mid-rapidity (possible autocorrelations).
  - **Nuclear modification factor: \( Q_{PPb} \)**
    - \( Q_{PPb} \) compatible with unity and with charged-particle for D-mesons.
    - **Hints of \( Q_{cp} > 1 \)**, possible modification of the production. From initial- or final-state effects?
  - **Elliptic flow at high multiplicity.**
    - **Positive \( v_2 \)** measured for heavy-flavour decay electrons at mid-rapidity and for inclusive muons at forward rapidity.
    - **Positive \( v_2 \)** is also observed for heavy-flavour decay muons at forward rapidity
Thank you for your attention!
Heavy flavour production cross-sections in pp

Heavy flavour production cross-sections in pp