Evolution of open charm production with event multiplicity with ALICE

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The study of charm production as a function of multiplicity is important to investigate the role of multi-parton interactions, color-reconnection mechanisms, and spectra modification in high multiplicity events with respect to minimum bias ones, and to dig into the possible presence of collective phenomena in high-multiplicity environments.

Moreover, charm cross-section measurements in pp collisions provide a useful test of QCD calculations while measurements in p–Pb collisions are useful to analyze Cold Nuclear Matter effects.

In this contribution, recent measurements of the evolution of the production yields with the event charged-particle multiplicity of prompt D-mesons and leptons from heavy-flavour hadron decays in pp collisions at $\sqrt{s}$ = 13 TeV are discussed. The results are compared to the J/Ψ measurement and to model calculations. The Λ_c^+/D^0 and D_s/D^0 yield ratios as a function of multiplicity in pp collisions at $\sqrt{s}$ = 13 TeV are also presented. The measurements in p–Pb of the centrality-dependence of the D-meson nuclear modification factor and of the elliptic flow of heavy-flavour decay leptons in high-multiplicity events are also discussed.

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1. Introduction

Measurements of charm meson and baryon production in proton-proton collisions are an important test for perturbative QCD calculations. They provide also the reference for measurements in p–Pb, a collision system important to investigate cold nuclear matter effects (like nuclear modification of parton distribution functions). Furthermore, the study of the charm production in pp and p–Pb collisions as a function of the charged-particle multiplicity of the event allows the investigation of effects related to multiple parton interactions and of color reconnection, which are expected to play a relevant role in charged particle production at high energy at the LHC. Possible modifications of the spectra in high-multiplicity pp and p–Pb collisions with respect to minimum bias ones might signal the presence of radial flow and collective phenomena typically observed in Pb–Pb collisions. The excellent particle identification and tracking capabilities of A Large Ion Collider Experiment (ALICE) [1] are exploited to analyse several charm-hadron decay channels, namely:

- hadronic decays: $D^0 \rightarrow K^-\pi^+$; $D^+ \rightarrow K^-\pi^+\pi^-$; $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^-$; $D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$; $\Lambda_c^+ \rightarrow pK^-\pi^+$; $\Lambda_c^+ \rightarrow pK_s^0$; $\Sigma_c^0 \rightarrow \Lambda_c^+\pi^-$; $\Sigma_c^{++} \rightarrow \Lambda_c^+\pi^+$, $\Xi_c^0 \rightarrow \Xi^-\pi^+$; $\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$; $\Omega_c^0 \rightarrow \Omega^-\pi^+$.

- semileptonic decays: B and D mesons $\rightarrow$ e + X; B and D mesons $\rightarrow$ μ + X; $\Xi_c^0 \rightarrow \Xi^- e^+\nu_e$; $\Lambda_c^+ \rightarrow \Lambda e^+\nu_e$.

The particle identification in the central barrel (pseudorapidity $|\eta| < 0.9$) is provided by the Time Projection Chamber (TPC) and the Time Of Flight (TOF) detectors, as well as by the Electromagnetic Calorimeter (EMCal) for high-pt electron identification. The track position is determined with high resolution by the Inner Tracking System (ITS) and TPC. At forward rapidity ($2.5 < y < 4$), muons are identified and reconstructed in the muon spectrometer.

The Silicon Pixel Detector (SPD) and the V0 detectors are used to estimate the multiplicity, which is defined as:

- SPD tracklets: track segments reconstructed from two hits in the detector layers (used at $|\eta| < 1$);

- V0M percentile: multiplicity based on the percentile distribution of the V0 amplitude, which is the weighted sum of charge deposition in the V0A and V0C scintillators ($2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$).

The multiplicity intervals estimated with both methods are converted to mean charged particle multiplicity density ($\langle dN_{ch}/d\eta \rangle$) of charged-primary particles N_{ch}.

## 2. Charm production in pp collisions

In this section, the charm production measurements as a function of multiplicity are discussed. Results will be expressed using the so-called self-normalised yield, defined as

$$\frac{d^2N_{mult}/(dydp_T)}{\langle d^2N_{int}/(dydp_T)\rangle} = \frac{Y_{mult}}{Y_{int}} \tag{1}$$

where $Y_{\mathrm{mult/int}}$ is the corrected yield respectively in multiplicity intervals and in the multiplicity-integrated case.

The measurements of D-meson and non-prompt J/ψ production as a function of multiplicity in pp collisions at $\sqrt{s}$ = 7 TeV were reported in [2]: the self-normalised yields of both particle species show a faster than linear increasing trend. Within uncertainties, the self-normalised yield evolution with multiplicity does not depend significantly on p_{T}.

The results for D mesons at $\sqrt{s}$ = 13 TeV are shown in Fig. 1 in six p_{T} intervals up to 24 GeV/c. A dependence on p_{T} is observed (thanks to the better precision of 13 TeV results compared to 7 TeV ones), and high-p_{T} intervals show a stronger increase of the self-normalised yields with multiplicity.
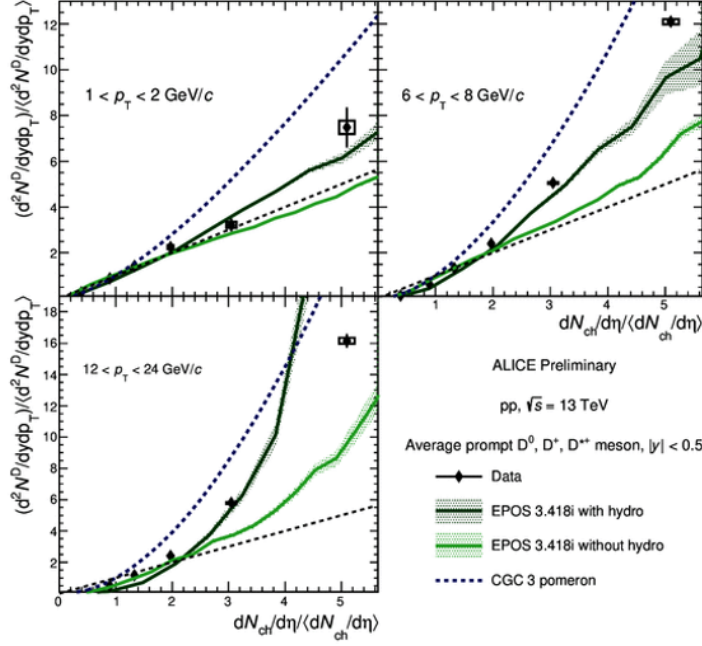

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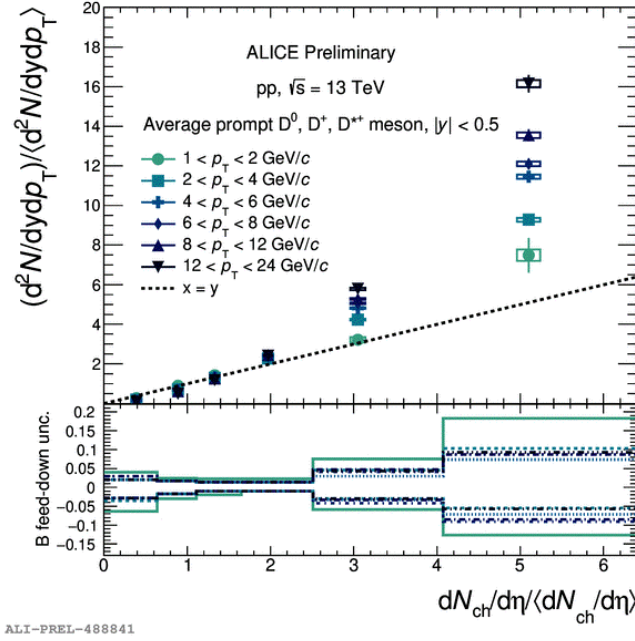
Figure 1: Average of D^0, D^+, D^{*+} meson self-normalised yields vs. charged particle multiplicity in pp collisions at $\sqrt{s}$ = 13 TeV at midrapidity in different p_{T} intervals. The b-hadron feed-down systematic uncertainties are shown in the bottom panel.

The average of D^0, D^+, D^{*+} meson results are compared to different Monte Carlo models in Fig. 2. The EPOS3 generator [3] with flux-tube initial conditions, generated in the Gribov-Regge multiple scattering framework, and hydrodynamical evolution describes reasonably well data, while EPOS3 without hydro and the 3-pomeron Color Glass Condensate (CGC) [4] respectively underestimates and overestimates them.

The self-normalised yields as a function of multiplicity of heavy-flavour hadron decay electrons in pp collisions at midrapidity at 13 TeV measured for p_{T} < 4.5 GeV/c are reported in Fig. 3 and compared to the default PYTHIA 8.2 tune, Monash 2013, in which both color reconnection (CR) and multiple parton interactions are included.

Furthermore, self-normalised yields of heavy-flavour hadron decay muons at forward rapidity (2.5 < y < 4) vs. multiplicity at $\sqrt{s}$ = 8 TeV in 5 different p_{T} intervals are reported in Fig. 4 compared to EPOS prediction without the hydrodynamical evolution enabled.

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Figure 2: Comparison of D-meson self-normalised yields as a function of charged-particle multiplicity to models data in three p_T intervals in pp collisions at $\sqrt{s}$ = 13 TeV.

Heavy-flavour electrons are well described by PYTHIA 8.2 data, while muons are underestimated by EPOS. Both measurements show a faster than linear trend vs. multiplicity. In both cases the multiplicity refers to the charged particles one in $|\eta| < 1$.

The self-normalised yields of J/ψ, D-meson average and heavy-flavour decay electrons compared in similar p_T intervals in Fig. 5 show similar trends.

In this contribution the production ratios Λ_c^+/D^0 and D_s^+/D^0 (Fig. 6) in pp collisions at 13 TeV are also presented. The results show a multiplicity dependence of the Λ_c^+/D^0 yield ratio that hints to a modification of hadronization mechanisms with multiplicity. The PYTHIA 8.2 Monash tune strongly underestimates the data, and does not reproduce the trend with p_T, while the CR mode 2 tune [5] qualitatively describes the p_T shape and multiplicity trend.

On the other hand, the D_s^+/D^0 ratio shows no significant multiplicity dependence.

3. Measurements in p–Pb collisions

An important observable in p–Pb collisions is the nuclear-modification factor R_{pPb}, calculated as

$$R_{pPb} = \frac{1}{A} \frac{d\sigma_{pPb}/dp_T}{d\sigma_{pp}/dp_T},\tag{2}$$

which is the ratio of the production cross section in p–Pb collisions to that in pp collisions scaled by the lead mass number A (equal to 208). Figure 7 shows that the R_{pPb} values of D mesons are
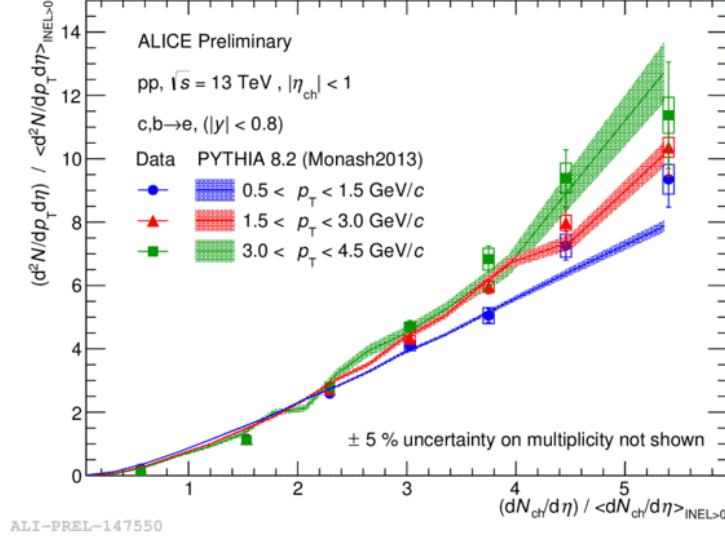
Figure 3: Heavy-flavour hadron decay electron self-normalised yields as a function of charged particle multiplicity compared to PYTHIA 8.2 results.
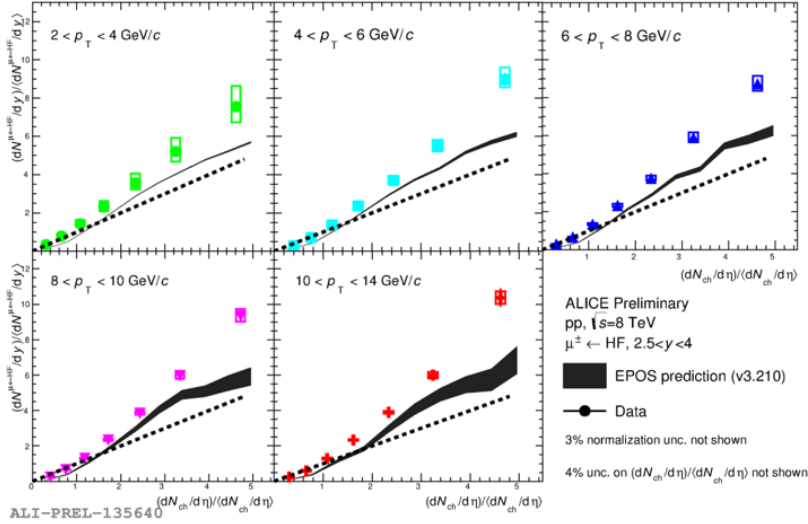

Figure 4: Heavy-flavour hadron decay muon self normalised yields as a function of charged particle multiplicity compared to EPOS predictions at forward rapidity.

compatible with unity in all the p_T intervals and the results are described by POWHEG+PYTHIA6 predictions. For the Λ_c^+ a significant suppression of the production below 2 GeV/c is visible, while the R_{pPb} tends to be above unity elsewhere. This trend could indicate a possible radial flow effect or a modification of the hadronization mechanisms in p–Pb collisions.

The data are compatible with POWHEG+PYTHIA6 up to 2 GeV/c and with POWLANG up to 4 GeV/c, but in the intermediate and high p_T intervals both models are not able to describe the Λ_c^+-baryon R_{pPb}.

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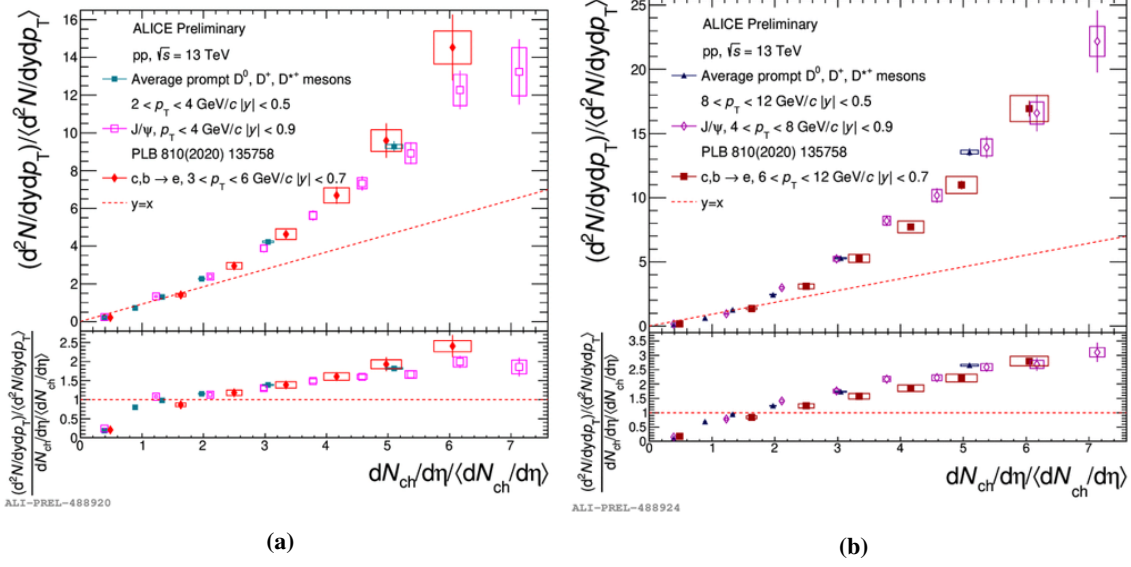
Figure 5: Comparison of self-normalised yields of D-meson average, J/ψ and heavy-flavour electrons at low (a) and high (b) p_T in pp collisions at $\sqrt{s}$ = 13 TeV.
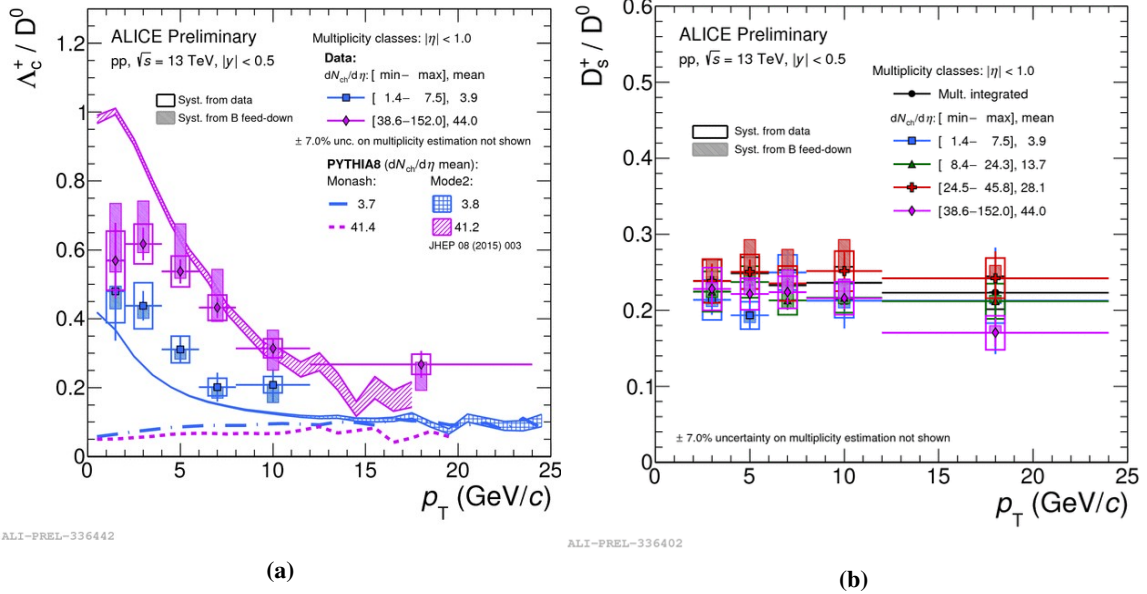
Figure 6: (a) Λ_c^+/D^0 and (b) D_s^+/D^0 ratios in different multiplicity intervals as a function of p_T. The Λ_c^+/D^0 data are compared to PYTHIA8 expectation.

The Q_{CP} of D mesons in p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV was also measured. It is defined as the ratio of prompt D-meson yield in a defined multiplicity interval with that in the 60-100 % centrality and it is computed as

$$Q_{CP} = \frac{(d^2 N^{\text{prompt D}}/dp_T dy)^i_{pPb}/\langle T_{pPb}\rangle_i}{(d^2 N^{\text{prompt D}}/dp_T dy)^{60-100\%}_{pPb}/\langle T_{pPb}\rangle_{60-100\%}},$$ (3)
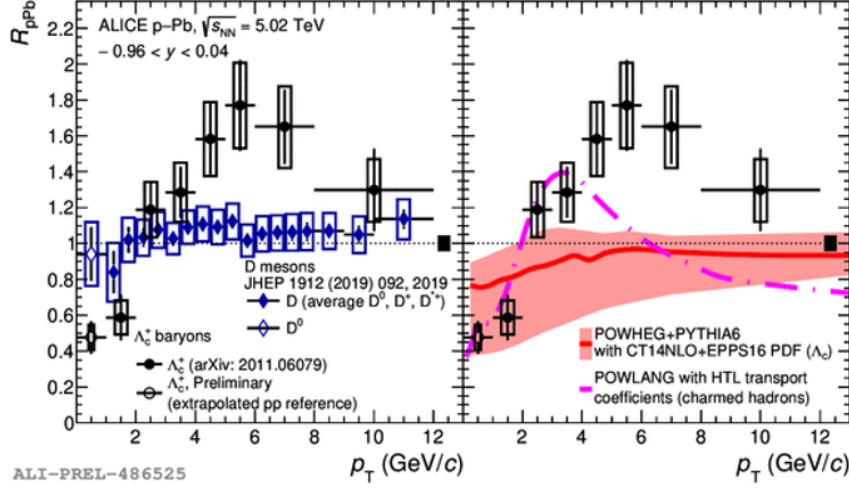
Figure 7: Λ_c^+ R_{pPb} as a function of p_T compared to D mesons results (left) and models (right) in p–Pb collisions at 5.02 TeV.

where $\langle T_{pPb} \rangle_i$ is the nuclear overlap function in a defined i multiplicity class.

In Fig. 8 the Q_{CP} is reported in four different centralities as a function of p_T and a hint of a Q_{CP} larger than unity at intermediate p_T is present, which might be caused by radial flow phenomena. In the figure also charged-particle data are shown and which are consistent with the D-meson ones [7].
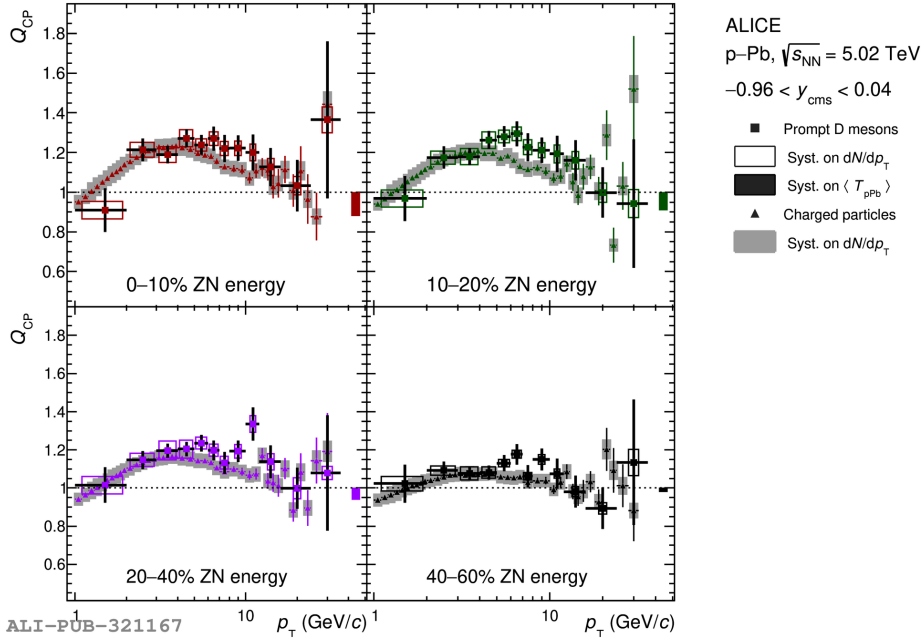
Figure 8: D-mesons Q_{CP} in 4 multiplicity intervals as a function of p_T [7].

The elliptic flow (v_2) was also measured for muons at forward rapidity and for heavy-flavour decay electrons at midrapidity in p–Pb collisions at $\sqrt{s_{NN}}$ = 8.16 and 5.02 TeV, respectively. The

results, displayed in Fig. 9, are compatible between the two lepton species. Both of them show positive elliptic flow in more central events, which gives us an indication that collective phenomena might be present in p–Pb collisions.
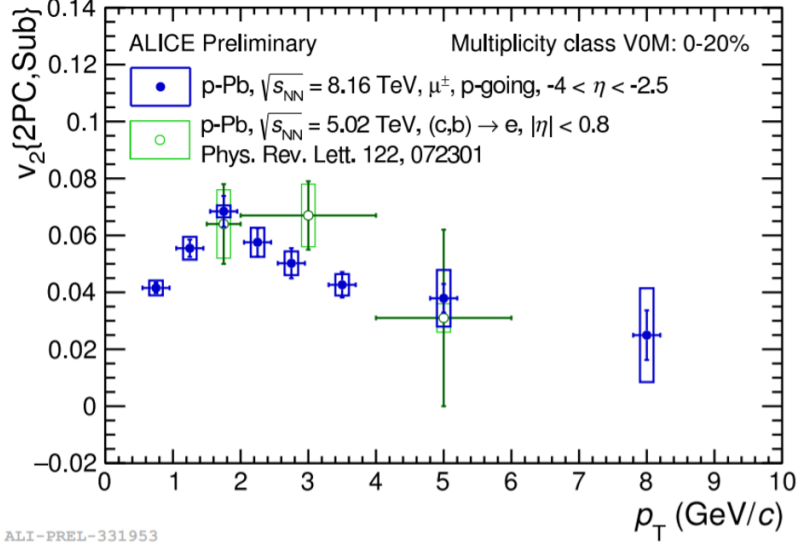
Figure 9: Elliptic flow of muons in p–Pb collisions at 8.16 TeV and heavy-flavour electrons at $\sqrt{s_{NN}} = 5.02$ TeV as a function of p_T.

4. Summary

The self-normalised yield measurements in pp collisions at $\sqrt{s} = 13$ TeV of D mesons, J/ψ and heavy-flavour decay electrons are compatible in similar p_T intervals: they all increase faster than linearly as a function of multiplicity and a significant p_T dependence was found. The results are reproduced well by EPOS3 with the hydrodinamic evolution for the D-meson average, while heavy-flavour electrons are described well by PYTHIA8 using the Monash 2013 tune.

Muon production at forward rapidity from heavy-flavour decays shows also a faster than linear trend vs. multiplicity.

The production ratio Λ_c^+/D^0 shows an enhancement compared to e^+e^- results, while similar values are observed for D-meson species ratios. The data are well reproduced by PYTHIA8 CR mode 2 tune. The observed trend suggests that charm fragmentation might not be universal across different collision systems.

In p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV the Λ_c^+ production was analysed. The R_{pPb} is compatible with POWLANG and POWHEG+PYTHIA6 only in lower p_T intervals.

The measurements of D-meson Q_{CP} and of the elliptic flow of muons and electrons from heavy-flavour hadron decays suggest that collectivity phenomena could have a role in high-multiplicity p–Pb collisions.

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