

# EVENT-ACTIVITY DEPENDENCE OF HEAVY-FLAVOR PRODUCTION AT THE ALICE EXPERIMENT\*

RÓBERT VÉRTESI 

for the ALICE Collaboration

HUN-REN Wigner Research Centre for Physics  
Konkoly-Thege Miklós út 29-33, 1121 Budapest, Hungary

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Heavy-flavor production at the LHC offers valuable tests of quantum-chromodynamics calculations, owing to the large masses of heavy quarks. Measurements of charm production as a function of event activity reveal new features of charm production and fragmentation, providing insights into the interplay between soft and hard processes. In addition, charm production in heavy-ion collisions addresses flavor-dependent quark transport properties in both hot and cold nuclear matter, helping to clarify the roles of coalescence and fragmentation in heavy-flavor hadron formation. This contribution summarizes recent measurements from the ALICE experiment on charm production as a function of charged-particle multiplicity in  $pp$  collisions at various energies, including the measurements of charm baryon-to-meson production yield ratios in  $pp$ ,  $p$ -Pb, and Pb-Pb collisions. New results on  $D^0$  production in  $pp$  collisions as a function of the transverse sphericity of the event are also presented.

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## 1. Introduction

Small collision systems (such as  $pp$  and  $p$ -Pb) with high final-state multiplicity exhibit similar signatures to those observed in heavy-ion collisions, where the formation of quark-gluon plasma (QGP) is expected. These signatures include strangeness enhancement and long-range multiparticle correlations (collectivity, often called “flow”) [1, 2]. The question naturally emerges whether quark-gluon plasma can be produced in such systems, or if there are vacuum-QCD effects that are responsible for this behavior.

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Heavy-flavor (HF) quarks work as hard probes down to low transverse momentum ( $p_T$ ), thus they can be used for pQCD benchmark measurements. Measuring the dependence of heavy-flavor production on charged-hadron multiplicity and event activity allows for the investigation of collective-like effects from small to large systems, the interplay between the hard- and soft-particle production, the role of multiparton interactions in heavy-quark production, and charm fragmentation across different collision systems.

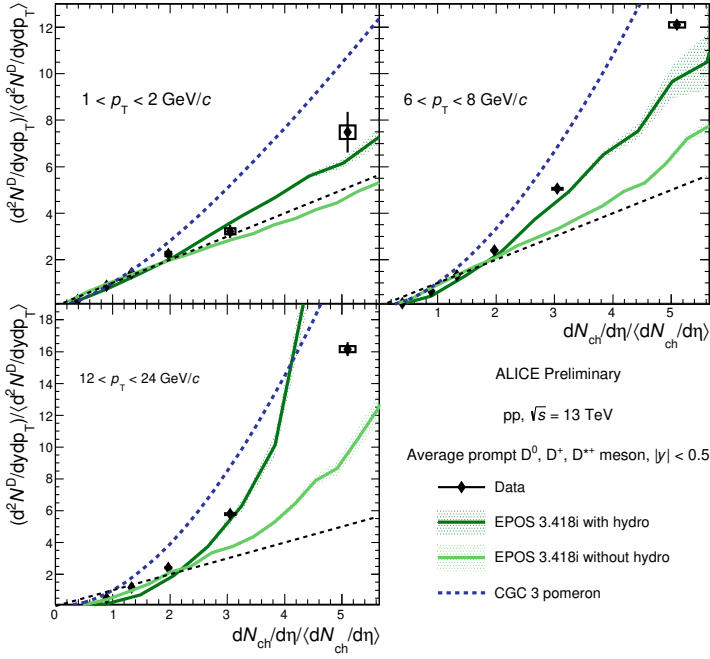
The ALICE experiment is described in detail in Ref. [3]. The central barrel is in a magnetic field and covers the pseudorapidity range  $|\eta| < 0.9$ . The Inner Tracking System (ITS) and the Time Projection Chamber (TPC) are used for charged-particle tracking. The ITS is responsible for the reconstruction of primary (collision) and secondary (decay) vertices, while the TPC can identify charged particles based on specific energy loss. The V0 detector, with a pseudorapidity coverage of  $-3.7 < \eta < -1.7$  and  $2.8 < \eta < 5.1$ , is used for event characterization. Photon and electron identification is facilitated by the Electromagnetic Calorimeter. There is a Muon Spectrometer in the forward direction  $-4 < \eta < -2.5$  that provides muon triggers and reconstructs their trajectories. Heavy-flavor hadrons can be reconstructed either from fully hadronic final states, or by observing leptons from semileptonic decay channels. Heavy-flavor identification is aided by secondary vertex reconstruction from charged-particle trajectories recorded by the ITS.

## 2. Results

The ALICE Collaboration has a broad heavy-flavor program. Only a fraction of recent preliminary results can be highlighted in the current contribution.

### 2.1. Event-activity-dependent production in *pp* collisions

The measurement of the self-normalized heavy-flavor hadron yields with respect to final-state particle multiplicity provides strong constraints for models. Figure 1 shows the results for  $D$  mesons at  $\sqrt{s} = 13$  TeV. The EPOS parton model with hydrodynamic evolution [4] captures the trends seen in data correctly. Note that PYTHIA 8 with multiple-parton interactions is capable of describing self-normalized heavy-flavor electron production properly [5]. Since the multiplicity-dependent production of HF hadrons is sensitive to auto-correlation, it requires a good simultaneous description of jets and the underlying event (UE). This difficulty can be mitigated by using multi-differential observables. One way to distinguish the soft and hard components is to use the transverse sphericity [6], an event-shape observable that approaches zero for jetty events and unity for events that are isotropic in the plane transverse to the beam axis. Figure 2 shows the sphericity-dependent  $D$ -meson production in several transverse-momentum bins in the



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Fig. 1. The average prompt  $D^0$ ,  $D^+$ , and  $D^{*+}$  self-normalised yields as a function relative charged-particle multiplicity in  $pp$  collisions at  $\sqrt{s} = 13$  TeV at central rapidity, compared with the EPOS calculations.

low- and high-multiplicity classes. The results show a hint of an enhanced  $D$ -meson production toward higher multiplicity in jetty events. This suggests that the effect of hard scatterings leads to an increase in charged-particle multiplicity on the average. Note that autocorrelations may also play a role in forming the steeper-than-linear trend.

## 2.2. Fragmentation in $pp$ collisions

The heavy-flavor production is usually described using the factorization hypothesis, that is, the production cross section of heavy-flavor hadrons can be expressed as the convolution of three independent factors: the parton distribution functions (PDF) of the incoming hadrons, the hard parton scattering cross section, and the fragmentation of the outgoing partons into heavy-flavor hadrons. The charm-quark fragmentation fractions into different hadrons  $f(c \rightarrow h_c)$  show a reduction of  $D^0$ -meson fractions by

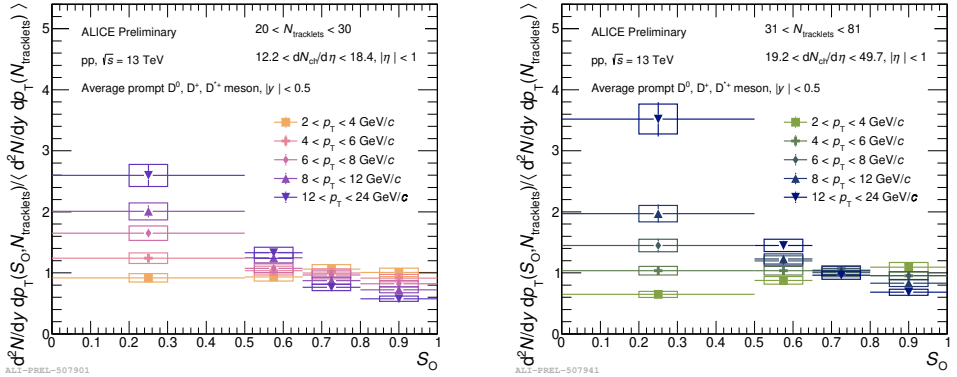


Fig. 2. Average  $D$ -meson self-normalized yield as a function of sphericity in  $pp$  collisions at  $\sqrt{s} = 13$  TeV in different  $p_T$  intervals for low (left panel) and high (right panel) multiplicity ranges.

about  $1/3$ , and an enhancement of charmed baryons in  $pp$  collisions both at  $\sqrt{s} = 5.02$  and  $13$  TeV, compared to  $e^+e^-$  collisions at HERA and LEP [7]. The  $\Lambda_c^+/D^0$  ratio indicates a significant excess in  $pp$  compared to  $e^+e^-$  collisions toward low- $p_T$  values. This shows that hadronization is not universal across different systems. Several models, based on the introduction of color junctions, statistical hadronization with augmented charm states, and charm-light quark coalescence, successfully describe the  $p_T$ -dependent trends of enhanced  $\Lambda_c^+/D^0$  [8–10]. In a recent ALICE publication [11], it was shown that the enhancement also depends on charged-hadron final-state multiplicity.

Contrary to charmed baryon-over-meson ratios, the new measurements in  $pp$  collisions at  $\sqrt{s} = 13.6$  TeV from the 3<sup>rd</sup> LHC data taking period (Run 3) show no strong  $p_T$  dependence in the strange to non-strange charmed-meson ratios  $D_s^+/D^+$ , as shown in Fig. 3 (left). This trend is captured by the Catania model [10]. However, it is overestimated by the POWLANG model [12], and it is also not well reproduced by PYTHIA 8 simulations either with or without color junctions [9, 13].

A fraction of charmed hadrons, the so-called non-prompt hadrons, come from decays of beauty hadrons. The non-prompt  $D^0$ -meson fraction, as measured in  $pp$  collisions by ALICE, is shown in Fig. 3 (right), together with theoretical calculations. Most of the calculations follow the trend correctly [9, 13–15], although the global scale is not reproduced well.

Figure 4 shows the ratio of the charmed-strange  $\Xi_c^0$  baryon production over that of charmed mesons and baryons, for different multiplicities. Although no multiplicity dependence is seen within uncertainties, there is a hint that the results depend on the  $p_T$ . The PYTHIA 8 model with color junctions [9] is unable to reproduce the observed ratio.

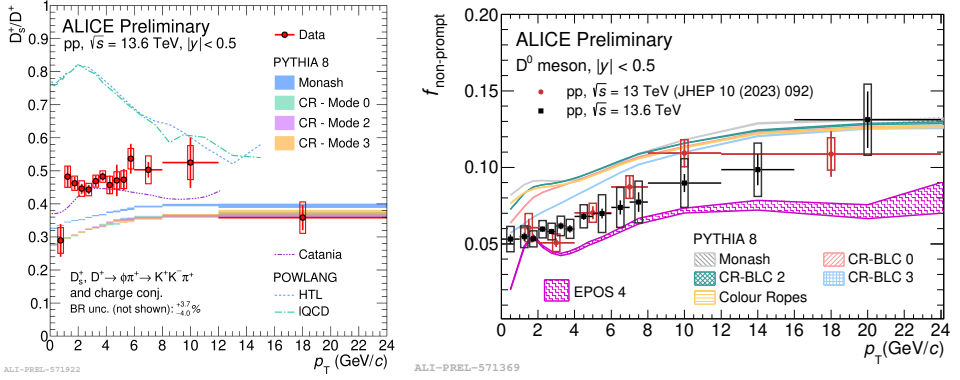


Fig. 3.  $D_s^+ / D^+$  production (left), and non-prompt fraction of  $D^0$  production (right) at midrapidity ( $|y| < 0.5$ ) in  $pp$  collisions at  $\sqrt{s} = 13$  TeV compared with theoretical predictions.

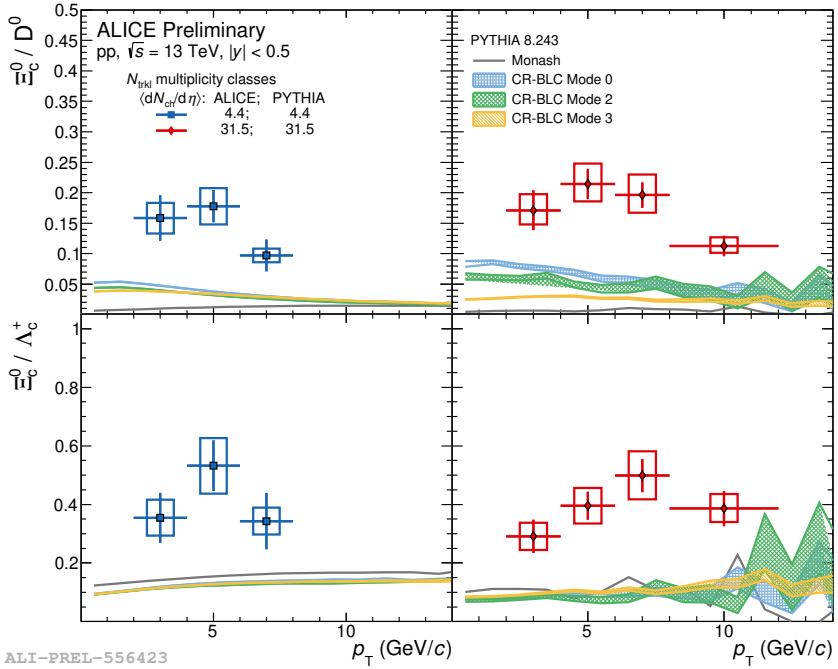


Fig. 4. The  $\Xi_c^0 / D^0$  (top) and  $\Xi_c^0 / \Lambda_c^+$  (bottom) ratios measured in  $pp$  collisions at  $\sqrt{s} = 13$  TeV for low (left) and high (right) multiplicity classes, at midrapidity ( $|y| < 0.5$ ). The results are compared to PYTHIA 8 results with and without color junctions.

### 2.3. Toward larger systems

The phenomenon of charmed-baryon enhancement comes from multiple sources in large systems created in heavy-ion collisions. These may include high-multiplicity vacuum-QCD effects such as multiple-parton interactions with color reconnection (which in general produce high charged-particle multiplicity events), hot nuclear-matter effects such as collisional and radiative energy loss of heavy quarks, their participation in hydrodynamical evolution, thermalization and coalescence, as well as cold nuclear effects like shadowing. Comparative measurements of baryons, strange and non-strange mesons from small to large collision systems can help clarify the picture. Figure 5 (left) shows the  $\Lambda_c^+/D^0$  ratios from  $pp$  and  $p$ -Pb collisions with different final-state charged-hadron multiplicities, while in Fig. 5 (right), the measurements from  $p$ -Pb are compared to semi-central and central Pb-Pb collisions. An enhancement pattern similar to that in light baryon-to-meson

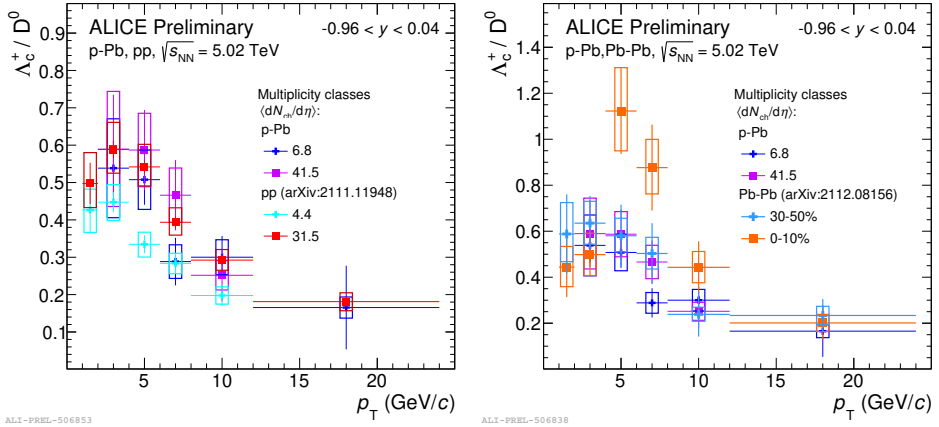


Fig. 5. The  $\Lambda_c^+/D^0$  ratio as a function of  $p_T$  in two multiplicity classes in the  $p$ -Pb collision at the  $\sqrt{s_{NN}} = 5.02$  TeV, compared to that in  $pp$  (left) and Pb-Pb (right) collisions.

ratios emerges at intermediate  $p_T$ . The high-multiplicity  $pp$ , low- and high-multiplicity  $p$ -Pb, and semi-central Pb-Pb collisions are consistent with each other, while the low-multiplicity  $pp$  measurements are separated. This suggests a threshold effect in the multiplicity dependence of the  $\Lambda_c^+/D^0$  ratios. A clearly stronger enhancement is present in central Pb-Pb collisions [16]. This trend is understood to result from the interplay between radial flow and coalescence [10, 17].

Note that while the  $p_T$ -dependent trends of charmed-hadron production are sensitive to collision systems and different final-state multiplicities, there is no evidence of multiplicity dependence of the  $p_T$ -integrated charmed baryon-to-meson ratios from small to large hadronic systems [11].

### 3. Summary and outlook

In summary, event-activity-dependent heavy-flavor measurements provide an opportunity to understand the complexity of  $pp$  collisions. Recent measurements have shown that hadronization is not universal across different collision systems, and explored the interplay between the effects in hot and cold nuclear matter and vacuum effects. Large systems can still be described within the standard picture of thermal equilibrium combined with hydrodynamical evolution.

While the first results from the LHC Run 3 data-taking period are ready, much more new data is expected in the near future. With the enhanced ITS and gas-electron-multiplier-based TPC, two orders of magnitude enhancement can be expected in  $pp$  luminosity compared to Run 1 and Run 2 together. Precision and differential measurements and novel observables are becoming available, which can be used to disentangle possible sources of the observed effects.

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