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Physics Preliminary Summary: D^0 meson yields as a function of the underlying event activity in pp collisions at $\sqrt{s} = 13$ TeV

The ALICE Collaboration*

Abstract

This public note presents the first measurement by the ALICE experiment of D^0 production as a function of the transverse event activity classifier R_T in pp collisions at $\sqrt{s} = 13$ TeV at central rapidity ($|\eta| < 0.8$). Events containing a leading particle with $p_T^{\text{lead}} > 5$ GeV/c that have above-average underlying event activity suggest a higher per-event D^0 yield in the toward region than events with below-average underlying event activity for $2 < p_T^{D^0} < 5$ GeV/c. However, for $p_T^{D^0} > 5$ GeV/c there is no observable dependence on R_T in the production of D^0 mesons. The results are also compared to PYTHIA 8 simulations with and without colour string junctions. Expectations for the transverse region from PYTHIA 8 simulations are also shown to allow for a cross-check with a future measurement using data from the Run 3 data taking period currently underway.

*See Appendix A for the list of collaboration members

1 Introduction

In recent years, the ALICE experiment, as well as other experiments at the LHC, found signatures of collectivity in events with a high final-state charged-particle multiplicity in small collision systems such as proton–proton (pp) and proton–lead (p–Pb) [1, 2]. Recently, similar effects were seen in pp collisions with low multiplicity [3]. While this phenomenon had already been observed previously in heavy-ion collisions and attributed to the quark–gluon plasma (QGP) in such events, the presence of QGP in small collision systems is debated due to much lower energy densities. Several theoretical works attempt to explain the collective behaviour in small systems with vacuum quantum chromodynamics (QCD) processes at the soft–hard boundary, such as mini-jet production [4] or multiple-parton interactions (MPI) [5, 6].

An event containing a large momentum-transfer scattering can be separated into the leading hard parton–parton interaction (jetty) part and the underlying event (UE), which includes all the secondary soft processes, as well as beam remnants. In most analyses, the leading hard scattering is treated as independent of the UE [7]. The underlying event can therefore be measured in the region far away from the jets. A simple but effective way to quantify the UE is via the introduction of the transverse event classifier R_{T} [8]. In models that rely on MPI to simulate particle production, a strong correlation is observed between the transverse activity R_{T} and the number of MPI processes in an event [9]. Measurements of UE properties using unidentified charged particles by the CDF experiment at the Tevatron in $\mathrm{p\overline{p}}$ collisions, as well as by the ALICE and CMS collaborations at the LHC in pp and p–Pb collisions show that the particle production in the azimuthal regions that are distant from the leading process is virtually independent of the momentum scale of the hard process above a certain transverse momentum (p_{T}) threshold [10–13]. Recently, the ALICE collaboration also published the R_{T}-dependent production yields of identified light charged hadrons [14].

Heavy-flavour probes at LHC energies provide powerful means to test perturbative QCD calculations [15] as well as to address fragmentation properties [16]. Besides that, pp collisions act as a reference for heavy-ion measurements, therefore it is essential to thoroughly understand the production of heavy quarks in these compact systems. The ALICE collaboration has carried out precise measurements of charm- and beauty-hadron production in both the meson and the baryon sectors [17, 18], as well as the production of jets [19, 20]. Production and fragmentation of heavy flavour is different from that of light-flavour partons because of both colour-charge and mass-related effects. While the majority of light-flavour jets are initiated by hard gluons, heavy-flavour jets predominantly stem from quarks produced during the initial hard process. Additionally, quark mass can affect not only the initial production but also the parton shower, through the dead-cone effect [21, 22]. Investigating and modelling the creation of heavy-flavour hadrons at the semi-soft boundary can aid in distinguishing between colour-charge and mass-related effects. The study of heavy-flavour production in pp collisions as a function of event properties such as final-state charged-particle multiplicity allows us to investigate the interplay between hard and soft QCD processes responsible for particle production in hadronic collisions and provides information on the role of MPI in the heavy-flavour sector. Multiplicity-dependent measurements of production and correlation of charmed hadrons have also been carried out by the ALICE collaboration to constrain the effect of MPI [23, 24]. By analysing heavy-flavour particle production with respect to the UE activity, the connection between the leading processes and the UE can be characterised [25]. Hadron- and jet-triggered events containing heavy-flavour have been thoroughly analysed in simulations, where a strong dependence of low-p_{T} heavy-flavour production on R_{T} is predicted, while no such dependence is expected for hard heavy flavour associated with the leading process [26].

In this public note, the first measurement of $\mathrm{D^0}$ production in pp collisions at $\sqrt{s} = 13$ TeV as a function of the transverse activity classifier R_{T} is presented. A more detailed overview of the underlying event observables is shown in Sec. 2, which is followed by the description of the performance of the ALICE detector and the analysed datasets in Sec. 3. The analysis procedures are outlined in Sec. 4, while the estimation of systematic uncertainties is detailed in Sec. 5. The results are presented and discussed in

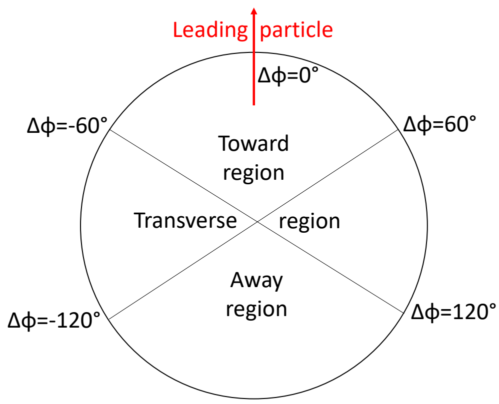

Fig. 1: Division of the transverse plane into toward, transverse and away regions. The azimuthal angles are determined with respect to the leading (highest-p_T) particle.

Sec. 6, in which comparisons to Monte Carlo model predictions are also shown.

2 Characterising the Underlying Event

The underlying event at central rapidity can be studied in the azimuthal range of the transverse plane which is distant from the jets stemming from the hardest scattering [27]. The direction of the hard process is identified with the direction of the leading (highest-p_T) charged particle in the final state. This definition is used for compatibility with the earlier results from the ALICE collaboration [12, 13]. The transverse plane is subdivided into three equally sized regions that depend on the azimuthal distance from the leading particle, as shown in Fig. 1. The region around the leading particle ($|\Delta\phi| < 60^o$), called the toward region, is expected to contain one of the most energetic jets. The away region is located at the opposite side of the transverse plane ($|\Delta\phi| > 120^o$) and contains the recoil jet in an ordinary back-to-back jet event. The transverse region, composed of two halves at $60^o < |\Delta\phi| < 120^o$, is less influenced by jets and sensitive to the UE. It is to be noted that in case of a higher charged-hadron transverse-momentum threshold ($p_T > 0.5$ GeV/c), the influence of jets by gluon radiation into the transverse region may not be negligible [28]. Measurements at the Tevatron and the LHC [10–13] show that the particle production in the toward and away regions increases with the transverse momentum of the leading charged particle, while in the transverse region the particle production reaches plateau at $p_T^{lead} \gtrsim 5$ GeV/c. This further reinforces the assumption that the particle production in the transverse region is disconnected from the leading process and is influenced almost solely by the UE. To ensure that the plateau region is sampled, only events containing a leading particle with $p_T^{lead} > 5$ GeV/c were considered for the analysis.

To quantify the underlying event in the analysis, the relative transverse activity R_T was used. This is defined as the ratio between the charged-particle multiplicity in the transverse region, N_T^{ch}, in a given event and the event-averaged multiplicity in the same region,

$$R_T = \frac{N_T^{ch}}{\langle N_T^{ch} \rangle} \,. \tag{1}$$

In the context of models relying on MPI to simulate particle production, a strong correlation is observed between the transverse activity R_T and the number of MPI processes in an event [8]. Low-R_T events correspond to an MPI-suppressed environment, where jetty events are expected to resemble those in

e^+e^- collisions more closely than an average pp event. The high-R_T case, on the other hand, represents high UE activity, where non-trivial vacuum-QCD effects such as MPI may become important.

3 Experimental setup and datasets

A complete description of the ALICE detector setup in LHC Run 2 and its performance can be found in Ref. [29]. In this analysis, the particle tracking and identification was performed by the combination of the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) detectors, which both cover the pseudorapidity interval $|\eta| < 0.9$ and are placed in a magnetic field of $B = 0.5$ T provided by a cylindrical solenoid. The ITS detector, which is the innermost subsystem of the ALICE detector composed of six cylindrical layers of silicon detectors, is involved in the tracking of emerging particles close to the interaction point (primary vertex) [30]. It also plays a crucial role in the reconstruction of the decay point of the heavy-flavour hadrons (secondary vertex). The TPC is a gaseous detector outside the ITS that serves as the main tracking device of the ALICE experiment and also provides means for charged-particle identification by measuring the specific ionisation energy loss ($\mathrm{d}E/\mathrm{d}x$) [31]. The identification of the charm-hadron decay products is further improved by the Time-Of-Flight (TOF) detector [32]. The trigger signal is provided by the V0 detector, consisting of two scintillator arrays covering the pseudorapidity intervals $-3.7 < |\eta| < -1.7$ and $2.8 < |\eta| < 5.1$ on the two sides of the nominal collision point [33].

In this analysis, data from the pp collisions at $\sqrt{s} = 13$ TeV from the data collection periods of 2016-2018 were used. This data sample contains about 1.7 billion recorded minimum-bias events, collected by requiring a coincidence between the two sides of the V0 detector, corresponding to an integrated luminosity $\mathscr{L}_{\rm int} = 29.4\ \mathrm{nb}^{-1}$. However, the condition for a leading particle with $p_{\rm T}^{\rm lead} > 5$ GeV/c brought the total number of the analysed events down to 17 million. Due to the relatively small sample size, the analysis was performed only in the toward region. Note that for D^0 mesons with $p_{\rm T}^{\mathrm{D}^0} \lesssim 5$ GeV/c the leading particles with $p_{\rm T}^{\rm lead} > 5$ GeV/c cannot originate from the D^0-meson decay, while at $p_{\rm T}^{\mathrm{D}^0} \gtrsim 5$ GeV/c about 90–95% of the leading particles with $p_{\rm T}^{\rm lead} > 5$ GeV/c are directly from D^0 decay products in the toward region.

4 Analysis procedure

The D^0 candidates were reconstructed from the $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ (and charge conjugates) decay channel with a branching ratio of $3.86 \pm 0.04\%$ [34]. To reduce the combinatorial background and optimise statistical significance, selections were applied on the secondary vertex topology similarly to earlier analyses (see e.g. Refs. [17, 35]). The selection requirements were mainly based on the displacement of the tracks from the primary vertex (d_0), the distance of closest approach (DCA) between the D-meson decay products, and the cosine of the pointing angle of the reconstructed D-meson momentum to the primary vertex $\cos(\theta_{\rm pointing})$. Additionally, the kaon–pion pairs corresponding to the D^0-meson candidate were required to be within 400 MeV around the D^0-meson mass and of at least 0.7 GeV/c transverse momentum each. The D^0 mesons were reconstructed in the $2 < p_{\rm T}^{\mathrm{D}^0} < 24$ GeV/c transverse momentum range. Charged-particle tracks were considered within the central rapidity range $|\eta| < 0.8$, with a transverse momentum of $p_{\rm T}^{\rm track} > 0.15$ GeV/c. The same condition was applied for charged particles that were used for the $R_{\rm T}$ estimation. The analysed set of events was split into two $R_{\rm T}$ classes: a low-$R_{\rm T}$ class containing events with below-average transverse activity ($0 < R_{\rm T} < 1$) and a high-$R_{\rm T}$ class containing events with above-average transverse activity ($1 < R_{\rm T} < 10$; note that there are no events observed above $R_{\rm T} = 10$). The raw yields were determined by fitting the invariant-mass distributions of D^0 candidates with a Gaussian function describing the peak region, and an exponential function to reproduce the background. Examples of the invariant-mass distributions are shown in Fig. 2 for D^0 mesons in different $p_{\rm T}^{\mathrm{D}^0}$ and $R_{\rm T}$ regions.

To account for the detection efficiency of the daughter particles, as well as for the geometrical properties

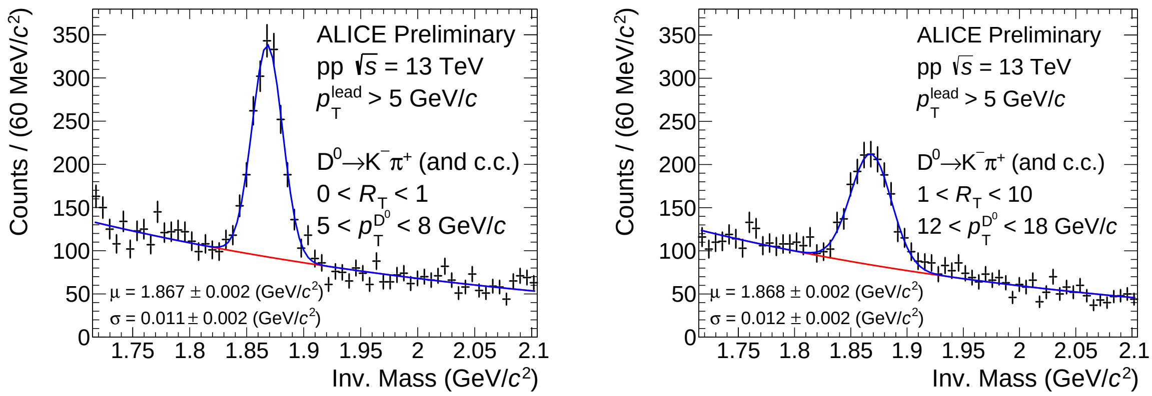

Fig. 2: Invariant mass distributions of D^0 candidates with $5 < p_T^{D^0} < 8$ GeV/c in $R_T < 1$ events (left) and with $12 < p_T^{D^0} < 18$ GeV/c for $R_T > 1$ (right).

of the detector, an acceptance-times-efficiency correction was applied to the raw yields. This correction was determined by simulating the D^0-meson production with the PYTHIA 8 Monte Carlo event generator [36] with the Monash tune [37] and then propagating the particles through a model of the detector system implemented in GEANT3 [38]. To obtain the acceptance-times-efficiency, the number of D^0 candidates passing the same set of topological selections as for the data was compared to the total number of generated D^0 mesons. The applied correction is presented in Fig. 3. It can be observed that the detection efficiency is independent of the transverse activity R_T both for prompt D^0 mesons (coming directly from charm hadronisation) and feed-down D^0 mesons (coming from beauty-hadron decays). The values of the acceptance-times-efficiency correction range between 6% and 40% depending on the origin and the transverse momentum of the D^0 mesons.

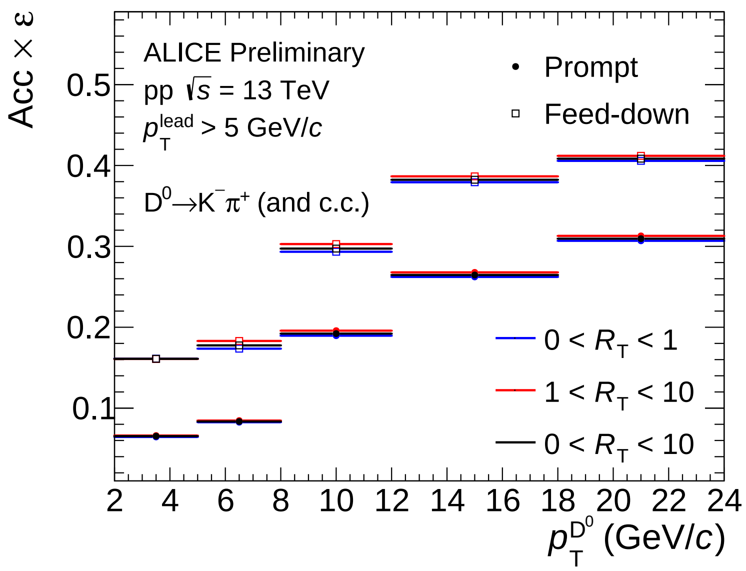

Fig. 3: Acceptance-times-efficiency corrections for prompt and feed-down D^0 mesons as a function of the $p_T^{D^0}$ for $R_T < 1$ case in blue, $R_T > 1$ case in red, as well as for the R_T-integrated case in black.

A fraction of the reconstructed D^0 mesons originates from the decay of beauty hadrons, which needs to be subtracted from the total yield. The fraction of prompt D^0 mesons was calculated based on the input from FONLL perturbative QCD calculations [39] as

$$f_{\mathrm{prompt}} = 1 - \left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}\right)^{\mathrm{FONLL}}_{\text{feed-down}} \times \frac{(\mathrm{Acc}\times\varepsilon)_{\text{feed-down}} \times \Delta y \Delta p_{\mathrm{T}} \times \mathrm{BR} \times L_{\mathrm{int}}}{N^{D_{\mathrm{raw}}}/2}, \quad (2)$$

where $\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}\right)^{\mathrm{FONLL}}_{\text{feed-down}}$ is the cross section of B mesons determined from the FONLL calculations [40] with the respective branching ratios (BR) of decays into D^0 mesons, $(\mathrm{Acc}\times\varepsilon)_{\text{feed-down}}$ is the acceptance-times-efficiency correction for feed-down D^0 mesons, Δy is the rapidity window, Δp_{T} is the width of the transverse momentum interval, L_{int} is the integrated luminosity and $N^{D_{\mathrm{raw}}}$ is the raw yield obtained from the data. The factor of $1/2$ in the denominator is used as the cross section is measured as an average of D^0 and $\overline{\mathrm{D}^0}$. Note that the FONLL spectrum for feed-down D^0 mesons is calculated for minimum-bias data, while the current analysis uses an additional condition of $p_{\mathrm{T}}^{\mathrm{lead}} > 5$ GeV/c. To account for this, an efficiency correction was applied to the FONLL spectrum. This correction was determined from PYTHIA 8 simulations, by calculating the $p_{\mathrm{T}}^{\mathrm{D}^0}$-dependent ratio of D^0 mesons in events with a $p_{\mathrm{T}}^{\mathrm{lead}} > 5$ GeV/c leading particle to those of minimum-bias events.

In the event sample considered in this analysis, the fraction of prompt D^0 mesons with $p_{\mathrm{T}}^{\mathrm{D}^0} < 5$ GeV/c is approximately 60%, significantly lower than what is obtained in the minimum-bias event sample [35]. For D^0 mesons having $p_{\mathrm{T}}^{\mathrm{D}^0} > 5$ GeV/c, the fraction is in the range of 85–90%, similarly to other D^0 measurements.

5 Systematic uncertainties

In the analysis, several sources of systematic uncertainties were investigated, accounting for detection and reconstruction efficiencies, data fitting stability, and the uncertainty from the simulated spectral shapes.

The systematic uncertainty of the reconstruction of D^0 candidates from their decay products originates from imperfections in the description of the D^0-meson kinematic properties and of the detector resolution and alignment in the simulation. This systematic uncertainty was estimated by comparing the corrected yields obtained by repeating the analysis with different sets of topological selection criteria, resulting in a significant modification of the raw yields, signal-to-background ratios, and efficiencies. The contribution of this systematic uncertainty was estimated in the range of 1–7% depending on the transverse momentum of the D^0 and R_{T} of an event.

The extracted D^0 yields depend on the fitting of invariant mass distributions, therefore an additional systematic uncertainty was determined by varying the fitting parameters. The variations included changing the lower and upper limits of the invariant mass distributions, rebinning the invariant mass histograms, as well as changing the background fitting function to the second-order polynomial. Apart from these, fixing of the Gaussian width was also applied. These resulted in a systematic uncertainty of 1–5%.

Another major source of systematic uncertainty was the classification of events by R_{T}. The R_{T} classifier, being determined from the charged-particle multiplicity in the transverse region, is very sensitive to particle detection at the boundary of two R_{T} bins, since events around $R_{\mathrm{T}} = 1$ can be assigned to the wrong R_{T} bin. To determine the magnitude of the systematic uncertainty caused by bin migration, a ratio was calculated between results from reconstructed data and the results from Monte Carlo simulations, where the R_{T} calculation of events is exact. The bin migration uncertainty varies between 5 and 11%.

The systematic uncertainty of the feed-down contribution to D^0 yields was determined by taking into account the uncertainty of the FONLL spectrum associated with factorisation and renormalisation scale variations, heavy quark mass variation, and the uncertainty associated with parton distribution functions. The results obtained with maximum and minimum FONLL predictions were compared to the default results, yielding an uncertainty of 1–27% depending on $p_{\mathrm{T}}^{\mathrm{D}^0}$.

The systematic uncertainty from the shape of the simulated $p_T^{D^0}$ spectrum is estimated by using FONLL as an alternative generator with respect to PYTHIA to simulate the $p_T^{D^0}$ distribution. The effect of this uncertainty was found to be negligible [35].

The uncertainty from the identification of charged hadrons stemming from D^0 decays is assessed by changing the track selection cuts. This source of systematic uncertainty was also considered negligible [35].

As the individual sources of systematic uncertainties were considered to be uncorrelated with each other, they were added in quadrature to obtain the total systematic uncertainty for each data point in the final result. The summary of all the systematic uncertainties is presented in Table 1.

Table 1: Contributions of the systematic uncertainty sources to the total systematic uncertainties for the below-average and above-average underlying event activity classes.

R_T	$p_T^{D^0}$ (GeV/c)	D^0 selection	Raw yield extraction	Bin migration	Feed-down	Total
0–1	2–5	6%	2%	11%	27%	30%
	5–8	3%	1%	6%	5%	8%
	8–12	1%	1%	6%	3%	7%
	12–18	2%	1%	6%	2%	7%
	18–24	2%	3%	6%	1%	7%
1–10	2–5	7%	5%	9%	20%	24%
	5–8	4%	1%	5%	8%	10%
	8–12	1%	1%	5%	5%	7%
	12–18	2%	3%	5%	3%	7%
	18–24	2%	4%	5%	3%	7%

6 Results and conclusion

The R_T-dependent production yield of D^0 mesons in the toward region is presented in Fig. 4. The yields are normalised with the number of events containing a $p_T^{lead} > 5$ GeV/c leading particle. The two R_T intervals are divided by the R_T-integrated yields. For $p_T^{D^0} > 5$ GeV/c the results are consistent with unity within uncertainties in the case of both R_T intervals. This indicates that D^0 mesons with high transverse momenta are created in connection to the leading process. However, for D^0 mesons in the lowest transverse-momentum interval $2 < p_T^{D^0} < 5$ GeV/c, a dependence on R_T is suggested by the data. It has to be noted that the leading particle condition $p_T^{lead} > 5$ GeV/c influences the transition between the R_T-dependent and the R_T-independent regions of D^0 spectrum. The results are also compared to PYTHIA 8 simulations with SoftQCD settings [36] using two different tunes. The first one is the default Monash tune [37], which mainly focuses on describing the minimum-bias and underlying event distributions accurately. The other is a model with colour reconnection beyond leading colour approximation (CR-BLC) Mode 2 [41], which adds junctions to PYTHIA colour strings and is capable of adequately reproducing heavy-flavour baryon-to-meson ratios [42]. Both models describe the data within uncertainties, with Monash showing a slightly larger difference between the two R_T classes at low $p_T^{D^0}$ than CR-BLC. However, simulations also show a dependence on R_T in the $5 < p_T^{D^0} < 8$ GeV/c interval, whereas there is no such hint in the data. Future more precise measurements may help determine the kinematic region where D^0 production becomes independent of R_T in the toward region.

The simulation expectations with PYTHIA 8 in the transverse region, where the D^0 meson production is not influenced by the leading particle selection, are also shown for comparison (Fig. 5) [26]. There is a clear separation between the low-R_T and high-R_T classes in the full $p_T^{D^0}$ range. The effect is slightly stronger for the CR-BLC Mode 2 than for the Monash tune, which is caused by the difference in the predicted underlying event by the two models. The increased data sample from the ongoing Run 3 data

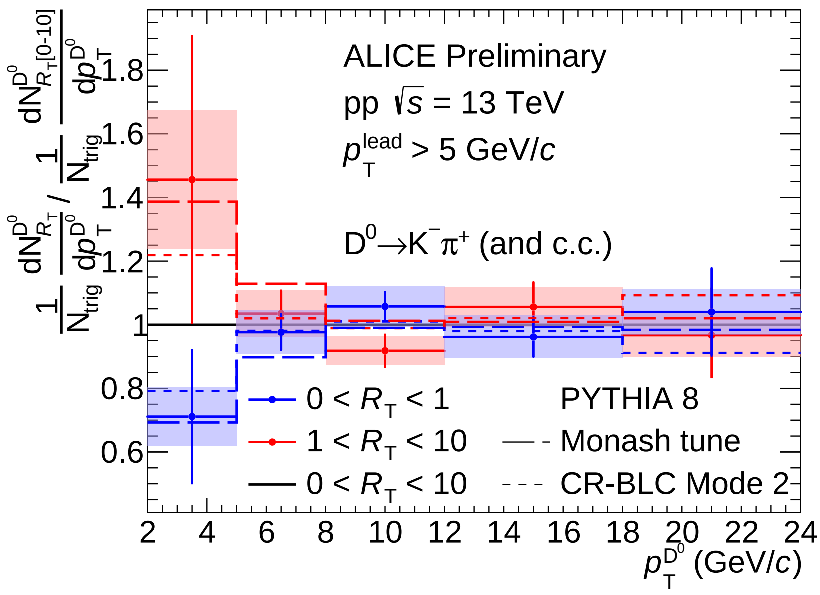

Fig. 4: Ratio of the R_T-dependent per-event D^0 meson yields to the R_T-integrated yield in the toward region, as a function of $p_T^{D^0}$, in pp collisions at $\sqrt{s} = 13$ TeV. The results are compared to model calculations from the PYTHIA 8 Monash and CR-BLC Mode 2 tunes. Boxes represent the total systematic uncertainty on the result.

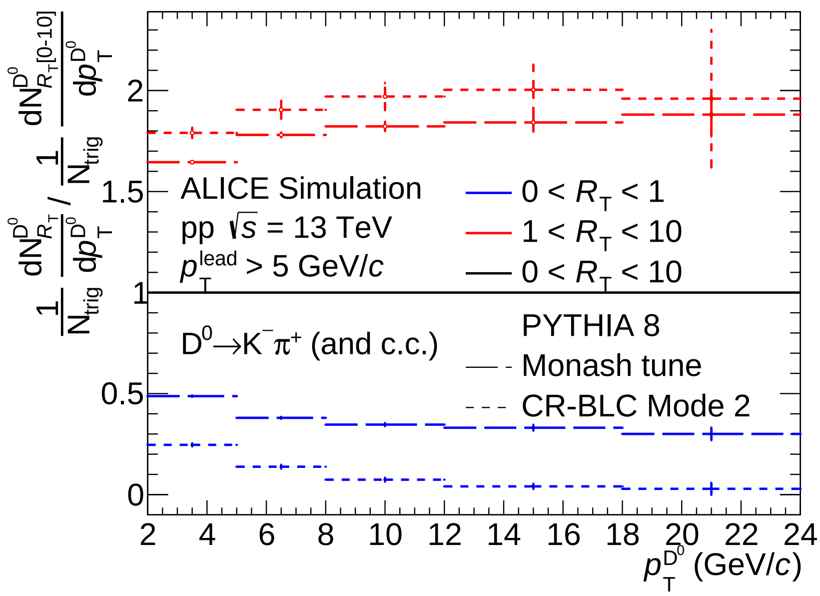

Fig. 5: Ratio of the R_T-dependent per-event D^0 meson yields to the R_T-integrated yield in the transverse region, as a function of $p_T^{D^0}$, in simulations of pp collisions at $\sqrt{s} = 13$ TeV from the PYTHIA 8 Monash and CR-BLC Mode 2 tunes.

collection period will allow for the measurement of R_T-dependent D-meson production in the transverse region.

In summary, the first measurement of D^0 production in pp collisions at $\sqrt{s} = 13$ TeV at central rapidity

($|\eta| < 0.8$), as a function of the transverse event activity classifier R_T, by the ALICE experiment is presented in this note. In the $2 < p_T^{D^0} < 5$ GeV/c region, events with above-average underlying event activity hint at a higher rate of D^0-meson production in the toward region than events with below-average underlying event activity, while there is no significant difference from unity for either case if $p_T^{D^0} > 5$ GeV/c. The results are consistent with PYTHIA 8 using both the Monash tune and a model with color reconnection beyond leading colour approximation. The integrated luminosity expected from the ongoing Run 3 data taking period will make it feasible to carry out R_T-differential studies of heavy-flavour production with the ALICE apparatus down to even lower transverse momentum, focusing on the transverse region which is representative of the underlying event.

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