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Light neutral-meson production in pp collisions at $\sqrt{s} = 13$ TeV

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Abstract

The momentum-differential invariant cross sections of π^0 and η mesons are reported for pp collisions at $\sqrt{s} = 13$ TeV at midrapidity ($|y| < 0.8$). The measurement is performed in a broad transverse-momentum range of $0.2 < p_T < 200$ GeV/c and $0.4 < p_T < 60$ GeV/c for the π^0 and η , respectively, extending the p_T coverage of previous measurements. Transverse-mass-scaling violation of up to 60% at low transverse momentum has been observed, agreeing with measurements at lower collision energies. Transverse Bjorken x (x_T) scaling of the π^0 cross sections at LHC energies is fulfilled with a power-law exponent of $n = 5.01 \pm 0.05$, consistent with values obtained for charged pions at similar collision energies. The data is compared to predictions from next-to-leading order perturbative QCD calculations, where the π^0 spectrum is best described using the CT18 parton distribution function and the NNFF1.0 or BDSS fragmentation function. Expectations from PYTHIA8 and EPOS LHC overestimate the spectrum for the π^0 and are not able to describe the shape and magnitude of the η spectrum. The charged-particle multiplicity dependent π^0 and η p_T spectra show the expected hardening with increasing multiplicity. This is demonstrated across a broad transverse-momentum range and up to events with a charged-particle multiplicity exceeding five times the mean value in minimum bias collisions. The absolute magnitude of the η/π^0 ratio shows a dependence on the charged-particle multiplicity for $p_T < 4$ GeV/c, qualitatively described by PYTHIA8 and EPOS LHC due to a rising contribution from feed-down of heavier particles to the π^0 spectrum.

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*See Appendix A for the list of collaboration members

1 Introduction

Over the last few decades, our understanding of particle production in high-energy hadronic collisions has increased significantly due to the experimental results obtained from the CERN Intersection Storage Rings (ISR), the CERN Super Proton-Antiproton Synchrotron (Sp \bar{p} S), Tevatron at Fermilab, RHIC and the LHC [1–14], as well as the ongoing development of theoretical and phenomenological models [15–22]. Theoretical models typically separate the particle production into the soft and hard regime, which describe processes with a small and large momentum transfer, respectively. Hard-scattering processes can be calculated using perturbative quantum chromodynamics (pQCD). These calculations rely on input from parton distribution functions (PDF) ($f(x)$) and fragmentation functions (FF) ($D(z)$), where Bjorken x represents the fraction of the proton’s longitudinal momentum carried by a parton and z is the fraction of the final-state hadron momentum to the parton momentum. With increasing collision energy, the measurement of a final-state hadron at fixed transverse momentum will probe smaller and smaller values of x , where the gluon contribution becomes dominant [19]. Hence, the measurement of the neutral meson production cross section at $\sqrt{s} = 13$ TeV gives further insights into the gluon to meson fragmentation. In addition, measurements of the η meson allow the investigation of a possible dependence of FFs on hidden strangeness [23]. A precise comparison of the differences in the hadronization process between two particles can be achieved by investigating the ratios of the production cross section of identified particles, such as the η/π^0 ratio. As the initial state of the collision is identical for both particles, the ratio is primarily sensitive to the effects arising from the differences in the parton-to-hadron fragmentation.

Global analyses based on collections of experimental data are used to determine, and regularly update, PDFs [20] and FFs [21, 22]. For example, first neutral pion measurements at the LHC [24] are included in the global analysis of parton-to-pion fragmentation functions [21], or similarly, the parton-to-pion FF reported in [22] include the ALICE charged pion measurements. On the other hand, global analyses of the η FF do not yet include data from the LHC [23], although η meson measurements are already available at various LHC collision energies in wide p_T ranges [24–30]. At low transverse momenta, where the production cross section of π^0 and η mesons has its maximum, particle production is driven by soft processes. Details of the description of particle production at low p_T , which is not calculable perturbatively and relies on phenomenological models, can be further improved by comparing experimental data with theoretical models and event generators such as PYTHIA8 [31] or EPOS [32], which are tuned to data from e^+e^- collisions as well as to early LHC data, depending on the generator. For PYTHIA8, the Monash 2013 tune [33] is commonly used at LHC energies. The PYTHIA8 Ropes variant [34, 35] was recently used to describe effects arising in high-multiplicity pp collisions. While PYTHIA8 relies solely on string fragmentation, EPOS is based on a model exploiting multiple scattering with pomerons, effectively assuming the formation of a quark–gluon plasma (QGP). The EPOS LHC tune [17] is based on early LHC data. In addition, improved knowledge of the different processes involved in particle production and more constrained parameters in hadronic models are of great importance in astrophysics to achieve a deeper understanding of ultra-high energy cosmic ray physics [12].

Furthermore, precise knowledge of the neutral meson production cross section is important for analyses of rare probes, including direct photons, dielectrons or electrons from heavy flavour decays. Due to the large abundance of the π^0 and η mesons in hadronic collisions, their decay photons account for more than 97% of all decay photons. Therefore, a high-precision measurement of the π^0 and η cross section is mandatory to attempt a direct photon measurement in pp collisions, especially at low transverse momenta where a thermal photon signal, possibly produced by a QGP droplet, is expected to be of the order of less than 2% compared to the decay photon background [36–38].

Phenomenological scaling models are often used to predict p_T spectra for particles for which there is no exact measurement at a given center-of-mass energy in the desired p_T or rapidity interval. Transverse mass (m_T) scaling is typically used to obtain the p_T spectrum of a heavy particle, taking the p_T spectrum of a lighter particle, measured in the same collision system, as an input [39, 40]. However, a violation

of this scaling, especially at low transverse momenta, is already reported in [41] and this violation was confirmed in [24–29, 39, 40]. Furthermore, measurements of identified charged particles [42] also show m_T scaling violation. In this work, we extend the studies of the validity of m_T scaling to neutral mesons in pp collisions at $\sqrt{s} = 13$ TeV. Transverse Bjorken x scaling (x_T scaling, with $x_T = 2p_T/\sqrt{s}$ at $y \approx 0$), can be used to predict hadron spectra for $p_T \gtrsim 3$ GeV/ c at collision energies where no measurement is available yet. This scaling relies on the power-law behavior of particle spectra in ultra-relativistic collisions at high transverse momenta [43–45]. This scaling was verified by experimental data at the Tevatron [4, 5], RHIC [6–9], CERN Sp \bar{p} S [3], and CERN LHC energies [42, 46]. However, scaling violations are expected due to the running of α_s and the scale evolution of PDFs and FFs. The broad p_T coverage of neutral meson measurements at the LHC allows a test of the x_T scaling over a very large x_T range.

Further understanding of the underlying particle-production mechanisms can be obtained by analyzing the p_T spectra of identified particles as a function of the event charged-particle multiplicity ($dN_{\text{ch}}/d\eta$). Recent studies at LHC energies in pp, p–Pb, and Pb–Pb collisions have revealed a smooth transition from small to large collision systems as a function of $dN_{\text{ch}}/d\eta$ for observables such as strangeness enhancement, elliptic flow, and modifications in the meson to baryon ratio [47–50]. These results suggest a common underlying mechanism, defining the chemical composition of the produced particles in all collision systems. The dependence of p_T spectra and particle ratios on $dN_{\text{ch}}/d\eta$ at LHC energies was studied for most of the light flavor hadrons [47–50] and has not yet been published for neutral mesons. Hence, this article provides the first constraints on the charged-particle multiplicity dependence of neutral mesons and of the η/π^0 ratio.

In this article, the measurements of the π^0 and η meson production cross section for inelastic collisions at $\sqrt{s} = 13$ TeV with ALICE are reported. Tests of m_T and x_T scaling are performed including measurements at lower collision energies. Moreover, the dependence of light neutral-meson production on the event charged-particle multiplicity is reported. Results are compared to pQCD calculations and to PYTHIA8 and EPOS LHC predictions. This article is organized as follows: the detectors relevant to the measurement are described in Sec. 2; details of the event selection and data samples are given in Sec. 3; the analysis methods are explained in Sec. 4, followed by a summary of the systematic uncertainties evaluation in Sec. 5; the results, as well as comparison to theoretical models are presented and discussed in Sec. 6; finally, the conclusions of the paper are given in Sec. 7.

2 Experimental setup

The π^0 and η mesons are reconstructed via their decays into two photons, $\pi^0 (\eta) \rightarrow \gamma \gamma$, with a branching ratio of $\text{BR} = 98.823 \pm 0.034\%$ and $\text{BR} = 39.41 \pm 0.20\%$, respectively, and via their Dalitz decay, $\pi^0 (\eta) \rightarrow \gamma \gamma^* \rightarrow \gamma e^+ e^-$, with a branching ratio of $\text{BR} = 1.174 \pm 0.035\%$ and $\text{BR} = 0.69 \pm 0.04\%$, respectively [51]. The reconstruction of the real photons is done using three fully independent reconstruction techniques: via energy deposits in the Electromagnetic Calorimeter (EMCal) [14], or in the Photon Spectrometer (PHOS) [52], and by using the Photon Conversion Method (PCM) utilizing e^+e^- pairs from converted photons reconstructed with the tracking detectors. The detectors relevant to this measurement, namely ITS, TPC, TRD, PHOS, EMCal, and the V0 and T0 detectors, are briefly described in this section. These detectors are situated inside the L3 magnet which provides a homogeneous magnetic field of $B = 0.5$ T or $B = 0.2$ T. A detailed description of the ALICE experiment during Run 1 and Run 2 and its performance can be found in [14, 53, 54].

The Inner Tracking System (ITS) [55] consists of six tracking layers, covering the full azimuthal angle and a pseudorapidity range of at least $|\eta| < 0.9$. Its main purpose is the precise estimation of the primary vertex. Additionally, the ITS information is used for pileup rejection and Particle Identification (PID) utilizing the specific energy loss (dE/dx). The two innermost layers consist of the Silicon Pixel Detector

(SPD), followed by two layers of the Silicon Drift Detector (SDD), and two layers of the Silicon Micro-Strip Detector (SSD). The SDD was absent in parts of the $B = 0.2$ T field data taking to limit the total dead time of ALICE and, therefore, maximize the number of collected events.

The Time Projection Chamber (TPC) [56] consists of a large cylindrical drift volume that covers a pseudorapidity range of $|\eta| < 0.9$ and 2π azimuthal angle. The TPC allows for the reconstruction of the momentum for charged particles as well as providing PID based on dE/dx . In the analysis reported in this article, the ITS and TPC are used to reconstruct photons converting in the detector material. The total material budget in the pseudorapidity range $|\eta| < 0.9$ up to $R = 180$ cm, including the material of the beam pipe, the ITS and the TPC is $(11.4 \pm 0.5)\%$ in radiation lengths (X/X_0) [24, 54]; R is calculated in the transverse plane to the beam axis. The data-driven calibration of the ALICE material budget [57] is applied in the presented analysis, reducing the systematic uncertainty on the material budget from 4.5% to 2.5% per photon.

The Transition Radiation Detector (TRD) [58] has a modular structure and its basic component is a multiwire proportional chamber (MWPC). It consists of 522 chambers arranged in 6 layers surrounding the TPC in full azimuth at a radial distance of 2.90 m to 3.68 m from the interaction point, and along the longitudinal direction in 5 stacks covering the pseudorapidity interval $|\eta| < 0.84$. A drift region of 3 cm precedes each chamber to allow the reconstruction of a local track segment, which can be used for matching TRD information with tracks reconstructed with ITS and TPC, or TPC only.

The EMCal detector is a sampling calorimeter used for photon and electron detection, as well as for event triggering. It consists of 17664 individual cells arranged in ten full-sized, six 2/3-sized, and four 1/3-sized supermodules, covering $|\eta| < 0.7$ for $80^\circ < \varphi < 187^\circ$ and $260^\circ < \varphi < 327^\circ$ with the exception of the PHOS hole ($|\eta| < 0.22$ for $260^\circ < \varphi < 320^\circ$). The cells have a size of about 6×6 cm² corresponding to a coverage of $\Delta\eta \times \Delta\varphi \approx 0.0143 \times 0.0143$. Each cell consists of 77 alternating layers of lead absorber and plastic scintillator, providing a radiation length of about $20 X/X_0$. The energy resolution of the EMCal is characterized by $\sigma_E/E = 2.9\%/E \oplus 9.5\%/\sqrt{E} \oplus 1.4\%$ with the energy E in units of GeV. A detailed description of the EMCal and its performance can be found in [52, 59, 60].

The PHOS is a homogeneous electromagnetic calorimeter made of lead tungstate crystals (PbWO₄) that functions as both absorber and scintillator [61]. It covers a pseudorapidity range of $|\eta| < 0.12$ over $\Delta\varphi = 70^\circ$ in azimuth. The detector is segmented into cells with 2.2×2.2 cm² corresponding to a coverage of $\Delta\eta \times \Delta\varphi \approx 0.0048 \times 0.0048$. The high granularity and homogeneous design results in a better energy resolution compared to the EMCal. The energy resolution of the PHOS can be parameterized with $\sigma_E/E = 1.3\%/E \oplus 3.6\%/\sqrt{E} \oplus 1.1\%$, where E is in units of GeV. Details of the PHOS and its performance are described in [61–63].

The V0 detectors consist of two scintillator arrays (V0A and V0C) covering $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. The detectors provide a fast charged-particle multiplicity measurement in the forward region and as such are used to provide the minimum bias (MB) trigger, requiring a hit in both the V0A and V0C, in coincidence with a bunch crossing, as well as a multiplicity trigger. Additionally, the V0 detector is used as a multiplicity estimator in the forward and backward regions.

3 Event selection and data sample

The data used in the analysis were collected in pp collisions at $\sqrt{s} = 13$ TeV from 2016 to 2018. While the majority of the data was recorded with a magnetic field of $B = 0.5$ T, a minimum-bias dataset with $B = 0.2$ T was additionally taken in three dedicated data-taking periods, one per year. Only events that fulfill the MB trigger condition are used in the analysis. Pileup events, where more than one collision occurs in the same bunch crossing, are rejected using the SPD layers to identify multiple vertices [54] as well as by rejecting events based on the correlation between the number of clusters and tracklets

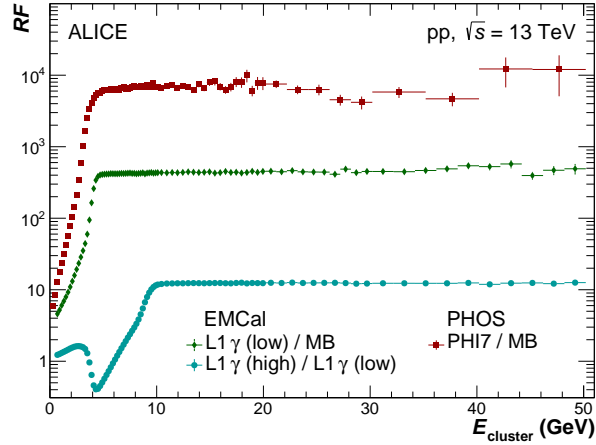


Figure 1: Trigger rejection factors for the EMCAL-L1 γ (low) (green), EMCAL-L1 γ (high) (cyan) and the PHOS-PHI7 (red) trigger as a function of the cluster energy.

reconstructed with the SPD layers. To reduce the fraction of out-of-bunch pileup, only collisions where the neighboring 4 bunch crossings, occurring every 25 ns for most of the data taking, do not contain a triggered collision are considered in the analysis. Additionally, only events with a reconstructed z -vertex position of $|z| < 10$ cm with respect to the intended collision point are accepted in the analysis.

A dedicated high-multiplicity trigger was used during most of the $B = 0.5$ T data taking to select pp collisions at the highest multiplicities. It triggers on a fixed amplitude in the V0 detector system corresponding to events with the 0.17% highest charged-particle multiplicities within the V0 detector acceptance. Only events within the saturation region of the trigger are selected for the analysis.

To enhance the spectrum at high transverse momenta, the EMCAL and PHOS detectors can provide their own level 0 (L0) trigger while the EMCAL additionally provides a set of level 1 (L1) triggers. The L0 trigger is set to an approximate threshold of $E_{L0, \text{EMCAL}}^{\text{thr}} \approx 2.5$ GeV for the EMCAL and $E_{L0, \text{PHOS}}^{\text{thr}} \approx 4$ GeV for the PHOS, referred to as PHI7 trigger in the following. The EMCAL provides L1 triggers for single particles (L1- γ) for which two different thresholds were configured during the data taking: $E_{L1\gamma\text{-low}}^{\text{thr}} \approx 4$ GeV for the lower threshold trigger and $E_{L1\gamma\text{-high}}^{\text{thr}} \approx 9$ GeV for the higher threshold trigger. A detailed description of the trigger system of the EMCAL, as well as its performance, is given in [52]. The enhancement achieved with these triggers compared to minimum bias collisions can be extracted from the ratio of the cluster spectra normalized per event recorded with the EMCAL and PHOS calorimeter triggers to the normalized cluster spectra obtained from minimum bias collisions with the respective calorimeter, as shown in Fig. 1. For the EMCAL-L1 γ (high) trigger, the ratio to the spectra of the EMCAL-L1 γ (low) triggered clusters was chosen in order to minimize statistical fluctuations. Above the trigger threshold, the ratio is not constant but exhibits a slight slope, which has been found to be an effect of acceptance holes from dead or masked trigger regions. To extract the trigger enhancement factors, the ratios shown in Fig. 1

Table 1: Number of events recorded for each event class together with the corresponding integrated luminosity. Except for parts of the minimum bias trigger class, the data was recorded at $B = 0.5$ T.

Trigger class	$N_{\text{evt}} (10^6)$	\mathcal{L}_{int}
Minimum bias ($B = 0.5$ T)	1516	$26.23 \pm 0.42 \text{ nb}^{-1}$
Minimum bias ($B = 0.2$ T)	581	$10.05 \pm 0.16 \text{ nb}^{-1}$
EMCAL-L1 γ (low)	116	$0.84 \pm 0.03 \text{ pb}^{-1}$
EMCAL-L1 γ (high)	90.5	$8.24 \pm 0.26 \text{ pb}^{-1}$
PHOS PHI7	48.6	$9.93 \pm 0.60 \text{ pb}^{-1}$
VOM high multiplicity	261	$7.09 \pm 0.39 \text{ pb}^{-1}$

Table 2: Definition of multiplicity classes used in the presented analysis together with the corresponding mean charged-particle multiplicity measured in $|\eta| < 0.5$ [65].

$\Delta\sigma/\sigma_{\text{MB}_{\text{AND}>0}}$	$\langle dN_{\text{ch}}/d\eta \rangle_{ \eta <0.5}$
0–0.01%	35.82 ± 0.47
0.01–0.05%	32.21 ± 0.41
0.05–0.1%	30.13 ± 0.38
0–1%	26.01 ± 0.34
1–5%	19.99 ± 0.24
5–10%	16.18 ± 0.20
10–20%	12.90 ± 0.17
20–30%	10.03 ± 0.13
30–50%	7.14 ± 0.10
50–70%	4.49 ± 0.06
70–100%	2.54 ± 0.04
0–100%	6.93 ± 0.09

are corrected for acceptance effects using a trigger emulation in the Monte Carlo (MC) simulation, after which a constant fit to the plateau region gives the trigger efficiency-corrected enhancement factor.

The number of analyzed MB events as well as the corresponding integrated luminosity (\mathcal{L}_{int}) for both magnetic field configurations, together with the high-multiplicity triggered data sample in the 0–0.1% multiplicity class, and the calorimeter-triggered samples are listed in Tab. 1. Events that are used for the multiplicity-dependent analyses require one charged particle in the ALICE acceptance of $|\eta| < 1$ (INEL>0). At least one SPD tracklet is required in these events in order to approximate this condition in the data. The multiplicity is determined using the integrated amplitude of the V0A and V0C detectors [64]. Table 2 summarizes the multiplicity classes, given as the fraction of the visible cross section $\Delta\sigma/\sigma_{\text{MB}_{\text{AND}>0}}$ of the MB trigger, used in the analysis together with the corresponding mean charged-particle density $\langle dN_{\text{ch}}/d\eta \rangle_{|\eta|<0.5}$ taken from [65].

4 Analysis method

4.1 Photon and virtual photon reconstruction

Photons and electrons hitting an electromagnetic calorimeter produce an electromagnetic shower that typically spreads over multiple cells. To retrieve the full energy of the original particle, the energy of adjacent cells is combined using a clusterization algorithm as described in [52] for the EMCal and in [61] for the PHOS. The clusterization thresholds are based on previous studies [52, 63] and are given in Tab. 3. The calibration procedures of the cells and the resulting clusters of the EMCal and PHOS are given in [52, 63]. To select clusters originating from photons, several selection criteria, listed in Tab. 3, are applied. The selection criteria for EMCal and PHOS clusters have the same motivation; however, the values differ because of differences in electronic noise, cell sizes, and the materials used in the two calorimeters. A minimum cluster energy E_{cluster} is required to minimize contributions from hadronic clusters and electronic noise. Out-of-bunch pileup is rejected by selecting clusters within a strict time window around the selected collision. Losses due to the width of the cluster-time distribution are negligible for EMCal; however, a sizable loss for PHOS at low and high cluster energies was found. This effect was emulated in the MC simulation in order to be corrected. Furthermore, the purity of γ clusters is enhanced by rejecting clusters likely to be produced from charged particles. This is accomplished through the use of a geometrical track-cluster matching approach, while additionally considering the disparity between the track momentum p_{track} and E_{cluster} . Only matched clusters that satisfy the condition $E_{\text{cluster}}/p_{\text{track}} < 1.75$ are rejected. The cluster shape σ_{long}^2 is used to further reduce the hadronic back-

Table 3: Collection of selection criteria applied to EMCal and PHOS clusters to select photons and merged π^0 candidates [52, 63].

	EMCal	PHOS
Seed threshold	$E_{\text{seed}} > 300$ MeV	$E_{\text{seed}} > 50$ MeV
Aggregation threshold	$E_{\text{agg}} > 100$ MeV	$E_{\text{agg}} > 15$ MeV
Cluster energy	$E_{\text{cluster}} > 700$ MeV	$E_{\text{cluster}} > 300$ MeV
Number of cells	$N_{\text{cell}} \geq 1$	$N_{\text{cell}} \geq 1$ $N_{\text{cell}} \geq 2$ for $E_{\text{cluster}} > 1$ GeV
Cluster time	$-20 < t_{\text{cluster}} < 25$ ns	$-30 < t_{\text{cluster}} < 30$ ns
Cluster shape γ	$0.1 < \sigma_{\text{long}}^2 < 0.7$	$\sigma_{\text{long}}^2 > 0.1$
Cluster shape merged π^0	$\sigma_{\text{long}}^2 > 0.27$	$\sigma_{\text{long}}^2 > 1.2 + 35.7/(E_{\text{cluster}} - 12.9)$
Charged particle veto	$ \Delta\eta < 0.01 + (p_{\text{T, track}} + 4.07)^{-2.5}$ $ \Delta\phi < 0.015 + (p_{\text{T, track}} + 3.65)^{-2}$ $E_{\text{cluster}}/p_{\text{track}} < 1.75$	$ \Delta\eta < 0.01 + (p_{\text{T, track}} + 4.37)^{-2.5}$ $ \Delta\phi < 0.015 + (p_{\text{T, track}} + 3.78)^{-2}$

Table 4: Selection criteria of the converted photon reconstruction with PCM for the two-photon (PCM- $\gamma\gamma$) and the Dalitz decay channel (PCM- $\gamma\gamma^*$). Both reconstruction methods use the same selection criteria except for extra TRD requirement in the PCM- $\gamma\gamma$.

	Nom. B	Low B
Track reconstruction		
$ \eta $	< 0.8	same
p_{T}	> 0.05 GeV/c	$p_{\text{T}} > 0.02$ GeV/c
$N_{\text{clusters}}/N_{\text{findable clusters}}$	$> 60\%$	same
Conversion radius	$5 < R_{\text{conv}} < 55$ cm $72 < R_{\text{conv}} < 180$ cm	same
Line cut	$R_{\text{conv}} > Z_{\text{conv}} \times ZR_{\text{Slope}} - Z_0$ $ZR_{\text{Slope}} = \tan(2 \times \arctan(\exp(-\eta_{\text{cut}})))$ $Z_0 = 7$ cm, $\eta_{\text{cut}} = 0.8$	same
Track identification		
$n\sigma_e$ TPC	$-3 < n\sigma_e < 4$	same
$n\sigma_\pi$ TPC	$n\sigma_\pi > 1$ at $0.4 < p < 3.5$ GeV/c $n\sigma_\pi > 0.5$ at $p > 3.5$ GeV/c	same
TRD tracklet or ITS hit	$\geq 1, -$	same
Conversion γ topology		
q_{T}	$< q_{\text{T}}^{\text{MAX}} \sqrt{1 - (\alpha/0.95)^2}$ GeV/c $q_{\text{T}}^{\text{MAX}} = \text{Min}(0.125 p_{\text{T}}^\gamma, 0.05)$	same $q_{\text{T}}^{\text{MAX}} = \text{Min}(0.2 p_{\text{T}}^\gamma, 0.035)$
$\psi_{\text{pair}}, \chi^2$	$ \psi_{\text{pair}} < 0.18 \exp(-0.055 \chi_\gamma^2)$ $\chi_\gamma^2/\text{ndf} < 50$	$ \psi_{\text{pair}} < 0.35 \exp(-0.075 \chi_\gamma^2)$ same
$\cos(\theta_{\text{PA}})$	> 0.85	same
Reject too close V^0 's	$\Delta R < 6$ cm && $(V^0 \triangleleft) < 0.02$ rad	same

ground as well as to differentiate between clusters consisting of one γ and clusters consisting of multiple γ originating mainly from the two-photon π^0 decays at high transverse momenta. The parameter σ_{long}^2 is defined as the larger eigenvalue of the covariance matrix of a cluster's energy distribution. For the EMCal, the covariance matrix is calculated in the η and ϕ directions [52], while for the PHOS, it is evaluated in the x and z directions on the front plane [61]. Consequently, σ_{long}^2 is dimensionless for the EMCal but measured in cm^2 for the PHOS.

Photons that convert into e^+e^- pairs in the detector material are reconstructed using a V^0 finder method [54] that pairs secondary oppositely-charged tracks from a common neutral vertex. Charged tracks are recon-

Table 5: Selection criteria applied in the PCM- $\gamma\gamma^*$ analysis to select primary e^+e^- tracks and to select virtual photons (γ^*).

Primary e^+ (e^-)	nom B	low B
Track reconstruction		
$ \eta $	0.9	same
p_T	> 0.125 GeV/c	> 0.05 GeV/c
DCA _{xy}	< 0.105 mm + 0.35 mm $/(\frac{p_T}{\text{GeV}/c})^{1.1}$	same
DCA _z	< 2 cm	same
$N_{\text{hits}}^{\text{ITS}}$	≥ 2	same
$N_{\text{clusters}}^{\text{TPC}}, N_{\text{clusters}}^{\text{TPC}}/N_{\text{findable clusters}}^{\text{TPC}}$	$\geq 70, > 60\%$	same
$\chi_{\text{ITS}}^2/N_{\text{hits}}$	< 36	same
$\chi_{\text{TPC}}^2/N_{\text{clusters}}$	< 4	same
Track identification		
e^\pm selection ($n\sigma_e$ TPC)	$-4 < n\sigma_e < 5$	same
π^\pm rejection ($n\sigma_\pi$)	$n\sigma_\pi > 2$ if $0.4 < p < 3.5$ GeV/c $n\sigma_\pi > 0.5$ if $p > 3.5$ GeV/c	same same
γ^* identification		
M_{γ^*}	< 0.015 GeV/c ² if $p_T < 1$ GeV/c < 0.035 GeV/c ² if $p_T > 1$ GeV/c	same same
$ \psi_{\text{pair}} $ rejection	< 0.5 if $0.00 < \Delta\phi < 0.02$ rad < 0.44 if $0.02 < \Delta\phi < 0.04$ rad < 0.07 if $0.04 < \Delta\phi < 0.06$ rad	< 0.98 if $0.00 < \Delta\phi < 0.02$ rad < 0.11 if $0.02 < \Delta\phi < 0.04$ rad

structed primarily with the ITS and the TPC. The V^0 candidates comprise K_S^0 , Λ , $\bar{\Lambda}$ decays and γ conversions, as well as random combinations not originating from the same mother particle. Different selection criteria were applied for the photon reconstruction: quality on the charged tracks, particle identification, and photon conversion topology. Details of the PCM- $\gamma\gamma$ and PCM- $\gamma\gamma^*$ analysis can be found in [24–30]. The complete list of applied selection criteria on the converted photons for the PCM- $\gamma\gamma$ and PCM- $\gamma\gamma^*$ decay channels is summarized in Tab. 4. For tracks that pass the quality criteria, electron selection and pion rejection are performed utilizing the specific energy loss dE/dx in the TPC. Selection and rejection criteria use the number of standard deviations around the expected electron and pion hypothesis ($n\sigma_e$, $n\sigma_\pi$), where σ is the standard deviation of the dE/dx measurement. Photon selection and further rejection of weak decays are based on the α - q_T plane known as Armenteros Podolanski plot [66]; α is the longitudinal momentum asymmetry between the positive and negative tracks, $\alpha = (p_L^+ - p_L^-)/(p_L^+ + p_L^-)$, and q_T is the transverse momentum of the decay particle with respect to the V^0 momentum. The ψ_{pair} angle between the plane that is perpendicular to the magnetic field ($x-y$ plane) and the plane defined by the opening angle of the pair is additionally used to select photon conversions, as they have a preferred emission orientation, in contrast to the distribution for virtual photons of Dalitz decays or random combinations. Furthermore, information on the photon χ^2 of the Kalman filter fit [67] in combination with the ψ_{pair} is used to enhance the photon purity. A selection based on the cosine of the pointing angle of $\cos(\theta_{\text{PA}}) > 0.85$ is performed, with θ_{PA} being the angle between the reconstructed photon momentum vector and the vector connecting the conversion point and the collision vertex. Moreover, it was found that V^0 's with similar conversion points and a small angle \angle between their momentum axes likely originate from the same photon. To avoid double counting, only the V^0 with the best χ^2 value is considered for the analysis. To reduce the out-of-bunch pileup contribution, a TRD tracklet or an ITS hit [58] was required for at least one track in the PCM- $\gamma\gamma$ analysis (TRD tracklet or ITS hit ≥ 1). Thus, V^0 's with TPC-only tracks are not used in this analysis. This is especially important for the low multiplicity event class in the multiplicity-dependent analysis, where otherwise a large correction would need to be applied.

The virtual photons of the Dalitz decay (γ^*) are reconstructed from primary electron-positron pairs. Primary tracks are required to have both ITS and TPC segments with the fit quality for the ITS and TPC track points satisfying a $\chi^2_{\text{ITS}}/N_{\text{hits}} < 36$ and $\chi^2_{\text{TPC}}/N_{\text{clusters}} < 4$, to have at least 70 TPC clusters and the fraction of TPC clusters to the number of findable clusters to be larger than 60%. The Distance of Closest Approach (DCA) to the primary vertex in the longitudinal direction ($\text{DCA}_z < 2$ cm) and in the transverse plane $\text{DCA}_{xy} < 0.105 \text{ mm} + 0.35 \text{ mm} / (p_T c / \text{GeV})^{1.1}$ are used to further enhance the γ^* purity. In order to reduce the contamination from photon conversions, tracks are required to have a hit in each SPD layer. Electron candidates are selected using tracks within an interval of $-4 < n\sigma_e < 5$ around the electron hypothesis. Pion contamination in the electron sample is reduced by a selection criterion on the γ^* invariant mass $M_{\gamma^*} < 0.015 \text{ GeV}/c^2$ and $M_{\gamma^*} < 0.035 \text{ GeV}/c^2$ for $p_T < 1 \text{ GeV}/c$ and $p_T > 1 \text{ GeV}/c$, respectively. Contamination from γ conversions in the γ^* sample is suppressed by a $\Delta\phi$ dependent selection on ψ_{pair} , and a $\Delta\phi$ dependent selection on $0 < \Delta\phi < 0.12$ rad where $\Delta\phi = \phi(e^+) - \phi(e^-)$. The complete list of selection criteria is given in Tab. 5.

4.2 Neutral meson reconstruction

In the presented measurement, the π^0 and η are reconstructed making use of an invariant mass analysis accompanied by two purity-based analyses for the π^0 at high p_T . In the invariant mass analysis, photons from the same or different (hybrid-method) reconstruction techniques are paired within the same event. The following photon combinations are considered in the analysis: EMC-EMC, PHOS-PHOS, PCM- $\gamma\gamma$ as well as the hybrid methods PCM-EMC and PCM-PHOS. The PCM- $\gamma\gamma^*$ decay-based analysis is performed using photons from the PCM method, while the γ^* is treated like a real γ except with a non-zero mass. A restriction on the opening angle between two-photon candidates is applied in the calorimeter-based and hybrid analyses. For the calorimeter-based methods, the opening angle is limited by the granularity of the detectors, as the distance between two clusters cannot fall below one cell. This is especially relevant for the EMCal due to the large cell size. To ensure the same behavior in the reconstructed signal and the estimated background, which will be described in the course of this section, the opening angle has to be greater than 17 mrad for EMCal while for PHOS the value is set to 5 mrad, which approximately corresponds to the length of a cell diagonal for both calorimeters. The resulting number of meson candidates as a function of the invariant mass and p_T contains both the π^0 and η signal at their respective rest mass as well as background coming from γ combinations that do not originate from the same π^0 or η decay. Examples of invariant mass distributions are shown in Fig. 2 for selected p_T ranges for the π^0 and η , respectively. The invariant mass distributions for all reconstruction techniques can be found in [68].

Two different approaches, event mixing and photon rotation, are used to describe the background. The mixed event technique is a well-established method to describe the background in invariant mass analyses [69, 70]. In this method, photon candidates from different events are paired, leading to totally uncorrelated candidates. Only events with similar z -vertex position and similar photon multiplicity were considered for the mixing. Eight z -vertex event classes and 4 multiplicity classes, each with a mixing depth of 80, were used in the analysis. For the EMC and PCM-EMC reconstruction methods, the mixed event distribution does not describe the background below the π^0 and η meson peaks. Correlations between the reconstructed photon candidates cannot be described by the event mixing method as this method by definition breaks all correlations. In order to only take out first-order correlations, meaning the correlation coming from the same mother particle (e.g. the photons from the neutral pions and η mesons), an in-event particle rotation approach was developed for the presented analysis. In this approach, it is assumed that a pair of photon candidates originates from the same mother particle. These photon candidates are rotated around the momentum vector of their reconstructed mother particle by 90° , keeping the combined momentum intact. The rotated candidates are paired with all other photon candidates in the event like in the same-event method, but excluding the combination of the two rotated candidates. Assuming the candidates come from the same mother particle decaying in two photons, this

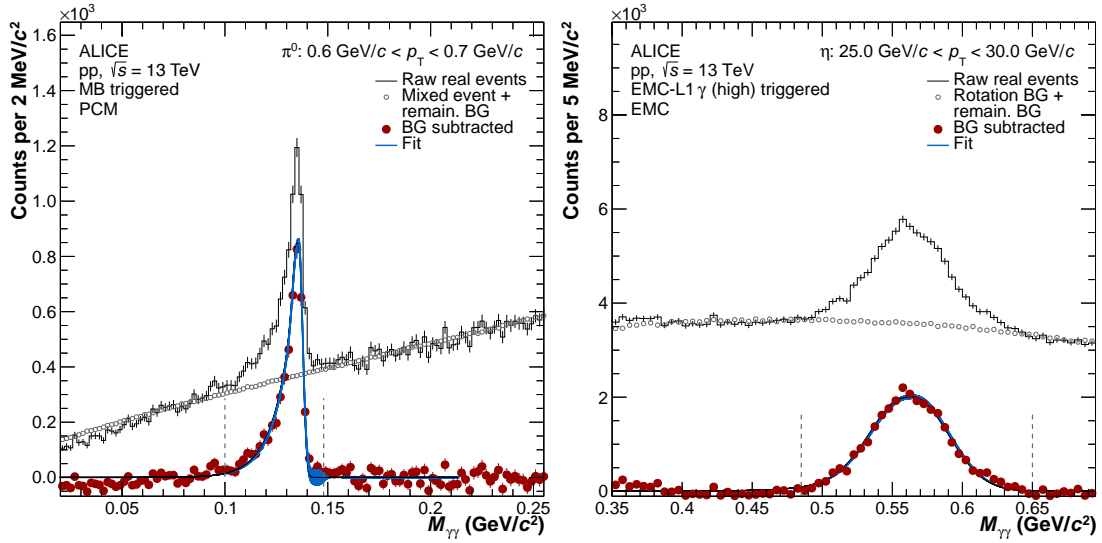


Figure 2: Invariant mass distribution of $\gamma\gamma$ pairs around the π^0 (left) and η (right) rest mass for the PCM and EMCal reconstruction methods, respectively. The extracted meson peak is shown in red, with the parametrization in blue and its uncertainty represented by a blue band.

process simulates a possible decay of the particle and, therefore, results in an accurate description of the background. Collisions where two or fewer photon candidates were found cannot be used to estimate the rotation background as at least three candidates are required. The shape of the background as a function of the number of photon candidates was found to vary only slightly, and hence, the rotation technique is suited to describe the background in the same-event distribution.

To extract the number of measured π^0 and η mesons, the estimated background has to be subtracted from the same-event distribution in each p_T interval. The background is scaled to the same-event distribution, either in a signal-free region to the left or right side of the π^0 (η) meson peak or by including a signal shape template from MC simulation in the fit, thus including the signal region in the fit. The scaling function is a constant for most reconstruction methods, while for the PHOS and PCM-PHOS methods, a second-order polynomial is used to account for a slight mismatch in the shape of the estimated background. The scaled background is then subtracted from the same-event distribution. The remaining signal is parameterized with a three-component function consisting of a Gaussian component to describe the distribution of $\gamma\gamma$ pairs, an exponential component at low invariant masses to describe bremsstrahlung of the PCM photons and energy loss of late-conversions in front of the calorimeter in case of the EMCal and PHOS photons. Furthermore, for the EMCal and PHOS triggered data, an exponential tail for $M_{\text{inv.}} > M_{\pi^0(\eta)}$ is used to account for overlapping clusters in these triggered events with a high cluster occupancy. For the PCM and PCM- $\gamma\gamma^*$ methods, an additional first-order polynomial function is included in the fit to correctly estimate any remaining background that was not described by the scaled mixed-event method. The mean of the Gaussian component of the parametrization gives an estimate for the peak position and is presented for the π^0 and η mesons in Fig. 3 (lower panels) as a function of p_T for the different reconstruction techniques. A good agreement between data and MC simulation is observed, indicating a good calibration of all included detectors. The peak width shown in Fig. 3 (top panels) is estimated by the full-width half maximum (FWHM) of the parametrization divided by 2.35, giving an approximation of the standard deviation of the combined parametrization. To obtain the raw π^0 and η -meson counts, the signal is integrated within a fixed window, whose size depends on the peak width of the specific reconstruction method, around the estimated peak position shown in Fig. 3.

At sufficiently high transverse momenta, the opening angle between the two photons from meson decays becomes smaller than the cluster size. In this regime, the classical invariant-mass technique is no longer applicable. The resulting cluster contains both decay photons and is as such elongated, which can be

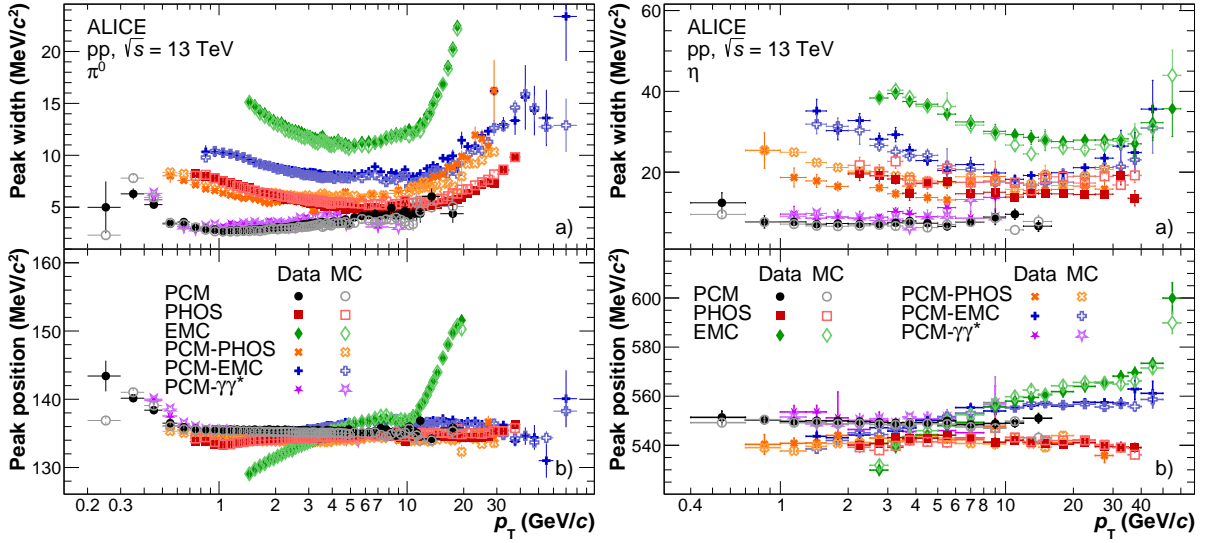


Figure 3: Peak position (a) and peak width (b) as a function of p_T for the π^0 (left) and η (right) for all reconstruction techniques and for data in closed markers and MC simulation in open markers. The values are extracted from a fit of the meson peak.

characterized by the cluster shape elongation parameter σ_{long}^2 . For the EMCal, cluster merging of photons originating from π^0 decays becomes dominant at $p_{T, \pi^0} \approx 16$ GeV/c [52], while for PHOS, due to higher granularity and a different cluster splitting algorithm, cluster merging starts to become relevant above $p_{T, \pi^0} \approx 30$ GeV/c. Clusters above $p_T = 16$ GeV/c in EMCal and $p_T = 30$ GeV/c in PHOS were used to reconstruct the neutral pions using a purity-driven analysis technique called merged EMCal technique (mEMC) and merged PHOS technique (mPHOS) [26, 30]. Figure 4 shows the probability distribution of clusters from data and MC simulation as a function of σ_{long}^2 in the transverse momentum ranges $100 < p_T < 110$ GeV/c and $60 < p_T < 100$ GeV/c for EMCal and PHOS, respectively. Additionally, the contributions of different particle species to the cluster spectrum, as obtained from the MC simulation, are shown. All selected clusters are shown as black markers, while clusters with a leading contribution from a photon originating from a π^0 decay are shown as red markers. Clusters originating from η decays, the largest background component in this analysis, are shown as blue markers. Additional background components are clusters from photons that do not originate from π^0 or η decays, shown in orange, clusters from electrons shown in green, and hadronic clusters that are represented by the open blue markers. To precisely estimate the number of π^0 mesons, the different background components have to be precisely understood and their relative abundance in the MC simulation has to be tuned to match their abundance in data. This will be discussed in Sec. 4.3. For the mEMC method, the π^0 raw yield is obtained by the integral of all clusters with a value of $\sigma_{\text{long}}^2 > 0.27$, while for PHOS this value is energy dependent (see Tab. 3) to allow for a better separation between single photon clusters and merged π^0 clusters.

The raw meson spectra are obtained for each dataset listed in Tab. 1 that is available for the respective reconstruction method. For the EMC, PCM-EMC and mEMC methods, this includes both EMCal-L1 γ triggers, where π^0 and η mesons are used from $p_T = 8$ (16) GeV/c onwards for the low (high) threshold. For the PHOS and PCM-PHOS methods, the PHOS PHI7 triggered data is used from $p_T = 10$ GeV/c onwards, while the mPHOS method starts from $p_T = 30$ GeV/c. Furthermore, for the PCM, PCM-EMC, and PCM- $\gamma\gamma^*$ method, data from the B = 0.2 T data-taking period is used, allowing the PCM method to reach down to $p_T = 0.2$ GeV/c in case of the π^0 . The raw spectra are individually corrected for detector effects, as discussed in the next section, and combined using the same combination method as described in Sec. 6.

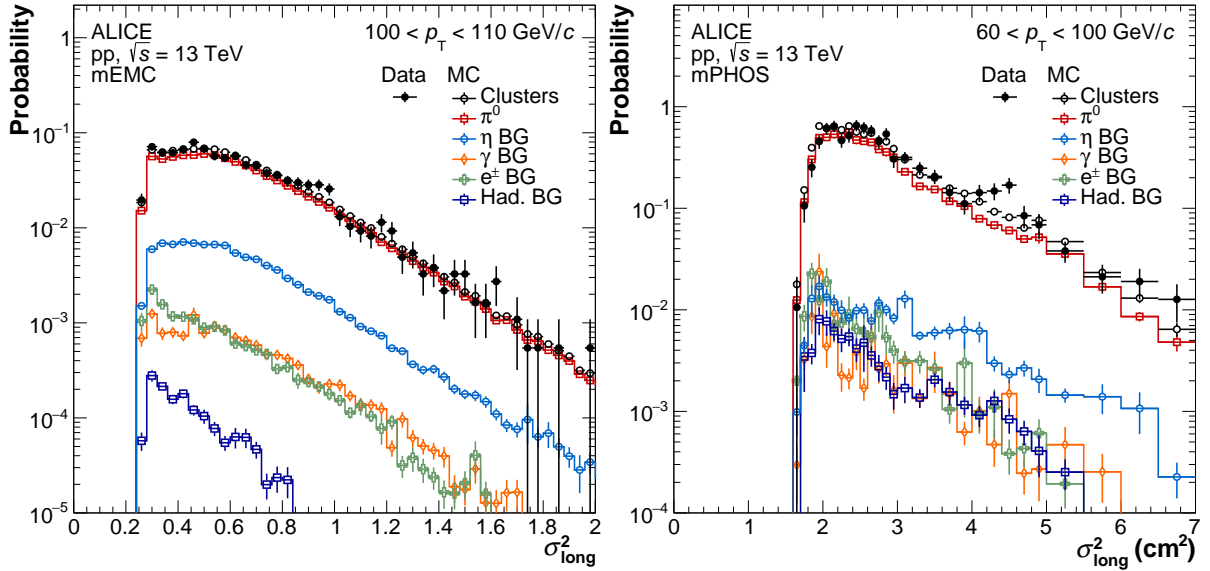


Figure 4: Distribution of σ_{long}^2 for EMCAL (left) and in PHOS (right) clusters in MC simulation. Clusters with a leading contribution from decay photons from π^0 are shown in black together with different background contributions in colored markers.

4.3 Corrections

As outlined in the previous section, the raw meson yields obtained with the different reconstruction methods must be corrected for detector effects and contamination from secondary particles. These corrections are presented in this section, starting with the correction for π^0 from weak decays, followed by the out-of-bunch pileup correction for the PCM method and the correction for contamination in the PCM- $\gamma\gamma^*$ measurement. Furthermore, the acceptance correction and reconstruction efficiency for all methods are presented, followed by the purity correction for the merged-cluster-based analyses. The section concludes with a discussion on the correction of inefficiencies of the triggers used for the analysis.

In the presented measurement, the production of primary neutral mesons is reported, and hence secondary neutral pions from weak decays of K_S^0 , K_L^0 , and Λ as well as from hadronic interactions with the detector material are subtracted [71]. A data-driven approach [36] is used to estimate the contributions from weak decays. In this approach, the measured spectra of these particles in MB events [42] and as a function of multiplicity [72] are used as input. As the measurement of K_S^0 , K_L^0 , and Λ does not cover the highest multiplicity intervals of the presented measurement, an extrapolation of these spectra from the 0–1% multiplicity interval to the multiplicity intervals above 0.1% was performed. To obtain the raw yield of π^0 from these decays, the detection efficiency and acceptance of secondary neutral pions are taken from MC simulation. The fraction of mesons from hadronic interactions is estimated using MC simulation including GEANT3 [73, 74] for the description of the interaction between the traversing particles from the collision and the detector material. The correction is of the order of up to about 8% at low p_T depending on the reconstruction method, while at high p_T it is about 3% at maximum.

The PCM analysis needs a correction to account for π^0 and η mesons produced in bunch crossings other than the triggered one, referred to as out-of-bunch pileup. The fraction of out-of-bunch pileup is obtained by using the DCA distribution of reconstructed photons. Photons originating from neighboring collisions but assigned to the current one, have a wider DCA distribution compared to photons from the triggered collision. In contrast to previous analyses, no TPC-only tracks are considered for the PCM analysis, and tracks always have a constraint by either the ITS or the TRD giving a much better timing resolution than for TPC-only tracks. TPC-only tracks typically contribute as the largest fraction to the out-of-bunch pileup. Therefore, the contribution in the presented analysis is much smaller than in previous

publications. The fraction of out-of-bunch pileup is estimated by fitting the underlying distribution. For the MB events, the correction is largest at $p_T \approx 1.5$ GeV/c and amounts to about 7%, decreasing to 4% at 20 GeV/c. For the multiplicity event class 70–100% the correction is 35% at $p_T \approx 2$ GeV/c while for the 0.0–0.01% the correction is about 3%. The strong dependence of the fraction of out-of-bunch pileup on the multiplicity originates in the difference in the number of mesons produced in the triggered collision, while the number of mesons from out-of-bunch pileup is constant on average.

Contamination in the virtual photon sample for the PCM- $\gamma\gamma^*$ measurement is kept to a minimum as laid out in Sec. 4.1. The remaining contamination of photon conversion electrons, misidentified as primary particles, is estimated using MC simulation: for the B = 0.5 T data, the contamination is between approximately 1% at around $p_T = 2$ GeV/c and 7% for high and low p_T while for the B = 0.2 T data, the contamination is slightly higher, from about 2.5% to 15%, with a similar p_T dependence as for the data collected with the nominal magnetic field.

Corrections for the geometrical acceptance and the reconstruction efficiency as well as impurities in the extracted signal are done using the PYTHIA8 Monash event generator in combination with a full GEANT3 detector simulation. While for the correction of the MB data, PYTHIA8 simulations with MB processes are used, the calorimeter-triggered data are corrected using PYTHIA8 simulations, generated in intervals of the initial hard scattering, with two jets in the final state. These simulations allow for small statistical uncertainties of the correction factor up to high p_T . The acceptance correction is performed by calculating the fraction of π^0 (η) produced within $|y| < 0.8$, where all decay products are within the geometrical limits of the detector used for the reconstruction. For the reconstruction efficiency, the same photon selection and signal extraction procedures as described in Sec. 4.2 are performed using the respective output of the MC simulation. The resulting peak properties of the extracted π^0 (η) are compared to data, as shown in Fig. 3, to verify the description of the data by the MC. The meson reconstruction efficiency ϵ_{rec} is calculated using the MC simulation by comparing the extracted raw π^0 (η) yield to all generated π^0 (η) within the geometrical acceptance. Hence, ϵ_{rec} contains loss effects due to the photon selection criteria (Sec. 4.1), energy resolution effects, as well as impurities in the signal extraction. To reduce statistical fluctuations, the PCM- $\gamma\gamma$ and PCM- $\gamma\gamma^*$ use verified reconstructed mesons for the ϵ_{rec} calculation, and hence no signal extraction is involved. It was checked that, within statistical fluctuations, both approaches result in the same correction factor. The reconstruction efficiency was studied as a function of multiplicity for each reconstruction method using the same mean charged-particle multiplicity in the simulation as in the data. A relative reduction of the efficiency of up to about 7% was found for the calorimeter-based methods. However, to decrease the statistical uncertainty, the multiplicity-integrated efficiency correction is used and scaled with a parametrization to the ratio of the multiplicity-dependent efficiency to the integrated efficiency. As the difference in efficiency originates from differences in the photon reconstruction efficiency, the change in efficiency is assumed to be identical for both the π^0 and the η meson.

A purity correction is employed in the merged cluster analysis to account for clusters from γ originating from η decays as well as prompt photons and electrons. The relative abundance of these background components is evaluated using data and MC-driven approaches: the relative abundance of the η meson compared to the π^0 is estimated with the constant fit to the η/π^0 ratio at high p_T shown in Fig. 8. The prediction from the simulation is then subsequently scaled to match the data. The additional contribution from prompt photons is estimated using PYTHIA8 γ -jet processes simulations where Compton scattering $qg \rightarrow q\gamma$, quark-antiquark annihilation $q\bar{q} \rightarrow g\gamma$ and, with a much smaller contribution, $q\bar{q} \rightarrow \gamma\gamma$ events are generated. Furthermore, electrons from decays of W^\pm and Z are not included in the simulation and their contribution is therefore estimated using MC based on the POWHEG [75, 76] event generator. Again the same efficiency as for primary electrons is assumed to estimate the relative abundance in the raw merged cluster yield of these electrons. The π^0 purity ranges from 88% (90%) at $p_T \approx 30$ GeV/c to 78% (82%) at the highest p_T for mEMC (mPHOS).

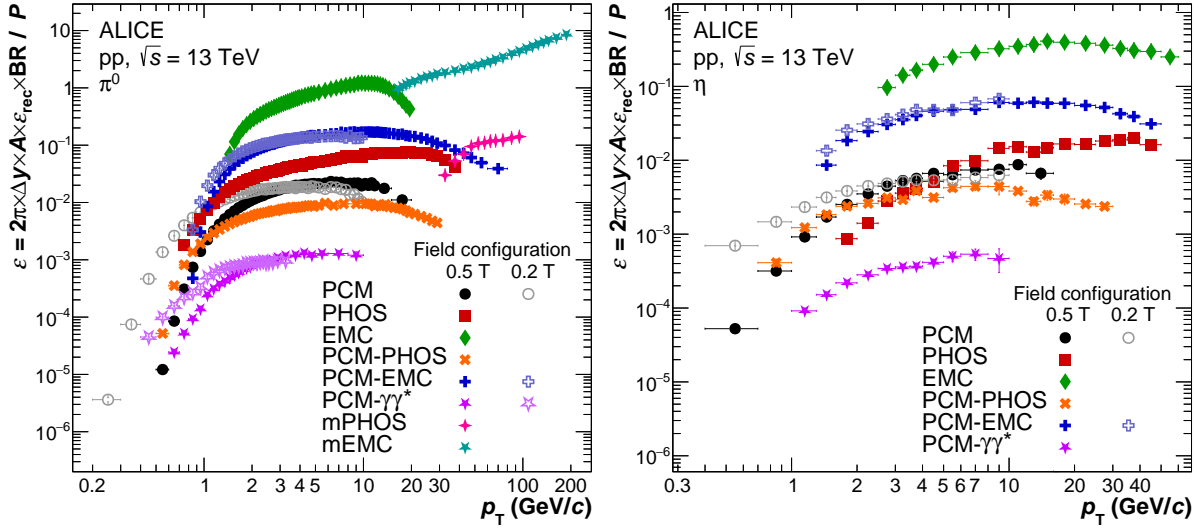


Figure 5: Correction factor for the π^0 (left) and η (right), including the reconstruction efficiency, acceptance, purity, branching-ratio and normalization for the azimuthal angle ϕ and rapidity y coverage, as a function of p_T for the different reconstruction methods.

The combined correction factors are presented in Fig. 5 for π^0 and η mesons. The correction factors include the geometrical acceptance (A), reconstruction efficiency (ϵ_{rec}), and purity (P) for the merged cluster analyses, as well as normalizations for the rapidity (Δy) and ϕ coverage (2π) and the branching ratio (BR), however excluding the EMCAL and PHOS trigger efficiency. An initial increase with p_T can be seen, as it becomes more likely that both photons are within the detector acceptance, and because the single-photon reconstruction efficiency increases with photon energy. At high transverse momenta, the π^0 meson correction factor for the EMCAL method drops due to the merging of both decay photons into the same cluster. For the PHOS method, this decrease is much less pronounced and the onset occurs at higher transverse momentum as the granularity of the calorimeter is much finer, and the effect is only expected above $p_T \approx 30$ GeV/ c .

The minimum bias trigger used for the presented analysis is not able to trigger on all events where π^0 or η mesons were produced. This results in a loss of signal, which is estimated using PYTHIA8 Monash 2013 while additionally taking PHOJET 1.12 [77] and EPOS LHC into account for the estimation of the systematic uncertainty. Below $p_T = 1$ GeV/ c the π^0 and η meson signal loss is up to 2%, while it is zero at high transverse momenta. The systematic uncertainty of this correction is estimated using different event generators and is of the order of 0.4% at maximum. The fraction of events lost due to the minimum bias trigger efficiency is compensated in the luminosity calculation [78].

The π^0 and η meson p_T spectra obtained using the calorimeter-triggered data have to be scaled down to correct for the higher integrated luminosity of the triggered data. The increase in luminosity can be derived by comparing the cluster spectra in triggered data to the cluster spectrum in minimum bias collisions as shown in Fig. 1. Additionally, a correction based on a trigger emulation in MC simulation has to be applied to the cluster spectra of the triggered data to correct for trigger inefficiencies due to masked trigger regions, resulting in an additional correction on the order of 5–7% for EMCAL and about 40% for PHOS. As the same trigger emulation is also used for the calculation of the reconstruction efficiency ϵ_{rec} , the absolute magnitude of the correction cancels for the calculation of the π^0 (η) cross section. However, a mild p_T dependence affects the shape of the triggered cluster spectra, thereby modifying the estimated trigger-rejection factor. Details on this correction for the EMCAL can be found in [79].

Table 6: Relative systematic uncertainties (%) of the π^0 spectrum for the different reconstruction methods.

Rec. method	PCM		EMC		PHOS		PCM- $\gamma\gamma^*$		PCM-EMC		PCM-PHOS		mEMC		mPHOS	
	1.45	6.5	1.45	6.5	1.45	6.5	1.45	6.5	1.45	6.5	1.45	6.5	52.5	95	52.5	95
p_T (GeV/c)																
Yield extraction	1.7	2.5	2.9	2.8	2.2	2.7	2.7	4.6	2.1	2.0	3.7	3.7	-	-	-	-
Cluster description	-	-	2.2	2.1	3.6	2.8	-	-	2.1	2.2	3.3	2.0	6.5	7.5	2.0	4.2
Cluster E calib.	-	-	2.2	2.2	2.0	2.0	-	-	2.1	1.6	2.0	2.0	2.1	2.1	3.2	3.2
Ch. particle veto	-	-	0.4	0.7	0.7	1.1	-	-	0.4	0.7	0.4	0.7	1.5	1.5	2.0	2.6
e^+e^- track rec.	0.0	0.1	-	-	-	-	2.0	2.0	0.3	0.3	0.3	0.3	-	-	-	-
e^+e^- PID	0.5	1.7	-	-	-	-	1.2	1.2	0.8	1.0	0.8	1.0	-	-	-	-
PCM photon PID	0.3	1.0	-	-	-	-	2.0	2.0	0.4	0.8	1.0	1.3	-	-	-	-
Efficiency	-	-	2.0	2.0	1.5	1.5	0.5	0.5	2.0	2.0	1.5	1.5	4.8	4.8	6.8	8.6
Outer material	-	-	4.2	4.2	2.0	2.0	-	-	2.1	2.1	1.0	1.0	4.2	4.2	1.7	1.7
Inner material	5.0	5.0	-	-	-	-	2.5	2.5	2.5	2.5	2.5	2.5	-	-	-	-
Norm. & pileup	3.3	3.2	-	-	-	-	-	-	-	-	-	-	2.8	2.8	-	-
Branching ratio	-	-	-	-	-	-	3.0	3.0	-	-	-	-	-	-	-	-
Total systematic	6.2	6.7	6.3	6.3	5.3	5.1	6.1	7.1	5.3	5.3	6.3	5.8	9.9	10.5	8.2	10.6
Total statistical	0.6	3.1	0.5	0.6	0.6	2.4	3.2	11.6	0.8	1.4	1.2	4.9	0.9	1.8	6.4	12.2

Table 7: Relative systematic uncertainties (%) of the η spectrum for the different reconstruction methods.

Rec. method	PCM		EMC		PHOS		PCM- $\gamma\gamma^*$		PCM-EMC		PCM-PHOS	
	2.75	7.0	2.75	7.0	2.75	7.0	2.75	7.0	2.75	7.0	2.75	7.0
p_T (GeV/c)												
Yield extraction	1.5	6.7	5.7	3.1	6.5	6.9	7.5	17.3	4.1	7.8	6.4	10.0
Cluster description	-	-	2.4	2.5	3.9	3.7	-	-	2.6	2.7	2.7	2.7
Cluster E calib.	-	-	2.2	2.2	1.5	1.5	-	-	2.1	1.6	2.0	2.0
Ch. particle veto	-	-	0.5	0.7	0.8	1.2	-	-	0.5	0.7	0.5	0.7
e^+e^- track rec.	0.3	0.3	-	-	-	-	2.0	2.0	0.3	0.3	0.3	0.3
e^+e^- PID	1.0	2.3	-	-	-	-	1.2	1.2	0.8	1.0	0.8	1.0
PCM photon PID	0.5	1.5	-	-	-	-	2.0	2.0	0.5	0.9	1.1	1.3
Efficiency	-	-	2.0	2.0	1.0	1.0	0.5	0.5	2.0	2.0	1.0	1.0
Outer material	-	-	4.2	4.2	2.0	2.0	-	-	2.1	2.1	1.0	1.0
Inner material	5.0	5.0	-	-	-	-	2.5	2.5	2.5	2.5	2.5	2.5
Norm. & pileup	3.0	2.9	-	-	-	-	-	-	-	-	-	-
Branching ratio	-	-	-	-	-	-	5.8	5.8	-	-	-	-
Total systematic	6.1	9.3	8.0	6.5	8.0	8.3	10.3	18.7	6.6	9.3	7.9	11.0
Total statistical	2.9	6.9	1.7	2.1	6.9	9.2	20.8	45.1	2.0	4.5	7.5	17.5

Table 8: Relative systematic uncertainties (%) of the η/π^0 ratio for the different reconstruction methods.

Rec. method	PCM		EMC		PHOS		PCM- $\gamma\gamma^*$		PCM-EMC		PCM-PHOS	
	2.75	7.0	2.75	7.0	2.75	7.0	2.75	7.0	2.75	7.0	2.75	7.0
p_T (GeV/c)												
Yield extraction	2.1	7.2	6.5	4.1	6.5	6.9	8.1	17.5	4.6	8.1	6.1	12.0
Cluster description	-	-	1.6	2.0	3.7	3.5	-	-	1.9	1.9	2.2	2.2
Cluster E calib.	-	-	-	-	-	-	-	-	-	-	-	-
Ch. particle veto	-	-	0.5	0.5	0.5	0.5	-	-	0.5	0.5	0.5	0.5
e^+e^- track rec.	0.2	0.3	-	-	-	-	2.0	2.0	0.3	0.3	0.3	0.3
e^+e^- PID	1.0	2.2	-	-	-	-	1.2	1.2	0.8	1.0	0.8	1.0
PCM photon PID	0.6	1.8	-	-	-	-	2.0	2.0	0.5	0.9	1.1	1.3
Efficiency	-	-	0.9	0.9	0.6	0.6	0.2	0.2	0.4	0.4	0.4	0.4
Outer material	-	-	-	-	-	-	-	-	-	-	-	-
Inner material	-	-	-	-	-	-	-	-	-	-	-	-
Norm. & pileup	2.6	2.8	-	-	-	-	-	-	-	-	-	-
Branching ratio	-	-	-	-	-	-	6.5	6.5	-	-	-	-
Total systematic	3.5	8.2	6.8	4.7	7.5	7.8	10.8	18.9	5.1	8.4	6.7	12.3
Total statistical	3.0	7.1	1.7	2.1	6.9	9.3	21.4	46.7	2.0	4.6	7.6	17.9

5 Systematic uncertainties

The basis for the evaluation of the systematic uncertainties of the meson spectra and the η/π^0 ratio are variations of all selection criteria presented in Sec. 4: the selection of photon candidates, meson candidates, and the signal extraction. Subsequently, the systematic uncertainties are estimated by comparing the corrected meson spectra obtained with the default setting to those obtained by using variations of each selection criterion. Furthermore, as done in previous measurements of the neutral-meson production, additional sources of systematic uncertainties (cluster energy calibration, inner material, outer material, and efficiency) were estimated and a more detailed breakdown of these sources is presented in [26, 27, 57, 63, 80]. Hence, in this paper, only the dominant sources of uncertainties will be discussed in detail. Tables 6, 7, and 8 show all the sources of systematic uncertainties considered in the analysis and their magnitude in two representative p_T intervals for π^0 , η mesons, and the η/π^0 ratio, respectively. The total systematic uncertainty, given at the bottom of the respective tables, is calculated by adding the single sources in quadrature, as no correlation between the different sources is expected. In the following, these components will be discussed briefly.

One of the leading sources of uncertainty of the PCM reconstruction method as well as the hybrid and PCM- $\gamma\gamma^*$ reconstruction methods is the uncertainty arising from the material budget. It represents the precision to which the material of the ALICE experiment between the collision vertex and the outer wall of the TPC is implemented in the MC simulation. This uncertainty was reduced compared to previous publications on neutral mesons [57]. An uncertainty of 2.5% per photon is assigned, leaving the PCM method with a total of 5% and the hybrid reconstruction methods with 2.5%.

As for the inner material, the uncertainty on the outer material describes the precision to which the detector material that lies between the TPC and the calorimeters is described in the MC. This includes both the material of the TRD and TOF detectors and their support structures. For the EMCal, this was studied in [27] where EMCal modules with and without TRD modules in front were present. An uncertainty of 4.2% for the EMCal was assigned, which is one of the leading uncertainties. For the PHOS detector, the uncertainty is estimated by comparing data with and without magnetic field, which affects the converted photons in the detector material differently. An uncertainty of 2% was found, which is much lower compared to the EMCal due to less material in front of the PHOS.

Systematic uncertainties on the e^+e^- track reconstruction, selection, and the subsequent PCM-photon PID are small compared to the material budget and the signal extraction, due to the excellent tracking performance of ALICE. In the case of the PCM- $\gamma\gamma^*$ measurement, the e^+e^- track reconstruction and selection also includes primary e^+e^- tracks, and thus, the systematic uncertainties are slightly larger compared to all other methods.

For the calorimeter-based invariant-mass reconstruction methods, the uncertainty of the cluster description, which comprises variations of the selection criteria given in Tab. 3, is one of the leading uncertainties. For EMCal, the uncertainty originating from the description of the σ_{long}^2 is the largest source within this category, while for the PHOS, the uncertainty related to the cluster timing is dominant at low and high p_T . Furthermore, the uncertainty on the cluster energy calibration, explained in detail in [52] for the EMCal, is estimated to be about 2% for both EMCal and PHOS. For PHOS the uncertainty is obtained by comparing the energy calibration estimated using e^+e^- track to cluster matching and by using the π^0 peak position.

For the purity-based calorimeter methods, the largest source of uncertainty is the description of the σ_{long}^2 in the MC, which is listed in the cluster description for the mEMC and the efficiency for the mPHOS. Furthermore, overlapping showers from two or more π^0 might not be correctly described by the MC, as it depends on the jet fragmentation. By varying the fraction of clusters with overlapping particles, an uncertainty of 5–8% was found.

To estimate the uncertainty for the signal extraction, the integration window, the fit range for the background as well as the background description is varied. For the π^0 , the uncertainty related to the signal extraction is rather small as the π^0 significance is high. However, for the η it becomes one of the dominating uncertainties at low and high p_T .

The multiplicity dependence of the different sources of systematic uncertainties was studied and found to be negligible within the statistical uncertainties for most of the sources, including variations of the cluster, conversion photon, and meson selection as listed in Tab. 3, 4, and 5. Multiplicity-dependent systematic uncertainties are assigned for the contribution from out-of-bunch pileup, the signal extraction as well as for the efficiency correction as outlined in the following. The contribution from out-of-bunch pileup was found to be up to 7% for the lowest multiplicity and negligible for the highest multiplicity intervals. Uncertainties assigned for the signal extraction for both the π^0 and η meson are evaluated for each multiplicity interval separately. Furthermore, the signal and event losses, by default estimated using PYTHIA8, are highly generator dependent. Thus, variations with EPOS LHC and PHOJET are considered to estimate the systematic uncertainty. Additionally, a systematic uncertainty that accounts for the efficiency correction, which slightly varies with multiplicity depending on the reconstruction method, is assigned by taking half the size of the estimated shift of the efficiency.

Systematic uncertainties for the ratios of the π^0 and η meson p_T spectra to the inclusive p_T spectrum, as presented in Sec. 6.4 cancel for all sources of uncertainties that are not multiplicity dependent. All multiplicity-dependent uncertainties are propagated to the ratios.

6 Results

6.1 π^0 and η meson inelastic differential cross section

The invariant differential π^0 and η cross sections are obtained according to Eq. 6.1 for each reconstruction method. The corrections to the raw meson yield ($N^{\pi^0(\eta)}$) discussed in Sec. 4.3 are applied, including the correction of the raw π^0 yield for secondary π^0 from weak decays ($N_{\text{sec}}^{\pi^0}$). Furthermore, the normalization of the integrated luminosity is taken from [78], while for the calorimeter-triggered data the enhancement factor is used in addition (see Tab. 1).

$$E \frac{d^3\sigma}{dp^3} = \frac{1}{2\pi} \frac{1}{p_T} \frac{1}{\mathcal{L}_{\text{int}}} \frac{1}{A^{\pi^0(\eta)} \epsilon_{\text{rec}}^{\pi^0(\eta)}} \frac{1}{BR} \frac{N^{\pi^0(\eta)} - N_{\text{sec}}^{\pi^0}}{\Delta y \Delta p_T} \quad (6.1)$$

The individual spectra obtained with the different reconstruction methods are combined via a weighted average [51], taking into account the correlation of the systematic uncertainties between the measurements using the Best Linear Unbiased Estimate (BLUE) method [81, 82]. The different reconstruction methods are statistically uncorrelated, and it is assumed that there is no correlation of systematic uncertainties between the PCM, the EMC, and the PHOS measurements. However, the hybrid methods PCM-EMC and PCM-PHOS are correlated to the PCM method as well as the respective calorimeter method, while the PCM- $\gamma\gamma$ and PCM- $\gamma\gamma^*$ are only correlated via the PCM- γ . Uncertainties related to the reconstruction of the conversion photons are fully correlated between the PCM-method with respect to the PCM-Calo methods or PCM- $\gamma\gamma^*$ method. In addition, the systematic uncertainty assigned for the cluster description and cluster energy calibration uncertainty is also fully correlated between the PCM-Calo and the Calo methods as well as for the EMC (PHOS) and merged mEMC (mPHOS) analyses. The uncertainty related to the signal extraction is assumed to be fully independent between the different methods.

Due to the finite bin width and the steeply falling π^0 and η spectrum, the bin center does not represent the true value of each respective bin [83]. Hence, the bin centers are shifted in p_T by assuming the spectral

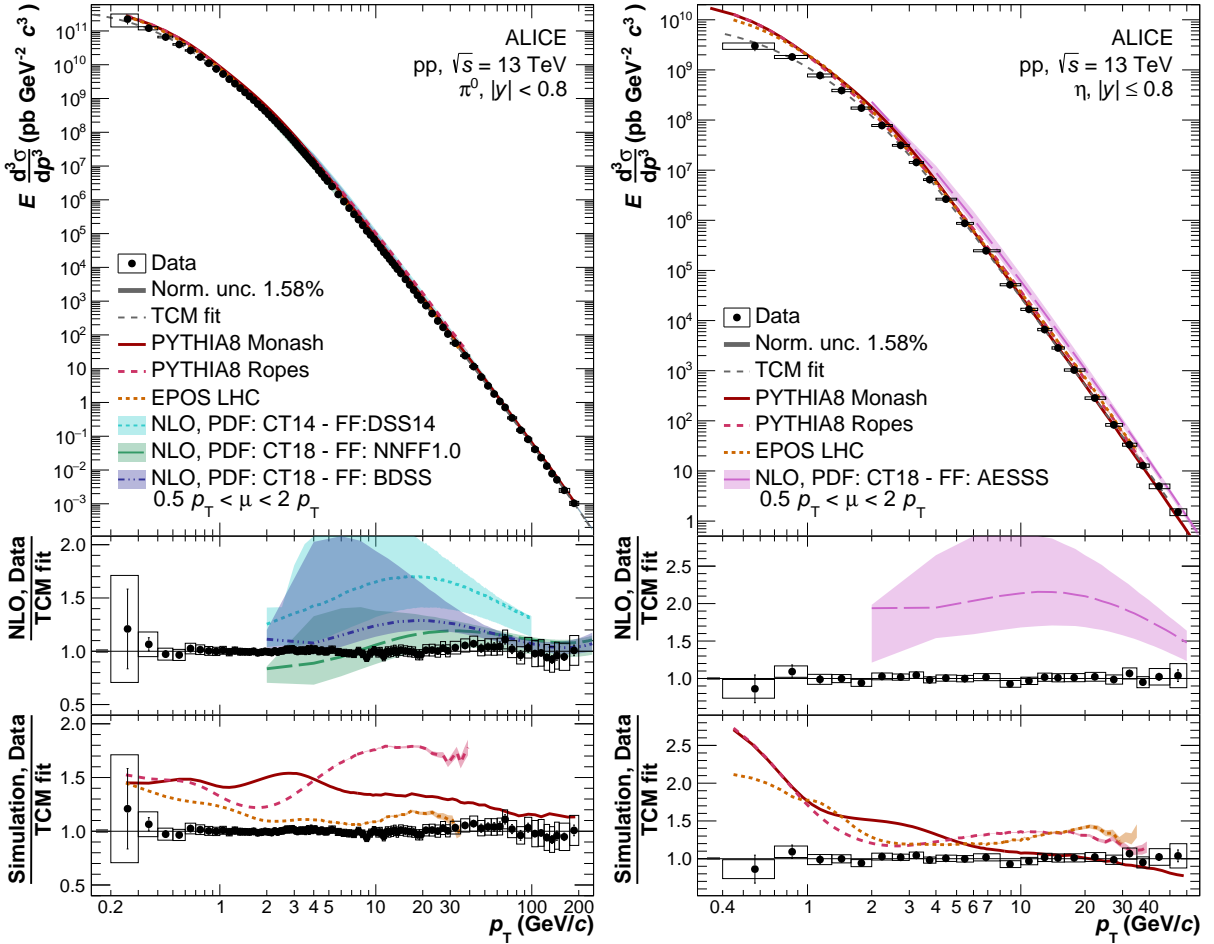


Figure 6: Invariant differential cross section of π^0 (left) and η (right) versus transverse momentum for pp collisions at $\sqrt{s} = 13$ TeV. The data are parametrized with a modified TCM model (see Eq. 6.2) and compared to predictions from PYTHIA8 Monash, PYTHIA8 Ropes, EPOS LHC and predictions from NLO pQCD calculations using recent PDFs and FFs. Ratio plots of the data and model calculations to the modified TCM fit of the data are shown in the lower panels. Statistical error bars are represented by vertical bars, and systematic uncertainties are shown as boxes.

shape obtained by a combined, modified two-component model (TCM) parametrization [84]

$$E \frac{d^3\sigma}{dp^3} = A_e \exp\left(-\frac{\sqrt{p_T^2 + M^2} - M}{T_e}\right) + A \left(1 + \frac{p_T^2}{T^2 n}\right)^{-n - m p_T}. \quad (6.2)$$

Here, M is the meson mass in GeV/c^2 , A_e and A (in $\text{pb GeV}^{-2} c^3$) are the normalization factors, T_e and T are the temperature parameters in GeV , and n is the power law order with $m p_T$ being a p_T dependent term to account for deviations of the π^0 spectrum from a pure power-law form at high transverse momenta. The relative correction due to the finite bin width is below 1% for the π^0 and below 2% for the η above $p_T = 0.8 \text{ GeV}/c$ while the first point has a correction of $\approx 3.6\%$. For the η/π^0 ratio, a shift in p_T cannot be performed as the π^0 and η spectra may have different spectral shapes and therefore need slightly different corrections. Hence, for the η/π^0 ratio, the shift is performed along the y -coordinate for both the π^0 and η spectra. The resulting correction is below 1% for all p_T bins as the spectral shapes of π^0 and η are similar.

Figure 6 shows the differential invariant cross section for the neutral pion (left) and the η meson (right) for a transverse momentum range of $0.2 < p_T < 200 \text{ GeV}/c$ and $0.4 < p_T < 60 \text{ GeV}/c$, respectively. The spectra are parameterized using a modified TCM parametrization (see Eq. 6.2). As [45] suggests, the

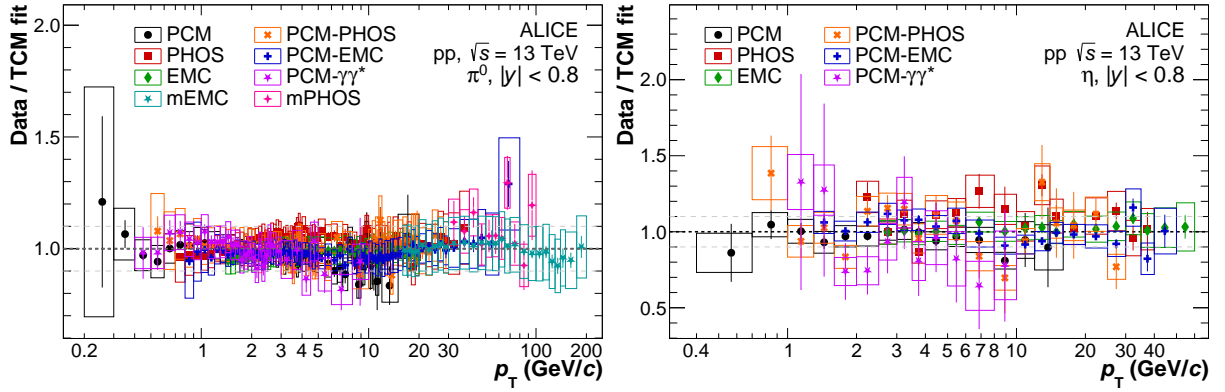


Figure 7: Ratio between each individual π^0 (left) and η (right) invariant differential cross section measurement, and the TCM fit to the combined spectrum. The statistical uncertainties are represented as vertical error bars whereas the systematic uncertainties are shown as boxes.

Table 9: Parameters of the modified TCM parametrization given in Eq. 6.2 for the neutral pion and the η meson as shown in Fig. 6.

	$A_e \times 10^{-9} \left(\frac{\text{pb} \times c^3}{\text{GeV}^2} \right)$	T_e (GeV)	$A \times 10^{-9} \left(\frac{\text{pb} \times c^3}{\text{GeV}^2} \right)$	T (GeV)	n	$m \times 10^3 \left(\frac{c}{\text{GeV}} \right)$
π^0	(427 ± 49)	0.157 ± 0.007	(26 ± 2)	0.65 ± 0.01	2.96 ± 0.01	(0.30 ± 0.05)
η	(5.95 ± 3.61)	0.173 ± 0.046	(3.15 ± 0.56)	0.81 ± 0.03	2.93 ± 0.01	-

deviation from the power-law shape at high p_T arises from the running coupling constant α_s and the scale evolution of the PDF and FF. All free parameters of the fit are given in Tab. 9. To compare the different measurements, the ratio of each one to the fit of the combined measurement is shown in Fig. 7. A very good agreement among the different measurement methods is obtained within the uncertainties over the full p_T range.

The measured invariant differential cross sections are compared to predictions from the event generators PYTHIA8 with the Monash tune and the Ropes variant as well as EPOS LHC. NLO pQCD calculations for the meson production cross sections are also shown in Fig. 6. The same factorization scale value μ ($0.5p_T < \mu < 2p_T$) is used for the factorization, renormalization, and fragmentation scales in these calculations. For the π^0 , the calculation using CT18 PDF [20] and NNFF1.0 FF [22] describes the measurement within the uncertainties. In contrast, the calculation using CT14 PDF [85] together with the DSS14 FF [21] overestimates the production rate, as also seen in previous results of neutral pions at LHC energies [30]. The calculation using the BDSS FF [86] describes the data well at low and large p_T and slightly overestimates the data for $5 \lesssim p_T \lesssim 50$ GeV/c. It is noteworthy that the NNFF1.0 FF is tuned exclusively to data from electron-positron annihilation, showcasing the universality of the FF. Furthermore, it uses a neural network approach to describe the data, giving it more free parameters and fewer constraints on the shape of the FF than traditional approaches as used in the DSS and BDSS FF. The DSS14 FF incorporates data from RHIC and early LHC measurements, including the neutral pion measurement in pp collisions at $\sqrt{s} = 7$ TeV [24]. The BDSS FF additionally incorporates a large fraction of recent neutral and charged pion results from RHIC and LHC. In contrast to the DSS14 FF, the BDSS FF achieves a good description of the data with a consistent set of FF by taking the theoretical scale dependence in the global QCD analysis into account [86]. The NLO pQCD prediction of the η meson production using CT18 PDF and the AESSS FF [23] overestimates the η as also seen in [30].

The prediction from PYTHIA8 overestimates the production of neutral pions over nearly the full p_T range for both variants. A similar result can be seen for charged pions [42]. The prediction from EPOS LHC is in better agreement with the π^0 data compared to PYTHIA8, especially for $p_T > 1$ GeV/c. Predictions for the η meson by both PYTHIA8 and EPOS LHC do not describe the spectrum and have a different p_T dependence than the measurement.

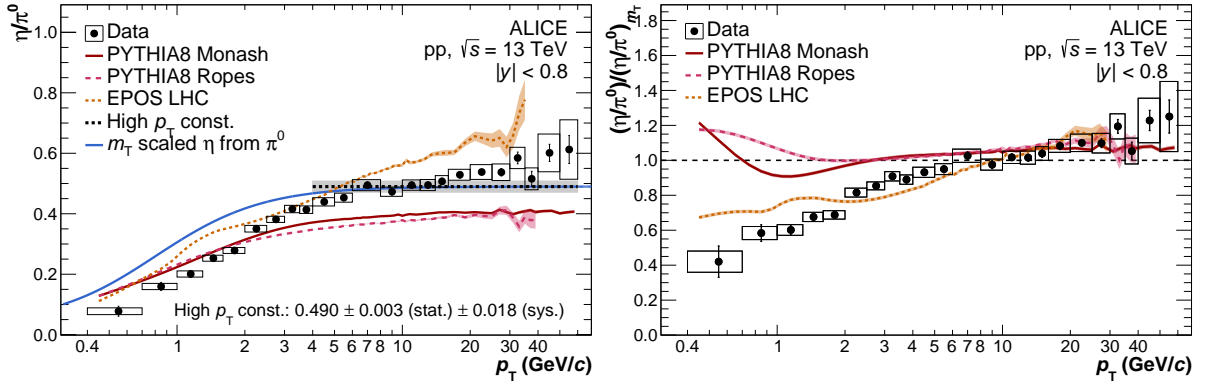


Figure 8: Left: the η/π^0 ratio as a function of p_T compared to expectations from PYTHIA8, EPOS LHC, and m_T scaling. Right: Ratio of data and model predictions to the respective m_T scaling prediction.

6.2 η/π^0 ratio and m_T scaling

Figure 8 (left) shows the η/π^0 ratio as a function of p_T from 0.4 GeV/c up to 60 GeV/c. The result is obtained by studying the π^0 production cross section in the same p_T intervals as used for the η meson for each reconstruction method. Systematic uncertainties are evaluated on the η/π^0 ratio directly to cancel systematic uncertainties that are common for both the η and the π^0 . The combination of the η/π^0 ratio follows the same principles as used in the combination of the production cross sections discussed before (see Sec. 6.1). The η/π^0 ratio significantly rises with p_T for $p_T < 4$ GeV/c as expected from the mass difference between the mesons. According to m_T scaling, the ratio should saturate at high p_T . Hence, a constant fit above $p_T = 4$ GeV/c is performed, giving a value of 0.490 ± 0.003 (stat.) ± 0.018 (sys), compatible with a universal asymptotic value of 0.487 ± 0.024 obtained in pp collisions at LHC and RHIC energies [39]. To verify the validity of m_T scaling, the expected ratio given by m_T scaling is also shown in Fig. 8 (left) for comparison. It is calculated using the parametrization of the π^0 cross section (Tab. 9) evaluated at the transverse mass of the η meson: $E d^3 N^\eta / dp^3 = C_m P_{\pi^0} \left(\sqrt{p_T^2 + m_\eta^2 - m_{\pi^0}^2} \right)$, with C_m being the aforementioned high- p_T constant. For $p_T > 4$ GeV/c the measurement is roughly compatible with m_T scaling, however, the data suggests a rising η/π^0 ratio. For $p_T < 4$ GeV/c the data is increasingly deviating from the m_T -scaling expectations as p_T decreases, reaching a deviation of 60% at $p_T = 0.550$ GeV/c. This was observed before [27, 28, 30, 41, 42] and can be explained by a large contribution from feed-down to the π^0 spectrum that is largest at low p_T [39–41]. The predictions from PYTHIA8 underestimate the measured η/π^0 ratio above $p_T \approx 3$ GeV/c which was also observed in previous comparisons of the η/π^0 ratio at lower center-of-mass energies [24, 27]. The prediction from the EPOS LHC event generator overestimates the measured η/π^0 ratio over the whole p_T range and does not describe the shape of the data.

To further investigate the validity of m_T scaling, the ratio of the measured η/π^0 ratio as well as the η/π^0 ratio obtained from the event generators is compared to a m_T -scaling prediction, which are presented in Fig. 8 (right) as a function of p_T . The m_T -scaling prediction was determined for the data and the predictions from the MC simulation event generators individually. While both PYTHIA8 tunes follow the m_T -scaling prediction within approximately 20%, the deviation of both EPOS LHC and the measurement to the m_T -scaling prediction increases up to 40% and 60% respectively, at $p_T \approx 0.5$ GeV/c.

6.3 x_T scaling

According to pQCD calculations, the production cross section, as presented in Sec. 6.1, can be expressed as a function of x_T ($x_T = 2p_T/\sqrt{s}$ at $y \approx 0$) and \sqrt{s} :

$$E \frac{d^3 \sigma}{dp^3} = F(x_T) / \sqrt{s}^{n(x_T, \sqrt{s})} \quad (6.3)$$

The power-law exponent $n(x_T, \sqrt{s})$ in Eq. 6.3 is approximately constant in the perturbative region above $p_T \approx 3$ GeV/c. A slight dependence is introduced by the running coupling of α_s and the scale evolution of the PDF and FF [45] as discussed previously. If x_T scaling holds, the production cross section of hadrons as a function of x_T is universal for different center-of-mass energies if scaled with $\sqrt{s}^n(x_T)$, as Eq. 6.3 suggests. The exponent $n(x_T)$ can be estimated for all possible combinations of two hadron spectra of the same species at two different center-of-mass energies ($\sqrt{s_1}$ and $\sqrt{s_2}$) using Eq. 6.4.

$$n(x_T, \sqrt{s_1}, \sqrt{s_2}) = -\frac{\ln(\sigma_{\text{inv}}(\sqrt{s_1}, x_T)/\sigma_{\text{inv}}(\sqrt{s_2}, x_T))}{\ln(\sqrt{s_1}/\sqrt{s_2})}. \quad (6.4)$$

The validity of x_T scaling was tested for recently published charged hadron measurements at LHC energies [42, 46] and previously also at lower collision energies [3–9]. Tests of x_T scaling, using the measured π^0 and η meson production cross sections at $\sqrt{s} = 13$ TeV, together with previous measurements of these particles in pp collisions at $\sqrt{s} = 0.9, 2.76, 7$ and 8 TeV [24, 26, 27], are presented in the x_T range from 6×10^{-4} to 3×10^{-2} and 6×10^{-4} to 9×10^{-3} for the π^0 and the η mesons, respectively. Figure 9 (left) shows the exponent $n(x_T, \sqrt{s_1}, \sqrt{s_2})$ for all available combinations of measurements for the π^0 (top) and the η (bottom) as a function of x_T . Arrows indicate the perturbative regime for each center of mass energy which is expected to start at $p_T = 3$ GeV/c. Below that point, a decrease of n can be perceived as soft physics, not calculable in pQCD, dominating the particle production. Above, a plateau region is observed that coincides for all pairs in the perturbative regime. For data points including the data from $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV, where the p_T spectra reach up to $p_T = 200$ GeV/c, a slight decrease of n with rising x_T can be seen. This trend is expected, as a pure power-law term is not able to describe the spectrum for $p_T \gtrsim 3$ GeV/c as shown in Sec. 6.1. However, as the dependence on x_T is only mild, an approximate scaling still holds true. To estimate n_{eff} a combined fit is performed using all data points in their respective perturbative regime. For the neutral pion, a value of $n_{\text{eff}, \pi^0} = 5.01 \pm 0.05$, while for the η meson $n_{\text{eff}, \eta} = 4.91 \pm 0.06$ is observed. The two values are in agreement within their respective uncertainties, even though their x_T range as well as the available number of input spectra are different. The fit uncertainty is estimated from the uncertainties of the fit parameters themselves, as well as by varying the assumption on the start of the perturbative region to $p_T = 2$ GeV/c and $p_T = 4$ GeV/c. Figure 9 (right) shows the scaled x_T spectra for the π^0 and the η . As expected, all spectra follow the same trend in their respective perturbative region, demonstrating the validity of x_T scaling over the x_T range 6×10^{-4} to 3×10^{-2} covered by the ALICE neutral meson measurements. The agreement of the scaled x_T spectra is shown in [68], where the ratio of the spectra to a parametrization is presented. The majority of the data agree within about 10% in the perturbative region. The value of $n_{\text{eff}, \pi^0} = 5.01 \pm 0.05$ is found to be in agreement with the value of $n_{\text{eff}, \pi^\pm} = 5.04 \pm 0.02$ for charged pions reported in [42] where similar center-of-mass energies are used. Additionally, it is in agreement with the expectations from pQCD calculations at LHC energies [45]. On the other hand, the exponent n is smaller than the one at lower collision energies [3–9], in agreement with an increase of hard scattering processes at LHC energies.

6.4 Cross section dependence on the charged-particle multiplicity

Neutral-meson production is measured in eleven charged-particle multiplicity intervals (see Tab. 2). The multiplicity is estimated using the VOM detector system at forward and backward rapidity to avoid autocorrelations with the presented neutral meson measurement at midrapidity. The highest multiplicity interval covers the 0.01% collisions with the highest forward charged-particle multiplicities. The extraction of the neutral meson corrected yield follows the same procedure as described for the inclusive measurement, with slight adjustments as mentioned in Sec. 4.3. Figure 10 shows the π^0 and η invariant yield as a function of p_T for the eleven VOM charged-particle multiplicity classes as well as for the inclusive case. The p_T coverage for the low and high charged-particle multiplicity intervals is limited compared to the inclusive spectrum as the statistics in each multiplicity interval are lower compared to the inclusive data. The individual spectra are scaled with a constant to allow a visible separation.

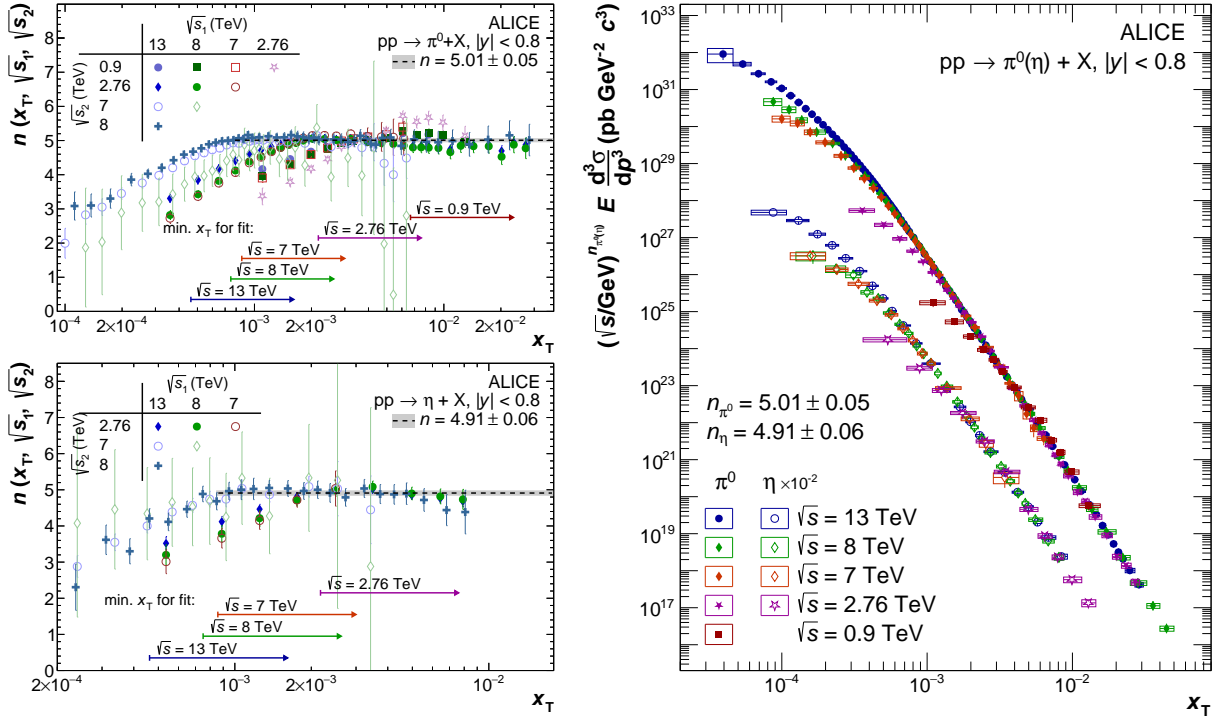


Figure 9: (left) Parameter n as a function of x_T for several π^0 (top) and η (bottom) spectra ratios at different collision energies. (right) Scaled differential invariant cross section of π^0 (left) and η (right) as a function of x_T at different collision energies from $\sqrt{s} = 0.9$ TeV to $\sqrt{s} = 13$ TeV [24–27].

To further investigate differences between the spectra obtained in different charged-particle multiplicity classes, Fig. 11 shows the ratios of the π^0 (left) and η (right) spectra to the p_T spectra obtained in the full INEL >0 event class. The ratios have a strong dependence on p_T and the charged-particle multiplicity, showing a clear rise and hardening of the meson production with multiplicity. The hardening of the spectra was previously reported for charged hadrons [87] as well as for charged pions, kaons, and protons [88]. These results extend the p_T range of the charged-particle multiplicity-dependent identified pion spectra from $p_T = 20$ GeV/ c to between $p_T = 50$ GeV/ c and 200 GeV/ c depending on the multiplicity class. Comparisons to PYTHIA8 with the Monash tune and the Ropes variant show a reasonable description by the models of both the hardening and the ordering of the π^0 and η spectra ratios. However, the Ropes variant performs slightly better than the Monash tune, as already observed for other multiplicity-dependent measurements [88, 89]. In contrast to PYTHIA8, EPOS LHC fails to describe the spectral shape at high p_T , where it deviates from the hardening with rising charged-particle multiplicity.

To further quantify the changing shape of the π^0 and η spectrum with the charged-particle multiplicity, an exponential fit is performed at low p_T , while at high p_T the spectrum is parametrized using a power-law function. The characteristic parameter for each of these two functions is shown in Fig. 12 as a function of the normalized mean charged-particle multiplicity $\langle dN_{\text{ch}}/d\eta \rangle_{\text{mult}}/\langle dN_{\text{ch}}/d\eta \rangle_{\text{INEL}>0}$ measured at mid rapidity ($|\eta| < 0.5$) for data together with the prediction from PYTHIA8 Ropes and EPOS. The exponential term is underestimated by both models for the π^0 , whereas the general trend of the power-law term is described by PYTHIA while EPOS shows a different trend with multiplicity. Comparisons including the PYTHIA8 Monash tune can be found in [68]. Discrepancies in the exponential term between the π^0 and η mainly arise from the different p_T intervals as the π^0 can be measured to much lower p_T compared to the η . The power-law exponents are in agreement with the measured ones for charged hadrons [87].

6.5 Multiplicity dependence of the η/π^0 ratio

The η/π^0 ratio is calculated in the same eleven charged-particle multiplicity intervals as the individual π^0 and η spectra, following the same procedure as described in Sec. 6.2 for MB collisions. Figure 13

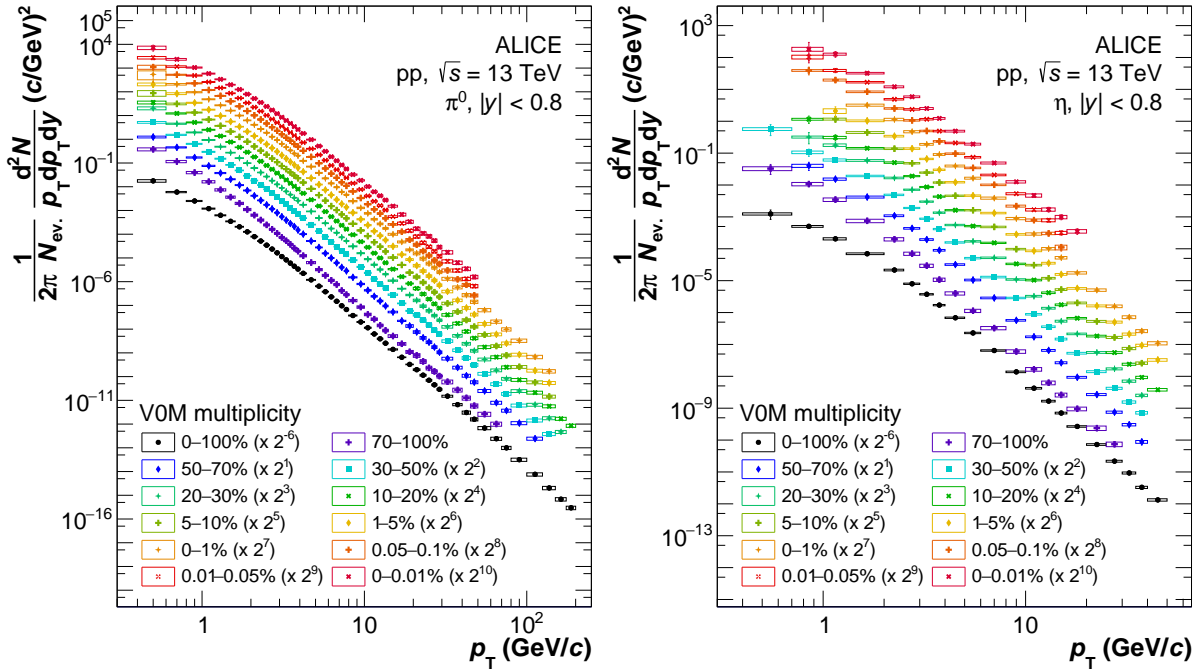


Figure 10: Invariant differential yields of π^0 (left) and η mesons (right) in each selected multiplicity class as defined in Tab. 2. Spectra are scaled for better visibility.

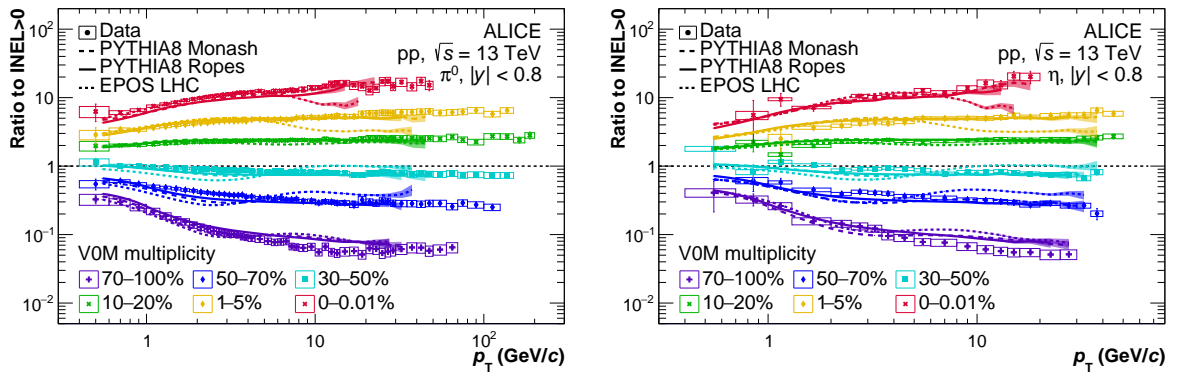


Figure 11: Ratios of the invariant differential yields of π^0 (left) and η mesons (right) to the spectra obtained in the INEL>0 event class together with predictions from PYTHIA8 with the Rope and Monash tunes as well as EPOS LHC.

(left) shows the η/π^0 -ratio for a high and low multiplicity interval, as well as for the inclusive data. To investigate a possible modification of the η/π^0 ratio with the charged-particle multiplicity, the ratio to the measurement in the integrated INEL>0 event class is performed for each multiplicity interval, obtaining the η/π^0 double ratios shown in Fig. 13 for a high and low multiplicity interval. The sources of systematic uncertainties of these ratios include the signal extraction as well as the uncertainty of the efficiency correction. These ratios are calculated for each reconstruction method and then combined via a weighted average [51] using the BLUE algorithm [81, 82].

A quantitative study of the different η/π^0 double ratios is done by calculating the average value of the ratio in two p_T intervals representing the low ($1 < p_T < 4$ GeV/c) and high p_T ($5 < p_T < 15$ GeV/c) regions. The results are shown in Fig. 13 (right) as a function of the normalized mean charged-particle multiplicity measured at midrapidity ($|\eta| < 0.5$). The systematic uncertainties for the data are calculated assuming fully correlated systematic uncertainties of the data points shown in the lower panel of Fig. 13. The uncertainty band for the generator curves is evaluated by taking the difference between

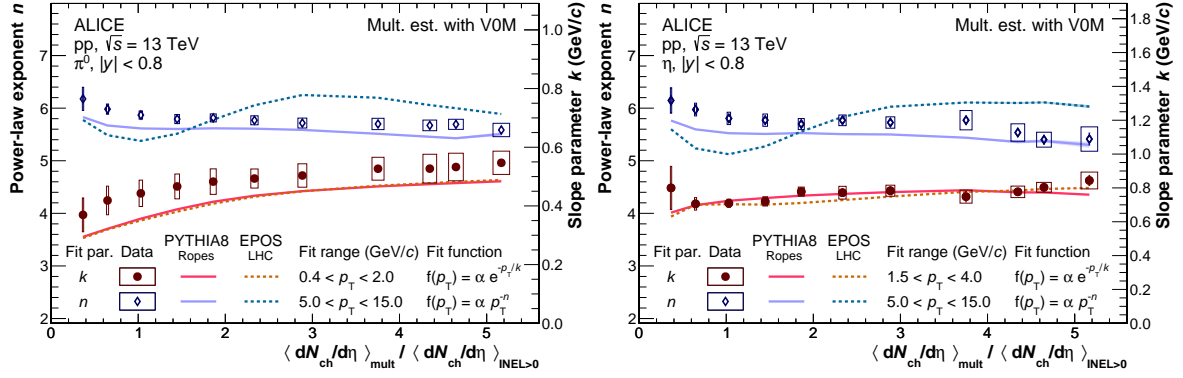


Figure 12: Parameters of a power-law fit and an exponential fit as a function of the charged-particle multiplicity density in units of the average multiplicity density for the INEL>0 event class for the neutral pion (left) and the η meson (right). The data are compared to predictions from PYTHIA8 Ropes and EPOS LHC.

the mean value and the largest and smallest value in the inspected p_T interval. A dependence of the η/π^0 ratio as a function of the normalized charged-particle multiplicity is observed for the low p_T interval $1 < p_T < 4$ GeV/c: an enhancement of the double ratio can be seen at low multiplicity while a suppression is visible for high multiplicities. The η/π^0 ratio in the high- p_T interval is in agreement with unity over the full multiplicity range, taking into account statistical and systematic uncertainties.

PYTHIA8 Ropes and EPOS LHC describe the behavior qualitatively, however with different magnitudes. The PYTHIA8 Monash tune shows the same trend as the Ropes variant as shown in [68]. In PYTHIA8, the dependence of the η/π^0 ratio is driven by an enhancement of π^0 mesons from feed-down of heavier particles, primarily ρ^\pm , ω and η mesons, with rising multiplicity. The fraction of these non-prompt (from hadronic decays) π^0 is largest at low p_T , resulting in the multiplicity dependence seen in Fig. 13 (right) for the low- p_T interval, while the high- p_T interval is nearly unaffected. A similar effect is also seen in the EPOS model. However, in contrast to PYTHIA8, where the ratio of prompt η to π^0 is approximately constant with multiplicity, EPOS shows a more pronounced dependence of the prompt and non-prompt η/π^0 ratio with multiplicity.

The results of the multiplicity dependence of the η/π^0 ratio can be compared to the K^\pm/π^\pm ratio due to the similar masses of the η and the π^0 to the charged kaons and charged pions, respectively. The K^\pm/π^\pm ratio as a function of the charged-particle multiplicity was reported in [88] where a slight enhancement of the p_T -integrated K^\pm/π^\pm ratio with rising multiplicity was found. However, for comparable p_T intervals ($0.5 < p_T < 0.55$ GeV/c, $2.4 < p_T < 2.6$ GeV/c) as presented in this paper for the η/π^0 ratio, no significant modification of the K^\pm/π^\pm ratio is observed. These results suggest that the enhancement for the kaon, containing a strange quark, is stronger than for the η , which only contains hidden strangeness.

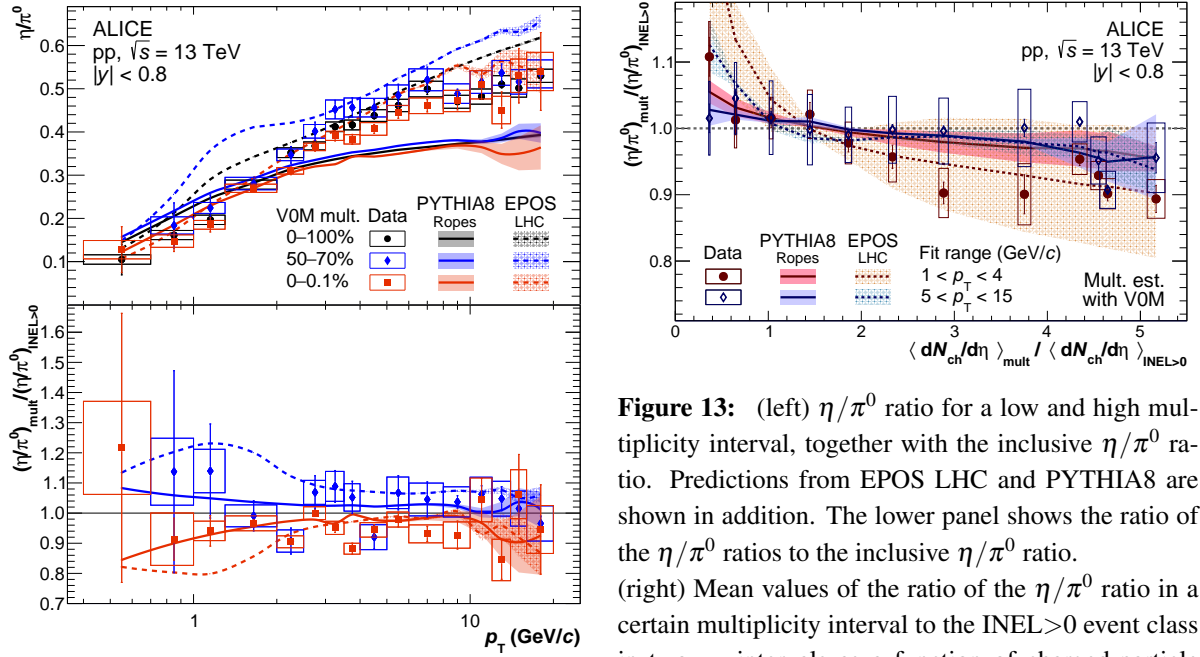


Figure 13: (left) η/π^0 ratio for a low and high multiplicity interval, together with the inclusive η/π^0 ratio. Predictions from EPOS LHC and PYTHIA8 are shown in addition. The lower panel shows the ratio of the η/π^0 ratios to the inclusive η/π^0 ratio. (right) Mean values of the ratio of the η/π^0 ratio in a certain multiplicity interval to the INEL>0 event class in two p_T intervals as a function of charged-particle multiplicity.

7 Conclusion

We have presented the measurement of π^0 and η mesons at midrapidity in inelastic pp collisions at $\sqrt{s} = 13$ TeV as well as the production of these mesons as a function of the charged-particle multiplicity. The p_T invariant differential cross sections are extracted in the kinematic range of $|y| < 0.8$ and $0.2 < p_T < 200$ GeV/c for the π^0 and $0.4 < p_T < 50$ GeV/c for the η . These results provide constraints to PDF and FF functions over an unprecedented kinematic range. A violation of m_T scaling is confirmed at $\sqrt{s} = 13$ TeV for $p_T < 4$ GeV/c as observed at lower energies, as well as a hint of m_T scaling violation at higher transverse momenta. The data are in agreement with x_T scaling predictions for LHC energies over the x_T range from 6×10^{-4} to 3×10^{-2} . The exponent n for π^0 x_T spectra agrees with the values obtained at LHC energies for charged pions and is slightly smaller than the one at RHIC energies.

Next-to-leading order pQCD calculations using the NNFF1.0 or the BDSS FF describe the π^0 transverse momentum spectrum better than calculations using the older DSS14 FF. Calculations for the η meson based on pre-LHC FF (AESSS) overestimate the data over the complete p_T range. Predictions from PYTHIA8 overestimate the π^0 spectrum and miss the slope and the yield of the η spectrum. The π^0 and η spectrum from EPOS LHC overestimate the data by about 10–20% at $p_T = 2$ GeV/c, while at lower p_T the deviation becomes larger.

The transverse momentum spectra show a hardening with increasing charged-particle multiplicity, as previously observed for other particle species. PYTHIA8 qualitatively describes the dependence of the spectra on the charged-particle multiplicity, while EPOS fails to describe the spectra above $p_T \approx 3$ GeV/c. The η/π^0 ratio shows a slight dependence on the charged-particle multiplicity at low transverse momenta. In low multiplicity events, the η/π^0 ratio shows a slight enhancement at low p_T , while a depletion at low p_T of up to 10% is observed for high multiplicities. For $p_T > 4$ GeV/c, no such dependence was found. This dependence is attributed to contributions from feed-down from heavier particles into the π^0 spectrum, which is most relevant at low transverse momenta. Hence, both PYTHIA8 and EPOS LHC are able to describe this dependence qualitatively.

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























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