π⁰ and η meson production in proton-proton collisions at \( s\sqrt{s} = 8 \text{ TeV} \)

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\( \pi^0 \) and \( \eta \) meson production in proton-proton collisions at \( \sqrt{s} = 8 \) TeV

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**Abstract** An invariant differential cross section measurement of inclusive \( \pi^0 \) and \( \eta \) meson production at mid-rapidity in pp collisions at \( \sqrt{s} = 8 \) TeV was carried out by the ALICE experiment at the LHC. The spectra of \( \pi^0 \) and \( \eta \) mesons were measured in transverse momentum ranges of \( 0.3 < p_T < 35 \) GeV/c and \( 0.5 < p_T < 35 \) GeV/c, respectively. Next-to-leading order perturbative QCD calculations using fragmentation functions DSS14 for the \( \pi^0 \) and AESSS for the \( \eta \) overestimate the cross sections of both neutral mesons, although such calculations agree with the measured \( \eta/\pi^0 \) ratio within uncertainties. The results were also compared with PYTHIA 8.2 predictions for which the Monash 2013 tune yields the best agreement with the measured neutral meson spectra. The measurements confirm a universal behavior of the \( \eta/\pi^0 \) ratio seen for NA27, PHENIX and ALICE data for pp collisions from \( \sqrt{s} = 27.5 \) GeV to \( \sqrt{s} = 8 \) TeV within experimental uncertainties. A relation between the \( \pi^0 \) and \( \eta \) production cross sections for pp collisions at \( \sqrt{s} = 8 \) TeV is given by \( m_\pi \) scaling for \( p_T > 3.5 \) GeV/c. However, a deviation from this empirical scaling rule is observed for transverse momenta below \( p_T < 3.5 \) GeV/c in the \( \eta/\pi^0 \) ratio with a significance of 6.2σ.

**1 Introduction**

Measuring identified particle production in proton-proton (pp) collisions over wide kinematic ranges is considered an informative probe of strong interactions at high energies. Quantum chromodynamics (QCD) is the fundamental theory of the strong interaction [1]. It succeeds in providing a qualitative description of a wide range of phenomena in hadronic collisions. At typical hadron collider energies its perturbative expansion (pQCD) permits a detailed quantitative comparison with experimental data. However, it remains a challenge to provide a consistent description of hadron spectra at all collision energies reached experimentally. In two categories: the “soft” scattering regime describing particle production involving small momentum transfers and “hard” scattering regime, responsible for producing particles with momenta of several GeV/c or more.

Only “hard” scattering processes with a sufficiently large transverse momentum transfer, \( Q^2 \), can be calculated using methods based on pQCD. High-momentum particles originate from the fragmentation of partons produced in scattering processes with large \( Q^2 \). The theoretical description of a “hard” scattering process can be factorized into parton distribution functions (PDFs), the QCD matrix element, and fragmentation functions (FFs). PDFs describe the fraction of the proton’s longitudinal momentum carried by a scattered parton, \( x \), and FFs describe the ratio of the observed hadron momentum to the final-state parton momentum, respectively. Comprehensive parametrizations of PDFs and FFs are derived from fits to the experimental data at various collision energies. The energies reached at the LHC [2] open up the domains in \( x \) and \( z \) not accessible at lower energy. In the past, experiments at the LHC also found discrepancies between the measured \( \eta \) and \( \pi^0 \) spectra [3–5] and pQCD calculations based on fragmentation functions, which include mostly data from experiments below the TeV scale [6]. Since the gluon distribution becomes more dominant with increased center of mass energy, \( \sqrt{s} \) [7], \( \pi^0 \) and \( \eta \) meson spectra at LHC energies provide new constraints on the gluon to light-flavor hadron fragmentation functions. Recent progress in comprehensive global QCD analysis of parton-to-pion fragmentation functions at next-to-leading order (NLO) [8] derived from inclusive pion production in semi-inclusive electron-positron annihilation, deep-inelastic scattering and pp collisions over a wide energy range, including the LHC results [3], achieves a good and consistent description of pion spectra, including the latest measurements of \( \pi^0 \) and \( \eta \) spectra pp collisions at \( \sqrt{s} = 2.76 \) TeV [9] and 7 TeV [3]. One of the conclusions of that analysis was that meson production fo
In the quark model, the $\pi^0$ consists of light-flavor quark-antiquark pairs, $u\bar{u}$ and $d\bar{d}$, whereas the $\eta$ additionally contains hidden strangeness, $s\bar{s}$. Measurements of both neutral mesons are thus of particular interest due to their different quark content as they help to constrain the PDFs and FFs [11] of the $s$ quark.

The majority of particles at low transverse momenta, $p_T$, are produced in “soft” processes involving a small $Q^2$. In this regime, the pQCD calculations are not applicable for description of the production mechanisms and phenomenological models are based on previous measurements of neutral meson production cross sections or other light mesons by other experiments at lower collision energies. Particle production measurements at transverse momenta down to a few hundred MeV/c, as reported here, are particularly important to further constrain such models.

The importance of precise identified particle production measurements is underlined by various empirical rules observed in relative particle yields which allow estimates of the hadronic background of rare probes such as direct photons, dileptons and heavy-quark production. Almost all lower-energy experiments from ISR to RHIC report the observation of such an empirical rule, so-called $m_T$ scaling, in particle production over wide $p_T$ ranges [12, 13]. The practical use of $m_T$ scaling is the ability to derive the $p_T$-dependent differential yields of most of particles from the well measured light-flavor mesons, like pions and kaons, by assuming that the meson spectra can be described as a function of transverse mass $m_T$: $Ed^3\sigma/dp^3 = C^h f(m_T)$, where the function $f(m_T)$ is universal for all hadron species, so that their spectra share the same shape up to a normalization factor $C^h$ [14]. In the context of rare probes, this empirical relation is hence widely used to estimate the various background sources, for which no measurements are available. However, phenomenological analyses of new data delivered by the LHC experiments show that $m_T$ scaling is violated at higher $p_T$ compared to lower collision energies [14,15]. Therefore, precise measurements of identified hadron spectra over wide transverse momentum ranges at different LHC energies are of particular importance for the quantitative description of particle production at the LHC.

In this paper, the differential invariant production cross sections, $Ed^3\sigma/dp^3$, of $\pi^0$ and $\eta$ mesons and the particle production ratio $\eta/\pi^0$ are presented, measured over wide $p_T$ ranges at mid-rapidity in pp collisions at $\sqrt{s} = 8$ TeV by ALICE. The new experimental results are compared with pQCD calculations using MSTW08 (PDF) [16] with DSS14 (FF) [8] for the $\pi^0$ and accordingly CTEQ6M5 (PDF) [17] with AESSS (FF) [11] for the $\eta$, as well as the PYTHIA8.210 Monte Carlo (MC) event generator [18] with the tunes Tune

This paper is organized as follows: In Sect. 2, the ALICE experiment is briefly described with the focus on the detectors used in this analysis, namely the calorimeters and the central tracking systems. Section 3 describes the datasets, the event selection and also introduces the calorimeter triggers used in this analysis. In Sect. 4, the reconstruction principles for neutral mesons are introduced. Furthermore, the determination of correction factors, which are used to calculate the differential invariant cross sections from the measured raw yields described. Section 5 discusses the various contributions to statistical and systematic uncertainties of the measurements. In Sect. 6, the $p_T$ differential invariant cross sections for $\pi^0$ and $\eta$ meson production in pp collisions at $\sqrt{s} = 8$ TeV are presented and compared with pQCD calculations. Subsequently, the measured ratio of $\eta/\pi^0$ is presented and compared to the same theoretical models. Section 7 concludes the paper with a summary of the obtained results.

2 Detector description

Neutral mesons, $\pi^0$ and $\eta$, decay into photons, which are reconstructed via two fundamentally different detection methods. The first method exploits the measurement of photons using electromagnetic calorimeters. Two such calorimeters are available in ALICE [21, 22]: the electromagnetic calorimeter (EMCal) [23] and the photon spectrometer (PHOS) [24]. The second method of photon detection makes use of photons converted into $e^+e^-$ pairs within the inner detector material located between the interaction point and a radius which corresponds to the midpoint between inner and outer field cage of the time projection cham (TPC) [25]. These electron–positron pairs, originating at secondary vertices ($V^0s$), are reconstructed by the main tracking systems in ALICE centered at mid-rapidity and consist of the inner tracking system (ITS) [26] and the TPC [2]. The aforementioned detectors are described below, noting detector configurations during pp data taking at $\sqrt{s} = 8$ TeV in 2012.

The EMCal detector [23] is a sampling electromagnetic calorimeter. Its active elements, called cells, are composed of alternating layers of lead and plastic scintillator providing a radiation length of 20.1 $X_0$. The scintillation light in each layer is collected by wavelength shifting fibers perpendicular to the face of each cell. The fibers are connected to 5 mm$^3$ active area Avalanche photo diodes (APDs) to detect the generated scintillation light. Each cell has a size of $\Delta \phi = 0.0143 \times 0.0143$ (approx. twice the Molière radius). Groups of 2×2 $\Delta \phi$ are combined into modules, which are further combined $\bar{u}$ arrays of 12×24 modules called supermodules. In total, th
number of 11,520 cells. The EMCal is located at a radial distance of 4.28 m at the closest point from the nominal collision vertex. The intrinsic energy resolution of the EMCal is parametrized as $\sigma_E/E = 4.8\%/E \oplus 11.3\%/\sqrt{E} \oplus 1.7\%$ with $E$ in units of GeV [27]. The relative energy calibration of the detector is performed by measuring, in each cell, the reconstructed $\pi^0$ mass in the invariant mass distribution of photon pairs built with one photon in the given cell. The achieved calibration level is estimated to be 3% and adds up quadratically to the constant term of the energy resolution.

The PHOS [21,24] is a homogeneous electromagnetic calorimeter composed of lead tungstate, PbWO$_4$. The size of its elementary active units, also called cells, is $\Delta \eta \times \Delta \phi = 0.004 \times 0.004 (\approx 2.2 \times 2.2 \text{ cm}^2)$. Thus, the lateral dimensions of the cells are slightly larger than the PbWO$_4$ Molière radius of 2 cm. APDs with an active area of 5 x 5 mm$^2$ detect the scintillation light generated within the detector cells. The spectrometer covers $\Delta \phi = 60^\circ$ in azimuth and $|\eta| < 0.12$ in pseudorapidity and is located at a distance of 4.6 m from the interaction point. It is operated at a temperature of $-25^\circ$ C, at which the light yield of PbWO$_4$ increases by about a factor of three compared to room temperature. The energy resolution of the PHOS is $\sigma_E/E = 1.8\%/E \oplus 3.3\%/\sqrt{E} \oplus 1.1\%$, with $E$ in units of GeV. The fine granularity of the detector enables the measurement of $\pi^0$ candidates up to $p_T \approx 50 \text{ GeV}/c$.

The ITS [26] consists of three sub-detectors each with two layers to measure the trajectories of charged particles and to reconstruct primary vertices. The two innermost layers are the silicon pixel detectors (SPD) positioned at radial distances of 3.9 and 7.6 cm. The middle two layers are silicon drift detectors (SDD) located at 15.0 and 23.9 cm relative to the beam line. The outer two layers are silicon strip detectors (SSD) located at radial distances of 38 and 43 cm. The two layers of SPD cover pseudorapidity ranges of $|\eta| < 2$ and $|\eta| < 1.4$, respectively. The SDD and SSD cover $|\eta| < 0.9$ and $|\eta| < 1.0$, accordingly.

The TPC [25] is a large (90 m$^3$) cylindrical drift detector filled with a gas mixture of Ne-CO$_2$ (90–10%). It covers a pseudorapidity range of $|\eta| < 0.9$ over full azimuth, providing up to 159 reconstructed space points per track. A magnetic field of $B = 0.5$ T is generated by a large solenoidal magnet surrounding the central barrel detectors. Charged tracks originating from the primary vertex can be reconstructed down to $p_T \approx 100 \text{ MeV}/c$ and charged secondaries down to $p_T \approx 50 \text{ MeV}/c$ [22]. The TPC provides particle identification via the measurement of energy loss, d$E$/d$x$, with a resolution of $\approx 5\%$ [25]. Beyond the outer radius of the TPC, the transition radiation detector (TRD) and the time-of-flight detector (TOF) provide additional particle identification information, as well as allowing for improved the EMCal and hence dominate the material budget in front of the EMCal. These detectors are missing in front of PHO in order to provide a minimal radiation length to profit from the high resolution of the spectrometer.

The V0 detector is made up of two scintillator arrays (V1 and V0C) [28] covering $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$. It is used to provide a minimum bias (MB) trigger [29] and reduce background events [22]. It is also used for luminosity determination as described in the next section.

In addition, the T0 detector [32] was used for luminosity determination. It consists of two arrays of Cherenkov counters, T0A and T0C, which respectively cover $4.61 < \eta < 4.92$ and $-3.28 < \eta < -2.97$. The T0 furthermore provides a precise timing signal to other detectors with a resolution better than 50 ps, used as starting signal for the TOF detector for example.

### 3 Datasets and event selection

During the data taking period of pp collisions at $\sqrt{s} = 8$ T in 2012, the LHC operated at high beam intensities of approximately $2 \times 10^{14}$ protons per beam. Collisions at the ALICE interaction point were realized using a so-called “magic satellite” bunch scheme, which involved proton collisions between the high intensity main bunches and low intensity satellite bunches. The interaction probability per bunch crossing was about 0.01, corresponding to a mean instantaneous luminosity of about $5 \times 10^{30} \text{ cm}^{-2} \text{s}^{-1}$. Background events caused by beam-gas interactions or detector noise are rejected in the analysis using the V0A and V0C timing information [22]. Pileup events, with more than one pp collision per bunch crossing, are rejected based on the pileup identification algorithms looking for multiple primary vertices in a single event [22]. Additionally, the SPD is used to reject background events by comparing the number of SPD clusters to the multiplicity of SPD track candidates found the respective collision. Only events with a z-vertex position of $|z| < 10$ cm in the global ALICE coordinate system are accepted for the analysis.

Two different types of triggers were used during data taking to select the events to be recorded: the minimum bias (MB) trigger and the calorimeter triggers, which are provided by the EMCal and the PHOS, to enhance statistics with high $p_T$ by selectively recording events with high energy deposits in the calorimeters. The MB trigger is a hard Level-0 (LO) trigger [29]. It requires at least one hit in central V0A and V0C [28]. Both calorimeters also provide Level-0 triggers: EMC-L0 [30] and PHOS-L0 [31]. These Level-0 calorimeter triggers are required to be in coincidence with the MB trigger.
$E_{EMC-L0} \approx 2 \text{ GeV}$ and $E_{PHOS-L0} \approx 4 \text{ GeV}$, respectively. A software Level-1 (L1) trigger is also deployed for the EMC which inspects events preselected by the EMC-L0 trigger [33]. The trigger algorithm is similar to the EMC-L0, but combines information from different trigger region units to enhance the trigger efficiency and overcome hardware boundary effects [33]. Additionally, a larger trigger threshold of $E_{EMC-L1} \approx 8.4 \text{ GeV}$ is set to further obtain statistics at higher transverse momenta.

In order to correctly normalize each trigger, the trigger rejection factors (RF) are determined by constructing the ratio of cluster energy spectra from MB and calorimeter triggered events as a function of the cluster energy, $E$, which are shown in Fig. 1. The ratios are expected to follow a constant for high cluster energies, the so-called plateau region, assuming the triggers only enhance the rate of clusters but do not affect their reconstruction efficiency. To reduce the statistical uncertainties, the RFs are always determined with respect to the next lower threshold trigger. The cluster energy ratios have a steeper turn-on respective trigger threshold energies. Since the EMC-L0 trigger becomes fully efficient only above its triggering threshold of $E_{EMC-L0} \approx 2 \text{ GeV}$, there is a change of slope visible in the turn-on region of the EMC-L1 trigger. The turn-on curve of the PHOS-L0 trigger also changes its slope due to a non-uniformity of the channels hardware gains. However, only the RF plateau regions are mainly relevant for analysis, as they are needed to correctly normalize the triggered data, which are found to be: $RF_{EMC-L0} = 67.0 \pm 1.1, RF_{PHOS-L0} = (12.4 \pm 1.5) \times 10^3$ and $RF_{EMC-L1} = (14.9 \pm 0.3) \times 10^3$. The last factor is obtained by multiplying the two given rejection factors of the two EMC triggers, see Fig. 1, as the RF for EMC-L1 to MB trigger is of interest.

The luminosity determination is based on the cross-section of the MB trigger condition, $\sigma_{\text{MB AND}}$, measured in a van der Meer (vdM) scan [34, 35]. The stability of the measured cross section throughout the whole data taking period is assessed by comparing the V0-based luminosity measurement with an independent luminosity signal, issued by the T0 detector. As discussed in Ref. [35], this comparison results in an overall normalization uncertainty of 2.6%, which includes contributions from both the vdm-based measurement and its stability over time. The integrated luminosity of each triggered sample is calculated with the number of analyzed events, $N_{\text{events}}$, the respective rejection factors, $RF$, and the MB cross section, $\sigma_{\text{MB AND}} = 55.80 \pm 1.45_{\text{(stat+sys)}} \text{ mb}$ [35], given by:

$$L_{\text{int}} = \frac{N_{\text{events}}}{\sigma_{\text{MB AND}}} \times RF,$$  \hspace{1cm} (1)

for which $RF = 1$ holds for the MB trigger. As the good run

![Fig. 1 Determination of RFs for the PHOS-L0 and EMC-L0/L1 triggers. In the plateau region, the RFs are obtained by fits of constants in the given cluster energy ranges, illustrated by the dotted lines. The uncertainties of the determined RFs are indicated by light color uncertainty bands, which are obtained by varying the fit ranges.]

4 Neutral meson reconstruction

Both $\pi^0$ and $\eta$ mesons are reconstructed via their two-photon decay channels with branching ratios of $98.823 \pm 0.039$ and $39.31 \pm 0.20%$ [36] by means of an invariant mass analysis. The neutral mesons are reconstructed using the two electromagnetic calorimeters, EMC and PHOS, a photon conversion method (PCM) and a hybrid method, PCM-EMC which combines one photon candidate from the PCM and one from the EMC, resulting in four (three) different methods for the reconstruction of $\pi^0$ ($\eta$) mesons. The reconstruction of $\eta$ mesons is not accessible by PHOS due to the limited detector acceptance and, compared to the $\pi^0$, the wide opening angle of the decay photons. The hybrid PCM-EMC method benefits from the high momentum resolution of PCM, a high reconstruction efficiency and, crucially, the triggering capabilities of the EMC. Moreover, an extended $p_T$ coverage is achieved compared to the standalone EM measurement, as there is no limitation due to cluster merging effects, discussed later in this section.

Photons and electrons/positrons generate electromagnetic showers when they enter an electromagnetic calorimeter. They usually spread their energy over multiple adjacent calorimeter cells. In order to reconstruct the full energy impinging particles, those adjacent cells need to be grouped into clusters, which is realized by a clustering algorithm. In the first step, the algorithm looks for the cell that recovers the highest energy in the event, exceeding the seed energy $E_{\text{seed}}$. After the identification of such a seed cell, adjacent cells with recorded energies above a minimum energy $E_{\text{seed}}$.
Table 1 The analyzed luminosities considering the individual statistics for the different reconstruction methods and triggers. The EMCal related measurements use the same list of good runs as indicated by the combined column. The uncertainties denoted with "sys" reflect the systematical uncertainty of RF determination, whereas "norm" represents the uncertainties entering from the cross section determination of MB trigger [35]

<table>
<thead>
<tr>
<th>Reconstruction method</th>
<th>$L_{\text{tot}}$ (nb$^{-1}$)</th>
<th>PHOS</th>
<th>PCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB trigger</td>
<td>$1.94 \pm 0.05 _{\text{norm}}$</td>
<td>$1.25 \pm 0.04 _{\text{norm}}$</td>
<td>$2.17 \pm 0.06 _{\text{r}}$</td>
</tr>
<tr>
<td>EMC/PHOS-LO trigger</td>
<td>$40.9 \pm 0.7_{\text{sys}} \pm 1.1_{\text{nom}}$</td>
<td>$135.6 \pm 16.8_{\text{sys}} \pm 3.6_{\text{nom}}$</td>
<td>-</td>
</tr>
<tr>
<td>EMC-L1 trigger</td>
<td>$615.0 \pm 15.0_{\text{sys}} \pm 16.0_{\text{nom}}$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

energy is smaller than the previous cell’s energy and does not aggregate the respective cell, if it recorded a higher energy than the previous one. The clustering process continues in the same way with the remaining cells, until all cells above the energy thresholds are grouped into clusters. Cluster energies are then calculated by $E = \sum^{N_{\text{cell}}} e_i$, where $e_i$ stands for the energy recorded by the indicated cell. The values of $E_{\text{seed}}$ and $E_{\text{min}}$ depend on the energy resolution and the noise level of the front-end electronics. For the EMCal, values of $E_{\text{seed}} = 500$ MeV and $E_{\text{min}} = 100$ MeV are chosen. For the PHOS, these parameters are set to $E_{\text{seed}} = 200$ MeV and $E_{\text{min}} = 15$ MeV. Large clusters due to overlapping photon showers in the PHOS are separated into individual clusters by an unfolding method based on the knowledge of the lateral shape of the electromagnetic shower [37].

Cell energies are calibrated for both calorimeters to provide best estimates for the cluster energies. After the cell-by-cell energy calibration of the EMCal [23,27], an improved correction for the relative energy scale as well as for the residual geometrical misalignment of the EMCal between data and MC simulations is derived by making use of the good momentum resolution of the PCM photon in the hybrid PCM-EMCal method. Using this method, the $\pi^0$ mass is evaluated as a function of EMCal cluster energy, $E_{\text{cluster}}$, for data and MC. Therefrom, a cluster energy correction is deduced for the simulation, for which the reconstructed $\pi^0$ masses are adjusted to the measured mass positions in data. For $E_{\text{cluster}} \approx 1$ GeV, the correction is of the order of 2% and rises up to 4% for higher energies. Thus, a precise energy calibration scheme for the relevant energy regions is available which is found to be consistent for the EMCal and hybrid PCM-EMCal methods for $\pi^0$ as well as $\eta$ mesons at the same time, hence demonstrating the validity of the procedure. After applying this calibration in the analysis, the $\pi^0$ and $\eta$ mass values in data and MC are obtained for each $p_T$ bin and their ratio is computed. Then, the ratios are plotted versus $p_T$ and fitted with a constant, giving access to the residual miscalibration of the meson mass values between data and MC. Such residual offsets of $0.005 \pm 0.043$ and obtained for PCM-EMCal, illustrating the performance of the calibration procedure. For the PHOS, the energy deposits in each cell is calibrated by adjusting the $\pi^0$ peak position in the invariant mass spectra of photon pairs to the true mass of the $\pi^0$ meson. The accuracy of this calibration procedure is estimated to be better than 1%. It is evaluated in a comparison of the $\pi^0$ peak width in calibrated data and MC simulations by introducing random, normal-distributed decalibration parameters to the MC simulation.

Photon identification criteria are applied to the sample reconstructed clusters in order to primarily select clusters generated by true photon candidates. For the photon reconstruction with PHOS, relatively loose identification cuts are applied because the shower overlap is negligible and the combinatorial background is found to be small in pp collision. A minimum cluster energy, $E_{\text{cluster}} > 0.3$ GeV, as well as a minimum number of cells forming a cluster, $N_{\text{cell}} \geq 3$, is required in order to reject electronic noise and minimize misidentifying particles which deposit about 270 MeV in the PHOS. For the EMCal, a minimum energy cut of $E_{\text{cluster}} > 0.7$ GeV is applied and the minimum number of cells grouped in a cluster is set to $N_{\text{cell}} \geq 2$. Furthermore, the selection criteria of $|\eta| < 0.67$ and $1.40 < \phi < 3.15$ rad are imposed for EMCal clusters. Pileup from multiple events, which can occur within a readout interval of the front-end electronics, is rejected by applying a cluster timing cut relative to the collision time of $-25 < t_{\text{cluster}} < 25$ ns for the PHOS and $-35 < t_{\text{cluster}} < 25$ ns for the EMCal. Thus, photon candidature can be obtained from different bunch crossings are removed with high efficiency of $> 99\%$. For the EMCal, all clusters match a primary charged track are rejected. This track matching procedure, referred to as general track matching, is a track $p_T$-dependent matching in $\eta$ and $\phi$, beginning for $|\Delta \eta| < 0.04$ and $|\Delta \phi| < 0.09$ for very low track momenta $p_T < 0.5$ GeV/c and going down to $|\Delta \eta| < 0.01$ and $|\Delta \phi| < 0.05$ for highest track momenta, using the $p_T$-dependent matching conditions $|\Delta \eta| < 0.01 + (p_T + 4.07)^{-2.5}$ and $|\Delta \phi| < 0.015 + (p_T + 3.65)^{-2}$. Applying these conditions a primary track to cluster matching efficiency of more than
10 GeV/c. To further enhance the photon purity and to reject neutral hadrons, a cluster shape cut of $0.1 \leq \sigma_{\text{long}}^2 \leq 0.7$ is applied for EMCal clusters, where $\sigma_{\text{long}}^2$ stands for the smaller eigenvalue of the dispersion matrix of the shower shape ellipse defined by the responding cells and their energy contributions to the cluster [9,39]. The lower threshold of $\sigma_{\text{long}}^2$ is chosen to remove contamination caused by neutrons hitting the APDs of the readout electronics.

Photons convert into lepton pairs within the detector material of ALICE with a probability of about 8.5%. The reconstruction of such photon conversion candidates using PCM may be divided into three major steps: (i) tracking of charged particles and secondary vertex ($V^0$) finding [37]; (ii) particle identification and (iii) photon candidate reconstruction and subsequent selection. The $V^0$s used in this analysis are obtained during data reconstruction using all available tracking information, recalculating the momenta of the daughter tracks under the assumption that both daughters are created with parallel momentum vectors at the $V^0$. The tracks associated with secondary vertices are required to have a minimum momentum of $p_T^{\text{track}} > 50$ MeV/c and at least 60% of clusters from the maximum possible number of clusters, that a particle track can create in the TPC along its path, need to be found. In order to reduce the contamination from Dalitz decays, conversion candidates are only considered with a vertex at a radial distance of at least $R > 5$ cm. In addition, a line-cut is applied to restrict the geometrical $\eta$ distribution of the $V^0$s in order to remove photon candidates that would otherwise appear outside the angular dimensions of the detector. The condition $R_{\text{conv}} > |Z_{\text{conv}}|^2 S_{2\eta R} - 7$ cm is applied with $S_{2\eta R} = \tan(2 \arctan(\exp(-\eta_{\text{cut}})))$ and $\eta_{\text{cut}} = 0.9$, where the coordinates $R_{\text{conv}}$ and $Z_{\text{conv}}$ are determined with respect to the nominal center of the detector. Additional constraints are imposed on $R_{\text{conv}} < 180$ cm and $|Z_{\text{conv}}| < 240$ cm to ensure that the reconstruction of secondary tracks is performed inside the TPC. Electrons and positrons from photon conversions are identified via their energy deposit, $dE/dx$, in the TPC. The difference of the measured $dE/dx$ value from the hypothesis of the electron/positron energy loss is used for particle identification. The $dE/dx$ of measured charged tracks is required to be within $-3 < n \sigma_e < 5$ of the expected energy loss, which is a $p_T$-dependent observable defined by $n \sigma_e = (dE/dx - \langle dE/dx \rangle_e) / \sigma_e$ with the average energy loss of the electron/positron, $\langle dE/dx \rangle_e$, and the Gaussian width of the fit to the measured $dE/dx$ distribution, $\sigma_e$. To further reduce charged pion contamination as the pion $dE/dx$-band begins to merge with the electron/positron $dE/dx$-band above $p > 4$ GeV/c, a cut based on the separation from the hypothesis of charged pion energy loss is applied in $n \sigma_{\pi}$, analogous to the previous definition. Tracks with energy losses closer to the pion line than $|n \sigma_{\pi}| > 1$ are removed.

Candidate contamination is further suppressed by a triangular two-dimensional cut, $|\Psi_{\text{pair}}| < \Psi_{\text{pair,max}}(1 - \chi^2_{\text{red}}/\chi^2_{\text{max}})$ with $\chi^2_{\text{max}} = 30$ and $\Psi_{\text{pair,max}} = 0.1$. This cut is based on the reduced $\chi^2$ of the Kalman filter [40] hypothesis of the $e^+e^-$ pair and on the angle $\Psi_{\text{pair}}$ between the plane perpendicular to the magnetic field of the ALICE magnet and the $e^+e^-$ pair plane. Furthermore, a cut on the cosine of the pointing angle of $\cos(\theta_{\text{DA}}) > 0.85$ is performed, where pointing angle, $\theta_{\text{DA}}$, is the angle between the reconstructed photon momentum vector and the vector joining the collision vertex. The remaining $K_0^0$, $\Lambda$ and $\bar{\Lambda}$ contamination removed by selecting $q_T < q_{T,\text{max}} \sqrt{1 - \alpha^2/\alpha_{\text{max}}^2}$ on Armenteros-Podolanski plot [41] with $q_{T,\text{max}} = 0.05$ GeV and $\alpha_{\text{max}} = 0.95$. Additionally, the PCM measurement requires an out-of-bunch pileup correction which estimates the contamination of photon candidates from multiple e+e- pairs overlapping in the TPC. The correction is based on the distance of closest approach (DCA) of the conversed photon candidates which is the smallest distance in between, $z$, the primary vertex and the momentum vector of the photon candidate. Photon candidates from different events generate a broad underlying Gaussian DCA distribution, which is fitted in order to estimate the out-of-bunch pileup contribution. The correction is found to $p_T$-dependent and ranges from 42% at low $p_T \approx 0.35$ GeV to 10% at high $p_T \approx 11$ GeV/c.

The hybrid PCM-EMCal method practically uses the same cuts on photon candidates as the respective standalone reconstruction methods. In contrast, the use of $4 < n \sigma_e < 5$ concerning the electron/positron energy hypothesis is used for the hybrid method and the $p_T$-rejection of the charged pion $dE/dx$ cut is loosened. Only the upper value of the cut on the short axis of the momenta is adjusted in order to reduce the shower shape of the EMCal and requires $\sigma_{\text{Long}}^2 < 0.5$ in order to further reduce contamination of hadrons [9]. Due to the timing constraint of the EMC restricting clusters to triggered bunch crossings, no DCA additional out-of-bunch pileup rejection is needed for the hybrid method. In addition to the general matching of primary charged particles to EMCal clusters already described a dedicated track matching procedure for the two charged $V^0$ daughters with respect to EMCal clusters is applied. T-cluster-$V^0$ track matching is the most important ingredient for the hybrid analysis, as pairing one leg of the $V^0$ candidate with the EMCal cluster generated by one of these second charged tracks itself, leads to an auto-correlation and a broad bump at the masses of the $\eta$ and $\pi^0$ mesons around 300 MeV/c. The same parameters from the generic track matching procedure are found to remove about 99% such candidates. The momentum distribution of photon pairs shown...
the neutral meson signal for photon candidate pairs from the same, real event. An opening angle cut of 17 mrad for the angle between the momentum vectors of the two paired photon candidates is applied for the EMCal measurement. Requiring a minimum separation between such pairs is needed to ensure a proper background description by event same events, such cluster configurations would overlap partially or even merge into single clusters, which has be explicitly considered for event mixing by not allowing cells with largest deposited energies of respective clust to be direct neighbors on the EMCal surface. For the PC and hybrid PCM-EMCal methods, an opening angle cut
Fig. 3 Example invariant mass spectra in selected $p_T$ slices in PCM (top left), PCM-EMCal (top right) and EMCal (bottom plots) in the $\eta$ mass region. The black histograms show raw invariant mass distributions before any background subtraction. The grey points show mixed-event and residual correlated background contributions, which have been subtracted from raw real events to obtain the signal display with red data points. The blue curves represent fits to the background subtracted invariant mass spectra. Additional examples of invariant mass distributions for the different methods are given in Ref. [38].

The pair of PCM and EMCal photon candidates. Furthermore, pairs are restricted to a rapidity of $|y| < 0.12$ for the PHOS and $|y| < 0.8$ for all other methods.

The uncorrelated combinatorial background is estimated by using an event mixing technique, in which photon candidates from different events are paired in order to prevent photon candidate multiplicity and transverse momentum ensure the mixing of similar events only. In contrast to several event combinations to extract the neutral meson signal, the mixed-event background is obtained with up to 80 different events, stored in each of the event pools, in order to minimize its statistical uncertainties. Therefore, the mixed-event background...
peak, just outside the peak integration interval, after which it is subtracted from the raw distribution. The background-subtracted signal is then fitted to determine the mass peak position and width of $\pi^0$ and $\eta$ mesons for every $p_\gamma$ bin. A function composed of a Gaussian modified by an exponential tail at the low mass side [42] is used for this purpose. The low mass tail accounts for late conversions of one or both photons for the EMCal method and for energy loss effects due to bremsstrahlung for the PCM and hybrid PCM-EMCal methods. To reflect the residual correlated background components which remain after the subtraction of the mixed-event background, the fitting is performed by including an additional first order polynomial function (deduced from MC simulations), which is also shown in Figs. 2 and 3 and which is further being subtracted from the invariant mass distribution. In contrast, a slightly different approach for the background description is followed for the PHOS as its limited acceptance results in a more complicated shape of the combinatorial background around the signal peak, especially at low $p_\gamma$. As both correlated and combinatorial backgrounds are influenced in the same manner, the ratio of the raw signal and mixed-event distributions is constructed and fitted with first or second order polynomial function outside the peak region. Then, the mixed-event distribution is scaled with the obtained polynomial function and subtracted from the raw signal, which can be followed in Fig. 2. A Crystal Ball function [43] is used as the main fit function for the PHOS method which also reproduces the tails at the low mass region to take into account the late conversion of photons in front of the calorimeter. The signal distribution is then obtained by subtracting the scaled mixed-event background from the raw invariant mass distribution. The resulting background-subtracted signal distributions as well as raw signals from real events, the normalized mixed-event and residual background distributions are shown in Figs. 2, 3 and in Ref. [38] for the $\pi^0$ and $\eta$ meson mass region, respectively, for given example $p_\gamma$ bins, illustrating the meson reconstruction over the full reported $p_\gamma$ range.

The neutral meson raw yields are extracted by integrating the background-subtracted invariant mass distributions. The integration windows are defined by the reconstructed mass position and width obtained by the respective fits of the signal distribution in a given $p_\gamma$ bin. For the PHOS method, the integration range for $\pi^0$ is asymmetrically defined as $[-5\sigma, +3\sigma]$ around reconstructed peak position, where $\sigma$ is the standard deviation of the Gaussian part of the Crystal Ball function to take the asymmetric shape into account. For the other methods, the integration windows for both neutral mesons are chosen to cover at least $[-3\sigma, +3\sigma]$ around the reconstructed peak position, where $\sigma$ is the standard deviation of the Gaussian part of the fit function. For each reconstructed $p_\gamma$ range, the signal extraction are shown in Fig. 4 as a function of reconstructed $p_\gamma$.

Corrections for geometrical acceptance and reconstruction efficiencies are evaluated using MC simulations PYTHIA8 [18] and PHOJET [44] event generators with minimum bias processes are used for this purpose. The correct factors for both MC productions are found to be consistent and, hence, are combined. To generate enough statistics high meson momenta to be able to correct the raw yields obtained with triggered data, a PYTHIA8 simulation is used that is enriched with jets, generated in bins of hard scatterings, $p_{T,\text{hard}}$. Particles generated by the event generators are propagated through the ALICE detector using GEANT3 which realistically reproduces interactions between the particles and the detector material. The reconstruction algorithms and analysis cuts are applied for real data. In Fig. 4, the reconstructed $\pi^0$ and $\eta$ meson peak positions and widths are compared as a function of between data and MC to confirm a proper detector response in the simulation. The normalized correction factors, $\epsilon$, each method, containing the specific detector acceptance as well as the full reconstruction efficiencies, are shown in Fig. 5. For the EMCal analysis, the correction factor for $\pi^0$ is observed to decrease for $p_\gamma \gtrsim 10$ GeV/c. This is due to the dead material, as well as the pure electromagnetic contributions, which are less relevant at higher momenta. Above a certain limit momentum, it is no longer possible to separate the two decay photons of the $\pi^0$, creating merged clusters that significantly reduce the reconstruction efficiency in the EMCal as seen in Fig. 5. Thus, the natural upper limit for the $\pi^0$ reconstruction with the EMCal is of the order of $p_{\pi^0} \approx 20$ GeV/c. In contrast, the PCM-EMCal hybrid approach overcomes this limitations of the EMCal cell segmentation and makes it possible to reconstruct $\pi^0$ mesons up to $p_\gamma \approx 35$ GeV/c as reported in this paper. For the PHOS, such cluster merging effects are negligible for the reported $p_\gamma$ range owing to the high granularity of the calorimeter. Since the opening angles of photons from $\eta$ meson decays are much larger compared to the $\pi^0$, merging effects are negligible for all approaches over the reported $p_\gamma$ range in this case.

The contributions of secondary $\pi^0$ from weak decays of hadron interactions with the detector material are estimated and removed for the $\pi^0$ measurements. Weak decays of $K_L^0$ and $A$ are obtained from Refs. [46, 48] with extrapolation.
Fig. 4 The left plots show reconstructed \( \pi^0 \) peak positions (left-bottom) and widths (left-top) of each reconstruction method compared to MC simulations for the transverse momentum bins used in the analysis. Corresponding plots for the \( \eta \) meson are on the right for peak masses (right-bottom) and widths (right-top).

Fig. 5 The normalized correction factors, \( \epsilon \), for each reconstruction method for \( \pi^0 \) (left) and \( \eta \) mesons (right) plotted versus \( p_T \) used in the analysis. The factors contain the detector acceptances and the respective reconstruction efficiencies, where acceptances are further normalized by the rapidity windows accessible with each method, and full azimuth coverage of 2\( \pi \), in order to enable a direct comparison between the different methods.

\[
\epsilon = 2\sqrt{\frac{A}{d}} A_{\text{rec}}
\]

These spectra are used as weights in a PYTHIA6.4 simulation, where the respective particle decays are simulated on generator level, taking into account the full decay kinematics. Using this procedure, the invariant yields of secondary \( \pi^0 \)s from weakly decaying particles are calculated for these secondaries and multiplied with the respective invariant yields from the generator level MC simulations to arrive at the secondary \( \pi^0 \) raw yields from the different particles. On the other hand, the \( \pi^0 \) raw yield from interactions with the detector material is purely obtained from: 

the reconstructed number of $\pi^0$s, as indicated in Eq. 2. The corrections are of the order of 1–3% for $K^0_S$, < 0.5% for $K^0_L$, < 0.02% for $\Lambda$ and 0.1–2% for material, varying within the given values for the different methods and triggers used.

As there are three different triggers available for the EMCal and hybrid PCM-EMCal methods, and two different ones for the PHOS measurement, each with its own statistical and systematic uncertainties, as well as correlations between the different systematical uncertainties, the results from each trigger class are properly combined in order to obtain the final result for each reconstruction method. Statistical uncertainties are ensured to be uncorrelated since different triggers use non-overlapping data samples. For the systematic uncertainties, the $p_T$-dependent correlation coefficients are determined. Only a few systematic uncertainties are found to be uncorrelated, such as the uncertainty of signal extraction and partly “efficiency” and “trigger” related uncertainties, for which further details are contained in Sect. 5. The correlation coefficients are found to be generally above 0.8. The respective $p_T$-dependent weights are calculated according to the BLUE algorithm [49–53], which are used to combine the spectra from each method.

5 Systematic uncertainties

Systematic uncertainties are respectively summarized in Tables 2, 3 and 4 for the neutral mesons $\pi^0$, $\eta$ and their ratio $\eta/\pi^0$. The values are given in percent and refer to relative systematic uncertainties of the measured values. The different example $p_T$ bins are listed for each reconstruction method in order to illustrate their relative strengths. An additional, more detailed description of the systematic sources and the determination of uncertainties for all methods except PHOS may be found in Ref. [9], which is fully applicable for this paper.

For the $\pi^0$ measurement by PHOS, the systematic uncertainty related to the signal extraction is evaluated by varying the fitting range and the assumptions about the mass peak background shapes. The systematic uncertainty related to material budget is taken from Ref. [3], which is estimated by comparing the results of the analysis with and without a magnetic field in the ALICE solenoid. Photons, which are converted to $e^+e^-$ pairs within the detector material, are mainly being reconstructed as clusters in the presence of a magnetic field. Without a field, the secondaries from photon conversions are less separated and can be dominantly detected as single clusters, building the correct invariant masses for $\pi^0$s in a di-cluster analysis. Therefore, comparing the $\pi^0$ spectra from data and MC with nominal and zero magnetic fields is a straightforward method to evaluate the uncertainty of the material budget description in simulations. Systematic uncertainties due to the cluster energy calibration are decomposed into the uncertainty of the energy scale of clusters and non-linearity effects. The energy sc

<table>
<thead>
<tr>
<th>$p_T$ interval</th>
<th>1.4–1.6 GeV/c</th>
<th>5.0–5.5 GeV/c</th>
<th>15.0–16.0 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>PCM</td>
<td>PCM-EMC</td>
<td>EMC</td>
</tr>
<tr>
<td>Signal extraction</td>
<td>4.8</td>
<td>1.9</td>
<td>2.3</td>
</tr>
<tr>
<td>Inner material</td>
<td>9.0</td>
<td>4.5</td>
<td>–</td>
</tr>
<tr>
<td>Outer material</td>
<td>–</td>
<td>2.1</td>
<td>4.2</td>
</tr>
<tr>
<td>PCM track rec.</td>
<td>1.0</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>PCM electron PID</td>
<td>1.8</td>
<td>0.6</td>
<td>–</td>
</tr>
<tr>
<td>PCM photon PID</td>
<td>1.7</td>
<td>0.5</td>
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</tr>
<tr>
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<td>4.4</td>
</tr>
<tr>
<td>Cluster energy calib.</td>
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<td>2.5</td>
</tr>
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<td>Track match to cluster</td>
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<td>3.1</td>
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<tr>
<td>Efficiency</td>
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<td>2.5</td>
</tr>
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<td>Trigg. nom. and pileup</td>
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<td>0.1</td>
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<tr>
<td>Total syst. uncertainty</td>
<td>11.1</td>
<td>6.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>1.5</td>
<td>1.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Table 3 Summary of relative systematic uncertainties in percent for selected $p_T$ bins for the reconstruction of $\eta$ mesons, see Table 2 for further explanations which also apply here

<table>
<thead>
<tr>
<th>$p_T$ interval</th>
<th>Method</th>
<th>2.0-2.4 GeV/c</th>
<th>5.0-6.0 GeV/c</th>
<th>18.0-20.0 GeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PCM</td>
<td>PCM-EMC</td>
<td>EMC</td>
<td>PCM-EMC</td>
</tr>
<tr>
<td>Signal extraction</td>
<td>5.1</td>
<td>9.0</td>
<td>9.3</td>
<td>7.3</td>
</tr>
<tr>
<td>Inner material</td>
<td>9.0</td>
<td>4.5</td>
<td>–</td>
<td>9.0</td>
</tr>
<tr>
<td>Outer material</td>
<td>–</td>
<td>2.1</td>
<td>4.2</td>
<td>2.1</td>
</tr>
<tr>
<td>PCM track rec.</td>
<td>1.5</td>
<td>1.8</td>
<td>–</td>
<td>2.0</td>
</tr>
<tr>
<td>PCM electron PID</td>
<td>2.4</td>
<td>1.8</td>
<td>–</td>
<td>2.2</td>
</tr>
<tr>
<td>PCM photon PID</td>
<td>3.6</td>
<td>2.9</td>
<td>–</td>
<td>6.3</td>
</tr>
<tr>
<td>Cluster description</td>
<td>–</td>
<td>3.1</td>
<td>4.6</td>
<td>–</td>
</tr>
<tr>
<td>Cluster energy calib.</td>
<td>–</td>
<td>3.2</td>
<td>3.5</td>
<td>–</td>
</tr>
<tr>
<td>Track match to cluster</td>
<td>–</td>
<td>1.5</td>
<td>4.0</td>
<td>–</td>
</tr>
<tr>
<td>Efficiency</td>
<td>–</td>
<td>5.0</td>
<td>4.3</td>
<td>–</td>
</tr>
<tr>
<td>Trg. nom. and pileup</td>
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<td>0.1</td>
<td>0.1</td>
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</tr>
<tr>
<td>Total syst. uncertainty</td>
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<td>13.0</td>
<td>13.1</td>
<td>13.6</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
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<td>12.1</td>
<td>16.8</td>
<td>18.3</td>
</tr>
<tr>
<td>Combined stat. unc.</td>
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<td>Combined syst. unc.</td>
<td>8.7</td>
<td>9.0</td>
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</table>

Table 4 Summary of relative systematic uncertainties in percent for selected $p_T$ bins for the determination of the $\eta/\pi^0$ ratio. The statistical uncertainties are given in addition to the total systematic uncertainties

<table>
<thead>
<tr>
<th>$p_T$ interval</th>
<th>Method</th>
<th>2.0-2.4 GeV/c</th>
<th>5.0-6.0 GeV/c</th>
<th>18.0-20.0 GeV/c</th>
</tr>
</thead>
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<tr>
<td></td>
<td>PCM</td>
<td>PCM-EMC</td>
<td>EMC</td>
<td>PCM-EMC</td>
</tr>
<tr>
<td>Signal extraction</td>
<td>5.9</td>
<td>9.0</td>
<td>9.3</td>
<td>8.2</td>
</tr>
<tr>
<td>PCM track rec.</td>
<td>1.5</td>
<td>1.9</td>
<td>–</td>
<td>2.0</td>
</tr>
<tr>
<td>PCM electron PID</td>
<td>2.4</td>
<td>1.9</td>
<td>–</td>
<td>2.2</td>
</tr>
<tr>
<td>PCM photon PID</td>
<td>3.6</td>
<td>3.2</td>
<td>–</td>
<td>6.3</td>
</tr>
<tr>
<td>Cluster description</td>
<td>–</td>
<td>3.5</td>
<td>4.9</td>
<td>–</td>
</tr>
<tr>
<td>Cluster energy calib.</td>
<td>–</td>
<td>3.4</td>
<td>4.2</td>
<td>–</td>
</tr>
<tr>
<td>Track match to cluster</td>
<td>–</td>
<td>1.5</td>
<td>3.9</td>
<td>–</td>
</tr>
<tr>
<td>Efficiency</td>
<td>–</td>
<td>5.4</td>
<td>4.5</td>
<td>–</td>
</tr>
<tr>
<td>Total syst. uncertainty</td>
<td>7.5</td>
<td>12.4</td>
<td>12.8</td>
<td>10.8</td>
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<tr>
<td>Statistical uncertainty</td>
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<td>Combined syst. unc.</td>
<td>7.1</td>
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Uncertainty of 0.1% is estimated from a comparison of the $\pi^0$ mass peak position for the two-photon invariant mass spectra in data and MC. This energy uncertainty is translated to an uncertainty of the $\pi^0$ yield by convolution with the shape of the $p_T$ spectrum. The systematic uncertainty due to the non-linearity correction is evaluated by introducing different non-linearity correction schemes and calibration parameters for each bin. Moreover, the combined statistical and systematic uncertainties are listed as well, see also explanations in caption of Table 2.
energy photon trigger analysis, which is estimated by comparing the trigger turn-on curve from data with MC simulations. “Trigger normalization & pileup” summarizes systematic uncertainties due to the trigger normalization factor and pileup effects. The uncertainty related to the trigger normalization factor is estimated by changing the range of the fit to determine the rejection factor (RF). Furthermore, the out-of-bunch pileup contribution is evaluated by varying the timing cut to accept clusters.

For the PCM measurement, the main source of systematic uncertainty is the material budget, for which the same value is used as previously calculated in Ref. [3]. The signal extraction uncertainty is estimated by changing the integration window around the invariant mass peak, the normalization range of the mixed-event background and by using different order polynomials as well as other fit functions to evaluate the remaining background contribution. “Track reconstruction” summarizes the systematic uncertainties found by requiring different numbers of TPC clusters and by applying different minimum transverse momentum cuts on tracks. The systematic uncertainties due to the electron identification (“electron PID” and “PCM photon PID”) are determined by varying the PID cuts, which are elaborated in Sect. 4, and by comparing the respective results. For PCM, the “trigger normalization & pileup” uncertainty is dominated by the uncertainty of the DCA2 background description for the out-of-bunch pileup estimation. Furthermore, it contains the systematic uncertainty due to the pileup rejection by the SPD due to its finite efficiency to remove pileup events.

For the EMCal, one main systematic uncertainty arises from the knowledge of the outer material budget, which is defined by all detector components from the radial center of the TPC up to the EMCal. The uncertainty is assessed by running the analysis only with/without TRD modules in front of the EMCal, since part of the data taking in 2012 occurred with the EMCal only partially obscured by the TRD. Since TRD and TOF have similar material budgets, the same uncertainty is assigned to the TOF as well, which covered the full polar angle so that a similar assessment as for the TRD is not feasible. Both uncertainties are quadratically combined to arrive at the given uncertainties which are listed in the tables. The signal extraction uncertainty contains the systematic uncertainties obtained from variations of the background normalization region, the choice of the background fit function and integration intervals, analog to the PCM method, as well as from variations of the minimum opening angle cut on the meson level. The systematic uncertainty denoted as “cluster description” reflects the mismatch of the description of the clusterization process between data and MC simulations, giving rise to modified reconstruction efficiencies, which includes the following cluster related quantities: minimum energy.

Moreover, cell timing cut variations are also included in the category. “Cluster energy calibration” considers the systematic uncertainties due to nonlinearity effects and the energy scale of clusters. Different nonlinearity schemes are used in this analysis from which this uncertainty is obtained. Moreover, the energy scale uncertainty is determined by obtaining the residual differences of reconstructed meson mass values from data and MC simulations. The systematic uncertainty induced by the charged particle veto on cluster level, introduced as “general track matching” in Sect. 4, is determined from variations of the matching residuals. The “efficiency” uncertainty reflects differences between MB MC generators for calculation of reconstruction efficiencies. Moreover, it contains the uncertainty of the actual trigger turn-on, obtained comparing the turn-on curves in data and MC. The uncertainties from the determination of trigger rejection factors (R as well as from the pileup rejection by the SPD, which has a finite efficiency for pileup removal, are summarized with “trigger normalization & pileup”.

For the hybrid method PCM-EMCal, the same cut variations are performed as for the standalone methods. However, given the fact that only one photon candidate of each event is used, most systematic uncertainties are found to be different size or behavior, e.g. the minimum opening cut variations. The “track matching to cluster” uncertainty reflects the V0-track to cluster matching, which is assessed by varying the matching residuals.

As indicated in Table 4, many uncertainties cancel for the η/π0 ratio, such as the material-related systematics. For the remaining categories, the respective uncertainties are added quadratically and cancel partially beforehand, if applicable.

6 Results

The invariant differential cross sections of π0 and η production are obtained by

\[
E \frac{d^3 \sigma_{pp \to \pi^0 + X}}{d p^3} = \frac{1}{2 \pi p_T} \frac{1}{L_{\text{int}}} \frac{A \cdot e_{\text{rec}}}{\Delta y \Delta p_T} \frac{N_{\pi^0(\eta)} - N_{\pi^0}^{\text{rec}}}{N_{\eta}^{\text{rec}}},
\]

where \(N_{\pi^0(\eta)}^{\text{rec}}\) is the number of reconstructed \(\pi^0(\eta)\) mesons in a given \(p_T\) bin, \(N_{\pi^0}^{\text{rec}}\) represents the estimated number of ordinary \(\pi^0\) mesons, \(L_{\text{int}}\) is the integrated luminosity, \(A \cdot \epsilon\) is the product of the geometrical acceptance and reconstruction efficiency, also referred to as \(\epsilon\) in Fig. 5, \(Br_{\pi^0(\eta)\to \gamma\gamma}\) is the branching ratio for the two-gamma decay channel \(\gamma\).
of-bunch pileup correction has to be noted for completeness and to be applied as well.

The invariant differential cross sections are independently calculated for each method. The final spectra are obtained by combining the results in the overlap regions using the BLUE method [49–53], properly taking into account the correlations of the systematic uncertainties of the different methods. Possible statistical correlations between the measurements, for instance due to the conversions at small distances relative to the beam axis, are negligible due to the small conversion probability and the small likelihood of reconstructing the respective electron in the calorimeters leading to a meson candidate which finally ends up in the respective integration window. As there are no common uncertainties present for PCM, EMCal and PHOS, all systematic uncertainties are considered to be completely uncorrelated in those cases. On the other hand, the correlations introduced by including the hybrid PCM-EMCal measurement have to be taken into account. By construction, there are different numbers of conversion photons entering the two methods. Thus, all systematic uncertainty sources from PCM are found to be partially correlated in the PCM-EMCal method. Half of the size of the material budget uncertainty, for example, is assumed to be uncorrelated. Furthermore, the uncorrelated systematic uncertainties from PCM-EMCal with respect to PCM are, with full size, all the calorimeter related uncertainties as well as trigger and efficiency uncertainties.

Due to finite bin widths of the measured production cross sections, the neutral meson spectra are shifted along the horizontal axis [54]. All bin width corrections are of the order of 1% and below. In contrast, the reported $\eta/\pi^0$ ratios are shifted along the vertical axis, as otherwise the ratio could not be computed and the different measurements could not be combined. The correction is below 1% for $p_T > 2$ GeV/c, but becomes significant for smaller momenta and rises to 8%.

The combined invariant cross sections of inclusive $\pi^0 \rightarrow \eta$ meson production cover transverse momentum ranges $0.3 < p_T < 3.5$ and $0.5 < p_T < 3.5$ GeV/c, respectively. Total uncertainties of the measurements, obtained by quadratically adding the combined statistical and systematic uncertainties, are of the order of 5% for the $\pi^0$ and 10% for the meson for most of the $p_T$ bins covered, increasing for lowest and highest momenta due to statistical limitations as well as systematic effects. Both combined neutral meson spectra are fitted with a two-component model (TCM), proposed Ref. [55], by using the total uncertainties for each $p_T$ bin. The functional form of the TCM is a combination of a Boltzrn component and a power-law part, which, in general, should be the dominant components at low and high $p_T$, respectively. The fit function is able to reproduce the spectra over the full $p_T$ range and is described as:

$$E \frac{d^3\sigma}{dp^3} = A_e \exp\left(-E_{T,\text{kin}}/T_e\right) + A \left(1 + \frac{p_T^2}{T^2n}\right)^{-n},$$

where $E_{T,\text{kin}} = \sqrt{p_T^2 + m^2} - m$ is the transverse kinetic energy with the meson rest mass $m$ and $A_e, A, T_e, T$ as well as $n$ are the free parameters. To compare the different methods, the ratios of spectra measured by each reconstruction method to the TCM fit of the combined spectrum shown in Fig. 6. The vertical error bars represent the statistical uncertainties, whereas the boxes quantify the bin width in horizontal direction and the systematic uncertainties in vertical direction. All measurements agree within uncertainty over the full $p_T$ range.

The $\pi^0$ and $\eta$ meson cross sections are also fitted with Tsalis function [56], which has been used in previous measurements of $\pi^0$ and $\eta$ meson production in pp collisions reported by ALICE [3,4]:

![Fig. 6](image-url)
Table 5 Parameters of the fits to the $\pi^0$ and $\eta$ invariant differential cross sections using the TCM fit [55] from Eq. 3 as well as using a Tsallis [56] from Eq. 4

<table>
<thead>
<tr>
<th>TCM</th>
<th>$A_c$ (pb GeV$^{-2}\cdot c^3$)</th>
<th>$T_c$ (GeV)</th>
<th>$A$ (pb GeV$^{-2}\cdot c^3$)</th>
<th>$T$ (GeV)</th>
<th>$n$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$</td>
<td>$(6.84 \pm 2.79) \times 10^{11}$</td>
<td>0.142 $\pm$ 0.020</td>
<td>$(3.68 \pm 0.89) \times 10^{10}$</td>
<td>0.597 $\pm$ 0.030</td>
<td>3.028 $\pm$ 0.018</td>
<td>C</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$(1.62 \pm 4.35) \times 10^9$</td>
<td>0.229 $\pm$ 0.203</td>
<td>$(2.89 \pm 1.81) \times 10^9$</td>
<td>0.810 $\pm$ 0.103</td>
<td>3.043 $\pm$ 0.045</td>
<td>C</td>
</tr>
<tr>
<td>Tsallis</td>
<td>$C$ (pb)</td>
<td>$T$ (GeV)</td>
<td>$n$</td>
<td>$\gamma$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>$(2.46 \pm 0.18) \times 10^{11}$</td>
<td>0.121 $\pm$ 0.004</td>
<td>6.465 $\pm$ 0.042</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta$</td>
<td>$(1.56 \pm 0.19) \times 10^9$</td>
<td>0.221 $\pm$ 0.012</td>
<td>6.560 $\pm$ 0.113</td>
<td>C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7 Invariant cross sections for neutral meson production are shown together with NLO pQCD predictions using PDF’s MSTW08 (CTEQ6M5) with FF’s DSS14 (AESSS) for $\pi^0$ ($\eta$) as well as PYTHIA8.210 calculations, for which two different tunes are available. The data points are fitted using a TCM fit, Eq. 3, and a Tsallis Eq. 4

where $C$, $n$ and $T$ are free parameters of the fit with $m$ and $m_T$ being the rest as well as the transverse mass of the meson. The fit parameters extracted from both the TCM and Tsallis low and high $p_T$ than the Tsallis counterpart [38]. This also reflected in the smaller values obtained for the reduced $\chi^2_{red}$ of the respective fits, which are also recorded in Table.
for both fits, as the total uncertainties of meson spectra are
used for their calculation. A direct comparison of TCM and
Tsallis fits can be found in Fig. 7, where both fits are plotted,
in addition to the measured spectra and theory calculations.

The measured invariant differential cross sections are
compared with NLO pQCD calculations [8,11] using
MSTW08 (PDF) [16] with DSS14 (FF) [8] for $\pi^0$ and
CTEQ6M5 (PDF) [17] with AESSS (FF) [11] for the $\eta$
meson. The same factorization scale value, $\mu_0 = 0.5 p_T <
\mu < 2 p_T$, is chosen for the factorization, renormalisation
and fragmentation scales used in the NLO pQCD calcula-
tions. For the $\pi^0$ the NLO PDF, pQCD and FF combina-
tion describes the RHIC data rather well [57], whereas for
$\sqrt{s} = 2.76$ TeV pQCD overpredicts ALICE data by 30% at
moderate $p_T$ and agrees at higher $p_T$ [9]. The ratios of
data and NLO pQCD predictions to the TCM fits of neutral
meson spectra are shown in Fig. 7. The largest uncertainty of
the NLO pQCD calculation is due to the choice of $\mu$. For
all $\mu$ values, these calculations overestimate the measured
data for both $\pi^0$ and $\eta$ mesons. This is also observed
for meson measurements at $\sqrt{s} = 2.76$ TeV by ALICE [9],
although better description of data is achieved for $\mu = 2 p_T$,
for which calculations are above data by 10–40% depending
on $p_T$. It has to be noted that FF uncertainties of NLO pQCD
calculations have been considerably reduced after includ-
ing the published $\pi^0$ measurement at $\sqrt{s} = 7$ TeV [3] for
DSS14. Including precise new data for $\eta$ meson production
measured at $\sqrt{s} = 2.76$, 7 and 8 TeV [3,9] will also help
to considerably reduce NLO pQCD uncertainty bands in that
case. In addition, the reported neutral meson measurements at
$\sqrt{s} = 8$ TeV are compared to PYTHIA8.210 [18] references;
Tune 4C [19] and Monash 2013 tune [20]. To enable a proper
comparison of the PYTHIA tunes with the measured neutral
meson spectra, $\pi^0$ from decays of long-living strange par-
ticles ($K^0_S$, $\Lambda$, $\Sigma$ and $\Xi$) are excluded. The Tune 4C calculation is about 30% above the $\pi^0$ measurement for $p_T > 1.5$ GeV/c. In contrast, the Monash 2013 tune reproduces the $\pi^0$ spectrum within 10% for almost the complete transverse momentum
range, although both tunes are not able to describe the
shape of the measured spectrum indicated by the bump at
approximately 3 GeV/c. Concerning the $\eta$ meson, both tunes
reproduce the measured spectrum for $p_T > 1.5$ GeV/c within
uncertainties. At lower momenta $p_T < 1.5$ GeV/c, both tunes
follow the same trend and deviate significantly in magnitude
and shape from data. The tuning parameters of the soft QCD
part of PYTHIA apparently fail to describe the measured $\eta$
meson spectrum below $p_T < 1.5$ GeV/c, whereas there is
further tension up to $p_T \approx 3.5$ GeV/c. On the other hand,
both PYTHIA tunes are consistent within uncertainties with the
measured $\pi^0$ spectrum for the low transverse momentum
interval $0.3 < p_T < 1.5$ GeV/c.

functions are used in this context: a TCM, Eq. 3, a Tsal
Eq. 4, and a modified Hagedorn [58] fit that is used as
default fit function, since it yields the best agreement w
data at lowest $p_T$ measured [38]. The obtained values for
and $\eta$ mesons are listed in Table 6, where statistical and
systematic uncertainties are quoted. The additional uncertain-
ty denoted with “fit syst” reflects the choice of the fit
function. Moreover, the introduced fit functions are also u:
to calculate the integrated yields, $dN/dy|_{y=0}$, for both na-
tral mesons in inelastic events. The cross section for inelas-
 tic pp collisions at $\sqrt{s} = 8$ TeV, $\sigma_{inel} = 74.7 \pm 1.7$ mb [59]
used for this purpose. The obtained yields are given in Ta-
ble 6, which are based on extrapolation fractions, $F_{extrap}$, of ab
45% for the $\pi^0$ and about 34% for the $\eta$ meson. Addi-
tionally, the integrated $\eta/\pi^0$ ratio is estimated and can be fo:
Table 6 as well. For the recent paper by ALICE on neu-

t meson production in pp collisions at $\sqrt{s} = 2.76$ TeV [9],

mean $p_T$ as well as the integrated yields are also calculated
the reported spectra, which are furthermore added to Ta-
Table 6. The inelastic pp cross section at $\sqrt{s} = 2.76$ TeV, quo
in Ref. [9] as well, is used to calculate the integrated yie
which include extrapolation fractions of about 59% for the
and about 52% for the $\eta$ meson. The obtained values for ($j$
and $dN/dy|_{y=0}$) for both neutral mesons are compared w
measurements of average transverse momenta of char
particles [60] and with results concerning charged-particle
multiplicity [61]. Due to a large extrapolation fraction of
$\pi^0$ and $\eta$ meson spectra with respect to charged par-
icles $\xi$, the given systematics for the lowest transverse momenta,
uncertainties of $p_T$ and $dN/dy|_{y=0}$ are found to be large.
Hence, the integrated $\eta/\pi^0$ ratios are also affected. Neverth
less, all values quoted in this paragraph are consistent with
experimental uncertainties with the results from charged-particle
measurements [47,62]. Within their substantial un-
certainties, the $\eta/\pi^0$ ratios at both pp energies are found to
consistent as well.

Both meson spectra, which are shown in Fig. 7, exi
a similar power-law behavior, $E^{d\sigma/dp^3} \propto p_T^{-n}$, w
$n_{\pi^0} = 5.936 \pm 0.012(\text{stat}) \pm 0.023(\text{sys})$ and $n_{\eta}$
5.930 \pm 0.029(\text{stat}) \pm 0.044(\text{sys}) for high momenta
$p_T > 3.5$ GeV/c. This is also reflected in the $\eta/\pi^0$ ratio wh
is shown in Fig. 8. The ratio is flat for $p_T > 3.5$ GeV/c wit
constant value of $C_\eta/\pi^0 = 0.455 \pm 0.006(\text{stat}) \pm 0.014(\text{sys})$
Despite of the inability of NLO calculations to describe in
vidual $\pi^0$ and $\eta$ meson spectra, the $\eta/\pi^0$ ratio is repro,
fairly well, as it can be followed from left part of Fig. 8. It
to be noted that a different FF for the $\pi^0$ is used to com
the theory curve, namely DSS07, since there is no recent c
ulation for the $\eta$ meson available which could be compa
the recent DSS14 $\pi^0$ prediction. The agreement of pQG
calculations with the data can be viewed as an indication t
Table 6: The mean transverse momenta, \( \langle p_\perp \rangle \), and integrated yields, dN/dy\( |_{y=0} \), for ALICE measurements of \( \pi^0 \) and \( \eta \) mesons at \( \sqrt{s} = 2.76 \) and 8 TeV are summarized [38]. It has to be noted that the uncertainties from the measurements of the inelastic cross sections are not included for the given numbers, which are \( +3.9\% \) (model) \( \pm 2.0\% \) (lum) for \( \sqrt{s} = 2.76 \) TeV [29] and \( \pm 2.3\% \) for 8 TeV [99]. Moreover, integrated \( \eta/\pi^0 \) ratios are quoted for the different energies.

| \( \sqrt{s} = 8 \) TeV | \( \langle p_\perp \rangle \) (GeV/c) | dN/dy\( |_{y=0} \) | \( F_{\text{exp}} \) |
|----------------|----------------|----------------|----------------|
| \( \pi^0 \)   | 0.431 ± 0.006 \( \pm \) 0.020 \( \pm \) 0.012 \( \pm \) 0.012 \( \pm \) 0.012 \( \pm \) 0.012 | 3.252 ± 0.128 \( \pm \) 0.020 \( \pm \) 0.012 \( \pm \) 0.012 \( \pm \) 0.012 | 45 |
| \( \eta \)     | 0.929 ± 0.110 \( \pm \) 0.126 \( \pm \) 0.085 \( \pm \) 0.085 \( \pm \) 0.085 \( \pm \) 0.085 | 0.164 ± 0.033 \( \pm \) 0.052 \( \pm \) 0.023 \( \pm \) 0.023 \( \pm \) 0.023 | 34 |
| \( \eta/\pi^0 \) | - | 0.050 ± 0.010 \( \pm \) 0.022 \( \pm \) 0.008 \( \pm \) 0.008 | - |

| \( \sqrt{s} = 2.76 \) TeV | \( \langle p_\perp \rangle \) (GeV/c) | dN/dy\( |_{y=0} \) | \( F_{\text{exp}} \) |
|----------------|----------------|----------------|----------------|
| \( \pi^0 \)   | 0.451 ± 0.008 \( \pm \) 0.014 \( \pm \) 0.152 \( \pm \) 0.152 \( \pm \) 0.152 \( \pm \) 0.152 | 1.803 ± 0.058 \( \pm \) 0.045 \( \pm \) 0.152 \( \pm \) 0.152 \( \pm \) 0.152 | 59 |
| \( \eta \)     | 0.647 ± 0.068 \( \pm \) 0.168 \( \pm \) 0.040 \( \pm \) 0.140 \( \pm \) 0.040 \( \pm \) 0.140 | 0.250 ± 0.050 \( \pm \) 0.168 \( \pm \) 0.040 \( \pm \) 0.040 \( \pm \) 0.040 | 52 |
| \( \eta/\pi^0 \) | - | 0.139 ± 0.028 \( \pm \) 0.040 \( \pm \) 0.061 | - |

Fig. 8: Left: \( \eta/\pi^0 \) ratio compared to NLO pQCD predictions using PDF CTEQ6M5 and FFs DSS07 for the \( \pi^0 \) and AESSS for the \( \eta \), and PYTHIA8.210 calculations using Tune 4C and Monash 2013 tune. The total uncertainties of the measured \( \eta/\pi^0 \) ratio are of the order of 10% for most of the \( p_\perp \) bins covered, increasing for lower and higher momenta due to limited statistics as well as systematic effects. Right: Comparison of the \( \eta/\pi^0 \) ratio to related, previous ALICE measurements as well as other experiments at lower collision energies, for which total uncertainties are drawn. Furthermore, a comparison to the \( \eta/\pi^0 \) ratio obtained with \( m_\tau \) scaling is added. The observed value of \( m_\tau \) scaling is tested by means of the \( M_\tau/\pi^0 \) ratio. For this purpose, the TCM parameterization of the measured \( \pi^0 \) spectrum, given in Table 5, is used to obtain the \( \eta \) spectrum via the application of \( m_\tau \) scaling by replacing the \( \pi^0 \) mass with the \( \eta \) mass and using the normalization ratio \( C_\eta/C_\pi^0 = 0.455 \). From these two spectra, the \( M_\tau/\pi^0 \) ratio is constructed, plotted as blue curve in the right part of Fig. 8. The measured \( M_\tau/\pi^0 \) ratio is consistent with the \( m_\tau \) scaling prediction (blue curve) above \( p_\perp \approx 3.5 \) GeV/c. However, for smaller transverse momenta of \( p_\perp < 3.5 \) GeV/c the ratio of and reaches about 45% at around 1 GeV/c. For the region below 3.5 GeV/c, \( m_\tau \) scaling is observed to be clearly broken with a significance of 6.2\sigma. Given this observation, and the observed \( M_\tau/\pi^0 \) ratios in pp collisions at \( \sqrt{s} = 2.76 \) TeV a 7 TeV, previously reported by ALICE [39], re-evaluated, and the \( M_\tau/\pi^0 \) ratio is consistent with the observed in our experiment at 8 TeV. Furthermore, the \( \eta/\pi^0 \) ratios are fitted with a constant for \( p_\perp > 3.5 \) GeV/c, yield values of \( C_\eta/\pi^0 = 0.474 \pm 0.015 \) (stat) \( \pm 0.024 \) (sys) 2.76 TeV and \( C_\eta/\pi^0 = 0.476 \pm 0.020 \) (stat) \( \pm 0.020 \) (sys) 7 TeV. They are consistent within uncertainties with the measured \( M_\tau/\pi^0 \) ratio at 8 TeV for the given \( p_\perp \) range. Therefore all three ALICE measurements are simultaneously fitted with a constant for \( p_\perp > 3.5 \) GeV/c in order to obtain a combi...
the region $p_\tau < 3.5$ GeV/c, all collision energies covered by
ALICE also agree within experimental uncertainties, so that
$\eta/\pi^0$ ratios may be claimed to be consistent within accuracy
for ALICE measurements in pp collisions at $\sqrt{s} = 2.76, 7$ and 8 TeV.

Before the LHC era, the precision of $\eta/\pi^0$ measurements
was not sufficient to probe $m_\tau$ scaling over broad ranges of
$p_\tau$ with high statistics. PHENIX and NA27 provide the $\eta/\pi^0$
ratio with highest accuracy at high and low $p_\tau$ and therefore
are compared to the reported measurement. PHENIX measure-
ments for pp collisions at $\sqrt{s} = 200$ GeV are available
only for $p_\tau$ region $> 2.25$ GeV/c [63], where $\pi^0$ and $\eta$
spectra are already described by $m_\tau$ scaling. However, PHENIX
notably does not apply any secondary $\pi^0$ correction concern-
ing weak decays, which further has to be taken into account
when comparing with data points from ALICE. Measure-
ments of $\pi^0$ and $\eta$ spectra in pp collisions at $\sqrt{s} = 27.5$ GeV
from NA27 [64] are used to obtain the $\eta/\pi^0$ ratio in the $p_\tau$
range of $0.4 < p_\tau < 1.6$ GeV/c. The paper does not mention
a secondary correction of $\pi^0$ spectrum; however, it cannot
significantly change the conclusions to be drawn from the
measurement. Although the NA27 measurement provides the
world’s most precise published data points for the $\eta/\pi^0$ ratio
at low $p_\tau < 2.0$ GeV/c in the pre-LHC era for pp collisions,
it is not conclusive concerning $m_\tau$ scalIng violation. The first
NA27 points at $p_\tau < 1$ GeV/c are consistent with both
the $m_\tau$ scaling curve and the new data from pp collisions
at $\sqrt{s} = 2.76, 7$ and 8 TeV within uncertainties, whereas
for $p_\tau > 1$ GeV/c the results of NA27 show a tendency to
be above the $m_\tau$ scaling prediction, although uncertainties
become significant. A clearer confirmation of the $m_\tau$ scal-
ing at low $p_\tau$ is observed for other particle species, such as
kaons, $\phi$ and $J/\psi$ in pp collisions at $\sqrt{s} = 200$ GeV [13].
Whether the magnitude of $m_\tau$ scaling violation depends on
the collision energy can be clarified in future by ongoing
analysis of hadron spectra measurements in pp collisions at
$\sqrt{s} = 13$ TeV delivered by the LHC.

7 Conclusion

The invariant differential cross sections of $\pi^0$ and $\eta$ mesons
in pp collisions at $\sqrt{s} = 8$ TeV have been measured at
mid-rapidity over a wide $p_\tau$ range by the ALICE experi-
ment, using four different reconstruction methods for the
$\pi^0$, and three for the $\eta$ meson. NLO pQCD calculations with
MSTW08 (PDF) with DSS14 (FF) for the $\pi^0$ and CTEQ6M5
(PDF) with AESSS (FF) for the $\eta$ meson overestimate the
measured spectra of both neutral mesons. This discrepancy
is also reported for pp collisions at $\sqrt{s} = 2.76$ TeV by
ALICE. However, the ratio of $n/\pi^0$ is reproduced by NLO
from PYTHIA8.2 Tune 4C describes the $\eta$ spectrum with
uncertainties for $p_\tau > 1.5$ GeV/c, but it is about 30% larger
than the measured $\pi^0$ production cross section. On the other
hand, the Monash 2013 tune agrees with the reported neutral
meson measurements within 10% for $p_\tau > 1.5$ GeV/c.
Both PYTHIA8.2 tunes are able to reproduce the $\pi^0$ spec-
trum below $p_\tau < 1.5$ GeV/c, but a deviation from this empirical
scaling law is found for $p_\tau < 3.5$ GeV/c with a significance of 6.2$\sigma$. Within experi-
mental uncertainties, the $\eta/\pi^0/\pi^0$ ratios measured by NA.
PHENIX and ALICE are in agreement for the cover-
transverse momentum intervals of each measurement, res-
erving pp collisions starting at center of mass energies
$\sqrt{s} = 27.5$ GeV up to $\sqrt{s} = 8$ TeV.

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