Neutral pion and eta meson production at midrapidity in Pb-Pb collisions at root $S_{NN}=2.76$ TeV

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Neutral pion and $\eta$ meson production at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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Neutral pion and $\eta$ meson production in the transverse momentum range $1 < p_T < 20$ GeV/c have been measured at midrapidity by the ALICE experiment at the Large Hadron Collider (LHC) in central and semicentral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. These results were obtained using the photon conversion method as well as the Photon Spectrometer (PHOS) and Electromagnetic Calorimeter detectors. The results extend the upper $p_T$ reach of the previous ALICE $\pi^0$ measurements from 12 to 20 GeV/c and present the first measurement of $\eta$ meson production in heavy-ion collisions at the LHC. The $\eta/\pi^0$ ratio is similar for the two centralities and reaches at high $p_T$ a plateau value of $0.457 \pm 0.013^{\text{stat}} \pm 0.018^{\text{syst}}$. A suppression of similar magnitude for $\pi^0$ and $\eta$ meson production is observed in Pb-Pb collisions with respect to their production in $pp$ collisions scaled by the number of binary nucleon-nucleon collisions. We discuss the results in terms of Next to Leading Order (NLO) pQCD predictions and hydrodynamic models. The measurements show a stronger suppression than observed at lower center-of-mass energies in the $p_T$ range $6 < p_T < 10$ GeV/c. For $p_T < 3$ GeV/c, hadronization models describe the $\pi^0$ results while for the $\eta$ some tension is observed.

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I. INTRODUCTION

Quantum chromodynamics (QCD) [1], the fundamental theory of strong interactions, predicts that, above a certain critical energy density, hadrons melt into a quark-gluon plasma (QGP) [2,3]. Such a state of matter is believed to have existed a few microseconds after the Big Bang [4]. One of the goals of lattice QCD calculations is the understanding of the properties of strongly interacting matter and the nature of the phase transition that depends on the values of the quark masses and number of flavors. For vanishing baryon chemical potential ($\mu$) and for quark masses above a critical quark mass, a deconfinement transition associated with chiral restoration takes place through a smooth crossover [5–8]. The study and characterization of the QGP gives information on the crossover transition as well as insights on the equation of state of deconfined matter [9,10]. These transitions are expected to have occurred in the early universe and therefore their study is also of relevance to cosmology [4].

Heavy-ion collisions at relativistic energies offer the possibility of studying the QGP by creating systems of dense matter at very high temperatures. Of the many observables that probe the QGP, measurements of $\pi^0$ and $\eta$ meson production over a large transverse momentum ($p_T$) range and in different colliding systems are of particular interest. At low $p_T$ ($p_T < 3$ GeV/c), light meson production in heavy-ion collisions gives insights about hadronization and collectivity in the evolution of the QGP. At high $p_T$ ($p_T > 5$ GeV/c), it helps quantify parton energy loss mechanisms [11,12]. High-$p_T$ particle suppression in heavy-ion collisions with respect to $pp$ collisions may be modified by cold nuclear matter effects, such as nuclear parton distribution function (nPDF) modifications with respect to the vacuum. Measurements in $pA$ collisions are thus needed to disentangle cold nuclear effects from the observed high-$p_T$ particle suppression in $AA$ collisions.

Other interesting probes of the QGP that can benefit from neutral meson measurements are studies of direct photon and heavy-flavor production measurements [13,14]. The $\pi^0$ and $\eta$ mesons are the two most abundant sources of decay photons (and electrons); as a consequence, they generate the primary background for these rare probes. The first measurement of direct photons at the Large Hadron Collider (LHC) [15] employed $m_T$ scaling and the $K^0_s$ reference measurement to estimate the $\eta$ contribution to decay photons. Forthcoming direct photon and heavy-flavor measurements at the LHC will be able to use the $\eta$ measurement directly.

Measurements of pion spectra at Relativistic Heavy Ion Collider (RHIC) [16,17] at low transverse momentum were observed to be well described by thermal models that assume a hydrodynamic expansion of a system in local equilibrium [18]. The comparison of these models to data suggested the presence of a thermalized system of quarks and gluons formed in the early stages of the collision. At LHC energies, the thermal models that describe the RHIC data also describe the ALICE charged pion spectrum [19] for $p_T > 0.5$ GeV/c. Modern versions of these models fold in their calculations hydrodynamic expansion, which accounts for transverse flow effects, simultaneous chemical, and thermal freeze-out and inclusion of high mass resonance decays from the PDG [1].
Among the many models that aim at explaining low-$p_T$ particle production, the equilibrium and chemical nonequilibrium statistical hadronization models (EQ SHM and NEQ SHM, respectively) have had their validity tested against LHC data from $p_T > 0.1$ GeV/c. The physics picture behind the NEQ SHM is a sudden hadronization of the QGP that leads to the appearance of additional nonequilibrium chemical potentials for light and strange quarks. The low-$p_T$ pion enhancement predicted by the NEQ relative to the EQ SHM can be interpreted as the onset of pion condensation in ultrarelativistic heavy-ion collisions at the LHC energies [20–24]. Both predictions can be further tested by measuring $\pi^0$ and $\eta$ production at LHC energies.

In the early RHIC program, a suppression of high-$p_T$ $\pi^0$ production was observed in heavy-ion collisions when compared to scaled $pp$ data [25]. This suppression was interpreted as a consequence of the energy loss of the scattered partons in the QGP generated in the collisions. From these observations, it was deduced that the dense QGP medium is opaque to energetic (hard) colored probes. Regarding high-$p_T$ particle production at the LHC, it must be considered that the energy density of the plasma is higher than measured at RHIC. This increase in energy density leads to a larger energy loss of high-$p_T$ partons with respect to those at both lower $p_T (<3$ GeV/c) and lower energy [26,27]. Moreover, it has been observed that baryons and strange mesons exhibit similar suppression as that of pions above 10 GeV/c. The measurement of another light meson, the $\eta$ meson, provides additional information about mechanisms of particle production and energy loss, while the measurement of both mesons at higher $p_T$ will give insight about the $p_T$ dependence of the suppression in this region.

The suppression due to the QGP can also be studied with the $\eta/\pi^0$ ratio. In heavy-ion collisions, gluons are expected to experience larger energy loss in the medium than quarks, due to gluons having a larger vertex coupling factor. The energy reduction due to the presence of the medium (jet quenching effect) [28] may alter gluon and quark fragmentation differently with respect to what is observed in $pp$ collisions. These differences between gluon and quark energy loss may introduce a modification in the suppression patterns observed for $\pi^0$ and $\eta$ mesons, due to a larger gluon component in the $\eta$ meson (note that the $\eta$ meson, unlike $\pi^0$, has a two-gluon component) [29]. An intermediate $p_T$ enhancement of the $\eta/\pi^0$ ratio in $AA$ collisions relative to $pp$ collisions would be an indication of the plasma-induced color dependence suppression [30–32]. The magnitude of this enhancement is sensitive to the initial values of the jet transport parameters and thus could be used to quantify the suppression.

In this paper, we present $\pi^0$ and $\eta$ meson production measurements from the ALICE experiment in the $p_T$ range $1 < p_T < 20$ GeV/c in Pb-Pb collisions at center-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV in two centrality classes, 0–10% and 20–50%. The results are measured at midrapidity using two complementary detection methods: the photon conversion method (PCM) and use of the Electromagnetic Calorimeter (EMCal) [33]. The $\pi^0$ results in the 0–10% centrality class have been combined with the previously published $\pi^0$ result measured with the Photon Spectrometer (PHOS) calorimeter [27]. The new $\pi^0$ measurement is updated with 10 times more statistics than the previous ALICE measurement [27] and extends the $p_T$ reach from 12 GeV/c to 20 GeV/c. The $\eta$ measurement is the first measurement of its kind at the LHC and has a wider $p_T$ reach than what was previously measured at RHIC [34].

The paper is organized as follows: A brief description of the detectors used and of the data sample is given in Sec. II. The analysis procedure is described in Sec. III. The results and the comparison to other experimental measurements and to theoretical predictions are presented in Secs. IV and V, respectively.

II. DETECTOR DESCRIPTION AND DATA SAMPLE

The ALICE experiment and its performance are described in detail in Refs. [35,36]. The main detectors used for the reconstruction of $\pi^0$ and $\eta$ mesons are located in the central barrel, operated inside a solenoidal magnetic field of 0.5 T directed along the beam axis.

The Inner Tracking System (ITS) is a high granularity and precision detector that measures the position of the primary collision vertex and the impact parameter of the tracks [37]. The ITS is composed of six cylindrical layers of silicon detectors positioned at radial distances from 4 to 43 cm. The two innermost layers of the ITS are Silicon Pixel Detectors (SPD) that cover the pseudorapidity regions $|\eta| < 2$ and $|\eta| < 1.4$. The next two layers are Silicon Strip Detectors (SSD) covering $|\eta| < 1$, while the two outer layers are Silicon Strip Detectors (SSD) covering $|\eta| < 0.9$.

The Time Projection Chamber (TPC) [38] is the main charged particle tracking and identification detector in the ALICE central barrel. It is a cylindrical drift detector filled with a Ne-CO$_2$ (90%-10%) gas mixture. This detector surrounds the ITS and is centered around the Interaction Point (IP) at a radial distance from 85 to 250 cm. The TPC has full azimuthal coverage and covers $|\eta| < 0.9$ for the full track length. Particles are identified through the measurement of their specific energy loss ($dE/dx$) in the detector with a 6.5% resolution in the 0–5% most central Pb-Pb [36,38]. The track’s transverse-momentum resolution is $\sigma(p_T)/p_T = 0.8\%$ at 1 GeV/c and 1.7% at 10 GeV/c in central Pb-Pb collisions [36,39].

The EMCal [33] is a sampling calorimeter composed of 77 alternating layers of 1.4-mm lead and 1.7-mm polystyrene scintillators. The EMCal is a fairly high granularity detector. It has a cell area of 0.0143 cm$^2$ and 0.0143 rad and an energy resolution of $\sigma(E)/E = 4.8\%$ at 11.3 GeV/c. In year 2010, it covered $|\eta| < 0.7$ and $\Delta\phi = 100^\circ$.

The main detectors used for triggering and characterization of the collision are the V0 [41] and the Zero Degree Calorimeters (ZDC) [42]. The V0 consists of two scintillator arrays located on opposite sides of the IP at 340 and 90 cm covering $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. The ZDC detectors are located at a distance of 114 m on both sides of the IP and detect spectator nucleons.

The Pb-Pb data sample used for this analysis was collected in the 2011 LHC run. During that period, about 358 ion bunches circulated in each LHC beam, with collisions delivering a peak luminosity of $4.6 \times 10^{34} \mu$b$^{-1}$s$^{-1}$, corresponding
to an average of about $10^{-3}$ hadronic interactions per bunch crossing. The minimum bias (MB) trigger was defined by the coincidence of signals in the two V0 arrays synchronized with a bunch crossing. An online selection based on the measured V0 amplitudes was employed to enhance central (0–10%) and semicentral (0–50%) events [36]. The ZDC and the V0 were also used for the rejection of pile-up and beam-gas interactions. The centrality class definition was based on the V0 amplitude distributions. The number of binary collisions ($N_{\text{coll}}$) for a given value of the centrality was extracted with the help of a Glauber model [43] as detailed in Refs. [39,44]. Only events with a reconstructed primary vertex within $|z_{\text{vtx}}| < 10$ cm of the nominal interaction vertex along the beam direction were accepted. The data are analyzed in two centrality classes: 0–10% and 20–50%, containing 1.9(1.6) $\times$ 10$^{7}$ and 1.3(1.1) $\times$ 10$^{7}$ events for PCM (EMCal), respectively. The minimum bias trigger cross section, $\sigma_{\text{MB}}^\text{p+p} = [7.64 \pm 0.22(\text{syst.})]$ b [44], was determined using van der Meer scans [45]. The integrated luminosity, corresponding to the number of analyzed events normalized by $\sigma_{\text{MB}}^\text{p+p}$ in each centrality percentile, is 20.1 $\mu$b$^{-1}$ and 4.8 $\mu$b$^{-1}$ for 0–10% and for 20–50%, respectively.

### III. ANALYSIS METHODS

The $\pi^0$ and $\eta$ mesons are reconstructed using the two-photon decay channel, $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$, with a branching ratio of (98.823 ± 0.034)% and (39.41 ± 0.20)% [1], respectively. With the photon conversion method, photons that convert in the detector material are measured by reconstructing the electron-positron pairs in the central rapidity detectors using a secondary vertex ($V^0$) finding algorithm [36]. This method produces a $V^0$ candidate sample on which the analysis quality selection criteria were applied, as done in Refs. [27,46]. Electrons, positrons, and photons are required to have $|\eta| < 0.9$. To ensure track quality, a minimum track momentum of 50 MeV/c and a fraction of TPC clusters overlap findable clusters (the number of geometrically possible track momentum of 50 MeV) above 0.6 have been required. Moreover, a maximum conversion radius of 180 cm delimits the TPC fiducial volume for good track reconstruction, while a minimum of 5 cm rejects Dalitz decays of the type $\pi^0(\eta) \rightarrow e^+e^-\gamma$. The specific energy loss $dE/dx$ should be within the interval $[-3 \sigma_{dE/dx}, +3\sigma_{dE/dx}]$ from the expected electron Bethe-Bloch parametrization value, where $\sigma$ is the standard deviation of the energy loss measurement. Pions are rejected by a selection of $3\sigma$ above the pion hypothesis in the range $0.4 < p < 2$ GeV/c and of $1\sigma$ for $p > 2$ GeV/c. The smaller rejection with respect to the previous Pb-Pb measurement translates into a larger efficiency at high $p_T$ for the $\pi^0$ and $\eta$ mesons. To further reject $K_0^0$, $\Lambda$, and $\Xi$ from the $V^0$ candidates, a selection is applied on the components of the momenta relative to the $V^0$, using the asymmetry of the longitudinal momentum of the $V^0$ daughters [$\alpha_{\text{v0}} = (p_{\text{v0}}^z - p_{\text{v0}}^+)/(p_{\text{v0}}^z + p_{\text{v0}}^+)$], and on the transverse momentum of the electron with respect to the $V^0$ momentum ($q_T = p_e \times \sin \theta_v n_e$). $V^0$ candidates are selected with a two-dimensional elliptic selection criterion of $(\alpha_{\text{v0}}/\alpha_{\text{max}}^\text{v0})^2 + (q_T/q_{\text{T, max}}^\text{v0})^2 < 1$, with $\alpha_{\text{v0}}^\text{max} = 0.95$ and $q_{\text{T, max}} = 0.5$ GeV/c, in order to increase the purity while optimizing efficiency of the photon sample. As conversion electrons have a preferred decay orientation, a selection on $\psi_{\text{pair}}$, the angle between the plane perpendicular to the magnetic field and the plane containing the electron and positron tracks, together with a cut on the photon $\chi^2$ of the Kalman filter [47], further suppresses the contamination from nonphotonic $V^0$ candidates. This cut, described in Ref. [48], is applied requiring $\chi^2_{p_{\text{T}, \text{max}}} = 20$ and $\psi_{\text{pair, max}} = 0.1$. To improve the signal significance, a $p_T$-dependent cut on the energy asymmetry of the photons $|\alpha| < 0.65\tanh[1.8(\text{GeV/c})^{-1}p_T]$ where $\alpha = (E_{\gamma_1} - E_{\gamma_2})/(E_{\gamma_1} + E_{\gamma_2})$, $p_T$ in GeV/c is applied.

For the measurement with the EMCal, photons stemming from meson decays are measured directly. Photonic hits in the detector are identified by energy deposits in the neighboring cells, which are grouped into clusters with a minimum size of two cells. A minimum energy per cell of 50 MeV is required. The cluster finding algorithm employs a seed energy of $E_{\text{seed}} = 0.3$ GeV, which is slightly above the minimum ionizing particle threshold [36]. EMCal clusters that coincide within a window of $|\Delta\eta| < 0.025$ and $|\Delta\phi| < 0.05$ radians of a charged particle reconstructed in the TPC and projected to the EMCal surface are rejected. Each selected EMCal cluster is then required to have a total energy of at least 1.5 GeV to remove low-energy pairs consisting of predominantly combinatorial background and particle conversions in the material. A loose photoline electromagnetic shower shape selection is applied to the clusters by looking at the eccentricity of the cluster via the weighted RMS of the shower energy along the major ellipse axis according to

$$\sigma_{\text{long}}^2 = \frac{s_{\text{yy}} + s_{\text{pp}}}{2} + \sqrt{(s_{\text{yy}} - s_{\text{pp}})^2/4 + s_{\text{pp}}^2},$$

where $s_{ij} = |i\rangle \langle j|$ are the covariance matrix elements; $i, j$ are cell indices in $\eta$ or $\varphi$ axes; and $|i\rangle$ and $|j\rangle$ are the second and the first moments of the cluster cells weighted with the cell energy logarithm [36,49–51]. The purpose of this loose shower shape selection 0.1 $< \sigma_{\text{long}} < 0.5$ photons sit in a narrow peak centered at 0.25) is to remove noisy and very deformed or asymmetric cluster shapes which result from the merging of different particle showers produced nearby in the calorimeter.

For the PCM and EMCal analyses, the reconstructed two-photon invariant mass is measured in bins of $p_T$ in the rapidity range $|y| < 0.85$ and $|y| < 0.7$, respectively. The $p_T$ ranges in which the separate methods contribute are reported in Table I. In addition, a minimum photon pair opening angle of 5 mrad is used to reject background in the PCM analysis.

The background under the neutral meson signal contains combinatorial and correlated contributions. The combinatorial background is estimated with the event mixing method by mixing photons from different events but with similar photon multiplicity and topological (vertex location on the $z$ axis and in the particular case of the PCM analysis the event plane angle) characteristics. The mixed event background is normalized to the reconstructed two-photon invariant mass in a region at higher mass with respect to the meson peak and...
TABLE I. Transverse momentum ranges for the $\pi^0$ and $\eta$ meson measurements. For the $\eta$ meson in both centralities and for the $\pi^0$ in 20–50% centrality class the combination is between PCM and EMCal. For $\pi^0$ in the 0–10%, the final results are obtained combining PCM, EMCal, as well as previously published results using the PHOS detector [27].

<table>
<thead>
<tr>
<th>$\pi^0$</th>
<th>PCM</th>
<th>EMCal</th>
<th>PHOS</th>
</tr>
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<tbody>
<tr>
<td>0–10%</td>
<td>1–14 GeV/c</td>
<td>4–20 GeV/c</td>
<td>1–12 GeV/c</td>
</tr>
<tr>
<td>20–50%</td>
<td>1–14 GeV/c</td>
<td>4–20 GeV/c</td>
<td>–</td>
</tr>
</tbody>
</table>

\[ \frac{d^3N}{dp^3} = \frac{1}{2\pi N_{\text{evt}} B_{\text{Ratio}} A e p_T \Delta p_T \Delta y}, \]

\[ \text{where } N_{\text{evt}} \text{ is the number of events in the centrality class considered, } B_{\text{Ratio}} \text{ is the branching ratio [1] for the process } \pi^0(\eta) \rightarrow \gamma \gamma, \text{ } A e \text{ are the corresponding acceptance and efficiency corrections, and } N_{\text{raw}} \text{ corresponds to the reconstructed } \pi^0(\eta) \text{ raw yield within the rapidity range } \Delta y \text{ and the transverse momentum bin } \Delta p_T. \]
The cross section is equal to the measured integral of the cross section over the corresponding bin [58]. For the $\eta/\pi^0$ ratio and $R_{AA}$ the bin-shift correction is done in $y$ coordinates. The $p_T$ ranges in which the measurements were performed are reported in Table I. In the overlap region a weighted average of the two results (or three when applicable) is performed using the inverse of the quadratic sum of the uncertainties (statistical and systematic) that are uncorrelated between the methods as weights [59–61].

Figure 2 shows the invariant differential yields of (a) $\pi^0$ and (b) $\eta$ meson measured in $pp$ [51] and Pb-Pb collisions in the two centrality bins under study. The $\pi^0$ meson measurements are in agreement with the previously published ALICE $\pi^0$ spectra [27] and extend the transverse momentum reach from 12 to 20 GeV/c. For the $\eta$ meson, the results presented here are the first measurement of its kind in heavy-ion collisions at the LHC and the first measurement of this meson to reach down to $p_T$ of 1 GeV/c in a collider experiment [34,62].

Both meson spectra have been parametrized over the full $p_T$ range by the function proposed in Refs. [63,64] that combines a Boltzmann factor at low $p_T$ with a power law at higher $p_T$. 

The invariant mass distribution of reconstructed photon pairs $M_{\gamma\gamma}$ for the $\pi^0$ and $\eta$ mesons measured with PCM [(a) and (b)] and EMCal [(c) and (d)] in the centrality class 0–10%. The black histograms show the signal before background subtraction while the red bullets show the signal after subtraction. The estimated background is indicated by the gray dashed lines. The blue lines are the fit to the invariant mass peak after the combinatorial and residual background subtraction (see text for description).
TABLE II. Summary of the systematic uncertainties in percentages for selected $p_T$ regions for the PCM and EMCal analyses.

<table>
<thead>
<tr>
<th></th>
<th>PCM 0–10%</th>
<th>20–50%</th>
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<tbody>
<tr>
<td></td>
<td>$\pi^0$ 1.1 GeV/c</td>
<td>5.5 GeV/c</td>
</tr>
<tr>
<td>Material budget</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>2.3</td>
<td>2.6</td>
</tr>
<tr>
<td>Yield extraction</td>
<td>1.5</td>
<td>2.1</td>
</tr>
<tr>
<td>$e^+/e^-$ identification</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td>Photon reconstruction</td>
<td>3.7</td>
<td>2.1</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th></th>
<th>EMCal 0–10%</th>
<th>20–50%</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$\pi^0$ 7.0 GeV/c</td>
<td>18.5 GeV/c</td>
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<tr>
<td>Signal extraction</td>
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<td>5.1</td>
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<tr>
<td>Photon identification</td>
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<td>8.0</td>
</tr>
<tr>
<td>Energy response</td>
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<td>8.6</td>
</tr>
<tr>
<td>Material budget</td>
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<td>5.0</td>
</tr>
<tr>
<td>Hijing simulation</td>
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<tr>
<td>Monte Carlo input</td>
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</tr>
<tr>
<td>Higher mass decays</td>
<td>4.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

FIG. 2. Invariant yields of the (a) $\pi^0$ and (b) $\eta$ meson in the centrality classes 0–10% (circles) and 20–50% (squares). The vertical error bars represent the statistical uncertainties while the boxes represent the systematic uncertainties. The Pb-Pb measurements are compared with the corresponding $pp$ invariant cross sections (stars) measured at the same center-of-mass energy [27,51]. The dashed black lines correspond to the fits to the data with the two-component function. See Table III and corresponding text for details.
TABLE III. Parameters of the fits to the differential invariant yields of $\pi^0$ and $\eta$ meson using the two-component function of Bylinkin and Rostovtsev [63,64]. The total uncertainties, i.e., quadratic sum of statistical and systematic uncertainties, are used for the fits.

<table>
<thead>
<tr>
<th></th>
<th>$\pi^0$</th>
<th></th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–10%</td>
<td>20–50%</td>
<td>0–10%</td>
</tr>
<tr>
<td>$A_c$ (GeV/c)$^{-2}$</td>
<td>162 ± 20</td>
<td>30 ± 7</td>
<td>15 ± 6</td>
</tr>
<tr>
<td>$T_c$ (GeV/c)</td>
<td>0.37 ± 0.01</td>
<td>0.38 ± 0.02</td>
<td>0.44 ± 0.03</td>
</tr>
<tr>
<td>$A$ (GeV/c)$^{-2}$</td>
<td>840</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>$T$ (GeV/c)</td>
<td>0.34 ± 0.01</td>
<td>0.50 ± 0.02</td>
<td>0.38 ± 0.03</td>
</tr>
<tr>
<td>$n$</td>
<td>3.00 ± 0.05</td>
<td>3.00 ± 0.05</td>
<td>3.0 ± 0.1</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>0.18</td>
<td>0.20</td>
<td>0.22</td>
</tr>
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</table>

high $p_T$,

$$
E \frac{d^3N}{dp^3} = A_c \exp\left(-\left(\frac{p_T^2 + M^2 - M}{T_c}\right)^2 + \frac{A}{\left(1 + \frac{p_T^2}{\sigma^2}\right)^2}\right),
$$

where $M$ is the meson mass (in GeV/c$^2$) and $A_c$, $A$, $T_c$, $T$, and $n$ are free parameters of the fit. The parameters resulting from the fits to the meson invariant yields in both centrality classes are reported in Table III. All parameters are free except for the amplitude $A$. The values are chosen after a systematic study of the two separate components of the Bylinkin-Rostovtsev function and of the parameter limits variation.

B. Particle ratios

The $\eta/\pi^0$ ratio measured in the two centrality classes is shown in Fig. 3(a). In Fig. 3(b), the measurement in the 0–10% centrality class is compared to the same ratio measured in $pp$ collisions at $\sqrt{s} = 2.76$ TeV [51], as well as to the $K^\pm/\pi^\pm$ ratio in the same centrality class and in the same collision system and energy [19], measured by ALICE. The $K^\pm/\pi^\pm$ ratio is of interest as the relative mass differences between these particles is similar to the one for the $\eta$ and $\pi^0$ mesons. At $p_T < 2$ GeV/c, the $\eta/\pi^0$ and the $K^\pm/\pi^\pm$ ratios in Pb-Pb are in agreement within uncertainties. At $2 < p_T < 4$ GeV/c, due to the large uncertainties in the $\eta/\pi^0$ ratio in Pb-Pb, no conclusion can be made on the significance of the difference between the $\eta/\pi^0$ ratio in $pp$ or the $K^\pm/\pi^\pm$ ratio in Pb-Pb. At $p_T > 4$ GeV/c, the value for all ratios is of similar magnitude. Moreover, a constant fit from 3 to 20 GeV/c gives a plateau value for the ratio of $0.457 \pm 0.013^{stat} \pm 0.018^{syst}$, in agreement with the value quoted in lower center-of-mass energy measurements [34].

C. The nuclear modification factor $R_{AA}$

The nuclear modification factor can be used to quantify particle production suppression in heavy-ion collisions with respect to $pp$ collisions. It is defined as

$$
R_{AA} (p_T) = \frac{d^2N/dy|_{AA}}{(T_{AA}) \times d^2\sigma/dp_Tdy|_{pp}},
$$

where the nuclear overlap function $(T_{AA})$ is related to the average number of inelastic collisions by $(T_{AA}) = \langle N_{coll} \rangle/e_{pp}^{inel}$.

FIG. 3. (a) $\eta/\pi^0$ ratio in the two centrality classes measured, 0–10% (circles) and 20–50% (squares). (b) Comparison of the $\eta/\pi^0$ measurement in the 0–10% centrality class (full circles) to the corresponding ratio in $pp$ collisions [51] (stars) and to the $K^\pm/\pi^\pm$ measurement in the same centrality class, system, and collision energy [19] (open circles).
and $\sigma^{pp}$ is the total inelastic cross section determined using van der Meer scans [65].

The mean number of collisions is $1501 \pm 165$ for the centrality class $0$–$10\%$ and $349 \pm 34$ for the centrality class $20$–$50\%$ [44]. The $\pi^0$ and $\eta$ meson spectra measured in $pp$ collisions at the same center-of-mass energy are obtained from Ref. [51].

The measured $R_{AA}$ is presented in Fig. 4 for the $\pi^0$ and the $\eta$ mesons. A $p_T$- and centrality-dependent suppression is clearly observed. For the most central collisions, the $R_{AA}$ has a maximum around $p_T \approx 1.5$ GeV/c and a minimum for $p_T \approx 7$ GeV/c, after which it increases. The increase at high $p_T$ could be due to the variation of the relative gluon and quark contributions to meson production as a function of $p_T$, with gluons being expected to suffer a stronger suppression than quarks due to a larger Casimir factor [66].

The suppression observed at high $p_T$ is consistent with recent ATLAS results [67] and may indicate a larger quark than gluon relative contribution for high-$p_T$ jet production in heavy-ion collisions at the LHC. A similar behavior is observed for semicentral events, though with a smaller suppression over the full transverse momentum range. The magnitude and pattern of the suppression is the same for the $\pi^0$ and $\eta$ mesons for $p_T > 4$ GeV/c despite the difference in mass. At lower $p_T$, the present accuracy is not enough to determine if the suppression is different for the two mesons.

The $R_{AA}$ values for both centrality classes are also compared to the ALICE charged kaon $R_{AA}$ [68] measured at the same center-of-mass energy and collision system (Fig. 4) and is of interest given the similar masses of kaons and $\eta$ mesons. This comparison indicates similar suppression patterns for $\eta$ and $K^\pm$ across the whole $p_T$ range and similar suppression between all particles for $p_T > 4$ GeV/c. This result is consistent with previous baryon and strange meson $R_{AA}$ results [68,69], indicating that the energy loss in the medium is likely a purely partonic effect.

### D. Comparisons to lower energy measurements

The nuclear modification factor in the $0$–$10\%$ centrality class is compared to previous $\pi^0$ measurements reported by the WA98 [70] and PHENIX collaborations [25,71] [Fig. 5, (a)] for center-of-mass energies per binary collision $\sqrt{s_{NN}}$ ranging from $17.3$ GeV (WA89) to $200$ GeV (PHENIX). Our results confirm a dependence of the suppression on the center-of-mass energy and indicate a larger suppression for increasing collision energy. At $p_T > 11$ GeV/c, the relative difference in suppression between the PHENIX and ALICE data is inconclusive due to the large uncertainties.

The $\eta$ meson $R_{AA}$ is compared to the corresponding PHENIX measurement [34] at $\sqrt{s_{NN}} = 200$ GeV [Fig. 5(b)]. Similarly to the $\pi^0$ case, the ALICE measurement shows a larger suppression compared to the PHENIX data in the region $5 < p_T < 14$ GeV/c.

### V. COMPARISONS TO MODELS

The $\pi^0$ and $\eta$ invariant $p_T$-differential yields are compared to predictions using a statistical hadronization model (SHM) [18,20] and the EPOS2 [72] event generator. Results from two versions of the SHM are presented here, an EQ and NEQ prediction. In the NEQ SHM, the mean particle multiplicities are described with the use of four thermodynamic parameters: temperature $T$, volume $V$, and two parameters to account for the nonequilibrium conditions—$\gamma_s$ and $\gamma_q$. The EQ SHM can be treated as a particular case of the NEQ when $\gamma_s = \gamma_q = 1$. The parameters of the model are determined by fits to the measured charged pion and kaon spectra [20]. While only these two particles are considered in the fits, the...
resultsing parameters are used to make predictions for other particles [73], e.g., the \( \eta \) meson, the \( \rho \) meson, and the proton. The EPOS generator addresses both low- and high-\( p_T \) phenomena, where the particle spectra include effects (low \( p_T \)) associated to hydrodynamic flow as discussed in Ref. [19]. At higher \( p_T \), the focus is shifted towards energy loss of high-\( p_T \) strings where strings are the by-product of hard scatterings.

Figure 6(a) shows the comparison to models for the 0–10% and 20–50% centrality classes while Figs. 6(b)–6(e) shows the ratio of data and theory calculations to the fit of the \( \pi^0 \)- and \( \eta \)-invariant yields.

The EQ and NEQ SHM predictions [bold lines in Figs. 6(b) and 6(c)] describe the shape of the \( \pi^0 \) measurement within the uncertainties for both centralities. For the \( \eta \) meson, in Figs. 6(d) and 6(e), the EQ model also describes the data within uncertainties. Conversely, the NEQ model predicts about half as many \( \eta \) mesons than actually measured in central collisions. The difference observed between the NEQ SHM and the data may point towards a different flow profile of the two mesons with a larger flow for the \( \eta \) than the \( \pi^0 \) [74]. Significant differences between the EQ and NEQ predictions are also observed for the \( \rho^0 \), \( \Sigma(1385) \), \( \Lambda(1520) \), and \( \Xi(1530) \) [73,75].

The \( \pi^0 \) and \( \eta \) mesons are only partially described by EPOS [dashed lines in Figs. 6(b)–6(e)]. While the comparison is reasonably close to the data points for the \( \pi^0 \) measurement in 0–10% [Figs. 6(b)], the model only describes the low-\( p_T \) part of the [Fig. 6(c)] semicentral \( \pi^0 \) and [Figs. 6(d) and 6(e)] \( \eta \) measurements. No theoretical uncertainties for the EPOS calculations are available at the time of writing.

The \( \eta/\pi^0 \) ratio for the centrality class 0–10% is compared to the Next to Leading Order (NLO) pQCD calculation by Dai, Chen, Zhang, and Wang (DCZW) [30], to the ratio from the EQ and NEQ SHM [20] predictions, and to the EPOS [72] generator in Fig. 7. The DCZW model is based on a higher-twist approach to jet quenching [76] where parton fragmentation functions are modified as a consequence of the parton energy loss. A generalized QCD factorization of twist-4 processes is used to calculate the scattering. The effective parton fragmentation functions Albino, Kniehl, Kramer (AKK) [77] and Aidala, Ellinghaus, Seele, Stratmann (AESS) [78]) are then incorporated into a NLO pQCD framework to describe the particle production suppression. Data and the DCZW prediction are in agreement within uncertainties. The EQ SHM prediction describes the \( \eta/\pi^0 \) ratio, while in comparison to the NEQ SHM prediction the ratio is underestimated as shown in Figs. 6(d) and 6(e). The EPOS curves describe the ratio up to 4 GeV/\( c \), as expected since the disagreement with the \( \eta \) meson measurement is larger at higher \( p_T \).

The measurements of \( R_{AA} \) for both mesons are compared to four NLO pQCD-based models in Fig. 8: DCZW [30], Wicks, Horowitz, Djordjevic and Gyulassy (WHDG) [79–81], Djordjevic et al. [82] (\( \pi^0 \) only), and Vitev et al. [83–86] (\( \pi^0 \) only). In the first three models, it is assumed that a fast-moving parton passing through hot partonic matter will lose its energy via induced radiation due to multiple parton scattering. The WHDG calculation models collisional and radiative energy loss processes in a Bjorken-expanding medium. It assumes that the color charge density of the medium is proportional to the number of participating nucleons obtained from a Glauber model. Hard parton-parton scatterings are then proportional to the number of binary nucleon-nucleon collisions. The Djordjevic et al. model also includes effects due to the finite size of the QCD medium, the finite magnetic mass and the running of the coupling [82,87–89]. The model of Vitev et al. is an application of the soft-collinear effective theory with Glauber gluons (SCETG) to study inclusive hadron suppression in nucleus-nucleus collisions. In this model, medium-evolved fragmentation functions are combined with all initial-state cold nuclear matter (CNM) effects (dynamical nuclear shadowing, Cronin effect and initial-state parton energy loss). The authors demonstrate that traditional
parton energy loss calculations can be regarded as a special soft-gluon emission limit of the general QCD evolution framework.

In the most central event class, the $\pi^0$ meson $R_{AA}$ is described for $p_T > 4$ GeV/c by the DCZW, Djordevic et al., and Vitev et al. models and for $p_T > 6$ GeV/c by WHDG [Fig. 8(a)]. For the DCZW predictions, the $\eta$ meson is described within uncertainties from $p_T > 8$ GeV/c; below this momentum, the DCZW model overestimates the $R_{AA}$ result [Fig. 8(c)]. The latter may indicate that the relative quark and gluon contributions to the $\eta$ meson production is overestimated at intermediate $p_T$ ($4 < p_T < 8$ GeV/c). On the other hand, the WHDG model predicts larger suppression than observed in the data for the $\eta$ meson in the centrality class 0–10% and for both mesons in the centrality class 20–50%. The Djordevic et al. and Vitev et al. models describe the $\pi^0$ meson suppression in both centrality classes within uncertainties.

VI. SUMMARY

We have presented measurements of $\pi^0$ and $\eta$ meson production at midrapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured with the ALICE detector. Independent and complementary techniques are used: pho-
FIG. 8. $R_{AA}$ of [(a) and (b)] $\pi^0$ and [(c) and (d)] $\eta$ meson compared to NLO pQCD predictions by the DCZW (solid bands) [30], WHDG (dashed bands) [81], Djordevic et al. [82] (crossed bands, $\pi^0$ only), and Vitev et al. [83–86] (empty bands, $\pi^0$ only) models in the two centrality classes measured.

The combination of these methods allowed measurements in a large transverse-momentum range, from 1 to 20 GeV/c. The results represent the first measurement of $\eta$ meson production in heavy-ion collisions at the LHC. The $\pi^0$ measurements are performed using data that correspond to a factor 10 increase in integrated luminosity with respect to the previous ALICE publication [27]. The higher statistics allowed for an improved measurement that probes the $p_T$ region up to 20 GeV/c.

The $\eta/\pi^0$ ratio is compared to NLO pQCD calculations, corresponding ALICE measurements in $pp$ collisions and to the $K^\pm/\pi^\pm$ ratio measured in Pb-Pb collisions at the same energy. For $p_T > 4$ GeV/c, these results indicate that the ratio in Pb-Pb is similar to the vacuum expectation, assuming this to be the $pp$ measurement. The ratio is also consistent with predictions from pQCD-based calculations within experimental uncertainties. No effects beyond one $\sigma$ related to the strange quark content, mass hierarchy between particles, or contributions from higher-mass resonance decays that may lead to discernible differences between $\eta/\pi^0$ and $K^\pm/\pi^\pm$ were observed.

The invariant yields of both mesons as well as the $\eta/\pi^0$ ratio are compared to predictions including a hydrodynamic approach focusing on low-$p_T$ phenomena. These comparisons show different levels of agreement for $\eta$ and $\pi^0$. EPOS slightly overestimates the production rates of the two mesons at low $p_T$ but shows a much larger deviation above 3–4 GeV/c. Both the EQ and NEQ SHM predictions describe the measured $\pi^0$ production rates. The data favors the EQ model description which agrees with the $\eta$ measurement. The NEQ model is disfavored by the data as it underestimates the results by a factor of two.

The $R_{AA}$ results show an increasing trend at high $p_T$ which may be explained by a larger quark to gluon con-
tribution in the production of neutral mesons. The $R_{AA}$ $\pi^0$ measurements, when compared to world data, confirm the center-of-mass energy dependence of the observed suppression when going from low (SPS) to higher (RHIC, ALICE) collision energies. Results of $R_{AA}$ for $\eta$ mesons are currently available only at two center-of-mass energies from the LHC and RHIC with sizable uncertainties. Due to the lack of precise world data, it is difficult to conclude on an energy dependence of the $\eta$ suppression.

The $R_{AA}$ results are additionally compared to NLO pQCD calculations. The WHDG model describes the suppression observed for the $\pi^0$ meson in the 0–10% centrality class within theoretical and experimental uncertainties. For the $\eta$ measurement, the model predicts a larger suppression than observed. In the 20–50% centrality class the predictions are in disagreement by several sigma with the ALICE data for both mesons. The DCZW model describes within uncertainties the $\pi^0$ measurement and the $\eta$ meson above 8 GeV/$c$. Below this $p_T$, the model predicts less suppression than observed. The Djordjevic et al. and Vitev et al. calculations describe well the $\pi^0$ production rates in both centrality classes. The disagreement observed between the $\eta$ measurements and the models may point to a overestimation (DCZW) or underestimation (WHDG) of the gluon to quark contributions to the $\eta$ meson production in heavy-ion collisions at LHC energies.

The presented results, when compared to models, highlight the lack of a full theoretical description of neutral meson production. The measurements presented in this paper will be essential to further constrain theoretical models and improve our understanding of the experimental results.

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