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

ALICE Collaboration\*

### Abstract

Neutral pion and  $\eta$  meson production in the transverse momentum range  $1 < p_T < 20$  GeV/ $c$  have been measured at mid-rapidity by the ALICE experiment at the Large Hadron Collider (LHC) in central and semi-central Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV. These results were obtained using the photon conversion method as well as the PHOS and EMCAL detectors. The results extend the upper  $p_T$  reach of the previous ALICE  $\pi^0$  measurements from 12 GeV/ $c$  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  $0.457 \pm 0.013^{stat} \pm 0.018^{sys}$ . 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 NLO pQCD predictions and hydrodynamic models. The measurements show a stronger suppression with respect to what was observed at lower center-of-mass energies in the  $p_T$  range  $6 < p_T < 10$  GeV/ $c$ . At  $p_T < 3$  GeV/ $c$ , hadronization models describe the  $\pi^0$  results while for the  $\eta$  some tension is observed.

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\*See Appendix A for the list of collaboration members

## 1 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 the 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 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/ $c$ ), measuring 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 [11–13]. 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 [14, 15]. 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 LHC [16] employed  $m_T$ -scaling and the  $K_S^0$  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 RHIC [17, 18] at low transverse momentum were observed to be well described by thermal models that assume a hydrodynamic expansion of a system in local equilibrium [19]. 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 [20] 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 NEQ SHM compared to the EQ can be interpreted as onset of pion condensation in ultra relativistic heavy ion collisions at the LHC energies [21–25]. 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 [26]. The 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 what was measured at RHIC. This increase of the energy density leads to a larger energy loss of high- $p_T$  partons with respect to those at both relative lower  $p_T$  ( $< 3$  GeV/ $c$ ) and lower energy [27, 28]. 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, will provide 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) [29] 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) [30]. An intermediate  $p_T$  enhancement of the  $\eta/\pi^0$  ratio in AA collisions relative to pp collisions would be an indication of the color dependence suppression induced by the plasma [31–33]. The magnitude of this enhancement is sensitive to the initial values of the jet transport parameters and thus it 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) [34]. The  $\pi^0$  results in the 0–10% centrality class have been combined with the previously published  $\pi^0$  result measured with the PHOS calorimeter [28]. The new  $\pi^0$  measurement is updated with ten times more statistics with respect to the previous ALICE measurement [28], 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 published at RHIC [35].

The paper is organized as follows: a brief description of the detectors used and of the data sample is given in Section 2. The analysis procedure is described in Section 3. The results and the comparison to other experimental measurements and to theoretical predictions are presented in Section 4 and 5, respectively.

## 2 Detector description and data sample

The ALICE experiment and its performance are described in detail in [36, 37]. 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 [38]. 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 Drift Detectors (SDD) covering  $|\eta| < 1$ , while the two outer layers are Silicon Strip Detectors (SSD) covering  $|\eta| < 0.9$ .

The Time Projection Chamber (TPC) [39] 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<sub>2</sub> (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 PbPb [37, 39]. 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 [37, 40].

The EMCal [34] 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  $\Delta\eta \times \Delta\phi = 0.0143 \times 0.0143$  rad and an energy resolution of  $\sigma_{E(\text{GeV})}/E = 4.8\%/E \oplus 11.3/\sqrt{E} \oplus 1.7\%$  [41]. In year 2011, it covered  $|\eta| < 0.7$  and  $\Delta\phi = 100$  degrees.

The main detectors used for triggering and characterization of the collision are the V0 [42] and the Zero Degree Calorimeters (ZDC) [43]. The V0 consists of two scintillator arrays located on opposite sides of the Interaction Point (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  $4.6 \times 10^{-4} \mu\text{b}^{-1}\text{s}^{-1}$ , which corresponds 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 semi-central (0–50%) events [37]. 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 [44] as detailed in [40, 45]. Only events with a reconstructed primary vertex within  $|z_{\text{vtx}}| < 10$  cm with respect to 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,  $\sigma_{\text{MB}}^{\text{PbPb}} = (7.64 \pm 0.22(\text{syst.})) \text{ b}$  [45], was determined using van der Meer scans [46]. The integrated luminosity, corresponding to the number of analyzed events normalized by  $\sigma_{\text{MB}}^{\text{PbPb}}$  in each centrality percentile, is  $20.1 \mu\text{b}^{-1}$  and  $4.8 \mu\text{b}^{-1}$  for 0–10% and for 20–50%, respectively.

### 3 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  $(98.823 \pm 0.034)\%$  and  $(39.41 \pm 0.20)\%$  [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 [37]. This method produces a  $V^0$  candidate sample on which the analysis quality selection criteria were applied, as done in [28, 47]. Electrons, positrons and photons are required to have  $|\eta| < 0.9$ . To ensure the track quality, a minimum track momentum of 50 MeV/ $c$  and a fraction of TPC clusters over findable clusters (the number of geometrically possible clusters which can be assigned to a track) 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  $[-3\sigma_{dE/dx}, +5\sigma_{dE/dx}]$  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  $K_s^0$ ,  $\Lambda$  and  $\bar{\Lambda}$  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 ( $\alpha_{V^0} = (p_L^{e^+} - p_L^{e^-}) / (p_L^{e^+} + p_L^{e^-})$ ), and on the transverse momentum of the electron with respect to the  $V^0$  momentum ( $q_T = p_e \times \sin\theta_{v^0,e}$ ).  $V^0$  candidates are selected with a two-dimensional elliptic selection criterion of  $(\alpha_{V^0}/\alpha_{V^0,\text{max}})^2 + (q_T/q_{T,\text{max}})^2 < 1$ , with  $\alpha_{V^0,\text{max}} = 0.95$  and  $q_{T,\text{max}} = 0.05$  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 [48], further suppresses the contamination from non-photon  $V^0$  candidates. This cut, described in [49], is applied requiring  $\chi_{\gamma,\text{max}}^2 = 20$  and  $\psi_{\text{pair,max}} = 0.1$ . To improve the signal significance, a  $p_T$ -dependent cut on the energy asymmetry of the photons  $|\alpha| < 0.65 \cdot \tanh(1.8 (\text{GeV}/c)^{-1} \cdot p_T)$  (where  $\alpha = (E_{\gamma_1} - E_{\gamma_2}) / (E_{\gamma_1} + E_{\gamma_2})$ ,  $p_T$  in  $\text{GeV}/c$ ) is applied.

For the measurement with the EMCal, photons stemming from meson decays are measured directly. Photon-like hits in the detector are identified by energy deposits in the neighboring cells, which are grouped into clusters with a minimum size of 2 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 [37]. 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 photon-like 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

$$\sigma_{\text{long}}^2 = \frac{s_{\eta\eta} + s_{\phi\phi}}{2} + \sqrt{\frac{(s_{\eta\eta} - s_{\phi\phi})^2}{4} + s_{\eta\phi}^2}, \quad (1)$$

where  $s_{ij} = \langle ij \rangle - \langle i \rangle \langle j \rangle$  are the covariance matrix elements,  $i, j$  are cell indices in  $\eta$  or  $\phi$  axes,  $\langle ij \rangle$  and  $\langle i \rangle, \langle j \rangle$  are the second and the first moments of the cluster cells weighted with the cell energy logarithm [37, 50–52]. The purpose of this loose shower shape selection  $0.1 < \sigma_{\text{long}}^2 < 0.5$  (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.

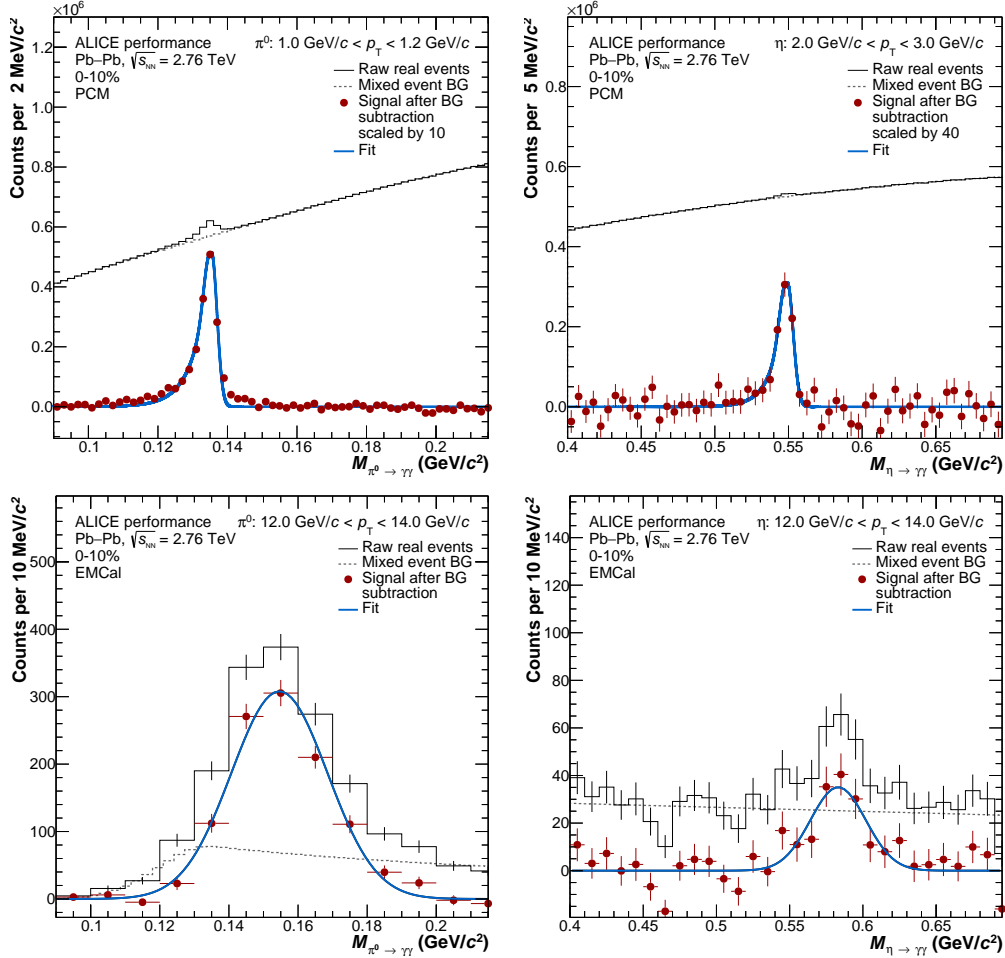
For the PCM and EMCal analyses, the reconstructed two-photon invariant mass is measured in bins of  $p_T$  in the rapidity range  $|y| < 0.85$  and  $|y| < 0.7$ , respectively. The  $p_T$  ranges in which the separate methods contribute are reported in Table 1. In addition, a minimum photon pair opening angle of 5 mrad is used to reject background in the PCM analysis.

	$\pi^0$			$\eta$	
	PCM	EMCal	PHOS	PCM	EMCal
0–10%	1 – 14 GeV/c	4 – 20 GeV/c	1 – 12 GeV/c	1 – 10 GeV/c	4 – 20 GeV/c
20–50%	1 – 14 GeV/c	4 – 20 GeV/c	–	1 – 10 GeV/c	4 – 20 GeV/c

**Table 1:** 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 [28].

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 position in  $z$  direction, 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 subtracted. Additionally, various fitting functions for the total background are also used in order to obtain the number of mesons and to evaluate the corresponding systematic uncertainty (EMCal). The resulting invariant mass distributions are fit with either a Gaussian combined with a low

mass exponential tail [53] (PCM, to account for electron bremsstrahlung) on top of a linear function (PCM, to account for residual background) or with a Crystal Ball distribution [54] (EMCal) in order to obtain the peak position and peak width [37]. After subtracting the total background, the yields are extracted for each  $p_T$  bin by integrating the invariant mass distributions in a mass window that depends on the peak position and resolution. Fig. 1 shows the invariant mass distribution for the  $\pi^0$  and  $\eta$  mesons reconstructed with PCM and EMCal.



**Fig. 1:** (Color online) Invariant mass distribution of reconstructed photon pairs  $M_{\gamma\gamma}$  for the  $\pi^0$  ( $\eta$ ) mesons measured with PCM in the top left (right) panel and EMCal in the bottom left (right) panel 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 with the grey dashed lines. The blue lines are the fit to the invariant mass peak after the combinatorial and residual background subtraction (see text for description).

Corrections for geometrical acceptance, reconstruction efficiency, secondary  $\pi^0$  from weak decays (the measured spectra of the relevant particles [55] are taken as input) and hadronic interactions and occupancy effects due to cluster overlaps (for EMCal) were estimated with a Monte Carlo simulation using HIJING [56] as event generator. The simulated particles are propagated through the apparatus via GEANT3 [57], where a realistic detector response based on experimental conditions is applied in order to reproduce the performance of the ALICE detector during data taking. The simulated events are then analyzed with the same reconstruction and analysis selection criteria applied to the experimental data.

It was verified that the detector resolutions were well reproduced by the Monte Carlo simulations [37]. The mass peak positions and widths measured in the data for each centrality interval for the PCM (EMCal) analysis were well reproduced within 0.5% (1.5%) or better, and the remaining discrepancies have

been taken into account in the systematic uncertainties associated with the difference of the energy scale and position of the calorimeter between data and Monte Carlo.

In the PCM analysis, the pile-up contribution is estimated by analyzing the distance of closest approach distribution for the photon candidates, as done in [28]. The effect of pile-up in the EMCAL analysis was verified to be negligible since the EMCAL cell timing resolution is an order of magnitude better than the bunch crossing spacing of 200 ns used in the 2011 Pb–Pb run.

For both methods, the systematic uncertainties were studied by varying the selection criteria used in the two analyses and by studying the resulting variations of the fully corrected spectra in individual  $p_T$  bins. The largest contribution to the systematic uncertainties for the PCM analysis comes from the uncertainty in the material budget [37], and amounts to 9%. Other sources of systematic uncertainties include the yield extraction, track reconstruction, electron identification and photon reconstruction (mainly for the  $\eta$  meson). The details of the PCM systematic uncertainties are listed in Table 2.

The main source of systematic uncertainties for the neutral meson detection with the EMCAL is associated with the particle identification criteria used to select photon pairs (PID).

The uncertainties due to the signal extraction in a given  $p_T$  interval are taken as the mean of the uncertainties obtained in all signal and background parametrizations. Variations on the values used for the meson identification selection criteria are also included and the root mean square (RMS) of these values is used as a systematic uncertainty.

The EMCAL detector energy response was determined by analyzing test beam data [41]. Comparisons of the mass peak position and the energy-to-momentum ratios of electron tracks [58] in data and Monte Carlo simulations quantify the overall systematic uncertainty due to the Monte Carlo description of the energy response and position of the calorimeter. This uncertainty amounts to 8.6% of the invariant yield measurements.

Other sources of systematic uncertainties are the material budget, the  $p_T$  distribution in simulations used for the extraction of efficiencies and the contribution from higher mass decays. The details of the EMCAL systematic uncertainties are listed in Table 2.

	PCM							
	0–10%				20–50%			
	$\pi^0$		$\eta$		$\pi^0$		$\eta$	
	1.1 GeV/c	5.5 GeV/c	2.5 GeV/c	5.0 GeV/c	1.1 GeV/c	5.5 GeV/c	2.5 GeV/c	5.0 GeV/c
Material budget	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
Track reconstruction	2.3	2.6	6.0	6.2	1.4	2.3	7.0	9.0
Yield extraction	1.5	2.1	6.4	7.0	2.5	2.8	10.0	11.0
$e^+/e^-$ identification	1.7	2.5	6.0	6.1	1.4	2.4	5.5	9.3
Photon reconstruction	3.7	2.1	13.7	13.6	2.1	2.2	8.0	8.6
	EMCAL							
	0–10%				20–50%			
	$\pi^0$		$\eta$		$\pi^0$		$\eta$	
	7.0 GeV/c	18.5 GeV/c	7.0 GeV/c	18.5 GeV/c	7.0 GeV/c	18.5 GeV/c	7.0 GeV/c	18.5 GeV/c
Signal extraction	2.9	5.1	4.2	5.5	7.5	5.8	6.0	7.1
Photon identification	9.5	8.0	4.6	6.0	7.5	4.5	14.1	5.0
Energy response	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6
Material budget	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Hijing simulation	8.6	10.0	8.6	10.0	2.0	5.3	2.0	5.3
Monte Carlo input	2.0	3.0	<1	1.5	<1	<1	<1	<1
Higher mass decays	4.0	2.0	-	-	3.2	2.0	-	-

**Table 2:** Summary of the systematic uncertainties in percent for selected  $p_T$  regions for the PCM and EMCAL analyses.

When computing the  $\eta/\pi^0$  ratio and the nuclear modification factor, fully and partially correlated errors, such as material budget and energy scale (EMCAL only), are taken into account.

## 4 Results

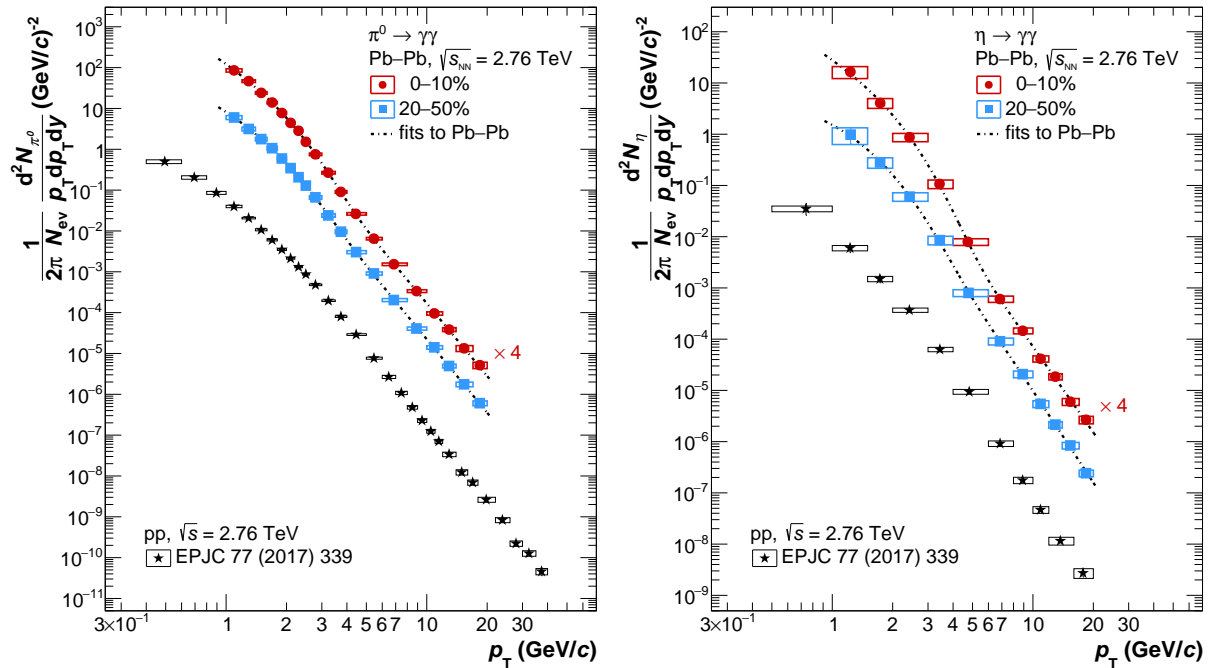
### 4.1 Invariant yields of the $\pi^0$ and $\eta$ meson

The invariant differential yields for  $\pi^0$  and  $\eta$  mesons have been calculated employing

$$E \frac{d^3N}{dp^3} = \frac{1}{2\pi N_{\text{evt}}} \frac{1}{BR A\epsilon} \frac{N_{\text{raw}}}{p_T \Delta p_T \Delta y}, \quad (2)$$

where  $N_{\text{evt}}$  is the number of events in the centrality class considered,  $BR$  is the branching ratio [1] for the process  $\pi^0(\eta) \rightarrow \gamma\gamma$ ,  $A\epsilon$  are the corresponding acceptance and efficiency corrections and  $N_{\text{raw}}$  corresponds to the reconstructed  $\pi^0(\eta)$  raw yield within the rapidity range  $\Delta y$  and the transverse momentum bin  $\Delta p_T$ . The horizontal location of the data points is shifted towards lower  $p_T$  from the bin center by a few MeV and illustrates the  $p_T$  value where the differential cross section is equal to the measured integral of the cross section over the corresponding bin [59]. 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 1. 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 [60–62].

Fig. 2 shows the invariant differential yields of  $\pi^0$  (left) and  $\eta$  mesons (right) measured in pp [52] 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 [28] 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 [35, 63].



**Fig. 2:** (Color online) Invariant yields of the  $\pi^0$  (left) and  $\eta$  (right) 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 [28, 52]. The dashed black lines correspond to the fits to the data with the two-component function. See Table 3 and corresponding text for details.

Both meson spectra have been parametrized over the full  $p_T$  range by the function proposed in Refs. [64,



65] that combines a Boltzmann factor at low- $p_T$  with a power law at high- $p_T$

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

where  $M$  is the meson mass (in  $\text{GeV}/c^2$ ),  $A_e$ ,  $A$ ,  $T_e$ ,  $T$  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 3. 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.

	$\pi^0$		$\eta$	
	0–10%	20–50%	0–10%	20–50%
$A_e (\text{GeV}/c)^{-2}$	$162 \pm 20$	$30 \pm 7$	$15 \pm 6$	$4.2 \pm 2.5$
$T_e (\text{GeV}/c)$	$0.37 \pm 0.01$	$0.38 \pm 0.02$	$0.44 \pm 0.03$	$0.42 \pm 0.06$
$A (\text{GeV}/c)^{-2}$	840	80	100	2
$T (\text{GeV}/c)$	$0.34 \pm 0.01$	$0.50 \pm 0.02$	$0.38 \pm 0.03$	$0.76 \pm 0.05$
$n$	$3.00 \pm 0.05$	$3.00 \pm 0.05$	$3.0 \pm 0.1$	$3.0 \pm 0.1$
$\chi^2/ndf$	0.18	0.20	0.22	0.14

**Table 3:** Parameters of the fits to the differential invariant yields of  $\pi^0$  and  $\eta$  mesons using the two-component function of A.A. Bylinkin and A.A. Rostovtsev [64, 65]. The total uncertainties, i.e. quadratic sum of statistical and systematic uncertainties, are used for the fits.

## 4.2 Particle ratios

The  $\eta/\pi^0$  ratio measured in the two centrality classes is shown in Fig. 3 (left). In Fig. 3 (right), the measurement in the 0–10% centrality class is compared to the same ratio measured in pp collisions at  $\sqrt{s} = 2.76$  TeV [52], as well as to the  $K^\pm/\pi^\pm$  ratio in the same centrality class and in the same collision system and energy [20], 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  $p_T < 2$   $\text{GeV}/c$ , the  $\eta/\pi^0$  and the  $K^\pm/\pi^\pm$  ratios in Pb–Pb are in agreement within uncertainties. At  $2 < p_T < 4$   $\text{GeV}/c$ , 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  $p_T > 4$   $\text{GeV}/c$ , the value for all ratios is of similar magnitude. Moreover, a constant fit from 3 to 20  $\text{GeV}/c$  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 [35].

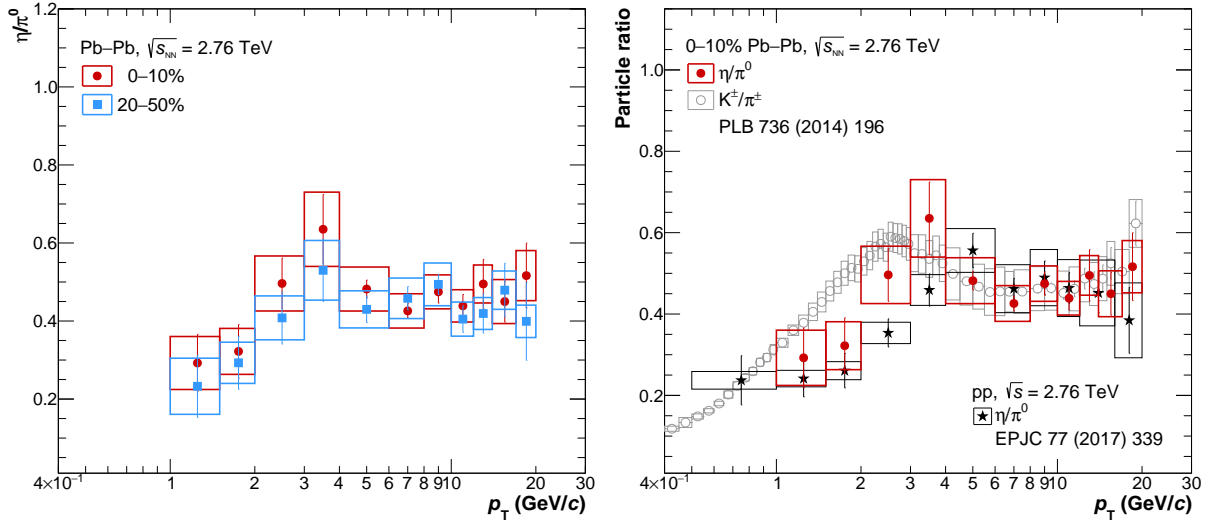
## 4.3 The nuclear modification factor $R_{AA}$

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

$$R_{AA}(p_T) = \frac{d^2N/dp_T dy|_{AA}}{\langle T_{AA} \rangle \times d^2\sigma/dp_T dy|_{pp}}. \quad (4)$$

where the nuclear overlap function  $\langle T_{AA} \rangle$  is related to the average number of inelastic collisions by  $\langle T_{AA} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{pp}$  and  $\sigma_{inel}^{pp}$  is the total inelastic cross-section determined using van der Meer scans [66]. The mean number of collisions is  $1501 \pm 15$  for the centrality class 0–10% and  $349 \pm 3$  for the centrality class 20–50% [45]. The  $\pi^0$  and  $\eta$  meson spectra measured in pp collisions at the same center-of-mass energy are obtained from [52].

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



**Fig. 3:** (Color online) Left:  $\eta/\pi^0$  ratio in the two centrality classes measured, 0–10% (circles) and 20–50% (squares). Right: comparison of the  $\eta/\pi^0$  measurement in the 0–10% centrality class (full circles) to the corresponding ratio in pp collisions [52] (stars) and to the  $K^\pm/\pi^\pm$  measurement in the same centrality class, system and collision energy [20] (open circles).

$p_T \approx 1.5$  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 [67].

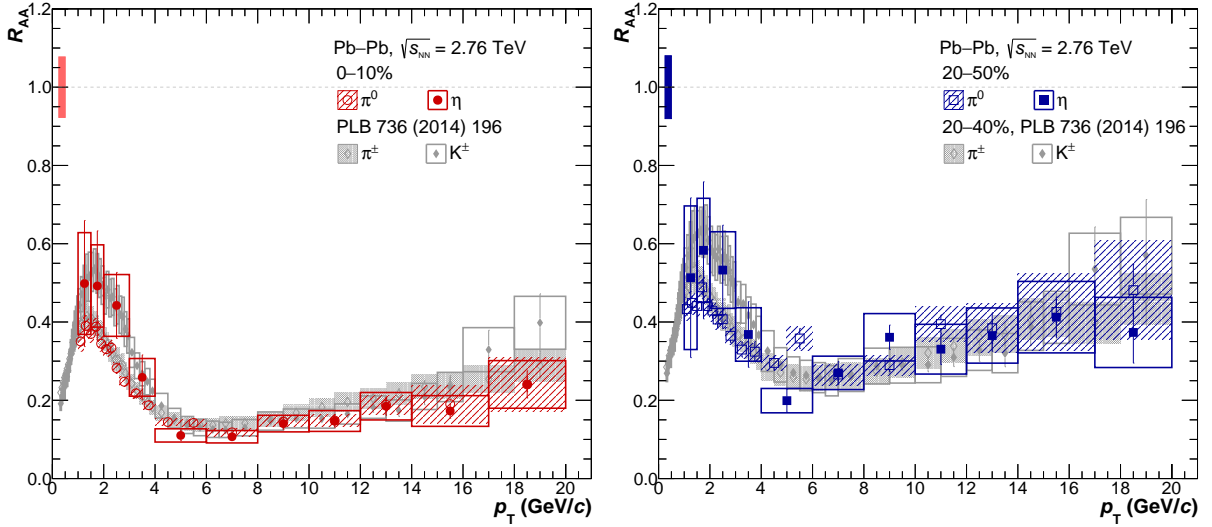
The suppression observed at high- $p_T$  is consistent with recent ATLAS results [68], and may indicate a larger quark than gluon relative contribution at high- $p_T$  jet production in heavy-ion collisions at the LHC. A similar behavior is observed for semi-central events, though with a smaller suppression 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  $R_{AA}$  [69] 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 [69] indicating that the energy loss in the medium is likely a purely partonic effect.

#### 4.4 Comparisons to lower energy measurements

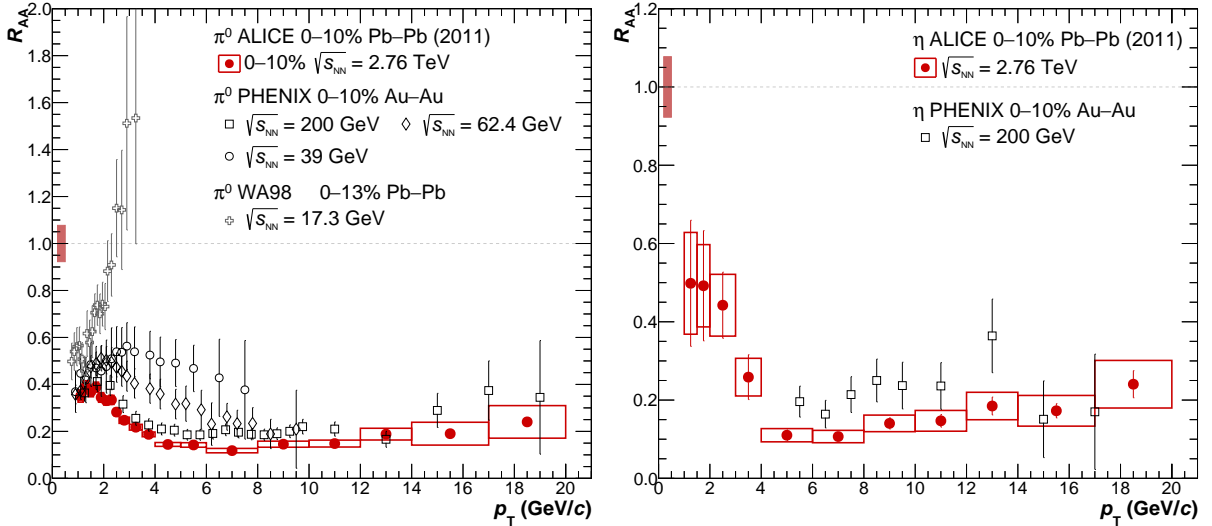
The nuclear modification factor in the 0–10% centrality class is compared to previous  $\pi^0$  measurements reported by the WA98 [70] and PHENIX collaborations [71, 72] (Fig. 5, left) for center-of-mass energies per binary collision  $\sqrt{s_{NN}}$  ranging from 17.3 GeV (WA89) to 200 GeV (PHENIX).

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 [35] at  $\sqrt{s_{NN}} = 200$  GeV (Fig. 5, right). 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.



**Fig. 4:** (Color online) Measured nuclear modification factor for the  $\pi^0$  (empty symbols) and  $\eta$  meson (full symbols) in the 0–10% (left) and 20–50% (right), compared to ALICE  $\pi^\pm$  and  $K^\pm$  [69] (open and full diamonds) in the same centrality classes. The boxes around unity represent quadratic sum of the uncertainty on  $\langle T_{AA} \rangle$  and on the pp spectrum normalization uncertainty.



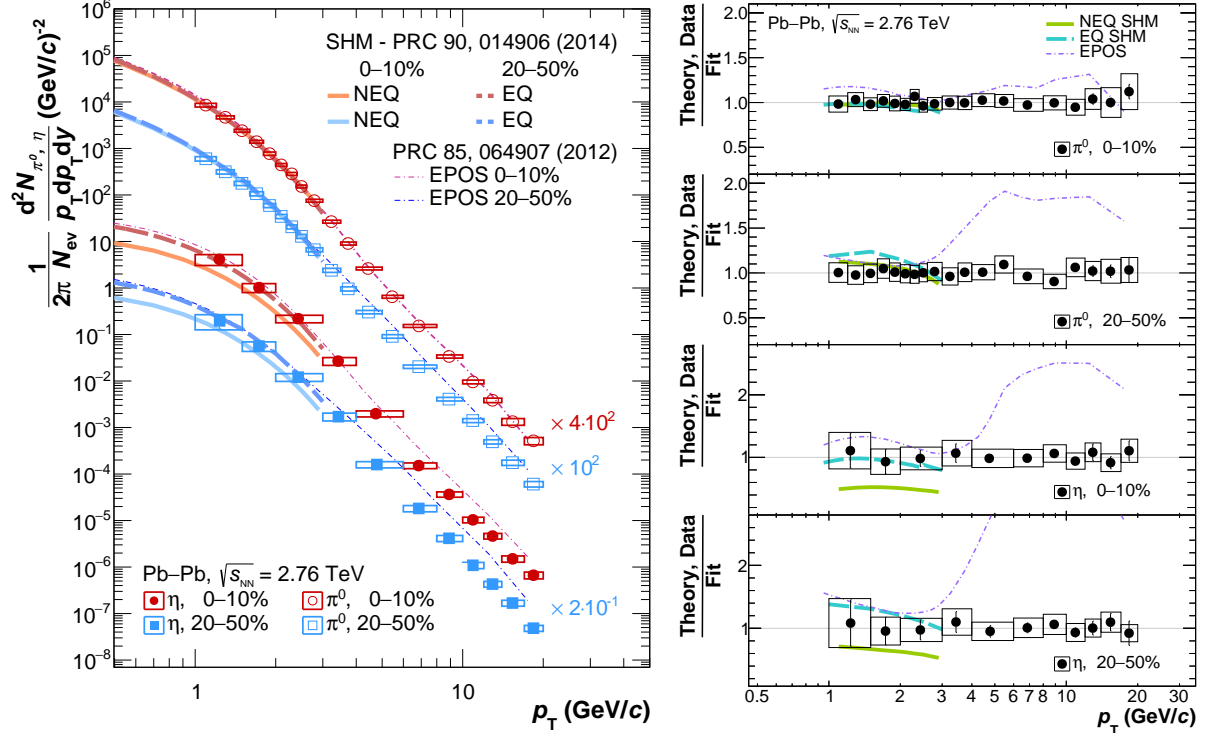
**Fig. 5:** (Color online)  $R_{AA}$  of the  $\pi^0$  (left) and  $\eta$  (right) mesons compared to data from lower center-of-mass energy results [35, 71, 72].

## 5 Comparisons to models

The  $\pi^0$  and  $\eta$  invariant  $p_T$ -differential yields are compared to predictions using a statistical hadronization model (SHM) [19, 21] and the EPOS2 [73] event generator. Results from two versions of the SHM are presented here, an equilibrium (EQ) and non-equilibrium (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 non-equilibrium 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 pions and kaons spectra [21]. While only these two particles are considered in the fits, the resulting parameters are used to make predictions for other particles [74], *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 contains effects (low- $p_T$ ) associated to hydrodynamic flow as it

was discussed in [20]. At higher  $p_T$ , the focus is shifted towards energy loss of high- $p_T$  strings where strings are the byproduct of hard scatterings.

Fig. 6 (left) shows the comparison to models for the 0–10% and 20–50% centrality classes while Fig. 6 (right) shows the ratio of data and theory calculations to the fit of the  $\pi^0$  and  $\eta$  invariant yields.



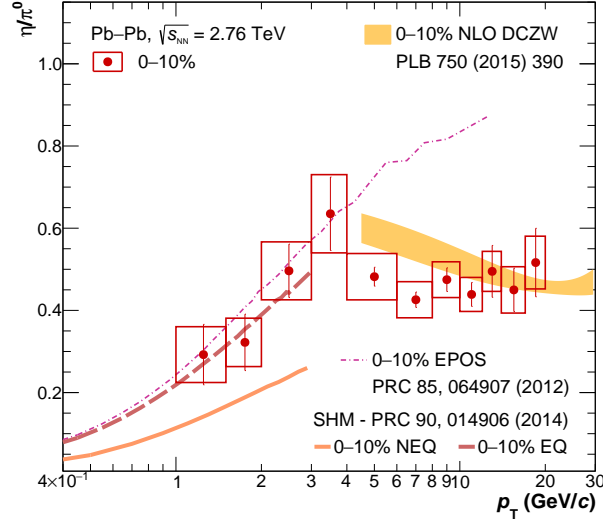
**Fig. 6:** (Color online) Left: Comparison of the  $\pi^0$  (open symbols) and  $\eta$  (closed symbols) meson invariant  $p_T$ -differential yields to EQ and NEQ SHM [21] and to EPOS [73] for the two centrality classes measured. Right: Ratio of data and theory calculations to the fit of the  $\pi^0$  and  $\eta$  invariant yields (see Fig. 2 and the left plot of this figure) in the two centrality classes measured. Black points show the data to fit ratio (vertical lines for statistical errors and boxes for systematic errors). The bold lines correspond to the ratio of the EQ and NEQ SHM predictions [21] to the data fit, while the thin dashed lines correspond to the same ratio for the EPOS predictions [73].

The EQ and NEQ SHM predictions (bold lines in Fig. 6, right) describe the shape of the  $\pi^0$  measurement within the uncertainties for both centralities. For the  $\eta$  meson, the EQ model also describes the data within uncertainties. Conversely, the NEQ model predicts about two times less  $\eta$  mesons in central collisions than what is measured. 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  $\eta$  compared to the  $\pi^0$  [75]. Significant differences between the EQ and NEQ predictions are also observed for the  $\rho^0$ ,  $\Sigma(1385)$ ,  $\Lambda(1520)$  and  $\Xi(1530)$  [74, 76].

The  $\pi^0$  and  $\eta$  mesons are only partially described by EPOS (dashed lines in Fig. 6, right). While the comparison is reasonably close to the data points for the  $\pi^0$  measurement in 0–10%, the model only describes the low  $p_T$  part of the semicentral  $\pi^0$  and  $\eta$  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 NLO pQCD calculation by DCZW [31], to the ratio from the EQ and NEQ SHM [21] predictions and the EPOS [73] generator in Fig. 7. The DCZW model is based on a higher twist approach of jet quenching [77] 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 (AAK [78] and AESS [79]) 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 the comparison to the NEQ SHM prediction the ratio



**Fig. 7:** (Color online) Comparison of the  $\eta/\pi^0$  ratio in the centrality class 0–10% (circles) to the NLO pQCD prediction by DCZW (solid band) [31] and to the EQ and NEQ SHM [21] and EPOS [73] predictions for the input yields (bold and thin dashed lines respectively).

is underestimated as it was concluded in Fig. 6 (right). 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  $p_T$ .

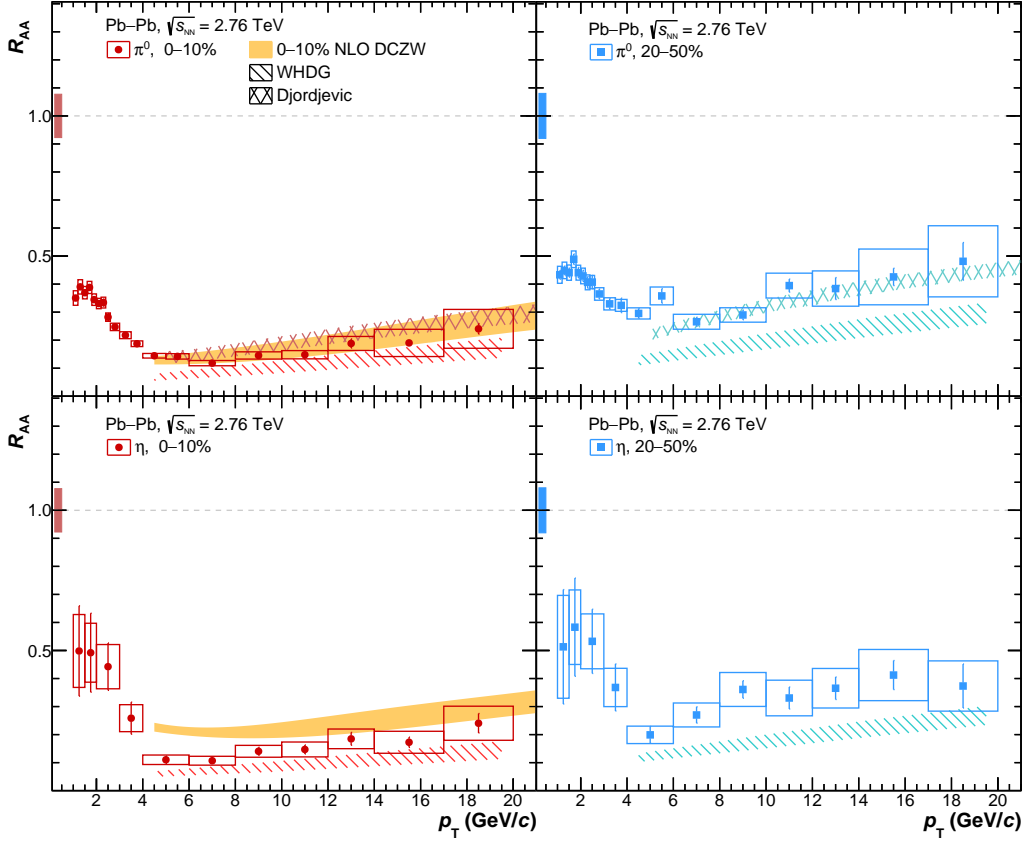
The measurements of  $R_{AA}$  for both mesons are compared to three NLO pQCD based models in Fig. 8: DCZW [31] (described above), WHDG [80–82] and Djordevic *et al.* [83] ( $\pi^0$  only). In all models, it is assumed that a fast moving parton passing through hot partonic matter will lose its energy 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 Djordevic *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 [83–86].

In the most central event class, the  $\pi^0$  meson  $R_{AA}$  is described for  $p_T > 4$  GeV/c by the DCZW and Djordevic *et al.* models and for  $p_T > 6$  GeV/c by WHDG (Fig. 8, top-left panel). 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, bottom-left panel). 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 what is 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.* model describes the  $\pi^0$  meson suppression in both centrality classes within uncertainties.

## 6 Summary

We have presented measurements of the  $\pi^0$  and  $\eta$  meson production at mid-rapidity in Pb–Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV measured with the ALICE detector. Independent and complementary techniques are used: photon detection with electromagnetic calorimetry and photon reconstruction through conversions using the tracking system. 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.



**Fig. 8:** (Color online)  $R_{AA}$  of  $\pi^0$  (top) and  $\eta$  mesons (bottom) compared to NLO pQCD predictions by DCZW (solid bands) [31], by WHDG (dashed bands) [82] and Djordjevic *et al.* [83] (crossed bands,  $\pi^0$  only) in the two centrality classes measured.

The  $\pi^0$  measurements are performed using data that corresponds to a factor 10 increase in integrated luminosity with respect to the previous ALICE publication [28]. The higher statistics allowed for an improved measurement that probes the  $p_T$  region above 12 GeV/ $c$  and 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 level 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 RAA results show an increasing trend at high  $p_T$  which may be explained by a larger quark to gluon contribution 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 energy results. 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 what is observed. In the 20–50% centrality class the predictions are in disagreement by several sigmas 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 what is observed. The Djordjevic *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 an 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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