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Nuclear modification factor of light neutral-meson spectra up to high transverse momentum in p–Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV

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ABSTRACT

Neutral pion (π^0) and η meson production cross sections were measured up to unprecedentedly high transverse momenta ($p_{\rm T}$) in p–Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV. The mesons were reconstructed via their two-photon decay channel in the rapidity interval $-1.3 < y < 0.3$ in the ranges of $0.4 < p_{\rm T} < 200$ GeV/c and $1.0 < p_{\rm T} < 50$ GeV/c, respectively. The respective nuclear modification factor ($R_{\rm pPb}$) is presented for $p_{\rm T}$ up to of 200 and 30 GeV/c, where the former was achieved by extending the π^0 measurement in pp collisions at $\sqrt{s} = 8$ TeV using the merged cluster technique. The values of $R_{\rm pPb}$ are below unity for $p_{\rm T} < 10$ GeV/c, while they are consistent with unity for $p_{\rm T} > 10$ GeV/c, leaving essentially no room for final state energy loss. The new data provide strong constraints for nuclear parton distribution and fragmentation functions over a broad kinematic range and are compared to model predictions as well as previous results at $\sqrt{s_{\rm NN}} = 5.02$ TeV.

1. Introduction

Measurements of identified hadron spectra in high-energy proton–proton (pp) collisions are well suited to constrain perturbative predictions from Quantum Chromodynamics (QCD) [1]. At large momentum transfer (Q^2) one relies in these perturbative QCD (pQCD) calculations on the factorization of computable short-range parton scattering processes such as quark–quark, quark–gluon and gluon–gluon scatterings from long-range properties of QCD that need experimental input. These non-perturbative properties are typically modeled by parton distribution functions (PDFs), which describe the fractional-momentum (x) distributions of quarks and gluons within the proton, and fragmentation functions (FFs), which describe the fractional-momentum (z) distribution of quarks or gluons for hadrons of certain species.

In high-energy proton–nucleus (p–A) collisions, nuclear effects are expected to significantly affect particle production, in particular at small x [2]. Previous measurements of neutral pions and charged hadrons in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV at the LHC [3–6] indeed revealed distinct deviations from binary-scaled pp collisions, confirming earlier results from deuteron–gold collisions at $\sqrt{s_{\rm NN}} = 0.2$ TeV at RHIC [7,8]. The modification at low $p_{\rm T}$ ($\sim$1 GeV/c), which is commonly attributed to nuclear shadowing, can be parameterized by nuclear parton distribution functions (nPDFs) [9,10]. However, the high parton densities reached at low $p_{\rm T}$ (x as small as $\sim 5 \cdot 10^{-4}$) make the Color Glass Condensate (CGC) framework [11] applicable which predicts strong particle suppression due to saturation of the parton phase space in nuclei [12]. Recently, also parton energy loss in cold nuclear matter was shown [13] to lead to suppressed particle yields at low $p_{\rm T}$, while the previously observed collective effects in small systems [14–16] also imply partonic rescatterings in hot nuclear matter to play a role [17,18].

In this letter, the nuclear modification of particle yields is quantified by

$$R_{\rm pPb} = \frac{1}{A_{\rm Pb}} \frac{{\rm d}^2\sigma_{\rm pPb}}{{\rm d}p_{\rm T}{\rm d}y} \Big/ \frac{{\rm d}^2\sigma_{\rm pp}}{{\rm d}p_{\rm T}{\rm d}y}, \quad (1)$$

where $A_{\rm Pb} = 208$ is the nuclear mass number of lead and ${\rm d}^2\sigma/({\rm d}p_{\rm T}{\rm d}y)$ are the π^0 or η meson cross sections measured in p–Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV and in the corresponding pp reference system at $\sqrt{s} = 8$ TeV. The new data constrain nPDFs and FFs over a large range in x, and Q^2, including the center-of-mass energy dependence based on comparisons to lower-energy data [6].

2. Experimental setup

The neutral mesons were reconstructed via their two-photon decay channels $\pi^0(\eta) \to \gamma\gamma$ using different reconstruction techniques provided by the various subdetector systems of ALICE [19,20]. Photons are either reconstructed using the Electromagnetic Calorimeter (EMCal), the Photon Spectrometer (PHOS) or via the Photon Conversion Method (PCM). The latter uses e^+e^- pairs from

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Table 1
Trigger rejection factor RF and total integrated luminosities based on the individual samples for the different reconstruction methods and triggers in pp collisions at $\sqrt{s} = 8$ TeV and p–Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV. The uncertainty associated with the determination of the MB cross section of 1.9% for p–Pb and 2.6% for pp is not included. The value in brackets corresponds to the high luminosity minimum bias data sample where TPC tracking is not available.

System/Trigger	RF	$\mathscr{L}_{\rm int}$ ($\rm nb^{-1}$)			
p–Pb		(m)EMC	PCM-EMC	PCM	PHOS
MB	–	0.018(0.041)	0.018	0.022	0.036
EMCal L1 (low)	288 ± 8	0.206	0.081	–	–
EMCal L1 (high)	991 ± 29	5.67	1.42	–	–
PHOS L0	$(1.66 \pm 0.02) \cdot 10^3$	–	–	–	1.68
PHOS L1	$(1.55 \pm 0.04) \cdot 10^4$	–	–	–	6.42
pp					
MB	–	1.94	1.94	2.17	1.25
EMCal/PHOS L0	64.6 ± 1.0	39.4	39.4	–	136
EMCal L1	$(1.47 \pm 0.06) \cdot 10^4$	606	606	–	–

conversions, which are reconstructed from tracks measured in the Inner Tracking System (ITS) [21] and the Time Projection Chamber (TPC) [21] at $|\eta| < 0.9$ inside a solenoidal magnetic field of $B = 0.5$ T. The EMCal [22,23] is a lead-scintillator sampling electromagnetic calorimeter at a radial distance of 4.28 m from the interaction point (IP) covering $\Delta\varphi = 100^\circ$ in azimuth for $|\eta| < 0.7$ in pseudorapidity during the 2012 pp data taking period. During the p–Pb data taking in 2016, additional modules [23] were available that extended the coverage to $\Delta\varphi = 107^\circ$ for $|\eta| < 0.7$ and added $\Delta\varphi = 60^\circ$ opposite in azimuth for $0.22 < |\eta| < 0.7$. The calorimeter provides an energy resolution of $\sigma_E/E = 4.8\%/E \oplus 11.3\%/\sqrt{E} \oplus 1.7\%$, with E in units of GeV. In its full configuration, it consists of a total of 18240 cells of transverse size 6×6 cm^2 each. The PHOS [24] is a lead tungstate electromagnetic calorimeter with 12544 channels at a distance of 4.6 m from the IP, covering $\Delta\varphi = 70^\circ$ and $|\eta| < 0.12$. Its high light yield combined with its cell size being only slightly larger than the Molière radius of 2 cm results in an energy resolution of $\sigma_E/E = 1.8\%/E \oplus 3.3\%/\sqrt{E} \oplus 1.1\%$.

3. Data samples and event selection

The p–Pb data at $\sqrt{s_{\rm NN}} = 8.16$ TeV were recorded in 2016. Equal magnetic rigidity for proton and Pb beams in the LHC resulted in a rapidity shift of $\Delta y_{\rm NN} = 0.465$ in the direction of the proton beam between the nucleon–nucleon center-of-mass and the laboratory reference system. The minimum bias (MB) event trigger required a coincidence at Level 0 (L0) of signals issued by the V0A and V0C detectors, which are two arrays of 32 scintillator tiles each covering full azimuth at $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively [25]. Additional triggers at L0 required an energy deposit above 2 GeV for EMCal and 4 GeV for PHOS, in 4×4 adjacent cells in coincidence with the MB trigger. Based on the L0 preselection, further hardware Level 1 triggers were issued, two for the EMCal with energy thresholds at 5.5 GeV and 8 GeV and one for the PHOS at 7 GeV. To account for the yield enhancement of the event triggers, the trigger rejection factors (RF) for the EMCal triggers were estimated through an error function fit to the ratio of the cluster energy spectra in their plateau regions above the respective trigger thresholds. A similar procedure was performed for the PHOS triggers, where RF is determined on the ratio of the corrected π^0 meson spectra instead. The trigger rejection factors from these fits are given in Table 1 for all event triggers. For the high threshold triggers, RF is obtained from the product $RF_{\rm EMCal-L1low/MB} \cdot RF_{\rm EMCal-L1high/low}$ or $RF_{\rm PHOS-L0/MB} \cdot RF_{\rm PHOS-L1/L0}$. Uncertainties on RF are given as combined statistical and systematic uncertainties where the latter part was determined via variations of the low E fit range. The integrated luminosities ($\mathscr{L}_{\rm int}$) of each trigger sample and for each reconstruction method were calculated based on the MB cross section of $\sigma_{\rm MB} = (2.09(2.10) \pm 0.04)$ b for the p–Pb (Pb–p) collisions [26] and the respective RF values as $\mathscr{L}_{\rm int} = RF \times N_{\rm events}/\sigma_{\rm MB}$ and are listed in Table 1. For PCM-EMC lower integrated luminosities are reported due to the lack of TPC readout in two thirds of the triggered data. The pp collision data set at a center-of-mass energy of $\sqrt{s} = 8$ TeV used in this analysis was recorded in 2012 and the respective integrated luminosities and RF values are listed in Table 1.

4. Analysis

Reconstructed tracks were used to determine the primary vertex of the collision, which was required to be within 10 cm from the nominal IP position along the beam direction. Pileup events (~1.5% in pp) containing multiple collisions within a 300 ns window were rejected if more than one primary vertex was reconstructed from SPD hits or if the number of SPD clusters was not correlated with the number of track candidates. The photon and meson reconstruction methods are analogous to those described in Refs. [6,27]. To achieve an optimal uncertainty cancellation on $R_{\rm pPb}$, the meson analyses were performed simultaneously for the p–Pb and pp data sets using identical methods and selections, where possible.

Photon reconstruction in the EMCal (PHOS) is based on grouping adjacent cells, with energy deposits above $E_{\rm cell}^{\rm min} = 100$ (20) MeV, into clusters starting with a seed cell of $E_{\rm cell}^{\rm seed} > 500$ (50) MeV. The thresholds for PHOS are lower due to its better energy resolution and finer granularity. Photon candidates in the EMCal were required to have $|\eta_\gamma| < 0.67$ and a minimum of two cells in the cluster ($N_{\rm cell}^{\rm cls} \geq 2$). In addition, clusters are required to have a primarily round shape by restricting the cluster elongation ($\sigma^2_{\rm long}$ [28]) to values between 0.1 and 0.5. The elongation $\sigma^2_{\rm long}$ is defined as

$$\sigma^2_{\rm long} = \frac{1}{2}\left[\sigma^2_{\varphi\varphi} + \sigma^2_{\eta\eta} + \sqrt{(\sigma^2_{\varphi\varphi} - \sigma^2_{\eta\eta})^2 + 4\sigma^4_{\varphi\eta}}\,\right], \quad (2)$$

where the values of $\sigma^2_{ab} = \langle ab\rangle - \langle a\rangle\langle b\rangle$ and $\langle a\rangle = (w_{\rm tot})^{-1}\sum w_i a_i$ are based on the weighted cell energy compared to the cluster energy and in relative η and ϕ direction to the seed cell of the cluster. The weighting is logarithmic with $w_i = \max(0, 4.5 + \log(E_i/E_{\rm clus}))$ where the sum of all w_i equals $w_{\rm tot}$ [28]. Small values of $\sigma^2_{\rm long}$ denote clusters with a round shape that are primarily of photonic origin, while large values of $\sigma^2_{\rm long}$ describe elongated clusters, which are primarily from hadronic sources or from overlapping showers.

In PHOS, $|\eta_\gamma| < 0.12$ was required and the criteria $\sigma^2_{\rm long} > 0.1$ and $N_{\rm cell}^{\rm cls} \geq 3$ were only applied to clusters with $E > 2$ GeV. Hadron

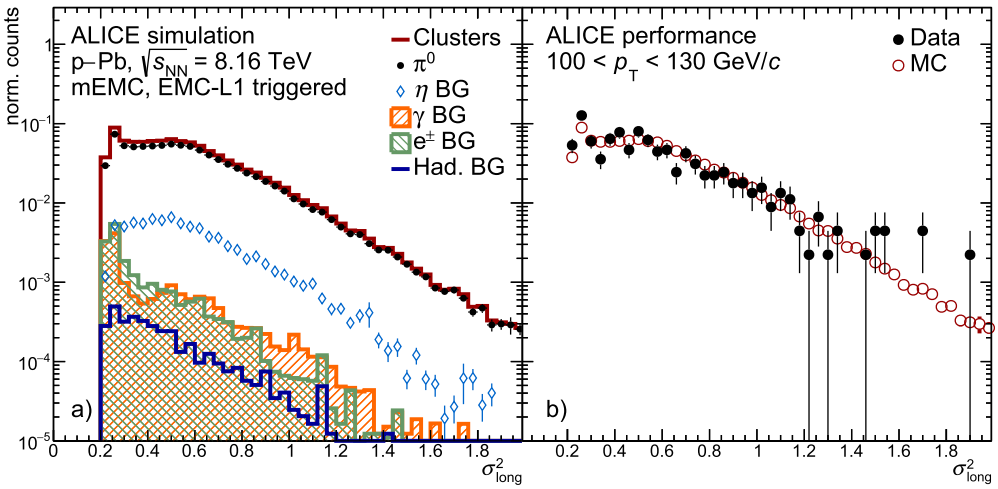

Fig. 1. Shower shape distribution for the elongation σ^2_{long} in PYTHIA 8 Monte Carlo simulations a) showing the various contributions to the full cluster sample for a high p_{T} example interval and b) compared to the σ^2_{long} distribution in data in the same p_{T} interval.

and electron contamination of the photon clusters in the EMCal was removed if an associated track was found with $E/p_{\text{track}} < 1.75$. The suppression of false matches with the E/p veto increased the photon efficiency by up to 50% at high p_{T} with respect to previous measurements [6,27]. Corrections for the non-linear energy response of the calorimeters were applied to the cluster energy. For the EMCal the correction was obtained from electron test beam data and from laboratory-based measurements of the low-gain shapers in the front-end electronics. The correction is sizeable only at low E (6% at 1 GeV) and at high E (14% at 200 GeV). It includes a residual relative energy-and-position correction, which is applied on simulated EMCal clusters to match the π^0 peak position in data. An improved description of the EMCal cluster properties in simulations was achieved by introducing a cross talk emulation within the same EMCal readout card as described in Ref. [29]. The resulting agreement of the π^0 mass peak position is better than 0.3% between data and simulation. For the PHOS, the energy non-linearity was corrected by fixing the reconstructed π^0 mass to the nominal PDG value [30].

Photon conversions were reconstructed by combining oppositely charged tracks, originating from a common vertex up to a radius of 180 cm, through a secondary vertex finder. Only tracks with a TPC $\mathrm{d}E/\mathrm{d}x$ within -3σ and $+4\sigma$ of the expected values for electrons were accepted, where σ is the $\mathrm{d}E/\mathrm{d}x$ resolution. Additionally, tracks with $p > 0.4$ GeV/c and $\mathrm{d}E/\mathrm{d}x$ up to 1σ above the expected value for pions were rejected. For tracks with $p > 3.5$ GeV/c, this was loosened to 0.5σ. The photon conversion selection criteria were further optimized with respect to previous measurements [27,31] to yield about 10% better efficiency at similar purity.

An invariant mass ($m_{\gamma\gamma}$) technique was used for the reconstruction of neutral pions and η mesons. For this, $m_{\gamma\gamma}$ was calculated for all possible combinations of photon candidates per event taking either both photons reconstructed by the same method (called PCM, EMC, and PHOS), or one photon reconstructed with PCM and one with EMC (called PCM-EMC). The invariant mass distributions were calculated in p_{T} intervals of the meson candidates (examples are shown in Ref. [32]). For each interval, the combinatorial background, obtained from event mixing, and residual correlated background were subtracted (see Ref. [32]). The remaining distributions were then integrated in $\sim 3\sigma$ around the fitted mass peak position to determine the raw yields.

Neutral pions with $p_{\text{T}} > 16$ GeV/c were measured with the merged-cluster (mEMC) method [31], which exploits single clusters in the EMCal that result from overlapping energy deposits of both decay photons in the same cluster due to the small opening angle for large pion momentum. The elongation ($\sigma^2_{\text{long}} > 0.27$) of clusters with $p_{\text{T}} > 16$ GeV/c was used to discriminate between single-photon ($\sigma^2_{\text{long}} \approx 0.25$) and merged-photon clusters. The σ^2_{long} distribution was obtained in p_{T}-intervals of the clusters and the integrated counts above 0.27 were used as raw π^0 candidate yields. An exemplary σ^2_{long} distribution at high p_{T} is shown in Fig. 1a in simulation, broken up into the individual contributions to the full cluster sample. Fig. 1b shows a comparison between the data and simulation σ^2_{long} distributions, highlighting their good agreement within uncertainties. The resulting π^0 purity is between 81–87% decreasing with p_{T} in p–Pb and 83–89% in pp collisions. It was determined via PYTHIA 8 [33] simulations with additional data-driven corrections, which increase the relative fractions of prompt photons by 1–3% and of η mesons by 2%. POWHEG-Box [34,35] simulations were used to determine an additional purity correction for electrons from weak decays of up to 3%.

Correction factors for reconstruction efficiency and kinematic acceptance (see Ref. [32]) were obtained from simulations of the detector response with GEANT3 [36] using DPMJET [37] and PYTHIA 8 [33] as event generators. The correction factors for secondary π^0 from long-lived strange hadron decays were obtained from a particle-decay simulation based on measured spectra and are dominated by contributions from $\mathrm{K}^0_{\mathrm{S}}$ and Λ decays [27,38]. They amount to about 1–6% and decrease with p_{T}. For the PCM method, an additional correction for out-of-bunch pileup of 7 to 15% decreasing with p_{T} was applied.

The spectra were normalized by the integrated luminosities of each trigger sample and meson reconstruction method as listed in Table 1.

The systematic uncertainties on the π^0 (η) cross sections contain contributions from the yield extraction of 1–10% (2–20%) depending on the reconstruction method and p_{T}. Further contributions from the imperfect description of the selection variables in the simulation amount to 1–4% (1–6%), while the p_{T}-independent material-budget uncertainties are 4.5% per PCM photon, 2.8% per EMCal photon and 2% per PHOS photon. Uncertainties arising from the out-of-bunch pileup determination reach 3–5% and global uncertainties on the trigger rejection factors are 2–3% [32]. For the mEMC analysis, the largest systematic uncertainty arises from the shower overlaps in jets, which depend on the jet fragmentation and affect the π^0 energy resolution in the EMCal. This uncertainty was estimated as 7–10%, obtained from varying the particle overlaps within clusters. The total uncertainties on the $\pi^0(\eta)$ cross

Table 2
Summary of relative systematic uncertainties in percent for selected p_T intervals for the π^0 and η meson cross sections σ_{p-Pb} and nuclear modification factors R_{pPb}. The statistical uncertainties are given in addition to the total systematic uncertainties for each bin. The combined statistical and systematic uncertainties, obtained by applying the BLUE method [39,40], are also listed for all reconstruction methods available in the given p_T bin, considering the uncertainty correlations for the different methods. The uncertainty from the σ_{MB} determination of 1.9%, see Ref. [26], is independent of the reported measurements and is separately indicated in the figures.

	Source	$\sigma^{\pi^0}_{p-Pb}$				$R^{\pi^0}_{pPb}$				σ^{η}_{p-Pb}			R^{η}_{pPb}			η/π^0_{p-Pb}		
	p_T (GeV/c)	1.6	5.5	17	115	1.6	5.5	17	115	2.75	7	22.5	2.75	7	22.5	2.75	7	22.5
PCM	photon reco.	10.7	9.1	–	–	0.7	1.5	–	–	9.5	10.5	–	2.0	3.0	–	2.7	4.6	–
	meson reco.	6.8	6.3	–	–	2.6	7.0	–	–	4.0	5.1	–	4.6	6.3	–	3.9	5.2	–
	pileup	5.5	3.3	–	–	5.9	6.3	–	–	4.9	4.1	–	6.1	6.1	–	2.6	1.9	–
	stat. uncertainty	2.2	6.7	–	–	3.0	9.2	–	–	12.0	25.9	–	18.7	37.3	–	12.9	25.9	–
PCM-EMC	PCM photon reco.	4.7	5.5	5.0	–	1.3	3.5	3.3	–	7.5	7.3	8.1	5.0	5.5	6.2	6.0	4.5	7.8
	γ cluster reco.	3.5	3.8	4.4	–	1.8	2.1	3.8	–	4.8	5.1	6.5	2.9	3.3	9.6	3.6	3.8	5.0
	meson reco.	2.4	1.0	1.5	–	2.9	2.3	2.2	–	3.3	4.7	14.4	5.5	5.4	8.3	3.7	6.3	14.4
	trigger and efficiency	1.0	1.0	3.0	–	0.5	3.2	4.9	–	1.0	2.0	3.0	0.2	3.2	4.9	1.4	1.4	1.4
	stat. uncertainty	2.2	3.7	3.6	–	2.6	5.7	5.3	–	14.2	11.4	16.4	0.0	0.0	0.0	14.1	14.0	12.5
EMC	γ cluster reco.	7.2	5.9	7.1	–	4.8	2.7	4.3	–	9.5	8.5	9.5	7.0	6.6	8.2	7.3	6.9	8.6
	meson reco.	3.5	4.1	7.3	–	5.1	4.7	7.0	–	23.7	7.3	3.0	29.4	8.3	4.8	23.9	7.9	8.6
	trigger and efficiency	2.3	2.4	4.1	–	1.7	1.7	4.5	–	2.3	3.0	3.8	2.6	2.6	5.1	2.0	2.5	2.5
	stat. uncertainty	3.1	2.0	4.2	–	4.4	3.1	5.3	–	20.8	7.9	6.9	23.9	15.4	27.8	20.9	8.1	12.5
PHOS	γ cluster reco.	3.2	3.7	3.8	–	2.0	2.0	2.0	–	4.1	4.2	4.2	–	–	–	0.0	0.0	0.0
	meson reco.	2.1	2.9	4.9	–	3.5	3.3	5.2	–	18.0	4.5	7.0	–	–	–	34.6	7.9	12.4
	trigger and efficiency	2.8	2.8	3.4	–	7.4	7.4	14.6	–	1.6	2.5	2.5	–	–	–	1.0	1.0	1.0
	stat. uncertainty	1.1	3.1	3.6	–	5.4	6.9	11.7	–	29.7	6.5	15.9	–	–	–	17.5	5.8	12.9
mEMC	meson PID	–	–	5.4	5.8	–	–	2.3	3.6	–	–	–	–	–	–	–	–	–
	cluster reco.	–	–	8.3	9.5	–	–	1.0	1.0	–	–	–	–	–	–	–	–	–
	trigger and efficiency	–	–	4.1	4.1	–	–	3.8	3.8	–	–	–	–	–	–	–	–	–
	stat. uncertainty	–	–	2.4	5.7	–	–	2.7	10.8	–	–	–	–	–	–	–	–	–
	combined syst. uncert.	3.6	3.9	4.9	11.9	2.7	2.9	2.9	5.4	5.6	5.3	6.1	5.9	6.8	11.5	8.6	4.5	8.2
	combined stat. uncert.	1.0	1.8	2.2	5.7	1.8	2.7	2.2	10.8	8.6	4.5	8.2	11.9	11.6	17.2	5.6	5.3	6.1

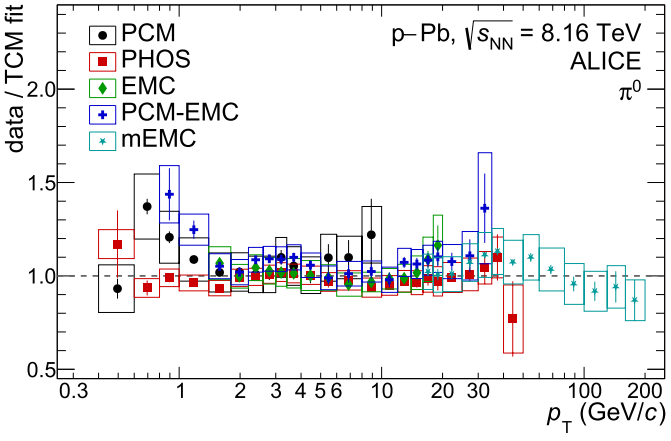

Fig. 2. Ratio of the neutral pion invariant differential cross sections to the two-component model (TCM) fit of the combined spectrum for the different reconstruction techniques PCM, PCM-EMC, EMC, PHOS and mEMC in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. Statistical uncertainties are given by the vertical error bars while systematic uncertainties are shown as boxes.

sections are between 5(8)% and 20(27)% and, due to uncertainty cancellations and correlations, between 7% and 24% on the η/π^0 ratio. For the R_{pPb}, the p_T-independent uncertainties cancel as well as a fraction of the remaining uncertainties resulting in a total uncertainty between 4(11)% and 25(32)%. A tabulated overview of the systematic uncertainty contributions for selected p_T-intervals is given in Table 2.

5. Results

The invariant differential cross sections and R_{pPb} measured by each method are consistent within their uncertainties, as shown in Fig. 2. For the calculation of R_{pPb} the spectra are shifted in the y-direction, while for the cross sections they are shifted along the p_T-axis to account for the finite bin width [46]. They were combined using the Best Linear Unbiased Estimate (BLUE) method [39,40] accounting for the partially correlated uncertainties. The resulting π^0 and η invariant differential cross sections for p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV are shown in Fig. 3 together with the π^0 cross section in pp collisions at $\sqrt{s} = 8$ TeV. In both cases, the high p_T reach of $p_T = 200$ GeV/c for the π^0 meson was enabled by the mEMC method, which allowed to significantly extend the previous pp measurement beyond 35 GeV/c [27]. The data is compared to a two-component model (TCM) fit [47], NLO calculations [41–43], and PYTHIA 8 [33,44] predictions using different nPDFs [9,10,45]. NLO calculations using the CT18 [48] PDF or nCTEQ15 [9] nPDF together with DSS14 [41] or AESSS [42] fragmentation functions generally overestimate the π^0 and η spectra, while predicting a steeper falling spectrum at high p_T. Additional NLO calculations based on the more recent NNFF1.0 [43] fragmentation functions are generally in good agreement with the data but tend to underestimate the spectra at low p_T. In Fig. 3 they are shown with factorization and renormalization scales varied from $\mu = p_T$ to $\mu = 0.5p_T$ and $2p_T$ and indicated by bands. PYTHIA 8 [33] calculations using EPPS16 [10] and nCTEQ15 [9] nPDFs describe the data, however without fully capturing the shape of the π^0 spectra, in particular at low and intermediate p_T, and with a tendency to underestimate the η spectra. For the η/π^0 ratio, presented in Fig. 3f, the differences in the shape and scale between data and calculations approximately cancel. The ratio is rather well described by the predictions and is consistent over the full p_T range between both collision systems. For $p_T > 4$ GeV/c, the η/π^0 ratio is $C^{\eta/\pi^0}_{pPb} = 0.479 \pm 0.009(\text{stat}) \pm 0.010(\text{syst})$, consistent with the previous measurement at a lower center-of-mass energy [6] and with $C^{\eta/\pi^0}_{pp} = 0.473 \pm 0.006(\text{stat}) \pm 0.011(\text{syst})$, the reevaluated η/π^0 ratio in pp collisions at 8 TeV.

To provide the pp reference for the R_{pPb}, the pp spectra measured at $\sqrt{s} = 8$ TeV were scaled to the p–Pb collision energy and

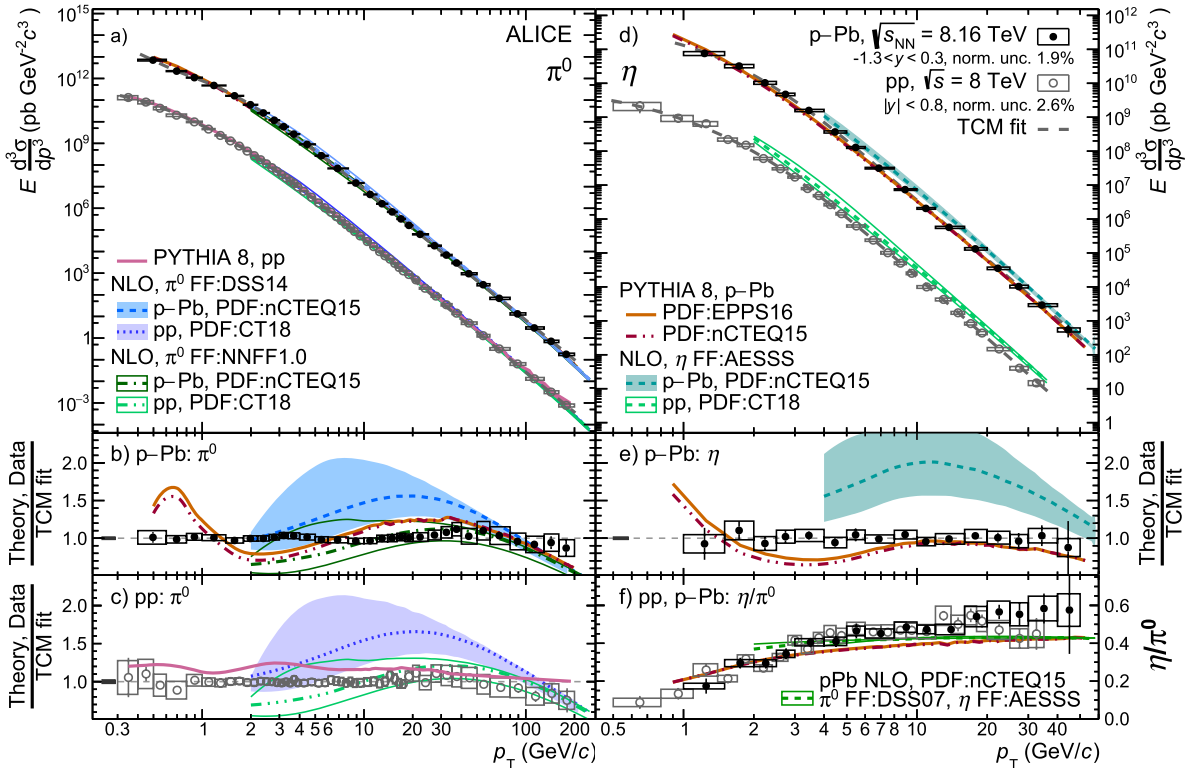

Fig. 3. Neutral pion a) and η meson d) cross sections for pp collisions at $\sqrt{s} = 8$ TeV and p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV together with TCM fits, NLO calculations [41–43] and PYTHIA 8 [33,44] predictions using different (n)PDFs [9,10,45]. Statistical uncertainties are shown as vertical bars; the systematic uncertainties as boxes. The ratios of the π^0 spectra in p–Pb and pp collisions to the TCM fits are shown in panel b) and c), respectively, together with the ratios of the calculations to the fits; panel e) shows the same for η mesons in p–Pb collisions. In panel f) the η/π^0 ratios in pp and p–Pb collisions are compared to theory predictions. The normalization uncertainty in the spectra ratio panels is indicated as a solid gray box around unity.

corrected for the rapidity difference, using the ratio of π^0 spectra generated with PYTHIA 8 Monash 2013 [44] for both kinematic regions, leading to a 1–2% increase over the whole p_T range. The resulting R_{pPb} at $\sqrt{s_{NN}} = 8.16$ TeV is shown in Fig. 4a for both mesons together with theory predictions and in Fig. 4b compared to data taken at $\sqrt{s_{NN}} = 5.02$ TeV. In the intermediate p_T region, the charged particle R_{pPb} exhibits an enhancement compared to the π^0 data, which is historically attributed to the stronger Cronin effect for baryons [49,50]. For $p_T > 10$ GeV/c, no deviation from unity is observed within uncertainties for both mesons, consistent with predictions and the ALICE π^0 and $h^{\pm}$ measurements at $\sqrt{s_{NN}} = 5.02$ TeV [6,51], in contrast to the moderate enhancement for charged hadrons seen by the CMS experiment [5]. Fitting with a constant function resulted in 1.00 ± 0.01 (0.96 ± 0.04) with a χ^2/NDF of 1.04 (0.45) for the π^0 (η) meson. Based on the spectral slopes, the data disfavor a more than 1% relative energy loss or an induced constant p_T-shift of more than 100 MeV from final-state effects in the region between 10 and 20 GeV/c for both mesons, consistent with the calculations in Ref. [18].

For $p_T < 10$ GeV/c, a suppression of similar magnitude is observed for both mesons within uncertainties. The suppression is described by NLO calculations using EPPS16 [10] and nCETQ15 [9] nPDFs (the latter tends to underpredict the data below 5 GeV/c), as well as by models using gluon recombination as the CGC-based calculations [12] or parton energy loss in cold nuclear matter in the framework of fully coherent energy loss (FCEL) [13].

The comparison of the π^0 R_{pPb} to the previous measurement at $\sqrt{s_{NN}} = 5.02$ TeV [6], as shown in Fig. 4c, is consistent with unity within uncertainties, but the data hints at a stronger suppression with increasing center-of-mass energy. A stronger suppression could originate from larger shadowing in the nPDFs, which due to the smaller x probed at 8.16 TeV predict a ratio of about 0.98 in the low p_T region, or from the increasing relevance of gluon saturation, as indicated by the CGC calculation [12]. The FCEL calculation predicts a negligible difference between the two collision energies excluding coherent energy loss as the cause of a stronger suppression. A constant fit for $p_T < 10$ GeV/c yields a ratio of $0.93 \pm 0.02_{tot} \pm 0.06_{norm}$, where the normalization uncertainty is dominated by the interpolation of the π^0 reference spectrum at 5.02 TeV.

6. Conclusion

In summary, cross sections for π^0 and η mesons in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV were measured for $0.4 < p_T < 200$ GeV/c and $1.0 < p_T < 50$ GeV/c, respectively, providing constraints for nuclear parton distributions and fragmentation functions over an unprecedented kinematic range for light mesons. By extending the reference π^0 measurement in pp collisions at $\sqrt{s} = 8$ TeV to the same p_T range using the mEMC method, the R_{pPb} for π^0 was measured up to 200 GeV/c. The R_{pPb} is consistent with unity above 10 GeV/c, as expected from calculations without parton energy loss, and strongly suppressed at low p_T, consistent with theory predictions that also include gluon shadowing or saturation effects.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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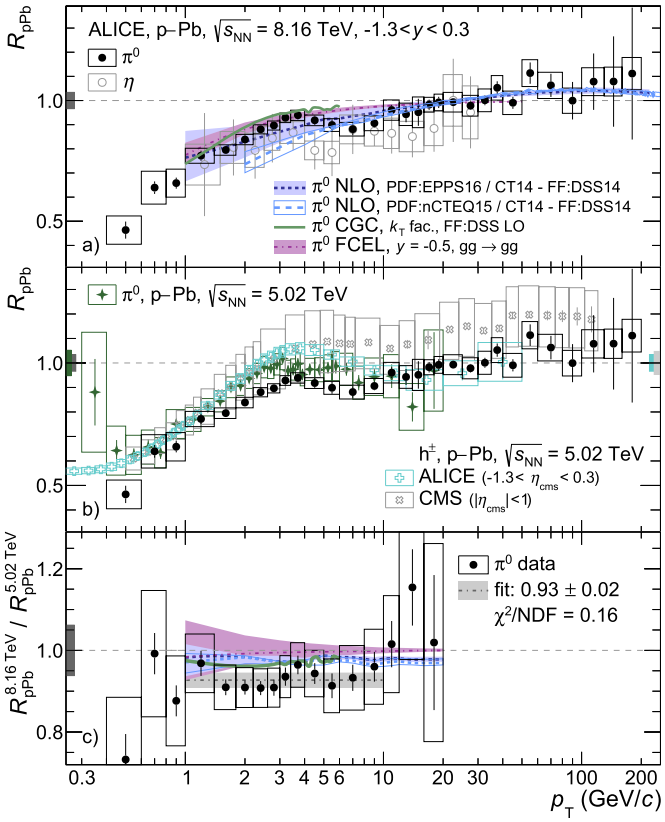

Fig. 4. a) R_{pPb} for π^0 and η mesons in p–Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV together with NLO [9,10], CGC [12] and FCEL [13] predictions. b) R_{pPb} for π^0 at $\sqrt{s_{NN}} = 8.16$ TeV compared with π^0 [6] and charged hadron measurements [5,51] at $\sqrt{s_{NN}} = 5.02$ TeV. c) Ratio of the π^0 R_{pPb} at $\sqrt{s_{NN}} = 8.16$ TeV to that at $\sqrt{s_{NN}} = 5.02$ TeV together with corresponding CGC and FCEL model predictions. Statistical uncertainties are shown as vertical bars; the systematic uncertainties as boxes. The overall normalization uncertainties are indicated as solid boxes around unity and amount to 3.4% in a) and b), and to 6.2% in c).

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