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Transverse momentum spectra and nuclear modification factors of charged particles in Xe–Xe collisions at $\sqrt{s_{\rm NN}} = 5.44$ TeV

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Abstract

Transverse momentum ($p_{\rm T}$) spectra of charged particles at mid-pseudorapidity in Xe–Xe collisions at $\sqrt{s_{\rm NN}} = 5.44$ TeV measured with the ALICE apparatus at the Large Hadron Collider are reported. The kinematic range $0.15 < p_{\rm T} < 50$ GeV/c and $|\eta| < 0.8$ is covered. Results are presented in nine classes of collision centrality in the 0–80% range. For comparison, a pp reference at the collision energy of $\sqrt{s} = 5.44$ TeV is obtained by interpolating between existing pp measurements at $\sqrt{s} = 5.02$ and 7 TeV. The nuclear modification factors in central Xe–Xe collisions and Pb–Pb collisions at a similar center-of-mass energy of $\sqrt{s_{\rm NN}} = 5.02$ TeV, and in addition at 2.76 TeV, at analogous ranges of charged particle multiplicity density $\langle {\rm d}N_{\rm ch}/{\rm d}\eta \rangle$ show a remarkable similarity at $p_{\rm T} > 10$ GeV/c. The comparison of the measured $R_{\rm AA}$ values in the two colliding systems could provide insight on the path length dependence of medium-induced parton energy loss. The centrality dependence of the ratio of the average transverse momentum $\langle p_{\rm T} \rangle$ in Xe–Xe collisions over Pb–Pb collision at $\sqrt{s} = 5.02$ TeV is compared to hydrodynamical model calculations.

*See Appendix A for the list of collaboration members

1 Introduction

Transverse momentum (p_T) spectra of charged particles carry essential information about the high-density deconfined state of strongly-interacting matter commonly denoted as quark-gluon plasma, that is formed in high-energy nucleus-nucleus (A–A) collisions [1]. Relativistic hydrodynamics is able to model the evolution of this medium [2, 3].

At low to intermediate p_T, typically in the range of up to 10 GeV/c, charged particle production is governed by the collective expansion of the system, which is observed in the shapes of single-particle transverse-momentum spectra [4, 5] and multi-particle correlations [2]. However, there is presently an intense debate as to whether the strikingly similar signatures observed in small collision systems (pp and p–A) are also of hydrodynamical origin [6–14]. A key ingredient of calculations in relativistic hydrodynamics is the initial energy density [2, 15, 16]. The number of produced particles and the volume of the medium are approximately proportional to the number of nucleons N_{part} that participate in the collision [17–19]. Thus, the particle density per unit volume is roughly independent of N_{part}. As a consequence, particle spectra at small transverse momentum should be similar in nucleus-nucleus collisions, independently of the mass number, when compared at similar values of N_{part} [20].

At high p_T, typically above 10 GeV/c, particles originate from parton fragmentation and are sensitive to the amount of energy loss that the partons suffer when propagating in the medium. In a simplified model, the energy loss depends on the number of scattering centers, which is roughly proportional to the energy density, and on the path length that the parton propagates in the medium [21]. For elastic collisions, the dependence is linear, while for medium induced gluon radiation, it is quadratic [22]. A description of experimental data lies in between those [23].

For hard processes, the production yield N_{AA} in nucleus-nucleus (A–A) collisions is expected to scale with the average nuclear overlap function $\langle T_{AA} \rangle$ when compared to the production cross section σ_{pp} in pp collisions. In the absence of nuclear effects, the nuclear modification factor

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \cdot \frac{\mathrm{d}N_{AA}(p_T)/\mathrm{d}p_T}{\mathrm{d}\sigma_{pp}(p_T)/\mathrm{d}p_T} \tag{1}$$

equals unity. The average nuclear overlap function is defined as the average number of binary nucleon-nucleon collisions $\langle N_{coll} \rangle$ per inelastic nucleon-nucleon cross section and is estimated via a Glauber model calculation [24]. At the Large Hadron Collider (LHC), particle production is observed to be strongly suppressed in Pb–Pb collisions by a factor of up to 7–8 around p_T = 6–7 GeV/c with a linear decrease at higher p_T but still a substantial suppression even above 100 GeV/c [5, 25].

The LHC produced for the first time collisions of xenon nuclei at a center-of-mass energy of $\sqrt{s_{NN}} = 5.44$ TeV during a pilot run with 6 hours of stable beams in October 2017. This allows for studying the dependence of particle production on the collision system size where xenon neatly bridges the gap between data from pp, p–Pb and Pb–Pb collisions. Here, the atomic mass numbers are $A = 129$ for xenon, and $A = 208$ for lead with half-density radii of the nuclear-charge distribution of r = (5.36 ± 0.1) fm and (6.62 ± 0.06) fm, respectively [24, 26]. The parameters of the nuclear-charge density distribution for ^{129}Xe are not yet measured but were extrapolated from neighboring isotopes and are thus less precisely known than for ^{208}Pb. While ^{208}Pb is a spherical nucleus, ^{129}Xe has a deformation parameter of $\beta_2 = (0.18 \pm 0.02)$.

This article reports transverse momentum spectra of charged particles at mid-pseudorapidity in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV measured with the ALICE apparatus at the LHC in the kinematic range $0.15 < p_T < 50$ GeV/c and $|\eta| < 0.8$ for nine classes of collision centrality, covering the most central 80% of the hadronic cross section. It is organized as follows: Section 2 describes the experimental setup and data analysis. Systematic uncertainties are discussed in Sect. 3. Results and comparison to model calculations are presented in Sect. 4. A summary is given in Sect. 5.

2 Experiment and data analysis

Collisions of xenon nuclei were recorded at an average instantaneous luminosity of about $2 \cdot 10^{-25}$ cm^{-2}s^{-1} and a hadronic interaction rate of 80–150 s^{-1}. A detailed description of the ALICE experimental apparatus can be found elsewhere [27].

2.1 Trigger and event selection

A minimum-bias interaction trigger was optimized for high efficiency on hadronic collisions. It required signals from both forward scintillator arrays covering $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C). Additionally, coincidence with signals from two neutron Zero-Degree Calorimeters (ZDC), ZNA and ZNC, was required in order to remove contamination from electromagnetic processes. Here A and C denote opposite sides of the experiment along the beamline. The offline event selection was optimized to reject beam-induced background. Background events were efficiently rejected by exploiting the timing signals in the two V0 detectors. Parasitic collisions are removed by using the correlation between the sum and the difference in arrival times as measured in each of the neutron ZDCs. In total, $1.1 \cdot 10^6$ minimum-bias collisions pass the event selection and were further analyzed.

This analysis is based on tracking information from the Inner Tracking System (ITS) [28] and the Time Projection Chamber (TPC) [29] which are located in the central barrel of ALICE. A solenoidal magnet provides momentum dispersion in the direction transverse to the beam axis. The nominal field strength in the ALICE central barrel is 0.5 T. However, in order to extend particle tracking and identification to the lowest possible momenta, it was reduced to 0.2 T in Xe–Xe collisions.

The ITS is comprised of six cylindrical layers of silicon detectors with radii between 3.9 and 43.0 cm. The two innermost layers, with average radii of 3.9 cm and 7.6 cm, are equipped with Silicon Pixel Detectors (SPD); the two intermediate layers, with average radii of 15.0 cm and 23.9 cm, are equipped with Silicon Drift Detectors (SDD) and the two outermost layers, with average radii of 38.0 cm and 43.0 cm, are equipped with double-sided Silicon Strip Detectors (SSD). The large cylindrical TPC has an active radial range from about 85 to 250 cm and an overall length along the beam direction of 500 cm. It covers the full azimuth in the pseudorapidity range $|\eta| < 0.9$ and provides track reconstruction with up to 159 points along the trajectory of a charged particle as well as particle identification via the measurement of specific energy loss dE/dx.

The collision vertex is determined using reconstructed particle trajectories in the TPC including hits in the ITS. All collisions with a reconstructed vertex position within ± 10 cm along the beam direction from the nominal interaction point are accepted. The collision centrality is defined as the percentile of the hadronic cross section corresponding to the measured charged particle multiplicity. The centrality determination is based on the sum of the amplitudes of the V0A and V0C signals [18, 19]. Averaged quantities characterizing a centrality class such as the number of participants $N_{\rm part}$, the number of binary collisions $N_{\rm coll}$, and the nuclear overlap function $T_{\rm AA}$ are calculated as the average over all events in this class by fitting the experimental distribution with a Glauber Monte Carlo model that employs negative binomial distributions to model multiplicity production [18, 19] (see Table 1). The analysis is restricted to the 0–80% centrality range in order to ensure that effects of trigger inefficiency and contamination by electromagnetic processes are negligible.

Centrality (%)	$\langle dN_{\rm ch}/d\eta\rangle_{\rm Xe-Xe}$	$\langle N_{\rm part}\rangle$	$\langle N_{\rm coll}\rangle$	$\langle T_{\rm AA}\rangle$ $(\rm mb^{-1})$	$\langle dN_{\rm ch}/d\eta\rangle_{\rm Pb-Pb}$
0–5	1167 ± 24	236 ± 2	949 ± 75	13.9 ± 1.1	1943 ± 54
5–10	939 ± 24	207 ± 3	737 ± 65	10.8 ± 1.0	1586 ± 46
10–20	706 ± 17	165 ± 3	511 ± 51	7.5 ± 0.7	1180 ± 31
20–30	478 ± 11	118 ± 4	303 ± 40	4.4 ± 0.6	786 ± 20
30–40	315 ± 8	82 ± 4	171 ± 27	2.5 ± 0.4	512 ± 15
40–50	198 ± 5	55 ± 4	92 ± 16	1.3 ± 0.2	318 ± 12
50–60	118 ± 3	34 ± 3	46 ± 9	0.7 ± 0.1	183 ± 8
60–70	65 ± 2	20 ± 2	22 ± 4	0.3 ± 0.1	96 ± 6
70–80	32 ± 1	11 ± 1	10 ± 2	0.14 ± 0.02	45 ± 3

Table 1: Averaged values of $\langle dN_{\rm ch}/d\eta\rangle$, $\langle N_{\rm part}\rangle$, $\langle N_{\rm coll}\rangle$ and $\langle T_{\rm AA}\rangle$ for nine centrality classes of Xe–Xe collisions [18, 19] at $\sqrt{s_{\rm NN}}$ = 5.44 TeV, and $\langle dN_{\rm ch}/d\eta\rangle$ for Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV [30].

2.2 Track selection

Primary charged particles within the kinematic range $|\eta| < 0.8$ and $0.15 < p_{\rm T} < 50$ GeV/c are measured. Here, primaries are defined as all charged particles with a proper lifetime τ larger than 1 cm/c that are either produced directly in the primary beam-beam interaction, or from decays of particles with τ smaller than 1 cm/c, excluding particles produced in interactions with the detector material [31]. The track selection is optimized for best track quality and minimum contamination from secondary particles. The selection criteria are identical to those of the previous analysis of Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV [5] except for the following changes in the parameterization on the transverse momentum dependence. The geometrical track length in the TPC fiducial volume [29] is $L/{\rm cm} > 130 - (p_{\rm T}/{\rm GeV}/c)^{-0.7}$, and the distance of closest approach to the primary vertex in the transverse plane is $|{\rm DCA_{xy}}|/{\rm cm} < 0.0119 + 0.049\,(p_{\rm T}/{\rm GeV}/c)^{-1}$. These changes reflect differences in particle tracking due to the reduced magnetic field. In order to reject fake tracks that contaminate the spectrum, especially at high $p_{\rm T}$, another selection is introduced: the uncertainty in the reconstructed $p_{\rm T}$ as estimated from the covariance matrix of the track fit must be less than ten times the standard deviation, when averaged over all tracks at that momentum.

2.3 Corrections

The doubly-differential transverse momentum spectra in Xe–Xe collisions are normalized by the number of events $N_{\rm ev}$ in each centrality class, and are given by

$$\frac{1}{N_{\rm ev}}\frac{d^2N_{\rm ch}}{d\eta\, dp_{\rm T}} \equiv \frac{N_{\rm ch}^{\rm rec}(\Delta\eta,\Delta p_{\rm T})}{N_{\rm ev}\cdot\Delta\eta\Delta p_{\rm T}}\cdot\frac{\delta_{p_{\rm T}}(\Delta p_{\rm T})}{\alpha(\Delta p_{\rm T})\cdot\varepsilon(\Delta p_{\rm T})}, \quad (2)$$

where N_{ch}^{rec} is the raw yield of reconstructed primary charged particles in each interval of pseudorapidity and transverse momentum $(\Delta\eta, \Delta p_T)$. The symbols $\alpha(\Delta p_T)$ and $\varepsilon(\Delta p_T)$ are the correction factors for detector acceptance and tracking efficiency, respectively. The correction due to the finite transverse-momentum resolution in the reconstruction of primary charged particles is denoted by $\delta_{p_T}(\Delta p_T)$. The efficiencies for trigger, event vertex reconstruction and tracking are estimated using Monte Carlo simulations with HIJING [32] as the event generator and GEANT3 [33] for particle propagation and simulation of the detector response. The trigger and vertex selections are fully efficient for the whole centrality range used in the analysis.

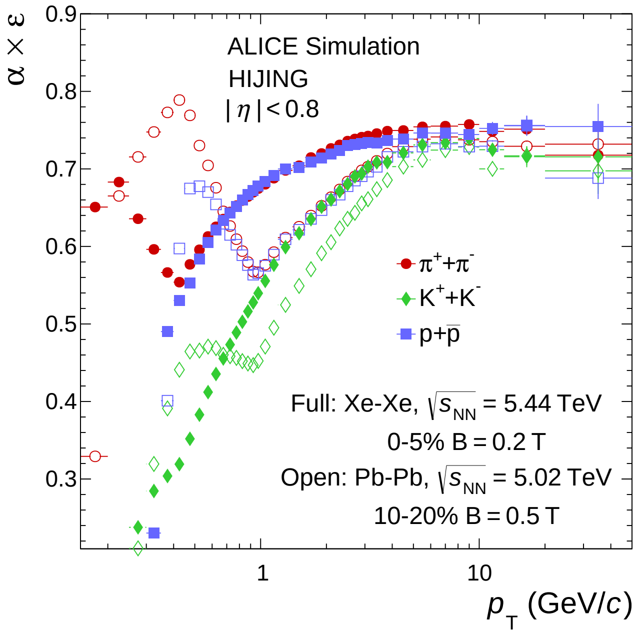

Fig. 1: Transverse momentum dependence of the acceptance times tracking efficiency for the 5% most central Xe–Xe collisions and comparison to the 10–20% centrality class for Pb–Pb collisions. The two centrality classes have similar multiplicity densities.

Contamination from secondary charged particles, i.e. from weak decays and interactions in the detector material, is subtracted from the raw spectrum by employing a data driven method [5]. Reconstructed trajectories of primary charged particles point to the collision vertex, while charged particles from weak decays and particles generated in the detector material preferentially point away from it. In order to distinguish between primary and secondary particles, the distance of closest approach to the collision vertex in radial direction, DCA_{xy}, is used. A multi-template function that consists of templates for primary particles, secondary particles produced from weak decays and secondary particles from interactions in the detector material is fitted to the DCA_{xy} distributions in each p_T interval.

The primary charged particle reconstruction efficiency is obtained from the Monte Carlo simulation. As discussed in detail in [5], this efficiency depends on the relative abundances of the various primary particles species. These relative abundances are adjusted in the simulation using a data-driven re-weighting procedure. The particle composition in Xe–Xe collisions is not yet known. However, bulk particle production scales with the average charged particle multiplicity density, $\langle dN_{ch}/d\eta \rangle$, independently of the collision system [34]. In Xe–Xe collisions, the weights from existing analyses [4, 5, 35–37] with Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV at equivalent values in $\langle dN_{ch}/d\eta \rangle$ are applied.

The acceptance times tracking efficiency for charged pions, charged kaons and (anti-)protons for 5% most central Xe–Xe collisions is shown in Fig. 1 as a function of the particle transverse momentum and compared to 10–20% Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The two centrality classes have similar multiplicity densities. The particular shape with a dip at $p_T \sim 0.4$ GeV/c arises from the geometrical length selection that is especially visible for pions. This dip corresponds to particles that cross the TPC sector boundaries under small angles. The decrease at low values of p_T is due to curling trajectories in the magnetic field which do not reach the required minimum track length in the TPC. In Pb–Pb collisions, the magnetic field was set to $B = 0.5$ T, which results in the dip being positioned around 1 GeV/c. At large p_T, above 7 GeV/c, the tracking efficiency is reduced by an increased local track density, i.e. high p_T particles are preferentially produced within jets, leading to a slight decrease in the track finding performance.

The transverse momentum of primary charged particles is reconstructed from the track curvature as measured by the ITS and the TPC [38]. The finite momentum resolution modifies the reconstructed charged-particle spectrum and is estimated by the corresponding covariance matrix element of the Kalman fit. The relative p_T resolution, $\sigma(p_T)/p_T$, depends on the momentum and amounts to approximately 4.5% at $p_T = 0.15$ GeV/c, it shows a minimum of 1.5% around $p_T = 1.0$ GeV/c, and increases linearly for larger p_T, approaching 9.3% at 50 GeV/c. The centrality dependence of the relative p_T resolution is negligible. To account for the finite p_T resolution, correction factors to the spectra for $p_T > 10$ GeV/c are determined using an unfolding procedure [39]. At transverse momenta below 10 GeV/c, these corrections are negligible. The p_T dependent correction factors are applied to the measured p_T spectrum and depend slightly on collision centrality because of the change in the slope of the spectrum, especially at high p_T. The correction factor δ_{p_T} deviates from unity by less than 1% below p_T = 15 GeV/c for all centrality classes, and by up to 3% (4%) in 0–5% (70–80%) central collisions above 15 GeV/c.

2.4 pp reference at $\sqrt{s}$ = 5.44 TeV

The p_T-differential cross section in pp collisions at $\sqrt{s} = 5.44$ TeV is needed to measure the corresponding nuclear modification factor. As there are no measurements of pp collisions at this energy, a reference is obtained by interpolating pp references [5, 39] as measured at $\sqrt{s}$ = 5.02 TeV and $\sqrt{s}$ = 7 TeV assuming a power-law dependence in each p_T interval, $d\sigma/dp_T(\sqrt{s}) \propto \sqrt{s}^n$. The statistical uncertainties of the pp reference are interpolated between the references at $\sqrt{s}$ = 5.02 TeV and 7 TeV assuming also a power-law dependence and are assigned to the interpolated reference. This interpolation method [39] is based on the observation that the cross section at a fixed transverse momentum approximately scales with collision energy like a power law.

As an alternative approach, the scaling of the measured cross section at $\sqrt{s}$ = 5.02 TeV to $\sqrt{s}$ = 5.44 TeV by using the ratio of spectra at those two energies obtained with the PYTHIA 8 (Monash tune) event generator [40] is studied. The ratio of the pp references at $\sqrt{s}$ = 5.44 TeV from the power-law interpolation and at $\sqrt{s}$ = 5.02 TeV is shown in Fig. 2 together with results obtained with the alternative method. The spectrum is harder at higher collision energy, with a small change in the total cross section of 4% below 1 GeV/c and an increase of about 10% at transverse momenta above 10 GeV/c.

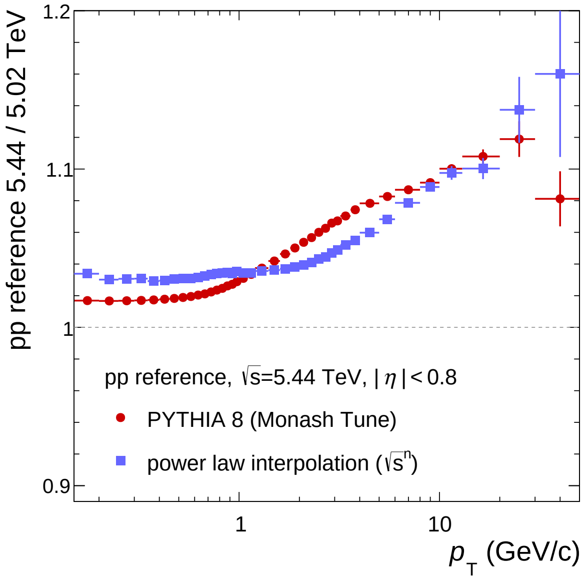

Fig. 2: Ratio of p_T-differential cross sections in pp collisions at $\sqrt{s} = 5.44$ TeV over 5.02 TeV using a power law interpolation and the event generator PYTHIA 8.

3 Systematic uncertainties

For the total systematic uncertainty, all contributions are added in quadrature and are summarized in Table 2.

centrality (%)	0–5 (%)	30–40 (%)	70–80 (%)
p_T range (GeV/c)	0.2–0.5 / 1–2 / 40–50	0.2–0.5 / 1–2 / 40–50	0.2–0.5 / 1–2 / 40–50
Source			
Vertex selection	0.2 / 0.2 / 0.2	0.8 / 0.8 / 0.8	0.8 / 0.8 / 0.8
Track selection	1.6 / 0.9 / 1.2	0.9 / 0.6 / 0.8	0.9 / 0.5 / 1.0
Secondary particles	1.4 / 0.2 / negl.	0.8 / 0.2 / negl.	0.6 / 0.2 / negl.
Particle composition	0.3 / 1.7 / 0.7	0.4 / 1.9 / 1.0	0.7 / 0.6 / 0.6
Tracking efficiency	1.9 / 1.2 / 0.4	2.2 / 1.2 / 0.4	2.2 / 1.4 / 0.6
Material budget	0.3 / 0.3 / 0.1	0.3 / 0.3 / 0.1	0.3 / 0.3 / 0.1
p_T resolution	negl. / negl. / 0.5	negl. / negl. / 0.7	negl. / negl. / 0.9
Sum, p_T dependent:	3.1 / 2.4 / 1.5	2.8 / 2.5 / 1.8	2.8 / 1.9 / 2.1
Centrality selection	0.1	0.8	3.2

Table 2: Contributions to the systematic uncertainty for the 0–5%, 30–40%, and 70–80% centrality classes in Xe–Xe collisions. The numbers are averaged in the p_T intervals from 0.2–0.5 GeV/c (left), 1–2 GeV/c (middle) and 40–50 GeV/c (right). For the p_T-dependent sum, contributions are added in quadrature.

The effect of the selection of events based on the vertex position is studied by comparing the fully corrected p_T spectra obtained with alternative vertex selections corresponding to $\pm$ 5 cm, and $\pm$ 20 cm. The difference in the fully corrected p_T spectra is less than 0.3% for central collisions and less than 0.5% for peripheral collisions.

In order to test the description of the detector response and the track reconstruction in the simulation, all criteria for track selection are varied within the ranges as described in the previous publication [5]. A full analysis is performed by varying one selection criterion at a time. The maximum change in the corrected p_T spectrum is then considered as systematic uncertainty. The overall systematic uncertainty related to track selection is obtained from summing up all individual contributions quadratically and it amounts to 0.6–3.0%, depending on p_T and centrality.

The systematic uncertainty on the secondary-particle contamination is estimated by varying the fit model using two templates, i.e. for primaries and secondaries, or three templates, i.e. primaries, secondaries from interactions in the detector material and secondaries from weak decays of K^0_s and Λ, as well as varying the fit ranges. The maximum difference between data and the two-component-template fit is summed in quadrature together with the difference between results obtained from the two- and three-component-template fits. The systematic uncertainty due to the contamination from secondaries is decreasing with increasing p_T. It dominates at low p_T with values up to 4% and is negligible above 2 GeV/c.

The systematic uncertainty on the primary particle composition is taken from [5]. An additional uncertainty is estimated by assuming the particle composition from a neighboring $\langle dN_{ch}/d\eta \rangle$ range to the matched one in the Pb–Pb analysis and is added quadratically. The sum peaks around 3 GeV/c with a maximum of 5% (less than 2%) for the 0-5% (70–80%) centrality class.

In order to estimate the systematic uncertainty due to the tracking efficiency, the track matching between the TPC and the ITS information in data and Monte Carlo is compared after scaling the fraction of secondary particles obtained from the fits to the DCA_{xy} distributions [5]. The difference in the TPC-ITS track-matching efficiency between data and simulation is assigned to the corresponding systematic uncertainty (see Table 2). It amounts to 2% in central collisions, and up to 3.5% in peripheral collisions.

The material budget in ALICE at $\eta \approx 0$ amounts to (11.4 ± 0.5)% in radiation lengths for primary charged particles that have sufficient track length in the TPC [38]. A difference in the amount of detector material leads to different amounts of secondary particles that are produced. After the subtraction of the contribution due to secondaries using the three-component DCA_{xy} fits, the differences on the secondary correction factor is negligible. A variation of the material budget within above limits leads to a p_T dependent systematic uncertainty on the tracking efficiency of 0.1–0.3%.

The uncertainty due to the finite p_T resolution is estimated using the azimuthal dependence of the $1/p_T$ spectra for positively and negatively charged particles. The relative shift of the spectra for oppositely charged particles along $1/p_T$ determines the size of uncertainty for a given angle. The RMS of the $1/p_T$ shift as distributed over the full azimuth is used as an additional increase of the p_T resolution. The uncertainty due to the finite p_T resolution is significant only at the highest momentum bin and amounts to 0.5% (0.9%) for the 0-5% (70–80%) centrality class.

The uncertainty due to the centrality determination is estimated by changing the fraction of the visible cross section (90.0 ± 0.5)%. The uncertainty is estimated from the variation of the resulting p_T spectra and amounts to $\sim$ 0.1% and $\sim$ 3.2% for central (0–5%) and peripheral (70–80%) collisions, respectively.

The systematic uncertainty of the pp reference at $\sqrt{s} = 5.44$ TeV has two contributions, which are added quadratically. For each p_T interval, the systematic uncertainty of the pp references at $\sqrt{s} = 5.02$ TeV and $\sqrt{s} = 7$ TeV are interpolated to $\sqrt{s} = 5.44$ TeV by using a power-law. This corresponds to interpolating between the upper and lower boundaries of the experimental data points as given by their systematic uncertainties. It assumes full correlation of systematic uncertainties at both energies.

The difference between the interpolated reference and the one using the PYTHIA 8 event generator is assigned as the other contribution to the systematic uncertainty in the pp reference, in each p_T interval. The systematic uncertainty in the pp reference has a minimum of 2.2% around 1 GeV/c and reaches its maximum of 7.7% at the highest momentum bin.

4 Results

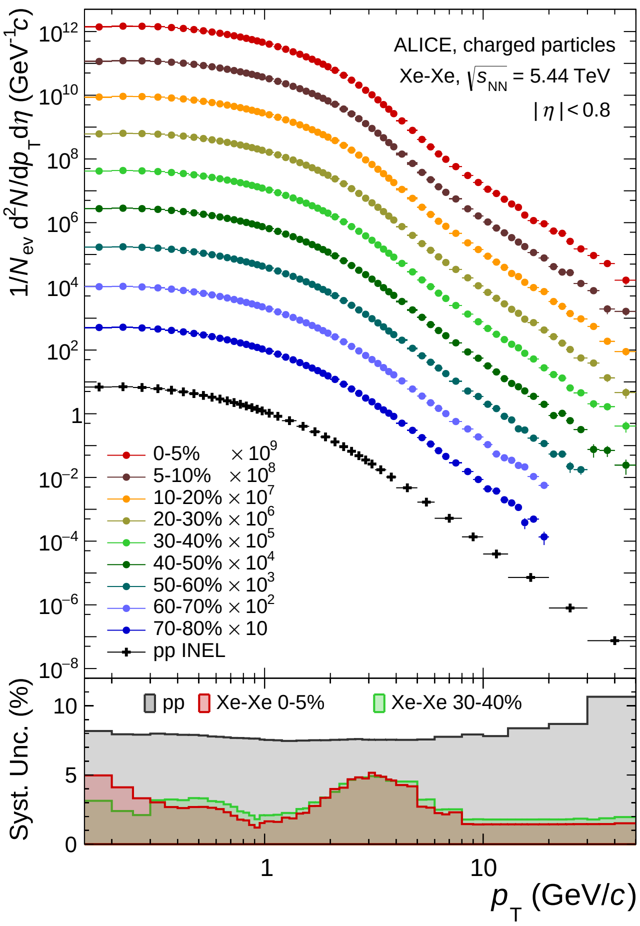

Fig. 3: Transverse momentum spectra of charged particles in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV in nine centrality classes together with the interpolated pp reference spectrum at $\sqrt{s} = 5.44$ TeV (top panel) and systematic uncertainties (bottom panel).

The transverse momentum spectra of charged particles in Xe–Xe collisions are shown in the top panel of Fig. 3 for nine centrality classes together with the interpolated pp reference spectrum at $\sqrt{s} = 5.44$ TeV. The latter is obtained from the interpolated p_T-differential cross section by dividing it by the interpolated inelastic nucleon-nucleon cross section of (68.4 ± 5.0) mb at $\sqrt{s} = 5.44$ TeV [18, 19].

The systematic uncertainty of the pp reference spectrum is dominated by the interpolation uncertainty, especially at momenta above 10 GeV/c. In the most-peripheral collisions, the p_T spectrum is similar to that of pp collisions and exhibits a power law behavior that is characteristic of hard-parton scattering and vacuum fragmentation. With increasing collision centrality, the p_T differential cross section is progressively depleted above 5 GeV/c.

Systematic uncertainties are shown in the bottom panel. At momenta between 0.4 and 10 GeV/c, the systematic uncertainty is dominated by the contribution from tracking and amounts to about 2–3%. It is almost independent of p_T above 10 GeV/c with a value of 1.4% (2.1%) for the 0–5% (70–80 %) centrality class.

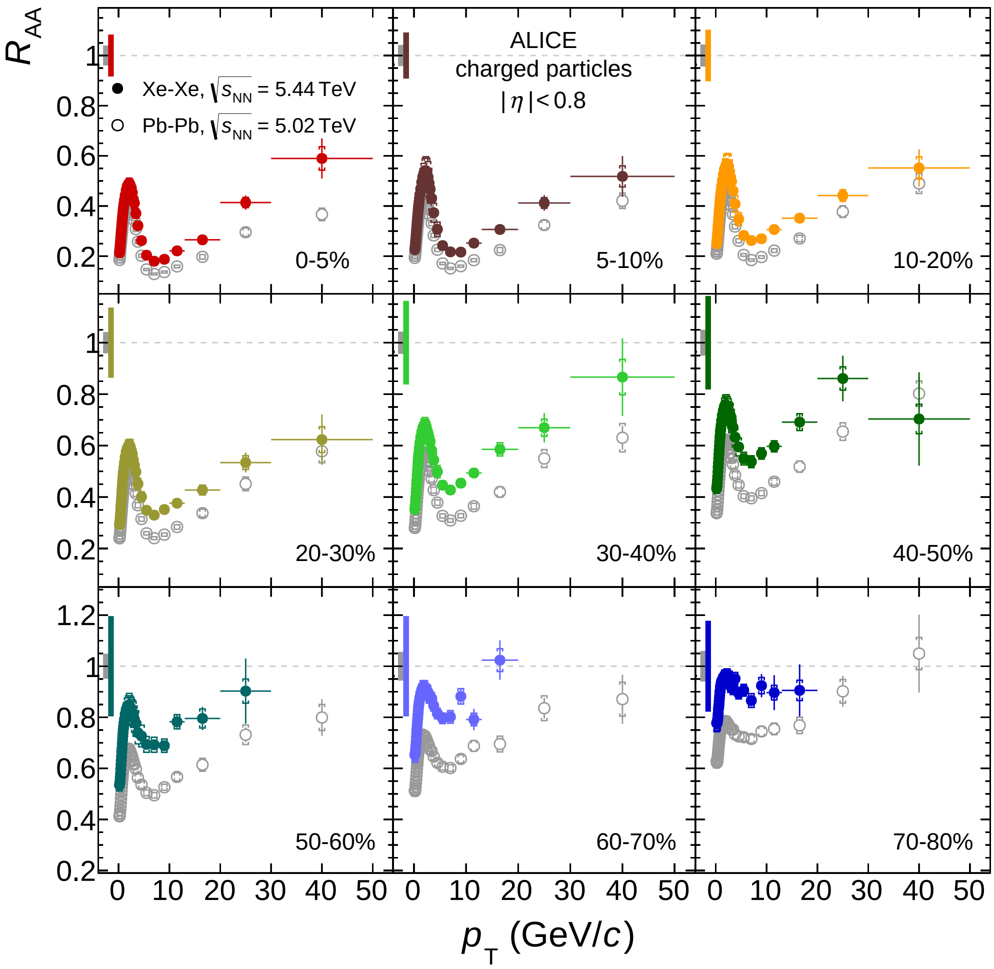

Fig. 4: Nuclear modification factor in Xe–Xe at $\sqrt{s_{NN}} = 5.44$ TeV (filled circles) and Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV (open circles) collisions for nine centrality classes. The vertical lines (brackets) represent the statistical (systematic) uncertainties. The overall normalization uncertainty is shown as a filled box around unity.

In order to determine the nuclear modification factor R_{AA}, the interpolated p_T-differential cross section is scaled by the average nuclear overlap function $\langle T_{AA} \rangle$. The resulting nuclear modification factor as a function of transverse momentum is shown in Fig. 4 for nine centrality classes. The overall normalization uncertainties for R_{AA} are indicated by vertical bars around unity. The uncertainties of the pp reference and the centrality determination are added in quadrature. The latter is larger for Xe–Xe collisions than for Pb–Pb because of the less precisely known nuclear-charge-density distribution of the deformed ^{129}Xe and the resulting larger relative uncertainty in $\langle T_{AA} \rangle$ [18, 19]. The nuclear modification factor exhibits a strong centrality dependence with a minimum around $p_T = 6$–7 GeV$/c$ and an almost linear rise above. In particular, in the 5% most central collisions, at the minimum, the yield is suppressed by a factor of about 6 with respect to the scaled pp reference. The nuclear modification factor reaches a value of 0.6 at the highest measured transverse-momentum interval of 30–50 GeV$/c$. For comparison, the nuclear modification factor R_{AA} in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in Fig. 4 as open circles for the same centrality classes as Xe–Xe. In both collision systems, a similar characteristic p_T dependence of R_{AA} is observed. In Pb–Pb collisions, the suppression of high-momentum particles is apparently stronger for the same centrality class but still in agreement with Xe–Xe collisions within uncertainties.

Nuclear modification factors from Xe–Xe and Pb–Pb collisions and their ratios at similar ranges of $\langle dN_{ch}/d\eta \rangle$ are shown in Fig. 5. In 5% most central Xe–Xe collisions, the nuclear modifi-

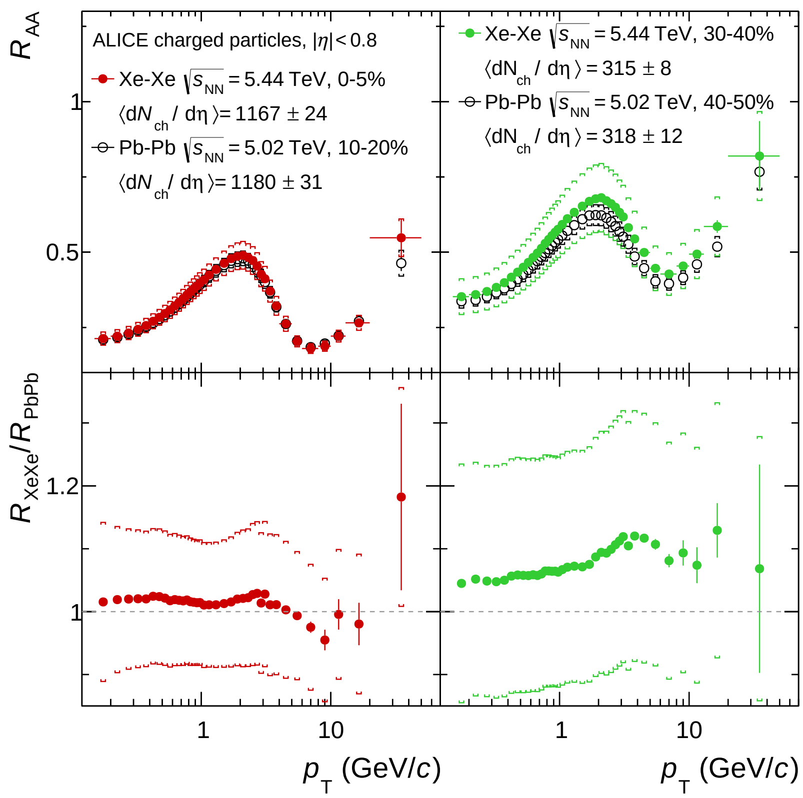

Fig. 5: Comparison of nuclear modification factors in Xe–Xe collisions (filled circles) and Pb–Pb collisions (open circles) for similar ranges in $\langle dN_{ch}/d\eta \rangle$ for the 0–5% (left) and 30–40% (right) Xe–Xe centrality classes. The vertical lines (brackets) represent the statistical (systematic) uncertainties.

cation factor is remarkably well matched by 10–20% central Pb–Pb collisions over the entire

p_T range. The values of $\langle N_{part} \rangle$ are 236 $\pm$ 2 (263 $\pm$ 4) for the 0–5% (10–20%) centrality class in Xe–Xe (Pb–Pb) collisions [30], and thus they deviate significantly, where a remarkable similarity in R_{AA} is found between both collision system. In the 30–40% Xe–Xe (40–50% Pb–Pb) centrality class, again agreement is found within uncertainties at also similar values of $\langle N_{part} \rangle$ of 82 $\pm$ 4 (86 $\pm$ 2). These findings of matching nuclear modification factors at similar ranges of $\langle dN_{ch}/d\eta \rangle$ are in agreement with results from the study of fractional momentum loss of high-p_T partons at RHIC and LHC energies [41].

A comparison of the nuclear modification factors as a function of $\langle dN_{ch}/d\eta \rangle$ in Xe–Xe and Pb–Pb collisions for three different regions of p_T (low, medium, and high) is shown in Fig. 6. A

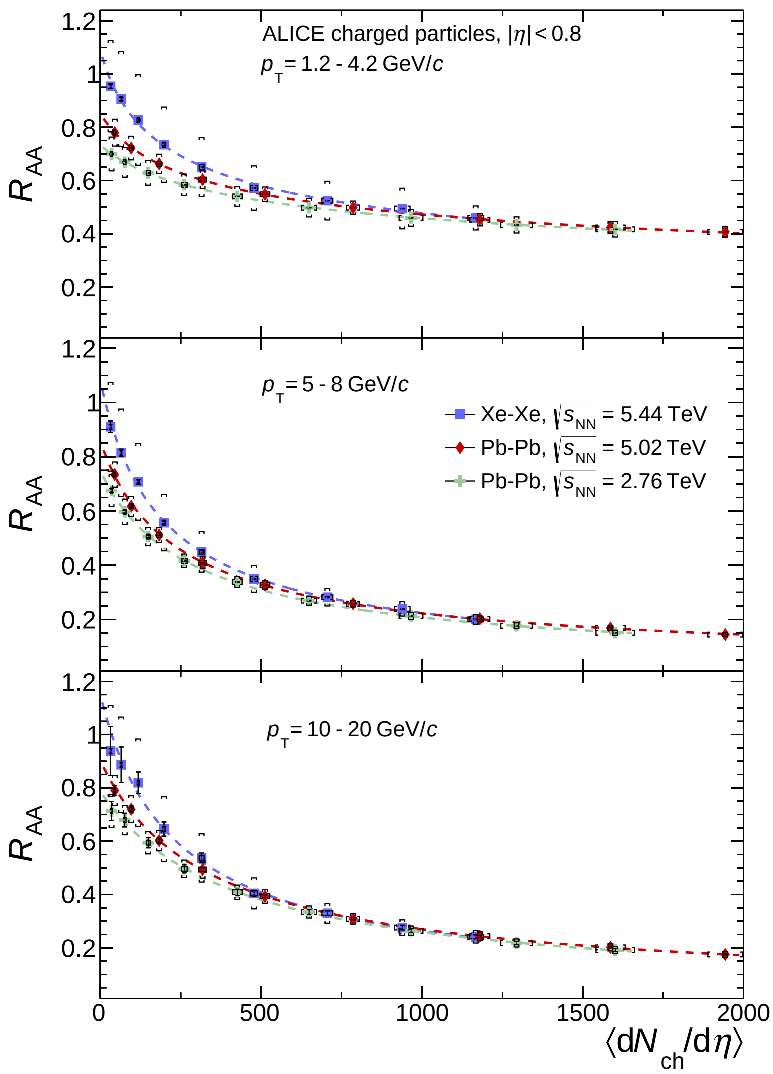

Fig. 6: Comparison of the nuclear modification factor in Xe–Xe and Pb–Pb collisions integrated over identical regions in p_T as a function of $\langle dN_{ch}/d\eta \rangle$. The vertical brackets indicate the quadratic sum of the total systematic uncertainty in the measurement and the overall normalization uncertainty in $\langle T_{AA} \rangle$.The horizontal bars reflect the RMS of the distribution in each bin. The dashed lines show results from power-law fits to the data and are drawn to guide the eye.

remarkable similarity in R_{AA} is observed between Xe–Xe collision at $\sqrt{s_{NN}} = 5.44$ TeV and Pb–

Pb collisions at $\sqrt{s_{NN}}$ = 5.02 and 2.76 TeV when compared at identical ranges in $\langle dN_{ch}/d\eta \rangle$, for $\langle dN_{ch}/d\eta \rangle > 400$. This holds both at low momentum where the hydrodynamical expansion of the medium dominates the spectrum and at high momentum, where parton energy loss inside the medium drives the spectral shape. At $\langle dN_{ch}/d\eta \rangle < 400$, the values of R_{AA} still agree within rather large uncertainties.

In a simplified radiative energy loss scenario when assuming identical thermalization times [42, 43], the average energy loss $\langle \Delta E \rangle$ is proportional to the density of scattering centers in the medium, which in turn is proportional to the energy density ε, and to the square of the path length L of the parton in the medium, $\langle \Delta E \rangle \propto \varepsilon \cdot L^2$ [22]. The energy density can be estimated from the average charged-particle multiplicity density [44] per transverse area, $\varepsilon \propto \langle dN_{ch}/d\eta \rangle / A_T$. In central collisions, the initial transverse area A_T is related to the radius r of the colliding nuclei, $A_T = \pi \cdot r^2$ [22]. Therefore, the comparison of the measured R_{AA} values in the two colliding systems could enable a test of the path length dependence of medium-induced parton energy loss.

To further address bulk production, the average transverse momentum $\langle p_T \rangle$ in the range from 0–10 GeV/c is derived. The spectra are extrapolated down to $p_T = 0$ by fitting a Hagedorn function in the range $0.15\ \mathrm{GeV}/c < p_T < 1\ \mathrm{GeV}/c$. The relative fraction of the extrapolated particle yield amounts to 8% (11%) for the 0–5% (70–80%) centrality class. Statistical uncertainties in $\langle p_T \rangle$ are negligible. Systematic uncertainties are estimated by varying each source of systematic uncertainty in the spectra at a time, by varying the fit range to $0.15\ \mathrm{GeV}/c < p_T < 0.5\ \mathrm{GeV}/c$, by changing the interpolation range to 0–0.2 GeV/c, and by assuming a constant yield below 0.15 GeV/c. All contributions are then added quadratically. The relative systematic uncertainty is 1.2% (1.1%) for the 0-5% (70–80%) centrality class.

The average transverse momentum is presented in the top panel of Fig. 7 for Xe–Xe collisions at $\sqrt{s}$ = 5.44 TeV (squares) and Pb–Pb collisions at $\sqrt{s}$ = 5.02 TeV (diamonds) for nine centrality classes. An increase of $\langle p_T \rangle$ with centrality is visible in both collision systems and is attributed to the increasing transverse radial flow. The bottom panel of Fig. 7 shows the ratios of $\langle p_T \rangle$ in both collision systems. The ratio is flat within uncertainties but allows for relative variations of up to two percent. Comparison to results from hydrodynamical calculations [42] are shown by the hashed areas for pions, kaons and protons. The calculations assume a boost-invariant longitudinal expansion of the medium. The initial density profile is taken from the TRENTo model with parameter $p = 0$ and is determined over the transverse plane a few million times. Each initial density profile is then numerically evolved by means of the viscous relativistic hydrodynamical code V-USPHYDRO with an equation of state from lattice QCD calculations with three quark flavors and physical quark masses. The hydrodynamic evolution starts at $\tau_0 = 0.6$ fm/c and stops when the temperature drops below 150 MeV, at which point the fluid transforms into hadrons. Hadronic rescatterings are neglected. While the calculations are not able to predict absolute particle spectra, predictions are made for the relative difference in $\langle p_T \rangle$ between both collision systems in order to study the system size dependence. The predicted trend of a larger $\langle p_T \rangle$ in 5% most central Xe–Xe collision and continuously lower values towards the 40–50% centrality class are consistent with the data.

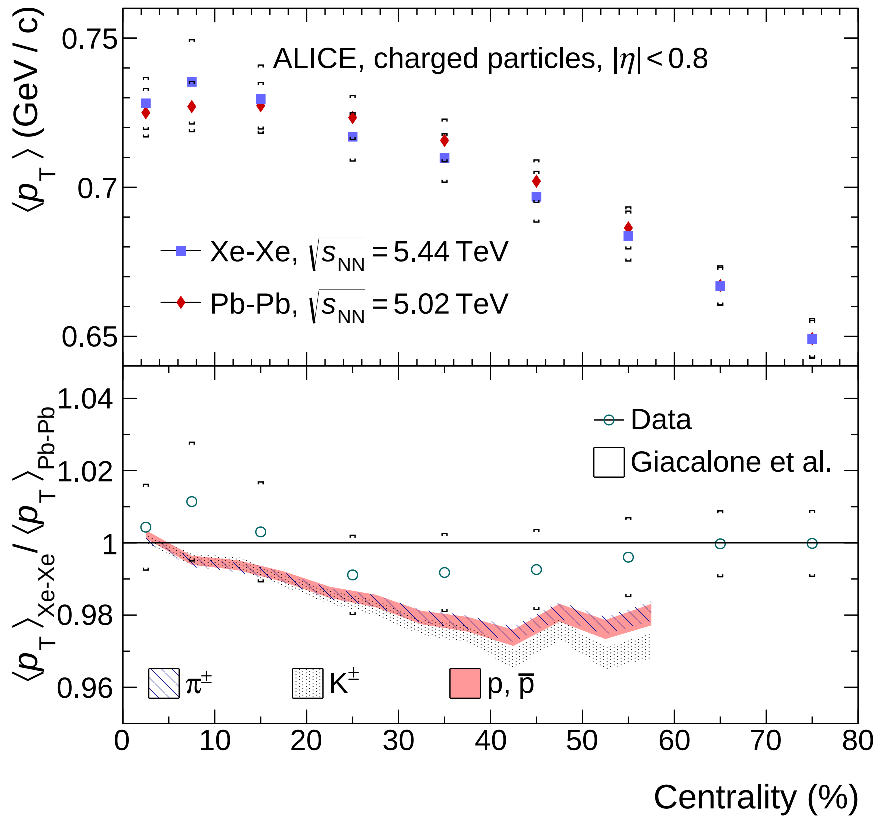

Fig. 7: Average transverse momentum in the p_T-range 0–10 GeV/c for Xe–Xe collisions at $\sqrt{s} = 5.44$ TeV (squares) and Pb–Pb collisions at $\sqrt{s} = 5.02$ TeV (diamonds) for nine centrality classes (top) and their ratios (bottom). The vertical brackets indicate systematic uncertainties. The hashed areas show results from hydrodynamical calculations [42].

5 Summary

Transverse momentum spectra and nuclear modification factors of charged particles in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV in the kinematic range $0.15 < p_T < 50$ GeV/c and $|\eta| < 0.8$ are reported for nine centrality classes, in the 0–80% range. A pp reference at $\sqrt{s} = 5.44$ TeV is obtained by the interpolation of the existing spectra at $\sqrt{s} = 5.02$ and 7 TeV. When comparing nuclear modification factors at similar ranges of averaged charged particle multiplicity densities, a remarkable similarity between central Xe–Xe collisions and Pb–Pb collisions at a similar center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV and at 2.76 TeV is observed. The comparison of the measured R_{AA} values in the two colliding systems could provide insight on the path length dependence of medium-induced parton energy loss. The observed scaling of the nuclear modification factor with the charged particle multiplicity density still holds at $\langle dN_{ch}/d\eta \rangle < 400$ within rather large uncertainties. The centrality dependence of the ratio of the average transverse momentum $\langle p_T \rangle$ in Xe–Xe collisions over Pb–Pb collisions is flat within uncertainties but allows for relative variations of up to two precent. Predictions from hydrodynamical calculations that take into account the significantly different geometries of both collision systems are consistent with the data.

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