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Measurement of transverse energy at midrapidity in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV

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Abstract

We report the transverse energy ($E_{\rm T}$) measured with ALICE at midrapidity in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV as a function of centrality. The transverse energy was measured using identified single particle tracks. The measurement was cross checked using the electromagnetic calorimeters and the transverse momentum distributions of identified particles previously reported by ALICE. The results are compared to theoretical models as well as to results from other experiments. The mean $E_{\rm T}$ per unit pseudorapidity (η), $\langle {\rm d}E_{\rm T}/{\rm d}\eta \rangle$, in 0–5% central collisions is 1737 $\pm$ 6(stat.) $\pm$ 97 (sys.) GeV. We find a similar centrality dependence of the shape of $\langle {\rm d}E_{\rm T}/{\rm d}\eta \rangle$ as a function of the number of participating nucleons to that seen at lower energies. The growth in $\langle {\rm d}E_{\rm T}/{\rm d}\eta \rangle$ at the LHC $\sqrt{s_{\rm NN}}$ exceeds extrapolations of low energy data. We observe a nearly linear scaling of $\langle {\rm d}E_{\rm T}/{\rm d}\eta \rangle$ with the number of quark participants. With the canonical assumption of a 1 fm/c formation time, we estimate that the energy density in 0–5% central Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV is 12.3 $\pm$ 1.0 GeV/fm^3 and that the energy density at the most central 80 fm^2 of the collision is at least 21.5 $\pm$ 1.7 GeV/fm^3. This is roughly 2.3 times that observed in 0–5% central Au–Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV.

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[*] See Appendix A for the list of collaboration members

1 Introduction

Quantum Chromodynamics (QCD) predicts a phase transition of nuclear matter to a plasma of quarks and gluons at energy densities above about 0.2-1 GeV/fm^3 [1, 2]. This matter, called Quark–Gluon Plasma (QGP), is produced in high energy nuclear collisions [3–13] and its properties are being investigated at the Super Proton Synchrotron (SPS), the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). The highest energy densities are achieved at the LHC in Pb–Pb collisions.

The mean transverse energy per unit pseudorapidity $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle$ conveys information about how much of the initial longitudinal energy carried by the incoming nuclei is converted into energy carried by the particles produced transverse to the beam axis. The transverse energy at midrapidity is therefore a measure of the stopping power of nuclear matter. By using simple geometric considerations [14] $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle$ can provide information on the energy densities attained. Studies of the centrality and $\sqrt{s_{\mathrm{NN}}}$ dependence of $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle$ therefore provide insight into the conditions prior to thermal and chemical equilibrium.

The $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle$ has been measured at the AGS by E802 [15] and E814/E877 [16], at the SPS by NA34 [17], NA35 [18], NA49 [19], and WA80/93/98 [20, 21], at RHIC by PHENIX [22–24] and STAR [25], and at the LHC by CMS [26], covering nearly three orders of magnitude of $\sqrt{s_{\mathrm{NN}}}$. The centrality dependence has also been studied extensively with $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle$ at midrapidity scaling nearly linearly with the collision volume, or equivalently, the number of participating nucleons at lower energies [20, 27, 28]. Further studies of heavy-ion collisions revealed deviations from this simple participant scaling law [21]. The causes of this deviation from linearity are still actively discussed and might be related to effects from minijets [29, 30] or constituent quark scaling [31, 32].

The ALICE detector [33] has precision tracking detectors and electromagnetic calorimeters, enabling several different methods for measuring E_{T}. In this paper we discuss measurements of $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle$ in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV using the tracking detectors alone and using the combined information from the tracking detectors and the electromagnetic calorimeters. In addition we compare to calculations of $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle$ from the measured identified particle transverse momentum distributions. Measurements from the tracking detectors alone provide the highest precision. We compare our results to theoretical calculations and measurements at lower energies.

2 Experiment

A comprehensive description of the ALICE detector can be found in [33]. This analysis uses the V0, Zero Degree Calorimeters (ZDCs), the Inner Tracking System (ITS), the Time Projection Chamber (TPC), the ElectroMagnetic Calorimeter (EMCal), and the PHOton Spectrometer (PHOS), all of which are located inside a 0.5 T solenoidal magnetic field. The V0 detector [34] consists of two scintillator hodoscopes covering the pseudorapidity ranges $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$. The ZDCs each consist of a neutron calorimeter between the beam pipes downstream of the dipole magnet and a proton calorimeter external to the outgoing beam pipe.

The TPC [35], the main tracking detector at midrapidity, is a cylindrical drift detector filled with a Ne–CO$_2$ gas mixture. The active volume is nearly 90 m^3 and has inner and outer radii of 0.848 m and 2.466 m, respectively. It provides particle identification via the measurement of the specific ionization energy loss ($\mathrm{d}E/\mathrm{d}x$) with a resolution of 5.2% and 6.5% in peripheral and central collisions, respectively.

The ITS [33] consists of the Silicon Pixel Detector with layers at radii of 3.9 cm and 7.6 cm, the Silicon Drift Detector with layers at radii of 15.0 cm and 23.9 cm, and the Silicon Strip Detector with layers at radii of 38.0 and 43.0 cm. The TPC and ITS are aligned to within a few hundred μm using cosmic ray and pp collision data [36].

The EMCal [37, 38] is a lead/scintillator sampling calorimeter covering $|\eta| < 0.7$ in pseudorapidity and 100° in azimuth in 2011. The EMCal consists of 11520 towers, each with transverse size 6 cm × 6 cm, or approximately twice the effective Molière radius. The relative energy resolution is $\sqrt{0.11^2/E + 0.017^2}$ where the energy E is measured in GeV [37]. Clusters are formed by combining signals from adjacent towers. Each cluster is required to have only one local energy maximum. Noise is suppressed by requiring a minimum tower energy of 0.05 GeV. For this analysis we use clusters within $|\eta| < 0.6$. The PHOS [39] is a lead tungstate calorimeter covering $|\eta| < 0.12$ in pseudorapidity and 60° in azimuth. The PHOS consists of three modules of 64 × 56 towers each, with each tower having a transverse size of 2.2 cm × 2.2 cm, comparable to the Molière radius. The relative energy resolution is $\sqrt{0.013^2/E^2 + 0.036^2/E + 0.01^2}$ where the energy E is measured in GeV [40].

The minimum-bias trigger for Pb–Pb collisions in 2010 was defined by a combination of hits in the V0 detector and the two innermost (pixel) layers of the ITS [8]. In 2011 the minimum-bias trigger signals in both neutron ZDCs were also required [41]. The collision centrality is determined by comparing the multiplicity measured in the V0 detector to Glauber model simulations of the multiplicity [8, 34]. These calculations are also used to determine the number of participating nucleons, $\langle N_{\rm part} \rangle$. We restrict our analysis to the 0–80% most central collisions. For these centralities corrections due to electromagnetic interactions and trigger inefficiencies are negligible. We use data from approximately 70k 0-80% central events taken in 2011 for the tracking detector and EMCal measurements and data from approximately 600k 0-80% central events taken in 2010 for the PHOS measurement. We focus on a small event sample where the detector performance was uniform in order to simplify efficiency corrections since the measurement is dominated by systematic uncertainties.

Tracks are reconstructed using both the TPC and the ITS. Tracks are selected by requiring that they cross at least 70 rows and requiring a χ^2 per space point < 4. Tracks are restricted to $|\eta| < 0.6$. Each track is required to have at least one hit in one of the two innermost ITS layers and a small distance of closest approach (DCA) to the primary vertex in the xy plane as a function of transverse momentum ($p_{\rm T}$), defined by $\mathrm{DCA_{xy}} < (0.0182+0.035/\ p_{\rm T}^{1.01})$ cm where $p_{\rm T}$ is in GeV/c. The distance of closest approach in the z direction is restricted to $\mathrm{DCA_z} < 2$ cm. This reduces the contribution from secondary particles from weak decays, which appear as a background. With these selection criteria tracks with transverse momenta $p_{\rm T} > 150$ MeV/c can be reconstructed. The typical momentum resolution for low momentum tracks, which dominate $E_{\rm T}$ measurements, is $\Delta p_{\rm T}/p_{\rm T} \approx 1\%$. The reconstruction efficiency varies with $p_{\rm T}$ and ranges from about 50% to 75% [41].

Particles are identified through their specific energy loss, dE/dx, in the TPC when possible. The dE/dx is calculated using a truncated-mean procedure and compared to the dE/dx expected for a given particle species using a Bethe-Bloch parametrization. The deviation from the expected dE/dx value is expressed in units of the energy-loss resolution σ [42]. Tracks are identified as arising from a kaon if they are within 3σ from the expected dE/dx for a kaon, more than 3σ from the expected dE/dx for a proton or a pion, and have $p_{\rm T} < 0.45$ GeV/c. Tracks are identified as arising from (anti)protons if they are within 3σ from the expected dE/dx for (anti)protons, more than 3σ from the expected dE/dx for kaons or pions, and have $p_{\rm T} < 0.9$ GeV/c. Tracks are identified as arising from an electron (positron) and therefore excluded from the measurement of $E_{\rm T}^{\pi,{\rm K,p}}$ if they are within 2σ from the expected dE/dx for an electron (positron), more than 4σ from the expected dE/dx for a pion, and more than 3σ from the expected dE/dx for a proton or kaon. With this algorithm approximately 0.1% of tracks arise from electrons or positrons misidentified as arising from pions and fewer than 0.1% of tracks are misidentified as arising from kaons or protons. Any track not identified as a kaon or proton is assumed to arise from a pion and the measurement must be corrected for the error in this assumption.

The PHOS and EMCal are used to measure the electromagnetic energy component of the $E_{\rm T}$ and to demonstrate consistency between methods. Data from 2011 were used for the EMCal analysis due to the larger EMCal acceptance in 2011. Data from one run in 2010 were used for the PHOS due to better detector performance and understanding of the calibrations in that run period. The EMCal has a larger acceptance, but the PHOS has a better energy resolution. There is also a lower material budget in front of the PHOS than the EMCal. This provides an additional check on the accuracy of the measurement.

3 Method

Historically most E_T measurements have been performed using calorimeters, and the commonly accepted operational definition of E_T is therefore based on the energy E_j measured in the calorimeter's jth tower

$$E_\mathrm{T} = \sum_{\mathrm{j}=1}^{\mathrm{M}} E_\mathrm{j} \sin\theta_\mathrm{j} \tag{1}$$

where j runs over all M towers in the calorimeter and θ_j is the polar angle of the calorimeter tower. The transverse energy can also be calculated using single particle tracks. In that case, the index, j, in Eq. 1 runs over the M measured particles instead of calorimeter towers, and θ_j is the particle emission angle. In order to be compatible with the E_T of a calorimetry measurement, the energy E_j of Eq. 1 must be replaced with the single particle energies

$$E_\mathrm{j} = \begin{cases} E_\mathrm{kin} & \text{for baryons} \\ E_\mathrm{kin} + 2mc^2 & \text{for anti-baryons} \\ E_\mathrm{kin} + mc^2 & \text{for all other particles.} \end{cases} \tag{2}$$

This definition of E_T was used in the measurements of the transverse energy by CMS [26] (based on calorimetry), PHENIX [22] (based on electromagnetic calorimetry), and STAR [25] (based on a combination of electromagnetic calorimetry and charged particle tracking). To facilitate comparison between the various data sets the definition of E_T given by Eqs. 1 and 2 is used here.

It is useful to classify particles by how they interact with the detector. We define the following categories of final state particles:

A $\pi^\pm$, $\mathrm{K}^\pm$, p, and $\overline{\mathrm{p}}$: Charged particles measured with high efficiency by tracking detectors

B π^0, ω, η, $\mathrm{e}^\pm$, and γ: Particles measured with high efficiency by electromagnetic calorimeters

C Λ, $\overline{\Lambda}$, K^0_S, Σ^+, Σ^-, and Σ^0: Particles measured with low efficiency in tracking detectors and electromagnetic calorimeters

D K^0_L, n, and $\overline{\mathrm{n}}$: Neutral particles not measured well by either tracking detectors or electromagnetic calorimeters.

The total E_T is the sum of the E_T observed in final state particles in categories A-D. Contributions from all other particles are negligible. In HIJING 1.383 [43] simulations of Pb–Pb collisions at $\sqrt{s_\mathrm{NN}}$ = 2.76 TeV the next largest contributions come from the $\Xi(\overline{\Xi})$ and $\Omega(\overline{\Omega})$ baryons with a total contribution of about 0.4% of the total E_T, much less than the systematic uncertainty on the final value of E_T. The E_T from unstable particles with $c\tau < 1$ cm is taken into account through the E_T from their decay particles.

When measuring E_T using tracking detectors, the primary measurement is of particles in category A and corrections must be applied to take into account the E_T which is not observed from particles in categories B-D. In the hybrid method the E_T from particles in category A is measured using tracking detectors and the E_T from particles in category B is measured by the electromagnetic calorimeter. An electromagnetic calorimeter has the highest efficiency for measuring particles in category B, although there is a substantial background from particles in category A. The E_T from categories C and D, which is not well measured by an electromagnetic calorimeter, must be corrected for on average. Following the convention used by STAR, we define $E_{\mathrm{T}}^{\mathrm{had}}$ to be the E_{T} measured from particles in category A and scaled up to include particles in categories C and D and $E_{\mathrm{T}}^{\mathrm{em}}$ to be the E_{T} measured in category B. The total E_{T} is given by

$$E_{\mathrm{T}} = E_{\mathrm{T}}^{\mathrm{had}} + E_{\mathrm{T}}^{\mathrm{em}}. \tag{3}$$

We refer to $E_{\mathrm{T}}^{\mathrm{had}}$ as the hadronic E_{T} and $E_{\mathrm{T}}^{\mathrm{em}}$ as the electromagnetic E_{T}. We note that $E_{\mathrm{T}}^{\mathrm{had}}$ and $E_{\mathrm{T}}^{\mathrm{em}}$ are operational definitions based on the best way to observe the energy deposited in various detectors and that the distinction is not theoretically meaningful.

Several corrections are calculated using HIJING [43] simulations. The propagation of final state particles in these simulations through the ALICE detector material is described using GEANT 3 [44]. Throughout the paper these are described as HIJING+GEANT simulations.

3.1 Tracking detector measurements of E_{T}

The measurements of the total E_{T} using the tracking detectors and of the hadronic E_{T} are closely correlated because the direct measurement in both cases is $E_{\mathrm{T}}^{\pi,\mathrm{K,p}}$, the E_{T} from $\pi^{\pm}$, $\mathrm{K}^{\pm}$, p, and $\overline{\mathrm{p}}$ from the primary vertex. All contributions from other categories are treated as background. For $E_{\mathrm{T}}^{\mathrm{had}}$ the E_{T} from categories C and D is corrected for on average and for the total E_{T} the contribution from categories B, C, and D is corrected for on average. Each of these contributions is taken into account with a correction factor.

The relationship between the measured track momenta and $E_{\mathrm{T}}^{\pi,\mathrm{K,p}}$ is given by

$$\frac{\mathrm{d}E_{\mathrm{T}}^{\pi,\mathrm{K,p}}}{\mathrm{d}\eta} = \frac{1}{\Delta\eta}\frac{1}{f_{p_{\mathrm{T}}\mathrm{cut}}}\frac{1}{f_{\mathrm{notID}}}\sum_{\mathrm{i}=1}^{\mathrm{n}}\frac{f_{\mathrm{bg}}(p_{\mathrm{T}}^{\mathrm{i}})}{\varepsilon(p_{\mathrm{T}}^{\mathrm{i}})}E_{\mathrm{i}}\sin\theta_{\mathrm{i}} \tag{4}$$

where i runs over the n reconstructed tracks and $\Delta\eta$ is the pseudorapidity range used in the analysis, $\varepsilon(p_{\mathrm{T}})$ corrects for the finite track reconstruction efficiency and acceptance, $f_{\mathrm{bg}}(p_{\mathrm{T}})$ corrects for the Λ, $\overline{\Lambda}$, and $\mathrm{K}_{\mathrm{S}}^{0}$ daughters and electrons that pass the primary track quality cuts, f_{notID} corrects for particles that could not be identified unambiguously through their specific energy loss $\mathrm{d}E/\mathrm{d}x$ in the TPC, and $f_{p_{\mathrm{Tcut}}}$ corrects for the finite detector acceptance at low momentum. Hadronic E_{T} is given by $E_{\mathrm{T}}^{\mathrm{had}}$ = $E_{\mathrm{T}}^{\pi,\mathrm{K,p}}/f_{\mathrm{neutral}}$ where f_{neutral} is the fraction of $E_{\mathrm{T}}^{\mathrm{had}}$ from $\pi^{\pm}$, $\mathrm{K}^{\pm}$, p, and $\overline{\mathrm{p}}$ and total E_{T} is given by E_{T} = $E_{\mathrm{T}}^{\pi,\mathrm{K,p}}/f_{\mathrm{total}}$ where f_{total} is the fraction of E_{T} from $\pi^{\pm}$, $\mathrm{K}^{\pm}$, p, and $\overline{\mathrm{p}}$. The determination of each of these corrections is given below and the systematic uncertainties are summarized in Tab. 1. Systematic uncertainties are correlated point to point.

3.1.1 *Single track efficiency×acceptance* $\varepsilon(\mathbf{p}_{\mathrm{T}})$

The single track efficiency×acceptance is determined by comparing the primary yields to the reconstructed yields using HIJING+GEANT simulations, as described in [45]. When a particle can be identified as a $\pi^{\pm}$, $\mathrm{K}^{\pm}$, p, or $\overline{\mathrm{p}}$ using the algorithm described above, the efficiency for that particle is used. Otherwise the particle-averaged efficiency is used. The 5% systematic uncertainty is determined by the difference between the fraction of TPC standalone tracks matched with a hit in the ITS in simulations and data.

3.1.2 *Background* $f_{\mathrm{bg}}(\mathbf{p}_{\mathrm{T}})$

The background comes from photons which convert to $e^{+}e^{-}$ in the detector and decay daughters from Λ, $\overline{\Lambda}$, and $\mathrm{K}_{\mathrm{S}}^{0}$ which are observed in the tracking detectors but do not originate from primary $\pi^{\pm}$, $\mathrm{K}^{\pm}$, p, and $\overline{\mathrm{p}}$. This is determined from HIJING+GEANT simulations. The systematic uncertainty on the background due to conversion electrons is determined by varying the material budget in the HIJING+GEANT simulations by ±10% and found to be negligible compared to other systematic uncertainties. The systematic uncertainty due to Λ, $\overline{\Lambda}$, and $\mathrm{K}_{\mathrm{S}}^{0}$ daughters is sensitive to both the yield and the shape of the Λ, $\overline{\Lambda}$, and $\mathrm{K}_{\mathrm{S}}^{0}$

spectra. To determine the contribution from Λ, $\overline{\Lambda}$, and K^0_S decay daughters and its systematic uncertainty the spectra in simulation are reweighted to match the data and the yields are varied within their uncertainties [46]. Because the centrality dependence is less than the uncertainty due to other corrections, a constant correction of 0.982 ± 0.008 is applied across all centralities .

3.1.3 *Particle identification* f_{notID}

The E_T of particles with $0.15 < p_T < 0.45$ GeV/c with a dE/dx within two standard deviations of the expected dE/dx for kaons is calculated using the kaon mass and the E_T of particles with $0.15 < p_T < 0.9$ GeV/c with a dE/dx within two standard deviations of the expected dE/dx for (anti)protons is calculated using the (anti)proton mass. The E_T of all other particles is calculated using the pion mass. Since the average transverse momentum is $\langle p_T \rangle$ = 0.678 ± 0.007 GeV/c for charged particles [47] and over 80% of the particles created in the collision are pions [42], most particles can be identified correctly using this algorithm. At high momentum, the difference between the true E_T and the E_T calculated using the pion mass hypothesis for kaons and protons is less than at low p_T. This is therefore a small correction. Assuming that all kaons with $0.15 < p_T < 0.45$ GeV/c and (anti)protons with $0.15 < p_T < 0.9$ GeV/c are identified correctly and using the identifed $\pi^\pm$, $K^\pm$, p, and $\overline{\mathrm{p}}$ spectra [42] gives f_{notID} = 0.992 ± 0.002. The systematic uncertainty is determined from the uncertainties on the yields.

Assuming that 5% of kaons and protons identified using the particle identification algorithm described above are misidentified as pions only decreases f_{notID} by 0.0002, less than the systematic uncertainty on f_{notID}. This indicates that this correction is robust to changes in the mean dE/dx expected for a given particle and its standard deviation. We note that either assuming no particle identification or doubling the number of kaons and protons only decreases f_{notID} by 0.005.

3.1.4 *Low* $\mathbf{p}_T$ *acceptance* $f_{p_{\mathrm{Tcut}}}$

The lower momentum acceptance of the tracking detectors is primarily driven by the magnetic field and the inner radius of the active volume of the detector. Tracks can be reliably reconstructed in the TPC for particles with $p_T > 150$ MeV/c. The fraction of E_T carried by particles below this momentum cut-off is determined by HIJING+GEANT simulations. To calculate the systematic uncertainty we follow the prescription given by STAR [25]. The fraction of E_T contained in particles below 150 MeV/c is calculated assuming that all particles below this cut-off have a momentum of exactly 150 MeV/c to determine an upper bound, assuming that they have a momentum of 0 MeV/c to determine a lower bound, and using the average as the nominal value. Using this prescription, $f_{p_{\mathrm{Tcut}}}$ = 0.9710 ± 0.0058. We note that $f_{p_{\mathrm{Tcut}}}$ is the same within systematic uncertainties when calculated from PYTHIA simulations [48] for pp collisions with $\sqrt{s}$ = 0.9 and 8 TeV, indicating that this is a robust quantity.

3.1.5 *Correction factors* f_{neutral} *and* f_{total}

Under the assumption that the different states within an isospin multiplet and particles and antiparticles have the same E_T, f_{neutral} can be written as

$$f_{\mathrm{neutral}} = \frac{2E_T^{\pi} + 2E_T^{K} + 2E_T^{p}}{3E_T^{\pi} + 4E_T^{K} + 4E_T^{p} + 2E_T^{\Lambda} + 6E_T^{\Sigma}} \tag{5}$$

and f_{total} can be written as

$$f_{\mathrm{total}} = \frac{2E_T^{\pi} + 2E_T^{K} + 2E_T^{p}}{3E_T^{\pi} + 4E_T^{K} + 4E_T^{p} + 2E_T^{\Lambda} + 6E_T^{\Sigma} + E_T^{\omega,\eta,e^\pm,\gamma}}. \tag{6}$$

where E_T^K is the E_T from one kaon species, E_T^π is the E_T from one pion species, E_T^p is the average of the E_T from protons and antiprotons, E_T^Λ is the average E_T from Λ and $\overline{\Lambda}$, and E_T^Σ is the average E_T from Σ^+,

Σ^-, and Σ^0 and their antiparticles. The contributions E_T^{π}, E_T^{K}, E_T^{p}, and E_T^{Λ} are calculated from the particle spectra measured by ALICE [42, 46] as for the calculation of E_T from the particle spectra. The systematic uncertainties are also propagated assuming that the systematic uncertainties from different charges of the same particle species (e.g., π^+ and π^-) are 100% correlated and from different species (e.g., π^+ and K^+) are uncorrelated. The contribution from the Σ^+, Σ^-, and Σ^0 and their antiparticles is determined from the measured Λ spectra. The total contribution from Σ species and their antiparticles should be approximately equal to that of the Λ and $\overline{\Lambda}$, but since there are three isospin states for the Σ, each species carries roughly 1/3 of the E_T that the Λ carries. Since the Σ^0 decays dominantly through a Λ and has a short lifetime, the measured Λ spectra include Λ from the Σ^0 decay. The ratio of $F = (E_T^{\Sigma^+} + E_T^{\Sigma^-})/E_T^{\Lambda}$ is therefore expected to be 0.5. HIJING [43] simulations indicate that $F = 0.67$ and if the E_T scales with the yield, THERMUS [49] indicates that $F = 0.532$. We therefore use $F = 0.585 \pm 0.085$.

The contribution $E_T^{\omega,\eta,e^{\pm},\gamma}$ is calculated using transverse mass scaling for the η meson and PYTHIA simulations for the ω, $e^{\pm}$, and γ, as described earlier. Because most of the E_T is carried by $\pi^{\pm}$, $K^{\pm}$, p, $\overline{\text{p}}$, n, and $\overline{\text{n}}$, whose contributions appear in both the numerator and the denominator, f_{total} and f_{neutral} can be determined to high precision, and the uncertainty in f_{total} and f_{neutral} is driven by E_T^{Λ} and $E_T^{\omega,\eta,e^{\pm},\gamma}$. It is worth considering two special cases. If all E_T were carried by pions, as is the case at low energy where almost exclusively pions are produced, Eq. 6 would simplify to $f_{\text{total}} = 2/3$. If all E_T were only carried by kaons, (anti)protons, and (anti)neutrons, Eq. 6 would simplify to $f_{\text{total}} = 1/2$.

In order to calculate the contribution from the η meson and its uncertainties, we assume that the shapes of its spectra for all centrality bins as a function of transverse mass are the same as the pion spectra, using the transverse mass scaling [50], and that the η/π ratio is independent of the collision system, as observed by PHENIX [51]. We also consider a scenario where the η spectrum is assumed to have the same shape as the kaon spectrum, as would be expected if the shape of the η spectrum was determined by hydrodynamical flow. In this case we use the ALICE measurements of η/π in pp collisions [52] to determine the relative yields. We use the η/π ratio at the lowest momentum point available, $p_T = 0.5$ GeV/c, because the E_T measurement is dominated by low momentum particles. Because no ω measurement exists, PYTHIA [48] simulations of pp collisions were used to determine the relative contribution from the ω and from all other particles which interact electromagnetically (mainly γ and $e^{\pm}$). These contributions were approximately 2% and 1% of E_T^{π}, respectively. With these assumptions, $E_T^{\omega,\eta,e^{\pm},\gamma}/E_T^{\pi} = 0.17 \pm 0.11$. The systematic uncertainty on this fraction is dominated by the uncertainty in the η/π ratio. We propagate the uncertainties assuming that the E_T from the same particle species are 100% correlated and that the uncertainties from different particle species are uncorrelated.

The f_{neutral}, f_{total}, and $f_{\text{em}} = 1 - f_{\text{total}}/f_{\text{neutral}}$ are shown in Fig. 1 along with the fractions of E_T carried by all pions f_{π}, all kaons f_K, protons and antiprotons f_p, and Λ baryons f_{Λ} versus $\langle N_{\text{part}} \rangle$. While there is a slight dependence of the central value on $\langle N_{\text{part}} \rangle$, this variation is less than the systematic uncertainty. Since there is little centrality dependence, we use $f_{\text{em}} = 0.240 \pm 0.027$, $f_{\text{neutral}} = 0.728 \pm 0.017$, and $f_{\text{total}} = 0.553 \pm 0.010$, which encompass the entire range for all centralities. The systematic uncertainty is largely driven by the contribution from Λ, ω, η, $e^{\pm}$, and γ since these particles only appear in the denominator of Eqs. 5 and 6. The systematic uncertainty on f_{total} is smaller than that on f_{neutral} because f_{neutral} only has E_T^{Λ} in the denominator.

These results are independently interesting. The fraction of energy carried by different species does not change significantly with centrality. Additionally, only about 1/4 of the energy is in E_T^{em}, much less than the roughly 1/3 of energy in E_T^{em} at lower energies where most particles produced are pions with the π^0 carrying approximately 1/3 of the energy in the collision. Furthermore, only about 3.5% of the E_T is carried by ω, η, $e^{\pm}$, and γ. Since charged and neutral pions have comparable spectra, this means that the tracking detectors are highly effective for measuring the transverse energy distribution in nuclear collisions.

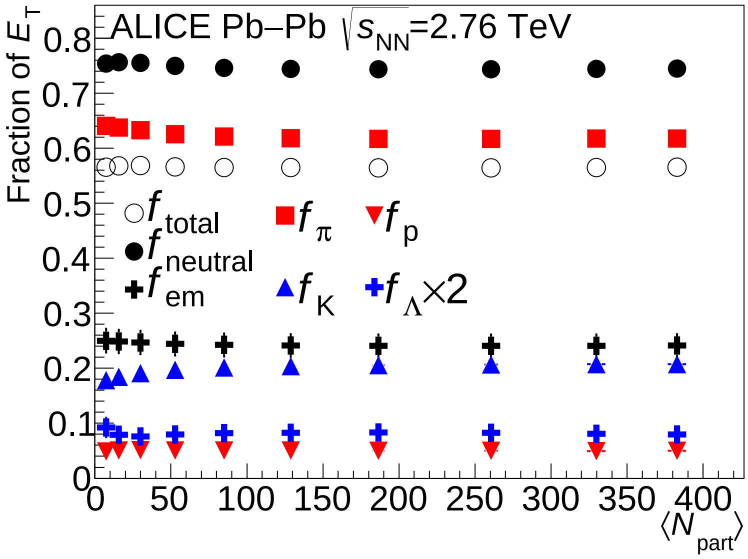

Fig. 1: Fraction of the total E_T in pions (f_π), kaons (f_K), p and $\overline{p}$ (f_p), and Λ (f_Λ) and the correction factors f_{total}, $f_{neutral}$, and f_{em} as a function of $\langle N_{part}\rangle$. The fraction f_Λ is scaled by a factor of two so that the data do not overlap with those from protons. Note that $f_{neutral}$ is the fraction of E_T^{had} measured in the tracking detectors while f_{total} and f_{em} are the fractions of the total E_T measured in the tracking detectors and the calorimeters, respectively. The vertical error bars give the uncertainty on the fraction of E_T from the particle yields.

Correction	Value	% Rel. uncertainty
$f_{p_{Tcut}}$	0.9710 ± 0.0058	0.6 %
$f_{neutral}$	0.728 ± 0.017	2.3 %
f_{total}	0.553 ± 0.010	3.0 %
f_{notID}	0.982 ± 0.002	0.2 %
$f_{bg}(p_T)$	1.8%	0.8%
$\varepsilon(p_T)$	50%	5%

Table 1: Summary of corrections and systematic uncertainties for E_T^{had} and E_T from tracking detectors. For centrality and p_T independent corrections the correction is listed. For centrality and p_T dependent corrections, the approximate percentage of the correction is listed. In addition, the anchor point uncertainty in the Glauber calculations leads to an uncertainty of 0–4%, increasing with centrality.

3.1.6 E_T^{had} distributions

Figure 2 shows the distributions of the reconstructed E_T^{had} measured from $\pi^\pm$, $K^\pm$, p, and $\overline{p}$ tracks using the method described above for several centralities. No correction was done for the resolution leaving these distributions dominated by resolution effects. The mean E_T^{had} is determined from the average of the distribution of E_T^{had} in each centrality class.

3.2 Calculation of E_T and E_T^{had} from measured spectra

We use the transverse momentum distributions (spectra) measured by ALICE [42, 46] to calculate E_T and E_T^{had} as a cross check. We assume that all charge signs and isospin states of each particle carry the same E_T, e.g. $E_T^{\pi^+} = E_T^{\pi^-} = E_T^{\pi^0}$, and that the E_T carried by (anti)neutrons equals the E_T carried by (anti)protons. These assumptions are consistent with the data at high energies where positively and negatively charged hadrons are produced at similar rates and the anti-baryon to baryon ratio is close to

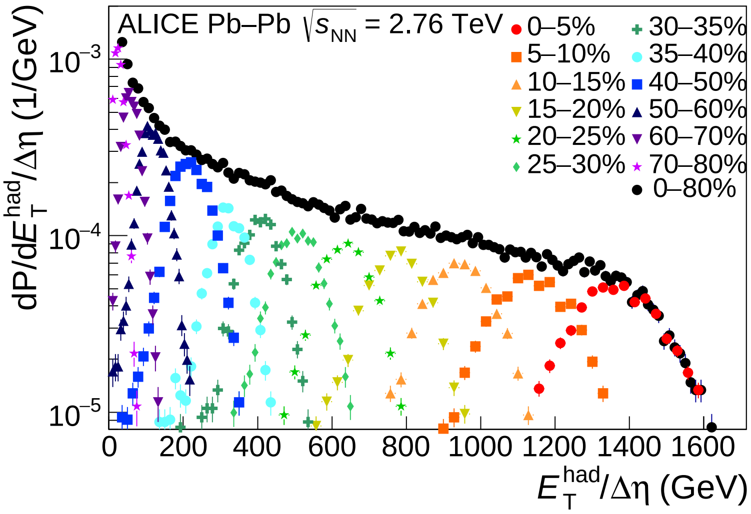

Fig. 2: Distribution of E_T^{had} measured from $\pi^{\pm}$, $K^{\pm}$, p, and $\overline{p}$ tracks at midrapidity for several centrality classes. Not corrected for resolution effects. Only statistical error bars are shown.

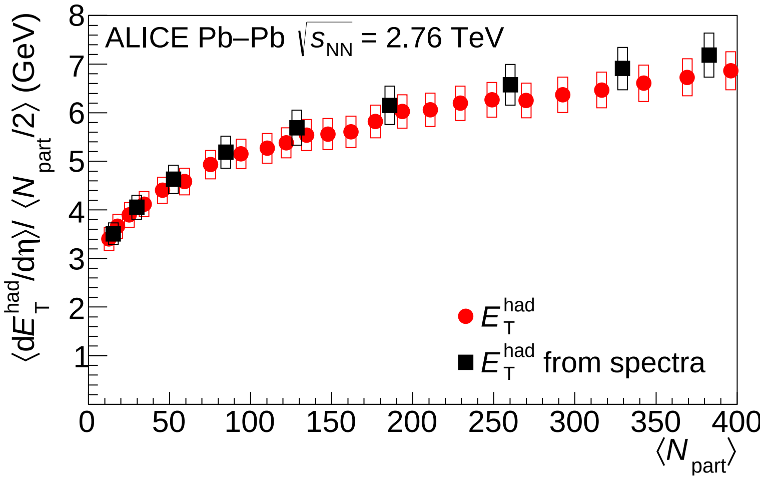

Fig. 3: Comparison of $\langle dE_T^{had}/d\eta\rangle/(\langle N_{part}/2\rangle)$ versus $\langle N_{part}\rangle$ from the measured particle spectra and as calculated from the tracking detectors. The boxes indicate the systematic uncertainties.

one [53, 54]. Since the Λ spectra [46] are only measured for five centrality bins, the Λ contribution is interpolated from the neighboring centrality bins. The same assumptions about the contributions of the η, ω, γ, and $e^{\pm}$ described in the section on f_{total} and $f_{neutral}$ are used for these calculations. The dominant systematic uncertainty on these measurements is due to the single track reconstruction efficiency and is correlated point to point. The systematic uncertainty on these calculations is not correlated with the calculations of E_T using the tracking detectors because these measurements are from data collected in different years. The mean E_T^{had} per $\langle N_{part}/2\rangle$ obtained from the tracking results of Fig. 2 are shown as a function of $\langle N_{part}\rangle$ in Fig. 3, where they are compared with results calculated using the particle spectra measured by ALICE. The two methods give consistent results. Data are plotted in 2.5% wide bins in centrality for 0–40% central collisions, where the uncertainty on the centrality is <1% [55]. Data for 40–80% central collisions are plotted in 5% wide bins.

3.3 Electromagnetic calorimeter measurements of $E_{\mathrm{T}}^{\mathrm{em}}$

The $E_{\mathrm{T}}^{\mathrm{em}}$ is defined as the transverse energy of the particles of category B discussed above, which are the particles measured well by an electromagnetic calorimeter. While the definition of $E_{\mathrm{T}}^{\mathrm{em}}$ includes π^0, ω, η, $\mathrm{e}^{\pm}$, and γ, the majority of the E_{T} comes from $\pi^0 \to \gamma\gamma$ (85%) and $\eta \to \gamma\gamma$ (12%) decays, meaning that the vast majority of $E_{\mathrm{T}}^{\mathrm{em}}$ arises from photons reaching the active area of the electromagnetic calorimeters. Reconstructed clusters are used for the analysis, with most clusters arising from a single γ. Clusters reduce contributions from detector noise to a negligible level, as compared to using tower energies as done by STAR [25]. However, clusters also require additional corrections for the reconstruction efficiency, nonlinearity, and minimum energy reconstructed. In addition, both the EMCal and the PHOS have limited nominal acceptances so an acceptance correction must be applied. Backgrounds come from charged hadrons in category A ($\pi^{\pm}$, $\mathrm{K}^{\pm}$, p, and $\overline{\mathrm{p}}$), kaon decays into π^0 from both category A ($\mathrm{K}^{\pm}$) and category C (K_{S}^0), neutrons from category D, and particles produced by secondary interactions with the detector material.

The corrected $E_{\mathrm{T}}^{\mathrm{em}}$ is given by

$$\frac{\mathrm{d}E_{\mathrm{T}}^{\mathrm{em}}}{\mathrm{d}\eta} = \frac{1}{\Delta\eta}\frac{1}{f_{\mathrm{acc}}}\frac{1}{f_{E_{\mathrm{Tmin}}}}\left(\sum_{\mathrm{j}} \delta_{\mathrm{m}} \frac{\sin\theta_{\mathrm{j}}}{\varepsilon_{\gamma} f_{E_{\mathrm{NL}}}} E_{\mathrm{j}} \; - \; E_{\mathrm{T}}^{\mathrm{bkgd}}\right) \tag{7}$$

where j runs over the reconstructed clusters in the calorimeter and $\Delta\eta$ is the pseudorapidity range used in the analysis. The correction factor f_{acc} corrects for the finite nominal azimuthal detector acceptance, $f_{E_{\mathrm{Tmin}}}$ is a correction for the minimum cluster energy used in the analysis, δ_{m} is zero when a cluster is matched to a track and one otherwise, ε_{γ} is the product of the active acceptance and the reconstruction efficiency in the nominal acceptance of the detector, $f_{E_{\mathrm{NL}}}$ is the correction for the nonlinear response of the calorimeter, and $E_{\mathrm{T}}^{\mathrm{bkgd}}$ is the sum of the contributions from charged hadrons, kaons, neutrons, and particles created by secondary interactions. These correction factors are discussed below and their systematic uncertainties are summarized in Tab. 2. All of the systematic uncertainties except for that due to the background subtraction are correlated point to point. Systematic uncertainties on measurements of $E_{\mathrm{T}}^{\mathrm{em}}$ from the EMCal and the PHOS and calculations of $E_{\mathrm{T}}^{\mathrm{em}}$ from the spectra are not correlated. Systematic uncertainties on hybrid measurements are dominated by systematic uncertainties on $E_{\mathrm{T}}^{\mathrm{had}}$ and are therefore dominantly correlated point to point and with the tracking detector measurements.

3.3.1 *Acceptance correction* f_{acc} *and cluster reconstruction efficiency* ε_{γ}

The correction for the acceptance is divided into two parts, the correction due to the nominal acceptance of the detector and the correction due to limited acceptance within the nominal acceptance of the detector due to dead regions and edge effects. To reduce edge effects, clusters in the PHOS are restricted to $|\eta| < 0.1$ and in the EMCal to $|\eta| < 0.6$. The correction f_{acc} accounts for the limited nominal acceptance in azimuth and is therefore 5/18 for the EMCal, which has a nominal acceptance of 100°, and 1/6 for the PHOS, which has a nominal acceptance of 60°. It does not correct for acceptance effects due to dead regions in the detector or for noisy towers omitted from the analysis. This is accounted for by the cluster reconstruction efficiency×acceptance within the nominal detector acceptance, ε_{γ}, calculated from HIJING+GEANT simulations using photons from the decay of the π^0 meson. The efficiency is calculated as a function of the energy of the cluster.

3.3.2 *Minimum cluster energy* $\mathbf{f}_{\mathbf{E}_{\mathrm{Tmin}}}$

There is a minimum energy for usable clusters analogous to the minimum p_{T} in the acceptance of the tracking detectors. A threshold of 250 MeV for PHOS and 300 MeV for the EMCal is applied. These energies are above the peak energy for minimum ionizing particles (MIPs), reducing the background correction due to charged hadrons. We apply the threshold in E_{T} rather than energy because it simplifies the calculation of the correction for this threshold and its systematic uncertainty. We use the charged pion spectra to calculate the fraction of $E_{\mathrm{T}}^{\mathrm{em}}$ below these thresholds. PYTHIA is used to simulate the decay kinematics and the measured charged pion spectra are used to determine the fraction of E_{T} from pions within the acceptance. As for the calculation of f_{total} for the measurement of $E_{\mathrm{T}}^{\mathrm{had}}$ described above, we assume transverse mass scaling to determine the shape of the η spectrum and the η/π ratio measured by ALICE [52] to estimate the contribution of the η meson to $f_{E_{\mathrm{Tmin}}}$. The uncertainty on the shape of the charged pion spectrum and on the η/π ratio is used to determine the uncertainty on $f_{E_{\mathrm{Tmin}}}$. This correction is centrality dependent and ranges from 0.735 to 0.740 for the PHOS and from 0.640 to 0.673 for the EMCal with a systematic uncertainty of 3.5–5%.

3.3.3 *Nonlinearity correction* $\mathbf{f}_{\mathbf{E}_{\mathrm{NL}}}$ *and energy scale uncertainty*

For an ideal calorimeter the signal observed is proportional to the energy. In practice, however, there is a slight deviation from linearity in the signal observed, particularly at low energies. A nonlinearity correction is applied to take this into account. For the EMCal this deviation from linearity reaches a maximum of about 15% for the lowest energy clusters used in this analysis. The systematic uncertainty for the EMCal is determined by comparing the nonlinearity observed in test beam and the nonlinearity predicted by HIJING+GEANT simulations and reaches a maximum of about 5% for the lowest energy clusters. The PHOS nonlinearity is determined by comparing the location of the π^0 mass peak to HIJING+GEANT simulations and cross checked using the energy divided by the momentum for identified electrons. The systematic uncertainty is derived from the accuracy of the location of the π^0 mass peak. The nominal correction is about 1% with a maximum systematic uncertainty of around 3% for the lowest energy clusters. The raw $E_{\mathrm{T}}^{\mathrm{em}}$ is calculated with the maxima and minima of the nonlinearities and the difference from the nominal value is assigned as a systematic uncertainty. The final systematic uncertainty on the measurement with the EMCal due to nonlinearity is about 0.8% and 1.3% for the PHOS. For both the PHOS and the EMCal, the energy scale uncertainty was determined by comparing the location of the π^0 mass peak and the ratio of energy over momentum for electrons. This systematic uncertainty is 2% for the EMCal [56] and 0.5% for the PHOS [57].

3.3.4 *Background* $\mathbf{E}_{\mathrm{T}}^{\mathrm{bkgd}}$

Charged particles (category A) are the largest source of background in $E_{\mathrm{T}}^{\mathrm{em}}$. Clusters matched to tracks are omitted from the analysis. The track matching efficiency determined from HIJING+GEANT simulations is combined with information from clusters matched to tracks to calculate the number and mean energy of remaining deposits from charged particles. The systematic uncertainty on this contribution comes from the uncertainty on the track matching efficiency and the uncertainty in the mean energy. The former is dominated by the uncertainty on the single track reconstruction efficiency and the latter is determined by comparing central and peripheral collisions, assuming that the energy of clusters matched to tracks in central collisions may be skewed by overlapping clusters due to the high occupancy.

The background contributions from both charged kaons (category A) through their $\mathrm{K}^{\pm} \rightarrow \mathrm{X}\pi^0$ decays and K_{S}^0 (category C) through its $K_{\mathrm{S}}^0 \rightarrow \pi^0\,\pi^0$ decay are non-negligible. The amount of energy deposited by a kaon as a function of p_{T} is determined using HIJING+GEANT simulations. This is combined with the kaon spectra measured by ALICE [42] to calculate the energy deposited in the calorimeters by kaons. The systematic uncertainty on the background from kaons is determined by varying the yields within the uncertainties of the spectra. Contributions from both neutrons and particles from secondary interactions are determined using HIJING+GEANT simulations. The systematic uncertainty on these contributions is determined by assuming that they scale with either the number of tracks (as a proxy for the number of charged particles) or with the number of calorimeter clusters (as a proxy for the number of neutral particles).

The background contribution is centrality dependent and ranges from 61% to 73% with both the background and its systematic uncertainty dominated by contributions from charged hadrons. This correction

	PHOS		EMCal	
	Correction	Uncertainty	Correction	Uncertainty
f_{acc}	6	0	3.6	0
Energy scale	–	0.5%	–	2%
ε_γ	40%	5%	80%	5%
$f_{E_{\mathrm{Tmin}}}$	0.735 – 0.740	3.5%	0.64 – 0.673	4.1 – 5.0%
$f_{E_{\mathrm{NL}}}$	$< 0.5\%$	1.3%	$< 5\%$	0.8%
f_{bkgd}	0.616 – 0.753	9 – 20%	0.659 – 0.732	8 – 13%
$E_{\mathrm{T}}^{\mathrm{em}}$	–	10 – 20%	–	10 – 15%

Table 2: Summary of corrections and systematic uncertainties for $E_{\mathrm{T}}^{\mathrm{em}}$. The approximate size of the correction is listed for ε_γ and the ranges are listed for centrality dependent corrections. The fraction $f_{\mathrm{bkgd}} = E_{\mathrm{T}}^{\mathrm{bkgd}}/E_{\mathrm{T}}^{\mathrm{raw}}$ where $E_{\mathrm{T}}^{\mathrm{raw}} = \sum_{\mathrm{j}} \delta_{\mathrm{m}} \frac{\sin\theta_{\mathrm{j}}}{\varepsilon_\gamma f_{E_{\mathrm{NL}}}} E_{\mathrm{j}}$ is given in order to compare $E_{\mathrm{T}}^{\mathrm{bkgd}}$ across centralities. In addition, the anchor point uncertainty in the Glauber calculations leads to an uncertainty of 0–4%, increasing with centrality.

is so large because $E_{\mathrm{T}}^{\mathrm{em}}$ comprises only about 25% of the E_{T} in an event while $\pi^{\pm}$, $\mathrm{K}^{\pm}$, p, and $\overline{\mathrm{p}}$ carry roughly 57% of the E_{T} in an event.

3.3.5 Acceptance effects

The limited calorimeter acceptance distorts the distribution of $E_{\mathrm{T}}^{\mathrm{em}}$ for events with very low $E_{\mathrm{T}}^{\mathrm{em}}$ because it is difficult to measure the mean E_{T} when the mean number of clusters observed is small (about 1–10). While it is possible to correct for acceptance, this was not done since the measurement of E_{T} from the tracking method has the highest precision. The hybrid method using both the calorimeters and the tracking detectors is therefore restricted to the most central collisions where distortions of the $E_{\mathrm{T}}^{\mathrm{em}}$ distribution are negligible.

3.3.6 $E_{\mathrm{T}}^{\mathrm{em}}$ distributions

No resolution correction was applied for the resolution leaving the distributions in Fig. 4 and Fig. 5 dominated by resolution effects. The resolution is primarily determined by the finite acceptance of the detectors in azimuth, limiting the fraction of $E_{\mathrm{T}}^{\mathrm{em}}$ sampled by the calorimeter. The distributions are broader for PHOS than EMCal because of the smaller azimuthal acceptance of the PHOS. The mean $E_{\mathrm{T}}^{\mathrm{em}}$ is determined from the average of the distribution of $E_{\mathrm{T}}^{\mathrm{em}}$ in each centrality bin. The $E_{\mathrm{T}}^{\mathrm{em}}$ per $\langle N_{\mathrm{part}}\rangle$ pair measured using the electromagnetic calorimeters is compared to that calculated using the measured pion spectra in Fig. 6, demonstrating that these methods lead to comparable results. The $E_{\mathrm{T}}^{\mathrm{em}}$ calculated from the spectra is determined using the same ratio of $E_{\mathrm{T}}^{\omega,\eta,\mathrm{e}^{\pm},\gamma}/E_{\mathrm{T}}^{\pi} = 0.171 \pm 0.110$ for all centralities.

4 Results

The $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta\rangle/(\langle N_{\mathrm{part}}/2\rangle)$ versus $\langle N_{\mathrm{part}}\rangle$ is shown in Fig. 7 using tracking detectors, using EMCal+tracking, using PHOS+tracking, and as calculated from the measured particle spectra. All methods lead to comparable results, although the systematic errors are largely correlated due to the dominant correction from the tracking inefficiency. The Glauber calculations of $\langle N_{\mathrm{part}}\rangle$ and its uncertainties are calculated as in [55] and the uncertainties on $\langle N_{\mathrm{part}}\rangle$ are added in quadrature to the uncertainties on E_{T}. As discussed above, the small number of clusters observed in the calorimeters in peripheral collisions make acceptance corrections difficult. Since the measurements with the tracking detectors alone has higher precision, only these measurements are used in the following.

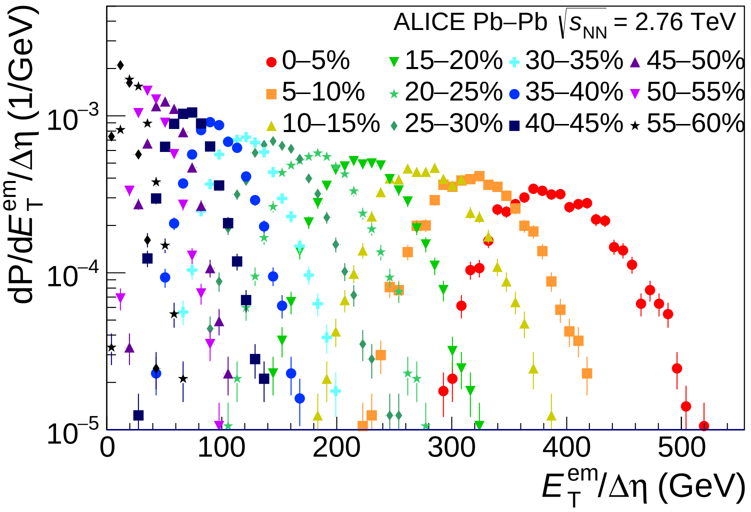

Fig. 4: Distribution of $E_{\mathrm{T}}^{\mathrm{em}}$ measured with the EMCal at midrapidity for several centrality bins. Not corrected for resolution effects. Only statistical error bars are shown.

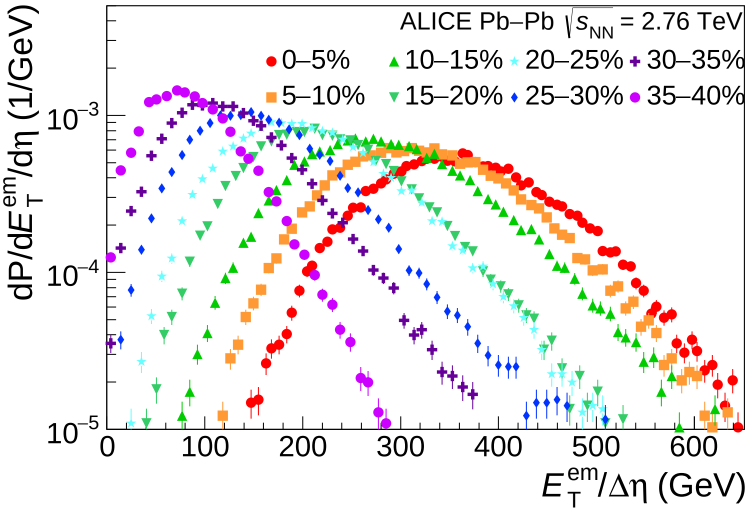

Fig. 5: Distribution of $E_{\mathrm{T}}^{\mathrm{em}}$ measured with the PHOS at midrapidity for several centrality bins. Not corrected for resolution effects. Only statistical error bars are shown.

Fig. 8 compares $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle/(\langle N_{\mathrm{part}}/2\rangle)$ versus $\langle N_{\mathrm{part}}\rangle$ in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV from CMS [26] and ALICE, and in Au–Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV from STAR [25] and PHENIX [22, 23]. Data from RHIC have been scaled by a factor of 2.7 for comparison of the shapes. The factor of 2.7 is approximately the ratio of $\langle p_{\mathrm{T}}\rangle\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ at the LHC [42] to that at RHIC [58, 59]. The shapes observed by ALICE and PHENIX are comparable for all $\langle N_{\mathrm{part}}\rangle$. STAR measurements are consistent with PHENIX measurements for the most central collisions and above the PHENIX measurements, although consistent within systematic uncertainties, for more peripheral collisions. CMS measurements are consistent with ALICE measurements for peripheral collisions but deviate beyond the systematic uncertainties for more central collisions. The E_{T} in Pb–Pb collisions is 1737 ± 6(stat.) $\pm$ 97 (sys.) GeV and the E_{T} per participant is 9.02 ± 0.03(stat.) $\pm$ 0.50 (sys.) GeV, two standard deviations below the value observed by CMS [26]. All methods resulted in a lower E_{T} than that reported by CMS, although the systematic errors on the measurements are significantly correlated. The corrections for the CMS data are determined by Monte Carlo [26] while the corrections for the ALICE measurement are mainly data-driven.

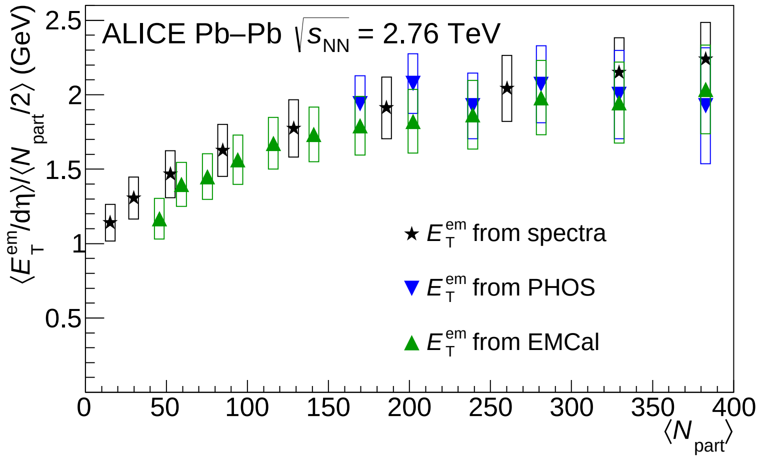

Fig. 6: Comparison of $\langle dE_T^{em}/d\eta\rangle/(\langle N_{part}/2\rangle)$ versus $\langle N_{part}\rangle$ at midrapidity from the PHOS, from the EMCal, and as calculated from the measured pion spectra. The boxes indicate the systematic uncertainties.

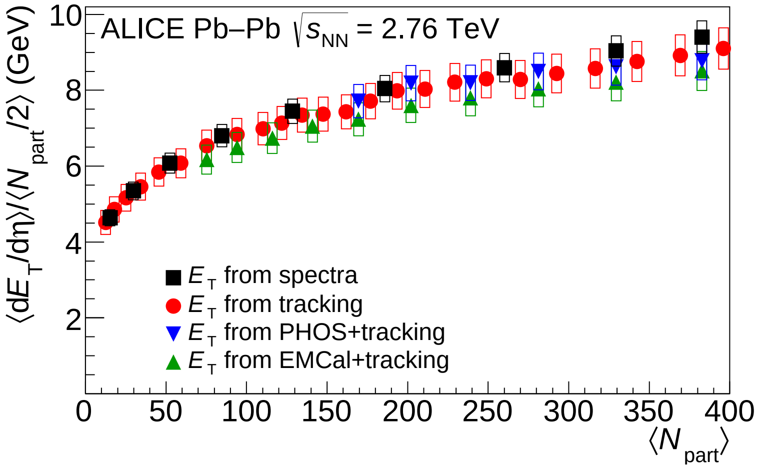

Fig. 7: Comparison of total $\langle dE_T/d\eta\rangle/(\langle N_{part}/2\rangle)$ versus $\langle N_{part}\rangle$ at midrapidity using tracking detectors, using EMCal+tracking, using PHOS+tracking, and as calculated from the measured particle spectra. The boxes indicate the systematic uncertainties.

PHENIX [24] reported that while $\langle dE_T/d\eta\rangle$ scaled by $\langle N_{part}\rangle$ has a pronounced centrality dependence, as seen in Fig. 8, $\langle dE_T/d\eta\rangle$ scaled by the number of constituent quarks, $\langle N_{quark}\rangle$, $\langle dE_T/d\eta\rangle/(\langle N_{quark}/2\rangle)$ shows little centrality dependence within the systematic uncertainties for collisions at $\sqrt{s_{NN}}$ = 62.4 – 200 GeV. This indicates that E_T might scale linearly with the number of quarks participating in the collision rather than the number of participating nucleons. Fig. 9 shows $\langle dE_T/d\eta\rangle/(\langle N_{quark}/2\rangle)$ as a function of $\langle N_{part}\rangle$. To calculate $\langle N_{quark}\rangle$ the standard Monte Carlo Glauber technique [28] has been used with the following Woods-Saxon nuclear density parameters: radius parameter $R_{WS} = 6.62 \pm 0.06$ fm, diffuseness $a = 0.546 \pm 0.010$ fm, and hard core $d_{min} = 0.4 \pm 0.4$ fm. The three constituent quarks in each nucleon have been sampled from the nucleon density distribution $\rho_{nucleon} = \rho_0 e^{-ar}$ with $a = 4.28\, fm^{-1}$ using the method developed by PHENIX [60]. The inelastic quark-quark cross section at $\sqrt{s_{NN}}$ = 2.76 TeV was found to be $\sigma_{qq}^{inel} = 15.5 \pm 2.0$ mb corresponding to $\sigma_{NN}^{inel} = 64 \pm 5$ mb [55]. The systematic uncertainties on the $\langle N_{quark}\rangle$ calculations were determined following the procedure described in [55]. Unlike at RHIC, we observe an increase in $\langle dE_T/d\eta\rangle/(\langle N_{quark}/2\rangle)$ with centrality below $\langle N_{part}\rangle \approx$200.

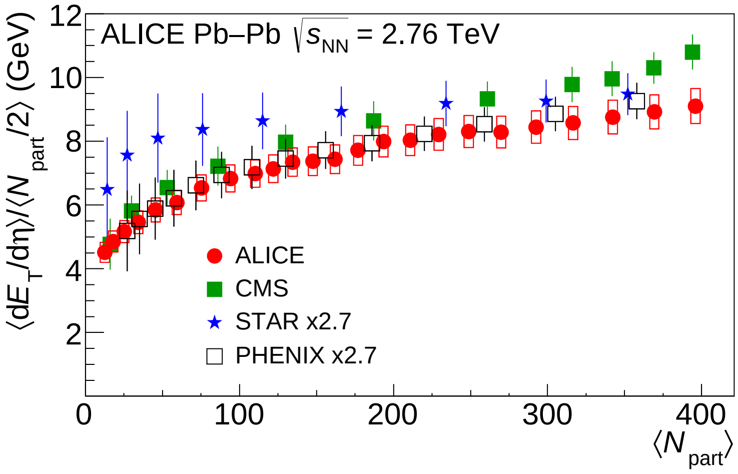

Fig. 8: Comparison of $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta\rangle/(\langle N_{\mathrm{part}}/2\rangle)$ at midrapidity in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV from CMS [26] and ALICE and in Au–Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV from STAR [25] and PHENIX [22, 23]. Data from RHIC were scaled by a factor of 2.7 for comparison of the shapes. The boxes indicate the systematic uncertainties.

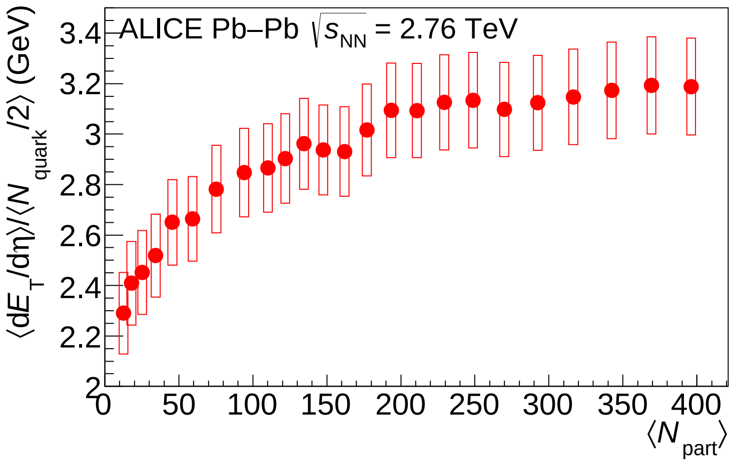

Fig. 9: Measurements of $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta\rangle/(\langle N_{\mathrm{quark}}/2\rangle)$ versus $\langle N_{\mathrm{part}}\rangle$ at midrapidity in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV. Note the suppressed zero. The boxes indicate the systematic uncertainties.

Figure 10 shows $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta\rangle/\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle$, a measure of the average transverse energy per particle, versus $\langle N_{\mathrm{part}}\rangle$ in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV from ALICE, and in Au–Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV from STAR [25] and PHENIX [22, 23]. No centrality dependence is observed within uncertainties at either RHIC or LHC energies. The $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta\rangle/\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle$ increases by a factor of approximately 1.25 from $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV [22, 23, 25] to $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV, comparable to the increase in $\langle p_{\mathrm{T}}\rangle$ from $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV [58, 59] to $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV [47]. The average transverse momentum, $\langle p_{\mathrm{T}}\rangle$, also shows little dependence on the charged-particle multiplicity except for peripheral collisions [47]. The absence of a strong centrality dependence in $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta\rangle/\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle$ is consistent with the development of radial flow seen in the spectra of identified particles [42] assuming kinetic energy is conserved during the hydrodynamic expansion.

Figure 11 shows a comparison of $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta\rangle/(\langle N_{\mathrm{part}}/2\rangle)$ versus $\sqrt{s_{\mathrm{NN}}}$ in 0–5% central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV from ALICE and CMS [26] and central collisions at other energies [22, 25, 60] at midrapidity. The data are compared to an extrapolation from lower energy data [22], which substan-

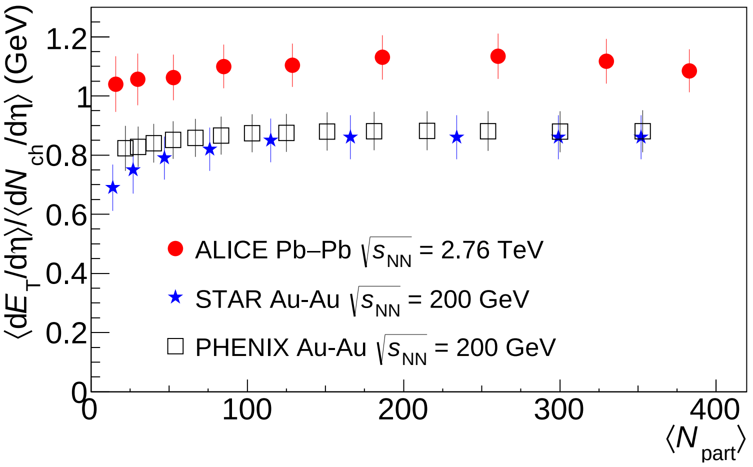

Fig. 10: Comparison of $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta \rangle / \langle \mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta \rangle$ versus $\langle N_\mathrm{part} \rangle$ at midrapidity in Pb–Pb collisions at $\sqrt{s_\mathrm{NN}}$ = 2.76 TeV from ALICE and in Au–Au collisions at $\sqrt{s_\mathrm{NN}}$ = 200 GeV from STAR [25] and PHENIX [22, 23].

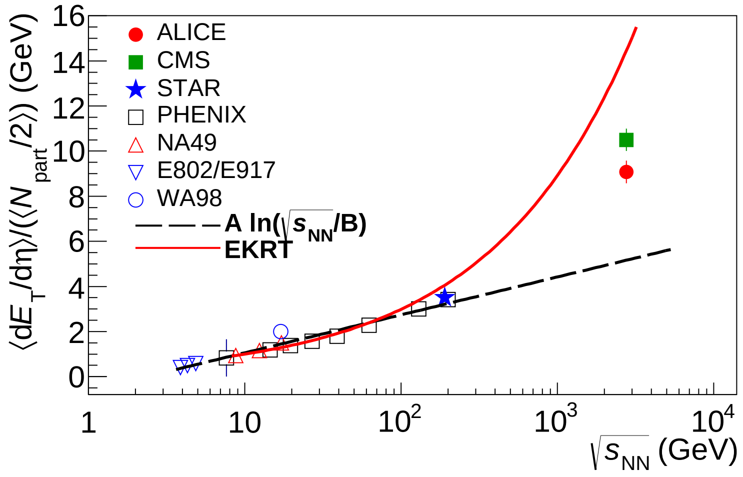

Fig. 11: Comparison of $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta \rangle / (\langle N_\mathrm{part}/2 \rangle)$ at midrapidity versus $\sqrt{s_\mathrm{NN}}$ in 0–5% central Pb–Pb collisions at $\sqrt{s_\mathrm{NN}}$ = 2.76 TeV from ALICE and CMS [26] and central collisions at other energies [22, 25, 60] at midrapidity. All measurements are from 0–5% central collisions except the NA49 data, which are from 0–7% collisions.

tially underestimates the $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta \rangle / (\langle N_\mathrm{part}/2 \rangle)$ at the LHC. The data are also compared to the EKRT model [61, 62]. The EKRT model combines perturbative QCD minijet production with gluon saturation and hydrodynamics. The EKRT calculation qualitatively describes the $\sqrt{s_\mathrm{NN}}$ dependence at RHIC and SPS energies [25]. However, at LHC energies EKRT overestimates E_T substantially, indicating that it is unable to describe the collision energy dependence.

Figure 12 shows a comparison of $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta \rangle / \langle \mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta \rangle$ versus $\sqrt{s_\mathrm{NN}}$ in 0-5% central Pb–Pb collisions at $\sqrt{s_\mathrm{NN}}$ = 2.76 TeV from ALICE and in central collisions at other energies. Previous measurements indicated that $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta \rangle / \langle \mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta \rangle$ had either saturated at RHIC energies or showed only a weak dependence on $\sqrt{s_\mathrm{NN}}$ [22, 25, 60]. An empirical extrapolation of the data to LHC energies assuming that both E_T and $\langle N_\mathrm{ch} \rangle$ have a linear dependence on $\sqrt{s_\mathrm{NN}}$ predicted that $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta \rangle / \langle \mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta \rangle$ would be 0.92 $\pm$ 0.06 [22] and we observe 1.06 $\pm$ 0.05. Increasing the incident energy increases both the particle production and the mean energy per particle at LHC energies, in contrast to lower energies ($\sqrt{s_\mathrm{NN}}$ = 19.6 –

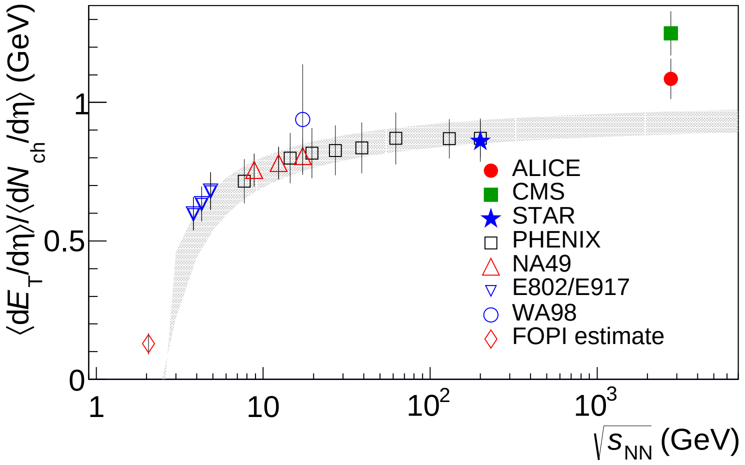

Fig. 12: Comparison of $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta\rangle/\langle \mathrm{d}N_\mathrm{ch}/\mathrm{d}\eta\rangle$ at midrapidity versus $\sqrt{s_\mathrm{NN}}$ in Pb–Pb collisions at $\sqrt{s_\mathrm{NN}}$ = 2.76 TeV from ALICE and measurements at other energies [15, 19, 21, 22, 25, 60, 63]. The band shows the extrapolation from lower energies with the width representing the uncertainty on the fit [22].

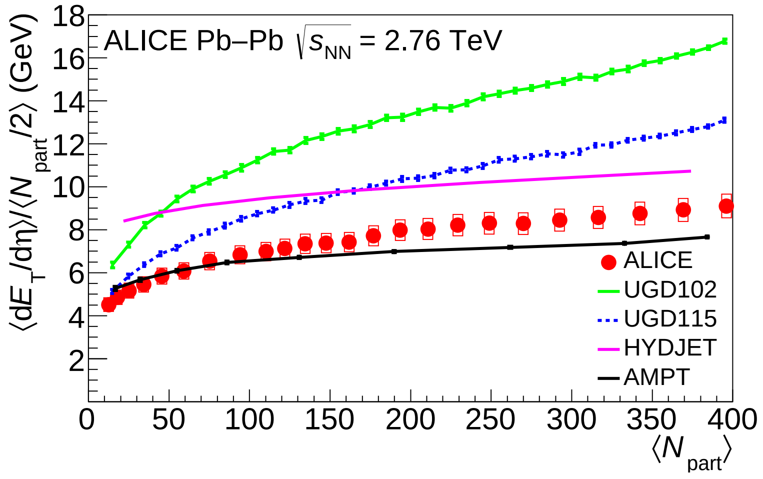

Fig. 13: Comparison of $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta\rangle/(\langle N_\mathrm{part}/2\rangle)$ versus $\langle N_\mathrm{part}\rangle$ at midrapidity to AMPT [64], HYDJET 1.8 [65], and UDG [66]. The boxes indicate the systematic uncertainties.

200 GeV) where increasing the incident energy only led to increased particle production [22].

Figure 13 shows a comparison of $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta\rangle/(\langle N_\mathrm{part}/2\rangle)$ versus $\langle N_\mathrm{part}\rangle$ to various models. AMPT [64] is a Monte Carlo event generator which builds on HIJING [43], adding explicit interactions between initial minijet partons and final state hadronic interactions. HYDJET 1.8 [65] is a Monte Carlo event generator that introduces jet quenching via gluon bremsstrahlung to PYTHIA [48] events. The curves labeled UDG are calculations from a Color Glass Condensate model [66] with different normalization K factors. None of the available models is able to describe the data very well, but we find that AMPT does best in describing the shape and level of $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta\rangle/(\langle N_\mathrm{part}/2\rangle)$. HYDJET describes the relative shape changes as a function of centrality as well as AMPT, but overestimates $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta\rangle/(\langle N_\mathrm{part}/2\rangle)$. Both CGC calculations overestimate $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta\rangle/(\langle N_\mathrm{part}/2\rangle)$ and predict a larger increase as a function of centrality than is observed in the data.

The volume-averaged energy density ε can be estimated from $\langle \mathrm{d}E_\mathrm{T}/\mathrm{d}\eta\rangle$ using the following expres-

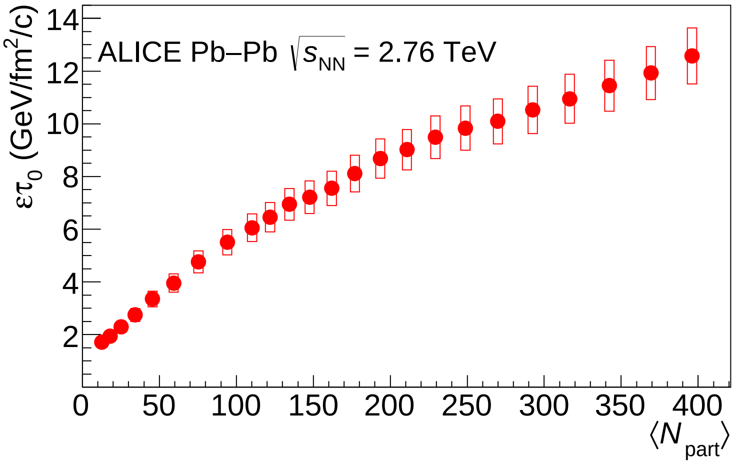

Fig. 14: $\varepsilon\tau_0$ versus $\langle N_{\rm part}\rangle$ estimated using Eq. 8, $R = 7.17$ fm, and the measured $\langle {\rm d}E_{\rm T}/{\rm d}\eta\rangle$. The boxes indicate the systematic uncertainties.

sion [14]

$$\varepsilon = \frac{1}{{\rm A}c\tau_0}{\rm J}\left\langle\frac{{\rm d}E_{\rm T}}{{\rm d}\eta}\right\rangle \tag{8}$$

where A is the effective transverse collision area, c is the speed of light, J is the Jacobian for the transformation between $\langle {\rm d}E_{\rm T}/{\rm d}\eta\rangle$ and $\langle {\rm d}E_{\rm T}/{\rm dy}\rangle$, and τ_0 is the formation time. The Jacobian is calculated from the measured particle spectra [42, 46]. While J has a slight centrality dependence, it is smaller than the systematic uncertainty so a constant Jacobian of J = 1.12 ± 0.06 is used. The formation time of the system τ_0 is highly model dependent and we therefore report $\varepsilon\tau_0$.

The transverse overlap area corresponding to the measured $\langle {\rm d}E_{\rm T}/{\rm d}\eta\rangle$ was determined by a calculation using a Glauber Monte Carlo method. Using the Glauber parameters from [55] and assuming each participating nucleon has an effective transverse radius of $R = (\sigma_{\rm NN}^{\rm inel}/4\pi)^{1/2} = 0.71$ fm results in $A = 162.5$ fm^2 for central collisions ($b = 0$ fm). This is equivalent to a transverse overlap radius of $R = 7.19$ fm, which is close to the value of 7.17 fm often used in estimates of energy densities using a Woods-Saxon distribution to determine the effective area [24, 60]. The centrality dependence of A is obtained by assuming it scales as $(\sigma_{\rm x}^2\sigma_{\rm y}^2 - \sigma_{\rm xy}^2)^{1/2}$ [67], where $\sigma_{\rm x}^2$ and $\sigma_{\rm y}^2$ are the variances and $\sigma_{\rm xy}^2$ is the covariance of the spatial distribution of the participating nucleons in the transverse plane in the Glauber Monte Carlo calculation. For 0–5% central collisions this leads to a reduction of A by 3% resulting in $\varepsilon\tau_0 = 12.5 \pm 1.0$ GeV/fm^2/c. For comparison using $R = 7.17$ fm gives $\varepsilon\tau_0 = 12.3 \pm 1.0$ GeV/fm^2/c, roughly 2.3 times that observed in 0–5% central Au–Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV. Some of this increase comes from the higher $\langle N_{\rm part}\rangle$ in central Pb–Pb collisions relative to central Au–Au collisions The energy density times the formation time $\varepsilon\tau_0$ is shown in Fig. 14 for R = 7.17 fm in order to be comparable to previous measurements [24, 60].

In addition to estimating the volume averaged energy density it is also interesting to estimate the energy density attained at the core of the collision area. This can be done by rewriting the Bjorken Eq. 8 as

$$\varepsilon_{\rm c}\tau_0 = \frac{\rm J}{c}\frac{\left\langle\frac{{\rm d}E_{\rm T}}{{\rm d}\eta}\right\rangle_{\rm c}}{A_{\rm c}} = \frac{\rm J}{c}\frac{\left\langle\frac{{\rm d}E_{\rm T}}{{\rm d}\eta}\right\rangle}{\langle N_{\rm part}\rangle}\sigma_{\rm c} \tag{9}$$

where $A_{\rm c}$ is the area of the transverse core, $\left\langle\frac{{\rm d}E_{\rm T}}{{\rm d}\eta}\right\rangle_{\rm c}$ is $\left\langle\frac{{\rm d}E_{\rm T}}{{\rm d}\eta}\right\rangle$ produced in the core, and $\sigma_{\rm c} = \langle N_{\rm part}\rangle_{\rm c}/A_{\rm c}$ is the transverse area density of nucleon participants at the core. The area $A_{\rm c}$ was chosen arbitrarily to be a circle with a radius of 1 fm at the center of the collision. Equation 9 assumes that the local energy density scales with the participant density in the transverse plane and that the measured value of $\left\langle \frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}\eta} \right\rangle / \langle N_{\mathrm{part}} \rangle$, which is averaged over the total transverse collision area, is also representative of the transverse energy production at the core, $\left\langle \frac{\mathrm{d}E_{\mathrm{T}}}{\mathrm{d}\eta} \right\rangle_{\mathrm{c}} / \langle N_{\mathrm{part}} \rangle_{\mathrm{c}}$. The increase of this quantity with increasing centrality indicates that this is a conservative estimate. From a Glauber Monte Carlo calculation we find for 0–5% centrality $\sigma_{\mathrm{c}} = 4.2 \pm 0.1$ nucleon/fm^2 resulting in a core energy density of $\varepsilon_{\mathrm{c}} \tau_0 = 21 \pm 2$ GeV/fm^2/c. For the most central 80 fm^2 (half the total overlap area) the energy density is still above 80% of the core energy density emphasizing that the core energy density may be more relevant for judging the initial conditions of the QGP than the volume averaged energy density.

5 Conclusions

We have measured $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle$ at midrapidity in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV using four different methods. All methods lead to comparable results, although the systematic uncertainties are largely correlated. Our results are consistent with results from CMS [26] for 10–80% central collisions, however, we observe a lower $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle$ in 0–10% central collisions. The $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle$ observed at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV in 0–5% central collisions is 1737 ± 6(stat.) ± 97 (sys.) GeV. The shape of the centrality dependence of $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle / (\langle N_{\mathrm{part}}/2 \rangle)$ is similar for RHIC and the LHC. No centrality dependence of $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle / \langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ is observed within uncertainties, as was observed at RHIC. Unlike at RHIC, we observe an increase in $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle / (\langle N_{\mathrm{quark}}/2 \rangle)$ with centrality below $\langle N_{\mathrm{part}} \rangle \approx 200$. Both $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle / (\langle N_{\mathrm{part}}/2 \rangle)$ and $\langle \mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta \rangle / \langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle$ in central collisions exceed the value expected from naive extrapolations from data at lower collision energies. Assuming that if the formation time τ_0 is 1 fm/c the energy density is estimated to be at least 12.3 ± 1.0 GeV/fm^3 in 0–5% central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV and the energy density at the core of the collision exceeds 21 ± 2 GeV/fm^3.

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A The ALICE Collaboration

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