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Scaling of charged particle multiplicity in Pb–Pb collisions at SPS energies

NA50 Collaboration

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Abstract

The charged particle multiplicity distribution $dN_{ch}/d\eta$ has been measured by the NA50 experiment in Pb–Pb collisions at the CERN SPS. Measurements were done at incident energies of 40 and 158 GeV per nucleon over a broad impact parameter range. The multiplicity distributions are studied as a function of centrality using the number of participating nucleons (N_{part}), or the number of binary nucleon–nucleon collisions (N_{coll}). Their values at midrapidity exhibit a power law scaling behaviour given by $N_{\text{part}}^{1.00}$ and $N_{\text{coll}}^{0.75}$ at 158 GeV. Compatible results are found for the scaling behaviour at 40 GeV. The width of the $dN_{ch}/d\eta$ distributions is larger at 158 than at 40 GeV/nucleon and decreases slightly with centrality at both energies. Our results are compared to similar studies performed by other experiments both at the CERN SPS and at RHIC.

1. Introduction

The pseudorapidity distributions of charged particles in Pb–Pb collisions at the CERN SPS have been measured with the multiplicity detector of the NA50 experiment [1]. The charged multiplicity information may help constrain different models of particle production, and quantify the relative importance of soft versus hard processes in the particle production mechanism at different energies. On this respect, an important test for models of particle production in heavy ion reactions is the study of its scaling properties with respect both to the number of participant nucleons (N_{part}) and to the number of binary collisions (N_{coll}).

A scaling with N_{part} is expected in scenarios dominated by soft processes, when the produced particles undergo a strong rescattering in the final state and the memory of the exact history of multiple collisions is lost. Then the participant nucleons can be assumed to contribute with the same amount of energy to particle production, and the scaling with N_{part} is approximately linear. This kind of law has already been shown to work at the SPS energies in describing the charged particle multiplicity in p–A [2] and in Pb–Pb collisions [3–5], and also the E_T measured in oxygen and sulphur induced reactions [6] and in Pb–Pb collisions [7].

On the contrary, a scaling with N_{coll} arises naturally in a scenario where nuclear collisions are modeled as a superposition of binary nucleon–nucleon collisions. Such a scaling is expected to be observed in a regime of nuclear reactions where hard processes dominate over the soft particle production, as could be reached at RHIC and LHC energies. First results from the experiments at RHIC [8–10], showing evidence of a large contribution of hard processes to particle production, seem to indicate that such a regime has already been reached at RHIC energies.

In this Letter the particle density at midrapidity ($dN/d\eta|_{\text{max}}$) is studied versus the centrality of the collision using values of N_{part} and of N_{coll} calculated in the framework of the Glauber model [11].

Another information relevant for constraining particle production models is provided by the study of the scaling of charged particle multiplicity versus $\sqrt{s}$. Results from the analysis presented in this Letter, at the two beam energies corresponding to $\sqrt{s} = 8.77$ and 17.3 GeV, are important to enrich the pattern outlined by the results of other experiments at the SPS and RHIC.

2. Experimental setup and data taking conditions

In this Letter we only refer to data collected with heavy ion collisions. For those runs, the NA50 apparatus [12] consists of a muon spectrometer, equipped with three centrality detectors (a Zero Degree Calorimeter, an Electromagnetic Calorimeter and a Multiplicity

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Detector) and specific devices for beam tagging and interaction vertex identification.

The data presented in this Letter are extracted from special runs taken with the Minimum Bias (MB) trigger, which requires a non-zero energy deposit in the ZDC, at low beam intensity (about 1/10 of the standard intensity used by the experiment).

The multiplicity and the angular distribution of charged particles in a wide acceptance window is measured by a silicon strip Multiplicity Detector (MD) [13–15].

The determination of the centrality of the collision is obtained by means of a Zero Degree Calorimeter (ZDC) [16] which measures the energy E_{ZDC} of the spectator nucleons travelling in the forward direction and by an electromagnetic calorimeter (EMCAL) which measures the neutral transverse energy E_T in the pseudorapidity range $1.1 < \eta < 2.3$.

Data collected at two different energies of the SPS Pb beam have been used: the first data sample was taken in 1998 at 158 GeV per nucleon beam energy, the second in 1999 at 40 GeV per nucleon energy. The data selection is described in Section 4.1 of Ref. [1].

3. Evaluation of N_{part} and N_{coll}

The aim of the present analysis is the study of the scaling properties of the charged particle production in Pb–Pb collisions as a function of centrality expressed in terms of the number of participant nucleons N_{part} and of binary collisions N_{coll}.

The NA50 apparatus allows to study the $dN_{ch}/d\eta$ distributions in Pb–Pb collisions as a function of the centrality of the collision, estimated using two independent observables (namely, the neutral transverse energy E_T and the forward energy E_{ZDC}) as explained in [1]. Centrality classes for the 158 GeV data sample have been defined in terms of cross-section fractions using both E_T and E_{ZDC}. For each cross-section interval, the average values of N_{part} and N_{coll} have been estimated in the framework of the Glauber model

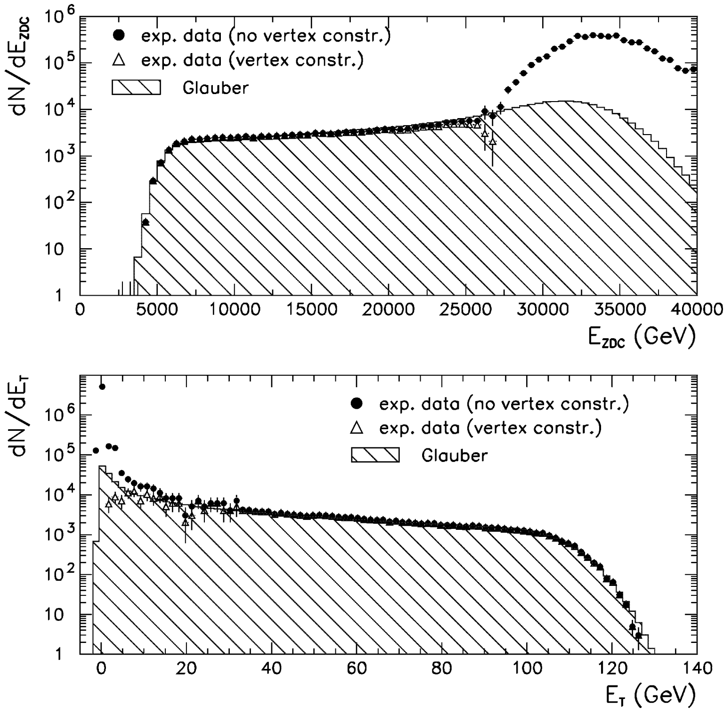


Fig. 1. Distributions of the forward energy E_{ZDC} and of the neutral transverse energy E_T in Pb–Pb collisions at 158 GeV per nucleon incident energy. Predictions of the Glauber model are superimposed (hatched histograms).

Table 1
Number of participant nucleons and of binary collisions calculated for the 158 GeV/nucleon data sample for the different centrality classes defined by the two independent (E_{ZDC} and E_T) centrality variables

Class	% of c.s.	E_{ZDC}^{min}–E_{ZDC}^{max} (GeV)	$\langle N_{part}\rangle$	RMS N_{part}	$\langle N_{coll}\rangle$	RMS N_{coll}
1	0–5	0–9385	354	22	802	66
2	5–10	9385–13150	294	23	634	63
3	10–15	13150–16490	246	25	501	64
4	15–20	16490–19180	205	26	395	65
5	20–25	19180–21475	173	28	316	66
6	25–35	21475–24790	129	35	214	74
Class	**% of c.s.**	**E_T^{min}–E_T^{max} (GeV)**	**$\langle N_{part}\rangle$**	**RMS N_{part}**	**$\langle N_{coll}\rangle$**	**RMS N_{coll}**
1	0–5	87.2–140.0	352	25	796	73
2	5–10	71.5–87.2	294	26	632	72
3	10–15	58.7–71.5	245	23	498	61
4	15–20	48.9–58.7	203	20	392	52
5	20–25	40.9–48.9	169	19	309	44
6	25–35	29.6–40.9	127	20	213	45

Table 2
Number of participant nucleons and of binary collisions calculated for the 40 GeV/nucleon data sample for the different centrality classes

Class	% of c.s.	E_T^{min}–E_T^{max} (GeV)	$\langle N_{part}\rangle$	RMS N_{part}	$\langle N_{coll}\rangle$	RMS N_{coll}
1	0–5	54.6–100.0	356	20	808	58
2	5–10	44.9–54.6	295	16	635	43
3	10–15	37.4–44.9	245	13	501	34
4	15–20	31.1–37.4	204	11	396	27
5	20–25	25.9–31.1	170	9	310	22
6	25–35	17.5–25.9	127	15	213	33

assuming that E_T is proportional to the number of participants and E_{ZDC} to the number of projectile spectators. Smearing effects due to the experimental resolution of the calorimeters have also been included in our calculation. In Fig. 1 we show a comparison between the E_T and E_{ZDC} Minimum Bias spectra calculated with the Glauber model and the experimentally measured ones with and without the vertex constraint based on the geometrical correlation between the two MD planes.[7] The agreement between the data and the model is remarkable.

In the Glauber calculations the nuclear density ρ has been parametrized by a Woods–Saxon distribution:

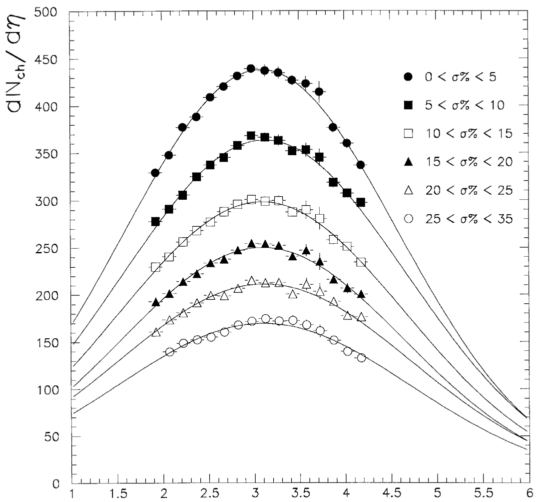
$$\rho(r) = \frac{\rho_0}{1 + e^{(r-r_0)/C}}$$

with parameters $r_0 = 6.624$ fm, $C = 0.549$ fm and $\rho_0 = 0.16$ fm^{-3} [17].

The results concerning N_{part} and N_{coll} at 158 GeV are reported in Table 1 where it can be seen that the E_T and E_{ZDC} based calculations are generally in good agreement.

For the 40 GeV data sample, due to the worse performance of the ZDC at such a low beam energy, only the analysis with the E_T based centrality selection has been performed resulting in a larger uncertainty on the centrality interval definition. The E_T distribution at 40 GeV/nucleon (as it can be seen in Fig. 3 of Ref. [1]) does not exhibit a sharp knee, as it does at 158 GeV. This can be connected to the calorimeter resolution and to the fact that not all the data sample cleaning cuts

[7] The vertex constraint rejects the non interacting Pb ions whose contribution dominates the spectra at high E_{ZDC}-low E_T.



Class	% of c.s.	$\eta_{\max}$	σ_{gaus}	$dN_{ch}/d\eta\vert_{\max}$
1	0−5	3.08 ± 0.01	1.50 ± 0.03	438 ± 4
2	5−10	3.12 ± 0.01	1.56 ± 0.02	363 ± 3
3	10−15	3.09 ± 0.02	1.57 ± 0.04	298 ± 3
4	15−20	3.09 ± 0.02	1.56 ± 0.04	250 ± 3
5	20−25	3.11 ± 0.02	1.62 ± 0.04	211 ± 3
6	25−35	3.10 ± 0.02	1.62 ± 0.05	169 ± 3

Fig. 2. Pseudorapidity distributions of charged particles in 158 GeV/nucleon Pb–Pb collisions obtained using E_{ZDC} as centrality estimator. Gaussian fits are superimposed.

were applied. In particular, it was not possible to use the E_T vs. E_{ZDC} correlation cut and the halo counter cut. For this reason, we decided to use the N_{part} distributions calculated without including the experimental smearing extracted from the fit to the observed E_T distributions of MB events. The values of $\langle N_{\mathrm{part}}\rangle$ obtained in this way turn out to be in good agreement with the ones obtained at 158 GeV/nucleon energy where the calorimeter resolution is taken into account. The average values of N_{part} and N_{coll} at 40 GeV per nucleon incident energy are reported in Table 2.

4. Data analysis

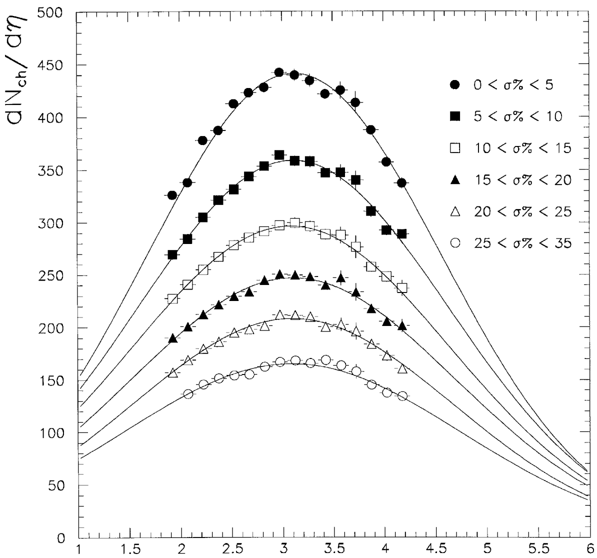
4.1. Properties of the pseudorapidity distributions

The pseudorapidity distributions of the primary charged particles for the different centrality classes have been calculated following the procedure explained in [1].

The $dN_{ch}/d\eta$ distributions thus obtained have been fitted with gaussian functions, to obtain an estimate of the charged particle pseudorapidity density at the peak ($dN_{ch}/d\eta|_{\max}$), of the peak position ($\eta_{\max}$) and of the gaussian width (σ_{gaus}). We emphasize that, thanks to the wide η coverage (~ 2.2 units) approximately symmetric around the peak, we do not need to fix the mid-rapidity point $\eta_{\max}$ at the theoretical value. Instead, we leave it as a free parameter of the fit.

The results of the fits for the 158 GeV data sample with the two independent centrality selections are shown in Fig. 2 (E_{ZDC} selection) and in Fig. 3 (E_T selection), together with tables listing the resulting fit parameters.

The results obtained with the two independent centrality estimators are in agreement within 1.5% except for the most peripheral class where the difference



Class	% of c.s.	$\eta_{\max}$	σ_{gaus}	$dN_{ch}/d\eta\|_{\max}$
1	0−5	3.12 ± 0.01	1.45 ± 0.02	441 ± 4
2	5−10	3.11 ± 0.01	1.53 ± 0.03	359 ± 4
3	10−15	3.08 ± 0.02	1.57 ± 0.04	296 ± 3
4	15−20	3.10 ± 0.02	1.60 ± 0.04	247 ± 3
5	20−25	3.10 ± 0.02	1.58 ± 0.04	208 ± 2
6	25−35	3.09 ± 0.03	1.65 ± 0.06	165 ± 3

Fig. 3. Pseudorapidity distributions of charged particles in 158 GeV/nucleon Pb–Pb collisions obtained using E_T as centrality estimator.

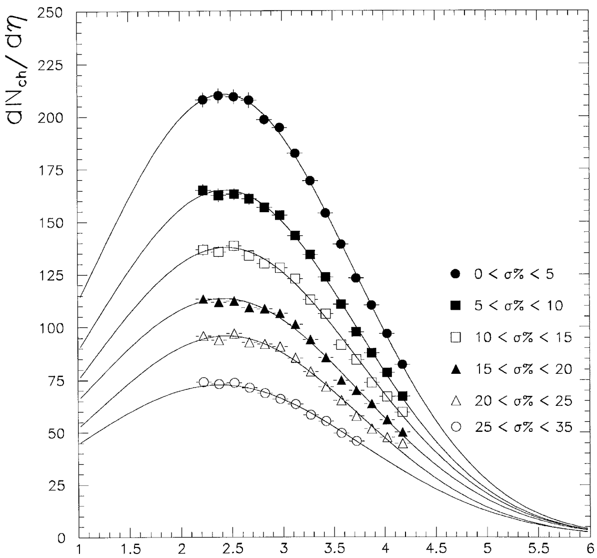
between the $dN_{ch}/d\eta|_{\max}$ values amount to $\simeq 2.5\%$, confirming the results presented in [1].

The midrapidity values resulting from the gaussian fits are compatible with the value $\eta_{\max} \simeq 3.1$ extracted from VENUS [18].

In Fig. 4, the particle pseudorapidity distributions obtained for the data collected at 40 GeV per nucleon beam energy are shown, as well as the values of $\eta_{\max}$, σ_{gaus} and $dN_{ch}/d\eta|_{\max}$ resulting from the gaussian fits. The $\eta_{\max}$ value expected from VENUS is 2.47 and is compatible with our results.

The comparison of our results on $dN_{ch}/d\eta|_{\max}$ with those of other SPS experiments is reported in Table 3 for the 158 and for the 40 GeV/nucleon data samples. The systematic error on our multiplicity evaluation amounts to 8% at 158 GeV/nucleon and to 10% at 40 GeV/nucleon [1].

The width of the gaussian fit to our pseudorapidity distribution is lower at 40 than at 158 GeV/nucleon, reflecting the fact that the available phase-space in rapidity increases with the center-of-mass energy. In Fig. 5 we compare our results on the width in central Pb–Pb collisions with existing data at SPS and AGS energies. First, we present the evolution with $\sqrt{s}$ of the gaussian width of $dN_{ch}/d\eta$ for our most central class (0–5%) of Pb–Pb collisions at 40 and 158 GeV per nucleon, together with the width measured in central Au–Au collisions by the E877 Collaboration [24] at 10.8 GeV/c per nucleon. The fit of our results, taken together with the E877 one, to the simple scaling law $\sigma_\eta = a + b \times \ln\sqrt{s}$ [25,26], gives $\sigma_\eta = (0.58 \pm 0.09) + (0.32 \pm 0.04) \times \ln\sqrt{s}$ (solid line), confirming the already observed fact that the width of the pseudorapidity distribution in central ion–ion colli-



Class	% of c.s.	η_{max}	σ_{gaus}	$dN_{ch}/d\eta\vert_{max}$
1	0−5	2.43 ± 0.03	1.27 ± 0.02	211 ± 4
2	5−10	2.43 ± 0.03	1.29 ± 0.02	165 ± 3
3	10−15	2.45 ± 0.03	1.31 ± 0.02	138 ± 2
4	15−20	2.42 ± 0.03	1.35 ± 0.03	114 ± 2
5	20−25	2.45 ± 0.03	1.31 ± 0.03	96 ± 1
6	25−35	2.38 ± 0.08	1.39 ± 0.06	73 ± 1

Fig. 4. Pseudorapidity distributions of charged particles in 40 GeV/nucleon Pb–Pb collisions obtained using E_T as centrality estimator.

sions at AGS–SPS energies appears to follow a simple logarithmic scaling law independent of system size.[8] It is interesting to note [32] that at 158 GeV/nucleon the width of the rapidity distributions is about twice as large as the one expected from a single thermal source located at midrapidity.

We have also reported in Fig. 5 the widths of the rapidity distributions of identified π^+, π^-, K^+ and K^- measured by the E802 Collaboration [33–35] in the 3–5% most central Au–Au collisions at 11.6 GeV/c per nucleon and by the NA49 Collaboration [20,23, 36] in the 7% (respectively 5%) most central Pb–Pb collisions at 40 (respectively 158) GeV per nucleon (dashed lines connect σ_y values for the same particle species). We note that the widths of the rapidity distributions for identified produced hadrons follow the same scaling vs. $\sqrt{s}$ as the width of the pseudorapidity distribution, and furthermore $\sigma_\eta \approx \sigma_y(\pi^+)$, with $\sigma_y(\pi^+) > \sigma_y(\pi^-) > \sigma_y(K^+) > \sigma_y(K^-)$.

Finally, we have reported in Fig. 5 the width of the pseudorapidity distribution in the $\approx 10\%$ most central O–Ag/Br collisions (between 14.6 and 200 GeV/c per nucleon) measured by the EMU01 Collaboration [37] (triangles and dashed-dotted line), which have the

[8] A similar scaling law actually holds also for the width of the pion rapidity distribution measured in p–p collisions for the same energy range [27–30]: $\sigma_y(\pi^+) \approx 0.59 \times \ln\sqrt{s}$ and $\sigma_y(\pi^-) \approx 0.54 \times \ln\sqrt{s}$. The gaussian width of $dN_{ch}/d\eta$ for particles having $\beta > 0.85$ (thus excluding slow protons) measured in p–p collisions at 100 and 200 GeV/c beam momentum [31] is within errors compatible with $\sigma_y(\pi^+)$ at the same energies, confirming a close relationship between pseudorapidity and rapidity widths. So, p–p collisions show a width (for π^+ and π^- rapidity distributions) which is similar to the one of central ion–ion collisions at AGS energy, but then rises slightly faster with $\sqrt{s}$, reaching $\approx 20\%$ higher values at the highest SPS energy.

Table 3
Comparison of charged particle pseudorapidity density at the peak (for central events) in the laboratory system with the results of other SPS experiments

158 GeV/nucleon			
Experiment	System	$\sigma/\sigma_{\text{tot}}$ (%)	$dN_{ch}/d\eta\vert_{\max}$
NA50	Pb–Pb	0–5	$439 \pm 3 \pm 35$
NA45 [19]	Pb–Au	0–5	385
NA49 [20]	Pb–Pb	0–5	435[a]
WA97/NA57 [4,21]	Pb–Pb	$\sim$ 0–4	397[b]
WA98 [3]	Pb–Pb	0–10	440
40 GeV/nucleon			
Experiment	System	$\sigma/\sigma_{\text{tot}}$ (%)	$dN_{ch}/d\eta\vert_{\max}$
NA50	Pb–Pb	0–5	$211 \pm 4 \pm 21$
NA45 [22]	Pb–Au	0.1–4.8	268[c]
NA49 [23]	Pb–Pb	0–7	>230[d]

[a] The NA49 experiment has reported dN/dy measurements for negative hadrons. The $dN_{ch}/d\eta|_{\max}$ value is calculated as $2.3 \cdot 0.97 \cdot (dN_{h^-}/dy)_{\max}$ (where 2.3 is the ratio N_{ch}/N_{h^-} and 0.97 is the correction factor from dN_{ch}/dy to $dN_{ch}/d\eta$, both evaluated with VENUS).

[b] The yield of negative hadrons (see Fig. 2 of Ref. [21]) in $|y - y_{\text{cm}}| < 0.5$ was converted to $dN_{ch}/d\eta|_{\max} \simeq 2.3 \cdot 0.97 \cdot (dN_{h^-}/dy)_{\max}$.

[c] The NA45/CERES experiment has reported the value $(dN_{h^-}/dy)_{\max} = 120$. The $dN_{ch}/d\eta|_{\max}$ was evaluated as: $dN_{ch}/d\eta|_{\max} \simeq 2.3 \cdot 0.97 \cdot (dN_{h^-}/dy)_{\max}$.

[d] The NA49 experiment has reported at 40 GeV dN_{ch}/dy measurements for identified pions and kaons. The $dN_{ch}/d\eta|_{\max}$ value is obtained by summing up the π^+, π^-, K^+, K^- and applying the factor 0.97. The contribution of protons is not included, so this is a lower limit.

same slope as our data but slightly smaller absolute values (note that slow protons are excluded from the EMU01 measurement).

We further observe a decrease of the width σ_η of $\approx 10\%$ at both 158 and 40 GeV/nucleon when going from our most peripheral class to our most central one. The narrowing of the shape of pseudorapidity distributions with increasing centrality has been observed by several other experiments, among which NA35 [38,39], WA80 [40,41], NA34/2 [42], HELIOS-Emulsion [43] and E802 [44].[9] This narrowing can be associated with the higher degree of stopping reached in the interaction [19], and is mostly due to the decreasing contribution of protons from target and projectile fragmentation. In fact, emulsion experiments, which report the distribution of shower particles ($\beta > 0.7$) excluding therefore slow protons from the target fragmentation, usually find a weaker dependence of σ_η on centrality (see, e.g., [45]).

[9] For example, in the almost symmetric system S–Al at 200 GeV/c per nucleon WA80 measured a decrease of σ_η from 1.55 to 1.3 (16%) when going from peripheral to central events (see Fig. 8 in Ref. [41]).

4.2. Centrality dependence of charged particle production

To evaluate the centrality dependence of particle production, the scaling behaviour of the $dN_{ch}/d\eta|_{\max}$ as a function of the number of participant nucleons N_{part} has been parametrized with the usual power law behaviour:

$$\left(\frac{dN_{ch}}{d\eta}\right)_{\max} \propto N_{\text{part}}^{\alpha}.$$

The fit has been performed with the technique explained in [46] to take into account also the error on the independent variable N_{part}. The error on the average value of the number of participants has been assumed to be proportional to the RMS of the distribution (quoted in Tables 1 and 2), and tuned on the basis of the deviations observed on $\langle N_{\text{part}}\rangle$ when varying the smearing parameters in the Glauber calculations. We thus assume $\delta N_{\text{part}} = 0.2 \cdot \text{RMS}$ for the 158 GeV sample and $\delta N_{\text{part}} = 0.4 \cdot \text{RMS}$ for the 40 GeV sample.

The value of the scaling exponent for the 158 GeV/nucleon data sample results to be $\alpha = 1.00 \pm 0.01$ with both the E_T and the E_{ZDC} centrality

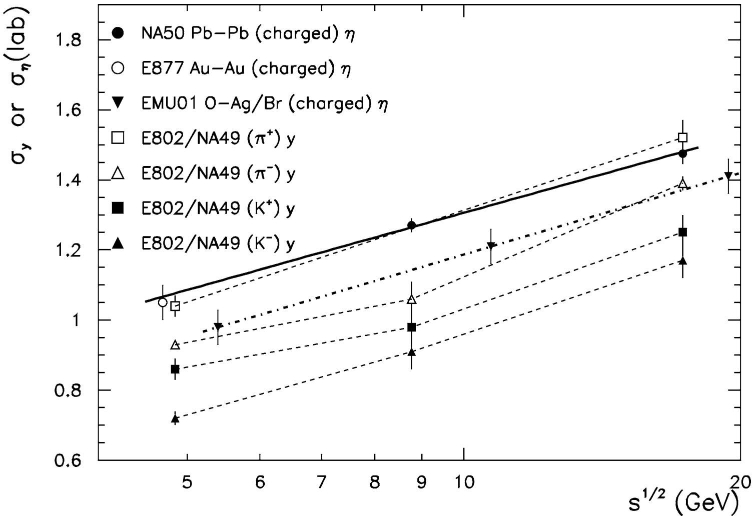


Fig. 5. Gaussian width of pseudorapidity or rapidity distributions as a function of center-of-mass energy for ion–ion collisions. See text for explanation.

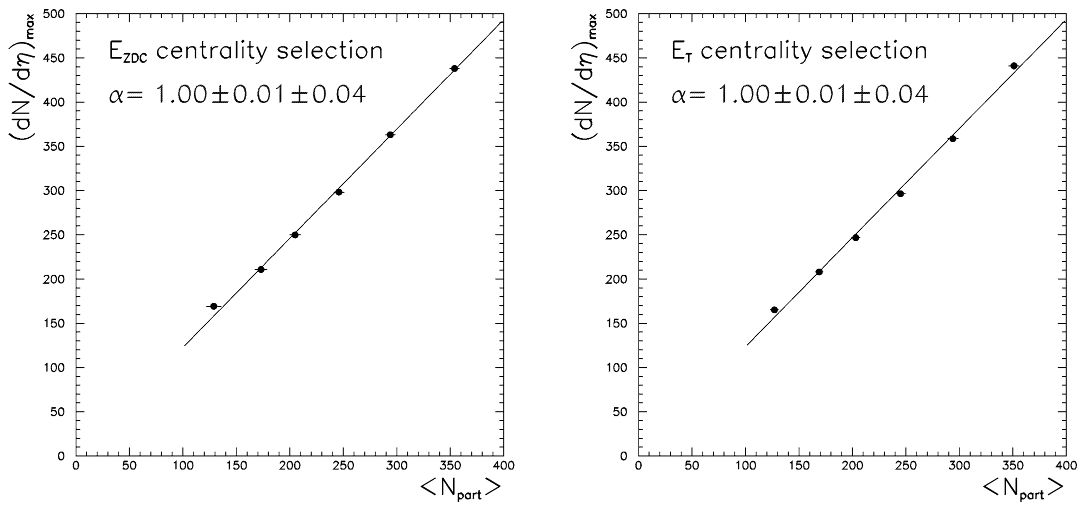


Fig. 6. Pseudorapidity density of N_{ch} at midrapidity as a function of the number of participants (N_{part}) in 158 GeV per nucleon Pb–Pb collisions with the two independent centrality selections. Power-law fits are superimposed.

selections, as it can be seen in Fig. 6. The systematic error on the α exponent has been estimated by a Monte Carlo simulation where the values of $\langle N_{\text{part}}\rangle$ have been varied inside their error bars independently for the 6 centrality classes. A systematic error of 0.04 on the exponent has thus been obtained. We can therefore conclude that both centrality selections lead to a scaling of the charged particle production with the number of participants characterized by an exponent:

$$\alpha_{158} = 1.00 \pm 0.01(\text{stat}) \pm 0.04(\text{syst}).$$

This value of α is in agreement with the Wounded Nucleon Model assumption that the average multiplicity in a collision is proportional to the number of participant (wounded) nucleons.

It has to be stressed that the value of the exponent α is strongly dependent on the value of $\langle N_{\mathrm{part}}\rangle$ and may vary significantly as a consequence of slight variations of $\langle N_{\mathrm{part}}\rangle$. Also the $\langle N_{\mathrm{part}}\rangle$ definition plays an important role [47,48]. For this reason we performed also power law fits using different $\langle N_{\mathrm{part}}\rangle$ evaluations. If the values of $\langle N_{\mathrm{part}}\rangle$ from VENUS 4.12 [18] are used, we obtain $\alpha = 1.08$ with the E_T centrality selection and $\alpha = 1.05$ with the E_{ZDC} selection. For the E_{ZDC} centrality selection we performed also the fit using a straightforward $\langle N_{\mathrm{part}}\rangle$ evaluation, namely, $\langle N_{\mathrm{part}}\rangle = 2 \cdot 208 \cdot (1 - E_{\mathrm{ZDC}}/E_{\mathrm{beam}})$ for which we obtain $\alpha = 1.02$.

Our results for the α exponent of the power law fit to the N_{part} dependence of $dN_{ch}/d\eta|_{\max}$ can be compared with the results of the WA98 [3] and WA97/NA57 [4] experiments at the SPS. The WA97/NA57 experiment uses a Glauber calculation of the number of participants and finds $\alpha = 1.05 \pm 0.05$, which is compatible with our result. The WA98 result ($\alpha = 1.08 \pm 0.03$) has been obtained using a VENUS based estimation of N_{part} and is in agreement with what we find using N_{part} extracted from VENUS.

A fit to the power law $dN_{ch}/d\eta|_{\max} \propto N_{\mathrm{coll}}^{\beta}$ has also been performed, obtaining for the exponent the values $\beta = 0.74$ and $\beta = 0.76$ with E_{ZDC} and E_T centrality selections, respectively. Therefore, we can conclude that N_{part} is well suited to describe the scaling of particle production with the centrality of the collision and that a scaling like N_{coll} is not observed at this energy.

Finally, a fit with the function $dN_{ch}/d\eta|_{\max} = A \times N_{\mathrm{part}} + B \times N_{\mathrm{coll}}$ has been done, in order to verify the possible presence of a term proportional to the number of collisions. The results of the fits for both centrality selections lead to values of B compatible with zero, indicating that the contribution from hard processes to charged particle production is negligible at this energy.

The data sample collected at 40 GeV per nucleon has also been fitted with $N_{\mathrm{part}}^{\alpha}$, leading to $\alpha = 1.02 \pm 0.02$. The systematic uncertainty on α, coming both from the same Monte Carlo evaluation used for the 158 GeV/nucleon data sample and from neglecting the experimental smearing in the Glauber calculations, is estimated to be 0.06. Therefore, the scaling exponent at 40 GeV/nucleon is determined to be:

$$\alpha_{40} = 1.02 \pm 0.02(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$

compatible with the value found at 158 GeV per nucleon. If the values of $\langle N_{\mathrm{part}}\rangle$ from VENUS 4.12 [18] are used instead, we obtain $\alpha = 1.10$, what confirms the already known fact [48] that VENUS gives an α value systematically ~ 0.08 higher than the analytical Glauber calculation.

4.3. Energy dependence of charged particle production

In order to examine the energy dependence of charged particle production and to compare our results with the ones obtained for other colliding systems, we study the charged particle pseudorapidity density at midrapidity per participant pair. The results are plotted in Fig. 7 as a function of N_{part} (evaluated with Glauber calculations). The error bars take into account the statistical error on $dN_{ch}/d\eta_{\max}$ as well as the uncertainty on $\langle N_{\mathrm{part}}\rangle$, while the 8% (respectively 10% at 40 GeV) systematic error on the multiplicity evaluation is not included.

In particular, at 158 GeV per nucleon for the 0–5% centrality range we obtain:

$$\left(\frac{dN_{ch}/d\eta|_{\max}}{0.5 \cdot \langle N_{\mathrm{part}}\rangle}\right) = 2.49 \pm 0.03(\mathrm{stat}) \pm 0.20(\mathrm{syst})$$

which is the average of the values obtained with the E_T and E_{ZDC} centrality selections. The systematic error accounts for the 8% systematic uncertainty on the multiplicity evaluation.

At 40 GeV per nucleon, for the 0–5% centrality range we obtain:

$$\left(\frac{dN_{ch}/d\eta|_{\max}}{0.5 \cdot \langle N_{\mathrm{part}}\rangle}\right) = 1.18 \pm 0.03(\mathrm{stat}) \pm 0.17(\mathrm{syst}).$$

The large systematic error bar is due both to the 10% systematic error on the multiplicity and to the uncertainty ($\approx 10\%$) on the evaluation of $\langle N_{\mathrm{part}}\rangle$ for the most central band.

The yield per participant pair thus obtained can be compared to the ones measured at higher energies by RHIC experiments PHOBOS [8,49], BRAHMS [10] and PHENIX [9]. Since RHIC measurements are performed in the center-of-mass frame, to make a quantitative comparison we need to convert our results, obtained in the laboratory frame, to the center-of-mass frame. For our data at 158 GeV, assuming pions, kaons and protons relative yields as measured by

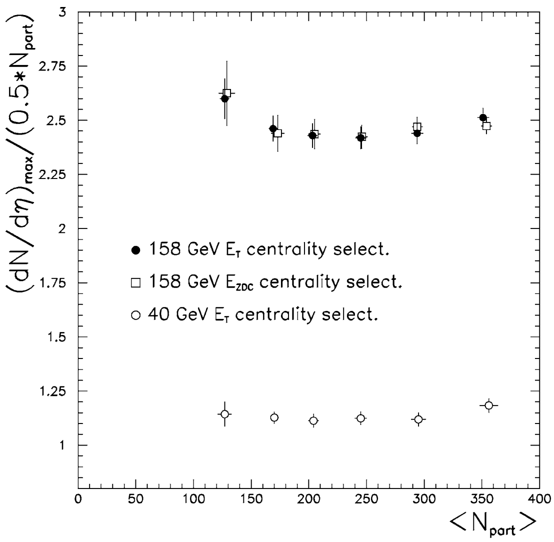


Fig. 7. Pseudorapidity density of N_{ch} at midrapidity per participant pair as a function of the number of participants N_{part} in 158 and 40 GeV/nucleon Pb–Pb collisions.

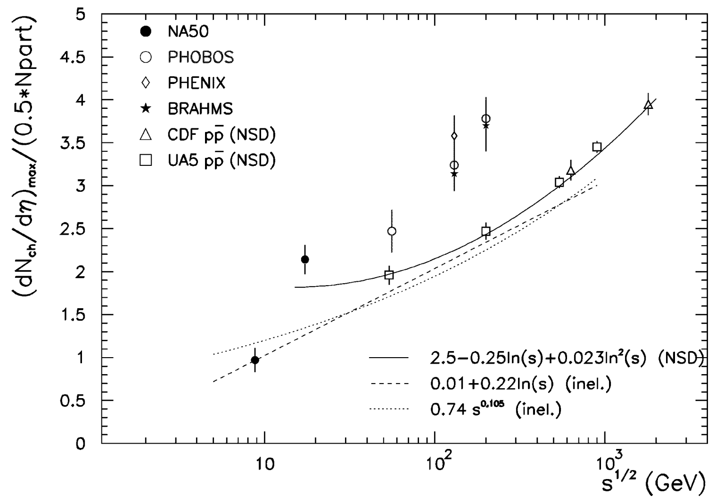


Fig. 8. Energy dependence of the pseudorapidity density per participant pair (in the center-of-mass frame) for the most central ion–ion collisions at SPS and RHIC. Fits to $p\bar{p}$ data are superimposed.

NA49 [5,20] and using the formula:

$$\frac{dN_{ch}}{d\mathbf{p}_T\,d\eta} = \sqrt{1 - \frac{m^2}{m_T^2\cosh^2 y}}\,\frac{dN_{ch}}{d\mathbf{p}_T\,dy}$$

the measured yield of 2.49 translates into 2.14 ± 0.17. At 40 GeV we use the relative yields as obtained with VENUS 4.12 since the proton fraction has not been yet measured. We estimate that the measured yield of 1.18 translates into 0.97 ± 0.14 in the center-of-mass frame. In Fig. 8, the pseudorapidity density per participant pair in the center-of-mass frame for the most central ion–ion collision at SPS and RHIC is shown together with some fits to $p\bar{p}$ data. It is important to point out that the yield per participant pair depends on the N_{part} calculation and therefore the comparison of our results with other experiments, which may use different models for the evaluation of

$N_{\rm part}$, is very delicate, even if $N_{\rm part}$ is not strongly model dependent for central collisions [47].

When comparing our results with the charged particle pseudorapidity density measured in nucleon–nucleon collisions we observe that our result at 40 GeV/nucleon is in agreement with the fit to data of inelastic $p\bar{p}$ interactions obtained by the UA5 experiment [50] assuming a logarithmic energy dependence, $dN/d\eta|_{\rm max} = (0.01 \pm 0.14) + (0.22 \pm 0.02)\ln s$. It is also compatible with the UA5 fit obtained assuming a power law energy dependence, $dN/d\eta|_{\rm max} = (0.74 \pm 0.04)s^{(0.105\pm0.006)}$. Therefore, we can conclude that the charged particle yield per participant pair at 40 GeV/nucleon is compatible with the one observed in nucleon–nucleon interactions at similar energies.

On the opposite our result at 158 GeV/nucleon is more than 50% higher than any of the mentioned fits for the corresponding center-of-mass energy. In addition our result at 158 GeV is also $\sim$ 20% higher than the fit ($dN/d\eta|_{\rm max} = 2.5 - 0.25\ln s + 0.023\ln^2 s$) of the yield obtained by CDF [51] in $p\bar{p}$ non-single diffractive interactions for much higher energies. The isospin effect ($\sim$ 10% among pp, pn and nn interactions [52]) cannot account for such a discrepancy as it can be argued also from the fact that our measurement at 158 GeV/nucleon results higher than the one obtained in pp interactions at 200 GeV [53] ($dN/d\eta_{\rm CM} \approx 1.55 \pm 0.04$ after conversion from the measured dN/dy). This comparison suggests a steep increase of particle production in central ion–ion collisions between 40 and 158 GeV which cannot be described by a simple energy scaling as observed in nucleon–nucleon collisions. Therefore, the particle production at 158 GeV/nucleon, although it scales approximately linearly with the number of participants, cannot be explained as an ordinary superposition of nucleon–nucleon interactions.

5. Conclusions

The charged particle pseudorapidity distributions $dN_{ch}/d\eta$ have been studied as a function of the number of participant nucleons $N_{\rm part}$ and of binary nucleon–nucleon collisions $N_{\rm coll}$ in Pb–Pb collisions at two different beam energies, namely, 158 GeV per nucleon ($\sqrt{s} = 17.3$ GeV) and 40 GeV per nucleon ($\sqrt{s} = 8.77$ GeV).

The maximum of the $dN_{ch}/d\eta$ distributions has been estimated by means of gaussian fits. The results obtained indicate a steep increase of particle production at SPS energies, which amounts to approximately a factor of 2 when going from $\sqrt{s} = 8.77$ GeV to 17.3 GeV.

The charged particle pseudorapidity density at midrapidity scales as $N_{\rm part}^{\alpha}$ with $\alpha = 1.00 \pm 0.01({\rm stat}) \pm 0.04({\rm syst})$ at 158 GeV per nucleon beam energy, in agreement with the Wounded Nucleon Model predictions. The presence of a contribution scaling like $N_{\rm coll}$ is not observed, so that hard processes seem to play a negligible role in charged particle production at 158 GeV per nucleon. This is also supported by the fact that the value of the α exponent is compatible with the one obtained from the data at 40 GeV per nucleon ($\alpha = 1.02 \pm 0.02 \pm 0.06$) where no contribution from hard processes is expected.

The increase of charged particle production at midrapidity between 40 and 158 GeV/nucleon cannot be described by the simple energy scaling observed in nucleon–nucleon collisions at similar energies.

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