

Multiplicity of charged particles in Pb–Pb collisions at SPS energies

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Abstract. The multiplicity of charged particles in the central rapidity region has been measured by the NA57 experiment in Pb–Pb collisions at the CERN SPS at two beam momenta: 158 A GeV/ c and 40 A GeV/ c . The value of $dN_{ch}/d\eta$ at the maximum has been determined and its behaviour as a function of centrality has been studied in the centrality range covered by NA57 (about 50% of the inelastic cross section). The multiplicity increases approximately logarithmically with the centre of mass energy.

1. Introduction

Ultrarelativistic heavy-ion collisions probe matter at extreme values of temperature and energy density, where the phase transition to the Quark Gluon Plasma phase is expected to occur [1]. The multiplicity of charged particles produced at central rapidity is in this context an important global observable, related to the entropy of the system formed in the collision [2] and to the initial energy density [3].

The NA57 experiment measures the event multiplicity with a dedicated Microstrip Silicon Detector (MSD). This measurement is used for the off-line estimate of the centrality of the interactions, i.e. the number of nucleons that participate in the collision [4]. This allows us to study the production of hyperons (Λ , Ξ , Ω and their antiparticles) in Pb–Pb collisions as a function of the collision centrality [5].

In this paper we use the charged particle multiplicity measured by the MSD to determine the maximum of the pseudorapidity distribution ($dN_{ch}/d\eta|_{max}$); in the following we describe the procedure employed to extract the peak value of $dN_{ch}/d\eta$ from the raw data at both beam momenta explored by NA57, 158 A GeV/ c and 40 A GeV/ c . The peak value of $dN_{ch}/d\eta$ is the variable most frequently used to characterize the multiplicity of the interaction, since it allows a comparison between different experiments, being independent of the detailed phase space acceptance. The measurement of the centrality for the sample at 40 A GeV/ c , presented here for the first time, is performed with a similar procedure as for the 158 A GeV/ c sample [4]. Our measurements cover a centrality range corresponding to the most central 53% of the total inelastic cross section.

2. The experimental set-up

The NA57 experiment is designed to study the production of strange particles in heavy ion collisions by reconstructing their charged decay products in a high granularity silicon pixel telescope placed in the magnetic field provided by the GOLIATH magnet (1.4 T central value). The complete NA57 set-up has been described elsewhere [6]; here we concentrate on the detectors that are relevant for the present analysis.

NA57 has collected data with a lead beam incident on a lead target (1% interaction length) at two beam momenta: 158 A GeV/ c and 40 A GeV/ c . A centrality trigger provided by six scintillators, placed around the beam line, 10 cm downstream of the target, selects about 60% of the most central total inelastic cross section. A special effort was made to reduce background sources in order to extend the centrality range towards peripheral events, the main limit coming from the empty target contamination. Care was also taken to reject double interaction events.

Two planes of microstrip silicon detectors (MSD) placed between the target and the telescope are used to sample the charged particle multiplicity. Each plane consists of three arms (fig. 1), each of them composed of 200 strips of pitches ranging from 100 μm to 400 μm . The strip geometries were chosen so as to keep the occupancy approximately

uniform ($\simeq 10\%$ for the most central Pb-Pb collisions). The magnetic field direction is orthogonal to the beam direction and parallel to the MSD planes.

The detector efficiency has been determined to be well above 99% by correlating the tracks reconstructed in the telescope with the hits recorded in the bottom arm in a special proton beam run where the MSD and the telescope were aligned on the beam.

In the 158 A GeV/ c configuration the two MSD planes are placed respectively 19.8 cm and 54.5 cm downstream of the target; in the 40 A GeV/ c configuration, the planes are positioned at 20.4 cm and 38.0 cm of the target. With this geometry, the first and the second plane cover approximately the pseudorapidity regions $1.9 < \eta < 3$ and $3 < \eta < 4$ for the 158 A GeV/ c configuration (central rapidity $y_{cm} = 2.9$), and $1.9 < \eta < 3$ and $2.4 < \eta < 3.6$ for the 40 A GeV/ c configuration (central rapidity $y_{cm} = 2.2$). The transverse momentum acceptance region extends down to a few MeV/ c ; the azimuthal acceptance is about 30% for both planes.

3. Multiplicity reconstruction

The reconstruction proceeds as described in the following. The detector provides analogue signals approximately proportional to the energy lost by the crossing particle. A run-by-run calibration^{||} is performed in order to equalize the strip signals and to remove the noisy strips (less than 1%). The number of clusters is determined, where a cluster is a group of contiguous strips above threshold.

The multiplicity of charged particles on the detector (hit multiplicity, N_{hit}) is then evaluated by an algorithm that takes into account the total energy deposited in the clusters: the cluster charge is compared with the expected values from 1, 2 and more particles, in order to account for clusters produced by the passage of more than 1 particle. The hit multiplicity distribution presented in this analysis is obtained from a sample of about 10^6 events covering the full data taking period.

The contribution to the triggered sample from interactions in air or in other materials along the beam line (*empty target* contamination) was evaluated using data collected without the target and then subtracted.

The hit multiplicity is corrected for event uncorrelated background hits, mostly due to δ -rays, estimated from “beam trigger” data. This contribution amounts to about 5 hits per event over the full MSD for both beam momenta.

The distribution of the hit multiplicity N_{hit} in the range $2 < \eta < 4$ for the 158 A GeV/ c data is shown in fig. 2 (top). The decrease at low multiplicity is due to the trigger condition. The empty target contribution is $\simeq 6\%$, concentrated at very low multiplicity.

In the 40 A GeV/ c configuration there is an overlap between the pseudorapidity coverage of the two planes, corresponding to the region $2.4 < \eta < 3$. In this region the multiplicity is determined by an average of the multiplicity measured by the two planes. A small distortion in the overlap due to the magnetic field is corrected for by simulation.

^{||} In normal conditions a run corresponds to about half an hour of data taking.

The distribution of N_{hit} in the range $1.9 < \eta < 3.6$ is shown in figure. 2 (bottom). The empty target contamination here is $\simeq 13\%$; the δ -ray contamination is about the same as at high energy. In either case the total measured multiplicity is not sensitive to the polarity of the magnetic field.

In order to obtain the charged particle multiplicity produced over the full azimuthal range (N_{ch}) a geometrical correction must be applied. The correction is determined by tracing Pb–Pb events generated by VENUS [7] through a GEANT [8] simulation of the apparatus, including the detailed magnetic field map and the full detector response. In this way charge sharing effects, secondary interactions, gamma ray conversions and particle decays are accounted for. This correction also account for the small extrapolation down to p_t equal to zero.

The resulting distribution of N_{ch} has been used to estimate the centrality of the interactions, as discussed in the next section.

The charged particle multiplicity produced in a restricted range of pseudorapidity η can be measured by selecting only the strips which cover the corresponding acceptance. We indicate by $N_{hit}(|\eta| < 0.5)$ and $N_{ch}(|\eta| < 0.5)$ the hit and the total charged multiplicity measured in one unit of η at the position of the maximum of the distribution ($\eta|_{max}$) ¶.

In fig. 3 the correlation between $N_{ch}(|\eta| < 0.5)$ and $N_{hit}(|\eta| < 0.5)$ is shown for the two beam momenta. The correlations obtained using two different Monte Carlo generators VENUS and RQMD [9] are in good agreement; the difference is less than 2% over the full range of multiplicity.

The peak value $dN/d\eta|_{max}$ can be obtained applying a correction factor f to $N_{ch}(|\eta| < 0.5)$, corresponding to the ratio between the peak and the average value in the central η unit. The factor f depends on the shape of the distribution. Values of the width σ of the η distribution were measured by other collaborations [10] [11], and a very weak dependence on the centrality was reported. This allows us to use the same value f for the whole centrality range spanned by NA57. Taking an average of the reported σ values and assuming gaussian shape we can estimate $f=1.02$ at 158 A GeV/c and $f=1.03$ at 40 A GeV/c.

4. Multiplicity classes and participants

4.1. 158 A GeV/c data

The distribution of N_{ch} , shown in fig. 4, is used to determine the centrality of the events and to estimate the number of participants defined as the number of wounded nucleons [12], i.e. the nucleons which suffer at least one primary inelastic collision. The procedure to extract the average number of wounded nucleons, $\langle N_{wound} \rangle$, has been described in detail in reference [4], where the multiplicity distribution has been fitted with a model (generalized wounded nucleon model), where the charged multiplicity ¶ $\eta|_{max} = 2.4$ and $\eta|_{max} = 3.1$ for 40 and 158 A GeV/c beam momenta respectively.

N_{ch} is assumed to be proportional to a power of the number of wounded nucleons: $N_{ch} \propto N_{wound}^\alpha$. The number of wounded nucleons is estimated from a geometrical model of the Pb-Pb collision (Glauber model [12]).

The data are reasonably well described with $\alpha=1$, as assumed in the standard approach (fig. 4, top). Allowing α to vary as a free parameter in the fit gives an improved description with values in the range 1.02-1.09. This produces a change in $\langle N_{wound} \rangle$ of about one unit; so for the 158 A GeV/c analysis we fix $\alpha=1$.

For the purpose of this study we divide the data into nine centrality classes. The centrality is indicated by the corresponding fraction of inelastic cross section σ_{inel} . The fractions are evaluated by a MonteCarlo based on the Glauber model, and reported in table 1. The inelastic cross section evaluated by the Glauber model, is $\sigma_{inel}^{glau} = 7.26$ barn. The trigger cross section measured from the rate of triggered events, the incoming flux and the target thickness is $\sigma_{trig}^{exp} = 4.15 \pm 0.11$ barn, in agreement with the value obtained with the Glauber fit, therefore the trigger cross section is 57% of the total. For this analysis we limit the centrality range to 50% of σ_{inel} . In table 1, we report for each centrality class, the average $dN/d\eta|_{max}$, the average number of wounded nucleons $\langle N_{wound} \rangle$ obtained by the fit (with $\alpha=1.0$) and the r.m.s. of their distribution are also reported.

Table 1. Average $dN/d\eta|_{max}$ and N_{wound} as a function of centrality (158 A GeV/c).

% of σ_{inel}	$\langle dN/d\eta _{max} \rangle$	$\langle N_{wound} \rangle$	r.m.s.
0–5	478 ± 10	349 ± 1	30
5–10	388 ± 9	293 ± 2	33
10–15	324 ± 9	245 ± 3	30
15–20	266 ± 8	201 ± 3	28
20–25	217 ± 7	165 ± 3	25
25–30	180 ± 7	136 ± 4	22
30–35	149 ± 6	114 ± 4	20
35–45	106 ± 5	81 ± 5	20
45–50	71 ± 4	51 ± 5	14

In table 2 the fraction and the absolute values of the cross section, integrated over the various centrality ranges are given, together with the corresponding average values of $dN/d\eta|_{max}$ and $\langle N_{wound} \rangle$.

In the standard NA57 analysis of the production of strange particles, the centrality dependence is studied using 5 centrality classes [5]. The resulting values of $\langle N_{wound} \rangle$ and the r.m.s. of the distributions in these classes are given in table 3 together with the empty target contribution, as discussed in section 3.

Table 2. Cross section, average $dN/d\eta|_{max}$ and N_{wound} for different centrality ranges (158 A GeV/c).

% of σ_{inel}	σ (barn)	$\langle dN/d\eta _{max} \rangle$	$\langle N_{wound} \rangle$
0–5	0.36 ± 0.01	478 ± 10	349
0–10	0.73 ± 0.02	434 ± 10	320
0–15	1.08 ± 0.03	398 ± 9	295
0–20	1.45 ± 0.03	361 ± 9	268
0–25	1.82 ± 0.05	332 ± 8	248
0–30	2.19 ± 0.05	309 ± 8	231
0–35	2.54 ± 0.07	288 ± 8	216
0–45	3.27 ± 0.09	244 ± 7	184
0–50	3.64 ± 0.10	226 ± 7	170

Table 3. NA57 standard centrality classes (158 A GeV/c).

bin	% of σ_{inel}	$\langle N_{wound} \rangle$	r.m.s.	% of empty target
4	0–5	349 ± 1	28	0
3	5–11	290 ± 2	36	0
2	11–23	209 ± 3	37	0
1	23–40	121 ± 4	30	0.9
0	40–53	62 ± 4	18	17

4.2. 40 A GeV/c data

The distribution of N_{ch} (shown in fig. 4, bottom), has been fitted using the same procedure as described above, excluding from the fit the low multiplicity region ($N_{ch} < 110$), where the empty target contribution is too large. The value $\alpha=1$ at 40 A GeV/c gives a poor fit; the distribution is well described with values of α in the range 1.09 to 1.12. The curve drawn in fig. 4 corresponds to $\alpha=1.10$.

The measured trigger cross section is $\sigma_{trig}^{exp} = 4.07 \pm 0.16$ barn, corresponding to about 56% of the inelastic cross section. This value is compatible with the result obtained from the Glauber fit of the multiplicity distribution. As in the case of the 158 A GeV/c data, we divide the data into nine centrality classes. For each centrality class, we indicate the average $dN/d\eta|_{max}$, the average number of wounded nucleons $\langle N_{wound} \rangle$ given by the fit (with $\alpha=1.10$) and the r.m.s. of the $\langle N_{wound} \rangle$ distribution.

Table 5 gives the fraction and the absolute values of the cross section integrated over various centrality ranges, the average values of $dN/d\eta|_{max}$ and $\langle N_{wound} \rangle$.

The centrality classes used for strange particle analysis at 40 A GeV/c are given in table 6. They are defined to give the same fractions of total cross section as in the 158 A GeV/c case. The $\langle N_{wound} \rangle$ and their r.m.s. in the case of $\alpha = 1.10$ are shown,

Table 4. Average $dN/d\eta|_{max}$ and N_{wound} as a function of centrality (40 A GeV/c).

% of σ_{inel}	$\langle dN/d\eta _{max} \rangle$	$\langle N_{wound} \rangle$	r.m.s.
0–5	348 ± 10	350 ± 1	27
5–10	275 ± 9	298 ± 1	31
10–15	225 ± 8	250 ± 2	29
15–20	185 ± 7	208 ± 3	27
20–25	150 ± 6	173 ± 4	24
25–30	122 ± 6	143 ± 4	22
30–35	97 ± 5	117 ± 5	20
35–45	69 ± 4	86 ± 5	19
45–50	46 ± 3	61 ± 5	15

Table 5. Cross section, average $dN/d\eta|_{max}$ and N_{wound} for different centrality ranges (40 A GeV/c).

% of σ_{inel}	σ (barn)	$\langle dN/d\eta _{max} \rangle$	$\langle N_{wound} \rangle$
0–5	0.36 ± 0.02	348 ± 10	346
0–10	0.73 ± 0.03	313 ± 10	318
0–15	1.09 ± 0.04	283 ± 9	295
0–20	1.44 ± 0.05	258 ± 9	273
0–25	1.82 ± 0.07	236 ± 8	253
0–30	2.18 ± 0.09	217 ± 8	235
0–35	2.53 ± 0.11	200 ± 7	218
0–45	3.26 ± 0.12	172 ± 7	191
0–50	3.64 ± 0.14	159 ± 6	177

together with the fraction of empty target contamination.

Table 6. NA57 standard centrality classes (40 A GeV/c).

bin	% of σ_{inel}	$\langle N_{wound} \rangle$	r.m.s.	% of empty target
4	0–5	346 ± 1	31	0
3	5–11	292 ± 1	41	0
2	11–23	208 ± 4	44	0
1	23–40	119 ± 5	36	8.5
0	40–53	57 ± 5	24	32

4.3. Energy dependence

In fig. 5 the ratio between $\langle dN_{ch}/d\eta|_{max} \rangle$ at 158 and 40 A GeV/ c beam momenta is plotted as a function of $\langle N_{wound} \rangle$. As a result of the above-mentioned difference of the exponent α between the two energies, the ratio decreases slowly with $\langle N_{wound} \rangle$, from 1.54 for the most peripheral to 1.37 for the most central events. The average ratio is 1.47.

In proton–proton collisions, the charged multiplicity at mid-rapidity is found to scale approximately with the logarithm of the centre of mass energy [14]. Assuming the same dependence to hold in Pb-Pb collisions one would expect: $dN_{ch}\eta|_{max}(158 A \text{ GeV}/c)/dN_{ch}d\eta|_{max}(40 A \text{ GeV}/c) \simeq \ln(17.3)/\ln(8.77)=1.31$. This value is indicated in fig. 5 by a horizontal line. In the same figure we also plot data from NA49 and NA50. The comparison between different experiments will be discussed in the next session.

5. Comparison with other experiments

A comparison between the number of participants as determined by NA57 and NA50 [11] is shown in fig. 6, for both 40 and 158 A GeV/ c samples. The NA57 points correspond to the first five classes of tables 1 and 4, while the NA50 range of centrality is 35% of σ_{inel} . A good agreement is observed. A maximum deviation of less than 3% (of the same order of the measurement error) is found in the 20-25% of σ_{inel} class for the 40 A GeV/ c sample.

In fig. 7 the values of $\langle dN/d\eta|_{max} \rangle$ from table 1 are compared with those measured by NA50 [11] at the same beam momentum (158 A GeV/ c).

There is good agreement for the most peripheral classes, whereas a systematic difference appears in the most central classes. As a consequence, the slopes of the correlations are slightly different. Both are compatible with a linear correlation. The value of α found by NA50 is $1.00 \pm 0.01(\text{stat}) \pm 0.04(\text{syst})$.

The NA49 collaboration has measured the multiplicity of identified charged particles at several energies [10]. An estimate to the total value of $dN/d\eta|_{max}$ can be obtained by summing the contributions from π , K , protons and their antiparticles. For the 158 A GeV/ c data we get $dN/d\eta|_{max} = 447 \pm 3$ for the 5% most central events (5% of σ_{inel}). The number of participants reported by the NA49 collaboration (362 ± 6) is larger than what is measured in the corresponding range by NA50 and NA57.

In order to have a further independent check of the multiplicity measurement we compare with the multiplicity of negative particles (h^-) measured in the WA97 telescope in Pb–Pb interactions at 158 A GeV/ c beam momentum. The values found by WA97 were obtained by extrapolating the yields measured in the acceptance window of the telescope ($p_t > 300$ MeV/ c) down to $p_t=0$, as described in [13]. This procedure does not take into account the effect of the “low p_t enhancement”, and so can underestimate the yields of negatives. To account for this, we made a new extrapolation using the p_t distribution of the negatives provided by VENUS, which is in good agreement with

experimental distributions down to very low values of p_t [7].

In order to scale from the $dN/d\eta_{negatives}$ to the $dN/d\eta_{charged}$ we multiply the yield of negatives by the ratio charged/negatives $r = 2.2$ obtained by NA49 [10]. The resulting values are plotted in fig. 7 as a function of $\langle N_{wound} \rangle$. A good agreement between NA57 and WA97 is obtained over the whole WA97 centrality range.

Fig. 8 shows the comparison among different experiments for the 40 A GeV/c data. We observe that at this energy the slopes of the correlation for NA50 and NA57 are in strong disagreement. For the most central class there is a factor 1.7 between the multiplicity measured by the two experiments. As discussed above, we obtain good fits with values of α in the range $1.09 < \alpha < 1.12$; the NA50 collaboration instead reports a value of $\alpha = 1.02 \pm 0.02(\text{stat}) \pm 0.06(\text{syst})$.

The NA49 collaboration has measured identified charged particles at 40 GeV [10] for the 7% most central events (instead of 5%). An estimate of $dN/d\eta|_{max}$ can be determined as before, by summing the contributions from π , K , protons and their antiparticles. The resulting value, plotted in fig. 8, is 286 ± 3 particles. At 7% centrality we measure a value of about 320 particles. Also in this case, the number of participants reported by NA49 is larger with respect to the determinations made by NA50 and NA57 at the same centrality.

In fig. 5 the ratio between $\langle dN_{ch}/d\eta|_{max} \rangle$ at 158 and 40 A GeV/c beam momenta for the NA50 data is shown as a function of $\langle N_{wound} \rangle$. The values are in the range 2.13-2.38, significantly larger than those measured by NA57.

The NA49 data at the two energies are given for two different centrality ranges. We therefore consider the ratio:

$$\frac{\langle dN_{ch}/d\eta|_{max} \rangle / \langle N_{wound} \rangle (158 A GeV/c)}{\langle dN_{ch}/d\eta|_{max} \rangle / \langle N_{wound} \rangle (40 A GeV/c)}$$

which gives the value 1.51. The horizontal position of the point in fig. 5 is the average between the participants of the most central classes at the two energies. As can be seen, the NA49 estimate is close to the measurement made by NA57.

6. Conclusions

We have measured the multiplicity of charged particles in Pb–Pb collisions at the CERN SPS at two beam momenta, 158 and 40 A GeV/c, in the pseudorapidity ranges $2 < \eta < 4$ and $1.9 < \eta < 3.6$ respectively. The multiplicity distributions are well described by a generalized wounded nucleon model where $\langle N_{ch} \rangle \propto N_{wound}^\alpha$. The value of α is compatible with 1 for the 158 A GeV/c data, and slightly larger than 1 for the 40 A GeV/c data.

The value of $dN_{ch}/d\eta$ at the maximum has been studied as a function of centrality over most of the centrality range covered by NA57. At 158 A GeV/c a good agreement is observed with the values determined extrapolating the WA97 results on negative particles, whereas some discrepancy is observed with NA50 and NA49 for the central

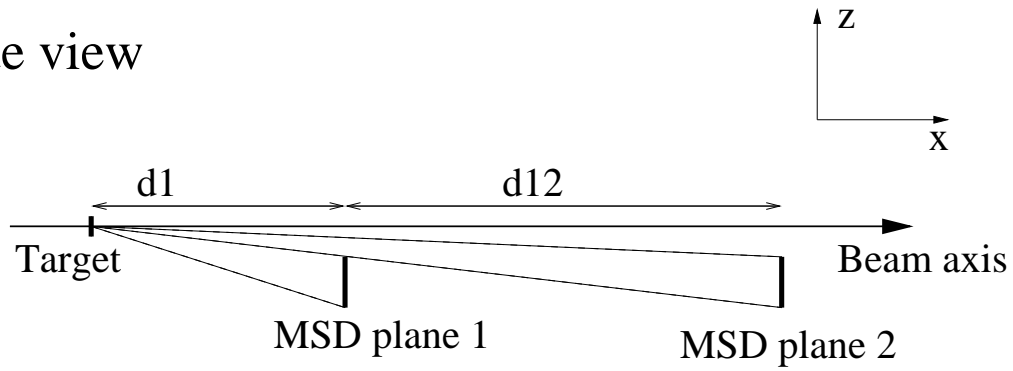
classes. At 40 A GeV/ c a strong disagreement among the three experiments is observed, when the measured energy dependence of the charged particle multiplicity is considered however, there is a good agreement between NA49 and NA57, whereas a disagreement with NA50 still persists.

We have compared the values of the participants for a given centrality determined by NA50 and NA57 over a wide centrality range, and found them to be very similar.

Finally, we find that the charged multiplicity at central rapidity is close to a logarithmic scaling with the centre of mass energy.

- [1] For a recent review on this subject see: Proceedings of “16th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions ” - Quark Matter 2002, Nucl. Phys. A**715** (2003); Proceedings of “17th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions ” - Quark Matter 2004, to be published on J. Phys. G.
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Side view



Front view

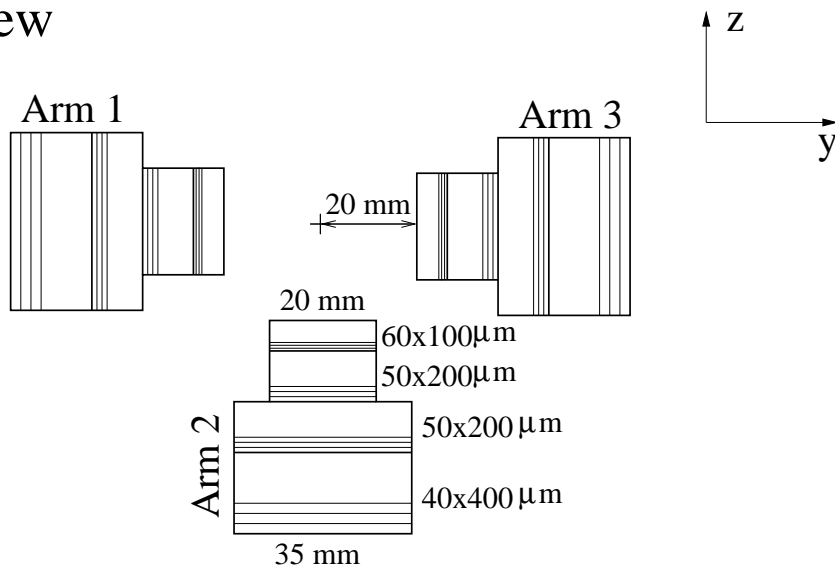


Figure 1. Layout of the Multiplicity Silicon Detectors (MSD). Only the lower arm is shown in the side view. See text for the values of the distances d_1 and d_{12} .

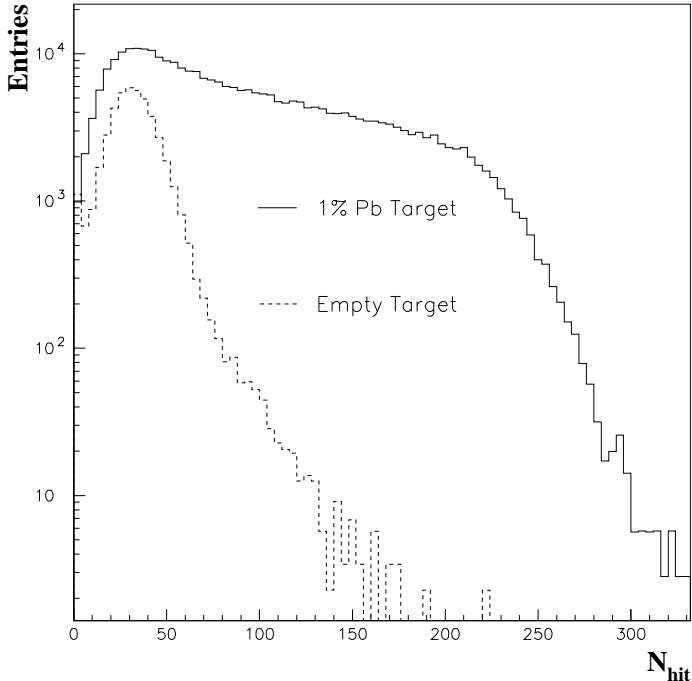
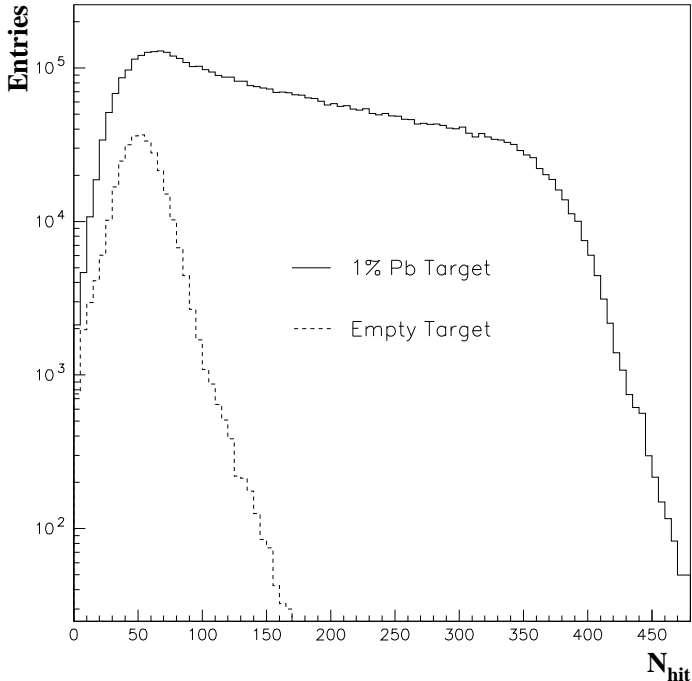


Figure 2. Hit multiplicity distribution at 158 *A* GeV/*c* (top) and 40 *A* GeV/*c* (bottom). The empty target contribution is also shown.

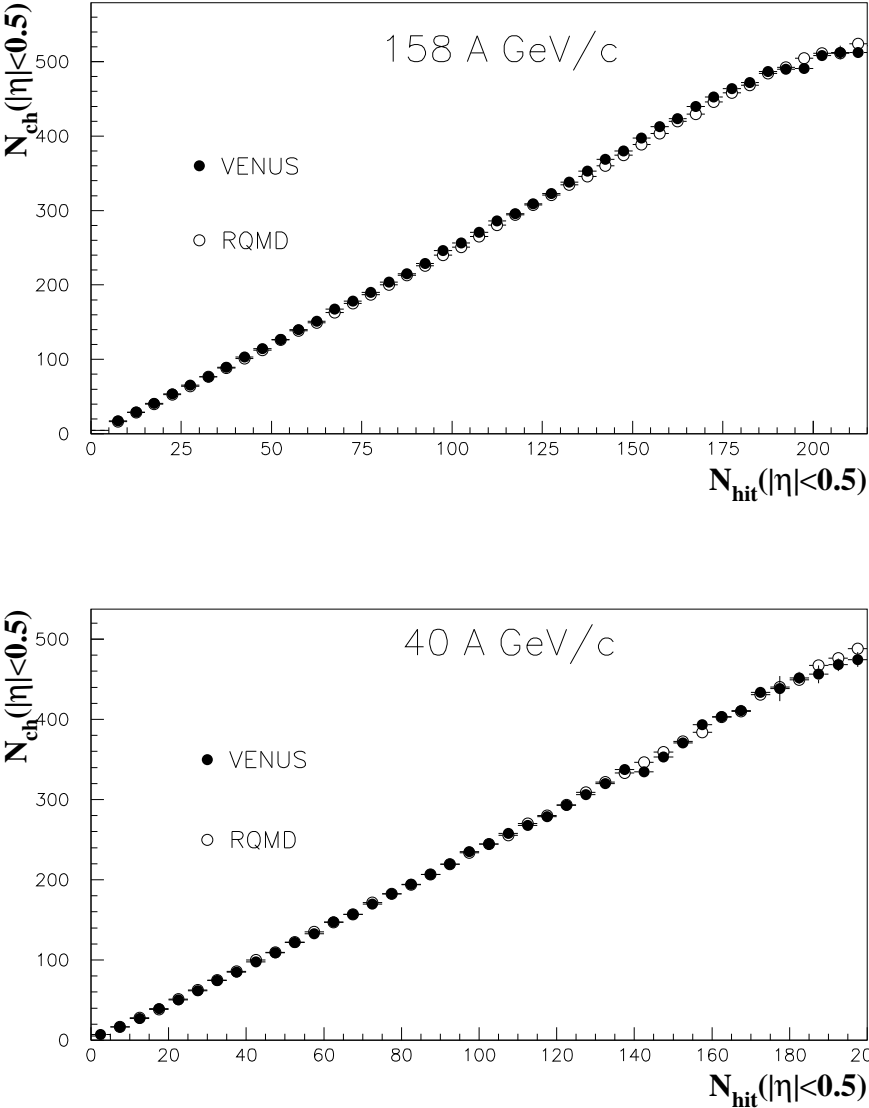


Figure 3. Correlation between charged particle multiplicity and hit multiplicity in one unit of pseudorapidity around central rapidity for 158 A GeV/c (top) and 40 A GeV/c (bottom) simulated data.

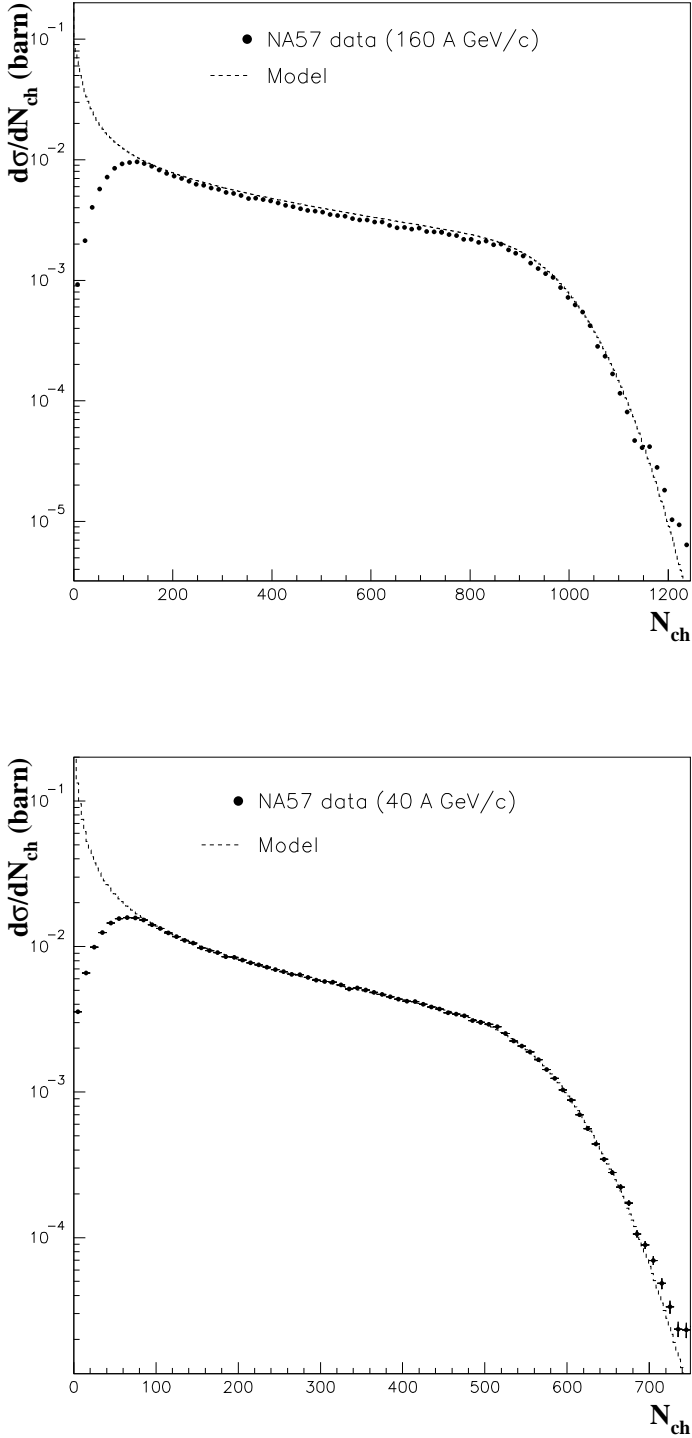


Figure 4. Experimental charged particle multiplicity distributions. Top: 158 A GeV/c data (range $2 < \eta < 4$); Bottom: 40 A GeV/c data (range $1.9 < \eta < 3.6$). The model with $\alpha = 1.00$ (top) and $\alpha = 1.10$ (bottom) is shown superimposed to the data.

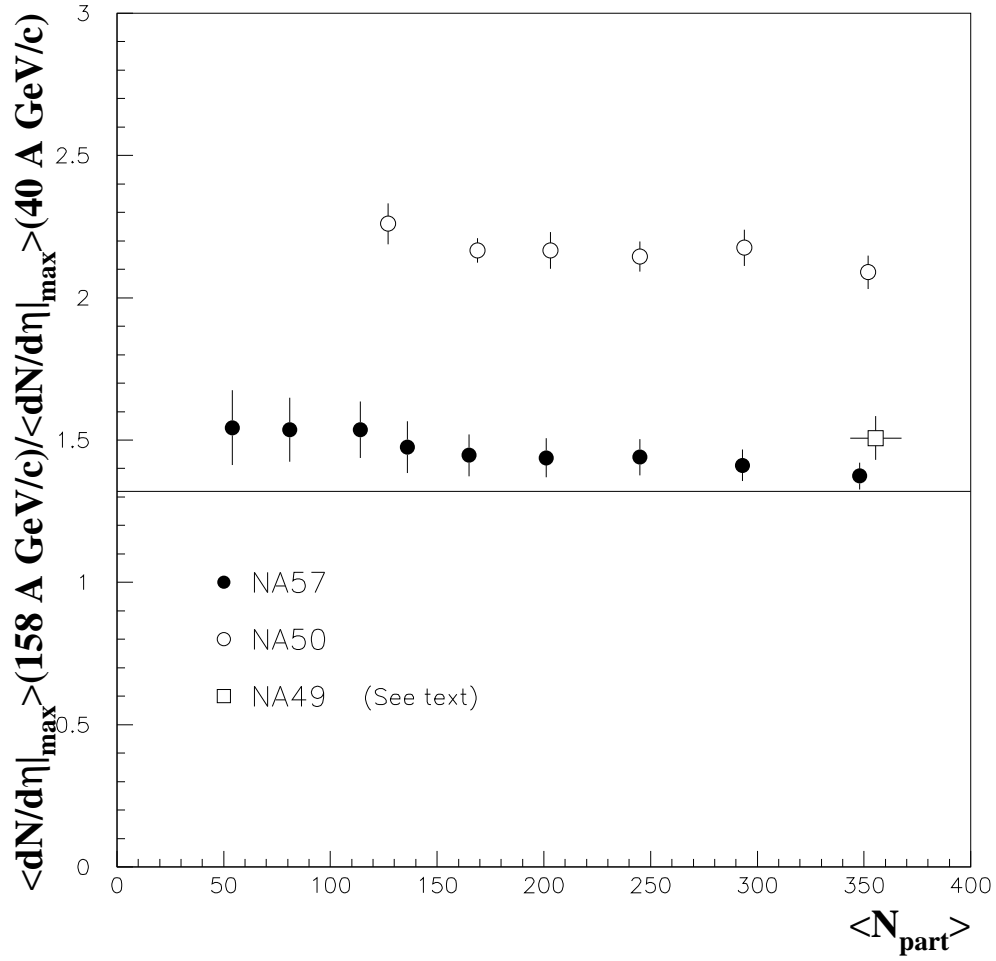


Figure 5. Ratio between $\langle dN/d\eta|_{max} \rangle$ at 158 and 40 A GeV/c as a function of the participants as measured by NA57 (fill circles), NA50 (open circles) and NA49 (open square). In the horizontal scale the average between the participants of the two centrality classes of NA49 is considered.

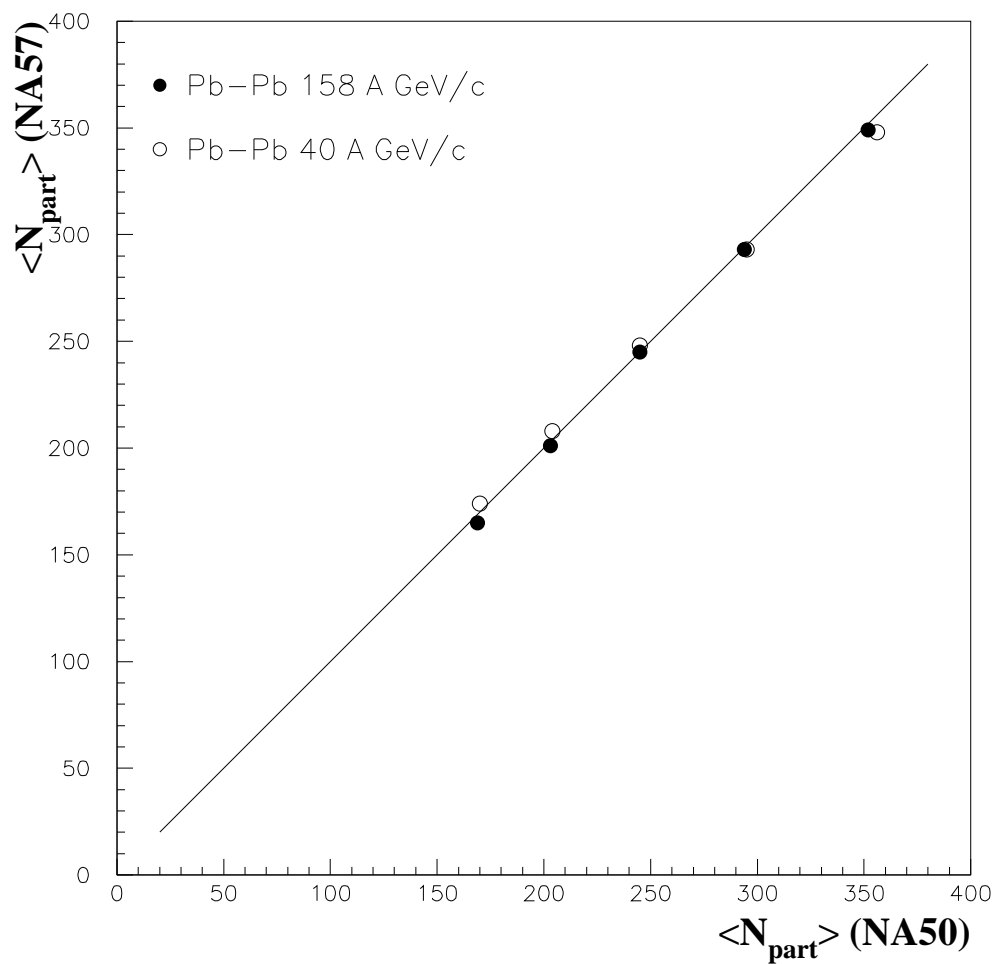


Figure 6. Comparison between the number of participants as determined by NA57 and NA50, for both 158 and 40 A GeV/c data. The full line indicates the diagonal; the error bars, where not shown, are contained within the symbols

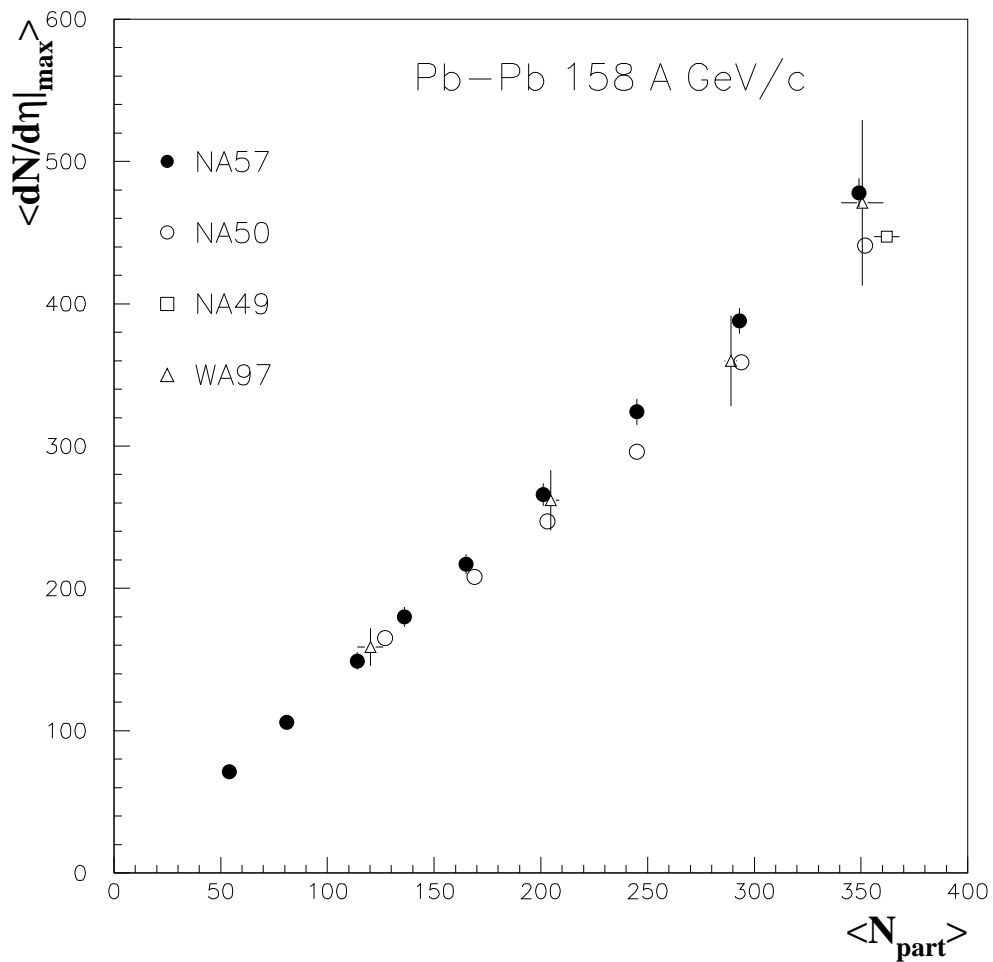


Figure 7. $\langle dN/d\eta|_{max} \rangle$ as a function of the average number of participants for the 158 A GeV/c data. The errors bars, where not shown, are contained within the symbols.

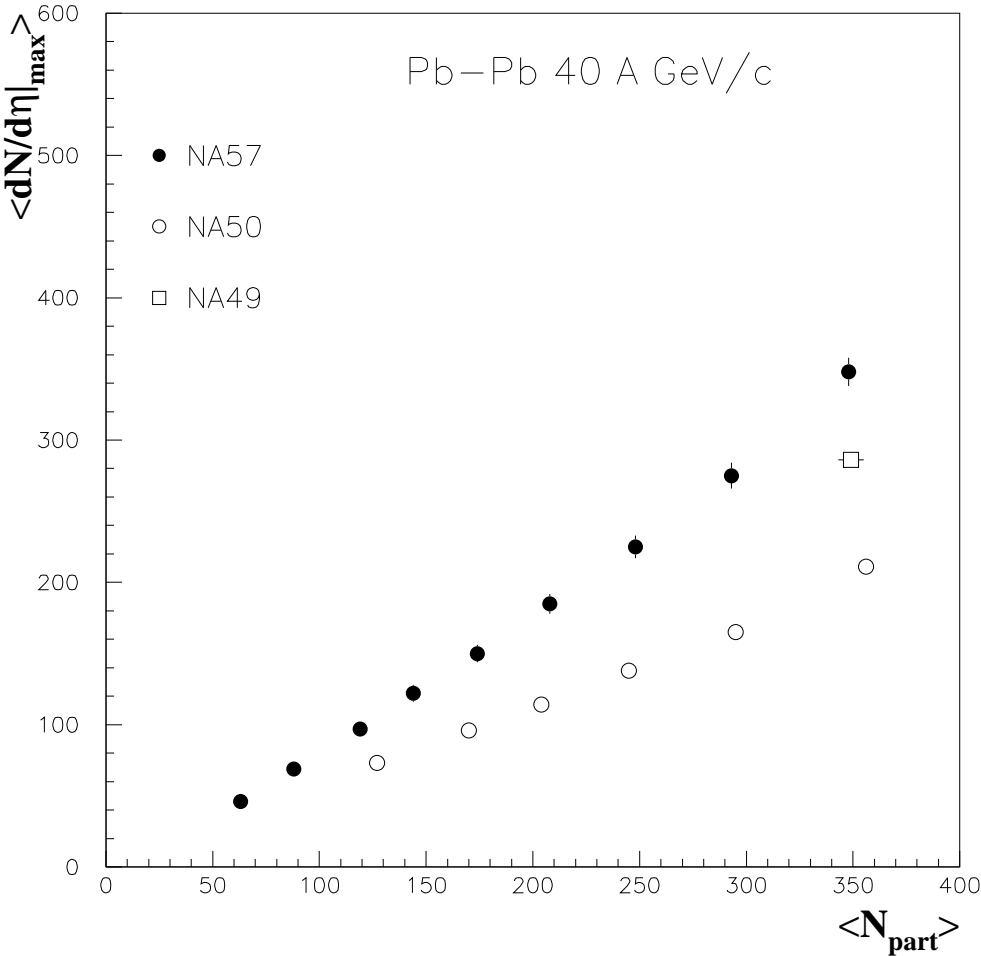


Figure 8. $\langle dN/d\eta|_{max} \rangle$ as a function of the average number of participants for the 40 A GeV/c data. The errors bars, where not shown, are contained within the symbols.