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Determination of the number of wounded nucleons in Pb+Pb collisions at 158 A GeV/c

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Abstract

The charged particle multiplicity distributions measured by two experiments, WA97 and NA57, in Pb + Pb collisions at $158\,A\,\mathrm{GeV}/c$ have been analyzed in the framework of the Wounded Nucleon Model (WNM). We obtain a good description of the data within the centrality range of our samples. This allows us to make use of the measured multiplicities to estimate the number of wounded nucleons of the collision.

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1 Introduction

The number of nucleons taking part in the collision is a fundamental parameter in the study of heavy–ion reactions at high energy since, for a given colliding system and beam energy, it determines the volume and the energy of the fireball. In heavy–ion experiments the centrality is usually estimated by measuring one or more of the following observables: charged particle multiplicity (N_{ch}), transverse energy (E_T) and energy deposited in a zero degree calorimeter (E_{ZDC}). The WA97 and NA57 experiments estimate the centrality using the charged particle multiplicity measured over the pseudorapidity range $2 < \eta < 4$.

The Glauber model [1] provides a simple geometrical interpretation of a collision between nuclei. In this model the projectile nucleons traverse the target nucleus in a straight line and can undergo several collisions with the nucleons of the target. The assumption is made that although a nucleon becomes excited as a result of successive collisions, it still interacts with the same cross section as the original nucleon. The Wounded Nucleon Model (WNM) [2] assumes that the average multiplicity in a collision is proportional to the number of nucleons which suffered at least one inelastic collision with another nucleon (*wounded nucleons*, N_{wound}). In previous papers [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15] we have called this variable number of participants (N_{part}). The WNM proved to be successful in describing the charged particle multiplicity in proton–nucleus (p + A) interactions [16]. In this paper we shall study the extent to which this proportionality also holds in Pb + Pb reactions. Such a scaling law has already been shown to work for E_T [17] in Pb + Pb collisions.

2 Multiplicity measurement

The NA57 and WA97 experiments have similar layouts, and in particular they employ the same multiplicity detectors (MSD, see figure 1). In NA57 however, a special effort was made to reduce various background sources in order to extend the centrality range covered towards lower values. The NA57 set–up has been described in Ref. [18]; the WA97 set–up, shown in figure 1, has been described in Ref. [19]. In both experiments a $158\,A\,\mathrm{GeV}/c$ lead beam is incident on a lead target with a thickness corresponding to 1% of the Pb + Pb interaction length. Scintillator petals, placed at 10 cm from the target and

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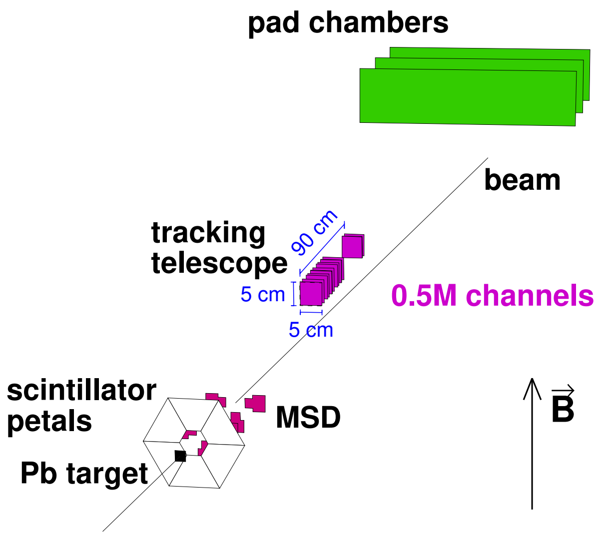

Figure 1: The WA97 set–up.

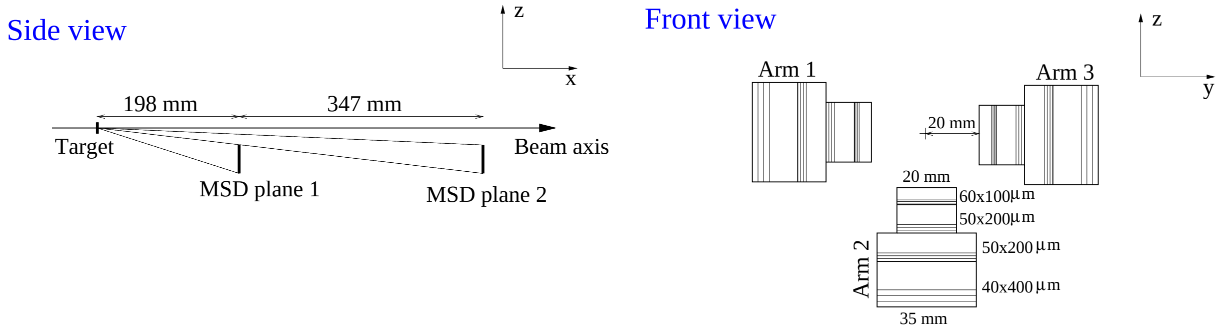

Figure 2: Layout of the micro–strip multiplicity detectors (MSD). For clarity on the side view only the lower arm is shown.

covering the pseudorapidity range $1 < \eta < 2$, provide a fast estimate of the multiplicity which is used at trigger level. For a more detailed study of the centrality of the collisions, the multiplicity of charged particles is measured by two planes of silicon micro-strip detectors (see figure 2), positioned respectively 20 cm and 55 cm downstream of the target. Each plane consists of three independent arms. The strip dimensions were chosen so as to keep the occupancy approximatively uniform. With this geometry, the first and the second plane cover the pseudorapidity region $2 < \eta < 3$ and $3 < \eta < 4$ respectively. The azimuthal acceptance is about 30% for both planes.

Each strip provides an analogue signal proportional to the energy lost by the traversing particle. The number of clusters is counted, where a cluster is defined as the number of contiguous strips above threshold. The multiplicity of charged particles on the detector (*hit multiplicity*, M_{hit}) is then evaluated by an algorithm that takes into account the total energy deposited in the clusters. This procedure includes a small correction for double hits, which are more frequent in the high multiplicity events. The hit multiplicity distribution for the WA97 and NA57 experiments are shown in figure 3. The drop at low multiplicities is the effect of the scintillator petals centrality trigger suppressing low multiplicity events.

The contribution to our triggered sample due to interactions in the air or other materials along the beam line (*empty target* contamination) was evaluated using data

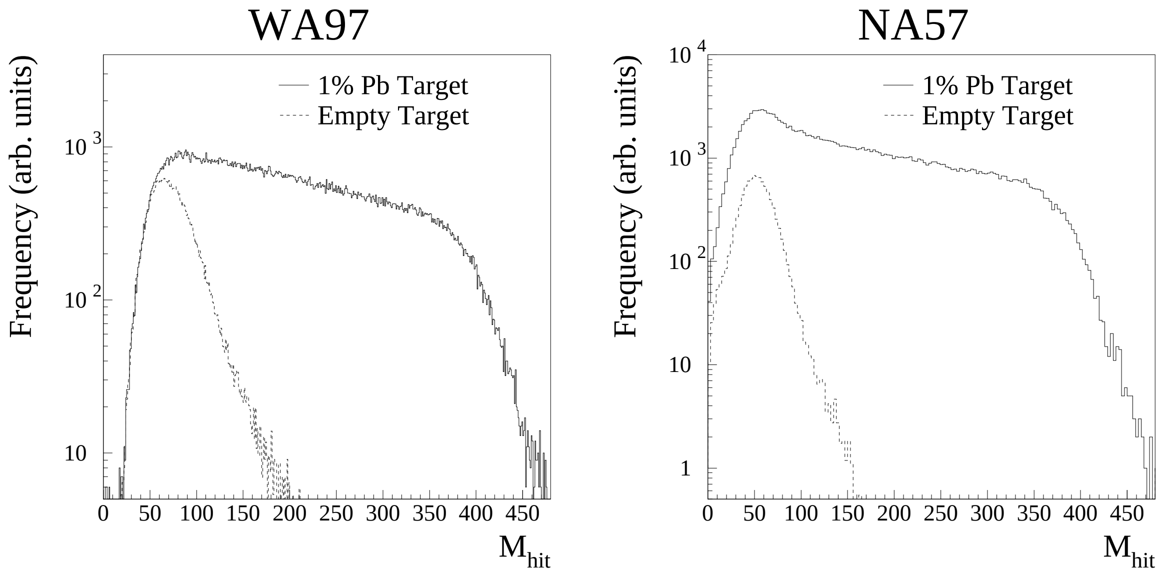

Figure 3: Hit multiplicity distribution of the triggered Pb + Pb events (solid histogram) and of the empty target sample (dashed histogram).

collected without the target and then subtracted from the MSD data. The empty target contamination was $\simeq 17\%$ of the triggered events for WA97 and $\simeq 6\%$ for NA57 (see figure 3). The hit multiplicity on the MSD detectors M_{hit} was then corrected for delta–rays and background hits. The delta–ray contribution to the measured multiplicity, coming mainly from the passage in air of any non interacting lead ion while the MSD is integrating the signals of a triggered event, amounts to about 2.5% of the maximum multiplicity for WA97 and to 0.7% for NA57. In order to obtain the charged particle multiplicity distribution in the pseudorapidity range $2 < \eta < 4$, the hit multiplicity was also corrected for geometrical acceptance, detector response (efficiency, double hits, charge sharing between contiguous strips), secondary interactions and gamma ray conversions, which have been estimated by a Monte Carlo simulation.

The measured multiplicity distribution is smeared due to fluctuations inherent in the experimental sampling process. Such a smearing has been evaluated by studying the relative multiplicity fluctuations between the two MSD planes. This sampling dispersion has been evaluated assuming that the two planes give independent measurements of N_{ch} since they cover two practically non–overlapping pseudorapidity intervals symmetric around mid–rapidity.

3 Wounded Nucleon Model fit to the data

We describe the multiplicity distribution in the framework of the WNM. We assume that the average charged particle multiplicity is proportional to the number of wounded nucleons, computed from the Glauber model [2]:

$$\langle N_{ch} \rangle = q N_{wound}, \tag{1}$$

where q is the proportionality constant. The only physical inputs to the model are the density distribution of the nucleons inside the nucleus and the nucleon–nucleon cross section. Since we are interested in non–diffractive particle production we use the nucleon–nucleon inelastic cross section $\sigma_{in} = 30\,\text{mb}$. The nuclear density ρ has been parametrized

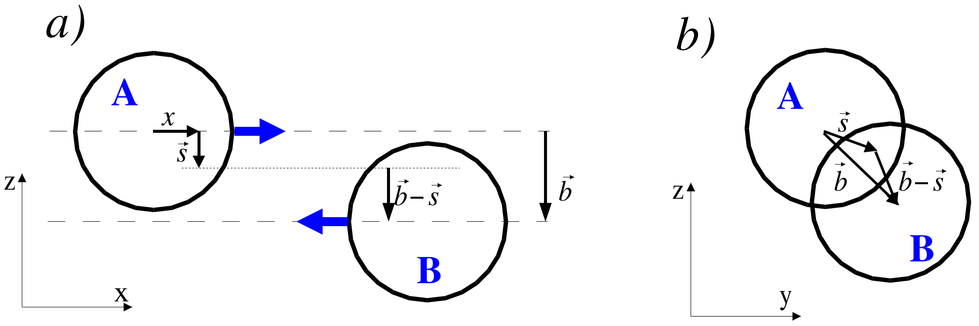

Figure 4: Schematic view of the interaction geometry along the collision axis (a) and on the plane perpendicular to the collision axis (b).

by a Woods–Saxon distribution:

$$\rho(r) = \frac{\rho_0}{1 + e^{(r-r_0)/C}} \ , \tag{2}$$

with parameters $r_0 = 6.62$ fm and $C = 0.546$ fm as measured in electron–nucleus scattering experiments [20].

A schematic view of the geometry of the collision and of the variables used in the following is shown in figure 4. The probability P of having exactly n nucleon–nucleon inelastic interactions for a collision with impact parameter $\mathbf{b}$ between the target nucleus A and the projectile B is [1]:

$$P(n, \mathbf{b}) = \binom{AB}{n} \left[T(\mathbf{b})\sigma_{\rm in}\right]^n \left[1 - T(\mathbf{b})\sigma_{\rm in}\right]^{AB-n}, \tag{3}$$

where the total thickness function $T(\mathbf{b})$ is written in terms of the nuclear thickness functions $T_{A,B}(\mathbf{b})$:

$$T(\mathbf{b})\sigma_{\rm in} = \int \mathrm{d}\mathbf{s}\, T_A(\mathbf{s})\, T_B(\mathbf{b} - \mathbf{s})\, \sigma_{\rm in}, \tag{4}$$

$$T_{A,B}(\mathbf{b}) = \int \rho_{A,B}(\mathbf{b}, x)\, \mathrm{d}x, \tag{5}$$

where x is the coordinate along the beam axis and $\mathbf{s}$ spans the plane perpendicular to the collision axis. The average number of wounded nucleons for a given impact parameter $\mathbf{b}$ is [17]:

$$\begin{aligned}\langle N_{wound}(\mathbf{b})\rangle = A \int T_A(\mathbf{s})\, \{1 - [1 - T_B(\mathbf{b} - \mathbf{s})\sigma_{in}]^B\} \mathrm{d}^2\mathbf{s} \\ + B \int T_B(\mathbf{b} - \mathbf{s})\, \{1 - [1 - T_A(\mathbf{s})\sigma_{in}]^A\} \mathrm{d}^2\mathbf{s}.\end{aligned} \tag{6}$$

For a fixed impact parameter the dispersion of the number of charged particles is given by the formula:

$$\sigma^2_{N_{ch}} = q^2 \sigma^2_{N_{wound}} + N_{wound}\sigma^2_q + (\sigma^{exp}_{N_{ch}})^2, \tag{7}$$

where $\sigma_{N_{wound}}$ is the dispersion of the number of wounded nucleons for a fixed impact parameter and σ_q is the dispersion of the number of charged particles per wounded nucleon.

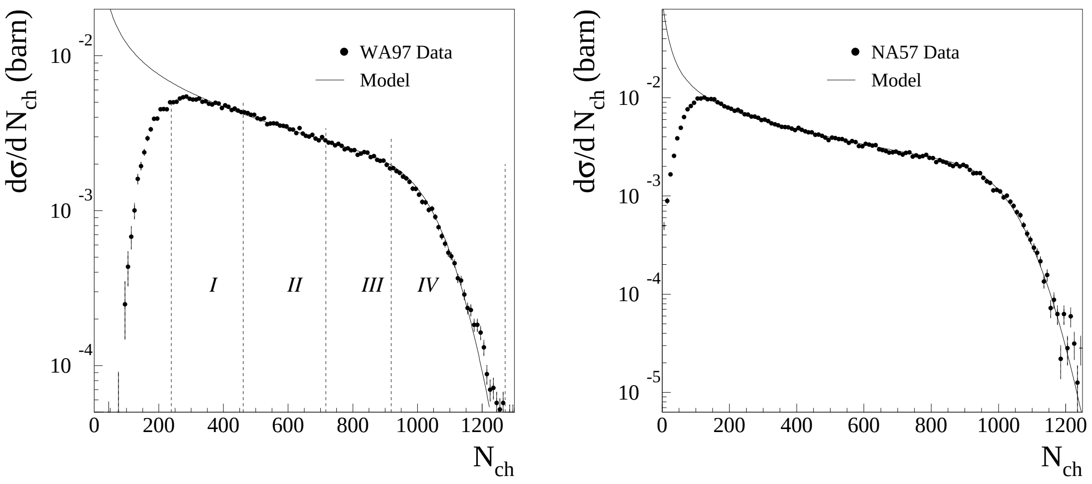

Figure 5: Fit of the multiplicity distributions with the Wounded Nucleon Model for the WA97 (left) and NA57 (right) experiments.

$\sigma_{N_{wound}}$ has been evaluated via a Monte Carlo implementation of the Glauber model. According to p + p data up to ISR energies, the dispersion σ_q is proportional to the charged particle multiplicity [21], *i.e.* $\sigma_q = aq$, where $a \simeq 1$ at SPS energies in the pseudorapidity range $2 < \eta < 4$ [22, 23]. The last term in equation (7) is the experimental sampling dispersion discussed previously.

The differential inelastic Pb + Pb cross section $\frac{\mathrm{d}\sigma_{in}^{\mathrm{Pb+Pb}}}{\mathrm{d}N_{ch}}$ can be written as:

$$\frac{\mathrm{d}\sigma_{in}^{\mathrm{Pb+Pb}}}{\mathrm{d}N_{ch}}(N_{ch}) = \int \mathrm{d}\mathbf{b}\,[1 - P(0,\mathbf{b})] \times \frac{1}{\sqrt{2\pi}\sigma_{N_{ch}}} \exp\left\{-\frac{(N_{ch} - q\,\langle N_{wound}(\mathbf{b})\rangle)^2}{2\sigma^2_{N_{ch}}}\right\}, \tag{8}$$

where $[1 - P(0, \mathbf{b})]$ is the probability of having at least one inelastic collision at impact parameter $\mathbf{b}$.

Figure 5 shows the WNM fit to the corrected WA97 and NA57 charged particle multiplicity distributions in the range $2 < \eta < 4$. We fitted simultaneously both the proportionality constant q and the absolute normalization. We indicate the value of the trigger cross section extracted from the fit normalization as σ_{trig}^{fit}. The parameters of the fit of $\mathrm{d}\sigma/\mathrm{d}N_{ch}$ are shown in table 1, where the quoted errors include both statistical (first error) and systematics (second error) contributions. The fitted trigger cross section for the WA97 experiment is compatible with the estimated experimental value of about 40% of the total Pb + Pb inelastic cross section. In the NA57 experiment the trigger cross section was measured with a 3% precision and its value, $\sigma_{\mathrm{trig}}^{\mathrm{exp}} = (4.29 \pm 0.12)$ barn, corresponding to 60% of the total nuclear inelastic cross section, is in agreement with the value obtained from the WNM fit.

Figure 5 also shows the four centrality classes used in the analysis of the WA97 experiment [4]. To compute the average number of wounded nucleons in each multiplicity class one needs to compute the distribution of N_{wound} with the constraint that the multiplicity falls in the selected bin. This has been done by inverting the equation (8)

Table 1: Parameters of the fit.

	WA97	NA57
q	$2.70 \pm 0.03 \pm 0.08$	$2.62 \pm 0.03^{+0.02}_{-0.05}$
σ_{trig}^{fit} (barn)	$3.14 \pm 0.09^{+0.11}_{-0.12}$	$4.42 \pm 0.14^{+0.15}_{-0.07}$
χ^2/d.o.f.	2.05	1.50

Table 2: Average N_{wound} and FWHM of the distribution for the four WA97 multiplicity classes.

	Bin 1	Bin 2	Bin 3	Bin 4
$\langle N_{wound} \rangle$	$120.1^{+5.7}_{-6.1}$	$204.6^{+4.1}_{-4.4}$	$289.0^{+2.5}_{-2.9}$	$350.6^{+0.9}_{-1.1}$
FWHM	79.7	90.3	81.3	72.1

in a Monte Carlo approach. Figure 6 shows the distribution of the number of wounded nucleons for each multiplicity bin according to the model. As can be seen in figure 5, the first multiplicity bin is the only one affected by the centrality trigger. For this bin a trigger efficiency has been calculated and accounted for [4]. The average values of N_{wound} together with the FWHM values of their distributions are listed in table 2.

4 Discussion

4.1 Particle yields as a function of centrality

The WA97 experiment measured the production of strange and multi–strange hadrons in p + A and in Pb + Pb collisions as a function of centrality. References [4, 5, 6, 8, 11] describe in detail the determination of the yields of negative hadrons (h^-), Λ, $\overline{\Lambda}$, Ξ^-, $\overline{\Xi}^+$, Ω^- and $\overline{\Omega}^+$ measured by the tracking telescope (see figure 1). Figure 7 shows, for the various particle species, the yields relative to their value in p + Be collisions as a function of the number of wounded nucleons obtained from the charged particle multiplicity as described in section 3. All the presented yields refer to one unit of rapidity centered around mid–rapidity and are extrapolated to full p_T. The values plotted correspond to p + Be, p + Pb and to the four centrality classes of the Pb + Pb system. The horizontal error bars of the Pb + Pb points represent the FWHM of the distribution of N_{wound} for a given centrality bin (see table 2). The number of wounded nucleons for the p + A systems have been computed in the framework of the Glauber model as an average over all inelastic collisions. In figure 7 the solid line represents what one would expect if the yields were proportional to the number of wounded nucleons all the way from p + Be to central Pb + Pb collisions.

As can be seen from figure 7, the value of the yields per wounded nucleon in Pb + Pb collisions is for all particles above its value in p + A collisions. This is true also for the h^- which show an enhancement of about 40% going from p + Be to Pb + Pb. In the Pb + Pb system however the yields of all particles are consistent with being proportional to the number of wounded nucleons in the covered centrality range. More quantitatively, we can fit the Pb + Pb yields Y of each particle with a power law:

$$Y \propto N_{wound}^{\alpha}. \tag{9}$$

Figure 8 shows the value of the exponent α for the various particle species; the result of the

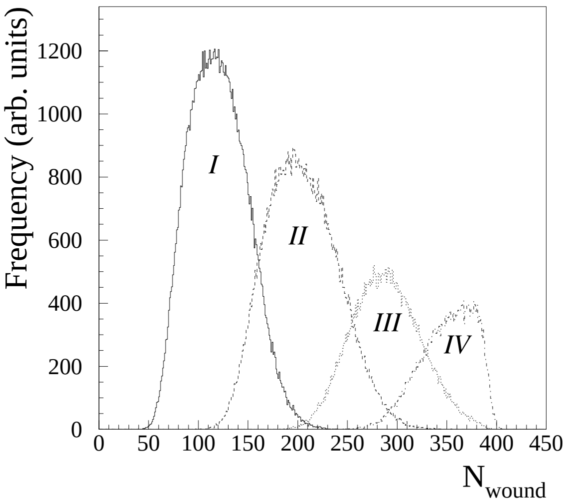

Figure 6: Distribution of the number of wounded nucleons in the four WA97 multiplicity bins.

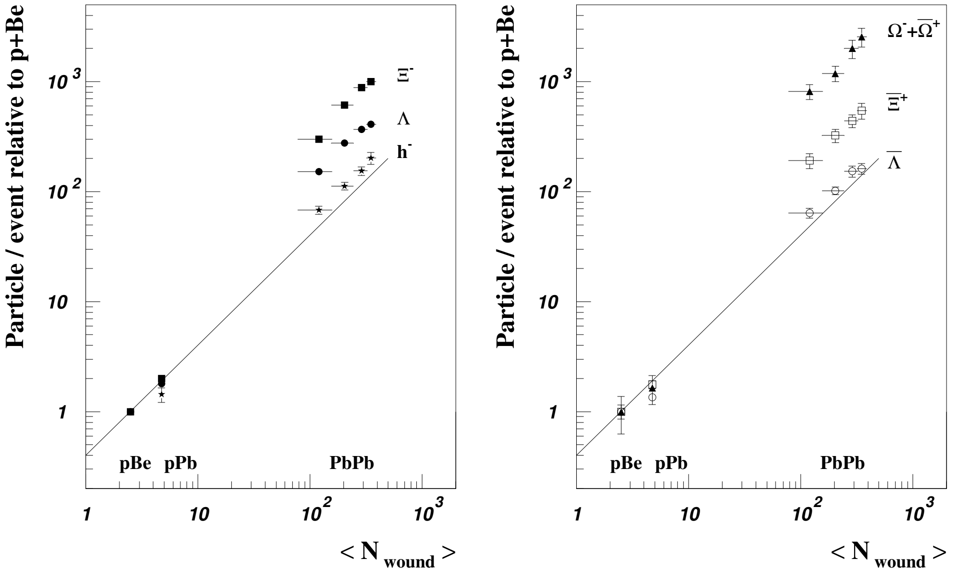

Figure 7: Yields relative to p + Be as a function of the number of wounded nucleons for h^-, Λ, $\overline{\Lambda}$, Ξ^-, $\overline{\Xi}^+$, $\Omega^- + \overline{\Omega}^+$ in p + Be, p + Pb collisions and for the four centrality classes of the Pb + Pb collisions.

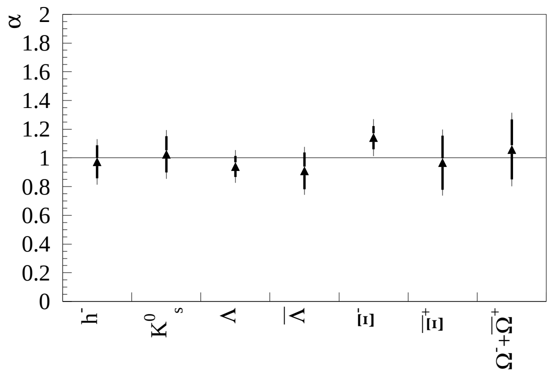

Figure 8: Value of the exponent α from a fit to eq. (9) for the various particle species measured by WA97.

Table 3: Result of the fits of the particle yields with equation 9.

Particle	α	χ^2/d.o.f
h^-	$0.97 \pm 0.12 \pm 0.04$	0.15
K^0_S	$1.02 \pm 0.13 \pm 0.04$	0.80
Λ	$0.94 \pm 0.07 \pm 0.04$	1.30
$\overline{\Lambda}$	$0.91 \pm 0.13 \pm 0.04$	0.31
Ξ^-	$1.14 \pm 0.08 \pm 0.05$	1.44
$\overline{\Xi}^+$	$0.97 \pm 0.19 \pm 0.04$	0.01
$\Omega^- + \overline{\Omega}^+$	$1.06 \pm 0.21 \pm 0.05$	0.47

fits is listed in table 3. The first errors correspond to the statistics of our samples (thick error bars in figure 8), the second to the systematic errors on the determination of $\langle N_{wound} \rangle$ in the multiplicity classes (thin error bars in the figure). The latter are fully correlated among the different particle species. The fact that the exponent α is about 1 for the h^- shows that we find the same centrality dependence for the multiplicity of charged particles as measured with the MSD and for the negative hadron multiplicity measured with the tracking telescope. It should be noted that, within the present statistics, the yields in Pb + Pb are found to be proportional to N_{wound} for all particle species considered.

4.2 Comparison with other experiments at the SPS

The WA98 experiment, which also uses a Glauber definition of wounded nucleons, obtains a dependence between the number of charged particles and the number of wounded nucleons in Pb + Pb collisions slightly different from the one presented here (equation (1)) [24]. They parametrize the rapidity density of charged particles at mid–rapidity by a power law:

$$\left(\frac{\mathrm{d}N_{ch}}{\mathrm{d}\eta}\right)_{\max} \propto N^{\alpha}_{wound}, \tag{10}$$

and find the exponent to be $\alpha = 1.07 \pm 0.02$. We performed the fit of the multiplicity distribution relaxing the Wounded Nucleon Model hypothesis and assuming a power law dependence $\langle N_{ch} \rangle \propto N_{wound}^{\alpha}$, leaving α as a free parameter. We find a value $\alpha = 1.05 \pm 0.05$ which is compatible both with our assumption of proportionality between N_{ch} and N_{wound} and with the WA98 result.

5 Conclusions

We have presented the charged particle multiplicity measurements performed by the WA97 and NA57 experiments in the pseudorapidity range $2 < \eta < 4$ in $\mathrm{Pb+Pb}$ collisions at 158 $A\,\mathrm{GeV}/c$. The Wounded Nucleon Model provides a good description of the multiplicity distributions both with respect to the shape and to the absolute normalization of the spectra. This allowed us to estimate the number of wounded nucleons in $\mathrm{Pb+Pb}$ collisions. The extended centrality range of the NA57 data sample should allow us to have a sizable statistics of events down to $N_{wound} = 40$–50. This will make it possible to study $\mathrm{Pb+Pb}$ collisions having a similar number of wounded nucleons to that obtained in central $\mathrm{S+S}$ collisions.

It should be stressed that the definition of the number of nucleons participating in the collision is not trivial, especially when going to peripheral interactions. However for central collisions between symmetric target–projectile systems the centrality scales tend to converge to the same number of participants. This clearly suggests the need of studying symmetric systems at intermediate masses, like Cu+Cu or Sn+Sn.

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