

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

The WA97 and NA57 Collaborations

F. Antinori¹², A. Badalà⁶, H. Bakke², R. Barbera⁶, H. Beker¹⁴, W. Beusch⁷, I.J. Bloodworth⁴, M. Botje¹⁸, R. Caliendo¹, M. Campbell⁷, E. Cantatore⁷, W. Carena⁷, N. Carrer¹², A.P. de Haas¹⁸, D. Di Bari¹, S. Di Liberto¹⁴, R. Divia⁷, D. Elia¹, D. Evans⁴, K. Fanebust², J. Fedorišin⁸, G.A. Feofilov¹⁶, R.A. Fini¹, J. Ftáčnik⁸, B. Ghidini¹, G. Grella¹⁵, M. Gulino⁶, H. Helstrup³, A.K. Holme¹¹, D. Huss¹⁰, A. Jacholkowski¹, G.T. Jones⁴, P. Jovanovic⁴, A. Jusko⁸, R. Kamermans¹⁸, J.B. Kinson⁴, W. Klempt⁷, K. Knudson⁷, A.A. Kolojvari¹⁶, I. Králik⁸, P. Kuijter¹⁸, V. Lenti¹, R. Lietava⁵, R.A. Loconsole¹, G. Løvholden¹¹, M. Lupták⁸, V. Manzari¹, M.A. Mazzoni¹⁴, G. Martinská⁸, F. Meddi¹⁴, A. Michalon¹⁷, M.E. Michalon-Mentzer¹⁷, M. Morando¹², E. Nappi¹, F. Navach¹, P.I. Norman⁴, A. Palmeri⁶, G.S. Pappalardo⁶, B. Pastirčák⁸, F. Pellegrini¹², J. Pišút⁵, N. Pišútová⁵, F. Posa¹, E. Quercigh⁷, F. Riggi⁶, D. Röhrich², G. Romano¹⁵, K. Šafařík⁷, L. Šándor^{7,8}, E. Schillings¹⁸, G. Segato¹², W. Snoeys⁷, P. Staroba¹³, O.I. Stolyarov¹⁶, M. Thompson⁴, T.F. Thorsteinsen^{2,†}, G. Tomasicchio¹, G.D. Torrieri⁴, F.A. Tsimbal¹⁶, T.A. Tulina¹⁶, R. Turrisi¹², T.S. Tveter¹¹, J. Urbán⁸, F.F. Valiev¹⁶, A. van den Brink¹⁸, P. van de Ven¹⁸, P. Vande Vyvre⁷, N. van Eijndhoven¹⁸, L. Vannucci⁹, A. Vascotto⁷, O. Villalobos Baillie⁴, I. Vinogradov¹⁶, T. Virgili¹⁵, M.F. Votruba⁴, J. Vrláková⁸, P. Závada¹³

¹ Dipartimento I.A. di Fisica dell'Università e del Politecnico di Bari and Sezione INFN, Bari, Italy

² Fysisk institutt, Universitetet i Bergen, Bergen, Norway

³ Høgskolen i Bergen, Bergen, Norway

⁴ School of Physics and Astronomy, University of Birmingham, Birmingham, UK

⁵ Comenius University, Bratislava, Slovakia

⁶ Dipartimento di Fisica dell'Università and Sezione INFN, Catania, Italy

⁷ CERN, European Laboratory for Particle Physics, Geneva, Switzerland

⁸ Institute of Experimental Physics SAS and P.J. Šafařík University, Košice, Slovakia

⁹ INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy

¹⁰ GRPHE, Université de Haute Alsace, Mulhouse, France

¹¹ Fysisk institutt, Universitetet i Oslo, Oslo, Norway

¹² Dipartimento di Fisica dell'Università and Sezione INFN, Padua, Italy

¹³ Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

¹⁴ Dipartimento di Fisica dell'Università "La Sapienza" and Sezione INFN, Rome, Italy

¹⁵ Dipartimento di Scienze Fisiche "E.R. Caianiello" dell'Università and INFN, Salerno, Italy

¹⁶ State University of St. Petersburg, St. Petersburg, Russia

¹⁷ Institut de Recherches Subatomiques, IN2P3/ULP, Strasbourg, France

¹⁸ Utrecht University and NIKHEF, Utrecht, The Netherlands

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Abstract. The charged particle multiplicity distributions measured by two experiments, WA97 and NA57, in Pb + Pb collisions at 158 A 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.

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 $2 < \eta < 4$.

[†] Deceased

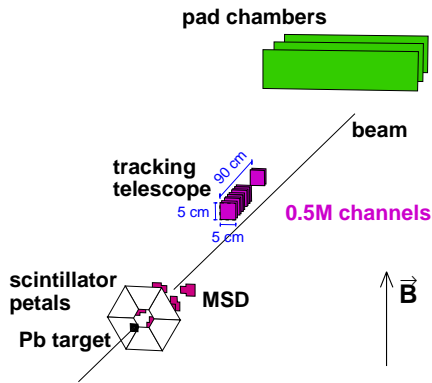


Fig. 1. The WA97 set-up

The Glauber model (see e.g. [1] and references therein) provides a simple geometrical interpretation of a collision between two 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 [3–15] 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 in oxygen and sulphur induced reactions [17] and in Pb + Pb collisions [18,19].

2 Multiplicity measurement

The NA57 and WA97 experiments have similar layouts, and in particular they employ the same multiplicity detectors (MSD, see Fig. 1). In NA57 however, a special effort was made to reduce various background sources in order to extend the covered centrality range towards more peripheral events. The NA57 set-up has been described in [20]; the WA97 set-up, shown in Fig. 1, has been described in [21]. In both experiments a 158 A 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 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 Fig. 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 approximately 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 a group 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 distributions of the total hit multiplicity in the two detector planes for the WA97 and NA57 experiments are shown in Fig. 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 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. Figure 3 shows the multiplicity distributions for the 1% Pb + Pb interaction length target and for the empty target runs. The error on the normalization due to the empty target subtraction was 6% for WA97 and 1.5% for NA57.

In order to obtain the charged particle multiplicity in the pseudorapidity range $2 < \eta < 4$ (N_{ch}), the hit multiplicity M_{hit} was corrected for:

- delta-rays and background hits; they were estimated from beam trigger data. As a consequence of the magnetic field, the delta-rays contributing to the measured multiplicity are produced near the detectors and come mainly from the passage in air of any non interacting lead ion while the MSD is integrating the signals of a triggered event. This contribution amounts to about 10 hits on the MSD for WA97 and to about 3 hits for NA57;
- geometrical acceptance;
- detector response (efficiency, double hits, charge sharing between contiguous strips); the correction for charge sharing and double hits depends on multiplicity and amounts to at most 10% for the central Pb + Pb events.
- secondary interactions and gamma ray conversions; this contribution amounts to about 5% of the measured multiplicity. It has been estimated by a Monte Carlo simulation and checked using data samples corresponding to targets of different thickness.

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

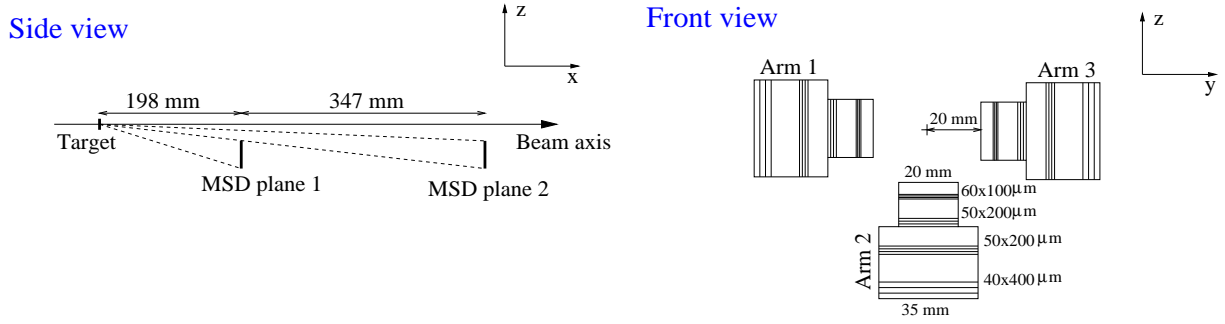


Fig. 2. Layout of the micro-strip multiplicity detectors (MSD). For clarity on the side view only the lower arm is shown

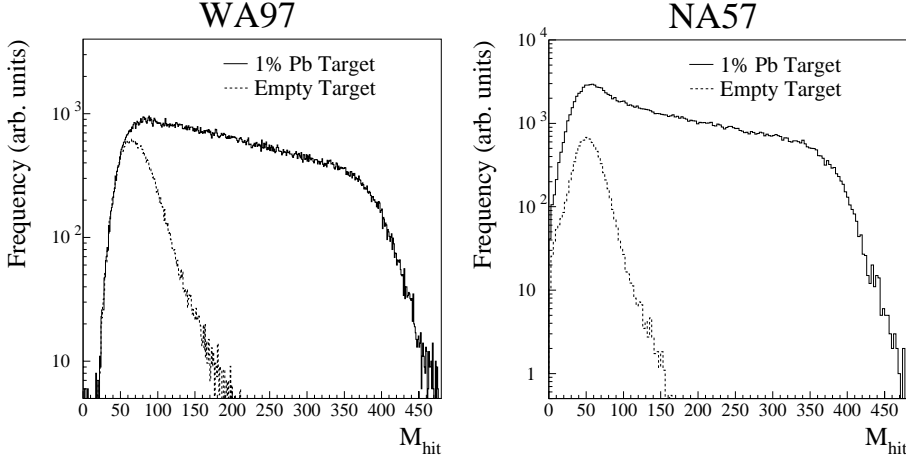


Fig. 3. Hit multiplicity distribution of the triggered events with a 1% Pb + Pb interaction length target (solid histogram) and of the empty target sample (dashed histogram)

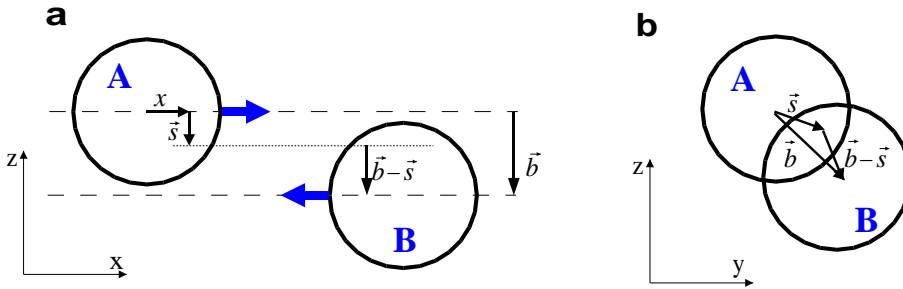


Fig. 4a,b. Schematic view of the interaction geometry along the collision axis **a** and on the plane perpendicular to the collision axis **b**

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]:

$$\langle N_{ch} \rangle = q N_{wound}, \quad (1)$$

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 $\sigma_{in} = 30$ mb. The nuclear density ρ has been parametrized by a Woods–Saxon distribution:

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

with parameters $r_0 = 6.62$ fm and $C = 0.546$ fm as measured in electron–nucleus scattering experiments [22].

A schematic view of the geometry of the collision and of the variables used in the following is shown in Fig. 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]:

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

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

$$T(\mathbf{b})\sigma_{in} = \int ds T_A(\mathbf{s}) T_B(\mathbf{b} - \mathbf{s}) \sigma_{in}, \quad (4)$$

$$T_{A,B}(\mathbf{b}) = \int \rho_{A,B}(\mathbf{b}, x) dx, \quad (5)$$

where x is the coordinate along the beam axis and \mathbf{s} spans the plane perpendicular to the collision axis. The average

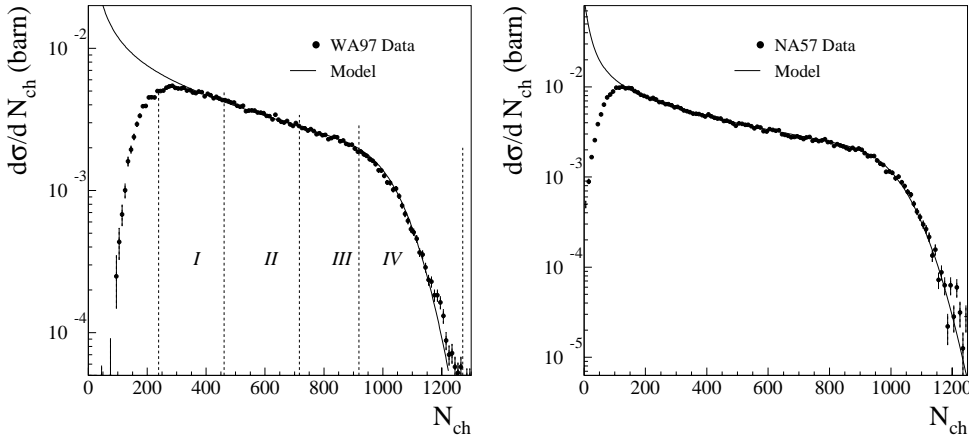


Fig. 5. Fit of the multiplicity distributions with the Wounded Nucleon Model for the WA97 (left) and NA57 (right) experiments

number of wounded nucleons for a given impact parameter \mathbf{b} is [19]:

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

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

$$\sigma_{N_{ch}}^2 = q^2 \sigma_{N_{wound}}^2 + N_{wound} \sigma_q^2 + (\sigma_{N_{ch}}^{exp})^2, \quad (7)$$

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. $\sigma_{N_{wound}}$ 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 [23], *i.e.* $\sigma_q = aq$, where $a \simeq 1$ at SPS energies in the pseudorapidity range $2 < \eta < 4$ [24, 25]. The last term in (7) is the experimental sampling dispersion discussed previously.

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

$$\begin{aligned} \frac{d\sigma_{in}^{Pb+Pb}}{dN_{ch}}(N_{ch}; q) &= \int d\mathbf{b} [1 - P(0, \mathbf{b})] \times \\ &\frac{1}{\sqrt{2\pi}\sigma_{N_{ch}}} \exp\left\{-\frac{(N_{ch} - q \langle N_{wound}(\mathbf{b}) \rangle)^2}{2\sigma_{N_{ch}}^2}\right\}, \end{aligned} \quad (8)$$

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

The corrected WA97 and NA57 charged particle multiplicity distributions in the range $2 < \eta < 4$ were fitted using the following equation:

$$\mathcal{A} \frac{d\sigma_{exp}}{dN_{ch}} = \frac{d\sigma_{in}^{Pb+Pb}}{dN_{ch}}(N_{ch}; q), \quad (9)$$

where $d\sigma_{exp}/dN_{ch}$ is the measured multiplicity distribution normalized to the trigger cross section, estimated

Table 1. Parameters of the fit

	WA97	NA57
q	$2.70 \pm 0.03 \pm 0.08$	$2.62 \pm 0.03^{+0.02}_{-0.05}$
\mathcal{A}	$1.07 \pm 0.03 \pm 0.04$	$1.03 \pm 0.03^{+0.04}_{-0.02}$
$\chi^2/\text{d.o.f.}$	2.05	1.50
σ_{trig}^{fit} (barn)	$3.14 \pm 0.03 \pm 0.11$	$4.40 \pm 0.03^{+0.16}_{-0.07}$

from the rate of triggered events, the incoming flux and the target thickness. We fitted simultaneously both the proportionality constant q and the absolute normalization \mathcal{A} . Figure 5 shows the WA97 and NA57 multiplicity distributions, scaled by the normalization factor \mathcal{A} , together with the fitted curve $\frac{d\sigma_{in}^{Pb+Pb}}{dN_{ch}}$. The fit range was $N_{ch} > 340$ for WA97 and $N_{ch} > 130$ for NA57. The parameters of the fit are shown in Table 1, where the quoted errors include both the statistical one (first error) and the systematic contribution due to the subtraction of delta-rays and background tracks (second error). To compare in absolute value the cross section from the WNM (8) and the experimental one, we can define a ‘‘fitted trigger cross section’’ as:

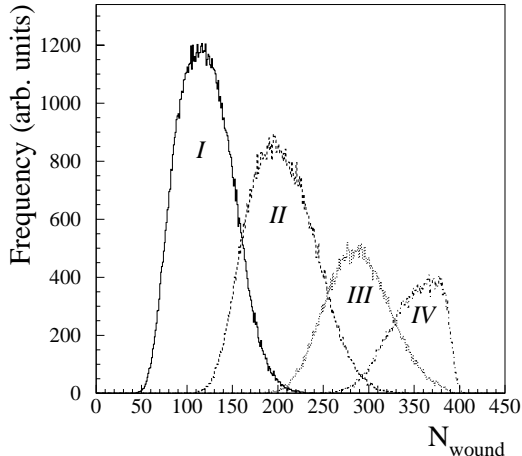
$$\sigma_{trig}^{fit} = W^{-1} \int \frac{d\sigma_{in}^{Pb+Pb}}{dN_{ch}}(N_{ch}; q) dN_{ch}, \quad (10)$$

where the integral is performed over the fitted multiplicity range. The fraction W , of events in the measured spectrum falling in the fitted range, accounts for the trigger efficiency. The results are shown in Table 1. 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, $\sigma_{trig}^{exp} = (4.29 \pm 0.12)$ 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

Table 2. Average N_{wound} and FWHM of the distribution for the four WA97 multiplicity classes. For the values of $\langle N_{wound} \rangle$ in parenthesis see Sect. 4.2

	Bin 1	Bin 2	Bin 3	Bin 4
$\langle N_{wound} \rangle$	$120.1^{+5.7}_{-6.1}$ (128.1)	$204.6^{+4.1}_{-4.4}$ (212.4)	$289.0^{+2.5}_{-2.9}$ (293.7)	$350.6^{+0.9}_{-1.1}$ (349.1)
FWHM	79.7	90.3	81.3	72.1

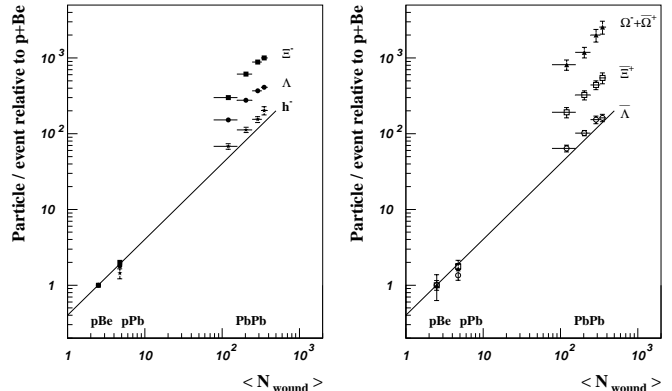
**Fig. 6.** Distribution of the number of wounded nucleons in the four WA97 multiplicity bins

the constraint that the multiplicity falls in the selected bin. This has been done by inverting equation (8) 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 Fig. 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 [4–6, 8, 11] describe in detail the determination of the yields of negative hadrons (h^-), Λ , $\bar{\Lambda}$, Ξ^- , $\bar{\Xi}^+$, Ω^- and $\bar{\Omega}^+$ measured by the tracking telescope (see Fig. 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 Sect. 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

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

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 Fig. 7 the particles are divided in two classes: those with at least one valence quark in common with the nucleon (plotted on the left) and those with no valence quark in common with the nucleon (plotted on the right). We have kept the two groups separate since it is empirically known that they may exhibit different production features (e.g. Λ and $\bar{\Lambda}$ have different rapidity spectra both in p + S and in S + S [26]).

In Fig. 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 interactions to central Pb + Pb collisions. As can be seen from the figure, 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. We have fitted the Pb + Pb yields Y of each particle with a power law:

$$Y \propto N_{wound}^\alpha. \quad (11)$$

Figure 8 shows the value of the exponent α for the various particle species. The errors combine the statistical errors on our samples (thick error bars) and systematic error on the determination of $\langle N_{wound} \rangle$ in the multiplicity classes due to the delta-rays and background tracks subtraction (thin error bars). The latter amounts to about 4% and is fully correlated among the different particle species. The

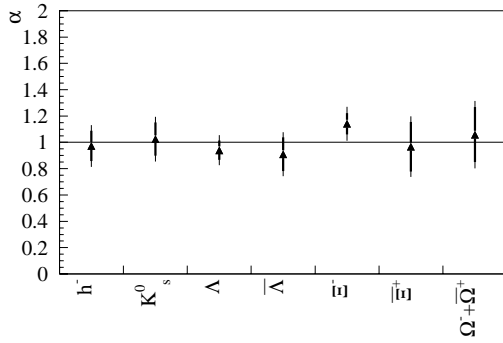


Fig. 8. Value of the exponent α from a fit to (11) for the various particle species measured by WA97 in Pb + Pb reactions

Table 3. Results of the fits to (11). The upper table refers to the fits to Pb + Pb data only; the bottom one includes the yields in p + Be

Fit to Pb+Pb yields			
Particle	α	χ^2	d.o.f
h^-	$0.97 \pm 0.07 \pm 0.04$	0.31	2
K_S^0	$1.02 \pm 0.13 \pm 0.04$	1.60	2
Λ	$0.94 \pm 0.08 \pm 0.04$	2.59	2
$\bar{\Lambda}$	$0.91 \pm 0.13 \pm 0.04$	0.62	2
Ξ^-	$1.14 \pm 0.08 \pm 0.05$	2.89	2
Ξ^+	$0.96 \pm 0.19 \pm 0.04$	0.02	2
$\Omega^- + \bar{\Omega}^+$	$1.06 \pm 0.18 \pm 0.05$	0.95	2

Fit to p+Be and Pb+Pb yields			
Particle	α	χ^2	d.o.f
h^-	$1.073 \pm 0.011 \pm 0.005$	1.07	3
Λ	$1.258 \pm 0.007 \pm 0.005$	21.1	3
$\bar{\Lambda}$	$1.051 \pm 0.012 \pm 0.005$	1.85	3
Ξ^-	$1.426 \pm 0.016 \pm 0.003$	15.8	3
Ξ^+	$1.291 \pm 0.036 \pm 0.003$	3.12	3
$\Omega^- + \bar{\Omega}^+$	$1.549 \pm 0.080 \pm 0.007$	7.44	3

fact that the exponent α is about one 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.

If we include the p + Be point, the fits generally worsen and the exponents depend strongly on the particle species. The results are summarized in Table 3. The K_S^0 in p + Be have not yet been analyzed, therefore they are not present in the bottom table. The first error on α is statistical, the second is the systematics due to the delta-rays and background tracks subtraction.

4.2 Comparison with other experiments at the SPS

The WA98 experiment, which also uses a Glauber definition of wounded nucleons, obtains a dependence be-

tween the number of charged particles and the number of wounded nucleons in Pb + Pb collisions slightly different from the one presented here (1) [27]. They parameterize the rapidity density of charged particles at mid-rapidity by a power law:

$$\left(\frac{dN_{ch}}{d\eta}\right)_{\max} \propto N_{wound}^\alpha, \quad (12)$$

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. Using a power law with $\alpha = 1.05$ in the fit to the multiplicity distribution, increases the average number of wounded nucleons in the multiplicity classes by at most 7% for the most peripheral one (values of $\langle N_{wound} \rangle$ in parenthesis in Table 2). The results from such a change of $\langle N_{wound} \rangle$ in the fit of the Pb + Pb yields (11) are still consistent with proportionality to N_{wound} for all particle species considered.

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 Pb + Pb collisions at $158 A \text{ GeV}/c$. 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 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 Pb + Pb collisions having a similar number of wounded nucleons to that obtained in central S + S collisions.

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