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Enhancement of central Λ, Ξ and Ω yields in Pb-Pb collisions at 158 A GeV/c

E. Andersen[3], F. Antinori[6,12], N. Armenise[2], H. Bakke[3], J. Bán[8], D. Barberis[7], H. Beker[6], W. Beusch[6], I.J. Bloodworth[5], J. Böhm[14], R. Caliandro[2], M. Campbell[6], E. Cantatore[6], N. Carrer[12], M.G. Catanesi[2], E. Chesi[6], M. Dameri[7], G. Darbo[7], A. Diaczek[13], D. Di Bari[2], S. Di Liberto[15],B.C. Earl[5], D. Elia[2], D. Evans[5], K. Fanebust[3], R.A. Fini[2], J.C. Fontaine[10], J. Ftáčnik[8], B. Ghidini[2], G. Grella[16], M. Guida[16], E.H.M. Heijne[6], H. Helstrup[4], A.K. Holme[6], D. Huss[10], A. Jacholkowski[2], G.T. Jones[5], P. Jovanovic[5], A. Jusko[8], V.A. Kachanov[17], T. Kachelhoffer[18], J.B. Kinson[5], A. Kirk[5], W. Klempt[6], B.T.H. Knudsen[3], K. Knudson[6], I. Králik[6], J.C. Lassalle[6], V. Lenti[2], R. Lietava[8], R.A. Loconsole[2], G. Løvhøiden[6,11], M. Lupták[8], V. Mack[10], V. Manzari[2], P. Martinengo[6], M.A. Mazzoni[15], F. Meddi[15], A. Michalon[18], M.E. Michalon-Mentzer[18], P. Middelkamp[6], M. Morando[12], M.T. Muciaccia[2], E. Nappi[2], F. Navach[2], P.I. Norman[5], B. Osculati[7], B. Pastirčák[8], F. Pellegrini[12], K. Píška[14], F. Posa[2], E. Quercigh[6], R.A. Ricci[9], G. Romano[16], G. Rosa[16], L. Rossi[7], H. Rotscheidt[6], K. Šafařík[6], S. Saladino[2], C. Salvo[7], L. Šándor[6,8], T. Scognetti[2], G. Segato[12], M. Sené[13], R. Sené[13], S. Simone[2], A. Singovski[17], W. Snoeys[6], P. Staroba[14], S. Szafran[13], M. Thompson[5], T.F. Thorsteinsen[3], G. Tomasicchio[2], G.D. Torrieri[5],T.S. Tveter[11], J. Urbán[8], G. Vassiliadis[1], M. Venables[5], O. Villalobos Baillie[5], T. Virgili[16], A. Volte[13], M.F. Votruba[5] and P. Závada[14]

Abstract

Λ, Ξ and Ω yields and transverse mass spectra have been measured at central rapidity in Pb-Pb and p-Pb collisions at 158 A GeV/c. The yields in Pb-Pb interactions are presented as a function of the collision centrality and compared with those obtained from p-Pb collisions. Strangeness enhancement is observed which increases with centrality and with the strangeness content of the hyperon.

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[1] Nuclear Physics Department, Athens University, Athens, Greece
[2] Dipartimento I.A. di Fisica dell'Università e del Politecnico di Bari and Sezione INFN, Bari, Italy
[3] Fysisk institutt, Universitetet i Bergen, Bergen, Norway
[4] Høgskolen i Bergen, Bergen, Norway
[5] University of Birmingham, Birmingham, UK
[6] CERN, European Laboratory for Particle Physics, Geneva, Switzerland
[7] Dipartimento di Fisica dell'Università and Sezione INFN, Genoa, Italy
[8] Institute of Experimental Physics, 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] Collège de France and IN2P3, Paris, France
[14] Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic
[15] Dipartimento di Fisica dell'Università "La Sapienza" and Sezione INFN, Rome, Italy
[16] Dipartimento di Scienze Fisiche "E.R. Caianiello" dell'Università and INFN, Salerno, Italy
[17] Institute of High Energy Physics, Protvino, Russia
[18] Centre de Recherches Nucléaires, Strasbourg, France

The study of relativistic heavy ion collisions provides a unique opportunity to search for a new predicted state of matter - the quark-gluon plasma (QGP). A number of experimental signatures which could signal the QGP have been proposed (for a recent review see [1]). They are being studied in a number of experiments at the BNL AGS and CERN SPS, but an unambiguous confirmation of QGP formation has not yet been achieved.

Strange particles produced in heavy ion collisions give important information on the collision mechanism. In particular, the enhanced relative yield of strange and multi-strange particles in nucleus-nucleus reactions with respect to proton-nucleus interactions has been suggested as one of the sensitive signatures for a phase transition to a QGP state [2, 3]. It is expected that the enhancement should be more pronounced for multi-strange than for singly strange particles [4].

In the QGP scenario the strangeness enhancement could be created as a result of the system rapidly reaching flavour equilibration. Strange quark pairs are easily produced in a gluon rich QGP environment, predominantly in gluon-gluon interactions. The equilibration time is estimated to be comparable with the interaction time of the high energy heavy-ion collision (a few fm/c).

Strangeness production can also be enhanced in a purely hadronic scenario (hot and dense hadronic gas), where the relative abundance of strange particles could grow gradually in a chain of rescattering processes. The characteristic time scale in this case is estimated to be much longer, of the order of 100 fm/c.

Three heavy ion experiments dedicated to the study of strangeness production were performed at the Omega spectrometer: WA85, WA94 and WA97. The WA85 and WA94 experiments utilised the 200 A GeV/c SPS sulphur beam. WA85 investigated strangeness production in p-W and S-W collisions, whereas WA94 studied p-S and S-S interactions. Both these experiments used a tracking system with multiwire proportional chambers modified to be sensitive only to a few particles emitted at central rapidity and $p_{\mathrm{T}} > 1$ GeV/c. Particle ratios measured by both experiments showed evidence for enhanced production of strange and multi-strange particles in nucleus-nucleus collisions with respect to proton-nucleus collisions [5, 6].

The encouraging results from WA85 and WA94 lead naturally to a question of how strangeness production will evolve when a truly heavy ion beam (Pb) is used. In view of the alternative explanations that exist (hadronic gas or quark-gluon plasma scenarios) for the features observed in the search of the quark-gluon plasma, it is important to look carefully for any indication which could suggest the onset of a new mechanism for strange particle production when going from proton to Pb induced collisions. A well known example of a possible change of regime is seen in the production of charmonium states where an abrupt drop in the J/ψ production has been observed by the CERN experiment NA50 [7].

The WA97 experiment is designed to study the yields of strange particles and antiparticles carrying one, two and three units of strangeness as a function of the number of nucleons taking part in the collision. The WA97 set-up, shown schematically in fig. 1, is described in detail in ref. [8]. The target and the silicon telescope were placed inside the homogeneous 1.8 T magnetic field of the CERN Omega magnet.

The 158 A GeV/c lead beam from the CERN SPS was incident on a lead target with thickness corresponding to 1% of the interaction length. Scintillator petal detectors behind the target provided an interaction trigger selecting the most central $\sim 40\%$ of Pb-Pb collisions. Two planes of microstrip multiplicity detectors covering for all p_{T}-values the pseudorapidity region $2 \lesssim \eta \lesssim 3$ (station 1) and $3 \lesssim \eta \lesssim 4$ (station 2), provided information for more detailed off-line study of the centrality dependence of particle ratios and spectra. In the proton reference runs at 158 GeV/c the protons were selected using CERN Cherenkov CEDAR detectors [9], and a trigger was applied demanding at least two tracks in the telescope, as required to find $\mathrm{V^0}$s.

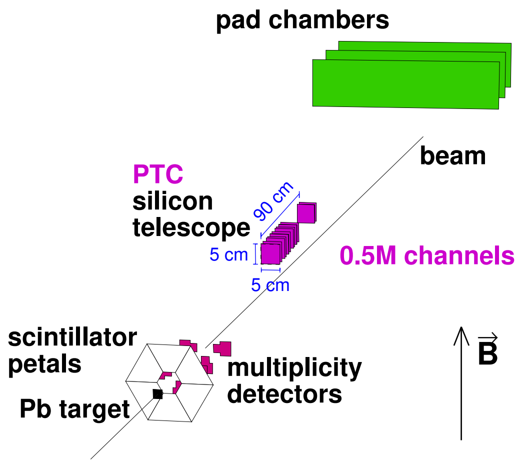

Figure 1: The WA97 set-up.

Table 1: Hyperon statistics used in the present analysis and expected increase in the statistics after processing all available data.

Particle	Pb-Pb		p-Pb	
	Present	Expected	Present	Expected
Ω^-	77	$\times 5$	15	
$\overline{\Omega}^+$	30	$\times 5$	4	
Ξ^-	715	$\times 5$	275	
$\overline{\Xi}^+$	187	$\times 5$	101	
Λ	447	$\times 1500$	515	$\times 200$
$\overline{\Lambda}$	301	$\times 300$	126	$\times 200$

The main feature of the WA97 spectrometer was the silicon telescope (Pixel-Tracking-Chamber - PTC) consisting of 7 planes of silicon pixel detectors with a pixel size $75 \times 500\ \mu\mathrm{m}^2$, and of 10 planes of silicon microstrips with a 50 μm pitch. The telescope had 5×5 cm^2 cross section and contained $\approx 0.5\times10^6$ channels. This tracking device was placed 60 cm downstream of the target (90 cm for the p-Pb reference run) slightly above the beam line and inclined (pointing to the target) in order to accept particles at central rapidity and medium transverse momentum.

The track recognition was done in the compact part of the silicon telescope (30 cm long, with 6 pixel and 5 microstrip planes). The momentum resolution of fast tracks was improved using the lever arm detectors (1 pixel and 5 microstrip planes) and three MWPC's with a cathode pad readout placed outside the magnet.

Up to now only a fraction of the available data sample on tape has been fully corrected for acceptance and reconstruction losses. The results presented here are based on the analysis of two data samples taken with lead (110 million events) and proton (120 million events) beams at 158 A GeV/c. Table 1 shows the hyperon samples used for the present analysis and the expected increase in statistics after processing and correcting all collected data.

The Λ, Ξ^-, Ω^- hyperons and their antiparticles were identified by reconstructing their

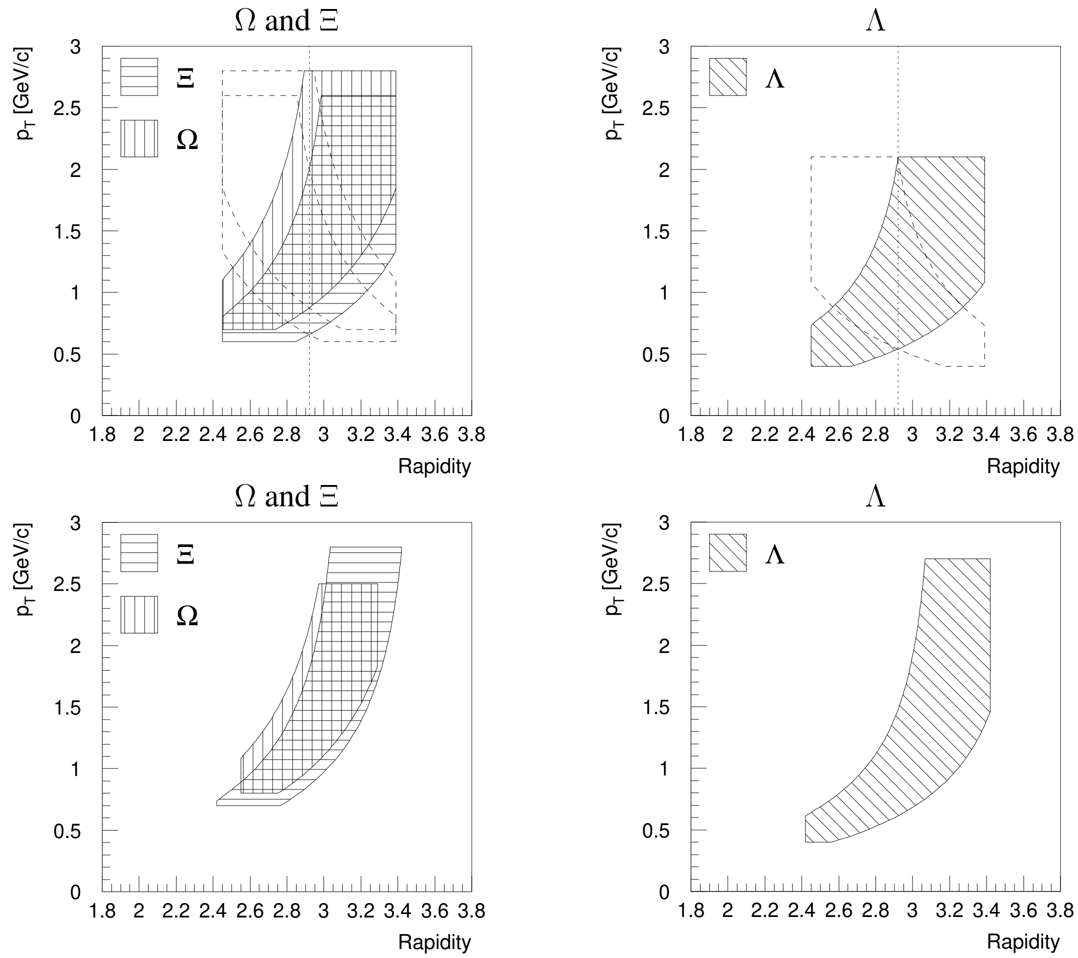

Figure 2: Acceptance windows for Λ, Ξ and Ω hyperons for Pb-Pb (top) and p-Pb (bottom) interactions. For Pb-Pb collisions, the symmetry of the system around midrapidity ($y_{cm} = 2.91$) allows one to symmetrize the acceptance windows by reflection around y_{cm}. The reflected windows are drawn with dashed lines.

decays into final states containing only charged particles:

$$
\begin{array}{lcl}
\Lambda & \rightarrow & \mathrm{p} + \pi^- \\
\Xi^- & \rightarrow & \Lambda + \pi^- \\
 & & \quad \hookrightarrow \mathrm{p} + \pi^- \\
\Omega^- & \rightarrow & \Lambda + \mathrm{K}^- \\
 & & \quad \hookrightarrow \mathrm{p} + \pi^-
\end{array}
$$

The details of the analysis, *i.e.* the extraction of the hyperon signals and the weighting for each reconstructed Λ, Ξ and Ω, are discussed in [10]. The data have not been corrected for feed-down. In the geometry of our experiment the feed-down for weak decays is expected to be of minor importance. It is estimated to be less than 5% for Λ and less than 10% for $\overline{\Lambda}$. In the particle spectra the mass resolution of the peaks was better than 6 MeV (FWHM).

The acceptance windows for Λ, Ξ and Ω from Pb-Pb and p-Pb collisions are shown in fig. 2. The double differential distributions for the hyperons were fitted in their respective acceptance windows using the expression

$$\frac{d^2N}{dm_{\mathrm{T}}dy} = f(y)\, {m_{\mathrm{T}}}^{\alpha} \exp(-\frac{m_{\mathrm{T}}}{T}) \tag{1}$$

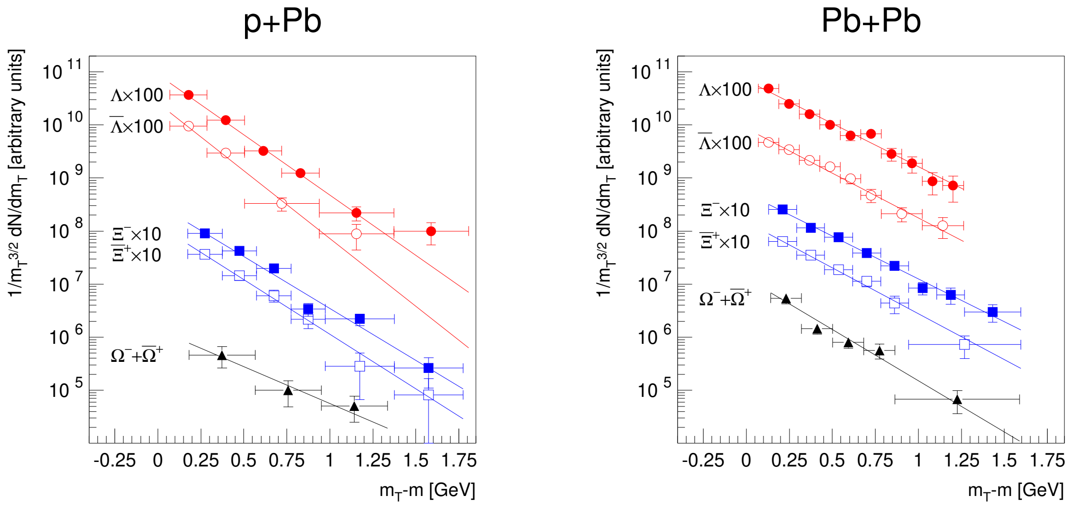

Figure 3: The m_T-spectra of Λ, $\overline{\Lambda}$, Ξ^-, $\overline{\Xi}^+$ and $\Omega^- + \overline{\Omega}^+$ in p-Pb interactions (left) and Pb-Pb interactions (right) with superimposed maximum likelihood fits.

The fit was performed using the method of maximum likelihood.

For the present analysis with limited statistics we have assumed the rapidity distributions to be flat for $|y - y_{cm}| < 0.5$, *i.e.* $f(y)$ = constant in expression (1). We have investigated the systematic error which this assumption could introduce in the case of the Λ and $\overline{\Lambda}$, where published data exist for p-Au [11] and p-S [12] collisions. The shapes of the rapidity distributions for these two species are very different; the Λ distribution shows a strong backward peak, while the $\overline{\Lambda}$ is produced centrally. It is found that using a flat rapidity distribution instead of one obtained from an empirical fit to the data of [11] gives a difference of $< 5\%$ on the slope and $< 5\%$ on the extrapolated yield (see below) in the case of the $\overline{\Lambda}$ and 10% and 6% respectively in the case of the Λ distribution.

The slopes of the transverse mass distributions have been fitted using expression (1), where we have chosen the value $\alpha = \frac{3}{2}$ in order to facilitate a comparison with WA85 [13] and WA94 [14] results. This value is appropriate for distributions where particles emitted by a single stationary fireball have been collected in a wide rapidity window, or when particles emitted by many fireballs moving relative to each other with a boost-invariant longitudinal velocity profile, have been collected in a narrow rapidity window. For details see [15].

The Λ, $\overline{\Lambda}$, Ξ^-, $\overline{\Xi}^+$ and Ω^- + $\overline{\Omega}^+$ m_T-spectra for Pb-Pb interactions are shown in fig. 3, extrapolated in rapidity to the common range $|y - y_{cm}| < 0.5$. The superimposed lines are the results of the maximum likelihood fits in the corresponding acceptance windows (see Fig. 2). Due to the limited statistics the combined data on Ω^- and $\overline{\Omega}^+$ were used, both for Pb-Pb and p-Pb data. Quoted errors are statistical only.

The inverse slope parameters T for Λ, Ξ and Ω measured in Pb-Pb and p-Pb collisions are summarised in table 2. The slopes obtained with $\alpha = 3/2$ have been used to obtain the particle ratios given in ref. [10]. The inverse slope parameter T increases from p-Pb to Pb-Pb for Λ and Ξ. For Pb-Pb one observes very similar inverse m_T-slopes for Λ and Ξ, while a decrease in T is suggested for the heavier Ω hyperon. For p-Pb the large error on T precludes firm conclusions regarding the Ω inverse slope. Table 2 also gives inverse slopes for $\alpha = 1$, to facilitate comparison with other experiments.

Table 2: Inverse $m_{\rm T}$ slope parameters T in MeV for p-Pb and Pb-Pb interactions.

	$\alpha = \frac{3}{2}$		$\alpha = 1$	
Particles	p-Pb	Pb-Pb	p-Pb	Pb-Pb
Λ	191± 8	267±15	203± 9	291±18
$\overline{\Lambda}$	170±14	257±17	180±15	280±20
Ξ^-	222±12	269±11	235±14	289±12
$\overline{\Xi}^+$	211±19	251±19	224±21	269±22
$\Omega^- + \overline{\Omega}^+$	312±86	225±22	334±99	237±24

The WA97 multiplicity detectors allow us to study hyperon production as a function of centrality. We have used the number of participant nucleons a measure of centrality. We estimated the number of participants in the collision from the multiplicity detector measurements using a Glauber model [16] for Pb-Pb interactions together with the assumption of proportionality between the number of participants and the multiplicity. The two multiplicity detector stations provide independent measurements of the number of participants which agrees within ± 1 %. Fig. 4 shows as an example, the charged particle multiplicity spectrum in the range $2 < \eta < 4$, obtained by correcting the multiplicity measured in detector station 2 for acceptance, detector response, secondary interactions in the target and empty target contributions. The model calculation, modified to account for the multiplicity detector resolution, is compared to the data. For multiplicities above 400 the model gives an excellent description of the multiplicity spectrum with only one free parameter, namely the ratio between the charged particle multiplicity and the number of participants. To obtain the hyperon yields in Pb-Pb as a function of the number of participants, the multiplicity spectrum is divided into four bins (fig. 4), and in each bin the average number of participants is calculated from the model. The bin widths were chosen so as to give similar numbers of Ω hyperons in each bin before weighting. In bin I the peripheral events are suppressed by our trigger, which selects the most central $\sim 40\%$ of the Pb-Pb inelastic cross section. Here the average number of participants is estimated as a weighted mean using as weight the ratio of the measured multiplicity to the model calculation. The above analysis represents a refinement of that presented in ref. [10]. For p-Pb interactions, the estimated number of participants corresponds to minimum bias collisions.

Fig. 5a shows the Λ, Ξ and Ω yields per event for p-Pb and Pb-Pb interactions as a function of the number of participants. The effect of the two track trigger in the p-Pb sample has been taken into account. Yields are extrapolated to the window $|y - y_{cm}| < 0.5$ and $p_{\rm T} > 0$ GeV/c according to expression (1). The vertical bars show statistical uncertainties only, and do not include systematic errors from feed-down nor from the assumption of a flat rapidity distribution in our acceptance window. As discussed above, these are estimated to be small relative to the current statistical errors. Horizontal bars show the root-mean-square values of the number of participants in the selected bins for Pb-Pb collisions, and the full range in p-Pb. Fig. 5b shows the hyperon yields expressed in units of the corresponding yield per p-Pb interaction (i.e. each yield is rescaled so that the value for p-Pb is set to one).

All Pb-Pb hyperon yields show a steady increase with centrality up to very central events. The hyperon yields in Pb-Pb are compared to a yield curve (full line) proportional to the number of participants $\langle N_{part} \rangle$ drawn through the p-Pb point in fig. 5b. It is observed that the Λ, Ξ and Ω yields increase with centrality from p-Pb to Pb-Pb interactions faster than the number of participants; for example, assuming a power law dependence $\langle N_{part} \rangle^{\alpha}$ for the ratio of Pb-Pb to

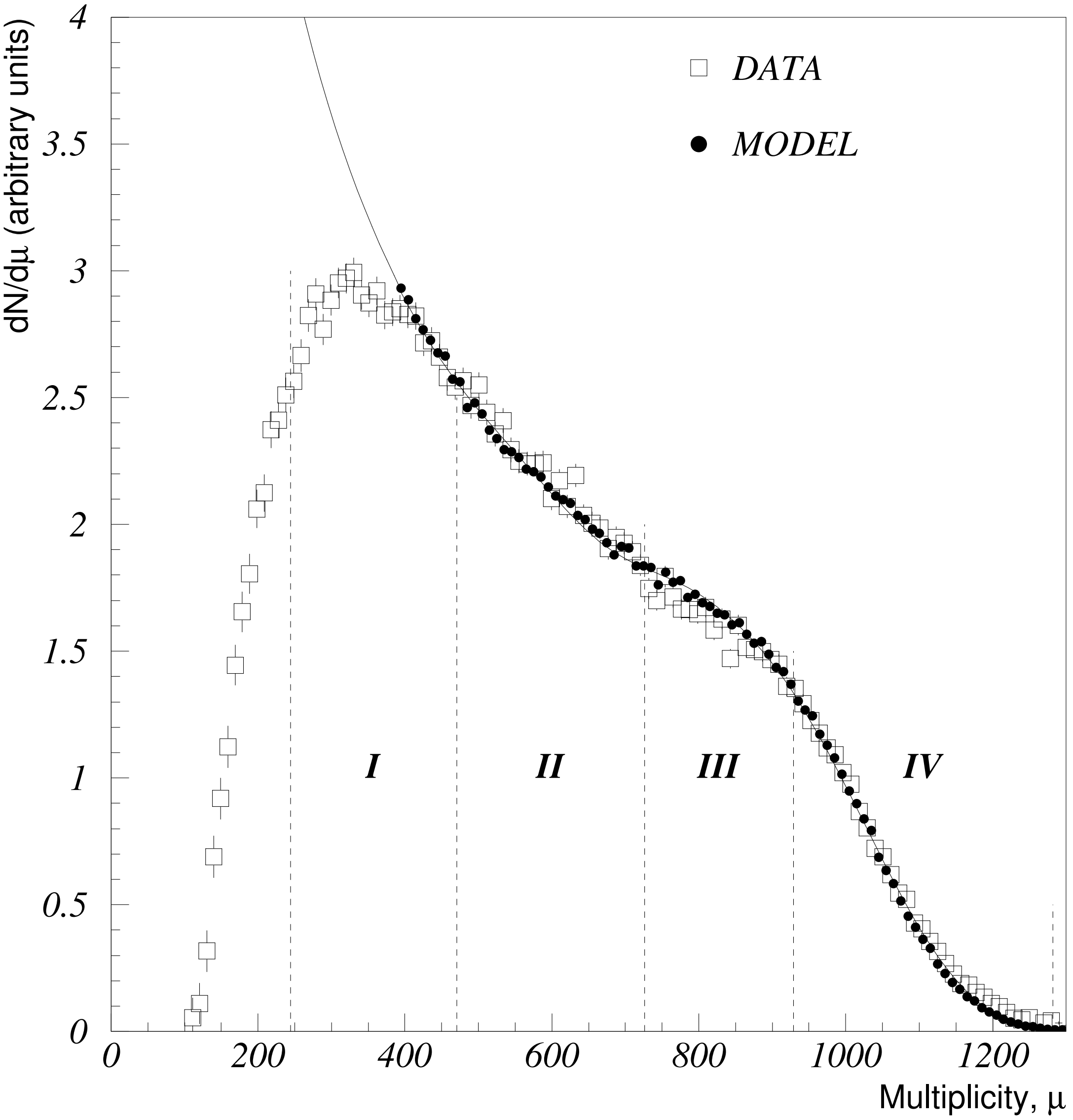

Figure 4: Charged particle multiplicity spectrum (squares) compared with a Glauber model calculation (points) modified by the multiplicity detector resolution. See text for details.

p-Pb yields, the Ω yield increases as $\langle N_{part}\rangle^{1.72\pm0.05}$ (see the dotted line in fig. 5b), the Ξ yield increases as $\langle N_{part}\rangle^{1.44\pm0.01}$ and the Λ yield increases as $\langle N_{part}\rangle^{1.30\pm0.01}$. Such an enhancement is also present before the extrapolation to the full $y - p_{\mathrm{T}}$ window. Taking again the Ω yields, where the largest difference between p-Pb and Pb-Pb slopes is observed, these would increase as $\langle N_{part}\rangle^{1.68\pm0.05}$ from p-Pb to Pb-Pb if the yields were calculated in the overlap of the respective windows in fig. 2, from which we infer that the observed enhancement is not an effect of the extrapolation.

This strangeness enhancement exhibits a pronounced $\Omega > \Xi > \Lambda$ hierarchy. In the extrapolated window the enhancement of yields from p-Pb to Pb-Pb are in the ratio $\Omega : \Xi : \Lambda =$

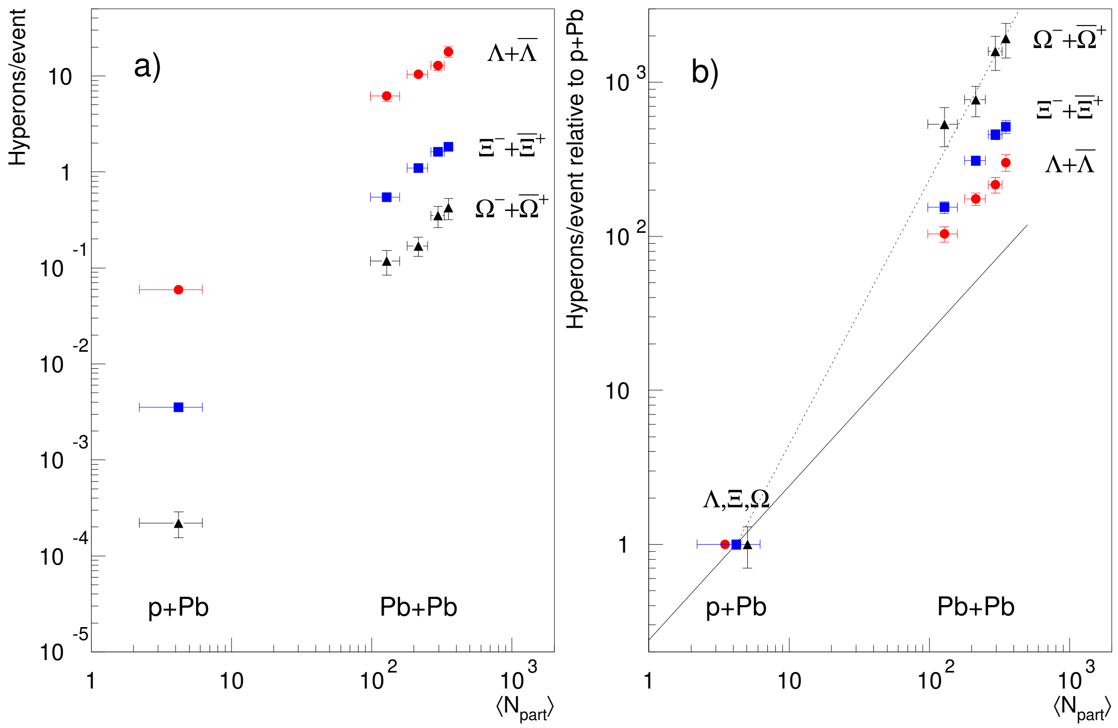

Figure 5: a) The Λ, Ξ and Ω yields expressed in units of yields per event. b) The Λ, Ξ and Ω yields expressed in units of yields observed in p-Pb collisions and compared to yield curves proportional to the number of participants $\langle N_{part} \rangle$ (solid curve) and to $\langle N_{part} \rangle^{1.72}$ (dotted curve). The proton points are stacked together on the horizontal scale. See text for details.

$770 \pm 260 : 240 \pm 20 : 130 \pm 10$, *i.e.* the Ω yield grows faster than that of the Ξ, and the Ξ yield faster than that for the Λ. For the overlap windows between p-Pb and Pb-Pb for each species the corresponding ratios are $630 \pm 200 : 280 \pm 20 : 144 \pm 10$.

In summary, we have observed a strong increase in the production at mid-rapidity of Λ, Ξ and Ω hyperons and antihyperons in Pb-Pb collisions with respect to p-Pb collisions. The yields increase with centrality faster than the number of participants, and the enhancements exhibit a marked $\Omega > \Xi > \Lambda$ hierarchy. The rapidity dependence of these enhancements needs to be investigated; we note that the NA49 collaboration observes no global strangeness enhancement in full phase space when going from S-S to Pb-Pb[17, 18].

An obvious question for future experiments, *e.g.* NA57 [19], is whether the increase in the hyperon production shown in fig. 5 is smooth with $\langle N_{part} \rangle$, or if any discontinuity is present at lower centrality values.

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