Production of hyperons and anti-hyperons in heavy-ion collisions at SPS: Experiments at the CERN Omega spectrometer

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Recent results from the CERN Omega spectrometer on the enhancement of strange and multiply strange particle production in nucleus-nucleus with respect to proton-nucleus collisions are summarized. In particular, the new data from the WA97 experiment on Ω, Ξ and Λ production in Pb–Pb and p–Pb collisions are presented and discussed.

1. INTRODUCTION

The study of heavy-ion collisions at high energies provides a unique opportunity to search for a new predicted state of matter - the quark-gluon plasma (QGP). A number of experimental signatures which should signal the QGP have been proposed (see, e.g., [1]). They are being pursued in a number of experiments at the AGS and SPS. Encouraging results are emerging; however the unambiguous confirmation of the QGP formation awaits further precise investigations.

Strange particles produced in a heavy-ion collision bear important information on the collision mechanism. Strangeness as a proper diagnostic tool has been recognized more than ten years ago. In particular, the enhanced relative yield of strange and multi-strange particles and antiparticles in nucleus-nucleus interactions with respect to hadronic reactions has been suggested as one of the sensitive signatures for a phase transition to a QGP state [2,3].

In the QGP scenario, such an enhancement could be created as a result of rapidly developing 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$/c$). The establishment of a similar enhancement is also possible in a pure 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 that case is much longer, of the order of 100 fm$/c$.

It is expected that the enhancement should be more pronounced for multi-strange than for singly-strange particles [4].

Three experiments at the CERN Omega spectrometer were devoted to the study of strange particles in both nucleus-nucleus and proton-nucleus collisions. In the next section we briefly summarize results of the WA85 and WA94 experiments performed in a beam of sulphur ions. Then we shall focus on the latest results of the WA97 experiment studying Pb–Pb collisions.

2. THE WA85 AND WA94 EXPERIMENTS

The WA85 and WA94 experiments utilized the 200 GeV$/c$ per nucleon SPS sulphur beam. WA85 has investigated strange particle production in p–W and S–W interactions, while WA94 studied p–S and symmetric S–S collisions. Both experiments were based on a tracking system of multiwire proportional chambers. The chambers were modified to be sensitive only to a few particles emitted at central rapidity and $p_t > 1$ GeV$/c$.

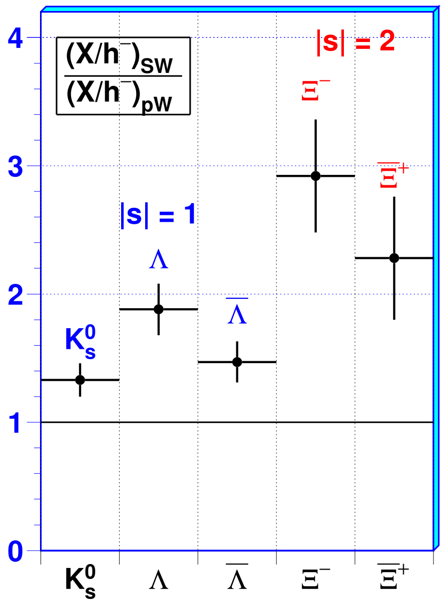

Figure 1. WA85 data on enhancement of strange particles in S–W with respect to p–W collisions normalized to the yields of negative particles.

The WA85 results [5], showing the enhanced strange particle production in S–W with respect to p–W collisions, are presented in Fig. 1 as a function of the strangeness content of the particles. The yields of strange particles are normalized to the yields of negatively charged ones, known to be predominantly pions. The observed enhancement is, in agreement with the above mentioned predictions, higher for double-strange Ξ hyperons than for singly-strange kaons and Λs.

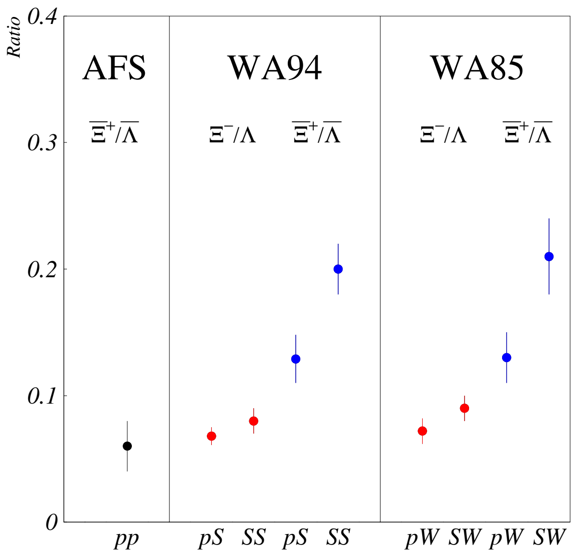

Figure 2. Compilation of AFS, WA94 and WA85 data on Ξ/Λ ratios.

WA94 [6] obtained similar ratios of strange particle yields in S–S with respect to p–S reactions. In Fig. 2 the comparison of WA85 and WA94 data on Ξ^-/Λ and $\overline{\Xi}^+/\overline{\Lambda}$ ratios with available pp data from the AFS experiment [7] is presented. Strange particle production processes exhibit a similar behaviour in S–S and S–W reactions.

In the WA85 data a signal of Ω has also been detected and the Ω/Ξ ratio has been estimated for the central S–W interactions [8]. In spite of quite limited statistics, data indicate that this ratio is significantly higher than the upper limit for the $\overline{\Omega}^+/\overline{\Xi}^+$ ratio obtained in pp collisions in a similar phase space window [7].

3. THE WA97 EXPERIMENT

The encouraging WA85 and WA94 results on strangeness enhancement led naturally to a question of how this enhancement will evolve when going to really heavy-ion (Pb–Pb) collisions, and how Ω hyperons, bearing 3 units of strangeness, will behave. The WA97 experiment performed in a 158 GeV/c per nucleon lead beam at the CERN SPS aimed at answering these questions. In order to cope with the increased track density, a new, more powerful tracking detector - the silicon telescope - has been utilized. This ensured the capability of the experiment to perform an efficient pattern recognition, precise measurement of particle characteristics and reliable reconstruction of multi-strange hyperon cascade decays.

3.1. Experimental set-up

The experimental set-up, shown schematically in Fig. 3, is described in detail in ref. [9].

Scintillator petal detectors located near the lead target provide a centrality trigger, selecting about 30% of the inelastic Pb–Pb cross section. Two planes of silicon microstrip detectors measure the charged particle multiplicity in the

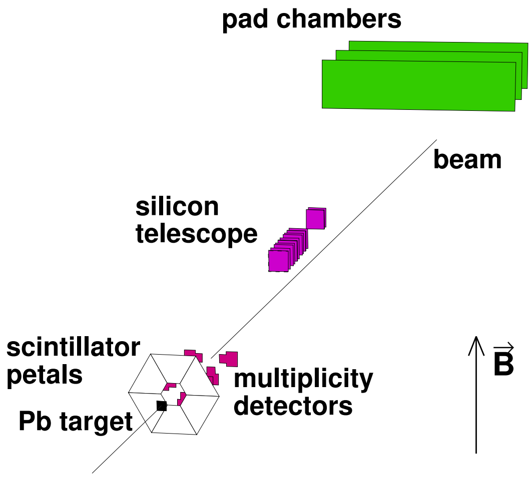

Figure 3. WA97 set-up. The target and all detectors (except for pad chambers) are placed inside the homogeneous field region of the 1.8 T Omega magnet.

pseudorapidity window $2 < \eta < 4$, providing information for more detailed off-line study of the multiplicity dependence of particle ratios and spectra.

The core of the WA97 set-up is the silicon telescope consisting of the novel pixel detectors [10] with a pixel size of 75×500 μm^2, and of silicon microstrip planes with a 50 μm pitch. The telescope (in the geometrical arrangement used in 1995 running) contained $\simeq 0.5 \times 10^6$ detecting elements and acted as a pixel tracking chamber (PTC). This precise tracking device was placed slightly above the beam line and inclined (pointing to the target) in order to accept particles at central rapidity and medium transverse momentum.

The reconstruction of tracks is done in the compact part of the PTC where silicon planes with surfaces of 5×5 cm^2 are closely packed over a distance of 30 cm. The momentum resolution of fast tracks is improved using the lever arm detectors which consist of additional pixel and microstrip planes and of three multi-wire proportional chambers with a pad cathode readout.

Fig. 4 shows an event from the 1995 lead run. This no-field event contains 153 reconstructed tracks, corresponding to an occupancy of about

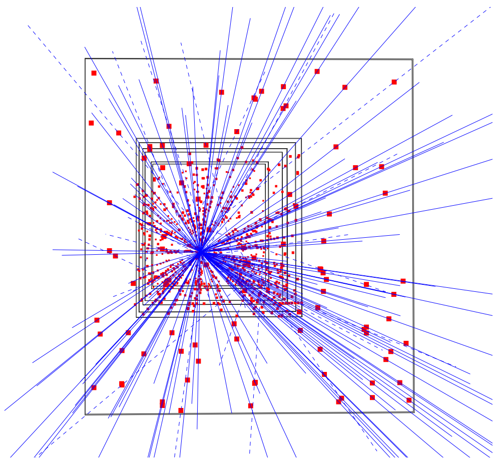

Figure 4. WA97 no-field event with 153 reconstructed tracks in the pixel tracking chamber.

0.2 % of the 72K channels provided by each pixel detector plane.

The WA97 experimental set-up is symmetric with respect to the magnetic bending direction and therefore its geometrical acceptance is the same for particles and antiparticles.

3.2. Data samples and selection criteria

The results presented here are based on the analysis of two data samples taken during 1995 running in the proton and lead beams with the same energy of 158 GeV per nucleon:

a) 110 million Pb–Pb events taken with the PTC placed at a distance of 60 cm from the target. The trigger selected central events corresponding to 30% of the inelastic cross section

b) 120 million p–Pb events taken with the PTC 90 cm from the target. The passage of at least two charged particles through the compact part of the PTC was required by the trigger.

The Λs were identified by reconstructing their decays to charged particles ($\Lambda \rightarrow p + \pi^-$). The Ξ^- and Ω^- hyperons (and the corresponding antihyperons) were identified by reconstructing their cascade decays, again containing only charged particles in the final state:

$$\Xi^- \rightarrow \Lambda + \pi^- , \quad \Lambda \hookrightarrow p + \pi^- \qquad\qquad \Omega^- \rightarrow \Lambda + K^- , \quad \Lambda \hookrightarrow p + \pi^-$$

For the Pb–Pb sample the Λ decay vertex is required to fall within a fiducial region starting at 30 cm from the target and ending just before the first plane of the PTC. The fiducial region for the cascade (Ξ, Ω)[1] decay vertex starts at 20 cm from the target. For the p–Pb sample all decays have to occur in the region starting at 40 cm from the target. Each decay track is required to pass through all planes of the compact part of the PTC. At the Λ vertex and at both vertices of the Ω or Ξ cascade decays, a distance of closest

[1] In the following, symbols Λ, Ξ and Ω refer both to hyperons and their antiparticles.

approach between the trajectories of decay particles of less than 1 mm is required. A standard set of cuts, analogous to those described in ref. [6], has been applied to eliminate the background[2]. The Λ candidates are required to be kinematically unambiguous with the decay of a K^0_s and the Ω candidates with the decay of a Ξ. The Λ, Ξ and Ω candidates are required to point back to the position of the primary vertex.

A search for the Ξ and Ω candidates and their reconstruction has been performed for all available p–Pb and Pb–Pb data. However, only a small part of the Λs produced in the Pb–Pb collisions were analysed until now. Processing of the remaining data is in progress.

To illustrate the quality of the data, Fig. 5 shows the reconstructed Ξ and Ω mass spectra for sample a).

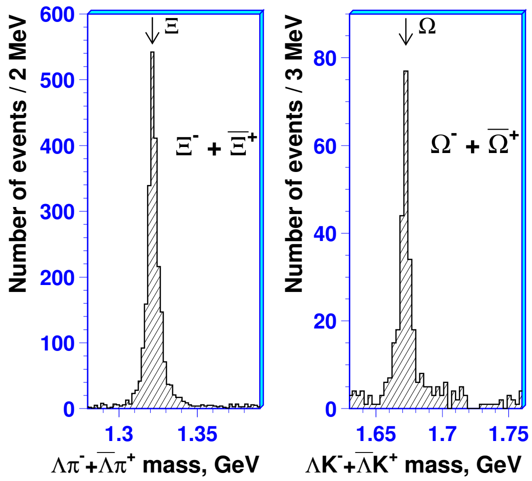

Figure 5. Reconstructed Ξ and Ω signals from Pb–Pb data.

The acceptance windows for Λ, Ξ and Ω from the Pb–Pb collisions, and the regions where the acceptance windows overlap, are shown in Fig. 6.

[2]In the analysis of the Pb–Pb data sample, the considerable number of reconstructed secondary tracks ($\simeq 20$ in the average) allowed an improvement of the determination of the interaction vertex position for individual events. Precise knowledge of the primary vertex position was used for efficient background elimination from Ξ and Ω mass spectra.

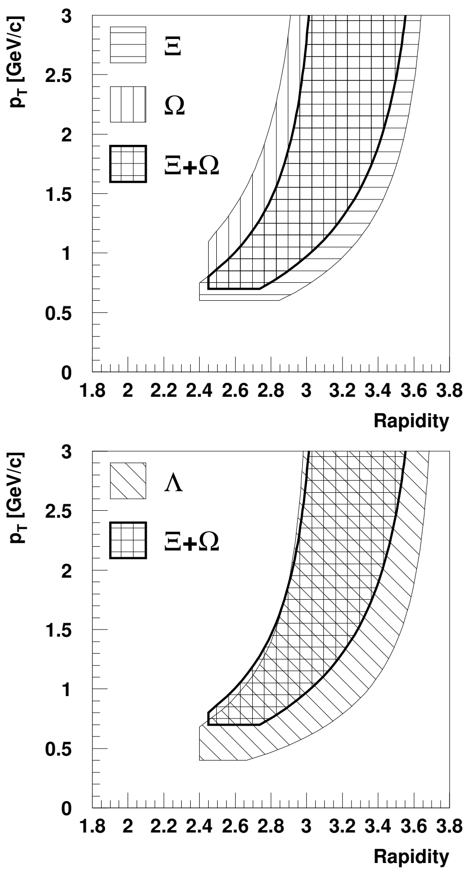

Figure 6. The acceptance in rapidity and p_{t} for Λ, Ξ and Ω in Pb–Pb collisions.

The acceptance windows (and their overlap region) for Ξ and Ω produced in p–Pb interactions are shown in Fig. 7. Our acceptance windows are of a quite complicated shape, but due to the symmetry of the Pb–Pb collision, a reflection of the data with respect to mid-rapidity (which in our case is equal to 2.91) could allow us to determine production cross-sections in a region more suitable for comparison with models and other experiments.

3.3. Correction of data for acceptance and efficiency

The data on hyperon production has to be corrected for geometrical acceptance and for detector and reconstruction efficiency.

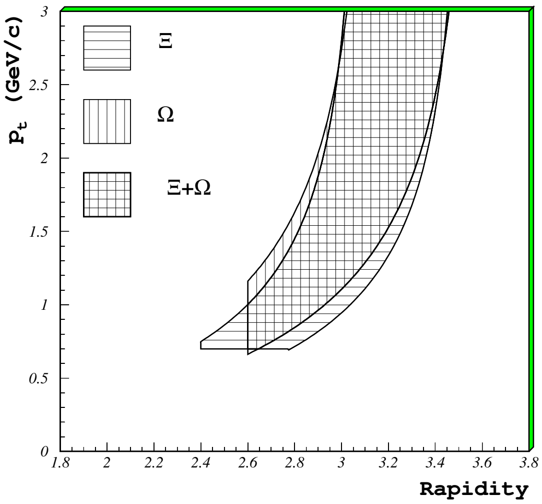

Figure 7. The acceptance in rapidity and $p_{\rm t}$ for Ξ and Ω in p–Pb collisions.

Weights for the reconstructed Λ, Ξ and Ωs are calculated by a GEANT based Monte-Carlo procedure on an event-by-event basis. For each particle a large sample of hyperon decays with the same (measured) rapidity, $p_{\rm t}$ and position of the primary vertex is generated. The tracks of the decay products are propagated through the WA97 set-up. The detector efficiencies for each read-out chip of the pixel planes have been determined and were taken into account.

For each Monte-Carlo event with all decay tracks passing the PTC the background tracks and the electronic noise are simulated by embedding the hits of the Monte-Carlo decay tracks into a real event with a hit multiplicity in the PTC close to that of the original hyperon event.

These mixed events were processed in the same way as the real ones for pattern recognition, track fitting and signal reconstruction and selection. The resulting weight is the number of Monte-Carlo hyperons generated divided by the number of Monte Carlo hyperons successfully reconstructed.

Up to now only part of the data has been corrected. The calculation of weights for the remaining data, which turned out to be a long, CPU intensive procedure, is well under way.

4. RESULTS

We present here the preliminary results of the analysis of data on hyperon and antihyperon production in Pb–Pb and p–Pb collisions. The particle ratios were determined from the subsamples of corrected data.

4.1. Transverse mass spectra

The $m_{\rm t}$ distributions have been studied for Λ and Ξ produced in the Pb–Pb collisions. As a result of an analysis it appears that the data - within the present statistical sensitivity and the accessible rapidity range - are consistent with flat rapidity distributions.

The statistics of presently available corrected data, especially for antihyperons, is quite limited. Therefore we attempted to obtain an estimate of the inverse slopes of $m_{\rm t}$ distributions using uncorrected data samples and larger statistics. Such a method is used for the first time in this experiment and therefore its results are to be considered as preliminary. More complete results will be presented in the near future.

The experimental $m_{\rm t}$ distributions were approximated by the theoretical ones convoluted with the experimental response function.

The theoretical spectra were estimated by the following Monte-Carlo procedure: The hyperons were generated with a flat rapidity distribution, with an exponential $m_{\rm t}$ dependence

$$\frac{1}{m_{\rm t}}\frac{{\rm dN}}{{\rm d}m_{\rm t}} \sim \exp(-m_{\rm t}/T)$$

and with an approximate distribution of the production vertex. The decay tracks were embedded into a real background event with a typical hit multiplicity distribution in the PTC. Then they were passed through the standard reconstruction and analysis software chain used in our experiment. Events fulfilling all cuts applied to the experimental data were used to construct the convoluted theoretical spectra.

The value of the inverse slope T was varied in order to obtain the best approximation (by a χ^2 estimator) of the experimental distribution. The value of T corresponding to the minimal χ^2 is considered to be a proper estimate of the inverse slope for the given particle. The values of T, obtained by this procedure, are shown in the table.

Particle	T [GeV/c^2]	Particle	T [GeV/c^2]
Λ	0.28 ± 0.01	Ξ^-	0.30 ± 0.02
$\overline{\Lambda}$	0.30 ± 0.01	$\overline{\Xi}^+$	0.28 ± 0.02

In Fig. 8 the m_t distribution for Ξ^- hyperons is shown. The agreement of experimental and Monte-Carlo spectra is statistically satisfactory (with $\chi^2/\mathrm{NDF} = 1.2$). The behaviour of the m_t spectra for Λ, $\overline{\Lambda}$ and $\overline{\Xi}^+$ is similar with χ^2/NDF ranging from 0.8 to 1.5 .

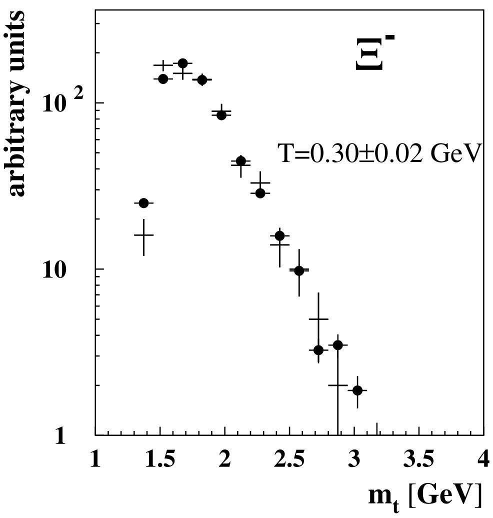

Figure 8. Uncorrected m_t distribution of Ξ^- from Pb–Pb interactions. + – experimental data, • – Monte-Carlo simulation.

As one can see from the table, the inverse slopes of m_t spectra for Λ, Ξ^- and their antiparticles are similar. They are systematically higher than the values found in the WA94 experiment for S–S collisions [6]. This difference could be a result of a higher collective flow in Pb–Pb collisions [11].

4.2. Ξ^-/Λ ratio

Cross sections and particle ratios are being calculated for Λ, Ξ and Ω using corrected data subsamples. Here we present results on the comparison of the new data on the Ξ^-/Λ ratio for Pb–Pb with data from the WA85 and WA94 experiments.

The ratio of Ξ^- and Λ yields in Pb–Pb has been calculated for $p_\mathrm{t} > 0.7$ GeV/c and one unit of central rapidity for two intervals of the collision centrality, whose central values correspond to 180 and 340 participating nucleons. The number of nucleons participating in the collision was estimated by means of the VENUS model from the measured multiplicities. These ratios are numerically the same as in the overlap window. They are shown in Fig. 9 together with the values recently obtained for p–S, p–W, S–S and S–W collisions. For the comparison these values, measured for one unit of central rapidity and for $p_\mathrm{t} > 1.2$ GeV/c, have been extrapolated down to $p_\mathrm{t} > 0.7$ GeV/c, the lower p_t limit for the Pb–Pb data. Such an extrapolation has been performed using the published slopes [5,6] of the m_t distributions.

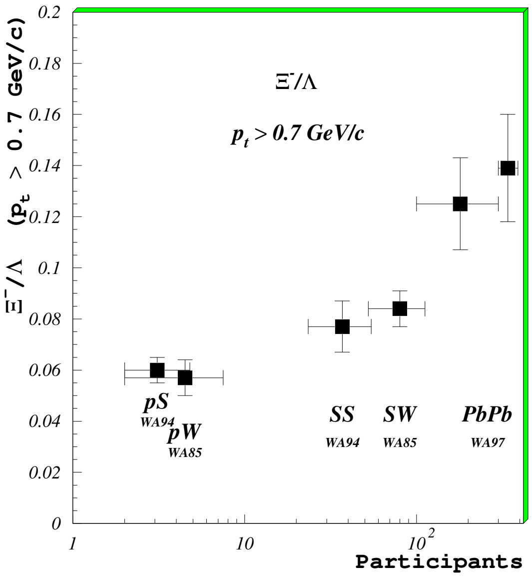

Figure 9. Compilation of the Ξ^-/Λ ratio for different colliding systems. Horizontal bars indicate approximate range of the number of participants for each reaction.

There is clearly an enhancement of Ξ^- relative to Λ at central rapidity when increasing the volume of the colliding nuclei. The expected increase of statistics should allow us to ascertain whether or not this ratio has a sudden increase when going from S–W to Pb–Pb reactions.

4.3. Ω/Ξ enhancement

The first indication that the Ω production is significantly enhanced with respect to Ξ in Pb–Pb compared to p–Pb reactions was presented a year ago [12]. Results of the current analysis of both uncorrected and corrected data samples confirm this conclusion.

The uncorrected Ω and Ξ signals resulting from processing of all available Pb–Pb and p–Pb data from the WA97 1995 runs are presented in Fig. 10. A striking difference between Ω/Ξ ratios in the p–Pb and Pb–Pb data is seen, showing an enhancement by a factor 2.5 going from p–Pb to central Pb–Pb collisions.

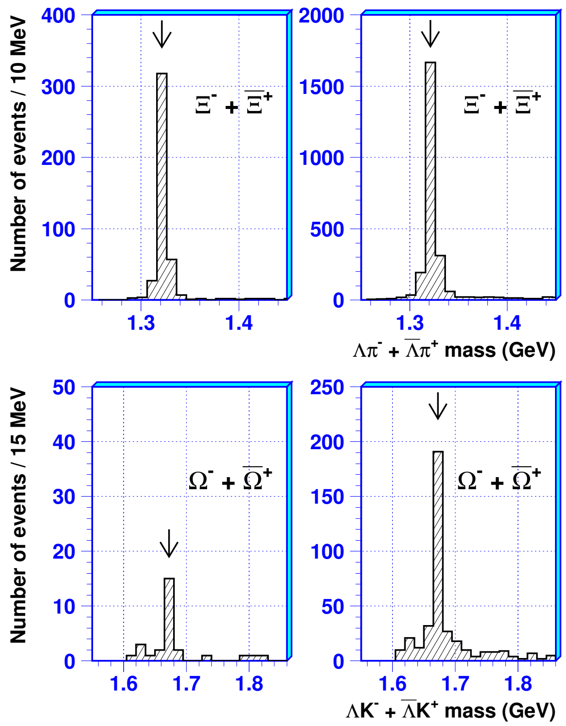

Figure 10. The uncorrected Ξ and Ω signals in p–Pb (left) and Pb–Pb (right) collisions. The arrows indicate the PDG table mass values.

The recent analysis of corrected data subsamples has confirmed the assumptions[3] made in the comparison of uncorrected signals. From the measurement of the $(\Omega^- + \overline{\Omega}^+)/(\Xi^- + \overline{\Xi}^+)$ ratio separately for p–Pb and Pb–Pb data in the overlap acceptance window we obtain

$$\frac{(\Omega^- + \overline{\Omega}^+ / \Xi^- + \overline{\Xi}^+)_{\mathrm{Pb-Pb}}}{(\Omega^- + \overline{\Omega}^+ / \Xi^- + \overline{\Xi}^+)_{\mathrm{p-Pb}}} = 3.2 \pm 1.1$$

Fig. 11 shows the Ω^-/Ξ^- ratio extracted from fully corrected p–Pb and Pb–Pb data samples. Up until now this is the only measurement of that ratio, performed in the same kinematic window (the overlapping region of p–Pb and Pb–Pb data). Again we can see an increase in production of a baryon with higher strangeness as compared to a baryon with lower strangeness.

This points to a pattern of strangeness enhancement, where there is an increase with the strangeness content of a particle.

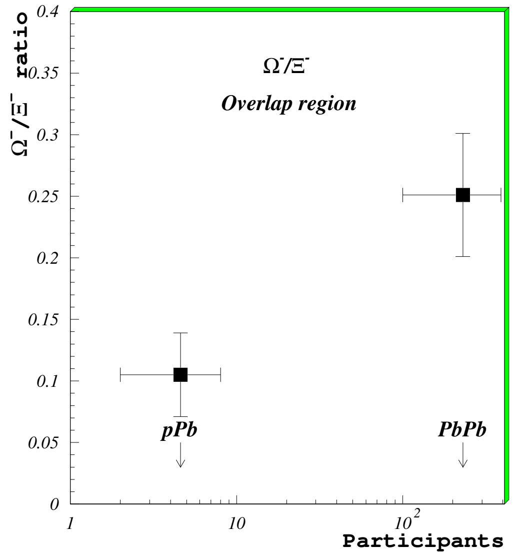

Figure 11. Ω^-/Ξ^- ratio for the p–Pb and Pb–Pb data. Horizontal bars indicate approximate range of the number of participants.

[3]a similar acceptance of Ω/Ξ ratio in samples a) and b); the same reconstruction efficiency of Ω and Ξ decays

5. CONCLUSIONS AND OUTLOOK

The preliminary WA97 results on hyperon and antihyperon production in Pb–Pb and p–Pb collisions are presented.

The enhancement of the $(\Omega^-+\overline{\Omega}^+)/(\Xi^-+\overline{\Xi}^+)$ ratio when going from p–Pb to Pb–Pb collisions was found to be 3.2 ± 1.1 (it is $\simeq 2.4$ for the Ω^-/Ξ^- ratio).

The Ξ^- hyperon production is in turn enhanced relative to Λ when going from p–S to Pb–Pb collisions by a factor of about 2 (the enhancement with respect to S–S is $\simeq 1.7$).

The inverse slopes of transverse mass distributions for Λ, $\overline{\Lambda}$, Ξ^- and $\overline{\Xi}^+$ have been estimated. They appear to be larger in Pb–Pb than in S–S interactions.

The Pb–Pb data sample analysed till now represents only a limited part of the full available statistics. Further analysis is in progress which should enable us to complete these results and to improve significantly their statistical precision.

REFERENCES

1. J.W. Harris and B. Müller, Annu. Rev. Nucl. Part. Sci. 46 (1996) 71.
2. J. Rafelski and B. Müller, Phys. Rev. Lett. 48 (1982) 1066; Phys. Rev. Lett. 56 (1986) 2334.
3. P. Koch, B. Müller and J. Rafelski, Phys. Rep. 142 (1986) 167.
4. J. Rafelski, Phys. Lett. B, 262 (1991) 333.
5. S. Abatzis et al., Nucl. Phys. A, 590 (1995) 307c; Proceedings of Strangeness '95, Tucson, Arizona, AIP Press (1995) 223.
6. S. Abatzis et al., Nucl. Phys. A, 590 (1995) 317c; Phys. Lett. B, 400 (1997) 239.
7. T. Åkesson et al., Nucl. Phys. B, 354 (1984) 1.
8. S.Abatzis et al., Phys. Lett. B, 316 (1993) 615; Phys. Lett. B, 347 (1995) 158.
9. G. Alexeev et al., Nucl. Phys. A, 590 (1995) 139c.
10. E.H.M. Heijne et al., Nucl. Instrum. Methods A, 349 (1994) 138;
    F. Antinori et al.,Nucl. Instrum. Methods A, 360 (1995) 91.
11. I.G. Bearden et al., Phys. Rev. Lett., 78 (1997) 2080.
12. WA97 Collaboration (presented by H. Helstrup), Proceedings of the Quark Matter '96 conference, Heidelberg, 1996; Nucl. Phys. A, 610 (1996) 165c;
    WA97 Collaboration (presented by L. Šándor), Proceedings of the XXVI International Symposium on Multiparticle Dynamics, Faro (Portugal), 1996; World Scientific, Singapore 1997, p.119.