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Strangeness enhancement at mid-rapidity in Pb-Pb collisions at 158 A GeV/c

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Abstract

K^0_S, Λ, Ξ, Ω and negative particle yields and transverse mass spectra have been measured at central rapidity in Pb-Pb and p-Pb collisions at 158 A GeV/c. Yields are studied as a function of the number of nucleons participating in the collision N_{part}, which is estimated with the Glauber model. From p-Pb to Pb-Pb collisions the particle yields per participant increase substantially. The enhancement is more pronounced for multistrange particles, and exceeds an order of magnitude for the Ω. For a number of participants, N_{part}, greater than 100, however, all yields per participant appear to be constant.

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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). Several experimental signatures which could signal the onset of the QGP phase have been proposed. (For a recent review see Ref. [1]). Recently, a number of experimental observations that could indicate a phase transition to QGP have been presented [2, 3, 4, 5].

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 with respect to proton-nucleus interactions has been suggested as one of the sensitive signatures for a phase transition to a QGP state [6, 7]. It is expected that the enhancement should be more pronounced for multi-strange than for singly strange particles [8]. For a recent review of the subject, see Refs. [9, 10].

The WA97 experiment addresses strangeness production in Pb-Pb collisions and 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 experimental set-up, its silicon telescope and the use of the multiplicity detectors is described in Ref. [4].

Recently we published data on the Λ, Ξ and Ω yields in Pb-Pb interactions as a function of collision centrality and compared with yields in p-Pb [4]. We observed a strong increase in the production at mid-rapidity for Λ, Ξ and Ω hyperons and anti-hyperons in Pb-Pb collisions with respect to p-Pb collisions and this enhancement exhibited a marked hierarchy, *i.e.* the Ω enhancement is larger than that of the Ξ, and the Ξ enhancement is larger than that of the Λ. The present letter elaborates on these findings with improved statistics (a factor of two higher than in the previous work). The analysis of $\mathrm{K^0_S}$ and negative particles (h^-) is now also included.

In the p-Pb runs we have collected data with two different trigger conditions:

a) at least two tracks in the telescope, as required to find V^0's;

b) at least one track in the telescope.

Sample a) was used for the strange particle study and sample b) for the h^- study. In both cases the effect of the trigger has been taken into account in the calculation of the particle yields. In the Pb-Pb sample the trigger corresponded to the most central 40% of the total inelastic cross section, see Ref. [4].

We selected as h^- those negative tracks which pointed to the interaction vertex.

The $\mathrm{K^0_S}$ were identified by their decay

$$\mathrm{K^0_S} \rightarrow \pi^- + \pi^+$$

To ensure that $\mathrm{K^0_S}$ is not ambiguous with Λ, a cut for $|\alpha_A| \leq 0.45$ was made in the Armenteros-Podolanski plot [11].

The Λ, Ξ^-, Ω^- hyperons and their antiparticles were identified by reconstructing their decays into final states containing only charged particles:

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

The details of the analysis, *i.e.* the extraction of the various particle signals and the weighting procedures are discussed in Refs. [4, 12, 13].

In the geometry of our experiment the feed-down from weak decays is expected to be of minor importance, and the Λ and Ξ data have not been corrected for feed-down from cascade decays. It is estimated to be less than 5% for Λ and less than 10% for $\overline{\Lambda}$. For both Ξ^- and $\overline{\Xi}^+$ the feed-down from Ω decays is less than 2%.

The mass resolution is better than 6 MeV (FWHM) for all signals.

The acceptance windows for Λ, Ξ and Ω from Pb-Pb and p-Pb collisions are shown in our previous publication [4]. For negatives h^- and K^0_S the acceptance windows are shown in Fig. 1. The differential distributions of the yield per event for each kind of particle were fitted in their respective acceptance windows using the expression

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

where m_T is the transverse mass, y is the rapidity and $\alpha = 1.5$. 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.* in expression (1) $f(y) =$ constant. We have investigated the systematic error which this assumption could introduce in the case of p-Pb for h^-, K^0_S, Λ and $\overline{\Lambda}$, where published data exist for p-Au [14] and p-S [15] collisions. We find that using a flat rapidity distribution, instead of one obtained from a fit to the published data [14], changes the values of T by less than 2%, 5%, 5% and 10%, in the case of the h^-, K^0_S, $\overline{\Lambda}$ and Λ distributions, respectively. The corresponding changes in the particle yields, defined by equation (2) below, are less than 10%, 5%, 5% and 6%.

For each particle species, the values for the slope T were calculated both for the p-Pb sample and Pb-Pb sample. These values, given in [12], are used in the analysis which follows.

The WA97 multiplicity detectors allow us to study particle yields as a function of collision centrality as measured by the number of participants N_{part}. To this purpose the multiplicity spectrum is divided into four bins and the average number of participants $\langle N_{part}\rangle$ for each bin is calculated as described in ref. [4]. For p-Pb the number of participants corresponds to the estimated average for minimum bias collisions. The particle production yield per event, Y, in each centrality bin is defined by the integral

$$Y = \int_0^\infty \mathrm{d}p_\mathrm{T} \int_{y_{cm}-0.5}^{y_{cm}+0.5} \mathrm{d}y\, \frac{\mathrm{d}^2 N}{\mathrm{d}y\,\mathrm{d}p_\mathrm{T}} \tag{2}$$

where the extrapolation to the window $|y - y_{cm}| < 0.5$ and $p_\mathrm{T} > 0$ GeV/c is done according to expression (1) using the values of T given in [12].

Figure 2 shows particle yields per event for p-Pb and Pb-Pb interactions as a function of the number of participants $\langle N_{part}\rangle$. The vertical error bars correspond to 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. For the h^- yield in p-Pb collisions, however, a 15% systematic error has been introduced to account for the uncertainties due to the single track background subtraction procedure. The horizontal bars show the root-mean-square values of the number of participants in the selected bins for Pb-Pb collisions, and the range corresponding to 80% of the cross section in p-Pb.

In Fig. 2 the particles are divided into two groups. Figure 2a shows the yields of particles with at least one common valence quark with the nucleon (Ξ^-, Λ, h^-) and of the K^0_S, which has contributions $\overline{d}s$ and $d\overline{s}$. Fig. 2b refers to particles with no common valence quark with the nucleon: $\overline{\Lambda}$, $\overline{\Xi}^{+}$ and $\Omega^{-}+\overline{\Omega}^{+}$. It is instructive to analyze them separately since the particles in the two groups are empirically known to exhibit different production features, *e.g.* Λ and $\overline{\Lambda}$ have different rapidity spectra both in p-S and S-S [14]. Figure 3a,b shows the particle 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). The particle yields in Pb-Pb are compared to a yield curve (full line) drawn through the p-Pb points and proportional to the number of participants, N_{part}.

All yields appear to increase with centrality from p-Pb to Pb-Pb faster than linearly with the number of participants. However, within our experimental centrality range for Pb-Pb, *i.e.* for $N_{part} > 100$, we observe that all particle yields per participant appear to be constant. This is illustrated in Fig. 3c and 3d, where we present the particle yield per participant, $\langle Y\rangle/\langle N_{part}\rangle$, as a function of $\langle N_{part}\rangle$.

For each particle species we then compute a global enhancement, E, going from p-Pb to Pb-Pb collisions, defined as

$$E = \left(\frac{\langle Y\rangle}{\langle N_{part}\rangle}\right)_{Pb-Pb} \Bigg/ \left(\frac{\langle Y\rangle}{\langle N_{part}\rangle}\right)_{p-Pb}, \tag{3}$$

where $\langle Y\rangle$ and $\langle N_{part}\rangle$ are averaged over the full centrality range covered by the experiment. E measures the enhancement at midrapidity for the various hadron species. The values E for each particle are displayed in Fig. 4. Similar enhancement values are obtained if we use the data before the extrapolation to the full $y - p_{\mathrm{T}}$ window. We note that the enhancement E increases with the strangeness content:

$$E(\Omega^{-}+\overline{\Omega}^{+}) > E(\overline{\Xi}^{+}) > E(\overline{\Lambda})$$

and

$$E(\Xi^{-}) > E(\Lambda) \approx E(\mathrm{K}^0_{\mathrm{S}}).$$

In summary, the strange particle yields per participant at central rapidity increase from p-Pb to Pb-Pb. The enhancement is more pronounced for multistrange particles, and exceeds one order of magnitude in the case of Ω. As pointed out in [16], such a behaviour contradicts expectations from hadronic rescattering models, where secondary production of multi-strange (anti)baryons is hindered by high mass thresholds and low cross sections. Within the participant range $N_{part} > 100$, corresponding to our Pb-Pb data, all yields are found to increase proportionally to N_{part}, as it would be expected if strange quarks are equilibrated in a deconfined and chirally symmetric quark gluon plasma.

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References

[1] J.W. Harris and B. Müller, Annu. Rev. Nucl. Part. Sci. **46** (1996) 71.

[2] M.C. Abreu *et al.*, Phys. Lett. **B410** (1997) 327 and Phys. Lett. **B410** (1997) 337.
L. Ramello *et al.*, (NA50 Collaboration), Charmonium production in Pb-Pb interactions at 158 GeV/c per nucleon, in Proceedings of the 13th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Tsukuba, Japan, December 1997, Nucl. Phys. **A638** (1998) 261c.

[3] G. Roland *et al.* (NA49 Collaboration), Recent results on central Pb-Pb collisions from experiment NA49, in Proceedings of the 13th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Tsukuba, Japan, December 1997, Nucl. Phys. **A638** (1998) 91c.

[4] E. Andersen *et al.*, Phys. Lett. **B433** (1998) 209.

[5] M. Kaneta *et al.* (NA44 Collaboration), Kaon and proton ratios from central Pb-Pb collisions at the CERN SPS, in Proceedings of the 13th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Tsukuba, Japan, December 1997, Nucl. Phys. **A638** (1998) 419c.

[6] J. Rafelski and B. Müller, Phys. Rev. Lett. **48** (1982) 1066,
J. Rafelski and B. Müller, Phys. Rev. Lett. **56** (1986) 2334.

[7] P. Koch, B. Müller and J. Rafelski, Phys. Rep. **142** (1986) 167.

[8] J. Rafelski, Phys. Lett. **B262** (1991) 333.

[9] U. Heinz, Strange messages: chemical and thermal freezeout in nuclear collisions, in Proceedings of the 4th International Conference on Strangeness in Quark Matter, Padova, Italy, July 1998, J. Phys. G: Nucl. Part. Phys. **25** (1999) 263.

[10] J. Rafelski, Quo vadis strangeness ?, in Proceedings of the 4th International Conference on Strangeness in Quark Matter, Padova, Italy, July 1998, J. Phys. G, Nucl. Part. Phys. **25** (1999) 451.

[11] J. Podolanski and R. Armenteros, Phil. Mag. **45** (1954) 13.

[12] R. Lietava *et al.* (WA97 Collaboration), Strangeness enhancement at mid-rapidity in Pb-Pb collisions at 158 A GeV/c, in Proceedings of the 4th International Conference on Strangeness in Quark Matter, Padova, Italy, July 1998, J. Phys. G: Nucl. Part. Phys. **25** (1999) 181.

[13] R. Caliandro *et al.* (WA97 Collaboration), Λ,Ξ and Ω production at mid-rapidity in Pb-Pb and p-Pb collisions at 158 A GeV/c, in Proceedings of the 4th International Conference on Strangeness in Quark Matter, Padova, Italy, July 1998, J. Phys. G: Nucl. Part. Phys. **25** (1999) 171.

[14] T. Alber *et al.*, Z. Phys. **C64** (1994) 195.

[15] A. Bamberger *et al.*, Z. Phys. **C43** (1989) 25.

[16] P. Braun-Munzinger and B. Müller, Summary report from the meeting Heavy Ion Physics at the SPS, HIPS-98, Chamonix, France, September 1998.

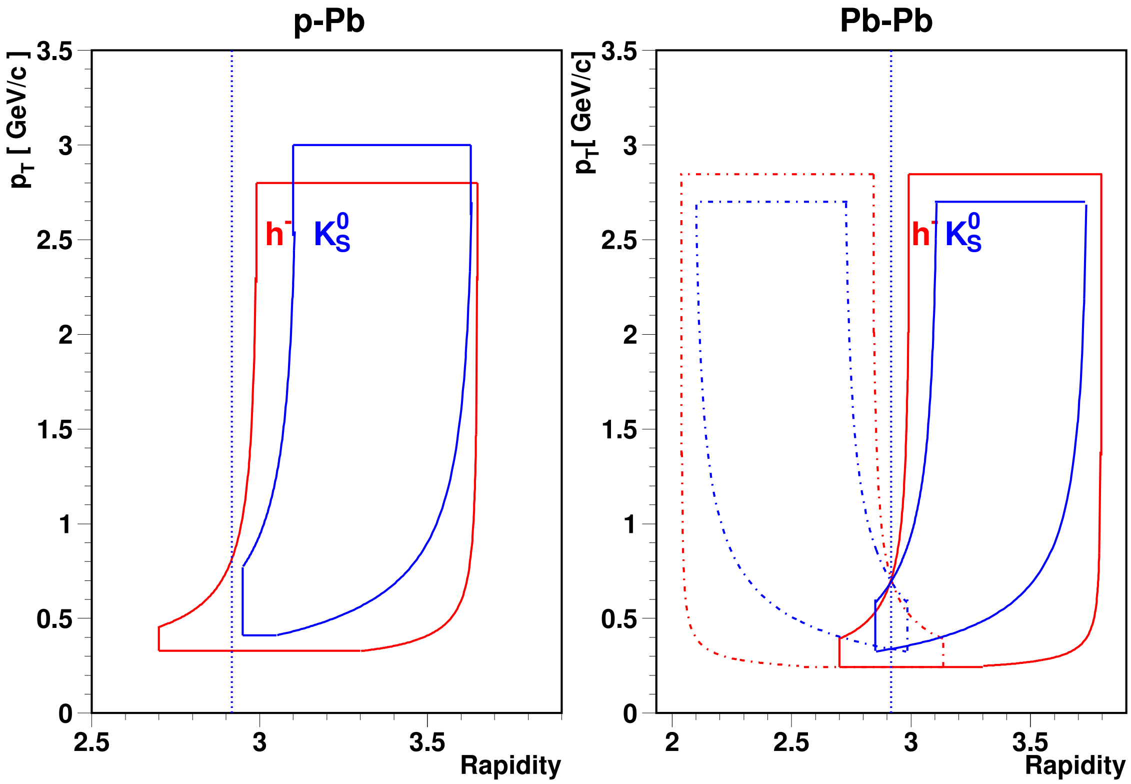

Figure 1: Acceptance windows for h^- (assumed to be pions) and K^0_S. For Pb-Pb collisions, the symmetry of the system around midrapidity allows reflection of the acceptance windows around y_{cm}.

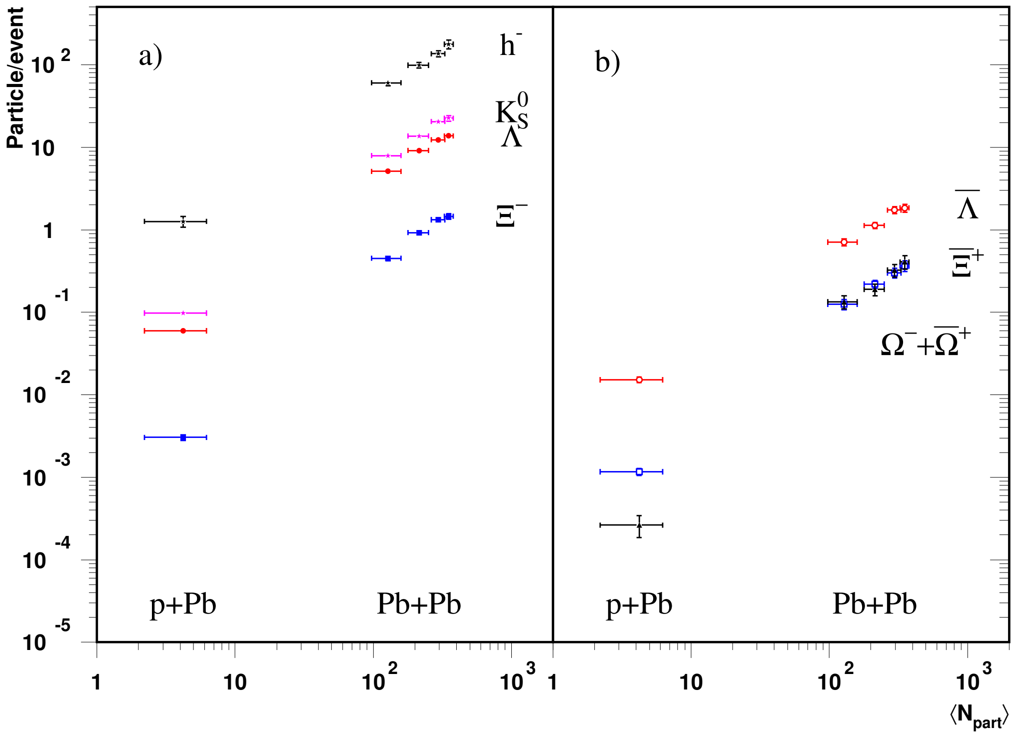

Figure 2: Yields, defined in equation (2), as a function of the number of participants for a) h^-, K^0_S, Λ and Ξ^-; b) $\overline{\Lambda}$, $\overline{\Xi}^+$ and $\Omega^- + \overline{\Omega}^+$. Note that the yields for $\overline{\Xi}^+$ and $\Omega^- + \overline{\Omega}^+$ are very similar.

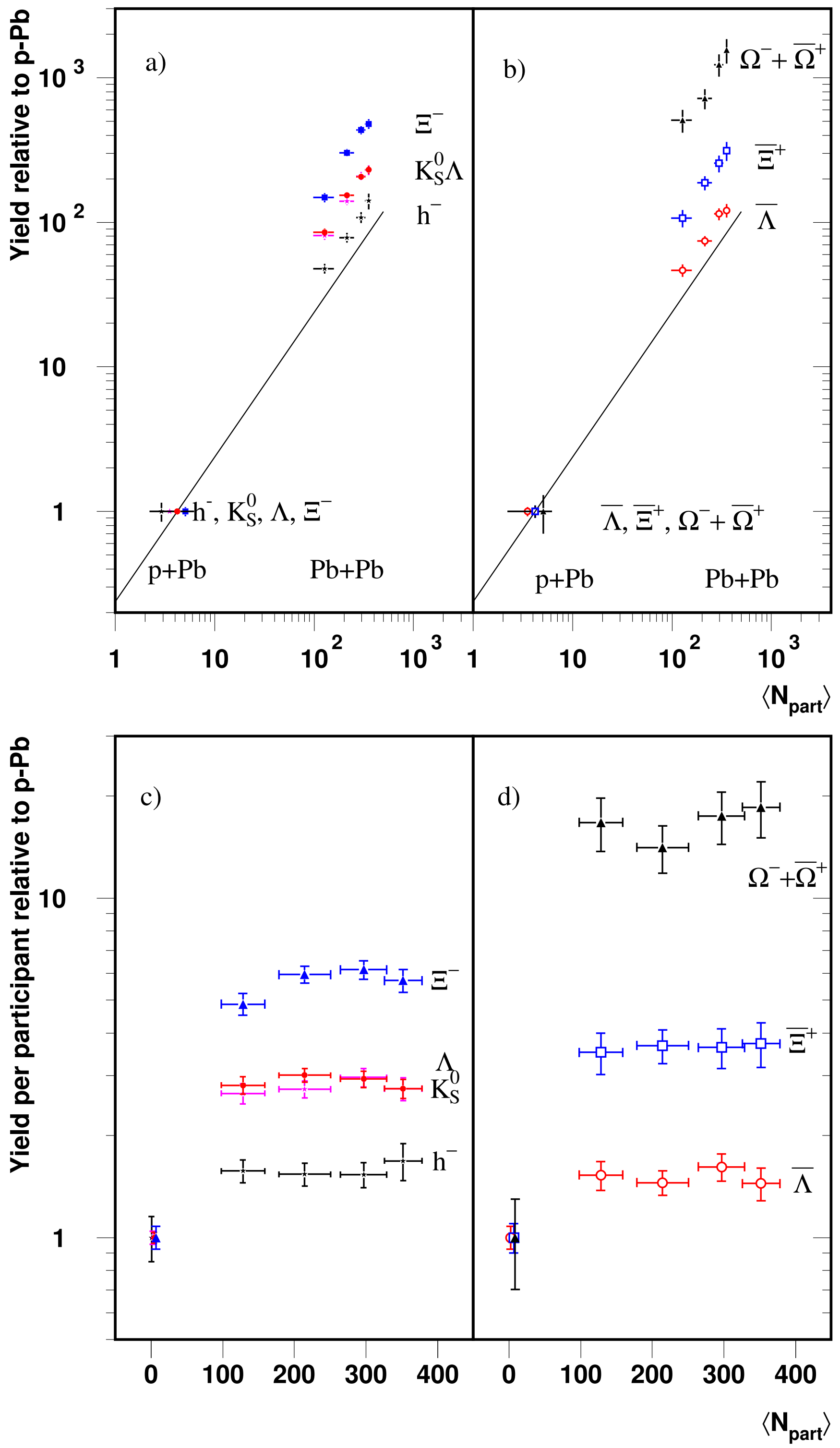

Figure 3: Yields, expressed in units of yields observed in p-Pb collisions, as a function of the number of participants for a) h^-, K^0_S, Λ and Ξ^-; b) $\overline{\Lambda}$, $\overline{\Xi}^+$ and $\Omega^- + \overline{\Omega}^+$. The solid line represents a function through the p-Pb point proportional to the number of participants $\langle N_{part} \rangle$. The corresponding yields per participant are shown in c) and d). The proton points are juxtaposed on the horizontal scale.

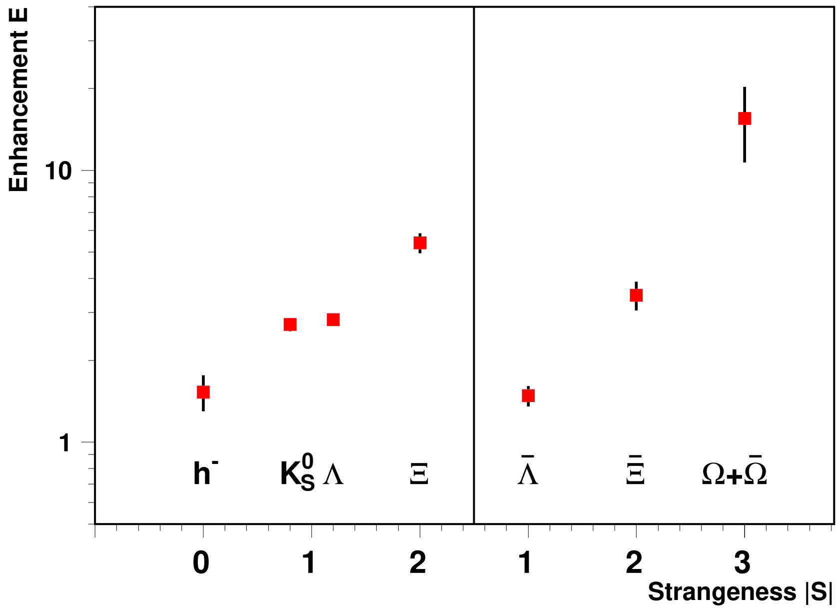

Figure 4: Strange particle enhancement versus strangeness content.