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## Strangeness and the Quark-Gluon Plasma: An Experimenter's Perspective

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# STRANGENESS AND THE QUARK - GLUON PLASMA:

## an experimenter's perspective

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# STRANGENESS AND THE QUARK - GLUON PLASMA:

## an experimenter's perspective.

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Abstract:
Current status of experimental results on strange particle production in relativistic nucleus - nucleus collisions is reviewed. Emphasis is placed on the relevance to the hypothetical quark-gluon plasma formation and the origin of the Universe.

### 1. Has the Universe always existed ... (instead of introduction )

For a very long time, due to the lack of adequately powerful theories and sensitive enough experimental techniques, the question of the origin of the Universe laid outside scientific reach (however, it often entertained philosophers and theologians). Only in this century, using Einstein's theory of general relativity (to extrapolate back in time) and some basic physical laws, astrophysicists ( who slowly begun to change their title to cosmologists) came up with the Big Bang model[1] of the beginning of the Universe. This model assumes that the Universe evolved, some 15 billion years ago, from a single, unbelievably small, dense, hot region. During the first few microseconds of this evolution, all matter existed as a quark-gluon plasma. As the Universe expanded and cooled down, more complex matter condensed out of the plasma, eventually forming all the elements observed today (most galaxies, including the Milky Way, were formed 8 billion years ago ).

The hot Big Bang model makes definite predictions about the Universe as it exists now (it predicts the formation of nuclei, the relative abundance of certain elements, etc.). Probably the most important prediction was of a phenomenon known as the cosmic background radiation - the glow of radiation left over from the initial explosion, which permeates the Universe. The cosmic background radiation was discovered experimentally in 1964. Thus, for the first time, hypotheses about the origin of the

[1] The idea of an expanding birth of the Universe, first proposed by George Gamow in 1948, successfully battled other theories concerning the origin of the Universe.

cosmos were supported by empirical evidence. Fig. 1 illustrates the evolution of the Universe as we understand it now. On the left hand side the vertical scale shows the temperature (in degrees K), on the right hand side - time since the Big Bang (in sec.).

Despite its successes, the Big Bang theory leaves many questions open. The trouble is that the study of the birth and evolution of the Universe has only one (!) event to analyze. Clearly scientists were not satisfied with the situation and, moreover, they were not willing to wait centuries for another event to happen ( the explosion and collapse of stars does not happen frequently!). Instead, they pursued vigorously work on re-creating in the laboratory conditions comparable to the first moments of the early Universe by colliding relativistic nuclei and creating "small bangs". Such collisions offer a unique opportunity to compress nuclear matter to several times its normal density and to heat it to temperatures in excess of $10^{12}$ degrees. To create and study the primordial quark-gluon plasma became the greatest, most exciting experimental challenge of our days. The possible existence of a quark-gluon plasma became a big issue not only in cosmology[2] (i.e. the early Universe, as discussed above, and its large scale structures, density fluctuations during QCD[3] phase transition, etc.), but also in astrophysics (the core of the neutron stars could be in a plasma phase, issues of the compressibility of matter, supernovae dynamics, etc.) and in QCD (since it is related to the long-range behavior where the theory is not yet well developed, and in particular to chiral symmetry restoration and deconfinement).

The experimental pilot program with heavy ion collisions began in fall of 1986. The first, exploratory, runs started at CERN SPS (Geneva, Switzerland) and at BNL AGS( Brookhaven, USA). The projectile ions were only moderate in size, with oxygen and sulfur runs at CERN and oxygen and silicon at BNL. The experiments quickly brought interesting results which were presented and extensively discussed at many conferences [1], among others during the First and the Second Rio Workshop on Relativistic Aspects of Nuclear Physics in 1989 and 1991 [2]. Recently, the BNL program was extended to gold beams, and at CERN lead beams are scheduled in the Fall of 1994.

In this lecture, the current status of selective experimental results on strangeness production in relativistic ion collisions at CERN and BNL is reviewed. Its relevance to possible phase transition and the formation of the quark-gluon plasma is discussed.

## 2. Strangeness as a messenger of plasma phase.

There may not be simple ways to detect a quark-gluon plasma in the laboratory at all, but much can be learned about this new form of highly excited nuclear matter by studying strange particles in general, and multistrange baryons in particular.

Along with our standard picture one expects that the quark-gluon plasma phase will be characterized by both colour deconfinement and partial restoration of chiral

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[2] Note that cosmologists are always putting us in our place. Not content to tell us that our sun is just one of billions of stars in the Milky Way, which itself is one of billions of galaxies in the Universe, some cosmologists would also have us believe that our entire Universe is only one in an infinitude of cosmos ...

[3] QCD = quantum chromodynamics

symmetry. Therefore, the production of strange particles is expected to be enhanced by the quark-gluon plasma as compared with a thermalized hadronic gas, as had been originally predicted by Jan Rafelski and collaborators [3] almost a decade ago. A recent review of simple, almost historic and somewhat correlated arguments (with some supporting calculations) why strangeness appears *a priori* to be a distinct diagnostic tool in search for plasma, can be found in reference 4.

However, I would like to state some of the main arguments:

- the symmetry of $\bar{s}$, $\bar{u}$, and $\bar{d}$, in statistical description,
- the strongly differing production rates in different phases of nuclear matter,
- the differing energy thresholds for strangeness production in hadronic gas and QGP,
- the high $s\bar{s}$-quark pair density in plasma ,
- and, perhaps most importantly, the presence of a large number of gluons in the plasma state.

The predicted large strangeness pair density in quark-gluon plasma (QGP) is the main point of interest; it is hard to imagine another scenario in which strange (and even harder in which multistrange[4] [5]) baryons would be so abundantly produced. Furthermore, the information contained in strange particles is expected to be preserved in the evolution of hadronic matter following the dissociation of QGP [3,6].

## 3. Remarks on Strange Particle Detection.

The majority of strange particles contain one strange quark ($\Lambda$, $\bar{\Lambda}$, family of kaons, triplet of $\Sigma$'s), and only cascades, $\Phi$ mesons (S=2) and omegas (S=3) are "exceptionally" strange and contain 2 and 3 strange quarks respectively.

All strange particles are unstable.

There are three types of decay modes for strange particles: strong, electromagnetic, and weak. Strangeness, which is an additive quantum number, is conserved both in strong and electromagnetic but not in weak reactions.

Strongly decaying particles have very short lifetimes ($< 10^{-20}$ s) and therefore their decay widths are at least of the order of a few MeV. The only way to detect such short-lived objects is by looking for the resonant peaks in the invariant mass spectrum of their possible decay products. The main problem then is to differentiate between the signal and non-resonant combinatorial background. In the case of elementary particle collisions, where the final state amounts to a few particles, the combinatorial background is not very large, and generally speaking - manageable. Relativistic heavy ion interactions (especially the central ones) produce, however, a few hundred particles in the final state. Therefore the combinatorial background is rising dramatically and finding resonant maximum on the invariant mass plot might become quite hopeless, unless some additional information can be used to reject a substantial part of the background. The most common strategy here is to select the decay mode into particles which are otherwise not very frequent in the final state.

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[4] High strangeness density in QGP should favor the formation of multistrange objects, whereas in hadronic gas phase multistrange baryons could be formed only as a result of a series of unlikely reactions.

The electromagnetic decay mode is not popular among strange particles. There is only one particle, $\Sigma^0$, which decays electromagnetically into $\Lambda$ and $\gamma$. Both $\Lambda$ and $\gamma$ are neutral, which in practical terms excludes invariant mass spectrum analysis. No $\Sigma^0$'s in heavy ion experiments have been observed to date.

Weakly decaying particles live long enough to allow for the detection of their decay vertices at measurable distances from the main interaction vertex (their production point). Average decay lengths are proportional to the momentum of the particle. Table 3 (borrowed from ref. 7) gives the average decay length per GeV for the weakly decaying strange particles, together with their main decay modes. There are two strategies which have been developed and are commonly used for the identification of weakly decaying strange particles:

1. Direct identification - via momentum measurements combined with dE/dx, TOF and Čerenkov light measurements,
2. Analysis of the decay topology - via the kinematic reconstruction of the decay vertex (the conservation of momentum and energy provide four constraint equations which have to be satisfied by the ensemble of particles entering and leaving the vertex, the fitting procedure provides criteria for the selection of the correct hypothesis).

So far all strange and multistrange baryons have been identified by their topological decays. Kaons have been detected by both direct and topological analysis. $\Phi$ mesons have been identified only by direct identification of their decay products both in K decay mode and in the lepton mode.

Figure 2 shows a few typical weak decay topologies in the presence of a magnetic field: a) for $\Lambda$ (S= +/- 1), b) for $\Xi$ (S= +/- 2), and c) for $\Omega$ (S= +/- 3). The continuous lines indicate the trajectories of charged particles, the dotted lines are trajectories of neutral particles. Note that in case of $\Xi$ and $\Omega$ decay (Fig. 2b and c) - the observed strange particles ($\Lambda$'s) are the second generation decay products (they do not originate from the main interaction vertex, but from the secondary one).

I would like to conclude these introductory remarks with a reminder that all observations are made only in the final stage of the reaction when particles, or their constituents, have already been subjected to the space-time evolution of the system and perhaps have undergone phase transition back to the hadronic phase as well, which complicates the interpretation of the observed characteristics of the strange particles. It might even make it impossible to distinguish between the hadronized products of the quark-gluon plasma and those of a chemically-equilibrated hadron gas. Nevertheless the enhancement of strange particle production reflects the interesting collision dynamics and may provide insights into mechanisms responsible for these phenomena. Saying that, let us start to review some experimental data ...

## 4. Experimental Results.

At the Quark-Matter Conference in 1988 (Lenox, USA) the NA35 experiment at CERN presented for the first time an observed significant enhancement in $\Lambda$, $\bar{\Lambda}$ and $K^o$

particle production in S+S at 200 GeV [8]. Initial estimates of energy densities in central collisions with CERN-SPS oxygen and sulfur beams was of the order of 2 GeV/fm$^3$ in a volume of about 90 fm$^3$ [9]. Because of the rather small volume there was not much hope for even partial thermalization or phase transition, although such high energy densities appear, in principle, to be sufficient [10]. Therefore the NA35 report on strangeness enhancement in S+S reactions was astonishing. At the same time the BNL E802 experiment reported the enhanced $K^+/\pi^+$ ratio in Si+Au at 14.5 GeV [11]. Since then, a number of experiments both at CERN SPS and at BNL AGS reported similarly abundant production of strange particles in relativistic heavy ion reactions. These initial observations triggered a lot of theoretical and experimental effort on both continents. Data available today is much more mature and understood; however, theory still does not offer explanation of the observed phenomena[5].

## 4.1. AGS

There are two major experiments on the AGS floor studying strangeness in heavy ion collisions: E802/859 and E810. Their experimental lay-outs are presented in Fig.3 and Fig.4.

Experiment E810 uses three TPC (Time Projection Chamber) modules in a magnetic field to measure charged tracks [12,13]. The detectors cover the forward hemisphere in the center-of-mass of the nucleon-nucleon system.

The main part of the E802 (and its successor the E859) spectrometer consists of a dipole magnet with four sets of tracking chambers, a time-of-flight wall, and a high pressure gas Cerenkov counter followed by a position-sensitive back counter [14,15]. Particles are measured in the angular range from 5° to 58° and identified up to momenta of 5, 3.5, and 8 GeV/c for pions, kaons, and protons, respectively. A small solid-angle Cerenkov counter complex extends the particle identification up to 15 GeV/c.

Both experiments see an appreciable strangeness signal in the 14.6 GeV/N Si+Au (Si+Pb) central collisions.

E802 experiment measures $K/\pi$ ratios in proton-nucleus and nucleus-nucleus collisions. While the pion yield remains roughly constant from p+Be to p+Au [15], the $K^+$ yield increases substantially, which causes an increased $K^+/\pi^+$ ratio for the heaviest targets as indicated in Fig.5 (top panel). For comparison, the bottom panel of Fig.5 shows the $K^-/\pi^-$ ratio. Better statistics are needed to conclude about the trend of the $K^-/\pi^-$ behavior. A much larger, ~ 20%, value of the $K^+/\pi^+$ ratio (the black squares on Fig.5) was observed in central Si+Au collisions [15]. Since the mass of the colliding species seems to be, in some sense, the controlling parameter, the $K^+/\pi^+$ ratio was studied as a function of the transverse neutral energy detected in the region $1.25 < \eta < 2.5$, which provides a measure of the total number of participants in the reaction. Fig.6 shows that the $K^+/\pi^+$ ratios for Si+Al and Si+Au collisions, as a function of the

[5] There are no available conventional models which could explain strangeness enhancement so far, which makes this research even more exciting !

transverse energy, are roughly the same at a given value of transverse energy. This indicates that the enhanced $K^+$ production seen in these rapidity intervals ($0.6<y<1.0$ and $1.0<y<1.4$) is proportional to the total amount of the nuclear matter (hot nuclear matter!) present in the overlap region.

Descriptions of $K^+/\pi^+$ enhancement in terms of rescattering of the produced hadrons in the surrounding matter, however, appear to be an oversimplification in view of the fact that the $K^+/p$ ratio for p + all different targets from Be to Au is essentially identical for all rapidities, and increases only slightly for Si+Au collisions [16].

An additional interesting challenge for proposed theoretical explanations of $K^+$ enhanced production with rescattering scenarios presents the fact that the experimental slope of the kaons exceeds that of the pions over the entire range of transverse mass (see Fig.7).

Information on $\Lambda$'s produced in heavy ion collisions (which is, by itself, very interesting) might influence our understanding of $K^+$ enhancement since a substantial fraction of the $K^+$'s are believed to come from the associated production NN -> N$\Lambda$K. The E810 experiment measured $\Lambda$'s and $K^o$'s in Si+Si and Si+Pb collisions [17]. Fig.8 shows rapidity distribution for $K_s^o$'s and $\Lambda$'s for Si+Si interactions. Open circles show measured rapidity distributions [18] for p+p -> $K_s^o$+X and p+p -> $\Lambda$+X at 12 GeV/c scaled up by a factor of 28. There is a clear pile-up of $\Lambda$'s and $K^o$'s at midrapidity which can not be described by scaled p+p data. We will see the same situation later on with the CERN data. The rapidity distributions were measured only for forward rapidities but reflected about y=1.7 ( $\sim Y_{cms}$ for the nucleon-nucleon system). The solid and dotted curves represent models, RANDOM and HIJET with N*, respectively, which are described in reference 17. The E859 experiment has confirmed and extended the previous E810 measurements of $\Lambda$'s, and has measured the yield of the $\bar{\Lambda}$ in Si+Au collisions. The ratio of $\bar{\Lambda}$ over $\Lambda$ integrated over the spectrometer acceptance is $(2.0 +/- 0.8)*10^{-3}$. Using this value and the absolute yield of $\Lambda$'s found by E810 and E859 the derived dN/dy for $\bar{\Lambda}$ is $(6 +/- 3)*10^{-3}$ [19].

The E810 experiment does not report any antilambda signal; E859 reports it on a minimal level. Although a very interesting result, it is still preliminary. Let us imagine for the moment the opposite result. Then, given the suppression of antiprotons [19] that is expected for a baryon-rich fireball consisting of either hadron gas or quark-gluon plasma, the observation of larger strange antibaryon yields would strongly suggest plasma formation, since without a QGP strange antibaryons should hardly be produced at this energy [20]. Therefore, the lack of $\bar{\Lambda}$ signal, assuming that the effect will survive future analysis, should be taken as evidence against QGP formation at the AGS.

The production of the $\Phi$ mesons, which carry "hidden strangeness" being made by a $s\bar{s}$ pair, was predicted to be a much more sensitive probe of the reaction dynamics and possible presence of plasma [21] than the $K^+/\pi^+$ ratio. Moreover, the $\Phi$ meson yield rate, according to lattice QCD calculations [25,26], is supposed to be strongly related to the changes of the quark mass [22,23,24] due to a chiral phase transition at high energy densities. The production of the $\Phi$ meson, decaying in $\Phi$ -> $K^+K^-$ in central Si+Au

collisions, has been measured recently by E859 by selecting events with identified $K^+K^-$ pairs. Fig.9 shows the invariant mass distribution of $K^+K^-$ pairs. The solid line is the fit to a function combining a relativistic Breit-Wigner and the background. The dashed line is the background distribution from mixing events[6]. The insert shows a clear $\Phi$ peak after subtraction of the background. The value for the mass and width of the $\Phi$ obtained from the fit are consistent with those of the Particle Data Book.

The E859 experiment also provided the first data on $K^+K^+$ interferometry in Si+Au at 14.5 GeV/c. Because of differing production and re-interaction cross-sections, kaons and pions could probe different stages of the interactions [27]. This is discussed in another lecture of this workshop.

Very recently, multistrange baryons which might be more sensitive to the existence of QGP (this will be discussed in some detail later on in connection with CERN data), were seen for the first time at AGS energies. The E810 experiment reported a cascade signal from Si+Pb collisions. Fig.10 shows a preliminary plot of $\pi-\Lambda$ invariant mass with the pronounced $\Xi$ peak around 1.32 GeV. Analysis is in progress.

Starting in 1993 the BNL-AGS accelerator complex provides experiments with the heaviest ion beams. The first collected data with gold projectiles is presently being analyzed. The first, very preliminary, results, which were presented at the American Physical Society Meeting in Asilomar, USA (Oct.93), show a $K^+/\pi^+$ ratio in Au+Au interactions significantly enhanced (as expected!) over the one observed in collisions with Si beams. However, for more mature results we need to wait a while.

## 4.2 CERN

A number of CERN heavy ion experiments report interesting results on strangeness. Data on strange baryons have been analyzed by the NA35, NA36 and WA85 collaborations. Their experimental set-ups are shown in Figures 11, 12 and 13.

The main detectors of the NA35 experiment are two large volume tracking devices, a streamer chamber (SC) inside a 1.5 Tesla magnet and a TPC positioned downstream of the magnet. Both detectors record the space trajectories of charged particles, from which the particle momenta are derived. The acceptances of the detectors for charged hadrons are complementary to each other and both together cover full phase space and even overlap (Fig.14), what makes this experiment truly unique not only at the CERN energy domain, but also in the entire field. Central events are selected by the absence of projectile spectators in the downstream veto calorimeter (Fig.11).

The NA36 spectrometer was especially designed to investigate strangeness production [28]. Therefore its main detector, a large volume TPC with a wire read-out, was constructed with two criteria in mind: large acceptance and very good two track resolution. The detector was positioned 1 cm above the beam to avoid projectile fragments and in a 3 Tesla magnetic field in order to prevent the low momentum tracks to show up in the active volume of the TPC. The ion beam was defined by a scintillator

[6] The invariant mass is calculated for a pair of kaons originating from the different events.

counter and three wire chambers. Interactions in the target were detected by a pair of silicon counters, one just before and one just after the target (Fig.12).

The WA 85 experiment uses the CERN Ω spectrometer equipped with 21 MWPC (multi-wire proportional chamber) planes operated with a "butterfly" geometry [29]. The sensitive region of the chambers is chosen to detect only a few tracks out of the hundreds produced at the central rapidities ($2.3<y<3$) and high $p_t$ ($p_t>1.0$ GeV/c) of a typical central S+W collision (Fig.13).

The first NA35 observation of the enhanced production of strange particles at 200 GeV/c [8] showed that the yields of strange particles relative to the yield of non-strange particles produced in central S+S collisions are higher than the corresponding yields in nucleon-nucleon interactions at the same energies. This observation and the lack of strangeness enhancement in nucleon-nucleus collisions [30] ruled out the possibility of interpretation with commonly used models based on the superposition of p-p or p-N collisions.

New results from the NA35 collaboration have shown that the enhanced strangeness production, extrapolated to the full phase space, is also present in central S+Ag collisions at 200 GeV/c [31, 32]. Due to the high track density $V^o$ (i.e. $\Lambda$, $\bar{\Lambda}$ or $K^o$, see Fig.2)[7] decays can be observed in the SC only in the backward cms hemisphere ($y<3$). For part of the experiment an additional 4 Tesla magnet was installed upstream of the main SC magnet with a gold target placed at its entrance which extended SC coverage for detection of $\Lambda$, $\bar{\Lambda}$ and $K^o$ to the region of $y>3$. Since in the forward rapidity region the $V^o$'s show a similar distribution in both S+S[8] and S+Au reactions their average was used as an estimate for the forward behavior of the S+Ag data. A comparison of the $\Lambda$ rapidity of S+Ag collisions and a scaled[9] distribution of minimum bias p+S interactions show (Fig.15) that not only the production is enhanced, but that this enhancement is most pronounced around midrapidity and increases with increasing target mass (Fig.16). Antilambda production is concentrated at midrapidity and the trend seems to be similar to the one seen in $\Lambda$'s, although the error bars are still very large (Fig.17). All kaons behave similarly. Fig.18 shows the rapidity distribution of $K^o$, which is enhanced by about a factor of 1.7. The trend in the charged kaon production is the same. The p+S data multiplied by a factor of 29 (the so called scaling factor, mentioned above), which was found to reproduce negative hadron production in S+Ag collisions, fall below the data for kaons, $\Lambda$'s and $\bar{\Lambda}$'s implying a relative enhancement of strange particle production. The strangeness suppression factor which was used to estimate the deviation from flavor symmetry at the quark level in the final state [30], has been found to be only half as strong in S+S and S+Ag collisions as in nucleon-nucleon and nucleon-nucleus collisions.

High statistic NA36 data covering the full range of event multiplicities very strongly supports the NA35 results. A very pronounced signal of gradually increasing strangeness enhancement that saturates at high multiplicities where all the projectile

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[7] Decay vertecies for $\Lambda$, $\bar{\Lambda}$, and $K^o$ (and sometimes unfortunately also conversion vertices for the fast $\gamma$'s) look like the letter "V" in the tracking detectors.

[8] For the S+S reaction the forward rapidity region is obtained from reflection symmetry.

[9] The scale factor adjusts the multiplicities of negativly charged hadrons.

nucleons are involved in the collision (central events) was observed in the S+Pb reactions. Analysis shows that the strangeness production in S+Pb is almost a factor of two higher than in p+Pb [33]. Fig.19 shows the rapidity distribution for both reactions. It is clear that the production mechanism in the case of p+Pb and S+Pb must differ greatly. In the p+Pb case $\Lambda$ particles are produced in the target rapidity area, which is expected due to the interactions with the present spectator matter, whereas in the S+Pb reaction a strong source of strangeness is positioned at midrapidity.

NA36 also collected some small amount of "minimum bias" data for S+S interactions. The results are shown together with the existing results [8] from the NA35 experiment in Fig.20 (the acceptance of NA36 was adjusted to match the one of NA35). The comparison shows not only that the production of $\Lambda$'s in both experiments grow faster with centrality (measured by the multiplicity of negative particles, mainly pions) than the production of negatives, but also very good agreement between these two experiments which assures the correctness of the analysis.

The enhanced population of strange particles observed at the CERN experiments is not predicted by models in which the produced particle system has passed through a phase of thermal equilibrium [34,35,36]. More successful in describing strangeness enhancement in heavy ion collisions at CERN energies appear to be macroscopic, non-equilibrium models based on a string picture which employ new mechanisms. The formation of "double strings" connected to the same leading quarks to enhance the production of baryons containing strange quarks was introduced to the VENUS model [37]. In the RQMD model a mechanism of string fusion into "color ropes" [38], which break faster, allowed more frequent production of strange quarks and diquarks resulting in enhanced $\bar{\Lambda}$ and $\bar{p}$ production. At the moment there are not yet $\bar{p}$ results at CERN energies to support these predictions, in addition to $\bar{\Lambda}$.

In addition to $\Lambda$, $\bar{\Lambda}$ and $K^o$ yields, the NA36 TPC allowed for the detection of $\Xi^-$ and $\Xi^+$ hyperon decays. This data is of great importance since, as it has been pointed out [39], the information on singly strange particles alone does not allow for the differentiation between the hadronic gas and the quark-gluon plasma phase scenarios. The relative abundances of strange (antistrange) baryons of the same or different strangeness content contain a unique characterization of a new form of matter.

The invariant mass distributions for cascades from NA36 are shown in Fig.21. Table 1 presents the summary of the different strange particle ratios together with the acceptance region in which they were detected. Contributions of $\Xi^-$ and $\Xi^+$ from the yields of $\Lambda$ and $\bar{\Lambda}$ were removed using Monte Carlo estimates [40]. The analysis of strangeness ratios from Table 1 [40] suggest that a saturation of strangeness phase spaces is not yet achieved in the collisions of S+Pb at 200 GeV/c. The obtained index of strangeness phase saturation is $\gamma_s = 0.48 +/- 0.13$, whereas for QGP $\gamma_s$ is estimated to be close to unity.

WA85, the second experiment which successfully extracted a signal of multistrange baryons in the high multiplicity environment, came up with slightly different ratios of the yields of strange particles [see Table 2], presumably due to the different phase space coverage. Both sets of ratios, together with the compilation of the $\Xi^-/\Lambda$ and $\bar{\Xi}/\bar{\Lambda}$ ratios from elementary particle experiments, are plotted in Fig.22.

Such an enhancement of $\Xi^-/\Lambda$ ratios in S+W and S+Pb with respect to p+p collisions cannot at present be explained. Rafelski has argued [41] that the observed ratios correspond to those found in a quark-gluon plasma that is about half equilibrated in its strangeness content. More recently, it was found [42] that multistrange ratios might be consistent with either a quark-gluon plasma or a hadronic gas at a temperature of 220 MeV and $\mu_B$=340 MeV. Davidson et al. [43] estimated that the ratios are close to those of a hadronic gas in complete chemical equilibrium. In any case, the only way that equilibrium can be attained during the short life of a hadronic fireball is via a quark-gluon plasma intermediate state.

The rare $\Omega^-$'s are of particular interest since they contain three strange quarks and therefore their production by rescattering is next to impossible. The first and only experimental information on omegas in heavy ion collisions was recently reported by WA85 [44]. From amazingly rich statistics of about 60 millions triggers only 7 +/- 3.6 $\Omega^-$'s and 4.0 +/- 2.0 $\bar{\Omega}^-$'s survived all cuts applied during analysis. The estimated ratio $\bar{\Omega}^-/\Omega^-$ for central rapidity (2.5<y<3) and high $p_t$ ($p_t$>1.6 GeV/c) is 0.57 +/- 0.41. This ratio is not yet corrected for possible differences in acceptance and efficiency for $\Omega^-$'s and $\bar{\Omega}^-$'s.

Concluding from the NA36 and WA85 strangeness enhancement seen for $\Xi$'s and $\bar{\Xi}$'s, one would naturally expect the same phenomenon in the case of $\Phi$ meson production, since $\Phi$'s also contain two strange quarks. This question was originally addressed by the NA38 collaboration [45], and later on also by the NA34-3 experiment [46] at CERN. They studied $\Phi$ and $\rho+\omega$ production in p+W and S+U collisions at 200 GeV/c by analyzing the low mass $\mu^+\mu^-$ spectra. The experimental apparatus of NA38, shown in Fig.23, consists of a target assembly followed by a hadron absorber based on light materials in order to have an improved mass resolution and a reduced level of background from pion and kaon decays[10]. The acceptance of the apparatus for dimuon pairs in the $\Phi$ region is 3<y<4 and $p_t$>0.6 GeV/c. The invariant mass plot of a dimuon for S+U and p+W interactions is presented in Fig.24. The insert shows the $\mu^+\mu^-$ spectrum before background subtraction, and a background spectrum determined from the like-sign pairs. Spectra were fitted by a Breit-Wigner function (for resonances) and by an exponential term to account for continuum contribution. The mass resolution was not sufficient to resolve $\rho$ and $\omega$ contributions. The relative yield $\Phi/(\rho+\omega)$ was measured as a function of a quality proportional to the energy density reached in the collision for two $p_t$ intervals: low $p_t$ (0.6<$p_t$<1.15 GeV/c) and high $p_t$ (1.15<$p_t$<3.0 GeV/c) - Fig.25. A clear rise is seen in the high $p_t$ region, whereas no trend can be noticed, mainly due to the large error bars, in the low $p_t$ interval. However, the measured ratio $\Phi/(\rho+\omega)$ is in any case two to three times larger in S+U than in p+W collisions. The $\Phi$ signal is also reported to be enhanced with respect to the continuum

[10] The branching ratio to the $\mu^+\mu^-$ decay mode is very low (~$10^{-4}$ ) therefore the experiment tries to get all the hadrons absorbed immediately just after the target since they contribute greatly to the background.

[47]. The p+W measured value for $\Phi/(\rho+\omega)$ is consistent with other p+p and p+N measurements reported previously [48], which suggests that the observed $\Phi$ abundance in S+U is not caused by scattering processes in nuclear matter.

The NA34/3 collaboration studied $\Phi$ and $\rho+\omega$ production in p+W and S+W collisions at a rapidity window shifted to higher values by about one unit. They confirm the results reported by NA38 [46]. This suggests that $\Phi$ enhancement may not be strictly limited to the midrapidity window and not necessarily exclusively related to the QGP scenario.

## 5. Before Concluding Remarks ...

One word about $p_t$ ($m_t$) spectra which seems, at first, to be completely beyond the scope of this lecture:

Pion spectra deviate from thermal model shapes at low $p_t$ (NA34, NA35, E810). The spectral "temperatures" for all other identified hadrons ($K^+$, $K^-$, $\Lambda$, $\bar{\Lambda}$, $\Phi$, $(\rho+\omega)$, $J/\psi$) gather around 200 MeV at the top CERN energies. These temperatures seems to be surprisingly high. However, it was already demonstrated [42] that a temperature of about 220 MeV would be required to reproduce not only the enhanced $K^+$ and $\Lambda$ yields (E802, NA35, NA36) but also the ratios $\Lambda/\pi$ (NA35), $\Phi/(\rho+\omega)$ (NA38, NA34-3) and $\Xi/\Lambda$ (WA85) which have 3 times the hadron-hadron values in central A+A collisions.

## 6. (Instead of ) Concluding Remarks.

The experimental and theoretical search for the transition to the quark-gluon plasma phase became, with time, one of the most promising long-term goals in the field. The first successful experiment involving phase transition from the plasma to the hadron phase was carried out by the early Universe. Attempts to create a "small bang" in the laboratory with heavy ion[11] collisions brought a remarkable wealth of data possibly containing information on the signatures of plasma transformation. There are, however, some fundamental differences between the Big Bang and "small bangs". The time scale of the phase transition during the early Universe expansion was relatively very slow (~10μs) whereas the "small bangs" are happening incredibly fast (at best $10^{-22}$s , i.e. the time which is approximately needed for a heavy ion projectile, e.g. a Au ion, to traverse a heavy target like another Au atom). The exceedingly slow, in hadronic terms, transformation of the early Universe allowed all the substantial structures to develop during the mixed phase[12], and practically all unstable particles to decay. There is no hope to re-create the "slow bang" in the laboratory since we are unable to generate the appropriate gravitation present during the Big Bang of the Universe to slow down

[11] not so heavy after all!

[12] Mixed phase of QGP and hadronic gas.

the expansion. However, we still ought to be able to gather information on critical parameters (mainly temperatures and energy densities) of the phase transition. Strangeness enhancement, in both aspects: 1) as a function of centrality and 2) in A+A in respect to p+p and p+A interactions, which were reported unanimously by E802, E810/859, NA35, NA36, NA38, NA34-3, and WA85, presents at this time probably the most outstanding and promising experimental results in this field. One has to bear in mind that all experiments were performed with systems too small and energies too low to expect formation of a sufficiently long lived quark-gluon plasma. In light of this fact presently reported data are very encouraging.

In spite of the intensive theoretical effort, no explanation has been found within the hadronic scenario for the 2-3 fold enhancement in $\Lambda$, K, $\Phi$ production observed in A+A experiments at AGS and CERN. One should not dilute this conclusion by attributing some fraction of this enhancement to the effects of multiple scattering processes in nuclear matter (e.g. associated production) present in the collision, because we do not see any traces of strangeness enhancement in a p+A channel, which was intensively investigated by all involved in strangeness program experiments (see NA35, NA36, NA38, etc.).

## Acknowledgments.

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References:

1. Proceedings of the Seventh International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Lenox, Massachusetts, USA, Sept.26-30,1988. - Nuclear Physics A498 (1989).
   Proceedings of the Eighth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions, Menton, France, May 7-11, 1990. - Nuclear Physics A525 (1991).
   Proceedings of the Ninth International Conference on Ultra-Relativistic Nucleus- Nucleus Collisions, Gatlinburg,Tennessee, USA, Nov. 11-15, 1991. - Nuclear Physics A544 (1992).
2. Proceedings of the Rio de Janeiro International Workshop on Relativistic Aspects of Nuclear Physics, August 28-30, 1989, Rio de Janeiro, Brazil, Word Scientific, 1990.

Proceedings of the 2-nd Rio de Janeiro International Workshop on Relativistic Aspects of Nuclear Physics, August 28-30, 1991, Rio de Janeiro, Brazil, Word Scientific, 1992.
3. P.Koch,B.Muller,J.Rafelski, Phys.Rep.142(1986)167.
4. J.Rafelski - Proceedings of a NATO Advanced Study Institute on Particle Production in Highly Excited Matter, Il Ciocco, Italy, July 12-24,1992, p.529.
5. J.Rafelski, Phys.Rep.88,331(1982).
6. H.Eggers,J.Rafelski - Preprint AZPH-Th/90-28.
7. E.Quercigh - Proceedings of a NATO Advanced Study Institute on Particle Production in Highly Excited Matter , Il Ciocco, Italy, July 12-24,1992, p.499.
8. J.W.Harris and NA35 Collaboration, Nucl.Phys.A498(1989)133c.
M.Gazdzicki and NA35 Collaboration, Nucl.Phys.A498(1989)375c.
9. A.Bamberger et al., Phys.Lett.B184(1987)271,
J.Bachler et al., Z.Phys.C52(1991)239.
10. for the recent review see e.g: T.Hatsuda, Nucl.Phys.A544(1992)27c.
11. M.Sarabura and E802 Collaboration, Nucl.Phys.A498(1989)409c.
12. S.E.Eiseman et al., Phys.Lett.B248(1990)254.
13. S.E.Eiseman et al., Phys.Lett.B297(1992)44.
14. R.Mattiello et al., Phys.Rev.Lett.63,1459(1989).
15. T.Abbott et al., Phys.Rev.D45,3906(1992).
16. T.Abbott et al., Nucl.Phys.A544(1992)237c.
17. R.S.Longacre and E810 Collaboration, BNL Preprint - 49446, August, 1993.
18. V.Blobel et al., Nucl.Phys.B69(1974)454.
19. G.S.F.Stephans and E802/859 Collaboration, Proceedings of the Quark-Matter Conference, Borlange, Sweden, June, 1993.
20. P.Koch, B.Muller, J.Rafelski - Phys.Rep.142(1986).
21. A.Shor, Phys.Rev.Lett.54,1122(1985).
22. R.D.Pisarski,F.Wilczek, Phys.ReV.D29,338(1984).
23. T.Hatsuta,T.Kunihiro, Phys.Lett.B185,304(1987)
24. E.V.Shuryak, Nucl.Phys.A525,3c(1991).
25. C.E.DeTar,J.B.Kogut, Phys.Rev.Lett.59,399(1987); Phys.Rev/D36,2828(987).
26. F.Karsch et al., Phys.Lett.188B,353(1987).
E.V.E.Kovacs et al., Phys.Rev.Lett.58,751(1987).
27. G.Stephans and E802/859 Collaboration, Proceedings of the Quark-Matter Conference, Borlange, Sweden, June, 1993.
28. C.Garabatos et al., NIM A283(1989)553.
29. W.Beusch et al., NIM A249(1986)391.
30. H.Bialkowska et al., Z.Phys.C55(1992)491.
31. D.Rohrich and NA35 Collaboration, Proceedings of the Quark-Matter Conference, Borlange, Sweden, June, 1993.
32. M.Gazdzicki and NA 35 Collaboration, Proceedings of the Quark-Matter Conference, Borlange, Sweden, June, 1993.
33. I.Sakrejda and NA36 Collaboration, Proceedings of Hadron Structure'92 Conference, Stara Lesna, Czecho-Slovakia, Sept.6-11,1992,p.108.
34. H.W.Barz et al., Nucl.Phys.A525(1991)435c.
35. J.Letessier et al., Preprint Universite Paris 7, PAR/LPTHE/92-27.
36. J.Cleymans,H.Satz, Z.Phys.C57(1993)135.

J.Badier et al., Phys.Lett.B122(1983)441.
37. K.Werner,J.Aichelin, Phys.Lett.B308(1993)372;
preprint HD-TVP-91-15 and HD-TVP-91-18, Heidelberd (1991).
38.H.Sorge et al., Phys.Lett.B289(1992)6.
H.Sorge,M.Berengues,H.Stocker,W.Greiner, Preprint LA-KR-92-1078.
39. J.Letessier, A.Tounsi, J.Rafelski, Phys.Lett.B292(1992)417.
40. J.M.Nelson and NA 36 Collaboration, Proceedings of the Quark-Matter Conference, Borlange, Sweden, June, 1993.
41.J.Rafelski, Phys.Lett.262B,333(1991).
42.J.Letessier,A.Tonusi,J.Rafelski, Preprint PAR/LPTHE/92-23,Paris(1992).
43.N.J.Davison,H.G.Miller,R.M.Quick,J.Cleymens, Phys.Lett.255B,105(1991)
44. S.Abatzis et al., Phys.Lett.B 316(1993)615.
45. O.Drapier et al., Nucl.Phys.A544(1992),209.
46. M.A.Mazzoni et al., Nucl.Phys.A544(1992)623.
47. R.Farreira et al., Nucl.Phys.A544(1992)497.
48. M.Aguilar-Benitez et al.,CERN-PPE/91-21.
K.J.Anderson, Phys.Rev.Lett.37(1976)799.
F.Martelli and NA34 Collaboration, Proc.Int.Europhys.Conf.on HEP, Geneva, 1991.

Tables:

1. Strange particle ratios from the NA 36 experiment.
2. Strange particle ratios from the WA85 experiment.
3. The average decay length per GeV for the weakly decaying strange particles, together with their main decay modes.

Figures:

1. Expansion of the Universe (figure borrowed from Ref.4)
2. Topologies of some weak decays of strange particles.
3. Experimental lay-out of E802.
4. Experimental lay-out of E810.
5. $K^+/\pi^+$ ratio as a function of rapidity for p+N and Si+Au reactions. The errors show statistical uncertainties only (E802).
6. $K^+/\pi^+$ ratio for two rapidity intervals versus the transverse energy in Si+Al and Si+Au collisions (E802).
7. Inclusive transverse momentum spectra for $\pi^+$'s, $\pi^-$'s, $K^+$'s, $K^-$s and protons produced in the rapidity interval $1.7<y<1.9$ in Si+Al and Si+Au collisions (E802/859).
8. Rapidity distributions for $K^o$'s and $\Lambda$'s from Si+Si collisions (E810).
9. Invariant mass distribution of $K^+K^-$ pairs. The solid line is the fit to a function combining a relativistic Breit-Wigner and the background. The dashed line is the background distribution from mixing events. The inserts shows the background-substracted $M_{inv}$ distribution (E859).
10. Invariant mass distribution of $\Xi$'s (E810).

11. Experimental lay-out of NA35.
12. Experimental lay-out of NA36.
13. Experimental lay-out of WA85.
14. Phase space coverage for negative particles in the TPC and SC of NA35.
15. Rapidity distribution of $\Lambda$'s from central S+Ag collisions compared to a scaled distribution from minimum bias p+S reactions (NA35).
16. Rapidity distribution of $\Lambda$'s from various central nucleus-nucleus collisions (NA35).
17. Rapidity distribution of $\bar{\Lambda}$'s from various central nucleus-nucleus collisions (NA35).
18. Rapidity distribution of neutral kaons from central nucleus-nucleus collisions compared to a scaled distribution from p+S reactions.
19. Rapidity distributions of $\Lambda$'s, $\bar{\Lambda}$'s, and $K^o$'s from S+Pb and p+Pb collisions (NA36).
20. $\Lambda$ production in the S+S reactions, comparison of NA35 and NA36 results.
21. Invariant mass distribution for $\Xi^-$ and $\Xi^+$ from S+Pb collisions (NA36).
22. Comparison of strangeness ratios from different experiments.
23. NA38 experimental set up.
24. $\mu^+\mu^-$ invariant mass spectra measured by the NA38 experiment for S+U and p+W collisions.
25. $\Phi/(\rho+\omega)$ ratio as a function of energy density (NA38).

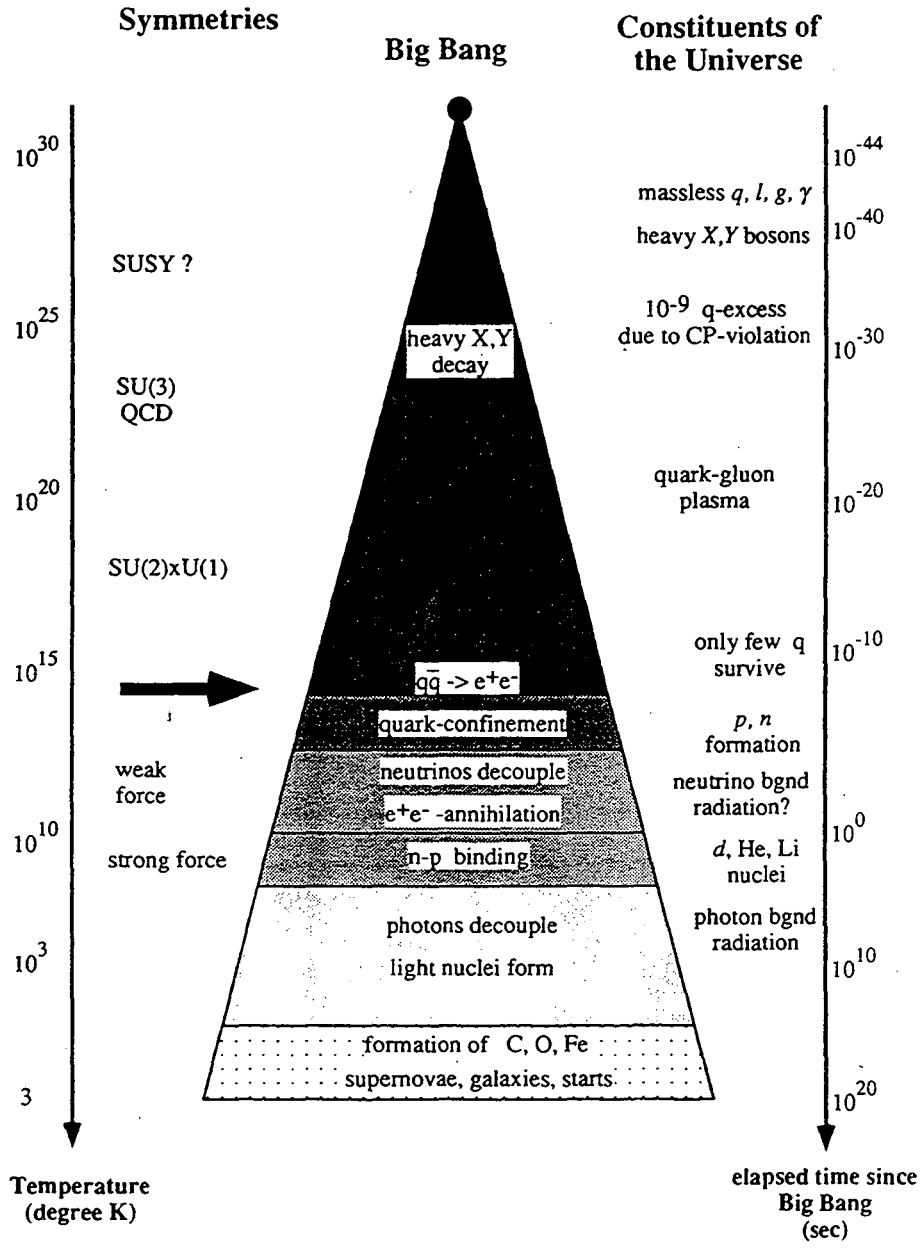

Symmetries
Big Bang
Constituents of the Universe
$10^{30}$
$10^{25}$
$10^{20}$
$10^{15}$
$10^{10}$
$10^{3}$
3
SUSY ?
SU(3) QCD
SU(2)xU(1)
weak force
strong force
heavy X,Y decay
$q\bar{q}$ -> $e^+e^-$
quark-confinement
neutrinos decouple
$e^+e^-$ -annihilation
n-p binding
photons decouple
light nuclei form
formation of C, O, Fe
supernovae, galaxies, starts
massless $q, l, g, \gamma$
heavy $X,Y$ bosons
$10^{-9}$ q-excess due to CP-violation
quark-gluon plasma
only few q survive
$p, n$ formation
neutrino bgnd radiation?
$d$, He, Li nuclei
photon bgnd radiation
$10^{-44}$
$10^{-40}$
$10^{-30}$
$10^{-20}$
$10^{-10}$
$10^{0}$
$10^{10}$
$10^{20}$
Temperature (degree K)
elapsed time since Big Bang (sec)

Figure 1.

# $\Lambda$, $\Xi$, $\Omega$ decay topology

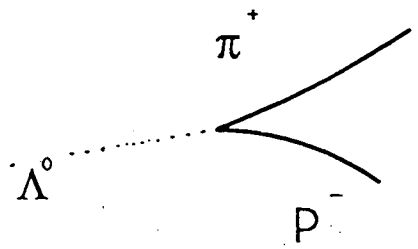
---

$\Lambda$ $S = \mp 1$

$\Lambda^0 \rightarrow p^{\pm} + \pi^{\mp}$

rate : 64.2 %

$c\tau$ = 7.98 cm

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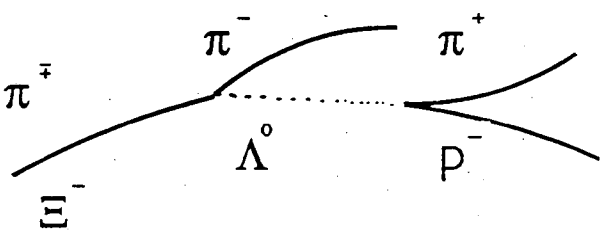
$\Xi$ $S = \mp 2$

$\Xi^- \rightarrow \Lambda^0 + \pi^{\mp}$

$\hookrightarrow p^{\pm} + \pi^{\mp}$

rate : 100 %

$c\tau$ = 4.92 cm

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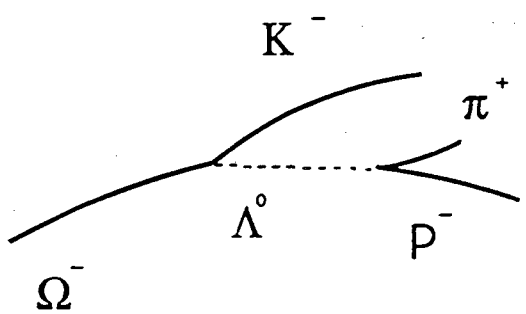
$\Omega$ $S = \mp 3$

$\Omega^{\mp} \rightarrow \Lambda^0 + K^{\mp}$

$\hookrightarrow p^{\pm} + \pi^{\mp}$

rate : 67.8 %

$c\tau$ = 2.46 cm

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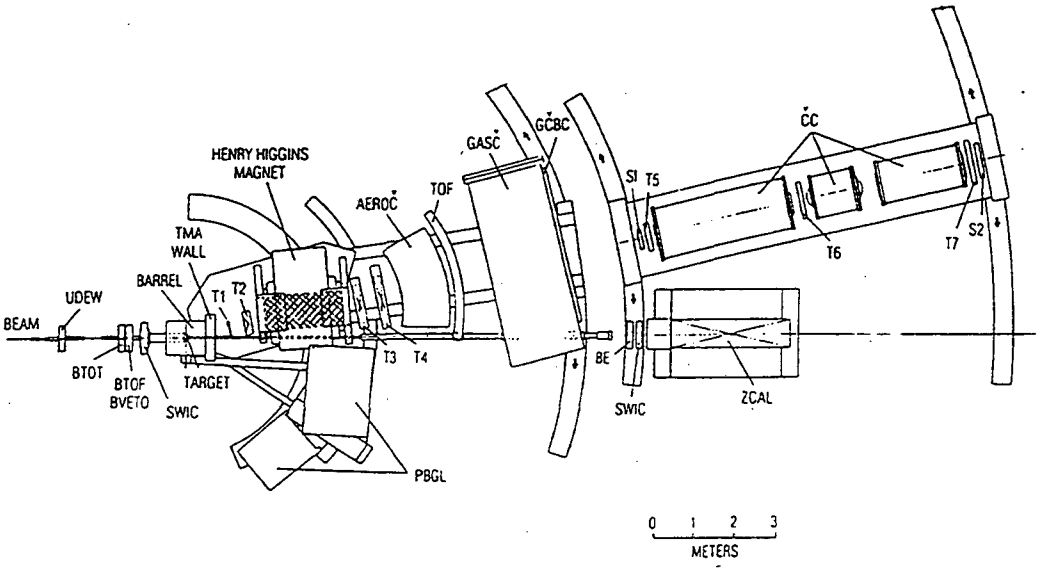


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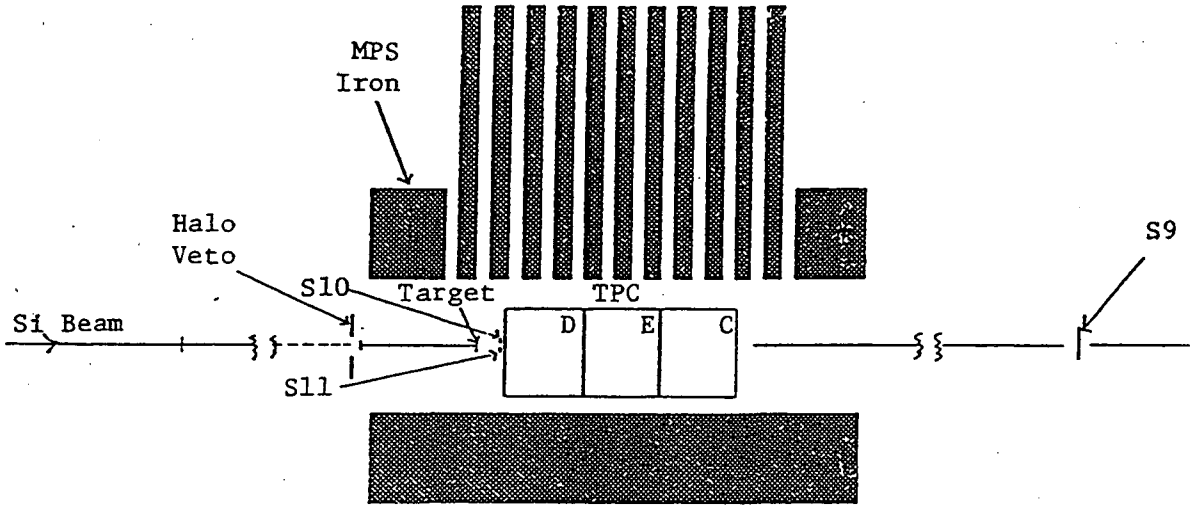


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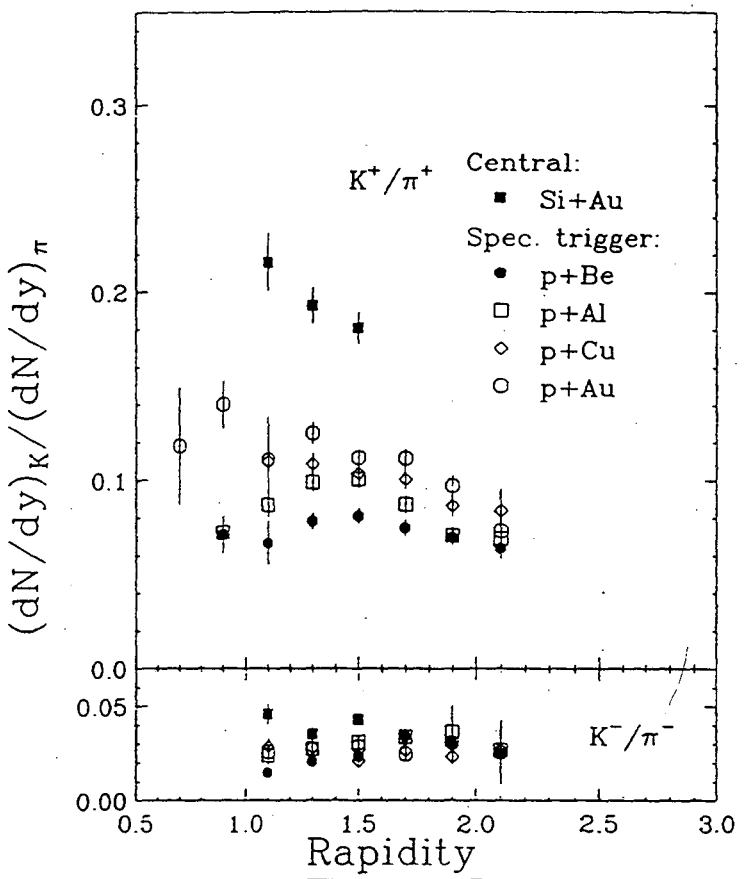


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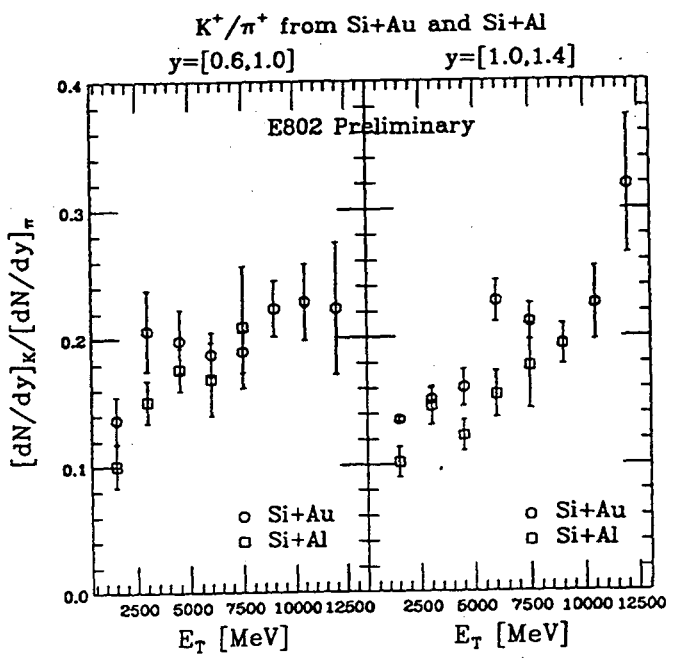


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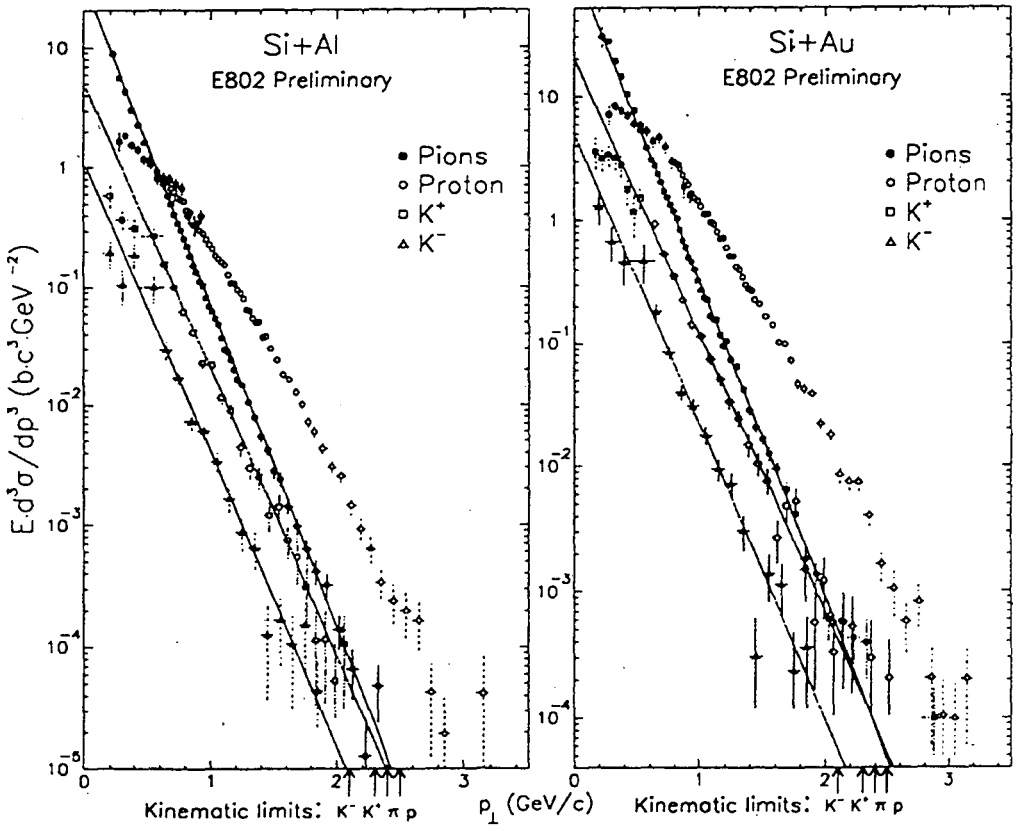


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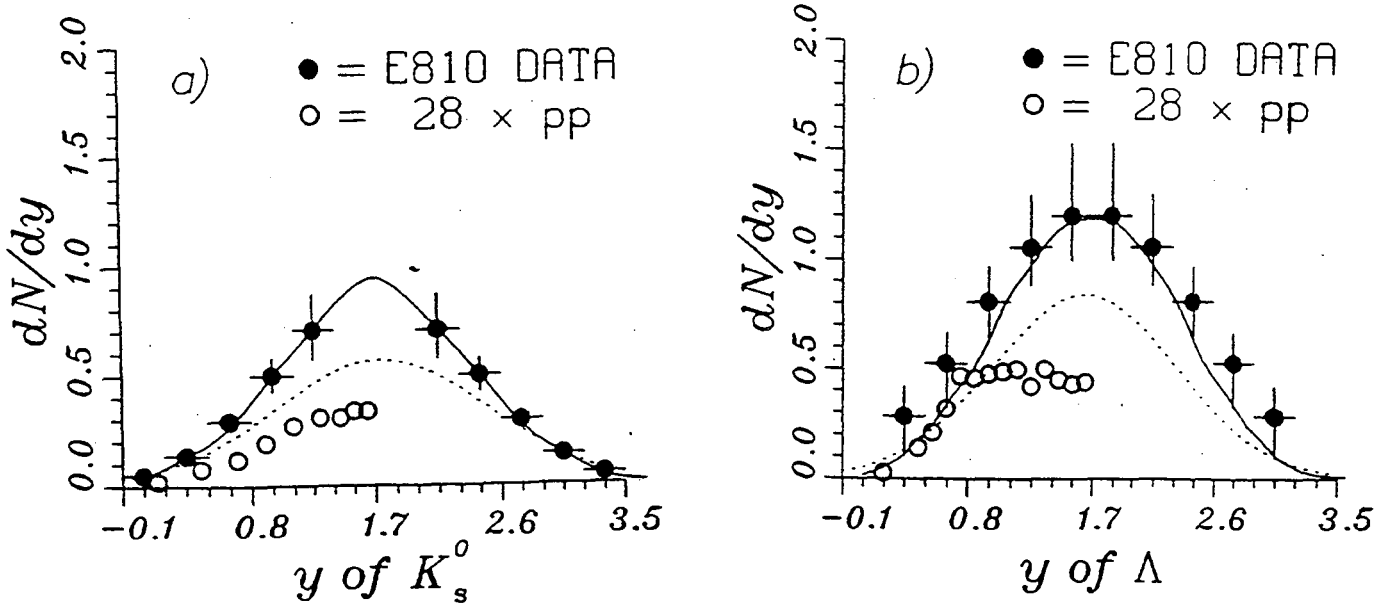


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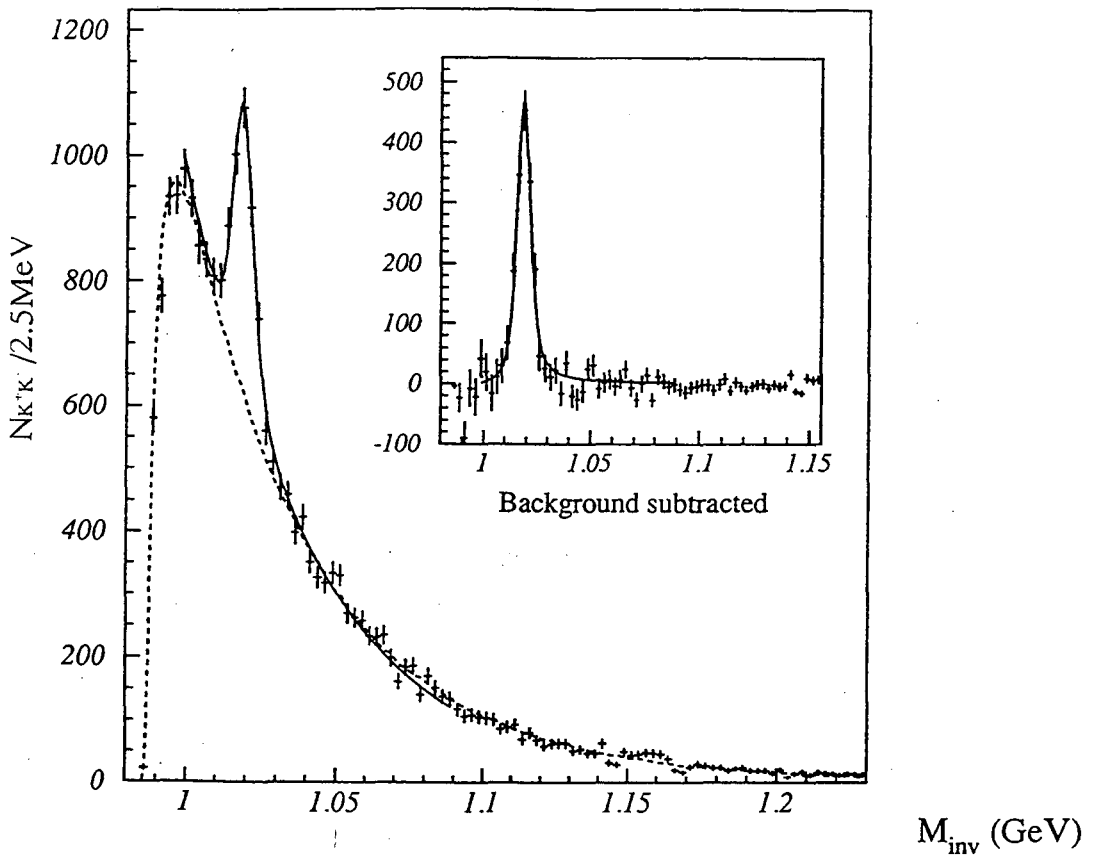


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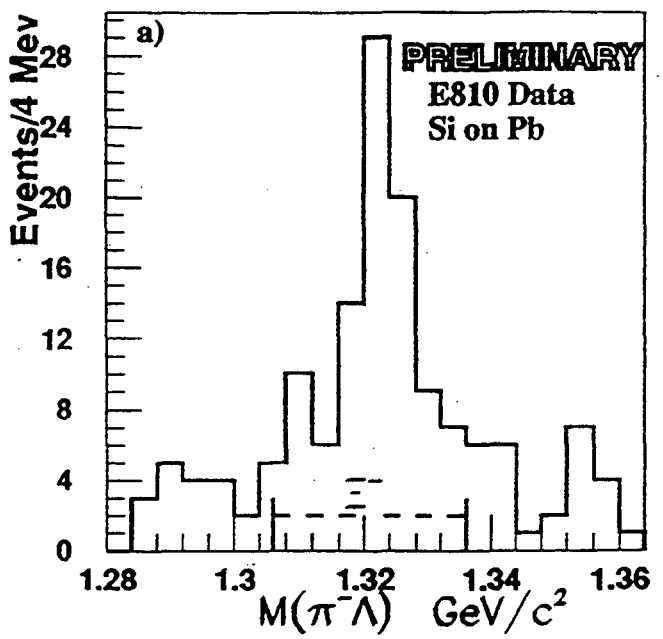


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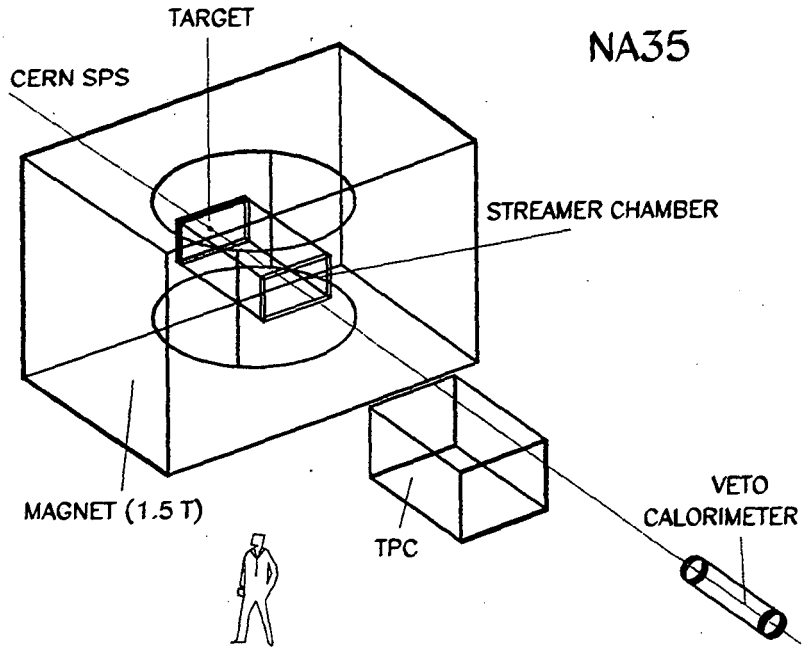


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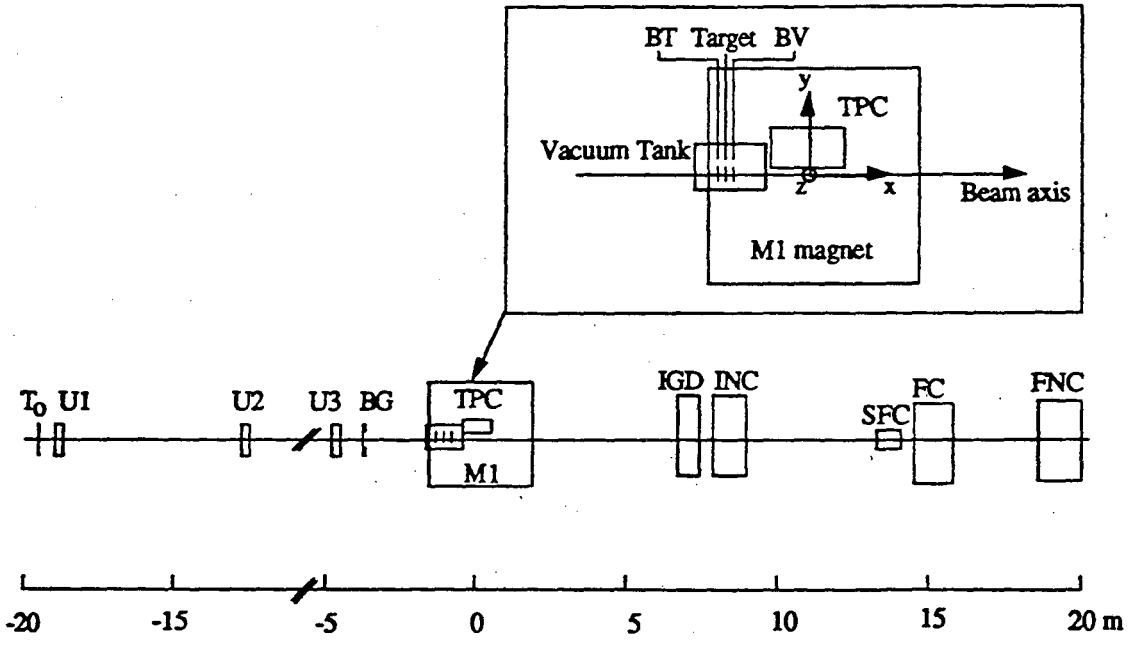


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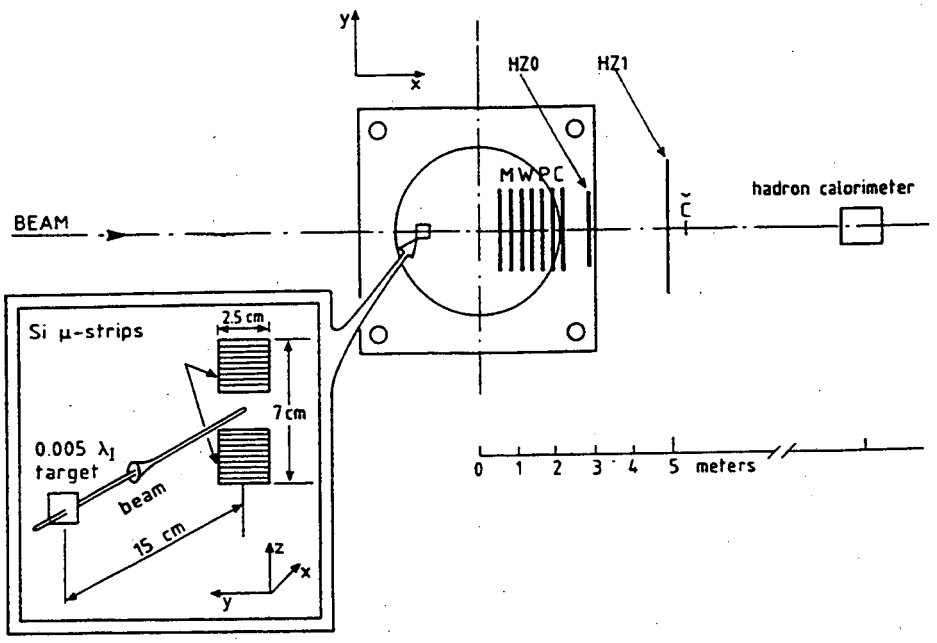


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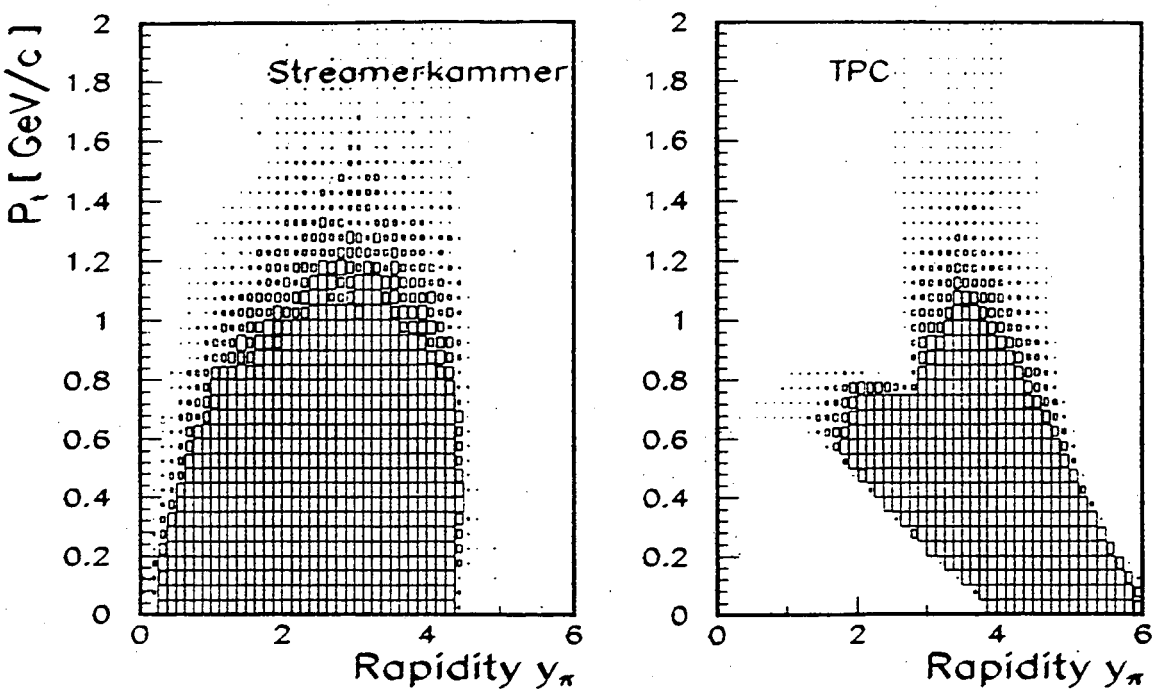


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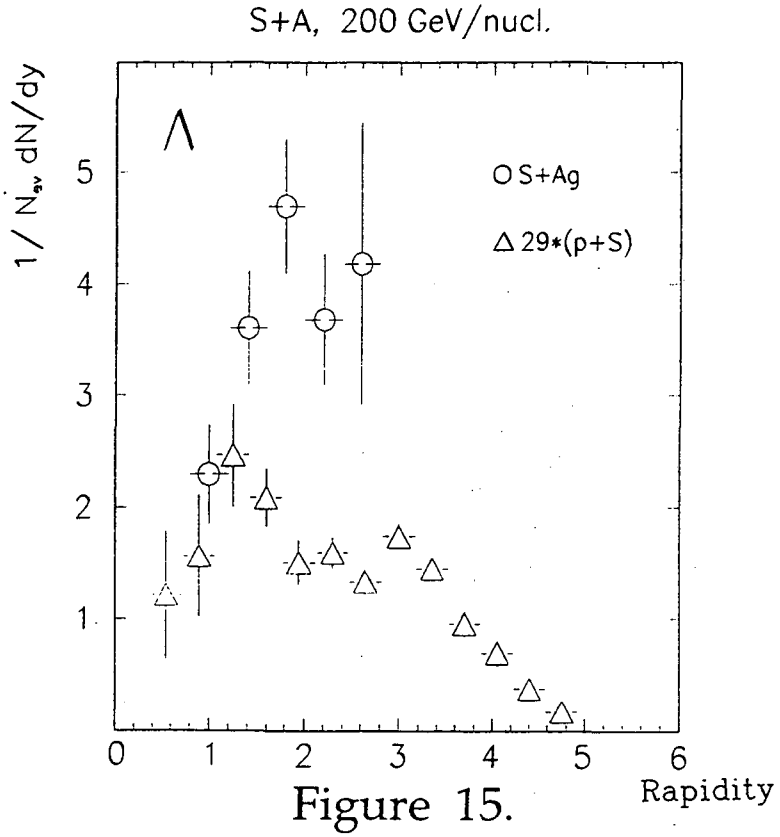


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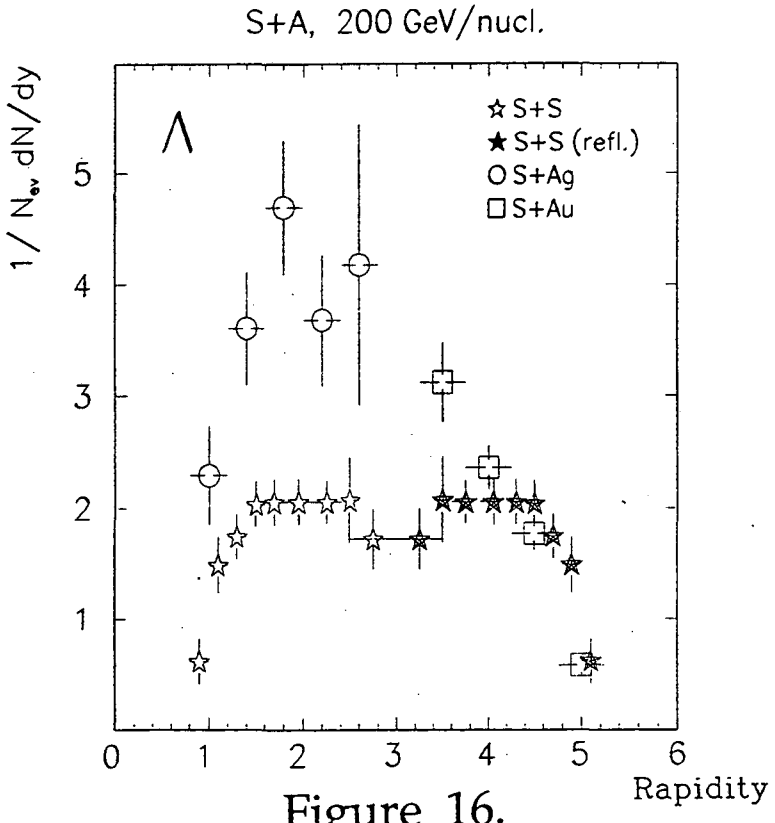


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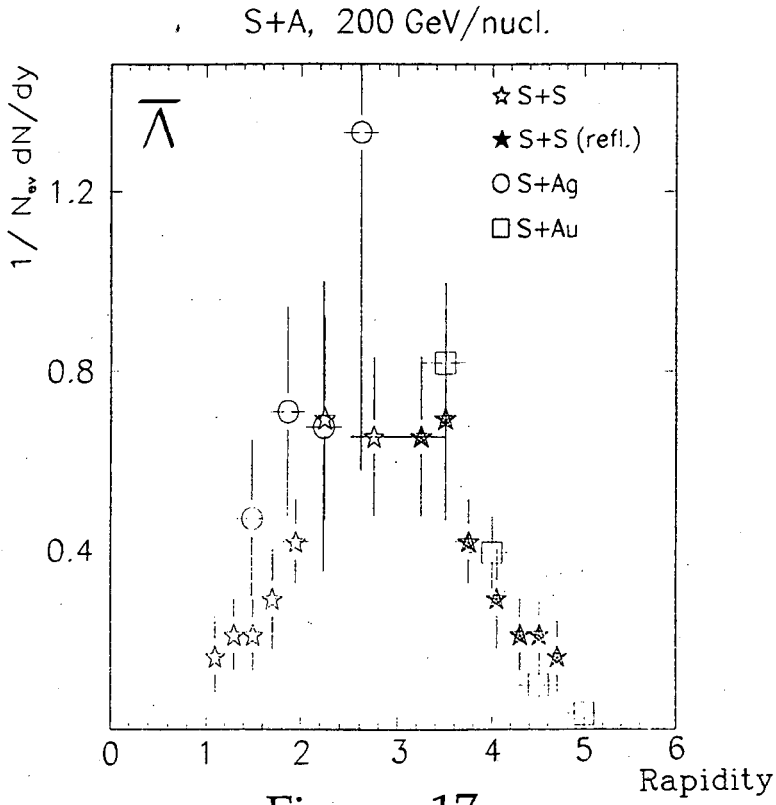


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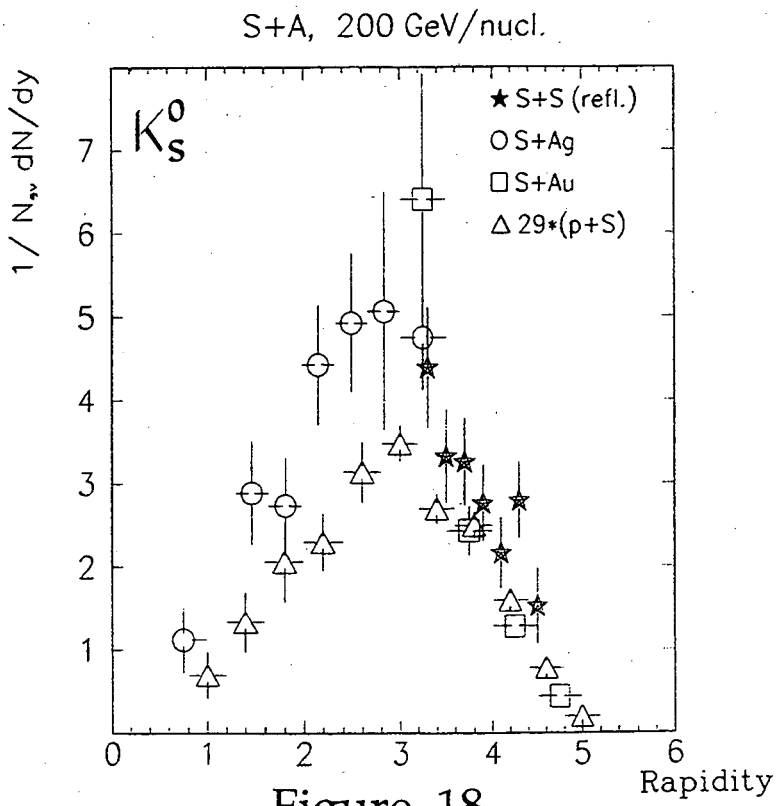


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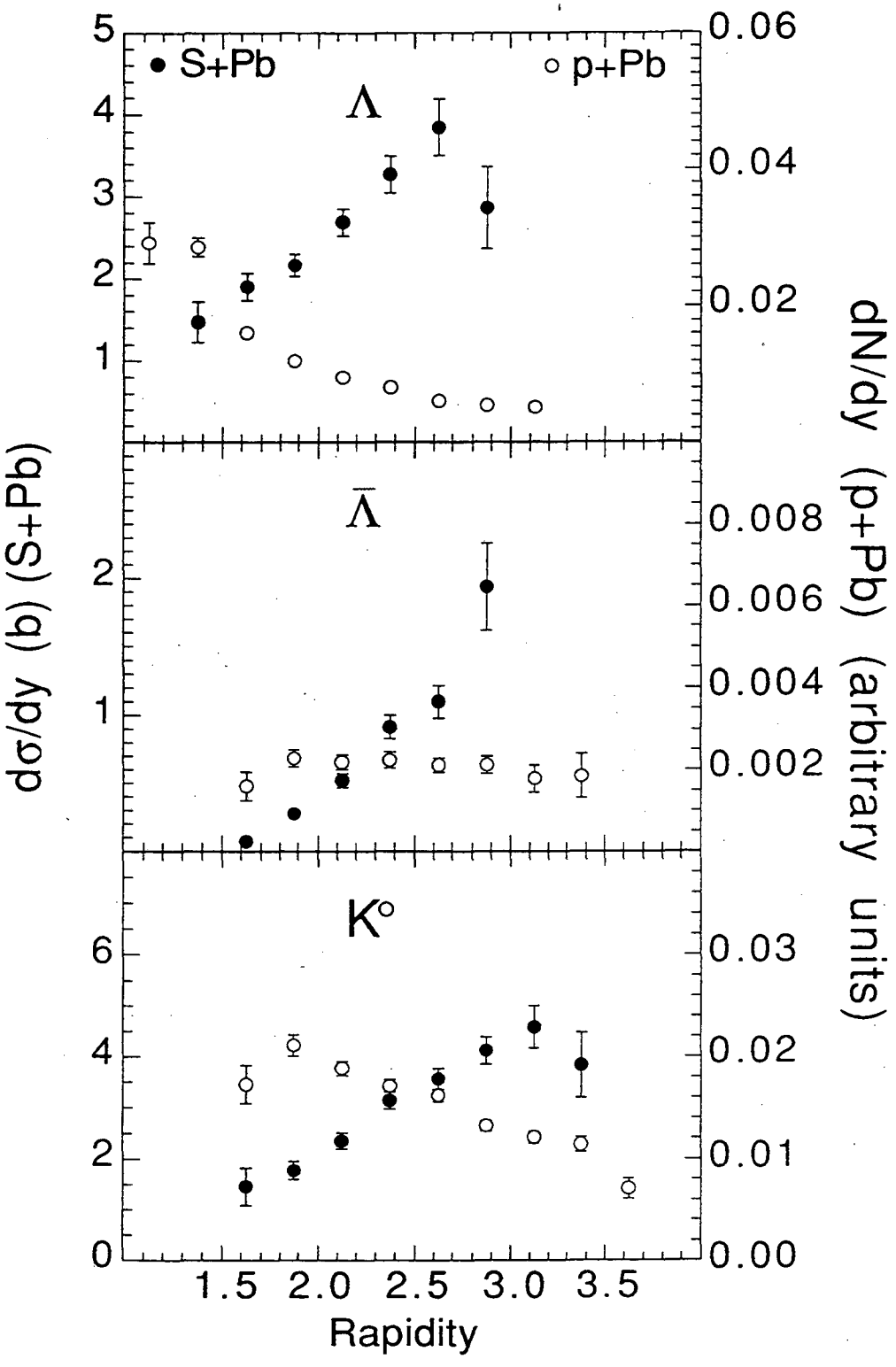

S+Pb
p+Pb
Λ
$\bar{\Lambda}$
K°
dσ/dy (b) (S+Pb)
dN/dy (p+Pb) (arbitrary units)
Rapidity
1.5
2.0
2.5
3.0
3.5
0.00
0.01
0.02
0.03
0.002
0.004
0.006
0.008
0.02
0.04
0.06

Figure 19.

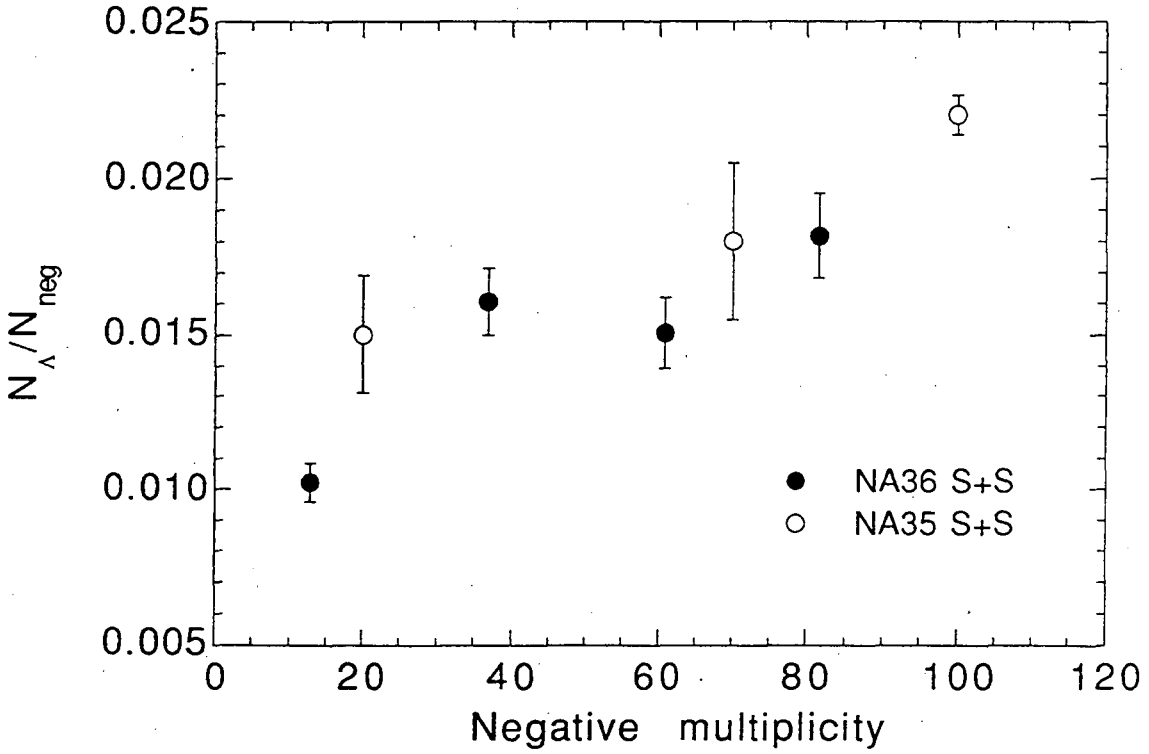
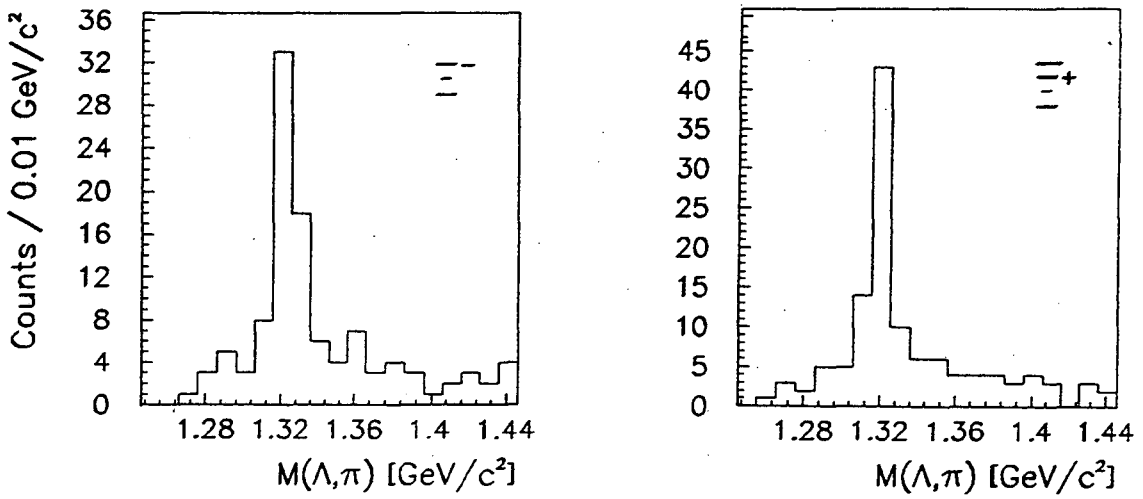



Figure 20.

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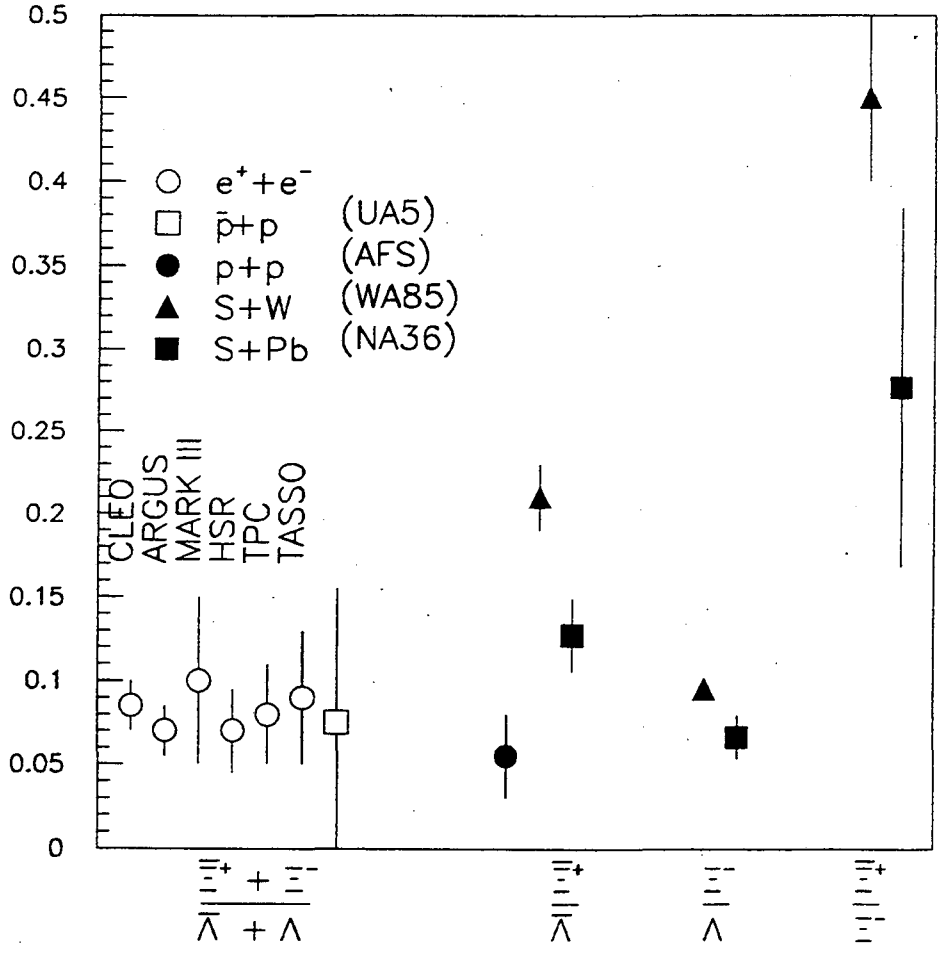
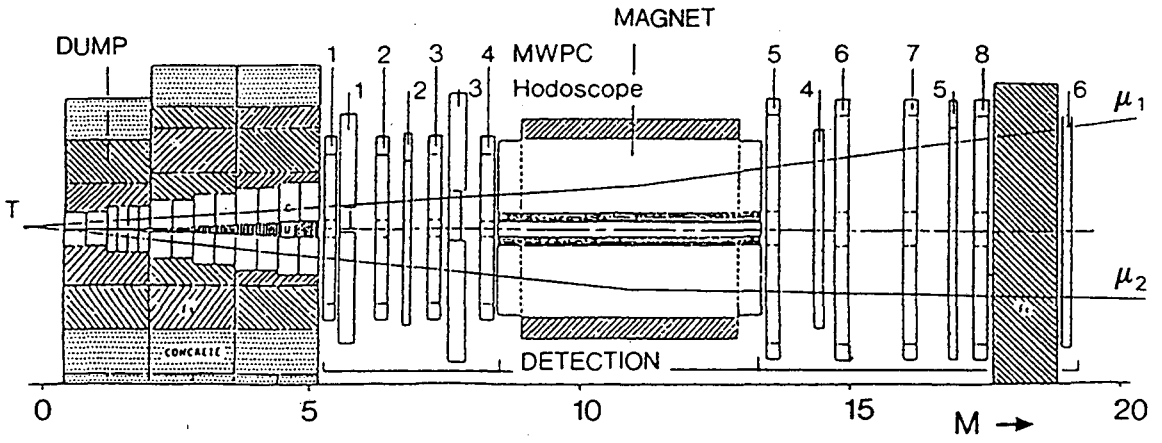

0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
e⁺+e⁻
p̄+p (UA5)
p+p (AFS)
S+W (WA85)
S+Pb (NA36)
CLEO
ARGUS
MARK III
HSR
TPC
TASSO

Figure 22.

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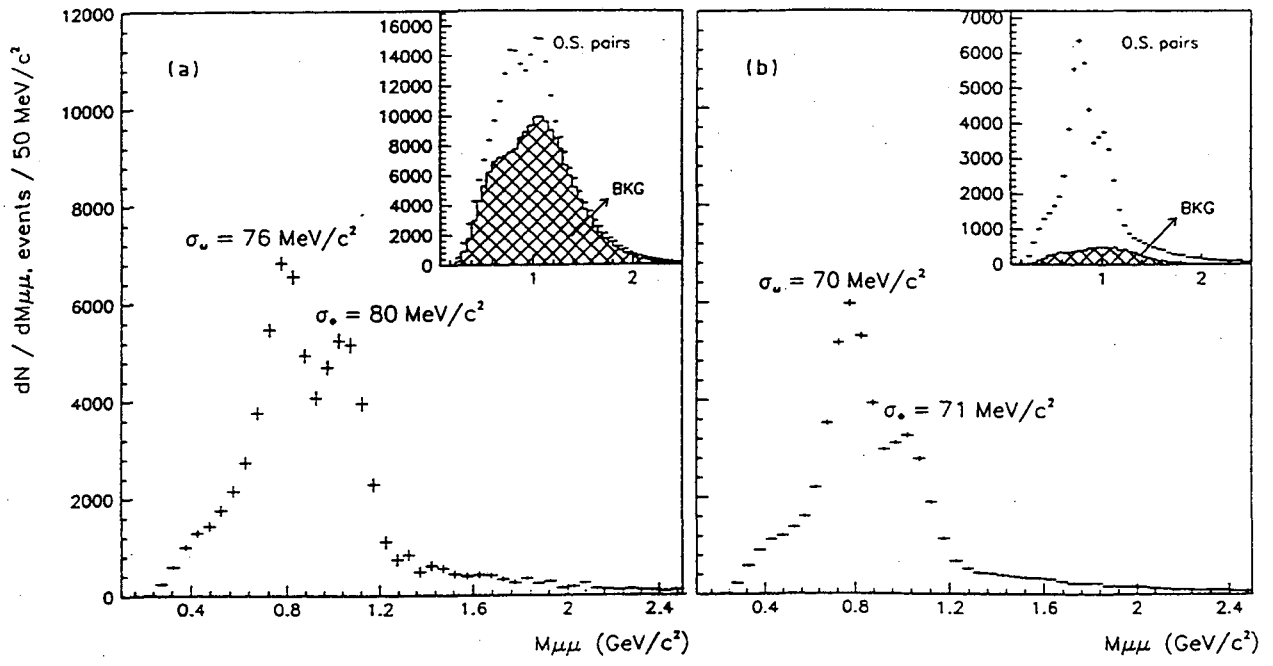


Figure 24.

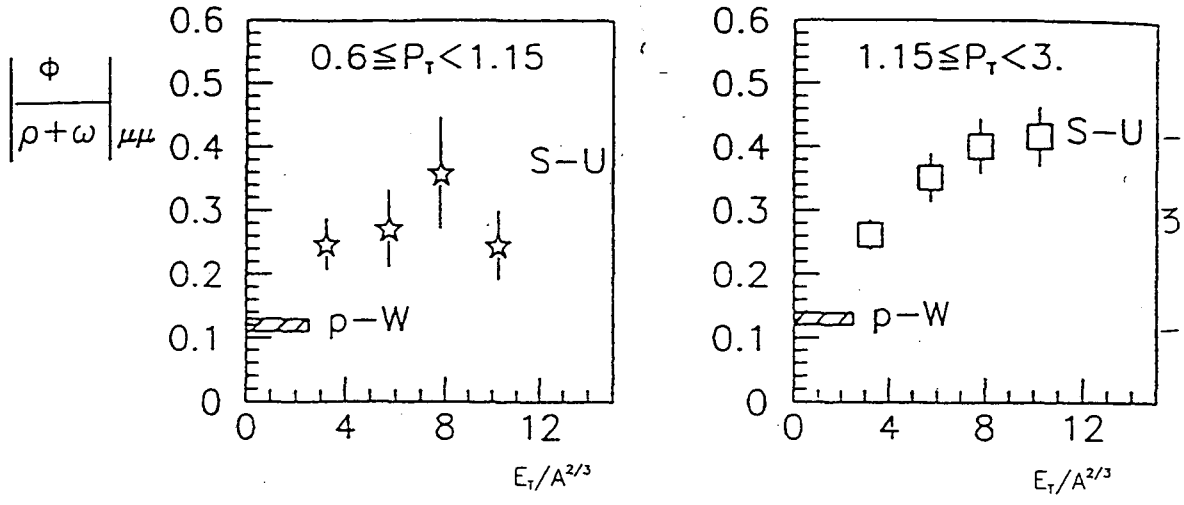


Figure 25.

# Table 1.

Summary of the different particle ratios and their respective acceptance intervals.

| | Particle Ratio | Acceptance |
|---|---|---|
| $\bar{\Lambda}/\Lambda$ | 0.207± 0.012 | $1.5 \leq y \leq 3.0$, $0.6 \leq p_t \leq 1.6$ GeV/c |
| $\Xi^+/\Xi^-$ | 0.276 ± 0.108 | $2.0 \leq y \leq 2.5$, $0.8 \leq p_t \leq 1.8$ GeV/c |
| $\Xi^-/\Lambda$ | 0.066 ± 0.013 | $1.5 \leq y \leq 2.5$, $0.8 \leq p_t \leq 1.8$ GeV/c |
| $\Xi^+/\bar{\Lambda}$ | 0.127 ± 0.022 | $2.0 \leq y \leq 3.0$, $0.6 \leq p_t \leq 1.8$ GeV/c |

# Table 2.

The ratios $\Xi^-/\Lambda$ and $\bar{\Xi}/\bar{\Lambda}$ in the region $2.4 < y_{lab} < 2.6$ and $1 < p_T < 2$ GeV/c for central S–W interactions.

| Exp. | int. | $\sqrt{s}$ (GeV) | $p_T$ (GeV/c) | $\Xi^-/\Lambda$ | $\bar{\Xi}/\bar{\Lambda}$ |
|---|---|---|---|---|---|
| WA85 | S–W | 19 | 1–2 | 0.11 ± 0.02 | 0.33 ± 0.11 |

# Table 3.

| | main decay modes | Fraction % | L/p [cm/GeV] |
|---|---|---|---|
| $K^{\pm}$ | $\mu^{\pm}\nu$ | 63.5 | 751.3 |
| | $\pi^{\pm}\pi^{0}$ | 21.2 | |
| | $\pi+\pi-\pi^{\pm}$ | 5.6 | |
| $K_s^0$ | $\pi^{+}\pi^{-}$ | 68.6 | 5.37 |
| | $\pi^{0}\pi^{0}$ | 31.4 | |
| $K_L^0$ | $\pi^{0}\pi^{0}\pi^{0}$ | 21.5 | 3122.2 |
| | $\pi^{+}\pi^{-}\pi^{0}$ | 12.4 | |
| | $\pi^{\pm}\mu^{\mp}\nu$ | 27.1 | |
| | $\pi^{\pm}e^{\mp}\nu$ | 38.7 | |
| $\Lambda$ | $p\pi^{-}$ | 64.2 | 7.1 |
| | $n\pi^{0}$ | 35.8 | |
| $\Sigma^{+}$ | $p\pi^{0}$ | 51.6 | 2.0 |
| | $n\pi^{+}$ | 48.4 | |
| $\Sigma^{-}$ | $n\pi^{-}$ | 100 | 3.7 |
| $\Xi^{0}$ | $\Lambda\pi^{0}$ | 100 | 6.6 |
| $\Xi^{-}$ | $\Lambda\pi^{-}$ | 100 | 3.7 |
| $\Omega^{-}$ | $\Lambda K^{-}$ | 67.8 | 1.5 |
| | $\Xi^{0}\pi^{-}$ | 23.6 | |
| | $\Xi^{-}\pi^{0}$ | 8.6 | |

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