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Multiply-Strange Baryon and Anti-Baryon Production in S+Pb Collisions at 200 GeV/c per Nucleon

NA36 collaboration

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Abstract

The yields of Λ, $\bar{\Lambda}$ and Ξ^-, $\bar{\Xi}^+$ have been measured close to mid-rapidity in sulphur reactions on a Pb target at 200 GeV/c per nucleon beam momentum. Fully corrected production ratios of $\bar{\Lambda}/\Lambda$, $\bar{\Xi}^+/\Xi$, Ξ^-/Λ and $\bar{\Xi}^+/\bar{\Lambda}$ are presented. The ratios have been analyzed both in the context of a rapidly disintegrating quark-gluon plasma and a hadronic resonance gas. Our analysis shows that the hadron gas model is sufficient to explain the observed particle yields.

An enhancement of strangeness production ($s\bar{s}$ quark pairs) has long been put forward as an important signature of quark-gluon plasma (QGP) formation [1]. This prediction arises primarily from the contribution of gluon interactions which drive the deconfined system toward a state of quark flavour-equilibrium [2,3]. An enhancement of Λ, $\bar{\Lambda}$ production, which is multiplicity dependent, has already been reported in sulphur induced reactions [4,5]. Furthermore, it has been shown that the rapidity distribution of Λ produced in central S+Pb collisions is shifted toward mid-rapidity [6], suggestive of the formation of a central rapidity fireball [7]. The crucial question is whether the observed trends in the data may be explained by the onset of the liberated colour degrees of freedom (a QGP), or interactions in a hot hadronic gas (HG). It has been suggested that even in a purely hadronic scenario, rescattering of produced particles and participant nucleons may account for the observed enhancement [8]. In this respect, the production of multiply strange baryons and especially anti-baryons may help to distinguish between the QGP and HG scenarios by providing a much more sensitive probe of the (anti)strange quark density achieved in the collision. In particular, the production of multiply strange anti-baryons in a hadronic scenario would be suppressed due to high production thresholds and the long time scales required for multi-step strangeness exchange reactions. Thus, a considerable enhancement of multiply strange anti-baryons would be highly suggestive of a QGP rather than a HG source.

The NA36 collaboration has measured the production of singly and doubly strange baryons and anti-baryons in S+Pb collisions by reconstructing the charged decays of Λ, $\bar{\Lambda}$ and Ξ^-, $\bar{\Xi}^+$ in a Time Projection Chamber (TPC) [9]. The TPC was situated 1.5 cm above the beam in a 2.7 Tesla magnetic field and approximately 60 cm downstream of a 5% interaction length Pb target. The polarity of the magnet was chosen so that positive particles were deflected preferentially into the acceptance of the detector. Due to the mass asymmetric final states of the decays, the acceptance for particle and anti-particle differ in this one field configuration. As a result a different region of acceptance in rapidity and transverse momentum (y,p_t) space has been selected for each particle ratio (see table 1).

The data analysis is based on 10^6 events with a maximum impact parameter of approximately 9 fm. The charged decays of Λ, $\bar{\Lambda}$ were reconstructed by identifying pairs of oppositely charged tracks compatible with having originated from a common vertex at least 20 cm downstream of the target. A simple set of geometrical cuts was found to remove the majority of the combinatorial background [10]. The most effective cuts required that the V^o point to the reconstructed production vertex and that the two daughter tracks be well separated at that position. The decay of Ξ^-, $\bar{\Xi}^+$ was reconstructed by finding a third charged track to form a second decay vertex with a reconstructed Λ, $\bar{\Lambda}$. A similar set of geometrical cuts was again found to remove most of the background [11]. In this case, the requirement that the V^o point back to the production vertex was relaxed and the Ξ decay vertex was required to be at least 10 cm downstream of the target.

A geometrical fit was applied to both the Λ, $\bar{\Lambda}$ and Ξ^-, $\bar{\Xi}^+$ candidates. The resulting invariant mass distributions for Λ, Ξ^- and $\bar{\Lambda}$, $\bar{\Xi}^+$ are shown in figure 1. The background of the Λ, $\bar{\Lambda}$ distributions consists mainly of K^o_s reconstructed under the $M(p,\pi)$ invariant mass hypothesis and a small combinatorial component. These contributions were subtracted using Monte-Carlo generated distributions normalized respectively to the measured K^o_s yield and the high invariant mass region remaining after K^o_s subtraction, $M(p,\pi) \in (1.15, 1.20\ GeV/c^2)$. The background in the case of the Ξ^-, $\bar{\Xi}^+$ mass distributions, consists only of a combinatorial component, which was subtracted using the high invariant mass region $M(\Lambda,\pi) \in (1.396, 1.446\ GeV/c^2)$.

The background subtracted yields of Λ, $\bar{\Lambda}$ and Ξ^-, $\bar{\Xi}^+$ have been further corrected for the reconstruction efficiency and geometrical acceptance within the defined y-p_t intervals, and unseen decay modes. The reconstruction efficiency was determined by using a detailed Monte-Carlo simulation of the TPC, whereby generated decays were embedded into real events. In this way, the multiplicity dependence of the reconstruction efficiency was made to be truly representative of the track densities observed in real data. In the case of the Λ and $\bar{\Lambda}$ correction, efficiency and acceptance tables were evaluated on a grid ($\Delta y = 0.25$, $\Delta p_t = 0.2$ GeV/c). Data were extracted independently both as a function of y and p_t, and corrected using the efficiency and acceptance averaged over the other variable. The distributions used for averaging were iterated using the corrected distributions until the averaging and corrected distributions converged. The difference in the total yield found by integrating the reconstructed y and p_t distributions is representative of a possible systematic error in the correction procedure of the order of 10%. In the case of Ξ^-, $\bar{\Xi}^+$ there were insufficient statistics to correct the data independently as a function of y and p_t. Here, the corrected yields of Ξ^-, $\bar{\Xi}^+$ were obtained by calculating the efficiency and acceptance averaged over both y and p_t using a Monte-Carlo generated distribution [12].

In order to obtain the fully corrected particle ratios, a further correction was required to remove the Ξ^-, $\bar{\Xi}^+$ contribution to the Λ, $\bar{\Lambda}$ yields. This was determined by using the Monte-Carlo number of Λ produced within acceptance for Ξ generated over full phase space [12], normalised within the acceptance to the corrected yield of Ξ measured in the experiment. The contributions of both charged and neutral Ξ were taken into account assuming that from isospin symmetry an equal number were produced in the collisions. The resulting contribution to the previously corrected Λ and $\bar{\Lambda}$ yields was found to be $5.4 \pm 1.1\%$ and $14.1 \pm 2.5\%$ respectively. The fully corrected particle ratios, after subtraction of the Ξ^-, $\bar{\Xi}^+$ contribution to the Λ, $\bar{\Lambda}$ yields, are listed in table 1. These ratios are also shown plotted in figure 2 in comparison with a previously published compilation of measurements [13], which includes the S+W measurement of the WA85 experiment. This previous measurement suggested that the $\bar{\Xi}^+/\bar{\Lambda}$ ratio might be enhanced by a factor of 5-6 over p+p collisions measured at the CERN ISR [14], but with large statistical uncertainty. A more recent, higher statistics result from WA85 has indicated that the enhancement factor is in the range 3-4 [15]. Our result, which is measured over a wider acceptance interval, indicates that the enhancement in the $\bar{\Xi}^+/\bar{\Lambda}$ ratio is at most a factor of 2-3 over the p+p result.

Particle Ratio		Acceptance
$\bar{\Lambda}/\Lambda$	0.117 ± 0.011	$2.0<y<2.5$, $0.6<p_t<1.6$ GeV/c
$\bar{\Xi}^+/\Xi^-$	0.276 ± 0.108	$2.0<y<2.5$, $0.8<p_t<1.8$ GeV/c
Ξ^-/Λ	0.066 ± 0.013	$1.5<y<2.5$, $0.8<p_t<1.8$ GeV/c
$\bar{\Xi}^+/\bar{\Lambda}$	0.127 ± 0.022	$2.0<y<3.0$, $0.6<p_t<1.6$ GeV/c

Table 1. Summary of the different particle ratios and their acceptance interval.

In the following discussion, an attempt has been made to judge whether the observed trends in the particle ratios can be taken as an indication of new physics (a quark-gluon plasma), or whether a hadronic scenario is sufficient to explain the data. Rafelski has suggested that it is possible to obtain a model independent interpretation of the strangeness production source using the values of the strange particle ratios measured at mid-rapidity [16]. The calculation starts from the probability for producing a composite particle at a particular Boltzmann energy E, and temperature T, from an uncondensed Fermi gas [16,17].

$$P \propto \prod g_i \lambda_i \gamma_i \exp\left(\frac{-E_i}{T}\right) \quad (1)$$

Here, g_i is a statistical factor including isospin, $\lambda_i = \exp(\mu_i/T)$ is the chemical fugacity in terms of the chemical potential μ_i, γ_i is a fractional quantity describing the phase space saturation of any given quark species and the product runs over the constituent quarks. In practice, γ is taken to be equal to unity for all but strange quarks. This leads to a convenient expression for the particle ratios in terms of the composite quark chemical potentials μ_i (i = u,d,s), γ_s and the temperature of the system. From the ratio of production probabilities $R_\Lambda = \bar{\Lambda}/\Lambda$ and $R_\Xi = \bar{\Xi}^+/\Xi^-$ it is possible to show [16,17] that,

$$\frac{R_\Lambda}{\sqrt{R_\Xi}} = \exp\left(\frac{-\mu_B}{T}\right)\exp\left(\frac{0.5\ \delta\mu_q}{T}\right) \tag{2}$$

where $\mu_B = 3\mu_q$ is the baryochemical potential as a function of the average non-strange quark chemical potential and $\delta\mu_q = \mu_d - \mu_u$ is a measure of the isospin asymmetry. If $\delta\mu_q$ is assumed to be small, the strange particle ratios may be used to extract a value for the baryochemical potential in units of the temperature of the system. However, since our ratios have been extracted in regions of common p_t and not $m_T = \sqrt{m^2 + p_t^2}$, they must first be extrapolated to regions of common m_T acceptance. Then the ratios are compared at the same Boltzmann energy, $E = m_T \cosh y$. In figure 3, the m_T distributions for Λ, $\bar{\Lambda}$ are shown together with a fit of the following form:

$$\frac{1}{p_t}\frac{dN}{dp_t} \propto \sqrt{m_T}\exp\left(\frac{-m_T}{T}\right) \tag{3}$$

The determination of the slope parameter T, which in the absence of any transverse flow is related to the temperature of a thermal source, has enabled the extrapolation of the Λ and $\bar{\Lambda}$ yields to the same m_T acceptance as Ξ^- and $\bar{\Xi}^+$. The extrapolation gives a value of $\bar{\Lambda}/\Lambda$ = 0.093 ± 0.017, in the Ξ m_T interval $\in$ (1.54, 2.23 GeV/c^2). This leads to calculated values of $\mu_B/T = 1.73 \pm 0.15$ and $\mu_s/T = 0.03 \pm 0.06$. Since the value for μ_s is small and compatible with zero, this implies that the system formed near central rapidity ($2.0 < y < 2.5$) contains nearly equal numbers of strange and anti-strange quarks. Whilst this is expected from a quark-gluon plasma source, it is not sufficient to rule out hadronic mechanisms. The key signature for quark-gluon plasma formation is the saturation of the strange quark phase space, due to the shorter time scales expected for strangeness production in the QGP [3].

The ratio of doubly to singly strange particle species may be used to extract a value for the strange quark saturation factor, γ_s, which appears in (1). This factor, which is equal for strange and antistrange quarks, cancels in the ratio of particle and antiparticle but may be determined by applying the calculated values of μ_B and μ_s to the Ξ^-/Λ and $\bar{\Xi}^+/\bar{\Lambda}$ ratios. Once again, the measured ratios have been extrapolated to regions of common m_T acceptance, so that the Boltzmann term in (1) cancels in the ratio. The corrected ratios are $\Xi^-/\Lambda = 0.122 \pm 0.024$, $m_T \in (1.54,\ 2.23\,\mathrm{GeV}/c^2)$ and $\bar{\Xi}^+/\bar{\Lambda} = 0.281 \pm 0.050$, $m_T \in (1.45, 2.07\,\mathrm{GeV}/c^2)$. An additional factor of 2 is also needed to correct for the fact that the measured Λ yield contains an equal contribution from Σ^0 decays and primordial Λ [16,17]. After applying this correction and taking the product of the two ratios, a value of $\gamma_s = 0.38 \pm 0.04$ was obtained. This differs from the expected value of $\gamma_s \approx 1$ in a plasma scenario, where strange quarks would be close to their equilibrium abundance.

An alternative scenario is that the observed ratios result from a thermal hadronic fireball. In a model for an ideal gas of hadrons and known hadronic resonances at fixed temperature and baryon density and which is assumed to be in equilibrium with zero net strange quark density [18], it is possible to tabulate the production rates of strange particles as a function of T and μ_B. The measured ratios and their experimental uncertainties can then be used to establish an allowed region of the T-μ_B plane, necessary to explain the observed yields of Λ, $\bar{\Lambda}$, Ξ^- and $\bar{\Xi}^+$. This is shown in figure 4 where the overlap (hatched) region indicates a common temperature and baryon chemical potential in the range $156 < T < 188$ MeV and $240 < \mu_B < 340$ MeV. Taking the central values, this analysis leads to a value of $\mu_B/T = 1.69$ compared to the value $\mu_B/T = 1.73 \pm 0.15$ obtained previously.

It is noteworthy that the derived temperature range is smaller than the slope parameter value obtained from the experimental m_T distributions of Λ, $\bar{\Lambda}$ shown in figure 3. Heinz et al. have suggested that there is circumstantial evidence for collective transverse flow in these reactions with a mean transverse source velocity $\beta_s = 0.3$ [19]. Under this assumption, the true temperature of the source can be expressed in terms of the effective temperature T_{eff} given by the slope of the m_T distributions and β_s as follows:

$$T = T_{eff}\sqrt{\frac{1-\beta_s}{1+\beta_s}} \qquad (4)$$

From the mean of the measured slopes of the Λ, $\bar{\Lambda}$ m_T distributions and $\beta_s = 0.3$, the true temperature of the source is calculated to be $T = 162 \pm 6$ MeV. This is compatible with the temperature range of $156 < T < 188$ MeV obtained in the framework of the thermal resonance hadron gas model and indicated by the overlap region in Figure 4.

In conclusion, the production ratios of $\bar{\Lambda}/\Lambda$, $\bar{\Xi}^+/\Xi^-$, Ξ^-/Λ and $\bar{\Xi}^+/\bar{\Lambda}$ have been measured close to the central rapidity region of S+Pb collisions at 200 GeV/c per nucleon beam momentum. The value of the $\bar{\Xi}^+/\bar{\Lambda}$ ratio has shown an enhancement of a factor of 2-3 over that which has been found in p+p collisions at the CERN ISR. A model independent analysis, which assumes only a thermalised source freezing out at some temperature T, leads to a small value for the strange quark chemical potential that is compatible with zero. The analysis also leads to a value of the strange quark abundance that is only approximately 40% of saturation density. We have shown that a model based on an equilibrium hadron gas at a temperature of approximately 160 MeV and with a mean baryon chemical potential of 260 MeV predicts strange particle ratios which are consistent with our data. The source temperature of 160 MeV is not in contradiction with the higher values obtained from the m_T distributions of Λ and $\bar{\Lambda}$ if an appreciable collective transverse flow develops in these reactions, as has already been suggested. Since the strange quark density is still far from saturation and the hadronic gas model is in agreement with these data, it is not necessary to introduce the quark-gluon plasma hypothesis to explain the observed particle yields.

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Figure 1. The $M(p,\pi)$ and $M(\Lambda,\pi)$ invariant mass distributions. The Λ and Ξ^- mass distributions are taken from $1.5 < y < 2.5$ and $0.6 < p_t < 1.8$ GeV/c. The $\bar{\Lambda}$ and $\bar{\Xi}^+$ distributions from $2.0 < y < 3.0$ and $0.6 < p_t < 1.8$ GeV/c.

Figure 2. A summary of the world data on various particle ratios involving Λ, $\bar{\Lambda}$, Ξ^- and $\bar{\Xi}^+$. The ratios and the corresonding acceptance intervals pertaining to this work are given in Table 1, and the world data in [13,15].

Figure 3. The transverse mass distributions for Λ, $\bar{\Lambda}$ in the acceptance interval of the Ξ^-/Λ and $\bar{\Xi}^+/\bar{\Lambda}$ ratios (see Table 1). The straight line is a fit (see text), whereby the slope parameter, T, for each distribution has been obtained.

Figure 4. The T-μ_B plane. The overlap region places a bound on both the temperature T and baryon chemical potential μ_B, consistent with one standard deviation of the measured particle ratios.

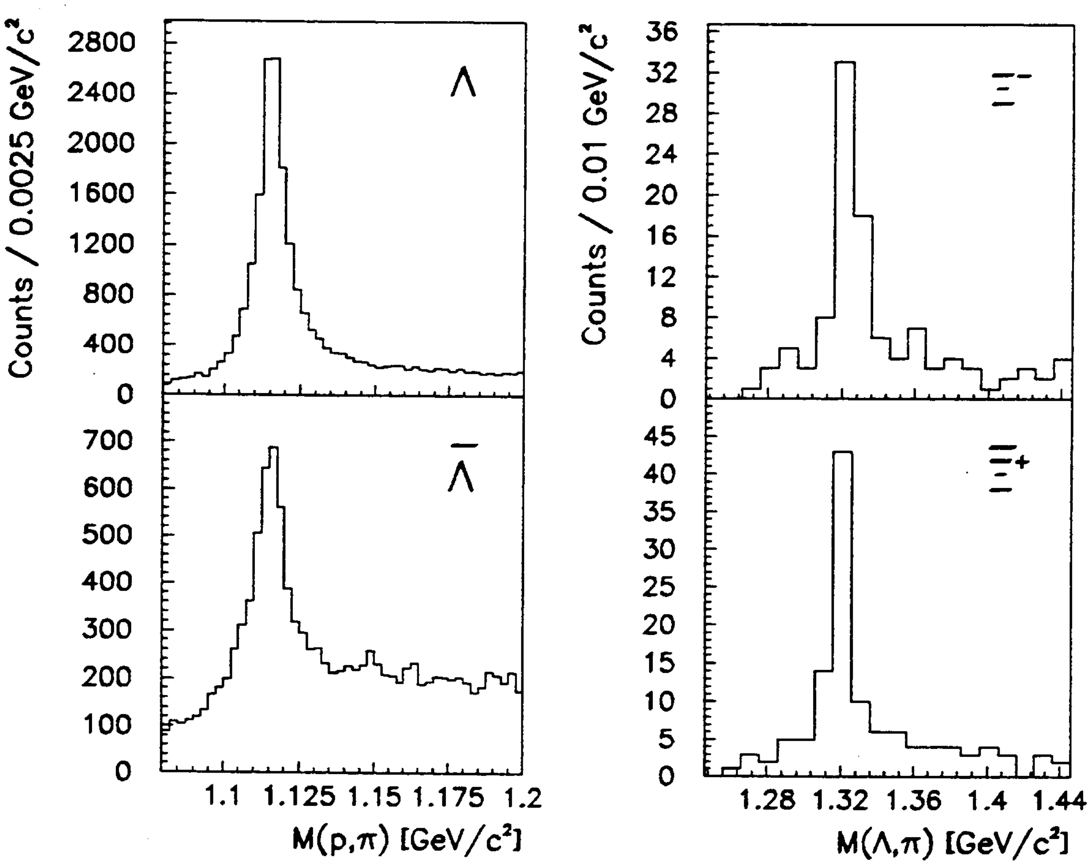

Counts / 0.0025 GeV/c^2
2800
2400
2000
1600
1200
800
400
0
Λ
700
600
500
400
300
200
100
0
$\bar{\Lambda}$
1.1
1.125
1.15
1.175
1.2
M(p,π) [GeV/c^2]
Counts / 0.01 GeV/c^2
36
32
28
24
20
16
12
8
4
0
Ξ^-
45
40
35
30
25
20
15
10
5
0
Ξ^+
1.28
1.32
1.36
1.4
1.44
M(Λ,π) [GeV/c^2]

Figure 1.

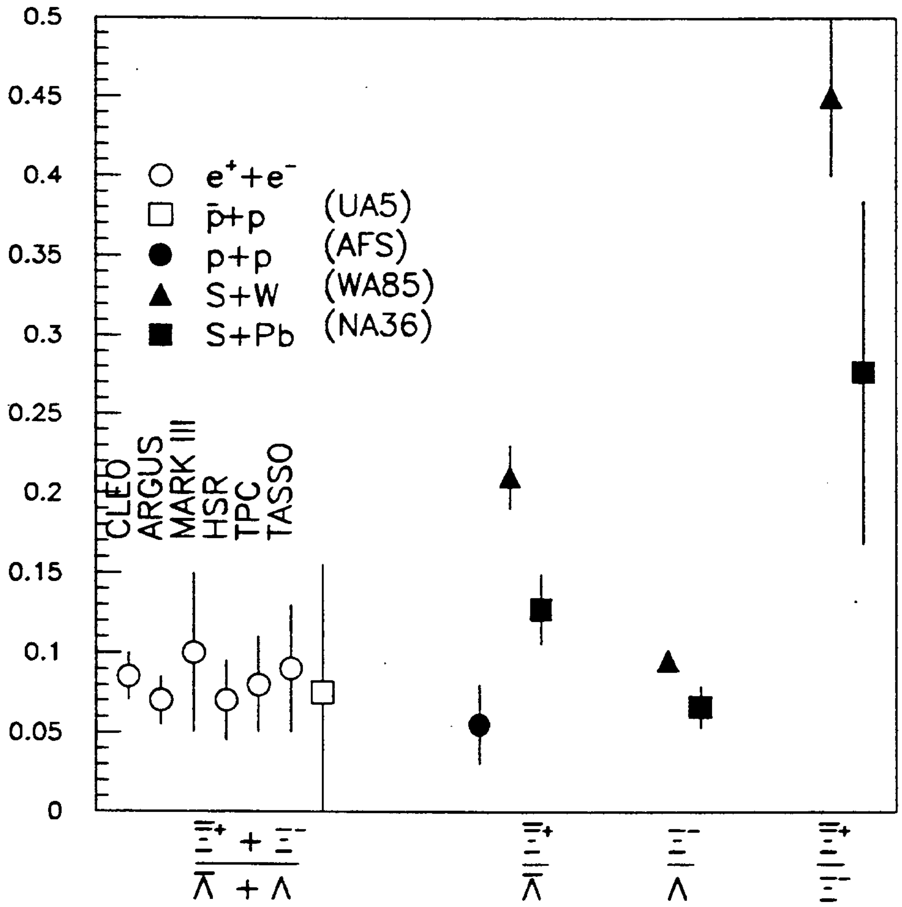
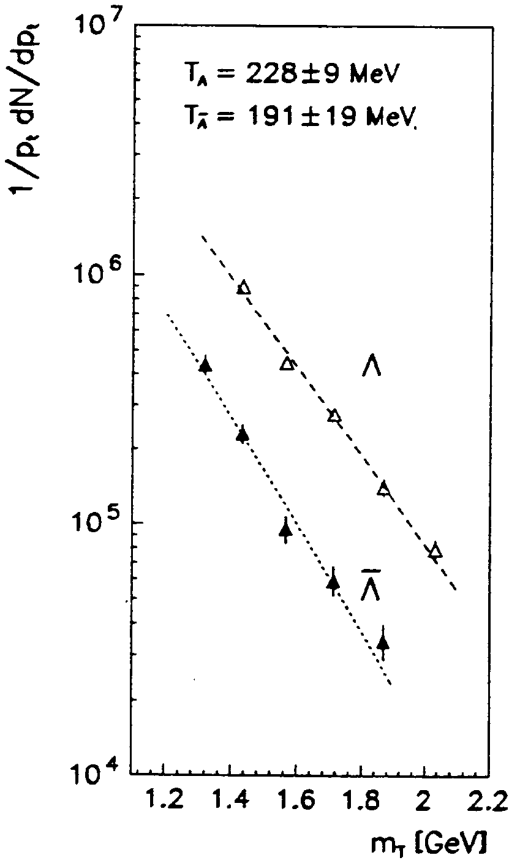
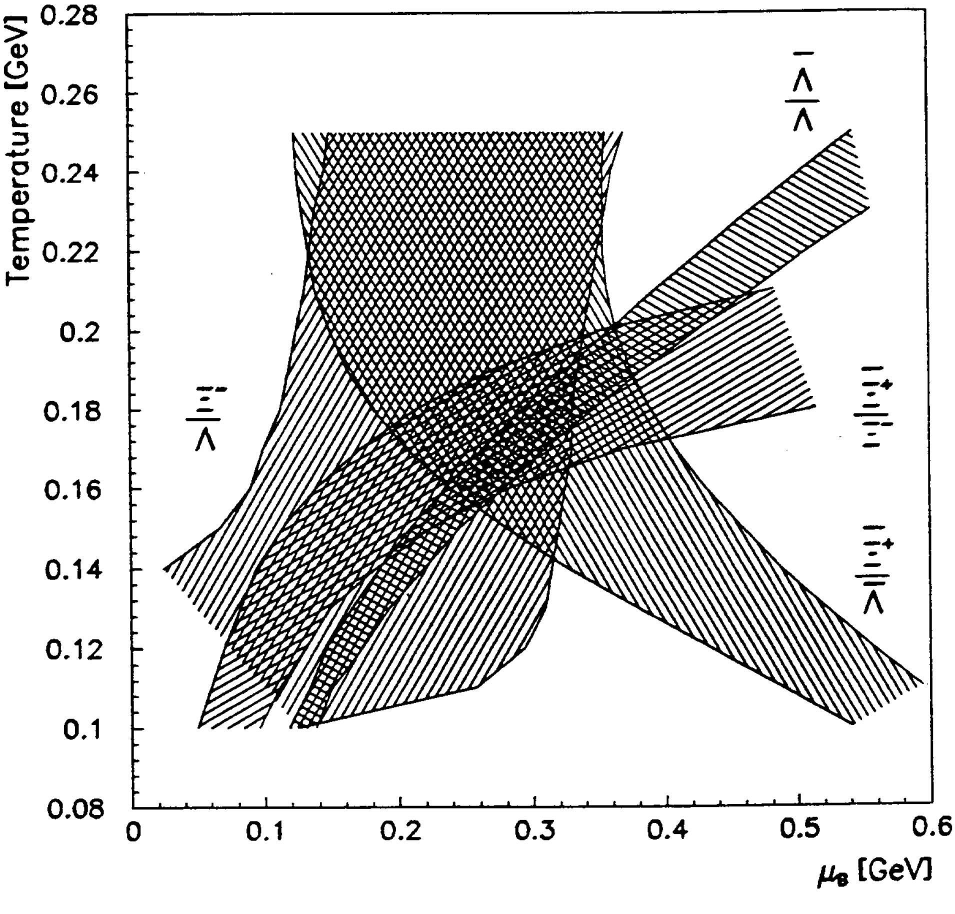

0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
e⁺+e⁻
p̄+p (UA5)
p+p (AFS)
S+W (WA85)
S+Pb (NA36)
CLEO
ARGUS
MARK III
HSR
TPC
TASSO

Figure 2.



T_Λ = 228±9 MeV
$T_{\bar{\Lambda}}$ = 191±19 MeV
Λ
$\bar{\Lambda}$
1/p_t dN/dp_t
m_T [GeV]

Figure 3.



Temperature [GeV]
0.28
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0
0.1
0.2
0.3
0.4
0.5
0.6
μ_B [GeV]

Figure 4.