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Λ transverse polarization measurement at mid-rapidity from Au+Au collisions at $\sqrt{s_{\rm NN}} = 130$ GeV

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Abstract

We report first results on transverse polarization of Λ hyperons at mid-rapidity in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV using the STAR TPC at RHIC. Our measurements of the Λ polarization, P, measured over the full kinematic range of $|x_f| < 0.03$ and $p_t < 5$ GeV/c is consistent with zero within 2σ. The Λ sample has also been binned in p_t. Again, the polarization measurement in each bin shows no significant deviation from zero.

Introduction

The spin structure of baryons has been studied extensively during the past three decades. In the past it was assumed that spin effects in hadronic reactions should be of little importance at high energies. At these energies the Λ production mechanism was assumed to proceed via many inelastic channels each naively contributing a different magnitude and sign to the average polarization. It was therefore unexpected that Λ hyperons produced in proton-proton (p-p) and proton-nucleus (p-A) collisions show a large polarization transverse to the production plane. The polarization effect was first observed in 1976 at FNAL in 300 GeV/c proton on Beryllium collisions [1]. Parity conservation in strong interactions requires that the spin of produced Λ is aligned normal to the production plane, which is defined by the vector $\hat{n}$:

$$\hat{n} = \frac{p_{beam} * p_{\Lambda}}{|p_{beam} * p_{\Lambda}|}$$

The data showed that the Λ in the fragmentation region are preferentially produced with their spin aligned anti-parallel (i.e. defined as negative polarization), rather than parallel (positive polarization), to the normal of the production plane.

Since then many experiments have systematically measured Λ hyperon polarization covering a large range of transverse momentum, p_t, and Feynman-x, $x_f = \frac{p_z(\Lambda)}{p_z(beam)}$. All experiments show consistently high polarization for high p_t and x_f [1–3].

The main properties of the p-p measurements can be summarized as follows:

a) the Λs are produced with a negative transverse polarization with respect to the production plane. This polarization is independent of the incident energy and shows only a small dependence on the system size in case of p-A reactions.

b) for the kinematic region $p_t < 1.5$ GeV/c the polarization increases linearly with p_t and x_f. The x_f dependence exhibits a steeper slope.

c) for the kinematic region $p_t > 1.5$ GeV/c the polarization saturates as a function of p_t, but it is still linearly increasing as a function of x_f.

Since the discovery of the Λ polarization, the polarization of a variety of hyperons and anti-hyperons has been measured over a wide kinematic range. The results show differing effects that cannot easily be described with present models (e.g. positive polarization for the Ξ^- [4], no polarization for the $\overline{\Lambda}$ [2, 5], and polarization for the $\overline{\Xi}$ [6]) .

Many attempts have been made to understand the origin of hyperon polarization. Originally, semi-classical parton recombination models assumed that the Λ polarization is exclusively carried by the s-quark, which is recombined with a u-d di-quark in a singlet state in order to form a Λ. The s-quark was either a slow sea-quark [7] or originated via quark-antiquark pair production through a tunnelling process in the color field [8]. Based on these recombination models a vanishing polarization of the Λ has been proposed as a possible signature for the formation of a Quark Gluon Plasma (QGP) in relativistic heavy ion collisions [9]. Recent measurements with polarized beams [10] seem to indicate, though, that the semi-classical di-quark, s-quark recombination model is inconsistent with the measured forward-backward asymmetry (A_N) and spin transfer asymmetry (D_{NN}). Also, other models like Regge-type models [11] or the more recent quark fragmentation model [12] do not necessarily lead to a change in the hyperon polarization in the case of a QGP.

Two measurements of transverse Λ polarization in heavy-ion collisions have been made at the AGS and at CERN [13, 14] though neither had conclusive results due to low statistics. Recently E896 at the AGS, a dedicated hyperon experiment, recorded a large Λ sample and measured a non-zero transverse polarization of the Λ in Au-Au collisions at 11.6 A GeV/c [16]. The x_f and p_t dependence of the polarization measured by E896 is comparable to the results from p-p and p-A measurements. These results indicate that the Λ production mechanism in A-A collisions at AGS is similar to the process in p-p collisions and that rescattering and final state interactions have only little effect on the Λ polarization. This paper presents the first measurement of transverse Λ polarization in relativistic heavy-ion collisions in a collider mode and at RHIC energies.

The STAR Experiment at RHIC

The STAR detector consists of several detector sub-systems located in a large solenoidal field. For the data presented here, the experimental setup consisted of a Time Projection Chamber (TPC), a Central Trigger Barrel (CTB), and two Zero Degree Calorimeters (ZDC) located 18m East and West of the center of the TPC along the beam axis. The TPC is a cylindrical drift chamber with its axis aligned along the beam direction providing complete azimuthal coverage. The TPC is surrounded by a cylinder of 240 scintillator slats forming the CTB, which measures energy deposition from traversing charged particles. The ZDC's measures beam-like neutrons from the fragmentation of colliding nuclei. The CTB signal is used in conjunction with the signals of the ZDC's in order to determine an experimental centrality trigger. Data used in this analysis were taken with a single trigger condition: a central trigger requiring a coincidence between both ZDC's and a high hit multiplicity in the CTB. This central trigger corresponds to the top 14% of the measured cross sections for Au+Au collisions. A further offline multiplicity cut selected the top 11% of the measured cross-section [15]

During the first year of RHIC running the beam crossing area was large. In order to restrict the data sample to events within the TPC coverage, the primary vertex position is required to be within ± 70 cm of the center of the TPC. The Λ particles are reconstructed from their weak decay topology $\Lambda \rightarrow p\pi^-$ using charged tracks reconstructed in the TPC. These tracks are projected back from the first TPC pad row (r = 55 cm) to find their closest approach to the primary vertex. Candidate tracks for the Λ reconstruction are selected by requiring a minimum distance of closest approach to the primary vertex. Particle assignments for p and π^- candidates are made by correlating the ionization energy loss (dE/dx) of charged particles in the TPC gas with their measured momentum. By truncating the largest 30% dE/dx values along the track, a sample of hits is selected to calculate the mean dE/dx. For the highest multiplicity events, the average dE/dx resolution was found to be about 11%. The measured dE/dx is reasonably described by the Bethe-Bloch function smeared with a resolution of width σ. Tracks within 2σ of the proton and pion Bethe-Bloch curves are selected for this analysis. Candidate tracks are then paired to form neutral vertices which are required to be offset from the primary interaction point. The reconstructed momentum vector of the parent particle is required to originate from the primary interaction.

The Λ mass resolution is typically about 3-4 MeV/c. Figure 1 shows an example of the invariant mass distribution for reconstructed Λ candidates in the rapidity region $|y| < 0.5$. The statistics available from the STAR year-1 dataset is a total of 73,000 Λs in 180,000 central events. The background underneath the Λ peak is dominated by combinatorics. K_s^0 also contribute because the dE/dx measurement cannot unambiguously distinguish between

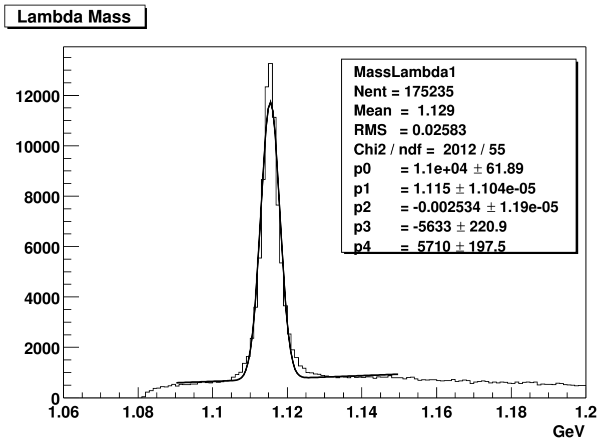

FIG. 1: Λ mass plot

protons and pions. To subtract the background a linear function fit is applied. It is estimated that the background contributes less than 15% to the total Λ sample.

Measuring Polarization via Decay Angles

The main method to measure Λ polarization is to measure the emission angle distribution of the decay proton in the Λ rest frame with respect to the production plane axis. Due to the parity violation in weak decays the $\pi^- p$ can be in a combination of $s_{1/2}$ and $p_{1/2}$ states. The angular distribution of the decay proton can then be written as

$$dw(\Theta) = 1/2(1 - \alpha cos\Theta)dcos\Theta$$

where α is an interference term between the s and p waves.

$$w(\xi, cos\Theta)dcos\Theta = A[1 + \alpha P(\xi)cos\Theta]dcos\Theta$$

where ξ is the angle between the Λ direction and the beam direction. This angle is a function of the transverse momentum p_t and the Feynman variable x_f. $P(\xi)$ is the level of polarization of the Λ, and Θ is the angle between the decay proton in the Λ rest frame and the normal to the production plane. By integrating over the full Λ momentum space the decay proton distribution as a function of emission angle Θ can be expressed as:

$$\frac{dN}{dcos\Theta} = A(cos\Theta)(1 + \alpha P cos\Theta)$$

where P is the level of polarization of the Λ, and Θ is the angle between the decay proton and $\hat{n}$ in the Λ rest frame. α is the s-p-wave interference term factor which is experimentally measured to be 0.642 +- 0.013 [17]. $A(cos\Theta)$ is the detector response correction factor which has to be determined through simulation of the geometry of the specific measurement device. The polarization in this analysis is measured by fitting a histogram of the $cos\Theta$ distribution to a first order polynomial between $cos\Theta$ = -1 to 1 . The polarization is then calculated as $P = \frac{P_1}{\alpha * P_0}$ where P_0 and P_1 are the first and second terms for the polynomial, respectively.

Effects of Symmetry in Polarization Measurements

As shown in the previous section the polarization of a Λ hyperon is measured by determining the decay angle of the proton with respect to the transverse plane. The sign of the $\hat{n}$ vector is odd in x_f, which means that the vector is switching direction according the sign of the x_f. Thus, the cosΘ distribution is odd in x_f, and subsequently the polarization is odd in x_f, *i.e.*

$$P(-x_f) = -P(x_f)$$

where P is the transverse polarization. The initial state of the collision is symmetric in x_f therefore any measurement of transverse polarization that integrates over positive and negative x_f must be zero.

$$\int_{-x_f}^{x_f} P(x'_f)dx'_f = 0$$

The STAR detector is symetric in z and covers a kinematic range $-0.03 < x_f < 0.03$, so we seperate our data into two subsets of Λ rapidity, y>0 ($x_f > 0$) and y<0 ($x_f < 0$), keeping in mind that the sum of the polarization of the two subsets must be zero. Previous Λ polarization measurements were made solely for one sign of x_f [1, 2] or combined the $x_f > 0$ and the $x_f < 0$ Λ samples by reversing the sign on the cosθ of the $x_f < 0$ sample [3]. Here we fit the two subsets seperately and present the sign reversed sum of the two polarization measurements in a seperate table (TableIII).

Analysis and Results

Λ polarization in STAR year-1 data was measured exclusively with the TPC which covers two units around mid-rapidity. Our analysis applies the standard cuts of the STAR Lambda analysis, which cuts the phase space coverage even further into one unit around mid-rapidity. This small rapidity coverage translates to a very small x_f-coverage (x_f=0.0-0.03) and a moderately high p_t-coverage (p_t=0-4.5 GeV/c). Figure 2 shows the p_t vs. x_f coverage for the Λ sample obtained with the STAR-TPC.

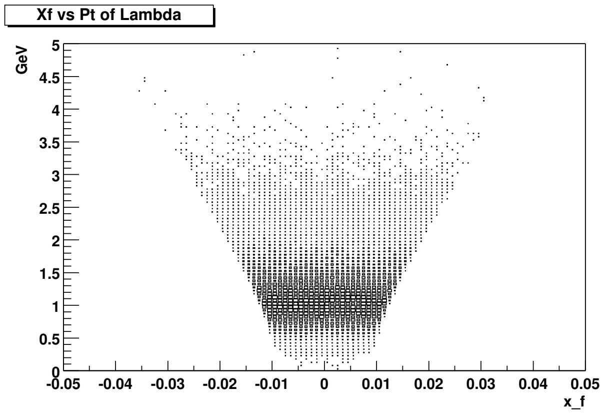

FIG. 2: x_f vs p_t distribution for the analyzed Λ sample

In this section we present the polarization for the integrated Λ sample and for the Λ sample divided into five p_t bins for both subsets in rapidity. For each p_t bin we correct for detector acceptance and for combinatoric background. In order to measure the polarization, the detector acceptance, $A(cos\Theta)$, is determined from *Monte Carlo* simulation. A sample of unpolarized Λs is simulated with GEANT and embedded into STAR central events and is then reconstructed using the STAR V0 analysis chain. Figure 3 shows the embedded sample $cos\Theta$ spectrum before reconstruction and the $cos\Theta$ distribution of the found embedded lambdas after reconstruction. The reconstructed $cos\Theta$ distribution is divided by the generated spectrum to obtain the detector acceptance function, $A(cos\Theta)$, also shown in Figure 3. The same procedure is repeated for each p_t bin and both rapidity regions.

The structure of the detector acceptance function is due to the correlation between the proton decay angle (Θ) and the p_t of the pion. Figure 4 shows the decay kinematics of two Λs, one with $\cos\Theta$ near 1 and the other near 0. For $\cos\Theta$ near zero, the p_t of the proton and the pion daughters is on average lower than for $\cos\Theta$ near ±1. This is easily understood

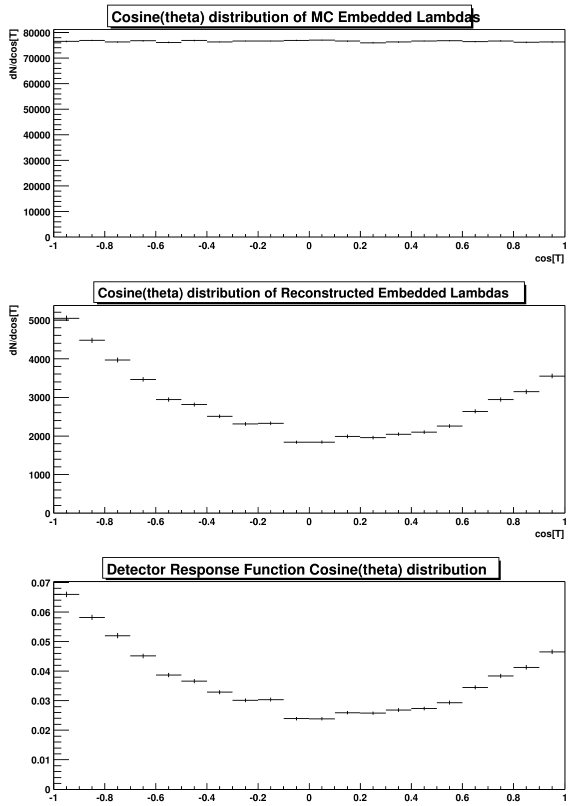

FIG. 3: Λ Embedded, Λ Reconstructed, Detector acceptance function, A(cosθ)

because the $\hat{n}$ vector is perpendicular to the p_t of the Λ. When the Λ decay axis in the Λ rest frame is perpendicular to the Λ p_t direction in the lab frame, cos$\Theta = \pm 1$. When the decay is in the transverse plane, cos$\Theta = 0$. For the decays corresponding to cosΘ near zero, the pion daughters' p_t in the Λ frame is aligned or anti-aligned with the Λ p_t. Since half the pions in these decays have a low pt ($<$ 150 Mev), they are not reconstructed efficiently causing the observed dip in the cosΘ distribution near cosΘ = 0. The additional slight asymmetry between cosΘ = 1 and cosΘ = -1 is also due to the sweeping effect of field on the negatively charged pion. More negative particles are swept out at positive cosΘ than at negative cosΘ.

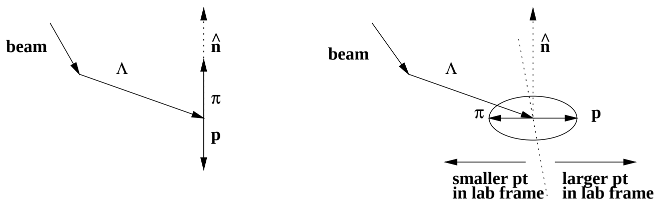

FIG. 4: Decay kinematics of Lambdas in the detector

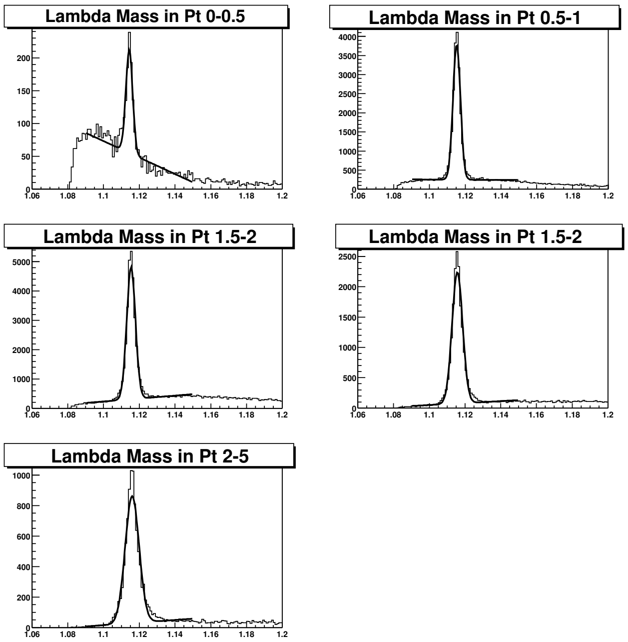

FIG. 5: Λ mass plots for each p_t bin

The mass spectrum for each p_t bin is fit to the sum of a gaussian and a line. Figure 5 shows the mass spectrum for each p_t bin. The signal is defined as those Λ candidates within 2σ of the fitted mass peak. Two background samples are chosen to be the Λ candidates within 3σ to 5σ on either side of the fitted peak in order to perform a sideband subtraction. Table I shows the statistics of each p_t bin for the full sample and for the $\pm$ rapidity subsets, (N_{sbs} is the number of Λs after sideband subtraction, N_{total} is the total number of Λ's before sideband subtraction, LHS and RHS are the samples for background subtraction on the left and right respectively, $\%BG$ is the percent of background contributing to the signal).

The corrected $cos\Theta$ spectrum for the integrated Λ sample is shown in Fig. 6. As shown in the previous section there is no polarization expected because of the symmetry of the system and the distribution yields a polarization of 0.0165 ± 0.0154 which is consistent with zero. The $cos\Theta$ distribution is then further divided in rapidity subsets and in p_t bins in order to see whether there is a p_t dependence of the polarization in the covered x_f range. Figure 7 shows the $cos\Theta$ distribution for each p_t bin in positive rapidity and negative rapidity. Table II summarizes the polarization from each $cos\Theta$ distribution for the full sample and for the $\pm$ rapidity subsets. Because the symmetry requires the polarization of the $\pm$ subsets to be of the same magnitude but different sign, we add the polarization of the subsets reversing

TABLE I: **Data yields and background fraction for various subsets used**

p_t (GeV/c)	N_{sbs}	N_{total}	LHS	RHS	%BG
		Λ rapidity -0.5 to 0.5			
0-5	64255	73793	3897	5641	12.9%
0-0.5	733	1225	311	181	40.16%
0.5-1	17026	19618	1276	1316	13.21%
1-1.5	25453	29196	1456	2287	12.82%
1.5-2	14912	16142	440	790	7.62%
1-5	7606	8259	149	540	7.9%
		Λ rapidity -0.5 to 0			
0-5	32565	37299	1951	2783	12.69%
0-0.5	361	616	161	94	41.4%
0.5-1	8662	9939	616	661	12.85%
1-1.5	12935	14805	737	1133	12.63%
1.5-2	7459	8086	219	408	7.75%
1-5	3828	4169	72	269	8.18%
		Λ rapidity 0 to 0.5			
0-5	31609	36494	1946	2858	13.16%
0-0.5	372	609	150	87	38.92%
0.5-1	8364	9679	660	655	13.59%
1-1.5	12518	14391	719	1154	13.02%
1.5-2	7453	8056	221	382	7.49%
1-5	3778	4090	77	235	7.6%

the sign of the negative set to obtain a final polarization. The results are shown in Table III.

FIG. 6: Polarization for the integrated Λ sample

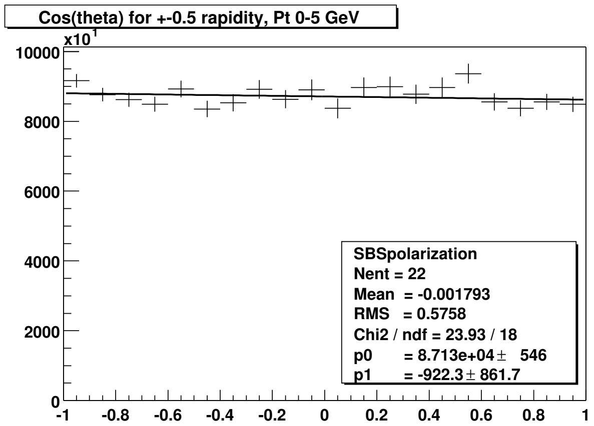

TABLE II: **Polarization for each p_t range and rapidity range**

p_t (GeV/c)	P(-0.5<y<0.5)	χ^2/dof	P(y>0)	χ^2/dof	P(y<0)	χ^2/dof
0-5	-0.0165 ± 0.0154	23.93/18	0.0274 ± 0.0219	26.1/18	-0.0575 ± 0.0216	17.23/18
0-0.5	-0.126 ± 0.147	8.018/8	-0.143 ± 0.205	2.911/8	-0.0843 ± 0.222	8.369/8
0.5-1	-0.0573 ± 0.0286	3.802/8	-0.0225 ± 0.0262	5.126/8	-0.0941 ± 0.0402	4.688/8
1-1.5	-0.00137 ± 0.0249	12.13/18	0.0231 ± 0.0356	13.01/18	-0.0252 ± 0.0349	14.9/18
1.5-2	0.0203 ± 0.0337	25.7/18	0.0806 ± 0.0472	15.06/18	-0.0339 ± 0.0482	25.85/18
2-5	-0.0106 ± 0.0450	20.65/18	0.0956 ± 0.0633	14/18	-0.0286 ± 0.0644	18.46/18

TABLE III: **Polarization for each p_t range**

p_t (GeV/c)	$\frac{P(y>0)-P(y<0)}{2}$
0-5	0.0423 ± 0.0154
0-0.5	-0.0293 ± 0.1511
0.5-1	0.0358 ± 0.0240
1-1.5	0.0242 ± 0.0249
1.5-2	0.0573 ± 0.0337
2-5	0.0621 ± 0.0452

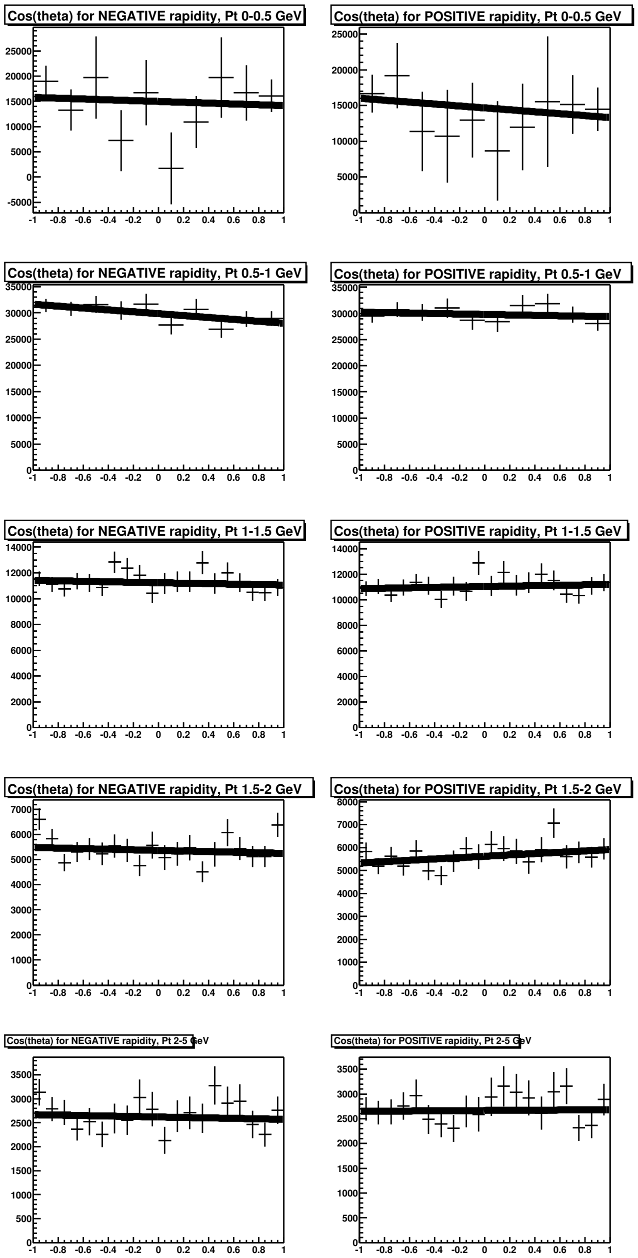

FIG. 7: Corrected Cosθ spectrum for each p_t bin in $\pm$ rapidity

Systematics

The only part of the STAR detector which is explicitly asymmetric in z, and as a result breaks the cosΘ symmetry, is the magnetic field of the detector, which has been folded into the detector response function. Thus, a measurement of the polarization over the full kinematic coverage of the STAR-TPC should be consistent with zero if there is no bias in our analysis. Figure 6 proves that the analysis yields a result consistent with zero in this case. In future studies this might be further constrained by studying the cosΘ in K_s^0 decays, where the true shape of the cosΘ distribution must be flat.

In addition, the quality of the line fit to the cosΘ distribution determines the magnitude of any non-linear discrepancies between the simulated detector response function and the measured distribution. From the quality of the fits shown on Figure 7 we deduce that the systematic error of our measurements is comparable to the quoted statistical error.

Conclusion

In summary, we have reported the first measurement of polarization for strange particle Λ from Au + Au collisions at $\sqrt{s_{\rm NN}}$ =130 GeV. The measured polarization in the kinematic range $p_t < 5$ GeV/c and $|x_f| < 0.03$, is consistent with zero within 2 σ and, taking into account the statistical and systematic errors in this analysis, the Λ polarization to be less than 5% over the full p_t range in this previously unexplored region of x_f.

It will be important to repeat this analysis with STAR in p-p reactions and in Au-Au collision data taken with the planned forward TPC's, which should enable Λ measurements over a larger range in x_f.

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[1] G. Bunce *et al.*, Phys. Rev. Lett. **36**, 1113(1976).

[2] B. Lundberg *et al.*, Phys. Rev. **D40**, 3557(1989).

[3] J. Felix *et al.*, Phys. Rev. Lett. **82**, 5213(1999).

[4] R. Rameika *et al.*, Phys. Rev. **D33**, 3172(1986).

[5] K. Heller *et al.*, Phys. Rev. Lett. **41**, 607(1978).

[6] P.M. Ho *et al.*, Phys. Rev. Lett. **65**, 1713(1990).

[7] T.A. DeGrand and H. Miettinen, Phys. Rev. **D24**, 2419(1981).

[8] B. Andersson *et al.*, Phys. Rep. **97**, 31(1983).

[9] A.D. Panagiotou, Phys. Rev. **C33**, 1999(1986).

[10] A. Bravar *et al.*, Phys. Rev. Lett. **78**, 4003(1997).

[11] R. Barni, Phys. Lett. **B296**, 251(1992).

[12] M. Anselmino *et al.*, Phys. Rev. **D63**, 054029(2001).

[13] T. Hallman *et al.*, (STAR Collaboration), HIPAGS 90 conference proceedings, (1990).

[14] A. Bamberger *et al.*, Z.Phys. **C29**, 61(1985).

[15] K.H. Ackermann *et al.* (STAR Collaboration), Phys. Rev. Lett. 86 (2001) 402

[16] R. Bellwied *et al.* (E896 Collaboration), QM2001 proc., Nucl. Phys. A (to be published)

[17] Particle Data Group, Phys. Rev. **D50**, (1994).