Λ hyperons in 2 A GeV Ni + Cu collisions

EOS Collaboration

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Abstract

A sample of Λ's produced in 2 A GeV ^{58}Ni + $^{\mathrm{nat}}$Cu collisions has been obtained with the EOS Time Projection Chamber at the Bevalac. Low background in the invariant mass distribution allows for the unambiguous demonstration of Λ directed flow. The Λ m_T spectrum at mid-rapidity has the characteristic shoulder-arm shape of particles undergoing radial transverse expansion. A linear dependence of Λ multiplicity on impact parameter is observed, from which a total $\Lambda + \Sigma^0$ production cross section of 112 ± 24 mb is deduced. Detailed comparisons with the ARC and RVUU models are made.

Key words:
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1 Introduction

Relativistic nucleus-nucleus collisions provide a unique opportunity for studying hot dense hadronic matter. At beam energies below 2 A GeV the focus has been on extracting information about the nuclear matter equation of state from measurements of the collective flow of nucleons and light fragments [1]. As the beam energy is increased, however, a complete description of the EoS should also include strange particle degrees of freedom. Recent theoretical studies have indicated that the in-medium properties of strange particles in nuclear matter at high densities and temperatures may be constrained by accurate measurements of their yields, spectra, and flow in heavy-ion collisions [2,3]. Preliminary experimental evidence of a directed flow signal for lambda particles has been provided by the EOS collaboration [4] and by the FOPI collaboration [5]. In this Letter we present the completed analysis of Λ sideward flow in the EOS data. In addition we present for the first time the EOS results on the total yield, the yields as a function of centrality and rapidity, and the collective transverse expansion of Λ's.

2 Experiment and data analysis

A full description of the EOS experimental setup can be found in Ref.s [6–8]. The heart of the setup is a Time Projection Chamber (TPC) which provides continuous three dimensional tracking and particle identification for particles with $Z \leq 8$. The EOS TPC has a rectangular geometry and operated in anti-parallel 1.3 T $\vec{\mathrm{B}}$ and 120 V/cm $\vec{\mathrm{E}}$ fields for this experiment. The target was situated as close to the TPC as possible, approximately 15 cm upstream of the first TPC pad row, in order to maximize acceptance. Because this placed it in a high magnetic field, copper rather than nickel was used as the target material. The ^{58}Ni beam supplied by the Berkeley Bevalac had an energy of 1.97 A GeV at the center of the target. The hardware trigger consisted of beam defining counters located some distance upstream and a trigger counter located just

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downstream of the target. The discriminator threshold on the downstream counter was set to veto the $\sim$25% most peripheral events. This trigger cutoff produces negligible bias in the data sample since, as demonstrated below, Λ's are predominantly produced in central events.

Λ's are reconstructed through the charged particle decay: $\Lambda \longrightarrow p + \pi^-$, which has a branching ratio of approximately 64%. After all TPC tracks in an event are found and the overall event vertex has been determined, each pair of $p\pi^-$ tracks is looped over and their point of closest approach is calculated. Pairs whose trajectories intersect at a point other than the main vertex are fit with a V0 hypothesis from which an invariant mass and momentum are extracted. The Λ candidates are then passed through a neural network filter [9] in order to reduce the combinatoric background. The resulting invariant mass distribution is shown in Fig. 1. Cutting around the peak in the distribution (1112 MeV/c^2 $\leq M_\Lambda \leq$ 1120 MeV/c^2) results in a sample of 1797 Λ candidates, of which around 40 are estimated to be background.

Acceptance correction factors have been calculated by passing a sample of 7.2×10^5 minimum bias 2 AGeV Ni + Cu ARC events through a detailed GEANT simulation of the EOS detector system and then through the same analysis chain as actual data. The ARC model [10] has been successful at reproducing a wide range of inclusive observables at AGS energies and it has been used to study directed flow in Au + Au collisions at Bevalac energies [11]. The parameterization of the TPC response in the EOS GEANT simulation code is similar to the parameterization in the FST simulation program used by the STAR collaboration [12]. Hit merging, spatial resolution, and ADC resolution parameters were empirically adjusted to match the data. The overall width and background of the reconstructed Monte Carlo Λ's are in good agreement with the data of Fig. 1.

Azimuthally integrated Λ efficiency factors are calculated on a 15×25 grid in (y, m_T) space from the formula:

$$\epsilon(y_i, m_{T,j}) = \frac{N_{rec}(y_i, m_{T,j})}{N_{MC}(y_i, m_{T,j})} \quad , \tag{1}$$

where N_{rec} and N_{MC} are the reconstructed and input number of Λ's, respectively, in the given bin. In principle the efficiency factors also depend on the multiplicity or impact parameter. Generating a sufficient number of GEANT events to calculate three dimensional efficiencies is impractical in the present case, however. Therefore, the approximation has been made that the efficiency factorizes into two pieces: $\epsilon(b, y, m_T) = \epsilon(b) \cdot \epsilon(y, m_T)$; with the $\epsilon(b)$'s being given by:

$$\epsilon(b_i) = \frac{N_{rec}(b_i)}{N_{MC}(b_i)} \ , \tag{2}$$

averaged over all values of y and m_T. In central and semi-central events tracking efficiencies are independent of impact parameter for the relatively light Ni + Cu system (maximum TPC multiplicity of around 70 tracks). In peripheral collisions, however, the presence of a forward going high Z fragment creates a hole in the TPC acceptance near beam rapidity. Although the factorization assumption is not valid for such events, the overall systematic error introduced is expected to be small, as the hole occurs in a region where there are few Λ's. At mid-rapidity, where the majority of Λ's are produced, the efficiency factors are very flat versus p_T over the entire range of impact parameters.

The overall acceptance for $\Lambda \longrightarrow p + \pi^-$, averaged over b, y, and p_T, is calculated to be about 16%. Approximately half of the loss is due to geometrical acceptance. Determination of the precise fraction decaying outside the solid angle of the detector is facilitated by the fact that, to first order, ARC reproduces the shape of the experimental distribution reasonably well. To second order, however, a small systematic uncertainty of $< 10\%$ might be introduced by the extrapolation of efficiency factors to regions of phase space where there are no counts. Some Λ's are also lost through inefficiencies in the track reconstrucion software. According to the simulations, over ninety percent of the Λ's which decay within the geometrical acceptance are reconstructed. Event display comparisons of data with Monte Carlo suggest that the true tracking efficiency may be lower by a few percent. The remainder of the experimental inefficiency is due to the cuts used to reduce the combinatoric background. More than 50% of the true Λ's which are reconstructed get thrown out by these cuts. Systematic error in the estimation of the magnitude of this loss mechanism is believed to be small. The total systematic error in the final cross section from all contributions is estimated to be ten to fifteen percent — half the size of the statistical error.

The open channels for Λ production in nucleon-nucleon collisions at this beam energy are $NN \longrightarrow \Lambda K N$ (1.58 GeV), $NN \longrightarrow \Sigma^0 K N$ followed by $\Sigma^0 \longrightarrow \Lambda\gamma$ (1.79 GeV), and $NN \longrightarrow \Lambda K N \pi$ (1.96 GeV). Λ's originating from Σ^0 decay ($c\tau = 2.2 \times 10^{-9}$cm) are experimentally indistinguishable from primary Λ's. In the ARC event sample approximately 23% of the Λ's arise from Σ^0 decay. These Λ's are included in all of the ARC comparisons shown below. All spectra, except for the sideward flow plots of Fig. 5, have also been corrected for branching ratios. The dependence of Λ yield upon centrality produces a natural weighting towards central events but no explicit centrality cuts have been applied. Attempts to study the effects of centrality cuts on the flow analyses were inconclusive due to insufficient statistics.

3 Results

The efficiency-corrected Λ center-of-mass rapidity spectrum, normalized to beam rapidity, is shown in Fig. 2 along with the ARC comparison. Both spectra peak near $y = 0$ as expected for this nearly mass-symmetric system. Within statistics, the widths of the distributions are similar; however, ARC appears to overestimate the total yield by approximately 50%. This is not necessarily a deficiency of the cascade assumption, however, as there is a relatively large uncertainty in the Λ cross section in *pp* collisions below 2 GeV. The solid curve of Fig. 2 represents the rapidity spectrum of an isotropic thermal distribution at the temperature of 106 MeV which is obtained by fitting an exponential to the mid-rapidity transverse mass spectrum of the data. The rapidity spectra for both the data and the model are considerably broader. This most likely indicates an insufficient number of rescatterings for the Λ's — which have a well known forward-backward distribution in elementary *pp* reactions — to become completely isotropic.

The dependence of Λ yield upon event centrality is shown in the top panel of Fig. 3. The impact parameter scale in this figure was derived by assuming a monotonic dependence of total observed charged particle multiplicity in the TPC versus impact parameter [13]. The data are well described by a straight line fit of $\langle N_\Lambda \rangle$ versus b: $\langle N_\Lambda \rangle = 0.1361(45) - 0.0153(7)b$ with a χ^2/ν of 0.6. The ARC model, on the other hand, predicts a linear dependence of Λ yield on the number of participants rather than on impact parameter. When plotted versus the number of participants, the data bend over and flatten out for the most central collisions. This behavior could be suggestive of a kind of "shadowing" effect in which late arriving nucleons from the projectile and target suffer softer collisions with matter already stopped in the collision zone. Since the initial beam energy is only marginally above threshold to begin with, Λ production from these late primary nucleons might be suppressed. The fact that the effect doesn't also show up in the cascade model, however, tends to cast doubt on this explanation.

The efficiency-corrected mean π^- multiplicities versus impact parameter are shown in the bottom panel of Fig. 3. The π^- efficiency is approximately 60% and independent of b. The π^- multiplicities of the data are not as well fit by a straight line as are the Λ's. The $\langle \pi^- \rangle$ dependence upon participant number is reasonably linear, however, consistent with previous observations [14]. Within statisitics, the Λ/π^- ratio is constant as a function of b with a value of 0.010 ± 0.001. For the most central events, ARC overpredicts the π^- yield by about 20%. ARC pion multiplicities bend over significantly when plotted versus the number of participants. The net result is a strong dependence of the Λ/π^- ratio on centrality in ARC.

The straight line fit of the upper panel of Fig. 3 intersects the abscissa at $b = 8.9 \pm 0.7$ fm. Integrating the fit out to this value of b yields a total cross section of $\sigma_{\Lambda+\Sigma^0} = 112 \pm 24$ mb. As mentioned above, a systematic error of the order of 15% from uncertainties in the acceptance corrections should be attached to this result. For the central 180 mb of the total reaction cross section, corresponding to impact parameters $b < 2.4$ fm, the extracted cross section is $\sigma_{\Lambda+\Sigma^0} = 20 \pm 3$ mb. This is somewhat higher than, but not in disagreement with, the 7.6 ± 2.2 mb cross section for central 1.8 A GeV Ar + KCl collisions of Ref. [15] when scaled by the approximately 50% increase in the number of participants. The parameterization used in Ref. [3] for the Λ production cross section predicts only a 10% increase in yield in going from a beam energy of 1.8 A GeV to 2.0 A GeV.

The mid-rapidity ($-0.25 \leq y \leq 0.25$) Λ m_T spectrum is shown in Fig. 4. In this representation, a purely thermal distribution would result in a straight line. The data of Fig. 4, however, have the characteristic shoulder indicative of a collective outward expansion depleting the low m_T region [16–21]. Nearly twenty years ago, Siemens and Rasmussen noted that the spectra of protons and pions measured at 90° in the center of mass at the Bevalac showed a pronounced shoulder at low p_T, which they attributed to collective expansion [16]. By assuming a spherically symmetric thermalized source at mid-rapidity expanding with a constant velocity, β_r, they were able to derive an analytical expression which, in terms of transverse mass, is:

$$\frac{1}{m_T^2}\frac{dn}{dm_T} \propto e^{-\gamma m_T/T}\left[\frac{\sinh\alpha}{\alpha}\left(\gamma + \frac{T}{m_T}\right) - \frac{T}{m_T}\cosh\alpha\right] , \tag{3}$$

where $\alpha = \beta_r \gamma p/T$ and $\gamma = (1-\beta_r^2)^{1/2}$.

Straightforward application of the Siemens-Rasmussen expression to the data of Fig. 4 gives $\beta_r = 0.36 \pm .02$ and T $= 51 \pm 1$ MeV with a χ^2/ν of 1.1. The interpretation of the fitted parameters is not so straightforward, however. Studies of EOS Au+Au data have shown that different assumptions about the expansion velocity profile are equally consistent with the observed m_T spectra. In general, the dependence upon the mean radial flow velocity and temperature cannot be expressed in simple analytical form as above but must be determined from Monte Carlo simulations. In the case of the present data no attempt has been made to extract β_r's or temperatures for other velocity profiles. The fit results should therefore be viewed as providing a quantitative measure of collective transverse expansion only within the context of the velocity profile assumption underlying Eq. 3.

The m_T spectrum of mid-rapidity protons from the same event sample also has a shoulder. An independent fit of the protons results in a β_r of $0.42 \pm .01$, in reasonable agreement with the β_r for the Λ's, with a χ^2/ν of 0.75. The proton's "temperature", however, is much higher: 81 $\pm$1 MeV. This difference is consistent with the picture of cold Λ's produced just above threshold undergoing an insufficient number of rescatterings to come into thermal equilibrium with the hotter protons.

A two parameter fit of the Λ's obtained by fixing β_r to zero gives T $= 106 \pm 5$ MeV with a χ^2/ν of 1.9. Fitting the protons with a pure exponential results in an inverse slope parameter T $= 142 \pm 1$ MeV with a χ^2/ν of 1.4. The rapidity spectrum obtained from the fit parameters of Eq. 3, assuming a spherically symmetric source, is indicated by the dashed curve of Fig. 2. The result is practically indistinguishable from a purely thermal distribution at the temperature of 106 MeV shown as the solid curve. The ARC Λ's in Fig. 4 show no evidence of a depletion at low m_T and are well fit by simple exponentials. The resulting inverse slope parameter is T $= 91 \pm 2$ MeV. The m_T spectra for ARC protons also show no evidence for transverse flow. Thermal fits give T $= 121 \pm 1$ MeV for filtered and T $= 126 \pm 1$ MeV for unfiltered ARC protons with χ^2/ν's of 1.3 and 1.2, respectively.

Detection of a majority of the charged particles in the TPC, along with the presence of directed flow for protons and heavier fragments, allows for the correlation of Λ production with the event reaction plane. The standard transverse momentum analysis of Danielewicz and Odyniec [22] has been performed on the 1797 Λ events. Details of the analysis along with preliminary results obtained from a smaller and less clean event sample are given in Ref. [4]. Briefly, a reaction plane for each event is determined from protons and nuclear fragments with $Z \leq 8$. The Λ transverse momentum is then projected onto the estimated reaction plane and averaged as a function of rapidity over all events.

The resulting $\langle p_x \rangle$ distributions, normalized to the proton mass, are shown in Fig. 5a for Λ's (filled circles) and protons (open squares). Both have been corrected for the 35° dispersion in the estimated reaction plane, as per the prescription of Ref. [22]. The conclusion of Ref. [4] has not changed — the Λ's "flow" in the same direction as the protons. The dashed lines of Fig. 5 represent straight line fits to the data over the region: $0 \leq y \leq 0.8$. The slopes, $(m_p/m) \times d\langle p_x \rangle/dy$, at mid-rapidity are given in the first column of Table 1. The fact that the Λ slope is consistent with zero within two standard deviations is somewhat misleading. Backward rapidity points have been excluded from the fits because reduced acceptance for $y_{cm} < 0$ leads to systematically lower values of $|\langle p_x \rangle|$. This effect can be clearly seen in the proton data points, which should be nearly antisymmetric about $y/y_{beam} = 0$ from symmetry considerations. The efficiency factors used to correct the y and m_T spectra have not been applied in the case of the event-by-event directed flow analysis. However, the direction of the correction can only be toward larger values of $|\langle p_x \rangle|$, which bolsters the conclusion of a non-zero positive Λ flow.

The analysis has also been performed on the ARC events. The results, both before and after the GEANT filter, are given in Table 1. Within statistical uncertainties the cascade is in agreement with the data for both protons and Λ's. A comparison of columns two and three of the table shows (again with large statistical errors) that the experimental acceptance and resolution do not distort the extracted flow values.

Also shown in Table 1 are flow values extracted from the relativistic transport code, RVUU, by the authors of Ref. [3]. Unlike ARC, where flow effects are produced by preservation of two-body scattering planes and an unequal weighting of attractive and repulsive orbits [11], RVUU incorporates a mean field potential for lambdas which increases the sidewards flow in the direction of the protons. The error bar on the RVUU value in Table 1 spans the range of flow values that were obtained in Ref. [3] from a $\pm 20\%$ adjustment in the relative strength of the vector part of the mean field. From the table it is seen that the two models produce approximately the same amount of flow for protons while ARC Λ's have, perhaps, slightly more flow. Our findings are consistent with the prediction of Ref. [3] that the magnitude of Λ directed flow is smaller than proton flow. Of course, the hypothesis of Λ flow and proton flow being equal cannot be confidently ruled out with the present statistics.

The roughly twofold difference between the proton $\langle p_x/m \rangle$ of the present work and the results of Ref. [5] is dominated by the $p_T/m > 0.5$ selection used in Ref. [5]. For the Λ's, both the transverse and sidewards flow analyses are very sensitive to the inclusion of combinatoric background. The protons from Λ decays have momentum vectors close to their parent particle's due to the low pion mass. Since non-decay protons, which are dominant in the formation of the combinatoric background, have both types of flow, false Λ's also show flow. In order to obtain pure Λ flow it becomes necessary to either: 1) reduce the background to an insignificant level as was done in the present analysis; or 2) perform a careful analysis of the flow of the background. Choosing the first option means sacrificing some statistics but avoids the inevitable complications and uncertainties of method 2. The Λ invariant mass plot of Ref. [5] includes a large combinatoric background. It is unclear whether or how much their reported Λ $\langle p_x/m \rangle$ are shifted towards their proton $\langle p_x/m \rangle$ by this background.

4 Conclusions

In summary, we have obtained a high quality sample of Λ's produced in 2 A GeV Ni + Cu collisions. To within 15% the acceptance is well understood, allowing efficiency corrections to be made with confidence. The $\Lambda + \Sigma^0$ production cross section has a linear dependence upon impact parameter and the Λ/π^- ratio is relatively flat versus impact parameter. A shoulder at low p_T

in the mid-rapidity Λ tranverse mass spectrum is most likely due to collective transverse expansion. Correlation of the Λ momentum with the reaction plane on an event-by-event basis reveals a positive directed flow consistent with the predictions of mean field theory. The ARC model reproduces the shape of the Λ rapidity spectrum and generates sidewards flow in agreement with the data but fails to reproduce the shoulders in the Λ and proton m_T spectra and the dependence of the Λ yield upon event centrality.

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References

[1] For a review see: W. Reisdorf and H. G. Ritter, Ann. Rev. Nucl. Part. Sci. **47**, 663 (1997).

[2] G. Q. Li, C. M. Ko, and Bao-An Li, Phys. Rev. Lett. **74**, 235 (1995).

[3] G. Q. Li, C. M. Ko, Phys. Rev. C. **54**, 1897 (1996).

[4] M. Justice *et al.* Nucl. Phy. **A590**, 549c (1995).

[5] J. Ritman *et al.* Z. Phys. A 352, 355 (1995).

[6] G. Rai *et al.*, IEEE Trans. Nucl. Sci. **37**, 56 (1990).

[7] H. Wieman *et al.*, Nucl. Phy. **A525**, 617c (1991).

[8] E. Hjort *et al.*, in *Advances in Nuclear Dynamics*, edited by B. Back, W. Bauer, and J. Harris (World Scientific, Singapore, 1993), p. 63.

[9] M. Justice, Nucl. Instrum. Methods Phys. Res. **A400**, 463 (1997).

[10] Y. Pang, T.J. Schlagel, and S.H. Kahana, Phys. Rev. Lett. **68**, 2743 (1992).

[11] D. E. Kahana *et al.*, Phys. Rev. Lett. **74**, 4404 (1995).

[12] STAR Conceptual Design Report, BNL-PUB-5347, 4C-21, (1992).

[13] C. Cavata *et al.*, Phys. Rev. C. **42**, 1760 (1990).

[14] J. W. Harris *et al.*, Phys. Lett. **153B**, 377 (1985).

[15] J. W. Harris *et al.*, Phys. Rev. Lett. **47**, 229 (1981).

[16] P. J. Siemens and J. O. Rasmussen, Phys. Rev. Lett. **42**, 880 (1979).

[17] H.W. Barz *et al.*, Nucl. Phys. **A531**, 453 (1991).

[18] S.C Jeong *et al.*, Phys. Rev. Lett. **72**, 3468 (1994).

[19] W.C. Hsi *et al.*, Phys. Rev. Lett. **73**, 3367 (1994).

[20] M.A. Lisa *et al.*, Phys. Rev. Lett. **75**, 2662 (1995).

[21] S. Wang *et al.*, Phys. Rev. Lett. **76**, 3911 (1996).

[22] P. Danielewicz and G. Odyniec, Phys. Lett. **157B**, 146 (1985).

Table 1
Flow values normalized to the proton mass in units of MeV/c.

	data	unfiltered ARC	filtered ARC	RVUU
p	133 ± 10	152 ± 4	141 ± 9	140
Λ	85 ± 43	163 ± 14	113 ± 31	96 ± 17

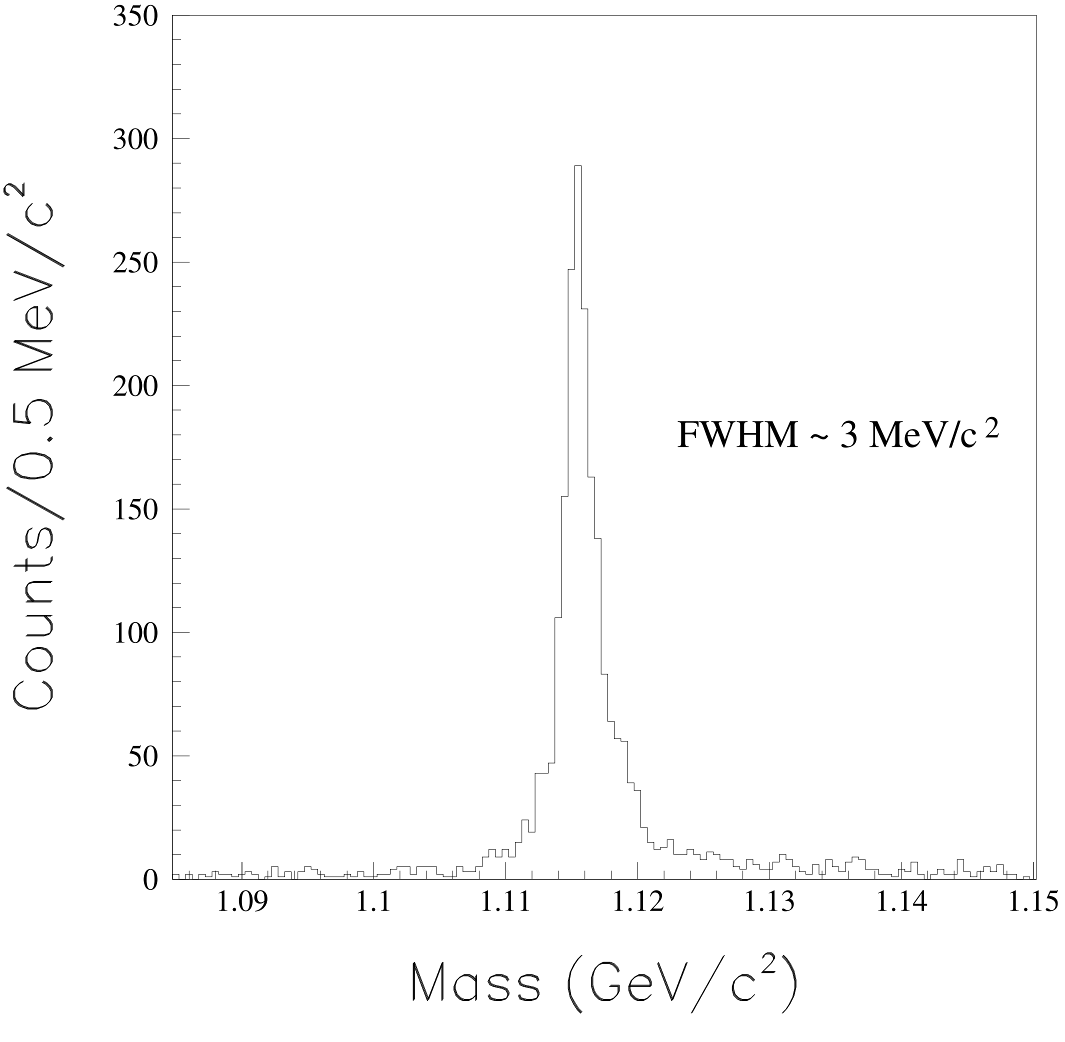

Fig. 1. Λ invariant mass spectrum.

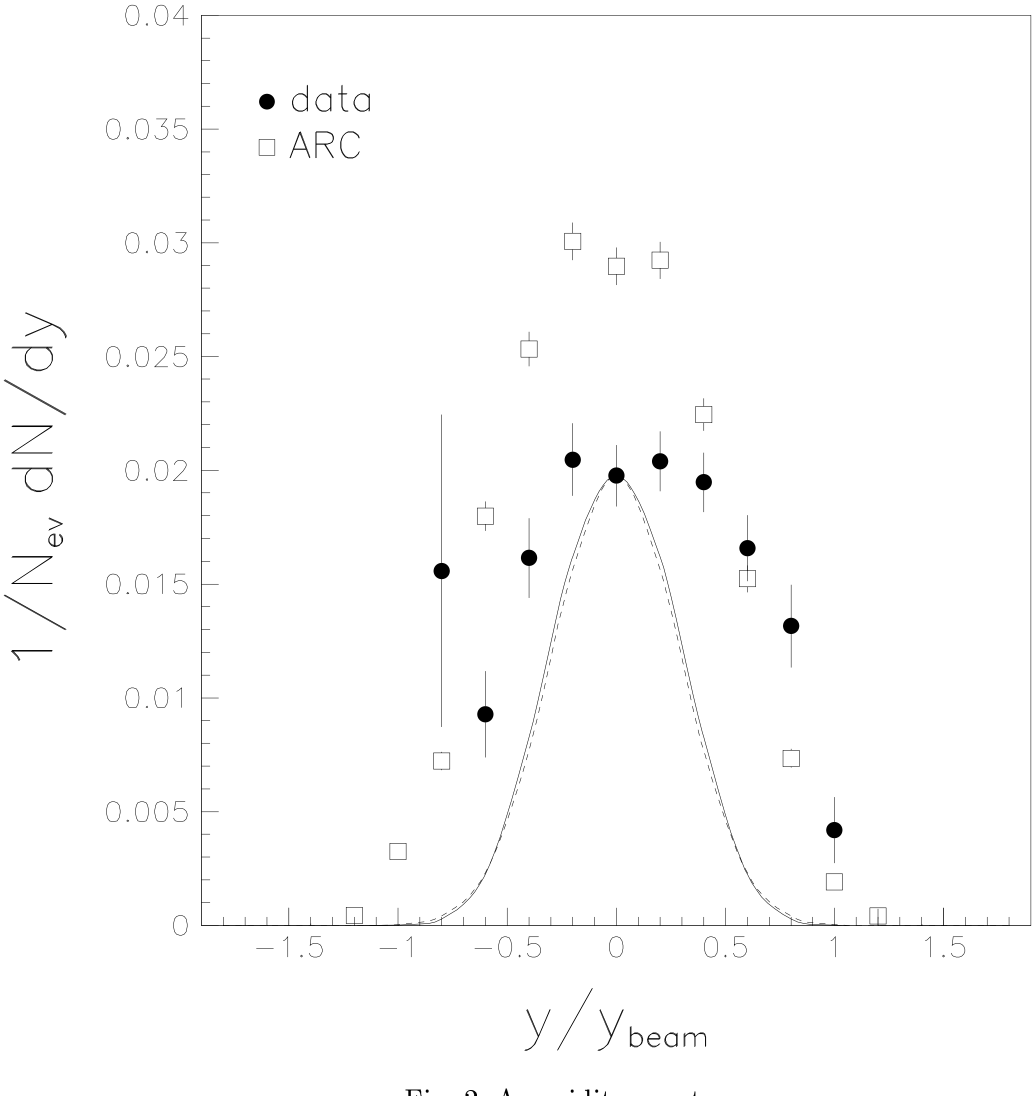

Fig. 2. Λ rapidity spectra.

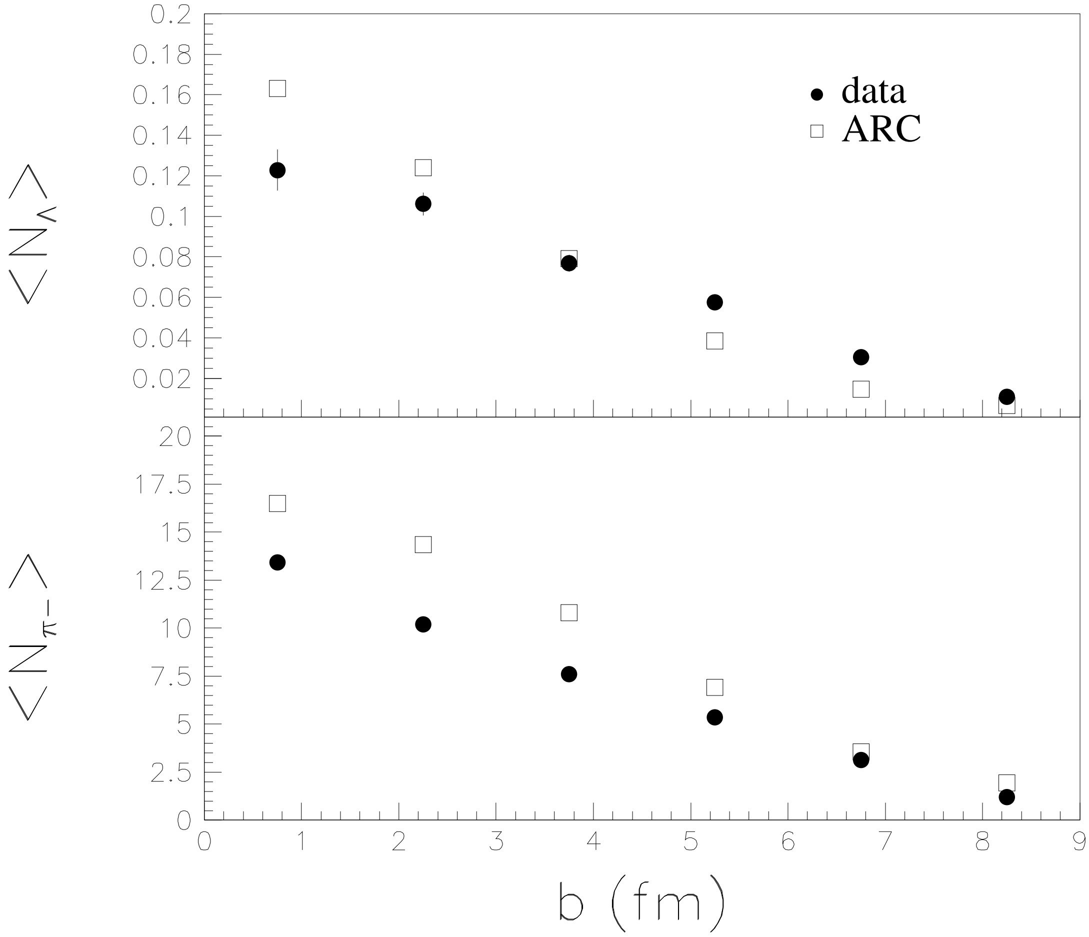

Fig. 3. Mean Λ and π^- multiplicities versus impact parameter.

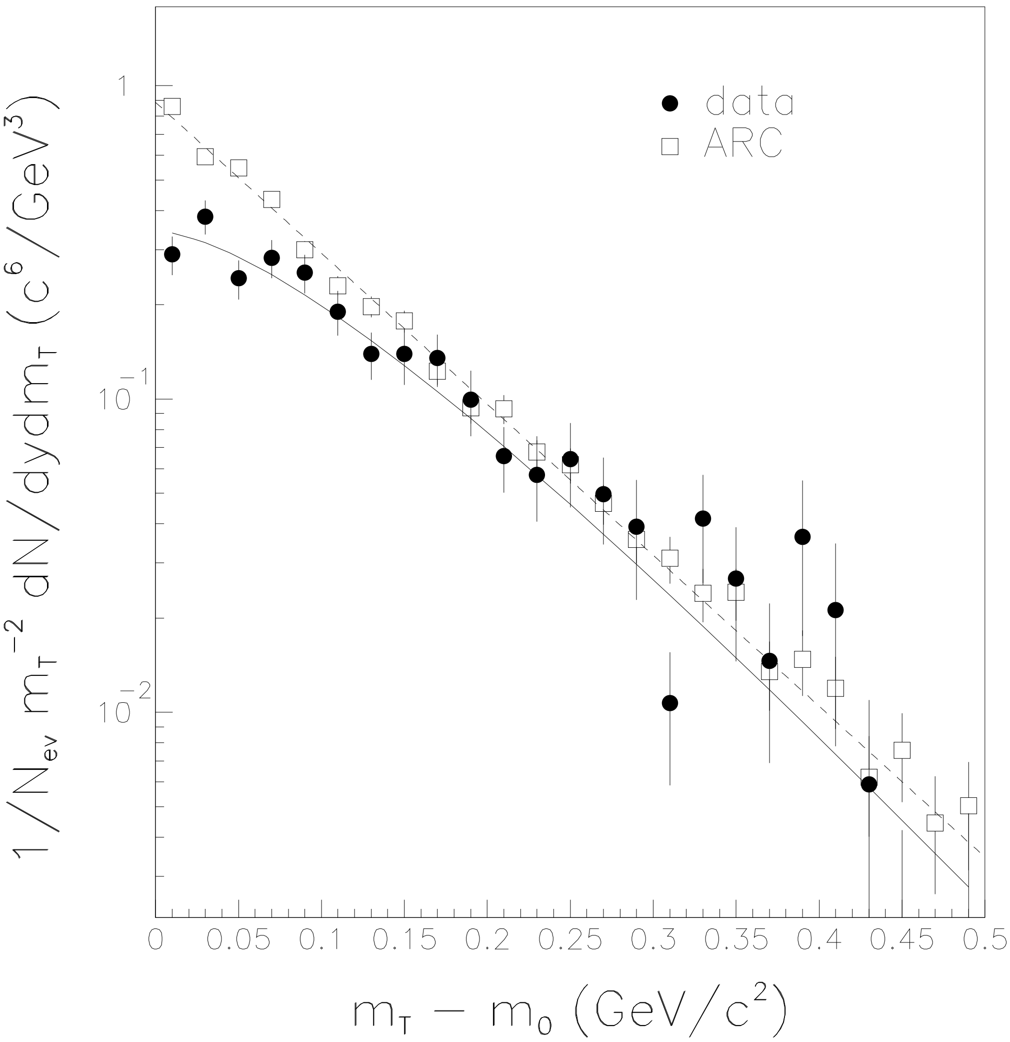

Fig. 4. Mid-rapidity Λ transverse mass spectra.

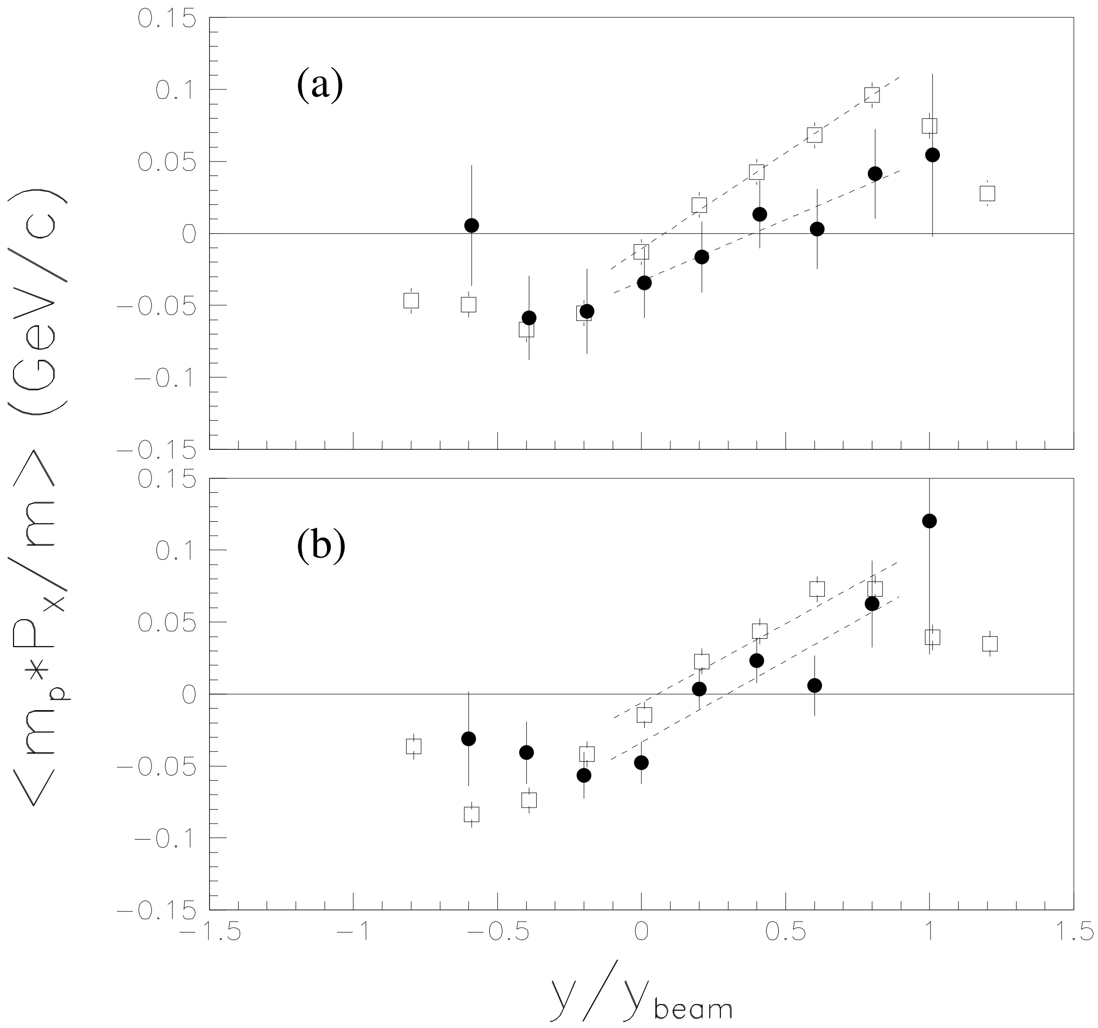

Fig. 5. Average in-plane momentum versus normalized rapidity for (a) data and (b) filtered ARC. Open squares represent protons, closed circles represent Λ's.