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Strange Baryon Production and Projectile Fragmentation in p-A Collisions at the AGS

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Abstract. Experiment E910 has studied proton-nucleus collisions at 12.3 and 17.5 GeV incident energies using a variety of targets. Centrality selection is provided via "grey" track multiplicity which can be statistically related to ν, the number of scatterings of the proton in the target nucleus. Previously published sermi-inclusive measurements of Λ production are discussed and preliminary measurements of "leading" Λ production in 17.5 GeV p-Au collisions are presented as a function of ν. The data indicate the the probability for the projectile to fragment into a strange baryon increases significantly with increasing $\nu$for $\nu \leq 3$ an extrapolation of the E910 data to nucleus-nucleus collisions can reproduce most of the enhancement in Λ production observed in Pb-Pb collisions at 40, 80, and 160 A $\cdot$ GeV. Preliminary measurements of Ξ^- production in 17.5 Gev p-Au collisions show a rapid in yield with increasing ν. The data are dicussed in the context of the Van Hove fragmentation model. Preliminary proton and pion spectra are presented for 12.3 GeV p-Be collisions. The data show a rapid degradation of outgoing proton momenta with increasing N_{grey} while only modest changes are observed in the pion fragmentation spectra.

Keywords: proton-nucleus, baryon, strange, fragmentation
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1. Introduction

It takes no special insight to realize that baryons play a crucial role in the dynamics of heavy ion collisions, particularly at AGS and SPS energies. The baryons are present in the initial state and the initial baryon-baryon interactions are responsible for determining the early evolution of a heavy ion collision. At SPS energies in particular, the initial multiple scattering between the baryons in the incident nuclei is thought to be essentially complete before hadron production commences [1] However, it is by no means clear that we understand the mechanisms by which baryons interact well enough to describe this multiple scattering process and thus correctly evaluate the properties of the matter from which particles will be produced. Cascade models [2] potentially provide the ideal tool for evaluating the results of the highly relativistic and non-equilibrium scattering between the incident baryons in nuclear collisions. However, most cascade models are developed from models of proton-proton (p-p) collisions and are primarily calibrated using p-p data. There's no *a priori* reason to expect that the resulting models will correctly describe the off-shell interactions of a baryon after it has interacted for the first time in the opposing nucleus. While we have known for some time that additional scatterings of the incident baryons after the first lead to increased stopping [3], we cannot claim a comprehensive understanding of the nucleon multiple scattering dynamis. This situation does not result from a lack of good ideas [4] but from our inability to perform detailed experimental tests of these ideas.

In principle, proton-nucleus (p-A) collisions provide an ideal "laboratory" for studying the nucleon multiple scattering process. In a heavy nucleus (e.g. Au), the incident nucleon may undergo more than six scatterings at small impact parameters so if the collision impact parameter could be directly measured, the nucleon multiple scattering dynamics could be studied over a large ν range. Unfortunately, there is no way to directly measure the impact parameter of p-A collisions, but it was shown some time ago that the number of so-called "grey" tracks is statistically well-correlated with the the number of scatterings of the nucleon in a nuclear target low-momentum protons knocked out of the nucleus due to the recoil of nucleons struck by the projectile. The measurement of the multiplicity of grey tracks, N_{grey}, event-by-event requires both large acceptance and the ability to identify protons at low momentum over most of this acceptance. Most past measurements using N_{grey} selection were based on visual detectors and thus suffered from poor statistics and limited particle identification capability at high momentum.

The advent of large, TPC-based spectrometers has revolutionized the study of p-A collisions by providing the necessary geometric coverage and extended particle identification capability in electronic detectors capable of recording data at much higher rates than earlier experiments based on bubble or streamer chambers. One experiment utilizing such a detector is experiment 910 at the Brookhaven National Laboratory AGS accelerator facility. E910 studied collisions of 12.5 and 17.5 GeV/c proton beams with Be, Cu, and Au targets [7]. E910 has measured the N_{grey} distributions for the three different targets at 17.5 GeV/c, and, using a variety of possible parameterizations of the relationship between N_{grey} and ν, has extracted an estimate of the average number of scatterings of the projectile nucleon in the different nuclear targets for each N_{grey} bin, $\langle\nu(N_{\mathrm{grey}})\rangle$[7]. In addition to obtaining $\langle\nu(N_{\mathrm{grey}})\rangle$, E910 obtained an estimate of the full probability distribution, $P(\nu; N_{\mathrm{grey}})$, for an incident nucleon to have undergone ν collisions given the measured grey track multiplicity. For experimental observables that vary non-linearly with ν, $\langle\nu(N_{\rm grey})\rangle$ will be inadequate and knowledge of the full $P(\nu; N_{\rm grey})$ distribution will be required.

2. Strange Baryon Production

2.1. Λ Production vs Centrality

An important early result from E910 was the measurement of Λ production in 17.5 GeV/c p-Au collisions as a function of $N_{\rm grey}$[8]. This was the first high-statistics measurement of the centrality dependence of strange particle production in p-A collisions, and it showed clear evidence for a faster than wounded-nucleon or number of participant ($N_{\rm part}$) growth of strange baryon multiplicity in p-A collisions using p-p data extrapolated to 17.5 GeV/c as a benchmark. Since $N_{\rm part}$ measures the number of baryons directly participating in the collision, if the Λ multiplicity grows faster with ν than $N_{\rm part} = \nu + 1$, either additional nucleons must be involved in the collision or the probability for a participating nucleon to emerge as a strange baryon must increase with ν[8]. E910 observed that the excess Λ yield over the $N_{\rm part}$ scaling of p-p data increased proportional to $\frac{1}{2}N_{pp}^{\Lambda}$ up to $\nu = 3$, at which point it approximately saturated. Since this proportionality constant is the average Λ yield per participant in a p-p collision, one possible interpretation of the data proposed by E910 was that the probability for the projectile to emerge from the collision as a Λ increased proportional to ν up to $\nu = 3$ and remained constant for larger ν [8].

This hypothesis has since been tested in a separate E910 analysis that identifies whether a detected Λ is the highest momentum or "leading" baryon observed in the final state. Since the leading baryons are expected to primarily result from fragmentation of the projectile, the leading Λ multiplicity may directly measure the probability that the projectile fragments into a Λ. Because leading neutrons are not detected by E910, cuts on the total longitudinal momentum carried by charged particles were applied to reject charge-exchange events in which a non-leading Λ would be falsely identified as a leading Λ. Preliminary results of this analysis are shown in Fig. 1. The multiplicity of leading Λ's, $N_{\Lambda}^{\rm lead}$, measured by E910 indeed increases proportional to ν with a slope that is consistent with $\frac{1}{2}N_{pp}^{\Lambda}$. Also, the leading Λ yield is observed to saturate near $\nu = 3$ though the statistical errors on the data are not sufficient for the saturation ν value to be determined accurately. Even after the charge-exchange cuts are applied, potential sources of systematic error in the measurement of $N_{\Lambda}^{\rm lead}$ remain. In particular, if the projectile is stopped so thoroughly that it fragments into a baryon with rapidity less than that of the target nucleons, a Λ resulting from target baryon fragmentation might be falsely identified as a leading Λ. However, this source of error is largely canceled by the mis-identification of a leading Λ from a similarly "over-stopped" baryon as a non-leading Λ. To evaluate the combined effects of all such systematic errors, events from the RQMD model [9] were analyzed in the same way as the E910 data. If it is assumed that RQMD does not include a mechanism that increases the probability for the projectile to fragment into a Λ with increasing, ν, then any change in the leading Λ multiplicity with ν would be due to systematic errors in the measurement procedure. The results shown in Fig. 1 indicate a minimal change in $N_{\Lambda}^{\rm lead}$ with increasing ν that is far too small to account for the E910 observation. This comparison suggests that the increased multiplicity of leading Λ's observed by E910 is not dominated by systematic errors. It also indicates that either RQMD does not have a mechanism to increase the leading Λ yield or that any increase is hidden by systematic errors. However, a comparison in Fig. 1 of the RQMD total Λ multiplicities with the E910 results indicates that the E910 Λ multiplicities are larger by an amount consistent with the growth observed in the leading Λ yield. Thus, it appears that RQMD does not include a mechanism that increases $N_{\Lambda}^{\rm lead}$ with increasing ν.

2.2. Implications for Nucleus-Nucleus Collisions

The E910 observations have profound consequences for the interpretation of strangeness enhancement in nucleus-nucleus collisions. In p-A collisions, only one nucleon scatters multiple times so the effect of an increased probability to fragment into a strange baryon is modest – a 50% increase in the total Λ yield for $\nu = 3$. However, in nucleus-nucleus collisions, the strange baryon yields may be enhanced substantially – naively by a factor of 3 in central collisions [8] if every nucleon were to undergo at least three scatterings. A detailed analysis applying the observed increase in the Λ fragmentation probability to nucleus-nucleus collisions will be shortly forthcoming from E910. As an example, Fig. 2 shows a comparison of NA49 measured net Λ ($\Lambda - \bar{\Lambda}$) multiplicities in central Pb-Pb collisions at three different energies [10] to a calculation applying the increased Λ fragmentation probability for multiply scattered baryons. Also shown are results of an $N_{\rm part}$ scaling of p-p data for the three energies. The figure clearly shows that the effect observed by E910 can account for nearly all of the observed enhancement in singly strange baryon production in Pb-Pb collisions over a $N_{\rm part}$ scaling of p-p data.

2.3. Ξ^- production vs centrality

Since the apparent enhancement of strange baryon production in nucleus-nucleus collisions increases with the strangeness content of the baryon [12], a natural question to ask is whether similar behavior is observed in p-A collisions. Figure 3 shows preliminary dn/dy distributions from E910 for Ξ^- production in 17.5 GeV p-Au collisions. The Ξ^- yield increases rapidly and the peak of the rapidity distribution shifts backwards with increasing $N_{\rm grey}$. The total Ξ^- multiplicity obtained by integrating dn/dy over the measured rapidity range is plotted in Fig. 4 along with estimated total yields obtained from fitting the dn/dy distributions to gamma distributions. The two methods give consistent results and show a Ξ^- yield that increases rapidly with ν up to $\nu = 3$ or 4. Since there are no viable measurements of inclusive Ξ^- production in p-p collisions at AGS energies, the best we can do to obtain a benchmark for the observed Ξ^- yields is extrapolate the measurements to

$\nu = 1$. This is difficult because the Ξ^- yield measured by E910 varies so rapidly with ν at small ν. However, we can confidently say that the Ξ^- yield increases by at least a factor of 4 between $\nu = 1$ and $\nu = 4$ based on a linear extrapolation of the measured p-Au yield for $\nu < 3$. Because the increase in yield is observed to extend in rapidity well above $y_N N$ for smaller ν values (where most of the increase takes place) we have reason to attribute much of the increased Ξ^- production to the fragmentation of the projectile. Then, a naive extrapolation of the E910 Ξ^- data to nucleus-nucleus collisions would predict a factor of 8 enhancement in Ξ^- production, consistent with WA97 observations. A more precise extrapolation of the E910 Ξ^- data to nucleus-nucleus collisions would require better knowledge of the $\nu = 1$ Ξ^- yield.

3. Interpretation of Strange Baryon Enhancement

The most urgent question implicitly posed by the E910 data is "what is the mechanism that enhances strange baryon yields in p-A collisions when the projectile undergoes multiple collisions in the target nucleus ?" Since there had been no compelling evidence until recently for strangeness enhancement in proton-nucleus collisions [11, 12] little attention has been paid to mechanisms that might produce the effect observed by E910. However, Capella *et al* have pointed out the break-up of the di-quark in string models could produce an increased yield of strange baryons by providing an additional opportunity to pick up a strange quark from the sea [13]. A similar result is implied by the much older Van Hove proton fragmentation model [15, 16]. In this model, the flavor of the baryon resulting from proton fragmentation in a hadron-proton (h-p) collision is determined by the number of valence quarks stripped from the proton during the collision and the flavors of the replacement quarks in the final state baryon. In the Van Hove fragmentation model, the suppressed yield of multiply strange baryons in h-p collisions is due to small probabilities for removing two or three quarks from the proton. However, it is reasonable to expect that when the proton undergoes multiple interactions, the probabilities for multiple quark stripping increase [14]. The model assumes that the flavors of the acquired replacement quarks are determined stochastically. Then, if we ignore the charge content of the fragmentation products of the proton and evaluate the probability for obtaining baryons of different strangeness content in terms of the number of stripped quarks (N_{s}) and a strange quark pick-up probability (γ), we obtain the results in Table 1. The table demonstrates an important consequence of the Van Hove fragmentation model: if the probability for stripping all three quarks from the projectile baryon becomes comparable to one in p-A collisions, then the yield of singly strange baryons from projectile fragmentation should be increased by approximately a factor of three (3) over p-p collisions as long as γ is $<< 1$ and independent of ν. Under these assumptions, the Van Hove model would be consistent with the increase in $N_\Lambda^{\mathrm{lead}}$ observed by E910 and also could explain the observed saturation of $N_\Lambda^{\mathrm{lead}}$ with increasing ν. If N_{s} varies approximately linearly with ν, then the Van Hove model could qualitatively explain all the features of the E910 Λ data.

To better test the validity of the Van Hove model, we have adopted a formalism [17] that describes nucleon-nucleon scattering at the quark level and can be used to calculate quark stripping probabilities in p-A collisions for different values of ν. This calculation relies on one free parameter that specifies the RMS of an assumed Gaussian distribution of quark locations relative to the center of the proton. This parameter together with the observed nucleon-nucleon inelastic cross-section constrains the quark-quark scattering cross-section required by the model. To predict strange baryon yields we must obtain an estimate for γ. At AGS energies $B\bar{B}$ processes are strongly suppressed so the yield of $S = 1$ baryons should provide a good estimate for γ. The p-p $\Lambda + \Sigma^0$ multiplicity extrapolated to 17.5 GeV/c has been estimated to be $N_\Lambda^{pp} = 0.054 \pm 0.002$ [8]. The yield from each fragmenting proton would then be 0.027 ± 0.001. Using measurements of various exclusive channels [18] we estimate that the $\Sigma^+ + \Sigma^-$ yield is between 35% and 50% of the $\Lambda + \Sigma^0$ yield. The resulting values for γ lie in the range $0.037 < \gamma < 0.041$. The resulting calculated Ξ^- yields using the Van Hove model and the constituent quark formalism are shown in Fig. 4. The calculation reproduces the qualitative variation of the measured Ξ^- yields with ν but under-predicts the data for $\nu < 3$ and over-predicts the data for $\nu > 4$. However, the main point here is not whether the model precisely describes the data. Instead, we simply wish to evaluate whether the basic idea of quark stripping and replacement could possibly account for the magnitude of the Ξ^- enhancement observed by E910 using a reasonable model for quark stripping probabilities. The comparison in Fig. 4 suggests that it can but does not prove that such a mechanism is actually responsible for the observed enhancement. The attractiveness and a serious shortcoming of the Van Hove fragmentation model is that it has no explicit dynamical content. Any mechanism that causes valence quarks to be removed during the multiple collision process could possibly produce a large enhancement in strange baryon production. We observe that to obtain calculated Ξ^- yields that are comparable to the E910 measurements, the probability for having all three valence quarks stripped from the projectile must be close to one. If only two quarks are stripped, the calculated yields will be too small by a factor of 3. For curiosities sake, we have applied the above described calculation to Pb-Pb collisions at 160 GeV/c using $\gamma = 0.1$. Figure 5 shows the result of calculating the enhancement in Ξ^- and Ω^- yields per participant over the corresponding quantity in p-Be collisions. Enhancements comparable to those observed by WA97 [12] are obtained for central collisions and the rapid onset and subsequent saturation of the enhancement with increasing $N_{\rm part}$ observed in the data is also reproduced. Although the agreement of the model with the data does not necessarily prove that the Van Hove fragmentation picture is correct, we accept it as a reasonable hypothesis that deserves further examination and testing.

4. Projectile Fragmentation

The stripping of valence quarks from the projectile baryon in p-A collisions suggested by the above analysis should have clearly observable effects on the fragmentation products of the projectile baryon. In particular, the momentum of the incident baryon will be rapidly degraded as its valence quarks are stripped away and replaced by quarks from the sea. This behavior is actually observed in the data. Figure 6 shows spectra for proton production in the projectile fragmentation region in 12 GeV/c p-Be collisions as a function of N_{grey}. Because of the small number of collisions that the projectile has in the Be nucleus, the N_{grey} bins shown essentially interpolate between collisions with mostly $\nu = 1$ ($N_{\text{grey}} = 0$) and collisions with mostly $\nu = 2$ ($N_{\text{grey}} \geq 3$). Thus, the p-Be data provides a very clean tool for studying the effects of a second collision on the momentum distribution of the fragmentation product baryons. The spectra in Fig. 6 are plotted as a function of $x =\equiv p_z/p_{\text{beam}}$ using momenta measured in the lab frame. We use this variable instead of x_F because it does not suffer from the ambiguity in the definition of center-of-mass frame in p-A collisions. However for $x > 0.3$ the two x variables are approximately the same. The data show that the second collision of the projectile results in a strong suppression of forward-going baryons. For comparison, we show in Fig. 7 π^- and π^+ x distributions from the same data set. The π^- spectra show little change with N_{grey} except in the region $x < 0.1$ where target fragmentation will contribute. The π^+ spectra show a modest decrease in yield at large x that is much smaller than reduction in yield observed for the protons at large x. The difference in behavior between the π^- and π^+ spectra is striking and worthy of a separate investigation. The comparison between the proton and pion spectra, however, shows that the proton momenta are much more rapidly degraded by second and subsequent scatterings in the Be target than the pion momenta. While there may be other possible explanations for the behavior of the projectile fragmentation spectra, they are qualitatively consistent with the behavior expected in a quark-stripping picture. A analysis of leading particle distributions using a a related picture [19] also explains the strong degradation of the leading baryon in terms of the breakup of the projectile due to the scatterin of its constituent quarks. We note that the p-Be proton x distributions are qualitatively consistent with the RQMD model which has explicitly implemented the multiple quark stripping mechanism [20] though the degradation observed in the E910 daata sets in more rapidly than predicted by RQMD.

5. Conclusions

The ability to study proton-nucleus collisions with high statistics and with control over collision centrality has opened up a new frontier in the study of nuclear interactions. In particular, such measurements can clearly shed new light on the dynamics of the projectile multiple scattering process. In addition to the E910 data on strange baryon production already published [8] or presented in preliminary form in this paper that show large increases in strange baryon production resulting from the multiple scattering of the projectile, measurements are now becoming available [21, 22] from NA49 that provide consistent conclusions. Namely, that the production of strange baryons is enhanced already in proton-nucleus collisions and that if the enhancement is attributed to the multiple scattering of the projectile, the extrapolation to nucleus-nucleus collisions can account for much of the observed enhancement in strange baryon production. These observations, of course, raise new questions about the origin of the enhancement and about our understanding of the multiple scattering physics. We have investigated one possible interpretation of the E910 strange baryon results in the context of the Van Hove fragmentation model. While we have used this particular model, there are many other similar approaches appliead in the literature. It is by no means clear that a quark-based model provides the correct explanation for the increase in strange baryon yields due to the multiple scattering of the projectile. However, the Van Hove model in particular is consistent with the data and this consistency raises some interesting questions that deserve consideration. Namely, how does this picture relate to the baryon junction model? Does the fact that the data require large probilities for having three stripped quarks mean that the likelihood for extracting the baryon junction can become large in central p-A collisions? Does it even make sense to talk about the junction at AGS energies given the large amount of energy required to excite the junction? Or does the multiple scattering of the projectile shift the effective center-of-mass to the nucleus frame making the full projectile energy available thus making junction excitation more reasonable? If the quark stripping picture is valid, how do we think about central nucleus-nucleus collisions in which the initial nucleon scattering process could produce a large density of baryons stripped of their initial valence quarks? The answers to these and related questions could provide significant insight into the physics of heavy ion collisions at fixed-target and collider energies.

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N_s	$P(s=0)$	$P(s=1)$	$P(s=2)$	$P(s=3)$
1	$(1-\gamma)$	γ	0	0
2	$(1-\gamma)^2$	$2\gamma(1-\gamma)$	γ^2	0
3	$(1-\gamma)^3$	$3\gamma(1-\gamma)^2$	$3\gamma^2(1-\gamma)$	γ^3

Table 1. Probabilities calculated in the Van Hove fragmentation model for obtaining baryons with strangeness content 0, 1, 2 and 3 from the fragmentation of the projectile baryon as a function of N_s, the number of stripped valence quarks (see text foir details). γ is the probability that a single valence quark is replaced by a strange quark.

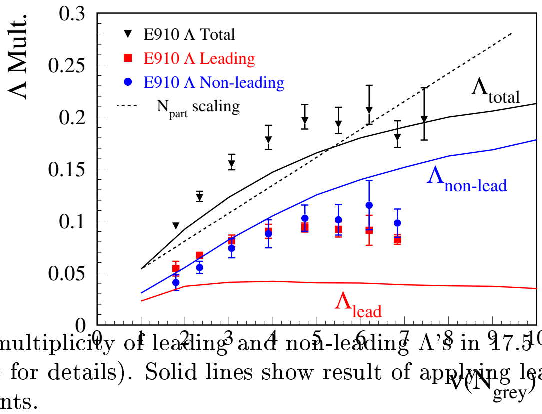

Fig. 1. The multiplicity of leading and non-leading Λ's in 17.5 GeV p-Au collisions (see text for details). Solid lines show result of applying leading Λ analysis to RQMD events.

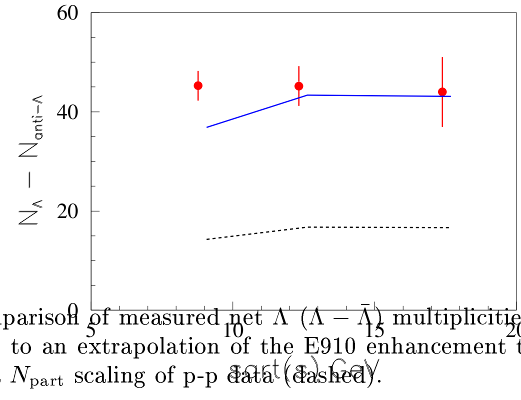

Fig. 2. Comparison of measured net Λ ($\Lambda - \bar{\Lambda}$) multiplicities in central Pb-Pb collisions [10] to an extrapolation of the E910 enhancement to Pb-Pb collisions (solid), and a N_{part} scaling of p-p data (dashed).

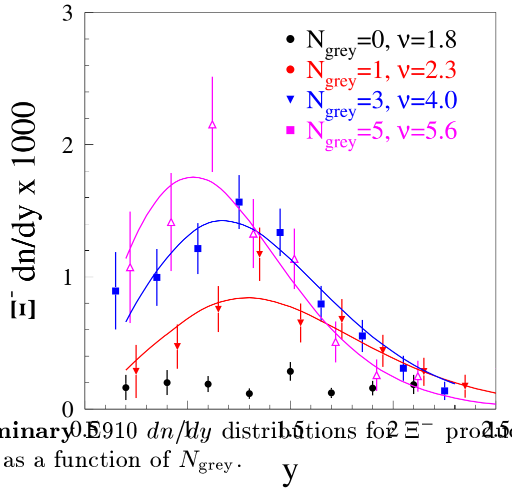

Fig. 3. Preliminary E910 dn/dy distributions for Ξ^- production in 17.5 GeV p-Au collisions as a function of $N_{\rm grey}$.

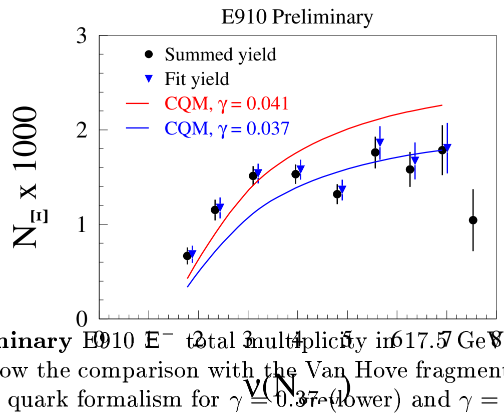

Fig. 4. Preliminary E910 Ξ^- total multiplicity in 17.5 GeV p-Au collisions vs $N_{\rm grey}$. Lines show the comparison with the Van Hove fragmentation model using the constituent quark formalism for $\gamma = 0.037$ (lower) and $\gamma = 0.041$ (upper).

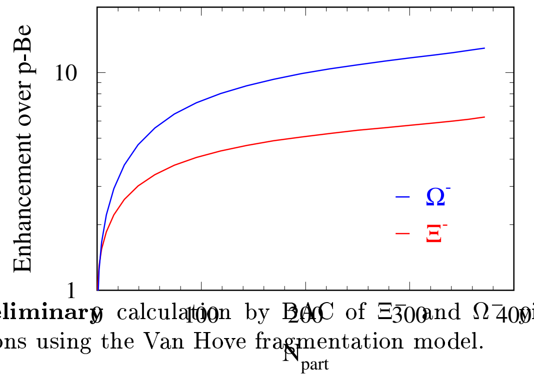

Fig. 5. Preliminary calculation by BAC of Ξ^- and Ω^- yields in 160 GeV Pb-Pb collisions using the Van Hove fragmentation model.

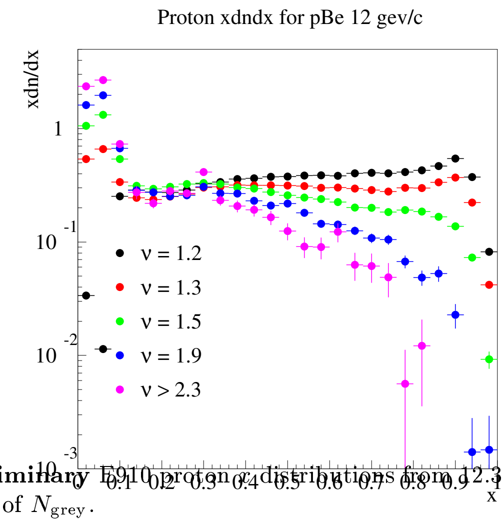

Fig. 6. Preliminary E910 proton x distributions from 12.3 GeV p-Be collisions as a function of N_{grey}.

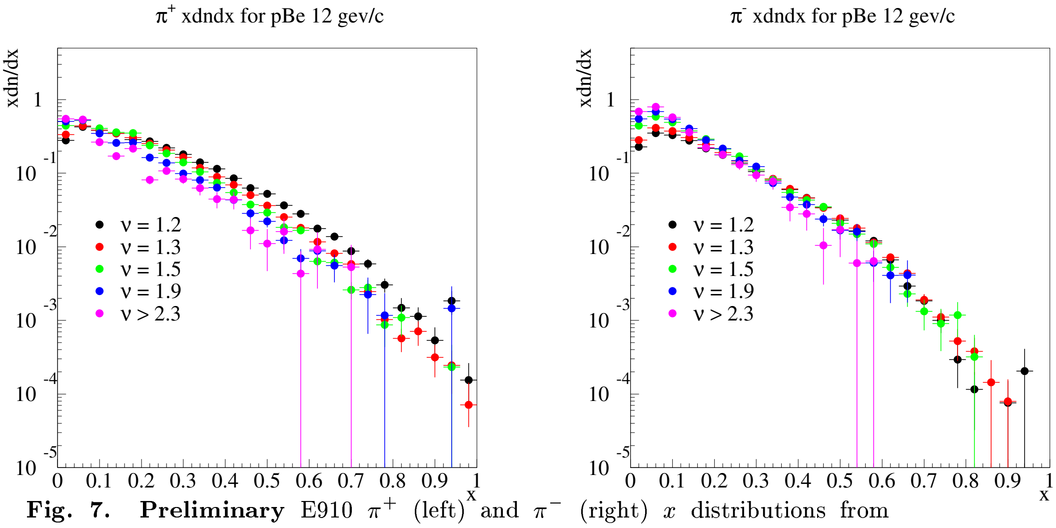

Fig. 7. Preliminary E910 π^+ (left) and π^- (right) x distributions from 12.3 GeV p-Be collisions as a function of $N_{\rm grey}$.