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Intranuclear Cascade Effects in Neutrino-Neon Interactions at the Tevatron

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Separation of Intranuclear Cascade Effects in Neutrino-Neon Interactions

SUMMARY

We have developed a method to separate ν-nucleon interactions from interactions with intranuclear cascade in $\nu - Ne$ scattering at a mean neutrino energy of 150 GeV. It was found that the multiplicity of charged particles in the forward direction is the same for events with and without cascade over a large W^2 region. In the backward direction the cascade events have a charged multiplicity higher than that for non-cascade events by about 2.3 units over a large W^2 range.

1 Introduction

The particle production have been widely studied in Deep Inelastic Scattering experiments to investigate the nature of hadron formation and the space-time development of the hadronization process. The interaction of hadrons immediately after their generation in breaking off the string differs from ordinary hadron-nucleon interactions as the produced hadrons consisting of valence quarks do not have the full system of sea quarks, antiquarks and gluons and have therefore a reduced probability for interaction [1]–[4]. The comparison of hadron production on nuclear targets with production on free nucleons provides important information about the space-time development of the hadronic states as well as the role of nuclear effects. The potentially interesting idea is that one might, instead of comparing interactions on different targets. use data from one target. We use such approach and compare the multiplicity and rapidity distributions for the neutrino-nucleon (ν-nucleus collision without cascade) and neutrino-nucleus interaction with cascade. Even more, interactions on protons and neutrons can be extracted and studied separately [11]. Several methods to classify (anti)neutrino nucleus interactions had been proposed: by the presence or absence of grey protons with momentum below 600 MeV/c [5] or by using the final state electric charge [6]. In this paper we examine criteria such as the mass of the target and the balance of longitudinal momenta of particles in the hadron center of mass system and consider correlation between them. The paper is divided as follows: Sect. II contains brief information about the data sample and Monte Carlo model, Sect. III describes the method to separate two data samples. Data on the multiplicity of particles in νNe interactions with and without intranuclear cascade are presented in Sect. IV and compared with the corresponding quantities obtained from other lepton experiments. Sect. V deals with rapidity distributions. Our conclusions are summarized in Sect. VI.

2 Experimental procedure

2.1 Experiment and Data Sample

The data came from Fermilab experiment E632 using the 15 foot Bubble Chamber as both target and detector. The Bubble Chamber was exposed to a wide-band beam of (anti)neutrinos originated from the decays of charged mesons produced by 800 GeV/c protons from the Tevatron. The average energy of the neutrino interactions was 150 GeV (110 GeV for antineutrino). The chamber was filled with a neon-hydrogen mixture containing 75% or 63% molar neon in two data runs (the target densities are 0.71 g/cm^3 and 0.54 g/cm^3, respectively). The chamber was equipped with the External Muon Identifier (EMI). Further experimental details are given in Ref.[7]. This study is based on charged current neutrino scattering:

$$\nu + N \rightarrow \mu^- + X, X \rightarrow hadrons$$

For each interaction we require a non-interacting leaving track with momentum $p > 5$ GeV/c, which is identified as a muon by the EMI. Range information was used to identify protons up to 1 GeV/c. Thus charged secondaries with momenta $p_{lab} > 1$ GeV/c were taken as pions. (We estimate that a number of protons and kaons among the positive particles with $p_{lab} > 1$ GeV/c is at most 20%)

In intranuclear cascade produced particles knock out cascade protons and neutrons of the residual nucleus and leave the nucleus in an excited state. This excitation energy is the basis

for nuclear evaporation and fragmentation. Therefore all identified protons with momentum $p < 300$ MeV/c were considered as evaporated and excluded from the analysis. According to MC simulations, in addition to evaporated protons, this cut remove 20÷25% of identified knocked out cascade protons. In Sect. IV and V we examine how this cut affects our final results.

The total number of ν Ne CC events in our sample is 5567.

The incident neutrino energy is equal to a sum of the muon and hadronic energies. The measured hadronic energy is corrected for missing neutrals by applying a suitable factor based on transverse momentum balance, so-called Bonn method [8]. The E^ν is calculated for each event according to the following formula:

$$E^\nu = p_{\|}^{\mu} + \sum p_{\|}^{h} \cdot [1 + \frac{|\vec{p}_{\perp}^{\,\mu} + \vec{p}_{\perp}^{\,h}|}{\sum |\vec{p}_{\perp}^{\,h}|}]$$

The average correction factor (the bracketed expression) is equal to 1.4. The events with correction factor more then 2 (9% of data sample) are excluded from analysis. The root mean squared (RMS) of error in E_ν determination for Monte-Carlo events is about 14%. Only events with neutrino energy 10 GeV $< E_\nu <$ 700 GeV are accepted for analysis. The events were required to contain in addition to the muon at least one charged track. Generally events with low multiplicities have big value of Bonn correction. Corrections for the effects of the energy determination procedure have been applied to the multiplicity distributions. On the whole they are relatively small: does not exceed 10% for the mean multiplicities and are not more than 30% for the smallest multiplicities. No corrections were made for the prong-dependent scanning inefficiencies.

In order to select DIS events, the following kinematic cuts are applied: $Q^2 > 1$ (GeV/c)^2 and $W > 2$ GeV, where $Q^2 = -q^2$ is the four-momentum transfer squared and W is the energy of particles in the hadron center of mass frame. These cuts leave 4476 νNe CC events.

Analysis of hadron production is made in the hadron center of mass system, which is determined in the following way:

$$\vec{p}_{\perp}^{\,h} = -\vec{p}_{\perp}^{\,\mu};\ p_{\|}^{h} = \sum p_{\|}^{h\ (corr)};\ W^2 = M_N^2 + 2M_N(E_\nu - E_\mu) - Q^2$$

Hadron properties in the hadron system rest frame are measured by the longitudinal variables Feynman x_F and rapidity y:

$$x_F = \frac{2p_{\|}^*}{W};\quad y^* = \frac{1}{2}\ln\frac{E^* + p_{\|}^*}{E^* - p_{\|}^*}$$

where E^* and $p_{\|}^*$ are the energy and the longitudinal (respectively to the current) momentum in the hadron center of mass system.

It should be noted that in the case of a neon-target the final state is affected by the intranuclear rescattering, which provides new particles and changes the direction of particles. But the overall hadron center of mass system is scarcely affected by nuclear cascade owing to the fact that it is defined using the neutrino and muon parameters.

2.2 Monte Carlo Model

Monte Carlo calculations are used to compare the experimental results with the theoretical predictions and to take a proper account of experimental inefficiencies. Ingredients in this

Monte Carlo calculation include the actual neutrino beam energy spectrum, adjusted for the cross-section, as well as experimental resolution and efficiencies of track measurements in the bubble chamber. The LEPTO 6.3 [9] program has been used to generate the energy of particles in the hadron center of mass sytem W, and the flavor of the struck quark. Only processes in the leading order parton level $W^{\pm}q \rightarrow q$ are generated. Unfortunately, there are only a few models incorporating lepton-nucleus interactions and rescattering occurring between produced particles and target spectators. For our purpose we choose the VENUS 4.10 program [10], which is used to simulate fragmentation, decays and rescattering processes. Nuclear evaporation and fragmentation is not included in this model. The VENUS program uses the cluster model for secondary interactions. Several approaches were developed to treat the rescattering process. In widely applied molecular dynamics models, the trajectories of all produced particles are followed and whenever two particles come close, an interaction of the type $h_1 + h_2 \rightarrow R_1 + R_2 ...$ occurs, where several resonances are produced, which may interact again. If such a model includes formation zone concept, the formation time τ is defined for each secondary from an exponential distribution with an average formation time τ_s [3]. But in high energy collisions an approach of independent binary interaction is unplausible, and in VENUS the cluster model was applied: when two or more objects are coming close to each other, they form one cluster rather than several resonances. Space-time evolution concerning final state interactions is introduced in VENUS by the reaction time. It is the time τ_r in the comoving frame before which the string as a whole is not allowed to interact at all. The default value of τ_r is fixed to 1.5 fm/c. Another rescattering parameters for lepton-nucleus interactions are "meson and baryon radii", which are related to interaction cross section.

3 Separation of ν–nucleon and intranuclear cascade Samples

An interaction of a neutrino with a neon nucleus may be considered as having two stages. First, the neutrino interacts with a single nucleon. Secondly, since the particles produced from this elementary process have partly to move through the nucleus, we have rescattering of produced particles with the spectators of the target nucleus, causing an intranuclear cascade. However in the case of interactions with a peripheral nucleon, the produced particles may leave the nucleus without any interaction. Such events are similar to νp or νn interactions apart from the fact that the nucleon has momentum due to the fermi motion of nucleons in the nucleus. It will be shown that these simple ν-nucleon interactions can be separated by a number of criteria, such as the mass of the target and the sum of the longitudinal momenta in the hadron system rest frame. Let us consider these criteria and their correlation in detail.

- The mass of the target

  From the conservation of energy and momentum and taking into account that $E^{\nu} = p^{\nu} = \sum p^i_{\|}$, we have:

  $$M_t = \sum E^i - E^{\nu} = \sum (E^i - p^i_{\|})$$

  The experimental distribution of M_t, normalized to unity, is shown in Fig.1a. In the case of the simple ν-nucleon interaction $M_t = M_{nucleon}$, but due to missed particles and errors in momenta of tracks, the distribution of M_t is smeared out. This smearing was simulated for events, generated by Monte Carlo, and results are shown in solid line on Fig.1a. The

dotted curve represents the fraction of Monte Carlo events without cascade. One can see that in the absence of intranuclear cascade M_t lies mainly in the region [0,1] GeV/c^2. Any additional interaction of the produced particles with a nucleon adds to M_t, but because of this smearing effect, the region $M_t < M_{nucleon}$ is partly contaminated by events with cascade. Our estimate using Monte Carlo is that in the region $M_t < M_{nucleon}$ there are no more than 30% of events with cascade and about 15÷20% of all ν–nucleon events are outside of this region.

- The sum of the longitudinal momenta in the hadron system rest frame

  In the hadron center of mass system the particles produced in ν-nucleon interaction have the total momentum equal to zero. Fig.1b illustrates the $P_{\|}^{*} = \sum p_{\|}^{*}$ distribution. By the same reasoning as for M_t, the distribution of $P_{\|}^{*}$ is smeared. Moreover, according to the Monte-Carlo (dotted curve for events without cascade), this distribution is shifted to 0.7 GeV/c because of misidentification and loss of particles. In case of intranuclear cascade particles produced in reinteractions move in the negative direction in the hadron center of mass frame and hence the sum of the longitudinal momenta $P_{\|}^{*}$ for such events is also negative.

- The total charge of the hadron system

  The electric charge of the hadron system, except for the first muon, is also can be used for separation of events with intranuclear cascade. If the neutrino interaction took place on a proton, the total charge of the hadron system $Q_{tot} = 2$, if on a neutron, then $Q_{tot} = 1$. Any additional interaction in cascade with proton increases the value of Q_{tot} by one, while an interaction with a neutron does not change it. A difficulty of this method is that it relies on the charge determination, meanwhile in our data sample 40% of events have at least one track with $\Delta p/p > 0.7$ and the determination of the charge for such a track cannot be reliable. The mass of the target and the sum of the longitudinal momenta are not so affected by tracks with large $\Delta p/p$.

The correlation between these criteria is pictured on Fig.1c. The dotted line corresponds to $M_t = 0.9$ GeV/c^2. We notice that starting from $P_{\|}^{*} > -1$ most of events have $M_t < 0.9$ GeV/c^2.

Using these parameters we have separated ν-nucleon events from νNe events with intranuclear cascade. According to Monte Carlo the best separation is obtained for the cut

$$M_t < 0.9\, GeV/c^2$$

and the combination of cuts on M_t and $P_{\|}^{*}$ does not improve the separation of two samples. Hence, all events with $M_t < 0.9$ GeV/c^2 are assumed to be "pure" ν-nucleon interactions, and the rest are events with intranuclear cascade.

This selection gives 2188 (49% from all events) ν-nucleon and 2288 (51%) of events with cascade. Taking into account admixed cascade events and ν-nucleon events which do not satisfy this cut, the corrected fraction of "pure" ν-nucleon is about 40% of all events. In our Monte Carlo simulation this quantity is varied from 28% to 44% depending on cascade parameters. Default values in Venus model overestimate cascade, so we tried to increase τ_r and reduce the "meson and barion radii". The best agreement with the experimental data was achieved for $\tau_r = 2.5 fm/c$ and default values of radii. The fraction of "pure" ν-nucleon in this case is equal to 37% (44% events have $M_t < 0.9$ GeV/c^2).

4 Charged hadron multiplicities

4.1 Average multiplicities

The average charged-particle multiplicities for charged-current neutrino interactions have been determined for both "pure" and cascade events and studied as a function of W^2.

The smearing of W due to the uncertainty in our estimate of the neutrino energy was studied by the Monte Carlo method for the two kinds of events separately. The mean values of W is 8.9 ± 0.1 GeV for ν-nucleon events and 8.8 ± 0.1 GeV for events with cascade. The average uncertainty in the determination of W due to neutrino energy uncertainty is estimated to be 15% (17%) for ν-nucleon (cascade) events. Effects arising from secondary interactions do not change the value of reconstructed W within the limits of experimental errors.

The average charged-particle multiplicities for the all νNe events and for the isolated νnucleon events are plotted as a function of $\log W^2$ in Fig.2. Until $W^2 \approx 700 GeV^2$ they follow straight lines almost parallel to each other. The lines are fitted in form $\langle n^{\pm} \rangle = A + B \cdot \ln W^2$ (solid lines) and parameters of the fit are given in Table 1 along with the results of previous lepton-hadron experiments. The dashed and the dotted lines on Fig.2 are the linear fit to the νn and νp data from Ref.[11], and the dash-dotted line is the fit to the νH data from Ref.[12]. They have almost the same slope but lie higher than separated νnucleon data. The difference between the mean multiplicity $\langle n^{\pm} \rangle$ obtained in Neon and in hydrogen is a measure of the multiplicity of charged particles produced in secondary interactions. In Ref.[11] it was shown that the difference between deuterium and hydrogen target varies between 0.3 and 0.5. For our two data samples using the fit from [12], the difference $\langle n^{\pm} \rangle_{\nu Ne} - \langle n^{\pm} \rangle_{\nu p}$ is between 0.5 and 1.

Table 1. Parameters of the linear fit $\langle n^{\pm} \rangle = A + B \cdot \ln W^2$.

Reaction	Intercept A	Slope B	W^2 range GeV^2	target	
νNe	1.94 ± 0.16	1.36 ± 0.04	4-900	Ne	this experiment
$\nu nucl$	-0.02 ± 0.15	1.30 ± 0.04	4-900	Ne	this experiment
νNe	0.54 ± 0.07	1.45 ± 0.02	4-900	Ne	Monte Carlo
$\nu nucl$	-0.26 ± 0.08	1.42 ± 0.02	4-900	Ne	Monte Carlo
νn	-0.20 ± 0.07	1.42 ± 0.03	4-140	D	Fermilab, [11]
νp	0.05 ± 0.08	1.42 ± 0.03	4-140	D	Fermilab, [11]
νp	0.37 ± 0.02	1.33 ± 0.02	4-350	H	BEBC, [12]
νp		1.35 ± 0.15	4-100	H	Fermilab, [13]
$\bar{\nu} p$	0.02 ± 0.20	1.28 ± 0.08	6-140	D	BEBC, [14]
$\bar{\nu} n$	0.80 ± 0.09	0.95 ± 0.04	2-140	D	BEBC, [14]
μp	-0.30 ± 0.16	1.22 ± 0.03	16-400	H	NA9, EMC [15]

4.2 Comparison of Forward and Backward Multiplicities for events with and without cascade

The multiplicities of charged particles in the forward ($x_F > 0$) and backward ($x_F < 0$) hemispheres have been studied separately. Fig.3 shows the mean multiplicities $\langle n^{\pm} \rangle_{F,B}$ as functions of W^2 for the complete sample of νNe events (Fig.3a), for separated parts of cascade (Fig.3b) and ν-nucleon (Fig.3c) events. As in the case of the overall multiplicities, each one satisfies a

linear approximation in the form $\langle n^{\pm}\rangle_{F,B} = A + B\cdot\ln W^2$. For the complete event sample, $\langle n^{\pm}\rangle_F$ and $\langle n^{\pm}\rangle_B$ lie almost on one line, however for the separated samples they diverge considerably. In cascade events, the average forward multiplicity $\langle n^{\pm}\rangle_F$ is smaller than that backward, $\langle n^{\pm}\rangle_B$. On the other hand for "pure" ν-nucleon interactions the situation is the opposite, the average forward multiplicity exceeds the average backward multiplicity in the whole range of W^2 and shows stronger increase with energy. The solid lines are approximations of deuterium-target data [11], and agree well with our results.

To investigate the effect of intranuclear rescattering on the multiplicity as a function of W^2, we subtracted $\langle n^{\pm}\rangle_{F,B}$ for ν-nucleon interactions from that of events with a cascade. It can be seen in Fig.4a that in the forward hemisphere the multiplicities at all W^2 are almost the same for events with and without cascade: $\langle n^{\pm}\rangle_F^{casc} - \langle n^{\pm}\rangle_F^{nucl} = -0.04 \pm 0.04$. But in the backward hemisphere the multiplicity is higher by 2.34 ± 0.06 units over a large region of W^2. The corresponding difference between the negative hadron multiplicities $\langle n^-\rangle_{F,B}^{casc} - \langle n^-\rangle_{F,B}^{nucl}$ has the same behavior: close to zero in the forward hemisphere and has an excess in 0.63 ± 0.03 units in the backward hemisphere. If we do not exclude protons with $p_{lab} < 300$ MeV/c from our experimental data sample, the difference in the backward hemisphere becomes 2.56 ± 0.06.

In the separation of the forward and backward jets we arbitrarily used selection $x_F > 0$ and $x_F < 0$, meanwhile the region of small x_F is contaminated by the products of resonance decays: resonances from the diquark region may decay into particles with small longitudinal momentum $p_{\|}^*$ and would have the value of x_F like those produced in the central part of the string. To eliminate complications due to resonances, we show the difference in multiplicities for events with and without cascade with the central region ($|x_F| < 0.05$) excluded in Fig.4b. One can see that they are very similar to those on Fig.4a with the difference in the forward hemisphere close to zero and the difference in the backward hemisphere ranges from 2.0 to 2.8 units over the all W^2 region. Areas between the lines are Monte Carlo predictions, which slightly underestimate cascade in the backward hemisphere.

5 Rapidity distributions for events with and without cascade

Fig.5a shows normalized rapidity distributions for ν-nucleon and cascade events. The distributions are normalized to the total number of events for each data sample, so that the ordinate at any point represents the average multiplicity of produced particles per an interval of rapidity. It may be noted that for the values of rapidity $y > 1$ the both distributions match almost exactly. For negative rapidity, in the target-fragmentation region, cascade events have significantly larger multiplicities.

The shape of rapidity distribution is slightly affected by the mass misidentification of particles: the rapidities of protons and kaons which are taken as pions increase by 0.5 to 2.0 units and this effect will be larger for faster particles. But this fact does not alter our analysis as rapidity distributions for events with and without cascade are changed in the same way. Protons produced in intranuclear cascade are rather slow and most of them can be identified.

Closer examination can be obtained by the ratio R(y) of normalized rapidities for cascade events to ν-nucleon interactions:

$$R(y) = \frac{[(1/N)dn/dy]_{\ with\ cascade}}{[(1/N)dn/dy]_{without\ cascade}}$$

The ratio R(y) is presented in Fig.5b. It can be seen that in the target fragmentation region the ratio $R(y)$ increases up to 10 times. In the leading quark fragmentation region this ratio within experimental errors is equal to 1.

To avoid effects due to proton contamination, we show the rapidity ratio $R^-(y)$ of negative particles. It is very similar to $R(y)$, which suggests that our data are not significantly affected by protons. The area between lines is the ratio for charged particles for Monte Carlo events with the reaction time $\tau_r = 2.5 fm/c$. It is in reasonable agreement with the experimental data, although it underestimates cascade in the backward region. Variations in τ_r from 1.0 fm/c to $3.5 fm/c$ change the distribution only slightly.

The same analysis has been made for the data sample with all protons included and with different criteria to separate ν-nucleon and cascade events and the results are shown in Fig.6. The essential features of the ratio $R(y)$ distribution remains as before: it increases up to 10 times in the region of negative rapidity and is around one in the quark fragmentation region. For the data sample with all protons included ($p_{lab} > 0$ GeV/c) there is a small depletion in the forward direction. Part of these protons came from evaporation and hence they do not arise directly from the physics of the interaction. These data show the limit of methodical deviation of results. All other distributions within errors are equal to 1.

The similar analysis of rapidity distributions was made in hadron interactions on nucleus targets at 200 GeV/c [16] and 250 GeV/c [17], and the ratio $R(y)$ in the projectile fragmentation region was found to be less than one, which was interpreted as the leading particle's loss of energy in collisions inside the nucleus. In Ref.[16] they also observed a plateau in the central region ($2 < y < 4$) with the value $R \approx 2$. In the target fragmentation region the ratio changes in wide range since different target used and differences in proton identification. In Ref.[17] the ratio for negative particles rise up to 10 on Al target, which agree with our results.

We also studied the ratio $R(y)$ for three different intervals of the W^2 and the results are presented at Fig.7. At the smallest values of $W^2 < 50$ GeV/c^2 this ratio is less than unity for more than one standard deviation: for $y > 2$ $R(y) = 0.6 \pm 0.1$ (statistical error). Monte Carlo model does not describe experimental data in this region. At larger intervals in W^2 it is consistent with one within experimental errors. Monte Carlo model gives reasonable description of experimental data for the $W^2 > 50$ GeV.

It should be remarked that the point, where a rise in $R(y)$ distribution begins, is moving towards the lesser values of rapidity with increasing of W^2, but this region of rapidity always corresponds to the mean particle momentum in the laboratory frame of order 1-2 GeV/c. This suggests that the particles which appear in intranuclear cascade usually have laboratory momentum less than 2 GeV/c and this value does not depend on W.

6 Conclusion

- The method to isolate ν-nucleon interactions in ν Ne scattering was developed. The fraction of events without intranuclear cascade is about 40% of all selected events.

- It is found that in the forward direction multiplicity of charged particles is approximately the same for ν nucleon events and for events with an intranuclear cascade over a large W^2 region.

- Intranuclear cascade adds 2.34 ± 0.06 units into the backward hemisphere multiplicity and is independent of W^2 in the region up to $W^2 \approx 700$ GeV^2.

- Particles with laboratory momentum less then 2 GeV/c make the biggest contribution into intranuclear cascade.
- Cluster model gives reasonable description of ν Ne interaction for the region of $W^2 > 50$ GeV. The data favor the formation time for a cluster $\tau_r = 2.5 fm/c$.

Acknowledgments

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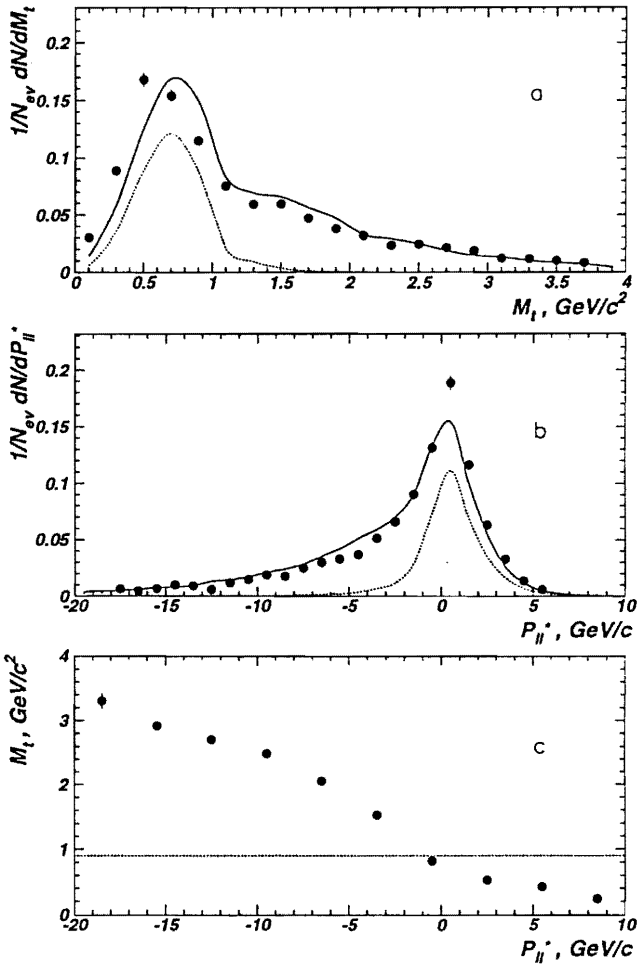

Figure 1: Criteria used to separate ν-nucleon interaction from interactions with intranuclear cascade (a,b) and their correlation (c). Histograms (a,b) are normalized to unity. The solid curves (a,b) are Monte Carlo simulations for νNe interaction, the dotted lines are Monte Carlo events without intranuclear cascade.

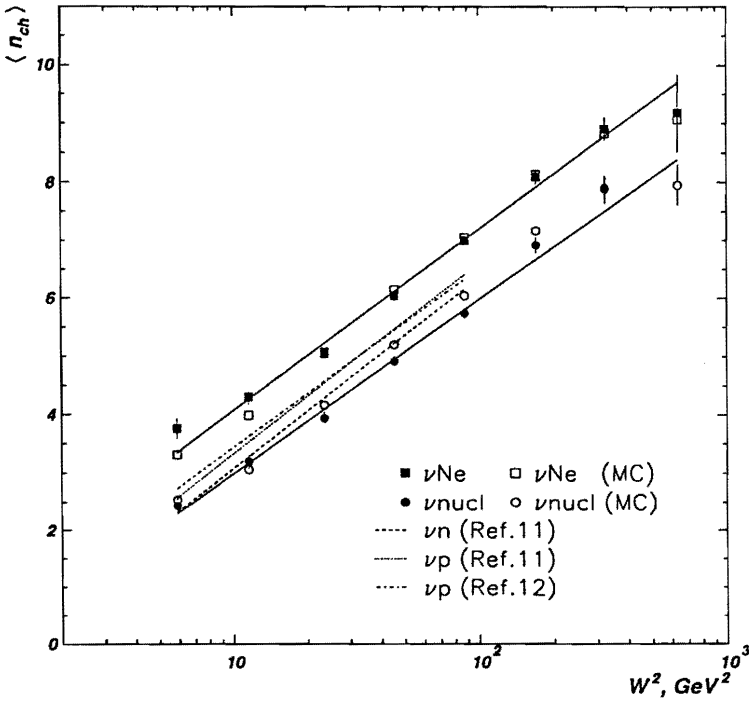

Figure 2: Average multiplicities of charged secondaries $\langle n^{\pm} \rangle$ versus W^2. The solid lines are linear fits.

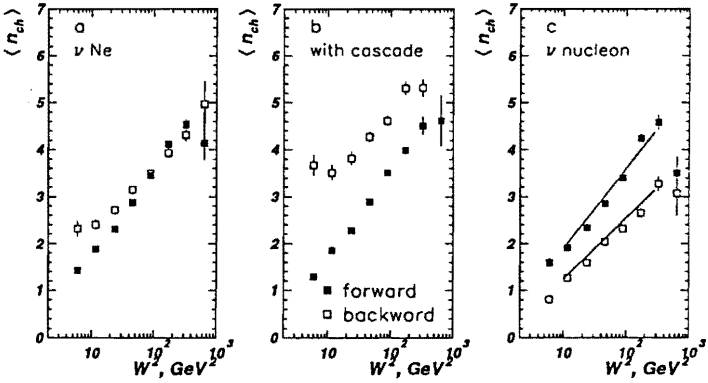

Figure 3: Average charged hadron multiplicities as a function of W^2 in the forward ($x_F > 0$) and backward ($x_F < 0$) hemispheres for all data sample (a), for selected events with (b) and without (c) cascade. The solid lines (c) are approximations of deuterium-target data [11].

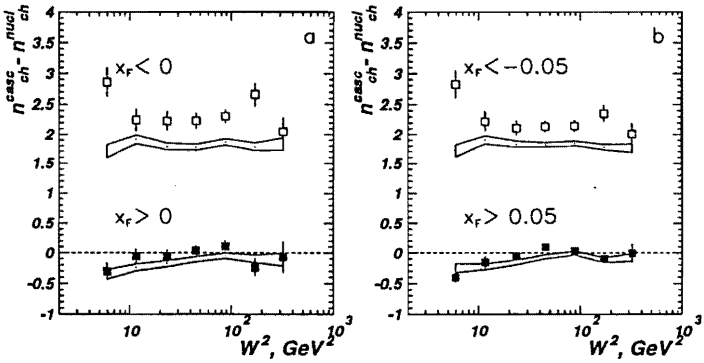

Figure 4: Difference in the forward and backward multiplicities for two data samples versus W^2 for (a) all charged tracks and (b) for charged tracks outside the central region ($|x_F| < 0.05$). Areas between the lines are Monte Carlo predictions with statistical errors.

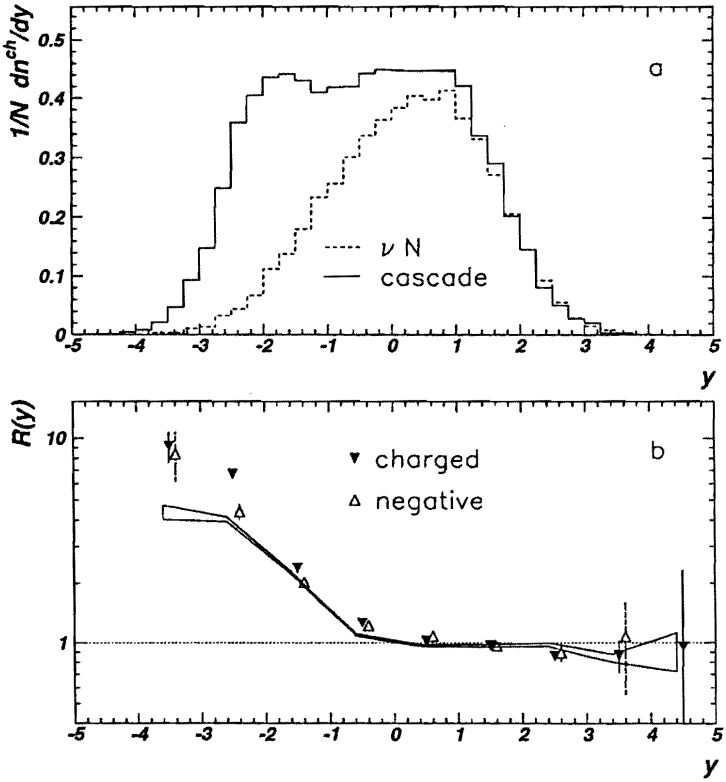

Figure 5: (a) Rapidity distributions of charged particles, normalized to the total number of events in each data sample, for events with (solid line) and without (dashed line) cascade. (b) Ratio of normalized rapidity distributions for events with intranuclear cascade to those without cascade for all charged tracks and only for negative tracks. The area between the lines is Monte Carlo with statistical errors.

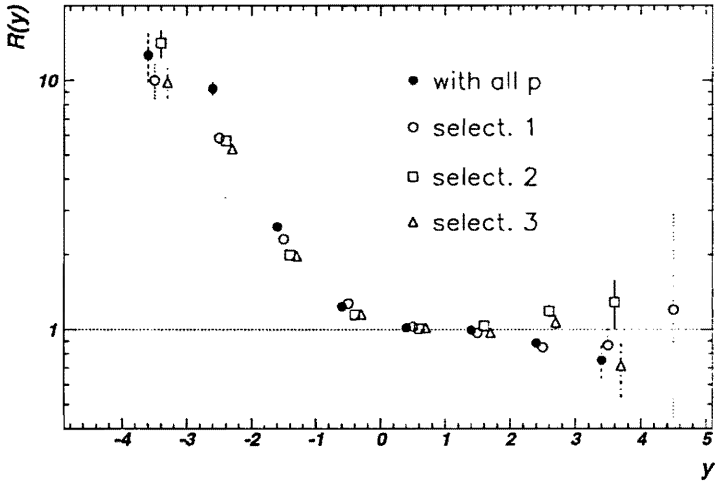

Figure 6: Ratio of normalized rapidity distributions for events with cascade to those without cascade for experimental data with all registered protons included in data sample; for different selection criteria to separate "pure" ν-nucleon interactions: (1) $M_t < 1$ GeV/c^2; (2) $|P_{\parallel}{}^{*} - 0.7| <$ 4 GeV/c; (3) combination of the two.

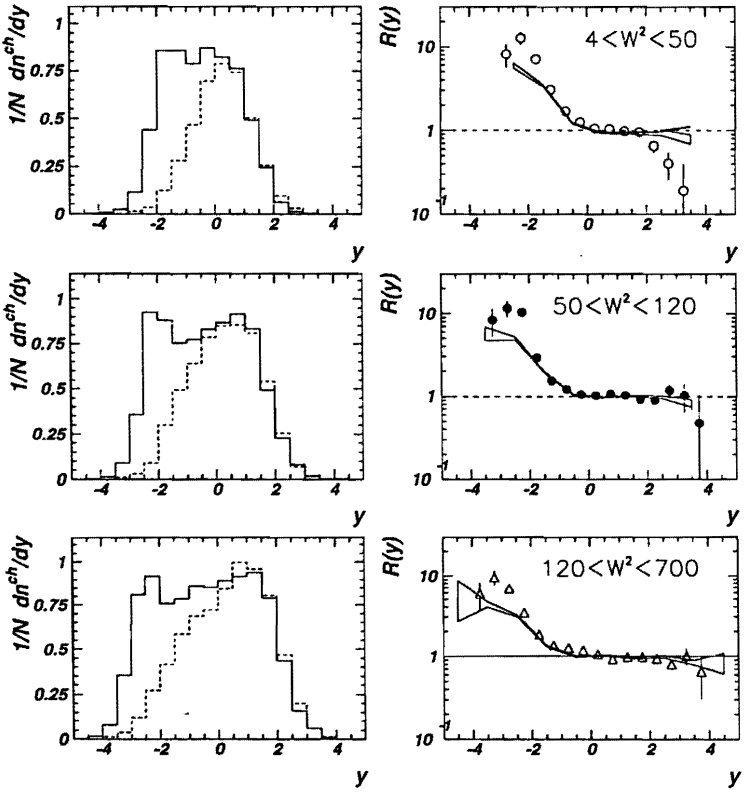

Figure 7: Rapidity distributions and ratios for different intervals of W^2. Areas between the lines are Monte Carlo predictions with statistical errors.