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*Presented by H.S. Budd at the 1988 Lake Louise Winter Institute.

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**DEPARTMENT OF PHYSICS AND ASTRONOMY**

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# NEUTRINO PRODUCTION OF OPPOSITE-SIGN DIMUONS AT THE TEVATRON*

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**ABSTRACT**

In a sample of 670,000 charged-current neutrino events, 1529 $\mu^-\mu^+$ events have been observed, with 30 GeV < $E_\nu$ < 600 GeV and $P_\mu$ > 9 GeV/c for both muons. A corresponding sample of 124,000 antineutrino events yields 284 $\mu^+\mu^-$ events. The rate and kinematic distributions of these events are consistent with single-charm production followed by muonic decay. These data are used to measure the strange quark content of the nucleon and charm muonic branching ratio.

## 1. INTRODUCTION AND THEORY

First reports[1] of opposite-sign dimuons in neutrino interactions indicated the presence of a new particle. These observations were followed shortly by direct observation[2] of an event $\nu + p \rightarrow \mu^- + \Sigma_c^{++}$ in a BNL bubble chamber. Further experiments in bubble chambers[3] and emulsion experiments[4] confirmed the observation of direct single-charm production by neutrinos. These observations and further experimental and theoretical studies showed that opposite-sign dimuons come mostly from muonic decay of charmed hadrons produced in neutrino interactions.

Figure 1 shows the Feynman diagram for charm production by a $\nu$ ($\bar{\nu}$). Charm hadrons in neutrino-induced interactions come from the production of a charmed quark from an s or d quark. Standard model theory predicts that the rate for charmed quark production by neutrinos in an isoscalar target is proportional to $(u(x)+d(x))\sin^2\theta_c+2s(x)\cos^2\theta_c$ where $\theta_c$ is the Cabibbo angle; $u(x)$, $d(x)$, and $s(x)$ are the quark density distributions of the u quark, d quark, and s quark, respectively, in the proton as a function of $x=Q^2/2M\nu$ and $Q^2=2E_\nu E_\mu(1-\cos\theta_\mu)$ with $\nu=E_{had}$. Similarly, charmed quark production by antineutrinos is proportional to $(\bar{u}(x)+\bar{d}(x))\sin^2\theta_c+2\bar{s}(x)\cos^2\theta_c$. In antineutrino induced production 90% of the $\mu^+\mu^-$ rate comes from the term $2\bar{s}(x)\cos^2\theta_c$.

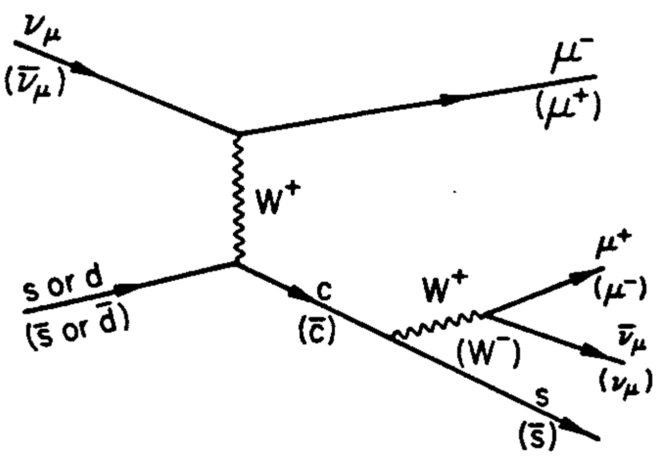


*Figure 1. Diagram for opposite-sign dimuon production through charm production and its semi-muonic decay.*

The threshold effect of the charmed quark mass $m_c$ is incorporated using the procedure of "slow rescaling" through the replacement of x by $x'=x+m_c^2/2M\nu$.[5] This substitution introduces a factor $x/x'=1-m_c^2/(2ME_\nu x')$ into the cross section for charm quark production.

The neutrino cross section for opposite-sign dimuon production from a isoscalar target is given by the formula:[6]

$$\frac{d^3\sigma(\mu^-\mu^+)}{dx'dydZ} = \frac{G^2ME_\nu}{\pi}\left[1-\frac{m_c^2}{2ME_\nu x'}\right][x'(u(x')+d(x'))\sin^2\theta_c+2x's(x')\cos^2\theta_c]\cdot D(Z)B(\text{charm}\to\mu X) \quad (1)$$

Where D(Z) is the fragmentation function of the charmed quark into the charmed hadron, and Z is the fraction of the available momentum taken by the charmed hadron in the W boson-nucleon center of mass frame. $B(\text{charm}\to\mu X)$ is the average semimuonic branching ratio of the mixture of charmed hadrons produced by neutrinos. The antineutrino cross section to produce opposite-sign dimuons, $\mu^+\mu^-$, is the same as (1) with the quark density functions u(x')+d(x') and s(x') replaced by the anti-quark density functions $\bar{u}$(x')+$\bar{d}$(x') and $\bar{s}$(x').

This high statistics experiment provides new opposite-sign dimuon data to test the above theory and to extract the strange sea content of the nucleon. Since this is the first experiment with $E_\nu$>300 GeV, the data provide a more detailed study of the charm quark threshold and energy dependence of the strange sea.

## 2. THE BEAM AND THE DETECTOR

Fermilab Experiment 744 ran in the quad triplet neutrino beam from February, 1985 to August, 1985. An 800 GeV proton beam from the Tevatron struck the production target. Three quadrupole magnets after the target focused the secondary hadrons forward, yielding a high intensity beam of neutrinos and antineutrinos ranging in energy from 30 to about 600 GeV. An integrated luminosity of $5\times10^{17}$ protons on target resulted in 1.7 million single-muon triggers. Figure 2 shows the energy distribution of the single-muon events passing all cuts, and Figure 3 shows the x distributions of these events.

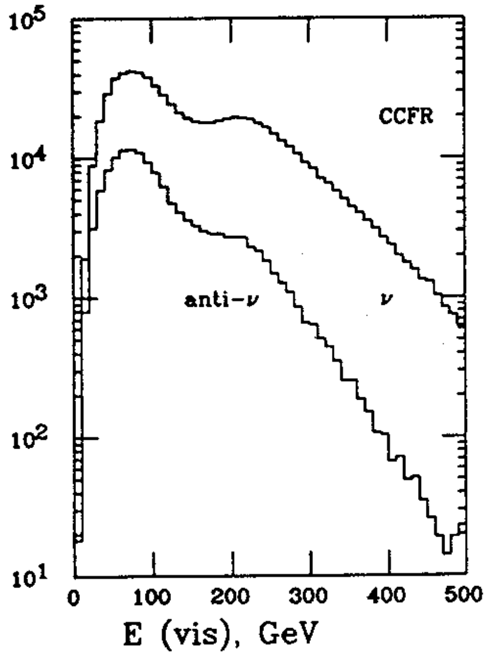


*Figure 2. The ν and ν̄ energy distribution for single μ events.*

The CCFR neutrino detector,[7 8] 920 m downstream of the hadron decay pipe, consists of a target calorimeter followed by a muon spectrometer. The calorimeter is made of 640 tons of 3 m square steel plates interspersed with drift chambers (every 20 cm of steel) and liquid-scintillator counters (every 10 cm of steel). The scintillator counters are read out with both ADCs and multi-hit TDCs. The spectrometer employs 3 toroidal magnets with a total transverse momentum kick of 2.4

GeV/c, 25 drift chambers, and 25 acrylic counters. The 25 drift chambers in the toroid are grouped in 5 clusters, with a chamber cluster downstream of each toroidal magnet and 2 clusters downstream of the spectrometer. The drift chambers have a position resolution of 250 $\mu$m.

The RMS hadron energy resolution in GeV has been measured in hadron beams to be $0.89\sqrt{E_{had}}$. The fractional RMS momentum resolution is 11%. The time of passage of a track is measured with a resolution of 5 ns using the toroid drift chamber clusters and scintillation counters instrumented with multi-hit TDCs.

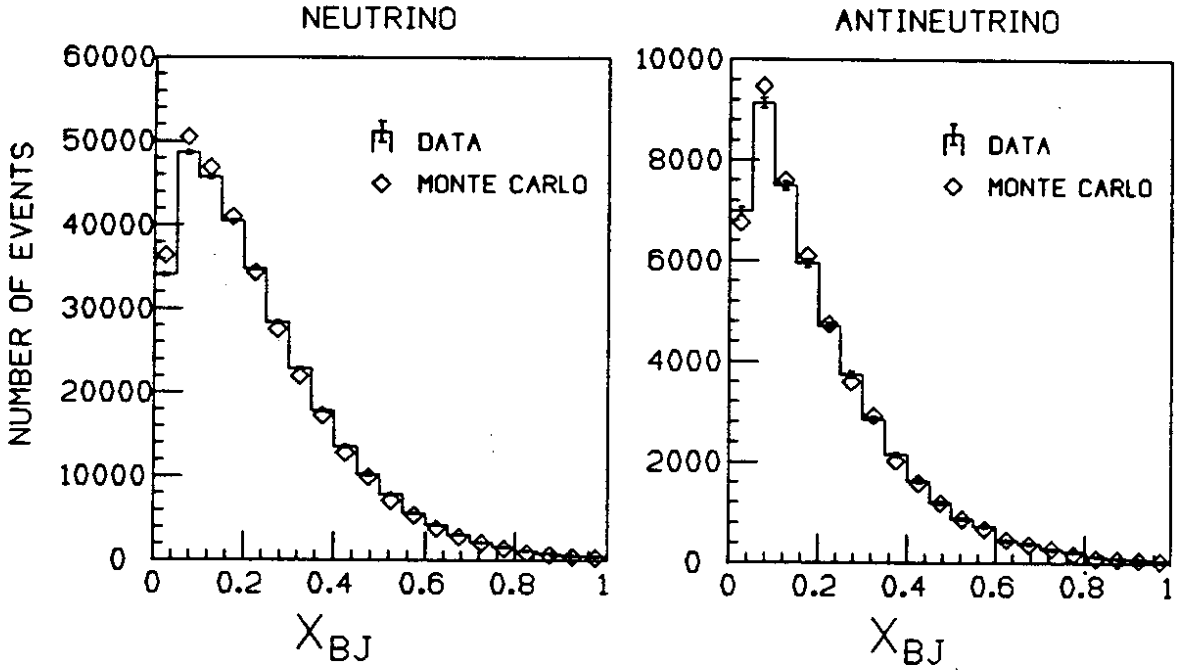


*Figure 3. X distributions of $\nu$ and $\bar{\nu}$ induced single-muon events.*

### 3. THE DATA SAMPLE

The events used in the dimuon analysis were required to satisfy the single-muon cuts. The neutrino must interact in the target fiducial mass, which is chosen to provide good hadron shower containment. The muon must pass through the good field region of the toroids. The tracks must pass a momentum fitting $\chi^2$ cut (1% of the single-muon events fail this cut). The track must also have a momentum greater than

9 GeV/c. Of the 1.7 million single-muon triggers, 670,000 $\nu$ induced and 124,000 $\bar{\nu}$ induced events pass these cuts. Most of the events which fail the cuts are outside the fiducial volume.

Both muons in dimuon events must pass the single-muon cuts. To remove single-muon events overlapping in time and space, we require the distance of closest approach between the two tracks be less than 15 cm and the fitted time difference between the 2 tracks be less than 28 ns (1.5 rf buckets). We measure the track seperation to an accuracy of 4 cm and track time to an accuracy of 5 ns. We reject trimuon events with an identified third muon with momentum greater than 3.1 GeV/c using pulse height in the counters.

The final dimuon sample contains 1813 opposite-sign dimuons and 116 same-sign dimuons.[9] Of the 1813 opposite-sign dimuons 1529 are assigned as $\nu$-induced and 284 as $\bar{\nu}$-induced by a procedure discussed below. Physicists have scanned ~ 6000 dimuon candidate events obtained using very loose selection criteria. From this procedure we estimate an inefficiency less than 1% for finding dimuons with the standard computer code.

Since the quadrupole triplet beam is a mix of neutrinos and antineutrinos, we use an algorithm for separating neutrino from antineutrino events. Single-muon events with an identified $\mu^-$ are assigned as neutrino events, while events with an identified $\mu^+$ are assigned as antineutrino events. For dimuon events we define the second muon, or nonleading muon, to be the muon which has the smaller momentum in the direction perpendicular to the axis of the hadron shower, $P_{had}=P_\nu-P_{\mu 1}$. If the leading muon is negative the event is labelled as a neutrino event, and if the leading muon is positive the event is labelled as an antineutrino event.

We have tested the leading muon algorithm with a Monte Carlo program. The antineutrino contamination in neutrino data is 1%, while the neutrino contamination in the antineutrino data is 28%.

## 4. SINGLE-CHARM ANALYSIS

Opposite-sign dimuons are produced by two sources. The first source is single-charm production followed by muonic decay. The second source is muonic decays of hadrons, mainly pions and kaons, in the hadron shower and produces 6% of the opposite-sign dimuons. This small contribution is modeled in the event Monte Carlo.[9] Other processes, such as trimuons, production of B hadrons, or two single-muon events overlapping in space and time, are negligible.

We use Equation (1) to model opposite-sign dimuon production. For this analysis we assume $m_c$=1.5 GeV/$c^2$. For the structure functions u(x)+d(x) and $\bar{u}(x)+\bar{d}(x)$ we use fits to the data from a CCFRR narrow band run.[10] The fits use Buras-Gaemers type parameterizations that are $Q^2$-dependent.[11] For the value of the Cabibbo angle we use $\sin^2\theta_c$=.053. For D(Z) we use the Peterson fragmentation function.[12]

$$D(Z) \propto \frac{1}{Z(1 - 1/Z - \epsilon/(1-Z))^2} \qquad (2)$$

where $Z=P_D^*/P_{max}^*$ and $P_{max}^*$ is the maximum possible momentum $P_D^*$ of the charmed hadron in the W boson-nucleon center of mass frame. The Argus group[13] fits the charmed fragmentation of $D^{*+}$ with the above formula and reports $\epsilon$=.19±.03. We use this value for the analysis and explore systematic errors by varying $\epsilon$ from .09 to .29.

The Monte Carlo calculation produces charmed hadrons with a distribution of transverse momenta $p_T$ with respect to the direction of the hadron shower using the formula:

$$dN/dp_T^2 \propto \exp(-ap_T^2) \quad \text{with } a=1.1 \qquad (3)$$

The value a=1.1 was determined from LEBC/EHS hadronic charm production data.[14]

For the relative branching ratios of charmed hadrons produced by neutrino interactions into the modes $\pi\mu\nu$, $K\mu\nu$, $K^*\mu\nu$, and $K\pi\mu\nu$, we use

$e^+e^-$ data from the Mark III experiment at SPEAR.[15] The overall branching ratio is a parameter fit to the dimuon data.

The strange sea content and charm semimuonic branching ratio are determined from the opposite-sign dimuon data. The data are used to determine the shape and normalization of s(x), which we assume is equal to $\bar{s}(x)$. We assume that the strange sea need not have the same x dependence as the nonstrange sea determined by the CCFRR narrow band measurements. To allow for a different x dependence for the strange sea, we let $s(x) \propto (1-x)^{\alpha}(\bar{u}(x)+\bar{d}(x))$. The opposite sign dimuon data determine the strange sea normalization via the parameter $\eta_s$:

$$\eta_s = \frac{2S}{U+D} \quad \text{where } S = \int_0^1 xs(x)dx \quad \text{and} \quad U+D = \int_0^1 x(u(x)+d(x))dx \qquad (4)$$

To extract $\eta_s$, $\alpha$, and the branching ratio (BR), we compare the absolutely normalized charm Monte Carlo x distribution to the x distribution of the neutrino and antineutrino opposite-sign dimuon data after subtracting the contribution from hadron decay. We preform a simultaneous $\chi^2$ fit by taking the difference between the charmed Monte Carlo events and the dimuon events using x bins of .05. We use neutrino data and Monte Carlo events for x<0.6 and use antineutrino data and Monte Carlo events for x<0.4.

## 5. RESULTS AND CONCLUSIONS

These data yield the following values for $\eta_s$, $\alpha$, and BR.

$$\eta_s = .068 \,^{+.012}_{-.010} \pm .005 \qquad \eta_s = 2S/(U+D)$$

$$BR = .102^{+0.010}_{-0.010} \pm .009$$

$$\alpha = 4.8 \,^{+1.1}_{-0.9} \pm 0.1 \qquad s(x) \propto (1-x)^{\alpha}(\bar{u}(x)+\bar{d}(x))$$

The first set of errors are statistical. The second set of errors are systematic and come from varying the Peterson fragmentation parameter $\epsilon$ from .09 to .29. These results are preliminary.

The ratio of the strange sea to nonstrange sea, $\kappa = 2s/(\bar{u}+\bar{d})$, can be extracted using $\eta_s$. We determine $\kappa$ using:

$$\kappa = \frac{2\eta_s}{2(\bar{Q}/Q) + (\bar{Q}/Q-1)\eta_s} \quad \text{where}^{10} \quad \bar{Q}/Q = .175 \pm .012 \qquad (5)$$

$$Q = \int_0^1 x(u(x)+d(x)+s(x))dx \quad \text{and} \quad \bar{Q} = \int_0^1 x(\bar{u}(x)+\bar{d}(x)+\bar{s}(x))dx$$

Formula (5) gives the value of $\kappa = .46 ^{+.10}_{-.08} \pm .04$, where the first error is statistical. The second error is systematic and includes the error in $\bar{Q}/Q$ which enters in calculating $\kappa$ from $\eta_s$.

The value of $\kappa$ indicates the sea is not SU(3) symmetric. $\kappa=1$ would indicate an SU(3) symmetric strange sea ($\bar{u}=\bar{d}=\bar{s}$), while $\kappa=0$ would indicate no strange sea.

Figure 4 presents the x distribution of the opposite-sign dimuons for neutrino and antineutrinos. The contributions from the valence and sea u(x)+d(x) quarks and strange sea quarks are shown. The Monte Carlo is the sum of u(x)+d(x), $\bar{u}(x)+\bar{d}(x)$, s(x), and $\bar{s}(x)$. The data agree well with the Monte Carlo and give a $\chi^2$ of 1.4 per degree of freedom.

Figure 4 also demonstrates which parts of the data are contributing to each variable. The antineutrino data are dominated by production from $\bar{s}(x)$. Hence, the value of $\alpha$ is determined mostly by the antineutrino data. The neutrino data with x>.3 are principally due to production from u(x)+d(x) with a small component from s(x). The neutrino data with x>.3 determine the branching ratio. $\kappa$ is determined by comparing the low x neutrino and antineutrino data to the high x neutrino data. The low x data are principally due to s(x) for neutrinos and $\bar{s}(x)$ for antineutrinos, which we are trying to determine, while the neutrino high x data are dominated by sum u(x)+d(x) which is known from the CCFRR narrow band structure functions. The ratio of these gives $\eta_s$ from which we extract $\kappa$.

The charm branching ratio to muons can also be calculated using the composition of charmed hadrons found in neutrino-emulsion interactions[4] folded in with the branching fractions of charmed hadrons to muons using $e^+e^-$ data from the Mark III.[16] The details of the calculation are given in Lang et al.[7] The branching fraction from this calculation is .109±.014, which is in good agreement with our experimental result.

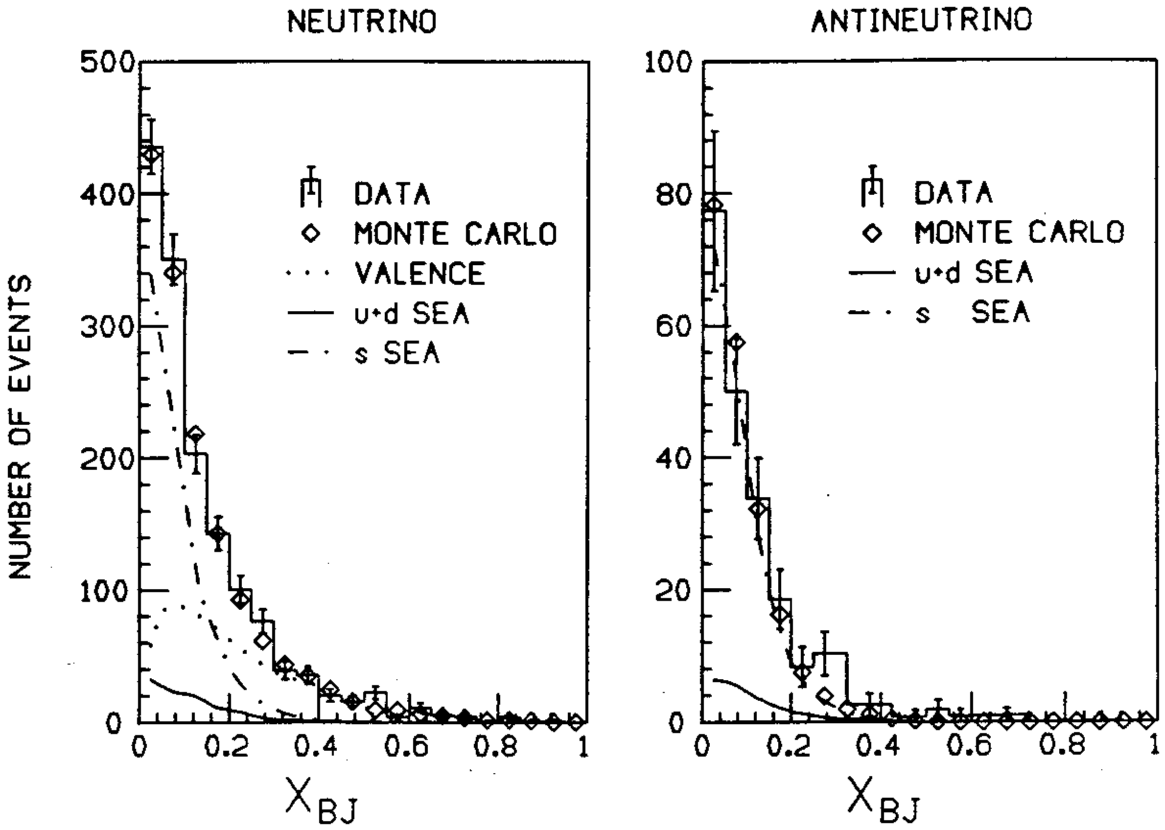


*Figure 4. X distributions of opposite sign dimuons events for $\nu$ and $\bar{\nu}$ induced interactions. The data have the hadron shower background subtracted. The Monte Carlo program generated events with $\eta_s$=.068, $\alpha$=4.8, and the charm branching ratio = .102. The $\nu$ ($\bar{\nu}$) plot is corrected for $\bar{\nu}$ ($\nu$) contamination. The contributions from valence quarks, nonstrange sea quarks, and strange sea quarks are also shown.*

The CDHS collaboration[17] gives a value of $U^2_{cd}\times BR$ of $(.41\pm.014)\times10^{-2}$ in the energy range 80 GeV$<E_\nu<$160 GeV. Assuming $U^2_{cd}=\sin^2\theta_c=0.053$, their value of the branching ratio is .078±.013, which is smaller than our value or the value obtained from $e^+e^-$ experiments. CDHS includes systematic errors, mostly due to charm fragmentation, in their value of $U^2_{cd}\times BR$.

Other experiments have measured $\eta_s$ and $\kappa$. The CDHS[17] collaboration has obtained $\eta_s$=.067±.016 in a wide band run without assuming a value of the charm branching ratio. They rely on a shape analysis of the neutrino x distribution. They use $\bar{Q}/Q$=0.16±.02[18] to get $\kappa$ = 0.52±0.09. The CCFRR[7] collaboration calculates $\kappa=.52^{+.17}_{-.15}$ for $100<E_\nu<230$ GeV, where a charmed branching ratio of .109±.014 (from $e^+e^-$) is used as an input. Using $\bar{Q}/Q$=.175, they get $\eta_s$=0.075±0.019. These values agree well with the value of $\kappa$ measured here.

Figure 5 shows a plot of $Z_{\mu 2}=E_{\mu 2}/(E_{had}+E_{\mu 2})$. The data and Monte Carlo for Figure 5 include the $\pi/K$ decay background. This quantity is sensitive to the form of the fragmentation function. The data are consistent with the form of the fragmentation function which is used.

Figure 6 shows the preliminary rate with hadron background subtracted for $\sigma(\mu^-\mu^+)/\sigma(\mu^-)$ and $\sigma(\mu^+\mu^-)/\sigma(\mu^+)$ as a function of energy. The rates are corrected for acceptance and for the $P_\mu>9$ GeV/c cut. Note that the errors are only statistical. Also plotted are the values for the Monte Carlo assuming $m_c=1.5$ GeV/$c^2$ and the values of $\eta_s$, $\alpha$, and BR previously determined above. Experimental points for the CDHS[17] and CCFRR[7] experiments are shown with only their statistical errors. We see good agreement between this experiment, the Monte Carlo, the narrow band CCFRR experiment, and the CDHS experiment.

In conclusion, the data are consistent with single-charm production. We find the strange sea is not SU(3) symmetric and has a preliminary value of $\kappa = .46^{+0.11}_{-0.09}$. We determine the muonic branching ratio of $\nu$ produced charm hadrons to be .102±.013, which is consistent with the value obtained from $\nu$-emulsion data and $e^+e^-$ data. In addition preliminary analysis of this experiment suggests that the strange sea has a softer x distribution than the nonstrange sea.[10]

Acknowledgements

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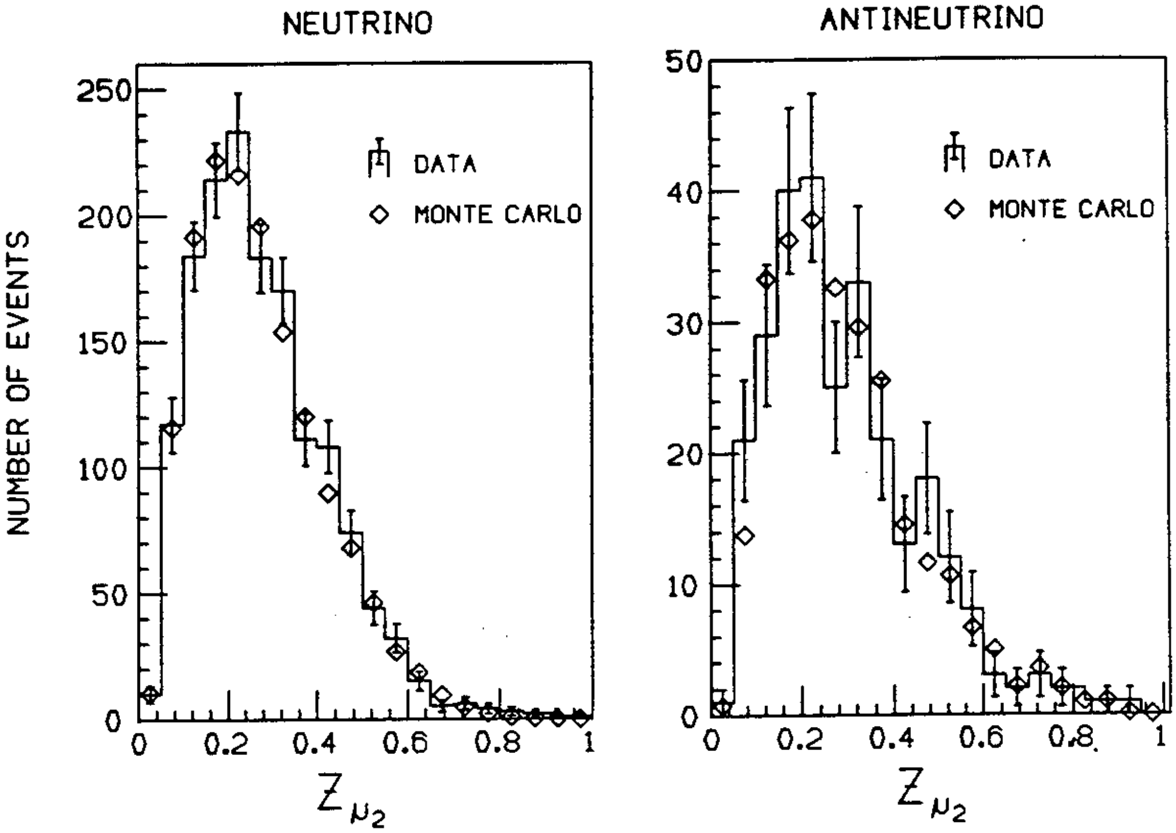


*Figure 5. Distribution of the variable* $Z_{\mu 2} = E_{\mu 2}/(E_{had}+E_{\mu 2})$ *for* $\nu$ *and* $\bar{\nu}$ *opposite-sign dimuon data and a Monte Carlo calculation that includes charm production and hadron shower background.*

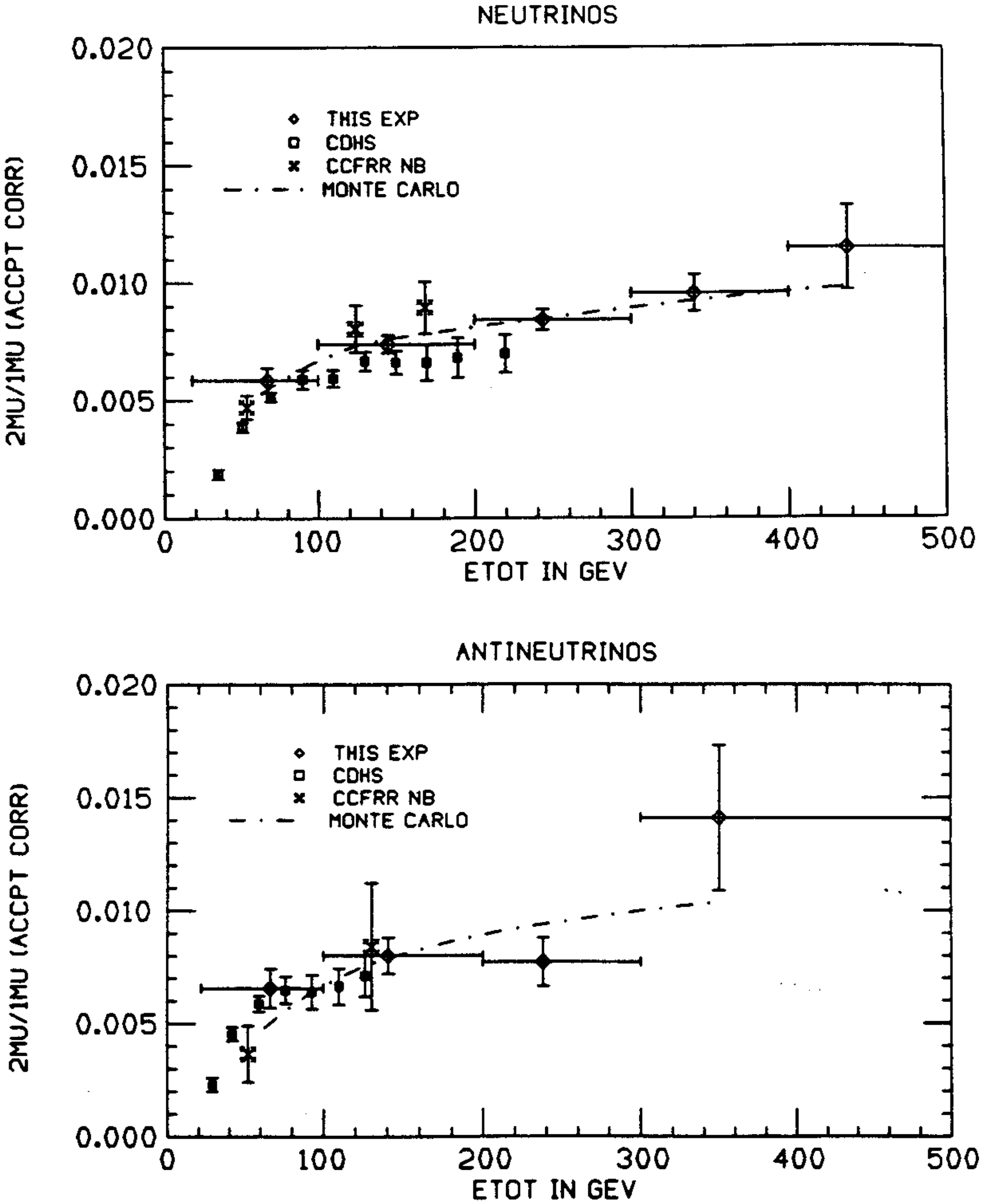


*Figure 6. Rates for $\sigma(\mu^-\mu^+)/\sigma(\mu^-)$ and $\sigma(\mu^+\mu^-)/\sigma(\mu^+)$ as a function of energy for this experiment, CDHS experiment(17), CCFRR narrow band experiment(7), and Monte Carlo are shown. The rates have been corrected for acceptance and a momentum muon cut. All errors shown are statistical.*

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