Nucleon Structure

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RECENT EXPERIMENTAL MEASUREMENTS OF THE

NEUTRINO CHARGED CURRENT CROSS SECTIONS

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I have been asked to review the recent experimental measurements of the neutrino charged current total cross sections. I will first introduce you to the formalism of the charged current neutrino cross sections, then review the previous measurements of these total cross sections and show the new data which has become available since the Hamburg Conference. The major part of my review will be devoted to a detailed discussion of the Cal Tech-Fermilab-Rochester-Rockefeller (CFRR) results[1] which is the major new result. These measurements are the first results of a new large neutrino detector and a new neutrino beam here at Fermilab. Furthermore, I am a member of that group.

The general form of the differential cross section for neutrino and antineutrino nucleon scattering may be written in the form:

$$\frac{d^2\sigma^{\nu,\nu}}{dxdy} = \frac{G^2mE}{\pi}\left[(1-y-\frac{mxy}{2E})\,F_2^{\nu,\bar{\nu}}(x,q^2) + \frac{y^2}{2}2\,x\,F_1^{\nu,\bar{\nu}}(x,q^2) \pm y(1-\frac{y}{2})\,x\,F_3^{\nu,\bar{\nu}}(x,q^2)\right] \qquad (1)$$

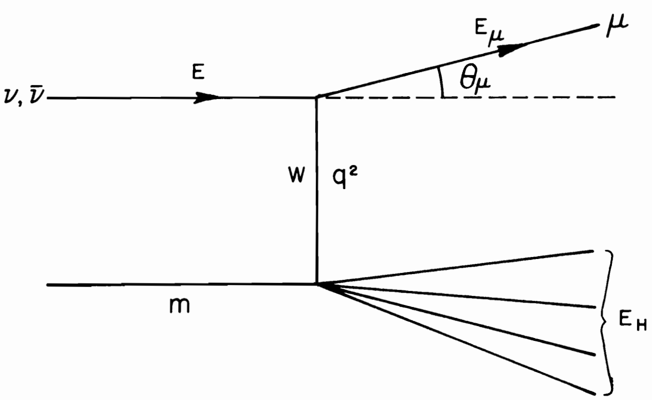

Fig. 1 Neutrino Deep Inelastic Scattering

where $q^2 = -4EE_\mu \sin^2\frac{\theta}{2}$

$\nu = E_H$

$x = \frac{q^2}{2m\nu}$

$y = \frac{\nu}{E}$

and F_i = nucleon structure functions.

If the above expression is integrated over both x and y and in the scaling limit ($E_\nu \to \infty$, Q^2, $\nu \to \infty$, $\frac{\nu}{Q^2}$ finite), the following total cross section is obtained:

$$\sigma^{\nu,\bar{\nu}} = \frac{G^2ME}{\pi}\int_0^1 dx[1/2\,F_2 + \frac{x}{3}(F_1 \mp F_3)] \qquad (2)$$

If this procedure is correct, the ν and $\bar{\nu}$ cross sections grow linearly with neutrino energy and the slopes of the rising cross sections are determined by integrals over the structure functions.

The usual local current-current weak interaction theory predicts that neutrino-lepton cross sections at high energy rise linearly with laboratory energy. Now as I have just shown; if, in addition, the deep inelastic structure functions scale in the dimensionless scaling variable x, the neutrino-nucleon cross section must rise linearly with laboratory energy as well. The behavior of the total neutrino (antineutrino) charged current cross section $\sigma_\nu(\sigma_{\bar{\nu}})$, on nucleons, therefore, provides simultaneously a directly interpretable check of both weak interaction theory and hadronic scaling.

Deviations from this simple picture are expected; in the low energy region from scaling violations[2] and in the high energy region from the effects of a finite mass non-local propagator, the so-called W-boson. Therefore, it is of interest to measure these cross sections with good accuracy over as large an energy region as possible and look for these deviations.

The measurements of these total cross sections in terms of the slope parameter σ/E are shown in Table I. The first five entries are data that were available in some form at the Hamburg Conference in 1977. The last six entries present new measurements. In the beginning (1973) there was Gargamelle[3]. This experiment established that the cross section was indeed linearly rising over the energy range of 1-10 GeV. The ANL experiment[4] (1977) confirmed these numbers. In 1977 results also started to come out of the new high energy machines at Fermilab and CERN. The Cal Tech-Fermilab-Rockefeller (CITFR)[5] group reported a measurement covering the range of 30-200 GeV/c. These data were taken with the then new narrow band neutrino beam and represented a major step forward in the difficult problem of flux normalization. Both the BEBC[6] and CDHS[7] groups presented preliminary data also at that time from the SPS narrow band beam. However, both of these groups had not yet done a full analysis of the systematic errors in their measurements. The BEBC data originally showed some energy dependence of the slope parameter but that has been traced to incorrect K/π ratios in the original paper. The values shown are corrected for the current K/π ratios used by the CDHS[7]. This year the CDHS data[7] has had the systematic errors included and now give the values shown on the fifth line.

A comment about these numbers is in order. In the antineutrino case, the slope values are consistent over the entire energy range of 1 to 200 GeV. The slope values for the neutrino data are not as consistent. The low energy experiments are grouped at one value and the high energy experiments are grouped at another value. If we compare this data to the asymptotic freedom predictions[2] we get a best fit of the Λ parameter to be $\Lambda = 0.5$. However, the two sets of experiments were taken in radically different energy regions and used two radically different techniques.

TABLE I

$\sigma_T/E_\nu \times 10^{38}$ cm^2/GeV

Exp.	E_ν	ν	$\bar{\nu}$
GGM [3]	1-10	0.74 ± 0.05	0.28 ± 0.02
ANL [4]	1-6	0.76 ± 0.03	
CITFR [5]	45-205	0.609 ± 0.030	0.290 ± 0.015
BEBC [6]	20-200	0.63 ± 0.05	0.29 ± 0.03
CDHS [7]	30-190	0.62 ± 0.03	0.30 ± 0.02
GGM [8]	3	0.69 ± 0.05	
	9	0.61 ± 0.06	
SKAT [9]	3-30	0.73 ± 0.08	
IHEP-ITEP [10]	3-30	0.74 ± 0.07	0.31 ± 0.03
ANL [11]	1-6	0.87 ± 0.03	
BEBC [12]	10-50	0.73 ±0.08	0.32 ± 0.06
CFRR [1]	50-260	0.67 ± 0.04	

In the last year much new data have become available. Those data are shown as the six entries in the lower half of Table I. The new GGM data[8] was taken at the CERN PS before Gargamelle was moved. Note that these slope values have moved down from the old numbers so that they are now in the vicinity of the high energy values. Two Serpukhov groups are reporting slope parameters in the energy region of 3-30 GeV. Both experiments are wide band neutrino beams, SKAT[9] was done in a heavy liquid bubble chamber and the IHEP-ITEP[10] experiment was done with counter techniques and an iron target. Both experiments show slope parameters in agreement with earlier low energy results; however, the errors are such that a strong statement cannot be made about differences with high energy results. The ANL[11] group is reporting a new value based on a wide band neutrino beam incident on a deuterium filled bubble chamber. This value, if the errors are correctly estimated, represents the strongest evidence for a difference in the slope parameters between low and high energy data. A BEBC[12] group is reporting new preliminary slope parameters taken with the CERN-SPS wide-band neutrino beam and a neon fill in BEBC. The statistics are so limited that no strong statement can be made. The last line shows the new CFRR[1] result for the neutrino slope parameter. I will discuss this result in detail in the latter part of this paper. This value represents an increase in the slope parameter of about one and one half to two standard deviations over the earlier high energy measurements moving the high energy values closer to the average of the low energy values.

With the exception of the new ANL point, it can be said that both the neutrino and antineutrino cross section's rise linearly in the region from 1 to 260 GeV each characterized by a single slope parameter, although the region below 20 GeV remains confused. In any case, to measure QCD effects by looking at the total cross section is a very difficult task.

There is a better way to look for QCD effects in neutrino deep inelastic scattering.

We are told by our distinguished theoretical colleagues that QCD can make anambiguous predictions for the quantity:

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_L(x,q^2)}{2xF_1(x,q^2)} = \frac{F_2(x,q^2) - 2xF_1(x,q^2)}{2xF_1(x,q^2)} \qquad (3)$$

Such a calculation[13] is shown in Figure 2. The naive parton model[14] predicts:

$$R_{NPM} \simeq 4(\langle K\rangle^2 \pm \Delta^2)/q^2 \qquad (4)$$

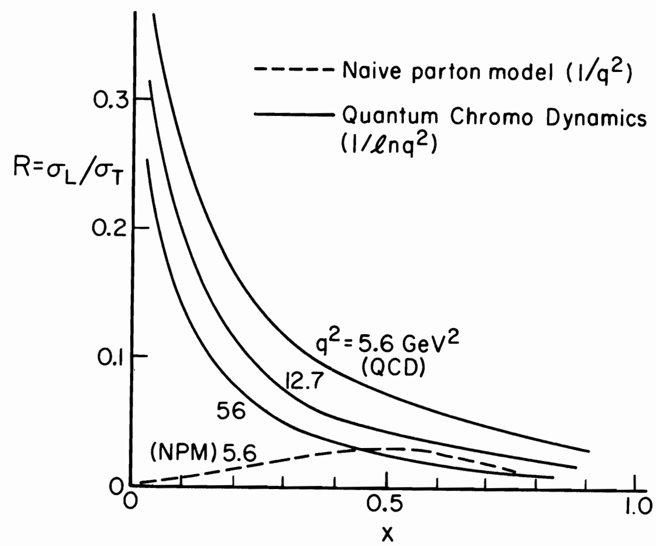

Fig. 2 Theoretical Prediction for σ_L/σ_T

where $\langle K\rangle^2$ is the "primordial transverse momentum of the quarks within hadrons and Δ represents corrections due to the binding of the quarks. Therefore, R should fall dramatically with q^2 and to be so small as to the unmeasurable for $q^2 \gg 1$ GeV^2. In QCD the quark P is predicted to rise with q^2 due to the exchange of virtual gluons. However, the coupling to the gluons should fall like $1/\ell n\,(q^2/\Lambda^2)$. In that case

$$R_{QCD} \;\alpha\; \frac{\alpha(x)q^2}{q^2} \quad \frac{1}{\ell n q^2} \;\simeq\; \frac{\alpha(x)}{\ell n q^2} \qquad (5)$$

where $\alpha(x)$ is some function of x. Specifically the value of the longitudinal structure function is given by[15]

$$F_L(x,q^2) = \frac{\alpha_s(q^2)}{2\pi}\; x^2 \left[\int_x^1 \frac{dy}{z^3}\, \frac{8}{3}\, F_2\,(z,q^2)\, dz + \int_x^1 \frac{dz}{z^3}\, 16\, \left(1 - \frac{x}{z}\right) G(z,q^2)\, dz \right. \qquad (6)$$

where $F_x(z)$ and $G(z)$ are z times the distributions in fractional momentum z, carried by the quarks and gluons, respectively. The coefficient is the quark-gluon coupling constant, $\alpha_s(q^2) = 12\pi/(33-2n)\ \ell n^{-1}\ q^2/\Lambda^2$. The integrals make it likely that $F_L(x,q^2)$ will be strongly peaked at small x as shown in Figure 2.

Since now all of the structure functions and R are expected to depend on both x and q^2, we must plot the y distributions with both x and q^2 fixed in order to measure them. One can always accommodate fixed x or q^2 by making specific angle and energy cuts. But, since $q^2 = 2mE_h x$, to fix both x and q^2 simultaneously, the y distribution must be made with E_h fixed. The alternative would be to extrapolate the data according to some theoretical predisposition but this might prejudice the results. Since $y = E_h/E_\nu$, the distributions must be made with E_h fixed and a variable E_ν. Hence data must be taken over a wide range of neutrino energies and all of these must be properly normalized.

With this experiment in mind a group of us from Cal Tech, Fermilab, University of Rochester, and Rockefeller University designed a neutrino beam and detector which would provide us with sufficiently high rates and have small enough systematic errors that we could attempt a precision measurement of the structure functions including a measurement of $R = \sigma_L/\sigma_T$. We are currently engaged in that measurement.

Today what I shall report on are the results from a preliminary run during the summer of 1978. This is a measurement of the neutrino charged current total cross section up to neutrino energies of 260 GeV. This measurement is interesting in its own right because it extends the knowledge of the linearity of the total cross section into a new energy region and is an important preliminary step in extracting the structure functions where an understanding of the relative and absolute normalization of the data is crucial. Since this is a presentation of first results from a new apparatus, I will spend a longer time than in customary in discussing the apparatus.

The experiment is located in the NØ beamline of the Neutrino Lab at Fermilab. The experiment has three major components as shown in Figure 3:

1. The new N-30 dichromatic neutrino beam[16] was designed specifically for this experiment. The parameters of the beam are shown in Table II. The beam is of a twisted design which has the property that it does not point at the detector until the final bend. This minimizes the wide band background present in the beam. The narrow momentum byte and small angular divergence along with the long geometry of the FNAL neutrino beams produces a newutrino energy spectrum which has a very clear separation between the neutrinos due to two body π decay and those due to two body K decay. We have run this beam at momenta between 90 and 300 GeV/c. It is capable of going to 350 GeV/c. The data I will discuss today was taken at beam settings of +200 GeV/c and +300 GeV/c.

TABLE II

N-30 Beam Parameters

Incident Proton Energy	400 GeV/c
Target Material	BeO
Incident Spot Size	2 x 0.5mm^2
Targetting Angles	
Horizontal:	11.96 mr
Vertical:	1.125 mr
Momentum Byte	±9%
Angular Divergence	
Horizontal:	±0.15 mr
Vertical:	±0.18 mr
Secondary Energy	90 - 300 GeV

2. The second component is the secondary flux monitoring system located in the 340m long evacuated decay pipe located downstream of the last beam magnet. There are two monitoring stations. The first station located at 140m contains ion chambers for total beam intensity monitoring and steering information, a segmented wire ionization chamber for beam profiles, an

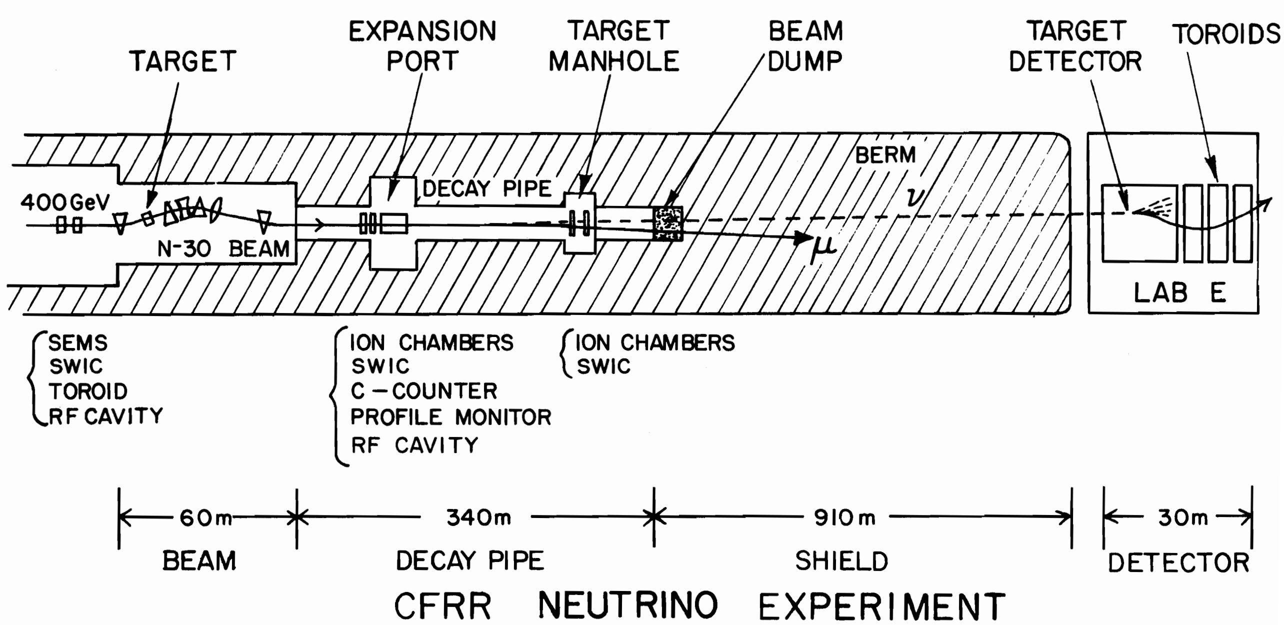

Fig. 3 Experimental Setup of CFRR Neutrino Experiment

integrating differential Cerenkov counter to determine particle fractions and an RF cavity for absolute intensity calibration. A second station located at 280m contains another set of ion chambers which allow us to determine the angle as well as the position of the secondary beam and serve as a backup for intensity monitoring and another segmented wire ionization chamber which allows us to determine the angular divergence of the beam. The ion chambers have been measured to be linear to better than 1% over our operating region. The two sets of split plate ion chambers allow us to maintain the position of the neutrino beam stable in our detector to ±3cm with a 1300m lever arm. The Cerenkov counter is designed to integrate the Cerenkov light during each beam pulse rather than count individual particles. This allows us to put the counter in the beam while we are running. The measured particle fractions are shown in Table III. The points at 200 GeV/c are in good agreement with our previous work[5] which used particle counting techniques. This agreement gives us confidence that the integrating technique is successful.

TABLE III

Polarity	P_π (GeV/c)	K/π	P/π
+	198 ± 18	0.15 ± 0.009	3.94 ± 0.08
+	289 ± 26	0.24 ± 0.012	36.8 ± 0.7

3. The third component is a separated function neutrino detector located downstream of a 910m muon shield. The characteristics of the detector are shown in Table IV. The entire detector weighs 1100 tons. The upstream portion is a 680 ton instrumented iron target followed by a 420 ton muon spectrometer. The entire detector can be moved into a hadron beam for calibration. The iron target is instrumented with liquid scintillation counters for calorimetry and with spark chambers to track muons. The resolutions show in the table are measured. The eighty scintillation counters in the target are somewhat unique in that they use the wave shifter technique[17]. Each counter is a hollow tank filled with liquid scintillator viewed by four phototubes through wave shifter bars. The light produced by the ionizing radiation is shifted into the blue and travels with total internal reflection to the edge of the counter where it crosses an air gap into the shifter bar where it is shifted into the green and goes to the phototube. Each counter has been tested to be linear in response all the way from a single muon up to a 300 GeV hadron shower. The balance of the tubes is maintained by a light flasher system and the overall gain of the counter is monitored by muons which go through the apparatus. The muon spectrometer is a magnetized iron toroid instrumented with acrylic scintillation counters also utilizing shifter bars to measure energy loss and with spark chambers to muons.

TABLE IV

CFRR Neutrino Detector

<u>Target/Calorimeter</u>	
Dimensions	3m x 3m x 20m
Weight	680 tons: Fe
Counters	10cm spacing
Hadron Energy Resolution	$\Delta E/E = 0.93/\sqrt{E}$(GeV)
Spark Chambers	20cm spacing
Angular Resolution	$\Delta\theta_\mu(\text{mrad}) = 0.30 + \frac{68}{p_\mu(\text{GeV/c})}$
<u>Muon Spectrometer</u>	
Dimensions	3.4m dia. x 10m
Weight	420 tons
Counters	20cm spacing
Hadron Energy Resolution	$\Delta E/E = 1.85/\sqrt{E}$(GeV)
Spark Chambers	80cm spacing
Muon Momentum Resolution	$\Delta p/p$ = 10%

The results presented here are based on 6000 charged current neutrino interactions found in a cylindrical fiducial volume 1.27m in radius and 13.2m long. For each event the hadron energy is corrected for the non-uniform response of the scintillation counters and the muon energy and angle were corrected for the effects of multiple scattering and energy loss in the iron. In addition, a geometric efficiency is calculated for each event. A correction was also made for the unsampled region of acceptance. This acceptance correction is less than 10% for low neutrino energies and decreases to about 2% for high energies. A subtraction is made for wideband background in the beam which we measure by taking data with the momentum collimator closed.

The calculation of the neutrino cross section is quite straightforward with a dichromatic beam. The events in any given radial bin on the target can be divided into high energy neutrinos from K decay and low energy neutrinos from π decay due to the nature of the beam. The neutrino flux into each radial bin from each type of decay is readily calculated from the measured composition, the properties of the beam, and two body decay kinematics. As an example, Figure 4 shows the measured high energy neutrino distribution in the radial bin from 0 to 50cm compared with the prediction of a Monte Carlo which simulates the beam.

The cross section divided by the energy is shown in Figure 5. The inner error bars are statistical. The outer error bars include systematic error. The high energy points are obviously limited by statistics. The low energy points have a significant systematic error due to steering problems which we have subsequently corrected. The overall preliminary result is:

$$\frac{\sigma_T}{E}_{\text{preliminary}} = (0.67 \pm 0.04) \times 10^{-38}\ \text{cm}^2/\text{GeV}.$$

In this experiment there is no indication at the present level of experimental precision for any deviation from linearity up to neutrino energies of 260 GeV.

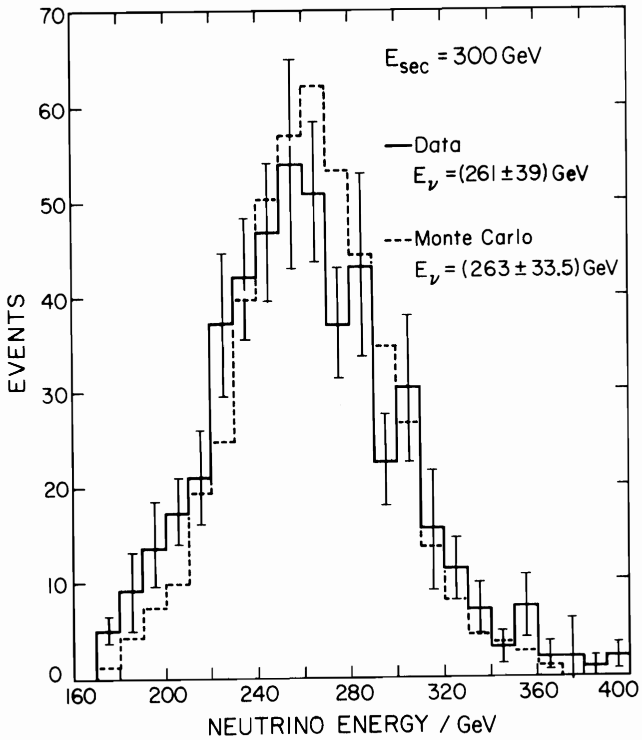

Fig. 4 Measured and Calculated Neutrino Energy Spectrum for Kaon Neutrinos in Radial Bin from 0 to 50cm.

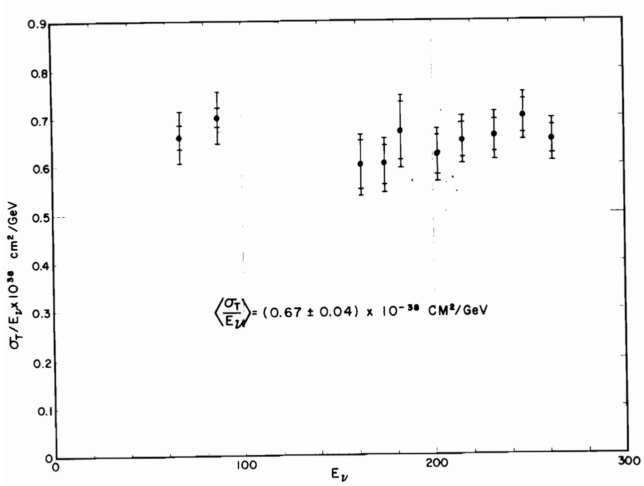

Fig. 5 σ_T/E_ν for this Experiment

The new CFRR neutrino detector is working quite well. The new N-30 dichromatic neutrino beam and the secondary flux monitoring systems are also working quite well. The systematic errors seem well under control. We are currently taking data in a long run where we expect to have sufficient precision to measure the structure functions including

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_2 - 2xF_1}{2xF_1}$$

and to reduce the errors on the absolute total cross section to approximately 3%.

In closing, I have shown in Figure 6 the experimental data for this parameter σ_T/E versus E for all of the newer and/or high statistics experiments earlier discussed in Table I. Where possible I have shown the statistical errors with the inner error bars and the total error including the systematic errors with the outer error bars. As you can see, one slope parameter can characterize all of the data above 20 GeV. The situation is more confused at the lower energies. Given the experimental errors involved and the spread in the different experiments below 20 GeV, I would find it hard to use this data to convincingly show asymptotic freedom effects using the slope parameter of the total cross section.

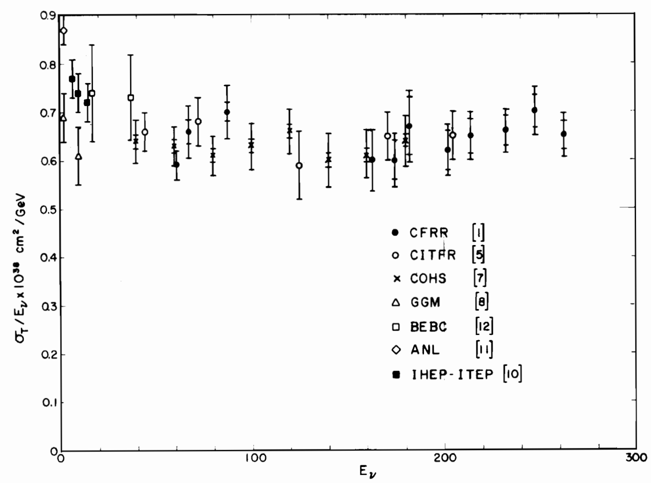

Fig. 6 σ_T/E_ν for all Recent Experiments

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Discussion

Q. (Rich Gaelick, University of Pennsylvania) You showed a nice plot at the end. Do you have a parametrization of that curve in terms of the slope parameter combined fit?

A. No I do not.

Q. (Zoltan Kunszt, DESY, Budapest, Roland Eotvos University) It was seen from your data that the systematic errors are definitely smaller than the CDHS. Could you comment?

A. That is what we believe.

Q. (Lincoln Wolfenstein, Carnegie-Mellon) Are you going to do antineutrinos and can one do antineutrinos with comparable accuracy?

A. We at the present time are engaged in a run. We have been running since the end of May on antineutrinos and we intend to run for several more weeks on antineutrinos.

Q. (Wolfenstein) Can you say what accuracy you will get?

A. We hope to do both neutrinos and antineutrinos with an accuracy of better than 3%.

Q. (Rosner, Minnesota) Can you place any lower limits on the W mass?

A. With 90% confidence, we can say it is above 20 GeV.