Review of ν and $\overline{\nu}$ Total Cross Section Measurements

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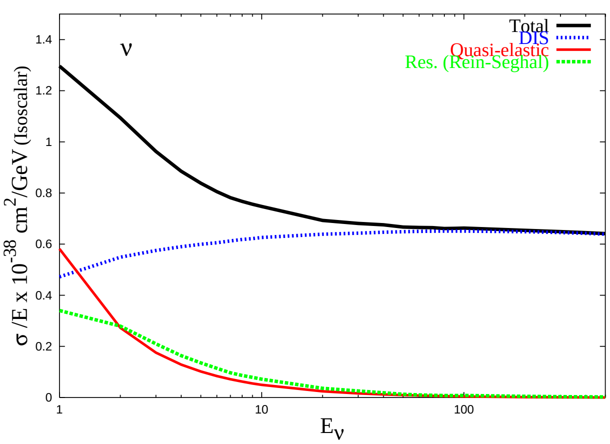
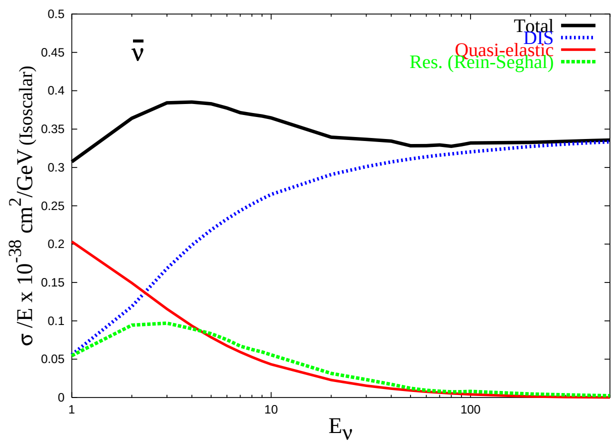
NuInt02, December 2002.

Outline

- Overview
- Neutrino Flux Determination.
- Total Cross section measurements
  - ↪ Low-moderate energy, $E_\nu < 30$ GeV (70's/early 80's).
  - ↪ High energy, $E_\nu > 30$ GeV (more recent).
- Relative Flux determination.
  - ↪ $r = \frac{\sigma^{\overline{\nu}}}{\sigma^{\nu}}$
  - ↪ Energy dependence ν and $\overline{\nu}$ total cross sections.
- Low-y inclusive cross section from NuTeV data.
  - ↪ Constrain models for low-energy contributions (QE, resonance).
- Summary and Conclusions

Total Cross Section Energy Dependence





$$\sigma_{\mathrm{TOT}} = \sigma_{\mathrm{QE}} + \sigma_{\mathrm{RES}} + \sigma_{\mathrm{DIS}}$$

- **Quasi-elastic** $\nu n \to \mu^- p, \overline{\nu} p \to \mu^+ n$

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G^2 \cos^2\theta_c}{8\pi E^2}\left[A(Q^2) \mp B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right]$$

$A(Q^2), B(Q^2), C(Q^2)$ depend on nucleon form factors; s, u Mandelstam vars.

- **Resonance** $\nu N \to \mu N^*$

Inelastic, Low-multiplicity final states, $\nu_\mu p(n) \to \mu^- \pi^+ p(n),\ \nu_\mu n \to \mu^- \pi^o p$

Excited baryon resonances decays (Rein Seghal, Ann. Phys **133**, p.79 1981).

- **Deep Inelastic (DIS)** $\nu N \to \mu X$

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G^2 M E}{\pi(1+\frac{Q^2}{M_w^2})^2}\left[F_2(x,Q^2)\left(\frac{y^2+(2Mxy/Q^2)}{2+2R_L(x,Q^2)} + 1 - y - \frac{Mxy}{2E}\right) \pm xF_3(x,Q^2)\left(y - \frac{y^2}{2}\right)\right]$$

General features

- $\frac{\sigma}{E}$ rises at low energy due to contributions from QE and Resonance processes.

  ↪ Both saturate at low energy (few GeV region).

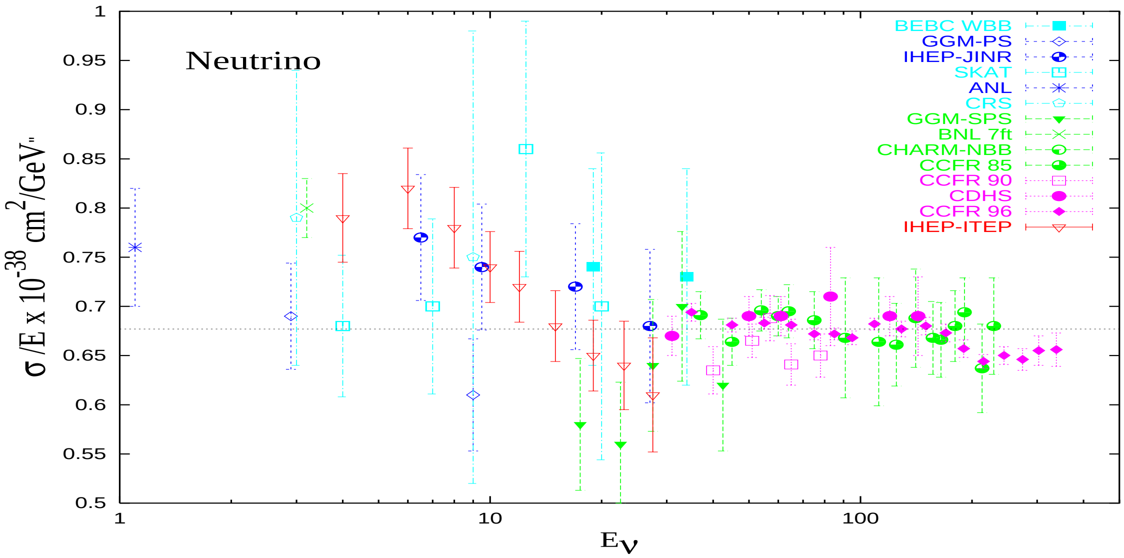
- At high energy $\frac{\sigma}{E}$ roughly flat and dominated by DIS.

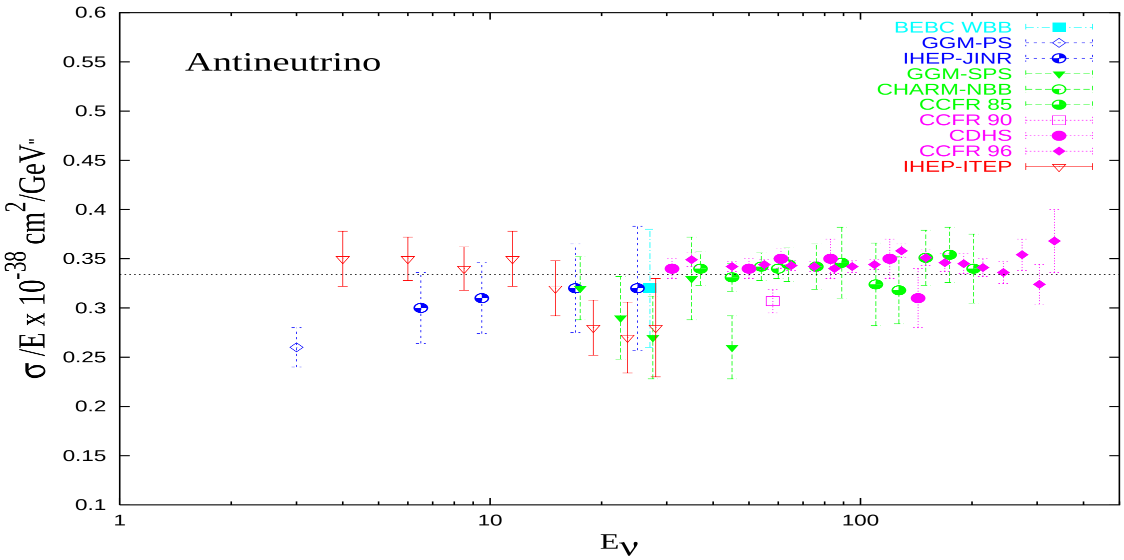
Cross section Modeling General Issue:

- Not clear how DIS/Resonances should be separated in models.

  ↪ Resonance processes are low Q^2 limit of DIS.

Overview of Data





(Ref. PDG 2002) Sorted by decade 1970's, 1980's, 1990's.

- Low energy data $E < 30\ GeV$ (Primarily 70's-early 80's)
  - ↪ Quasi-Elastic, Resonance, and DIS all important.
  - ↪ Low statistics, precision $\sim 10\%$
- High energy measurements $E > 30\ GeV$ (mid-80's-90's)
  - ↪ Cross section dominated by DIS (well understood).
  - ↪ High statistics, precision few percent.

Neutrino Flux Measurement

- Main systematic for absolute cross section measurements.
- Difficult task using indirect information.

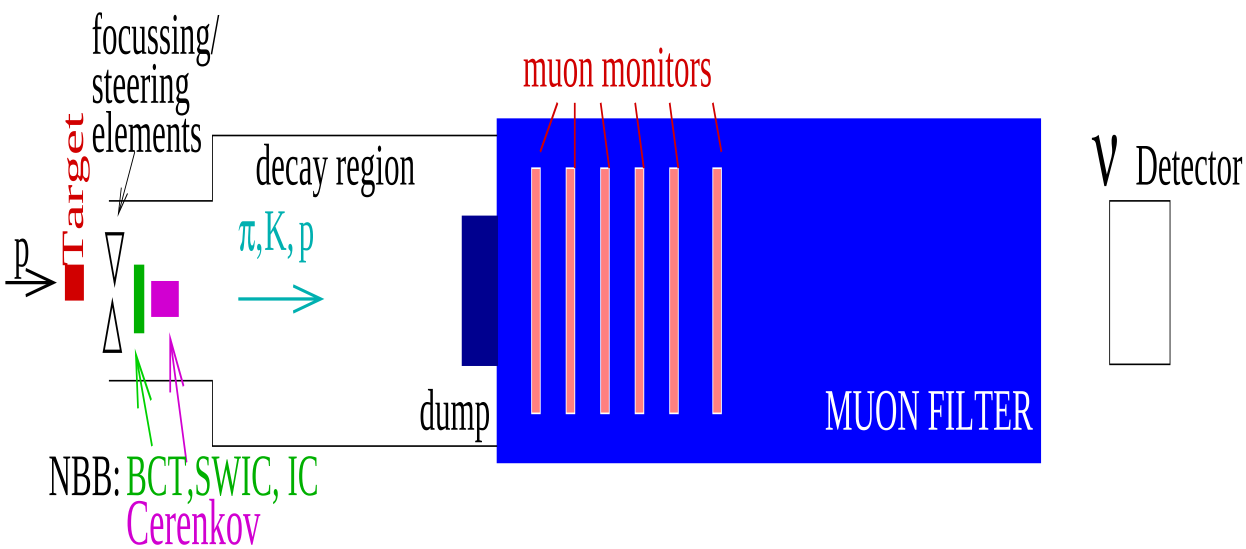
  ↪ Monitor $\nu(\overline{\nu})$ parent particle ($\pi^\pm \to \nu\mu^\pm$, $K^\pm \to \nu\mu^\pm$) intensity, energy, & spatial distribution and relate to $\nu(\overline{\nu})$ flux.

Measurements:

- Integrated intensities: (protons, charged secondaries)
- Energy and spatial distribution of (π, K, p, μ) after the target.
- Energy and spatial distribution of $\nu(\overline{\nu})$ interactions at detector.

Beam Simlation connects measured quantities with neutrino flux/spectra.

- Knowledge of particle production.
- Simulation of beam optics



- Total beam intensity (Beam toriod).
- Secondary intensities (SWICS, Ionization Chambers)
- Particle composition (Cerenkov, muon distribution/energy.)

Wide band beam (WBB)

- Maximizes acceptance for secondaries, large $\frac{\Delta P}{P}$
- Broad Energy range for secondaries in decay pipe, difficult to measure particle composition (also need energy).
- Typical experiment: Total beam intensity, tertiary muons at several stations in muon filter, neutrinos at detector.
- Flux determination $\tilde{>}$10%

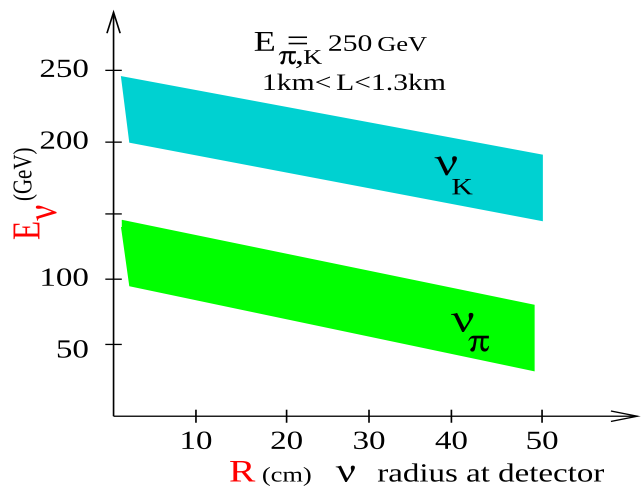
↪ Beam simulation: π,K energy/composition, absolute intensity calibrations.

Narrow band beam (NBB)

- Selects a small momentum bite for secondaries just after target.
- Strong position vs Energy correlation for ν from π vs ν from K.

$$E_\nu = \frac{E_{\pi,\mathrm{K}}\left[1-\left(\frac{m_\mu}{m_{\pi,\mathrm{K}}}\right)^2\right]}{\left[1+\left(\frac{R}{L}\gamma_{\pi,\mathrm{K}}\right)^2\right]}$$

$R = \nu$ radius at the detector.
$L =$ neutrino path length.
$\gamma_{\pi,\mathrm{K}} = \frac{E_{\pi,\mathrm{K}}}{m_{\pi,\mathrm{K}}}$
$\theta = \frac{R}{L}$ neutrino decay angle.

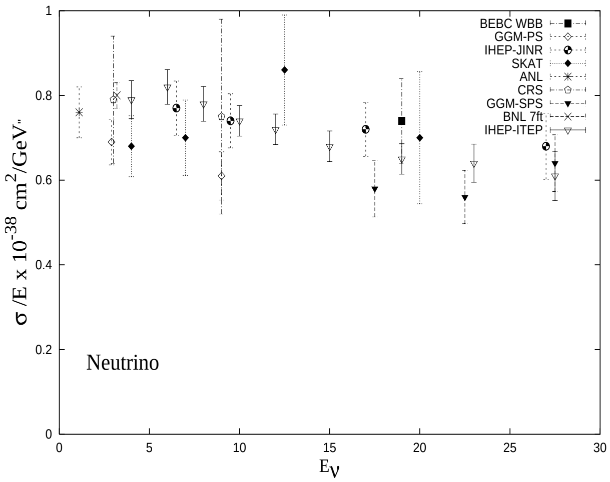


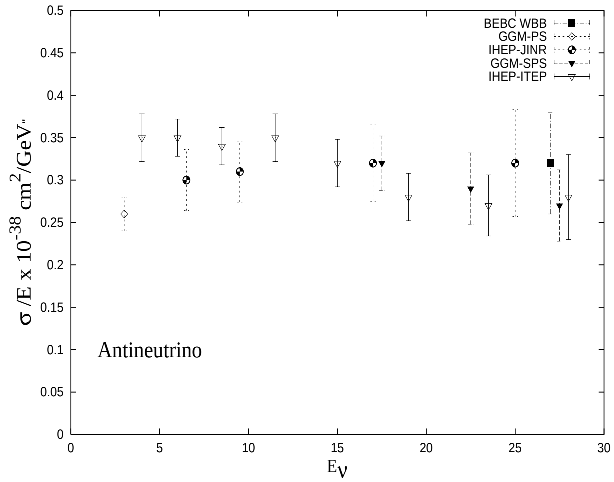
↪ Additional constraint on flux simulation.

- Measurement of particle flux and composition in decay pipe π, K, $p \rightarrow$ (energy is known).
- Measurement of muons distribution,range; Monitoring of halos/losses in decay pipe.
- Overall flux systematics reduced to 3-5% level.

↪ Intensity calibration (3-5%), π/K beam composition.

Low Energy Data





- Fine grained detectors
  - ↪ Bubble Chambers
    - ⋆ Gargamelle
    - ⋆ BEBC
    - ⋆ ANL 12 ft.
    - ⋆ BNL 7ft
    - ⋆ SKAT
  - ↪ Exception: IHEP (1996) Al Calorimeter
- Low-moderate statistics
- Main systematic: Flux determination.
  - ↪ Wide-band beams.
  - ↪ Typical flux systematic 10%
- Measurement of E_ν at Low energy
  - ↪ Account for energy from missing neutrals ⇒ large corrections at low energy.

Low Energy Data (cont'd)

Expt.	year	E (GeV)	precision ($\frac{\sigma^\nu}{E}$)
GGM-PS	'79	3,9	8-9%
ANL 12ft.	'79	1	9%
BNL 7ft	'80	3,9	19%,30%
SKAT	'79	4-20	11-20%
IHEP	'96	4-30	6-10%
GGM-SPS	'81	17-43	10-12%
BEBC	'79	19,34	13%

Bottom line: Measurements in this energy range $\gtrsim$ 10% level.

- Data do not strongly contsrain total cross section at low energies.

  ↪ More precise data is needed in this energy range.

- All three components DIS, QE, Resonance have substantial contributions in this region. (E$<$10 GeV)

$$\sigma_{\rm TOT} = \sigma_{\rm QE} + (\sigma_{\rm RES} + \sigma_{\rm DIS})$$

- Total cross section measurements are needed in addition to exclusive channels

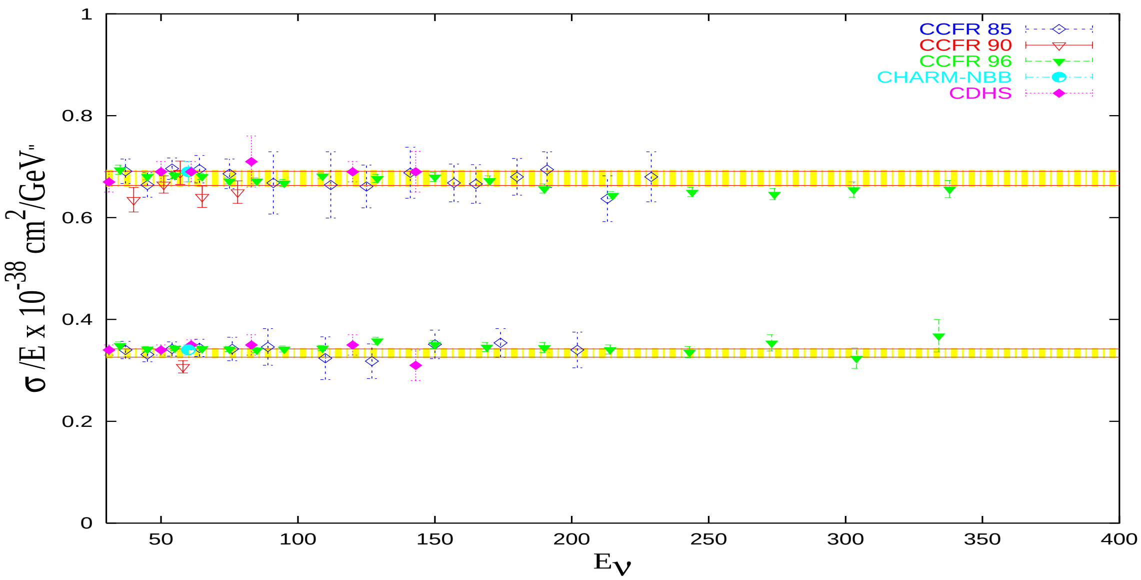
  ↪ Understand $\sigma_{\rm TOT}$ vs E in this region.

  ↪ Model relative contribution from low-multiplicity channels.

High Energy Data

Cross section dominated by DIS (well understood)

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G^2 ME}{\pi(1+\frac{Q^2}{M_w^2})^2}\left[F_2(x,Q^2)\left(\frac{y^2+(2Mxy/Q^2)}{2+2R_L(x,Q^2)}+1-y-\frac{Mxy}{2E}\right) \pm xF_3(x,Q^2)\left(y-\frac{y^2}{2}\right)\right]$$



- Measurements taken over wide energy range 30-330.
- High statistical precision, (systematics dominated)

  ↪ Typical detectors Calorimeter:
  - ⋆ CDHSW (Iron)
  - ⋆ CCFR (Iron)
  - ⋆ CHARM (Marble)
- Absolute Flux measurement improved by employing Narrow band beams.

High Energy (cont'd)

Expt.	Target	E (GeV)	$\frac{\sigma^{\nu}}{E} \times 10^{-38}$ cm^2/GeV	$\frac{\sigma^{\overline{\nu}}}{E} \times 10^{-38}$ cm^2/GeV
CCFR(84)	Iron	30-230	0.669±0.024 (3.5%)	0.340±0.02 (5.9%)
CDHSW(87)	Iron	10-160	0.686±0.019 (2.8%)	0.339±0.01 (2.8%)
CHARM(88)	$CaCO_3$	10-160	0.686±0.02 (2.9%)	0.335±0.01 (3%)
CCFR(90)	Iron	30-75	0.659±0.039 (5.9%)	0.307±0.02 (6.5%)
Average		30-200	0.677±0.014 (2%)	0.334 ± 0.008 (2.4%)

Bottom Line:

- Statistical errors are $\sim$ $10\times$ small than systematics for this data.
- Flux uncertainty reduced to ~3-5%
- World average 30 GeV<E<200 GeV

  ↪ $\frac{\sigma^{\nu}}{E}$ to 2%,

  ↪ $\frac{\sigma^{\overline{\nu}}}{E}$ to 2.4%.

Measurement of $r = \frac{\sigma^{\overline{\nu}}}{\sigma^{\nu}}$

Known more precisely than either absolute cross section:

- Some systematics (i.e. intensity monitor calibrations) in absolute flux measurement calculation cancel in ratio.
- Relative flux techniques can also be used.
  - ↪ Measure $r = \frac{\sigma^{\overline{\nu}}}{\sigma^{\nu}}$
  - ↪ Precise measurements of cross section Energy dependence.

Expt.	Target	E (GeV)	r	Prec.
CCFR(84)	Iron	30-230	0.499±0.025	5%
CDHSW(87)	Iron	10-160	0.495±0.010	2%
CHARM(88)	$CaCO_3$	10-160	0.488±0.013	2.6%
CCFR(90)	Iron	30-75	0.467±0.028	5.9%
CCFR(96)	Iron	30-330 (WBB)	0.509± 0.010	2%
Average		30-200	0.500±0.007	1.4%

- Precision 2-5%
- World average 1.4%

Relative Flux Techniques

- Normalization is known $\rightarrow$ determines energy dependence.
- Can be used to determine flux shape in WBB.

1. "y-intercept method" $y \rightarrow 0$ limit of the cross section.
   $\rightarrow$Constant (indep. of energy) and equal for ν, $\overline{\nu}$.
   $\frac{1}{E}\frac{d\sigma^{\nu}}{dy}_{\lim y\rightarrow 0} = \frac{1}{E}\frac{d\sigma^{\overline{\nu}}}{dy}_{\lim y\rightarrow 0} = \int_0^1 F_2(x,Q^2)dx \approx C$
   Fit $\frac{dN}{dy}$ for intercept, $\frac{1}{E}N(\mathrm{E})_{y=0} = C\Phi(\mathrm{E})$
2. "Fixed ν_o method": Integrate data at low ν
   Write $\frac{dN}{d\nu} = \Phi(E)\frac{d\sigma}{d\nu}$ as a polynomial in $y(=\frac{\nu}{E_\nu})$

$$\frac{dN}{d\nu} = \Phi(E)A\left(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}\right)$$

$$A = \frac{G_F M}{\pi}\int F_2(x)dx$$
$$B = -\frac{G_F M}{\pi}\int \left(F_2(x) \mp xF_3(x)\right)dx$$
$$C = B - \frac{G_F M}{\pi}\int F_2(x)\left(\frac{1+2Mx/\nu}{1+R(x)} - \frac{Mx}{\nu} - 1\right)dx$$

At low ν ($\nu < \nu_o$) and high $E_\nu \rightarrow (\frac{\nu}{E})$, and $(\frac{\nu}{E})^2$ terms are small.

- Fit to $\frac{dN}{d\nu}$ determines $\frac{B}{A}$ ($\frac{C}{A}$).
- Relative Flux is determined by integrating up to a fixed $\nu = \nu_o$ and applying corrections up to order $(\frac{\nu}{E})^2$.

$$\Phi(\mathrm{E}) = \int_0^{\nu_0}\left(\frac{\frac{dN(\mathrm{E})}{d\nu}}{1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2}}\right)d\nu$$

- This ignores implicit (small) ν dependence in F_2,xF_3 from scaling violations, $Q^2 = 2M\nu x$ in $F_2(x,Q^2), xF_3(x,Q^2)$.
  New measurement by NuTeV will correct for this $\delta r \approx -1.5\%$

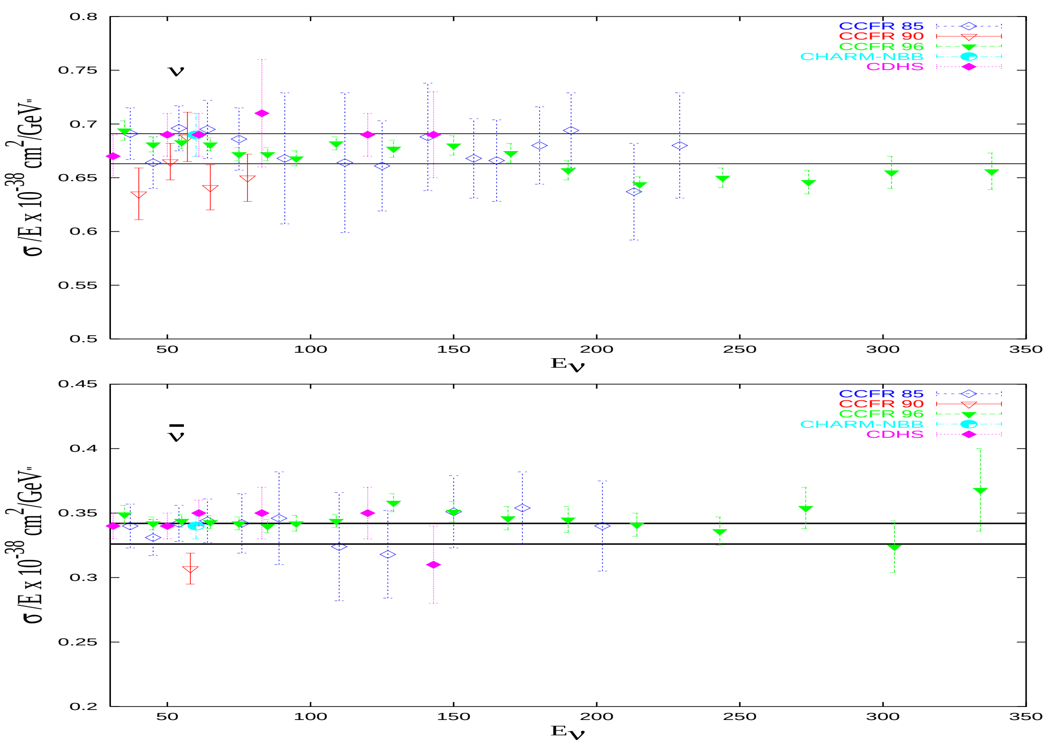
$\frac{\sigma}{E}$ at High Energy

- Highest energy data (CCFR) normalize to world average :

$$\frac{\sigma^\nu}{E} = 0.677 \pm 0.014 \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV}\ (30 < E_\nu < 200)$$

and apply relative flux technique.

- Allows precise determination of the energy dependence of $\frac{\sigma}{E}$.



- Measure energy slope of partonic level cross section:

$$\frac{\Delta(\frac{\sigma^\nu}{E})}{\Delta E} = (-2.2 \pm 0.8)\%\ /100\ \mathrm{GeV}.$$

$$\frac{\Delta(\frac{\sigma^{\bar\nu}}{E})}{\Delta E} = (-0.2 \pm 1.3)\%\ /100\ \mathrm{GeV}.$$

NuTeV Measurements

- Improved knowledge of E_μ and E_{HAD} energy scales. (E_μ Important in relative flux technique).

  ↪ E_{HAD} to 0.43%, E_μ to 0.5% (2$\times$ improvement over CCFR).

- Cross section ratio measurement for NuTeV will be systematically improved by including scaling violations correction (implicit ν dependence in $F_2(x,Q^2), xF_3(x,Q^2)$) in "fixed ν" relative flux technique.

- Potential improvement in r, $\frac{\sigma^\nu}{E}$, $\frac{\sigma^{\overline{\nu}}}{E}$.

  ↪ Measurement of Structure Functions
  $F_2(x,Q^2), xF_3(x,Q^2)$, $R(x,Q^2)$

- Examine Low-y (low-ν) inclusive cross section.

  ↪ QE, resonance production populate the low-y region.

  QE and resonance events:
  $y,\nu \rightarrow 0$, $Q^2 \rightarrow 0$,
  $x \rightarrow 1$

  $\nu = E_{\mathrm{HAD}}, \quad y = \frac{\nu}{E_\nu}$
  $x = \frac{Q^2}{2m\nu}$
  $W^2 = M^2 + 2ME_{\mathrm{HAD}} + Q^2$

  ↪ Comparison with models: Constrain models for low-energy contributions (QE, resonance).

NuTeV Low ν Data

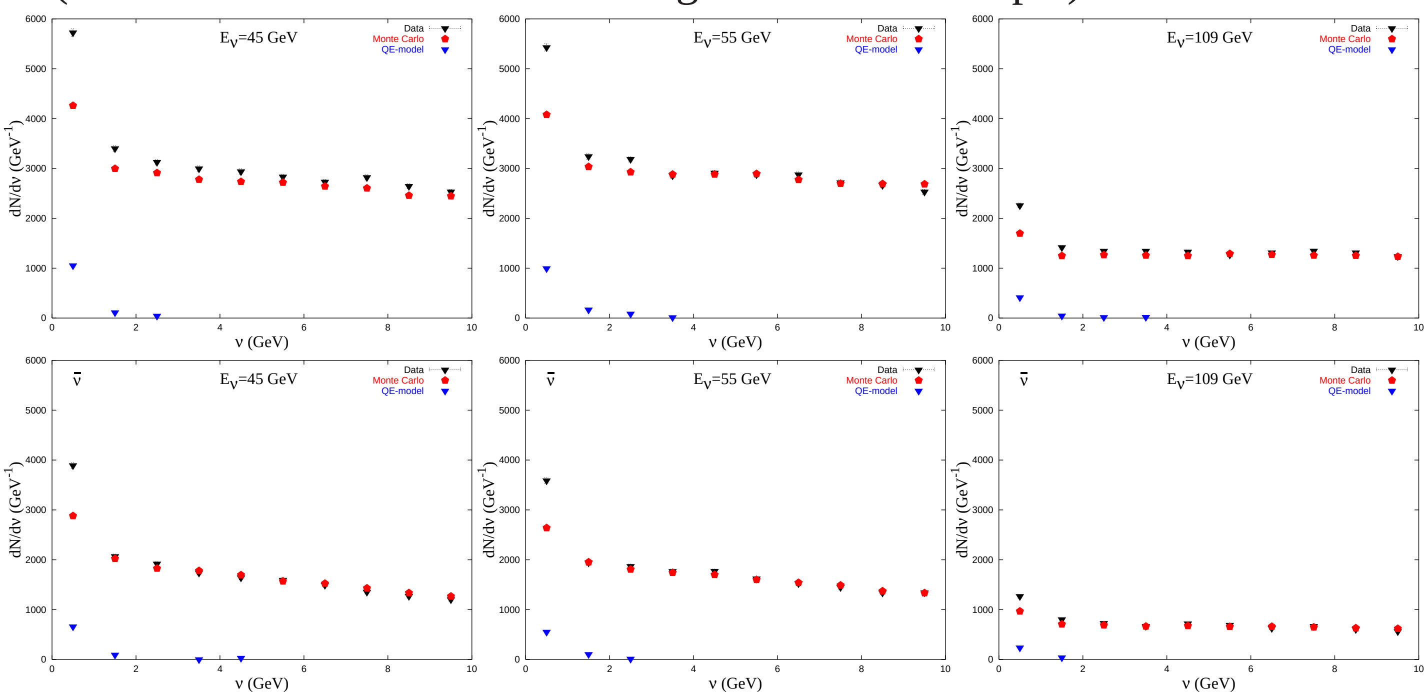
Low ν (low y) data Sample:

- $E_\mu > 15\ GeV$
- Fiducial cuts.
- $\nu (= E_{\rm HAD}) < 10$ GeV

- NuTeV data - energy range $30 < E_\nu < 300 GeV$

(Thesis of N. Suwonjandee)

(MC Flux and Normalization using ν >10 GeV sample)



- Measure and understand low ν excess

  $\hookrightarrow$ (Smearing at low $E_{HAD} \rightarrow$ Testbeam data down to 5 GeV.)

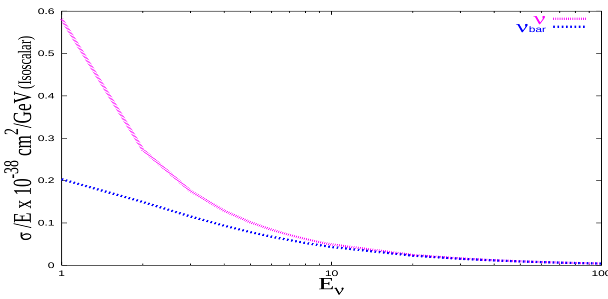
- This model does not account for peak at low ν.

NuTeV Cross Section Model

$$\sigma_{tot} = \sigma_{\rm DIS} + \sigma_{\rm QE}$$

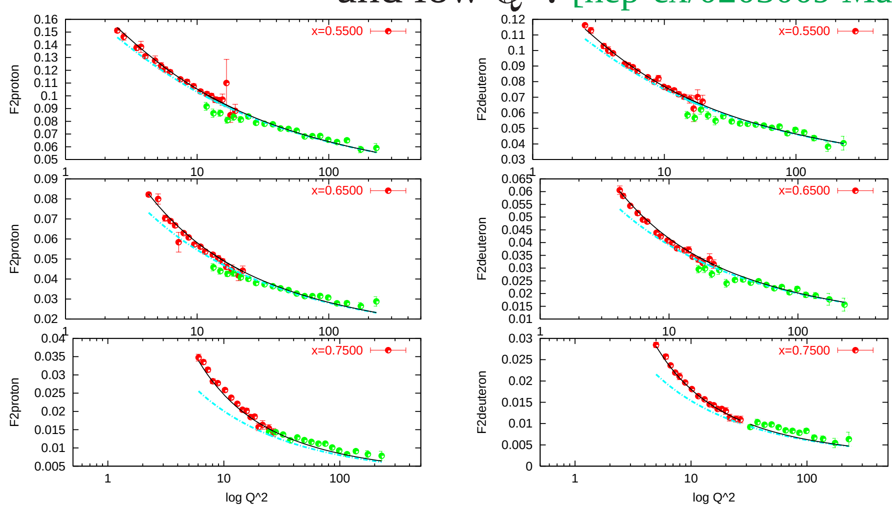
$\sigma_{\rm QE}$ $\quad \nu n \rightarrow \mu^- p,$

$\quad \overline{\nu} p \rightarrow \mu^+ n$



$\sigma_{\rm DIS}$

- $q(x, Q^2)$ and $\overline{q}(x, Q^2)$ distributions, extracted from fits to NuTeV data (R_L and charm production from other data, low $Q^2 \rightarrow 0.25$ GeV evolution from GRV).
- Fit to ep, ed data (SLAC,BCDMS) to parameterize Target Mass and Higher Twist effects in $F_2(x, Q^2)$ important at high x and low Q^2. [hep-ex/0203009 May 2002 A.Bodek and U.K.Yang]

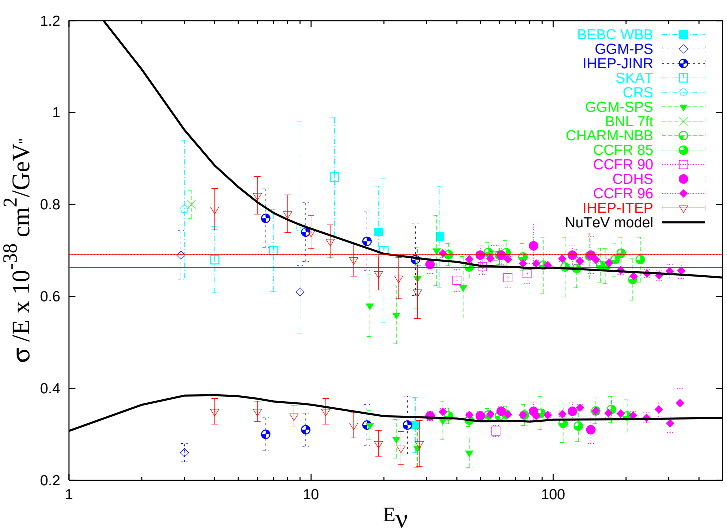


$$\mathrm{x}' = \mathrm{x}\frac{\mathrm{Q}^2 + \mathrm{B}}{\mathrm{Q}^2 + \mathrm{A}\mathrm{x}}$$

$$\mathrm{F}_2 \rightarrow \left(\frac{\mathrm{Q}^2}{\mathrm{Q}^2 + \mathrm{C}}\right)\mathrm{F}_2(\mathrm{x}', \mathrm{Q}^2)$$

A	0.57
B	0.22
C	0.06
χ^2/dof	792/312

- Models total cross section data (ν and $\overline{\nu}$) down to $\sim$ 5 GeV.
- Low ν data suggest additional contribution, needed, $\sigma_{\rm RES}$



Conclusions and Summary

Low energy region (E<30 GeV)

- Total cross section only know to $\gtrsim$10%
  - $\hookrightarrow$ Most of data are from measurements 70's & 80's
    - ⋆ Statistical precision.
    - ⋆ Flux measurement (WBB).
    - ⋆ Neutrino energy reconstruction.
- More precise Total cross section vs Energy measurement needed in this region.
  - $\hookrightarrow$ Need both $\sigma_{\rm TOT}$ and exclusive reactions to understand low Q^2 DIS and Resonance pieces.
  - $\hookrightarrow$ Perhaps higher energy data at low y can help constrain models in this region.

High energy region (E>30 GeV)

- ν and $\overline{\nu}$ cross sections are know to $\sim$2% in this region.
- Future : high precision measurement of r and energy dependence (NuTeV).
  - $\hookrightarrow$ High-Energy (DIS) cross section well understood.