Workshop on Intersections of Nuclear Physics with Neutrinos and Electrons

Physics of Mutual interest to both
the Electron- and Neutrino-Scattering Communities

With emphasis on what Neutrino Scattering Brings to the Mix

Jefferson Laboratory Neutrino Workshop
4 May 2006

Jorge G. Morfín
Fermilab

SESSION 2. Structure Functions and Form Factors

- Overview from CTEQ – Fred Olness
- Vector and Axial Form Factors – Arie Bodek
- Quark distributions at large x – Wally Melnitchouk
- Nucleon and Nuclear Structure Function Measurements in the resonance region at low Q^2 – Eric Christy
- Medium modification of the form factors - Kuzuo Tsushima

Neutrino Quasi-elastic Scattering

Prime example of how combining data helps both communities

$$\frac{d\sigma}{d|q^2|}\begin{pmatrix}\nu n \to l^- p \\ \overline{\nu} p \to l^+ n\end{pmatrix} = \frac{M^2 G^2 cos^2\theta_c}{8\pi E_\nu^2}\left[A(q^2) \mp B(q^2)\frac{(s-u)}{M^2} + \frac{C(q^2)(s-u)^2}{M^4}\right]. \qquad (2)$$

In this expression, G is the Fermi coupling constant and θ_c is the Cabibbo mixing angle ($G = 1.16639 \times 10^{-5}\mathrm{GeV}^{-2}$). The functions A, B, and C are convenient combinations of the nucleon form factors.

Contraction of the hadronic and leptonic currents yields:

$$A = \frac{(m^2 - q^2)}{4M^2}\left[\left(4 - \frac{q^2}{M^2}\right)|F_A|^2 - \left(4 + \frac{q^2}{M^2}\right)|F_V^1|^2 - \frac{q^2}{M^2}|\xi F_V^2|^2\left(1 + \frac{q^2}{4M^2}\right) - \frac{4q^2 Re F_V^{1*}\xi F_V^2}{M^2} \qquad (3)\right.$$

$$\left. + \frac{q^2}{M^2}\left(4 - \frac{q^2}{M^2}\right)|F_T|^2 - \frac{m^2}{M^2}\left(F_V^1 + \xi F_V^2|^2 + |F_A + 2F_P|^2 + \left(\frac{q^2}{M^2} - 4\right)\left(F_S|^2 + F_P|^2\right)\right)\right]$$

$$B = -\frac{q^2}{M^2} Re F_A^*(F_V^1 + \xi F_V^2) - \frac{m^2}{M^2} Re\left[\left(F_V^1 + \frac{q^2}{4M^2}\xi F_V^2\right)^* F_S - \left(F_A + \frac{q^2 F_P}{2M^2}\right)^* F_T\right] \qquad (4)$$

$$C = \frac{1}{4}\left(|F_A{}^2 + F_V^1{}^2 - \frac{q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2 - \frac{q^2}{M^2} F_T|^2\right), \qquad (5)$$

Axial Form Factor from Neutrino Quasi-elastic Scattering

From neutrino scattering - From electron scattering

$$\frac{d\sigma}{d|q^2|}\begin{pmatrix}\nu n \to l^- p \\ \bar{\nu} p \to l^+ n\end{pmatrix} = \frac{M^2 G^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(q^2) \mp B(q^2)\frac{(s-u)}{M^2} + \frac{C(q^2)(s-u)^2}{M^4}\right]. \quad (2)$$

In this expression, G is the Fermi coupling constant and θ_c is the Cabibbo mixing angle ($G = 1.16639 \times 10^{-5}\mathrm{GeV}^{-2}$). The functions A, B, and C are convenient combinations of the nucleon form factors.

Contraction of the hadronic and leptonic currents yields:

$$A = \frac{(m^2 - q^2)}{4M^2}\left[\left(4 - \frac{q^2}{M^2}\right)|F_A|^2 - \left(4 + \frac{q^2}{M^2}\right)|F_V^1|^2 - \frac{q^2}{M^2}|\xi F_V^2|^2\left(1 + \frac{q^2}{4M^2}\right) - \frac{4q^2 Re F_V^{1*}\xi F_V^2}{M^2}\right. \quad (3)$$

$$B = -\frac{q^2}{M^2} Re F_A^*(F_V^1 + \xi F_V^2) \quad (4)$$

$$C = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 - \frac{q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2\right) \quad (5)$$

Electron Scattering ⟷ Neutrino Scattering

- Jefferson Lab (Jlab) has performed precision experiments to determine the electroproduction form factors. The axial form factors are not as accessible at Jlab.
- Here neutrino scattering (V & A Currents) can help. CVC allows us to determine $G^V_E(q^2)$ and $G^V_M(q^2)$ from the elastic nucleon form factors from electroproduction:

$$F_V^1(Q^2) = \frac{G_E^V(Q^2) - \tau G_M^V(Q^2)}{1-\tau} \qquad \xi F_V^2(Q^2) = \frac{G_M^V(Q^2) - G_E^V(Q^2)}{1-\tau}$$

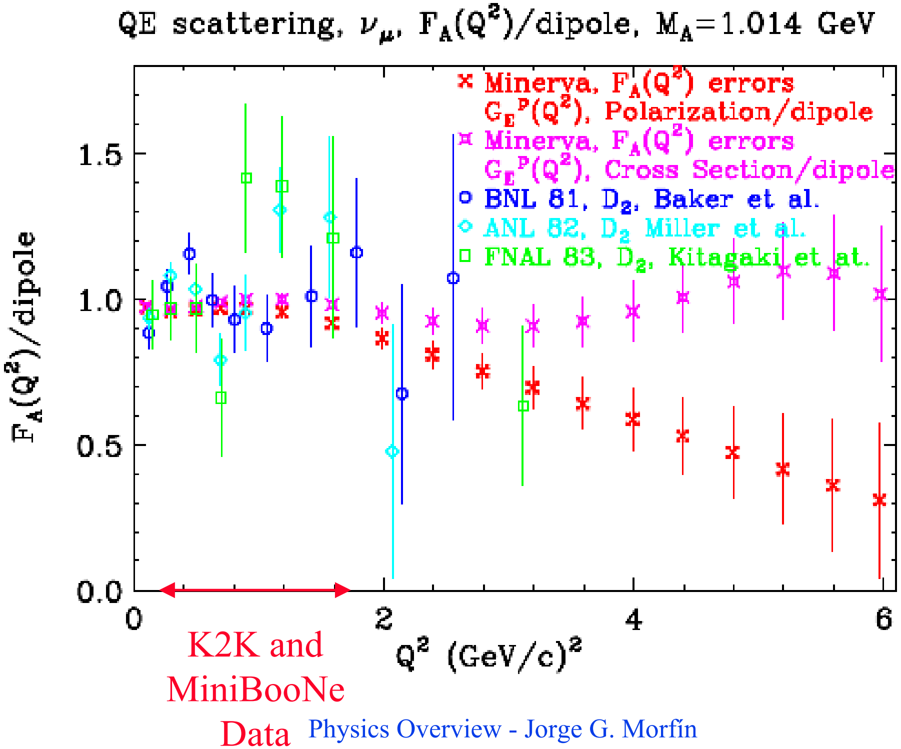
- Then F_V^1 and F_V^2 for νN elastic cross sections can be expressed in terms of G^V:

$$G_E^V(Q^2) = G_{ep}(Q^2) - G_{en}(Q^2),$$
$$G_M^V(Q^2) = G_{mp}(Q^2) - G_{mn}(Q^2)$$

with $\tau = q^2/4M^2$.

Neutrino Experimental Measurements of $F_A(Q^2)$

- Expect input from on-going experimental efforts:
  - K2K near detector analysis - Japan
  - MiniBooNe analysis - Fermilab
  - NOMAD and CHORUS - CERN
- Near Future effort - MINERνA



PDFs - Challenges for Global QCD Analysis

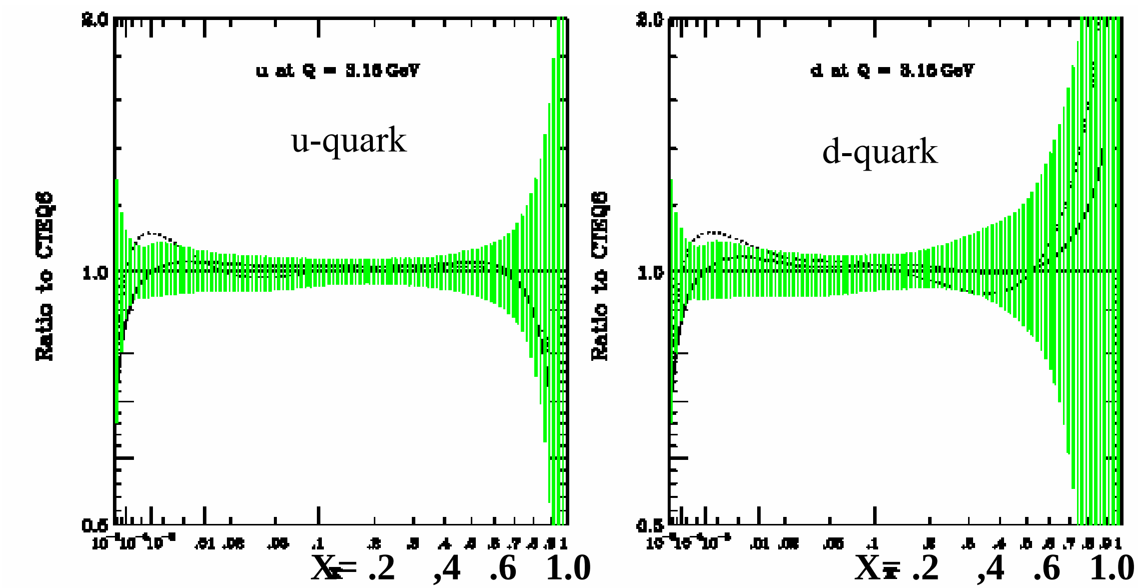
Wu-Ki Tung - DIS06

In spite of steady progress in over 20 years of global analysis of PDFs, it is surprising how much knowledge is still missing on the parton structure of the nucleon !

- Gluon Distribution;
- Small-x and **Large-x behavior of all distributions**;
- **Strange distribution**;
- Charm and bottom distributions;
- Quantifying uncertainties of all PDFs.

Structure Functions → High x_{Bj} Parton Distributions

Neutrino and electron scattering look at quarks at high-x?



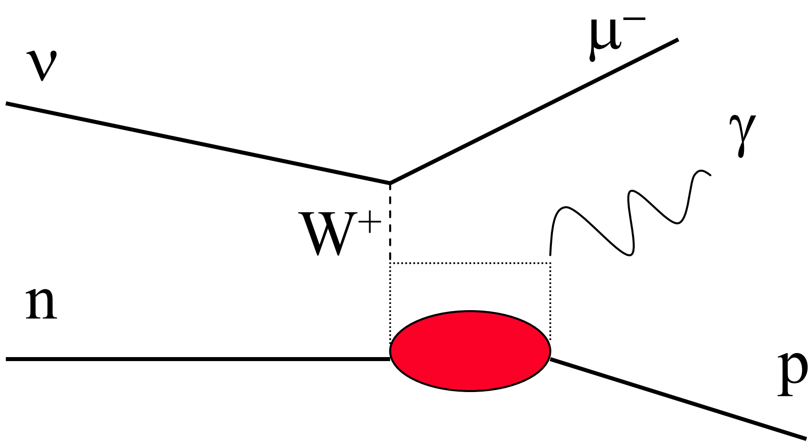
- Ratio of CTEQ5M (solid) and MRST2001 (dotted) to CTEQ6 for the u and d quarks at $Q^2 = 10\ GeV^2$. The shaded green envelopes demonstrate the range of possible distributions from the CTEQ6 error analysis.

- Recent high-x measurements indicate conflicting deviations from CTEQ:

  E-866: CTEQ u_V too **high,**

  NuTeV and now <u>(DIS2006) HERA:</u> CTEQ u_V & d_V too **low**

Generalized Parton Distribution Functions
Weak Deeply Virtual Compton Scattering



W> 2 GeV, t small, E_γ large -
Exclusive reaction

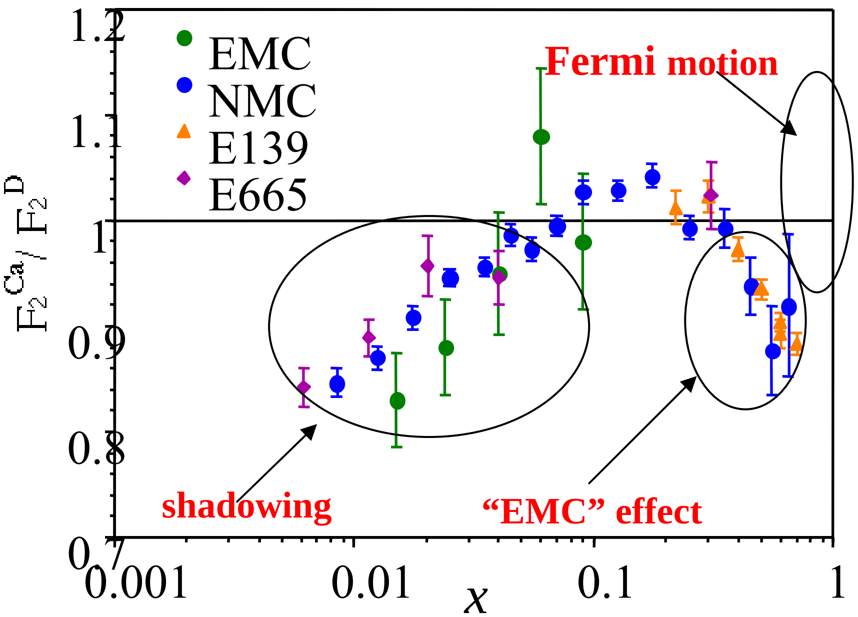
- GPDs can be measured with neutrinos
- Weak DVCS would allow flavor separation of GPDs

SESSION 3. Nuclear PDFs and Shadowing

- Global analysis for determining PDFs in nuclei - Shunzo Kumano
- Nuclear Modifications of Structure Functions - Roberto Petti
- Flavor dependence of the nuclear EMC effect -Ian Cloet

Knowledge of Nuclear Effects with Neutrinos: Essentially NON-EXISTENT

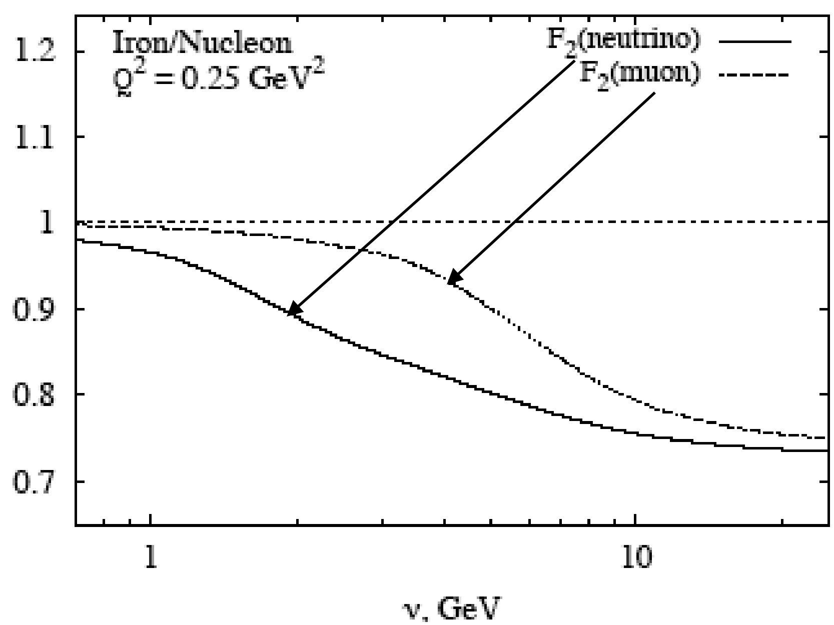
- F_2 / nucleon changes as a function of A. Measured in μ/e - A, **not in ν – A**
- **Good reason to consider nuclear effects DIFFERENT in ν - A.**
  - **Presence of axial-vector current.**
  - **Shadowing: different for ν - A.**
  - **NuTeV " favors smaller nuclear effects at high-x than are found in charged-lepton scattering"**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**



Shadowing with the Axial Current

Work of Kulagin and Petti

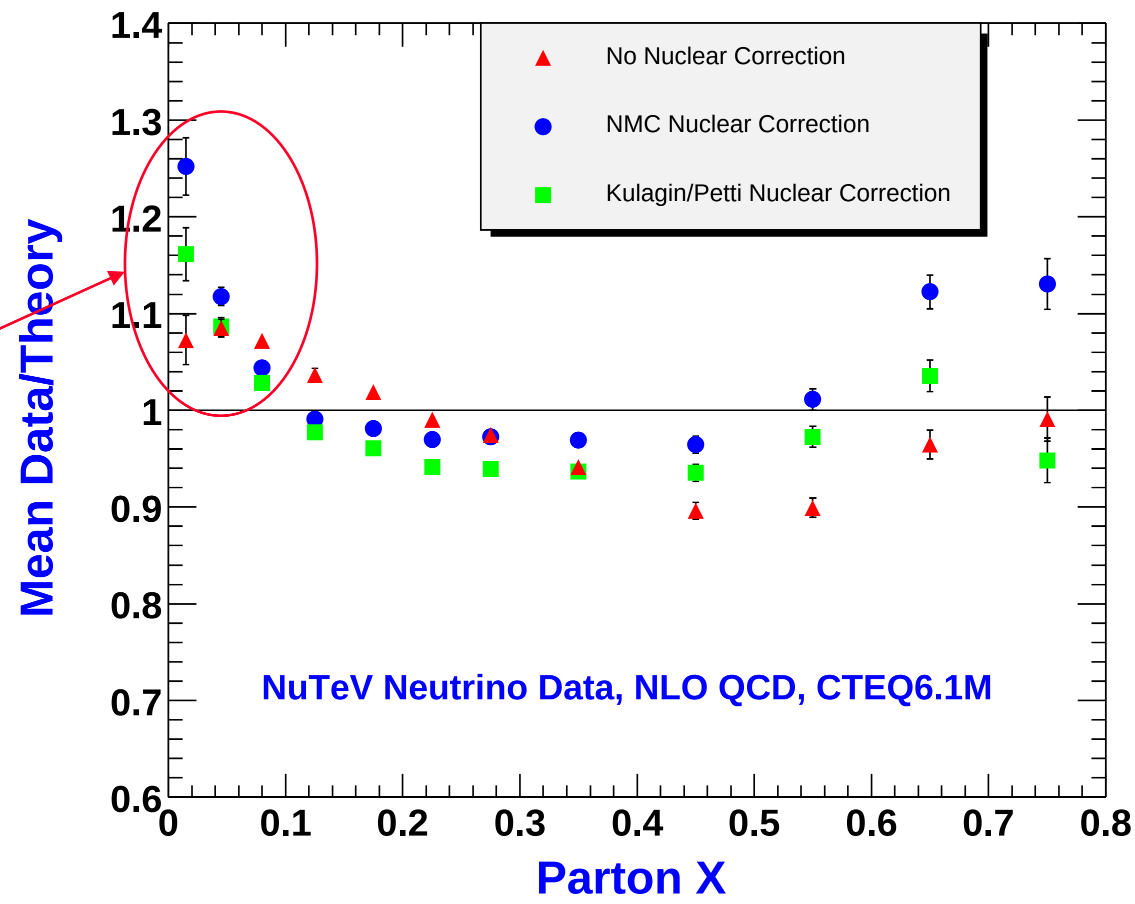
- With neutrinos the axial current would imply a different range of shadowing:
  - Coherence length shadowing condition: $L_c = 2\nu / (m_\pi^2 + Q^2)$ **(not** m_A^2**)** $\geq R_A$
  - **L_c calculated with m_π allows low ν - low Q^2 shadowing**
  - An effect only measurable with neutrino scattering



Kulagin

Attempt by CTEQ to introduce ν nuclear corrections to the fit with new NuTeV cross sections

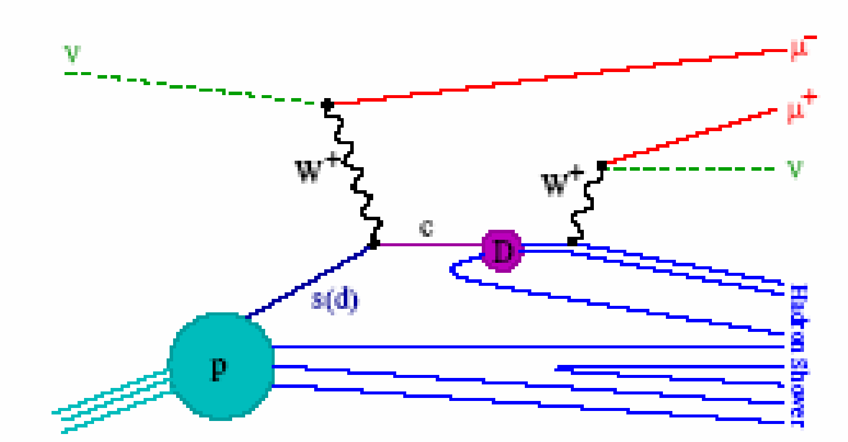
Our old nemesis - "the low-x ν problem" won't go away!



SESSION 4. Strangeness Content of the Nucleon

- Theory overview – Ross Young
- Neutrino measurements of strangeness, s-sbar, strange axial form factor – Rex Tayloe
- Electron scattering measurements – Dave Armstrong
- Strange nucleon form factors from ep and νp elastic scattering - Steve Pate

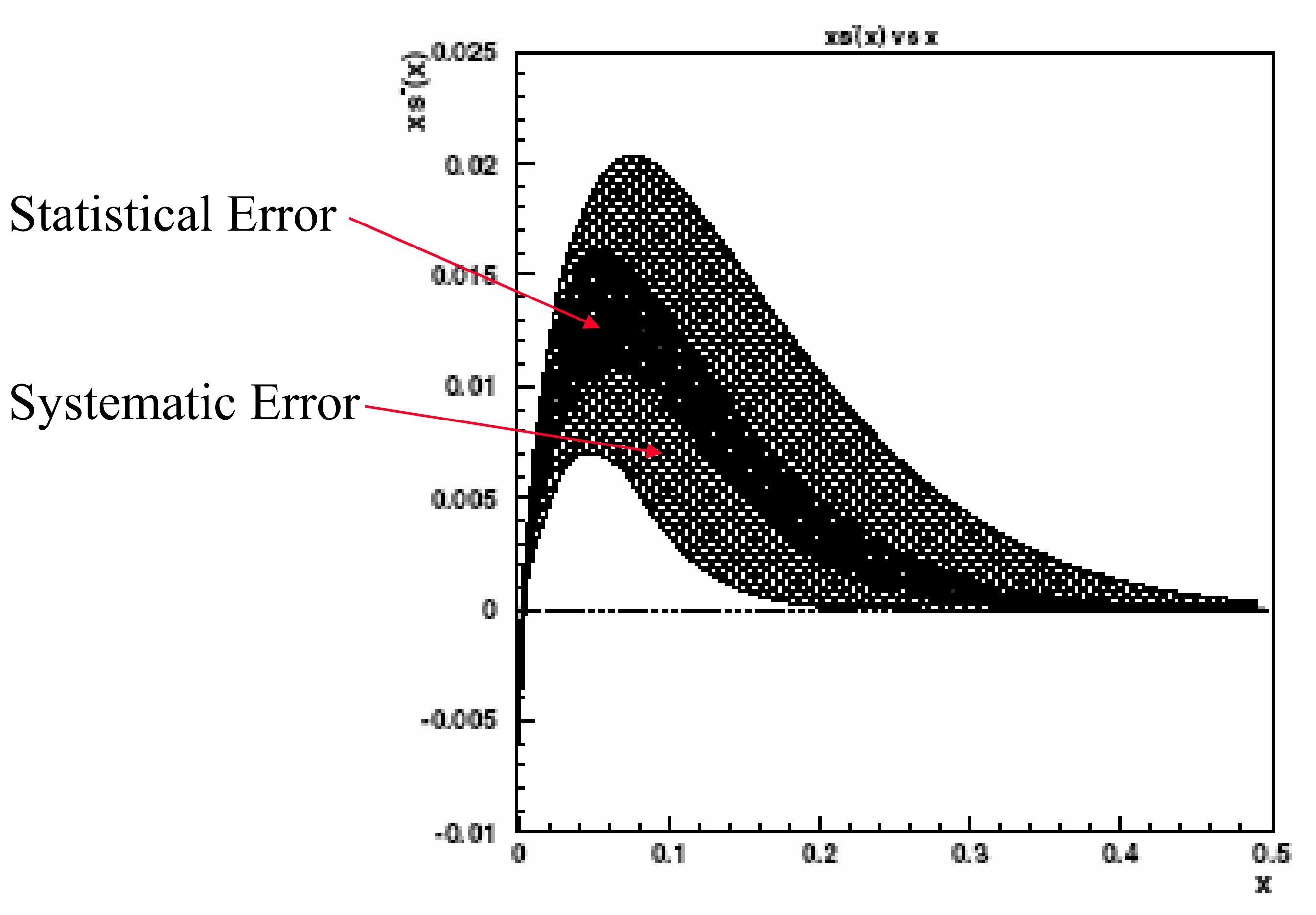
How Neutrinos study the Strange Sea



- Recent high-statistics study of s and $\bar{s}$ by the NuTeV Collaboration - D. Mason presentation at DIS2006
- Now concentrating on the strange sea asymmetry NLO analysis:
  - $s^-(x) = s(x) - \bar{s}(x)$ extracted to be positive over most of the x range.
- Can also measure strange axial form factor $G_A^S(Q^2)$ via ν+N QE
  - Natural area where combining ep + νp data yields rich results

Find Strange Asymmetry to be Positive

over most of x range

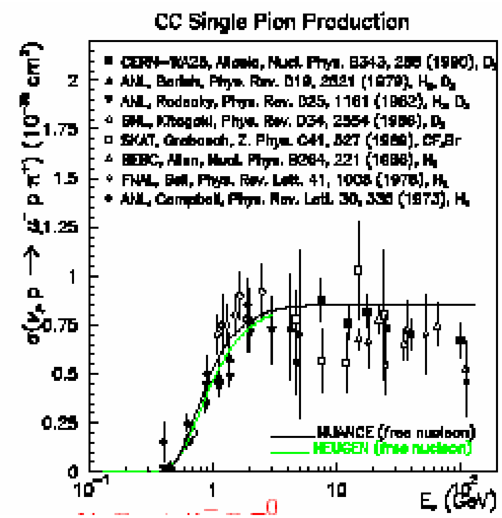


SESSION 5. Resonance production

- Dynamical model of electroweak production of nuclear resonances - Harry Lee
- Resonance production by electrons and neutrinos - Olga Lalakulich
- One-Pion Production in the MiniBooNe and K2K Experiments - Yoshinari Hayato
- MAID model – Mark Jones

Neutrino one-Pion Production: enter the Axial current

miserable existing sample of events



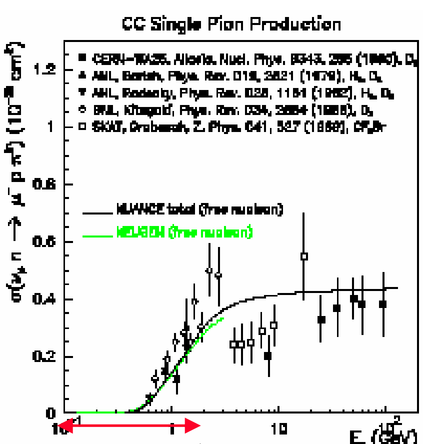
CC

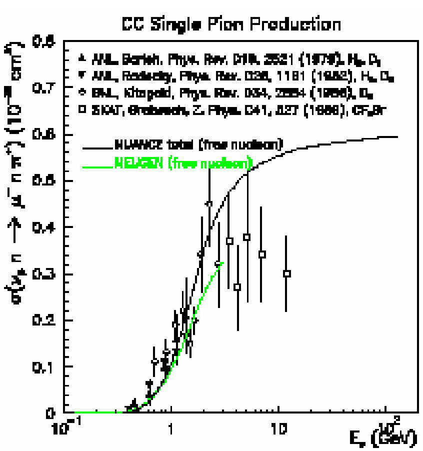
$\nu p \to \mu^- p \pi^+$

S. Zeller - NuInt04

$\nu n \to \mu^- p \pi^0$

$\nu n \to \mu^- n \pi^+$





K2K and MiniBooNe

Typical samples of NC 1-π

- ANL
  - $\nu\ p \to \nu\ n\ \pi^+$ (7 events)
  - $\nu\ n \to \nu\ n\ \pi^0$ (7 events)
- Gargamelle
  - $\nu\ p \to \nu\ p\ \pi^0$ (240 evts)
  - $\nu\ n \to \nu\ n\ \pi^0$ (31 evts)

For the last 25 years have had only the Rein-Sehgal model for pion production by neutrinos.

Now renewed interest with new experimental studies of resonance production.

SESSION 6. Nuclear medium effects and hadron propagation in nuclei

- Mulit-pion production – status and issues in Hall B – Steve Manly
- Hadron formation lengths - Will Brooks
- Nuclear effects in neutrino scattering – Luis Alvarez-Ruso

SESSION 7. Low Q^2 Modeling

- Overview of the Bodek-Park-Yang model – Un-Ki Yang
- Low energy neutrino cross sections - Hallsie Reno
- Low Q^2 structure functions – Roberto Petti
- Importance of the low Q^2 region in neutrino-nucleus scattering experiments – Makoto Sakuda
- What Monte Carlos need - Hugh Gallagher
- Models for electron scattering – Peter Bosted
- Electron- and Neutrino-nucleus scattering in the impulse approximation regime - Omar Benhar

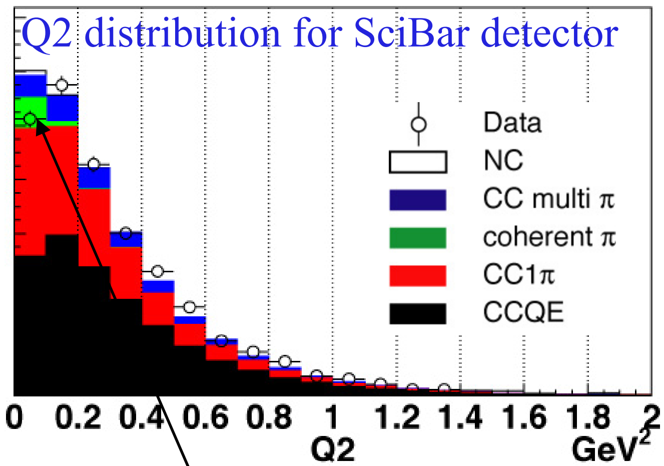
eA and νA Scattering at Low Q^2

- Differences - Electron and Neutrino Scattering at low Q^2
  - Only vector current in eA while axial vector also contributes to νA
  - Vector current conserved (CVC) while axial current only partially (PCAC)
  - F_2^ν approaches a non-zero value as $Q^2 \longrightarrow 0$
  - Confirmed by CCFR in 2000

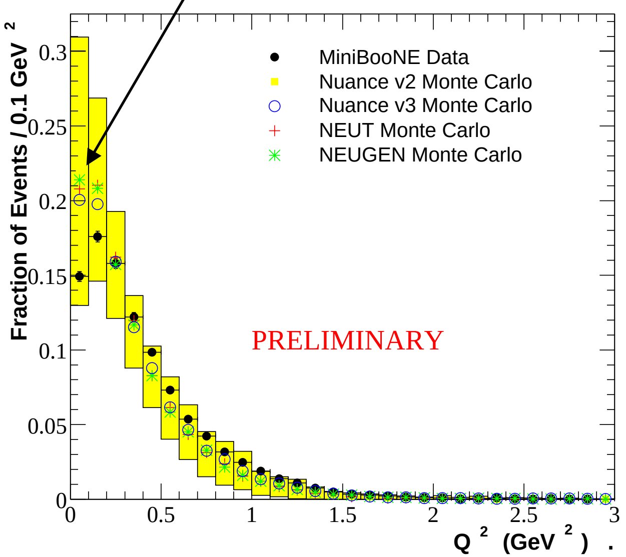
- Similarities - Electron and Neutrino Scattering at low Q^2
  - Same bumpy road going from perturbative to non-perturbative region
  - Need to consider dynamic higher twists as well as kinematic HT (TMC)
  - Help from local duality, although **not confirmed** with neutrino scattering
  - Help from phenomenological approach to PDFs at low Q
  - Large x resummation to (NLO) QCD approach improves T/D agreement

Something Happening at low Q^2 with νA Scattering

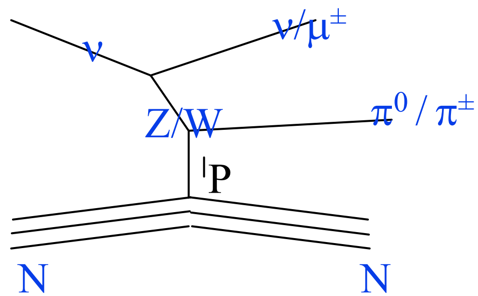
(recall shadowing at lower E_H for ν scattering)



Larger than expected rollover at low Q^2



- Coherent Pion Production (ν+A-->ν /μ^-+A+ π)

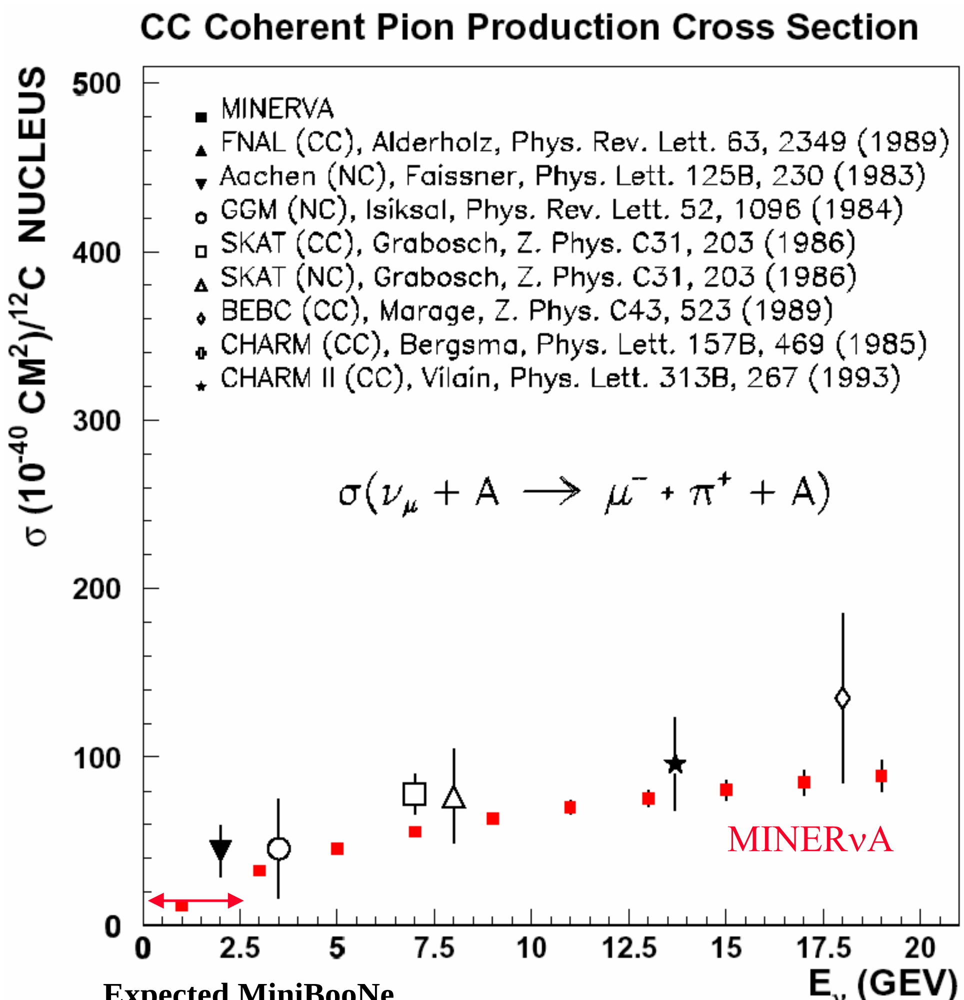


- K2K expect 470 CC coherent events according to Rein-Sehgal. **Find 7.6 ± 50.4.**

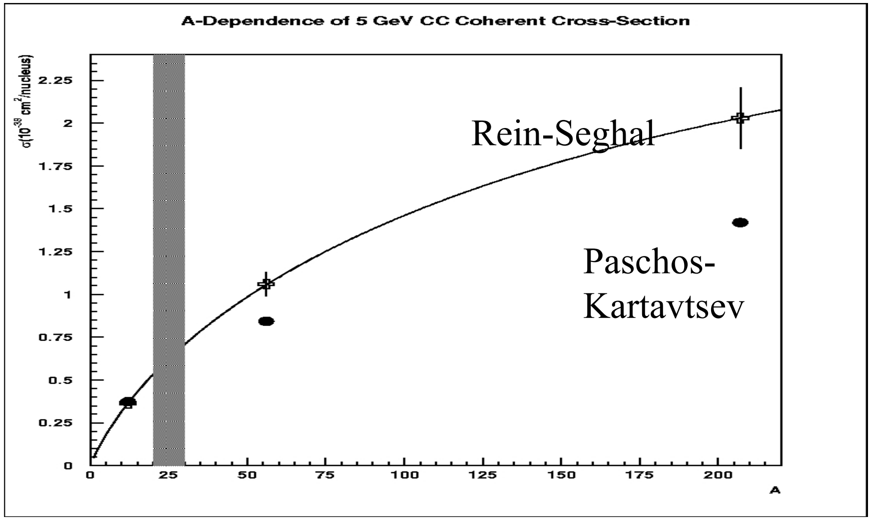
Summary

- Many similar challenges in investigating and understanding the physics for the neutrino and electron scattering communities.
- By combining the results of experimental and theoretical studies from the two communities we increase our knowledge by much more than a factor of two.

MINERνA Measurement of Coherent Pion Production



Expected MiniBooNe
and K2K measurements



Strange and Charm Particle Production

- Theory: Initial attempts at a predictive phenomenology stalled in the 70's due to lack of constraining data.
- MINERvA will focus on exclusive channel strange particle production - **fully reconstructed events** (small fraction of total events) but still
- **Important for background calculations of nucleon decay experiments**
- With extended $\overline{\nu}$ running could study single hyperon production to greatly extend form factor analyses
- New measurements of charm production near threshold which will improve the determination of the charm-quark effective mass.

Existing Strange Particle Production

Gargamelle-PS - **15** Λ events. FNAL - $\approx$ 100 events
ZGS -30 events BNL - 8 events
Larger NOMAD **inclusive** sample expected

MINERνA Exclusive States

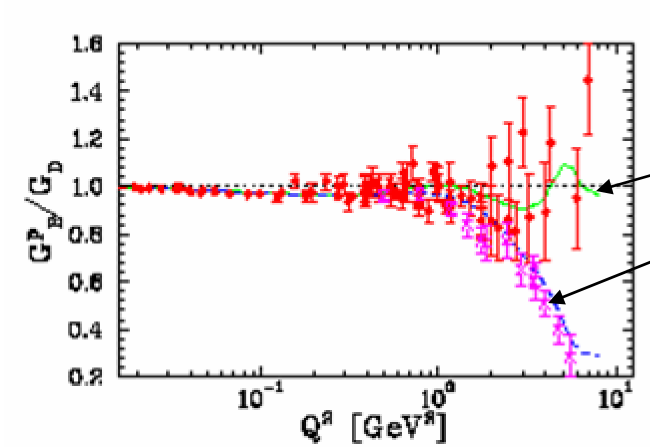
400 x earlier samples

3 tons and 4 years

$\Delta S = 0$	
$\mu^- K^+ \Lambda^0$	42 K
$\mu^- \pi^0 K^+ \Lambda^0$	38 K
$\mu^- \pi^+ K^0 \Lambda^0$	26 K
$\mu^- K^- K^+ p$	20 K
$\mu^- K^0 K^+ \pi^0 p$	6 K
$\Delta S = 1$	
$\mu^- K^+ p$	65 K
$\mu^- K^0 p$	10 K
$\mu^- \pi^+ K^{0n}$	8 K
$\Delta S = 0$ - Neutral Current	
$\nu K^+ \Lambda^0$	14 K
$\nu K^0 \Lambda^0$	4 K
$\nu K^0 \Lambda^0$	12 K

Input from Electroproduction Experiments

- Jefferson Lab (Jlab) has performed precision experiments to determine the electroproduction form factors.
  - An interesting diversion caused by the different results from Rosenbluth and polarization techniques in extracting the form factors.



  - The 2000 Jlab "polarization" measurement did not agree with earlier "Rosenbluth" measurements at higher Q^2 .
  - A Super-Rosenbluth experiment failed to resolve the discrepancies .
  - The "polarization" technique is viewed as more systematically reliable?