

JUPITER - JLab Unified Program to Investigate Targets and Electroproduction of Resonances

In collaboration with The **MINERvA** Neutrino Experiment at FermiLab
(**Main INjector ExpeRiment v-A**)

A collaborative Effort Between Nuclear Physics and HEP Communities

JUPITER 1 - Hall C Inclusive Reactions
Arie Bodek (Rochester) - Co-spokespersons

E04-001 Approved by Jlab PAC Jan 2004

**Measurement of F_2 and σ_L/σ_T on Nuclear-Targets
in the Nucleon Resonance Region - E04-001**

JUPITER 1 - Jlab E04-004

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- R. Ent, D. Gaskell, M. Jones, D. Mack, S. Wood - Thomas Jefferson National Accelerator Facility, Newport News, VA
- J. Arrington - Argonne National Laboratory, Argonne, IL
- H. Gallagher - Tufts University, Medford, MA
- J. Dunne - Mississippi State University, Mississippi State, MS
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Neutrino cross sections at low energy

- Many dedicated neutrino oscillation experiments (K2K, MINOS, CNGS, MiniBooNE, and JHF) are in the few GeV region.
- Neutrino cross section models at low energy are *crucial* for precise next generation neutrino oscillation experiments.
- The high energy region of neutrino-nucleon scatterings (30-300 GeV) is well understood at the few percent level in terms of the quark-parton model (PDFs) constrained by data from a series of $e/\mu/\nu$ DIS and collider experiments. In addition, nuclear effects have been measured at high Q^2 .
- *However*, neutrino cross sections in the low energy region are poorly understood. (especially the resonance and low Q^2 DIS contributions) --- aim to know them to the 2 % level.
- ***Renewed interest of the High Energy Physics community in joining the Medium Energy community in understanding QCD/ nucleon/ nuclear structure at low energies.***

Currently - low energy neutrino data worse than where electron scattering was in the 1960's

- In the 1960's: Electron scattering data was poor. We measured the momentum sum rule, but we *never thought* that we will investigate the Q^2 dependence of many QCD sum rules (logarithmically varying with Q^2). A few examples include.
- (1) The Bjorken Sum rule in Polarized lepton scattering
- (2) The Gross-Llewellyn-Smith Sum (GLS) sum rule in neutrino scattering
- (3) The Gottfried Sum Rule (proton-neutron) in electron/muon DIS scattering

In 2002:

- (1) Q^2 dependence of Bjorken and GLS rules has been used to extract $\alpha_s(Q^2)$
- (2) Gottfried Sum is used to extract $(\bar{d}-\bar{u})$

In a few years, next generation neutrino beams will have fluxes known to 2%. Aim at testing current-algebra (exact sum rules) like the Adler Sum rule with data from MINERvA

However, input from electron scattering experiments is crucial to understand the vector part (Need to Understand both Vector and Axial contributions in neutrino scattering)

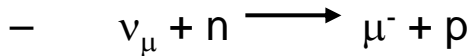
Crucial Input for Neutrino Monte Carlos

- Neutrino experiments need good models of cross sections and final states to extract cross sections
- Neutrino Monte Carlo models *must* be based on understanding of the physics, and checked by data
- Proposal to develop a collaborative program between the high and medium energy communities to develop reliable global models linking electron and neutrino scattering measurements

- Nuclear data necessary for comparison with neutrino measurements
- No R= L/T separated structure function measurements exist on nuclei in the resonance region
- In the resonance region, nuclear effects may be large, different from the DIS region, and Q^2 dependent.

Neutrino Cross Sections at Low Energy

□ Quasi-Elastic / Elastic ($W=M$)



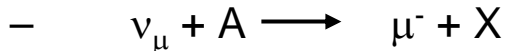
- Input from both electron and neutrino experiments and described by form factors, need axial form factor and nuclear corrections

□ Resonance (low Q^2 , $W < 2$)

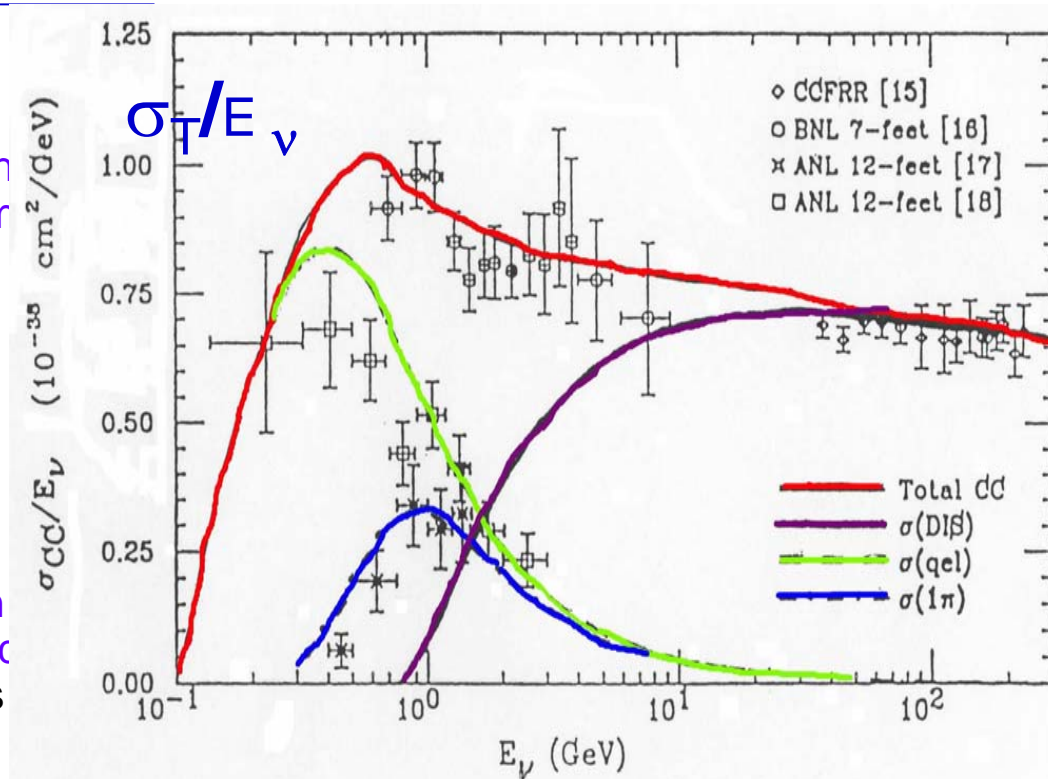


- Can be well measured in electron scattering, but poorly measured in neutrino scattering (fits by Rein and Seghal). **Need R**, axial form factors nuclear corrections

□ Deep Inelastic (DIS)



- well measured in high energy experiments and well described by quark-parton model, *but doesn't work well at low Q^2* . **Need low Q^2 structure functions, R**, axial structure funct. and nuclear corrections



- **Challenge:** to describe all these three processes at all neutrino (and electron/muon) energies.
 - (Need to understand duality, QCD, low Q^2 sum rules, transition between DIS and resonance)

Neutrino scattering, and physics at low energies e.g.

Extraction of Axial form factor (on Carbon) **Requires both understanding of the nuclear effects (from electron scattering on Carbon). And Vector Form Factors from Electron Scattering on H and D.**

For Neutrino Oscillations

Are near and far detectors enough - **can we do the physics of neutrino oscillations without a detailed understanding of Neutrino Cross Section and Vector and Axial cross form factors and structure functions on Carbon?**

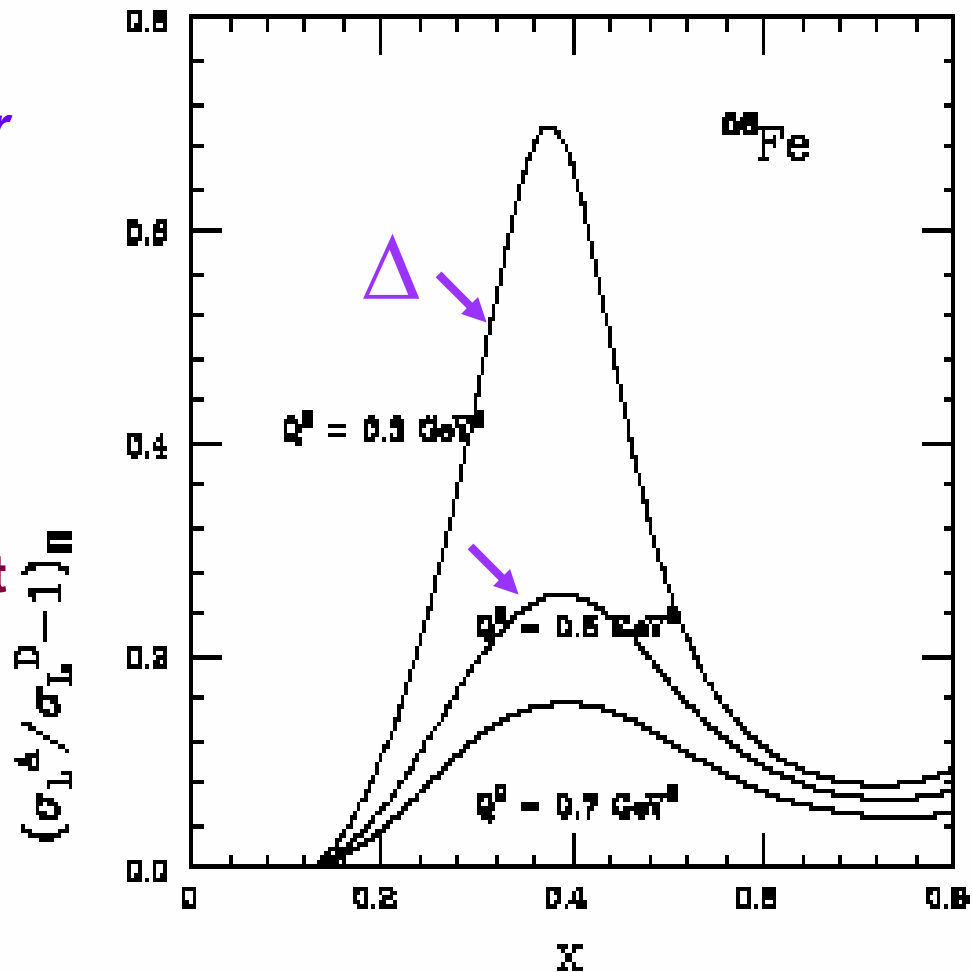
How many clocks does one need to get the precise time

A person with only one watch always knows what time it is (as backup he can also have a Monte Carlo simulation of the Clock)

A person with two clocks - never knows the right time---

A study of the nuclear dependence of R is also of interest to the nuclear physics community because it is a uniquely sensitive signature of nuclear pions - what is considered a technical complication for HEP experiments which must use nuclear targets -

is a field of interest to another community



Plot from G. A. Miller (Phys.Rev. C 64,022201(2001)) showing the predicted sensitivity of the inclusive *longitudinal* cross section ratio of Iron to Deuterium due to pion excess. It is large at low Q² and in the resonance region

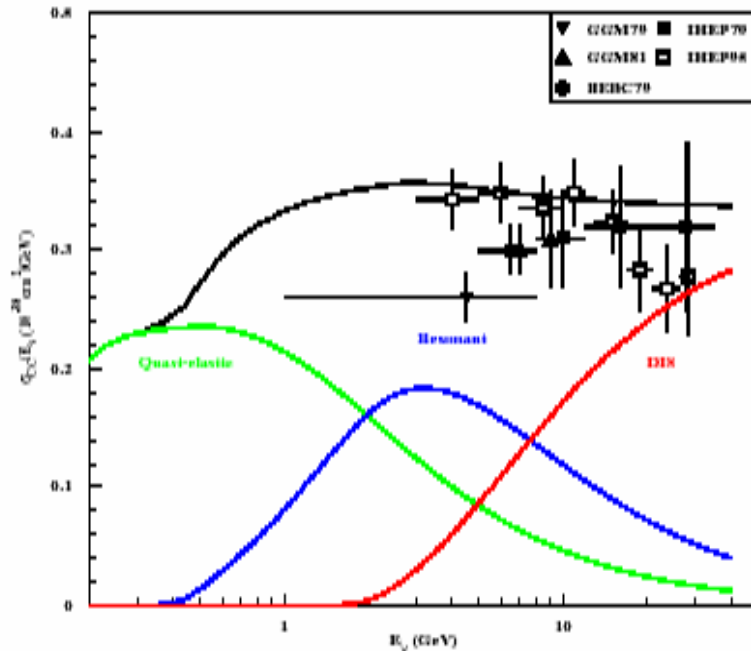
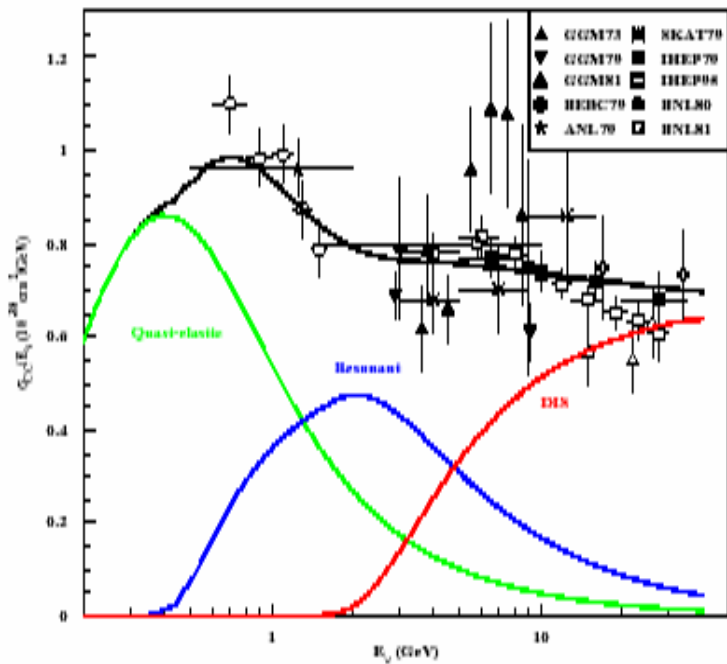
R directly effects neutrino, anti-neutrino cross section measurements

$\sigma^{\nu N}$ fractional error $\sim 0.5\Delta R$

$\sigma^{\bar{\nu} N}$ fractional error $\sim 1.5\Delta R$

$\Delta R = 0.2$ implies 10% error on $\sigma^{\nu N}$, 30% error on $\sigma^{\bar{\nu} N}$

(Neutrino, Anti-neutrino cross sections / Energy) versus E



$$R = 2K / (Q + \bar{Q})$$

$$\sigma^{\nu N} = \frac{G_F^2 M E_\nu}{\pi(1 + Q^2/M_W^2)^2} \left[Q^{\nu N} + (1/3)\bar{Q}^{\nu N} + K^{\nu N} \right]$$

$$\sigma^{\bar{\nu} N} = \frac{G_F^2 M E_\nu}{\pi(1 + Q^2/M_W^2)^2} \left[\bar{Q}^{\bar{\nu} N} + (1/3)Q^{\bar{\nu} N} + K^{\bar{\nu} N} \right]$$

JUPITER Hall C - (a) Hydrogen data already taken - in Analysis stage.

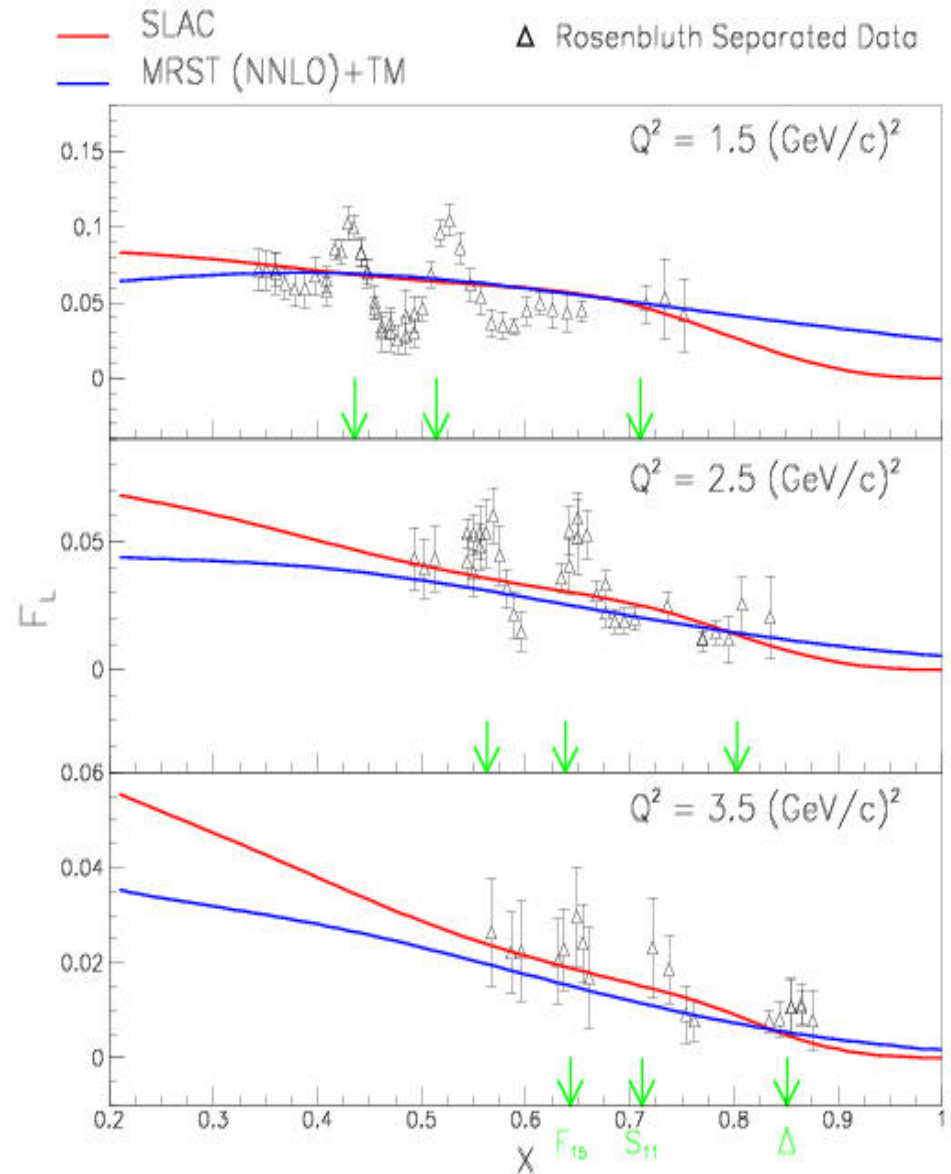
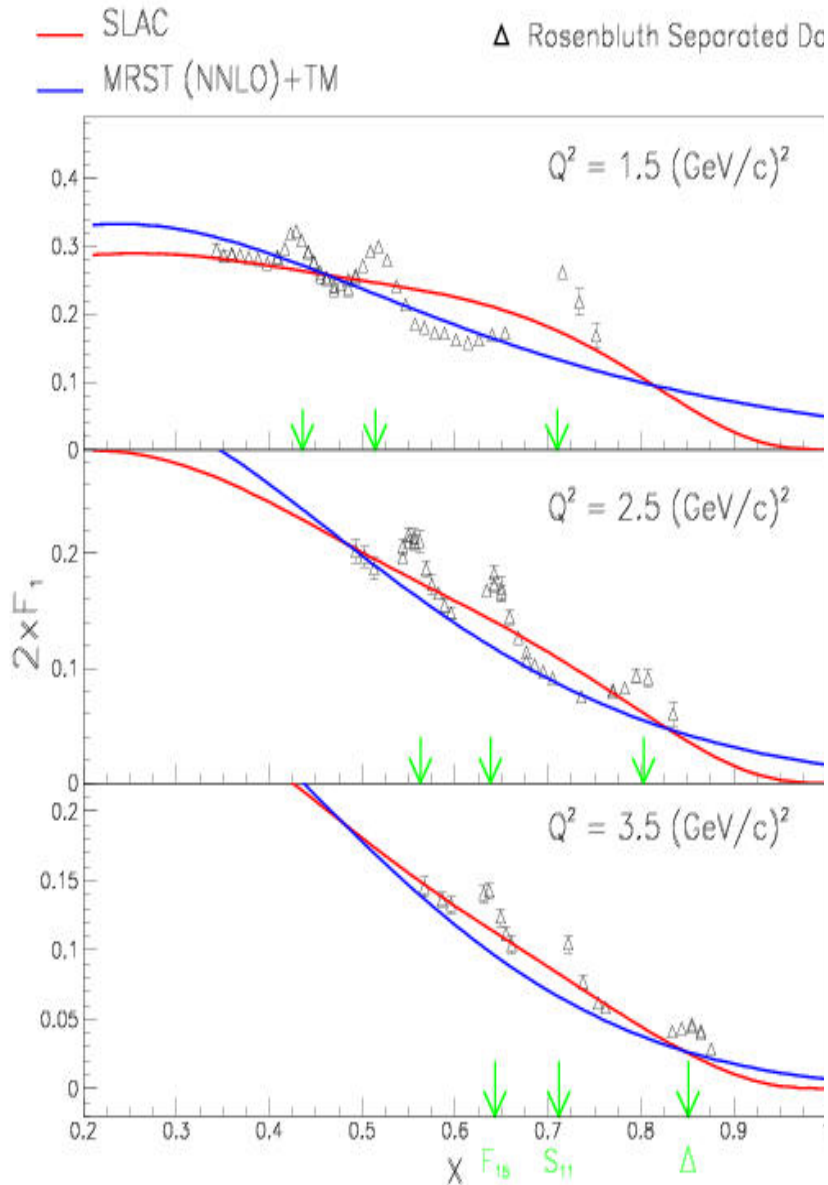
Exp. E94-110 Longitudinal / Transverse Separations on Hydrogen in the Resonance Region

JUPITER Hall C - (b) Beam Time for deuterium approved by PAC Exp. E02-109 Longitudinal / Transverse Separations on Deuterium in the Resonance Region

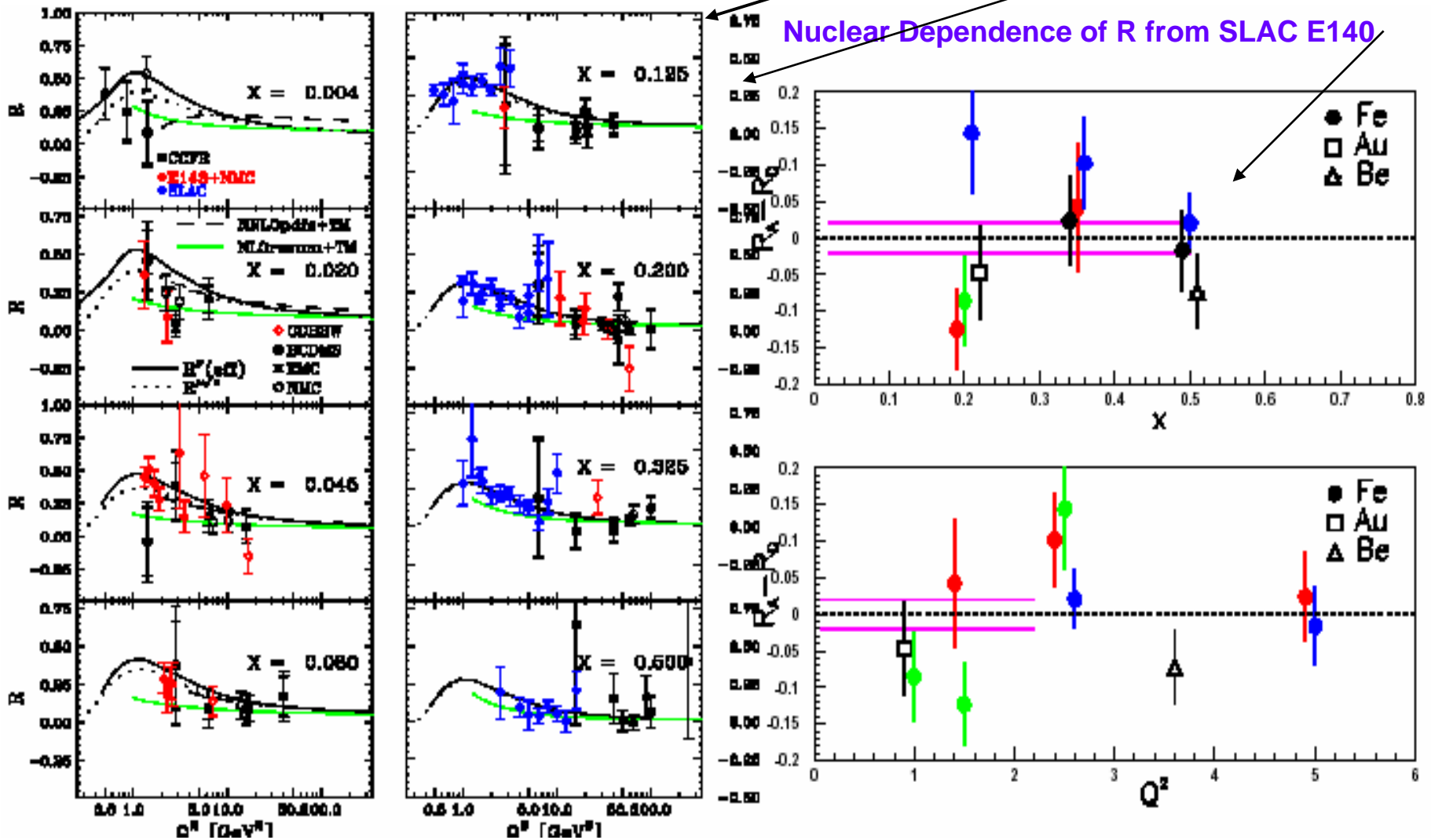
JUPITER Hall C - (c) Beam Time for Nuclear Targets approved by PAC Exp. E04-001

Both Deuterium and Nuclear Target Data run to be taken together, and are approved for a total 18 days of beam time (1 month of calendar time), in summer 05. (A. Bodek (Rochester) and C. Keppel (Hampton/Jlab Co-spokespersons)

JUPITER Hall C - Hydrogen data in analysis: Exp. E94-110 Longitudinal / Transverse Separations on Hydrogen



Existing DIS Measurements on R - Most of the data from DIS Experiments (SLAC -Blue and CCFR-black)



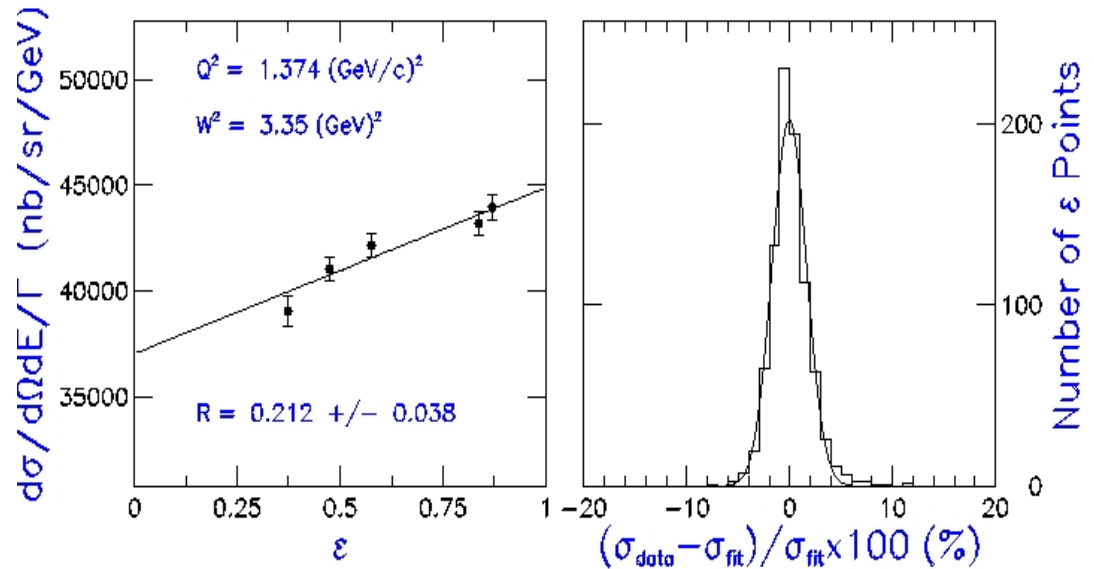
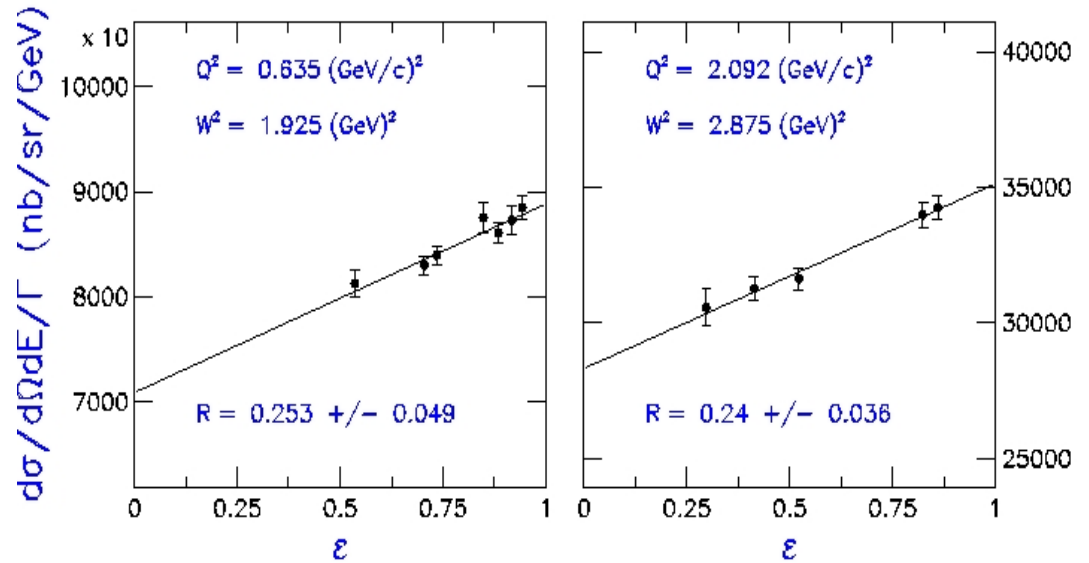
Back to the future - In 1983 we went back to SLAC to do SLAC E140 because, new precision both R and $F_2^{\text{Iron}}/F_2^{\text{D}}$ in the DIS region were essential for precision HEP PDFs.

**Rosenbluth separations
done for H,
also to be done for
D2 and nuclear Targets
Third GENERATION
electron scattering
technology**

**•180 L/T separations total
(most with 4-5 ϵ points)**

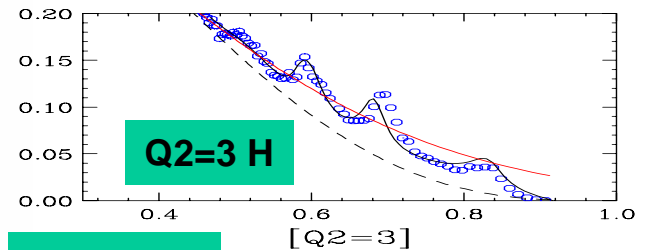
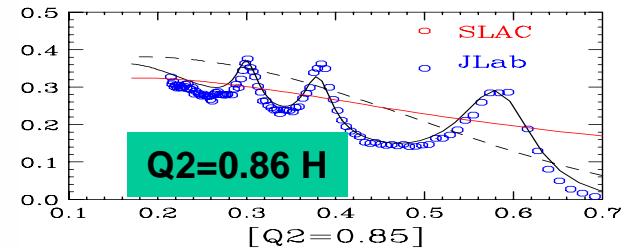
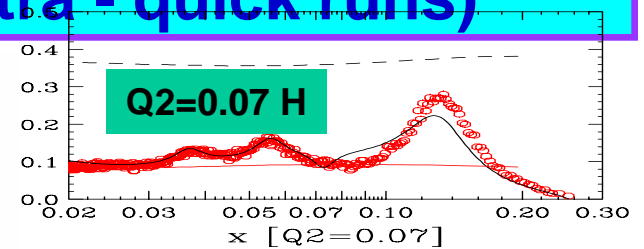
**•Spread of points about
the linear fits is fairly
Gaussian with $\sigma \sim 1.6\%$ -
consistent with the
estimated pt-pt
experimental uncertainty**

**•expect same data quality
for D2 and Nuclear
Targets - if E140 type
nuclear targets are
introduced again to Jlab.**

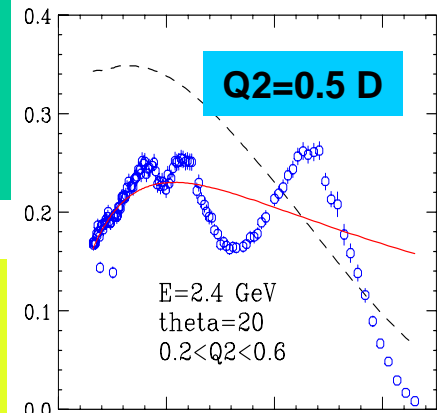


E04-001 Run Plan Δ Region Part Only - Match E02-109 (and add one or two lower Q^2 spectra - quick runs)

Q_{Δ}^2 (GeV/c) ²	E (GeV)	ϵ_{Δ}	$Rate_{\Delta}$ (Hz)	D ₂ Time (Hours) E02 109	Nucl. Tgts
Δ 0.5	1.16	0.54	1 K	0.5	E04-001
	1.64	0.78	1 K	0.5	C - 0.06
	4.04	0.97	1 K	0.5	Quartz - 0.06
1.0	1.64	0.53	1 K	0.5	Si - 0.06
	2.28	0.77	1 K	0.5	
	4.52	0.95	1 K	0.5	
2.0	2.28	0.43	65	0.5	Ca - 0.06
	3.24	0.73	285	0.5	Fe - 0.06
	5.64	0.92	1 K	0.5	
3.0	3.24	0.51	16	2	Cu - 0.06
	4.04	0.70	40	1	
	5.64	0.86	172	0.5	
			sub-total	8	24
4.0	3.24	0.23	1	22	C - 0.06
	4.04	0.51	3	8	
	5.64	0.77	53	1	
5.0	4.04	0.29	1	22	Cu - 0.06
	4.52	0.42	3	8	
	5.64	0.66	6	4	
			sub total	65	40
				Total D	Total-Nucl
			Δ	73	64
				E02-109	E04-001



24 hours
All nuclear
Targets Δ
For $Q^2 < 4$



40 hours
C and Cu
Targets Δ
For $Q^2 = 4$
+ $Q^2 = 5$

Summary JUPITER -1 and relation to MINERvA

- Substantial reduction in systematic uncertainties for vector and axial neutrino cross section measurements (MINERvA/JUPITER)
 - Global interest in systematics for neutrino oscillation measurements, now in few GeV regime
 - Brings two active communities to both Jefferson Lab and Fermilab.
- R at low Q^2 measured on H and large, R_A essentially unknown
 - Contributes large uncertainty in dilution factors for spin structure measurements (timely to measure)
 - Resonance region at low Q^2 large contribution to moments (F2)
- Unique sensitivity to nuclear pions (Miller) - JUPITER
- Beam time savings running concurrently D2 and Nuclear
 - Do 30 days of physics in *18 days (save 12 days) in summer 2005*
 - Build on existing expertise, analysis machinery

Additional Slides

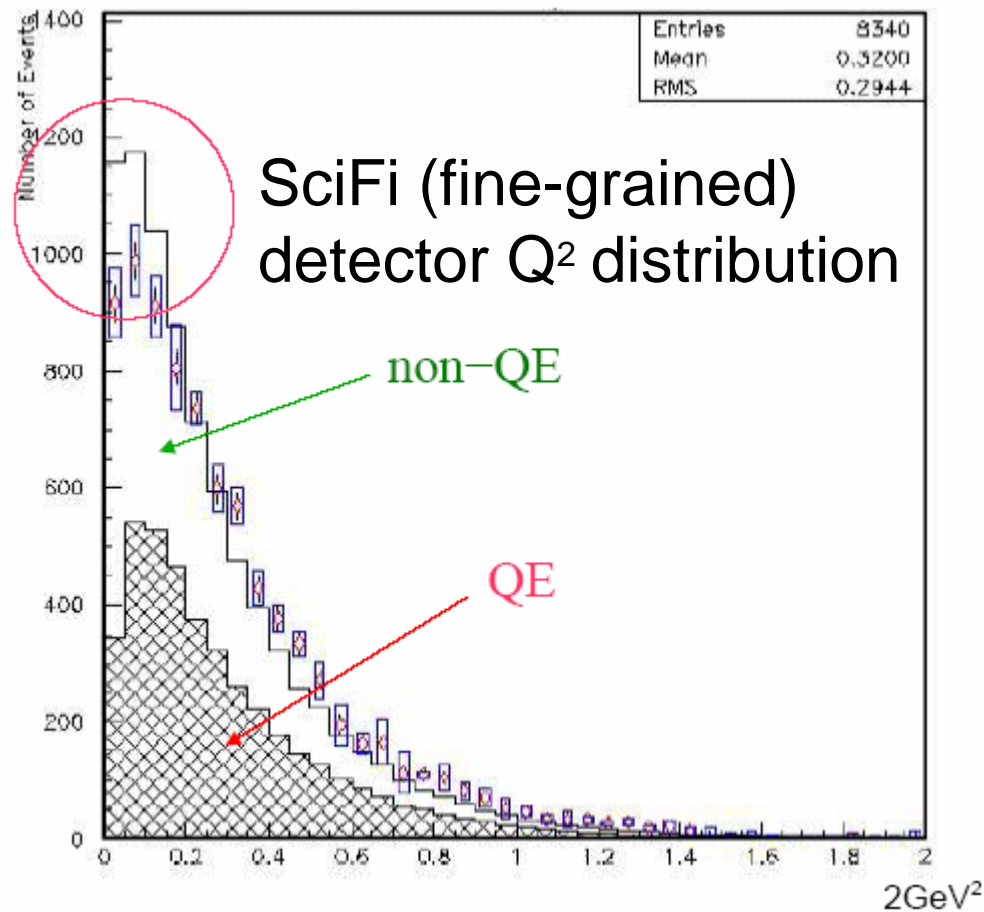
K2K (KEK to SuperK) and M_A

K2K has both a near detector and a far SuperK detector -
Example of how even two detectors were not enough

- *How using outdated vector form factors affected the K2K analysis*

In 2002: They used Dipole form and $Gen=0$ (i.e. wrong R elastic)

- K2K found unexpected results in Q^2 distribution of quasi-elastic events in the near detector
 - blue box is correlated energy scale error
- Initially, was incorrectly fixed by increasing M_A
- Bodek-Budd-Arrington pointed out that the K2K experiment
- was using outdated σ_{QE} -vector



In addition, need both precise input from electron scattering (JUPITER) - AND need to know neutrino fluxes and cross sections very well (MINERvA)

- Difference between the fudged cross-section (to match the observed Q^2 distribution) and the true cross-section

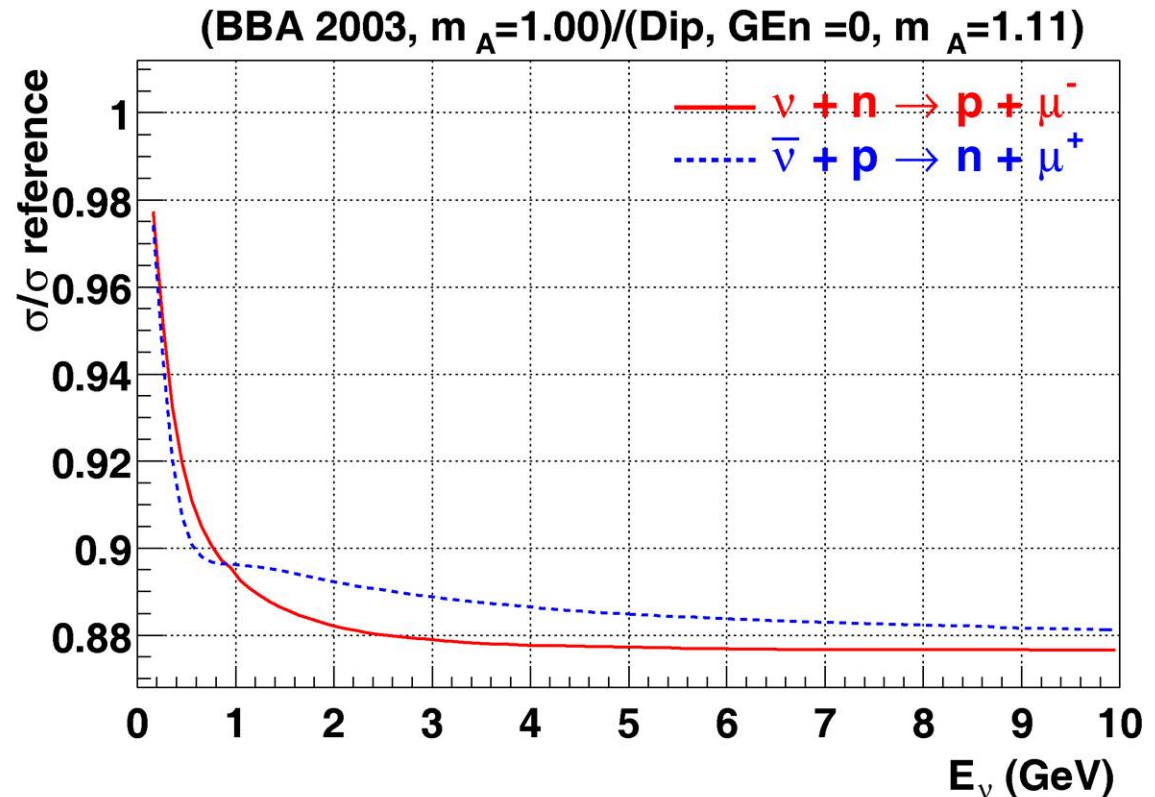
- End result:

K2K assigned systematic of 20% in the absolute rate at far detector

- Note:

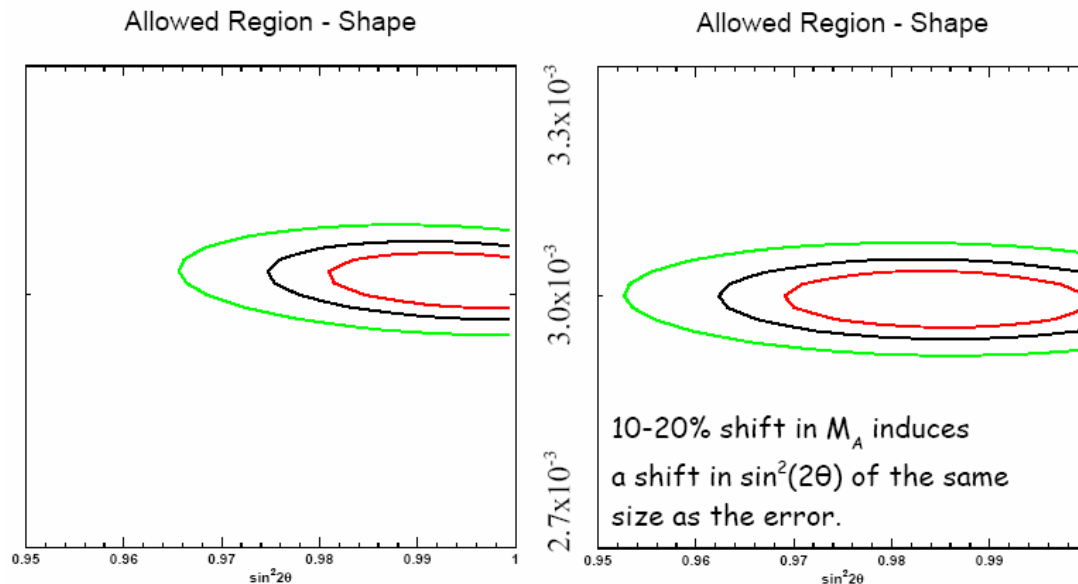
mean energy is 0.7 GeV

(plot from Bodek-Budd-Arrington, NUINT02 proceedings)



K2K and M_A (cont'd - C)

- Chris Walter (BU) at NUINT02: effect of difference between correct and fudged solution if one is in data and one is in MC.



ΔM_A "Data": 1.11(QE) / 1.21(1π) / Bodek

ΔM_A MC: 1.01

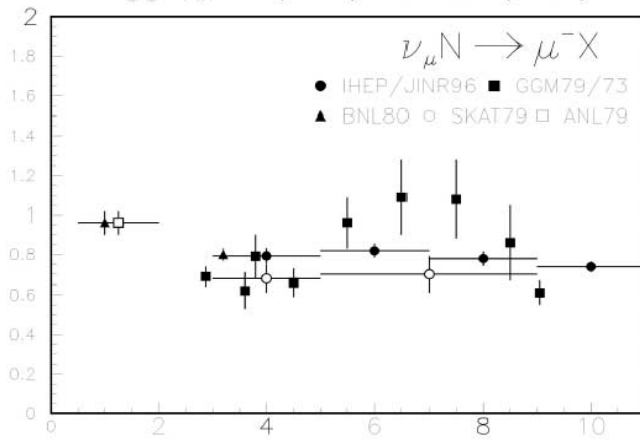
this is a "toy" analysis of ν_μ disappearance at J-PARC Phase I-

Conclusion: Neutrino experiments alone cannot determine both vector and axial structure function. Need data from both electron and neutrino experiment in combination,

ν_μ Charged Current Process

: both differential cross sections and final states are of interest

- **Neutrino mass ΔM^2 and Mixing Angle:** charged current cross sections and final States are **needed:** The level of neutrino charged current cross sections versus energy provide the baseline against which one measures ΔM^2 at the oscillation maximum and mixing angles (aim to study CP viol.)

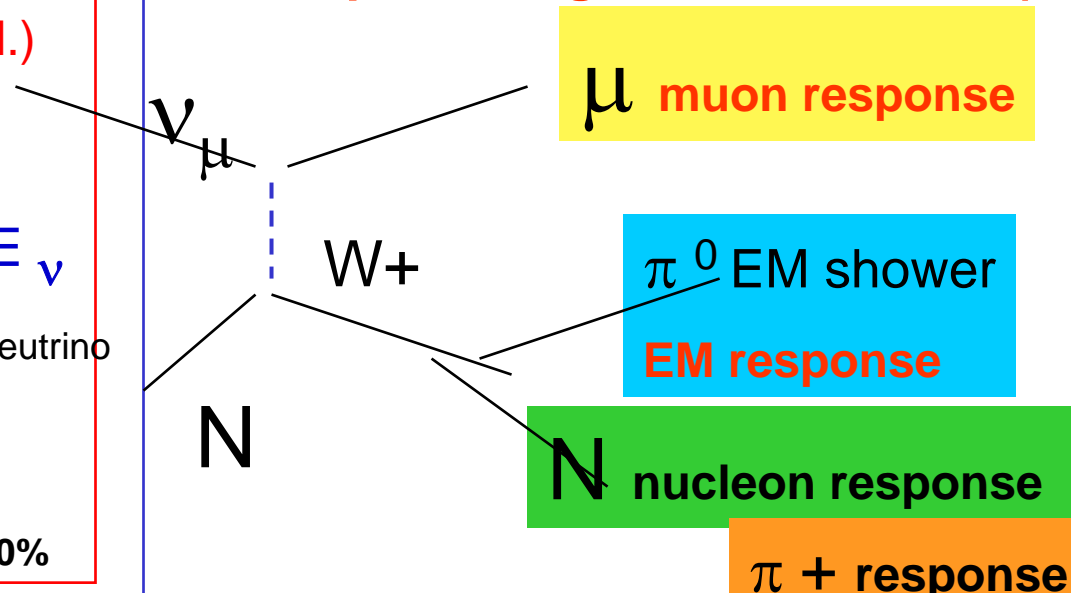


$$\sigma_T/E_\nu$$

Poor neutrino data

E_ν Low energy current flux errors 10% to 20%

- Measurement of the neutrino energy in a detector depends on the composition of the final states (different response to charged and neutral pions, muons and final state protons (e.g. Cerenkov threshold, non compensating calorimeters etc)).



μ muon response

π^0 EM shower
EM response

N nucleon response

π^+ response

JUPITER/MINERvA help pin down cross sections -aim 2% and Study CP Violation

ν_μ Neutral Current Process

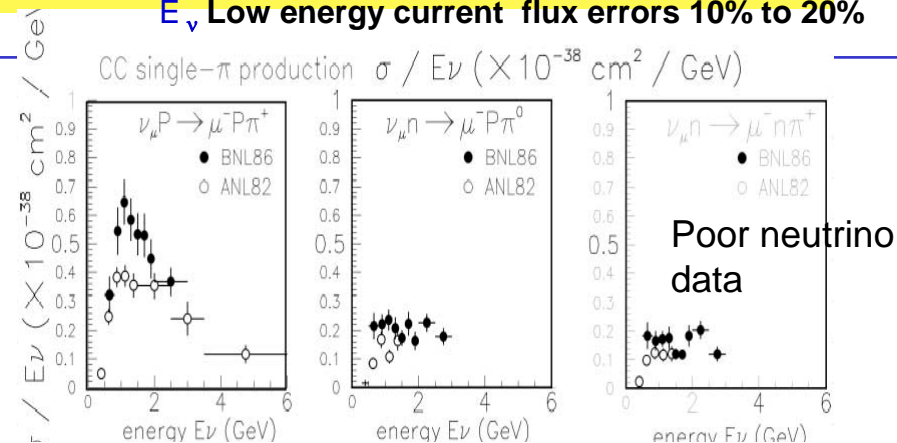
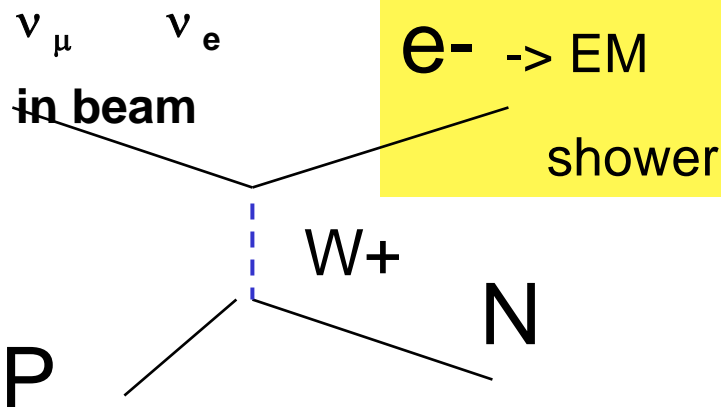
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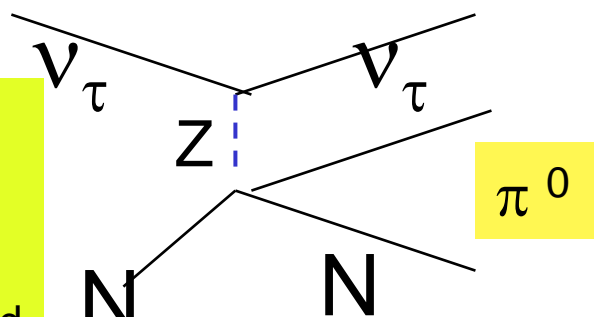
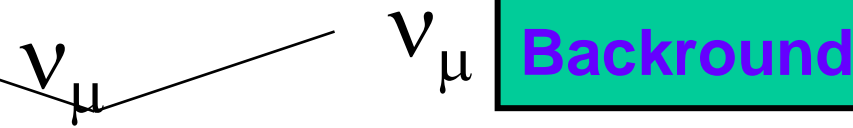
What do muon neutrinos oscillate to?

• **SIGNAL** $\nu_\mu \rightarrow \nu_e$

transition ~ 0.1% oscillations
probability of $\nu_\mu \rightarrow \nu_e$.



• **Background:** Electrons from misidentified π^0 in NC events without a muon from higher energy neutrinos are a background



SIGNAL $\nu_\mu \rightarrow \nu_\tau$

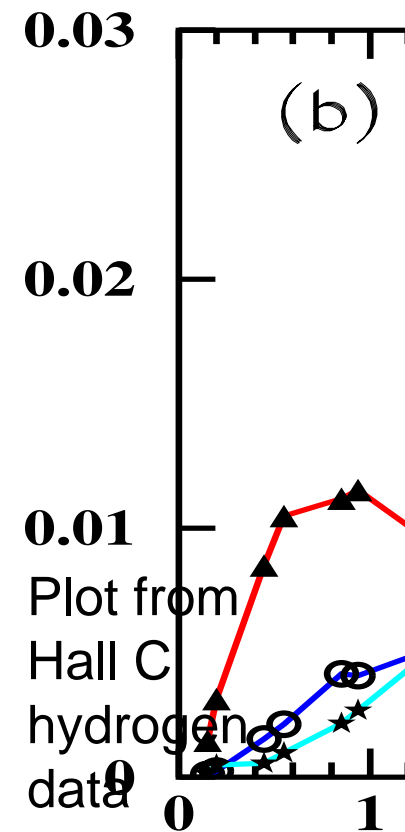
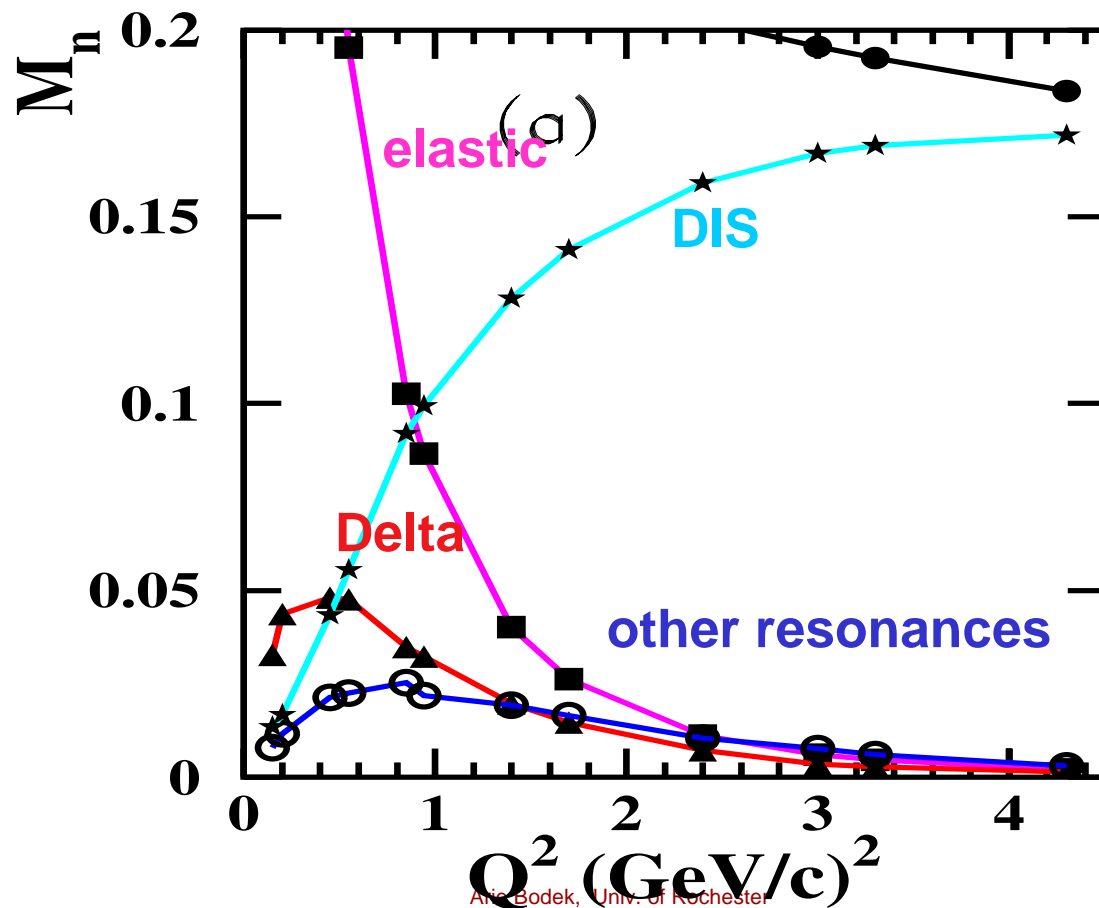
Can observe ν_τ events below τ threshold Vs. sterile ν

π^0 EM shower
FAKE electron

Need to pin down cross sections -aim 2%-Study CP Violation

Low Q^2 Moments Dominated by Resonance Regime....the uncertainty propagates (F2 and R in resonance region)

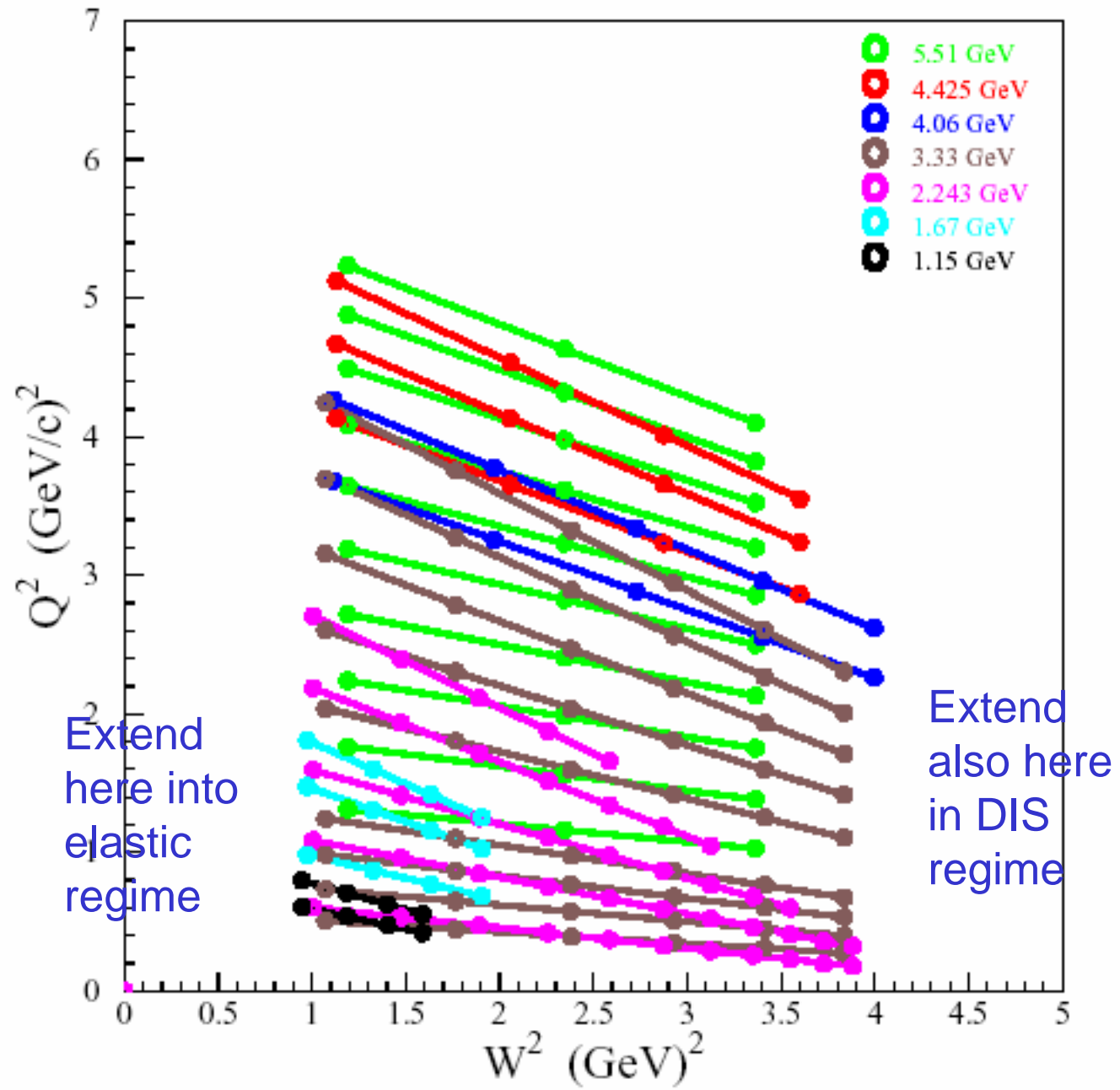
at $Q^2 = 0.5$, resonance region contribution to moment is 30%



Of Interest also to Nuclear Community - Nuclear R (and F2) measurements also needed to obtain dilution factors for spin structure measurements on polarized nucleons (since all polarized targets are diluted by other materials)

- F_1 and F_2 measurements on p, d, ^4He , C, kapton, ^{14}N , ^{15}N , Al needed to obtain dilution factors for NH_3 , ND_3 targets
- RSS in Hall C, Eg1 in Hall B *need this now*
- future GDH in Hall B and SANE in Hall C need this
- dilution factors particularly sensitive in resonance region

The lack of this data is currently the dominant systematic uncertainty on the dilution factor, and on the final results for g_1 - timely need! So sometimes, scattering from nuclear targets also is complication in the study of single nucleons.



Run Plan Including All Resonance - Efficient to take both D2 and Nuclear data together

	D- Time Required (Hours) E02-109	Nucl. Tgts. (Hours) E04-001
Data acquisition (Deuterium Δ)/+Nucl. Tgts.	73	64
Data acquisition (Deuterium $W^2 > \Delta$)/+Nucl. Tgts.	40	38
Data acquisition (Dummy)	60	
Data acquisition (hydrogen elastics)	24	
Data acquisition (hydrogen resonance region)	16	
Data acquisition (additional positrons)	22	
D Angle changes (12)/+Nucl. Tgt Changes	3	10
Spectrometer momentum changes (60)	15	
Major beam energy changes (1)	8	
Minor beam energy changes (5)	20	
D Checkout /+ Nucl. Rad correction Tests	24	10
Total	305 E02-109	120 E04-001

Separately - Each experiment E02-109 - D2 and E04-001 - Nuclear targets takes about 15 days

Bodek, Univ. of Rochester

13 days of beam to do D2 only

5 days increment To do nuclear targets

Outline of a Program in Investigating Nucleon and Nuclear Structure at all Q^2 - Starting with P 04-001 (PART 1 of JUPITER program)

(a) Study Nucleon Structure and Nuclear Effects

(b) Provide basic measurements needed for the next generation neutrino oscillation experiments.

- Study Nuclear dependence of Rvector, F2vector and F1vector and compare to Models (e.g. Pion excess) using P04-001 data on nuclear targets.
- Update Vector Form Factors and Rvector of the large number of **resonances** in the Nucleon, e.g. within *Rein-Seghal-Feynman Quark Oscillator model* (and other resonance models) by fitting all F2 and R Electron Resonance data **E94-110 (H)** , **E02-109 (D)** (+ SLAC + photoproduction+ and other data)

* *[propose to run P04-001 on nuclear targets at the same time as E02-109 (D)]*

PART II- JUPITER Program: Include existing Hall B data on final states to help separate resonance and continuum on nucleon and nuclear targets (collaborate with theorists)

PART III - Collaborate with MINERvA Neutrino Experiment

Improve on **Inelastic Continuum** modeling of Vector F2 and R (e.g. using a formalism like Bodek/Yang) using Jlab, SLAC, H and D data, photoproduction and HERA data.

Within these models, convert EM Vector Form Factor to **Weak Vector Form Factors** - use the Various isospin rules $I=1/2$ and $I=3/2$ of elastic, resonance and inelastic Form Factors fits to H and D data **E94-110, E02-109**

Investigate if the Model predictions for Vector Scattering in neutrino reactions satisfy QCD sum rules and duality at high Q^2 and **Adler Vector Sum rules at ALL Q^2 .**

Investigate if the Models predictions for Axial scattering in neutrino reactions satisfy QCD sum rules and duality at high Q^2 and **Adler Axial Sum rules at ALL Q^2 .**

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1. Apply nuclear corrections for DIS and resonance region to predict **Neutrino and Antineutrino Vector Part on nuclei** from PR 04-001 - Requires 5 days of running - Also use E99-118 and SLAC E140 and other for DIS A dependence.
2. Compare predictions to existing **low statistics neutrino data** and to **new precise neutrino data** to become available (MINERvA, and JHF- Japan) - Do the predictions from models (which satisfy all sum rules and duality) model the neutrino and antineutrino data well?
3. In parallel - **Final states in nuclear targets** to be investigated in a collaboration with **Hall B experiments** in electron experiments and in **new neutrino experiments**.

Things can be learned from electron scattering	Things that are learned in neutrino scattering
<ul style="list-style-type: none"> • Nucleon + Resonance Vector Form Factors, Vector Continuum F2 at all Q², R_{vector} = σ_L/σ_T in great details. • Pion Excess and Nuclear effects on various targets in res, and quasielastic region (vector scattering) as a function of Q² • Hadronic Final States in electron scattering 	<ul style="list-style-type: none"> • Check on Current Algebra sum rules and understanding duality - • Axial vector contribution to F2 at low Q² • Different nuclear effects in neutrino scatt. • Account for R_{axial} different from R_{vector} • Hadronic final states in neutrino scattering

Collaborative approach between High Energy and Nuclear Physics community

High x and low Q² PDFs for e/neutrino, Resonance form factors, nuclear corrections

1. Electron scattering exp. at JLAB P04-001 - **5 Days of DATA and -> Lots of analysis+ follow-up with investigation of final states**

2. New Near Detector neutrino expts. at Fermilab-NUMI/JHF - --> **Years of data** e.g. MINERvA + JHF

Radiative Corrections Checks, e.g. SLAC E140

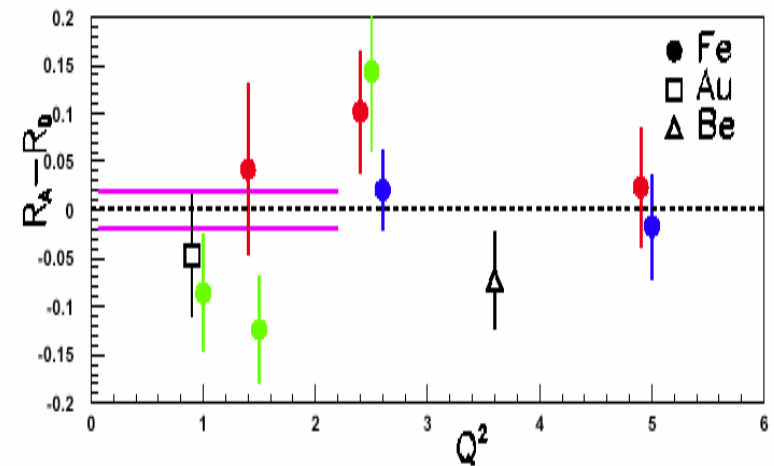
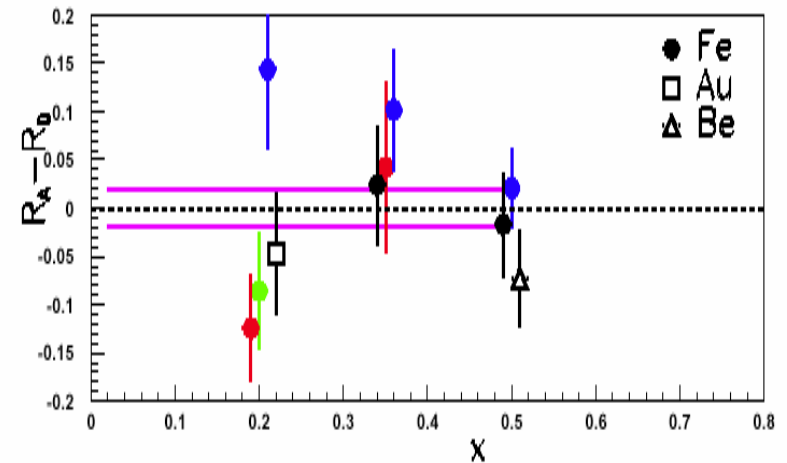
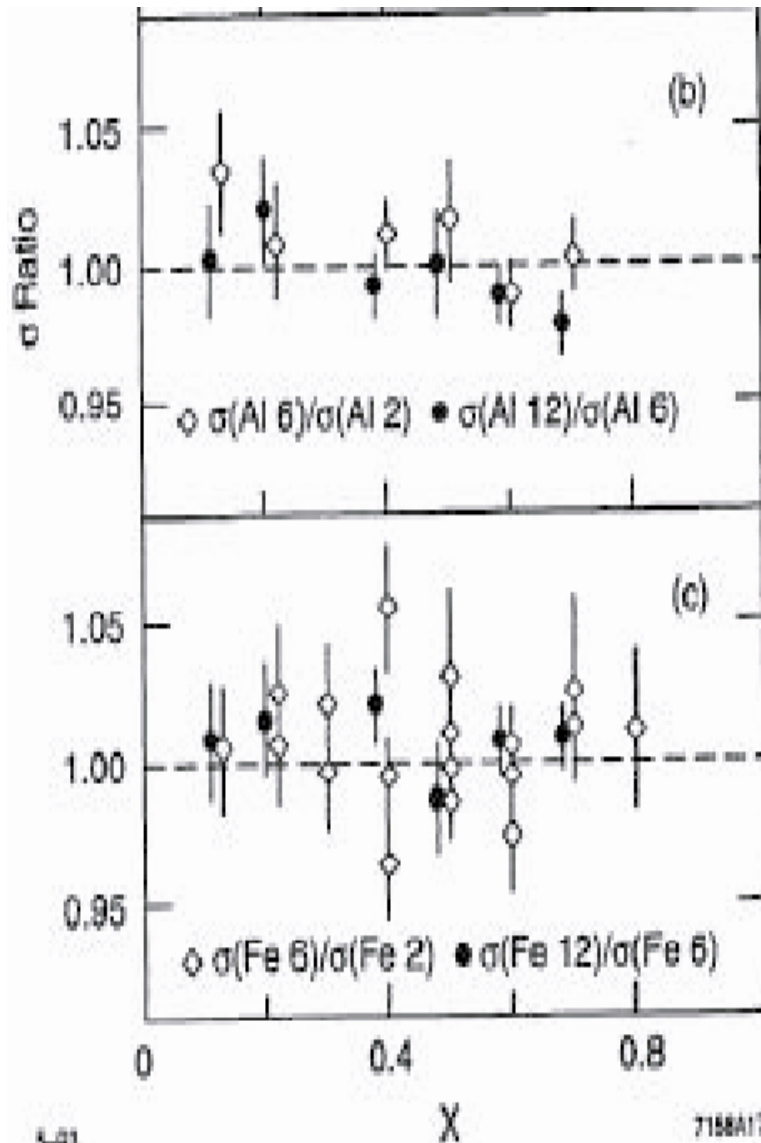


FIG. 1. The SLAC E140 data set of $R_A - R_D$ on deuterium in the Deep Inelastic Region.

$$\frac{d\sigma^{\nu, \bar{\nu}}}{dq^2} = \frac{M^2 G_F^2 \cos^2 \theta_c}{8\pi E_\nu^2} \left[A(q^2) \mp \frac{(s-u)B(q^2)}{M^2} + \frac{C(q^2)(s-u)^2}{M^4} \right];$$

Updated recently
By Bodek, Budd and
Arrington 2003

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

Axial

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

Vector

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

We have not shown terms in $(m_l/M)^2$, and $F_P(q^2)$ is multiplied by $(m_l/M)^2$. (Note, $F_P(q^2)$ is included in the calculations.) The formulas for $F_V^1(q^2)$ and $\xi F_V^2(q^2)$ are

$$F_V^1(q^2) = \frac{G_E^V(q^2) - \frac{q^2}{4M^2} G_M^V(q^2)}{1 - \frac{q^2}{4M^2}}; \quad \xi F_V^2(q^2) = \frac{G_M^V(q^2) - G_E^V(q^2)}{1 - q^2/4M^2}$$

Vector form factors
From electron
scattering
Via CVC

We use the CVC to determine $G_E^V(q^2)$ and $G_M^V(q^2)$ from the electron scattering form factors $G_E^p(q^2)$, $G_E^n(q^2)$, $G_M^p(q^2)$, and $G_M^n(q^2)$.

$$G_E^V(q^2) = G_E^p(q^2) - G_E^n(q^2); \quad G_M^V(q^2) = G_M^p(q^2) - G_M^n(q^2)$$

Vector

Many of the neutrino experiment have assumed the form factors are the dipole approximation.

$$G_D(q^2) = \frac{1}{(1 - q^2/M_V^2)^2}; \quad M_V^2 = 0.71 \text{ GeV}^2$$

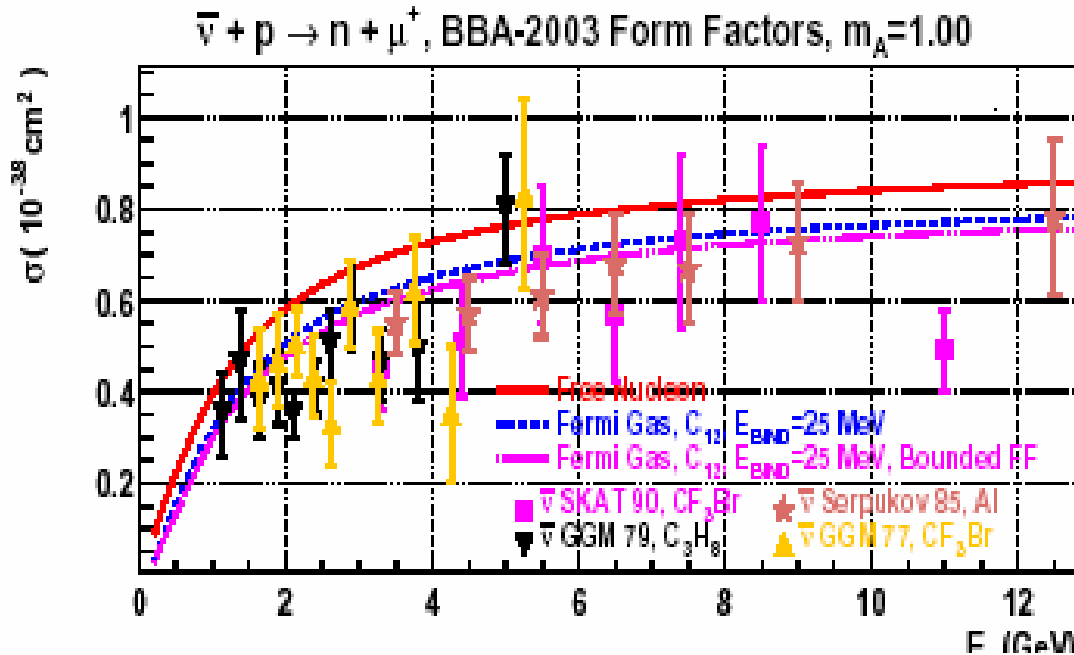
$$G_E^p = G_D(q^2), \quad G_E^n = 0, \quad G_M^p = \mu_p G_D(q^2), \quad G_M^n = \mu_n G_D(q^2)$$

Neutrino experiments use
Dipole form factors with
Gen=0 -Because this is
what was put in the LS
paper (**not exactly**
correct)

The axial form factor is given by

$$F_A(q^2) = \frac{g_A}{(1 - \frac{q^2}{M_A^2})^2}$$

Axial form factor from
Neutrino experiments



However, quasielastic neutrino cross sections are not well measured so Models are used to predict the cross section. Vector form factors are Measured in electron scattering and axial form factors are extracted from The Q^2 dependence of neutrino events (since the neutrino flux is not Known very well in previous experiments). Note

$$\text{Relastic} = 4 (M^2/Q^2)(\text{GeV/Gm})^2$$

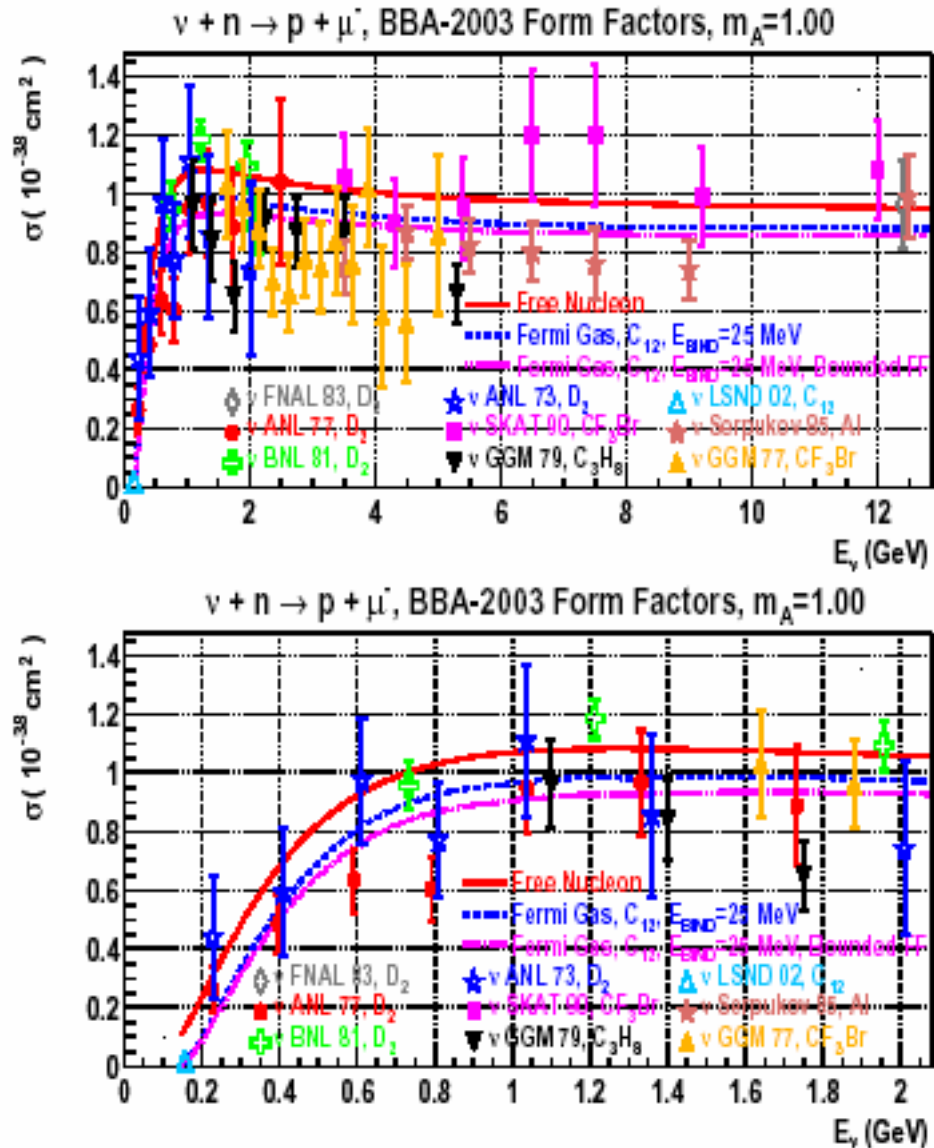


FIG. 2. Compilation of experimental measurements of the neutrino quasi-elastic cross sections.

Next - Resonance Models

e.g. Current Matrix Elements from a Relativistic Quark Model - *Phys. Rev. D* 3, 2706–2732(1971) R. P. Feynman, M. Kislinger, and F.

Ravndal referred to as the *FKR Model* - A relativistic equation to represent the symmetric quark model of hadrons with harmonic interaction is used to define and calculate matrix elements of vector and axial-vector currents.

Improvements on parameters within this Resonance Model:

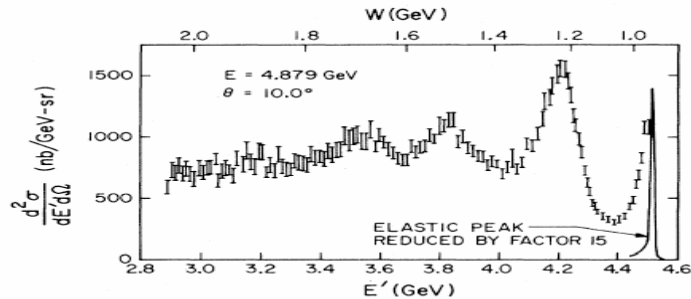
D. Rein and L. M. Sehgal, *Annals Phys.* 133, 79 (1981) ;D. Rein, *Z. Phys. C.* 35, 43 (1987) These are coded in MC generators - but there are also other proposed recently.

Recent models (e.g. Sato and Lee model) are more refined and includes meson cloud --> Non zero R and a better predictions for the axial couplings.

Resonance Model applied to Photo-production Electroproduction/Neutrino-production

Photoproduction: FKR: Kneis, Moorhouse, Oberlack, Phys. Rev. D9, 2680 (1974)

Electroproduction: FKR: F. Ravndal, Phys. Rev. D4, 1466 (1971)



$$\sigma_T(W) = \frac{4\pi^2\alpha}{K^*} \frac{1}{2} (|f_+|^2 + |f_-|^2) \frac{\Gamma/2\pi}{(W-M)^2 + \Gamma^2/4}, \quad (18)$$

$$\sigma_S(W) = \frac{4\pi^2\alpha}{K^*} \left(\frac{-q^2}{Q^{*2}} \right) |f_0|^2 \frac{\Gamma/2\pi}{(W-M)^2 + \Gamma^2/4},$$

Harry Lee from Argonne has offered to work with Us on modeling of resonance electro-production and neutrino-production. He has done work on the Delta region: **Electroproduction**: Phys. Rev. C63.-55201 (2001) **Neutrino productions** : nucl-th/0303050 (2003)

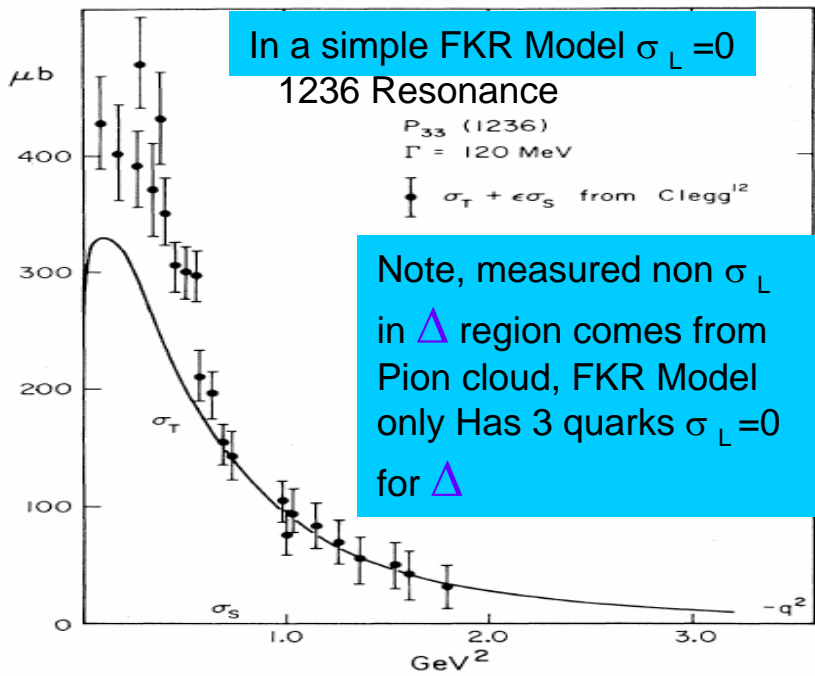
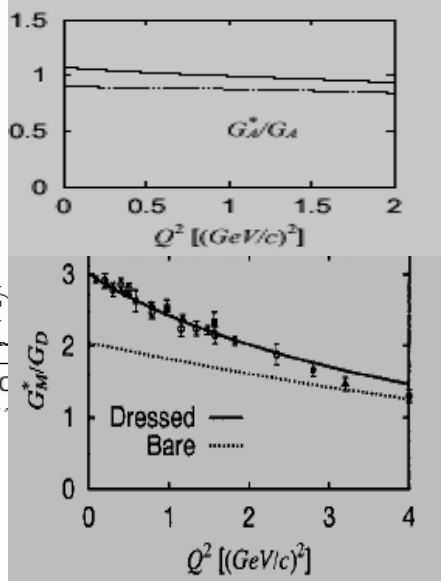
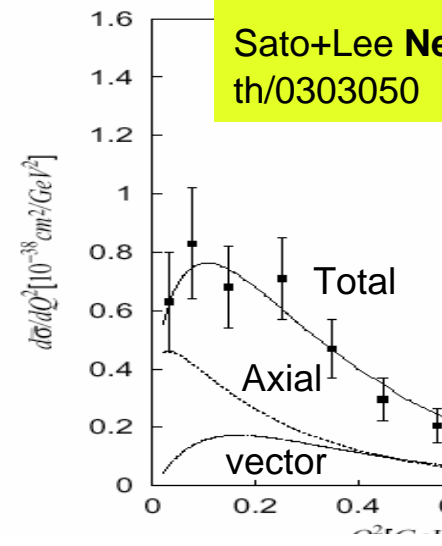


FIG. 3. Resonance cross section at $W = 1236 \text{ MeV}$ with proton target. Data from Ref. 12.



IV. RESULTS AND DISCUSSION

Electroproduction Δ Region Δ Region

Neutrino production

Correct for Nuclear Effects measured in e/ μ expt.

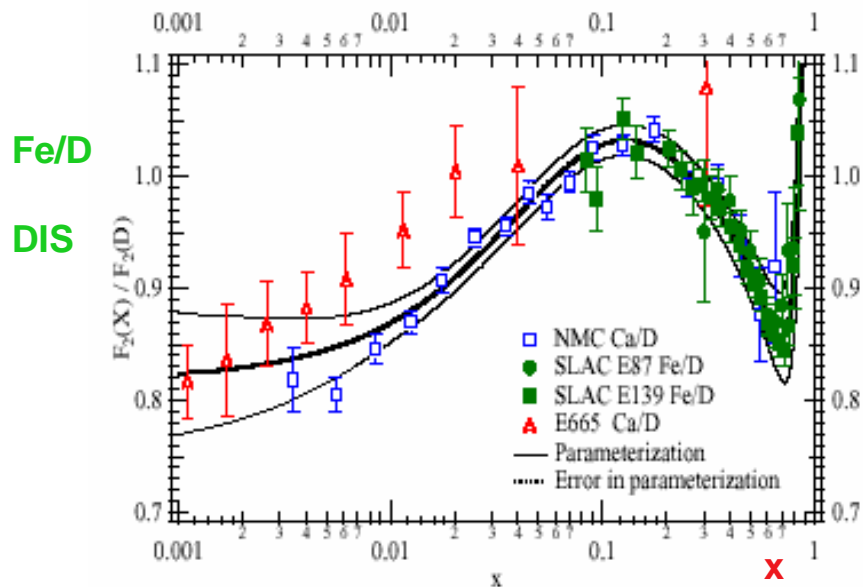
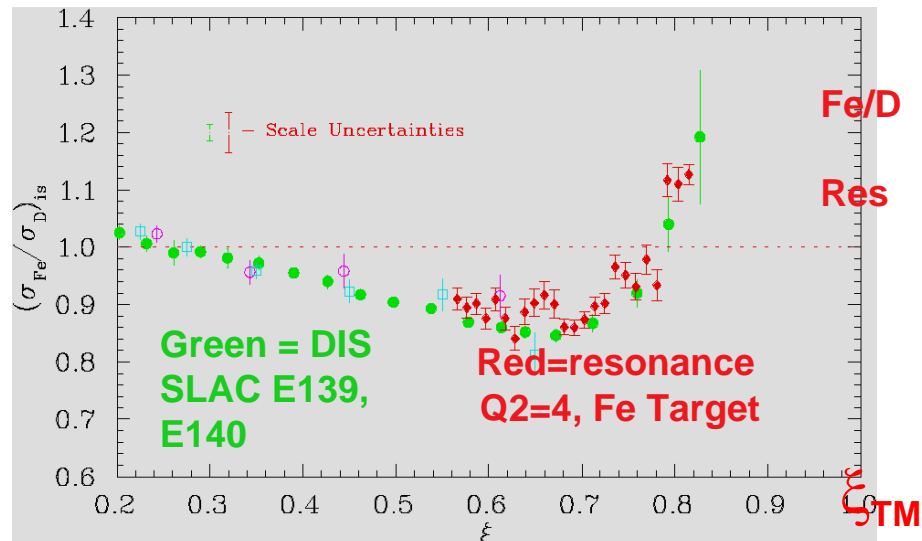


Figure 5. The ratio of F_2 data for heavy nuclear targets and deuterium as measured in charged lepton scattering experiments (SLAC, NMC, E665). The band shows the uncertainty of the parametrized curve from the statistical and systematic errors in the experimental data [16].

$$\xi_{TM} = [Q^2] / [M_v (1 + (1 + Q^2/v^2)^{1/2})]$$



Comparison of Fe/D F_2 data in resonance region (JLAB) versus DIS SLAC/NMC data in ξ_{TM} (However, what happens at low Q^2 ? Is it versus ξ_W or other scaling variable. What happens when R is large at low Q^2 in the resonance region?)

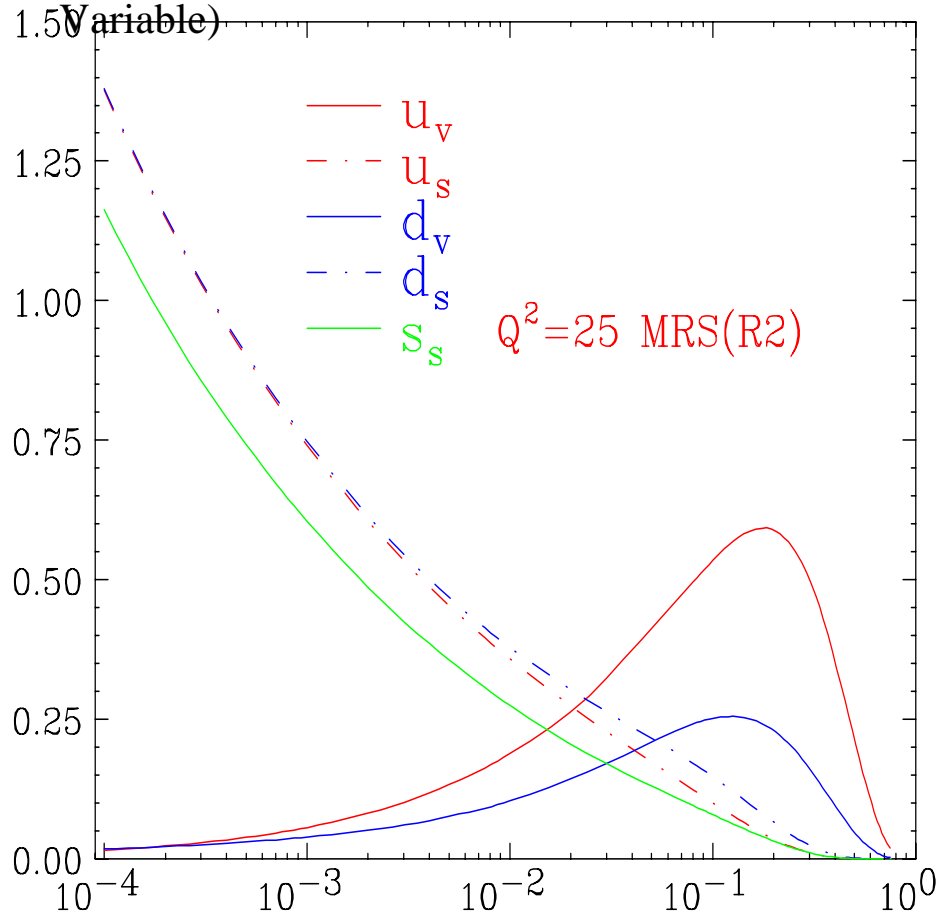
From SLAC E87, E139, E140, and Muon Scattering

$$\xi_{SW} = [Q^2 + B] / [M_v (1 + (1 + Q^2/v^2)^{1/2}) + A]$$

(People involved in E139, E140 Bodek, Rock, Bosted are also in E03-110...)

How are PDFs Extracted from global fits to High Q² Deep Inelastic e/ μ / ν Data

MRSR2 PDFs xq is the probability that a Parton q carries fractional momentum $x = Q^2/2M\nu$ in the nucleon (x is the Bjorken Variable)



For data on nuclei, need nuclear Corrections.

Note: additional information on Antiquarks from Drell-Yan and on

Gluons from p-pbar jets also used.

$$u_v + d_v \xrightarrow{\text{from}} F_2^{\nu} \approx x(u + \bar{u}) + x(d + \bar{d})$$

Valence, Sea

Strange dist. $x F_3^{\nu} \approx x(u - \bar{u}) + x(d - \bar{d})$

$$u + \bar{u} \xrightarrow{\text{from}} F_2^p \approx \frac{4}{9} x(u + \bar{u}) + \frac{1}{9} x(d + \bar{d})$$

$$d + \bar{d} \xrightarrow{\text{from}} F_2^n \approx \frac{1}{9} x(u + \bar{u}) + \frac{4}{9} x(d + \bar{d})$$

$$\left\{ \begin{array}{l} \text{nucleaffects} \\ \text{typically ignored} \end{array} \right\} \mu F_2^n = 2 \frac{\mu F_2^d}{\mu F_2^p} - 1$$

$$d/u \xrightarrow{\text{from}} ppW \text{ Asymmetry} \approx \frac{d/u(x_1) - d/u(x_2)}{d/u(x_1) + d/u(x_2)}$$

At high x , deuteron binding effects introduce an uncertainty in the d distribution extracted from F_2^d data (but not from the W asymmetry data). $X = Q^2/2M\nu$ Fraction momentum of quark

Duality, QCD Sum Rules, and Current Algebra Sum Rules.

Local duality and Global duality appears to work for $Q^2 > 1.5 \text{ GeV}^2$ in electron scattering: This is basically a consequence of the fact that if target mass effects are included, higher twists are small and **QCD sum rules are approximately true for $Q^2 > 1.5 \text{ GeV}^2$** .

(e.g. **momentum sum rule** - quarks carry about 1/2 of the proton momentum) F_2^{eP} , F_2^{eN} are related to PDFs weighted by quark charges).

At high Q^2 , duality also seems to work for nuclear corrections.

What happens at low Q^2 ?

Adler Sum rule **EXACT** all the way down to $Q^2=0$ includes W_2 quasi-elastic

S. Adler, Phys. Rev. 143, 1144 (1966) Exact Sum rules from Current Algebra. Sum Rule for W_2 **DIS LIMIT is just $Uv-Dv=1$**

- $\beta^- = W_2$ (Anti-neutrino -Proton)
- $\beta^+ = W_2$ (Neutrino-Proton) $q_0=v$

The vector current part of the original sum rule of Adler for neutrino scattering can be written

$$\int_0^\infty dq_0 [\beta^{(-)}(q_0, q^2) - \beta^{(+)}(q_0, q^2)] = 1. \quad (18)$$

If we explicitly separate out the nucleon Born term in Eq. (18), we have

Elastic Vector = 1 $Q^2=0$
Elastic Vector = 0 high Q^2

$$[F_1^V(q^2)]^2 + q^2 \left(\frac{\mu^V}{2M_N} \right) [F_2^V(q^2)]^2 + \int_{M_\pi + (q^2 + M_\pi^2)/2M_N}^\infty dq_0 [\beta^{(-)}(q_0, q^2) - \beta^{(+)}(q_0, q^2)] = 1,$$

Vector Part of W_2 , 0 at $Q^2=0$, 1 at high Q^2 -Inelastic

[see Bodek and Yang hep-ex/0203009] and references therein at fixed $q^2 = Q^2$

$$g_A(q^2)^2 + \int_{M_\pi + (q^2 + M_\pi^2)/2M_N}^\infty dq_0 [\beta^{(-)}(q_0, q^2) - \beta^{(+)}(q_0, q^2)] = 1,$$

Elastic $g_A = (-1.267)^2$ $Q^2=0$

Elastic $g_A = 0$ high Q^2

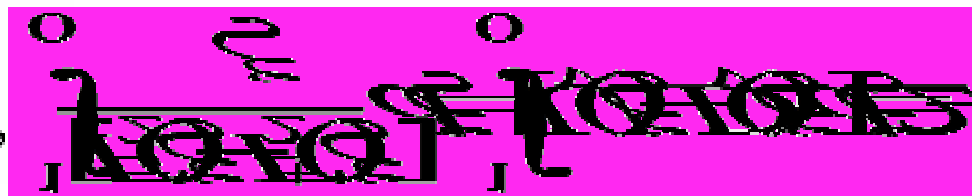
Axial $W_2 = \text{non zero at } Q^2=0$

Axial $W_2 = 1$ at high Q^2 , Inelastic

Adler is a number sum rule at high Q^2

DIS LIMIT is just $Uv-Dv$.

$$\int_0^\infty dq_0 [\beta^{(-)}(q_0, q^2) - \beta^{(+)}(q_0, q^2)] = 1 \text{ is}$$



$F_2^- = F_2$ (Anti-neutrino -Proton) = $v W_2$

$F_2^+ = F_2$ (Neutrino-Proton) = $v W_2$

we use: $d(q_0) = d(v) = (v) d\xi / \xi$

+ Similar sum rules for W_1 , W_3 , and strangeness changing structure functions

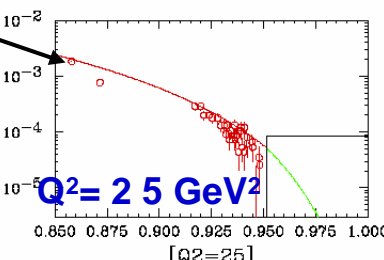
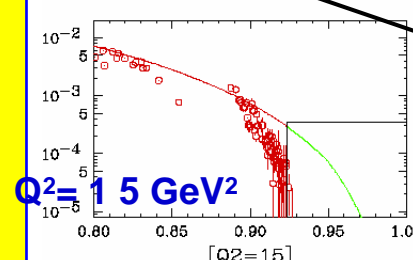
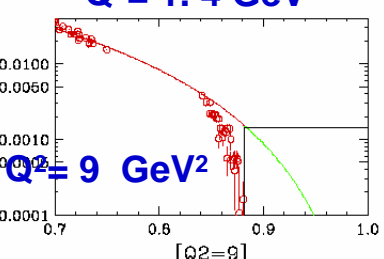
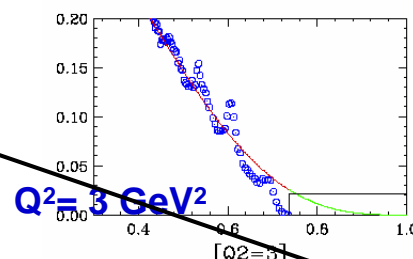
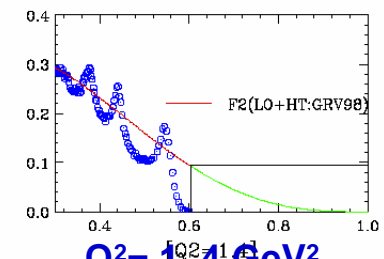
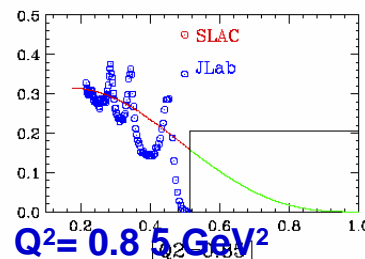
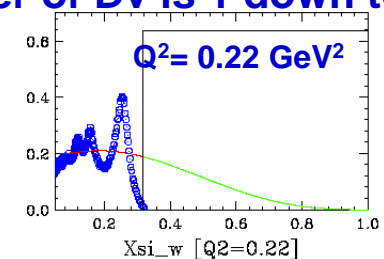
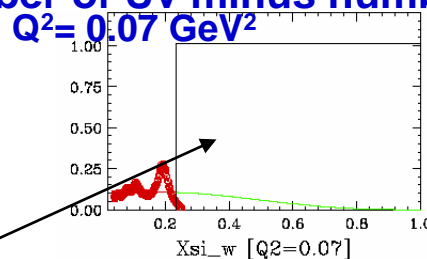
When does duality break down

Momentum Sum Rule has QCD+non- Perturbative Corrections (breaks down at $Q^2=0$) but ADLER sum rule is EXACT (number of U_v minus number of D_v is 1 down to $Q^2=0$).

Elastic peak

Int F2P Elastic	Q2	Int Inelastic
1.0000000	0	0
0.7775128	0.07	
0.4340529	0.25	
0.0996406	0.85	
0.0376200	1.4	
0.0055372	3	
0.0001683	9	
0.0000271	15	
0.0000040	25	0.17

DIS high Q2
Integral F2p



- In proton :
- QPM Integral of F2p =
- $0.17 \cdot (1/3)^2 + 0.34 \cdot (2/3)^2 = 0.17$ (In neutron=0.11)
- Where we use the fact that
- 50% carried by gluon
- 34% u and 17% d quarks

Adler sum rule (valid to $Q^2=0$) is the integral
Of the difference of F_2/x for Antineutrinos
and Neutrinos on protons (including elastic)

Tests of Local Duality at high x, high Q² vs. Q²=0 Electron Scattering Case

- INELASTIC High Q² x-->1.
- QCD at High Q² Note d refers to d quark in the proton, which is the same as u in the neutron. d/u=0.2; x=1.
- $F_2(e-P) = (4/9)u + (1/9)d = (4/9 + 1/45)u = (21/45)u$
- $F_2(e-N) = (4/9)d + (1/9)u = (4/45 + 5/45)u = (9/45)u$
- Elastic/quasielastic +resonance at high Q² dominated by magnetic form factors which have a dipole form factor times the magnetic moment
- $F_2(e-P) = A G_{MP}^2(e) + B G_{MP}^2(\text{res } c=+1)$
- $F_2(e-N) = A G_{MN}^2(e) + B G_{MN}^2(\text{res } c=0)$

• DIS LIMIT High Q²

• $F_2(e-N) / F_2(e-P) = 9/21 = 0.43$

• TAKE ELASTIC TERM ONLY

• $F_2(e-N) / F_2(e-P) (\text{elastic High } Q^2) = \mu^2(N) / \mu^2(P) = (1.913/2.793)^2 = 0.47$

Different at low Q², where Gep, Gen dominate.

Close if we just take the elastic/quasielastic x=1 term.

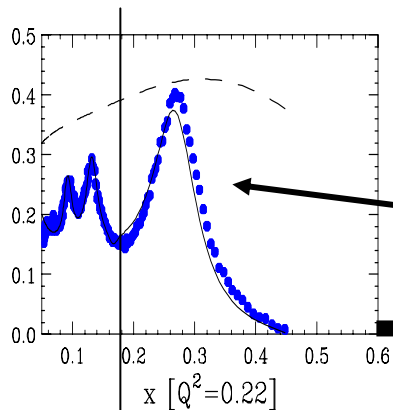
$Q^2 = 0$ ElasticLimit

Gen/Gep (Q²=0) = 0 Since Gen=0.

NEUTRINOS

On nucleons

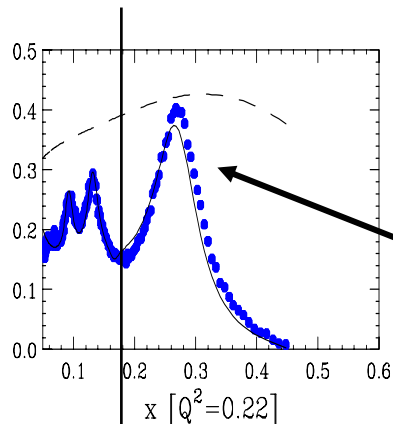
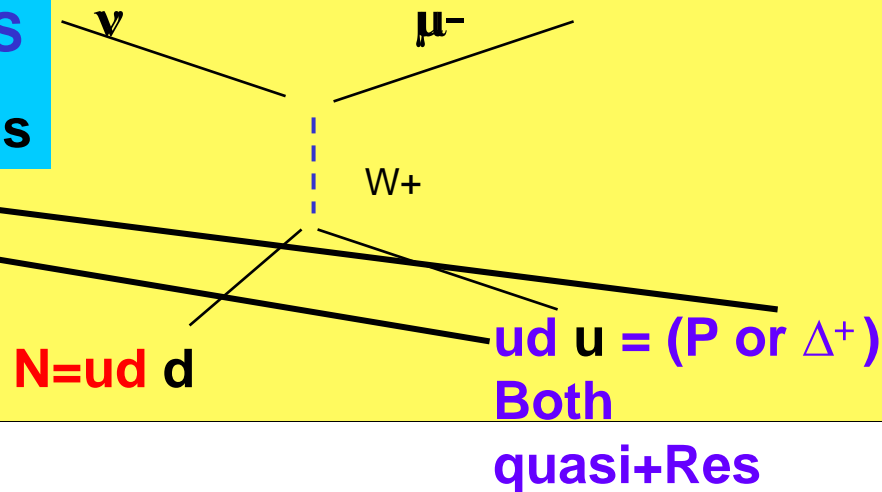
On neutrons both quasielastic and resonance+DIS production possible. First resonance has different mixtures of $l=3/2$ and $l=1/2$ terms. Neutrino and electron induced production are related using Clebsch Gordon Coeff. (Rein Seghal model etc)



1st reson

$X = 1$
quasielastic

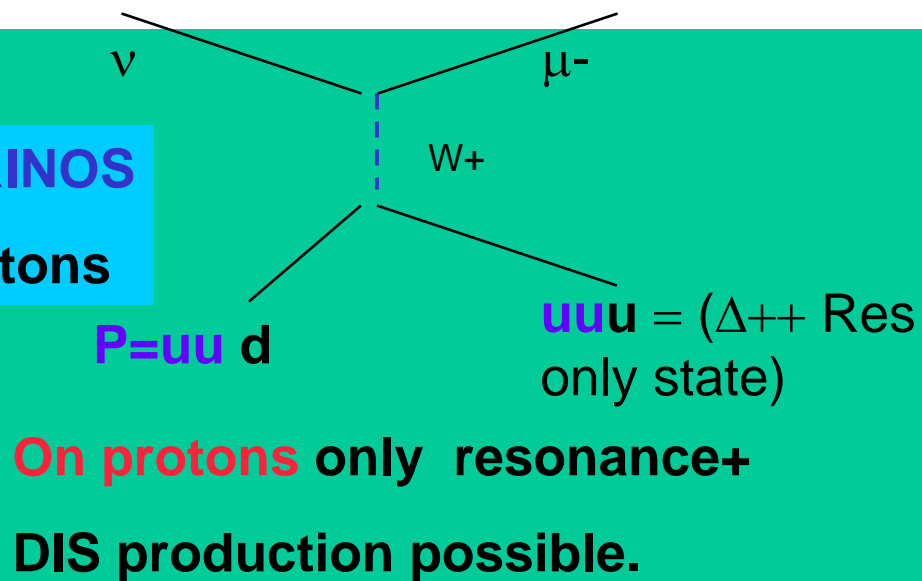
NEUTRINOS
On Neutrons



1st reson

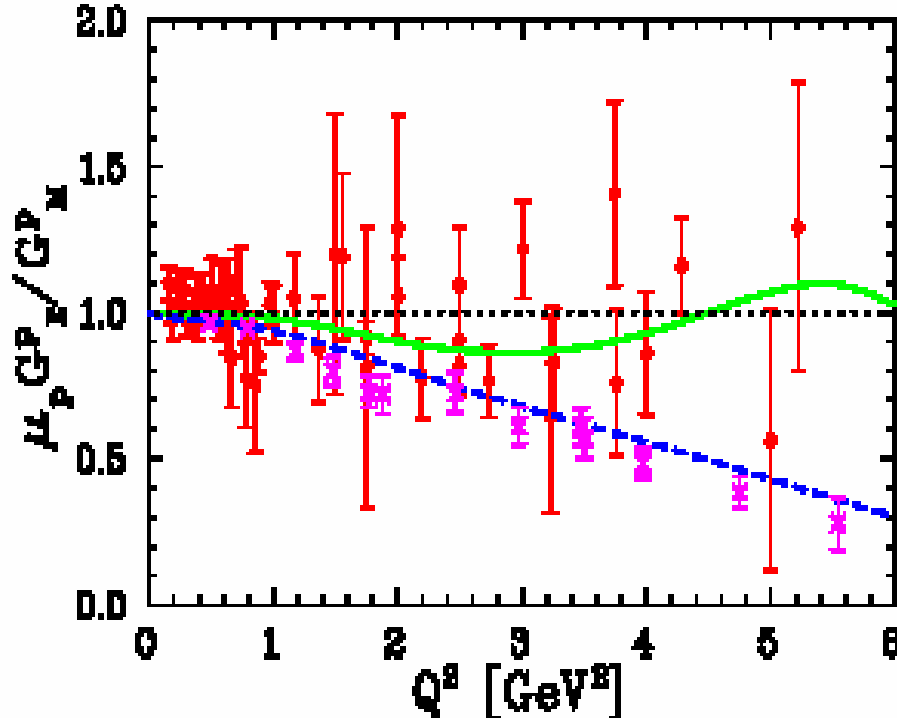
0
 $X = 1$
zero

NEUTRINOS
On Protons



Local Duality at $x=1$ limit breaks down at all Q^2 , What if we include higher resonances?

And Reverse Case for antineutrinos



Two Photon
Effects In
radiative
corrections Are
NOT significant
for this program.

FIG. 13. Ratio $\mu_p G_E^p / G_M^p$ as extracted by Rosenbluth separation measurements (circles) and as obtained by polarization measurements (stars).

For elastic scattering the ratio R is related to the ratio of form factors by the following expression $R_{elastic} = (4M^2/Q^2)(G_E/G_M)^2$, or $R_{elastic}^p = (0.481/Q^2)(\mu_p G_E^p/G_M^p)^2$. For the mean Q^2 of this experiment of 2.5 GeV^2 the data in figure 13 show that $R_{elastic}^p = (0.19)(0.88)^2 = 0.14 \pm 0.04$ from the fit to the Rosenbluth separation data and $R_{elastic}^p = (0.192)(0.72)^2 = 0.10 \pm 0.02$ from the fit to the polarization transfer data. If this difference is to be attributed to two-photon effects, then it implies a 4% epsilon dependence in the radiative corrections and an uncertainty in R of 0.04 ± 0.02 . *The uncertainty from two-photon effects in the inelastic radiative corrections is actually lower than this estimate because modern radiative corrections programs for inelastic electron and neutrino scattering (e.g. Bardin) already include two photon effects at the parton level.*