Using Neutrinos to Study the Structure of the Nucleon

GHP09 - Denver, CO
30 April 2009

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Fermilab

Neutrino Experiments have been studying Nucleon Structure for over 30 years

- For example, Gargamelle made one of the first measurements of Λ_{ST} in the early 1970's using sum rules and the x-Q^2 behavior of the structure functions F_2 and xF_3 measured off heavy liquid while BEBC followed with QCD studies using ν + p and ν + D scattering.
- Interacting with the weak current means a **much smaller interaction rate** than e/μ scattering however **can select which set of quarks involved in the interaction via ν or $\overline{\nu}$**
- There followed a long string of ν scattering experiments with **increasing statistics** and **decreasing systematic errors** culminating with the ….

Latest ν DIS Scattering Results - NuTeV

High energy neutrino scattering experiment at Fermilab

NuTeV accumulated over 3 million neutrino/antineutrino events with $20 \leq E_\nu \leq 400$ GeV.

NuTeV considered 23 systematic uncertainties in the analysis of nucleon structure functions.

NuTeV σ agrees with an earlier experiment using essentially the same detector for $x_{Bj} < 0.4$. However, NuTeV is systematically higher at high x: 4% at x = 0.45, 10% at x = 0.55, 20% at x = 0.65.

NuTeV F_2 and xF_3 agrees with **theory** for medium x.
At low x: different Q^2 dependence.
At high x (> 0.6): NuTeV is systematically higher.

NuTeV agrees with **charged lepton** data for x < 0.5.
Perhaps smaller nuclear correction at high-x for neutrino scattering.
Neutrino experiments need heavy nuclear targets to accumulate sufficient statistics. Must correct nucleus to nucleon.

Current open questions to be addressed via neutrino scattering

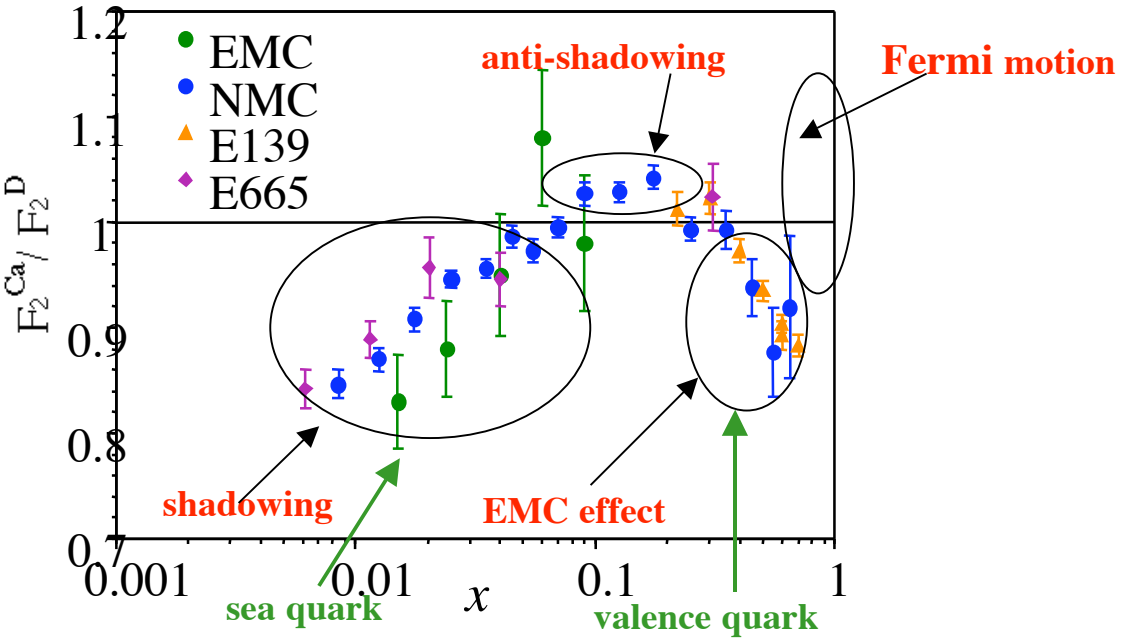
- High-x: What is happening with the valence quarks as x --> 1.0.
  NuTeV gives opposite indication compared to E866 (D-Y experiment)
- Low W: What is happening in the transition region between 1-π resonance production and DIS.
- All x and Q^2 : What will we learn if we can measure all six ν / $\bar{\nu}$ structure functions to yield maximal information on PDFs.

Before answering these questions!

- All x and Q^2 : **Are nuclear effects with neutrinos the same as those (often) measured with charged leptons?**

Systematic Experimental Studies of Nuclear Effects with Neutrinos:

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 are **DIFFERENT in ν - A**.
  - Presence of **axial-vector current.**
  - Different nuclear effects for valance and sea --> **different shadowing for xF_3 compared to F_2.**
- Recently **Sergei Kulagin** and **Roberto Petti** predicted **ν + A effects**

Kulagin-Petti Model of Nuclear Effects

Systematic approach to predict nuclear effects for ν+A

hep-ph/0412425 **Phys.Rev.D76:094023,2007**

- Global Approach - aiming to obtain quantitative calculations covering the complete range of x and Q^2 with thorough physics basis for fit to data.
- Different effects on structure functions (SF) are taken into account:

$$F_i^A = F_i^{p/A} + F_i^{n/A} + F_i^{\pi/A} + \delta F_i^{\rm coh}$$

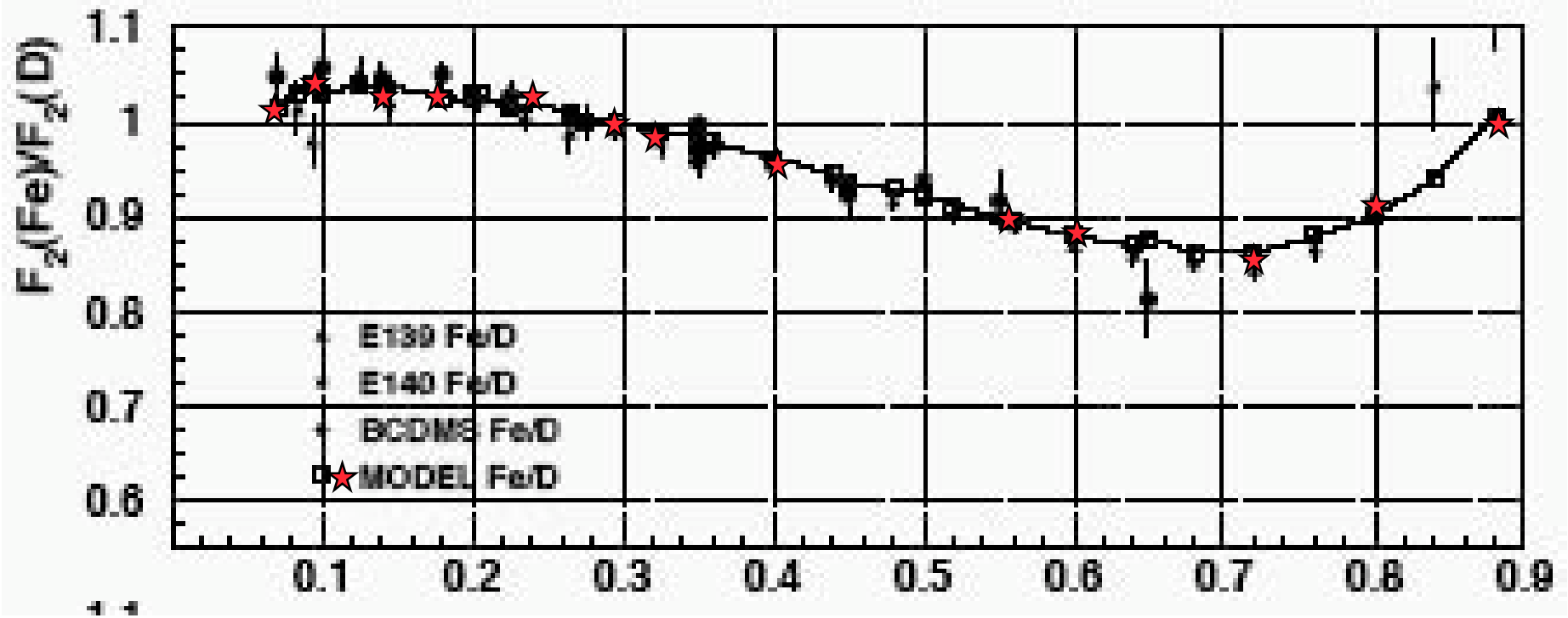
- $F_i^{p(n)/A}$ bound proton(neutron) SF with Fermi Motion, Binding (FMB) and Off-Shell effect (OS)
- $F_i^{\pi/A}$ nuclear Pion excess correction (PI)
- $\delta F_i^{\rm coh}$ contribution from coherent nuclear interactions: Nuclear Shadowing (NS)

- **Fermi Motion** and **Binding** in nuclear structure functions is calculated from the convolution of nuclear spectral function and (bound) nucleon SFs:
- Since bound nucleons are off-mass shell there appears dependence on the nucleon virtuality $\kappa^2 = (M + \varepsilon)^2 - k^2$ where we have introduced an **off-shell structure function $\delta f_2(x)$**

$$F_2(x, Q^2, k^2) = F_2(x, Q^2)\left(1 + \delta f_2(x)(k^2 - M^2)/M^2\right)$$

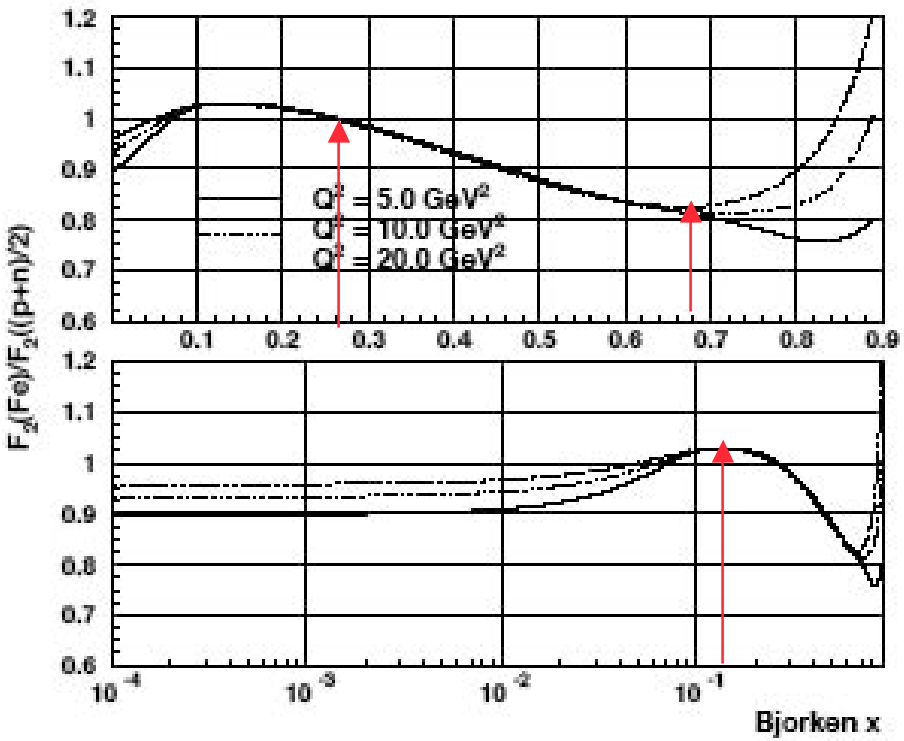
- Leptons can scatter off mesons which mediate interactions among bound nucleons yielding a **nuclear pion correction**

Kulagin-Petti compared to e/μ+Fe data
F_2 (e/μ+Fe) / F_2 (e/μ+D)

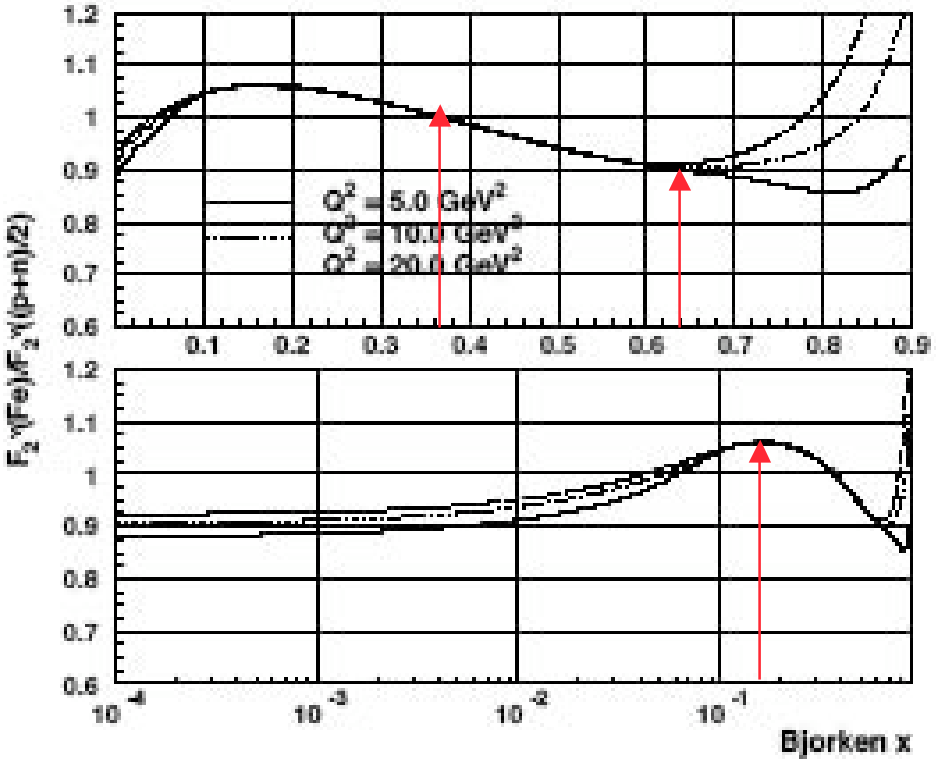


Charged Lepton

F_2 (μ+Fe) / F_2 (μ+N) compared to F_2 (ν+Fe) / F_2 (ν+N)



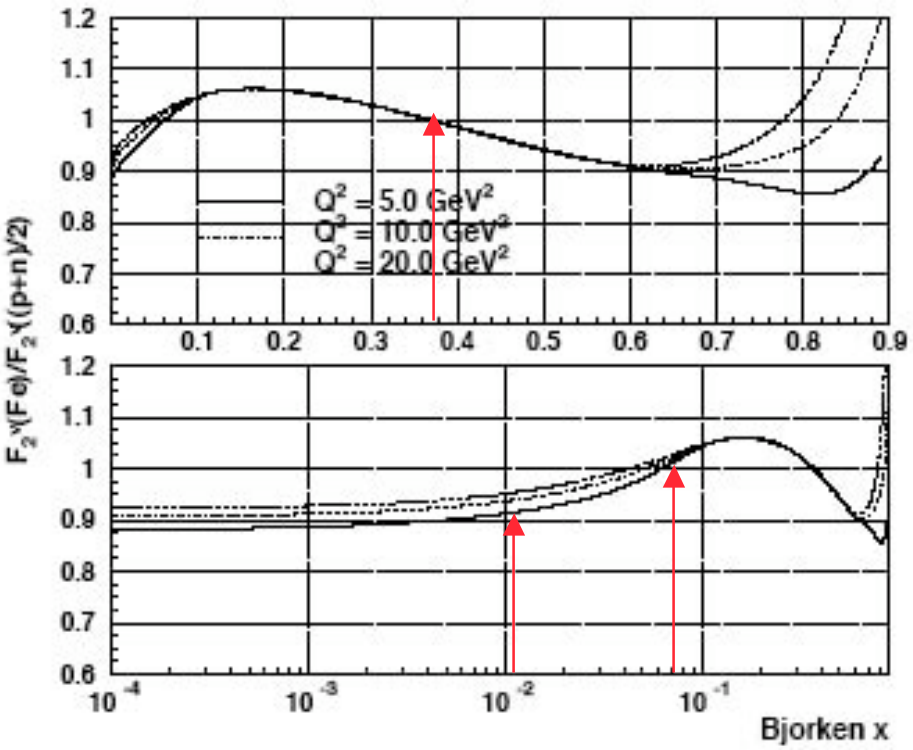
Charged Lepton



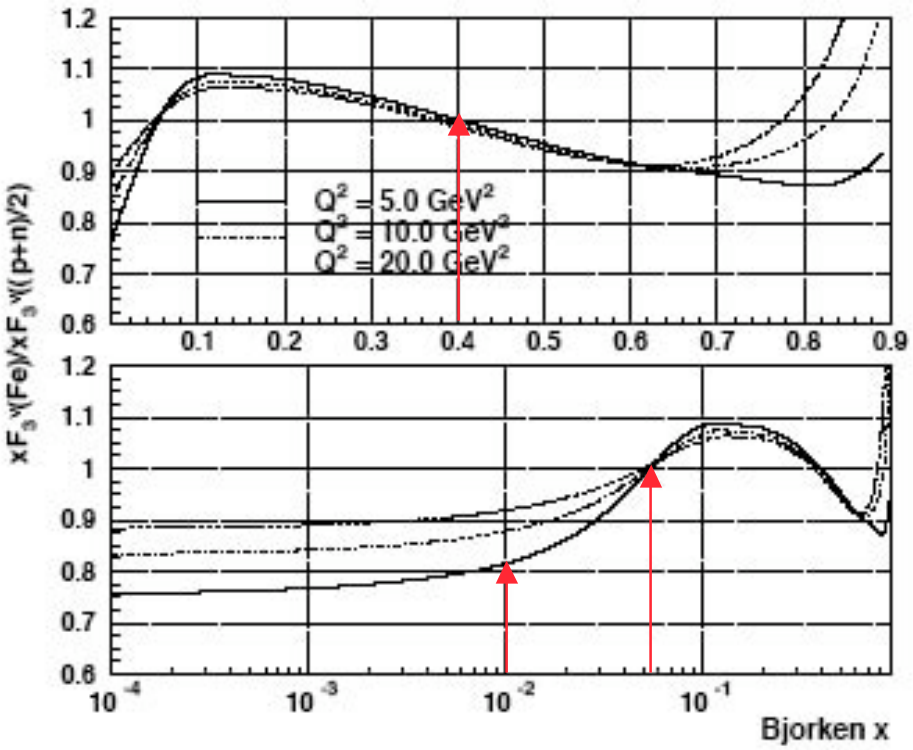
Neutrino

Kulagin-Petti: ν-Fe Nuclear Effects

We now can investigate high-x NuTeV data!



F_2



xF_3

Investigating the Behavior of Quarks at High-x

The Impact of New Neutrino DIS and Drell-Yan Data on Large-x Parton Distributions

Joey Huston - MSU, Cynthia Keppel - Hampton, Steve Kuhlmann - ANL,
JGM - Fermilab, Fred Olness - SMU, Jeff Owens - Florida State,
Jon Pumplin and Dan Stump - MSU

Published in **Phys.Rev.D75:054030,2007**.
e-Print: **hep-ph/0702159**

Converting NuTeV Fe data to nucleon equivalent using charged lepton correction factor and Kulagin-Petti correction factor

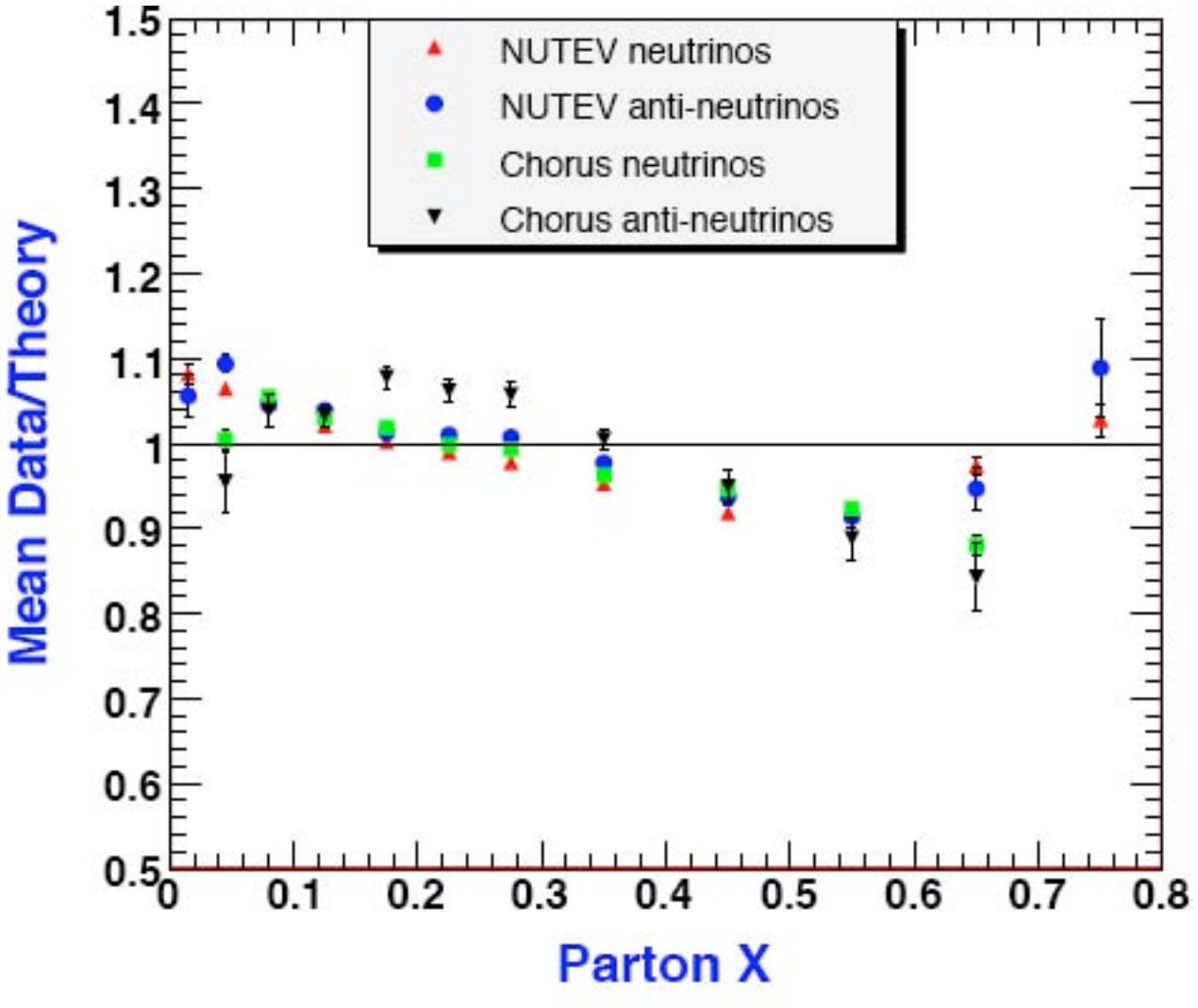
CTEQ High-x Study

Ratio: NuTeV ν+Fe (and CHORUS ν+Pb) data to ν+nucleon

- Form reference "nucleon" from PDFs determined from nucleon (as opposed to nuclear) scattering results:
  - BCDMS results for F_2^p and F_2^d
  - NMC results for F_2^p and F_2d/F_2^p
  - H1 and ZEUS results for F_2^p
  - CDF and DØ result for inclusive jet production
  - CDF results for the W lepton asymmetry
  - E-866 results for the ratio of lepton pair cross sections for pd and pp interactions
  - E-605 results for dimuon production in pN interactions.
- Correct for deuteron nuclear effects

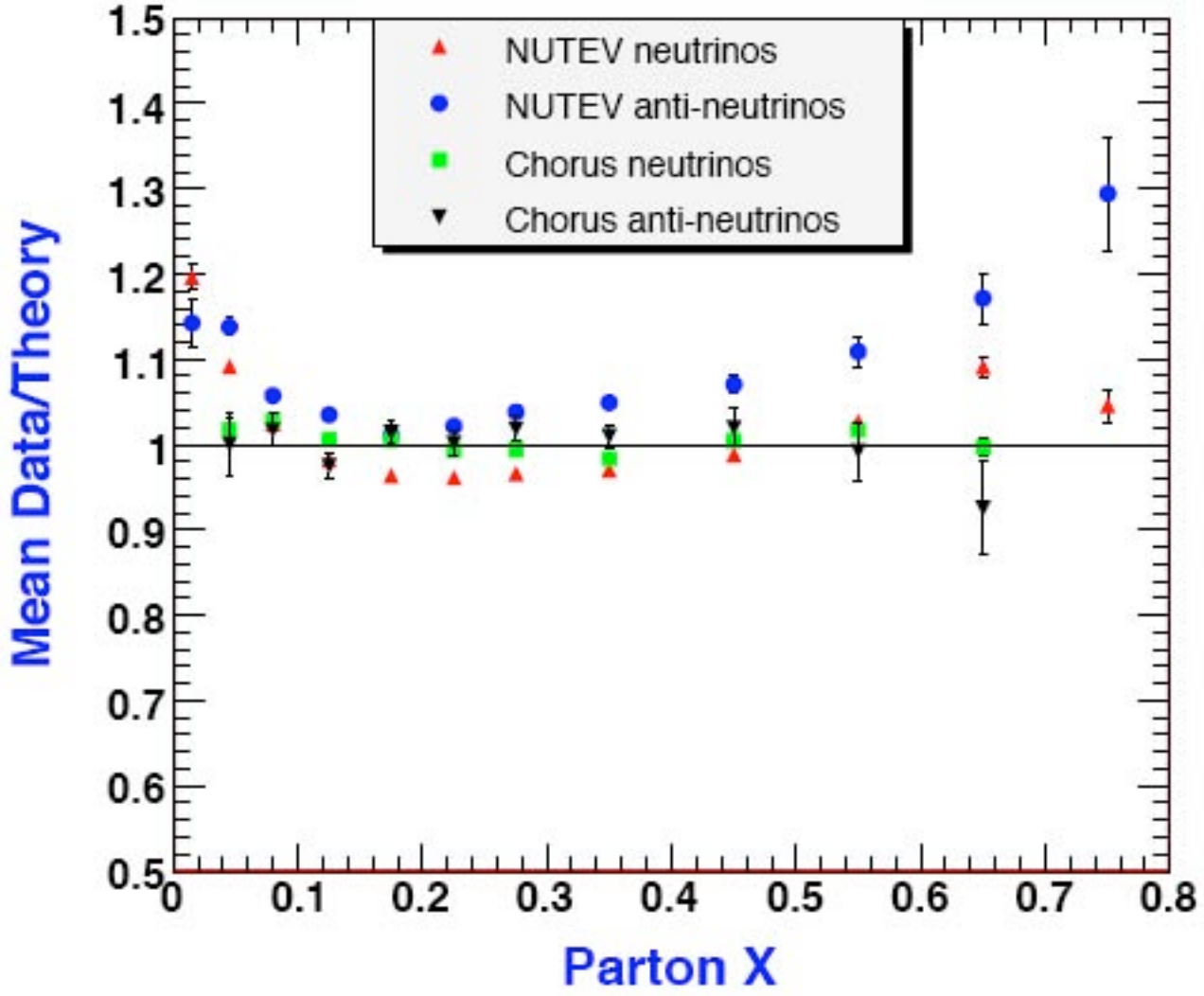
NuTeV(Fe) and CHORUS (Pb) ν scattering (σ) results compared to reference fit

no nuclear corrections



NuTeV σ(Fe) & CHORUS σ(Pb) ν scattering results compared to reference fit

If Kulagin-Petti nuclear effects correct - points should be at "1.0"



If neither charged-lepton nor Kulagin-Petti nuclear corrections compatible with NuTeV measurements..??

Nuclear PDFs from Neutrino Deep-inelastic Scattering

I. Schienbein (SMU & LPSC-Grenoble), J-Y. Yu (SMU)
C. Keppel (Hampton & JeffersonLab) J.G.M. (Fermilab),
F. Olness (SMU), J.F. Owens (Florida State U)

e-Print: **arXiv:0710.4897** [hep-ph]
Phys.Rev.D77:054013,2008

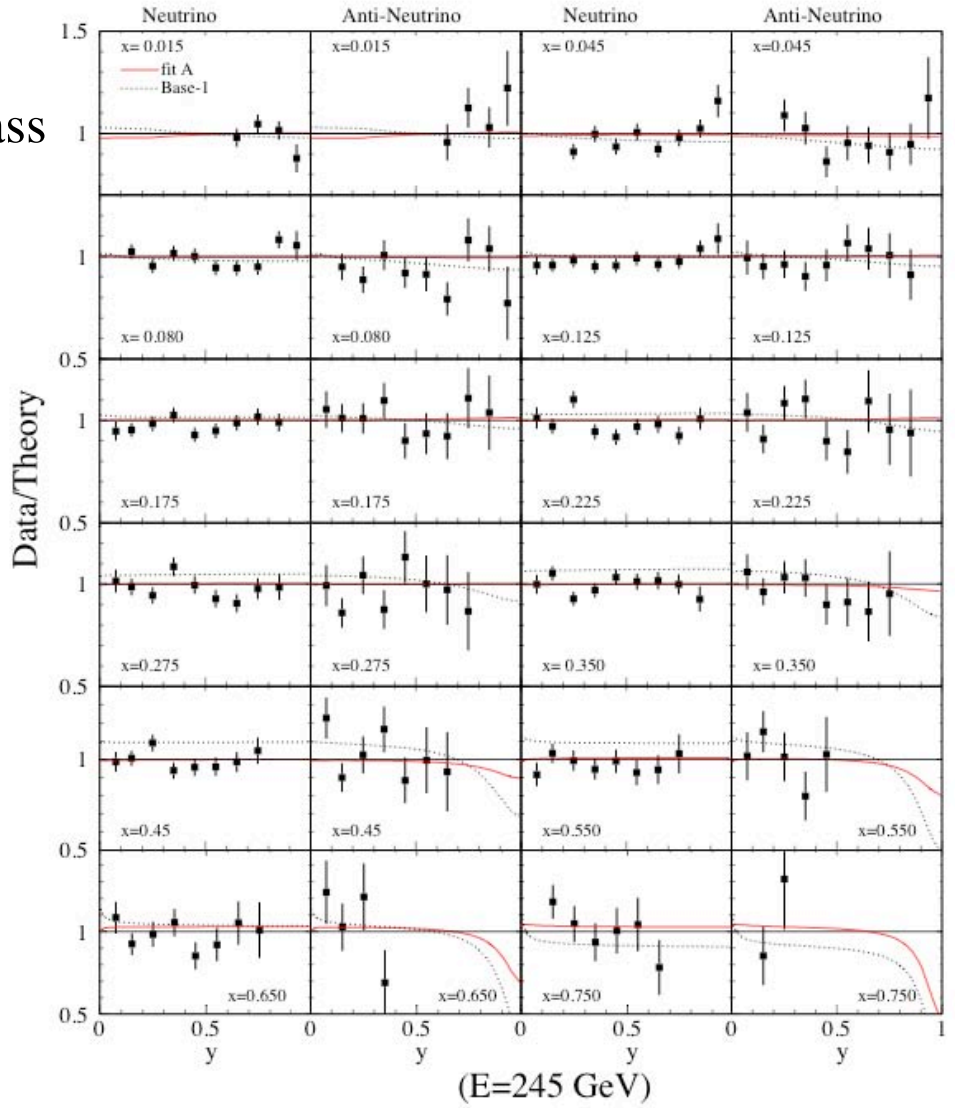
Sample NuTeV Data vs Theory

Use ACOT - heavy quark mass Effects - in NLO QCD.

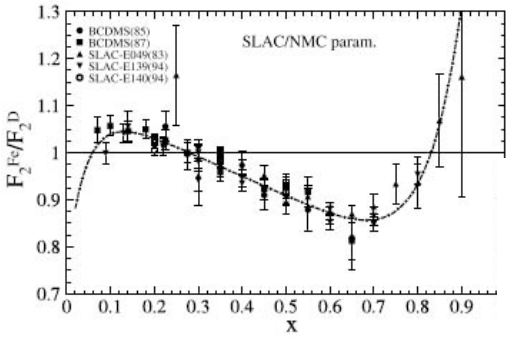
Q > 2.0 GeV, W > 3.5 GeV

Use same reference fit as in first publication

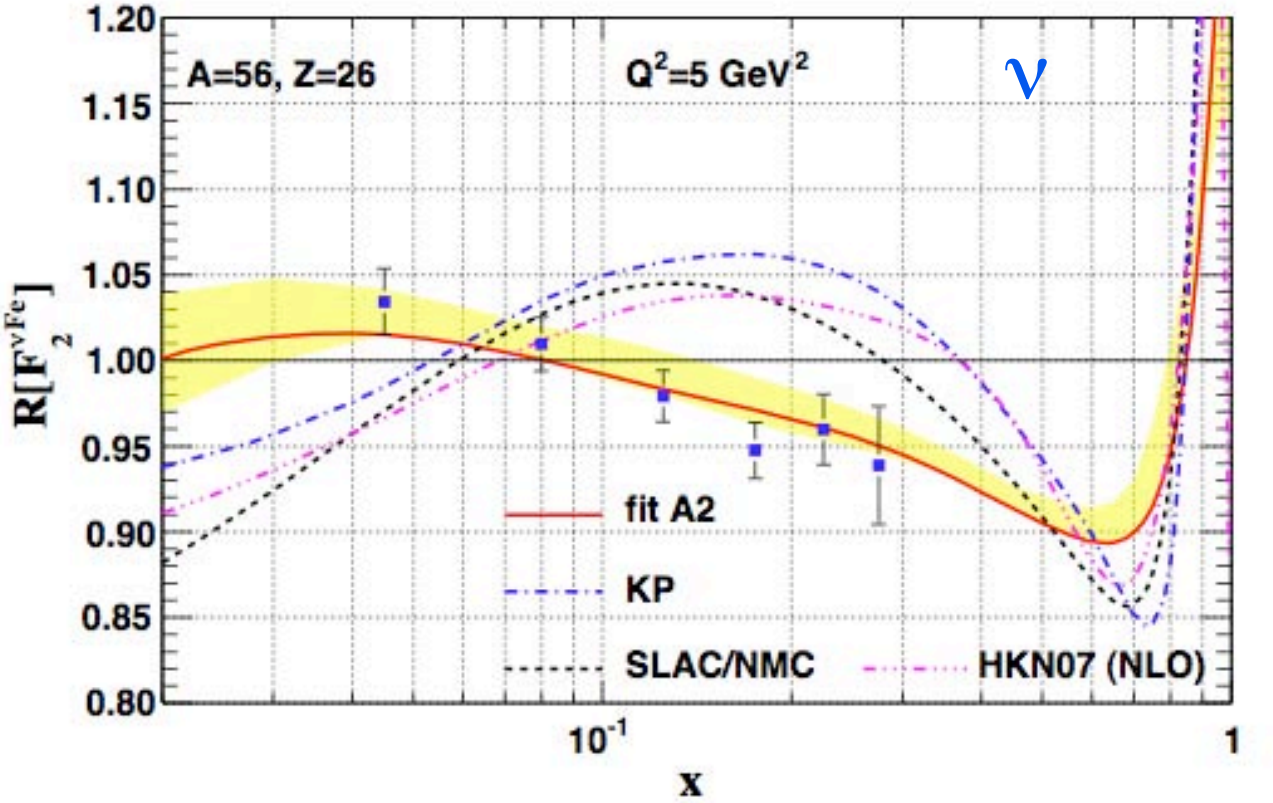
Double-differential cross sections



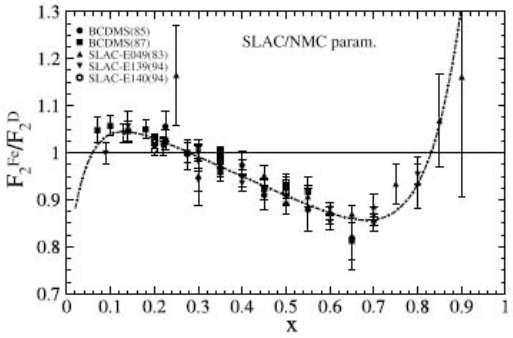
F_2 Structure Function Ratios: ν-Iron

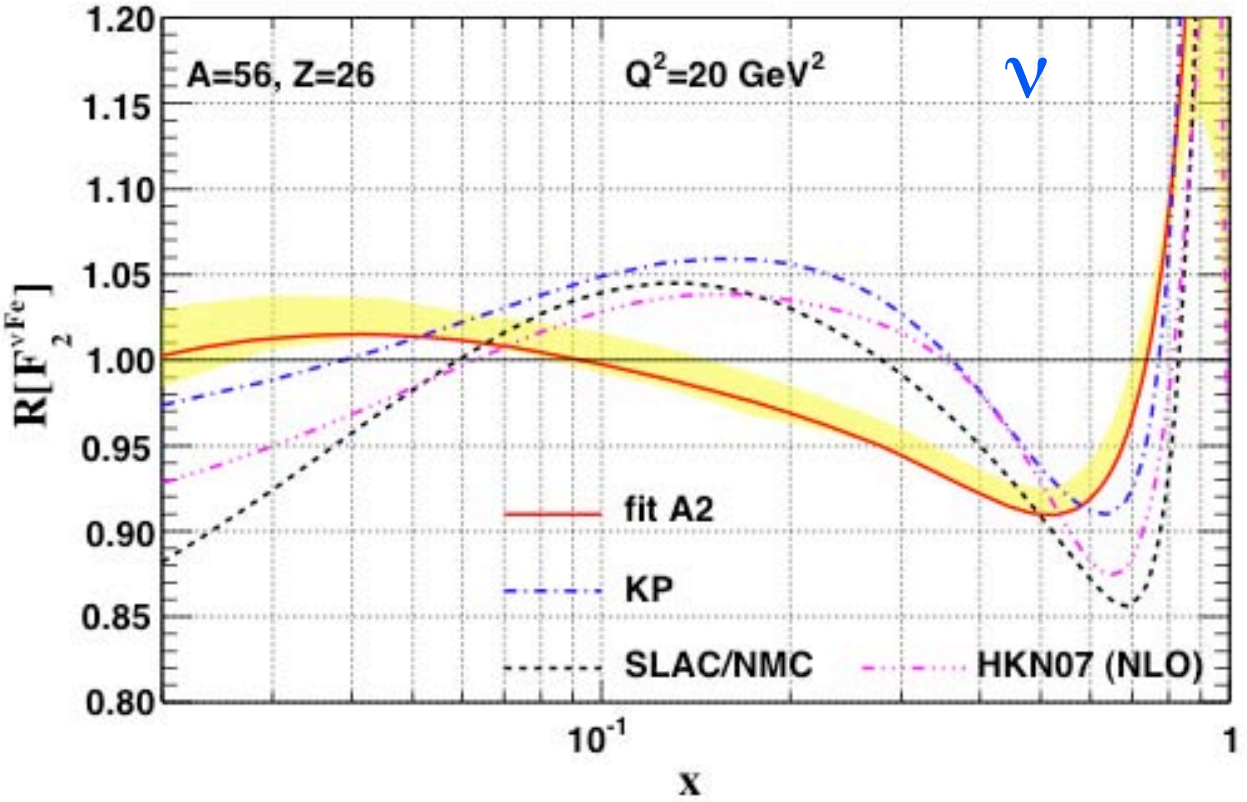


- Use ACOT - heavy quark mass Effects - in NLO QCD.
- Q > 2.0 GeV, W > 3.5 GeV
- Use same reference fit as in first publication

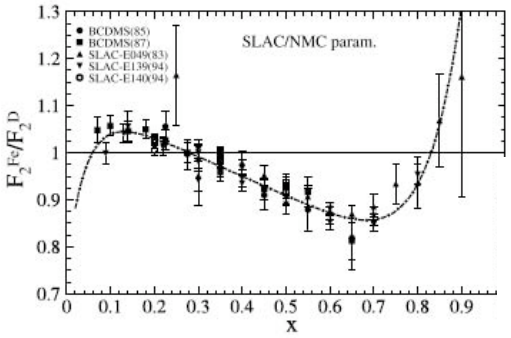


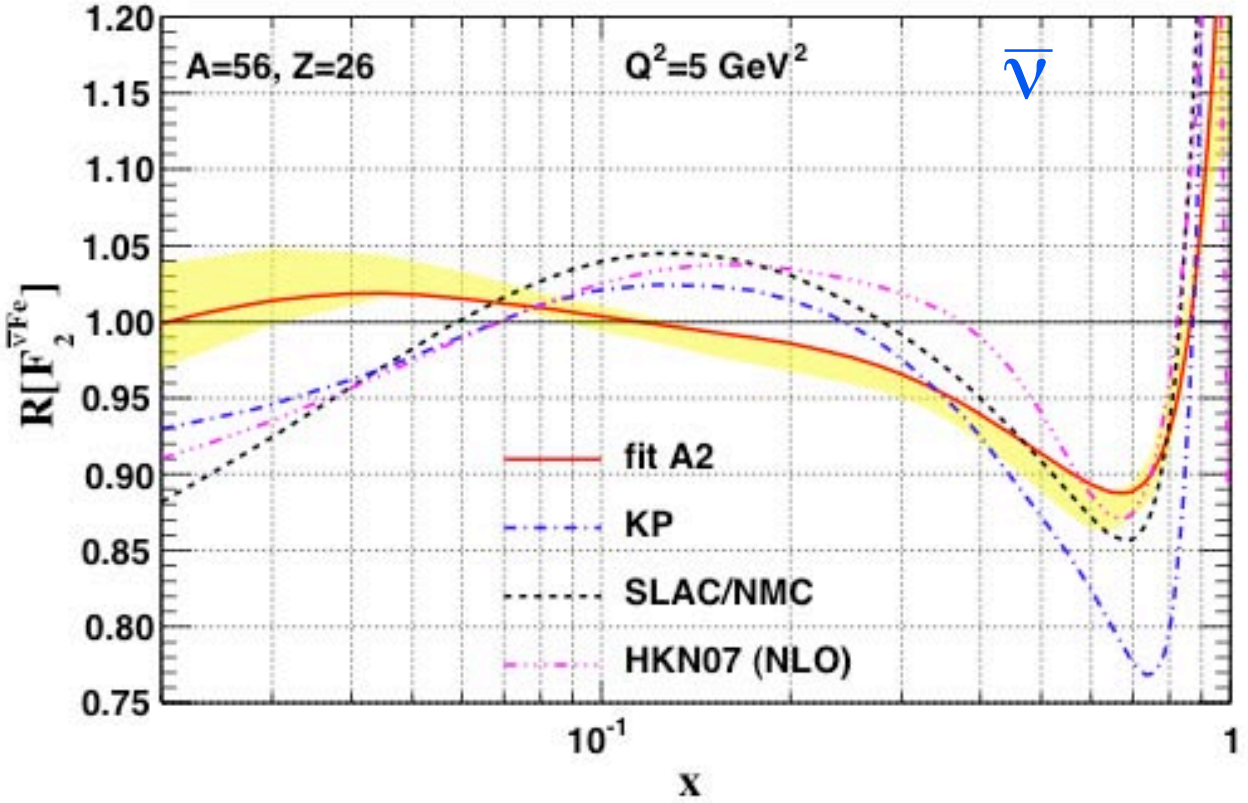
F_2 Structure Function Ratios: ν-Iron



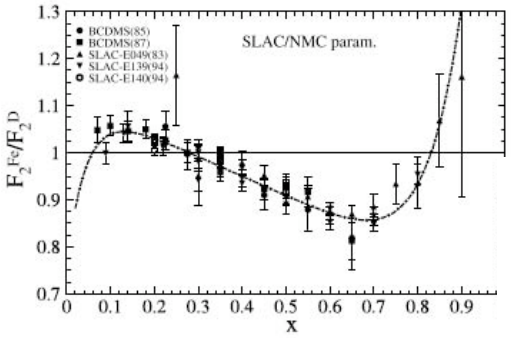


F_2 Structure Function Ratios: $\bar{\nu}$-Iron



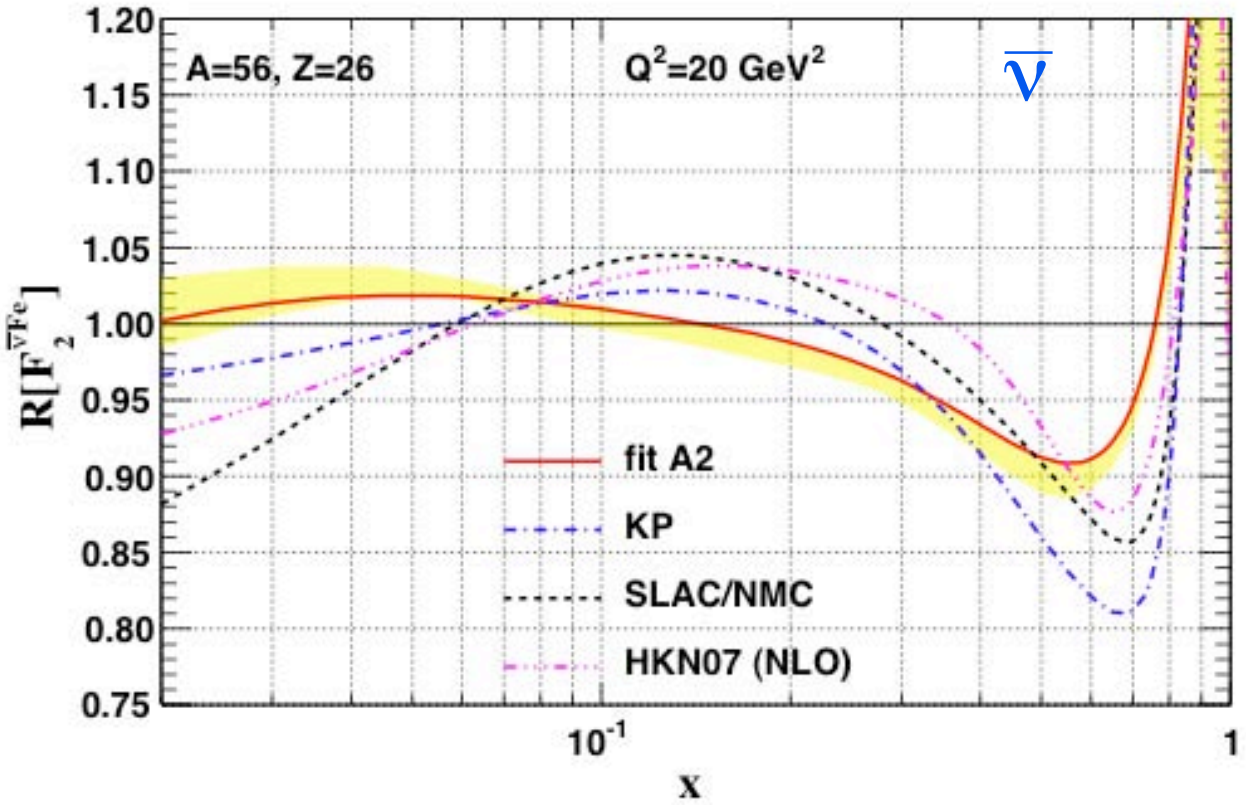


F_2 Structure Function Ratios: $\bar{\nu}$-Iron



Be careful!

One analysis of one experiment on one nucleus



Need a High-statistics, Precise Study of ν Scattering off several nuclei

The MINERνA Experiment

MINERvA Institutions

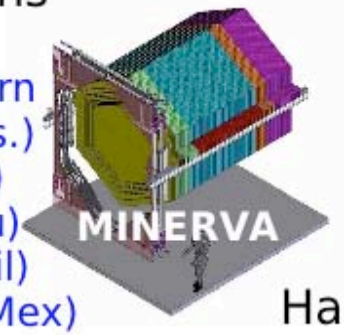
Tufts
William & Mary
FNAL
Duluth
Texas
Athens

NOVA

MINOS

Pitt

Northwestern
MCLA (Mass.)
UNI (Peru)
PUCP (Peru)
CBPF (Brazil)
Guanajuato (Mex)



Dortmund
INR, Moscow

Theory

Jefferson Lab

Hampton
James Madison
Rutgers

Irvine

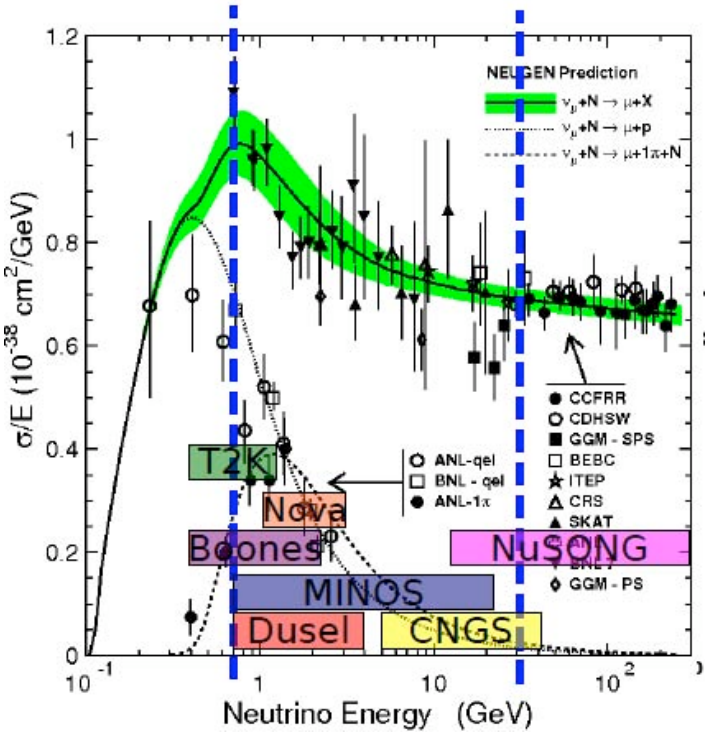
T2K

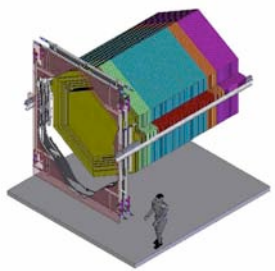
Rochester

Nuclear

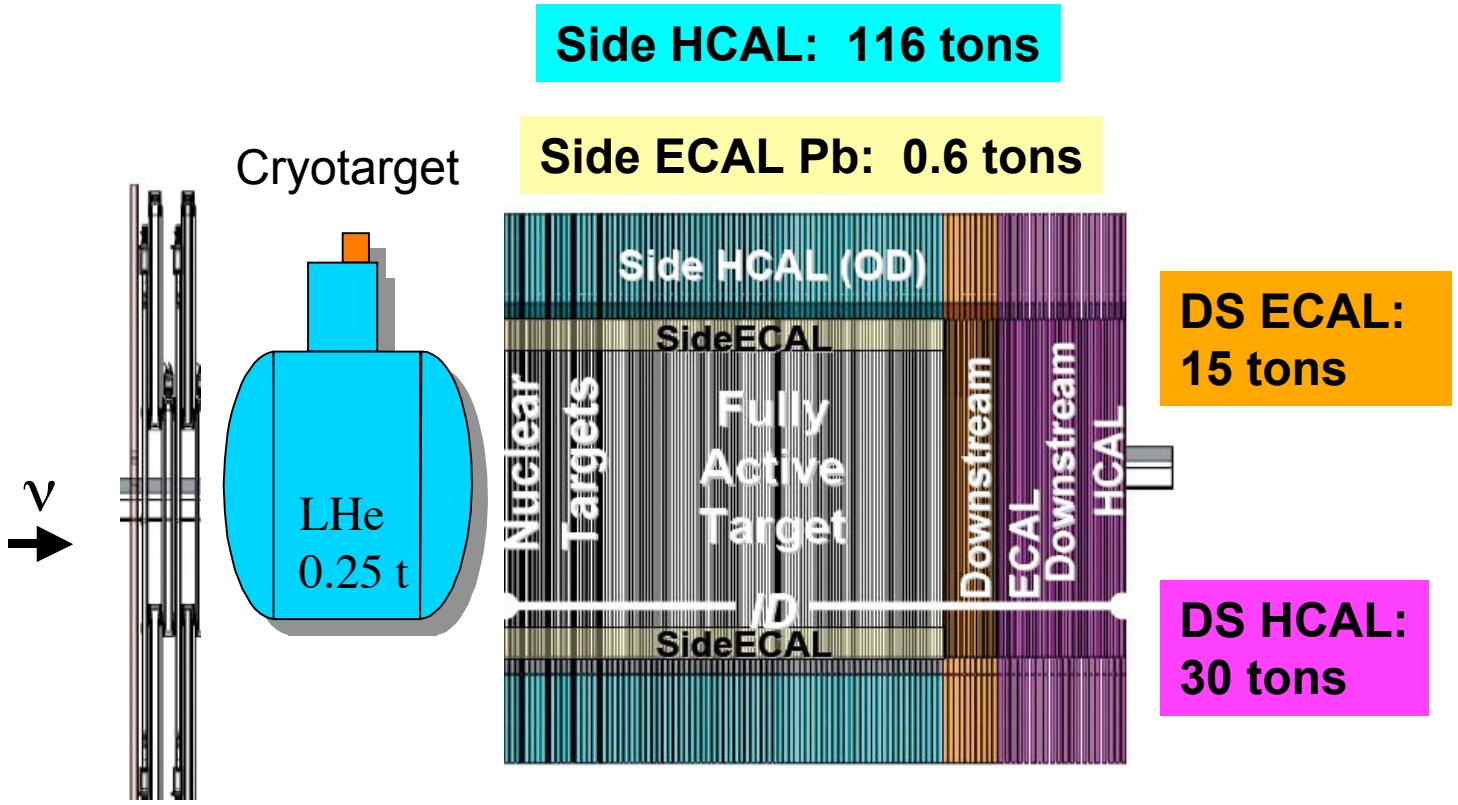
MINERνA ν Scattering Physics Program

- Quasi-elastic
- Resonance Production - 1pi
- Resonance Production - npi / Transition region - resonance to DIS
- Deep-Inelastic Scattering
- Coherent Pion Production
- Strange and Charm Particle Production
- σ_L , Structure Functions and PDFs
  - **High-x parton distribution functions**
- Nuclear Effects - including nuclear PDFs
- Generalized Parton Distributions





Complete MINERνA Experimental Set-up

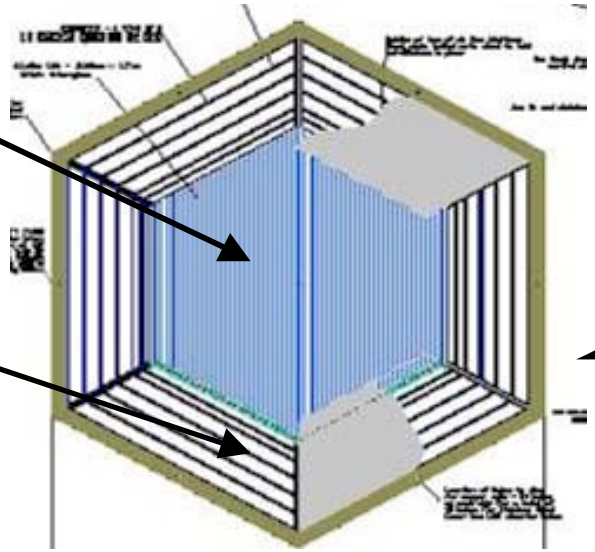


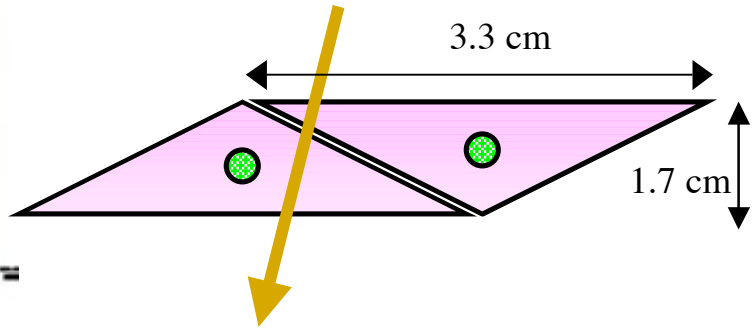
Active Target Module

- Planes of strips are hexagonal
  - Inner detector: active scintillator strip tracker (triangular extrusions using charge sharing) rotated by 60° to get stereo U and V views
  - Pb "washers" around outer 15 cm of active target for side ECAL
  - Outer detector: frame, side HCAL
  - XUXV planes → module

Inner, fully-active strip detector

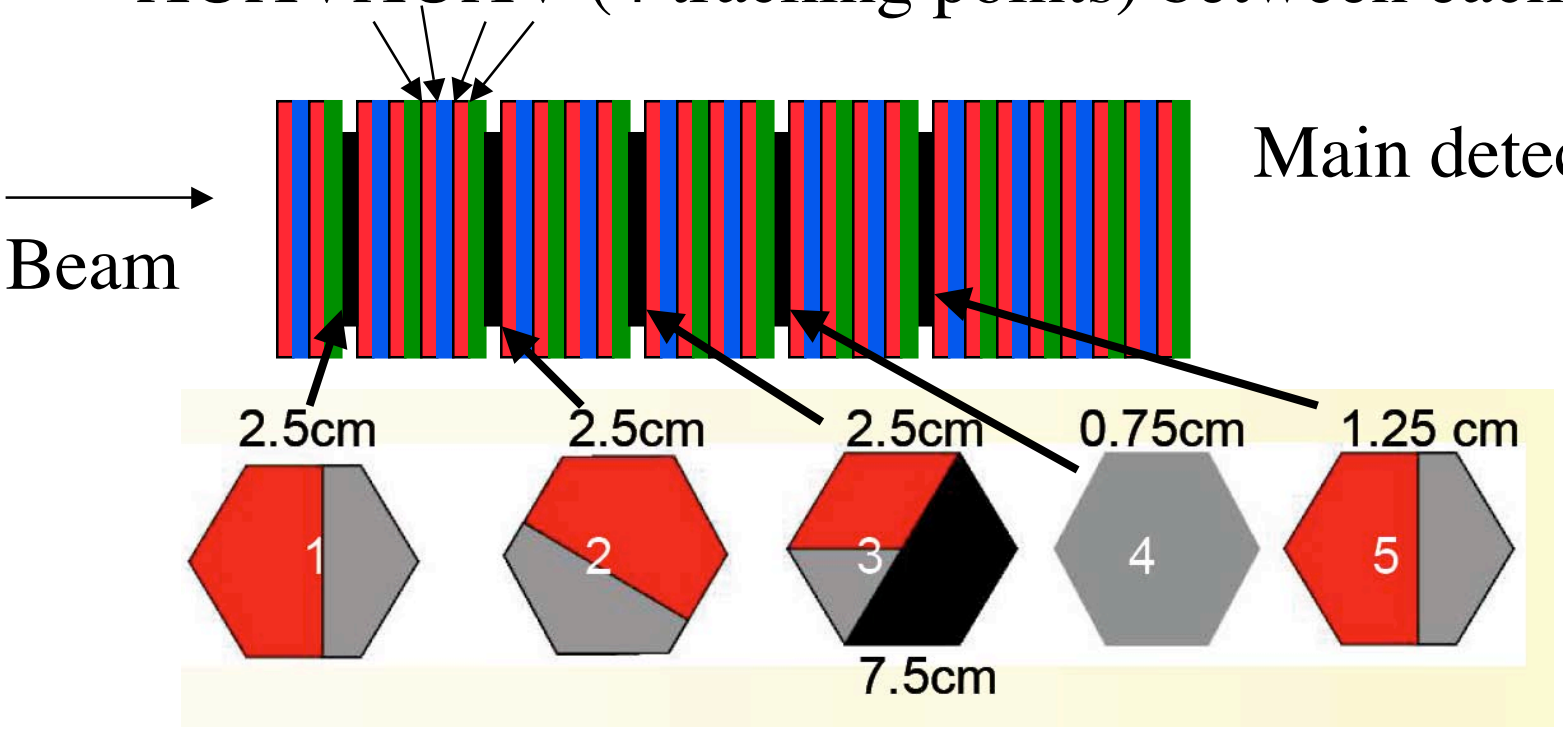
Outer Detector Hadronic Calorimeter and muon identifier





Solid Nuclear Target Region

XUXVXUXV (4 tracking points) between each layer



Carbon, Iron, Lead – mixed elements in layers to give similar systematics

MINERνA Event Rates

14.5 Million total CC events in the current run-plan

7 Million NC events

Run-plan assumes 4.**0**x10^{20} **in LE and** 12.**0**x10^{20} **ME NuMI beam configurations**

Fiducial Volume = 3 tons CH, 0.2t He, 0.15t C, 0.7t Fe and 0.85t Pb

Expected CC event samples:

9.0 M ν events in 3 tons of CH

0.6 M ν events in He

0.4 M ν events in C

2.0 M ν events in Fe

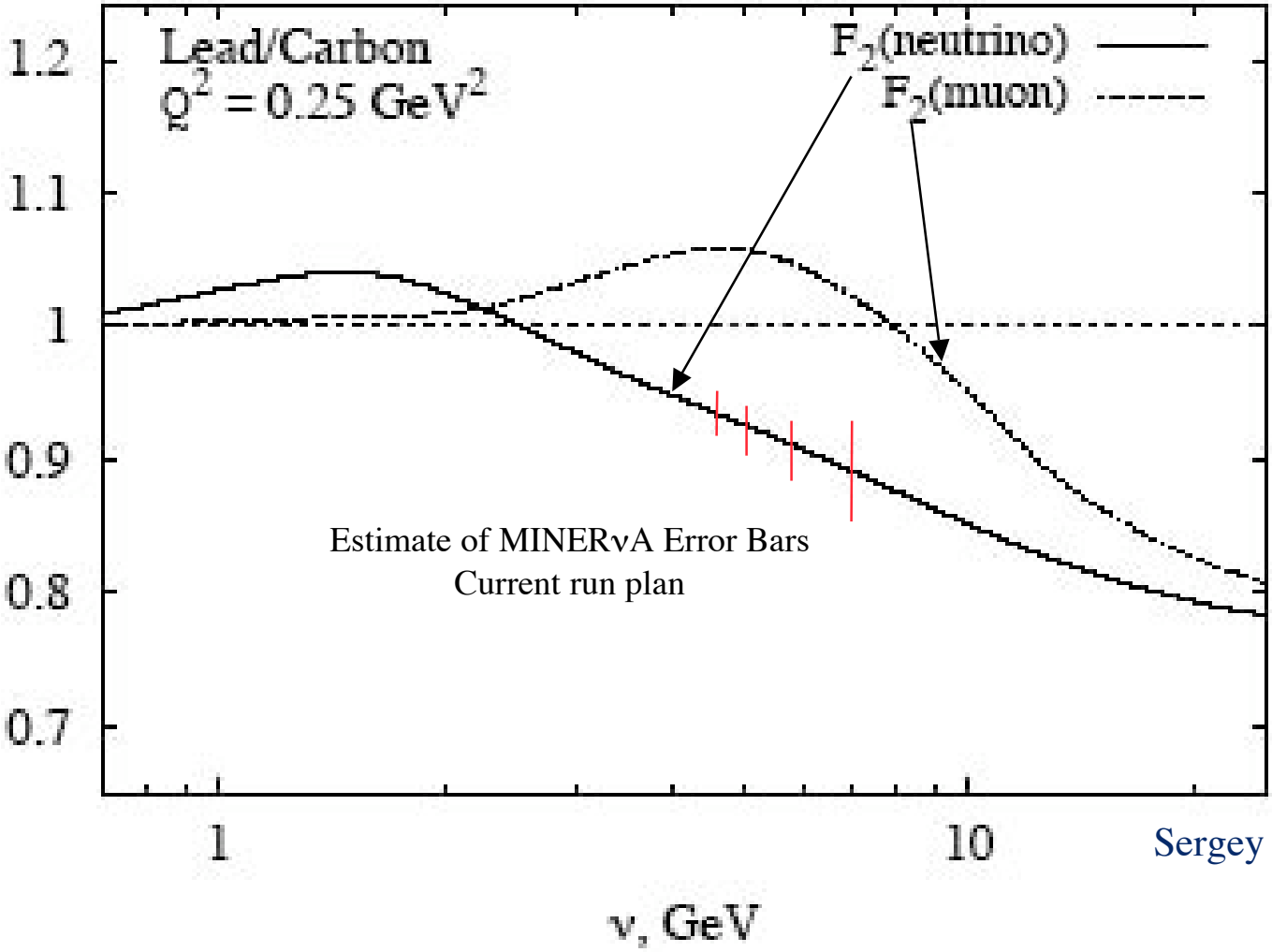
2.5 M ν events in Pb

Main CC Physics Topics (Statistics in CH)

◆ Quasi-elastic	**0.8 M events**
◆ Resonance Production	**1.7 M total**
◆ Transition: Resonance to DIS	**2.1 M events**
◆ DIS, Structure Funcs. and high-x PDFs	**4.3 M DIS events**
◆ Coherent Pion Production	**89 K CC / 44 K NC**
◆ Strange and Charm Particle Production	**> 240 K fully reconstructed events**
◆ Generalized Parton Distributions	**order 10 K events**
◆ Nuclear Effects	**He: 0.6 M, C: 0.4 M, Fe: 2.0 M and Pb: 2.5 M**

MINERνA Measurement of Nuclear Effects

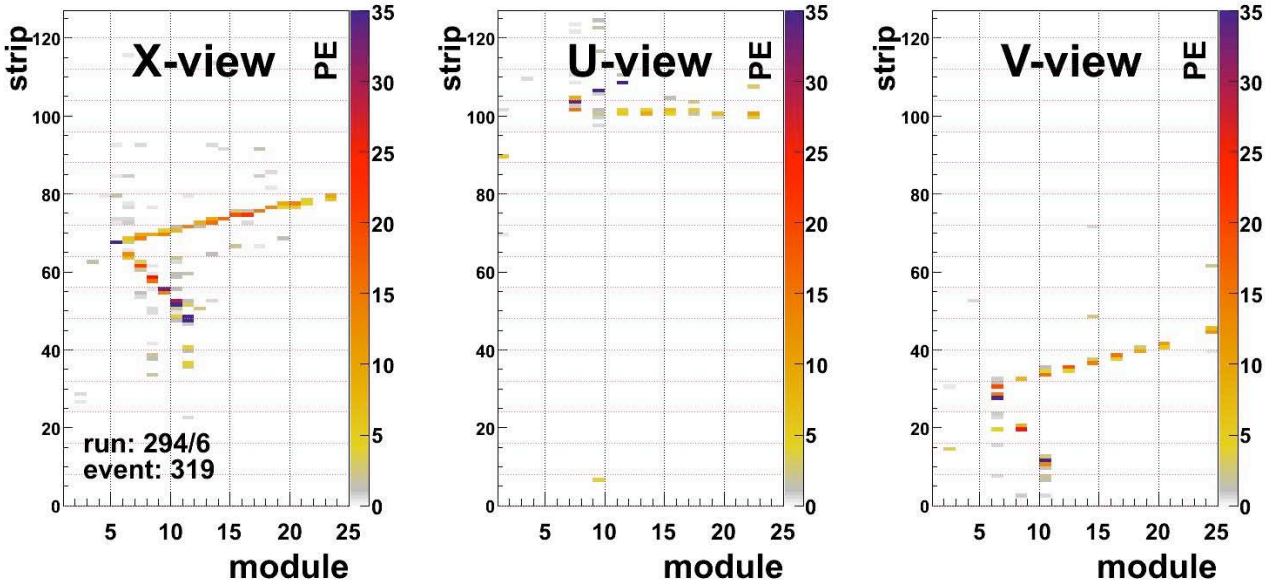
The Axial-vector Current and Shadowing



Sergey Kulagin

20% Full-sized Prototype in NuMI Beam

We are taking first neutrino event data as I speak



Conclusions: ν nuclear effects

- NuTeV ν-Fe scattering seems to see little or no evidence for shadowing
- Differences in nuclear effects between ν and $\bar{\nu}$, Fe and Pb are small in the region $0.1 < x < 0.6$
- The Kulagin-Petti corrections for Fe **over-correct** with respect to the reference fit when applied to the NuTeV Fe results.
- **Except at very high x, correction factors differ in both shape and magnitude from charged lepton and K-P correction factors**

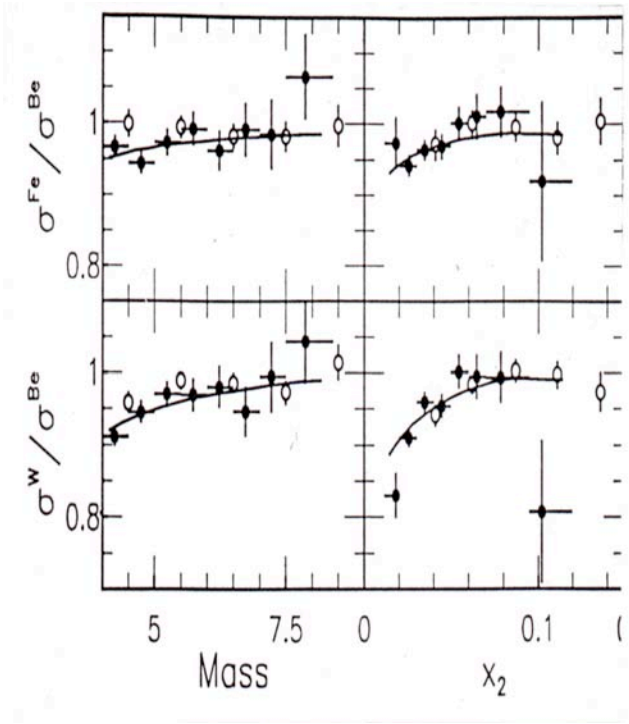
Conclusions: MINERνA

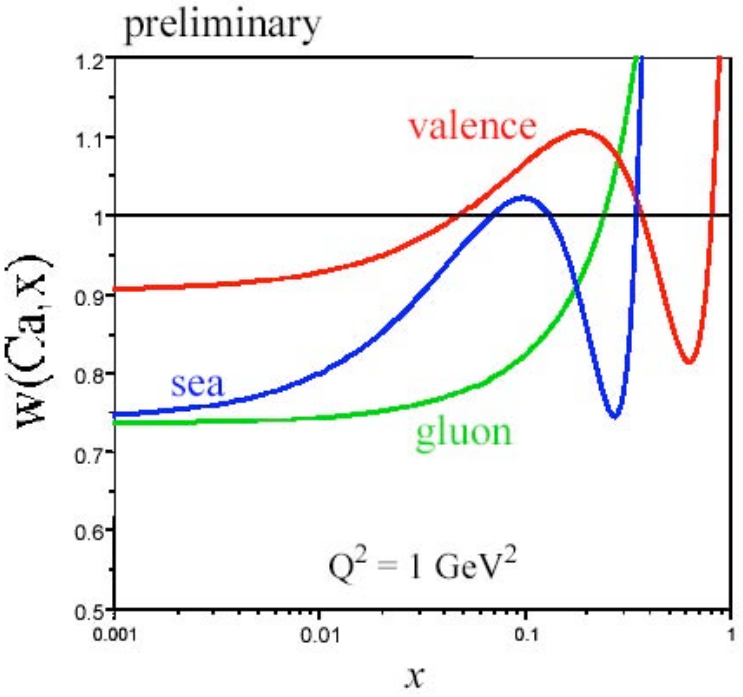
- The MINERνA experiment brings together the expertise of the HEP and NP communities.
- MINERνA will accumulate significantly more events in important exclusive channels across a wider E_ν range than currently available as well as a huge sample of DIS events.
- With He, C, Fe and Pb targets MINERνA will enable a systematic study of nuclear effects in ν-A interactions, suspected to be different than well-studied e-A effects.
- MINERνA is currently taking neutrino data with a Tracking Prototype and will begin taking data with the full detector a year from now.

Additional Details

Nuclear Effects

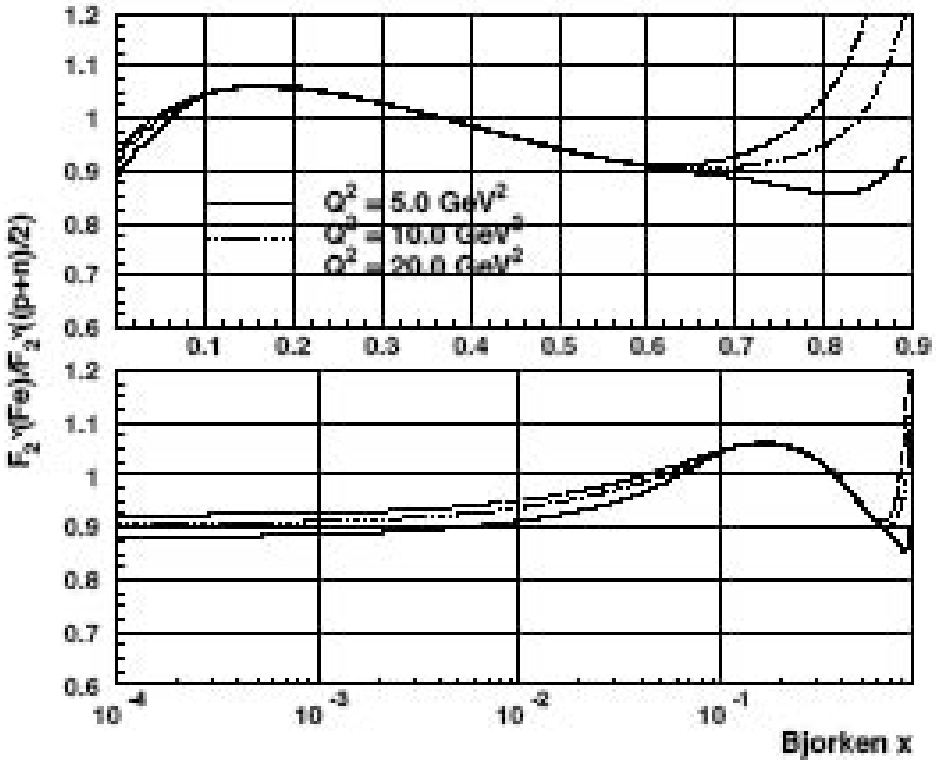
A Difference in Nuclear Effects of Valence and Sea Quarks?

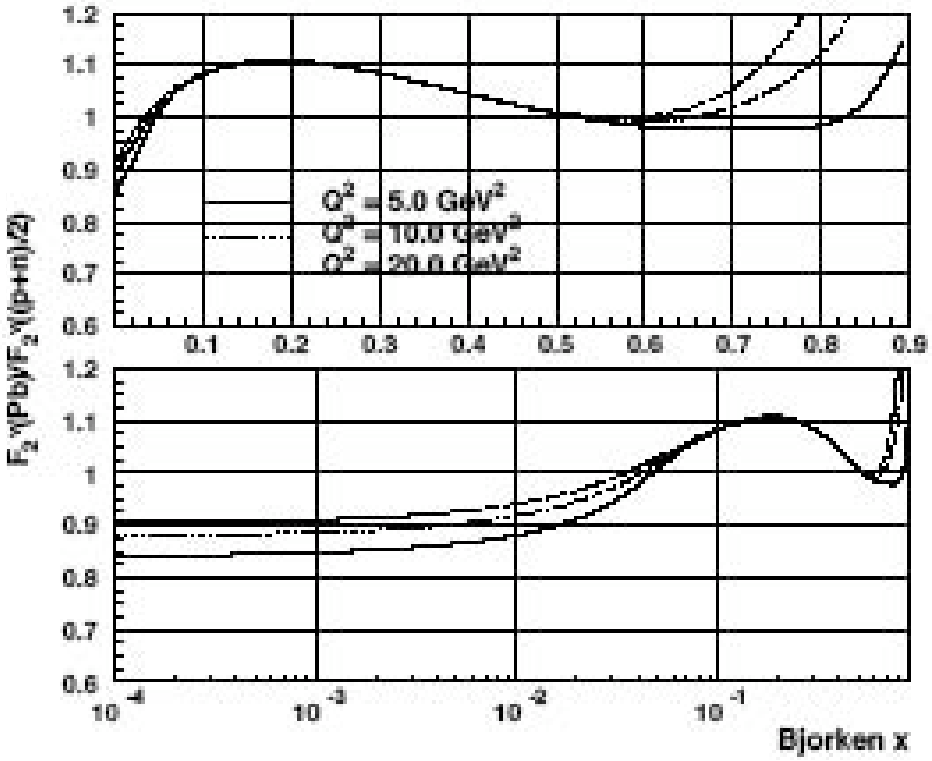




- Nuclear effects similar in Drell-Yan and DIS for x < 0.1. Then no "anti-shadowing" in D-Y while "anti-shadowing" seen in DIS (5-8% effect in NMC).
- This quantified via **Nuclear Parton Distribution Functions**: K.J. Eskola et al and S. Kumano et al. Currently, Ingo Schienbein and Ji Young Yu + CTEQ nPDF fits
- **Recently Sergei Kulagin and Roberto Petti provided first look at ν + A effects**

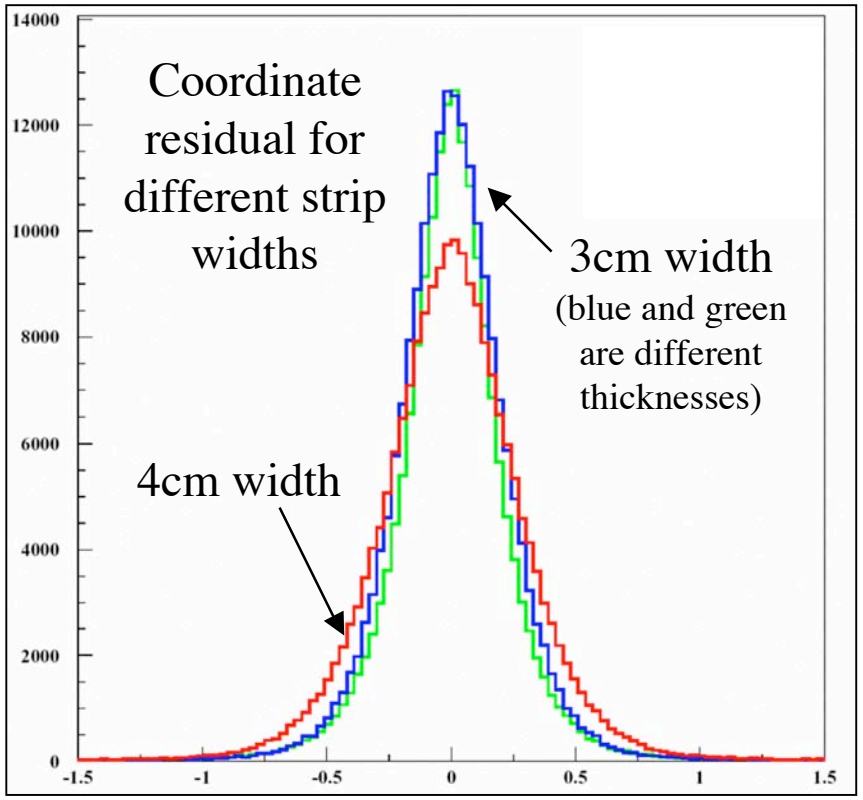
$F_2(\nu+A) / F_2(\nu+N)$





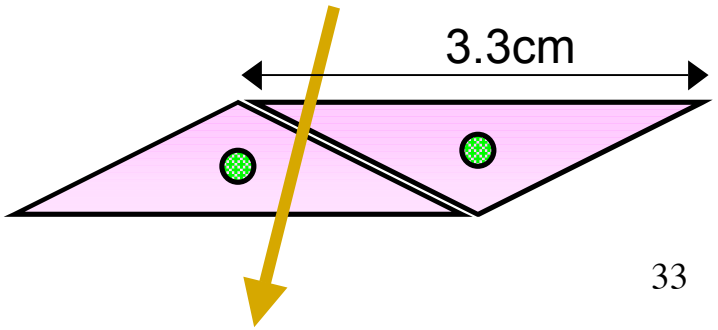
Fe Pb

Performance: Optimization of Tracking in Active Target



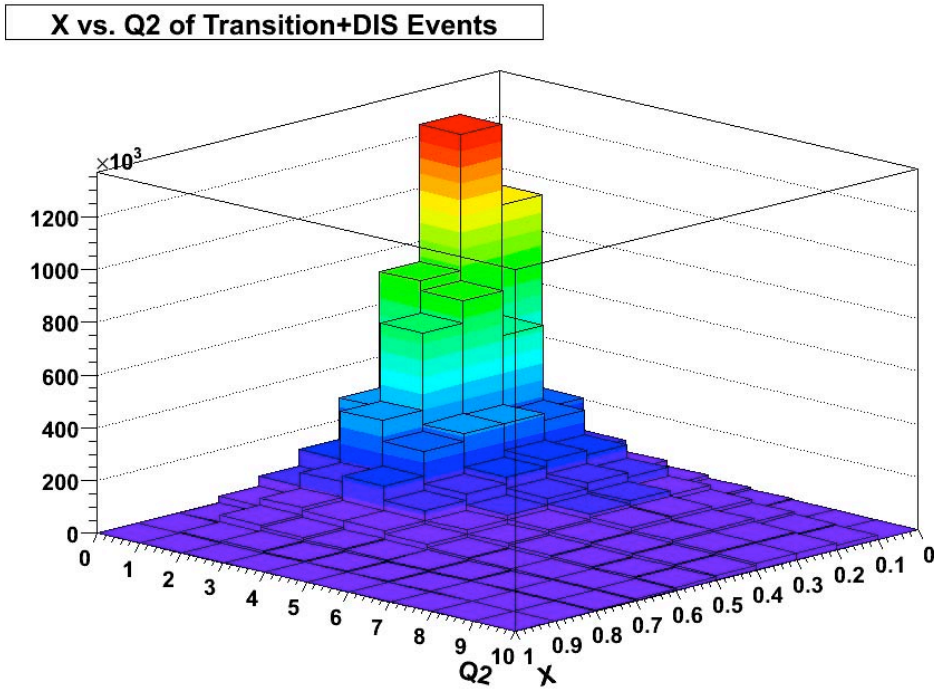
- technique pioneered by D0 upgrade pre-shower detector

- Excellent tracking resolution w/ triangular extrusion
  - σ~3 mm in transverse direction from light sharing
  - More effective than rectangles (resolution/segmentation)
  - Key resolution parameters:
    - transverse segmentation and light yield
    - longitudinal segmentation for z vertex determination

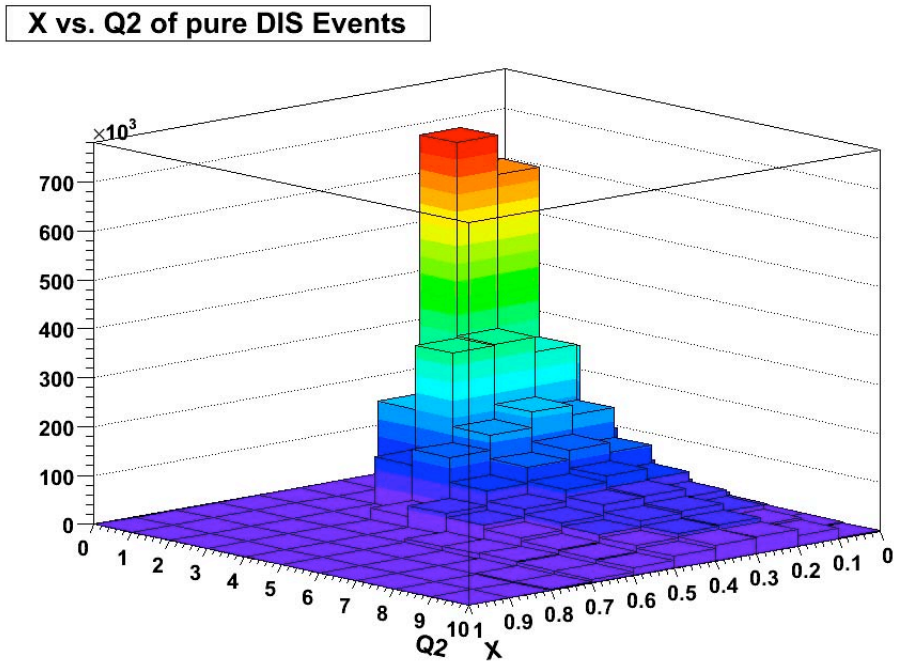


Event Distribution in x - Q^2

Based on 9.0 M ν events on CH.



84 K events with
X > 0.65 and
Q^2 > 2 GeV^2



Additional 5.5 M
events on He, C,
Fe and Pb targets

Parton Distribution Functions:
What Can We Learn With All Six Structure Functions?

Recall Neutrinos have the ability to directly resolve flavor of the nucleon's constituents: ν interacts with d, s, $\bar{u}$, and $\bar{c}$ while $\bar{\nu}$ interacts with u, c, $\bar{d}$ and $\bar{s}$.

Using Leading order expressions:

$$F_2^{\bar{\nu}N}(x,Q^2) = x\left[u + \bar{u} + d + \bar{d} + 2\bar{s} + 2c\right]$$

$$F_2^{\nu N}(x,Q^2) = x\left[u + \bar{u} + d + \bar{d} + 2s + 2\bar{c}\right]$$

$$xF_3^{\bar{\nu}N}(x,Q^2) = x\left[u + d - \bar{u} - \bar{d} - 2\bar{s} + 2c\right]$$

$$xF_3^{\nu N}(x,Q^2) = x\left[u + d - \bar{u} - \bar{d} + 2s - 2\bar{c}\right]$$

Taking combinations of the Structure functions

$$F_2^{\nu} - xF_3^{\nu} = 2\left(\bar{u} + \bar{d} + 2\bar{c}\right)$$

$$F_2^{\bar{\nu}} - xF_3^{\bar{\nu}} = 2\left(\bar{u} + \bar{d} + 2\bar{s}\right)$$

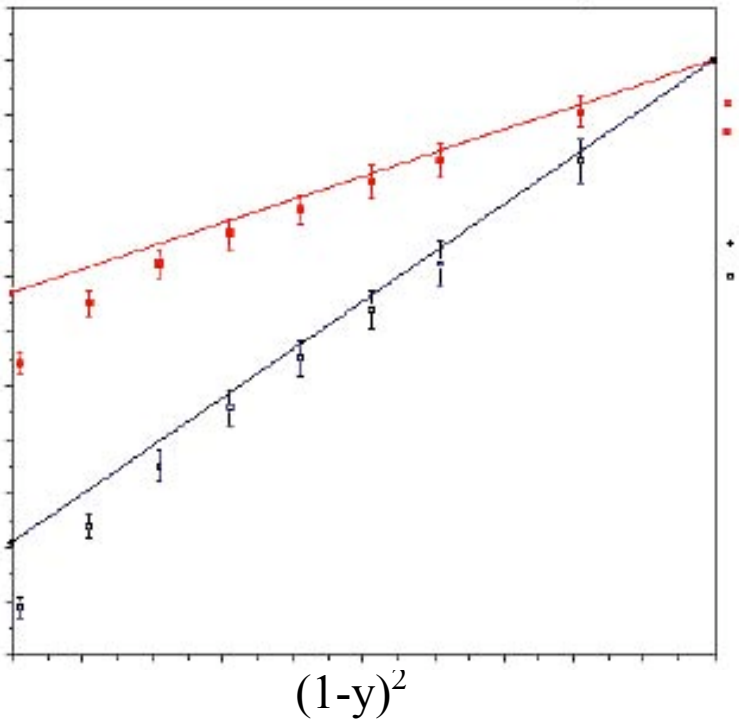
$$xF_3^{\nu} - xF_3^{\bar{\nu}} = 2\left[(s + \bar{s}) - (\bar{c} + c)\right]$$

Physics Results: Six Structure Functions for Maximal Information on PDF's

$$\frac{d\sigma^{\nu A}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{1}{2}\left(F_2^{\nu A}(x,Q^2) + xF_3^{\nu A}(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^{\nu A}(x,Q^2) - xF_3^{\nu A}(x,Q^2)\right)\right] + y^2 F_L$$

$$\frac{d\sigma^{\bar{\nu}A}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left[\frac{1}{2}\left(F_2^{\bar{\nu}A}(x,Q^2) - xF_3^{\bar{\nu}A}(x,Q^2)\right) + \frac{(1-y)^2}{2}\left(F_2^{\bar{\nu}A}(x,Q^2) + xF_3^{\bar{\nu}A}(x,Q^2)\right)\right]$$

$$\frac{\sigma\left(x,Q^2,(1-y)^2\right)}{G^2/2\pi x}$$



Neutrino
Statistical + 5% systematic

Anti-Neutrino
Statistical only

$R = R_{whitlow}$

X = 0.1 - 0.125
Q^2 = 2 - 4 GeV^2

Meant to give an impression only!

Kinematic cuts in (1-y) not shown.

High-x PDFs

ν - p Scattering

$$F_2^{\nu p} = 2x\,(d + \bar{u} + s)$$

$$F_2^{\bar{\nu} p} = 2x\,(\bar{d} + u + \bar{s})$$

At high x

$$\frac{F_2^{\nu p}}{F_2^{\bar{\nu} p}} = \frac{d}{u}$$

Add in…

$$xF_3^{\nu p} = 2x\,(d - \bar{u} + s)$$

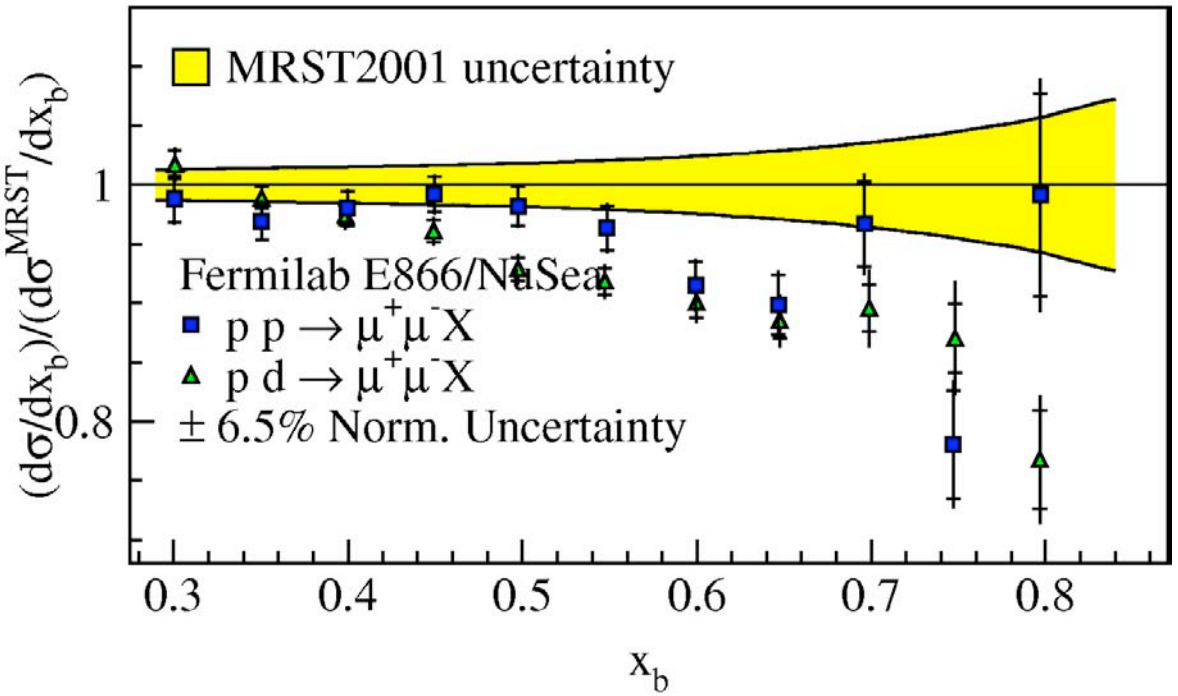
$$xF_3^{\bar{\nu} p} = 2x\,(-\bar{d} + u - \bar{s})$$

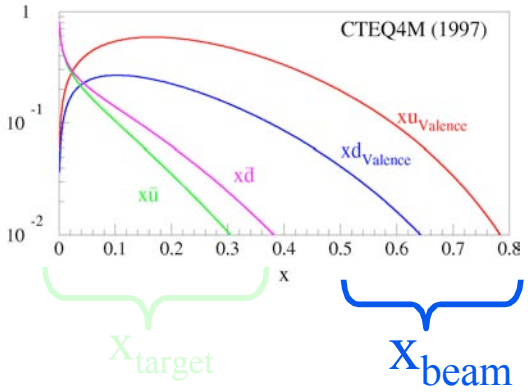
$$F_2^{\nu p} - xF_3^{\nu p} = 4x\bar{u}$$

$$F_2^{\bar{\nu} p} + xF_3^{\bar{\nu} p} = 4xu$$

Further indications that the valence quarks not quite right at high-x??

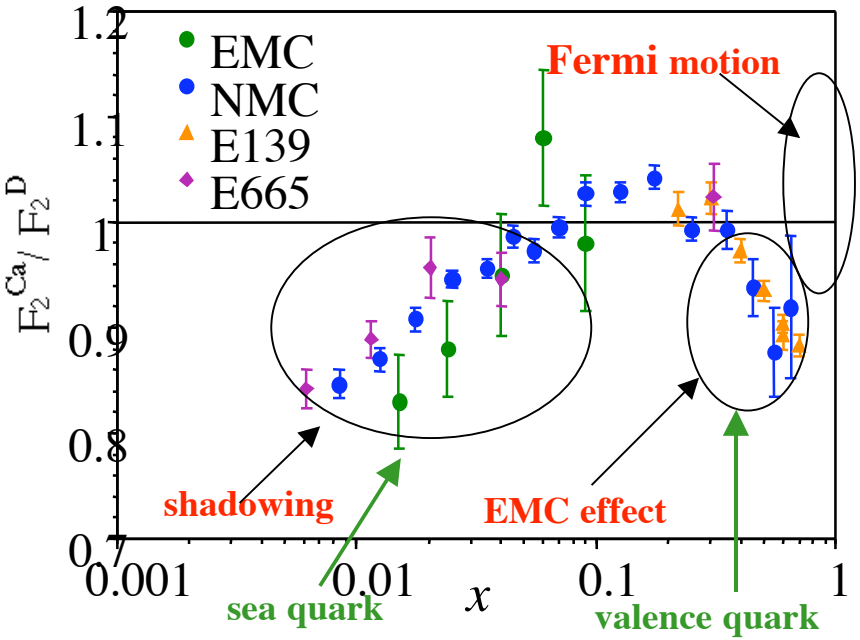
E866 -Drell-Yan Preliminary Results (R. Towell - Hix2004)

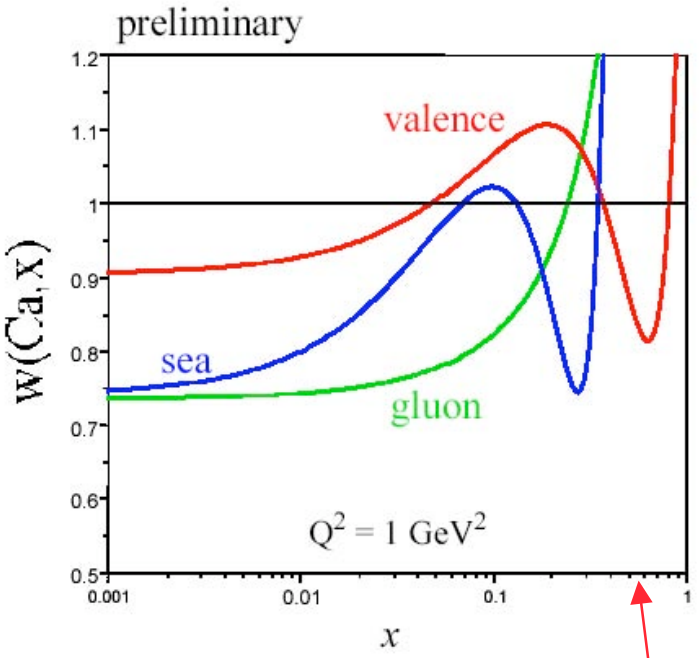




- **x_{beam} distribution measures *4u + d* as *x--> 1*.**
- **Both MRST and CTEQ *overestimate* valence distributions as *x* --> *1* by 15-20%.**
- **Possibly related to *d/u* ratio as *x* --> *1*, but requires full PDF-style fit.**
- *Radiative corrections have recently been calculated. (Not yet fully applied)*

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 are DIFFERENT in ν - A.**
  - **Presence of axial-vector current.**
  - **SPECULATION: Much stronger shadowing for ν -A but somewhat weaker "EMC" effect.**
  - **Different nuclear effects for valance and sea --> different shadowing for xF_3 compared to F_2.**
  - **Different nuclear effects for d and u quarks.**