Status of Cross Section Measurements and Nuclear Effects Studies

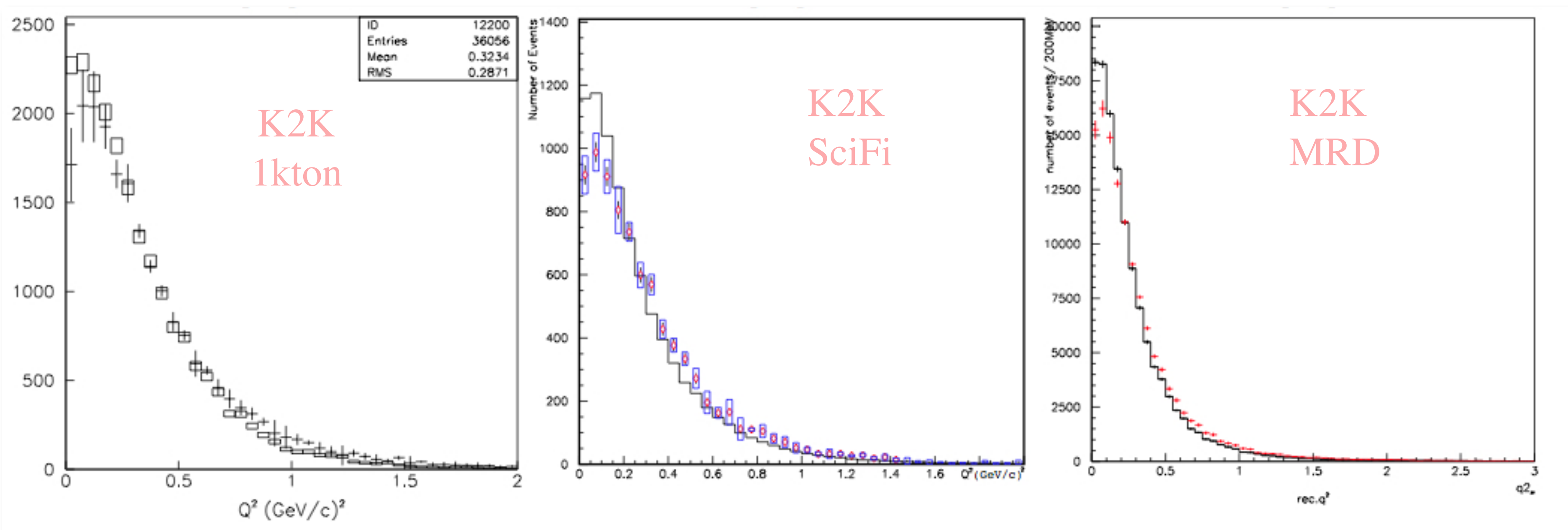
Jorge G. Morfin
Fermilab

IDS-NF
Near Detector Workshop
30-31 July 2011

Parts based on NuInt11 Summary by Sam Zeller, Fermilab

Quasi-elastic Scattering – Recent History

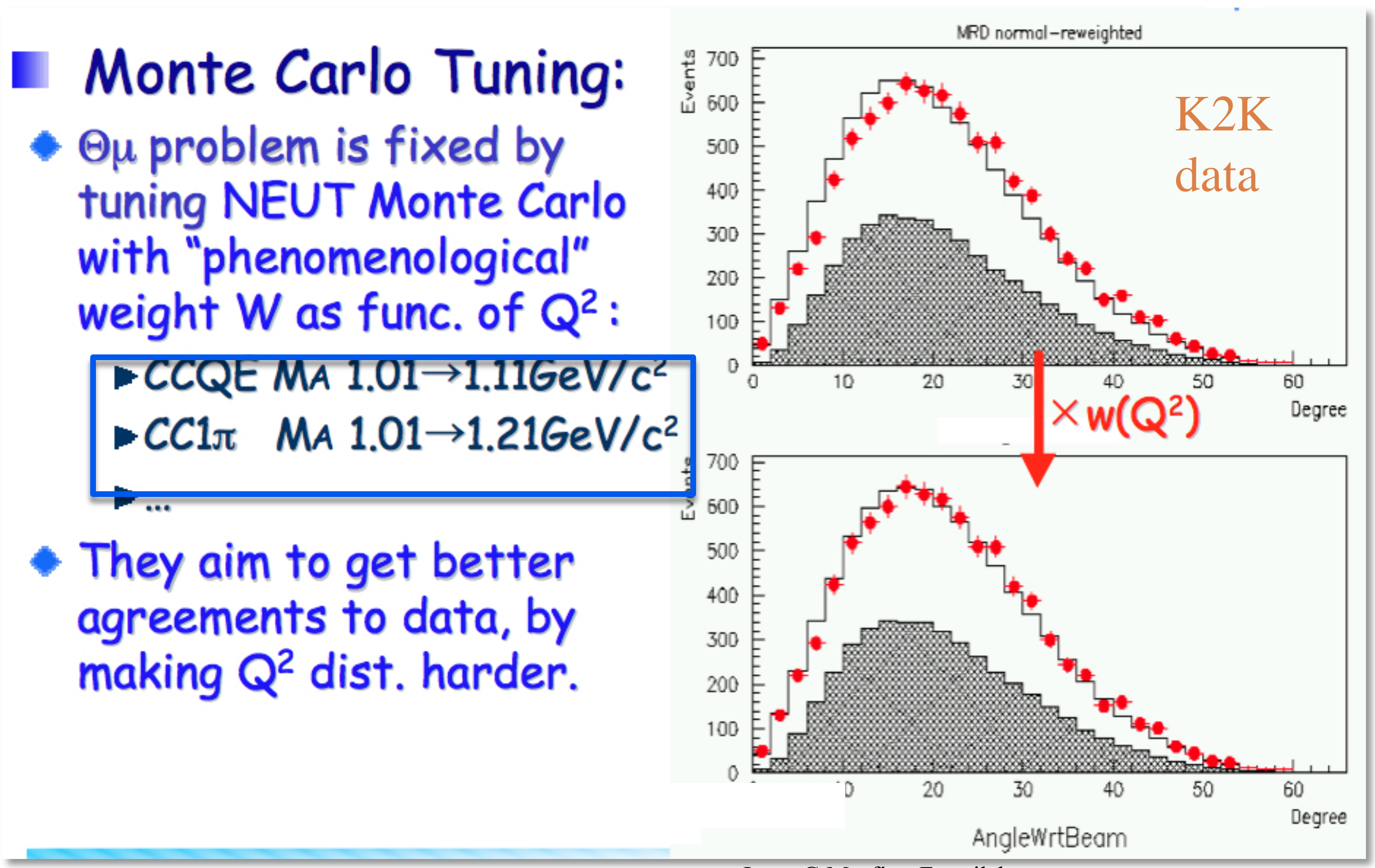
- Q^2 discrepancy first noted in K2K ν_μ CC data (T. Ishida, **NuInt01**)



- initial focus was on low Q^2
- relatively normalized comparisons

M_A starts to grow…

it was recognized early on that data-MC agreement could be improved by increasing M_A



(T. Ishida, **NuInt02**)

By 2009 Four New Measurements (SciBooNE almost)

Experiment	Target	Cut in Q^2 [GeV^2]	$M_A [GeV]$
K2K[4]	oxygen	$Q^2 > 0.2$	1.2 ± 0.12
K2K[5]	carbon	$Q^2 > 0.2$	1.14 ± 0.11
MINOS[6]	iron	no cut	1.19 ± 0.17
MINOS[6]	iron	$Q^2 > 0.2$	1.26 ± 0.17
MiniBooNE[7]	carbon	no cut	1.35 ± 0.17
MiniBooNE[7]	carbon	$Q^2 > 0.25$	1.27 ± 0.14
NOMAD[8]	carbon	no cut	1.07 ± 0.07

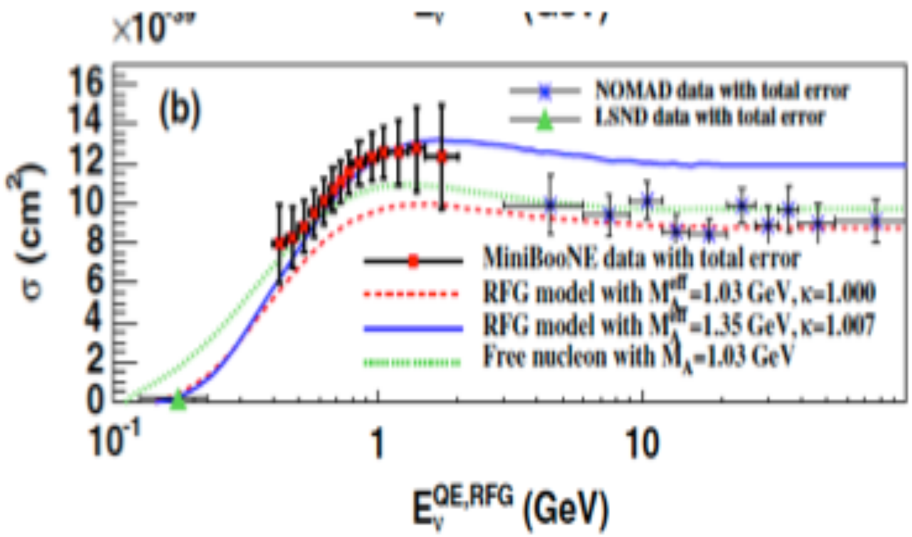
(J. Sobczyk, **NuInt11**)

- several experiments fit QE data (often excluding problematic low Q^2)
- most favor $M_A > 1.0$ GeV,

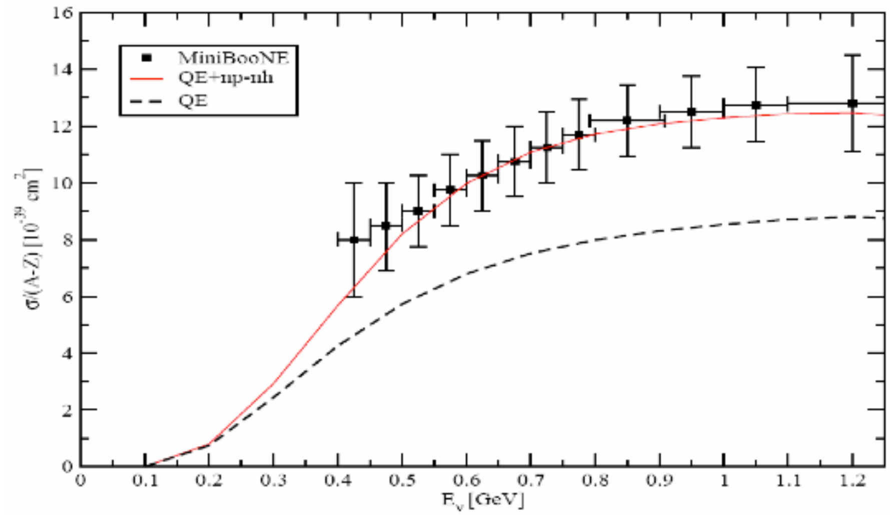
•Except for the higher E_ν NOMAD data that did not

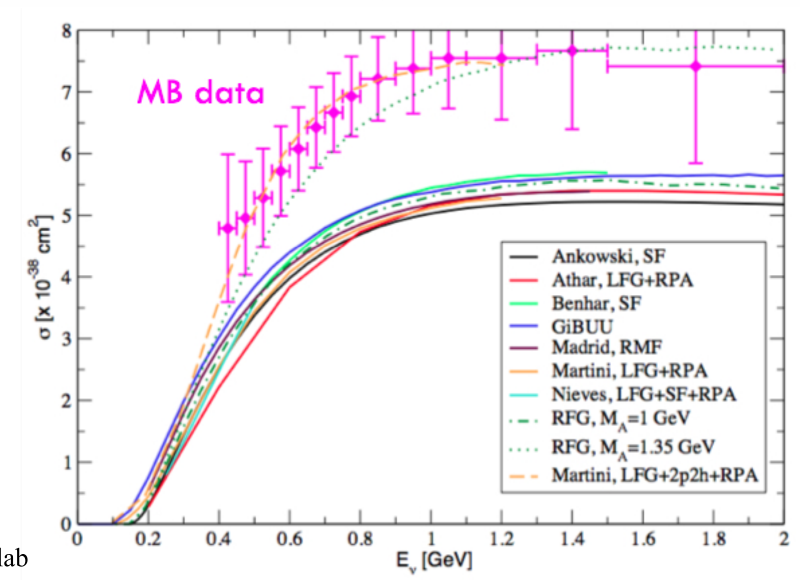
The situation today

- ~30% difference between low and high energy QE measurements



- MB QE σ normalization can be matched by increasing M_A … or adding np-nh effects





QE History

- problem of low Q^2

↓

- problem of axial mass

↓

- problem of np-nh
 (more complex nuclear effects: SRC + MEC)

QE History

- problem of low Q^2
  - κ parameter (MiniBooNE); RPA
  - modeling of CC π backgrounds which contribute at low Q^2
- problem of axial mass
- problem of np-nh
  (more complex nuclear effects: SRC + MEC)

QE History

- problem of low Q^2
- problem of axial mass
- include np-nh effects (more complex nuclear effects: SRC + MEC)

- M_A provides a convenient tool to describe exp. data in shape (2D) & normalization with Fermi Gas

  (important for osc experiments)

- However there is an alternative path involving a more sophisticated nuclear model

Beyond Impulse Approximation

The problem of CCQE axial mass leads us to theoretical frameworks going beyond simple theory of CCQE and Impulse Approximation presented before.

- large contribution from two-body current?!
- one of the central themes of NuInt11
- not a new idea in the NuInt community!

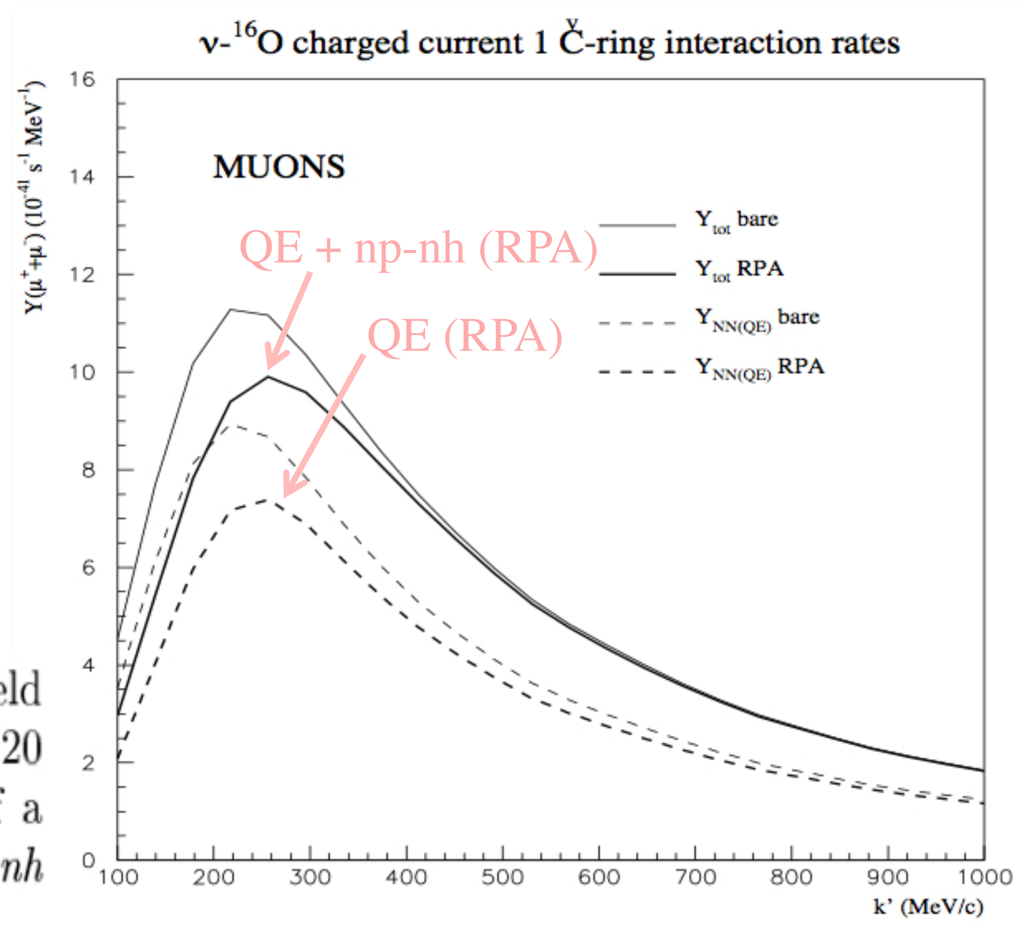
(J. Sobczyk, **NuInt11**)

- Calculations by M.J. Dekker *et al* PLB 266 (1991) 249.

- S.K. Singh and E. Oset, Nucl. Phys. A542, 587 (1992)

np-nh Effects

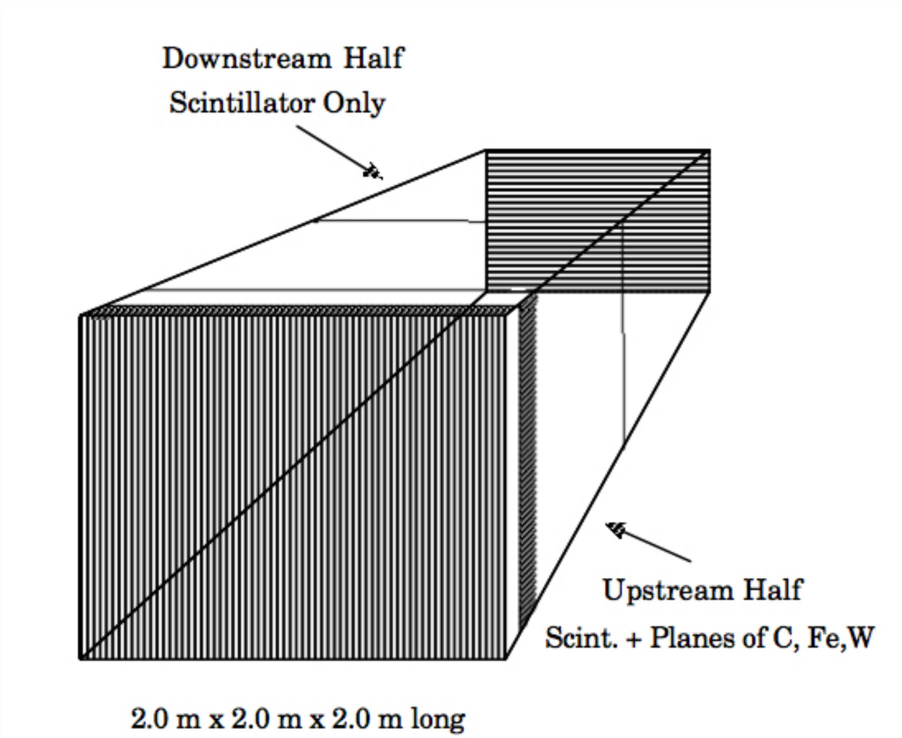
- first recognized at NuInt01
- work motivated by 1-ring "π-less" events in Super-K (= QE + np-nh)



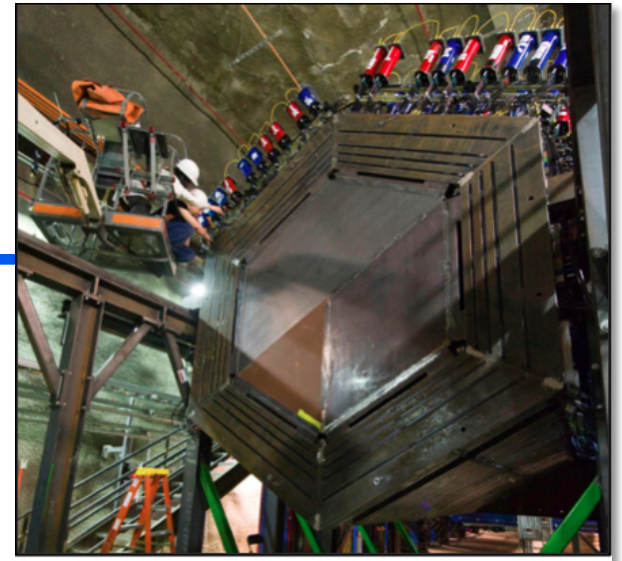
we see an enhacement of the total yield with respect to the free quasi-elastic around 20 %. This result points out the importance of a good evaluation of such neutrino induced *np-nh* excitations.

(J. Marteau, **NuInt01**)

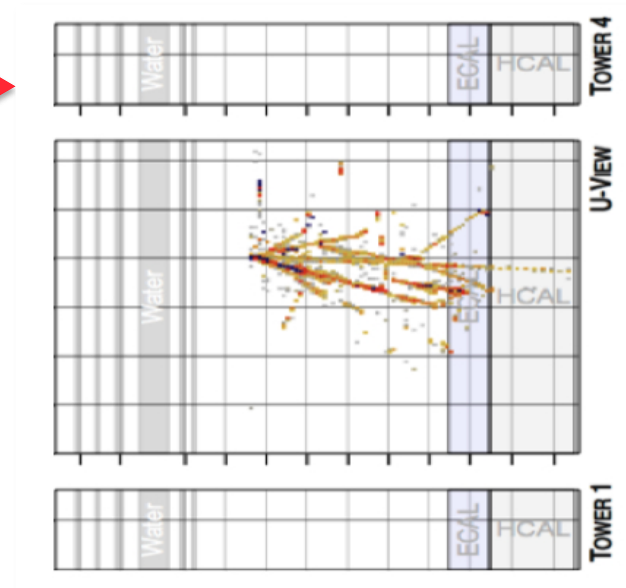
MINERνA



(J. Morfin, **NuInt01**)



nuclear targets (He, C, Fe, Pb, H_2O, CH)

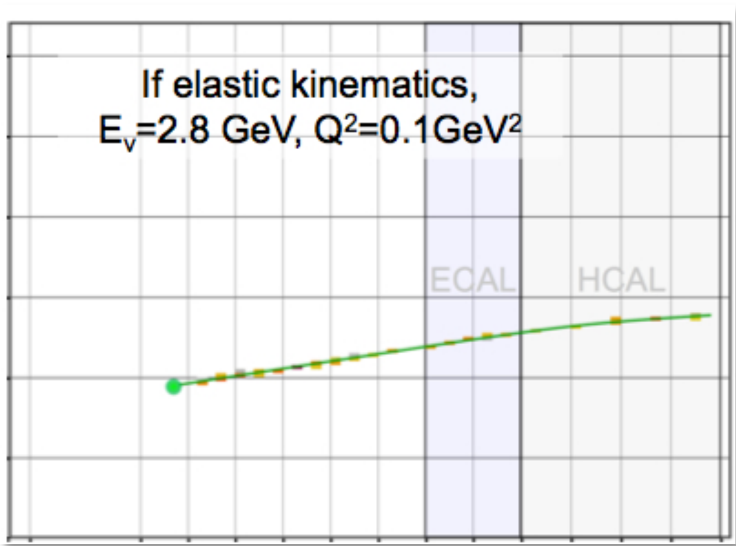


(D. Schmitz, **NuInt11**)

- taking data in NuMI beam since March 2010
- has "grown up" with NuInt series

MINERνA $\bar{\nu}$ QE

$$\bar{\nu}_{\mu}\, p \rightarrow \mu^{+} n$$



- appeal: cleaner measurement
- less sensitive to modeling of proton rescattering (unlike ν case)
- less ambiguity as to whether selection includes np-nh or not?

$$\nu_{\mu}\, n \rightarrow \mu^{-}\, p\, p$$

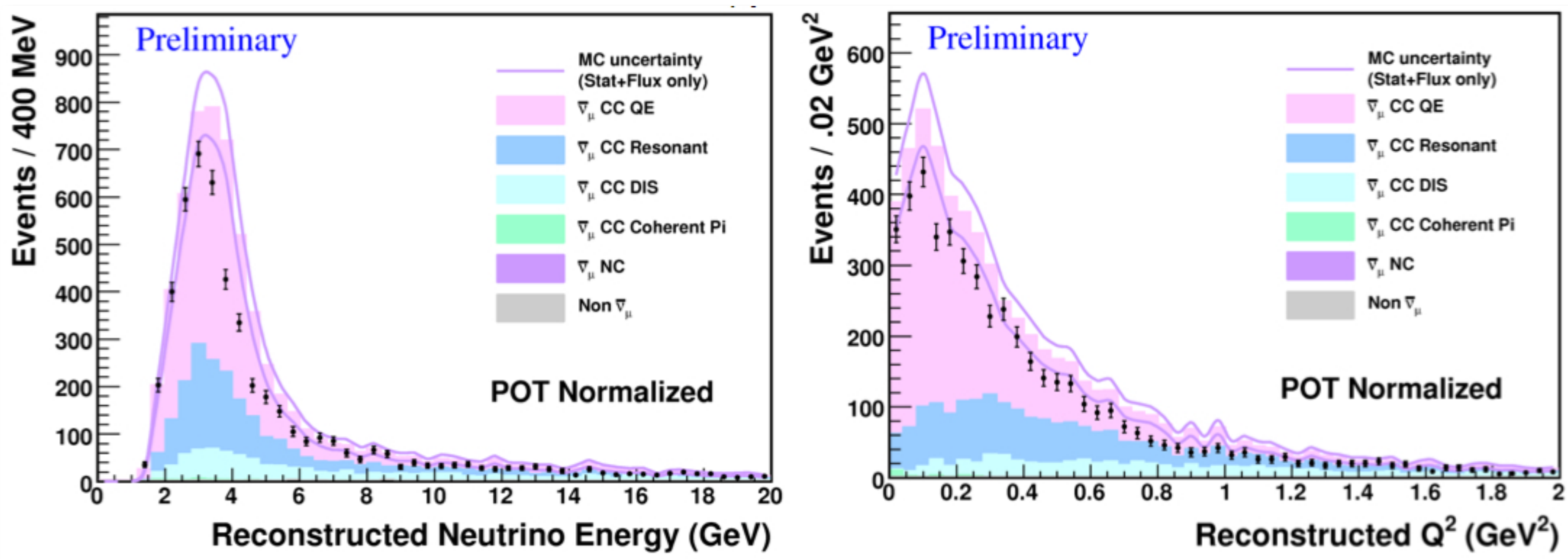
$$\bar{\nu}_{\mu}\, p \rightarrow \mu^{+}\, n\, n \quad (?)$$

- will pursue several QE reconstruction/selection approaches
- this analysis: 1 track + no recoil
- With higher energy ME beam exposure: 800k QE produced

(K. McFarland, **NuInt11**)

MINERνA $\bar{\nu}$ QE

$$\bar{\nu}_\mu p \to \mu^+ n$$



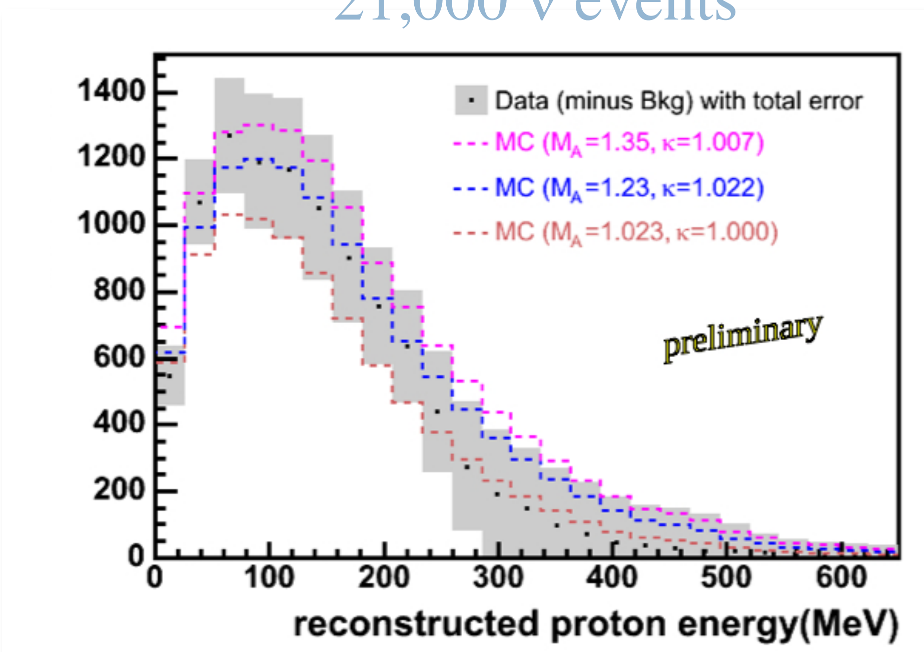
- event deficit is flat in Q^2, not flat in E_ν
- MC = GENIE (RFG, Bodek-Ritchie tails, M_A=0.99 GeV, standard p_F & E_B)
- food for thought

(K. McFarland, **NuInt11**)

NC Elastic Scattering

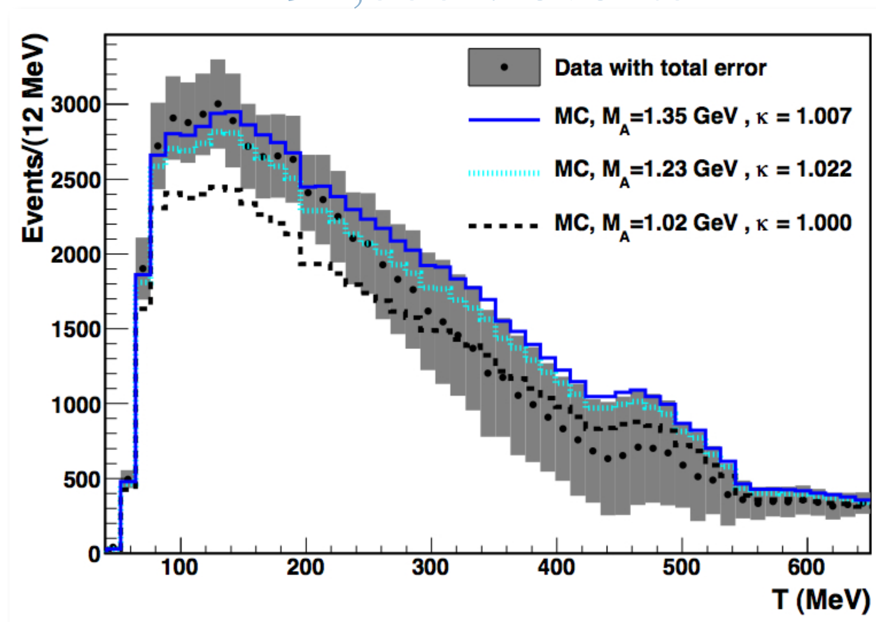
- 1st results on antineutrino NC EL scattering from MiniBooNE

21,000 $\bar{\nu}$ events



(R. Dharmapalan, **NuInt11**)

94,000 ν events



(R. Tayloe, D. Perevalov, **NuInt09**)

- see same general trend as ν case, but plan to study in more detail
- differential σ's soon!

Pion Production – Recent Theoretical Work

- π production in GiBUU (O. Lalakulich)

- N-Δ weak transition (K. Gradzyk)

- dynamical models of π production (S. Nakamura)

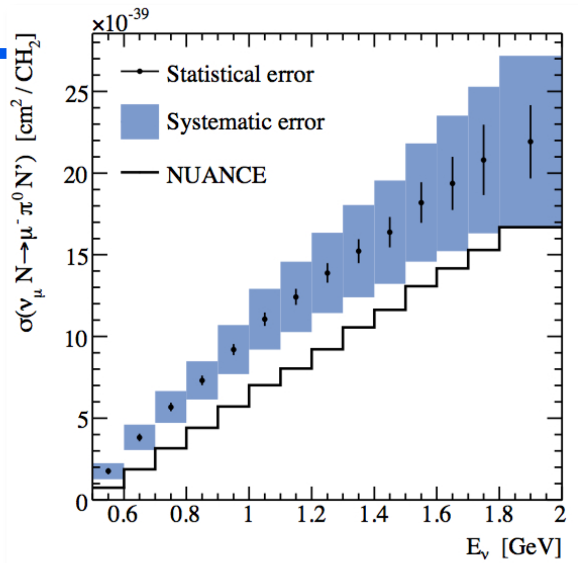
- also, strange particle production (S. Athar)

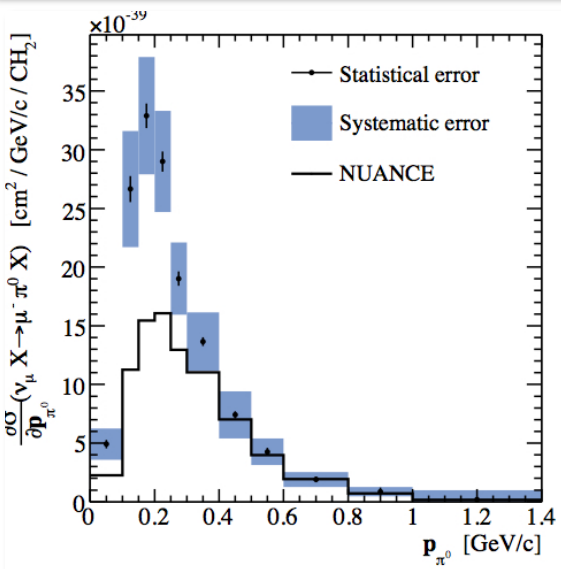
Pion Production

• there has been a steady stream of pion measurements that have been published over the years:

- **K2K**: NC $1\pi^0$/CC ratio (2005)
- **K2K**: CC coherent π^+/CC ratio (2005)
- **K2K**: CC π^+/QE ratio (2008)
- **SciBooNE**: CC coherent π^+/CC ratio (2008)
- **MiniBooNE**: NC coherent π^0 fraction (2008)
- **SciBooNE**: NC π^0/CC ratio (2009)
- **NOMAD**: NC coherent π^0 (2009)
- **MiniBooNE**: CC π^+/QE ratio (2009)
- **SciBooNE**: NC coherent π^0/CC ratio (2010)
- **K2K**: CC π^0/CC (2010)
- **MiniBooNE**: NC π^0 (2010)
- **MiniBooNE**: CC π^0 (2011)
- **MiniBooNE**: CC π^+ (2011)

MiniBooNE CC π^0





- provides measure of:

(initial interaction) * (FSI) * (initial state nuclear effects)

(-) π^0 absorption

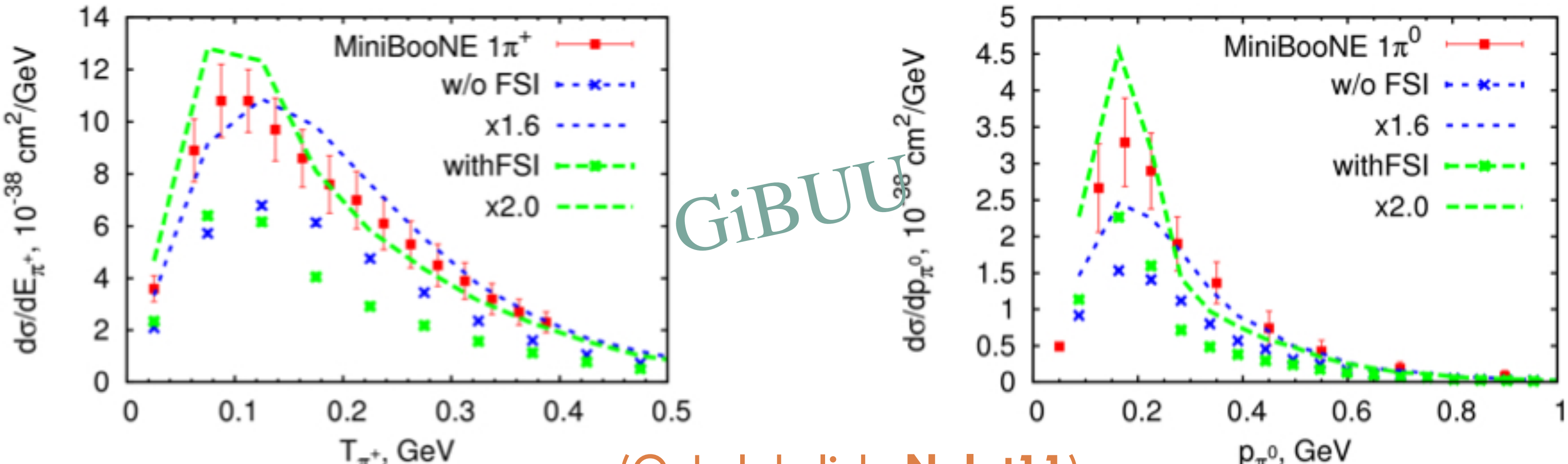
(+) $\pi^{+/-} \to \pi^0$

n,p $\to \pi^0$

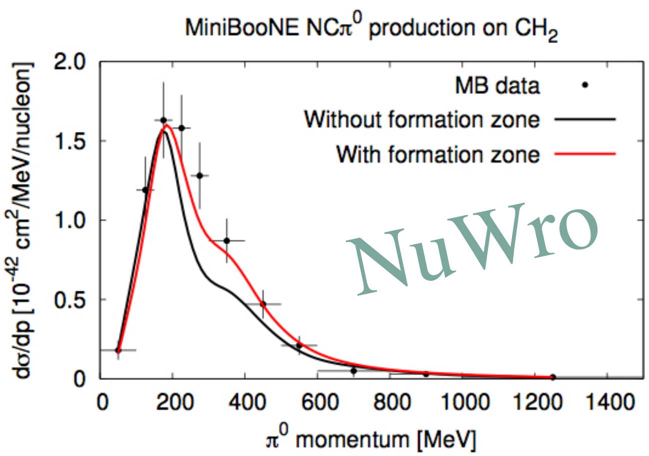
also, np-nh?

(R. Nelson, **NuInt11**)

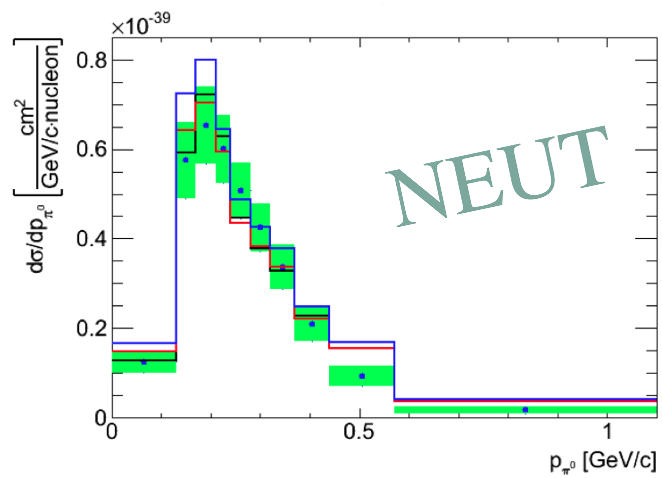
Data Already Being Used



(O. Lalakulich, **NuInt11**)



(T. Golan, **NuInt11**)



(P. dePerio, **NuInt11**)

SciBooNE π Production

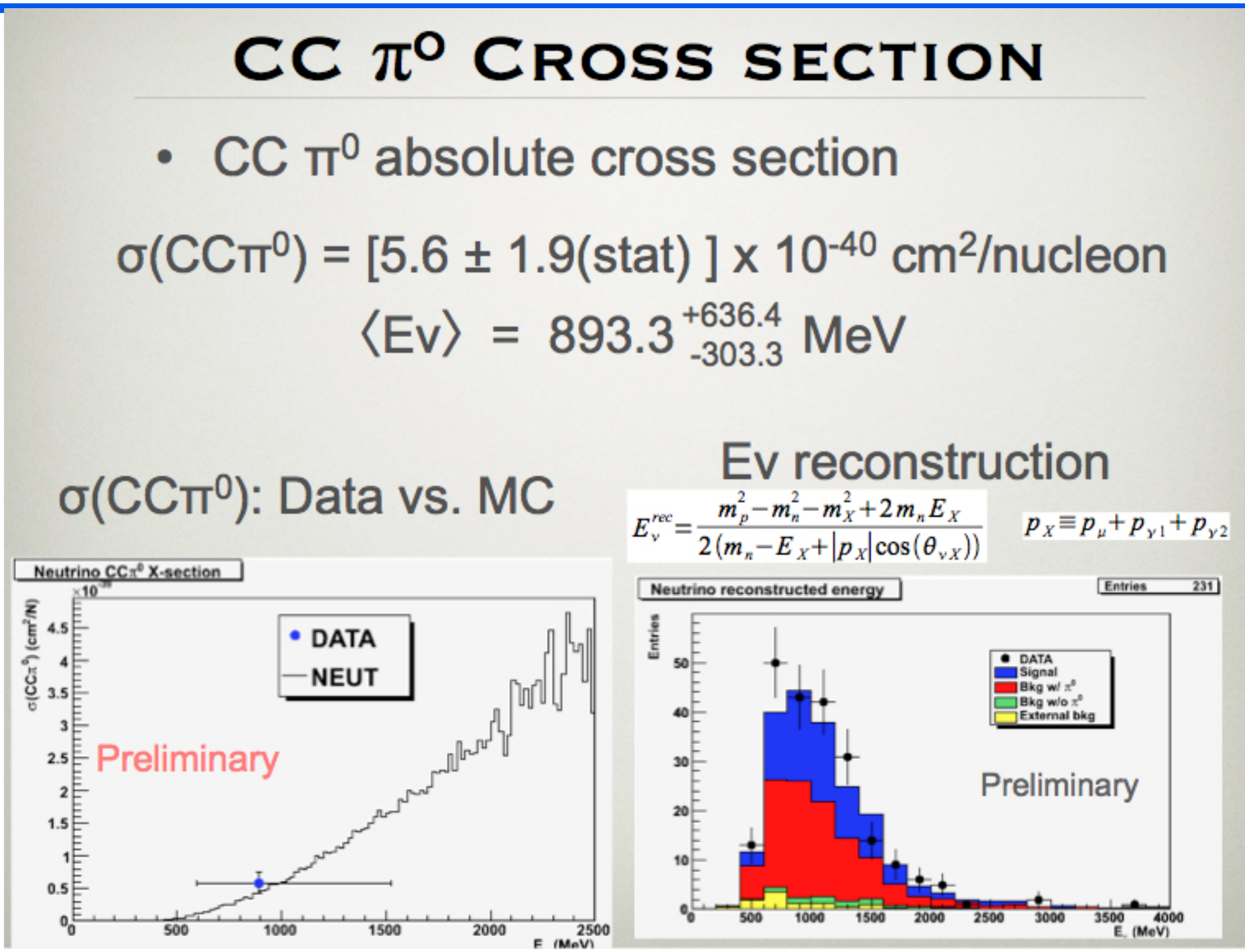
Contents

- SciBooNE pion production measurements
  - ν CC coh-π^+: Phys.Rev.D78, 112004 (2008)
  - ν NC-π^0: Phys.Rev.D81, 033004 (2010)
  - ν NC coh-π^0: Phys.Rev.D81, 111102 (2011)
  - $\bar{\nu}$ CC coh-π^-: Preliminary results
  - ν CC-π^0: Preliminary results

} brand new!

(H. Tanaka, **NuInt11**)

SciBooNE CC π^0



- absolute σ measurement, working on systematics

(H. Tanaka, **NuInt11**)

Coherent π Production

- comprehensive review of theoretical calculations (L. Alvarez-Ruso, **NuInt11**)
  - both PCAC and microscopic approaches
  - 12 different theoretical calculations

Homework

- Extend microscopic models to higher energies LAR,S. Dytman, work in progress
- Clarify the role of nonlocality in the Δ propagation
- Understand SciBooNE $CC\pi^+/NC\pi^0$ measurement

- two new experimental results presented at NuInt11 (one NC, one CC) …

Coherent π Production Puzzle

- comprehensive review of theoretical calculations (L. Alvarez-Ruso, **NuInt11**)
  - both PCAC and microscopic approaches
  - 12 different theoretical calculations

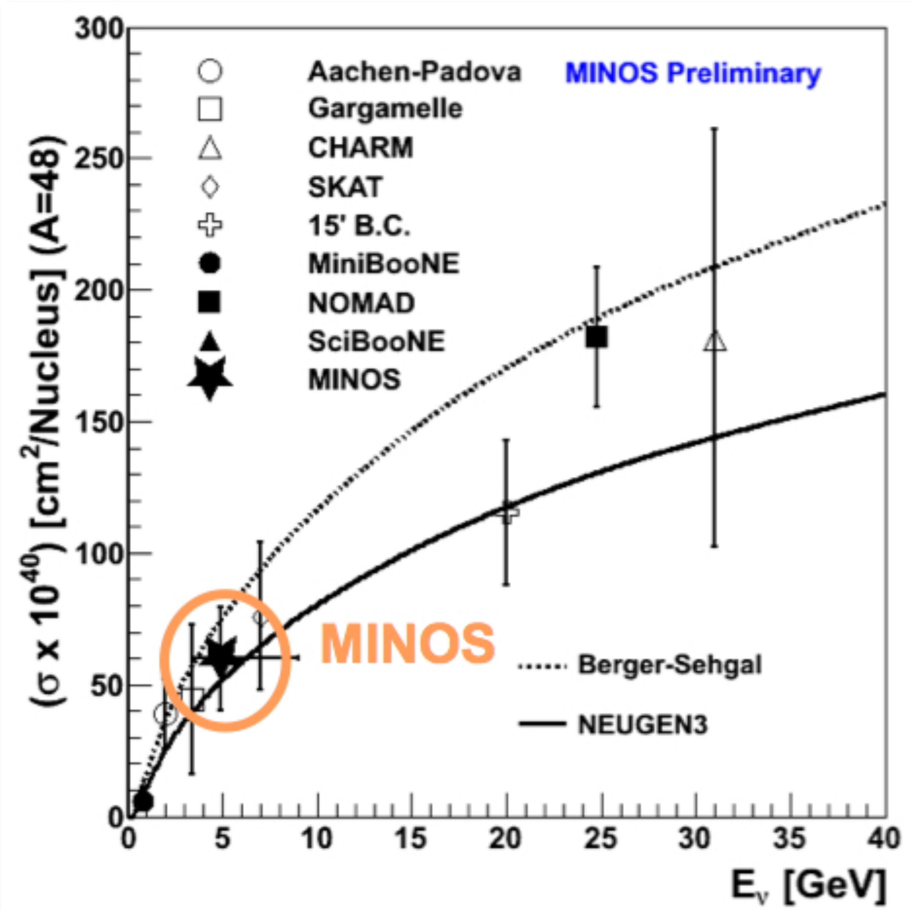
- do we see this process or not? NC/CC differences

ν NC coherent π^0

- K2K
- MiniBooNE
- NOMAD
- SciBooNE
- MINOS (D. Cherdak, new!)

all see some level of non-zero NC coherent π^0

MINOS Coherent π^0



- new data point in between existing low (K2K, MB, SB) and high energy (NOMAD) measurements
- 1st measurement of NC coherent π^0 for A>30 and 1st evidence on iron
- also working on $\overline{\nu}$ analysis

(D. Cherdak, **NuInt11**)

Coherent π Production Puzzle

- do we see this process or not? NC/CC differences

ν NC coherent π^0

- K2K
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all see some level of non-zero NC coherent π^0

ν CC coherent π^+
$\bar{\nu}$ CC coherent π^-

- K2K ν
- SciBooNE ν

no evidence set limits

- SciBooNE $\bar{\nu}$ (H. Tanaka, new!)

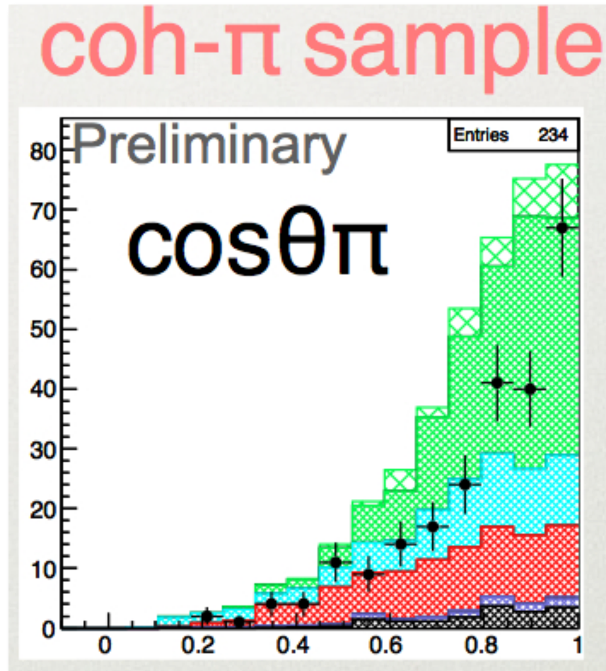
SciBooNE $\bar{\nu}$ CC Coherent π^-

- 1^{st} modern measurement of coherent π production using antineutrinos

(H. Tanaka, **NuInt11**)

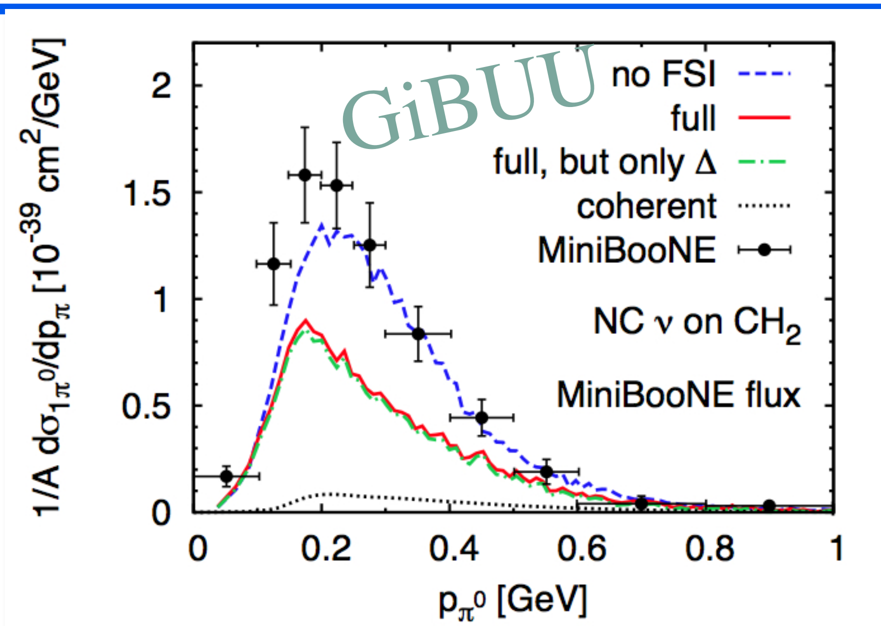
$$\frac{\sigma(\bar{\nu}\text{ CC coh-}\pi) + r\cdot\sigma(\nu\text{ CC coh-}\pi)}{\sigma(\bar{\nu}\text{ CC}) + r\cdot\sigma(\nu\text{ CC})} = (\,1.13 \pm 0.34(\text{stat})\,^{+0.31}_{-0.36}(\text{sys})\,) \times 10^{-2}$$

Preliminary



- $\bar{\nu}$ CC coh-π: preliminary results
  - Cross section ratio ~2σ away from zero
  - Data hint that non-zero CC coh-π events in very forward region (than R-S model)

NC π^0 Production

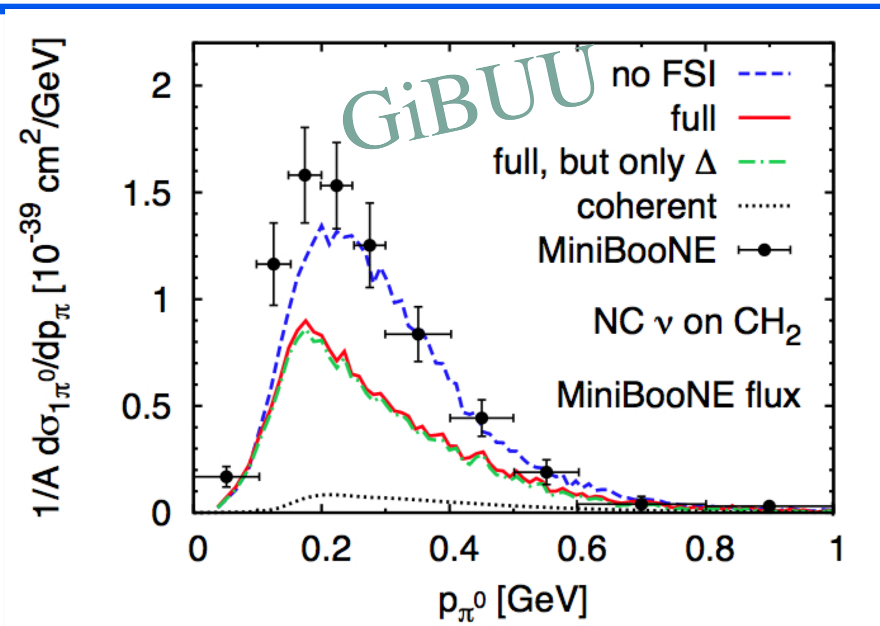


(U. Mosel, **NuInt11**)

- possible origins:
  - elementary cross section too small
  - neutrino-flux prediction (cf. discrepancy in QE channel)
  - “data” contains “MC”: model dependence

• suggestion of np-nh effects

NC π^0 Prod



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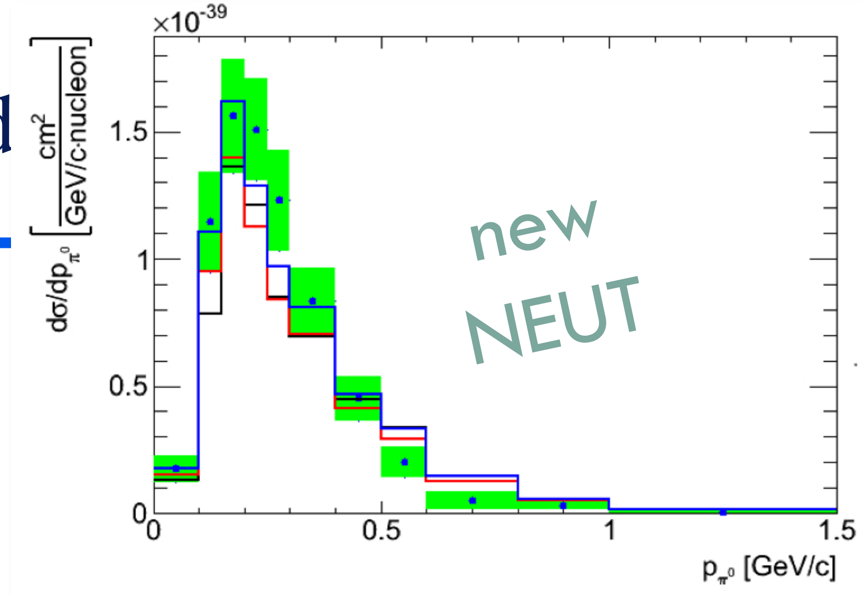

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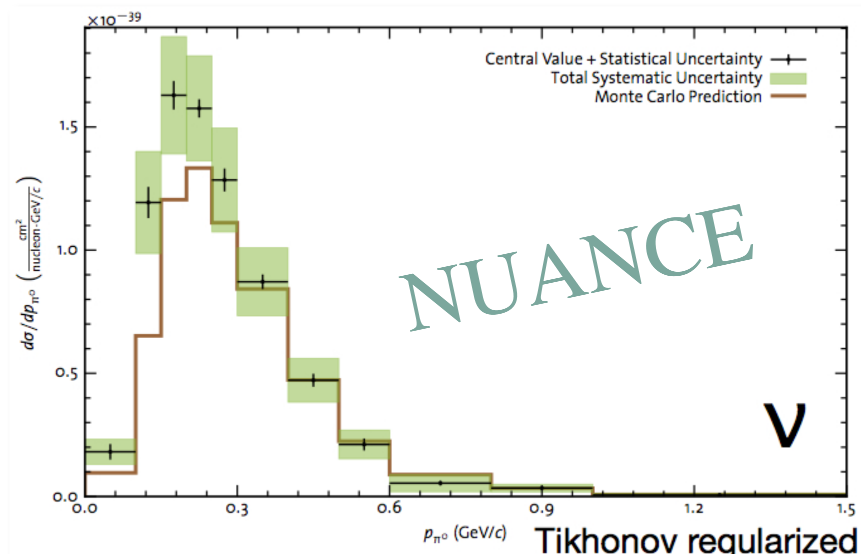

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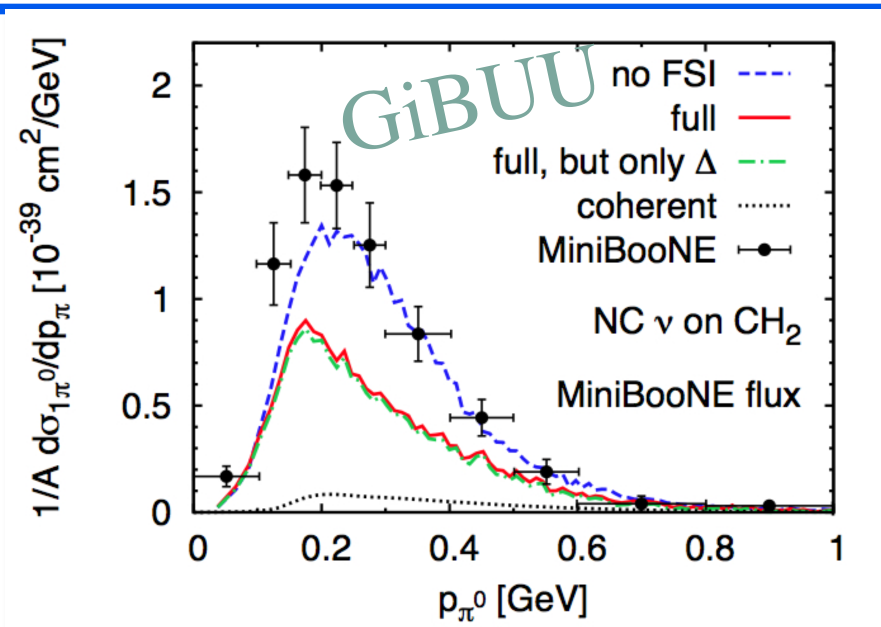
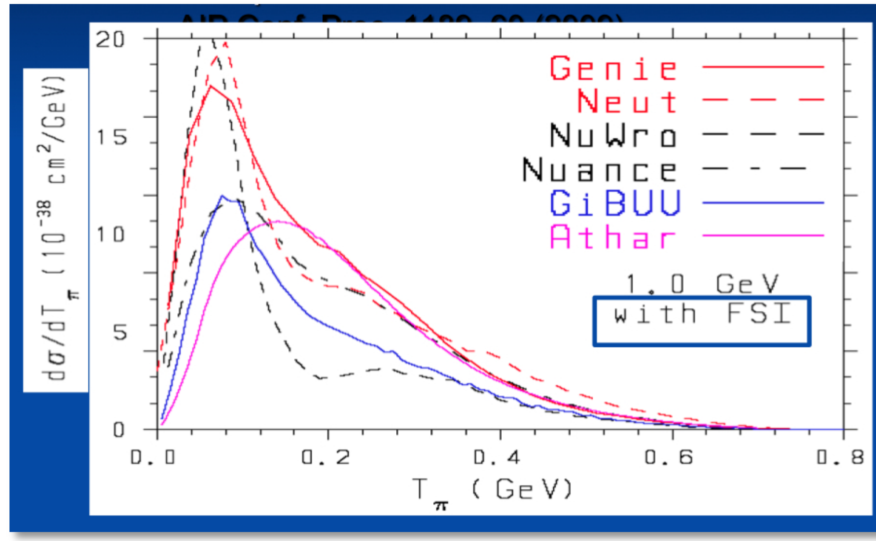
NC π^0 Production



(U. Mosel, **NuInt11**)

- what about FSI?

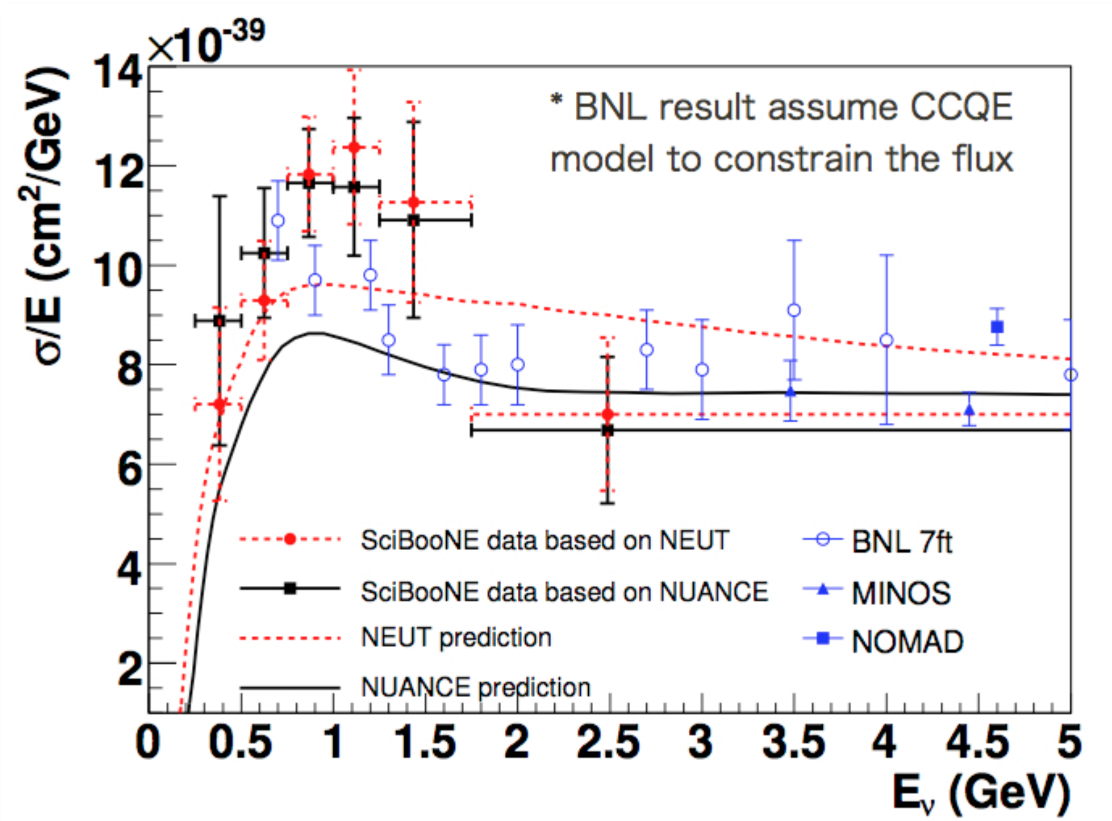


- possible origins:
  - elementary cross section too small
  - neutrino-flux prediction (cf. discrepancy in QE channel)
  - “data” contains “MC”: model dependence

- suggestion of np-nh effects

- certainly need to understand before drawing any conclusions about np-nh in π channels

Total CC Inclusive



(Y. Nakajima, **NuInt11**)

- 1st measurement of CC inclusive σ on ^{12}C at low energy from SciBooNE

- important because measures combination of:

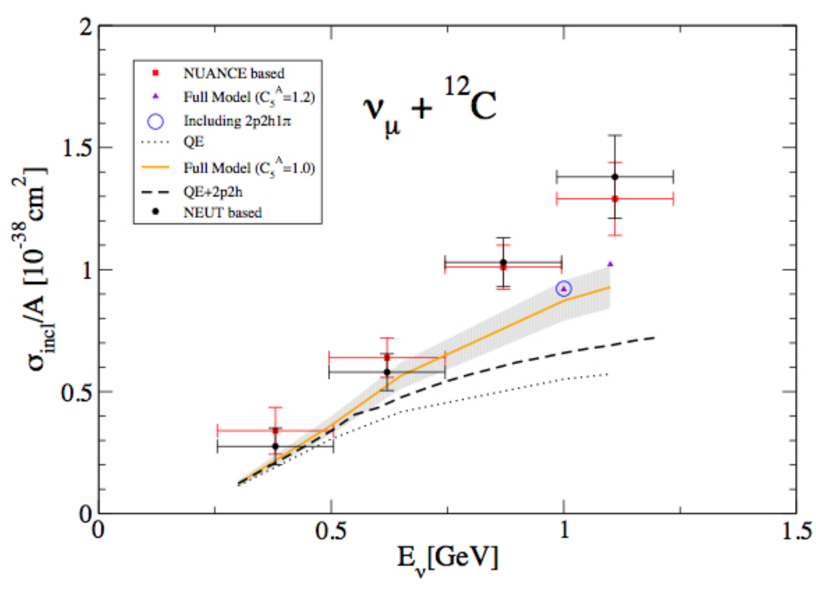
  + QE
  + np-nh
  + Δ, N* → π̸

  QE-like

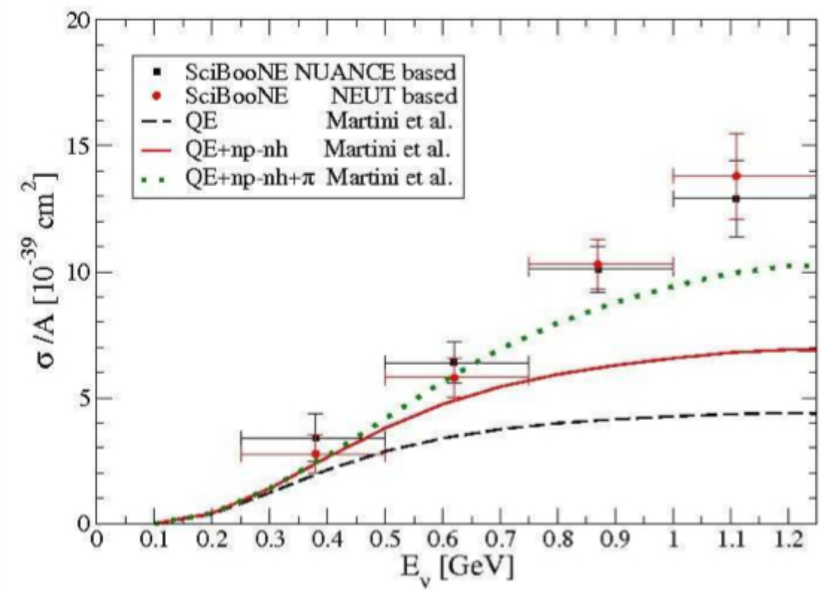
  + Δ, N* → 1π, multi-π
  + DIS …

Total CC Inclusive

- provides an important **starting point** (before get to exclusive modes)
- already being used by theorists …



Nieves et al., arXiv:1102.2777



M. Martini, PRC 80 (2009)

(L. Alvarez-Ruso, **NuInt11**)

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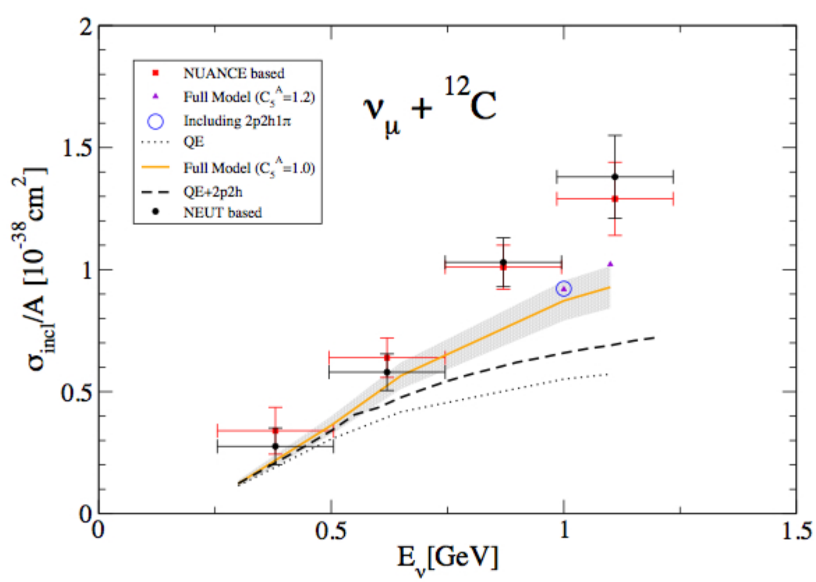


Nieves et al., arXiv:1102.2777

Next steps:

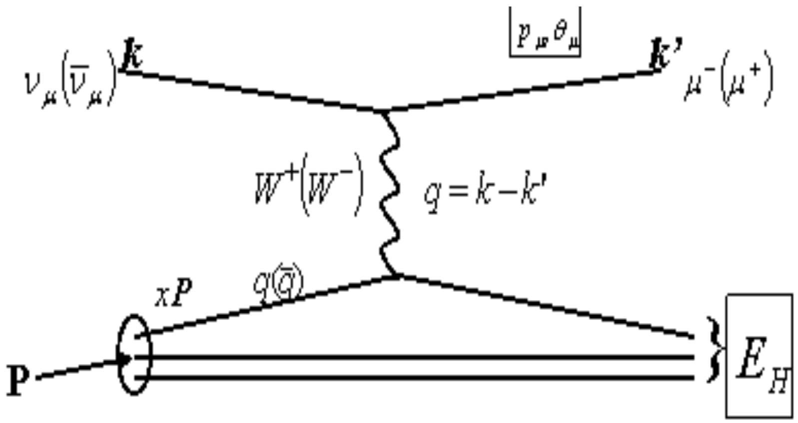
- $d^2\sigma/dT_\mu d\theta_\mu$
- A dependence
  (how evolves with nuclear target)

(L. Alvarez-Ruso, **NuInt11**)

W < 2 GeV - What's left for NF-ND?

- What you'll hear often from this summary: To get maximal new neutrino scattering physics results from the NF-ND we need a **hydrogen/deuterium target.** Need to measure well the basic non-nuclear cross sections.
- A **hydrogen/deuterium target** is also very helpful to pin down the flux by measuring the QE cross section near $Q^2 = 0$!
- Most of the high-Q^2 effects will not be studied by the time of the NF-ND
- The high resolution tracker will be able to add considerably to our knowledge of the transition region: from the Delta through the non-perturbative QCD region to pQCD.

The Parameters of ν DIS



$$Q^2 = 4E_\nu E_\mu \sin^2\frac{\theta}{2},$$ Squared 4-momentum transferred to hadronic system

$$x = \frac{Q^2}{2ME_{HAD}},$$ Fraction of momentum carried by the struck quark

$$y = \frac{\nu}{E_\nu} = \frac{E_{HAD}}{E_\nu},$$ Inelasticity

Differential cross section in terms of structure functions:

$$\frac{1}{E_\nu}\frac{d^2\sigma^{\nu(\bar\nu)}}{dxdy} = \frac{G_F^2 M}{\pi\left(1+Q^2/M_W^2\right)^2}\left[\left(1-y-\frac{Mxy}{2E_\nu}+\frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R(x,Q^2)}\right)F_2^{\nu(\bar\nu)} \pm \left(y-\frac{y^2}{2}\right)xF_3^{\nu(\bar\nu)}\right]$$

Structure Functions in terms of parton distributions (for ν-scattering)

$$F_2^{\nu(\bar\nu)N} = \sum\left[xq^{\nu(\bar\nu)N}(x) + x\bar{q}^{\nu(\bar\nu)N}(x) + 2xk^{\nu(\bar\nu)N}(x)\right],$$

$$xF_3^{\nu(\bar\nu)N} = \sum\left[xq^{\nu(\bar\nu)N}(x) - x\bar{q}^{\nu(\bar\nu)N}(x)\right] = x\left(d_V(x) + u_V(x)\right) \pm 2x\left(s(x) - c(x)\right),$$

$$R = \frac{\sigma_L}{\sigma_T}$$

Neutrino Experiments have been studying QCD for about 40 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 liquids.
- BEBC followed with QCD studies using ν + p and ν + D scattering.

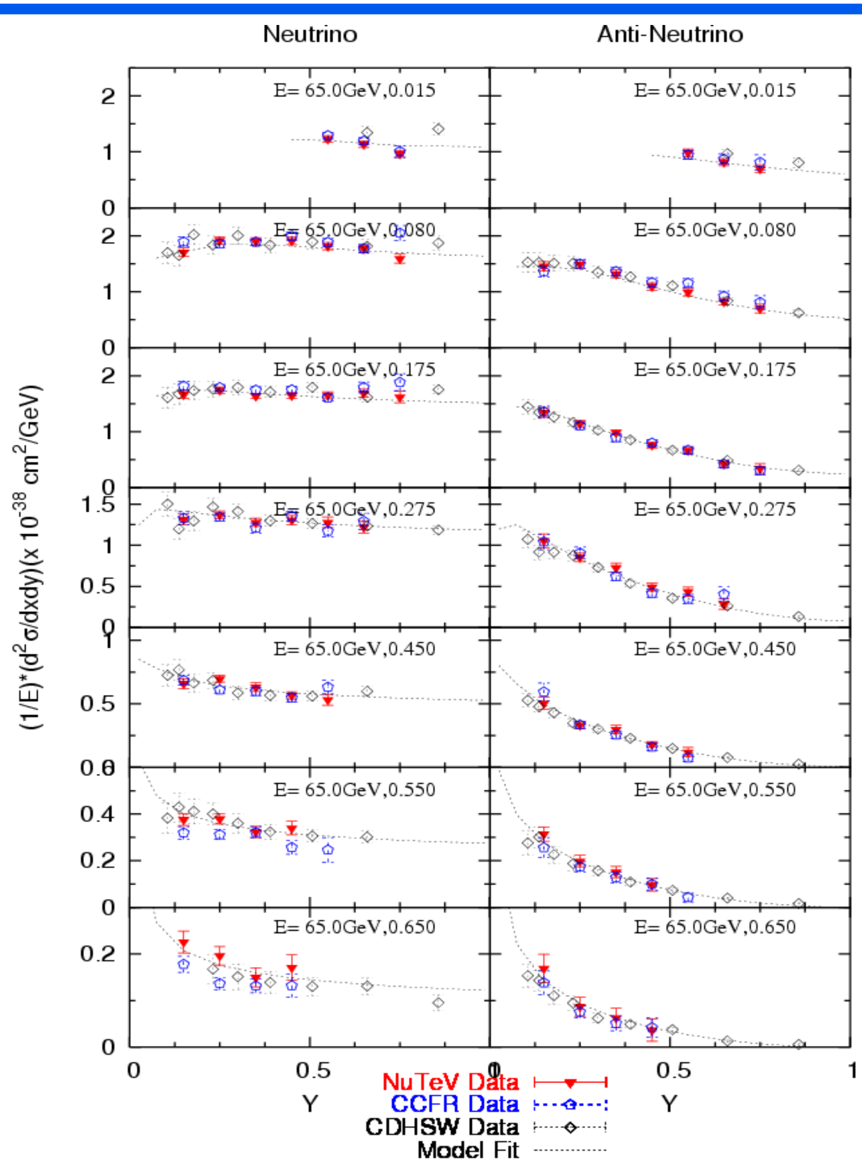
Most "Recent" DIS Experiments

- There followed a long string of ν scattering experiments with **increasing statistics** and **decreasing systematic errors** ….

	E_ν range (< E_ν>) (GeV)	Run	Target A	E_μ scale	E_{HAD} scale	Detector
NuTeV (CCFR)	30-360(120)	96-97	Fe	0.7%	0.43%	Coarse
NOMAD	10-200(27)	95-98	Various (mainly C)	--	---	Fine-grained
CHORUS	10-200(27)	95-98	Pb	2%	5%	Fine-grained
MINOS	3-15	05-10	Fe	2.5%	5.6%	Coarse

NuTeV CC Differential Cross Section

$d\sigma/dy$ for different E_ν

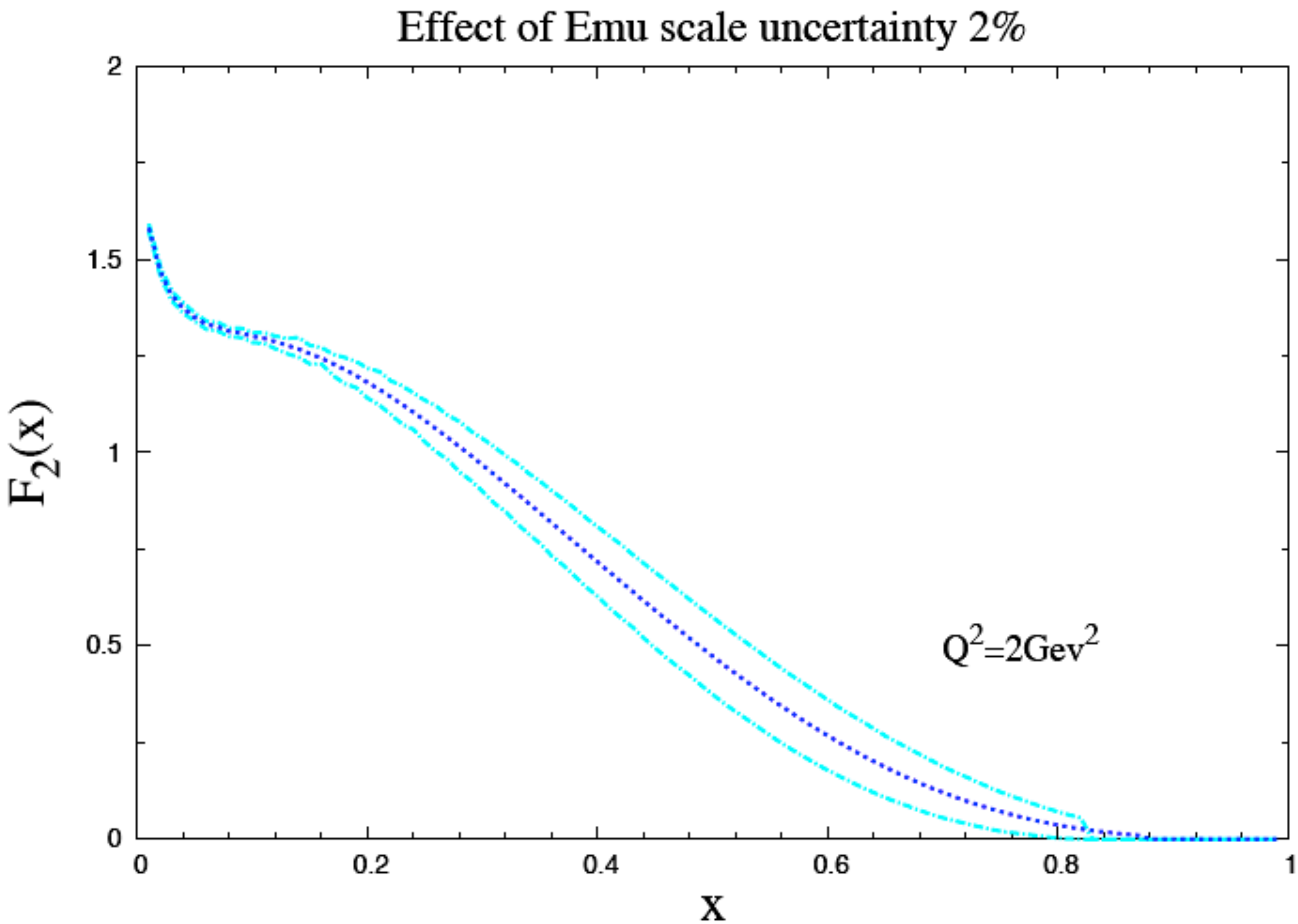


	E_μ scale	E_{HAD} scale	E_ν range (GeV)
CDHSW	2%	2.5%	20-200
CCFR	1%	1%	30-360
NuTeV	0.7%	0.43%	30-360

- NuTeV has increased statistics compared to other ν-Fe experiments.
- Significant reduction in the largest systematic uncertainties : - E_μ and E_{HAD} scales

Estimated systematic error: E_μ scale

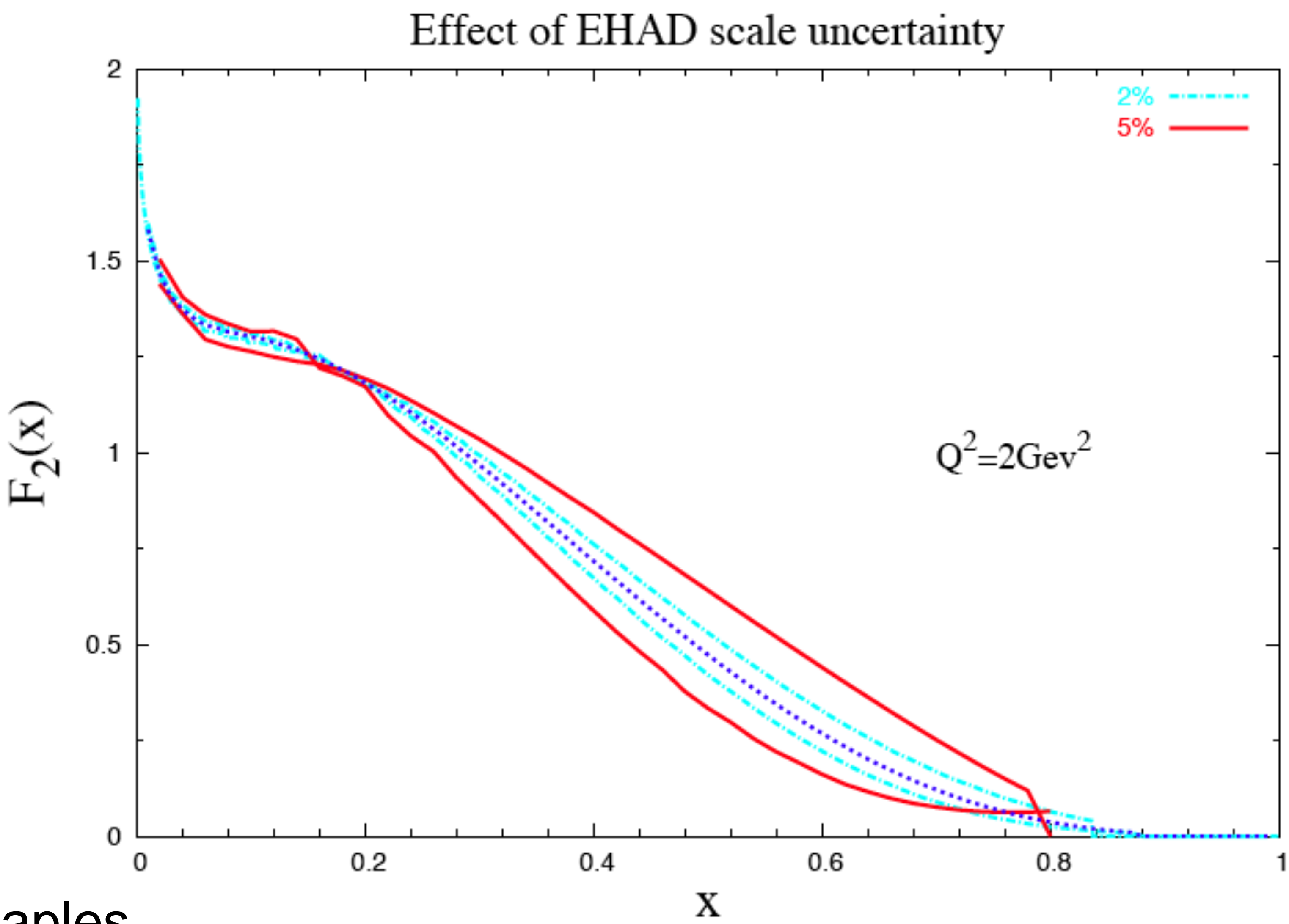
NuTev achieved 0.7%



D. Naples

Estimated systematic error: E_{had} scale

NuTev achieved 0.43%



D. Naples

F_2 and xF_3 Measurement

F_2

$$\left[\frac{d^2\sigma}{dx\,dy}^{\nu} + \frac{d^2\sigma}{dx\,dy}^{\bar{\nu}}\right]\frac{\pi}{G_F^2 ME} = 2\,\overline{F}_2\left(1 - y - \frac{Mxy}{2E} + \frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R}\right) + y\left(1-\frac{y}{2}\right)\;\Delta xF_3$$

- Perform 1-parameter fit for F_2
- ΔxF_3 model
- R_L model

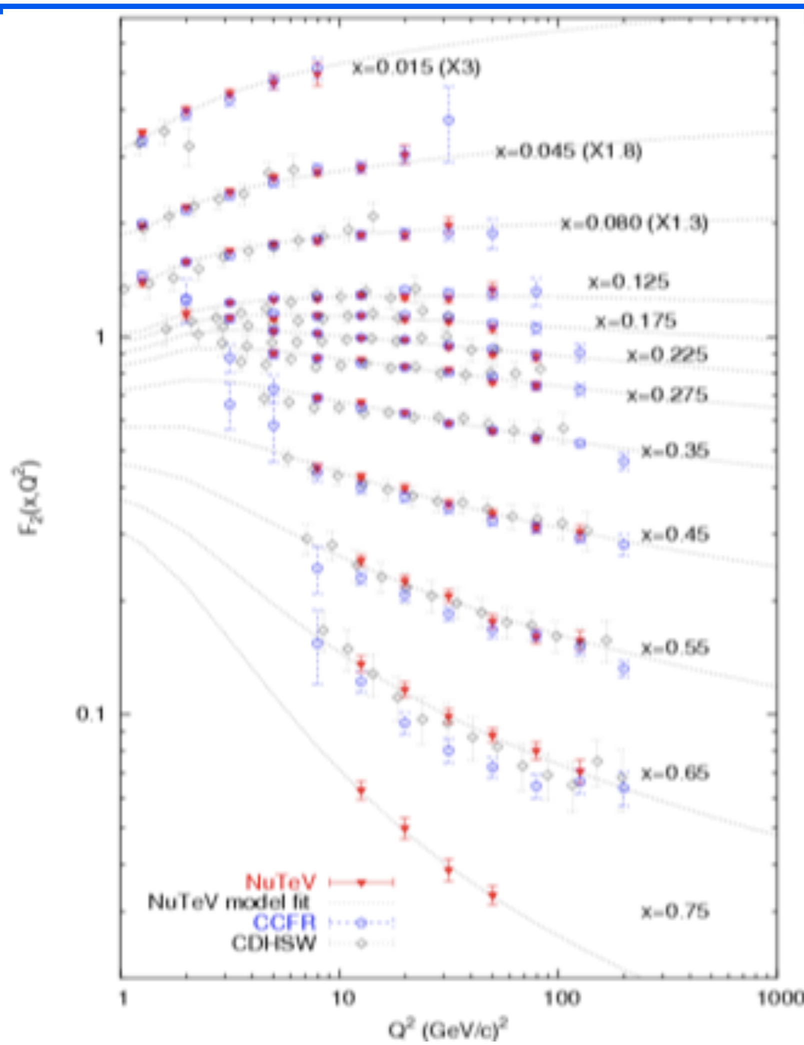
xF_3

$$\left[\frac{d^2\sigma}{dx\,dy}^{\nu} - \frac{d^2\sigma}{dx\,dy}^{\bar{\nu}}\right]\frac{\pi}{G_F^2 ME} = \Delta F_2\left(1 - y - \frac{Mxy}{2E} + \frac{y^2}{2}\frac{1+4M^2x^2/Q^2}{1+R}\right) + 2\,y\left(1-\frac{y}{2}\right)\;x\overline{F}_3$$

- Perform 1-parameter fit for xF_3
- ΔF_2 is very small and is neglected

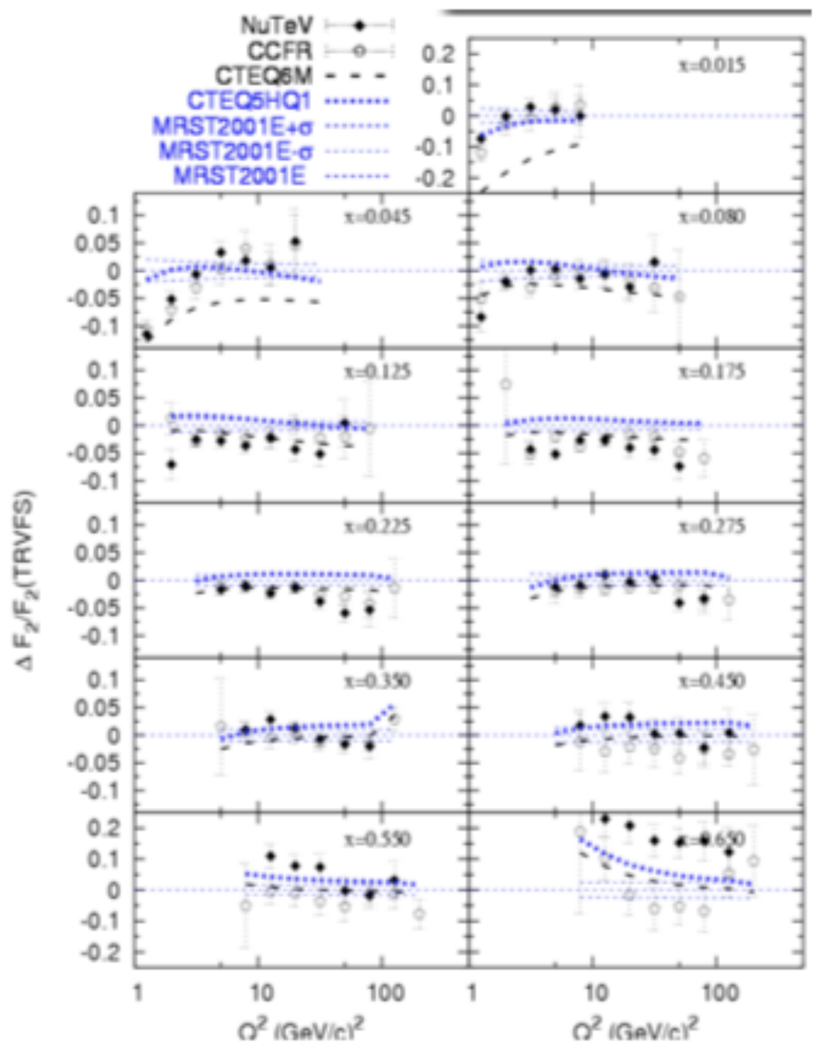
- Radiative corrections applied
- Isoscalar correction applied

NuTeV F_2 Measurement

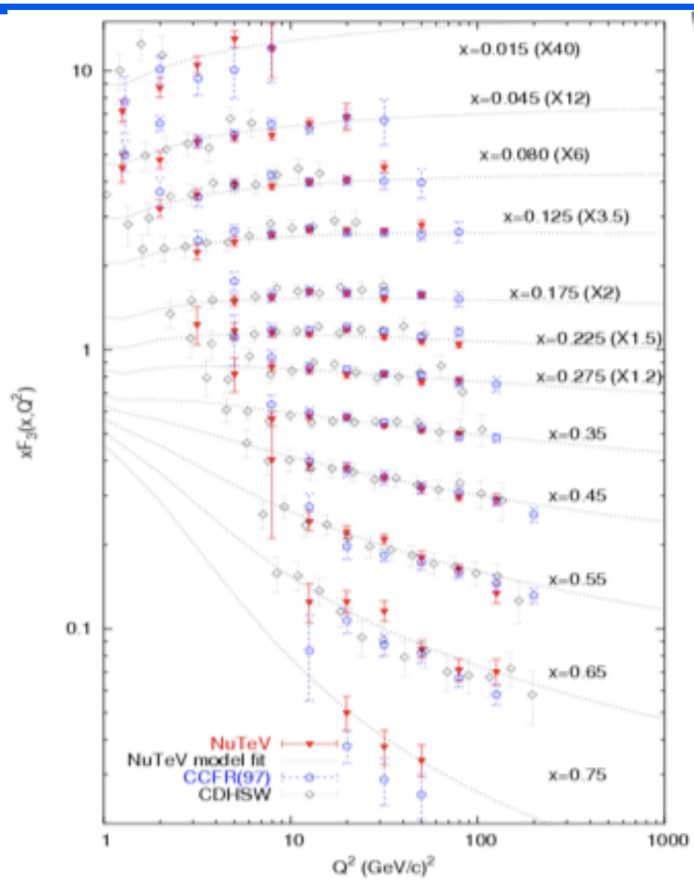


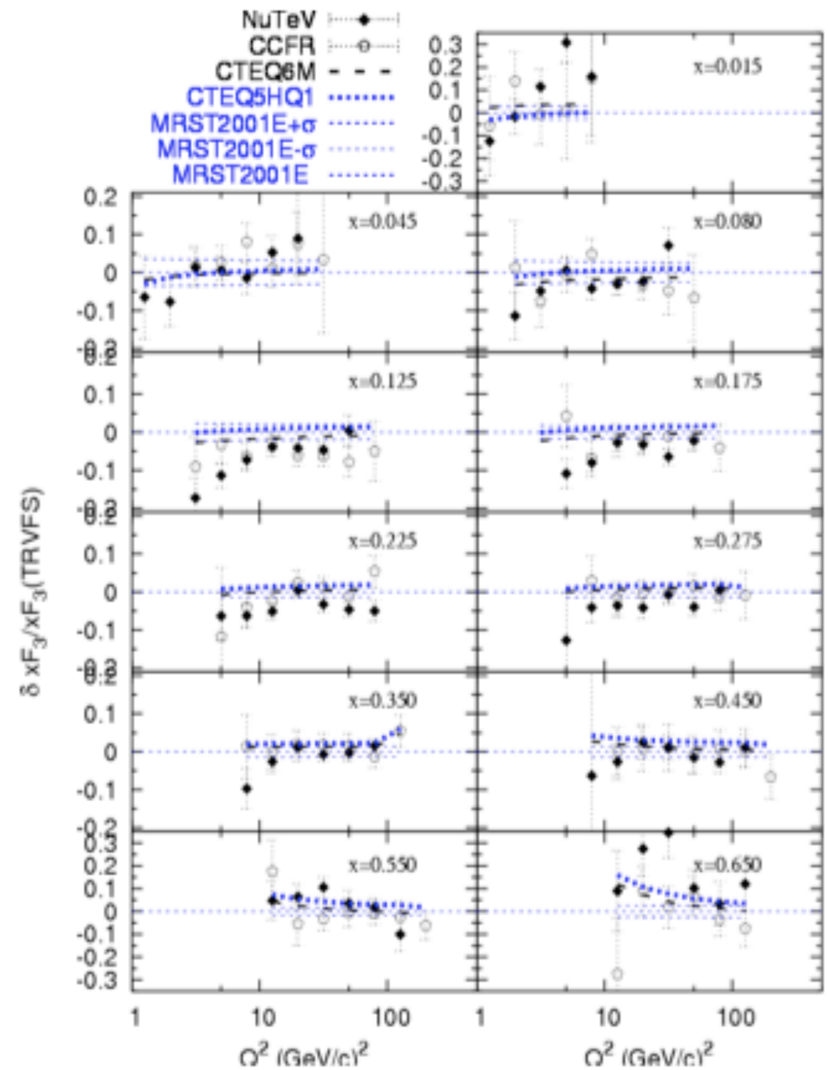
- At $x>0.4$ NuTeV is systematically above CCFR

- Comparison of NuTeV F_2 with global fits



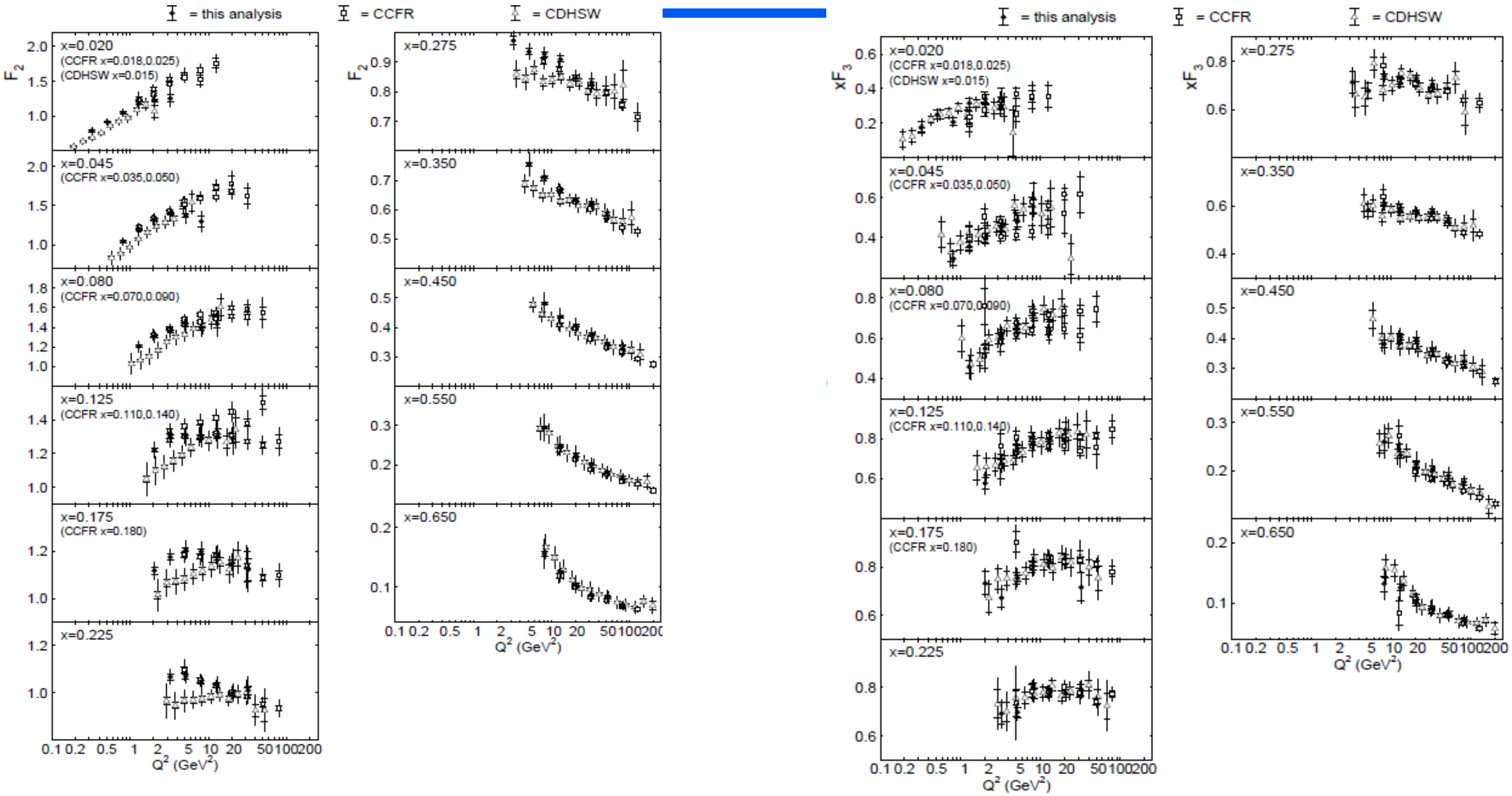
NuTeV xF_3 Measurement





- At $x>0.5$ NuTeV is systematically above CCFR
- NuTeV F_2 agrees with theory for medium x.
- At low x different Q^2 dependence.
- At high x (x>0.5) NuTeV is systematically higher.

CHORUS Structure Functions: ν Pb



- First ν-Pb differential cross section and structure functions
- CHORUS measurement favors CCFR over NuTeV
- Much larger systmatic errors than the NuTeV experiment

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:

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

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

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

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

Taking combinations of the Structure functions

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

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

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

Summary ν Scattering Results – NuTeV

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

NuTeV considered 23 systematic uncertainties.

NuTeV σ agrees with other ν experiments and theory for medium x.
At low x different Q^2 dependence.
At high x (x>0.6) NuTeV is systematically higher.

NuTeV extracts the **strange quark** distribution via charm production using both ν and $\bar{\nu}$ and gets a value of $S^-(x)$

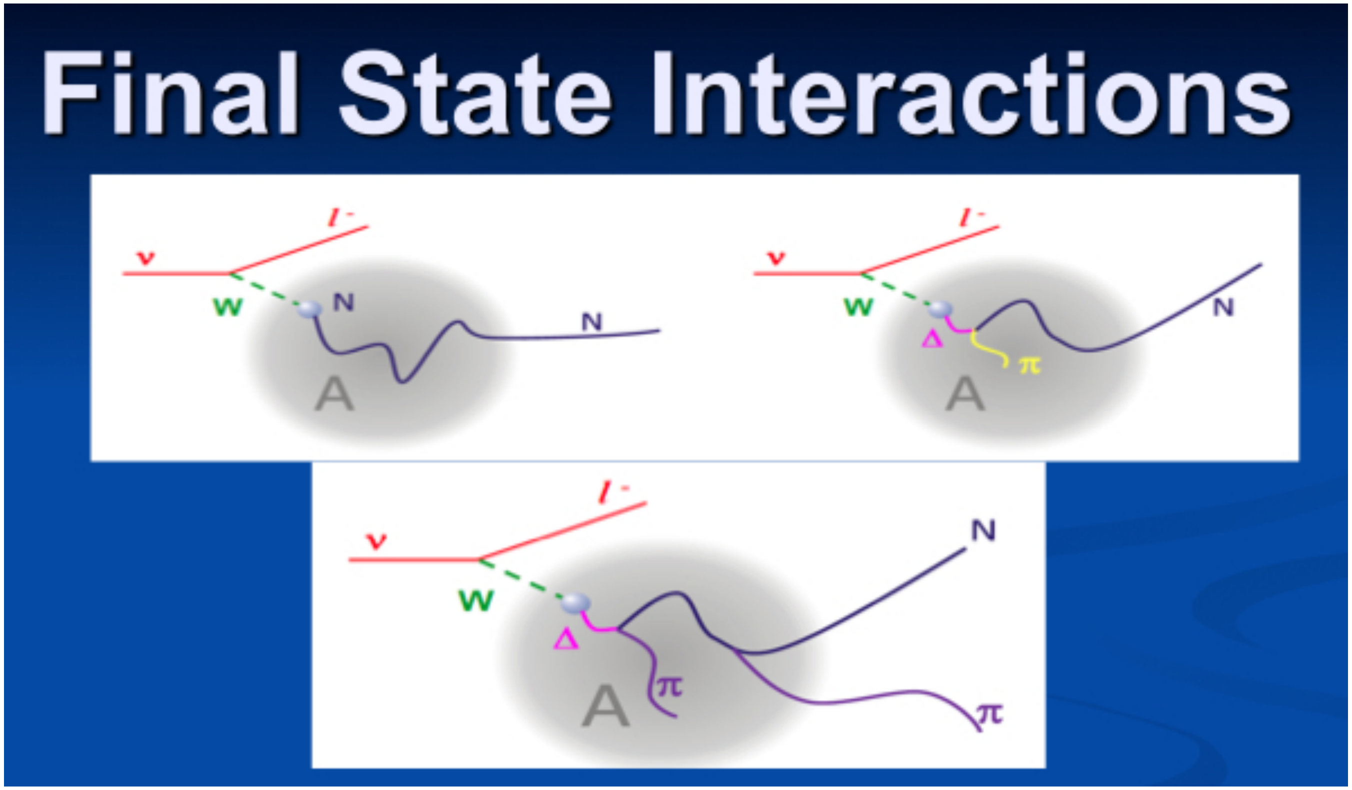
All of the NuTeV Results are for ν – Fe interactions and where necessary have assumed the nuclear corrections for neutrino interactions are the same as $l^\pm$. Is this really the case?

Nuclear Effects in Neutrino Interactions

- Target nucleon in motion - spectral functions (Benhar et al.)
- Certain reactions prohibited - Pauli suppression
- Quasi-elastic form factors are modified within the nuclear environment. (Butkevich/Kulagin, Tsushima et al.)
- Meson exchange currents – short-range correlations
- Produced topologies are modified by final-state interactions modifying topologies and reducing detected energy.
  - Convolution of $\delta\sigma(n\pi) \otimes$ formation zone uncertainties $\otimes$ π-absorption uncertainties yield larger oscillation-parameter systematics
- **Cross sections and structure functions are modified and parton distribution functions within a nucleus are different than in an isolated nucleon. Observations from an on-going CTEQ analysis.**

Nuclear Effects

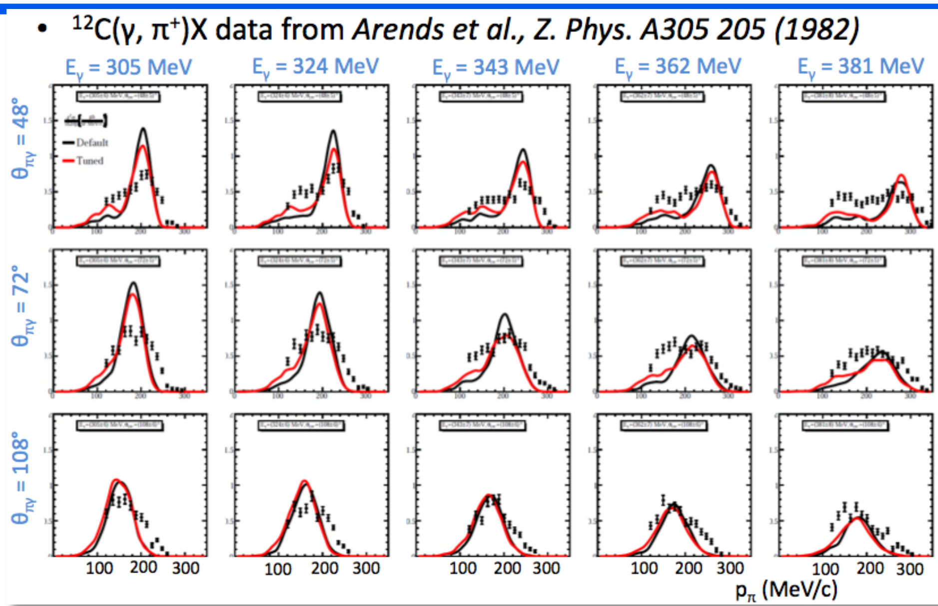
- complication in modern experiments which use nuclear targets
- complex FSI modeled by event generators in a variety of ways



- GiBUU
- GENIE
- NEUT
- NUANCE
- NuWro

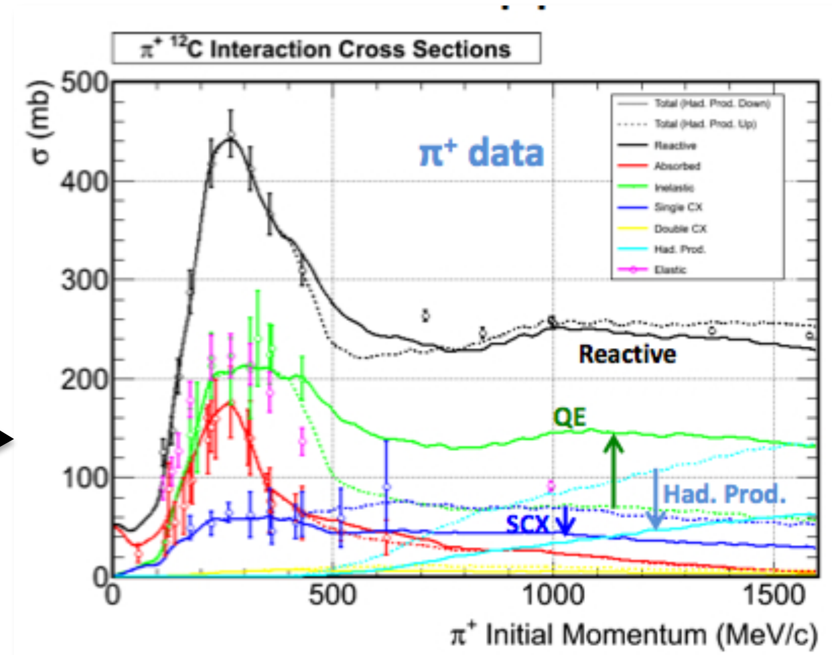
(U. Mosel, **NuInt11**)

Improved FSI Model in NEUT



← photoproduction data

π-nucleus data →

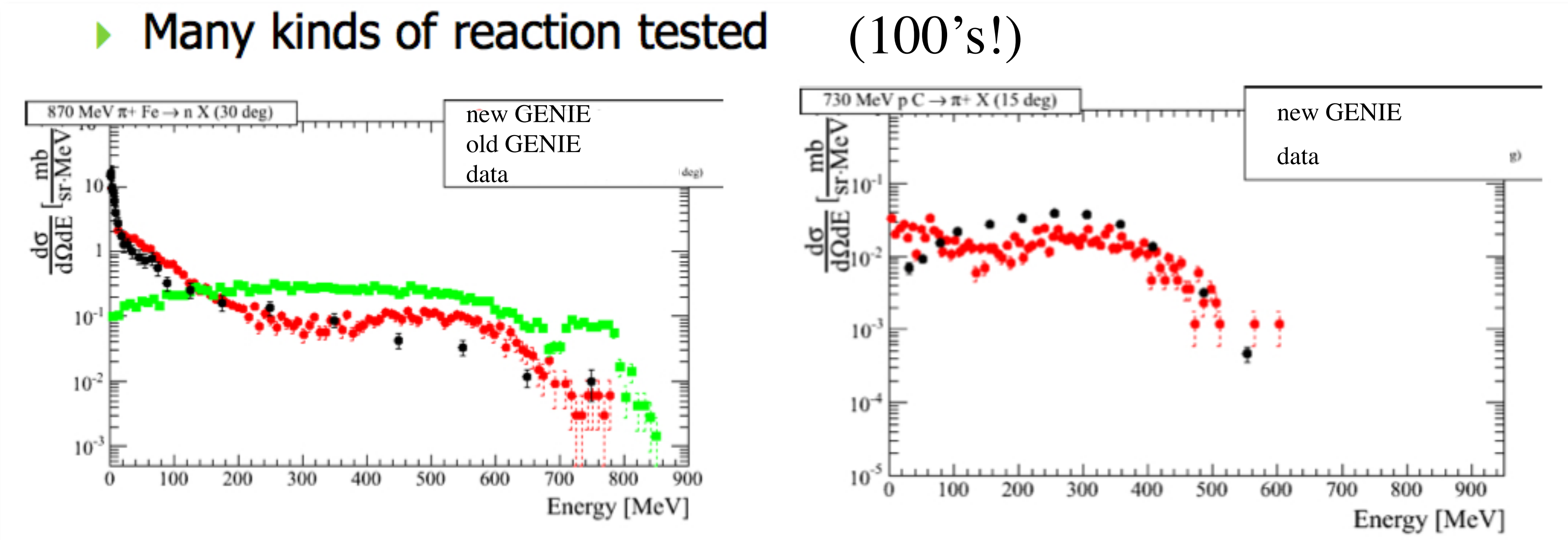


+ comparisons to MB ν data

(P. dePerio, **NuInt11**)

GENIE FSI Model

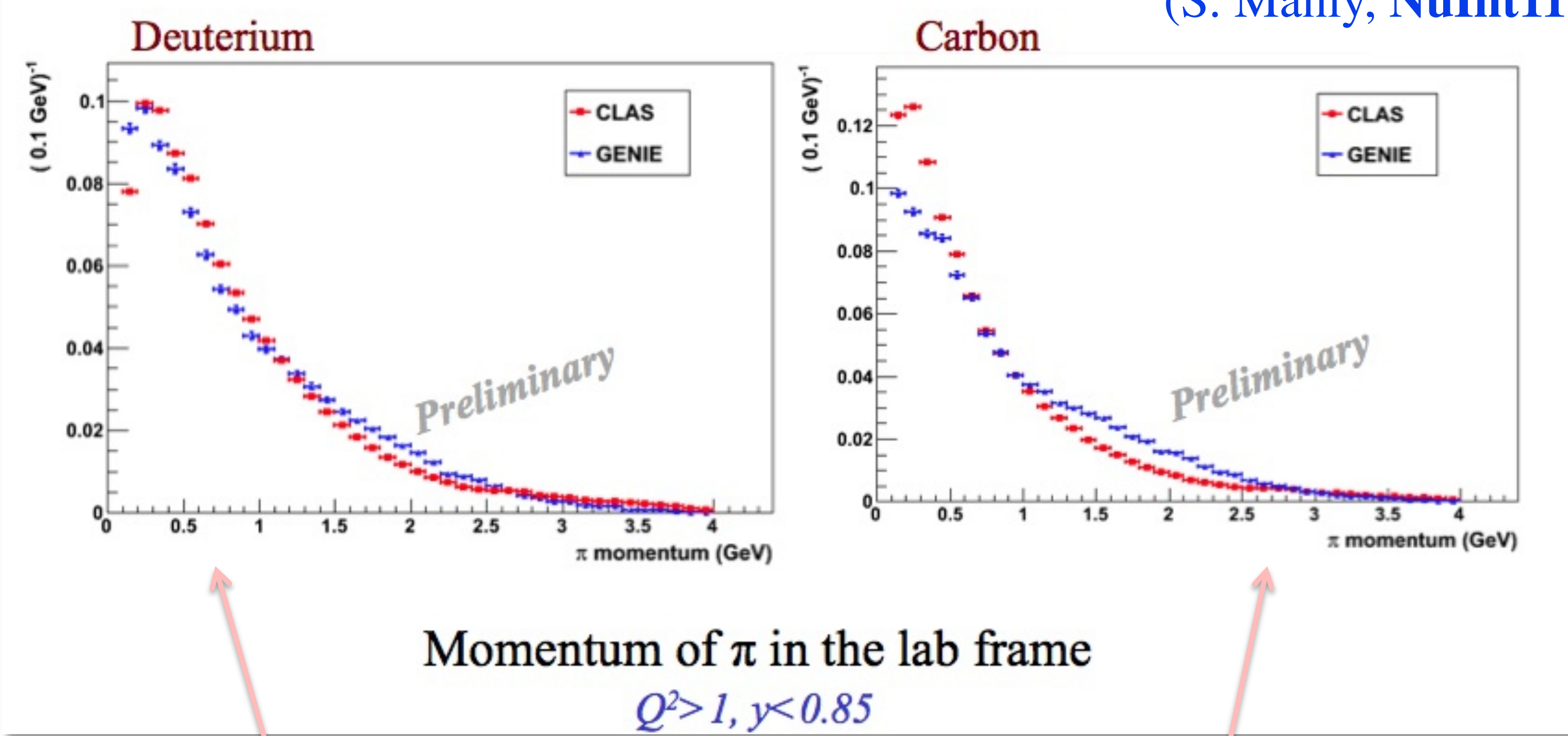
- next GENIE will have new hA & hN models (GENIE v2.8)
- even with a schematic model can fit a lot of features



(S. Dytman, **NuInt11**)

Tests of GENIE with CLAS Data

(S. Manly, **NuInt11**)



tests modeling
of initial interaction

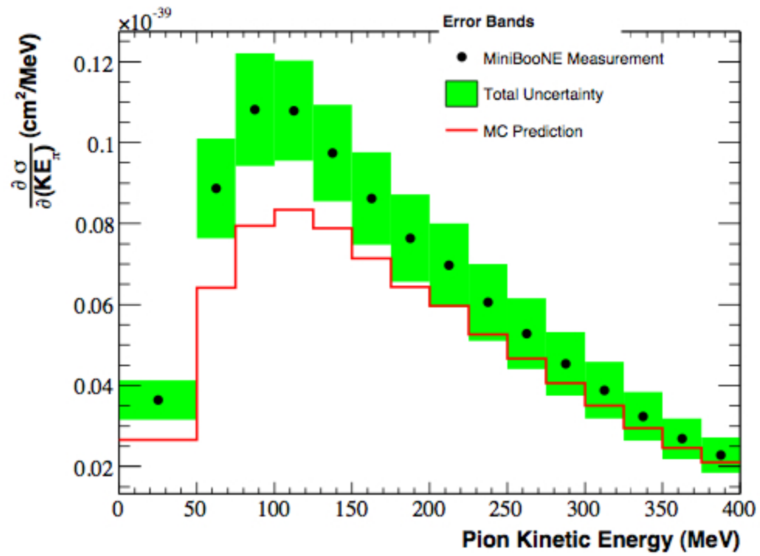
tests modeling of FSI
and nuclear effects

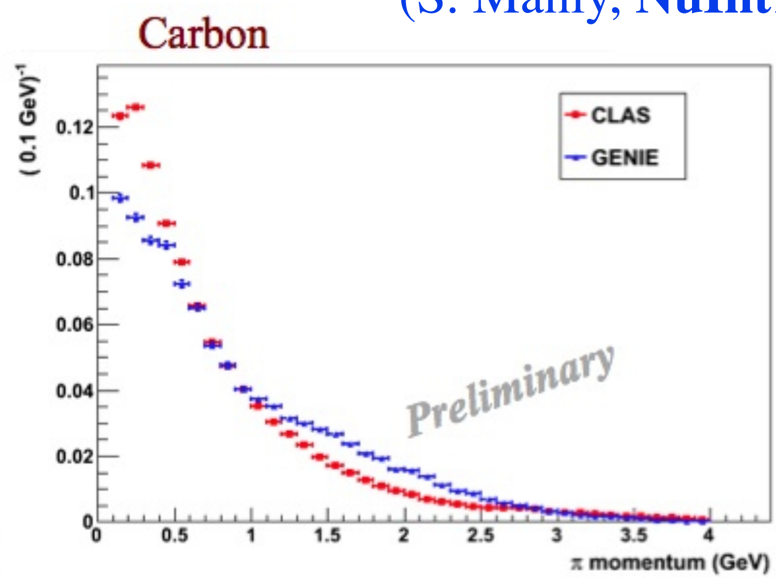
• side by side comparison is very nice!

Tests of GENIE with CLAS Data

(R. Nelson, **NuInt11**)

(S. Manly, **NuInt11**)



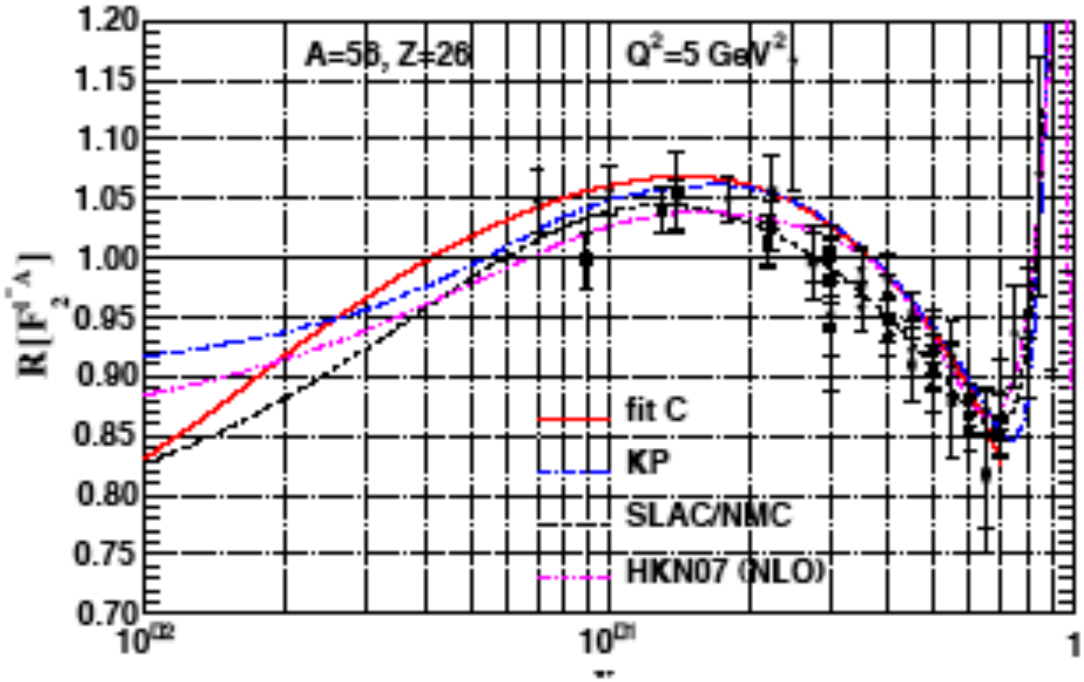


ν data compared to NUANCE

e⁻ data compared to GENIE

- generators seem to underpredict lowest momentum π's

Nuclear Structure Function Corrections
$\ell^{\pm}$ (Fe/D_2)



- F_2 / nucleon changes as a function of A. Measured in μ/e - A, **not in ν − A**
- **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.**

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. Olness (Florida State U)

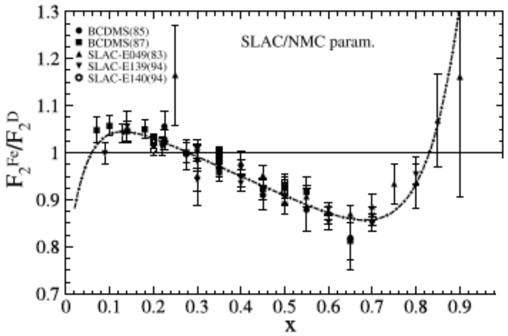
e-Print: **arXiv:0710.4897** [hep-ph]

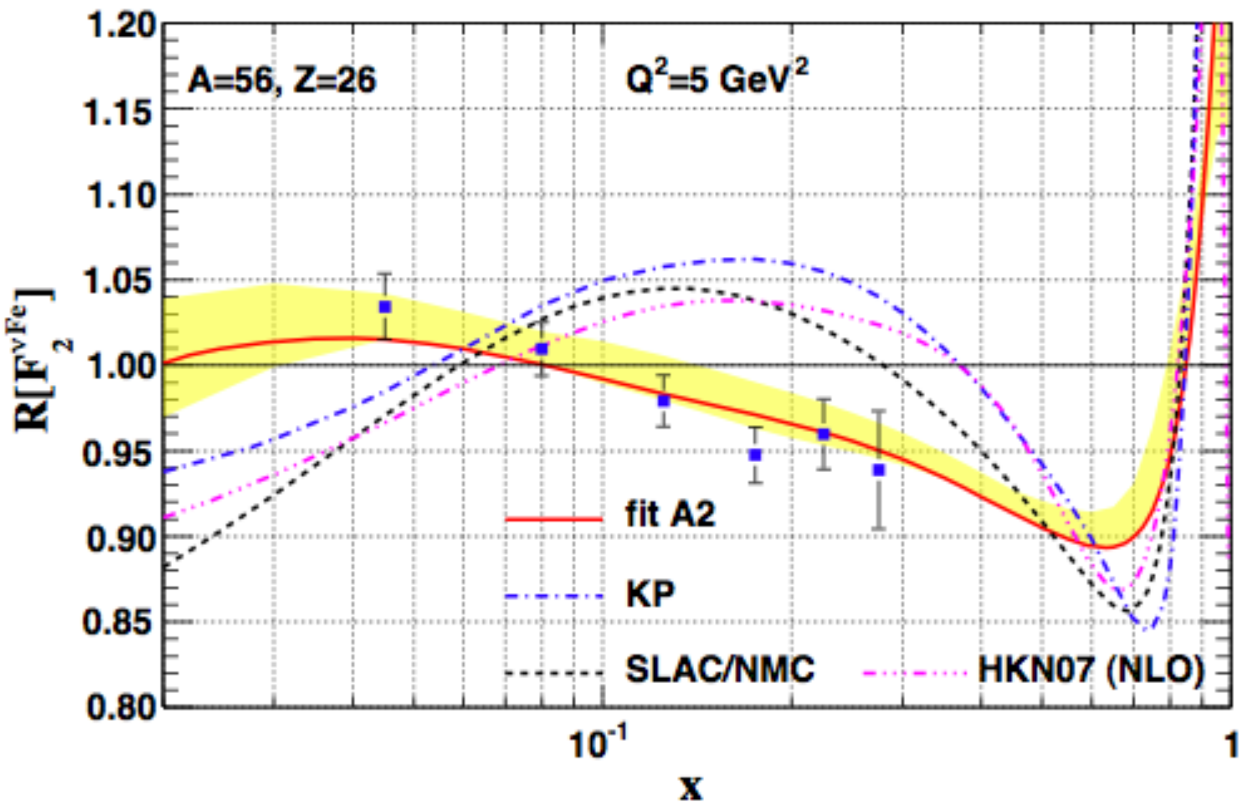
Use the NuTeV neutrino / antineutrino data presented earlier

Make Our Own "D_2" (n+p)

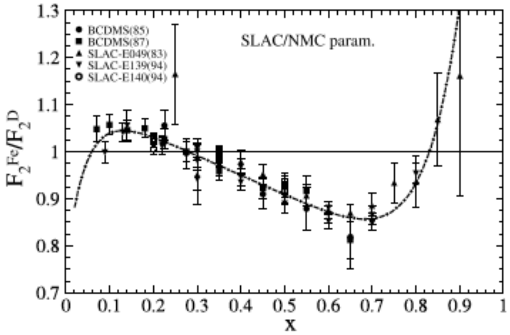
- Form reference fit mainly nucleon (as opposed to nuclear) scattering results:
  - BCDMS results for F_2^p and F_2^d
  - NMC results for F_2^p and F_2d/F_2^p
  - H1 and ZEUS results for F_2^p
  - CDF and DØ result for inclusive jet production
  - CDF results for the W lepton asymmetry
  - E-866 results 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

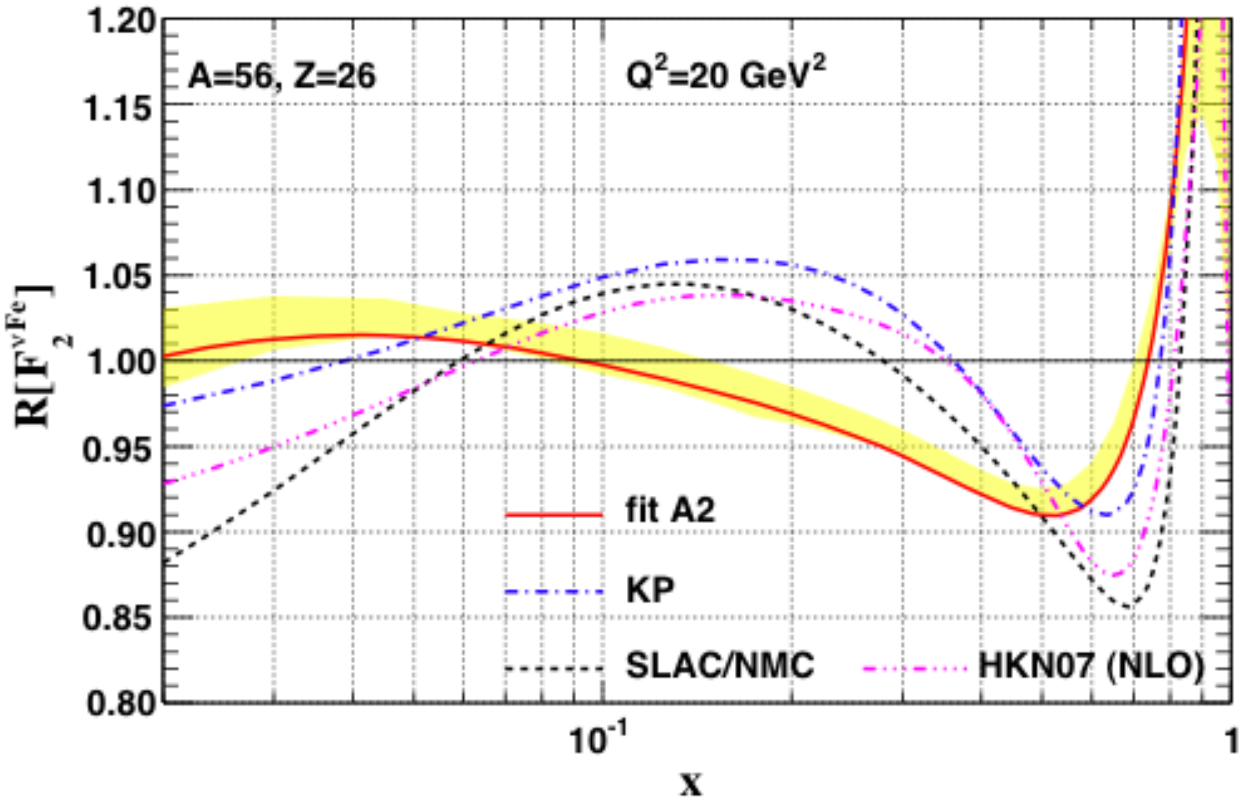
F_2 Structure Function Ratios: ν-Iron



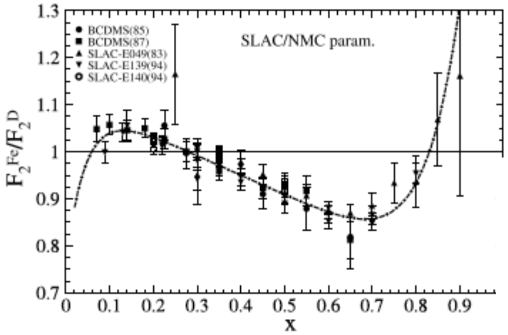


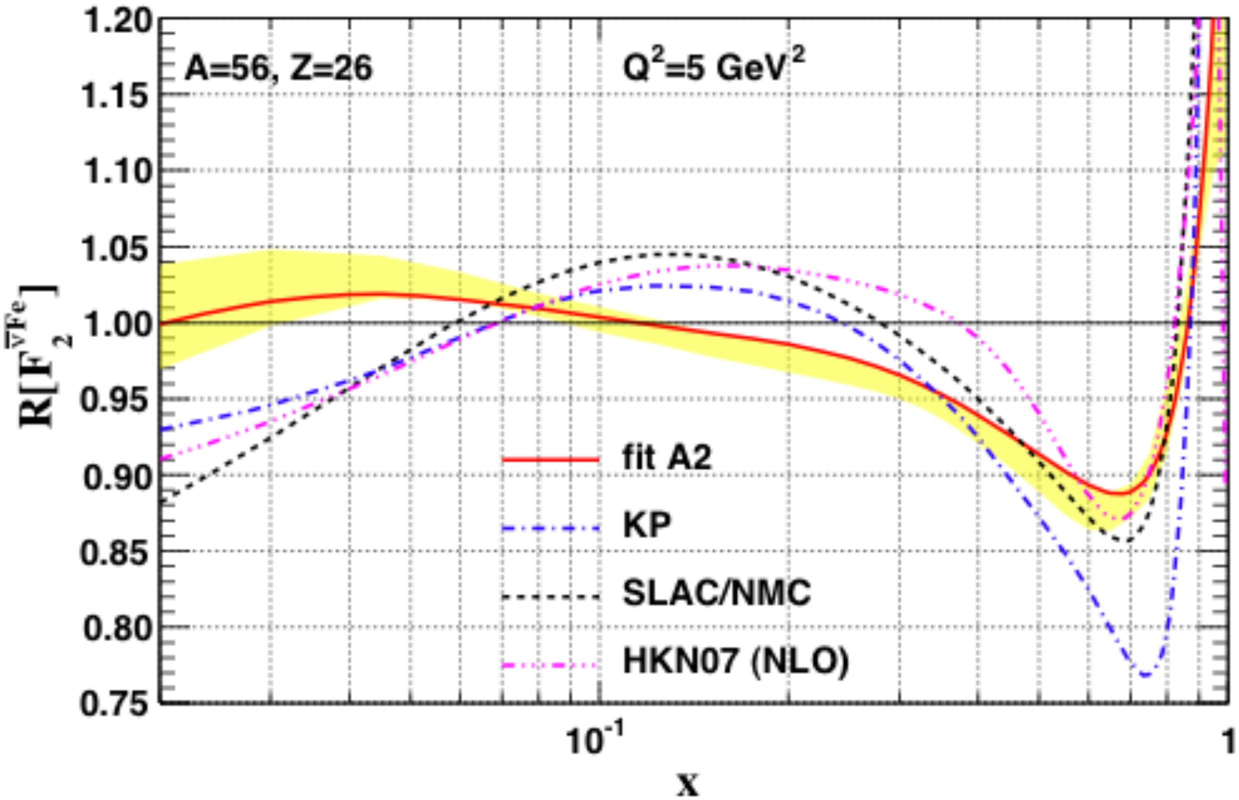
F_2 Structure Function Ratios: ν-Iron



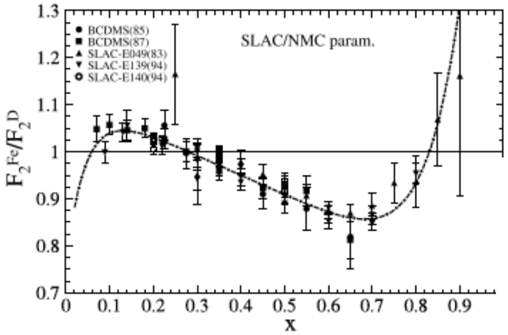


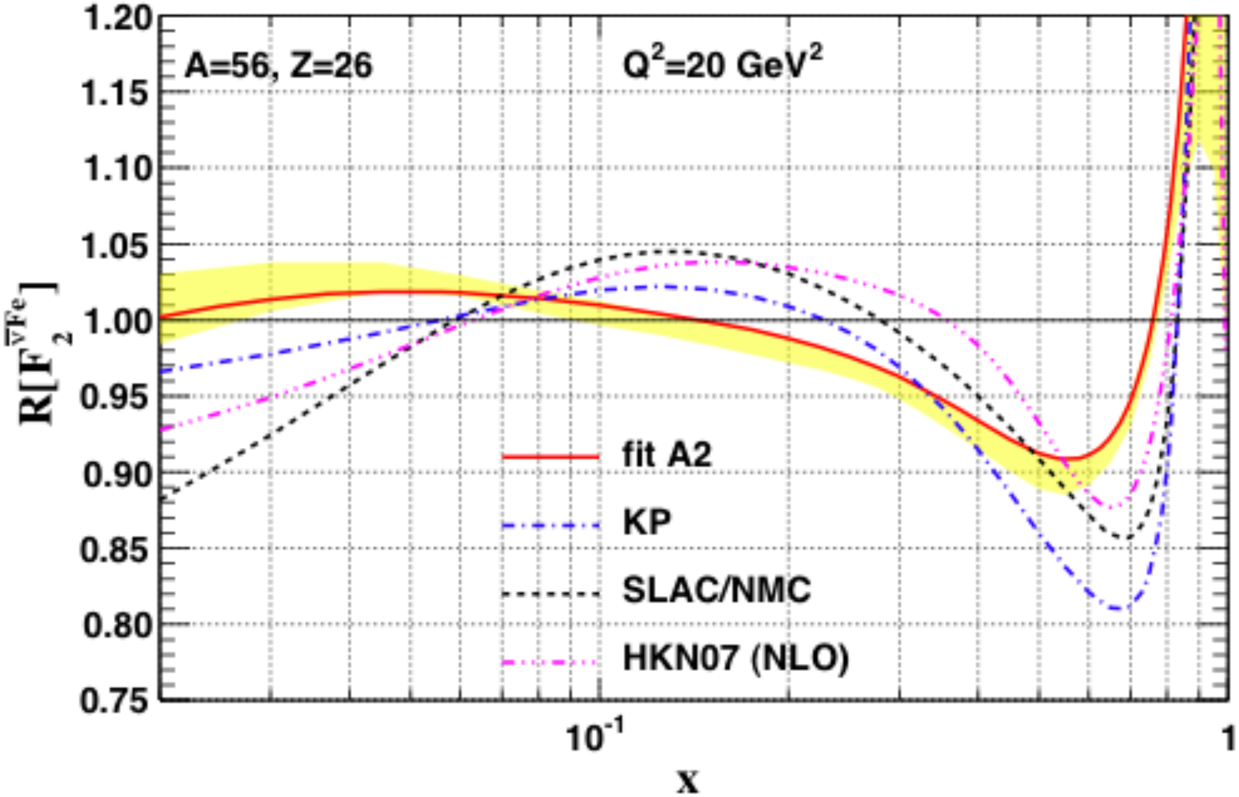
F_2 Structure Function Ratios: $\bar{\nu}$-Iron





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





Conclusions-Nuclear Effects

- All high-statistics neutrino data is off nuclear targets. Need nuclear correction factors to include data off nuclei in fits with nucleon data.
- Nuclear correction factors (R) might be different for neutrino-Fe scattering compared to charged lepton-Fe. Current results are from one experiment on one nuclear target… careful.

- There are many physics topics that will be awaiting the intensity and precision of a high-resolution detector in the high-intensity neutrino factory flux to give us the results we need.!