Structure Function Uncertainties and Neutrino Oscillation Experiments

Outline:

1. Neutrino oscillation experiments
2. Characteristic systematics worries
    - low Q^2 suppression in nuclei
    - E_ν from few-GeV calorimetry
    - ν_e appearance backgrounds
3. MINOS cross section modeling and plans

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DIS05 – Madison, WI
April 29, 2005

ν Oscillation Experiments

The Pontecorvo-Maki -Nakagawa-Sakata matrix

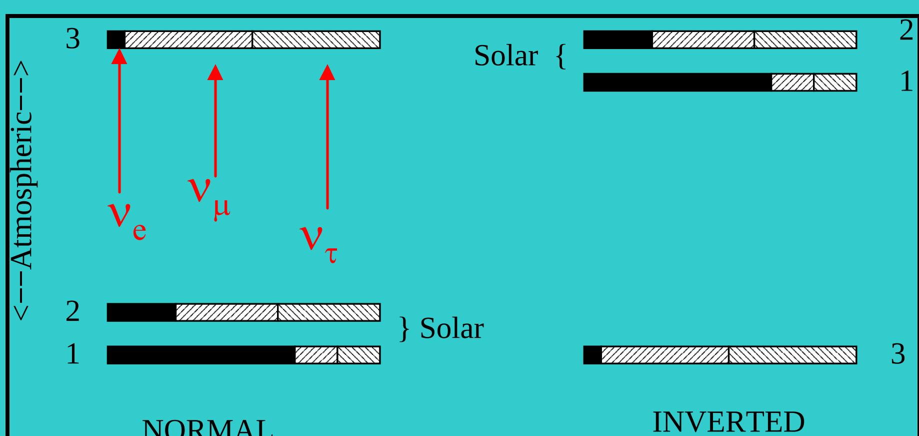
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillations between all 3 flavors at each Δm^2
3 sets of 3 equations like these →

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2_{32} L / E_\nu)$$

$$P(\nu_\mu \to \nu_e) = \cos^2\theta_{13} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{32} L / E_\nu)$$

$$P(\nu_e \to \nu_\tau) = \cos^2\theta_{13} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{32} L / E_\nu)$$



Goals of next generation of expts:

1) Better precision on parameters
2) Observing Oscillations
3) θ_{13} and δ_{CP} in the PMNS matrix
4) “Normal” or “Inverted” mass hierarchy

ν *Oscillation Experiments*

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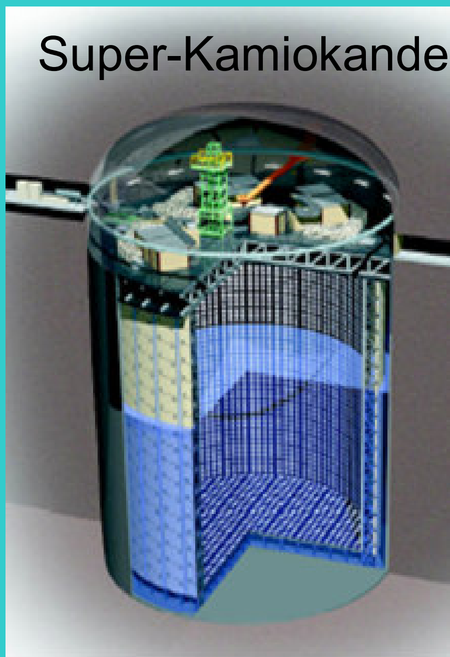
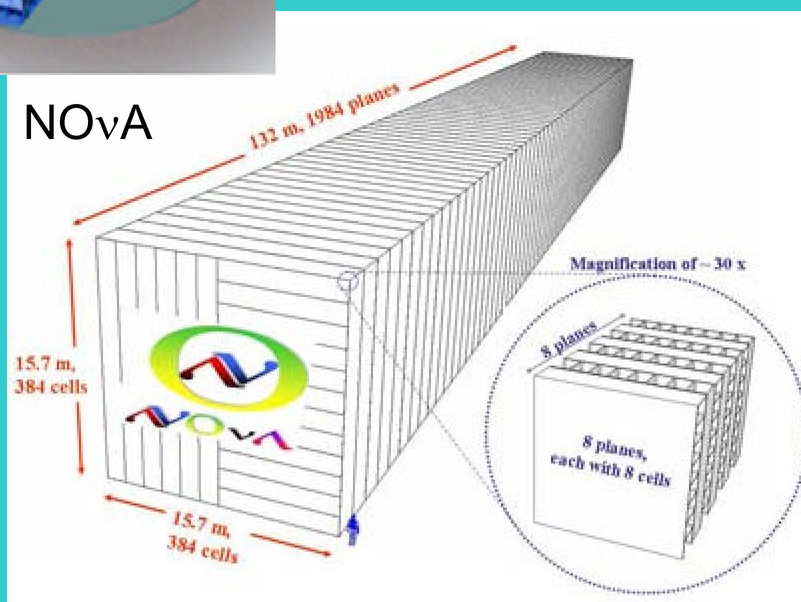
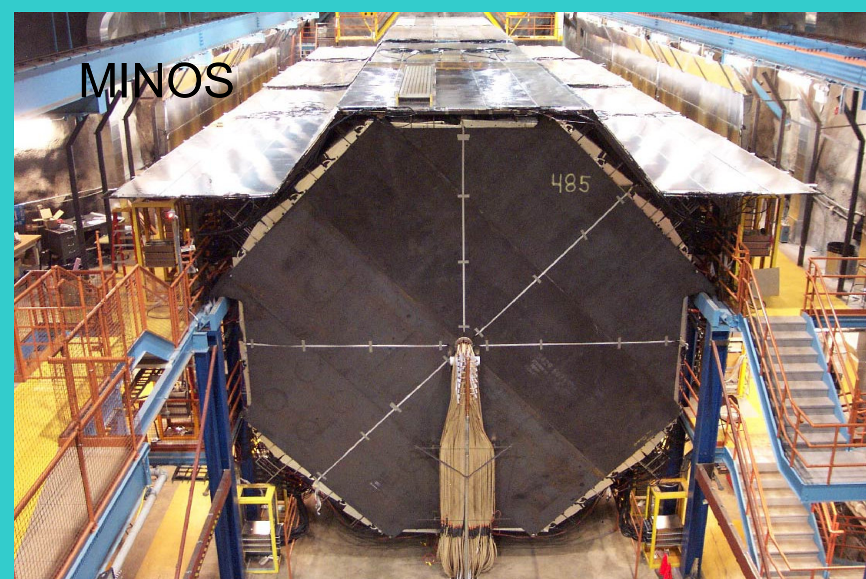
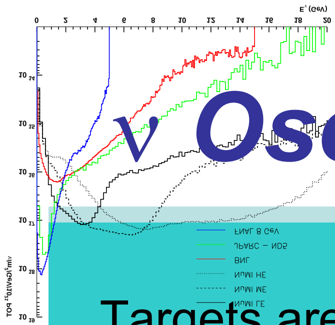


Current/Future long baseline experiments;

Expt.	Dates	E_n (GeV)	Mass (kt)
K2K	1998-2005	1	50
MINOS	2005+	~ 3-10	5.4
T2K	2008+	0.7	50
NOνA	?	2.2	30







ν Oscillation Experiments

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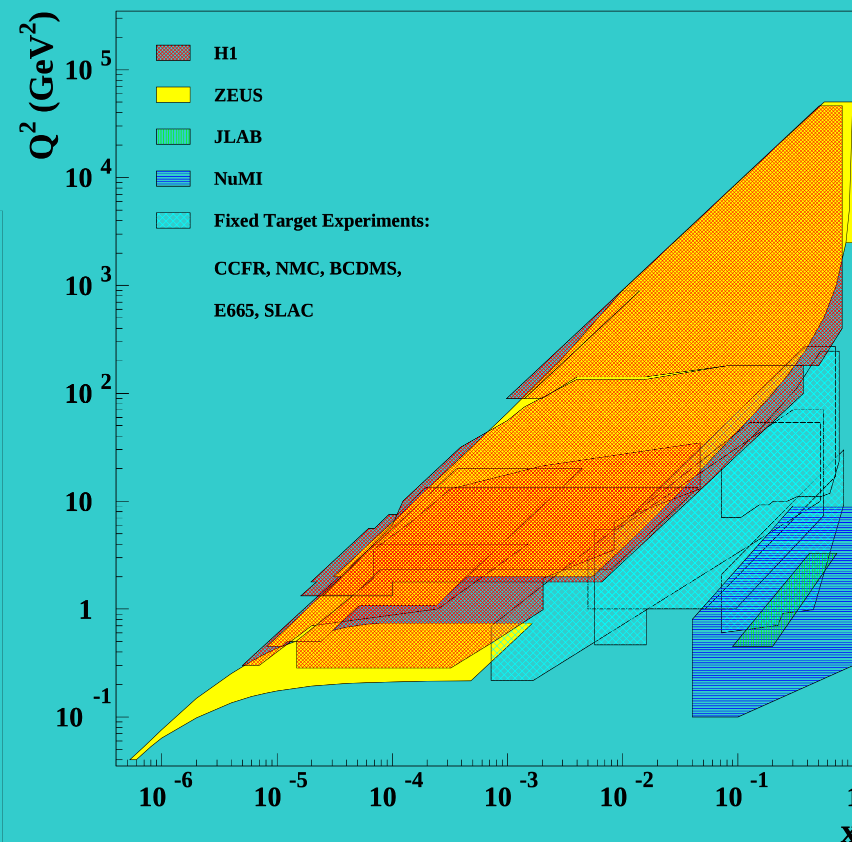
Targets are mainly CH_2, H_2O, or Fe.
Variety of options for beam energies:
- On/off-axis conventional beams,
- "SuperBeams"



Large degree of overlap between the kinematics of the NuMI beam and those under exploration at JLab and elsewhere.

Kinematic Coverage

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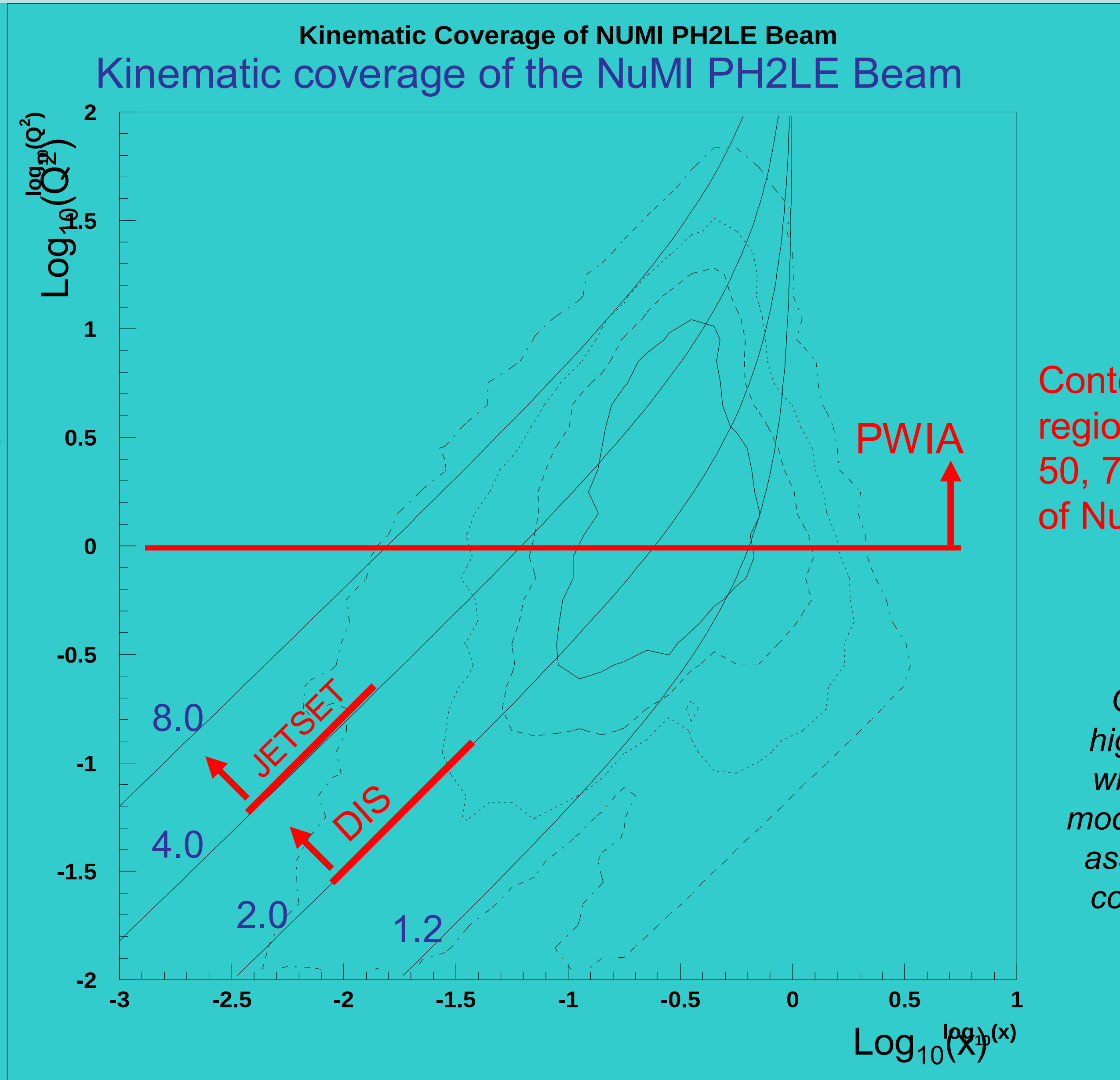
Lines are constant W (GeV)

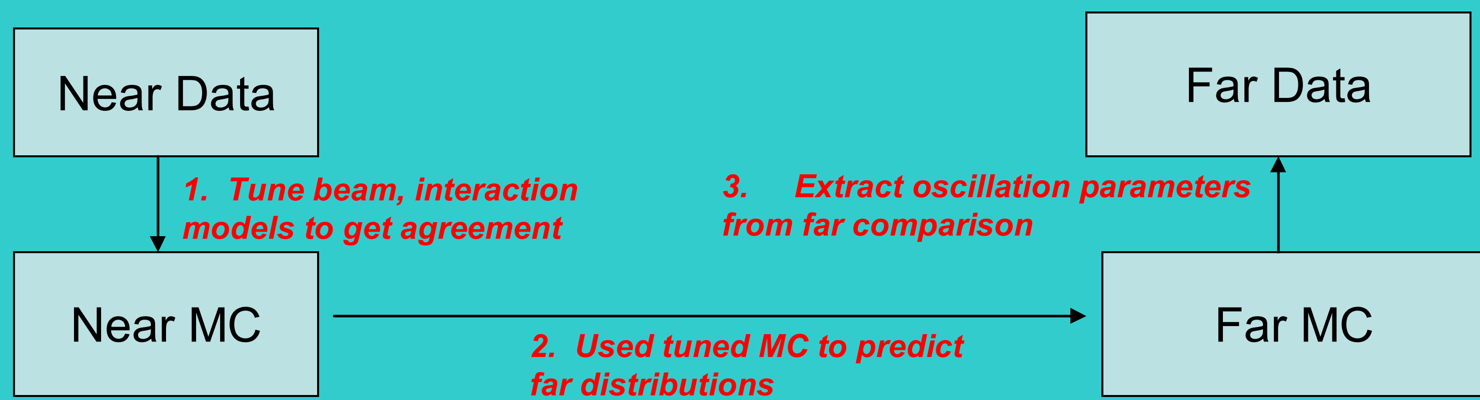


Contours are regions containing 50, 75, 90, and 99% of NuMI events

Orange lines highlight regions where particular models / theoretical assumptions are considered valid

Near Detectors

Structure functions, cross sections, nuclear effects… that stuff is messy! That's why we built a near detector…



"Near/Far comparison" does cancel many systematics, but:

1. Near and far detectors slightly different (2% relative uncertainty for MINOS)
2. Alternate ways of describing ND data might extrapolate to FD differently
3. Near and far beams different – decay kinematics and beam optics (smaller effect), oscillations (bigger effect)
4. Not everything cancels: Δm^2 is coupled to E_ν, knowledge of the absolute neutrino energy scale is required.

Oscillation Experiments

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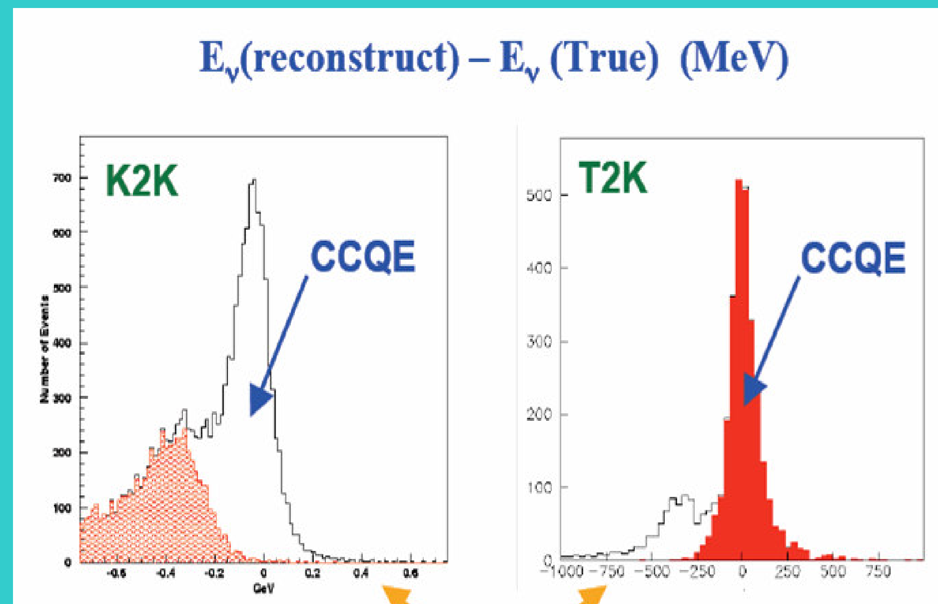
Most important uncertainties related to cross sections and modeling of neutrino-nuclear interactions in nuclei depend on beam energy and analysis.

θ_{23} measurements:
- Δm^2 measurement coupled to E_ν
- Understanding neutrino energy scale
- K2K – E_ν based on QEL reconstruction
- MINOS – Calorimetry / NC mis-id at low E_ν

θ_{13} measurements:
- understanding NC backgrounds
- π^o production



T. Nakaya, NuINT04

Complete understanding of systematic uncertainties and sensitivities involves many sources:
- near – far extrapolations
- cross sections – inclusive and exclusive (topological identification)
- hadronization models – affect NC/CC mis-id, ν_e background
- nuclear physics – on cross section and re-scattering of produced particles

Example: E_ν from Calorimetry

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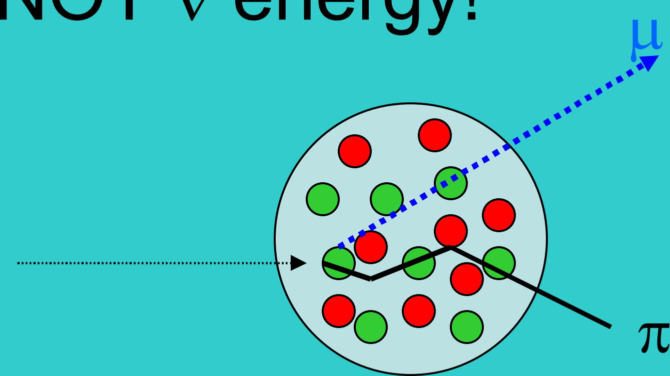
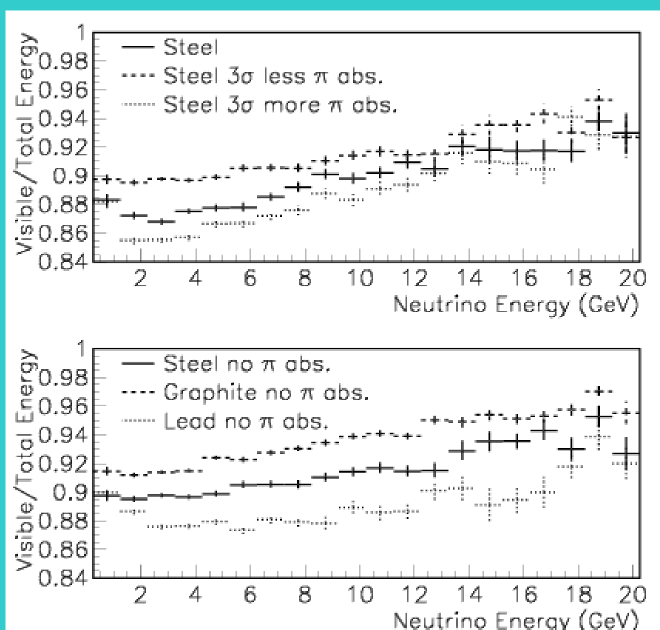
Visible Energy in Calorimeter is NOT ν energy!

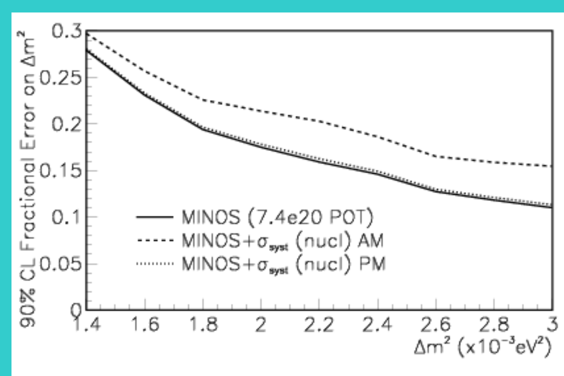
- π absorption, rescattering
- final state rest mass

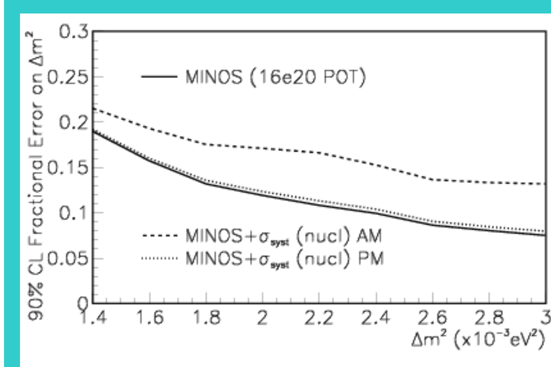


(D. Harris et al., hep-ex/0410005)



Nuclear effects studied in charged lepton scattering, from deuterium to lead, at high energies, but nuclear corrections may be different between e/μ and ν scattering





Example: Low Q^2 suppression

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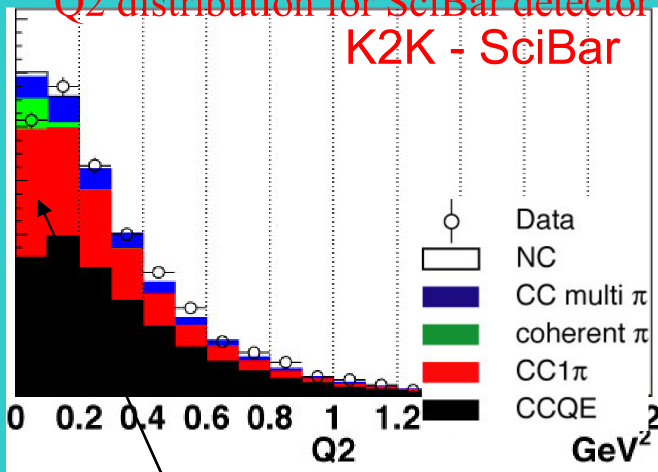
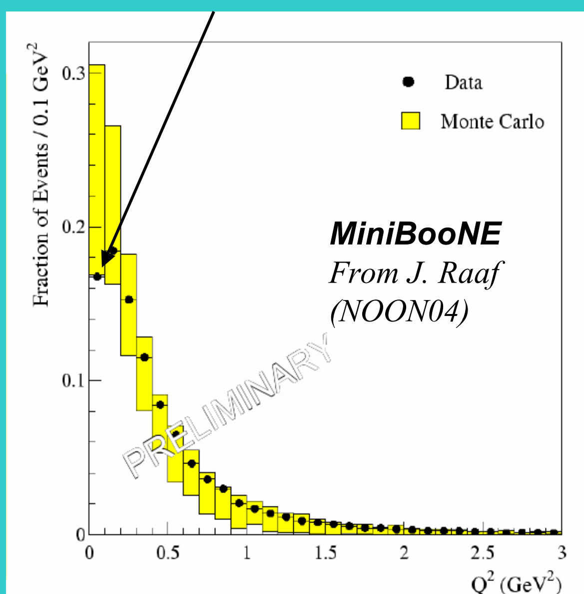
Q2 distribution for SciBar detector



Larger than expected rollover at low Q^2



One such effect is the larger than expected suppression of events at low Q^2 from K2K and miniBoone.

All "known" nuclear effects taken into account: Pauli suppression, Fermi Motion, Final State Interactions.

Variety of explanations examined:

- Pauli blocking of Δ states?
- Smaller than expected CC coherent contribution?
- Missing lepton mass terms in resonance production cross sections.
(Lalakulich-Paschos,Phys.Rev.D71:074003,2005)
- Nuclear shadowing (Kopeliovich, hep-ph/0409079)

Importance of using correct form factors (non-dipole) for M_A extraction → affects Q^2 distribution shape (Budd, Bodek, Arrington, hep-ex/0410055).

After considerable study, K2K parametrized the deficit, folded back into their MC for the far detector. No effect on the oscillation fits (but low statistics).

Example: Future θ_{13} Expts

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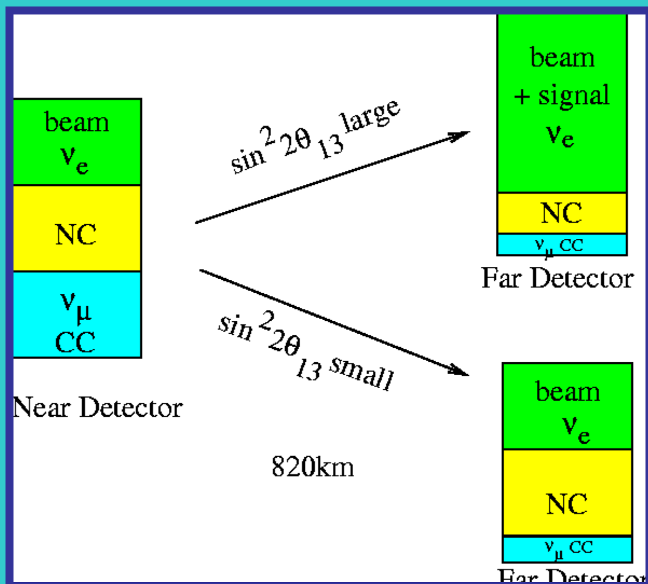
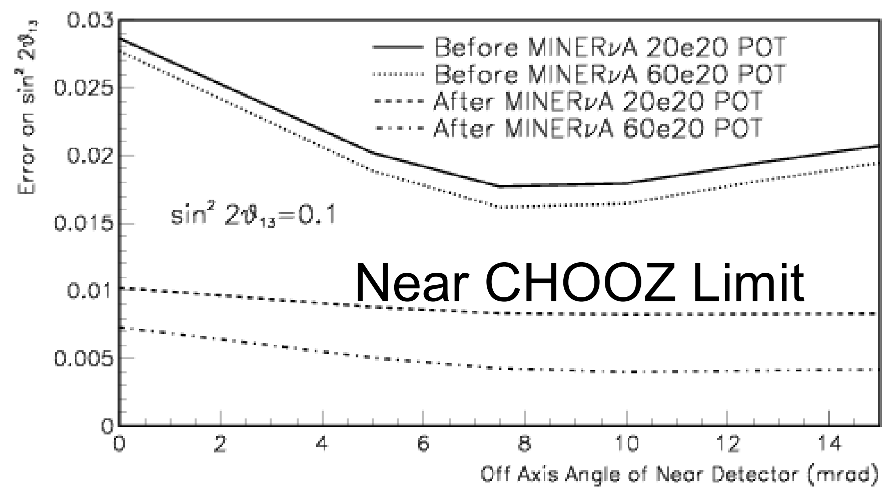
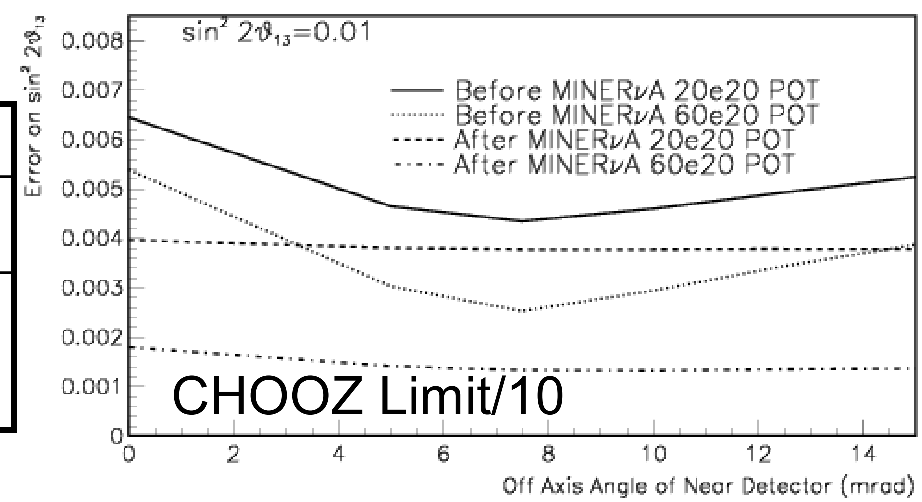
(D. Harris et al., hep-ex/0410005)







Process	QE	RES	COH	DIS
$\delta\sigma/\sigma$ NOW (CC,NC)	20%	40%	100%	20%
$\delta\sigma/\sigma$ after MINERνA (CC/NC)	5%/na	5%/10%	5%/20%	5%/10%

Without MINERνA, NOνA may be limited by cross section systematics

Model Tuning (MINOS)

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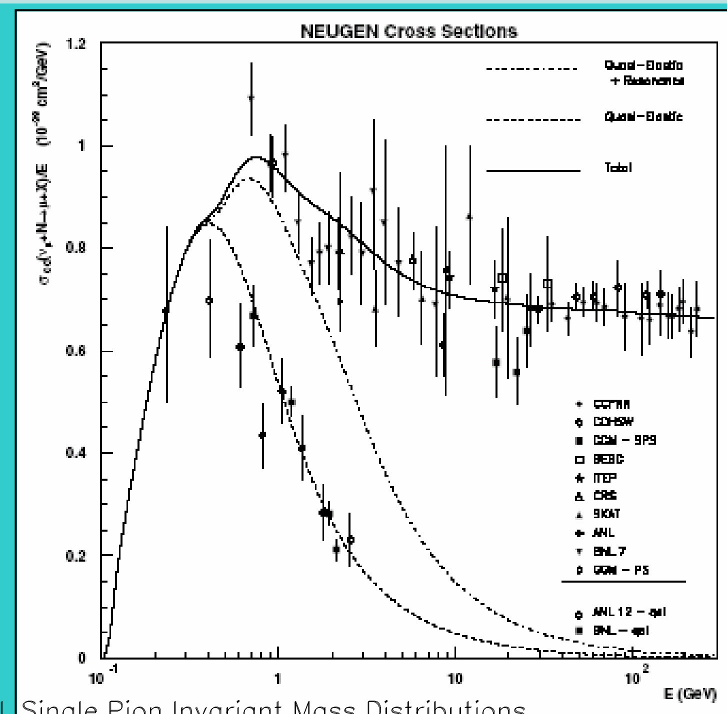
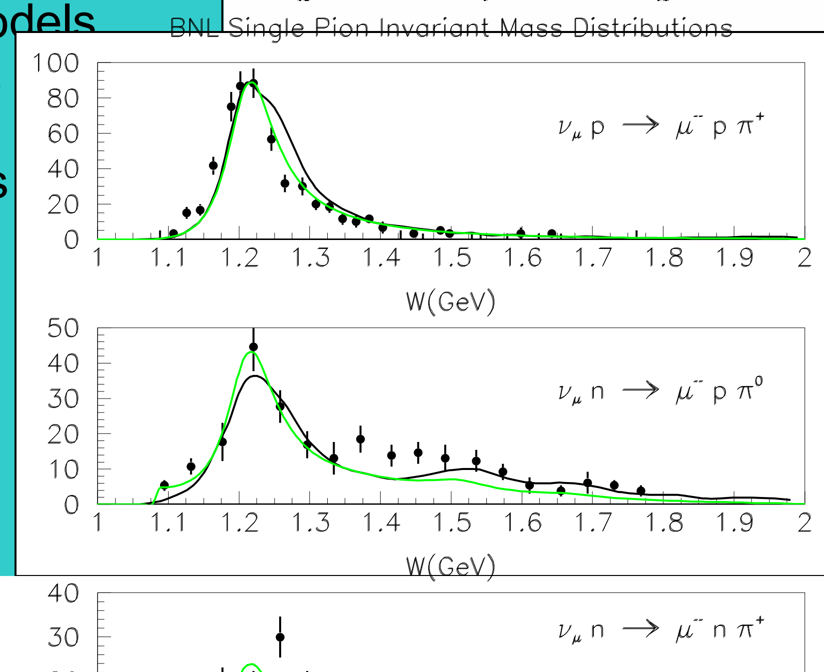
Modeling of ν-nucleus interactions had been based primarily on old models and tuned primarily to neutrino bubble chamber data.

- LO DIS calculations
- Rein-Seghal model for W<2 GeV (Annals of Physics 133, 79,1981)
- FGM for nuclear effects



There has been a renewed interest in the subject, and many papers in the last 4 years detailing improvements to the modeling

1) JLAB data / improving resonance models
   - Lalakulich-Paschos,Phys.Rev.D71:074003,2005
   - T. Sato et al. Phys. Rev. C67, 065201 (2003)
2) Nuclear modeling / spectral functions
   - O. Benhar, NuINT 02
   - Nieves et al. nucl-th/0408008
   - J. E. Amaro et al. nucl-th/0409078
3) Bridging the pQCD/non-pQCD gap
   - Bodek et al. hep/ph/0411202



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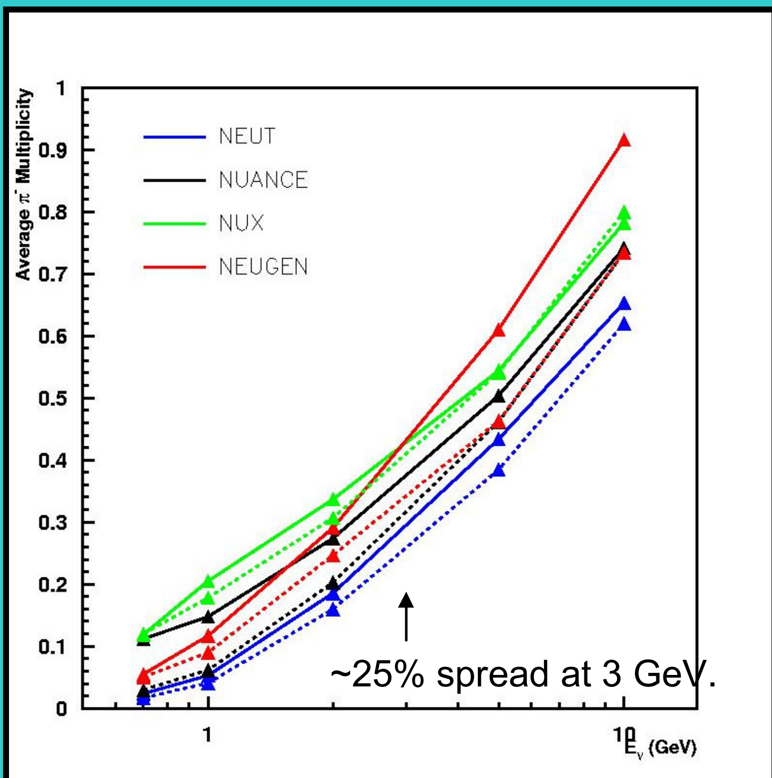
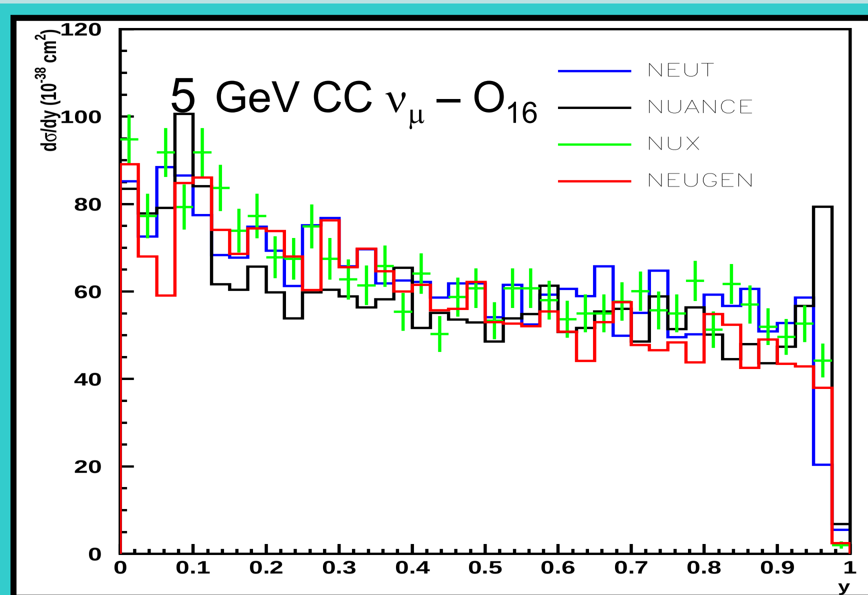
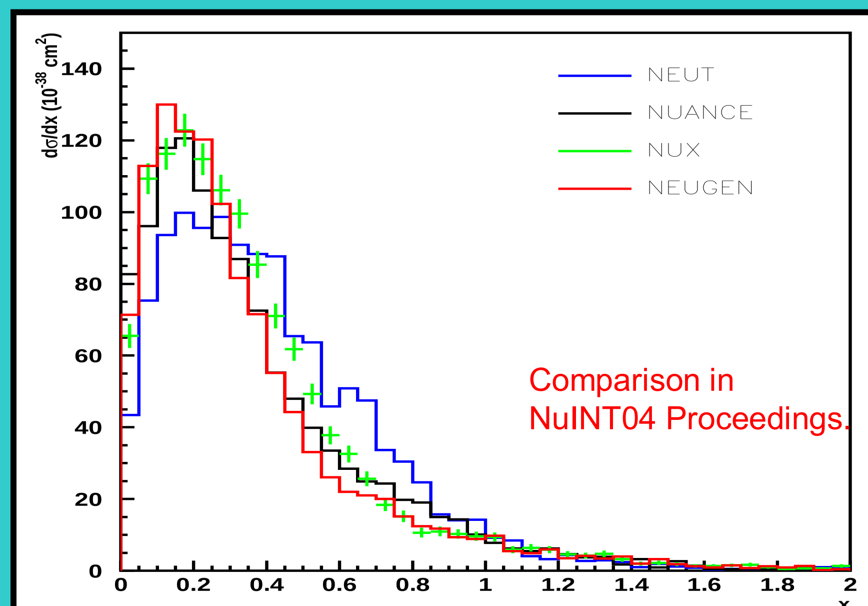
NUANCE (SuperK/K2K/miniBoone):
D. Casper, hep-ph/0208030
NUX-FLUKA (NOMAD/ICARUS):
F. Battistoni *et al.* NuINT 02 Proceedings
NEUT (SuperK/K2K):
Y.Hayato, Nucl. Phys. Proc. Suppl. **112**, 171 (2002)
NEUGEN (MINOS, Soudan 2):
H. Gallagher, Nucl. Phys. Proc. Suppl. 112 188 (2002)







Model Tuning (MINOS)

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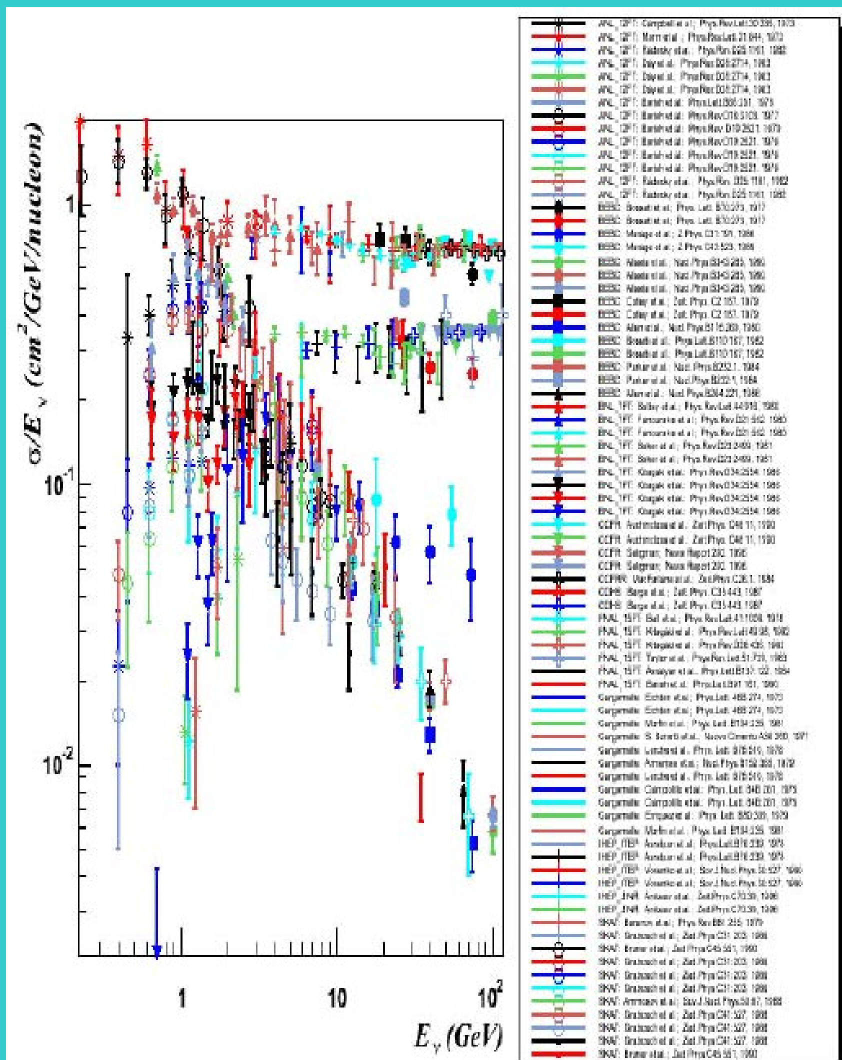
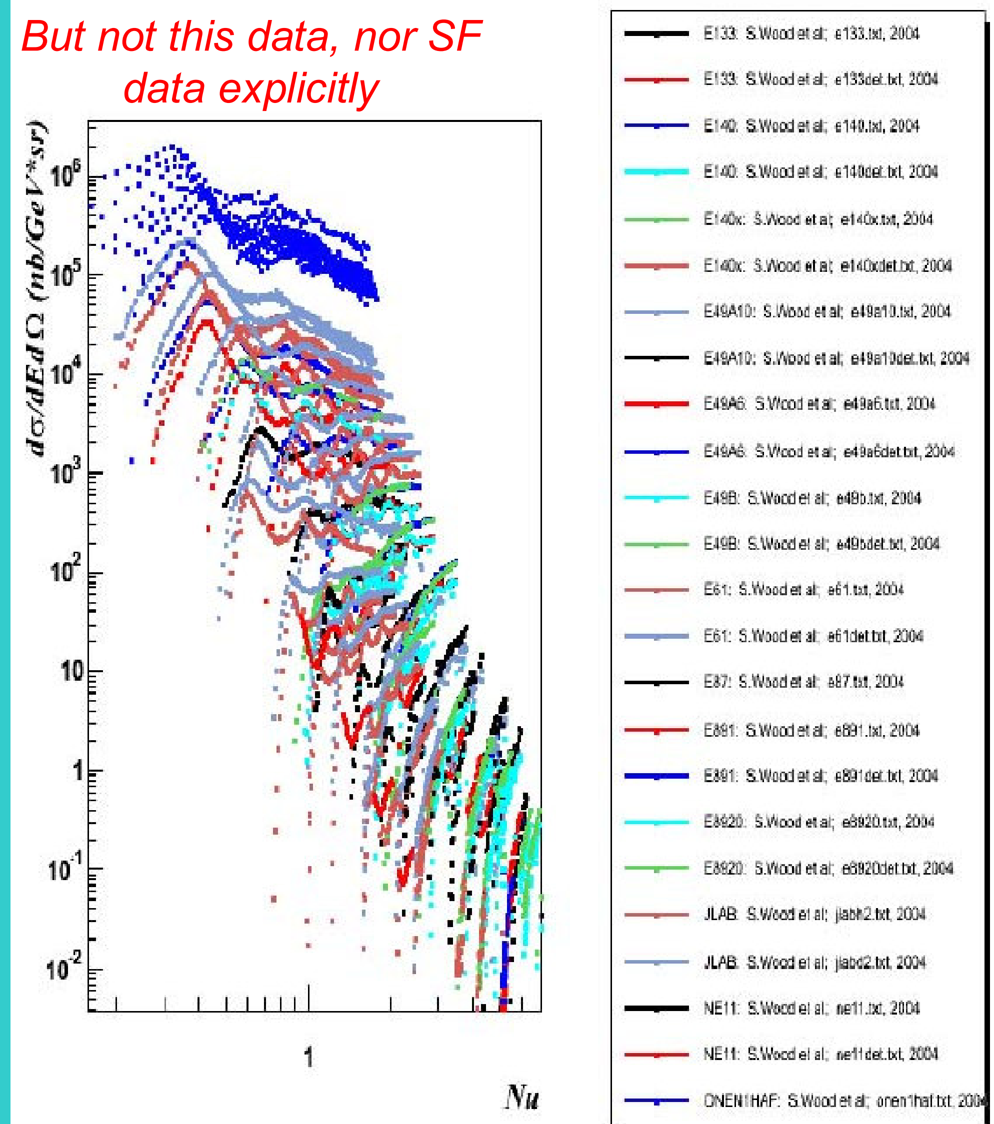
Past tunings have used this data – ν cross sections



But not this data, nor SF data explicitly



Model Tuning (MINOS)

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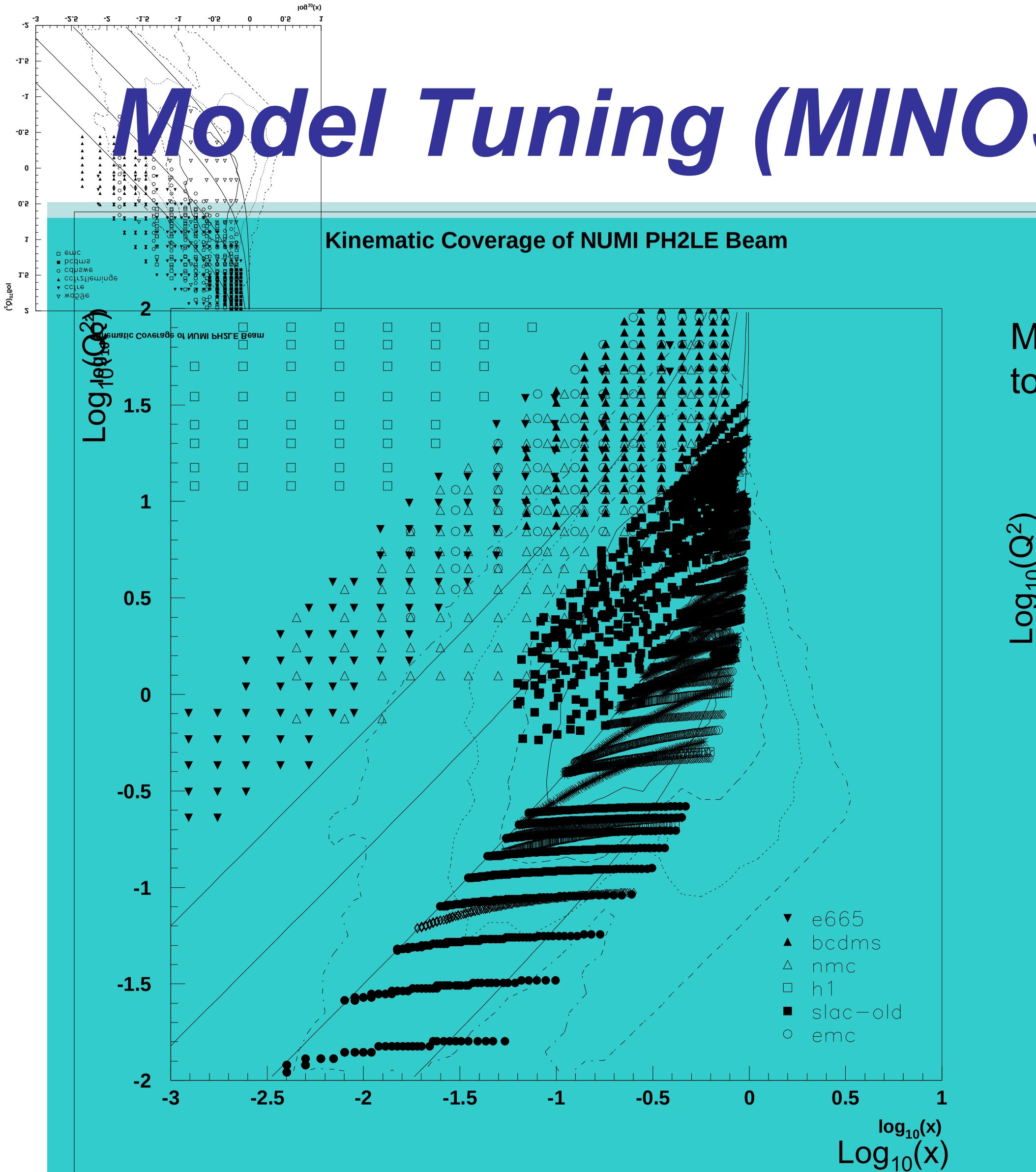


Mostly structure function data,
together with some cross section data.

Nuclear targets

$Log_{10}(Q^2)$

H_2/D_2 targets

JUPITER data will help fill in here

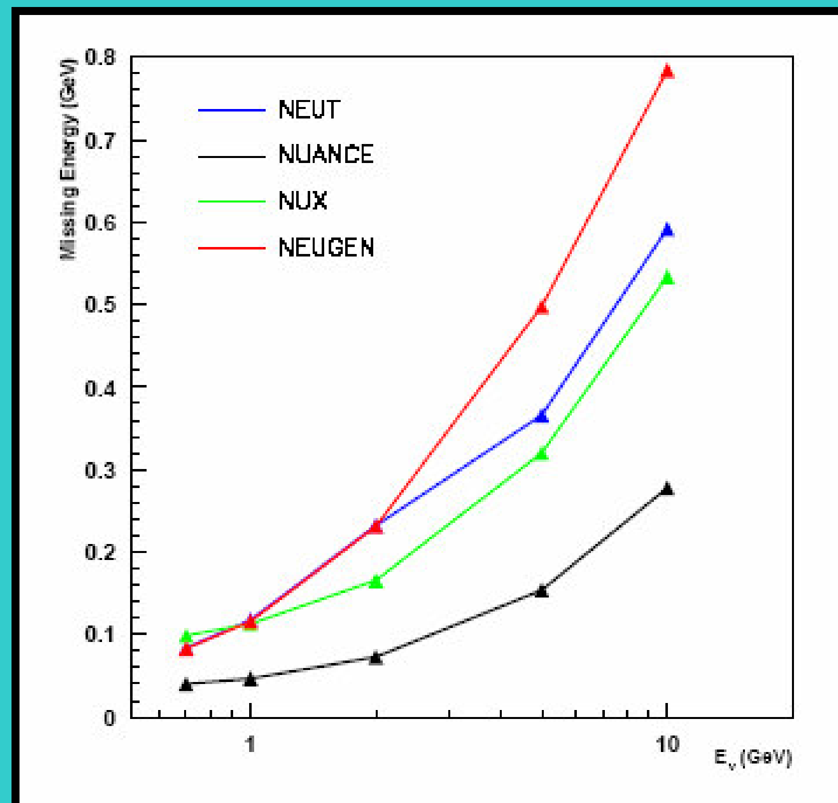
$Log_{10}(x)$

Model Tuning (MINOS)

Well understood: (better than 10%)
- High energy (E>10 GeV) CC cross section (few %)
- location of peak of the beam spectrum
- Quasi-elastic / Δ cross section (>0.1 GeV^2 or so)
- y-distributions at higher energies (E>10 GeV)

Somewhat well known: (~ 10-20%)
- flux normalization and shape
- low energy CC total cross sections
- x-distributions at medium energy

Not very well known:
- non-scaling contribution (QEL/RES) at low Q^2
- hadronic system multiplicities, e/h, and leading pion distributions
- intranuclear rescattering – “missing energy”



Model Tuning (MINOS)

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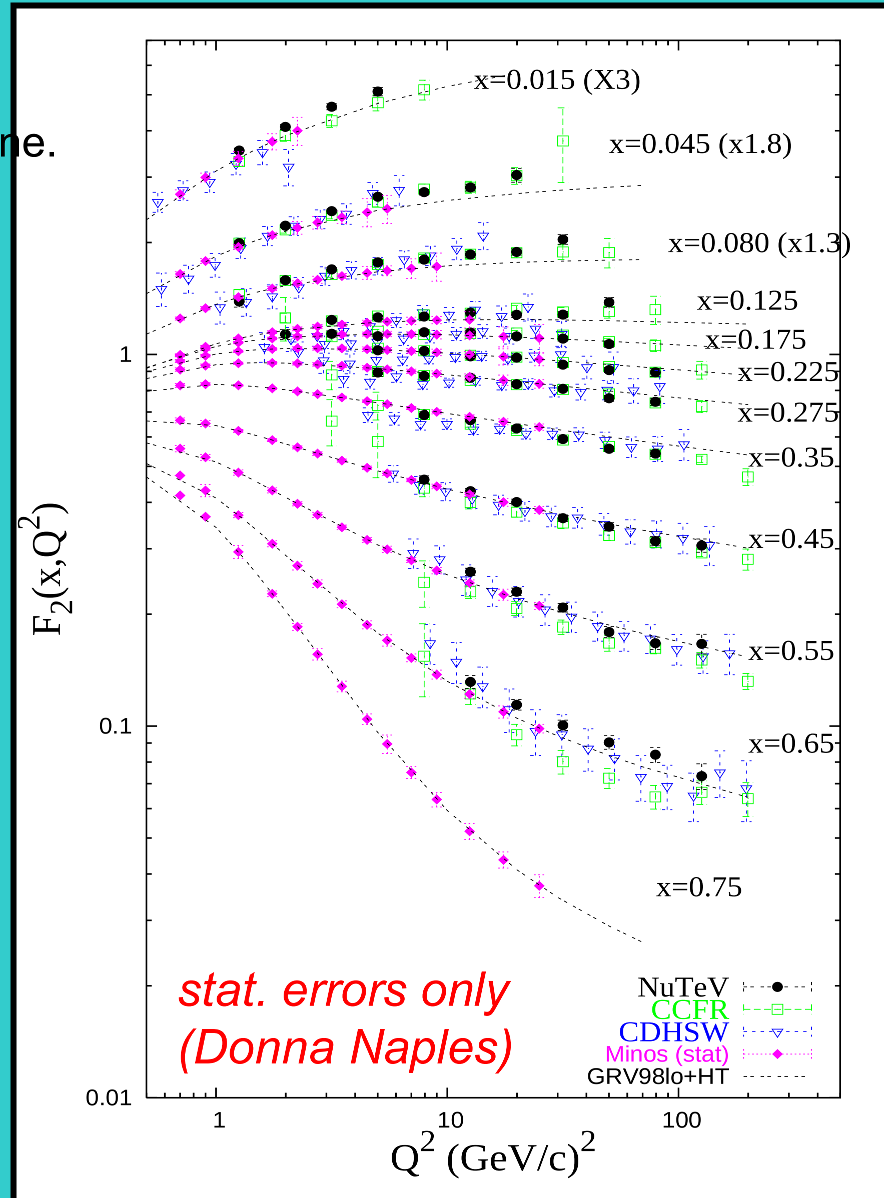
The MINOS near detector will have very high statistics: 78k-257k CC ν_μ events/10^{20} POT/ton depending on the beam tune.

Challenge comes in having to simultaneously tune beam and interaction physics models. By the end of MINOS we expect improved knowledge on the beam from MIPP and on cross sections from Minerva (see J. Morfin talk tomorrow).

General approaches:
“bottoms-up” – identify areas of disagreement and try to identify and improve models

“top-down” – simply parametrize differences in the measured distributions.

In the middle are “physics-based” parametrizations, for example the Bureas-Gaemers iron PDF fits used by NuTeV. (Donna Naples, U. Pittsburgh).



Conclusions

1. Correct modeling of ν-A cross sections over a broad range in kinematics and A important for current and future experiments.

2. Additional contributions related to hadronization and modeling of intranuclear cascade.

3. Building a decent simulation and tuning to experimental data requires close communication between experimentalists and theorists, as well as experimentalists and experimentalists.