What do Monte Carlos Need?

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Jefferson Lab Neutrino Workshop
May 4-5,2006

Outline

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- History
- The uses of a Monte Carlo
- Getting better models (physics)
- Getting better models into Monte Carlos

Editorial disclaimer:

my generator comments are based primarily on my experience with the NEUGEN and GENIE event generators.

In addition the physics topics I emphasize will have a bias towards questions of importance for the MINOS experiment.

History

Pre-2001 (K2K, miniBoone, NuINT) a causal observer might be excused for thinking that low energy neutrino interactions were a well understood topic.

Bubble chamber experiments successfully studied low energy phenomena with modest statistics:

Extraction of dipole $F_A(Q^2)$ with M_A=1.032 +- 0.036 GeV/c^2

Measurements of Δ production

Observation of coherent production

A time of blissful ignorance…*The Rein-Sehgal model is decades old and all simulations use it. It must be right!*

The resurgence of interest sparked by neutrino oscillation experiments has led to new measurements, new surprises, and new challenges.

MINOS - a principal beneficiary!

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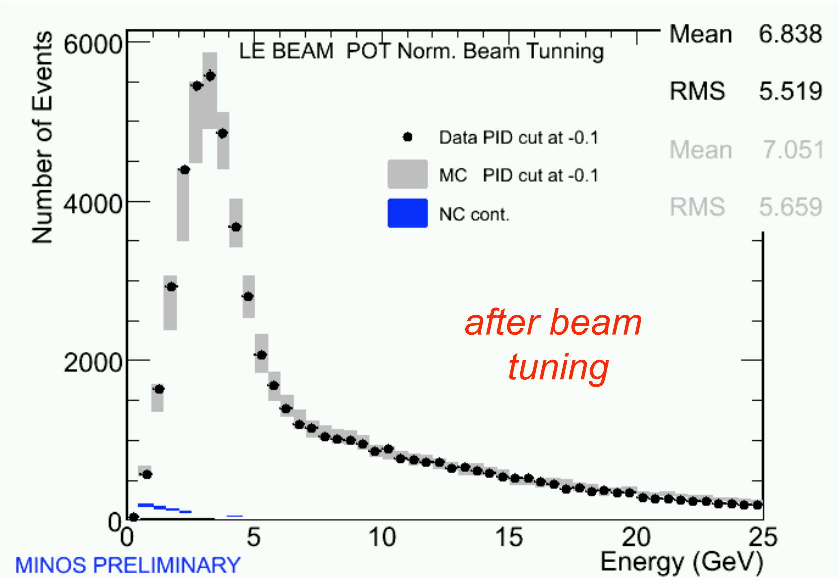
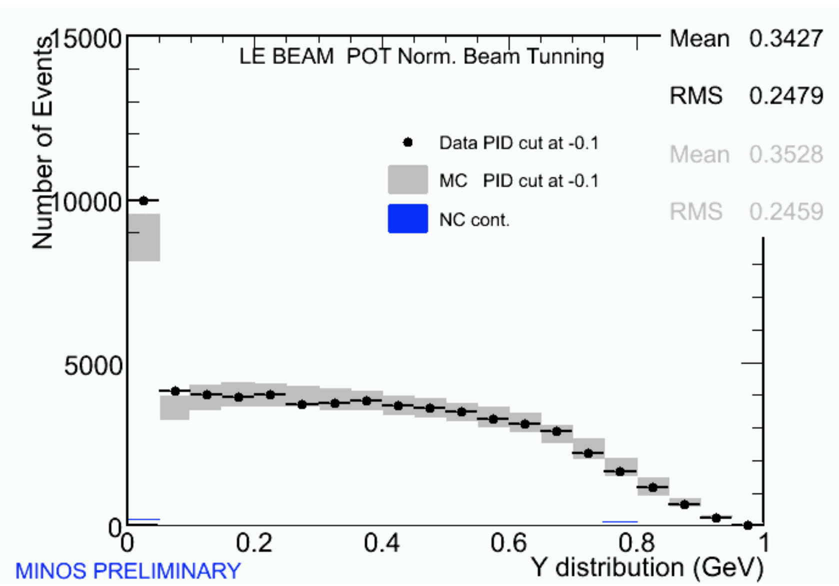




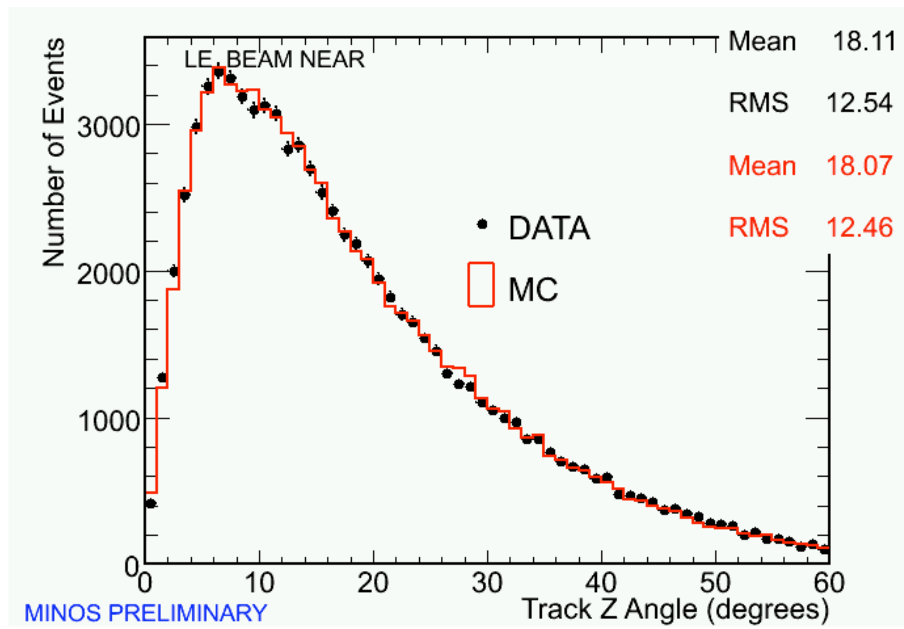
Comparisons to Electron Scattering Data: S. Wood NuINT 01,02,04, M. Sakuda NuINT01, E. Hawker NuINT04

Cross Section Modeling - A. Bodek, U. Yang, NuINT01,02,04

Formation Zones - Ammosov NuINT01, D. Autiero NuINT04

Pion Absorption in Nuclei - R. Ransome NuINT04

Neutrino Scattering Database - M. Whalley NuINT04



Consumers of Simulations

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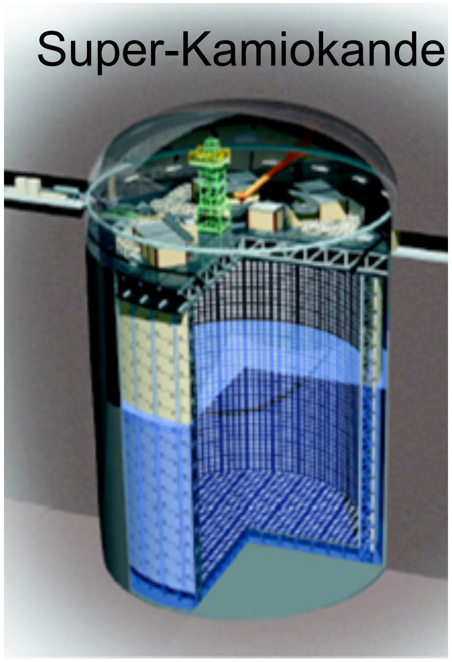
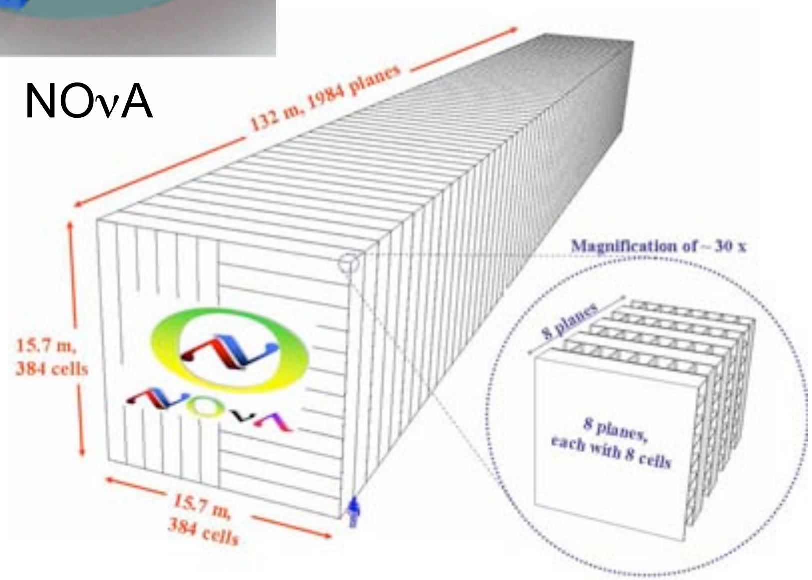
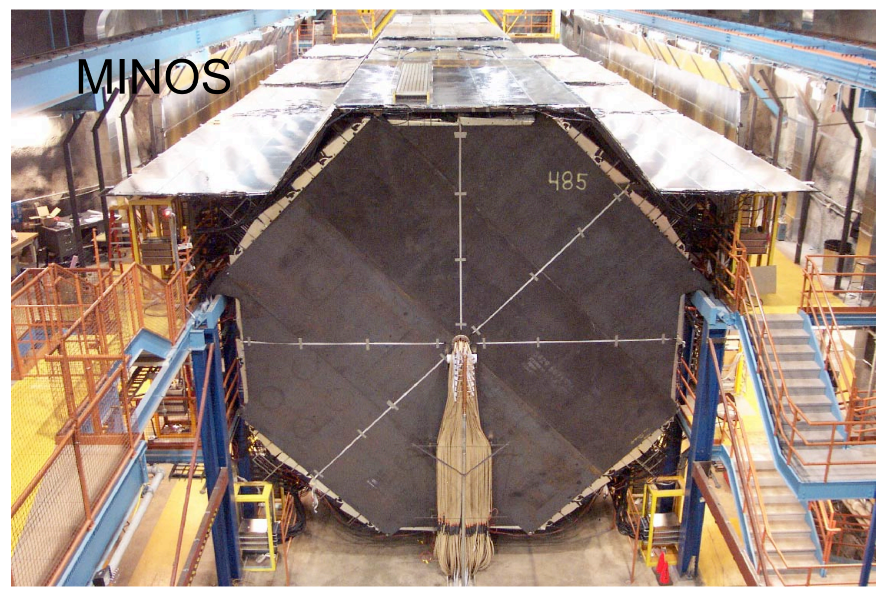


Current/Future long baseline experiments;

Expt.	Dates	E_ν (GeV)	Mass (kt)
K2K	1998-2005	1	50
MINOS	2005+	~ 3-10	5.4
T2K	2008+	0.7	50
NOνA	?	2.2	20





Monte Carlos

Monte Carlo simulations play a number of important roles in neutrino experiment.

1. Detector design
   - technology choices
   - signal/background seperation
2. Analysis
   - determing efficiencies, purities, acceptance corrections
   - defining the null hypothesis
   - Basis for parameter fitting to new physics hypotheses
3. Systematics evaluations
   - studying the variation in the result with respect to a change in an aspect of the simulations.

Accurate simulations are an ingredient in getting the right detector, the right answer, and the right errors!

Monte Carlo Realities

The production of new Monte Carlo event samples for an experiment is a labor and CPU-intensive activity.

Typically consumes several months of real time.

Validation of Monte Carlos to external data is crucial.

Being able to handle changes to the underlying physics models via re-weighting event samples is useful for reducing the time required for many tasks.

i.e. Use model A to generate a MC sample and want to switch to model B, apply to every event in the sample a weight: $(d^2\sigma/dxdy)_B/(d^2\sigma/dxdy)_A$

neugen3

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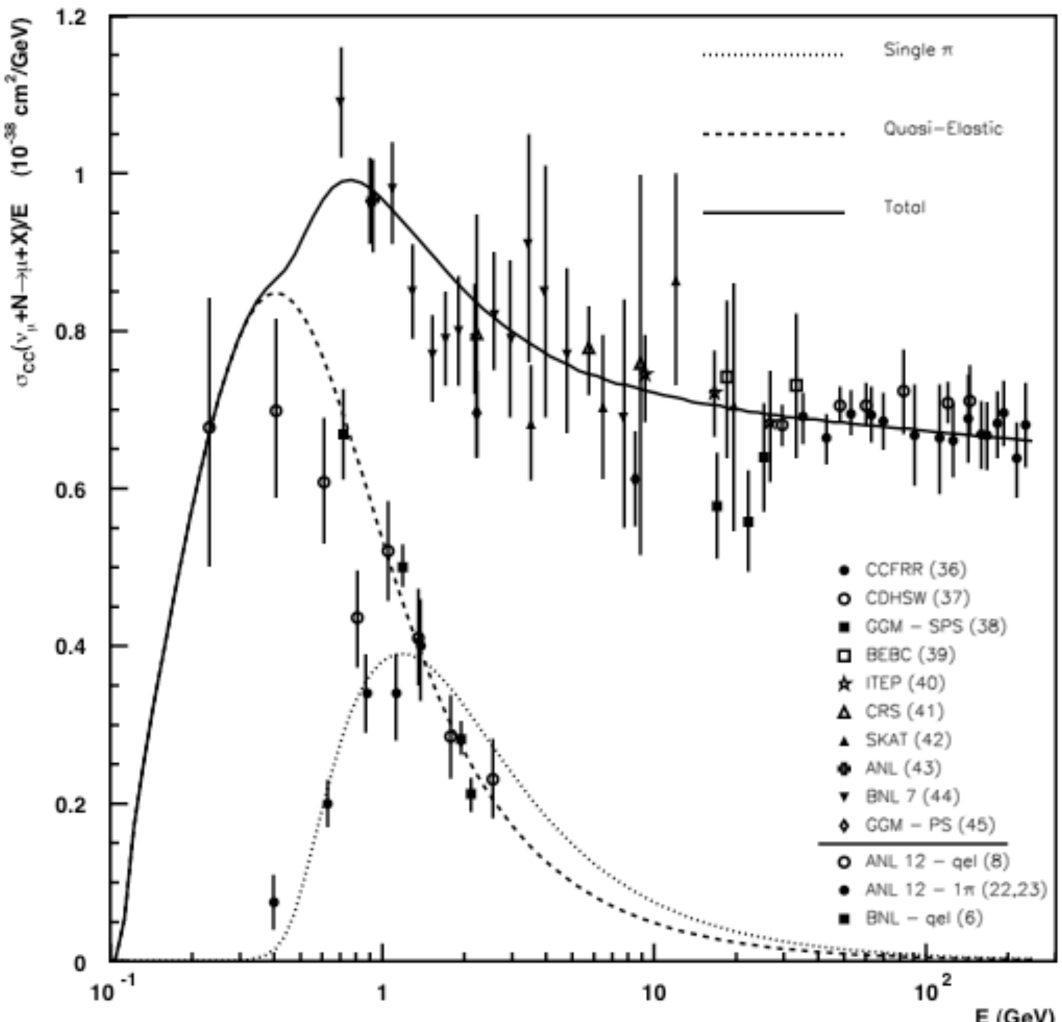
Quasi-Elastic: dipole parametrization of form factors with m_a=1.032 GeV/c^2.

Resonance Production:
Rein-Seghal model for W<1.7 GeV/c^2.
(Annals Phys. **133**: 79, 1981)

DIS: Bodek-Yang modified LO model.
For W<1.7 GeV tuned to electron and neutrino data in the resonance / DIS overlap region.
(Bodek-Yang, Nucl. Phys. Proc. Suppl. **139**: 113-118, 2005 and H. Gallagher, NuINT05 Proceedings)

Coherent Production:
Rein-Seghal (Nucl. Phys. B **223**: 29, 1983)



Nuclear model: Fermi Gas model (A. Bodek, J.L. Ritchie, Phys.Rev.D23:1070,1981). Pauli blocking of QEL scattering and intranuclear rescattering of produced π using the INTRANUKE package (R. Merenyi et al., Phys. Rev. D **45**: 743, 1992).

NuMI Kinematic Coverage

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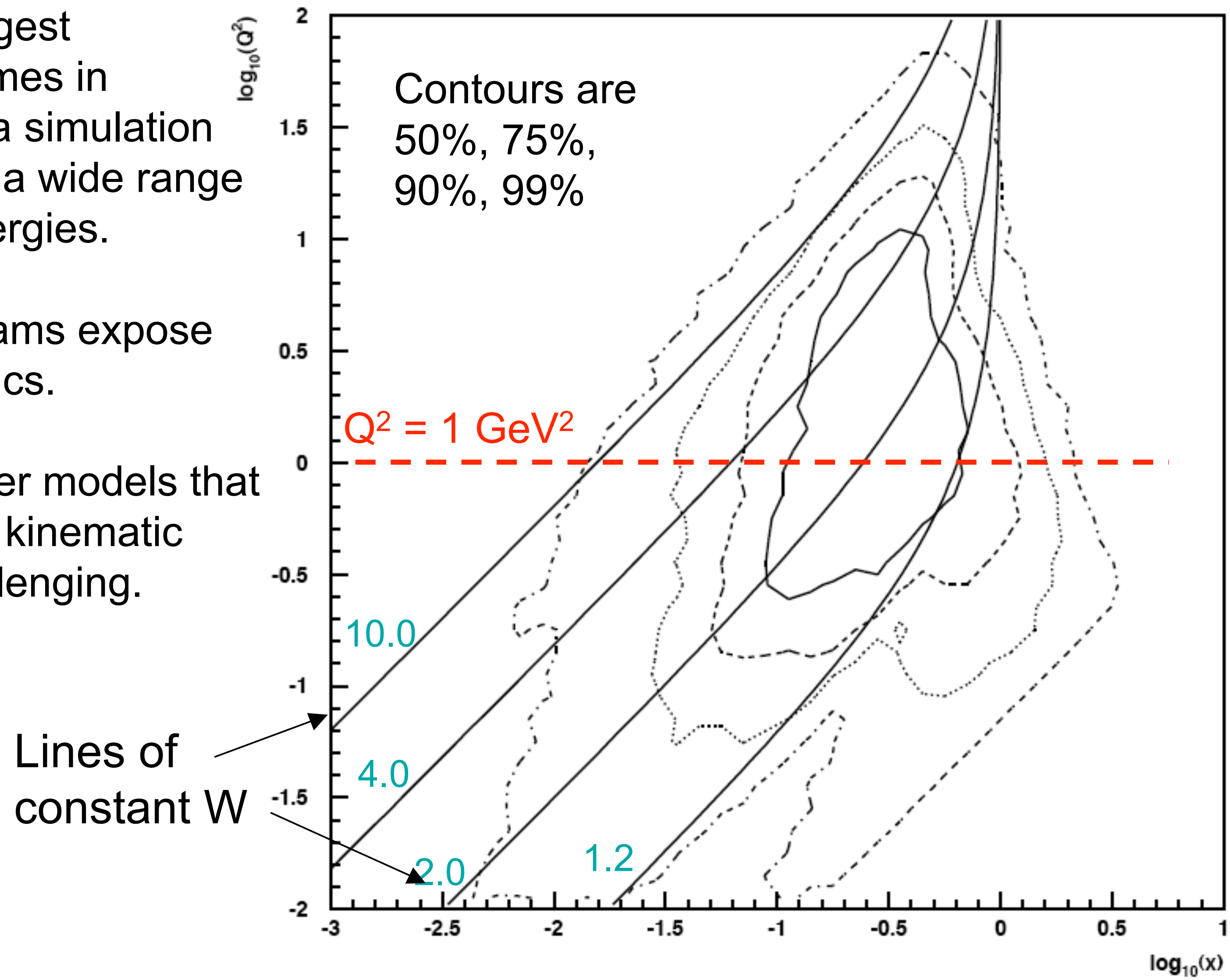
One of the biggest challenges comes in trying to build a simulation that can cover a wide range of neutrino energies.

Wide band beams expose broad kinematics.

Piecing together models that cover different kinematic regions is challenging.



Low E Beam Kinematics

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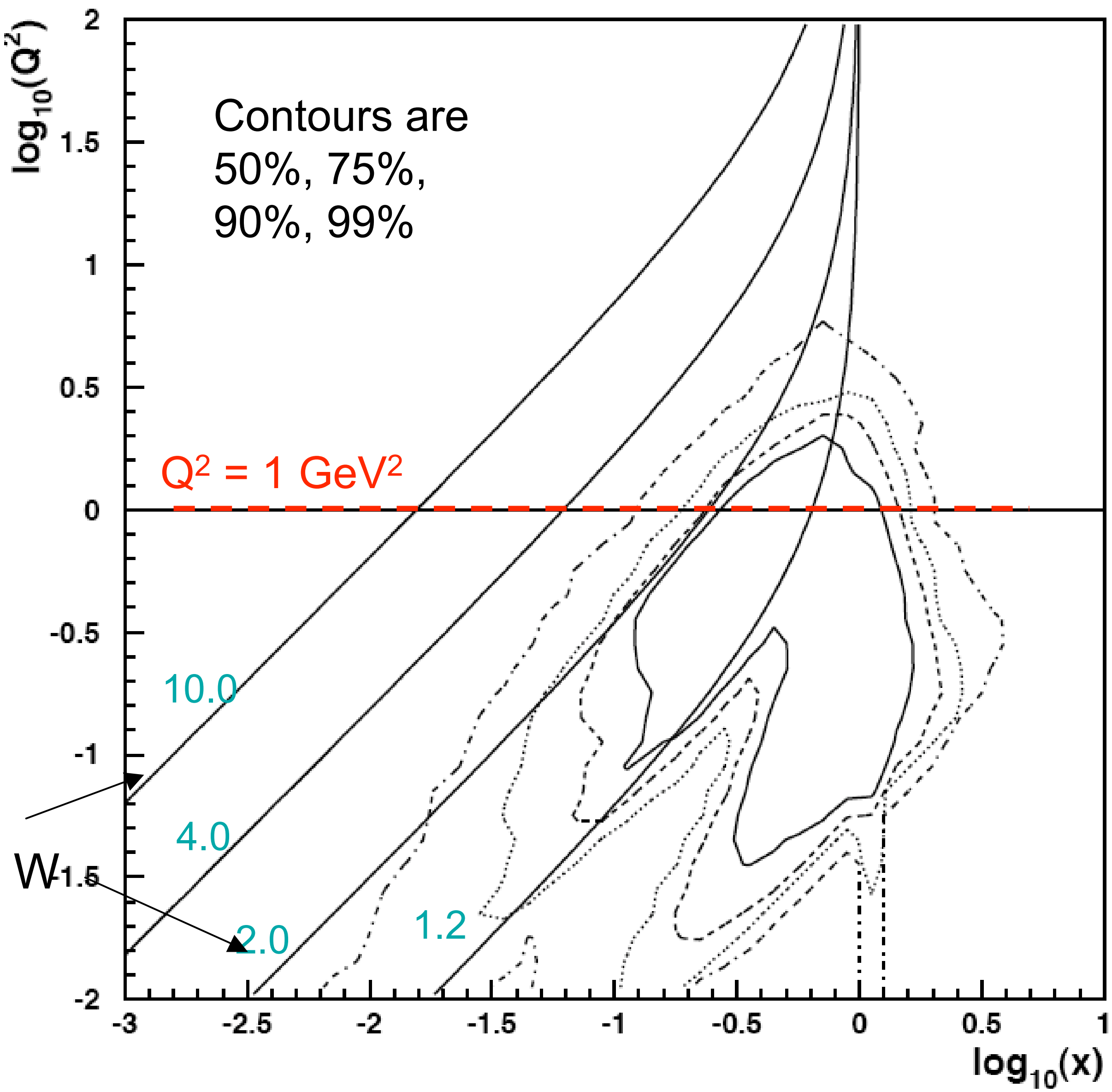
Low energy beams

Kinematic exposure from a 4-vector calculation using a cartoon miniBoone flux.

(a guess, for illustrative purposes only)

Quasi-elastic, Δ, gap between them of primary importance, everything is low Q^2!

Lines of constant W



Free nucleon cross sections

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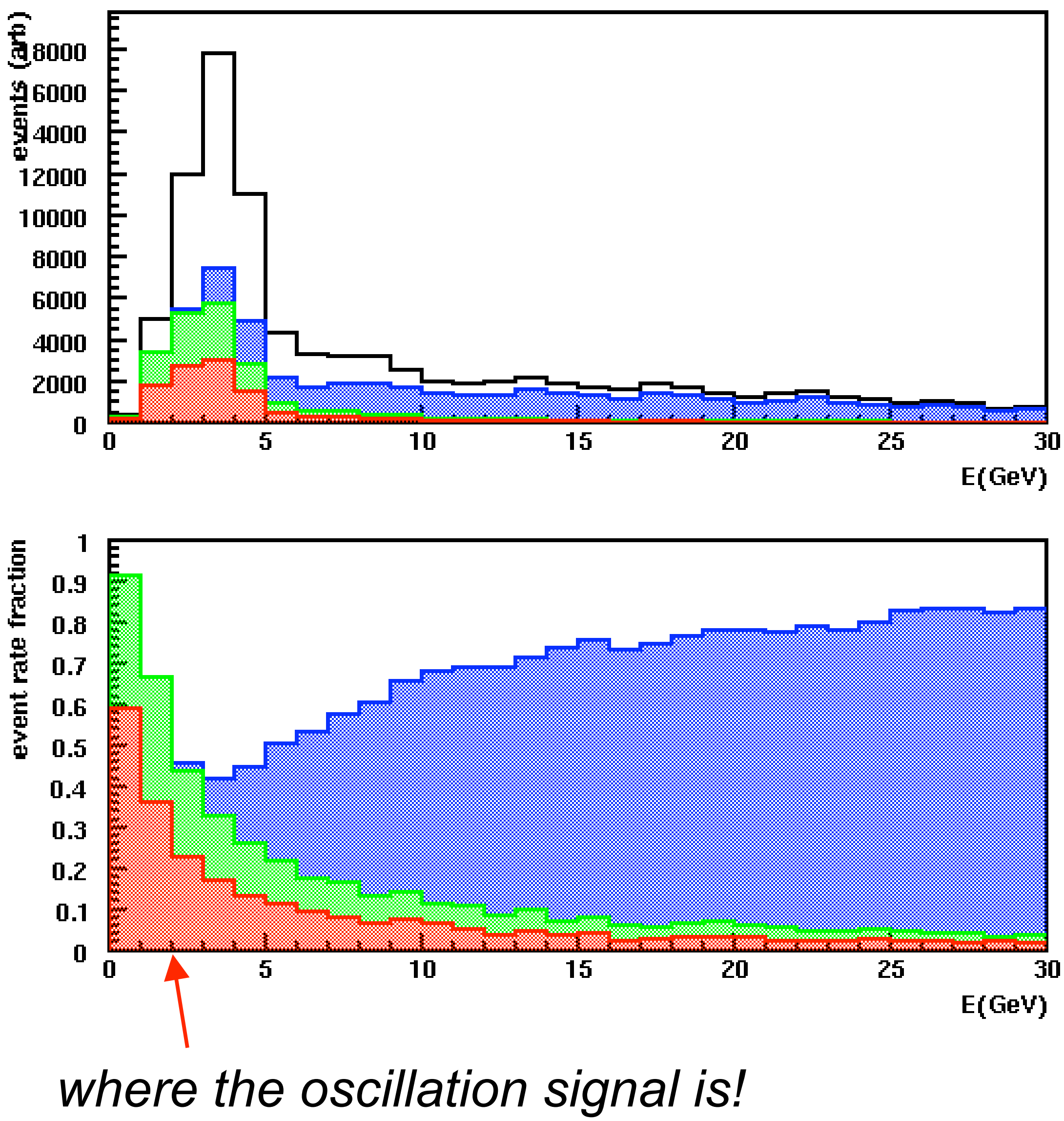
Previous experiments focused on 3 regimes:

Quasi-elastic scattering (red)
Delta Production (green)
"safe DIS": $Q^2 > 1\ GeV^2$,
$W > 2$ GeV (blue)

Large fraction of events in our peak region are in the "mystery" region in terms of detailed knowledge of the kinematics.

Free nucleon models:

- DIS low Q^2 modeling
- resonance modeling
- DIS / resonance transition region



Intranuclear Rescattering

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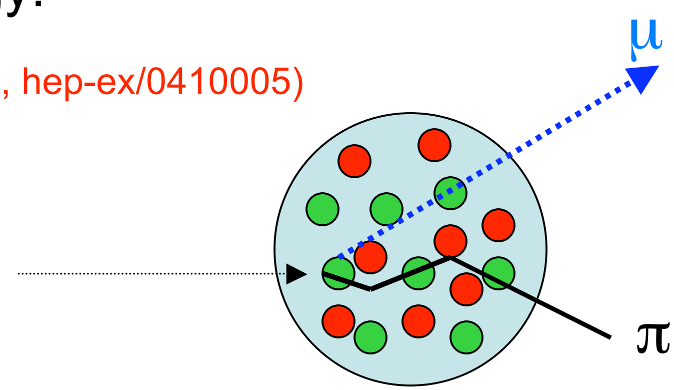
Visible Energy in Calorimeter is NOT ν energy!

π absorption, rescattering
final state rest mass
nuclear binding energies

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



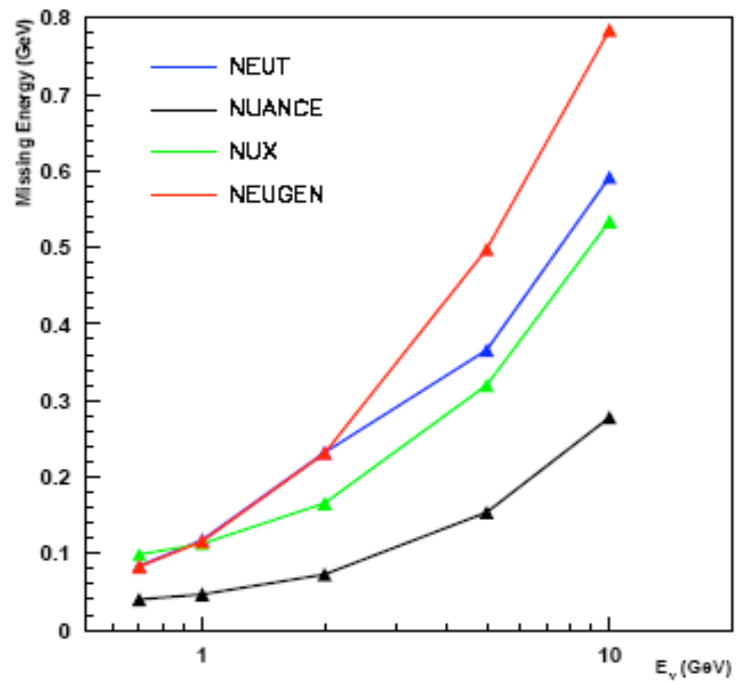
$$E_\nu = E_\mu + E_{had}(vis) + E_{miss}$$

"Missing energy" determined from Monte Carlo.
Very dependent on detector thresholds.

How to estimate the uncertainty in this aspect of the simulation?

Understanding the relevance of external data.

In MINOS we have been very fortunate in that a nuclear experimentalist, ***Steve Dytman*** is leading the task of improving this piece.



Intranuclear Rescattering

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Tuning parameters in cascade MC to data.

If a proton rescatters on the way out of the nucleus what happens to that energy? (additional particle production at elastic kinematics in CLAS?)

How does charge exchange modify the amount of electromagnetic energy in the hadronic shower? (CLAS - Steve Manly)

Single pion charge ratio as a function of A and (W,Q^2)?

$$\frac{(dN/dW(1\pi^0)/dN/dW(1\pi^{+/-}))_A}{(dN/dW(1\pi^0)/dN/dW(1\pi^{+/-}))_D}$$

How good is our simulation of formation zone effects (HERMES expert?).

Simulation of nuclear evaporation - de-excitation?

S. Manly is leading an analysis of CLAS data
HERMES / formation zone expert?

INTRANUKE Tuning

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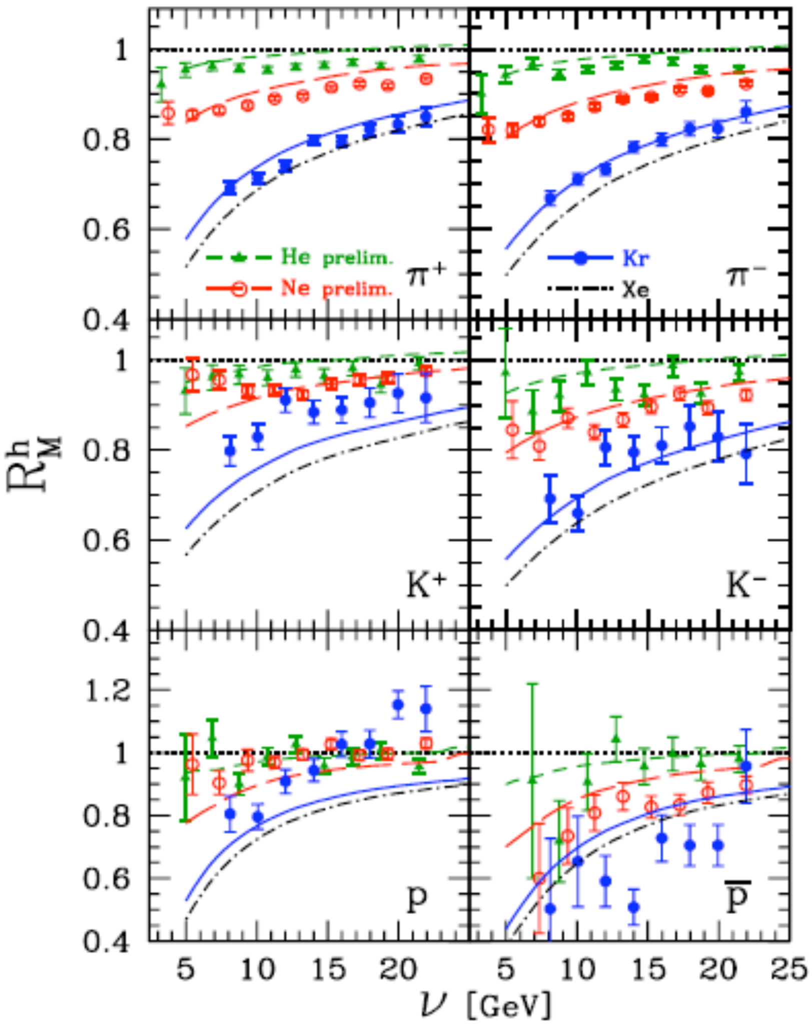
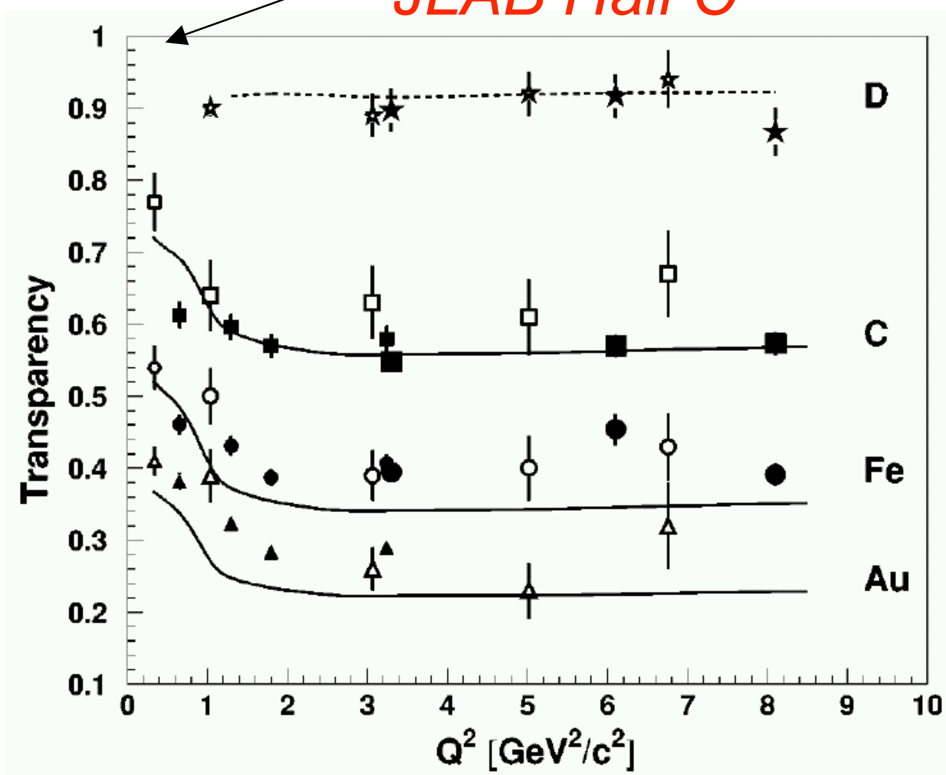


HERMES hep-ph/0502072

$$R_M^h(z) = \frac{1}{N_A^{DIS}} \frac{dN_A^h(z)}{dz} \Big/ \frac{1}{N_D^{DIS}} \frac{dN_D^h(z)}{dz}$$

Proton transparency
JLAB Hall C



Things That Go Bump in the Night

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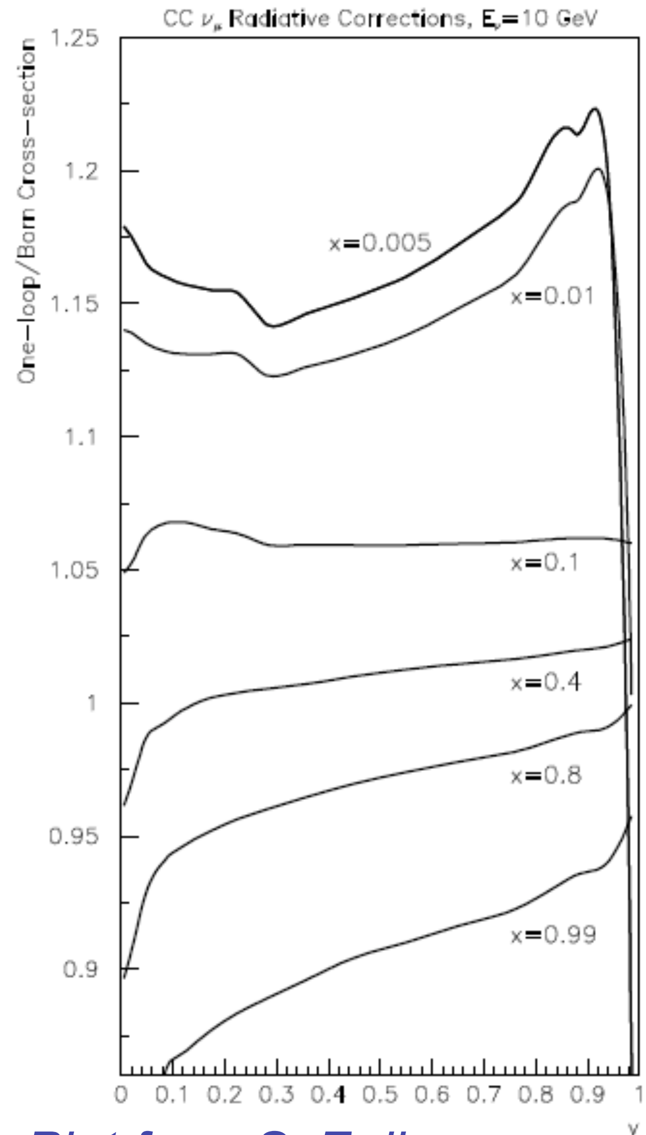
Radiative Corrections

Most ν experiments use venerable code by Bardin and Dokuchaeva (JINR-E2-86-260) which is calculated for DIS scattering.

Appropriateness of this calculation (or others) to DIS scattering at these much lower energies?

Am not aware of neutrino radiative correction calculations for exclusive channel processes?

Are radiative corrections for neutrino quasi-elastic scattering negligible?



Plot from S. Zeller

Hadronization Models

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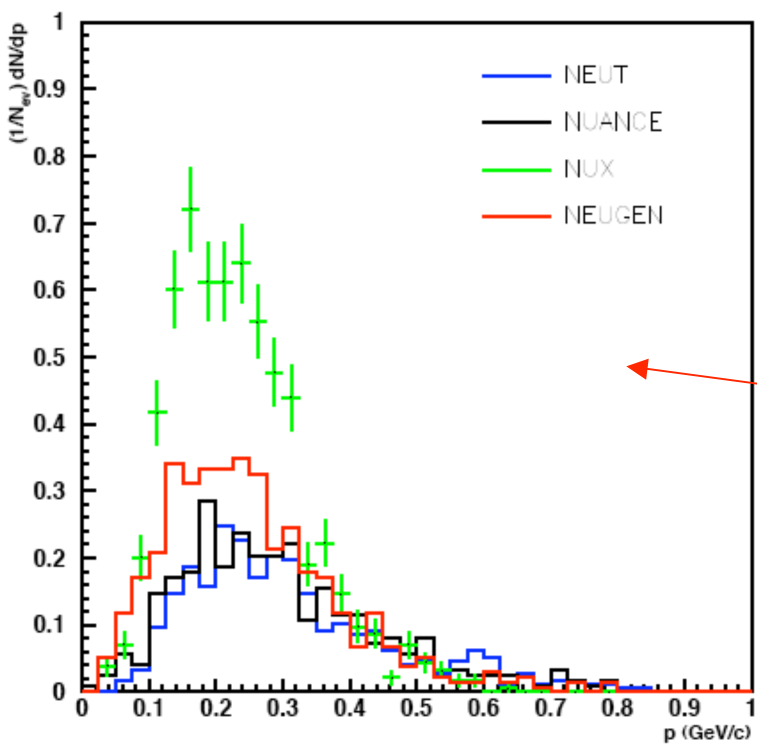
How to determine the hadronic final state?

- Exclusive channel / isospin CG coefficients
- Empirical models based on e.g. KNO scaling
- Independent fragmentation models (FF)
- Standard higher energy models (JETSET)

Recent progress by the Wroclaw group presented at NuINT05.

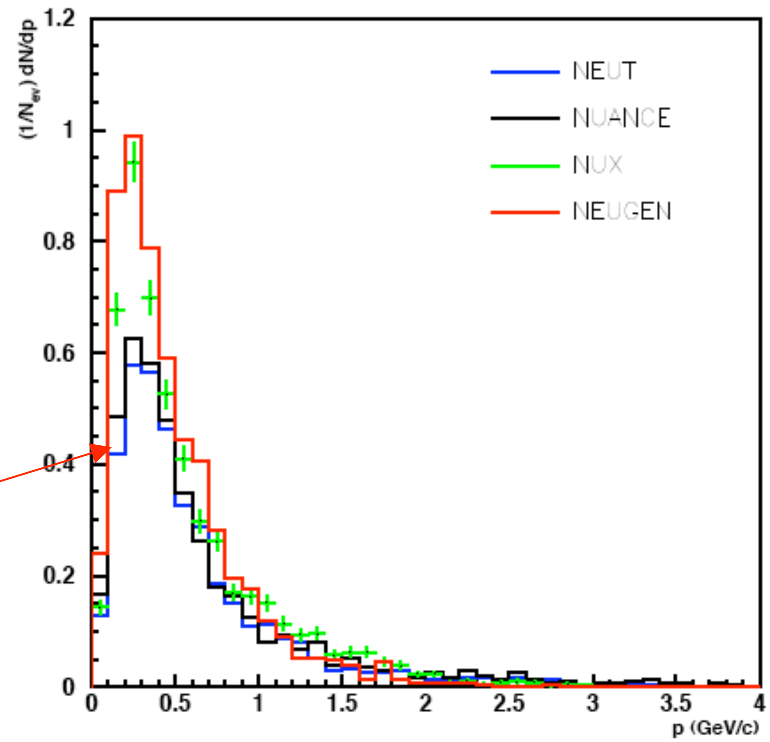


Inclusive π^0 spectrum for antineutrino-proton scattering.

1 GeV

5 GeV

H. Gallagher, NuINT04



Monte Carlo Improvements

The theory has improved dramatically in the past five years and the simulations have yet to catch up.

I think a principal goal should be getting to a point where new models can be incorporated into simulations and evaluated on the timescale of months not years.

Encourage collaboration on software and physics development through, for instance, the GENIE collaboration.

The Monte Carlo World

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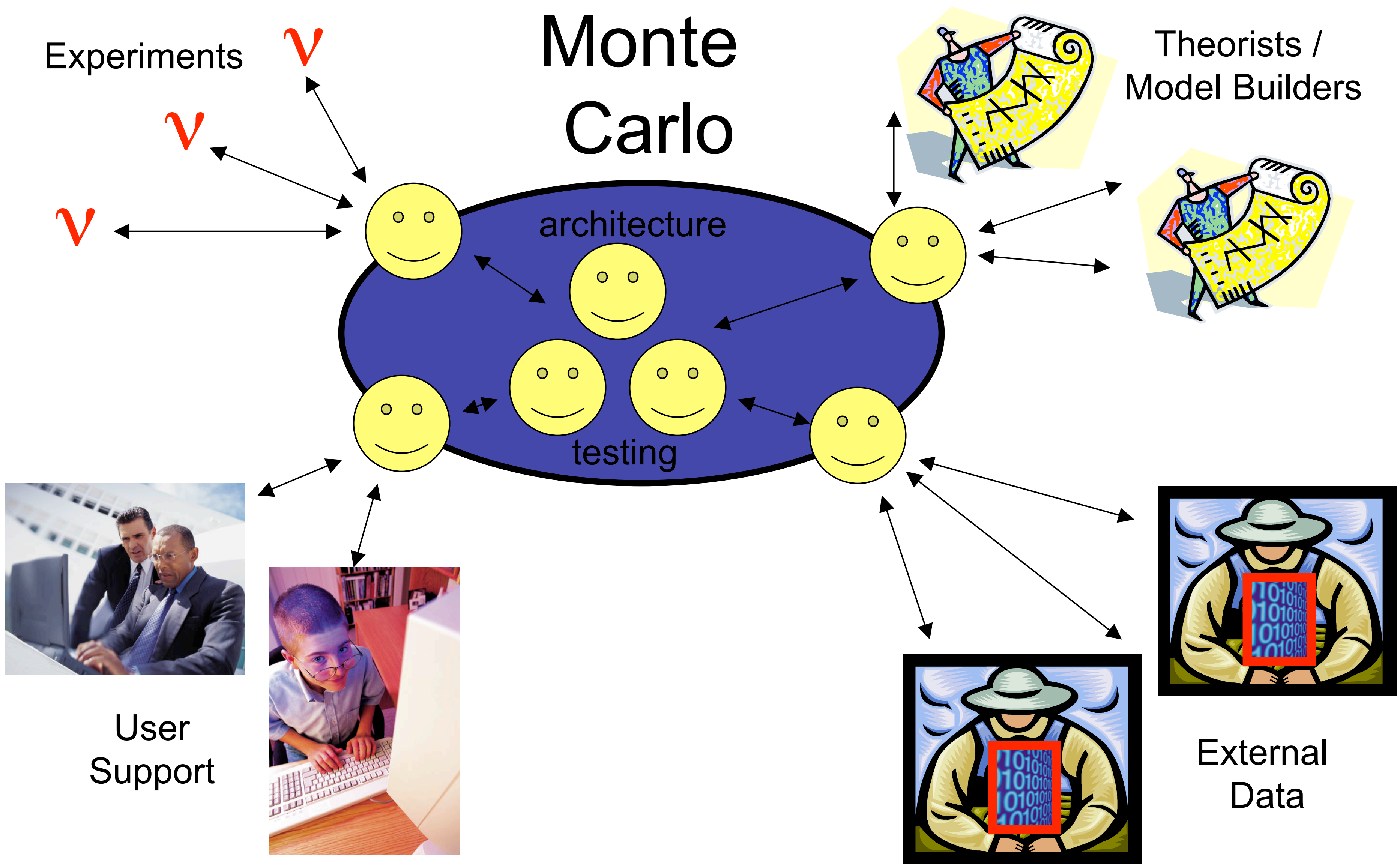

Speeding Model Adoption

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Some suggestions from my vantage point:

1) Provide code. Models now are more complicated than in the past and coding from papers is prone to error.
2) Well-defined MC interfaces for different kinds of calculations (form factors, structure functions) and code interfaces.
3) Clearly state range of validity of models.
4) Nuclear calculations - deuterium up to lead.
5) For nucleon cross section calculations, all combinations of neutrino/anti-neutrino, proton/neutron, and CC/NC.
6) For cross section calculations, provide predictions for analogous electron scattering processes where appropriate.
7) Attempt to give an estimate of the uncertainty on the model and the sources (theoretical assumptions, uncertainties in model parameters).
8) Providing guidance on how to combine model with other aspects of the simulation.

Making sure that an expert's ***known unknowns*** don't become an experiments ***unknown unknowns*****.**

Conclusions

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Adoption of much of the recent work described here could lead to major improvements in the accuracy of neutrino-nucleus simulations for numerous experiments.

- Low Q^2 DIS modeling
- Handling the resonance-DIS transition region
- nuclear modifications to cross sections, particularly at low Q^2
- Constraining intranuclear rescattering models with electron scattering data.
- Free nucleon hadronization
- Radiative corrections

Continued dialog on implementation, in particular combining models will be important.

Backup Slides

Outline

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1. Historical - topics of current controversy… QEL, coherent
2. MINOS benefits from work: Rein-Sehgal and Ransome model
   1. MINOS angular distribution, y-distribution
3. Beams/detectors: T2K / MINOS / NoVA
   1. kinematic coverage of each, materials of each
4. What MCs are used for and when
5. Calculations
   1. nuclei, NC/CC, probes, include electron scattering
   2. Estimates or statements about uncertainties
6. Overlap of kinematic region with calculations / assumptions
7. Specific elements
   1. Radiative corrections
   2. External data experts: CLAS and HERMES
   3. Intranuclear rescattering questions
   4. Resonance models / nuclear effects in kinematics
   5. Continued focus on single pion production mechanisms - coherent
   6. hadronization models
   7. Nuclear modifications to qel, D at low Q2
   8. Further insights on resonance / DIS overlap region
8. GENIE and global collaboration

MINOS Tuning Plans

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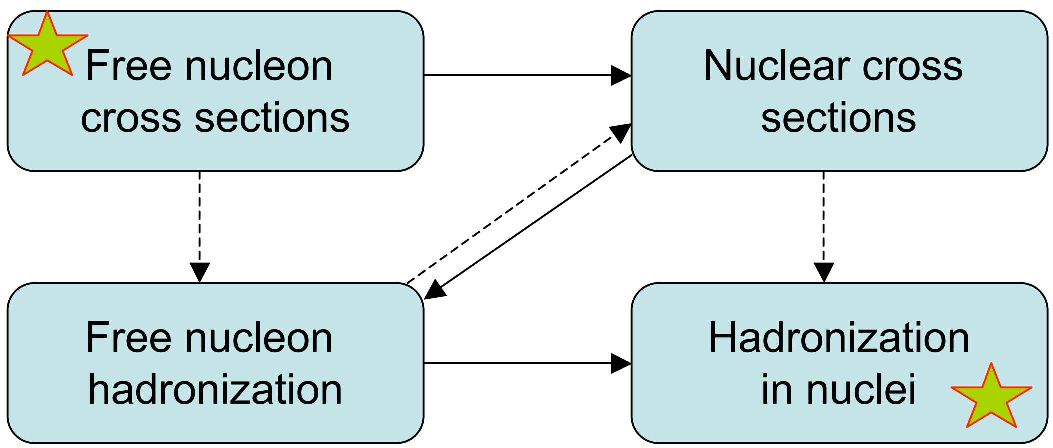
Identify the interaction model pieces most important for MINOS.

Identify the "best" models for describing the relevant physics.

Identify the relevant external data for tuning / model testing.

Produce a tuned MC and determine model uncertainties.

The plan:



★ = most important

Also an important operational distinction between the top and bottom rows, cross section model changes can be handled by reweighting existing MC events. Big advantage.

F_2

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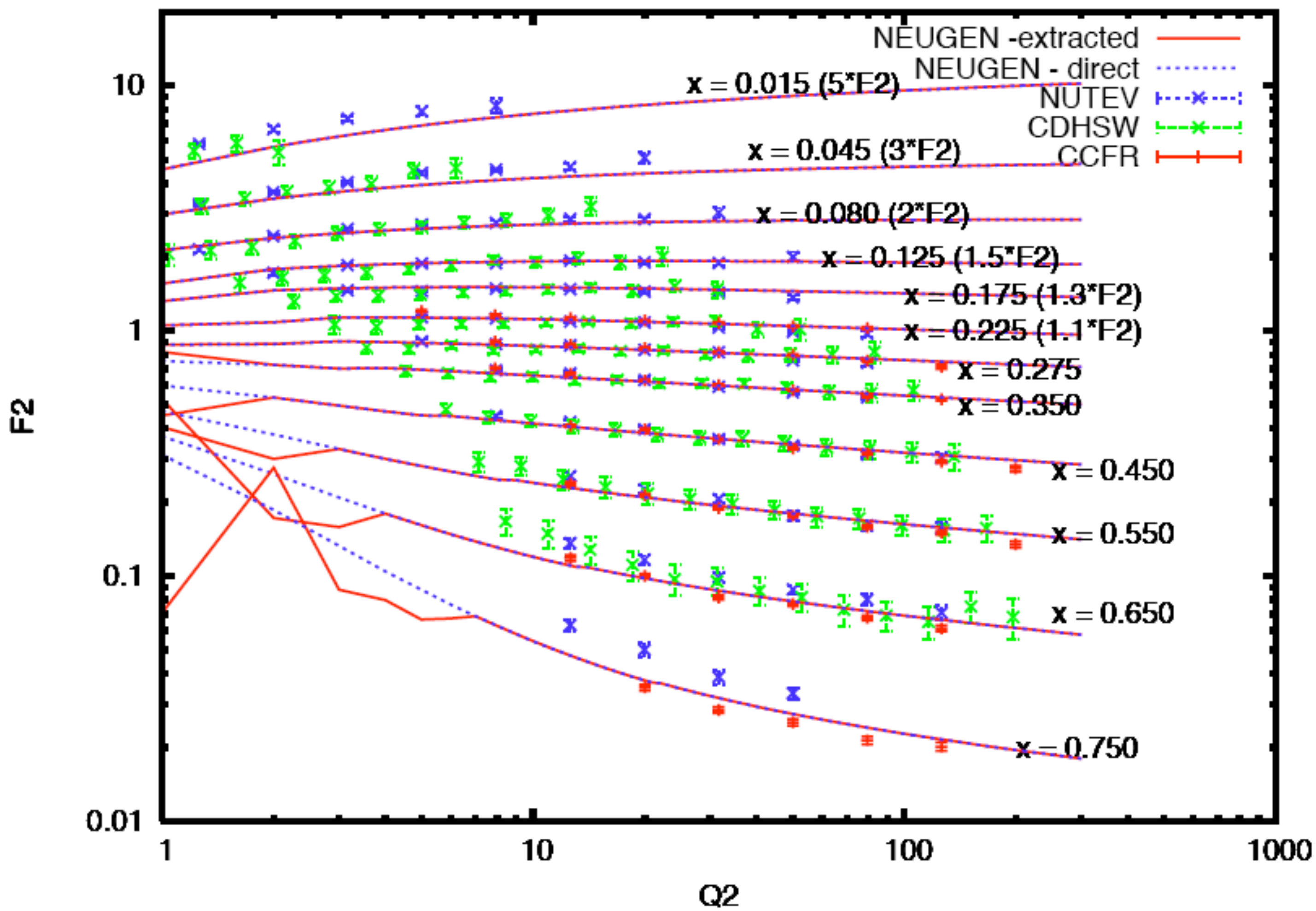

D. Bhattacharya, D. Naples

xF_3

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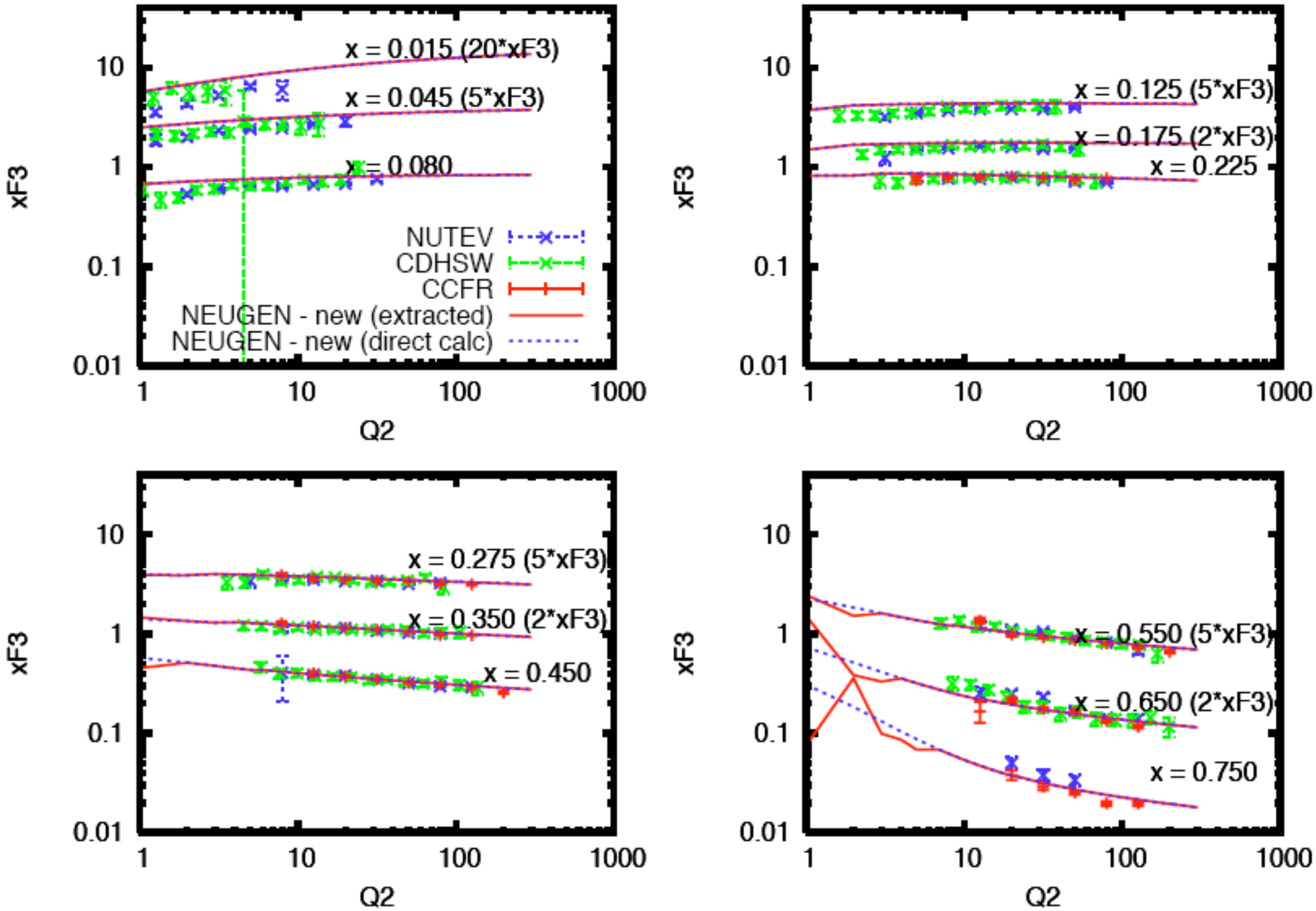
D. Bhattacharya, D. Naples



DIS/Resonance Overlap

Several approaches have been proposed:

Resonance model up to a “safe” DIS regime?

- The original Rein-Seghal philosophy.

Use modified QCD model (Bodek-Yang) alone?

- Resonances are washed out by Fermi motion in iron..
- If duality holds, get correct total cross section.

Use an explicit model for the Δ?

- Well measured in both electron and neutrino experiments.
- Dominant inelastic feature for low energy experiments.

Priorities for MINOS

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Top priorities in the DIS/Resonance region:

Get the total cross section right. Important for prediction of energy distributions in the Near Detector. The shape of the cross section in the few-GeV region in particular.

Get the single pion cross sections right, dominant background for ν_e searches.

Getting the Q^2 dependence, y dependence right. Affect acceptance.

Less important: Getting the detailed shape of the inclusive cross section in the resonance region right. Washed out by Fermi Motion.

However… for lower energy studies (MINOS Atmospheric neutrinos, or NOvA), in which the Δ plays a prominent role, include it explicitly.

Basic Options - Rein-Seghal

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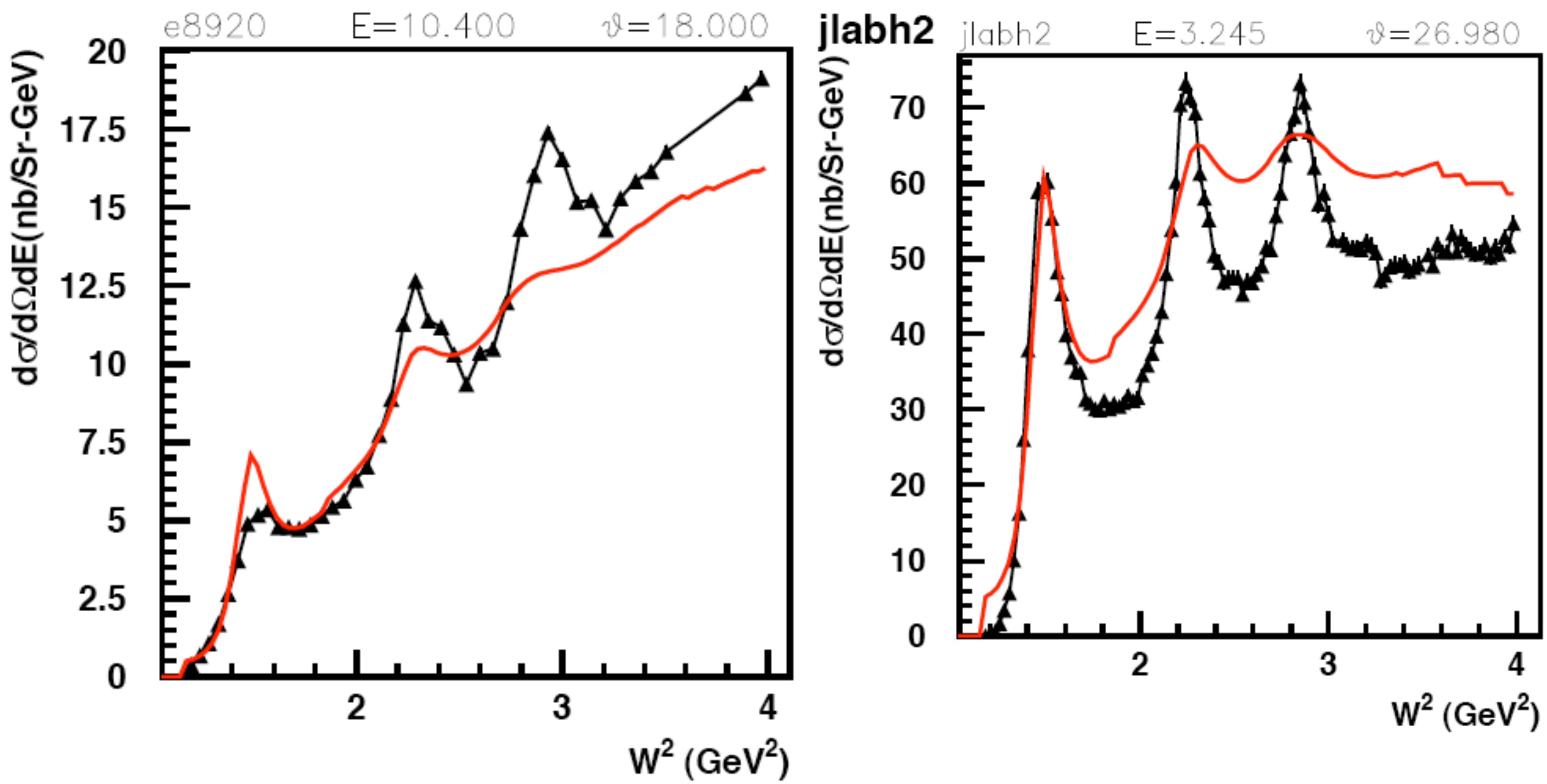

incoherent sum of resonances in Rein-Seghal implementation.
Q2 dependence not modified according to Paschos, Sakuda et al hep-ph/0408185

NEUGEN tuning model

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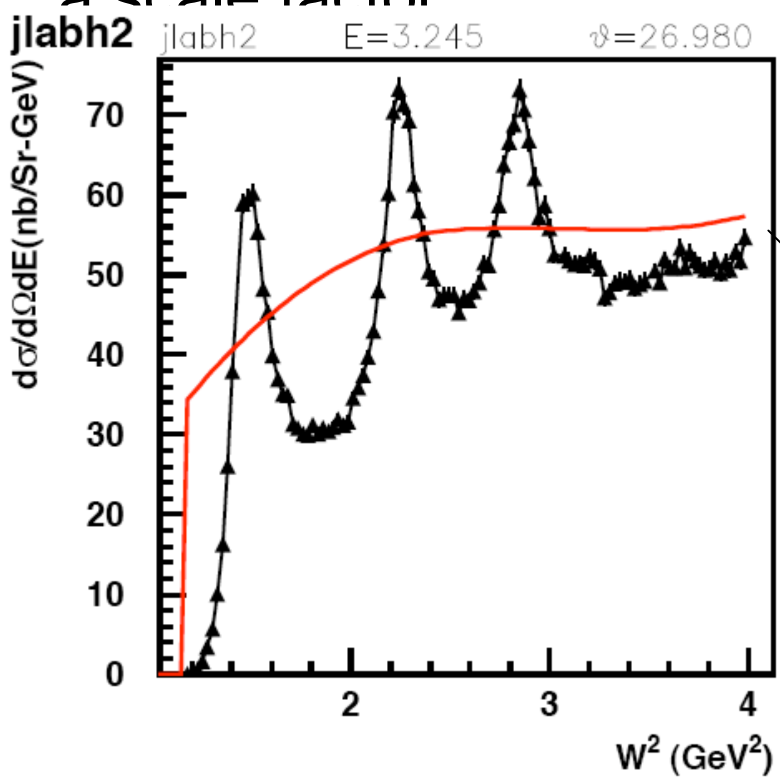
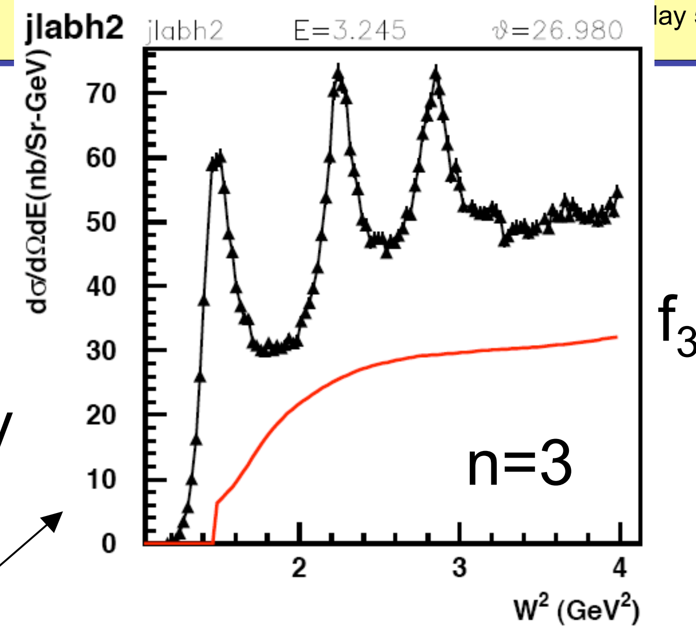
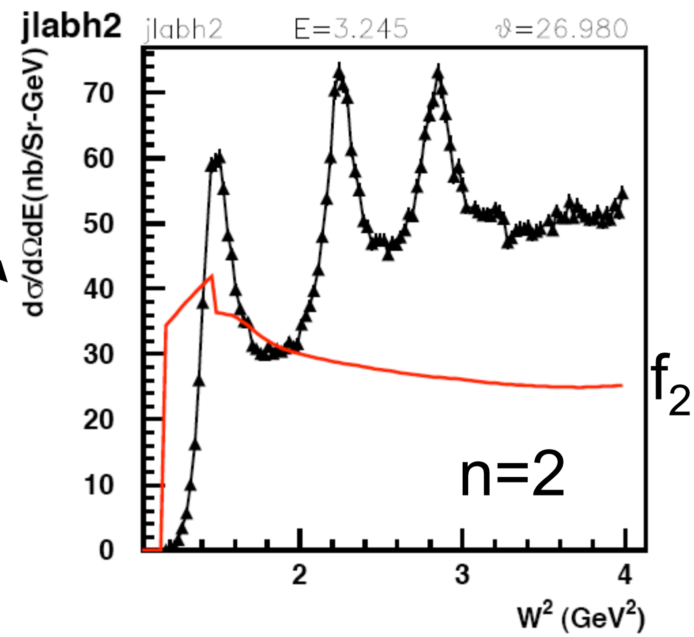
Break the DIS inclusive cross section up into multiplicity contributions and adjust each by a scale factor







Intranuclear Rescattering Model

Figuring out how to tune these models is something of a challenge and can be quite experiment specific.

pion scattering comparisons (NUANCE/miniBoone)
neutrino analyses (NOMAD / CHORUS, ANL-BEBC)
proton transparency - JLAB HALL C
dedicated analyses of CLAS data (Manly/Bradford)
formation zone comparisons (HERMES)

Conclusions

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For MINOS simulations we have retuned the generator using the Bodek-Yang model and compared with existing SF data. More data (NOMAD and Jupiter) would be very valuable.

In the resonance region, tuning is based on comparisons to electron scattering data, neutrino single pion data, and duality constraints. Other multiple pion channels and differential distributions are then used for checking model consistency.

Future work will involve re-tuning the hadronization model.

There are a number of areas where MINOS simulations could benefit from improved models!

Example: Low Q^2 suppression

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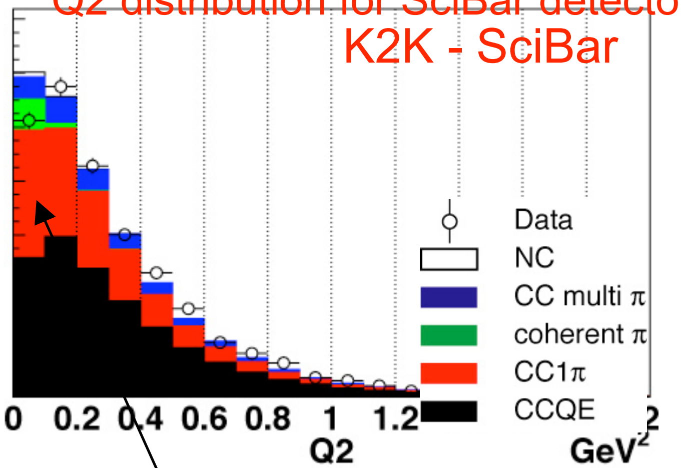
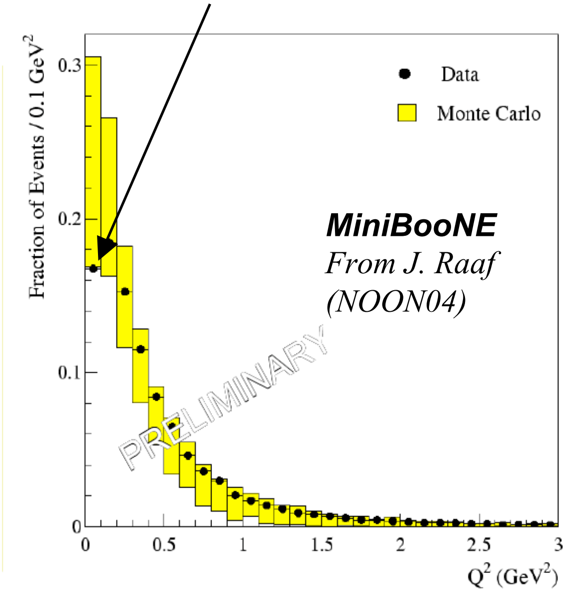
Q2 distribution for SciBar detector



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).