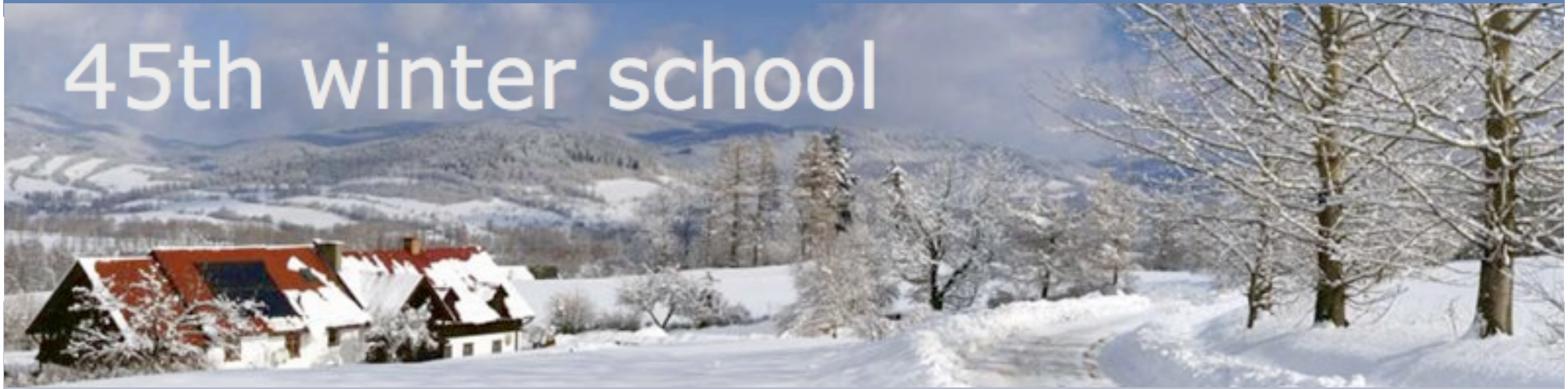
Event Generator Validation and Systematic Error Evaluation for Oscillation Experiments

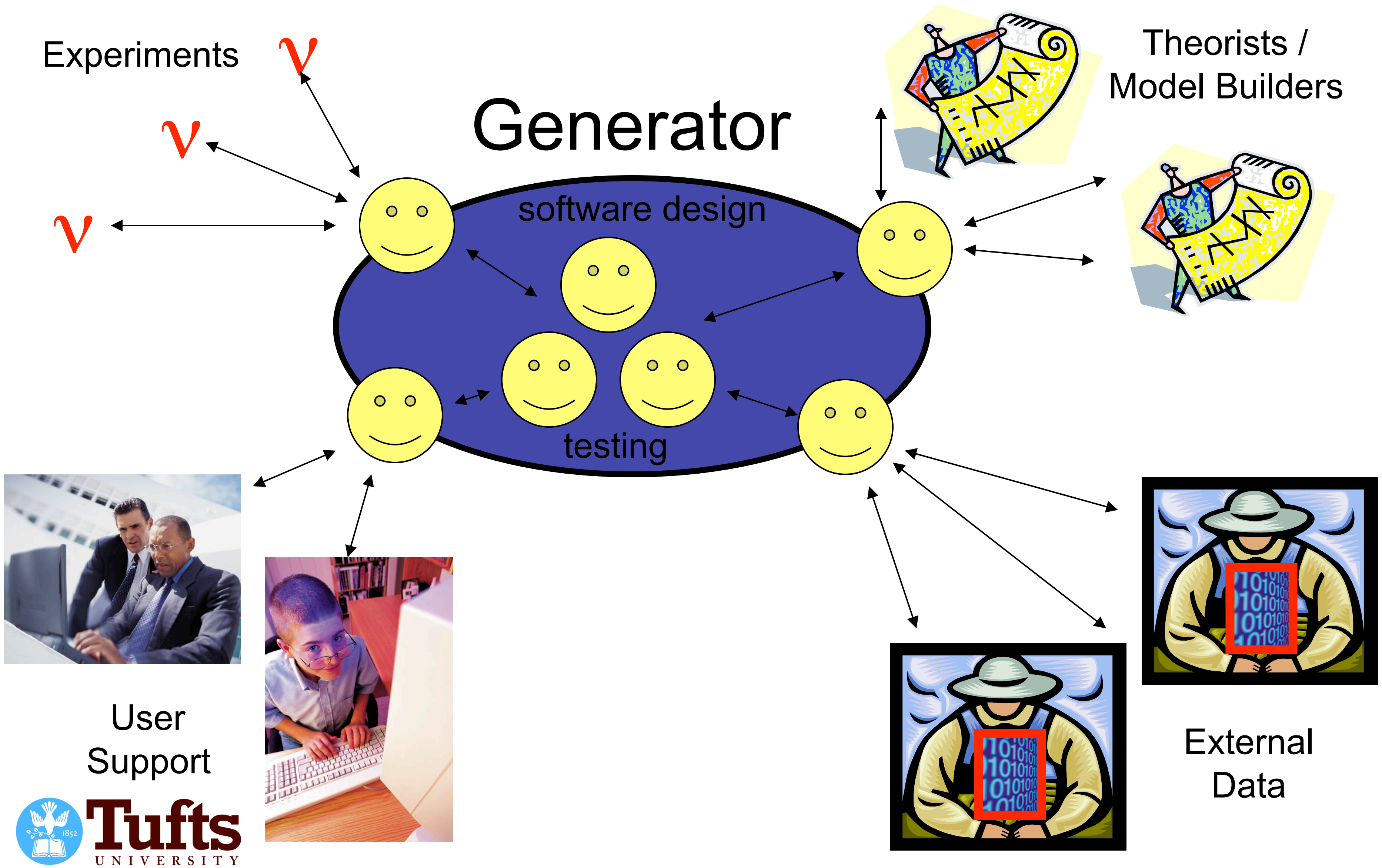


Hugh Gallagher, Tufts University
45th Karpacz School
Lądek-Zdrój, Poland
Feb. 10, 2009

Outline

1) Introduction: Models and Event Generators in HEP
2) Physics Models Overview
3) MINOS Physics analyses and simulations uncertainty
    - Shower energy scale for CC events
    - Hadronic system modeling for ν_e appearance
4) Evaluation of Systematic errors for MINOS
5) Conclusions

Physics Simulations



Experiments ν ν ν

Generator

software design

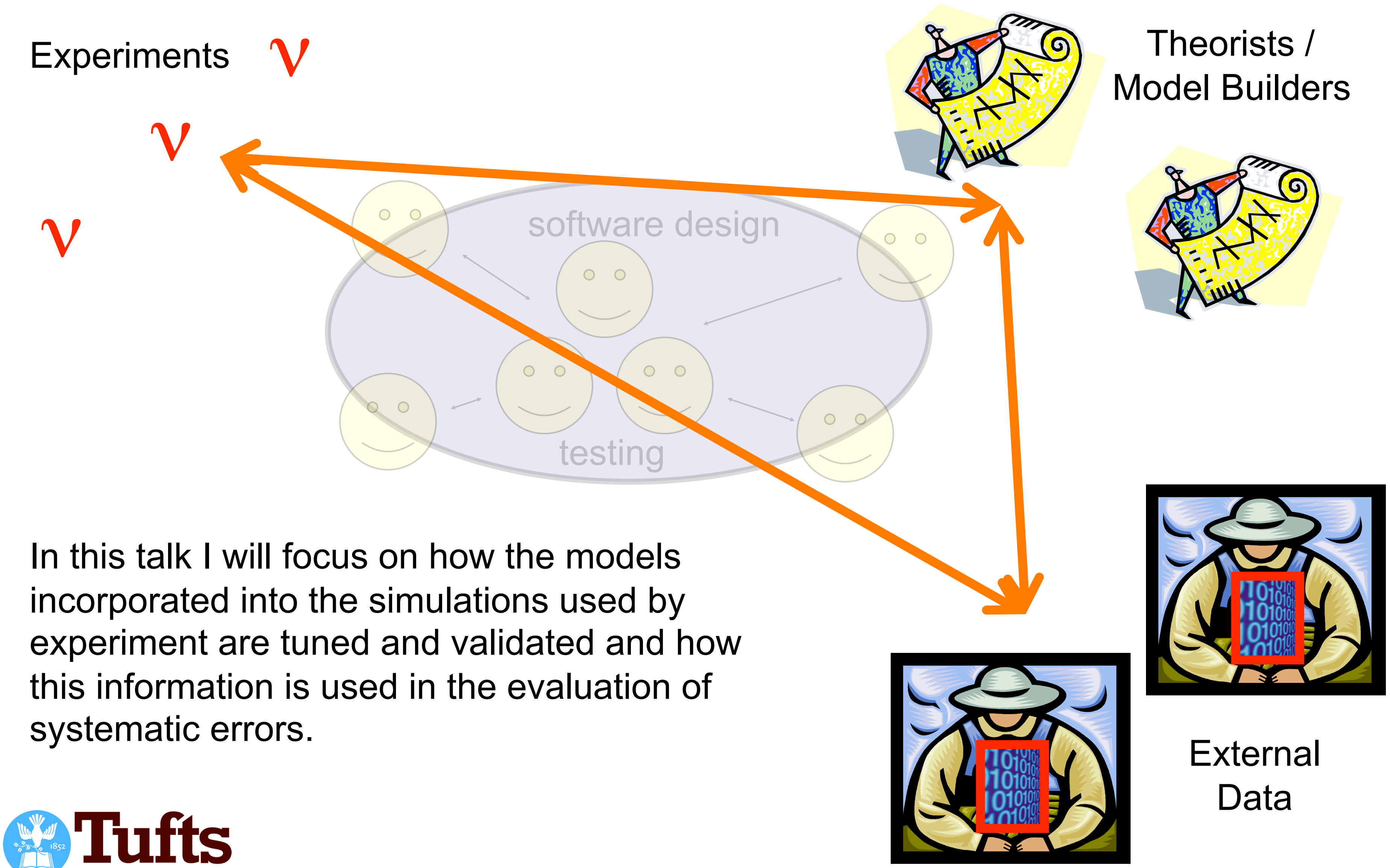
testing

Theorists / Model Builders

External Data

User Support

Physics Simulations



Experiments ν ν ν

Theorists /
Model Builders

External
Data

In this talk I will focus on how the models incorporated into the simulations used by experiment are tuned and validated and how this information is used in the evaluation of systematic errors.

GENIE

GENIE (*www.genie-mc.org*) is a Universal Object-Oriented Neutrino Generator that is supported and developed by an international collaboration of neutrino interaction experts spanning all major neutrino experiments. GENIE is a large-scale software project under development and it currently consists of about 110,000 lines of C++ code (~400 classes organized in ~40 packages).

neugen3 is a Fortran event generator originally developed for the Soudan 2 experiment and used previously by the MINOS, NoVA, and Minerva experiments as the basis for simulations.

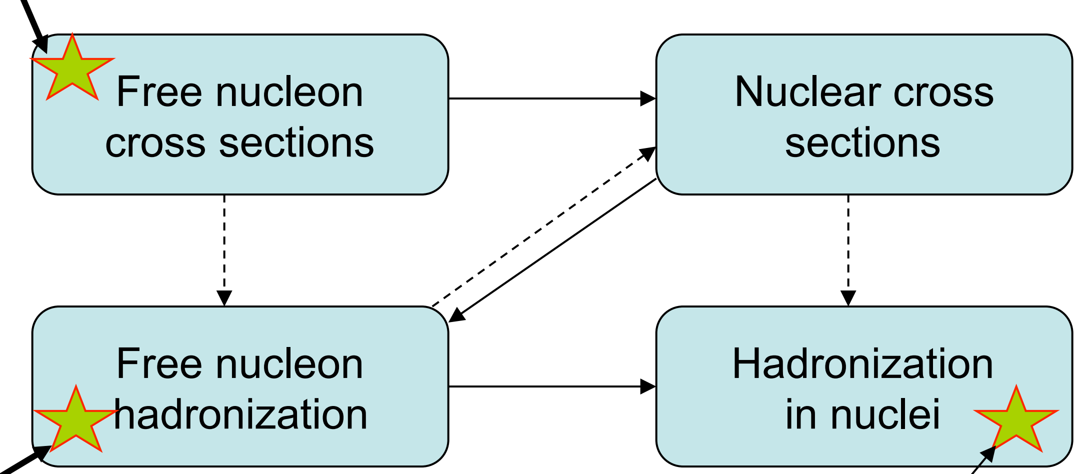
Physics model development and validation work for MINOS until 2006 was carried out in parallel for GENIE and neugen3, at which point the physics models in the two were equivalent.

Subsequent development work has been for GENIE only.

Physics Model and MINOS

Cross Section Model
(D. Bhattacharya, D. Naples, J. Morfin, R. Gran, HG, C. Andreopoulos, S. Mishra, M. Kordosky)

1. *BBBA form factors*
2. *Rein-Sehgal resonance production model*
3. *Bodek-Yang construction for inelastic*
4. *Rein-Sehgal coherent cross section*



Free nucleon cross sections

Nuclear cross sections

Free nucleon hadronization

Hadronization in nuclei

AGKY hadronization model
(C. Andreopoulos, HG, P. Kehayias, T. Yang)
AIP Conf. Proc.967:269-275 (2007)

1. JETSET for W>3 GeV/c^2
2. Retuned KNO-based model for lower W.

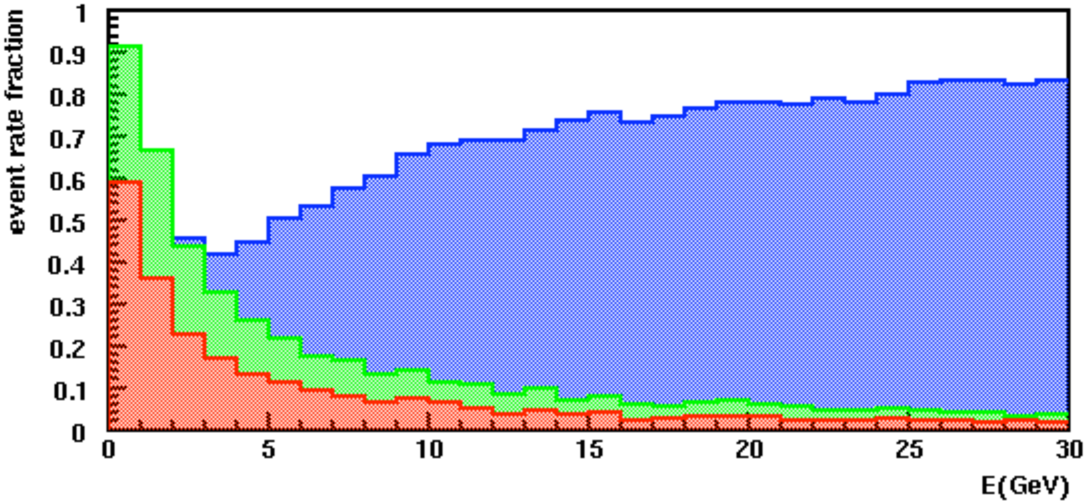
INTRANUKE - hA
(S. Dytman, H.G., M. Kordosky, T. Mann, J. Morfin)

AIP Conf.Proc.896:178-184 (2007).

Challenges at a few GeV!

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 the few-GeV regime important to oscillation experiments are in the “mystery” region in terms of detailed knowledge of the interaction mechanisms.

Free nucleon scattering models:
DIS low Q^2 modeling
resonance modeling
DIS / resonance transition region

Cross Section Model

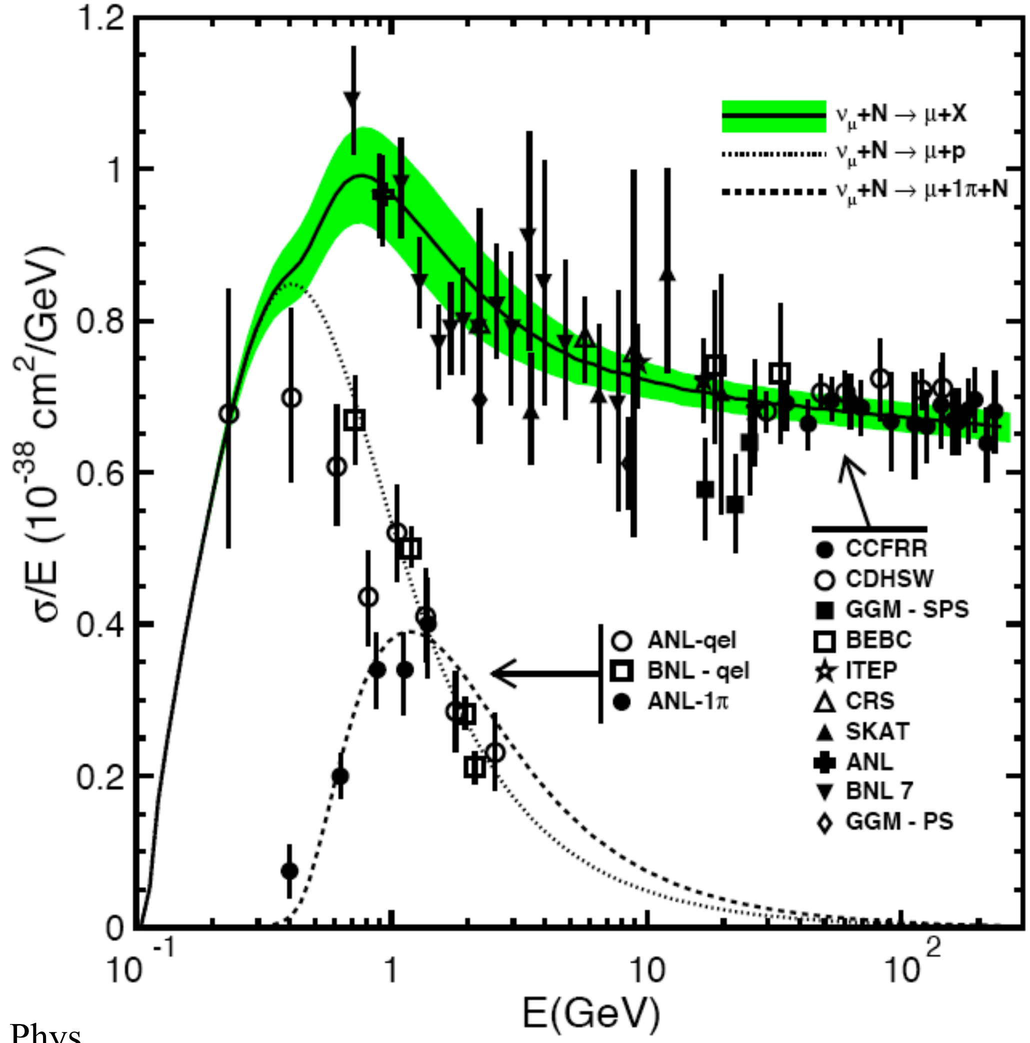
Quasi-Elastic: BBBA parametrization (arXiv: 0709.3538) of form factors with m_a=0.99 GeV/c^2.

Resonance Production:
Rein-Sehgal model for W<1.7 GeV/c^2 with m_a=1.12 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*)*
With improved low Q^2 treatment for CC interactions (Rein&Sehgal, hep-ph/0606185)

LO charm production with m_C=1.43 GeV/c^2,
QEL charm (R2.2.0). S.G.Kovalenko, Sov.J.Nucl.Phys. 52:934 (1990)



Cross Section Model

A standard combination: Llewellyn-Smith + Rein-Sehgal + Bodek-Yang

Quasi-Elastics:
- Which form factors?
- Value of m_A?

Resonance Production:
- Which form factors?
- Value of m_A?
- interference between resonances?
- Updated to include lepton mass terms and psuedo-scalar terms?

Non-resonant Inelastic model:
- Construction of xF_3
- Consistent use of x_{HT}
- Low Q^2 behavior of terms like $F_1 = F_2(1+4M^2x^2/Q^2)/(2x(1+R))$
- Tuning of total cross section at high energy to match world data

Combining Resonant and DIS models to avoid double counting!

Combining Cross Sections

Tune model to give the correct single pion cross section and the correct total cross section (as determined by integrating the DIS model alone).

$$\frac{d\sigma}{d\theta dE'}^{DIS} = \frac{d\sigma}{d\theta dE'}_{j}^{B-Y} \Theta(W_{cut}-W)\sum_{k=1}^{10} f_k$$

f_4, f_5… = 1
f_2 determined from single π fit
f_3 determined from

$$= \int_{W_{min}}^{W_{cut}} dW \int dQ^2 \frac{d\sigma^{R-S}}{dQ^2 dW} + \sum_{k=1}^{10} f_k \int_{W_{min}}^{W_{cut}} dW \int dQ^2 \frac{d\sigma^{B-Y}}{dQ^2 dW}$$

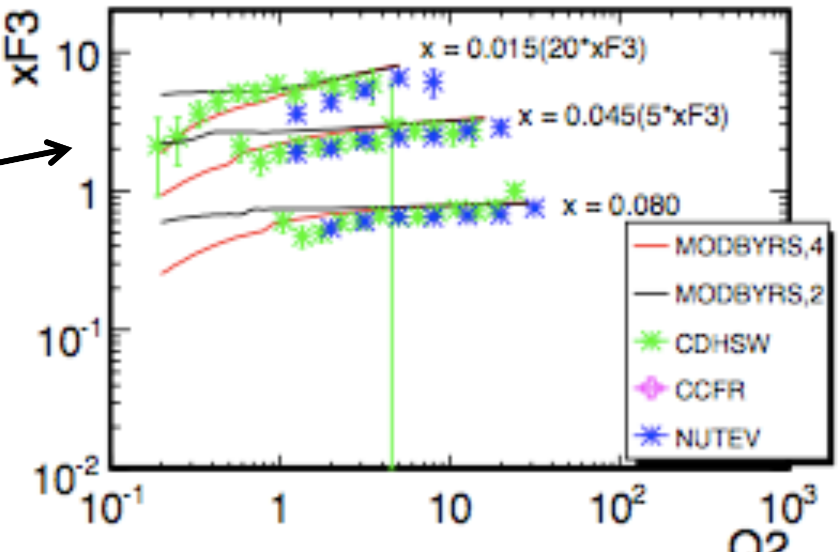
σ Model Validation and Tuning

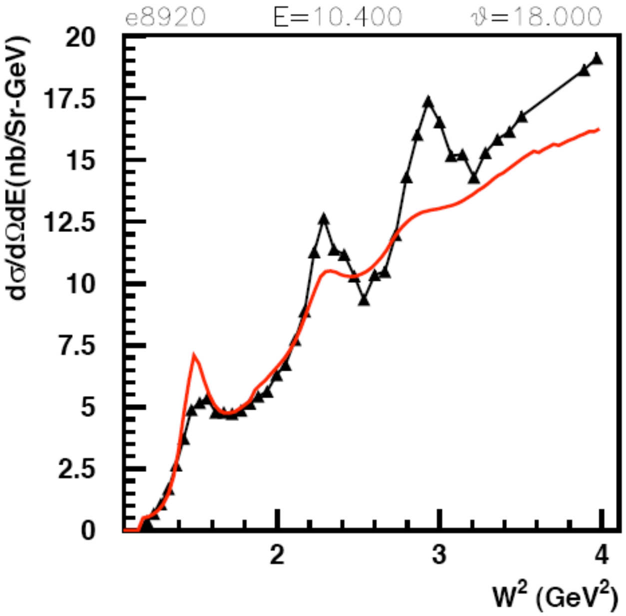
In tuning the cross section model we proceed in several stages:

1) Examine the agreement between the Bodek-Yang model and electron and neutrino structure function data above the resonance region.

2) Examine the agreement between the resonance model and electron scattering data in the resonance region.

3) Tune remaining parameters to neutrino total cross section and single pion data.



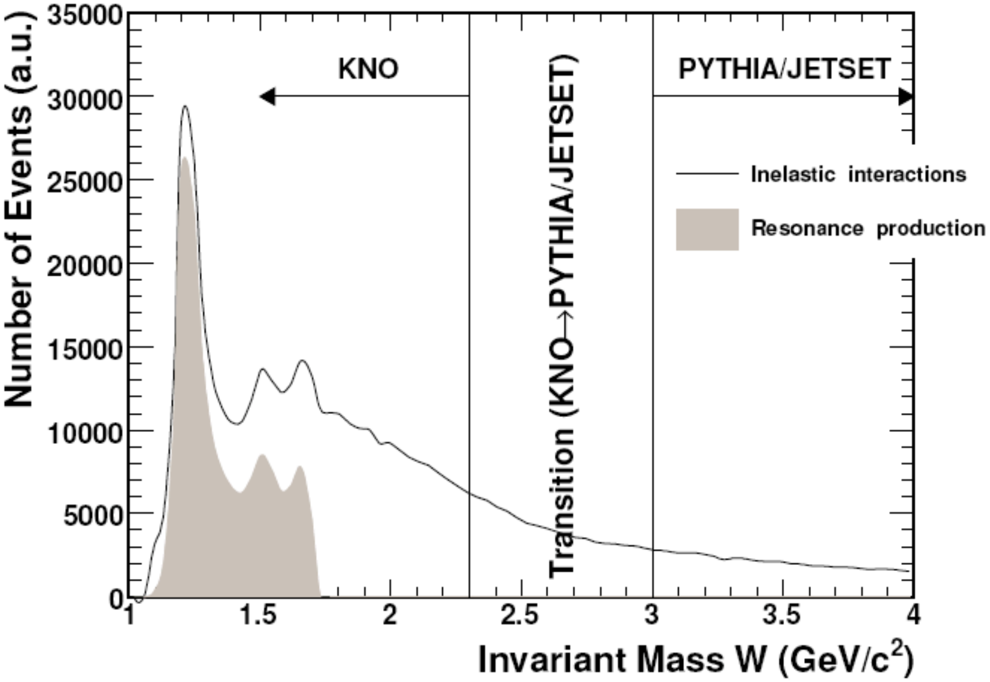


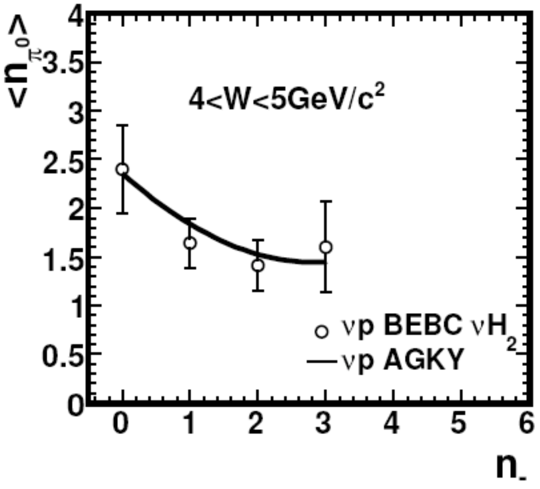
AGKY Hadronization Model

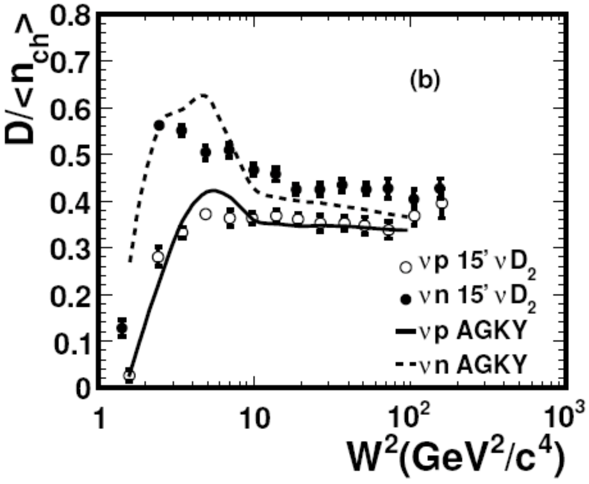
T. Yang et al., “A Hadronization Model for the MINOS Experiment”, AIP Conf. Proc.967:269-275 (2007).

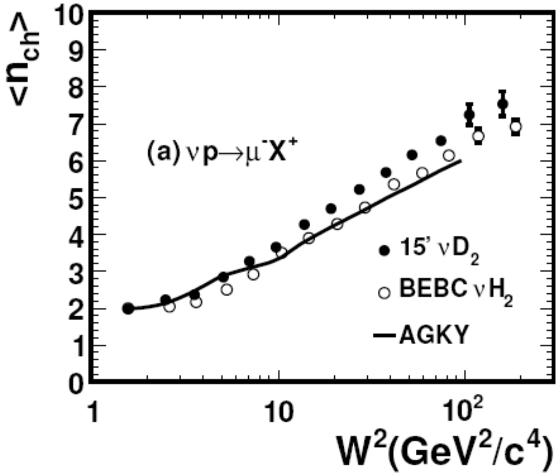
AGKY model - combining an empirical model (“KNO”) with JETSET at high invariant mass.

Extensively tuned to bubble chamber data.









AGKY Hadronization Model

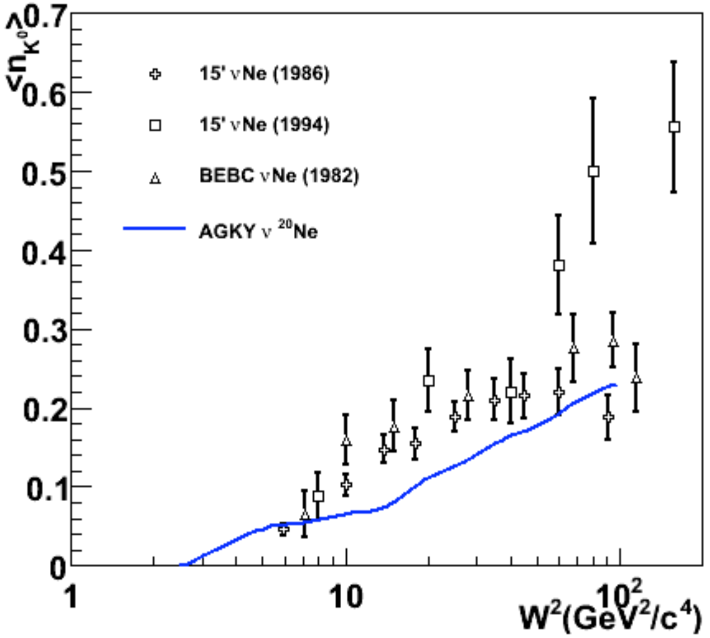
Select particle content:

$$\langle n_{ch} \rangle = a + b \ \log W^2$$

$$\langle n_{tot} \rangle = 1.5 \langle n_{ch} \rangle$$

$$\langle n \rangle \times P(n) = f(n / \langle n \rangle)$$

State	Probability
$\pi^0 \pi^0$	30%
$\pi^+ \pi^-$	60%
$K^0 K^-$	2.5%
$K^+ K^-$	2.5%
$\overline{K^0} K^+$	2.5%
$\overline{K^0} K^0$	2.5%

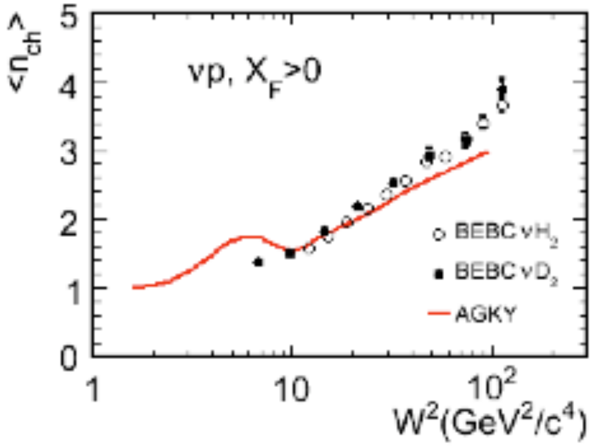


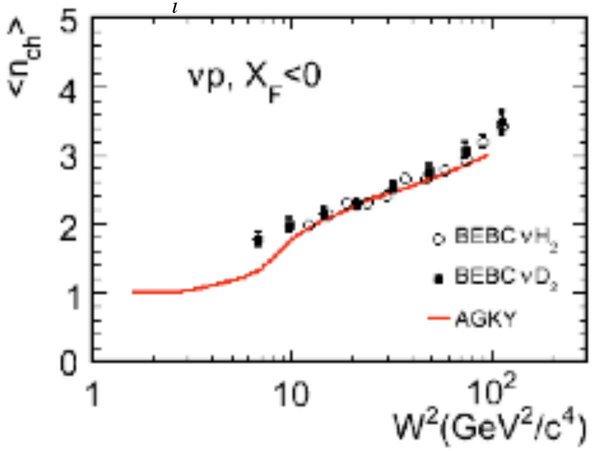
Assign 4-vectors in CM:

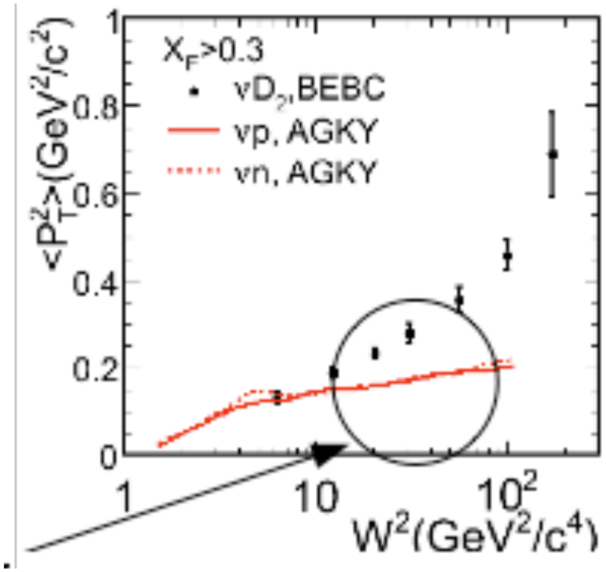
Select baryon 4-momentum from empirical distribution $P(x_F,p_t)$.

Phase space decay remaining hadronic system

"P_T squeezing" – rejection factor $\prod_i \exp(-Ap_{T,i})$







INTRANUKE-hA

S. Dytman, AIP Conference Proceedings, Volume 896, pp. 178-184 (2007).

1. Transport hadrons through the nucleus to decide whether or not they interact. This transport is done with a realistic nuclear model and πN total cross sections. Roughly account for quantum mechanical nature of scattering at low momentum by $R_{eff} = R_{nuc} + 0.5 * \lambda$.

2. If an interaction occurs, decide what kind. ("fate": elastic, charge exchange, inelastic, absorption, or π production). These "fate probabilities" for π-Fe interactions are taken from data.

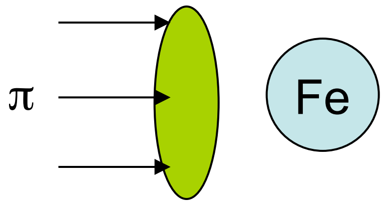
3. For each fate, determine the outgoing particles and their 4-momenta.

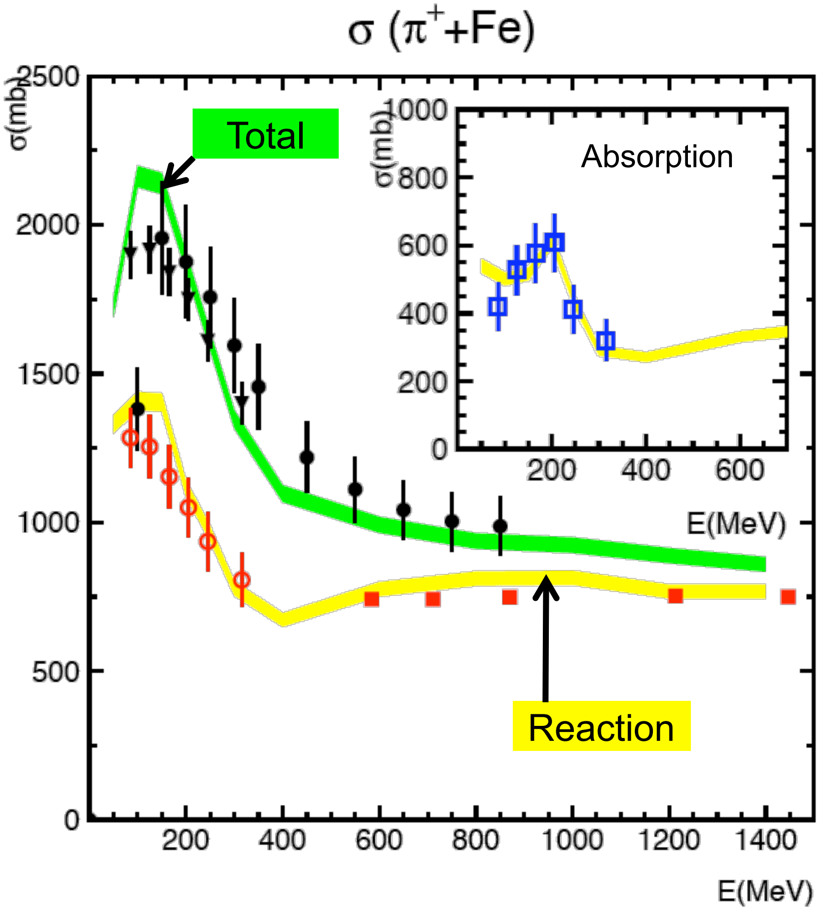
Formation Zones: SKAT parametrization: formation time= 0.342 fm/c.
V. Ammosov, NuINT01.

Intranuclear Rescatting

The model is compared *to hadron scattering data:*

$$\sigma_X = \frac{N_X}{N} A$$





And *neutrino data*:

R. Merenyi et al., PRD 45 (1992), 743.

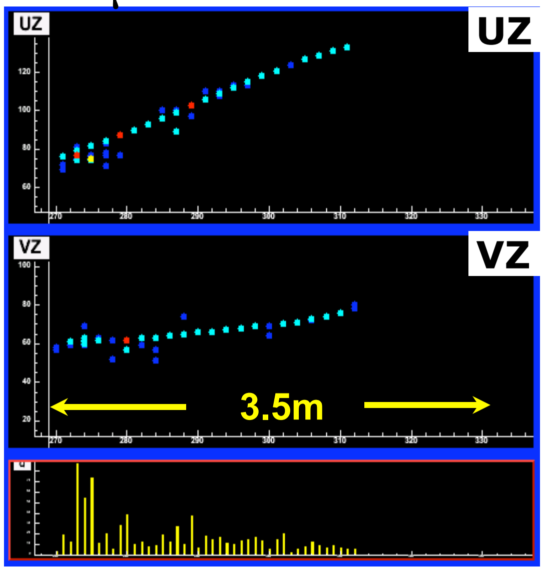
CC ν_μ-neon (BEBC) and ν_μ-deuteron (ANL-412) interactions weighted to match the shape of the atmospheric neutrino spectrum.

Pion Fate	Simulation	Data
Absorption	18.3 ± 0.5%	22 ± 5%
Charge Exchange	2.8 ± 0.1%	10 ± 8%

MINOS: Event Topologies

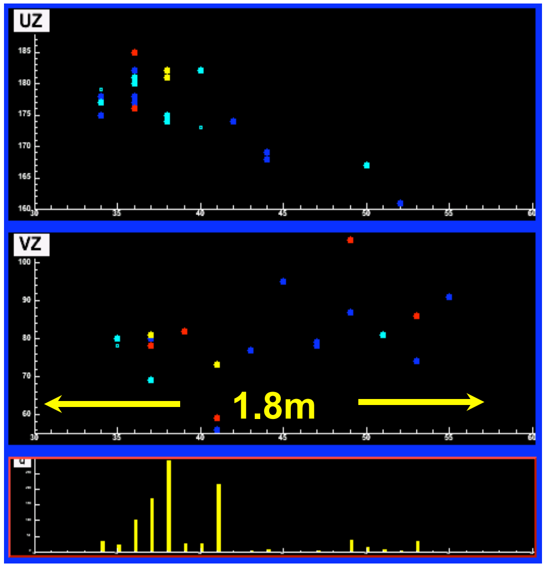
Monte Carlo

ν_μ CC Event



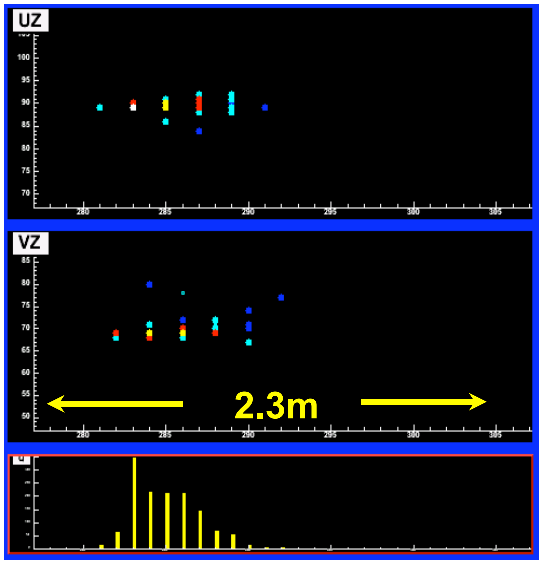
- long μ track+ hadronic activity at vertex

NC Event



- short event, often diffuse

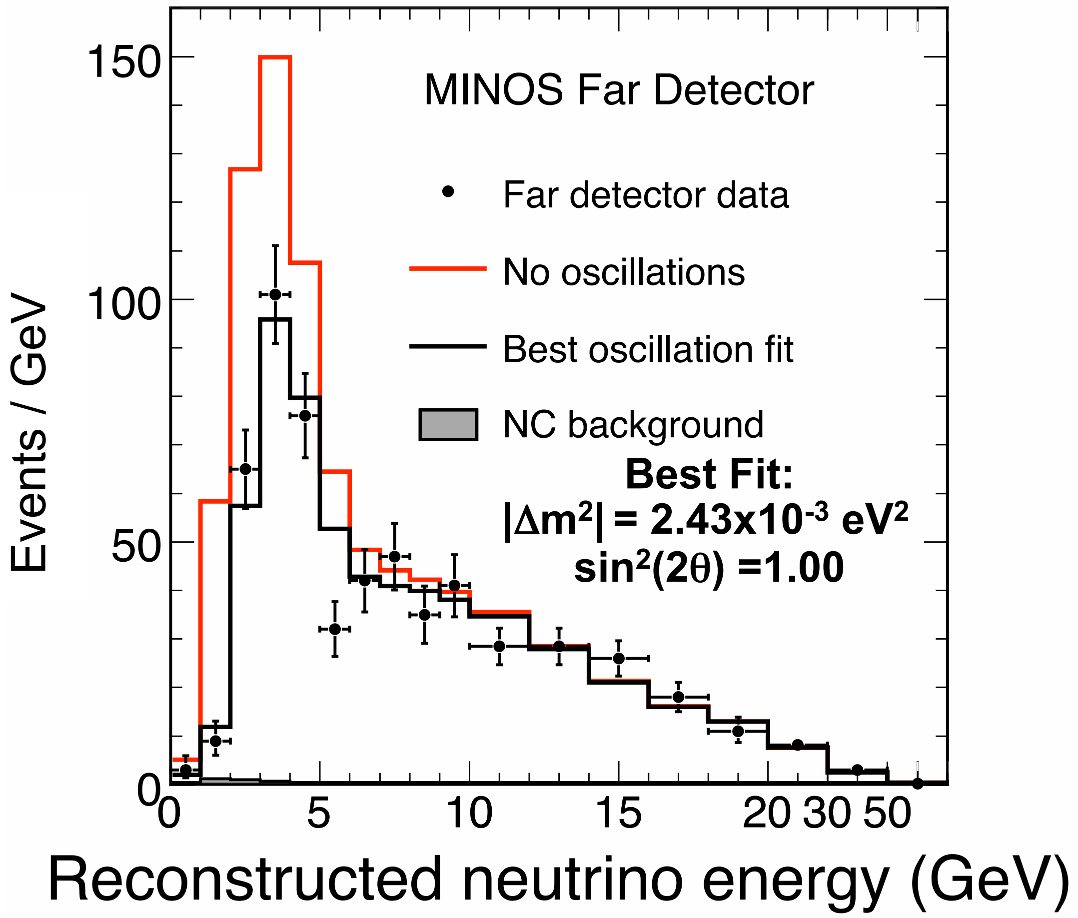
ν_e CC Event



- short, with typical EM shower profile

$$E_\nu = \underset{\underset{55\%/\sqrt{E}}{\uparrow}}{E_{\text{shower}}} + \underset{\underset{6\%\text{ range, }10\%\text{ curvature}}{\uparrow}}{P_\mu}$$

MINOS Δm^2 Measurement



$$\chi^2 = \sum_{nbins} (2(e_i - o_i) + 2\, o_i \ln(o_i / e_i)) + \sum_{nsys} \frac{\Delta s_j^2}{\sigma_{s_j}^2}$$

Fit the energy distribution to the oscillation hypothesis:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Including the three largest sources of systematic uncertainty as nuisance parameters:

- Absolute hadronic energy scale: 10.3%
- Normalization: 4%
- NC contamination: 50%

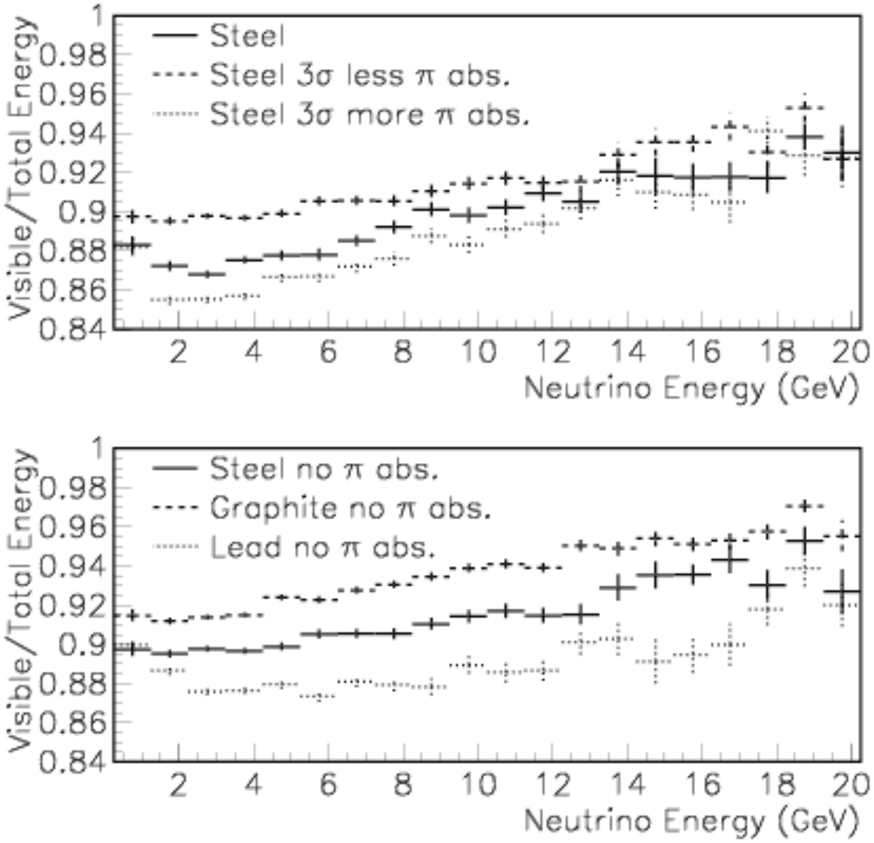
χ^2/ndof = 90/97

Neutrino Energy Calibration

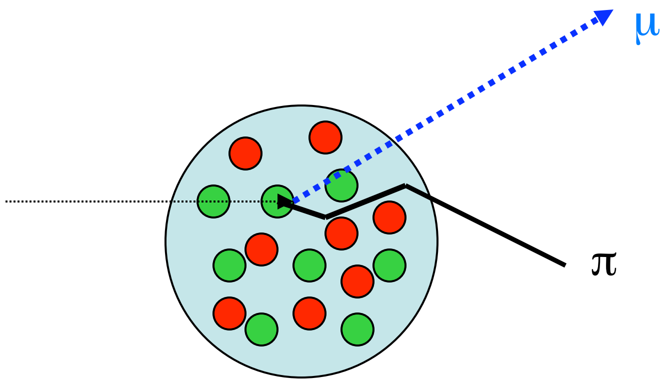
Visible Energy in Calorimeter is NOT ν energy!

- absorption, rescattering
- e/h response of detector

“Ramifications of Intranuclear Re-Scattering in MINOS”, M. Kordosky, Nucl. Phys.Proc.Suppl.159:223-228 (2006).



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



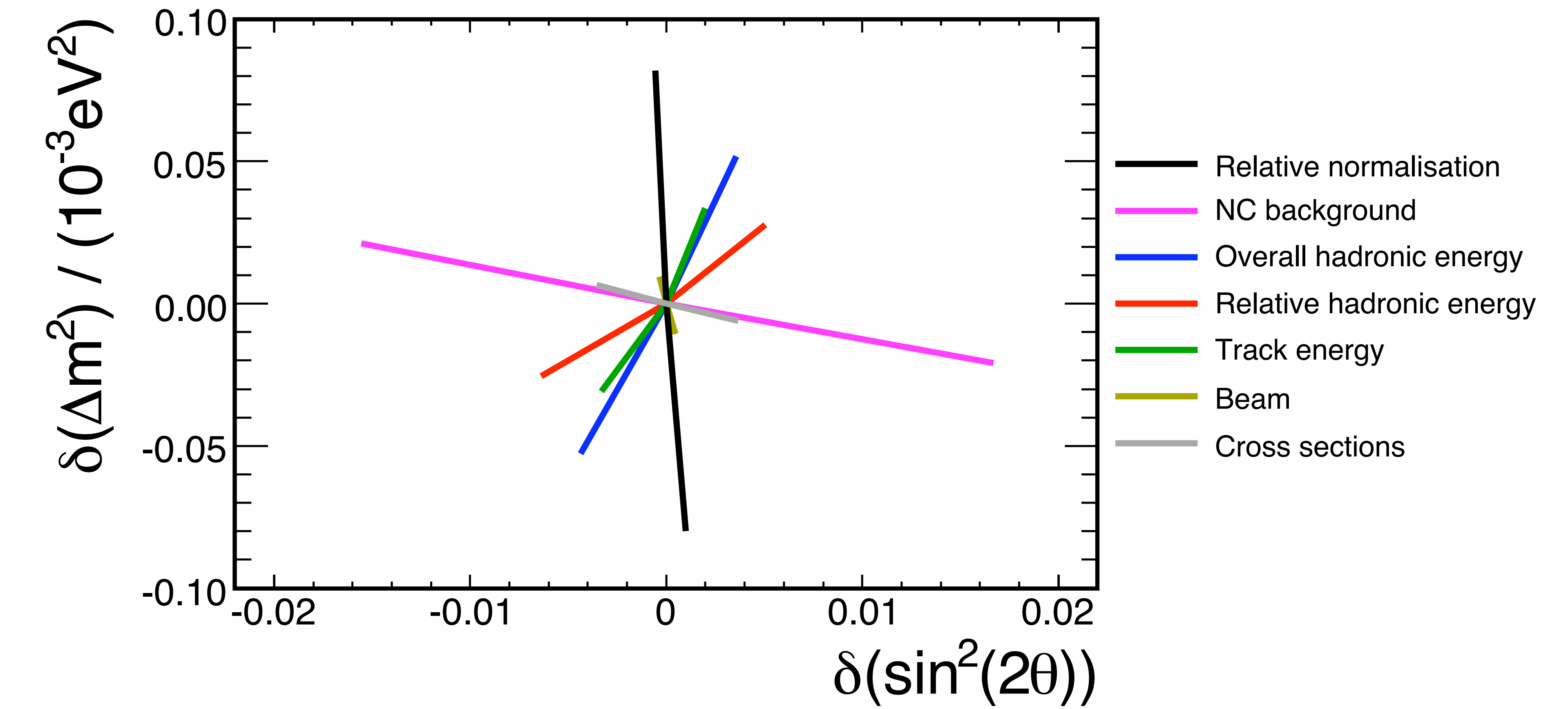
Detectors are calibrated primarily using cosmic ray muons and single particle test beams.

Determining response to neutrino-induced hadronic showers introduces model uncertainty.

Does not simply cancel in a near/far comparison.

Systematic Uncertainties

The impact of different sources of systematic uncertainty were evaluated by fitting modified MC in place of the data:



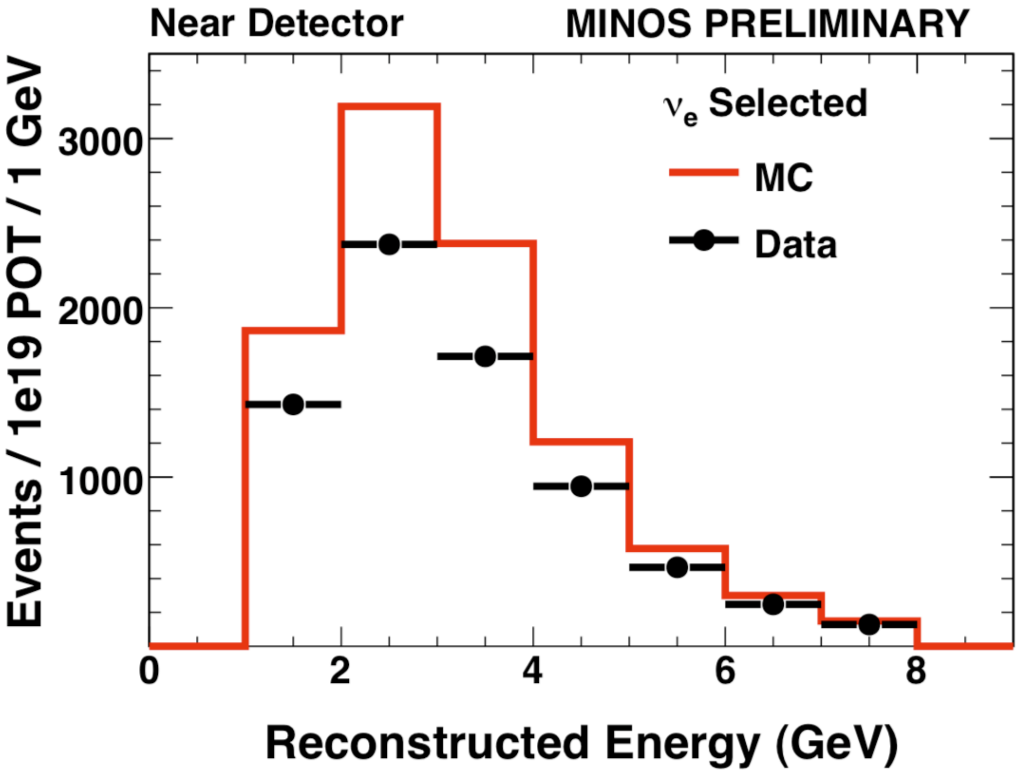
MINOS: ν_e Appearance

Search for ν_e appearance in a beam that is 98.7% ν_μ.

Select ν_e CC in the near and far detector with a neural network.

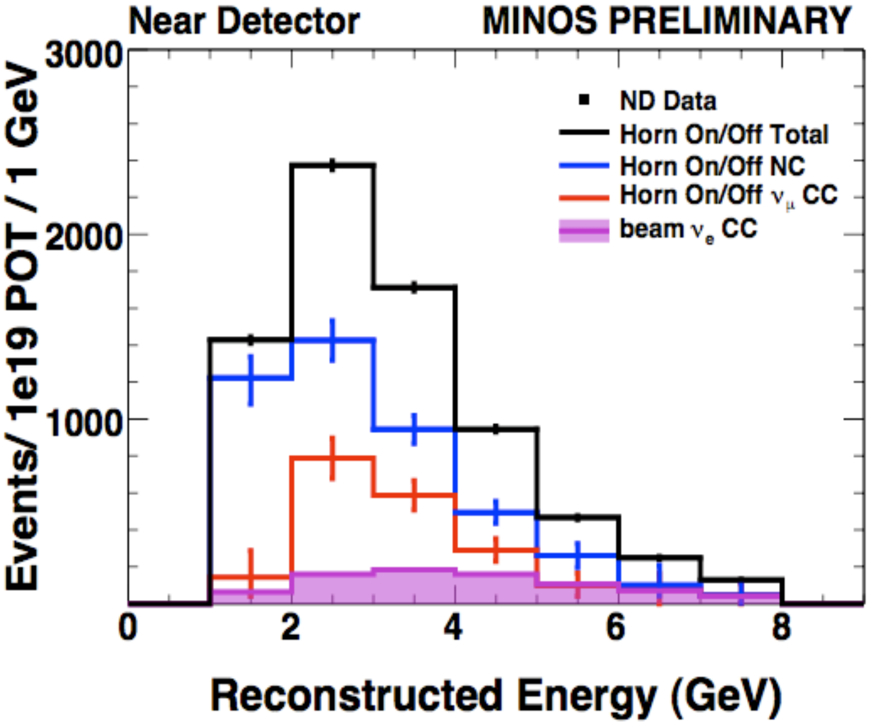
ND measures a mix of beam ν_e, NC and ν_μ CC events.

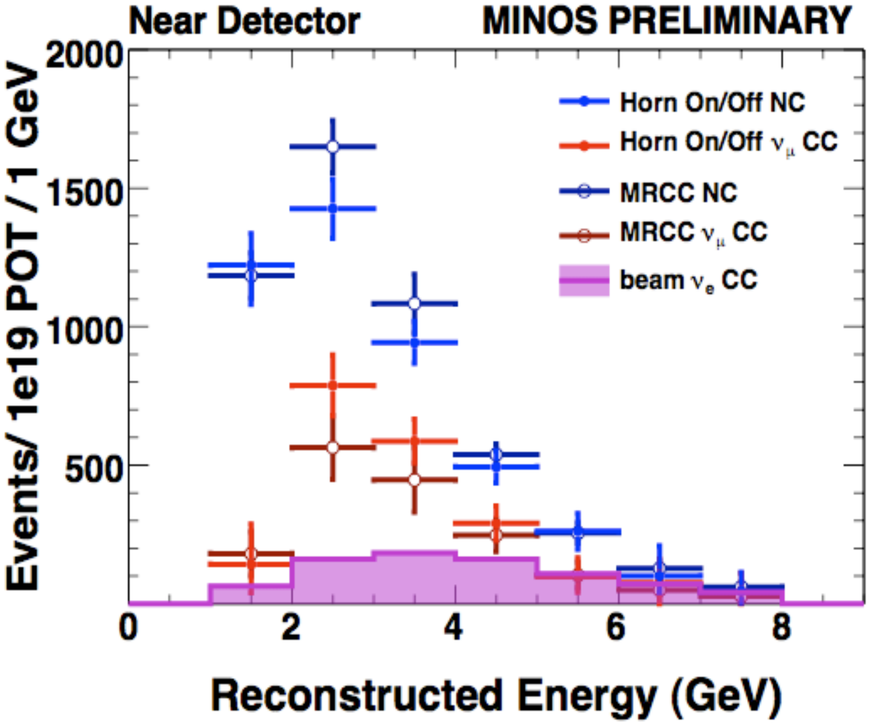
Solution: use two independent data driven methods to estimate NC and CC ν_μ backgrounds



MINOS: Data-Driven Methods

- Two data-driven background estimation methods:
  - Horn On/Off – use a second beam configuration and the constraint of the relative ratios of NC and ν_μ CC background between the beams
  - MRCC – Muon removed hadronic showers from ν_μ CC events
- Good agreement in the NC and ν_μ CC background





Evaluating Systematic Errors

Experiments have devised a number of different methods for determining the systematic errors associated with model uncertainties. Assuming that the uncertainty in a particular model aspect has been estimated one can:

1) Generating entirely new Monte Carlo samples with the model shifted by some amount (1 σ). Analyze data with the new Monte Carlo to determine the change in the result.
2) If the effect of the model change is in a parametrization in one of the models, and one can quickly calculate the probability for generating a particular event given a particular model, one can reweight the standard Monte Carlo sample to achieve the same result as in (1).
3) Perform other estimates based on parametrizations of detector response ‘fast MC’.
4) Estimate systematic errors using data-based techniques from independent samples.

MINOS: σ Model Uncertainties

Overall Model Uncertainties, including nuclear effects:

- Total cross section: 3.5%
- M_A: 15% for both quasi-elastic and resonance production
- Transition region parameters: $r_{ij2}\pm 0.1$, $r_{ij3}\pm 0.2$.

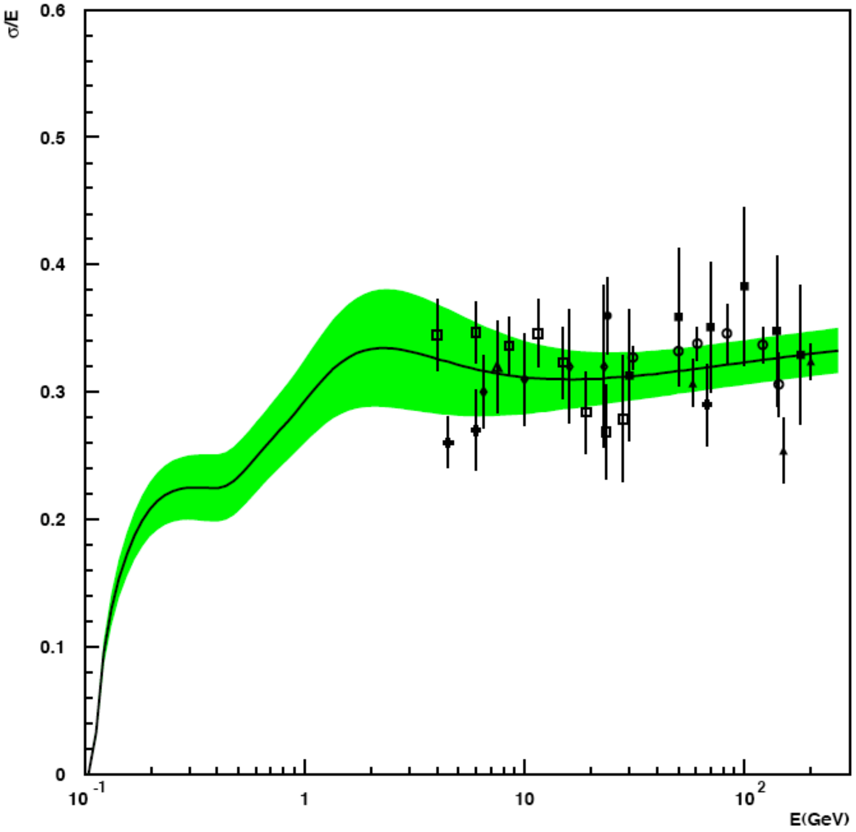
Anti-neutrino/neutrino cross section uncertainty:

- overall: 4%
- QEL/RES: 8%
- Transition region parameters: $r_{132}\pm 0.2$, $r_{i42}\pm 0.2$.

ν_τ: Pseudo-Scalar Form Factor

$$F_P' = (1.05 + 0.095Q^2)F_P$$

Significantly smaller than Hagiwara et al., Phys. Lett. B591, 113-118 (2004).



MINOS: Shower Energy Scale

“Hadronic Shower Energy Scale Uncertainty in the MINOS Experiment”
S. Dytman, H. Gallagher, M. Kordorsky, arXiv:0806.2119 (2008).

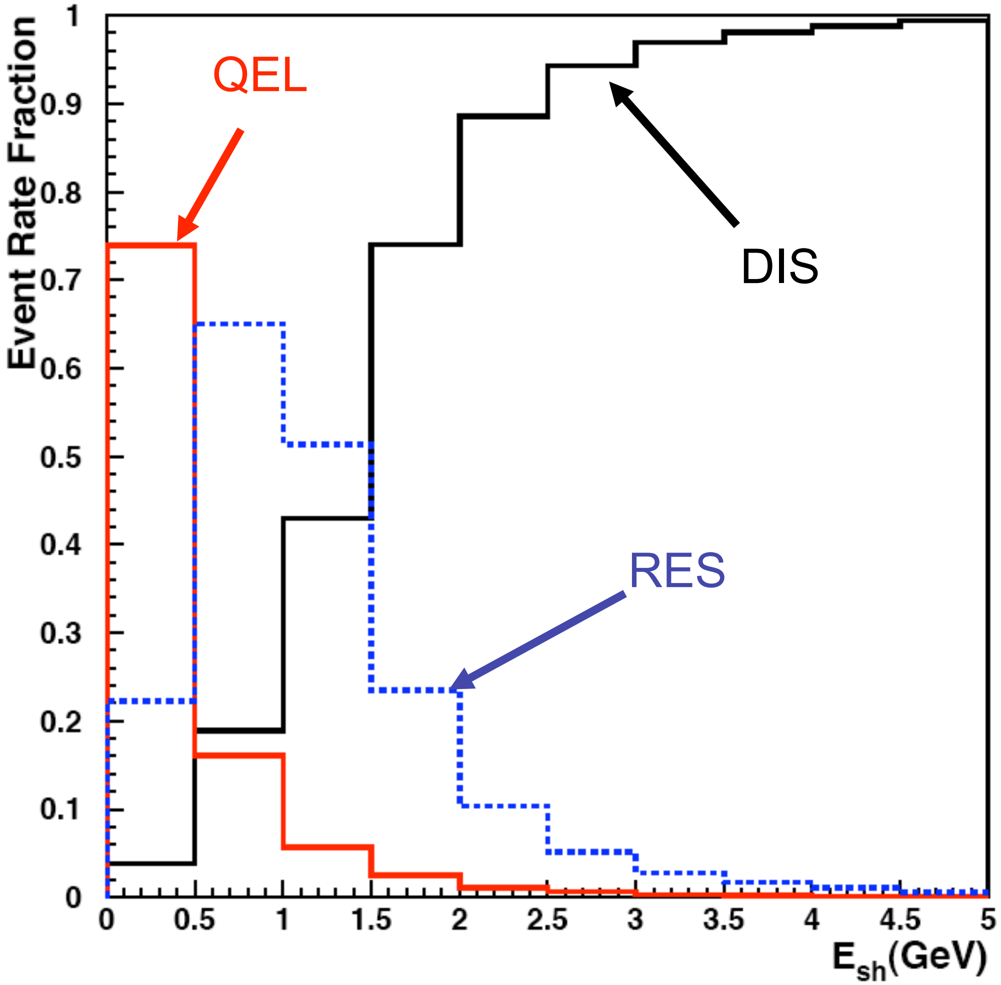
Estimates presented here were determined by comparing 4-vector simulations using an approximate detector response (ADR) model.

Samples with a generator “tweak” were compared with a nominal sample from neugen v3.5.5.

Δ(response) =

(tweaked-nominal)/nominal

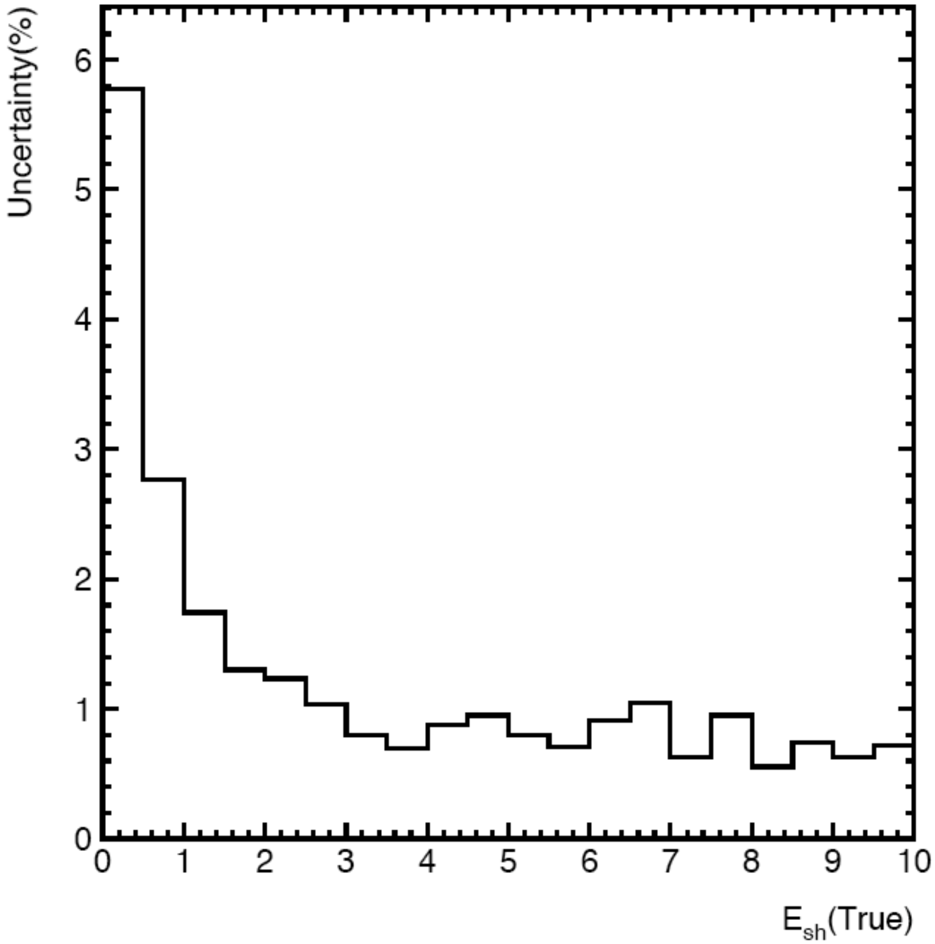
- in bins of true Esh



MINOS: Shower Energy Scale

INTRANUKE External Data Inputs

branching ratios	
parameter	1σ uncertainty (%)
π charge-exchange	50
π elastic	10
π inelastic	40
π absorption ★	30
π secondary π production	20
N absorption ★	20
N secondary π production	20
N elastic	30
cross-sections	
parameter	1σ uncertainty (%)
π total cross-section	10
N total cross-section	15



MINOS: Shower Energy Scale

We also tried to identify the key assumptions in the model and evaluate their impact.

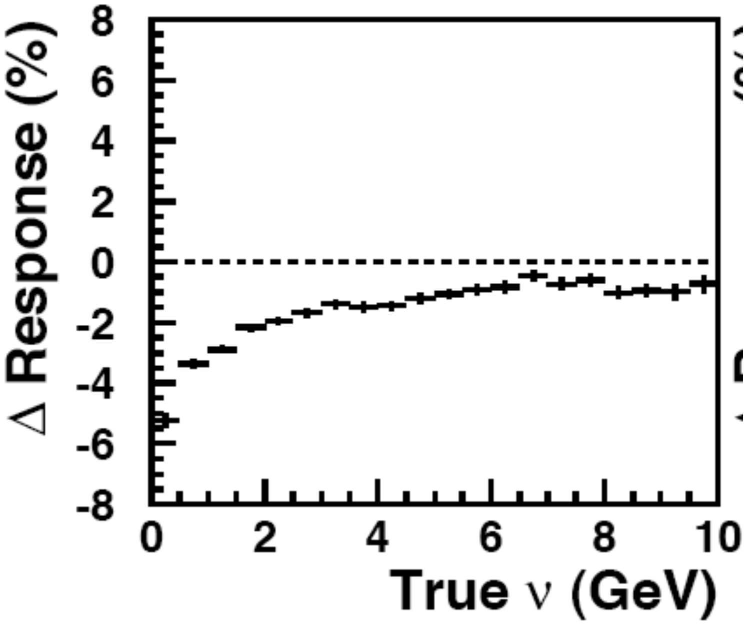
Assumption 1: classical model – how to reproduce the measured pion scattering cross sections at low momentum? $R_{eff} = R_{nuc} + 0.5 * \lambda$.

Looked at how much the size parameter could vary based on comparisons to π-Fe scattering data and neutrino data.

Neutrino data have poor statistics:
$\delta a \sim 0.6$.

Pion data: $\delta a \sim 0.08$

Took the more conservative $\delta a \sim 0.60$
Size parameter to 1.10.



MINOS: Shower Energy Scale

Another key assumption is the treatment of “Missing Energy” in pion absorption. Inspired by “Ransome Model” - R.D. Ransome Nucl.Phys.Proc.Suppl.139:208-212,2005.

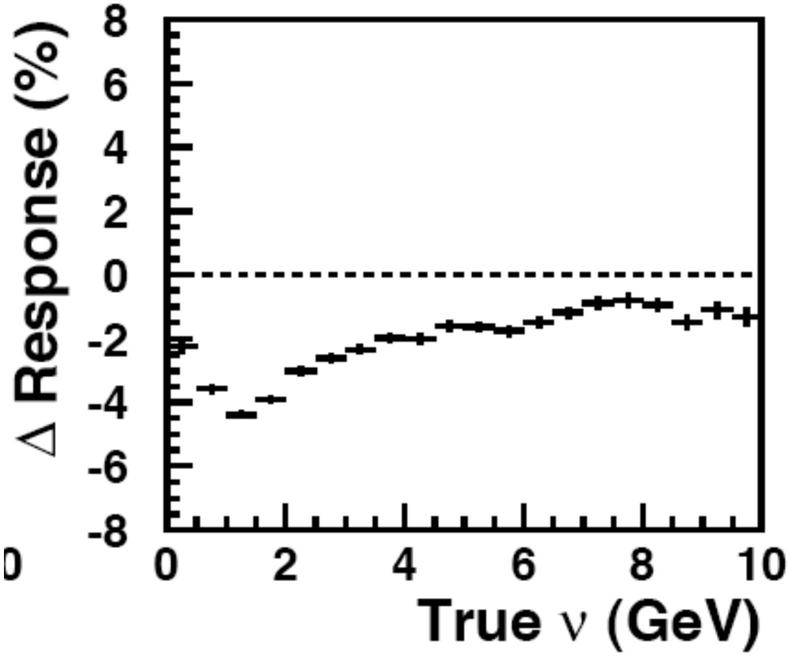
Pion energy is converted to kinetic energy of a multi-nucleon cluster.

“Effective” vs. “Explicit” missing energy:
Explicit missing energy - invisible to a perfect detector, e.g. binding energy

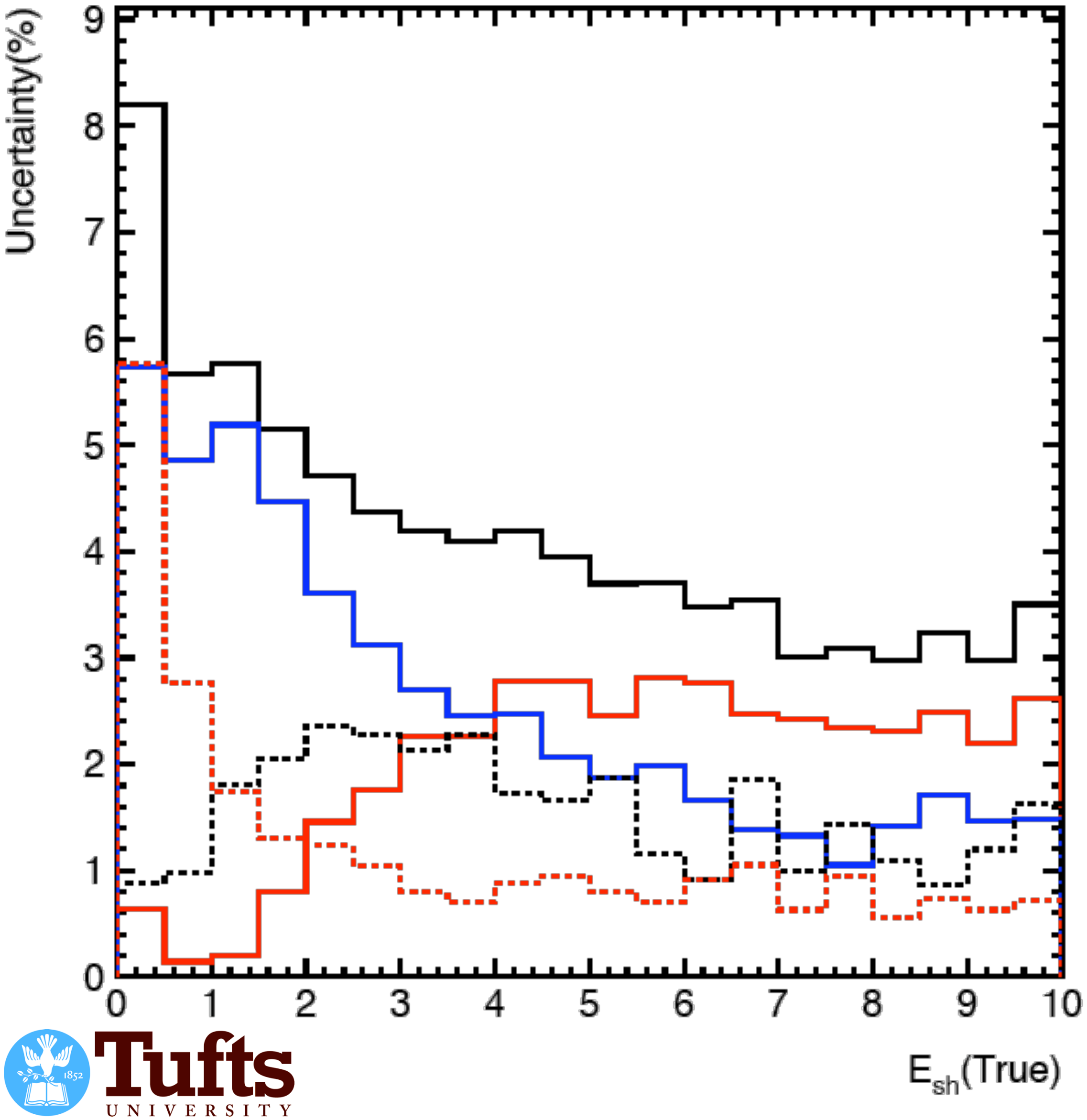
Effective missing energy - energy that is invisible to the MINOS detector - e.g. low energy nucleons.

Intranuke treatment of absorption assumes that “Effective Missing Energy” dominates.

Change the number of nucleons produced in absorption reactions from 4 to 8.



MINOS: Shower Energy Scale



Black = total

blue = Intranuke assumptions

solid red = hadronization

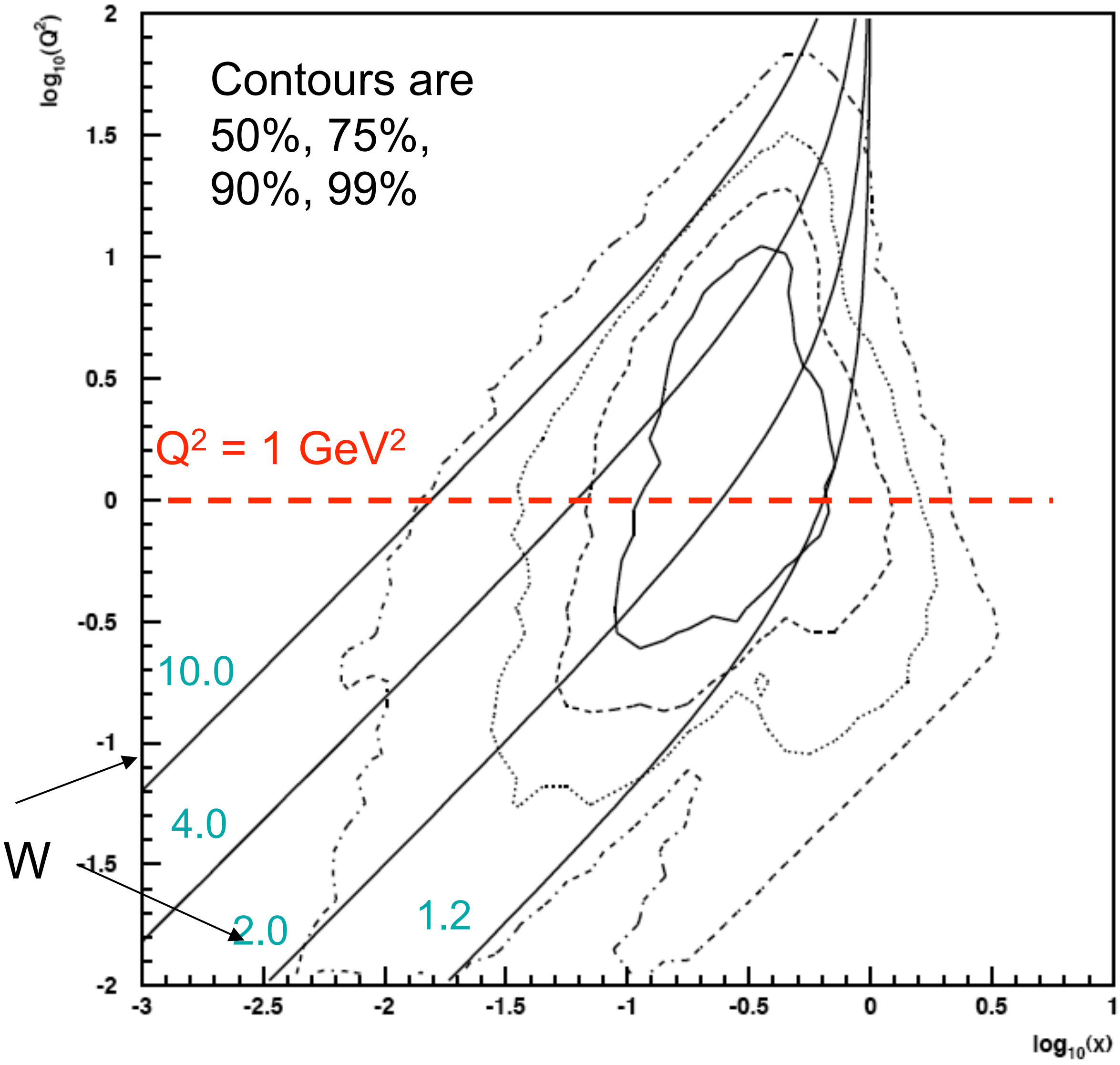
dashed red = Intranuke inputs

dashed black = formation zone

Overall number = 8.2%

NuMI Kinematic Coverage

Plot at right shows the kinematic Coverage of the NuMI LE beam (default for MINOS)



Contours are 50%, 75%, 90%, 99%

Lines of constant W

Theory Needs: General Wish List

Experiments make use of theoretical work in numerous ways, including incorporation into event generators.

- Code for models so that they can be incorporated into event generators for direct use by experiment.

- Models with estimates of errors.

- Clear statements about the appropriate kinematic range for models and suggestions about merging with other models.

- Key parameters are input – makes reweighting possible.

Theory Needs: Some Specifics

In addition there are some specific issues beyond those already discussed that impact experiments.

Intranuclear rescattering uncertainties and calorimetric measurements.

- “Missing Energy” for nuclear models – binding, recoil kinetic energies, and KE of nucleons with $p<400$ MeV/c.

Modeling of formation zones over a broad kinematic range.

Hadronization models in the low invariant mass region.

Uncertainty in the pseudoscalar form factors.

Tufts
UNIVERSITY