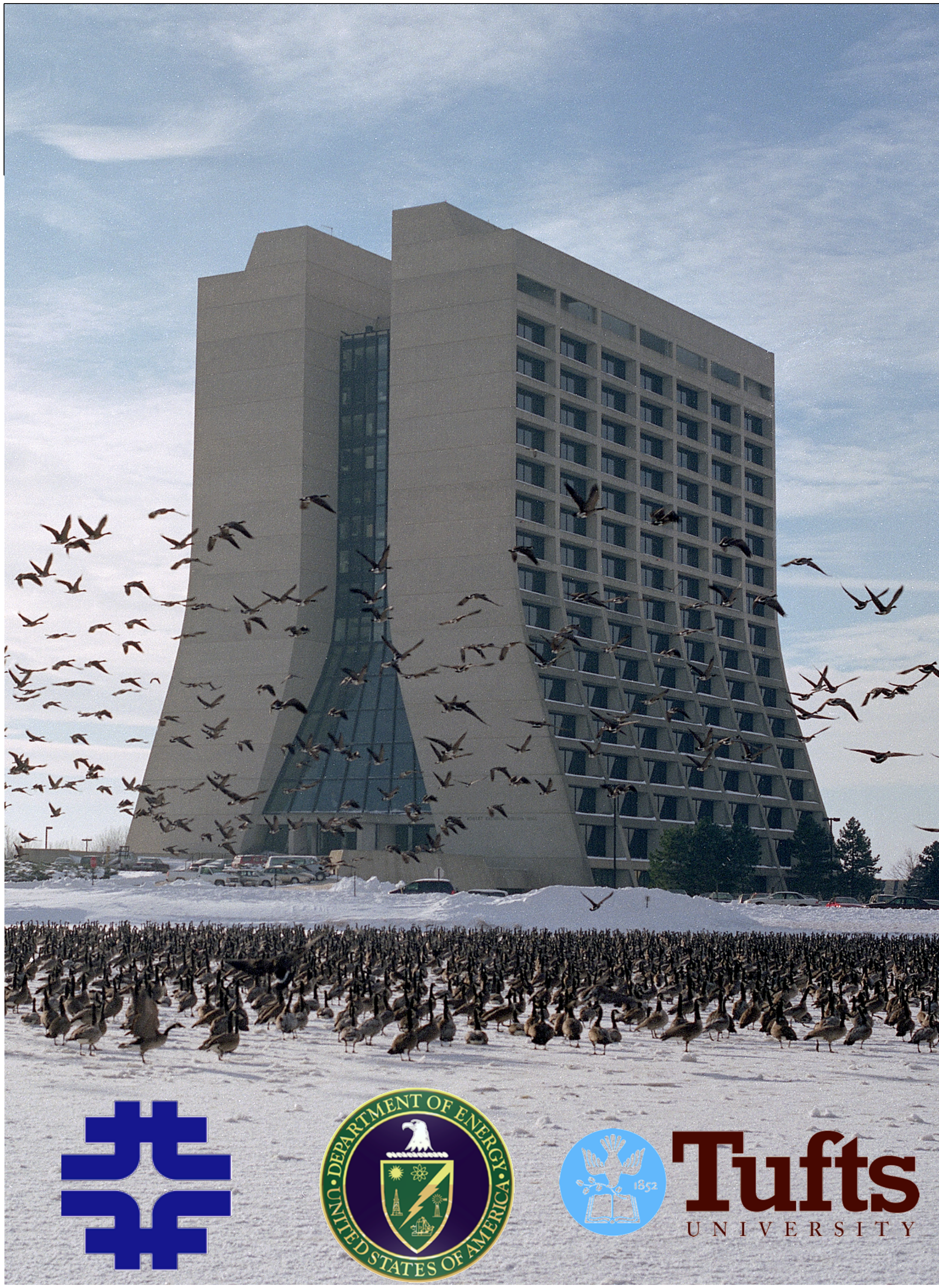


GENIE Overview

Hugh Gallagher, Tufts University
Costas Andreopoulos, RAL

Workshop on Computing for Neutrino Experiments
Fermilab - Mar 13, 2009

Outline

1) Event Generators – so what?

2) Physics Models Overview
   - *What's there, what's not*

3) Related Tools

4) GENIE Organization and Interaction with Experiments

Borrowing heavily from Costas' slides from the Karpacz Winter School, Feb.09. http://wng.ift.uni.wroc.pl/karp45/

What is GENIE?

Generates Events for Neutrino Interaction Experiments

A Neutrino Monte Carlo Generator (and extensive toolkit)

Validity:
from few MeV to many hundreds of GeV / handles all nuclear targets

Large scale effort:
110,000 lines of C++

Modularity / Flexibility / Extensibility:
Models can be swapped in/out. Models can be easily reconfigured. All done consistently.

Licensed:
To ensure openness and synergies between experiments

State of the art physics:
GENIE has lots of developers & support. Draws heavily from many people's expertise

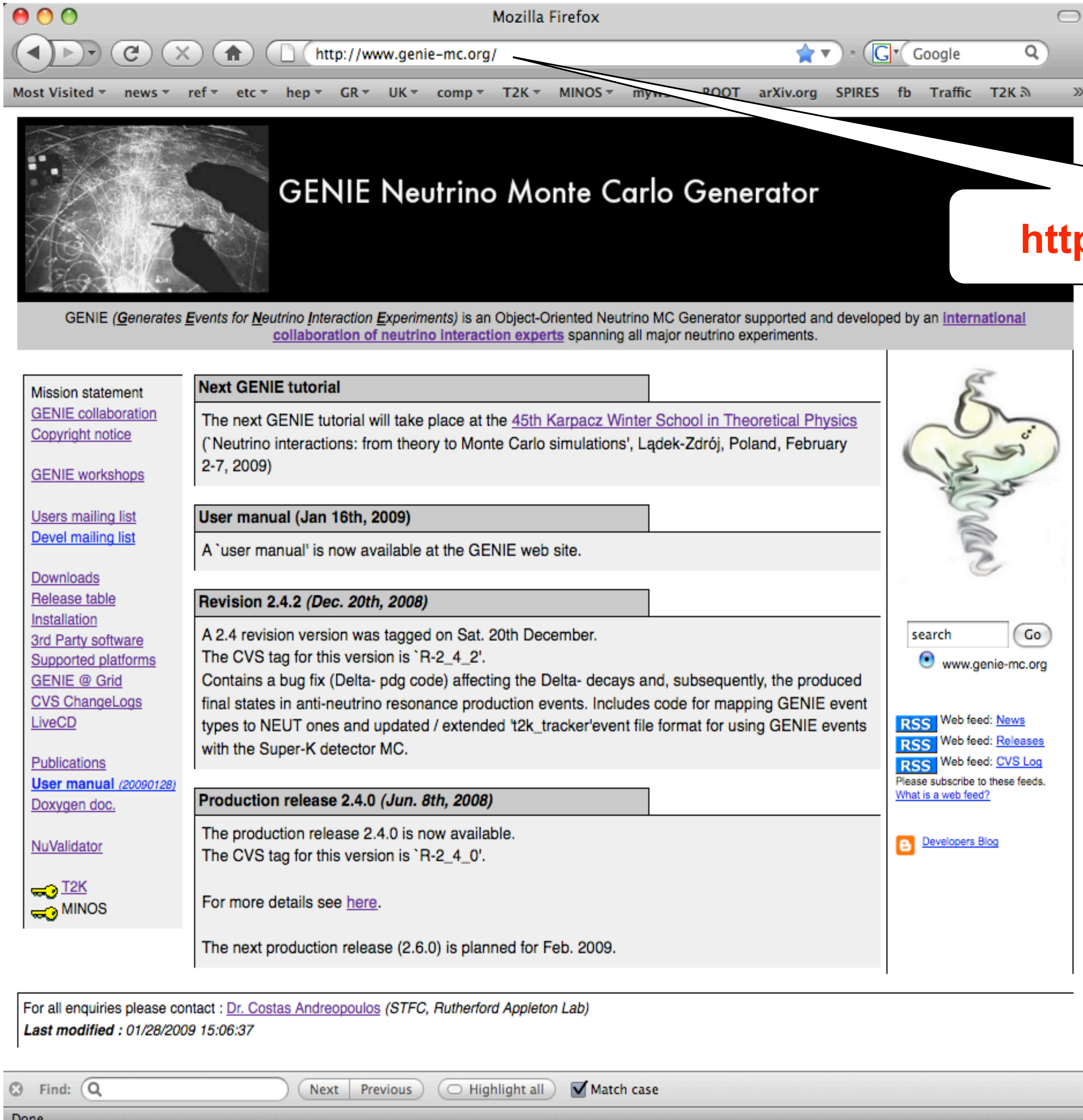
GENIE

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.



http://www.genie-mc.org

Official GENIE web site

You can find:

- *Physics documentation*
- *A user manual*
- *Release tables*
- *Download instructions*
- *Installation instructions*
- *Doxygen documentation*
- *News feeds*
- *...*
- *...*

Physics Simulations

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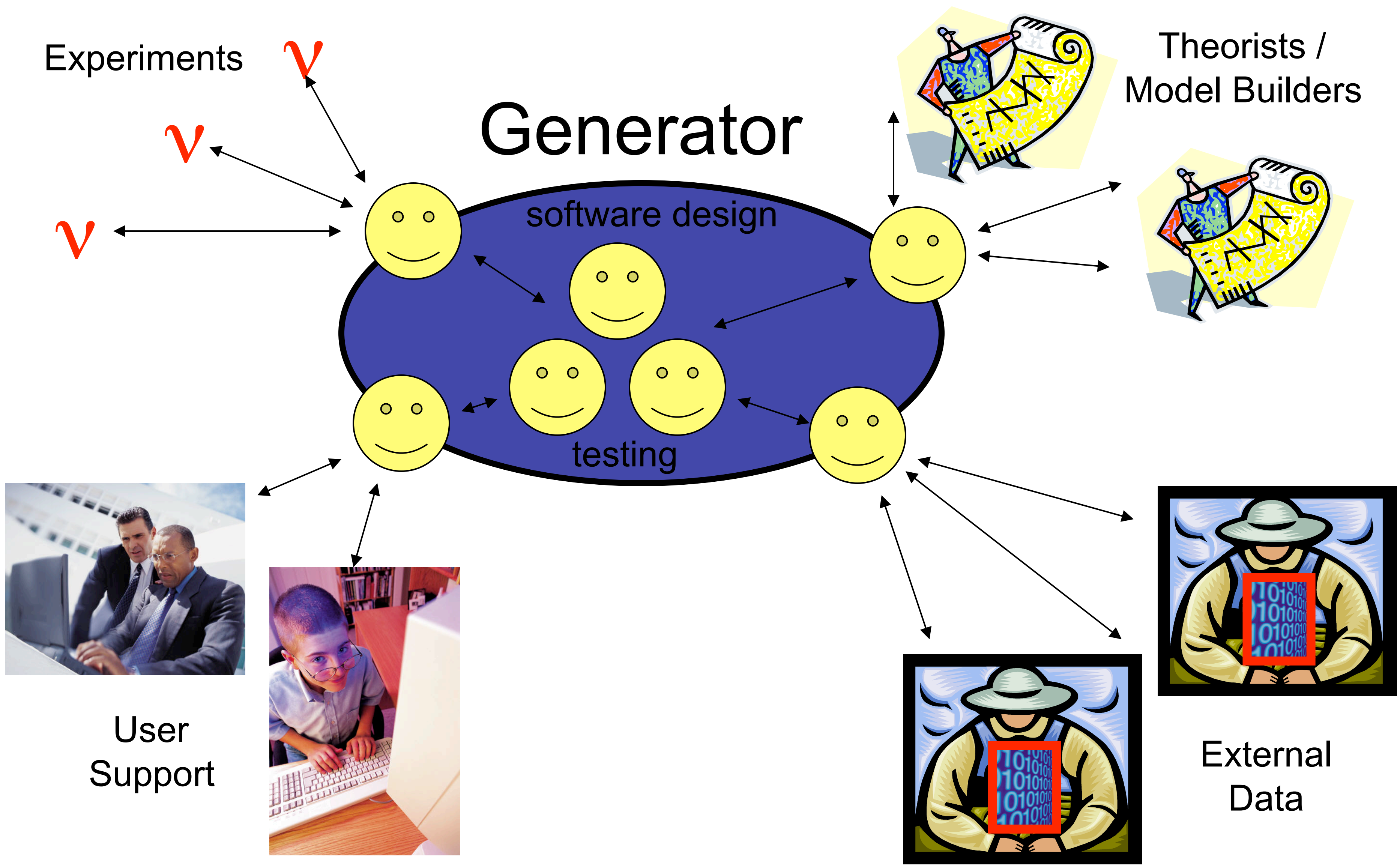


Generator Use Cases

The 5 most common uses cases:

1. What is the cross section for X?
2. Can I get some neutrino events for interaction X?
3. Are you sure about X?
4. Are you sure you’re sure about X?
5. How sure are you about X?

Generator Use Cases

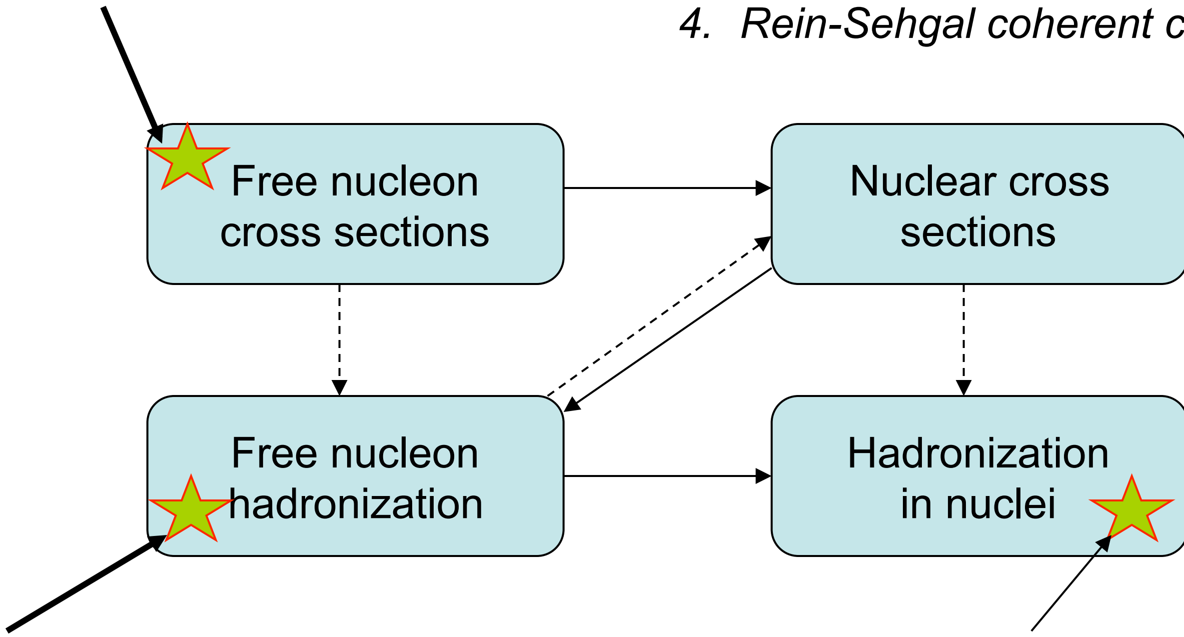
The 5 most common uses cases:

1. What is the cross section for X?
   - Cross section libraries
   - Databases of existing measurements
2. Can I get some neutrino events for interaction X?
   - Event Generator
3. Are you sure about X?
   - Package validation – is it doing what we want?
4. Are you sure you're sure about X?
   - Comparisons to external data
5. How sure are you about X?
   - Systematic error evaluation (external data and theoretical)

Physics Model

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*



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!

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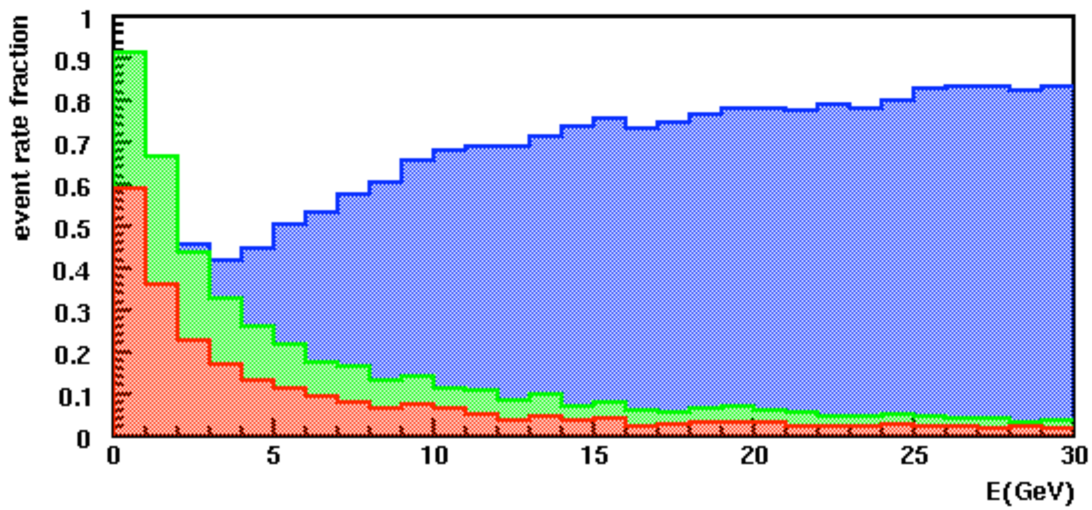
Previous experiments focused on 3 regimes:

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



Large fraction of events in 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

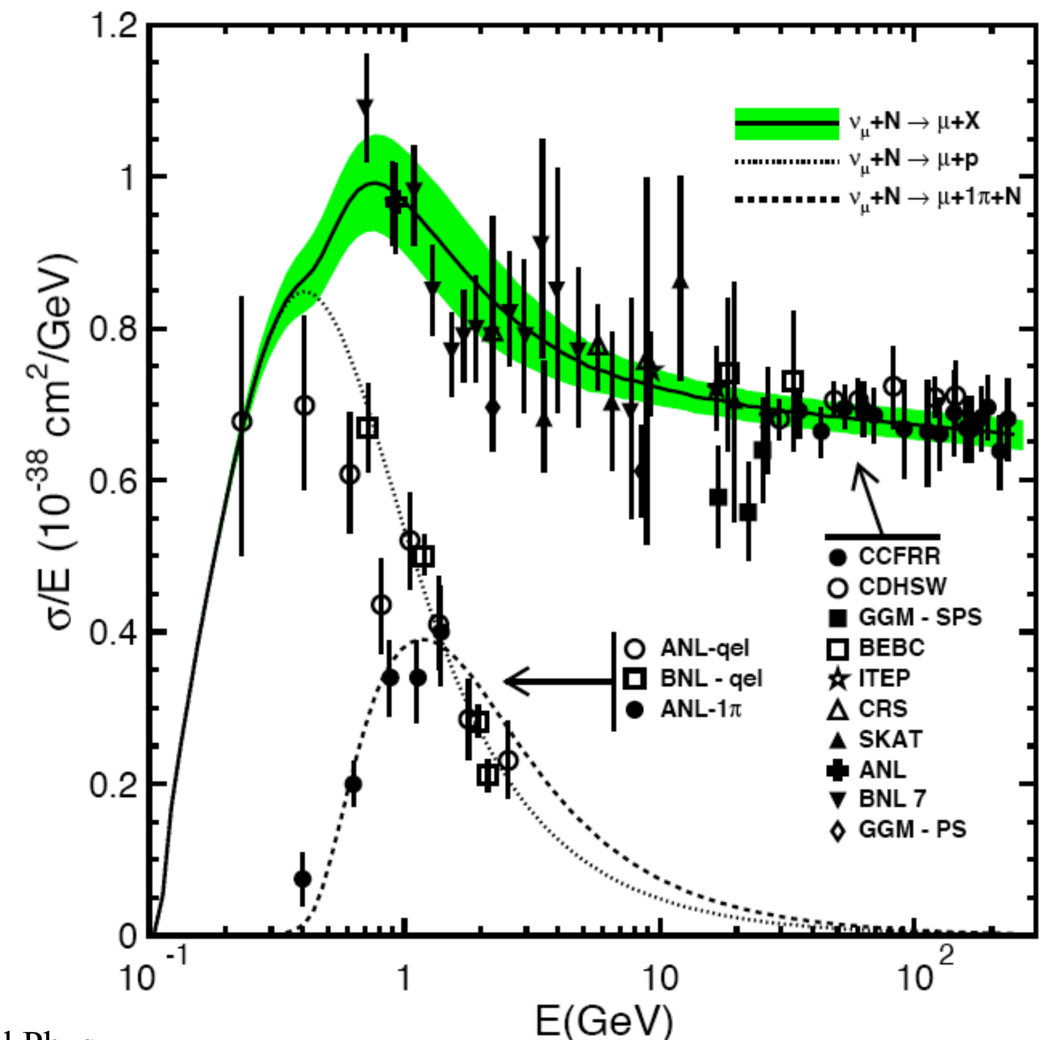
Quasi-Elastic: BBBA parametrization (arXiv: 0709.3538) of form factors with m_a=0.99 GeV/ c^2.

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

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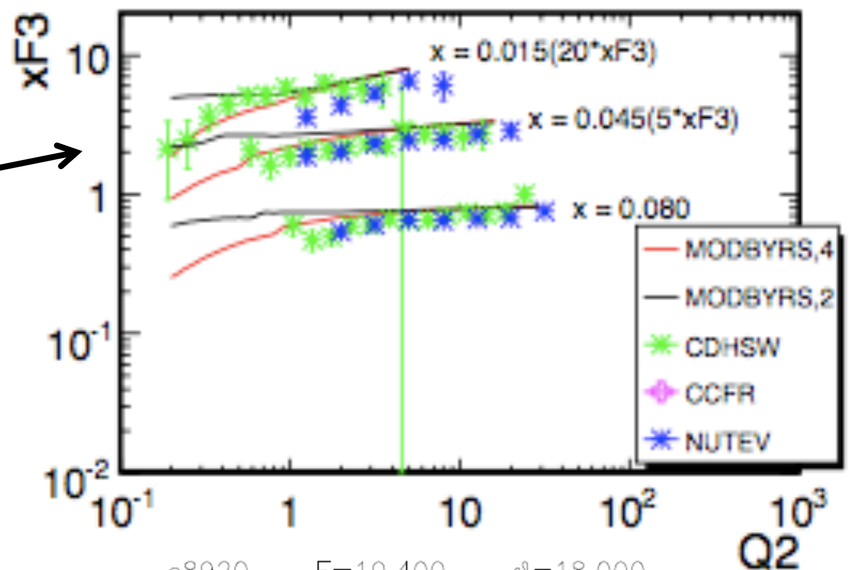
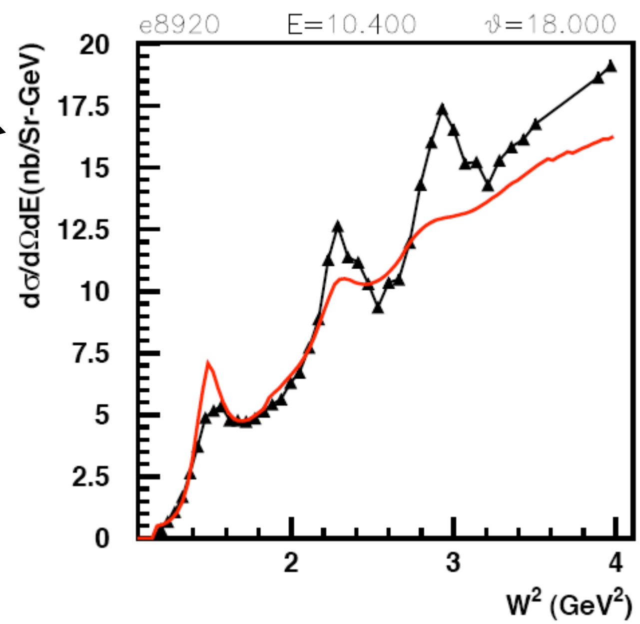
In tuning the cross section model we proceed in several stages:

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.



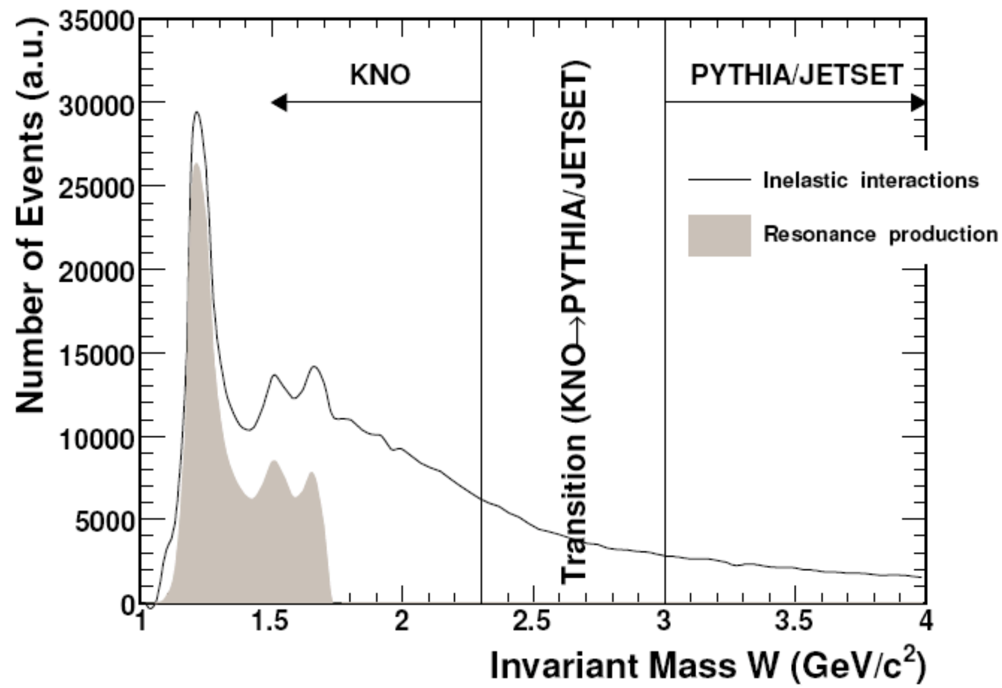
3) Tune remaining parameters to neutrino total cross section and single pion data.

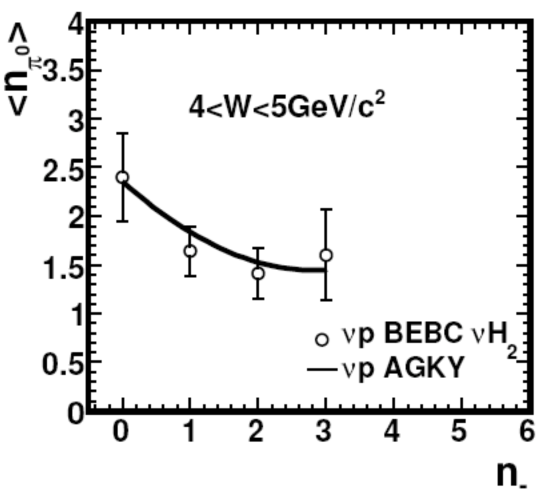
AGKY Hadronization Model

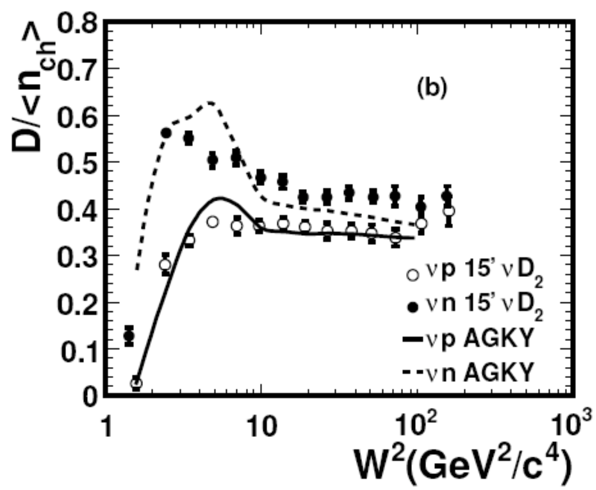
T. Yang et al., "A Hadronization Model for the MINOS Experiment", AIP Conf. Proc.967:269-275 (2007).

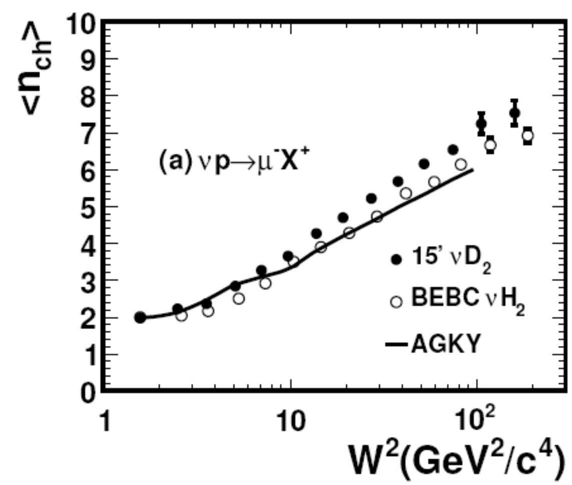
AGKY model - combining an empirical model ("KNO") with JETSET at high invariant mass.

Extensively tuned to bubble chamber data.









AGKY Hadronization Model

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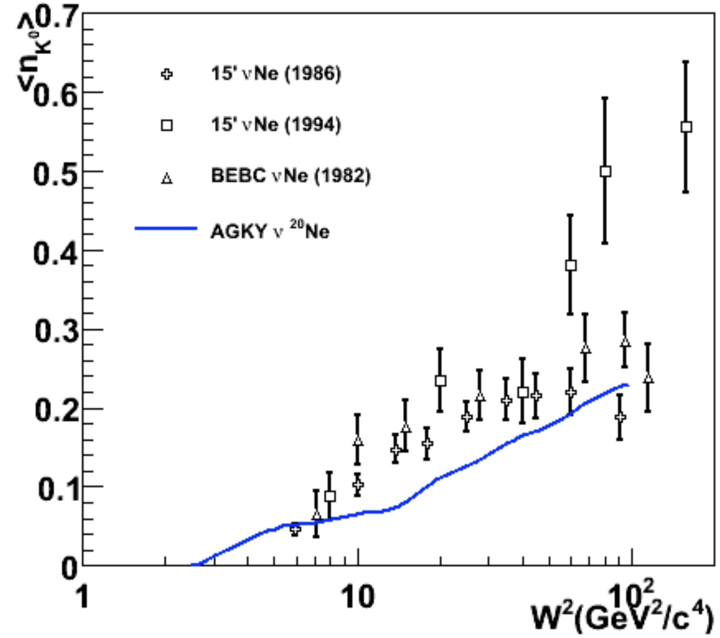
Select particle content:

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

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

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

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%

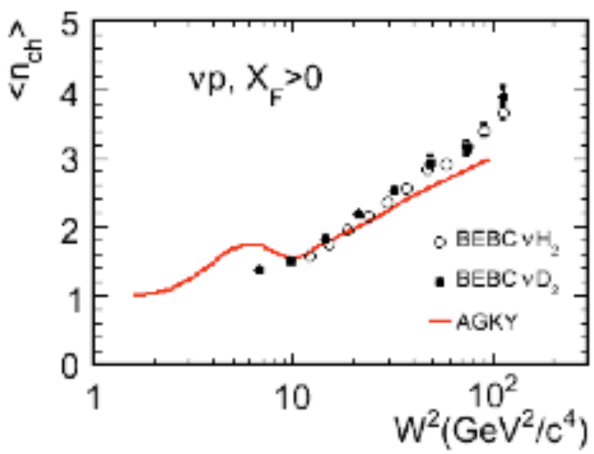


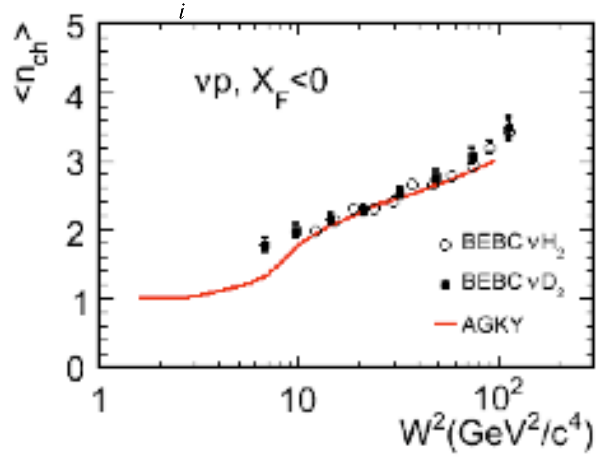
Assign 4-vectors in CM:

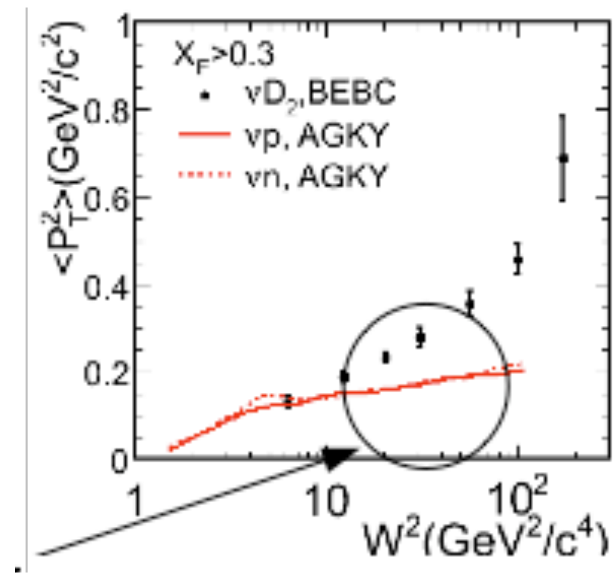
Select baryon 4-momentum from empirical distribution $P(x_F,p_t)$.

Phase space decay remaining hadronic system

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





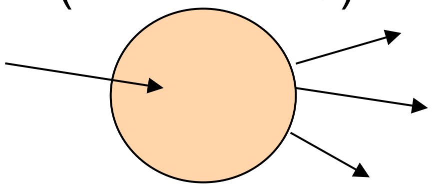


The GENIE hadron transport modelling

Currently **have 2 alternative models** (using different techniques) –

Development of both is **led by Steve Dytman**

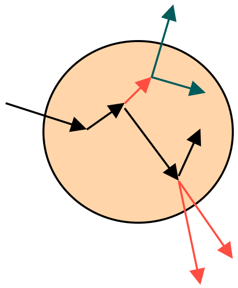
Intranuke / hA
(effective MC)



Anchored to a large body of experimental data
(including hadron+nucleus data)

available since 2.0.0

Intranuke / hN
(true cascade MC)



Builds everything up from hadron-nucleon xsecs

In advanced development stage
to become available soon

Intranuclear Rescattering

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

Hugh Gallagher
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For Neutrino Expts
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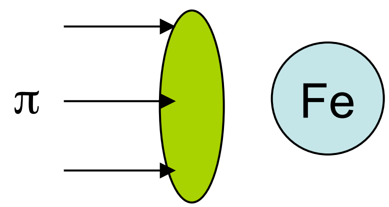
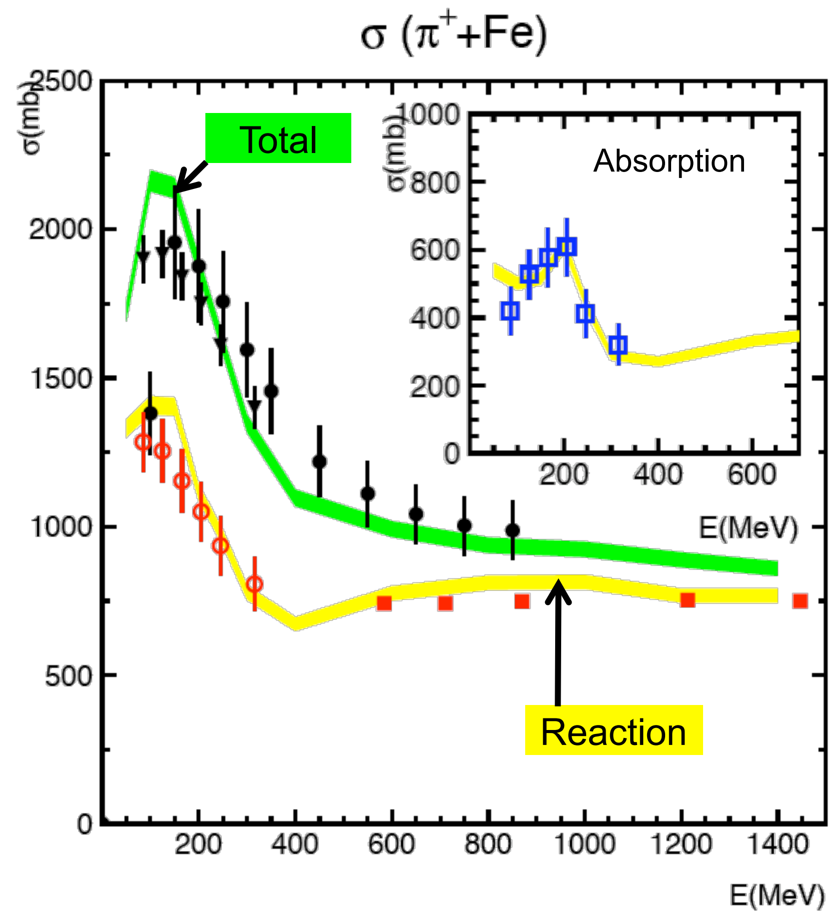
The model is compared *to hadron scattering data:*

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





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%

What's Needed / What's coming

Release 2.6.0 – next month

- *Updates to the BY model.*
- *Updates to the RS model form factors.*
- *Global cross section model re-tuning.*
- *Added diffractive scattering.*
- *Improvements in AGKY strange particle production.*
- *Finalized simulation of nucleon emission from short range nucleon-nucleon correlations.*

What's Needed / What's Coming

Release 2.8.0 – later 2009

- *New INTRANUKE/hN model fully validated*
- *Upgraded nuclear model based on spectral functions fully validated*
- *Added elastic coherent scattering.*
- *Added option for non-isotropic 2-body RES & DIS decays using the angular distributions of D.Allasia, Nucl.Phys.B343 (1990) 285-309.*
- *Added option for W-dependent baryon (target fragment) xF distribution in the AGKY hadronization model.*
- *Collected & released many of the GENIE physics validation tools*
- *Formation-zone modifications.*

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

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For Neutrino Expts
Fermilab, Mar 13, 2009

Overall Model Uncertainties, including nuclear effects:

- Total cross section: 3.5%
- M_A: 15% for both quasi-elastic and resonance production
- Transition region parameters: $r_{ij2}\pm0.1$, $r_{ij3}\pm0.2$.

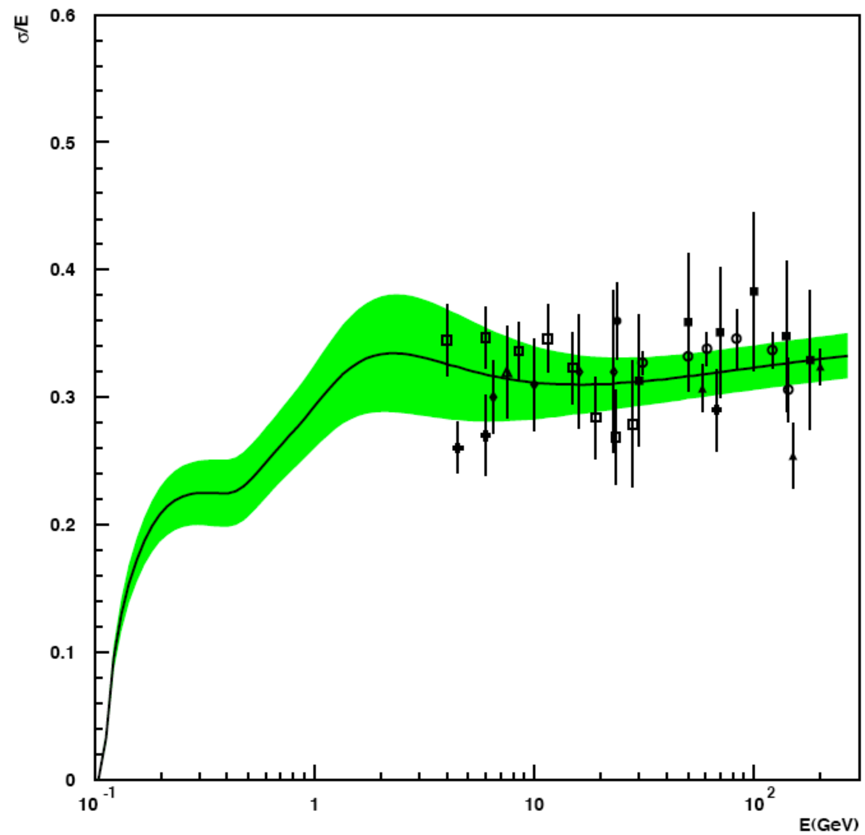
Anti-neutrino/neutrino cross section uncertainty:

- overall: 4%
- QEL/RES: 8%
- Transition region parameters: $r_{132}\pm0.2$, $r_{i42}\pm0.2$.

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).



The GENIE Tool-kit

Many tools are included in GENIE.
Of particular importance to experimentalists is the ability to :

Handle interaction modelling uncertainties using event reweighting

- can propagate a host of uncertainties and generate err envelopes for any observable
- can fit interaction models to near detector data / tune MC

Generate events for realistic detector geometries & neutrino fluxes

- **Off-the shelf components for <u>very complex</u> event generation cases**
  - *Flux changing across the detector*
  - *Complex geometries, multiple target materials*
  - *Beam-related backgrounds by interactions in non-active materials (cavern walls, etc)*

- **Important for high statistics experiments**

We can have concrete examples at the practical sessions

Event reweighting

Use one sample to emulate another...

Can be used to propagate vA uncertainties to analyses, bug-fix precious large samples

2 popular use-cases

- **Reweight from a fixed set of {models/configuration} A to another fixed set B**

eg reweight a generated sample to an improved / bug-fixed release

- **Given a set of models, reweight for changes in the configuration**

eg, given QEL model, propagate effect of Ma uncertainty

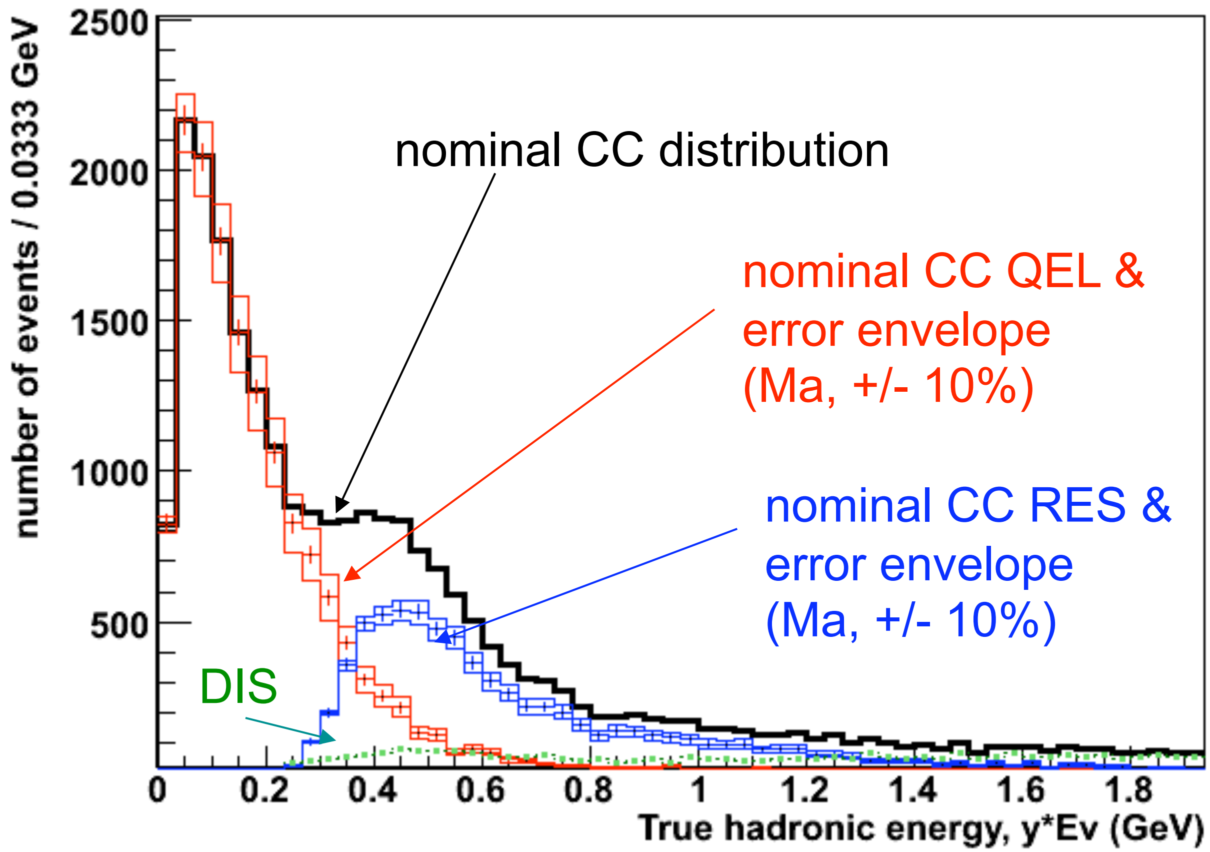
What can be reweighed ?

- **Quite easily / generically**
  - *The cross section model*
- **Less easily / generically but perfectly doable**
  - *Many aspects of the hadronization model*
  - *Many aspects of the Intranuclear hadron transport model*
- **Not easily or not at all doable**
  - *Nuclear model?*
  - *Cascades?*
  - *External (black-box) packages – eg JETSET, FLUKA*

Cross section reweighing: example

Example GENIE nd280 numu+O16

Tweaked Ma-QEL and Ma-RES by +/- 10%



Costas Andreopoulos, *Rutherford Appleton Lab.*

NuValidator

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Distributed as part of GENIE:

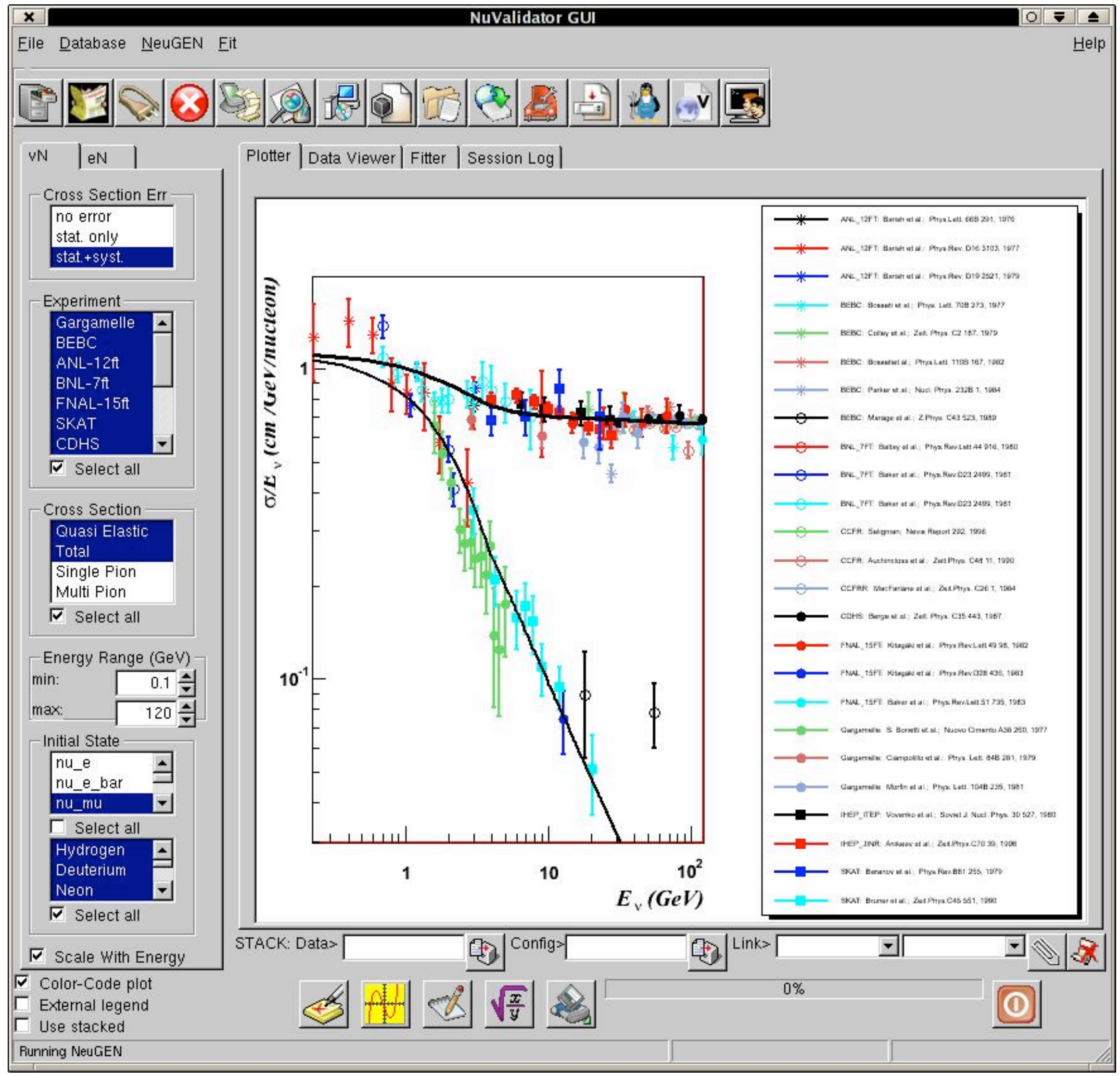
Optional package in the build process.

Loads external data for model comparison into mySQL database.

Primary data source is:

Durham Neutrino Cross Section Database
(M. Whalley, NuINT04)

http://durpdg.dur.ac.uk/hepdata/online/neutrino/



GENIE for event generation

Generating full MC samples brings together:

Beam simulation (flux histograms, beam ntuples)

detector geometry (locations, densities, isotopic composition)

event generator (cross sections, produces events)

GEANT4 (energy losses in active elements)

detector simulation (converting energy deposition to readout)

reconstruction

GENIE contains "event generation drivers" to handle the job of bringing the fluxes, geometry and generator together to produce initial neutrino interactions distributed throughout the detector.

GENIE for event generation

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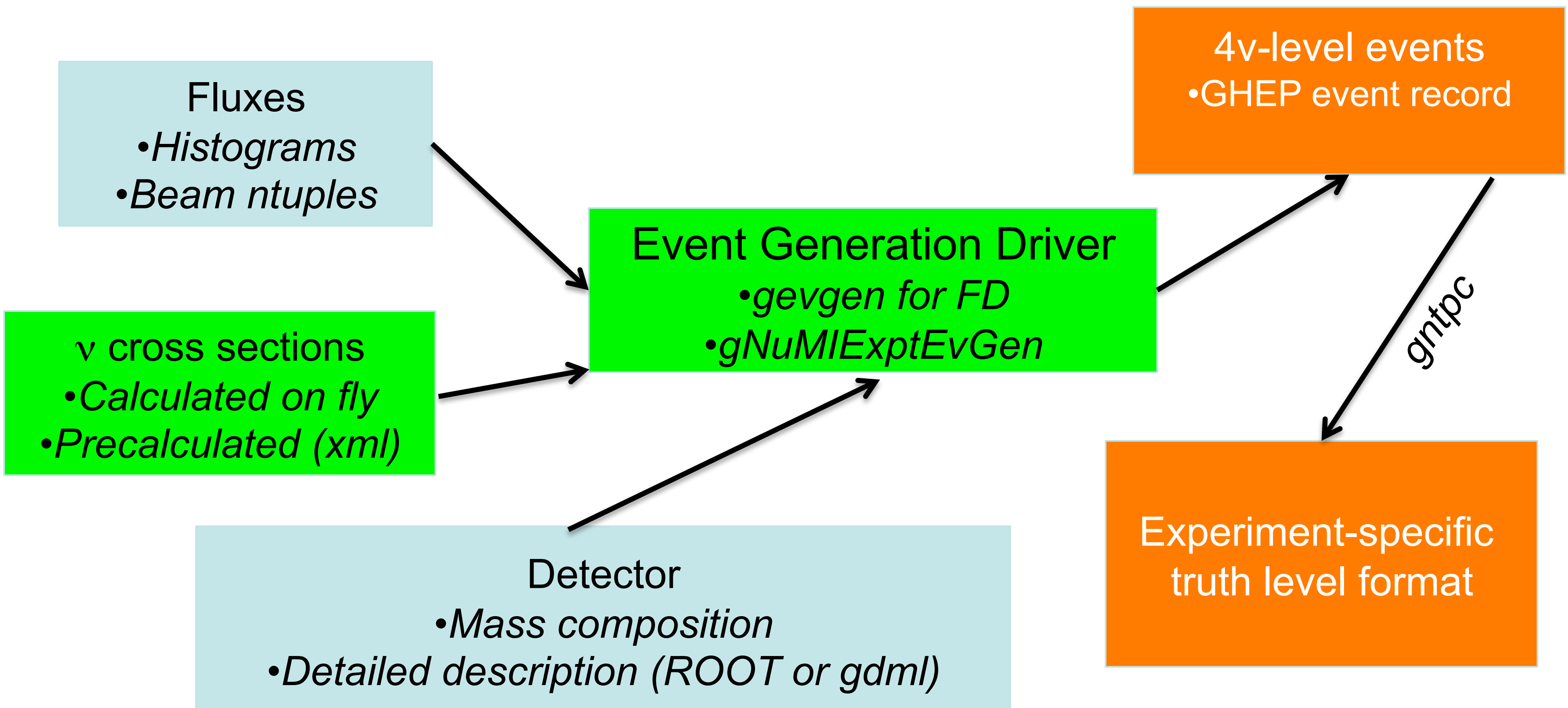
The basic model is that event generation and particle tracking through the detector (GEANT) happen in separate stages.



Event Generation + GEANT?

In my experience the MC is particularly vulnerable to mistakes that can affect analyses. Errors can easily hide in fully reconstructed MC samples.

New MC samples appear relatively infrequently (every year or so?) and when they are produced many, if not all, of the inputs have changed.

Establishing rigorous validation procedures for all inputs and sticking to them is vital. Kregg Arms did an outstanding job at this for MINOS.

Separating generation from detector simulations helps here!!

Generator Tuning

Why package the data with GENIE?

- Important for when data or models change over time.
- Important for piecing together different models.
- Important to be able to evaluate for ourselves the goodness-of-fit of models
- Important for being able to evaluate systematics associated with the models.

"Default tuning". What should a user who is trying to design a new experiment in a particular energy range get by default. "Black box" mode.

Experimental versions. How do experiments individually tune pieces of the program to fit their data? How do these changes get propagated back to the main program and the default configuration?

Food for Thought

This model where the event generator is not “in-house” is new to many of us.

Work by the key developers (read: Costas) is driven by experimental needs and timelines.

What is the best way for a collaboration to interface with the GENIE collaboration?

- Clearly stated deadlines (we need a new version tagged and validated by XXX).
- Clearly stated priorities for model development work.
- Providing effort for model development work.
- Participating in the validation efforts for official GENIE releases.
- Cultivating expertise on the package within the collaboration.

Backup Slides

Backup Slides

NuMI Kinematic Coverage

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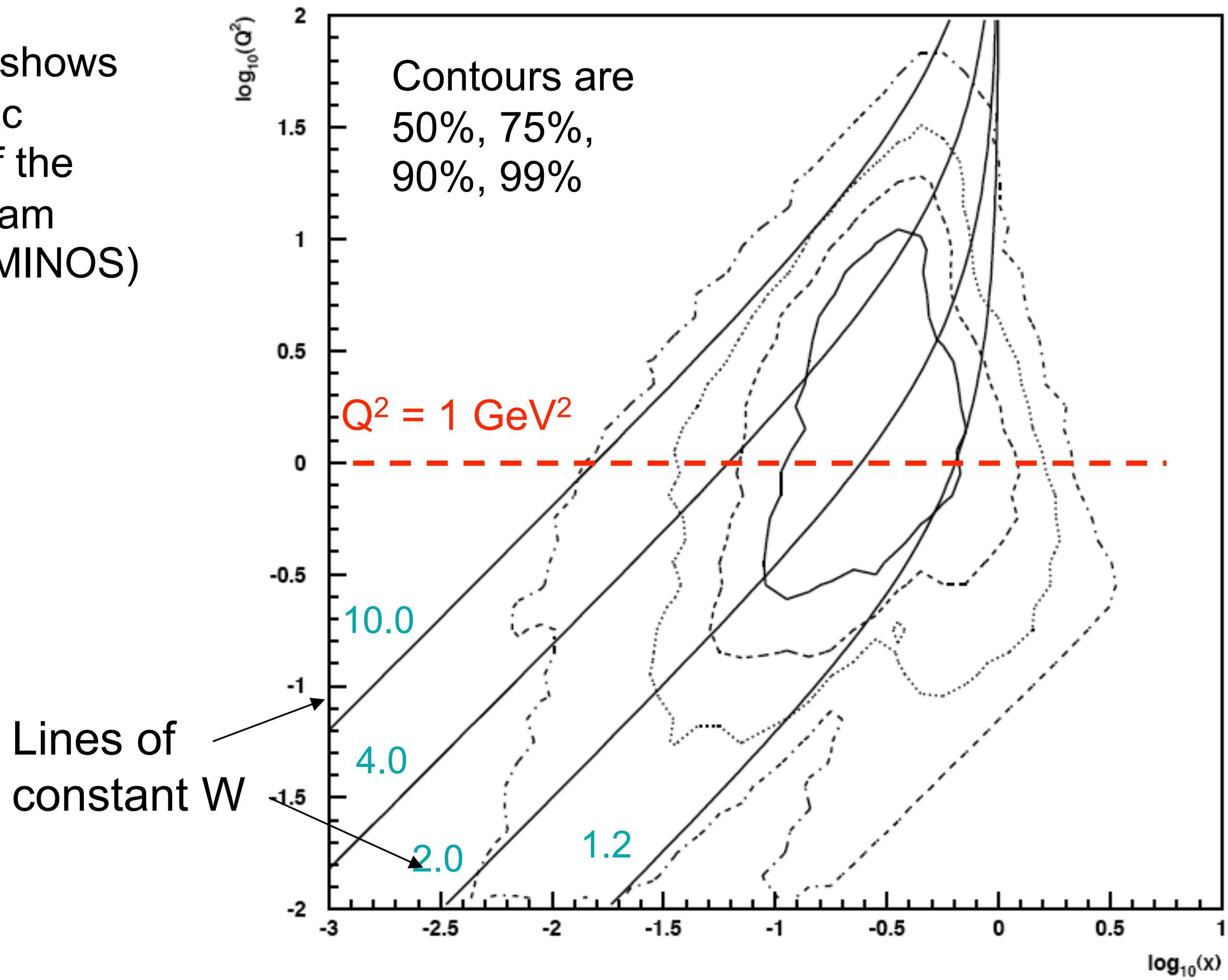
Plot at right shows the kinematic Coverage of the NuMI LE beam (default for MINOS)



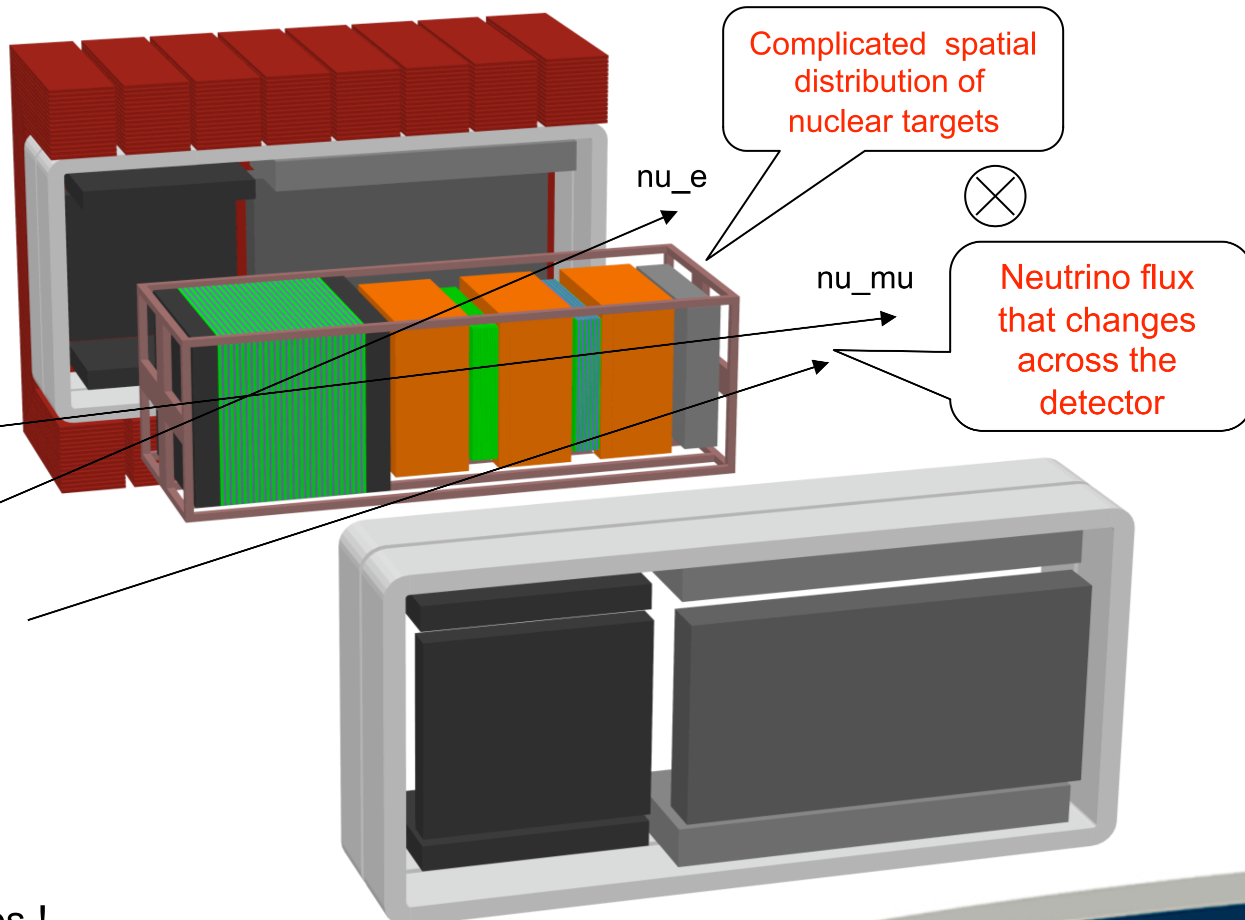
Using fluxes / geometries

Event generation:
A complicated convolution of things:

Neutrino generator's job is:
Generate an event once it is handed over an initial state
(nu + target, at a given energy)

The **problem** here is
how to select that initial state
(and take into account its energy and spatial dependence)

Eg in MINOS:
6 neutrino flavours X
~60 (!) isotopes in detector geom =
360 possible initial states



BTW, the generator should handle all these initial states !

Neutrino fluxes and detector geometries

A number of concrete flux and geometry drivers are included. More can be trivially added

fluxes

- *GJPARCNuFlux*: An interface to the JPARC neutrino beam simulation [8] used at SK, nd280, and INGRID.
- *GNuMIFlux*: An interface to the NuMI beam simulations [9] used at MINOS, NOvA, MINERvA and ArgoNEUT.
- *GBartolAtmoFlux*: A driver for the Bartol atmospheric flux by G. Barr, T.K. Gaisser, P. Lipari, S. Robbins and T. Stanev (cite)
- *GFlukaAtmo3DFlux*: A driver for the FLUKA-based 3-D atmospheric neutrino flux by A. Ferrari, P. Sala, G. Battistoni and T. Montaruli [?]
- *GCylindTH1Flux*: A generic flux driver, describing a cylindrical neutrino flux of arbitrary 3-D direction and radius. The radial dependence of the neutrino flux is configurable (default: uniform per unit area). The flux driver may be used for describing a number of different neutrino species whose (relatively normalised) energy spectra are specified as ROOT 1-D histograms. This driver is being used whenever an energy spectrum is an adequate description of the neutrino flux.
- *GMonoEnergeticFlux*: A trivial flux driver throwing mono-energetic flux neutrinos along the +z direction. More that one neutrino species can be included, each with its own weight. The driver is being used in simulating a single initial state at a fixed energy mainly for probing, comparing and validating neutrino interaction models.

geometry

- ROOT/Geant4-based geometries
- Simple target mix, eg. "*40%O16 + 20%C12 + 40%H1*"

Expt.-specific event generation drivers

Using these off-the-self components to build expt-specific event generation drivers

A driver that handles the JPARC beam-line experiments was added in v2.4.0

- *Handles the JNUBEAM flux simulation outputs*
- *Handles the SuperK, nd280, Ingrid, 2km, detector geometries / target mix...*

A driver that handles the NuMI beam-line experiment is being added in v2.5.1

- *Handles the GNUMI flux simulation outputs*
- *Handles the MINOS, MINERvA, … , … detector geometries*