Event Generator Review

Hugh Gallagher

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European Physics Society – HEP 2011

Grenoble, July 22, 2011

Thanks to: C. Andreopoulos, S. Dytman, Y. Hayato, T. Leitner, U. Mosel, G. Smirnov, J. Sobczyk, S. Zeller

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

1852

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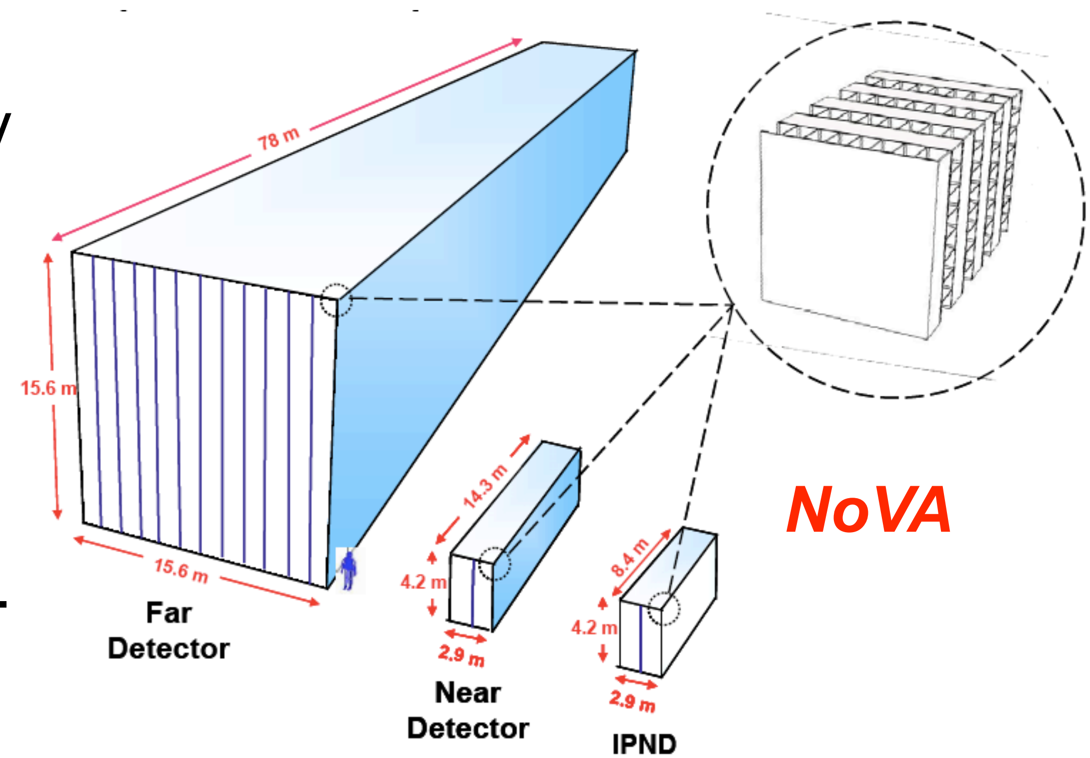
Use by Experiments

Neutrino event generators are unique among the tools required to successfully envision, design and execute experiments in that they play vital roles "from cradle to grave".

Infancy – generators are used to estimate sensitivity of proposed experiments and in making detector design optimization decisions.

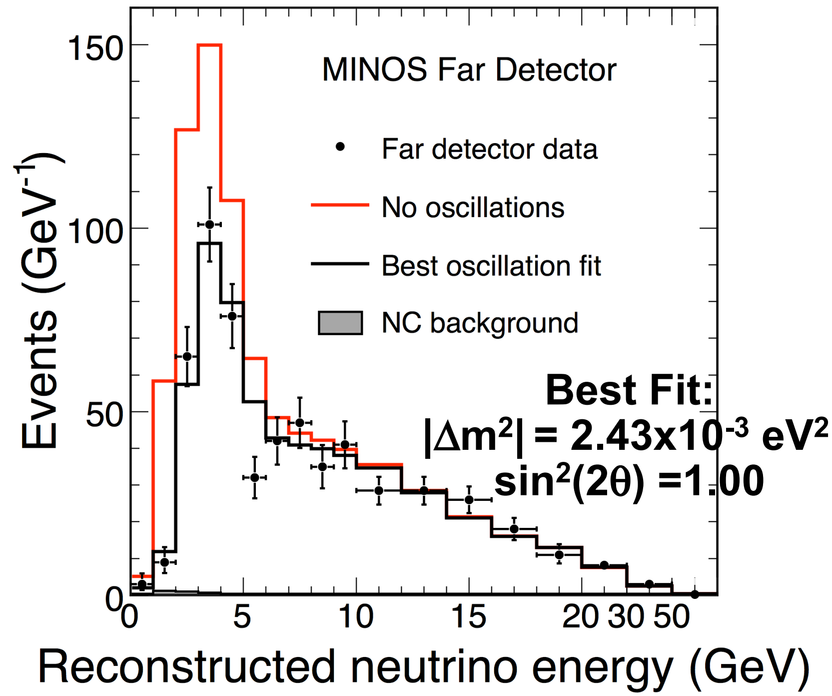
Resolution vs. statistics vs. background rejection vs. ?



Use By Experiments

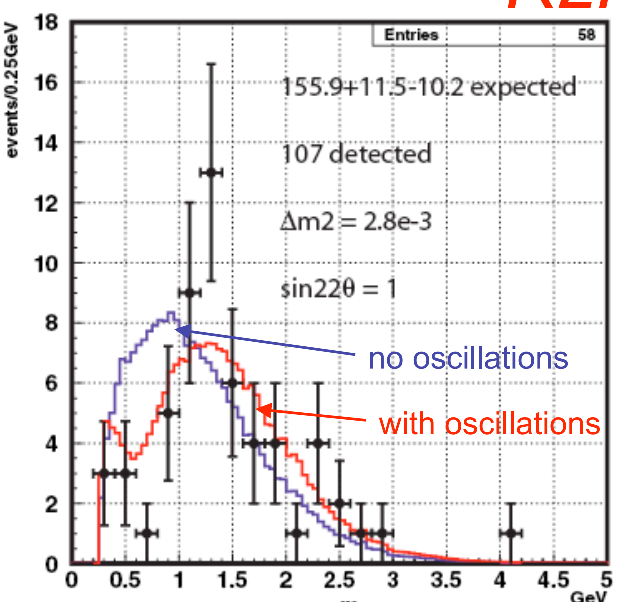
Event generators provide the backdrop against which any putative signal is measured and provide the best "expectation" in the absence of new physics.

MINOS



MINOS: Neutrino 2008.

K2K



E. Aliu et al. Phys. Rev. Lett. ***94****, 081802 (2005).*

Particularly crucial in the early days of an experiment as discrepancies between data and expectation are being investigated.

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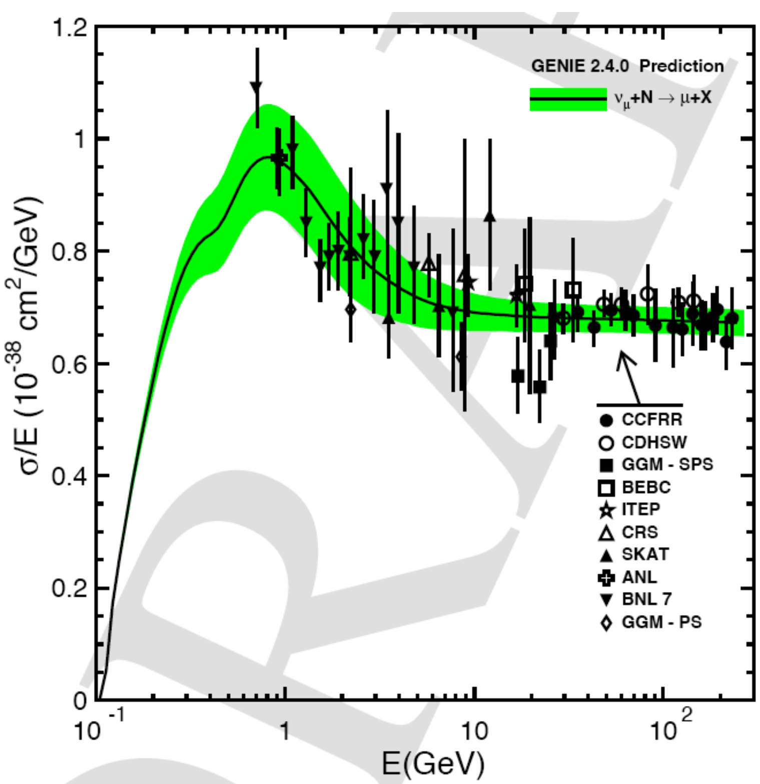
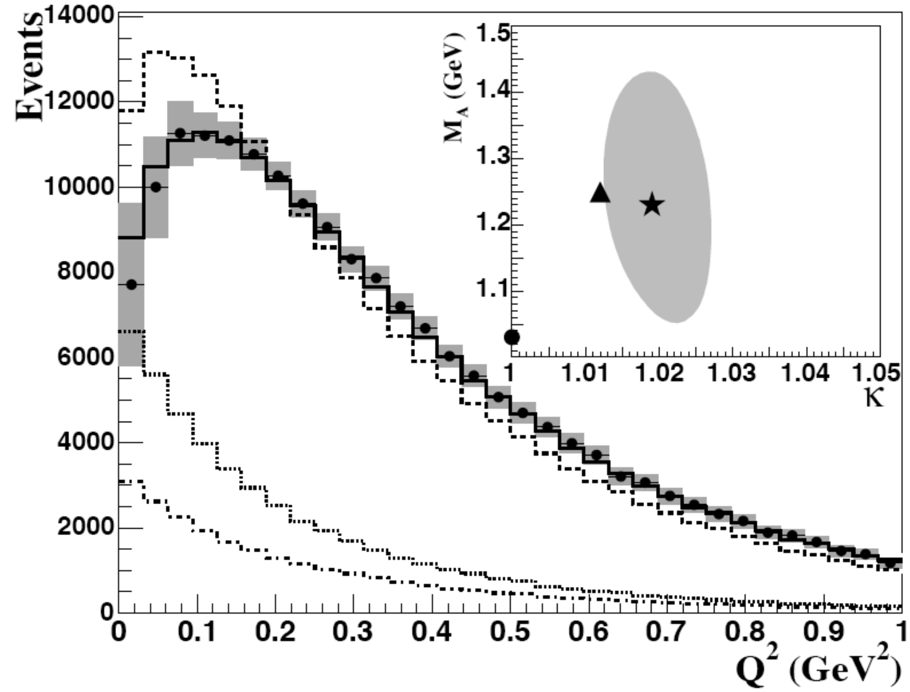
As the interface to the models, event generators are used in analyses all the way up to the final steps.



miniBoone – CCQE-like



Fitting models to data.

Evaluation of model-related systematic uncertainties.

Practicalities

The generation of large analysis Monte Carlo samples for an experiment can consume significant manpower and computing resources. Separate Monte Carlo samples required for each detector/beam configuration.

Rough numbers from MINOS ND Generation:

One Monte Carlo job produced files of around 16k events each, taking 6 hours and producing files of around 600 MB. Around 70k files generated total, ~25TB of data.

Producing an analysis sample for the ND (1.5 times data) required 4.5 months real-time of dedicated running at four sites, with a total of around 440 cores.

Requires a MC Coordinator (Kregg Arms) as well as production site managers.

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Event Generators - Challenges

In addition to these diverse uses, experiments are sensitive to different aspects of the physics and integrate these packages into their analyses in a variety of ways.

Unique Challenges

Experiments: Rapidly evolving

Theory: Rapidly evolving

Describing physics over a broad kinematic range

Lack of a ‘canonical’ package

SPIRES: ti ‘neutrino’ and ‘quasielastic’

Years	Theory	Experiment	Total
1965-1969	2	1	3
1970-1974	6	1	7
1975-1979	2	3	5
1980-1985	0	13	13
1986-1990	2	6	8
1991-1994	10	1	11
1995-1999	5	1	6
2000-2004	23	1	24
2005- 2010	39	20	59
Total	89	47	136

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Event Generation

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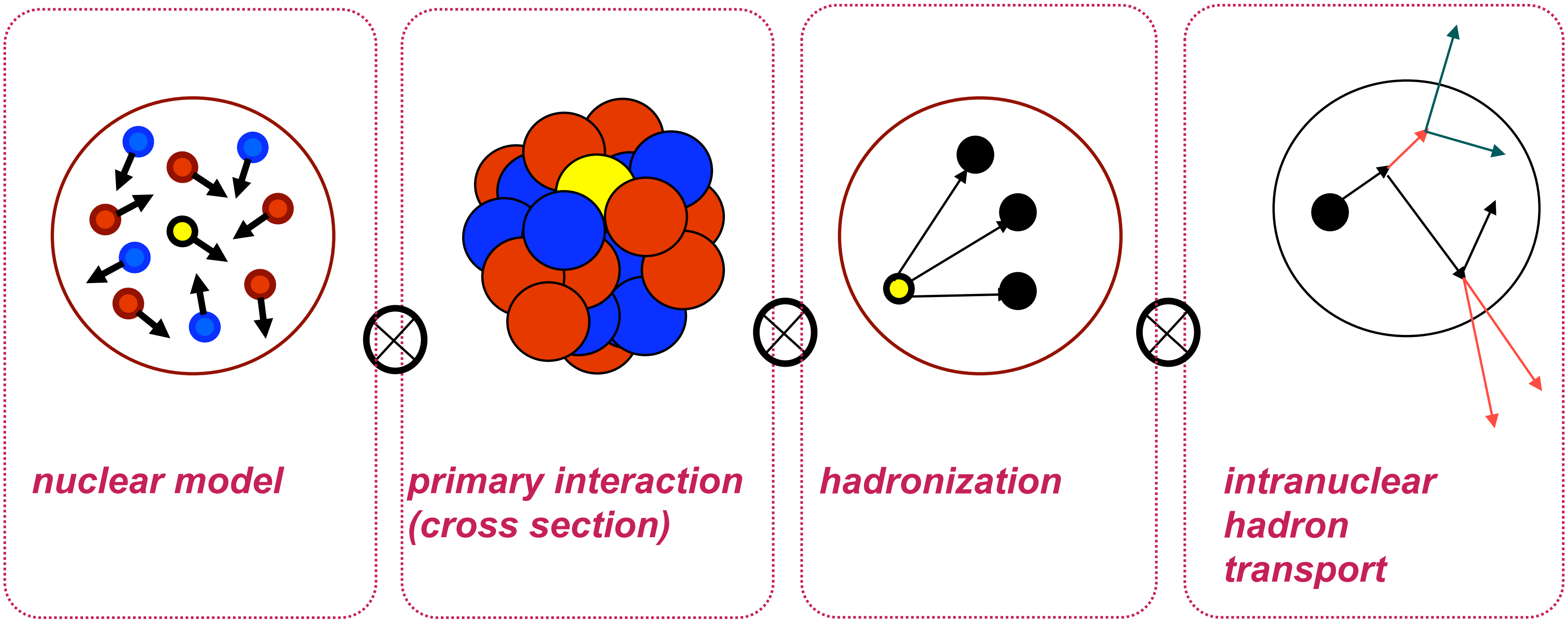
1) Choose E_ν, flavor, and target nucleus from (σ_{tot}, ϕ, ρ, L)
2) Choose interaction type j from $\sigma_{tot} = \sum \sigma_j$
3) Choose kinematics (x,y) from cross section model for σ_j (with nuclear mods)
4) Determine particles in hadronic system (inside the nucleus)
5) Propagate particles in hadronic system through the nucleus, decay

C. Andreopoulos



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Physics Models

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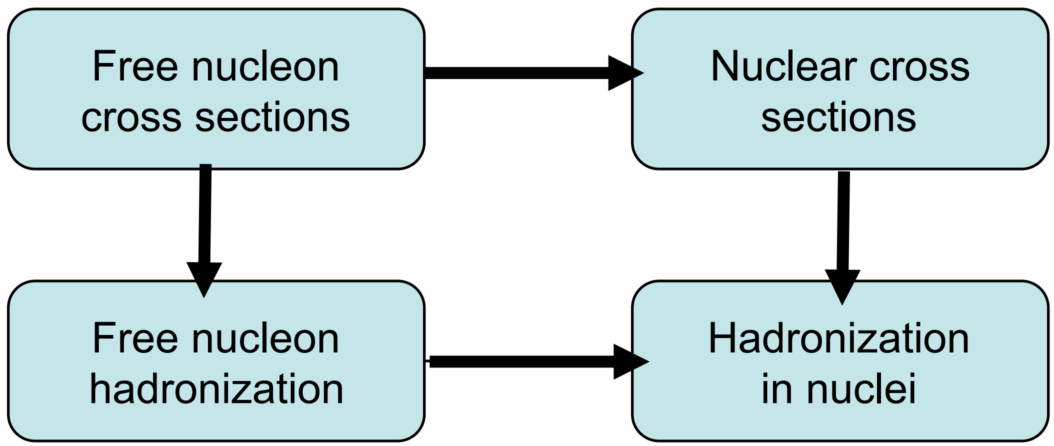
Cross Section Model

1. *Quasi-elastic: form factors*
2. *Resonance production: model choice, form factors*
3. *Non-resonant Inelastic: transition to DIS*

Nuclear Cross Section Model

1. *Coherent production*
2. *Modifications due to Fermi motion, nuclear binding, shadowing, N-N correlations…*



Hadronization Model

1. *Resonance states: C-G coefficients*
2. *Non-resonant inelastic: string-based (JETSET), phenomenological models*

Hadronization Model in Nuclei

1. *Hadron formation zones*
2. *Hadron re-interactions in the target nucleus*

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Challenges – Cross Sections

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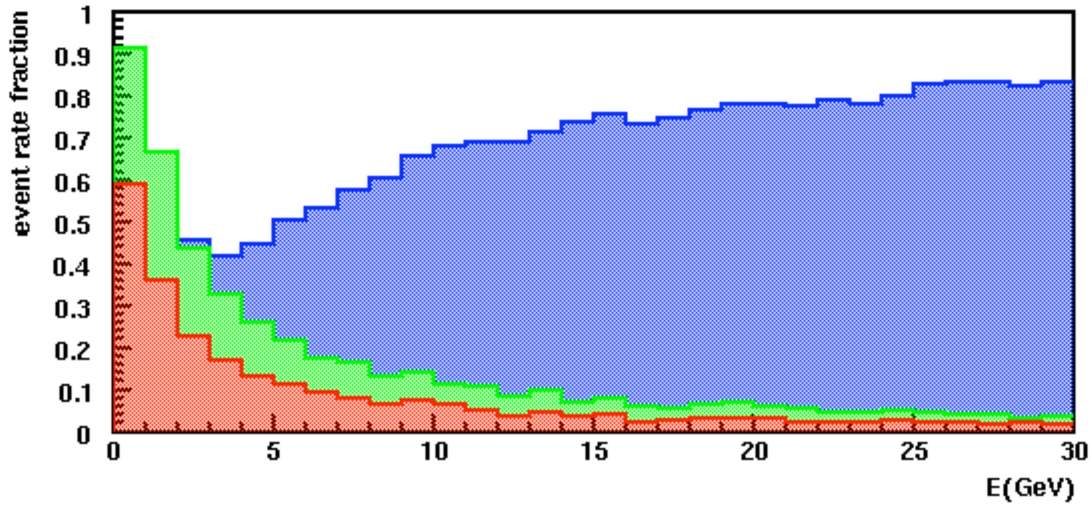
Previous experiments (pre 2000) focused on 3 regimes:

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

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Challenges - hadronization

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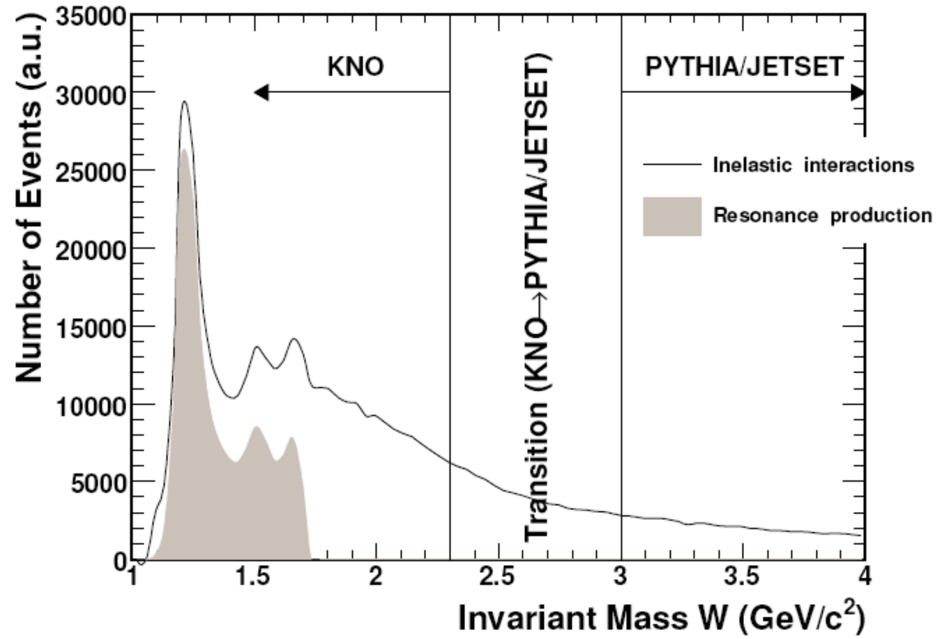
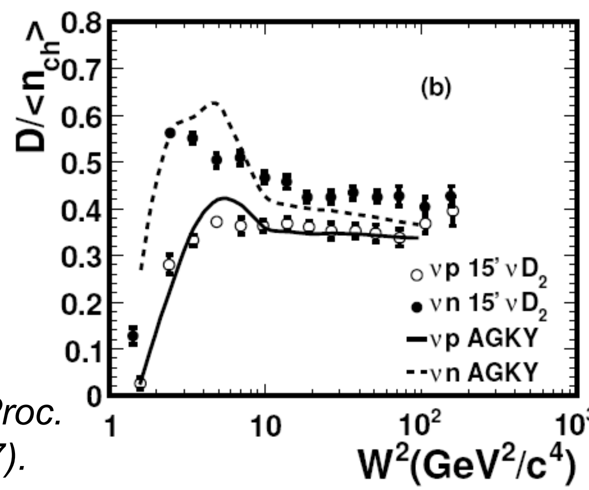
For few-GeV neutrinos a large fraction of data come from non-resonant inelastic states which have invariant masses too low to be comfortably handled by standard packages like JETSET. (45% of events for E_ν= 3 GeV).

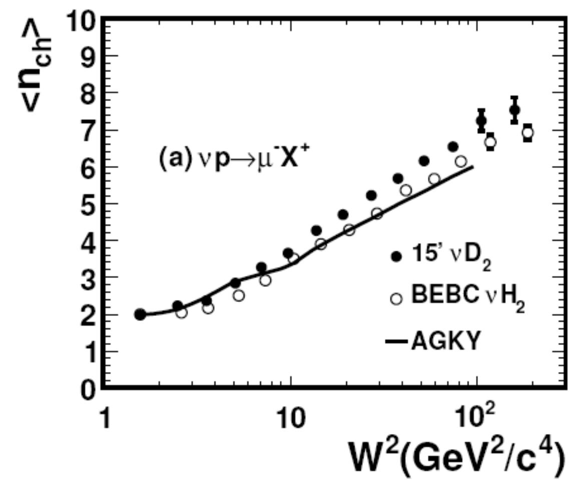
Tuning done to bubble chamber experiments, where measurements of charged hadrons was easier than neutral hadrons.

“Gap” in a key area - neutral pion measurements from free nucleons at low invariant mass.

T. Yang, NuINT07.







T. Yang, AIP Conf. Proc. 967:269-275 (2007).

Challenges – Nuclear Physics

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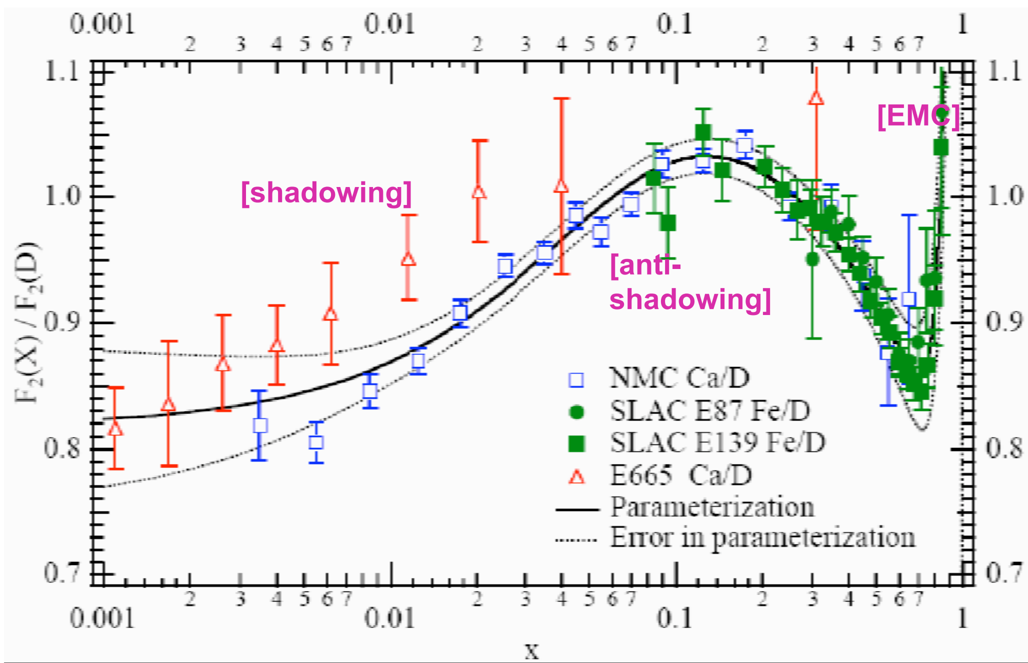
Fermi gas, spectral functions, other nuclear models.

Effects of short and long-range correlations, MEC, 2p-2h processes

Effects of final state interactions, intranuclear rescattering…

Modifications of structure functions (shadowing, EMC effect).



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Where are the events?

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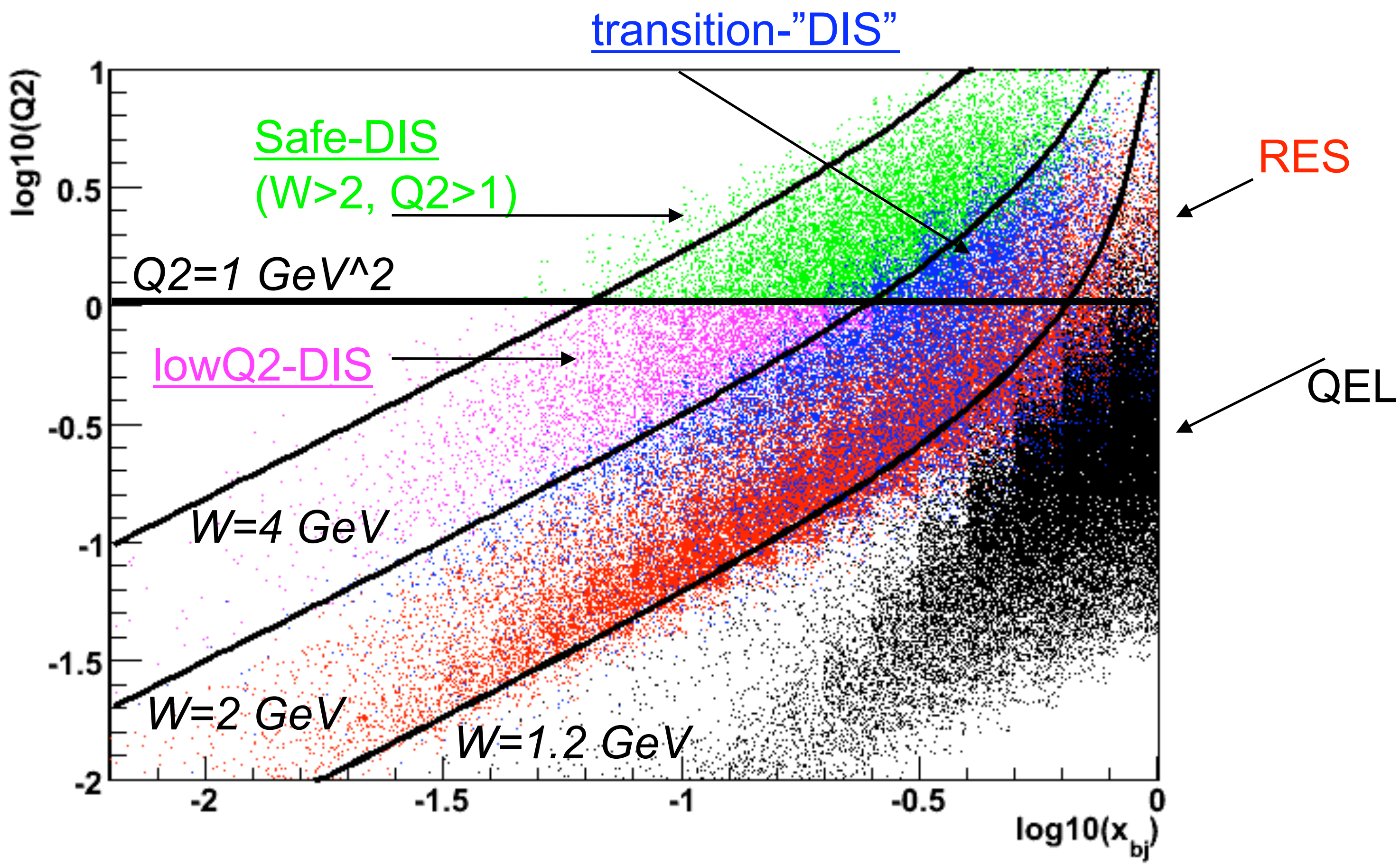
Kinematical coverage

JPARC neutrino beam @ nd280 site



Validation and Tuning

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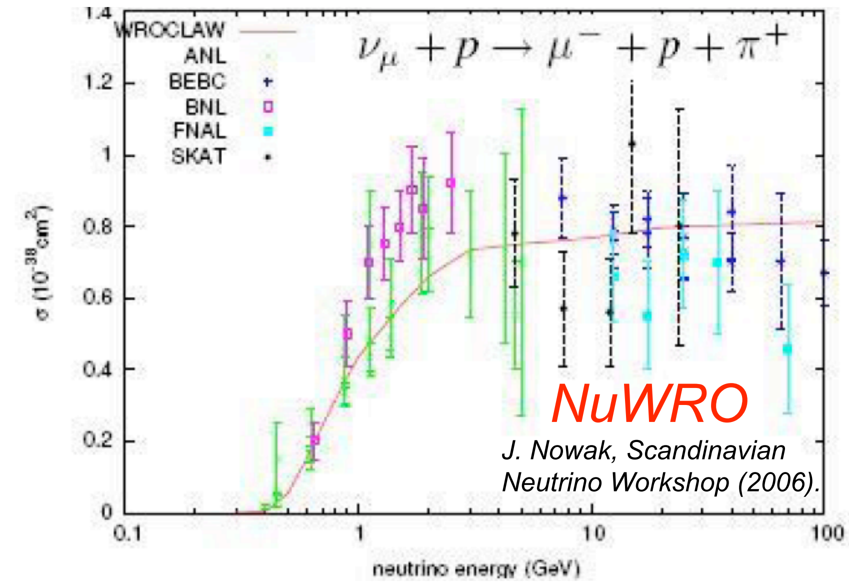
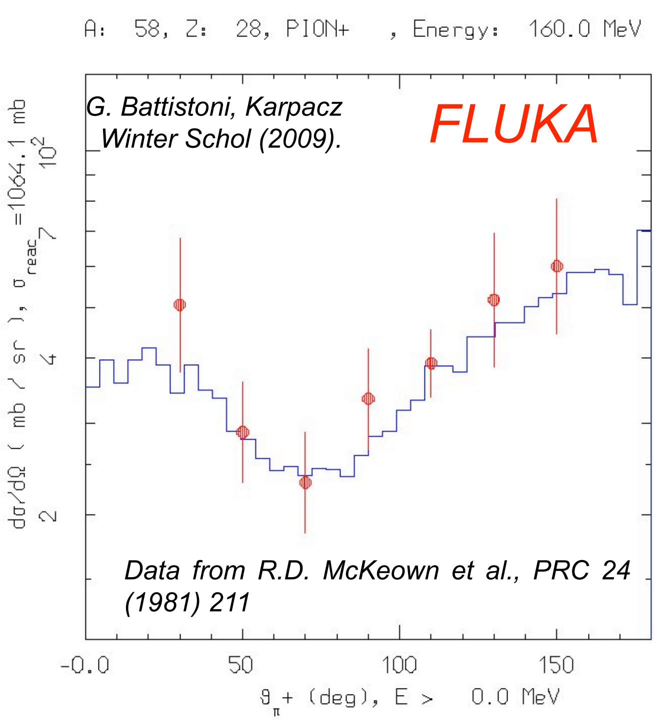
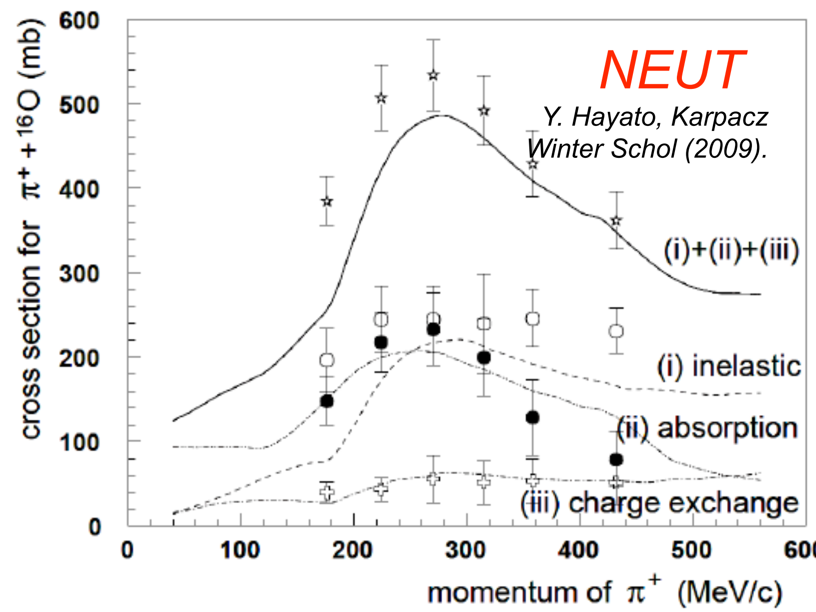
Neutrino Event Generators are tuned and validated using a wide variety of experimental data: neutrino data, charged lepton data, hadron scattering data, photo-production data all have relevance.







Oscillation experiments and ν physics models

- MINOS: ν_μ disappearance
- K2K: ν_μ disappearance
- miniBoone: ν_e appearance
- NoVA/T2K: ν_e appearance
- CHORUS/OPERA: tau appearance
- NOMAD: tau appearance
- Future multi-purpose expt (e.g. SUSY proton decay)

Cross section models:

- Low Q^2 DIS / transition region
- NC
- $\sigma_{1\pi}/\sigma_{qel}$
- Coherent production
- Charm production
- Hadonization modeling

Nuclear model:

- Low Q^2 scattering
- FSI - topology changes
- FSI – effect on calorimetry

Misc:

- Rare electron-like processes
- Tau polarization
- $\Delta S=1$ anti-neutrino modes

FLUKA

FLUKA: A. Fassò, A. Ferrari, J. Ranft, P.R. Sala
http://www.fluka.org

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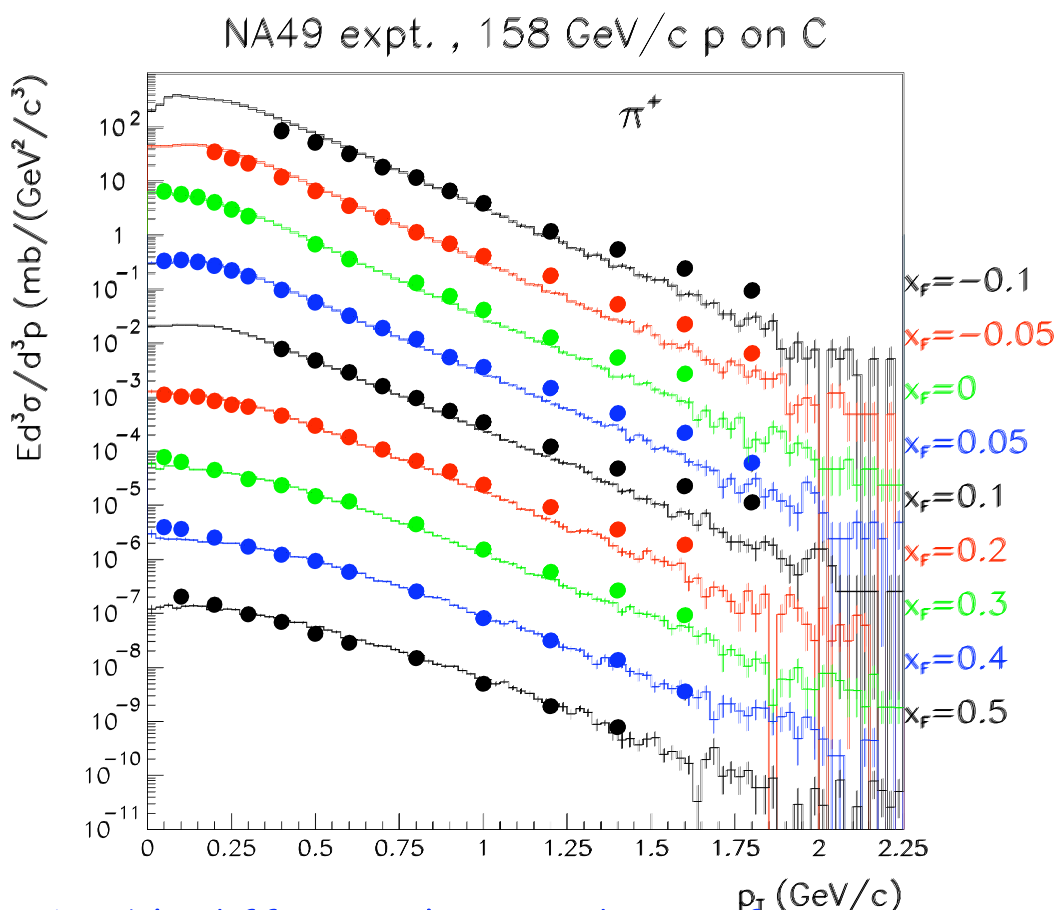
Build on success of FLUKA: Over 2000 users in cosmic ray physics, accelerator design, particle physics detector simulation, shielding design, dosimetry, medical applications…

Based on original and well-tested microscopic models, minimizing free parameters. An integrated set of physics models – not a toolkit. Correlations preserved within interactions and among shower components.

The same models should be valid in neutrino interactions.

Nonelastic hA interactions at high energies



Double differential $\pi+$ production for p C interactions at 158 GeV/c, as measured by NA49 (symbols) and predicted by FLUKA (histograms)

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Neutrino generators in FLUKA

QEL included since 1997

NUX-FLUKA (A. Rubbia): DIS only, for ICARUS collaboration.

Work on a DIS generator (NunDIS) and resonance production (NunRES) generator totally embedded in FLUKA started around 2005, available now in beta version in the standard FLUKA 2008 release.

GRV98-LO with extrapolation to $Q^2=0$

$$F_i(Q^2, x) = \frac{2Q^2}{Q_0^2 + Q^2} F_i(Q_0^2, x)$$

Resonance production based on Rein-Sehgal, with non-resonant component from NunDIS.

Hadronization using FLUKA routines. Recent improvements include a new treatment for low mass states, improving agreement with single pion data.

Transition fro RES to DIS: linearly transition in σ as a function of W

To be used by ICARUS.

GENIE

Primary author: C. Andreoupoulos
Hep-ex:arXiv(0905.2517)

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Users: T2K, MINOS, Minerva, NOVA, ArgoNEUT, microBoone, EU Lar R&D.

QEL: BBBA05 FF, M_A is 0.99 GeV/c^2

Resonance: Rein & Sehgal (K, ρ, η production, Δ-Nγ)

Coherent-π: Rein-Sehgal

DIS: GRV94/GRV98 with Bodek-Yang

DIS and QEL charm (S.G.Kovalenko, Sov.J.Nucl.Phys.52:934 (1990))

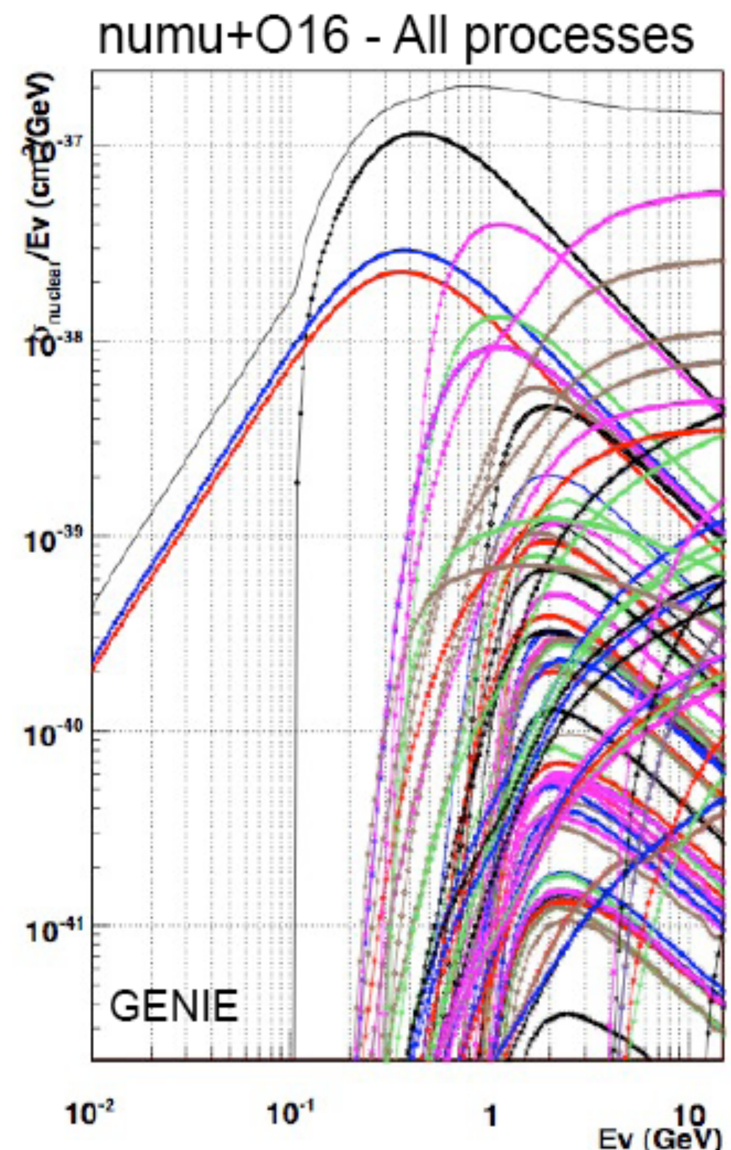
1π and 2π channels tuned in transition region to electron scattering and neutrino data.

Nuclear Model: RFGM with NN correlations

Hadronization Model: AGKY – transitions between KNO-based and JETSET
T. Yang, AIP Conf. Proc.967:269-275 (2007)

Formation zone: SKAT μ^2=0.08 GeV^2

Intranuclear Rescattering: cascade model
INTRANUKE-hA *(S. Dytman, AIP Conf Proc, 896, pp. 178-184 (2007))*
anchored to π,p/n-Fe data, scaled to all nuclei



Collaborations with theorists crucial: Alvarez-Ruso, Benhar, Paschos

GENIE *www.genie-mc.org*

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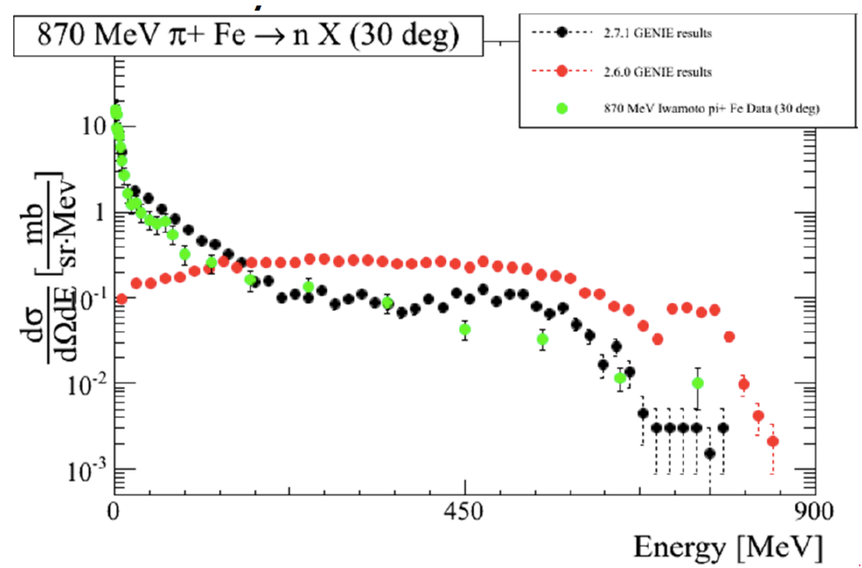
Coming in GENIE 2.8.0:

INTRANUKE-hN (S. Dytman, NuINT11)
Full INC code: 2 and 3-body cross sections +
Fermi motion, extensive use of PWA data (SAID)
Goal is to describe π,p,n,K in nuclei up to 2 GeV KE
Comparisons to hundreds of hadron-nucleus distributions

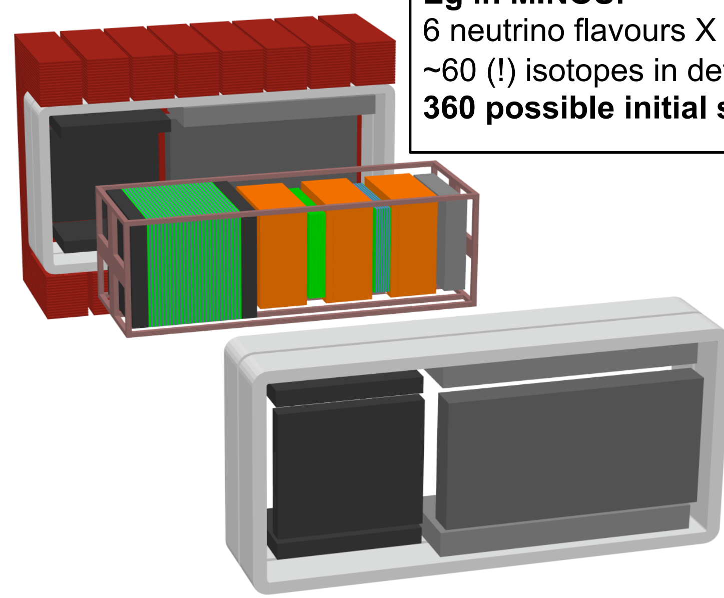


Numerous developments over the past several years have focused on software infrastructure needed by experimental users.

Flux Drivers

- Speed optimizations when generating events over complex detector geometries with neutrinos drawn from beam-line simulation ntuples.
- Inclusion of atmospheric neutrino flux drivers.

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



Event Reweighting

- Allows for efficient use of MC computing resources
- Evaluation of systematic errors

Dobson and Andreopoulos, Acta Physica Polonica B40:9, 2613 (2009).

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NEUT

Primary author: Y. Hayato

Nucl.Phys.Proc.Suppl.112:171-176,2002

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Initially developed for Kamiokande, used by SuperKamiokande, K2K, T2K, SciBooNE.

Generates events on all target nuclei

QEL: dipole FF

Resonance: Rein & Sehgal, including
- lepton mass effects
- K, ρ, η production
- Δ-Nγ decay

Coherent-π: Rein-Sehgal

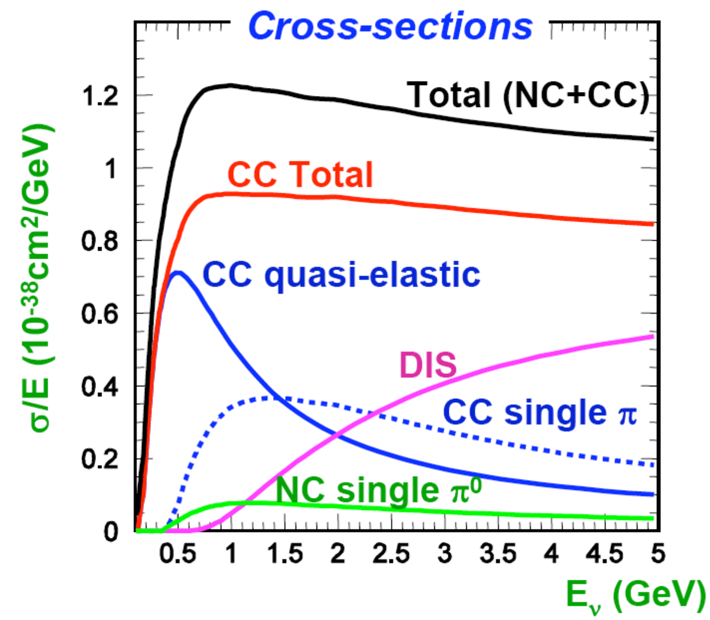
DIS: GRV94/GRV98 with Bodek-Yang

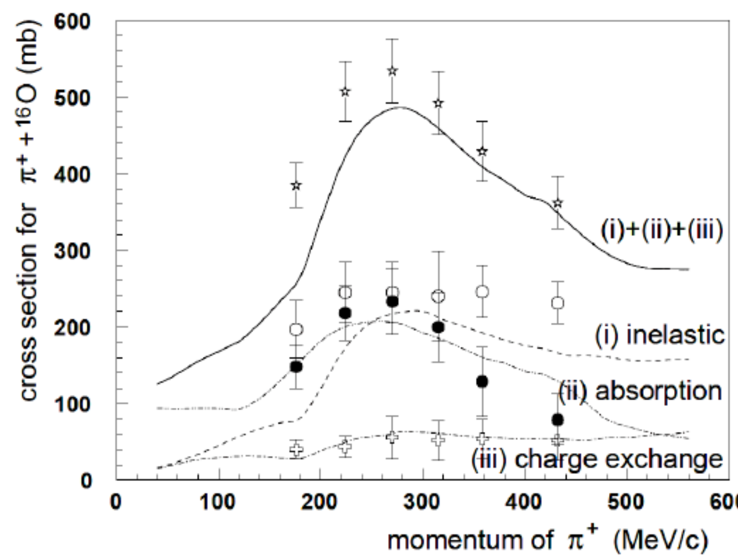
All 1π resonance-produced for W<2 GeV/c^2

Nuclear Model: RFGM Smith-Moniz

Formation zone: SKAT μ^2=0.08 GeV^2

Intranuclear Rescattering: cascade model
- p_π<500 MeV/c: radius and momentum dependent mfp
  k_F has radius dependence
- Kinematics from phase shift analysis of π-N scattering
- p_π>500 MeV/c: π−N σ used, multi-π prod taken from data





NEUT

Primary author: Y. Hayato

Nucl.Phys.Proc.Suppl.112:171-176,2002

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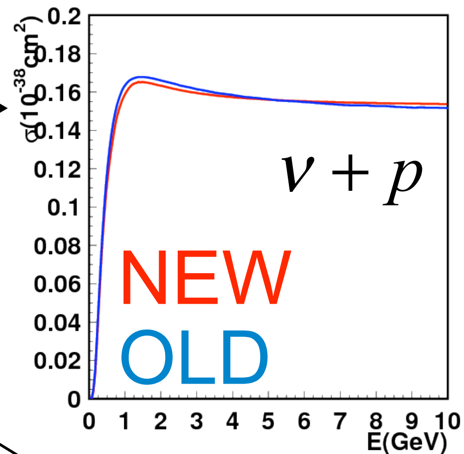
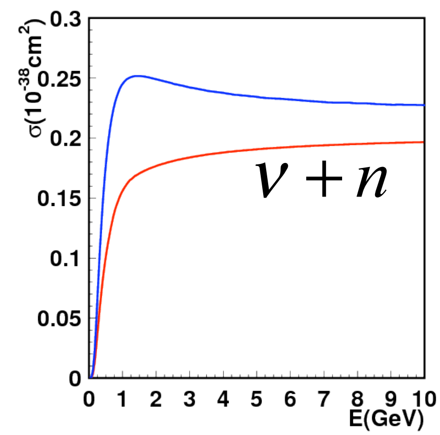
NC Elastic Scattering Cross Section

- Calculated from form factors, BBBA05
- Spectral function calculation for nuclei





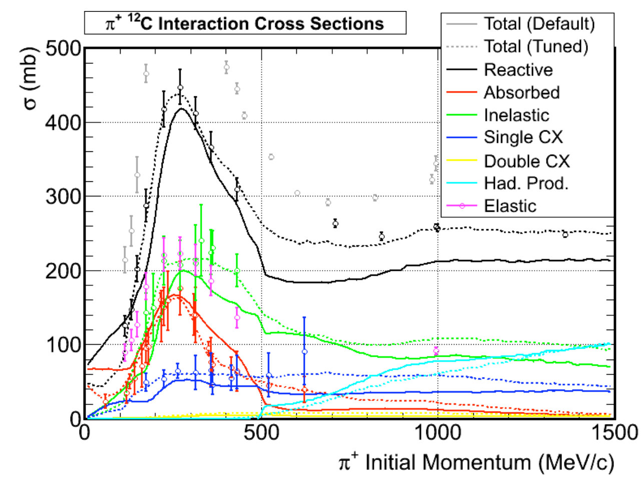
Gamma Ray Emission from ^{16}O

- Recent results from (e,e'p) experiment
- Energy of γ from excited state
  (K. Kobayashi et al., nucl-ex/0604006)
- Energy of γ following pion absorption
  (H.D. Engelhardt et al., NPA258, 480 (1976))

	Shell model	LDA (PRD72,053005)
p1/2 (g.s.)	0.25	0.165
p3/2 (6.32 MeV)	0.41	0.343
s1/2	0.25	0.123

π Interactions in Nuclei

- Tune pion mean free paths in nucleus using pion scattering data, density dependence from the model of Salcedo, Oset, Vincente-Vacas, Garcia-Reno
- Comparisons with π scattering data and π photo-production data.
- Incorporate model for nucleon ejection after pion absorption, multiplicities and charge determined from experimental data
  (Rowntree et al., Phys. Rev. C60 (99) 054610)



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NUANCE

Primary Author: D. Casper
Current maintainer: S. Zeller
http://nuint.ps.uci.edu/nuance

Originally developed for IMB, used also by SuperKamiokande, MINOS, MiniBooNE, ArgoNEUT.

QEL: BBA03 FF, M_A is 1.103 or 1.234 GeV/c^2

Resonance: Rein & Sehgal formalism, including

- Interference between resonances
- K, ρ, η production
- Δ-Nγ decay

Coherent+diffractive -π: Rein-Sehgal

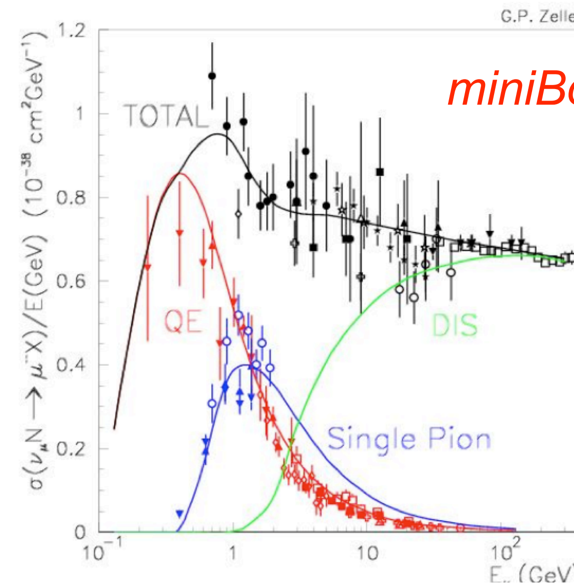
DIS: Bodek-Yang modification

LUND-based hadronization (KNO-based if fails)

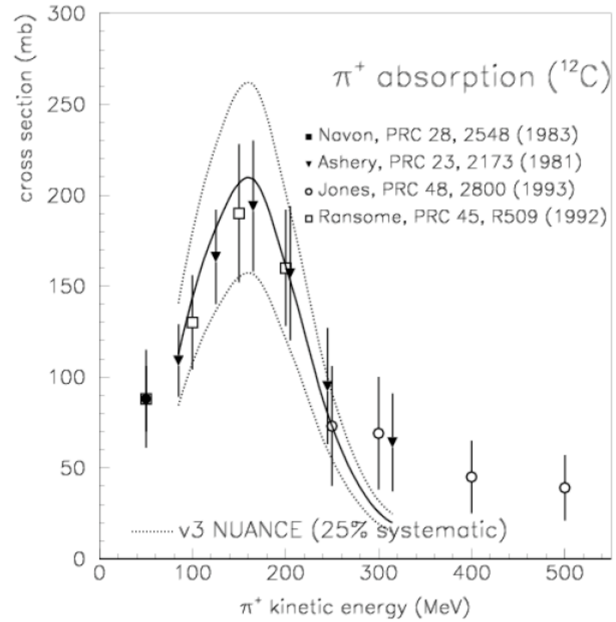
Nuclear Model: RFGM Smith-Moniz (κ)

Intranuclear Rescattering: cascade model

- Measured cross sections and angular distributions are used for p-N and N-N reactions.
- Nuclear de-excitations from ^{16}O and ^{12}C simulated.



miniBoone



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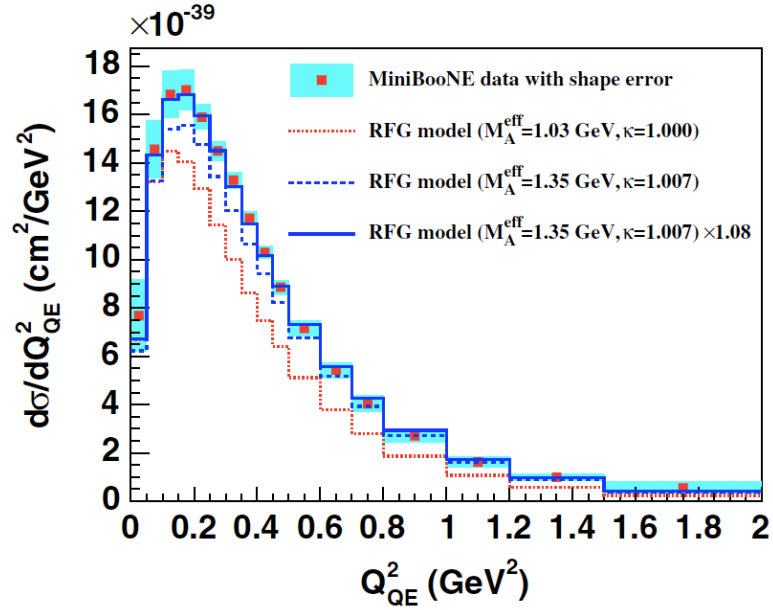
Many recent MiniBooNE improvements:

- *Parameter (κ) to control low Q^2 suppression of QEL*
- *Adjustment of coherent/resonant π production*
- *Incorporation of updated vector and axial-vector form factors in the Rein-Sehgal model for pion production (including modern g_A)*
- *Added non-isotropic Delta decays*
- *De-excitation photon emission model for carbon*
- *Added Delta radiative decays including invariant-mass dependent branching fraction*
- *Added reweighting capabilities within MiniBooNE MC*
- *Incorporation of updated vector form factors for pion production into the framework of the Rein-Sehgal model. (J. Nowak, AIP Conf. Proc 1189, 243 (2009))*
- *tuned final state interaction model for pion propagation (namely, pion absorption and charge exchange cross section normalizations) based on external pion-carbon data*



MiniBooNE: A. A. Aguilar-Arevalo et al. Phys. Rev. D 81, 092005 (2010)

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NuWRO

Primary Authors: C. Juszczak, J. Nowak, J. Sobczyk

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First neutrino event generator to be developed by a theory group (Wroclaw University).

Duality-inspired treatment of transition region.
Alvarez-Ruso, Singh, Vascas Phys. Rev. 57 (1998) 2693 for Δ production (K. Graczyk), Bodek-Yang DIS.
Smooth transition from Δ to DIS for single pi.

Careful comparison between PYTHIA fragmentation and experimental data.

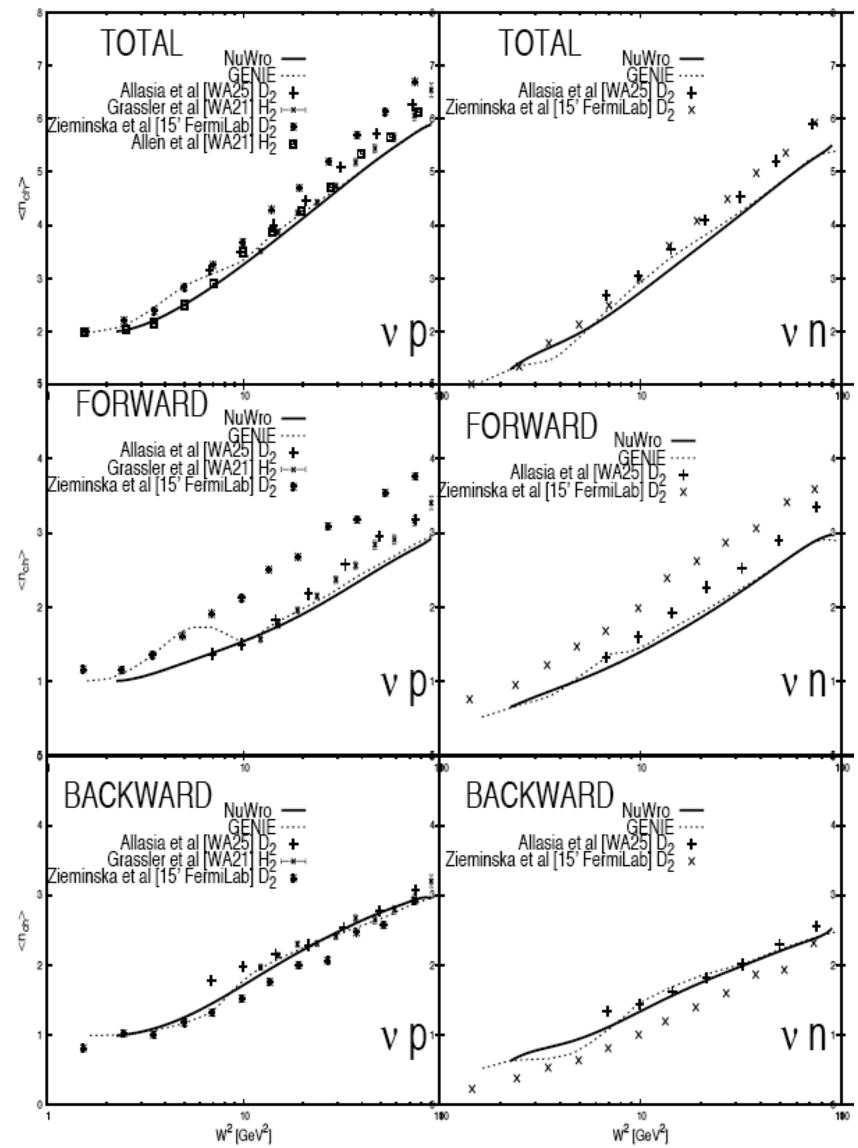
Implementation of Spectral Functions as an alternative to the Fermi Gas model.

Intranuclear cascade modeling:

•Uses the model of Oset in the Delta region

•Work underway on formation zones

Efficient detector interface (T2K ND280).



J. Sobczyk, PoS(NUFACT08)141

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GiBUU

Primary Authors: T. Leitner, O. Buss, U. Mosel, L. Alvarez-Ruso

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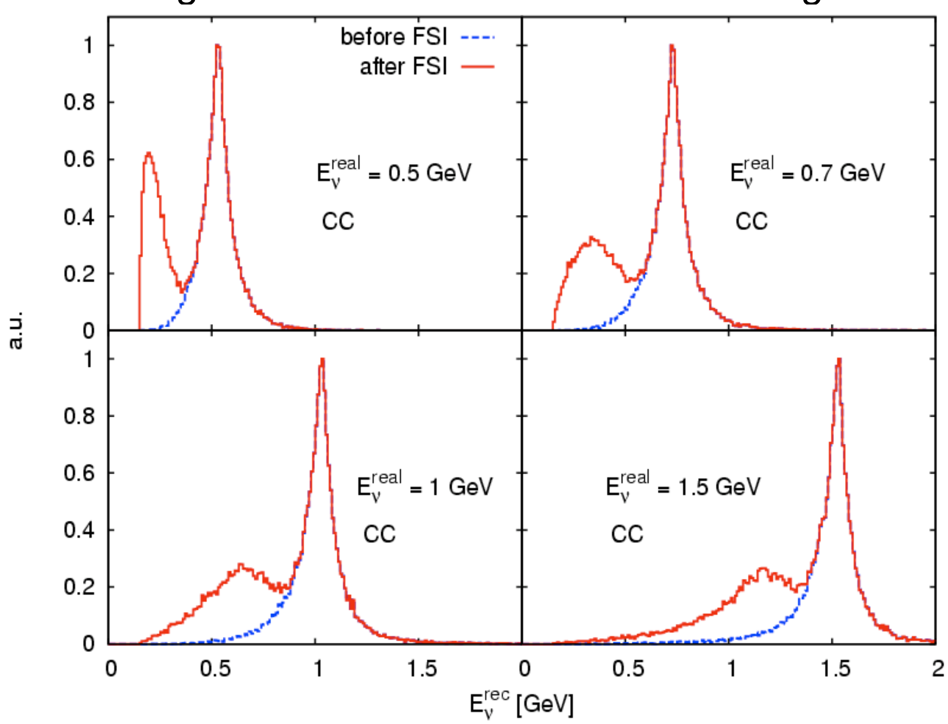
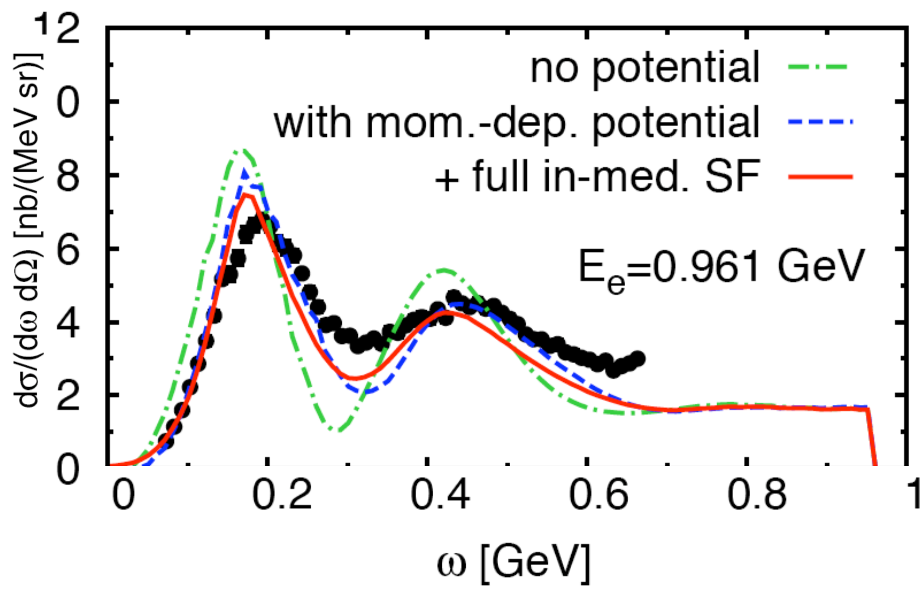
Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) is a semiclassical transport model in coupled channels. Takes into account numerous nuclear effects: local density approximation, mean-field potentials and in-medium spectral functions.

Extensively checked against data for heavy-ion collisions, eA, γA, pA, πA.

Is being extended to MINOS/OPERA energies.



$e + {}^{12}C \rightarrow e' + X, \theta = 37.5^o$



QEL, Δ, 13 N* and non-resonant single-pion channels. Recent electron scattering data used for state-of-the-art parametrizations of vector form factors, axial refit to neutrino-scattering data.

Involves solving a set of coupled 8-dimensional integral-differential equations. → speed implications

Details Matter!

See "Comparison of Models of Neutrino-Nucleus Interactions", S. Boyd et al., AIP Physics Proc 1189, 60 (2009).

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!

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Conclusions

Generators on the market today – FLUKA-NuNDIS, GENIE, GiBUU, NEUT, Nuance, and NuWRO, while they share some common ingredients, bring a variety of different physics models and software engineering approaches to the task of neutrino event generation.

Future challenges and opportunities:

Slowly incorporating what has been learned in electron scattering: moving away from fast, venerable models, like the FGM or Rein-Sehgal model.

Missing processes? np-nh excitations produce sizable cross section!?

Balancing speed, experimental convenience and accuracy

Upcoming experiments (MINERνA, T2K ND, ArgoNEUT, OPERA, MicroBooNE…) will be vital to improvements.

Bridging the gap between theory and experiment:

- Having code provided by theorists
- Experimental results presented with a minimum of model-based correction

Backup Slides

Quasi-Elastics

Hugh Gallagher
EPS 11
Grenoble, France
July 22, 2011

Identify "QEL-like" events:

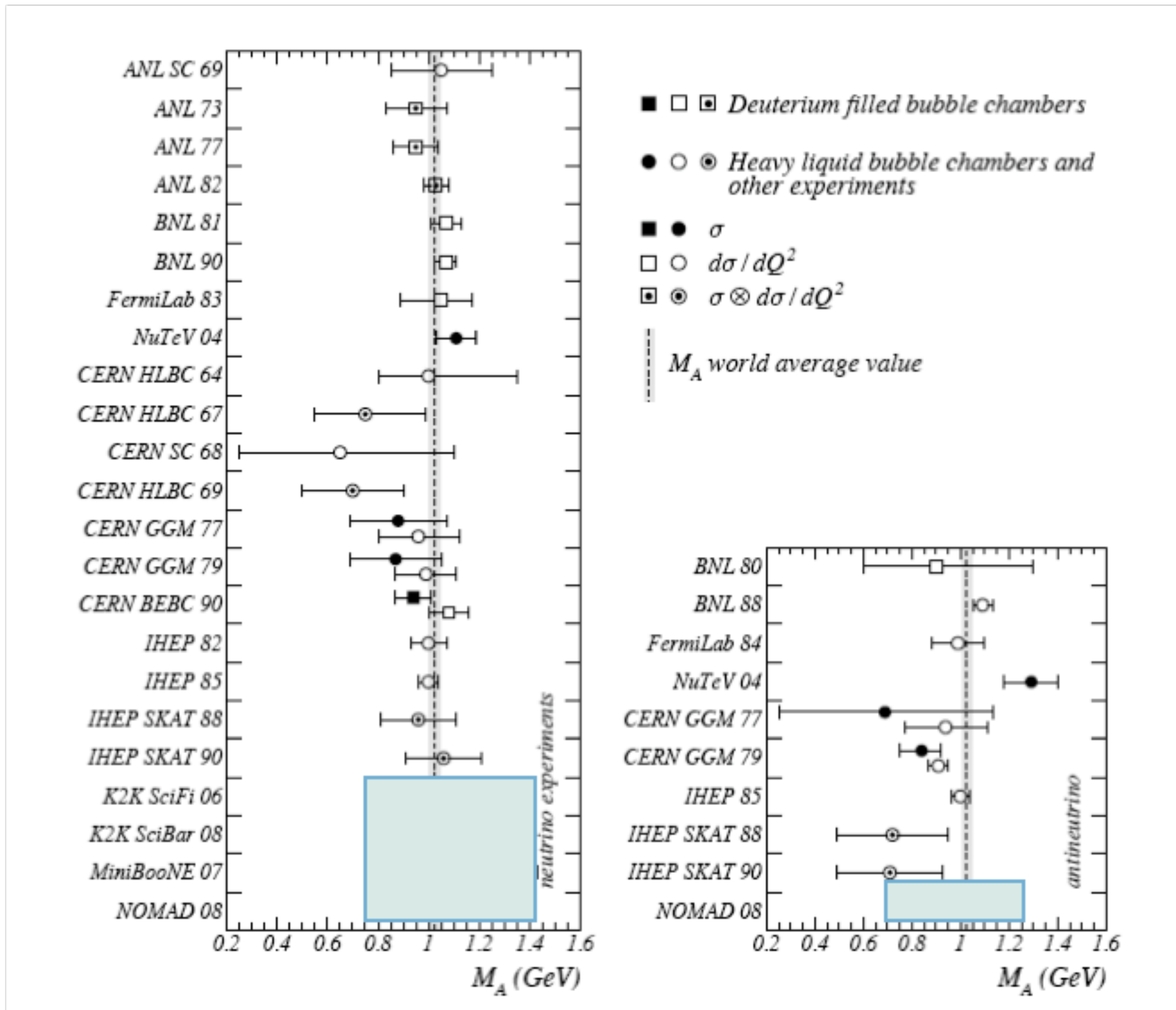
$$\nu_\mu + n \rightarrow \mu^- + p \qquad \bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

1-track events
2-track events
2nd track proton-like

$$E_\nu = \frac{ME_\mu - m_\mu^2/2}{M - E_\mu + p_\mu \cos\theta_\mu}$$

$$Q^2 = -2E_\nu(E_\mu - p_\mu \cos\theta_\mu) + m_\mu^2$$

Numerous measurements from the era of bubble chamber experiments with hydrogen and deuterium targets painted a fairly consistent picture:



M_A=1.026±0.021 GeV (Bernard et al., J.Phys.G 28, R1 (2002))

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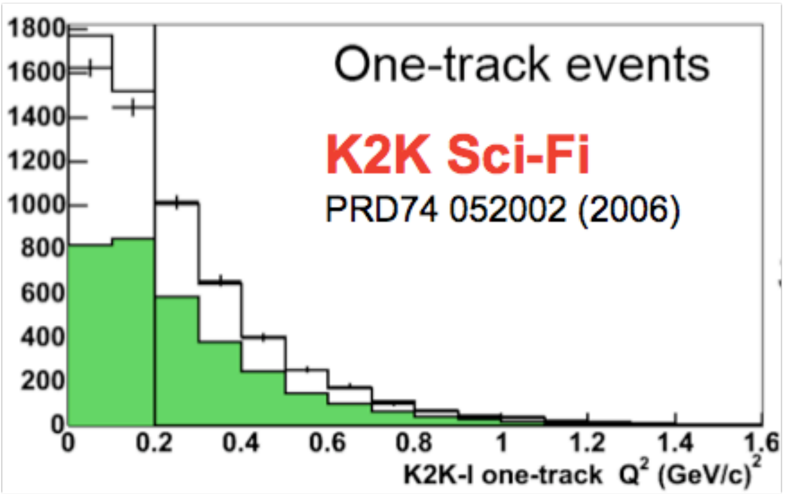
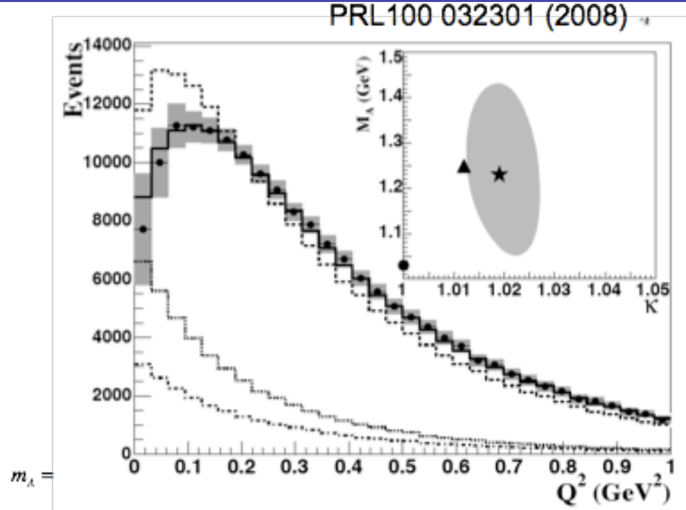
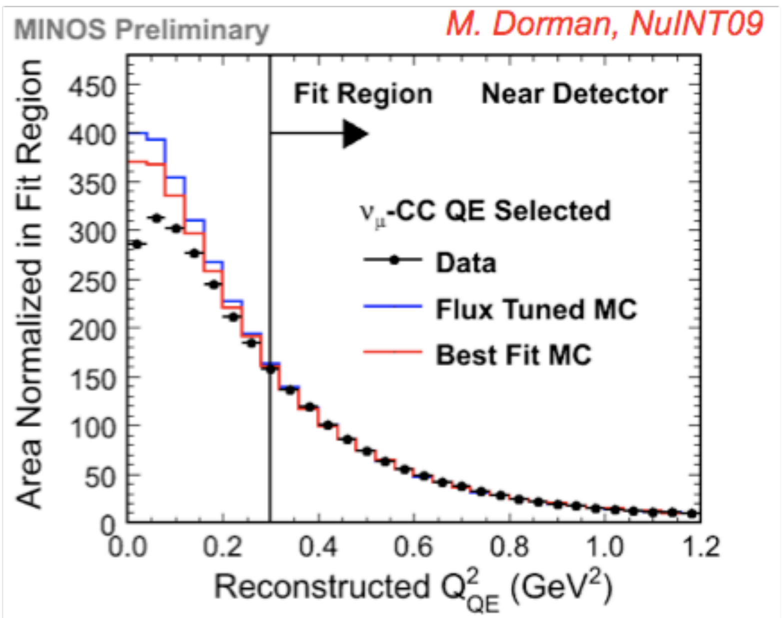
Quasi-Elastics



miniBoone
PRL100 032301 (2008)





Fast-Forward to Today: Low Q^2 - nuclear effects

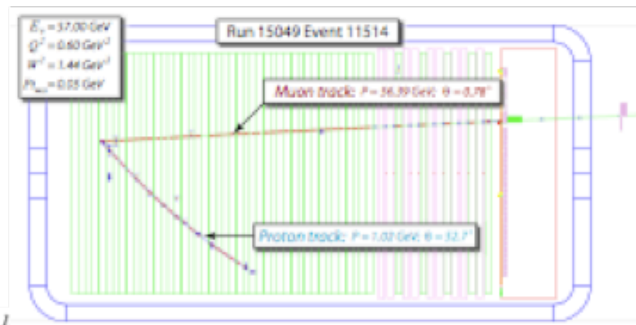
K2K: M_A=1.20±0.10 GeV

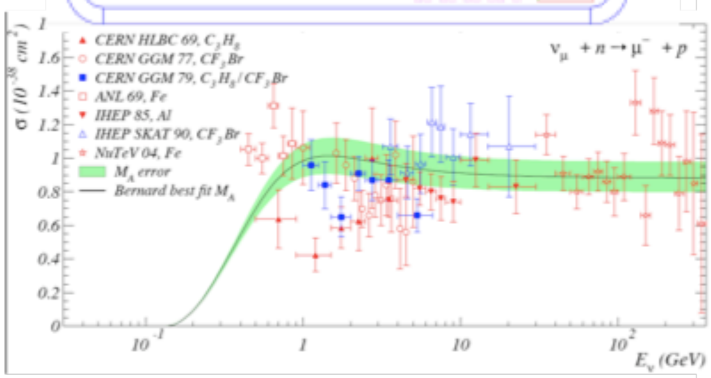
miniBoone: M_A=1.23±0.20 GeV

MINOS(Preliminary) Effective M_A^{QE} = $1.26\ ^{+0.12}_{-0.10}$ (fit) $^{+0.08}_{-0.12}$ (syst) GeV

Quasi-Elastics

OLD vs. NEW (carbon): NOMAD

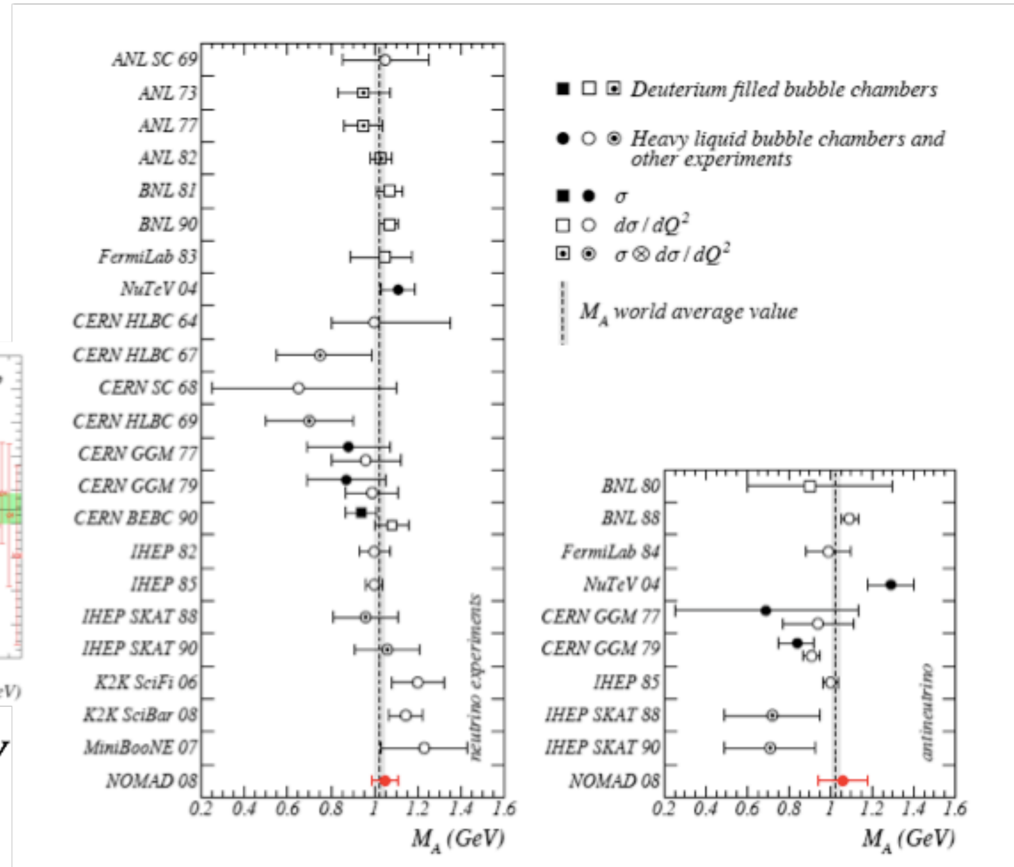




$$M_A = 1.05 \pm 0.02(stat) \pm 0.06(syst)\ GeV$$

Consistent with value from antineutrinos and Q^2 shape fit.

V. Lyubushkin, NuINT09 **arXiv:0812.4543**



miniBooNE (09)
Katori, NuINT09

M_A^{eff} = 1.35 ± 0.17 GeV (stat+sys)
κ = 1.007 $^{+0.007}_{-\infty}$ (stat+sys)
χ^2/ndf = 47.0/38

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Quasi-Elastics

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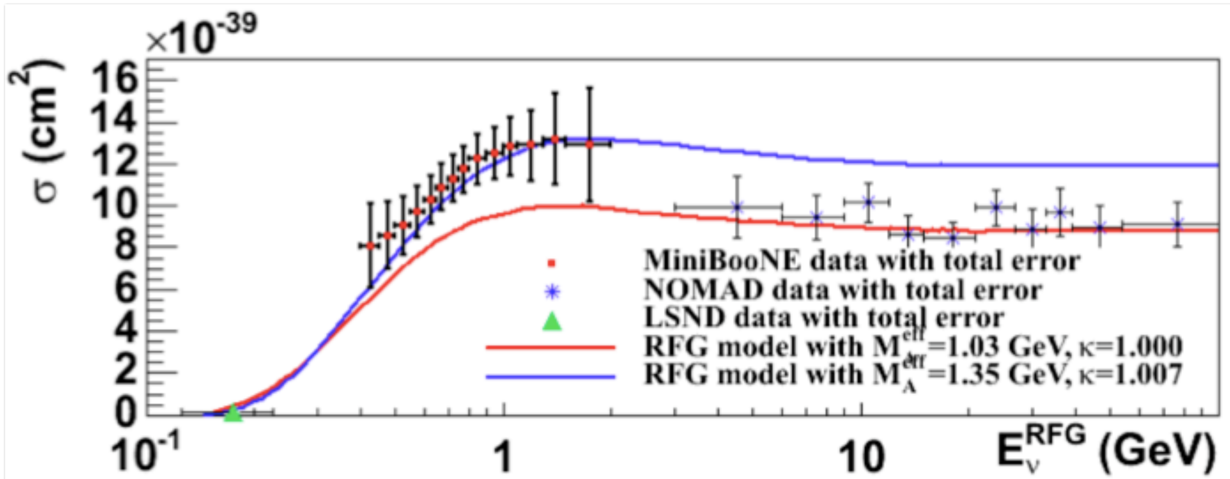

If this discrepancy is a nuclear effect, it has some curious features:

- Affects shape of Q^2 distribution at moderate Q^2 values.
- Increases total QEL-like cross section.
- Similar sized discrepancy for iron and carbon.
- Less evident in antineutrinos at higher energy (NOMAD).
- Less evident in neutrino-carbon at higher energy (NOMAD, but with different selection).

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np-nh Scattering processes

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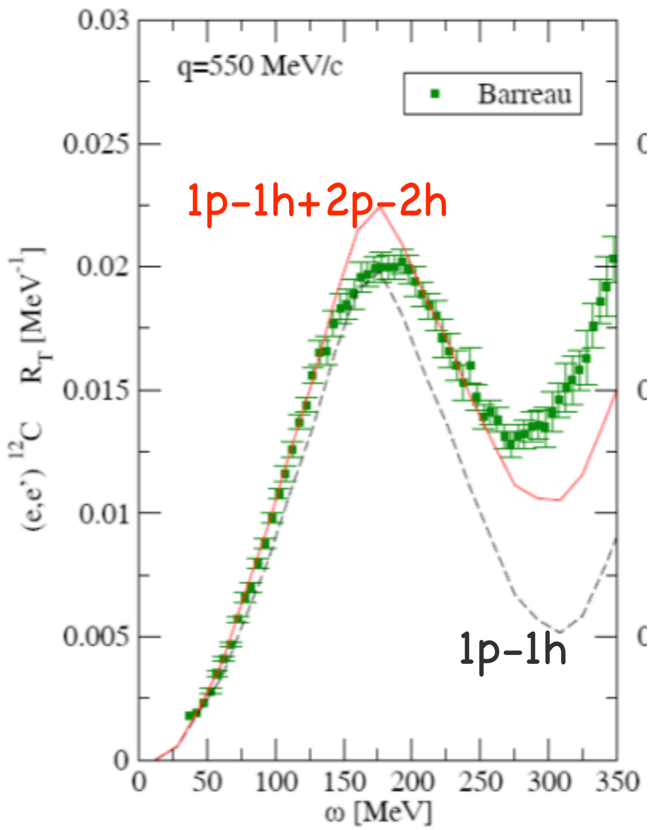
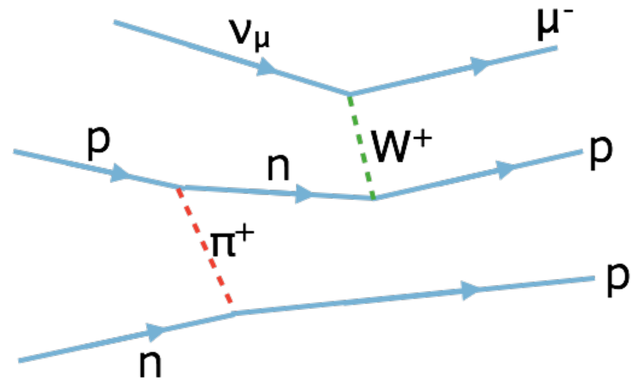
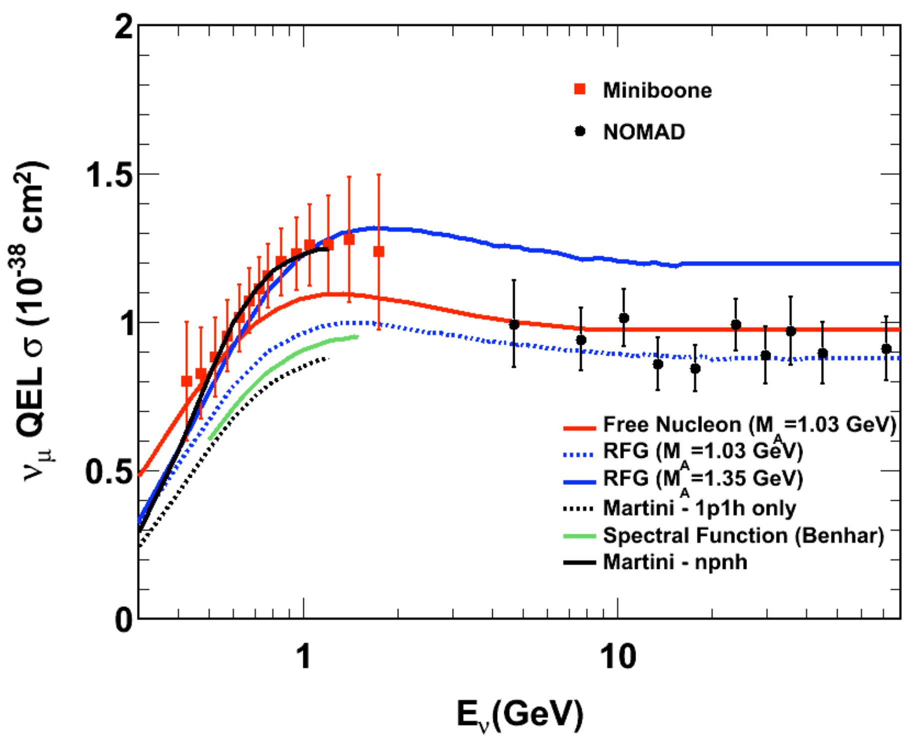
July 22, 2011

Q: In neutrino-nucleus scattering there are processes which do not occur on free nucleons!







Martini and Ericson,
Phys. Rev. C 80 065501 (2009)
Phys. Rev. C 81 045502 (2010)

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Physics Simulations

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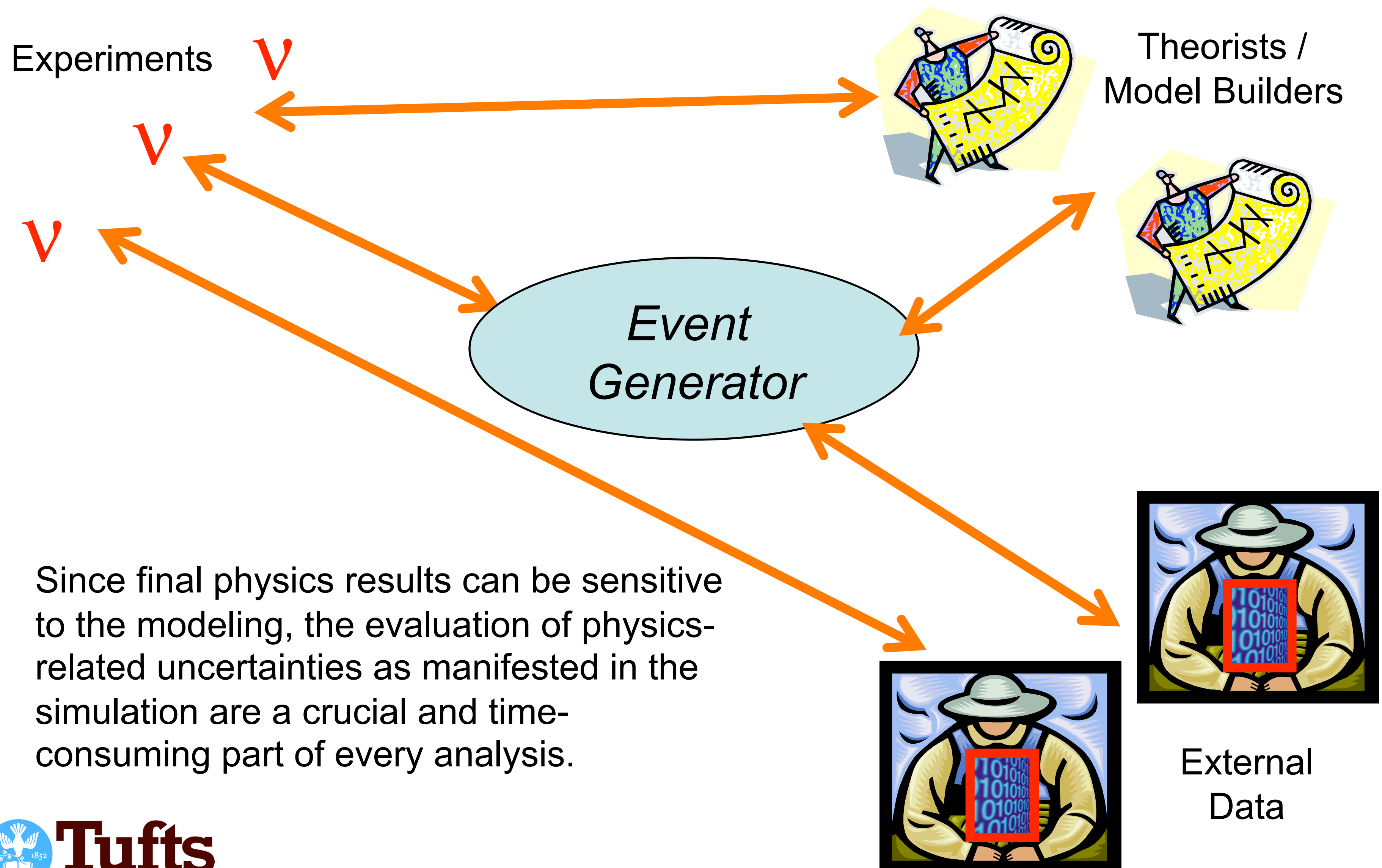

Since final physics results can be sensitive to the modeling, the evaluation of physics-related uncertainties as manifested in the simulation are a crucial and time-consuming part of every analysis.

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Evaluating Systematic Errors

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EPS 11
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July 22, 2011

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 parameterization 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 parameterizations of detector response 'fast MC'.

4) Estimate systematic errors using data-based techniques from independent samples.

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MINOS: σ Model Uncertainties

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July 22, 2011

Overall Model Uncertainties, including nuclear effects:

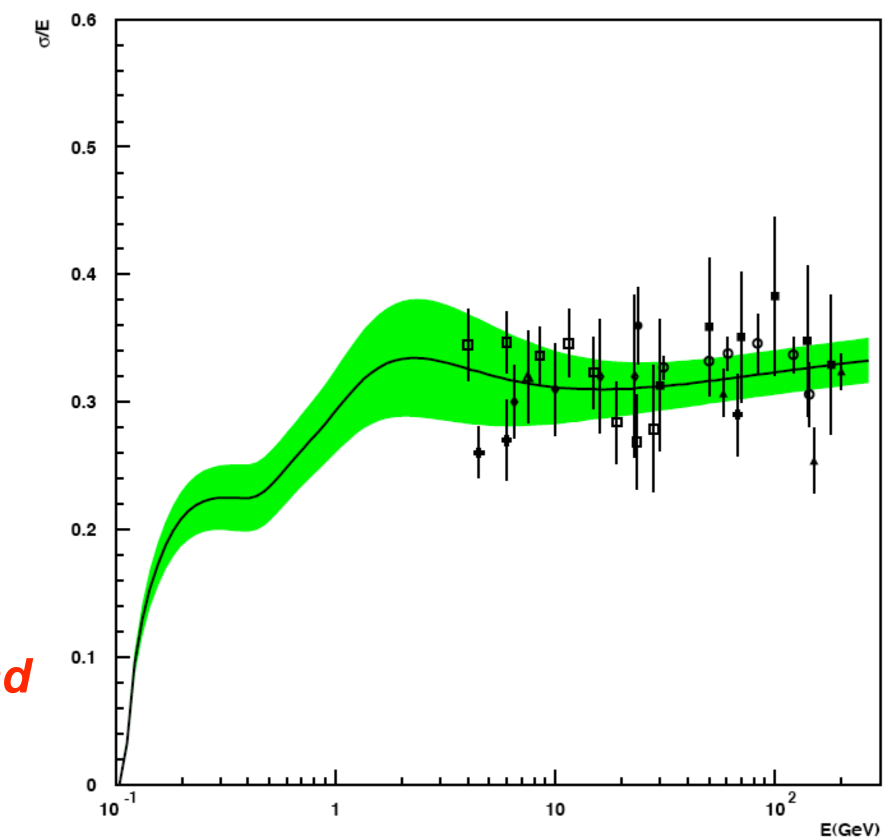
- Total cross section: 3.5%
- M_A: 15% for both quasi-elastic and resonance production
- Transition region parameters: r_{ij2}±0.1, r_{ij3}±0.2.

Anti-neutrino/neutrino cross section uncertainty:

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

ν_τ: Pseudo-Scalar Form Factor

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



For these tasks the input of theorists, and the NuINT series, have been vital!

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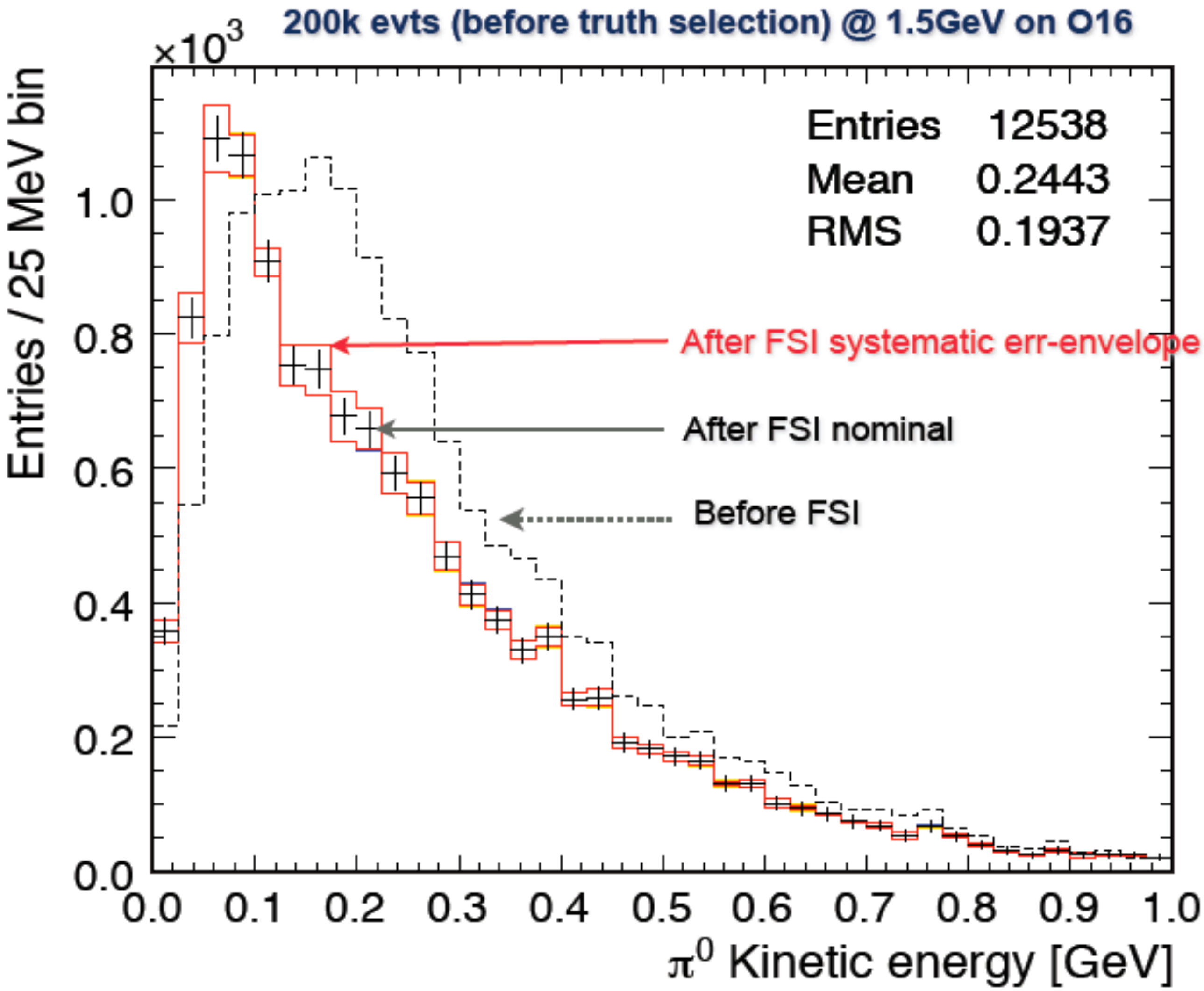
Example: NC $1\pi^0$ topology error envelope



Select single π^0 topology:
- 14,783 before FSI
- 12,538 after FSI

Scan intranuke/hA phase space:
- Treat Pion and Nucl fates independently.
- Treat mfp parameter separately.
- Add above three in quadrature.

(~170 parameter configs)

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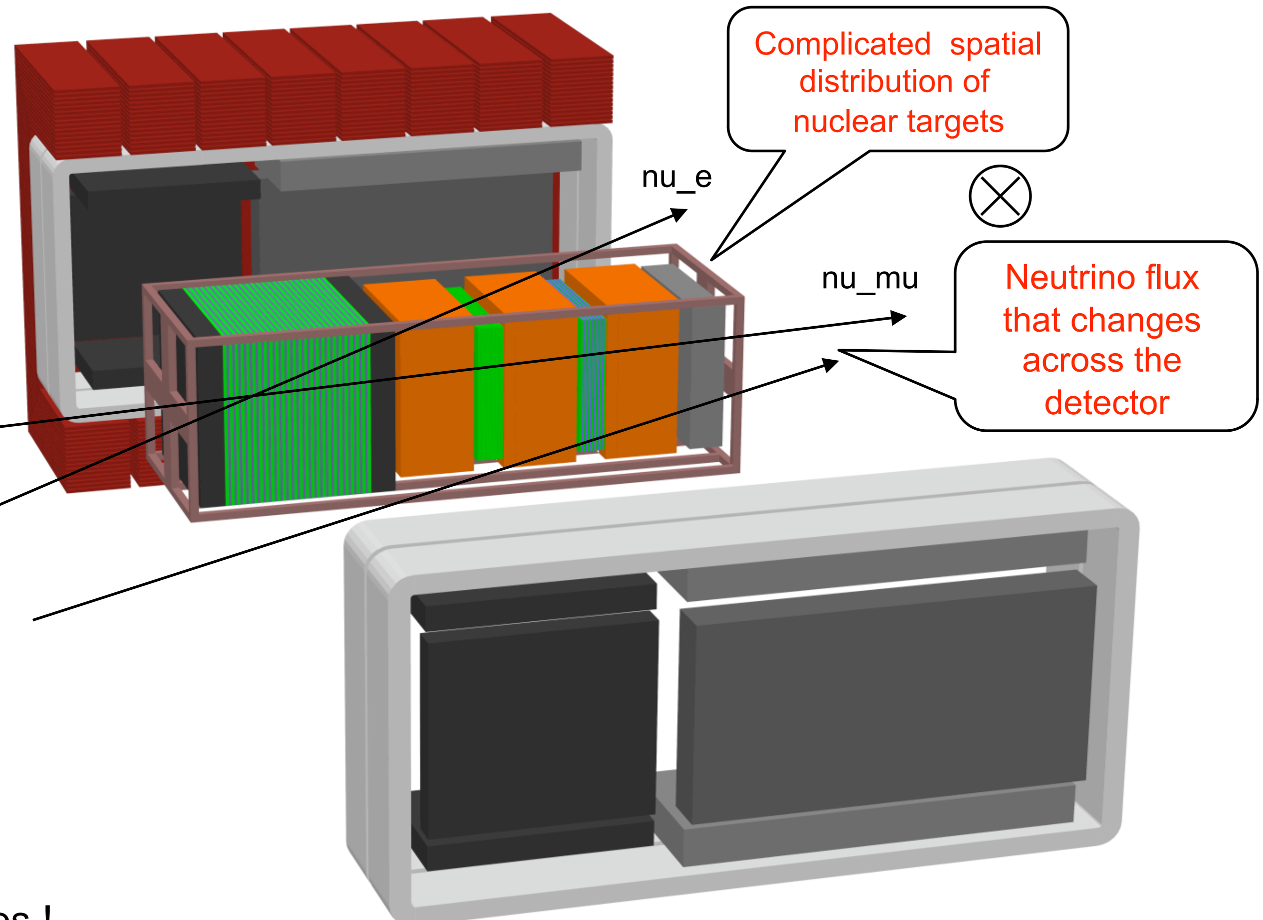
Flux and Detector

C. Andreopoulos

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 !

GENIE: 5 events/sec for ND280
70 events/sec for simple initial state (E_ν=1 GeV).

9. Deep Inelastic scattering ν + N → l + hadrons

Avoid double counting : the resonance region to the DIS region

W < 2GeV : Restrict # of mesons to be larger than 1
Exclude 1 meson production
by using multiplicity function <n>(W)
Because non-resonant background is already included
in the single π production.

Multiplicity is determined based on the experimental result.
Current version: S. J. Barish et al. Phys. Rev D.17,1 (1978)
(There are recent reports from CHORUS collaboration.
Eur.Phys.J.C51:775-785,2007)

$$\langle n_\pi \rangle = 0.09 + 1.83 \ln(W^2)$$

W > 2GeV : Use PYTHIA to generate vectors.

	W < 2GeV	W > 2GeV
# of π = 1	Rein & Sehgal	PDF + Custom kinematics (Bodek & Yang Corr.)
# of π > 1	Use PDF + PYTHIA (Bodek & Yang Corr.)	Use PDF + PYTHIA (Bodek & Yang Corr.)

As for the parton distribution function,
we use the correction suggsted by Bodek and Yang.

NuWRO: J. Nowak, Scandinavian Neutrino Workshop (May 2006)

Single pion production cross section has a form

$$\frac{d\sigma^{SPP}}{dW} = \frac{d\sigma^{\Delta}}{dW}(1-\alpha(W)) + \frac{d\sigma^{DIS}}{dW}F^{SPP}(W)\alpha(W) \qquad (1)$$

$$\begin{aligned} \alpha(W) &= \Theta(W_{min}-W)\frac{W-W_{th}}{W_{min}-W_{th}}\alpha_0 \\ &+ \Theta(W_{max}-W)\Theta(W-W_{min})\frac{W-W_{min}+\alpha_0(W_{max}-W)}{W_{max}-W_{min}} \\ &+ \Theta(W-W_{max}) \end{aligned}$$

We observe that the best values of parameters are

$W_{min} = 1.3GeV,\ W_{max} = 1.6GeV$

Non-resonant background is simulated by appropriate DIS contribution. $\alpha_0 \in (0, 0.3)$ (depending on the channel)

Intranuclear Rescattering

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Grenoble, France
July 22, 2011

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.

GENIE: Transition Region

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Grenoble, France
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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

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

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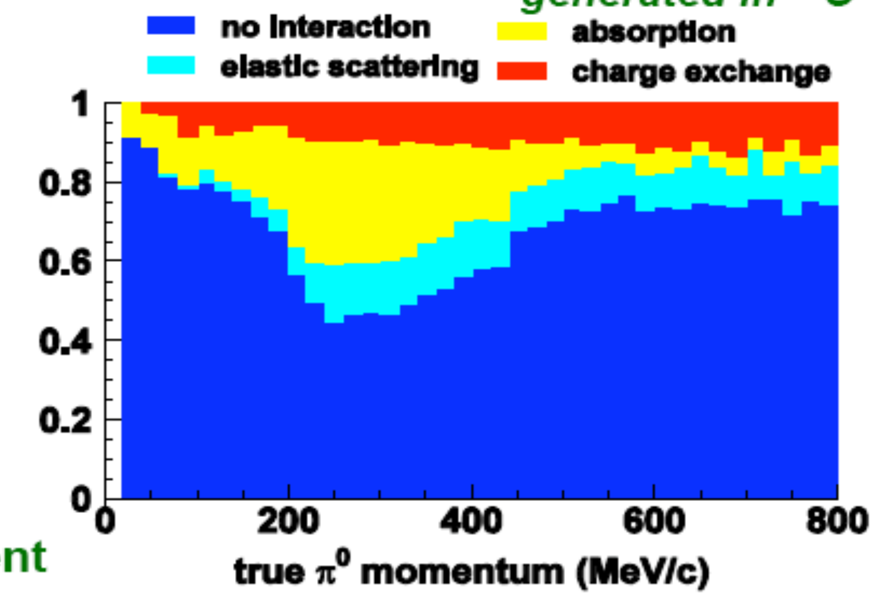
11. Nuclear effects (Final state interactions of hadrons)

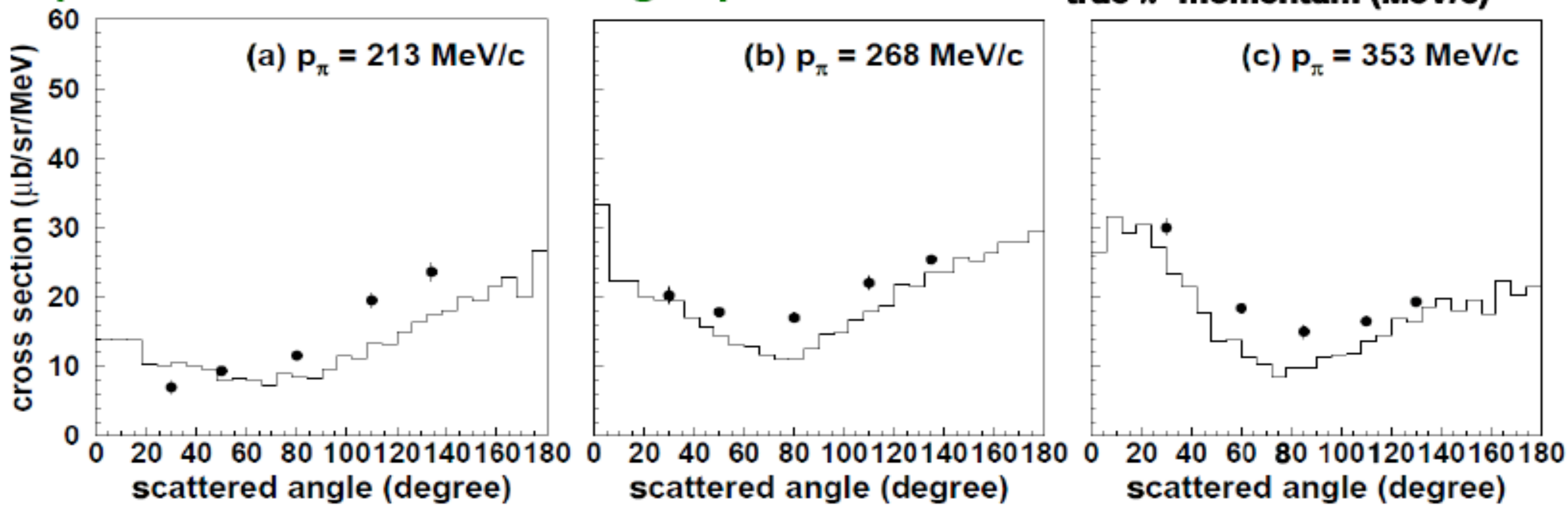
Checked with π^+ ^{16}O scattering or photo - π production experiments.

Monte-Carlo simulation reproduces various distributions quite well.

Interaction probabilities of π *generated in ^{16}O*



Comparison with π^+ ^{16}O scattering experiment



“quasielastic” and “neutrino”

Years	Theory	Experiment	Total
1965-1969	2	1	3
1970-1974	6	1	7
1975-1979	2	3	5
1980-1985	0	13	13
1986-1990	2	6	8
1991-1994	10	1	11
1995-1999	5	1	6
2000-2004	23	1	24
2005- 2010	39	20	59
Total	89	47	136