Neutrino Event Generators

Hugh Gallagher
Tufts University
Intensity Frontier Neutrino Subgroup
SLAC, March 7, 2013

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

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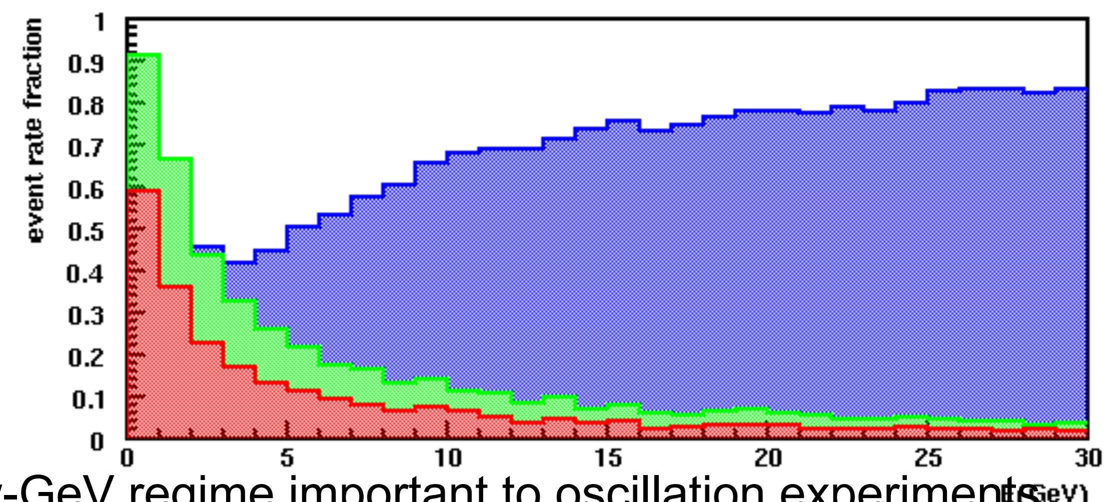
Use by Experiments

Event generators play an important role for experiments from 'cradle to grave'.

- –Sensitivity studies
- –Detector optimization
- –Data analysis
- –Systematic error evaluation

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.

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Event Generation

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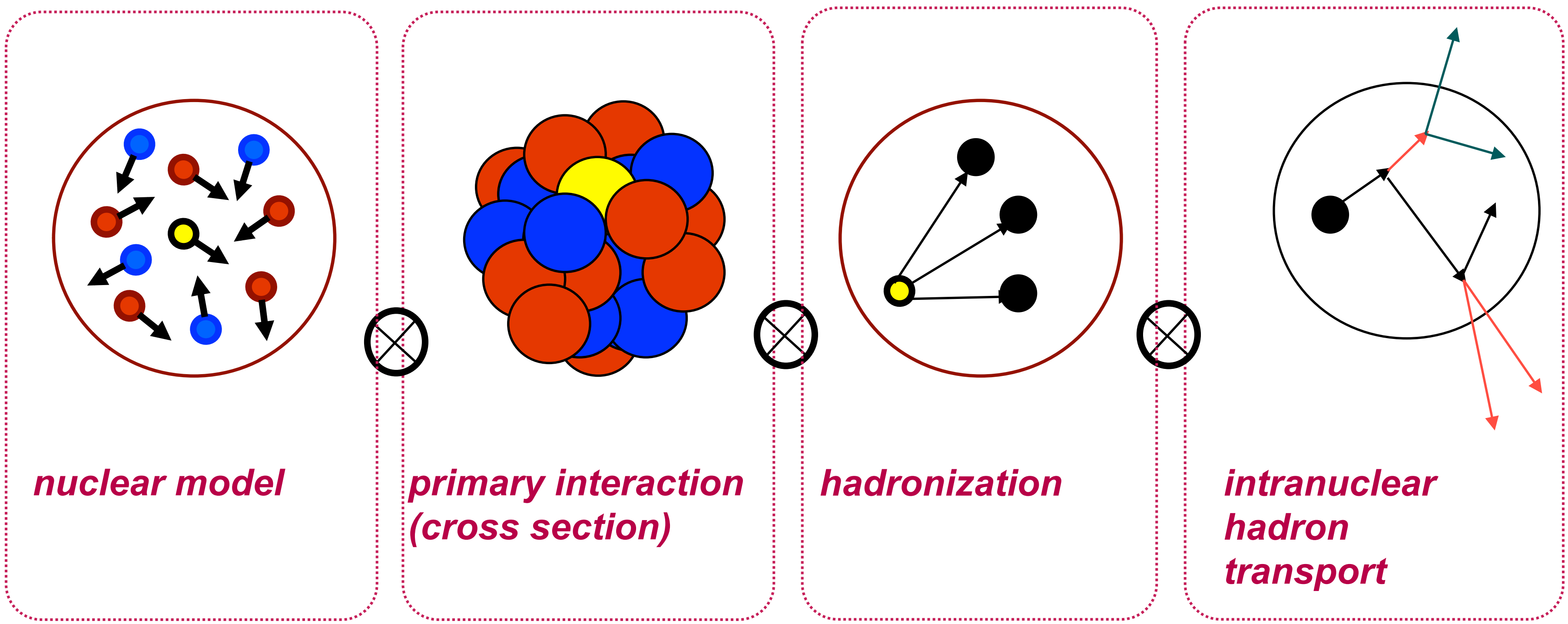
Intensity Frontier Workshop
SLAC
Mar. 7, 2013

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



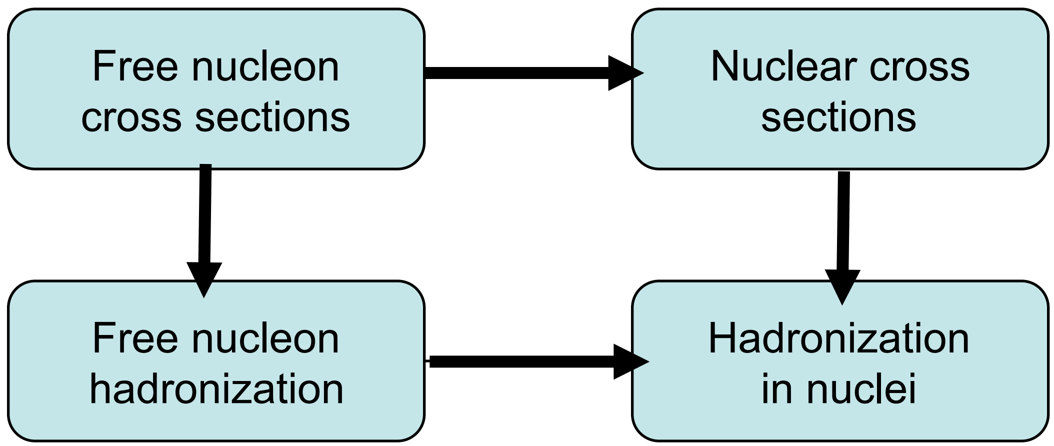
Physics Models

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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Tuning / Validation

ν Neutrino Data

Bubble Chambers (ANL, BNL, SKAT, BEBC, FNAL), CCFR, NuTEV, MINOS, T2K, NOMAD, MiniBooNE, SciBooNE, ArgoNEUT

- Total CC cross sections
- Exclusive channel (e.g. QEL, 1π) cross sections
- Single and doubly-differential cross sections
- Cross section ratios
- Hadronic system measurements

e Charged Lepton Data

Inclusive electron scattering:
electron scattering in the resonance region[1]
hydrogen/deuterium targets (eN), (eA also)
e scattering in the quasi-elastic region[2]
nuclear targets (eA)

e/μ : structure function measurements

[1]: S. Wood, http://www.jlab.org/resdata/
[2]: D. Day, http://faculty.virginia.edu/qes-archive, arXiv: nucl-ex/0603032

π Hadron Scattering Data

pion, kaon, hadron - nucleus scattering experiments

- total and reaction cross sections
- differential distributions of produced particles

t Theoretical Constraints

The Obvious: e, p, charge, baryon #

Adler and Gross-Llewellyn-Smith sum rules

Quark-Hadron Duality

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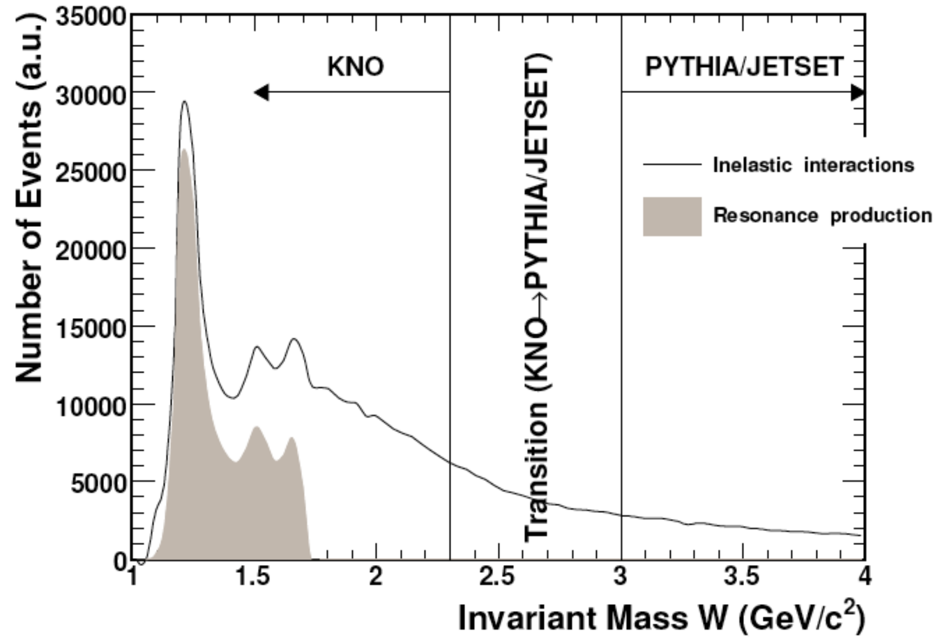
Challenges - hadronization

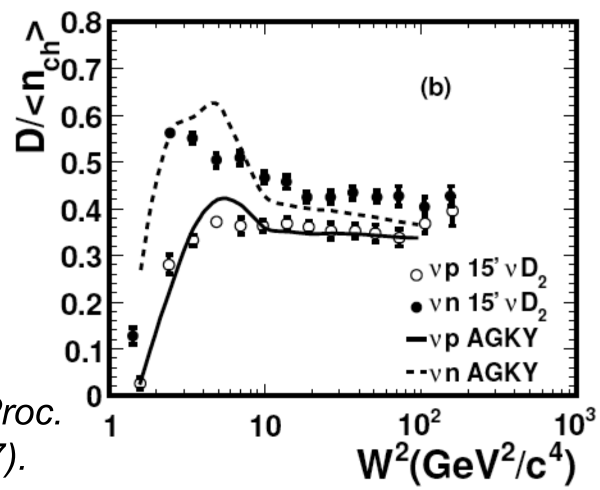
T. Yang, NuINT07.

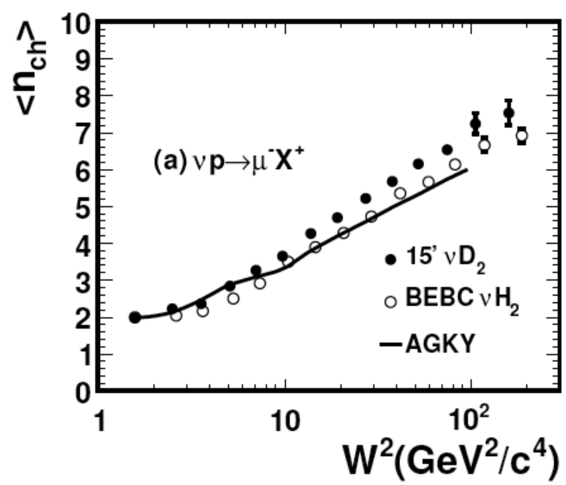
For few-GeV neutrinos a large fraction of data come from non-resonant inelastic states which have invariant masses too low to be comfortably handled by standard packages like JETSET. (45% of events for E_ν= 3 GeV).



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

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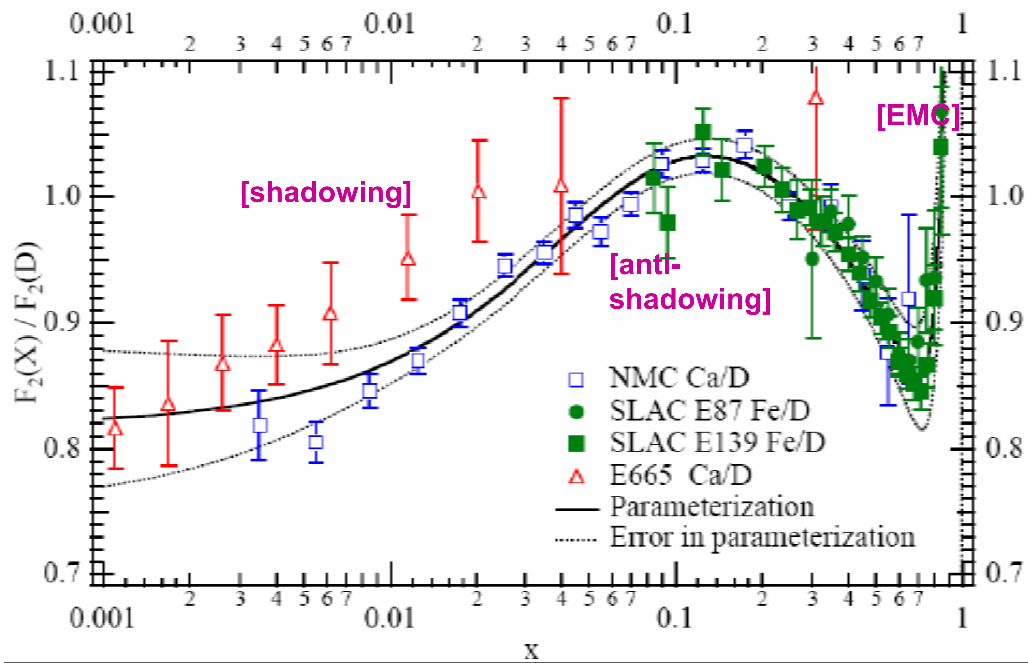
Challenges – Nuclear Physics

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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Different from Collider Experiments!

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

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FLUKA

FLUKA: A. Fassò, A. Ferrari, J. Ranft, P.R. Sala

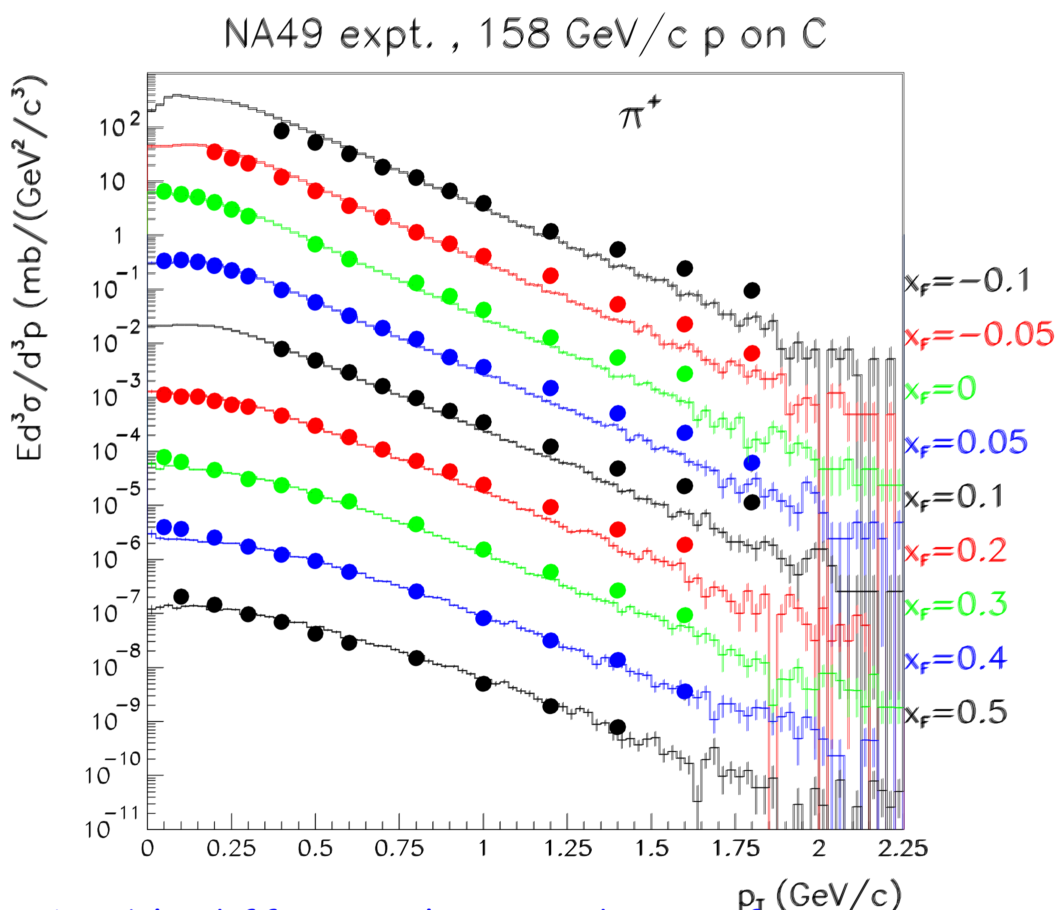
http://www.fluka.org

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)

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.

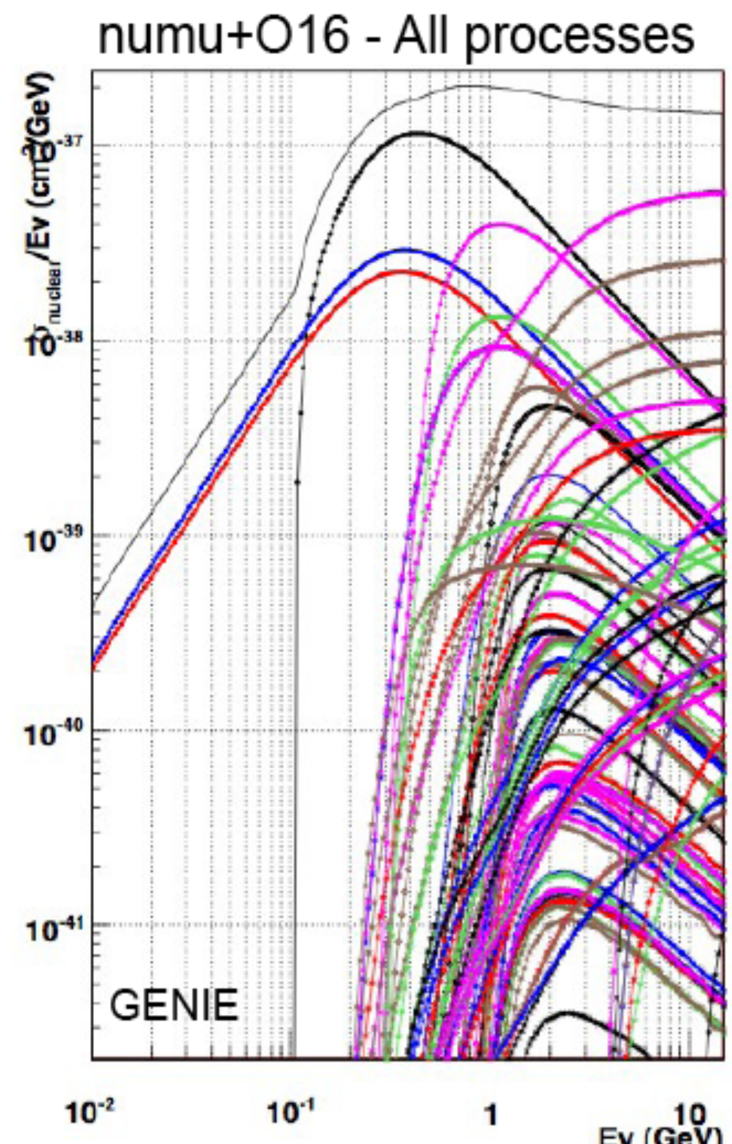
Nuclear Model: RFGM with NN correlations

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

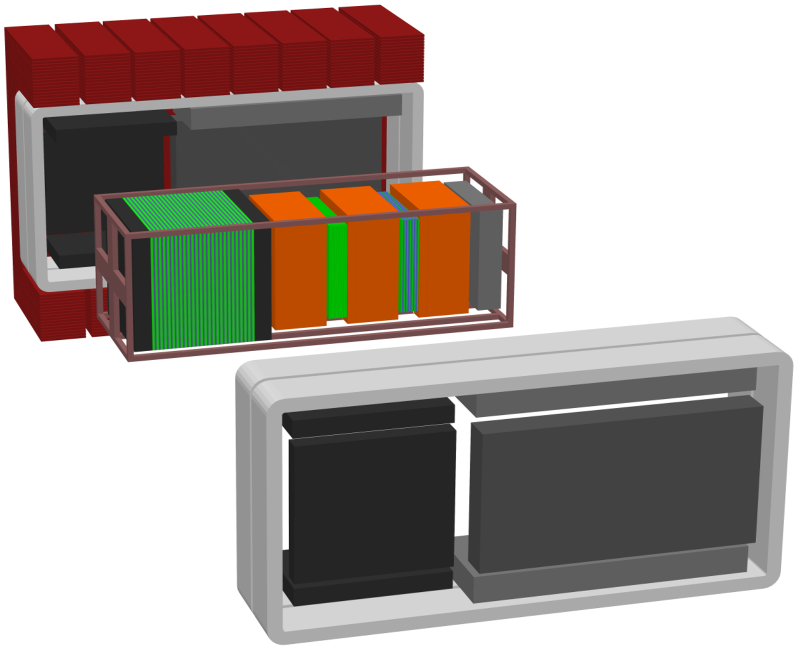


Collaborations with theorists crucial: Alvarez-Ruso, Benhar, Paschos

Coming in GENIE 2.10.0:

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
Model for 2p-2h scattering mechanisms

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

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

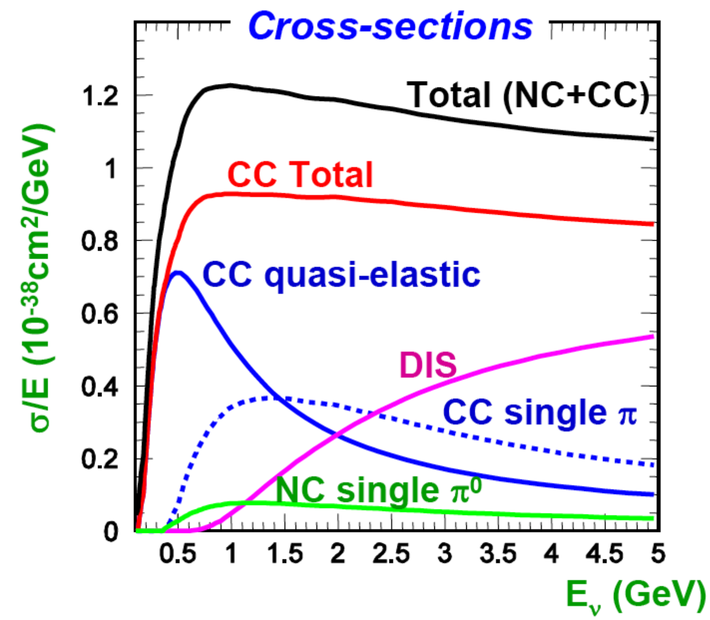
All 1π resonance-produced for $W<2$ GeV/c^2

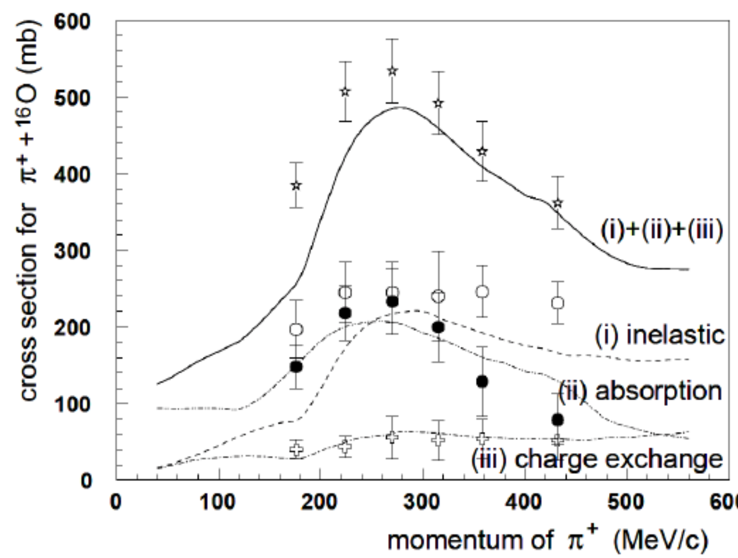
Nuclear Model: RFGM Smith-Moniz

Formation zone: SKAT $\mu^2=0.08$ GeV^2

Intranuclear Rescattering: cascade model

- $p_\pi<500$ MeV/c: radius and momentum dependent mfp
  - k_F has radius dependence
- Kinematics from phase shift analysis of π-N scattering
- $p_\pi>500$ 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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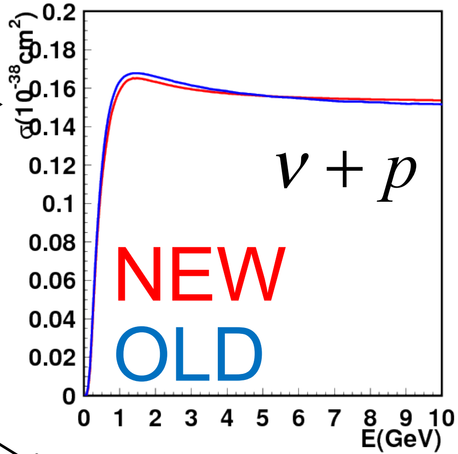
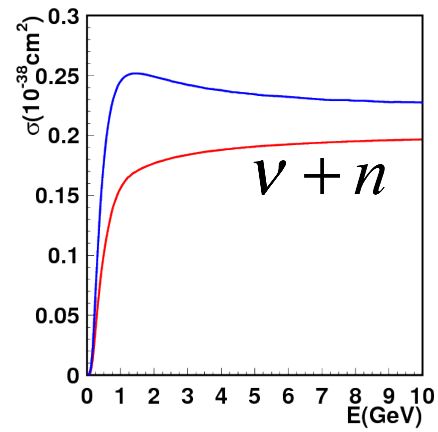
NC Elastic Scattering Cross Section

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





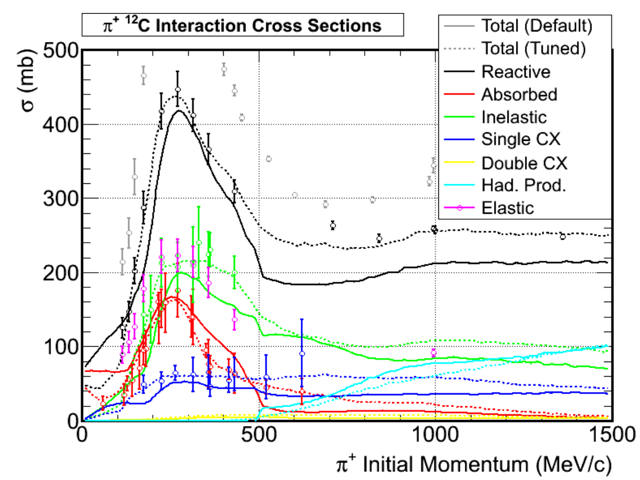
Gamma Ray Emission from ^{16}O

- 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

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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

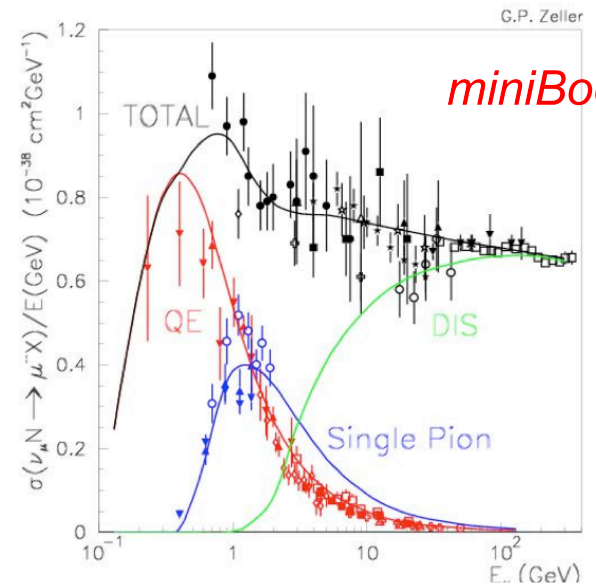
DIS: Bodek-Yang modification

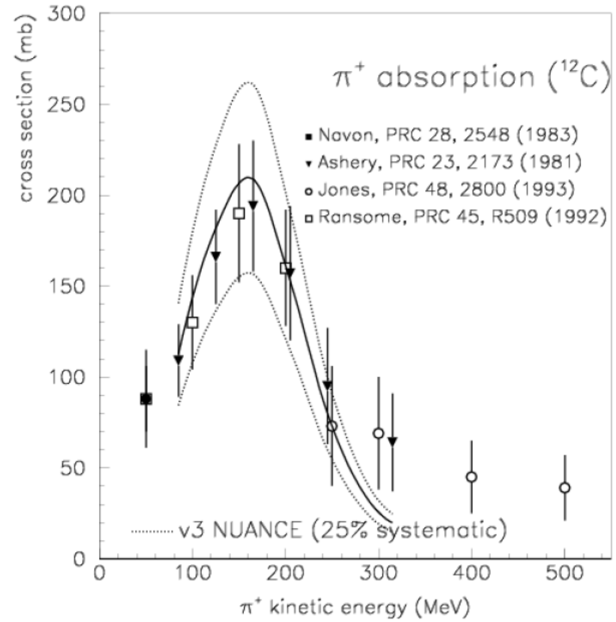
LUND-based hadronization (KNO-based if fails)

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.





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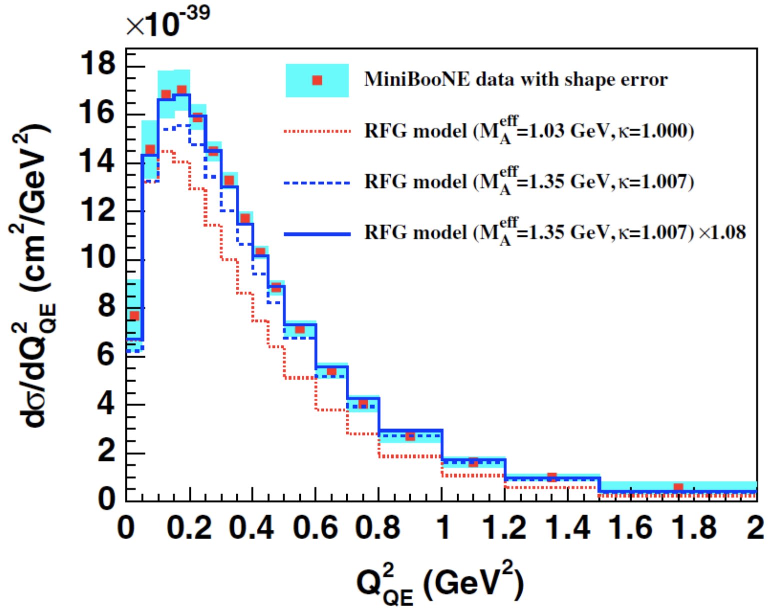
NUANCE

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

Many 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)

NuWRO

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

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.

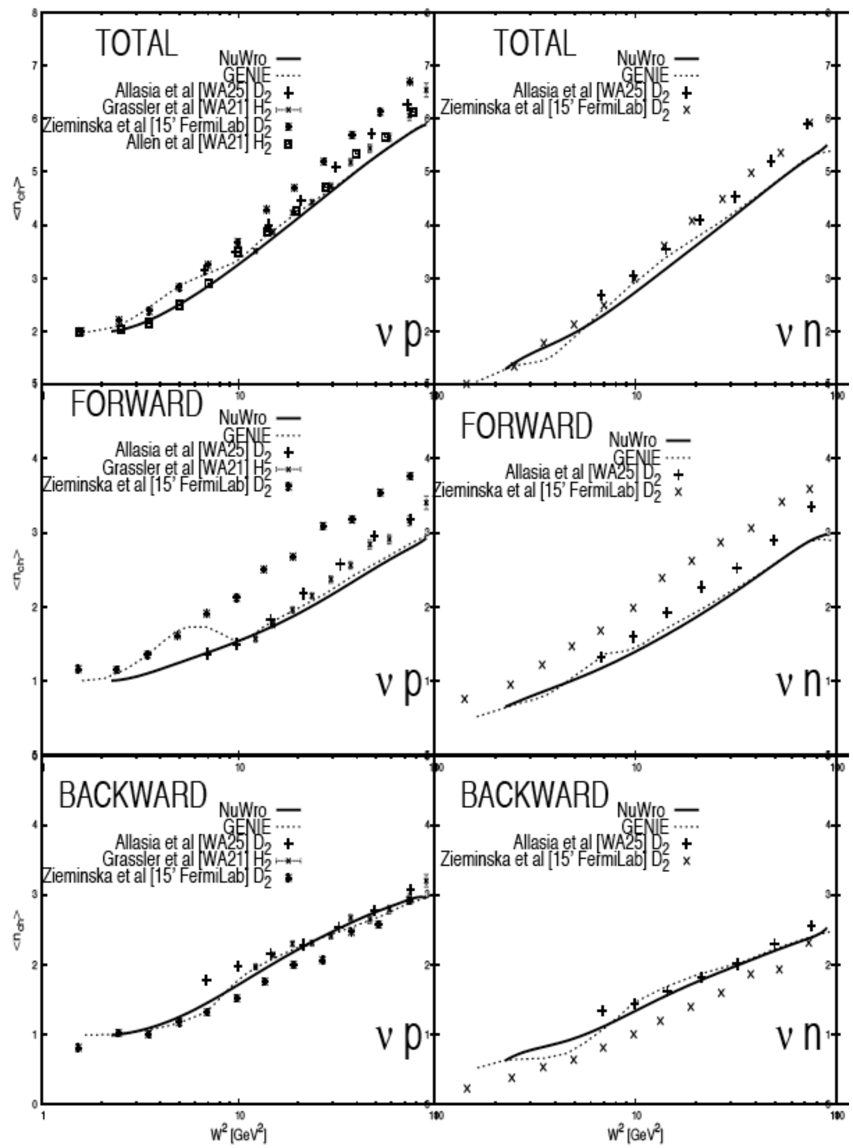
Implementation of Spectral Functions as an alternative to the Fermi Gas model.

Intranuclear cascade modeling:

•Uses the model of Oset in the Delta region

•Modeling of formation zones / coherence length effects

•MEC model included



J. Sobczyk, PoS(NUFACT08)141

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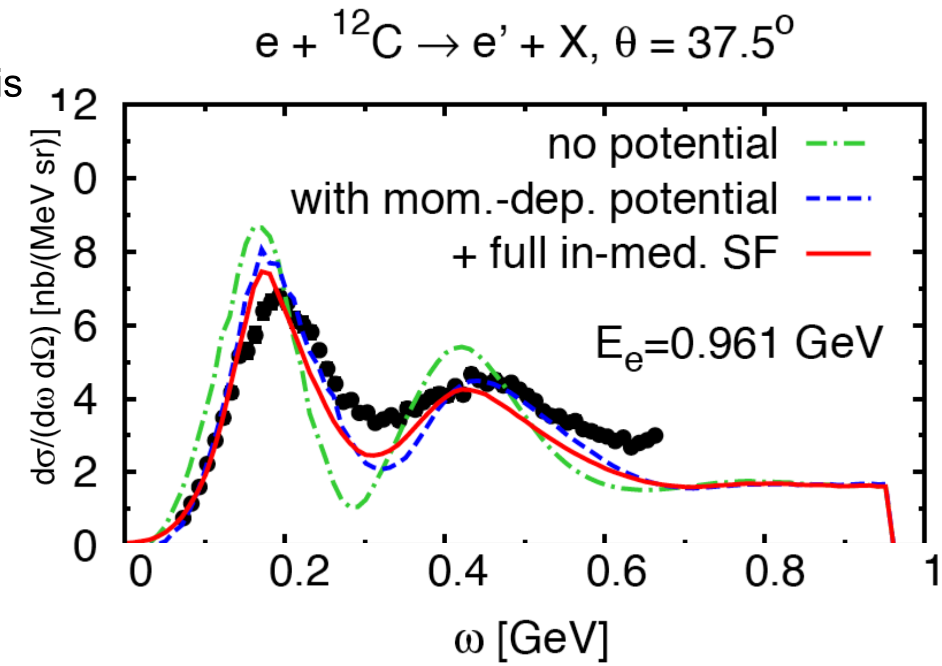
GiBUU

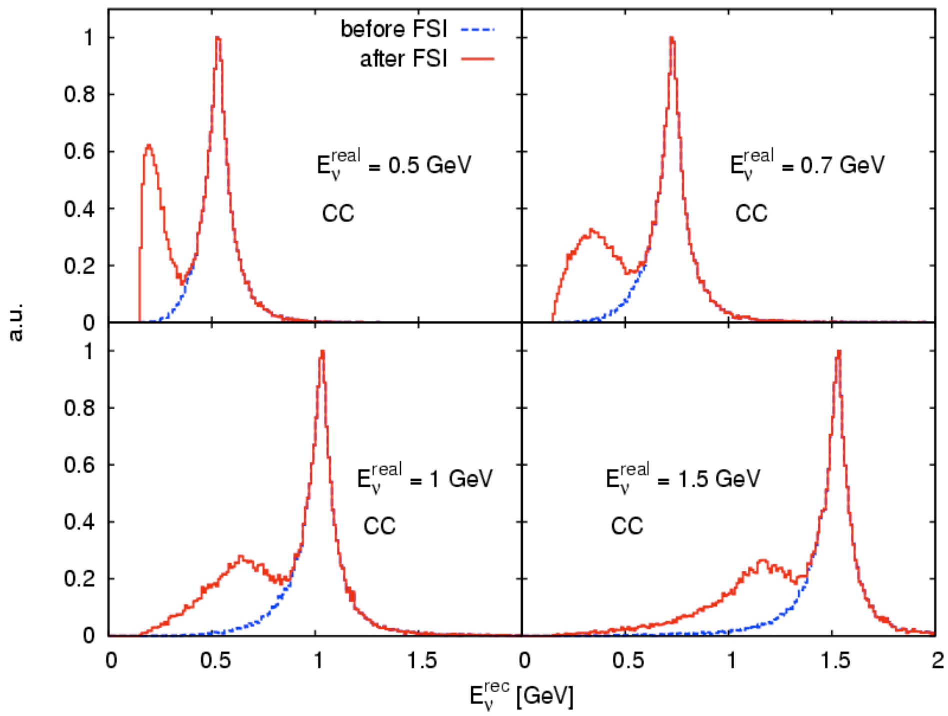
Primary Authors: T. Leitner, O. Buss, U. Mosel, L. Alvarez-Ruso

O. Lalakulich et al, PRC86: 0146107 (2012)

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.



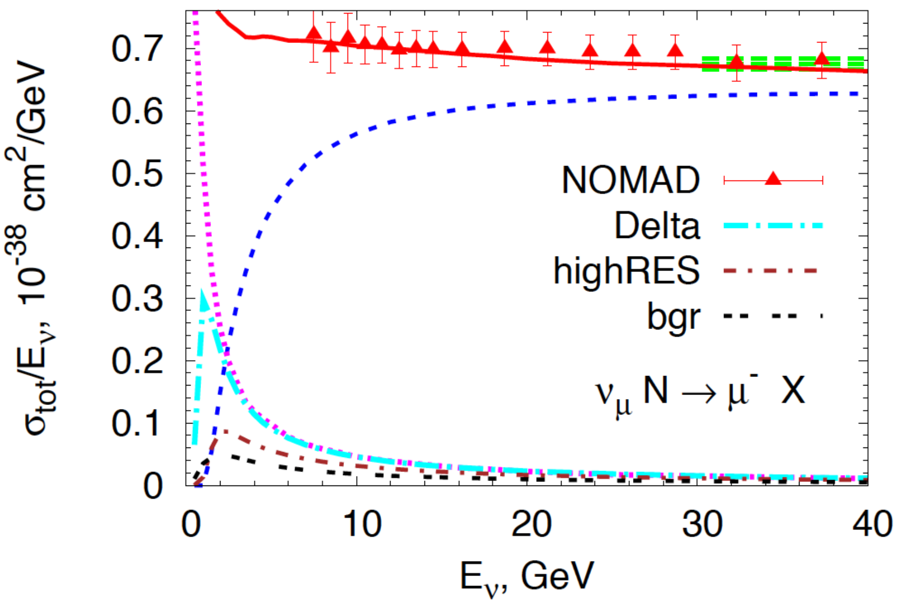


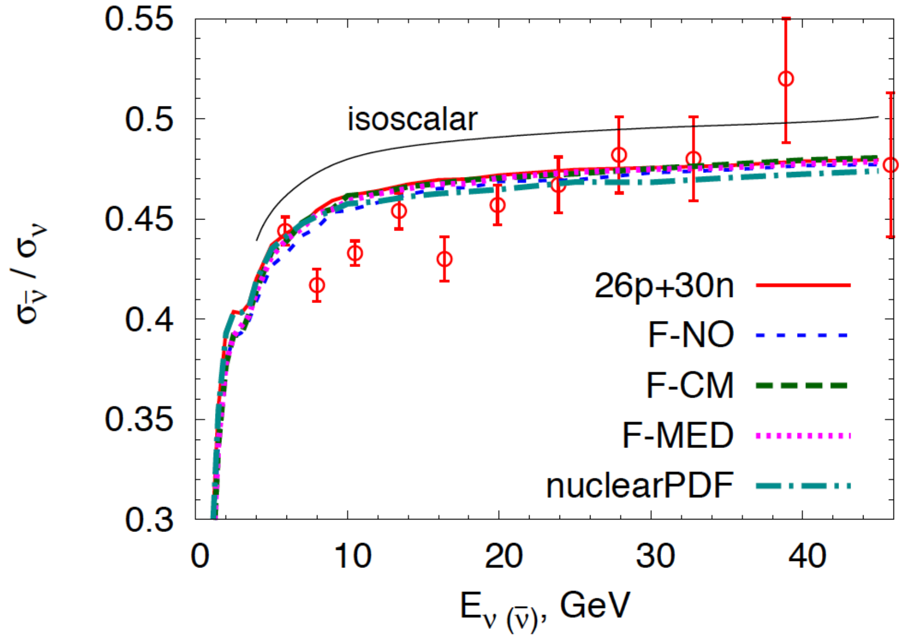
QEL, Δ, 13 N* and non-resonant single-pion channels. Recent electron scattering data used for state-of-the-art parametrizations of vector form factors, axial refit to neutrino-scattering data.

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

O. Lalakulich et al, PRC86: 0146107 (2012)

Neutrino comparisons are done without fine tuning, use default parameters.

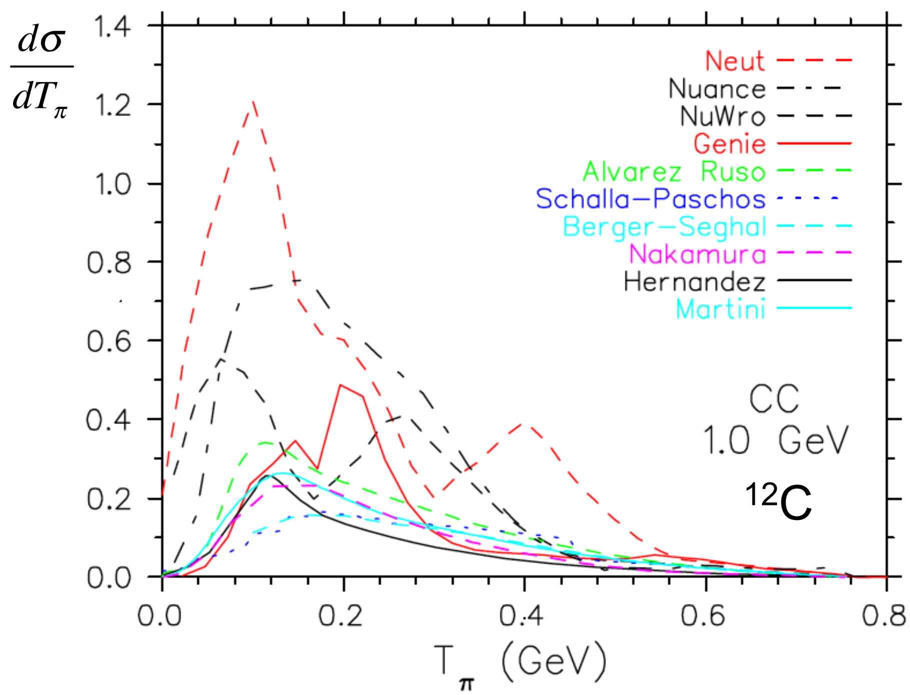




Comparisons

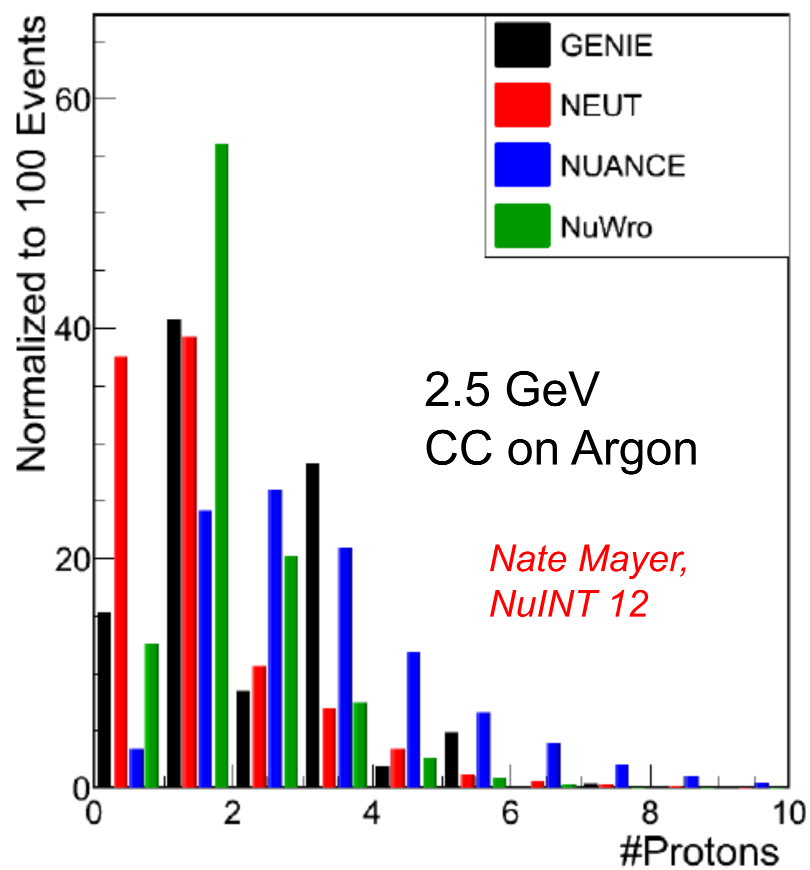
Generator comparisons have been a staple of the NuINT Conference Series.
Differences are sobering, uncovering sources can be more tricky.
Often due to different free nucleon ingredients rather than sophisticated nuclear physics.

Coherent production



Boyd et al., AIP Conf.Proc. 1189 (2009) 60-73

Proton Multiplicity (On Argon)



Nate Mayer, NuINT 12

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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

Need to compare fundamentals..

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!
Treating SIS!!

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Multi-Nucleon Processes

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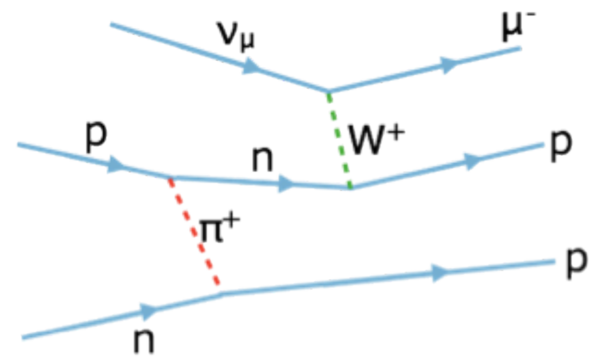
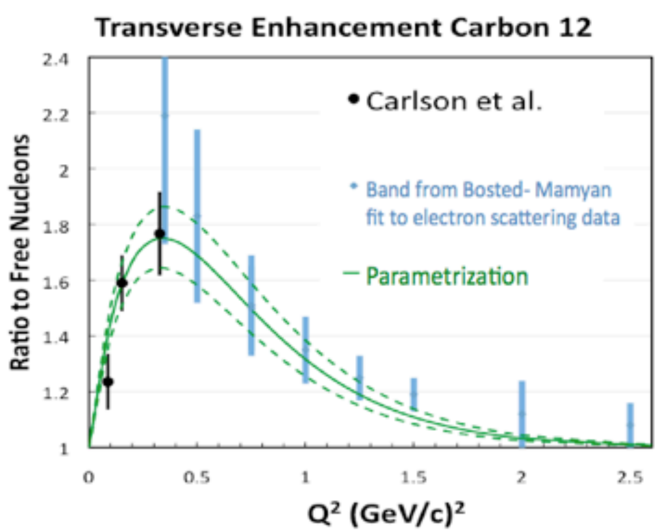
Significant recent theoretical work on the impact of scattering mechanisms involving multiple nucleons[1,2,3]

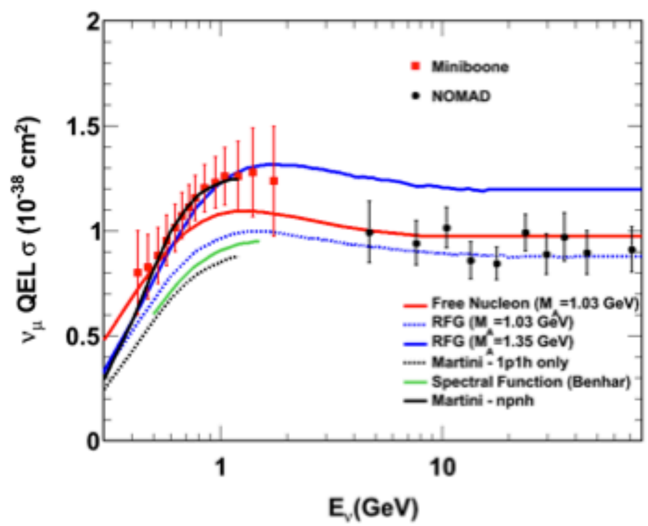
Our main conclusion is that MiniBooNE data are fully compatible with former determinations of the nucleon axial mass...Besides, we have found that the procedure commonly used to reconstruct the neutrino energy for quasielastic events from the muon angle and energy could be unreliable for a wide region of the phase space, due to the large importance of multinucleon events.

Nieves et al, Phys. Lett. B707 (2012)



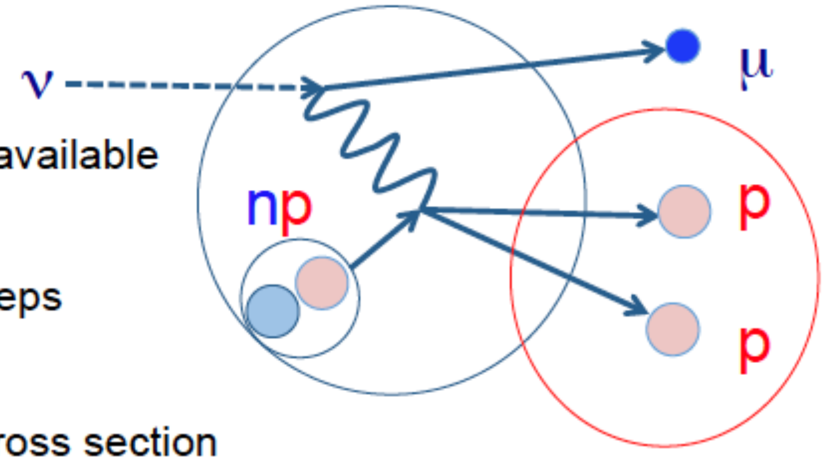
In addition, phenomenological description of the missing strength in electron scattering via empirical enhancements to the magnetic form factor[4,5]:





[1] Martini et al. PRC84 (2011) 055502 [2] Nieves et al. Phys Lett. B707 (2012) 72 [3] Amaro et al. PRD84 (2011) 033004
[4] Bodek et al. Eur. Phys. J C71 (2011) 1726 [5] S. Dytman et al. private communication

2. MEC simulation in GENIE



Currently, hadronic kinematic distributions are not available from any models in the market

Therefore implementation of MEC takes several steps

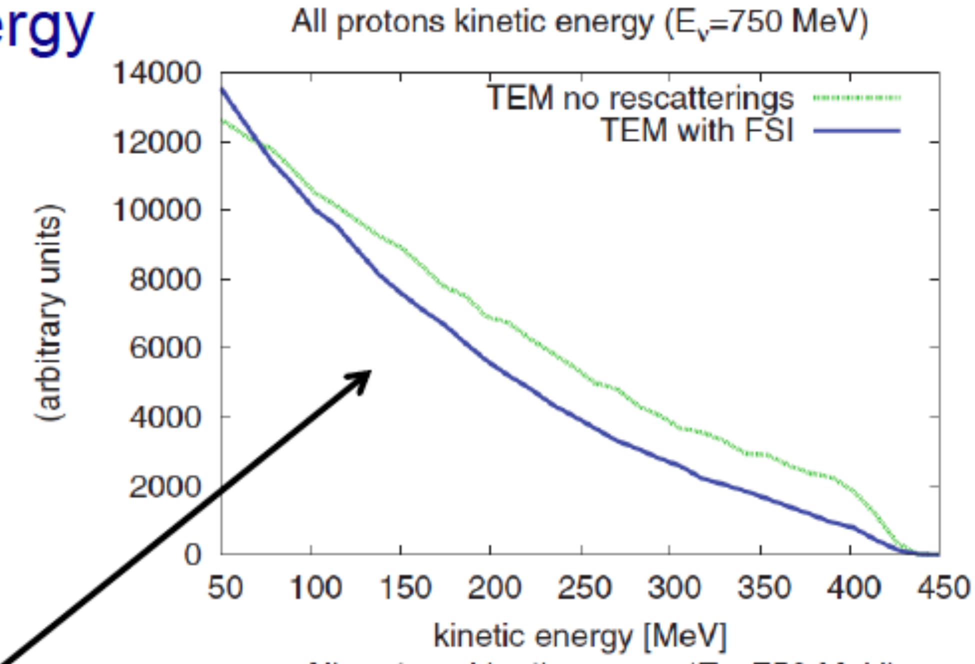
(1) specify leptonic model
- Choose a model to generate lepton differential cross section
- Energy-momentum transfer is specified from the model
- Verify the model using e-scattering data

(2) specify hadronic model
- Model how to pick up 2 nucleons
- Model how to share the energy-momentum transfer, to knock-out 2 nucleons

(3) specify FSI model
- Outgoing lepton and nucleons undertake standard FSI model in GENIE

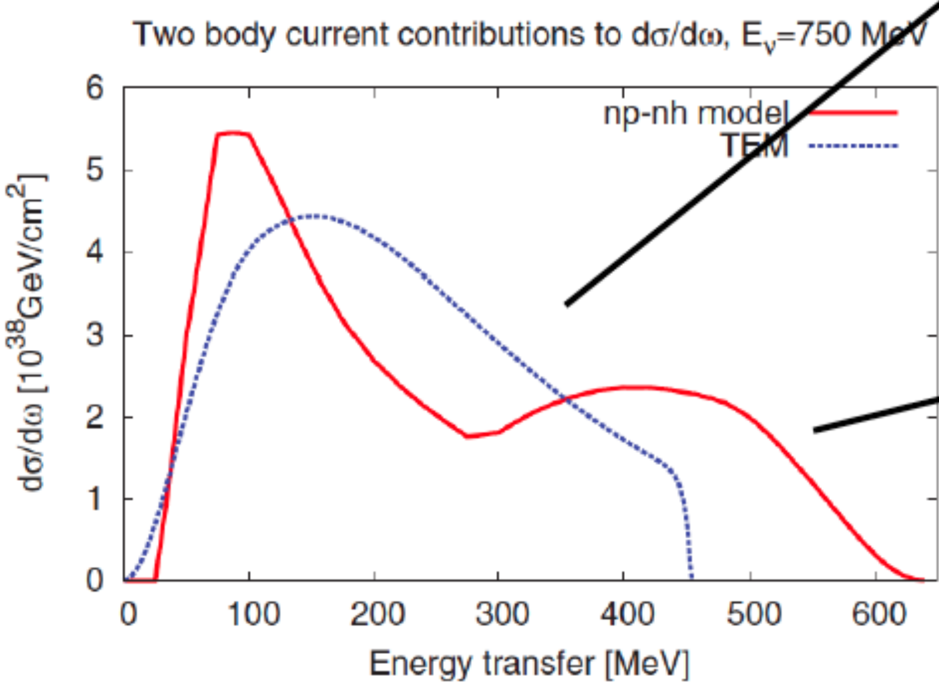
Sobczyk, PRD86(2012)015504

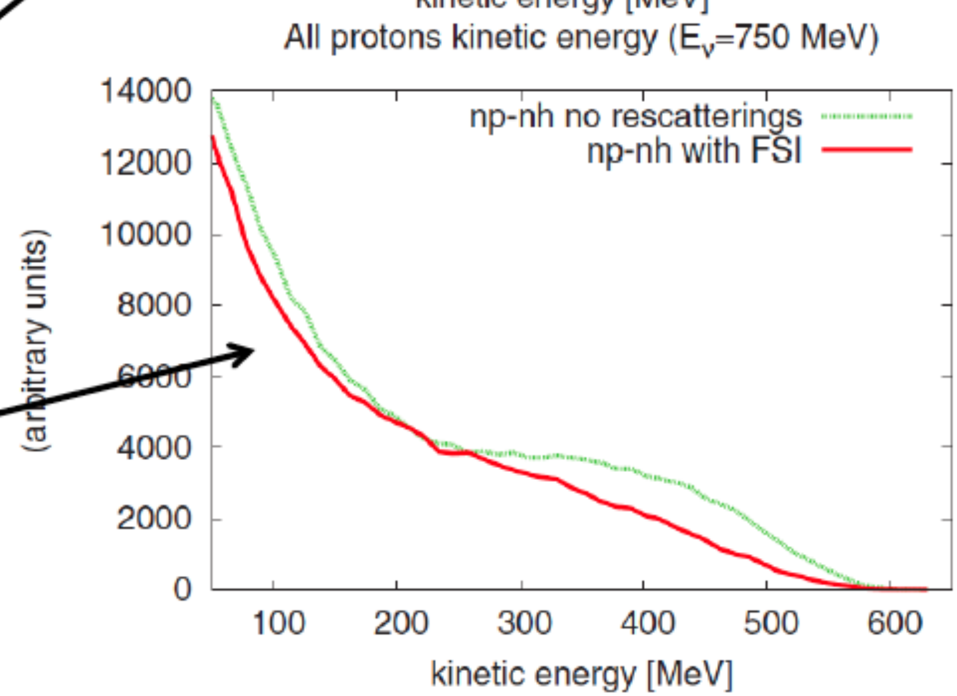
4. Sum of all nucleon kinetic energy



NuWro
- 2 choices of MEC model
  - np-nh model (based on Marteau model)
  - TEM (Transverse enhancement model)
- Nucleon cluster model similar to GENIE (more attention to energy balance)

Different predictions on energy transfer provide different predictions on total kinetic energy, but after FSI, most of structure is gone





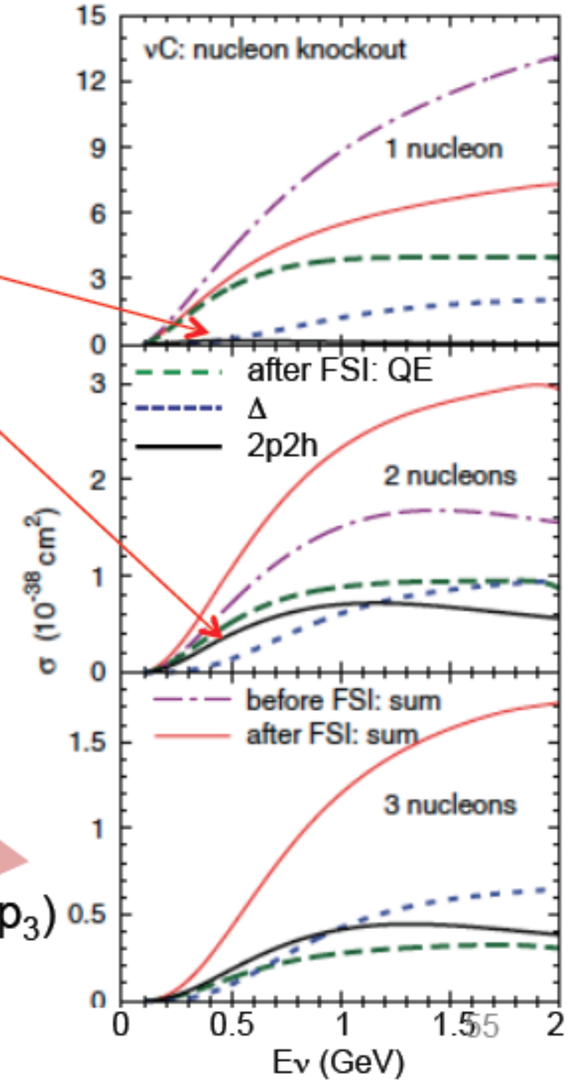
Lalakulich et al, PRC86(2012)014614

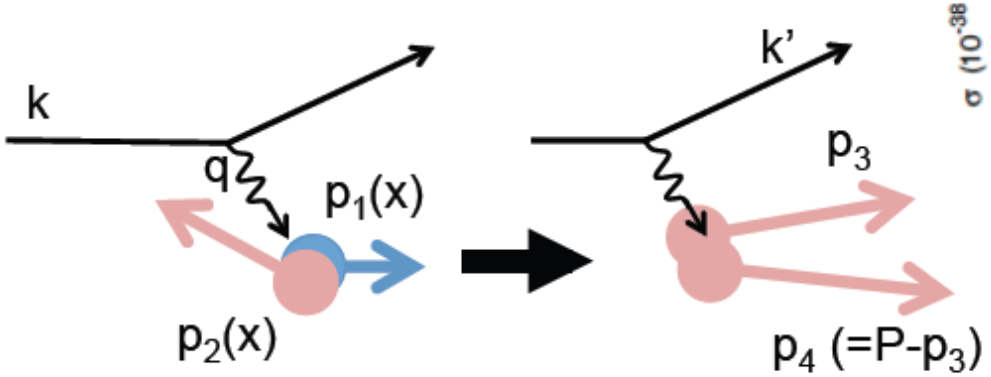
4. Total cross section, with N-nucleons

GiBUU
- A special care is paid for the phase space
- 2 nucleons start from same location)
- hadronic tensor is transverse projector (model II)
- FSI controls final state particles

2p-2h doesn't contribute to 1 nucleon knockout
- MEC model shouldn't enhance 1-nucleon knock out

GiBUU ν_μ-^{12}C total cross section for multi-nucleon knockout (after FSI)





MC implementation of MEC model

	GENIE	NuWro	GiBUU
What kind of Leptonic model?	Dytman model	np-nh model and TEM	Transverse projector for hadronic tensor
how to choose 2 nucleon momentum?	From Fermi sea, independently	From Fermi sea, independently	From Fermi sea, independently
how to choose 2 nucleon location?	both are random	both are random	both are random, but same location
Any correlations?	no	no	no, but xs is weighted by phase space density
what kind of pairs? n-p or n-n?	n-p : n-n = 1 : 4	n-p : n-n = 3 : 1	n-p : n-n = 3 : 1
How to share energy-momentum transfer by 2 nucleons?	nucleon cluster model	nucleon cluster model	not clear

Conclusions / Opinions

In preparation for looking forward, we should look back. Our community has been talking about many of these issues for over a decade now (NuINT01 was start).

Progress:

- Substantial increase in relevant theoretical (nuclear) work.
- Lots of new data.
- Experiments now strive to present results with a minimum of model-based corrections.
- Increased emphasis on comparisons / tuning to external data first.

Less so:

- Many of the heavily-used generators lag the theoretical state of the art (spectral functions are a particularly painful example for me personally).
- Relatively limited collaboration between experimentalists and theorists on generator development. Getting this right involves ***close collaboration***.
- Still an abundance of generators.

Opinions

What have been some of the barriers? How can we move forward?

Experimentalist's vs. Theorist's perspectives/needs:

- Tension between describing one's data and having correct physics.
- A lot of the necessary theory work is not theoretically interesting:
  - Calculations needs to cover NC/CC, all nuclei, all flavors!
  - How to combine with other models?
  - How to extrapolate? (Easy answer: Don't!)
- Different incentives and reward systems within our sub-disciplines.
- Practical considerations for code development
  - Needs to be reasonable fast to run in MC
  - Code is in C++ or Fortran
- Geography: to first order experimentalists (US/Japan), theory (Europe)

Generator development by experimentalists for experiments often involves:

- Integration with detailed beamline simulations and complicated detector geometries,
- Reweighting existing MC samples
- Evaluation of systematic errors through external data comparisons.

Particle Physics vs. Nuclear Physics:

- Most experiments have little exposure to theoretical nuclear physics in our training, and it shows!

Tufts UNIVERSITY