Neutrino Generators

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Tufts University

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NuFACT 15
CBPF - Rio de Janiero

Image: http://urban-echo.co.uk/wp-content/uploads/2015/04/Rio-De-Janerio-Beach-6.jpg

INTRODUCTION

1) Event Generators in Neutrino Physics

2) Generator Updates

- GENIE
- GiBUU
- NEUT
- NuWRO

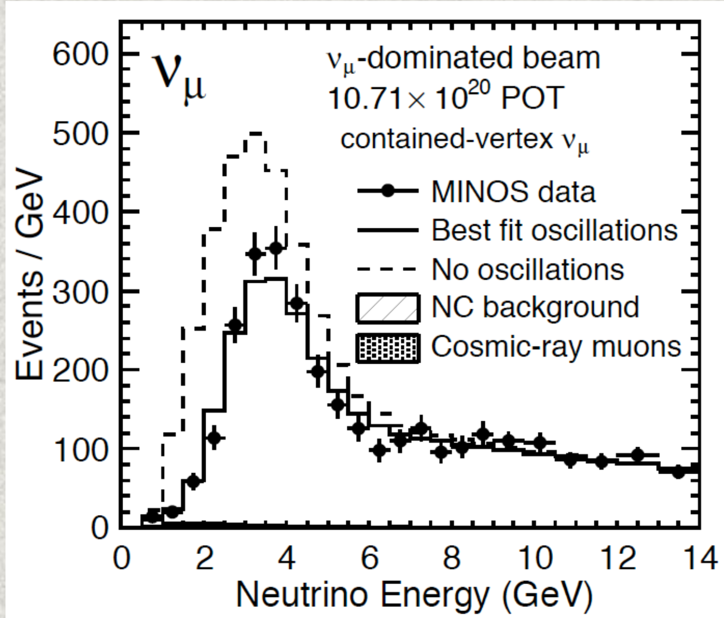
3) Progress, Challenges, and Opinions.

Their Role

MINOS

In an analysis context, important for:

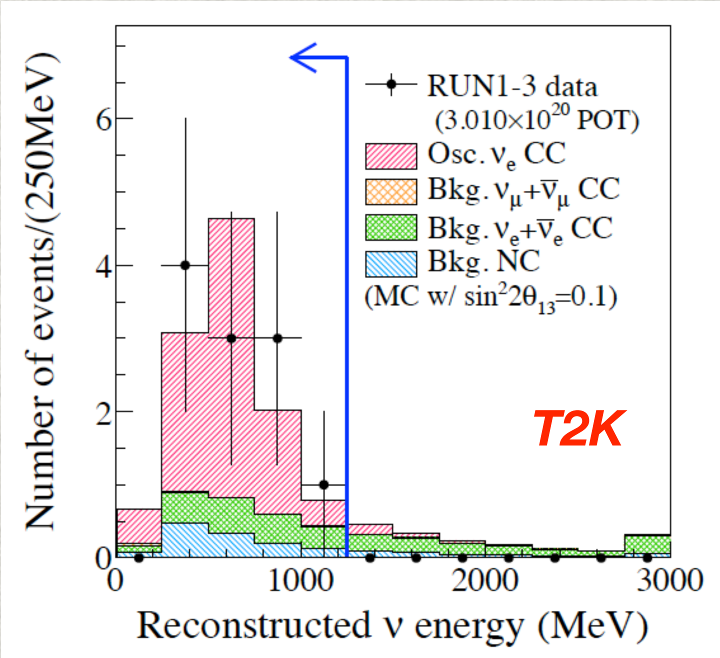
- background estimation
- unfolding
- connecting observed to true quantities (e.g. neutrino energy)
- systematic error evaluation



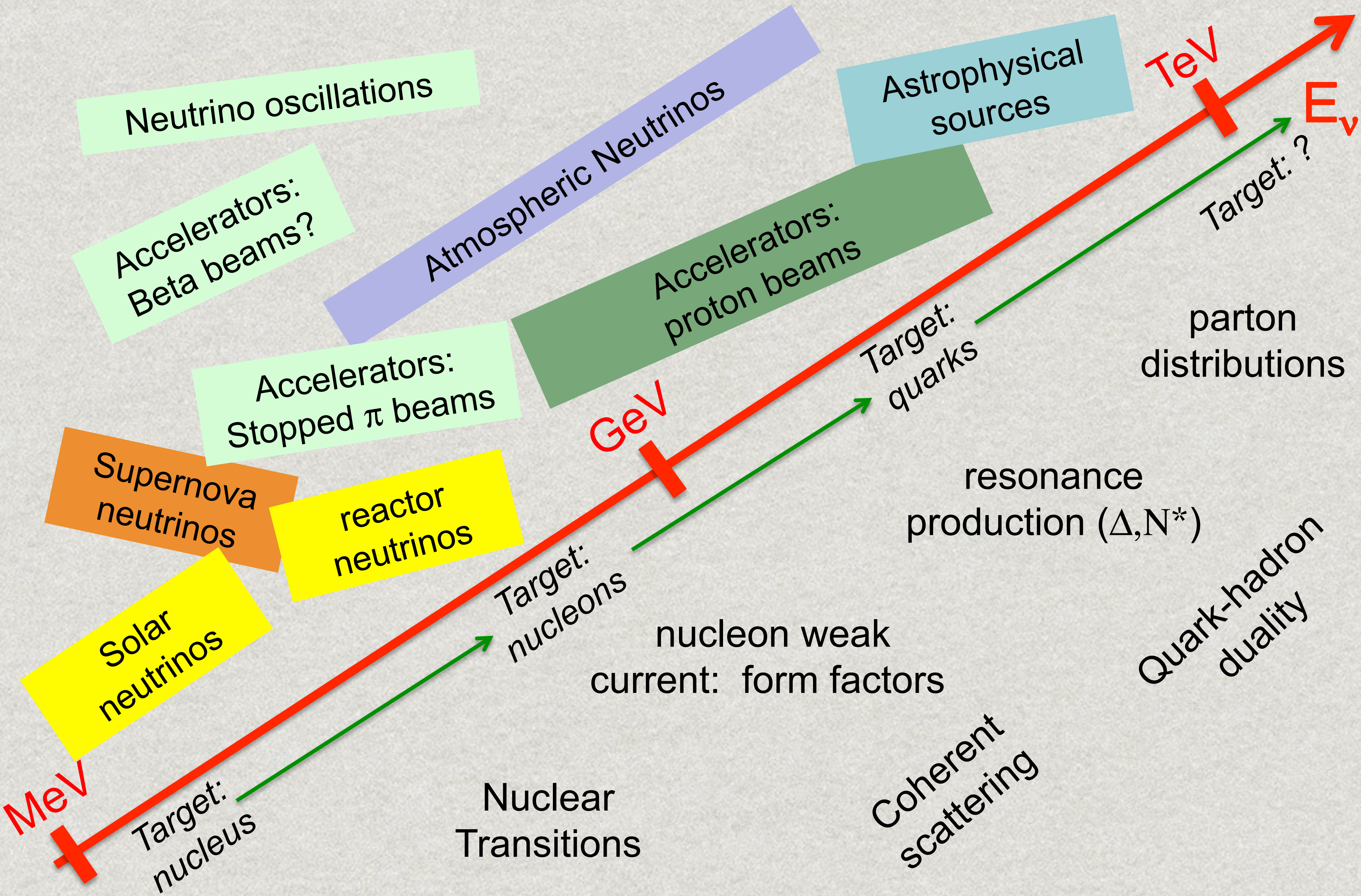
Adamson et al., Phys.Rev.Lett. 110 (2013) 251801

Crucial for use as an 'effective model' in the context of an oscillation fit, where we are often less interested in ***how good the model is***, and more interested in ***how wrong it could be.***

Some similarities, many differences, when compared with event generators in other areas of physics.



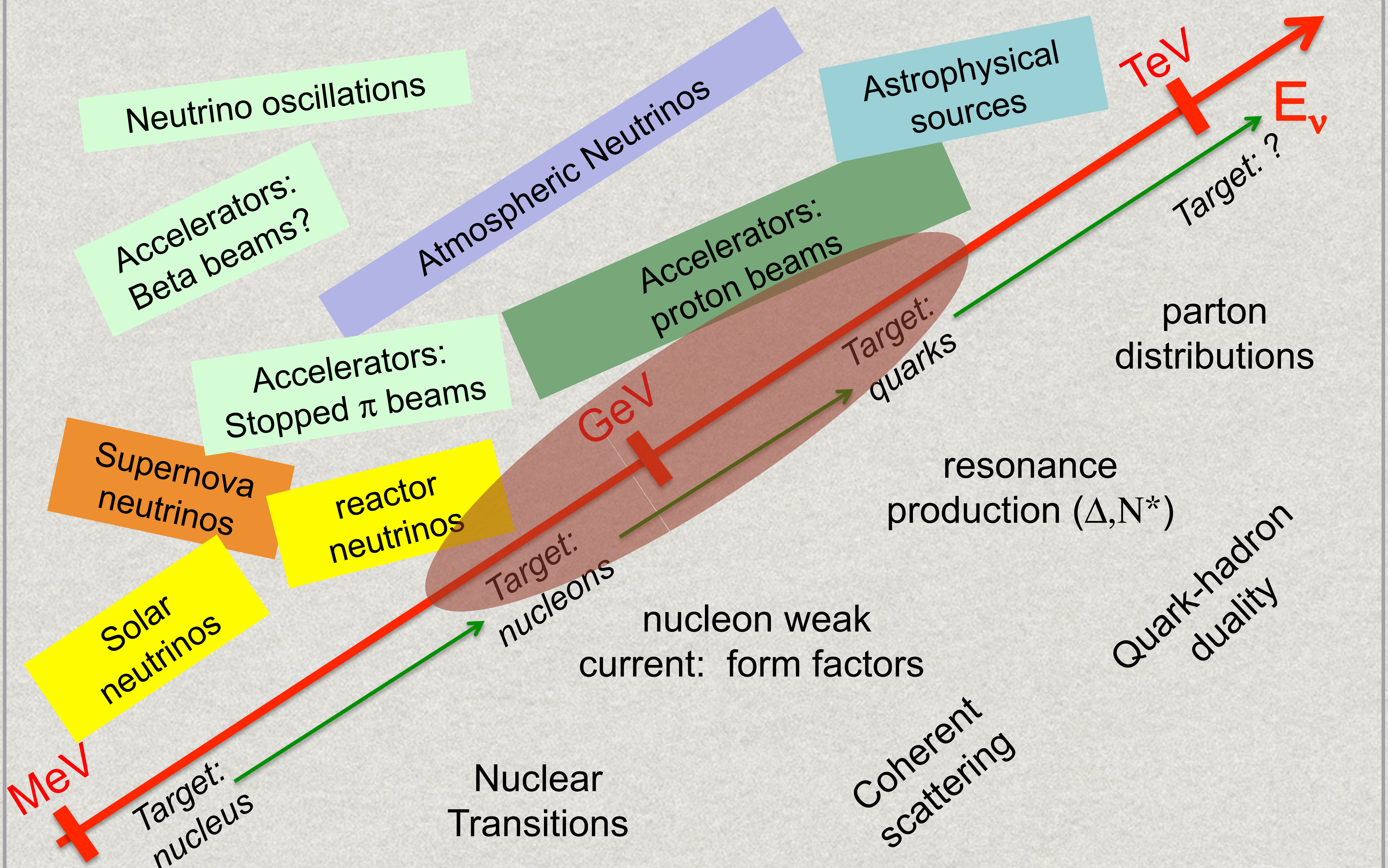
Abe et al., Phys.Rev. D88 (2013) 032002

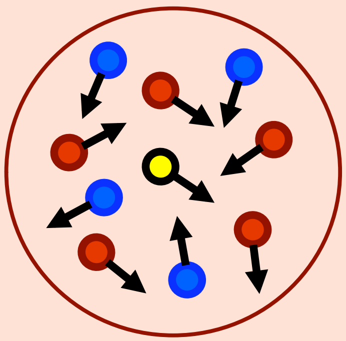


J. Formaggio and G. Zeller, Rev.Mod.Phys. 84, 1307 (2012).

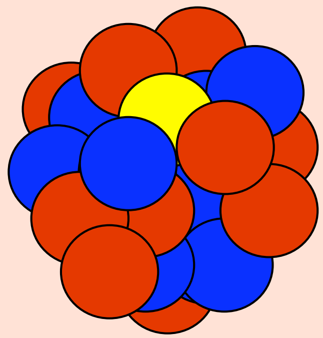
The Full Spectrum

ANIS: A. Gazizov and M. P. Kowalski, Comput.Phys.Commun. 172, 203 (2005)
NEGN: D. Autiero, Nucl.Phys.Proc.Suppl. 139, 253 (2005)
NUANCE: D. Casper, Nucl.Phys.Proc.Suppl. 112, 161 (2002)
FLUKA: G. Battistoni et al., Acta Phys.Polon. B40, 2491 (2009)

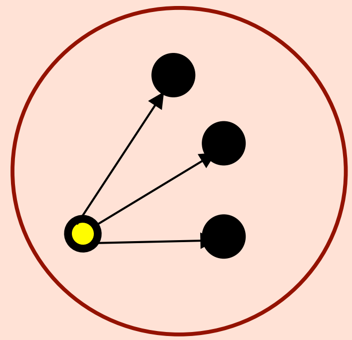




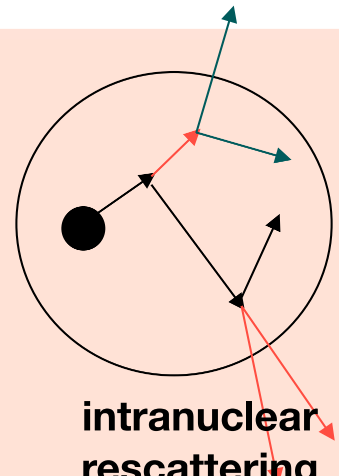
nuclear model



fundamental
scattering mechanism



hadronization
(in nuclei)



intranuclear
rescattering

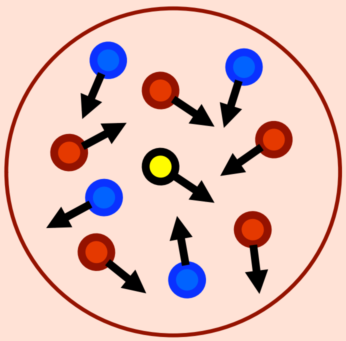
THEORY

- Full nuclear-many body theory
- Relativistic Green’s functions
- Spectral functions
- Relativistic Fermi Gas

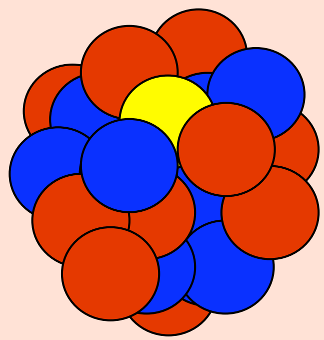
- Elastic/Quasi-elastic
- Production of baryon resonances
- Parton-level inelastic scattering
- ... more rare (few % processes

- Resonance decays
- Empirical fragmentation models
- PYTHIA (string fragmentation)
- Formation zones
- Coherence lengths

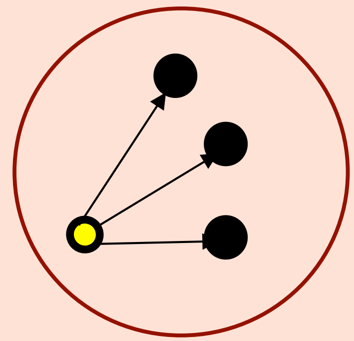
- optical models
- intranuclear cascade simulations
- transport calculations



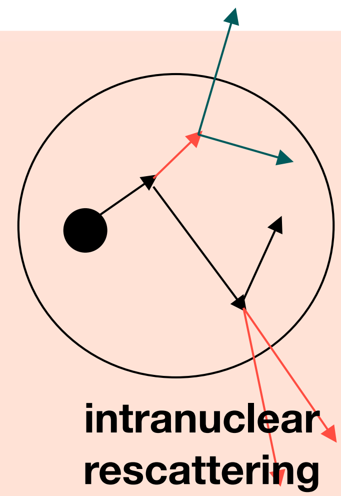
nuclear model



fundamental scattering mechanism



hadronization (in nuclei)



intranuclear rescattering

THEORY

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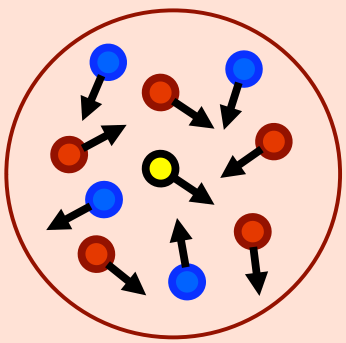
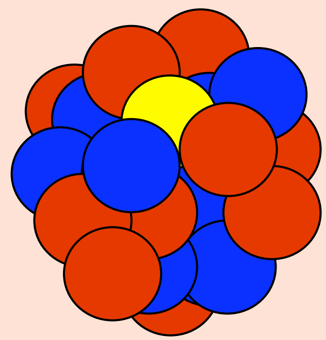
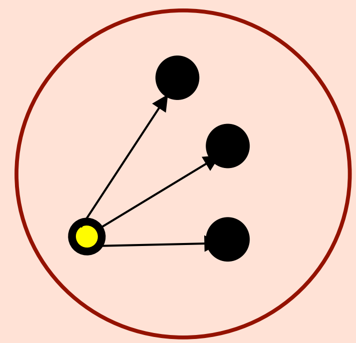


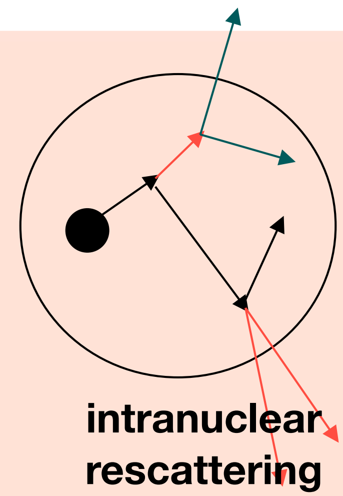
nuclear model



fundamental scattering mechanism



hadronization (in nuclei)



intranuclear rescattering

DATA

Inclusive electron scattering:

hydrogen/deuterium targets (eN)

nuclear targets (eA)

in the quasi-elastic and resonance regions

hadron attenuation

e/μ : structure function measurements

e

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

ν

pion, kaon, hadron - nucleus scattering experiments

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

π

NuWRO

Authors: C. Juszczak, J. Sobczyk, J. Nowak, T. Golan.

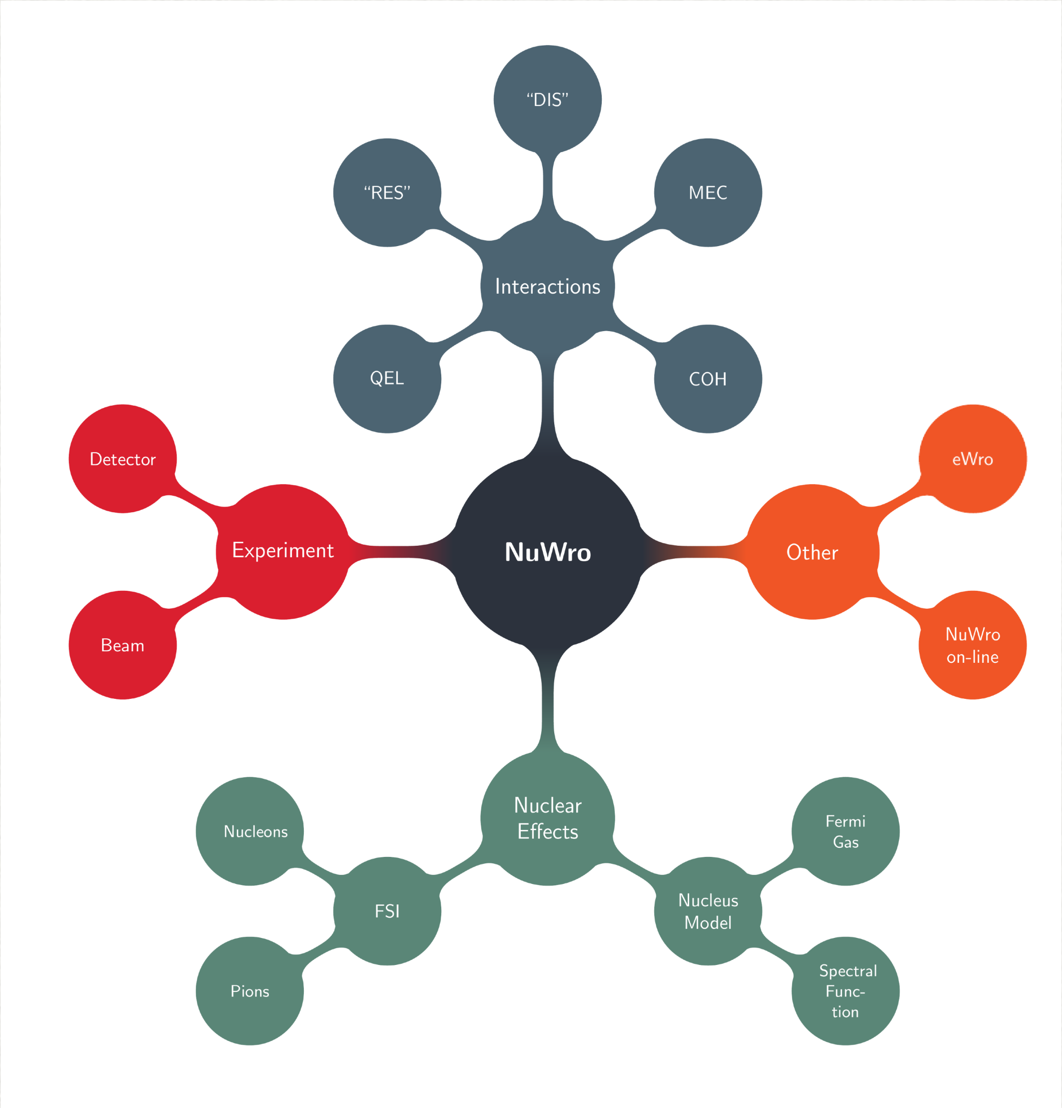
Contributors: K. Graczyk, J. Zmuda and others

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

http://borg.ift.uni.wroc.pl/nuwro/

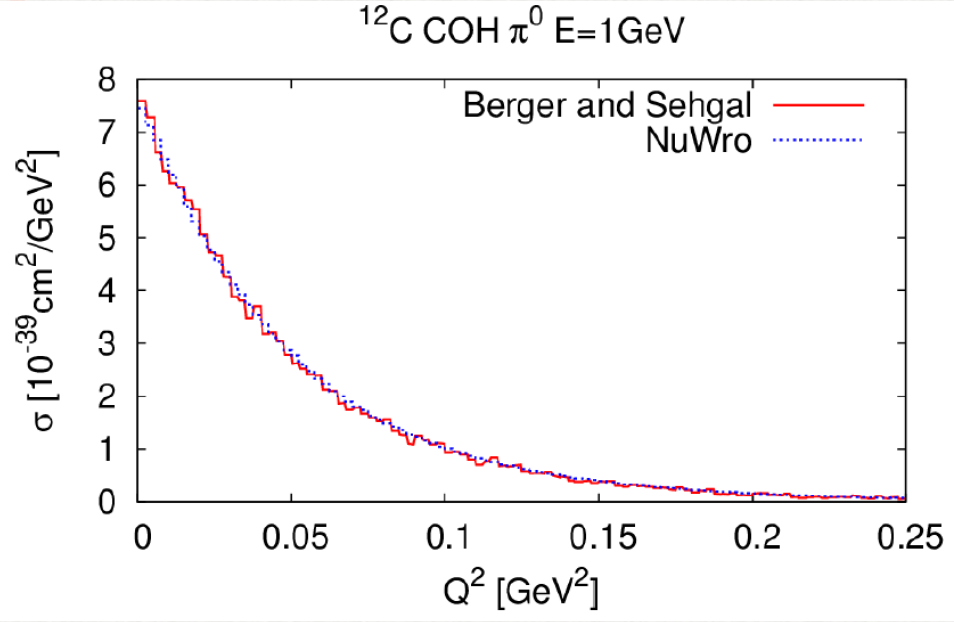
Recent Developments:

- New coherent pion production model
- Improved pion angular distribution from Delta decays
- Work in progress in electron scattering module.



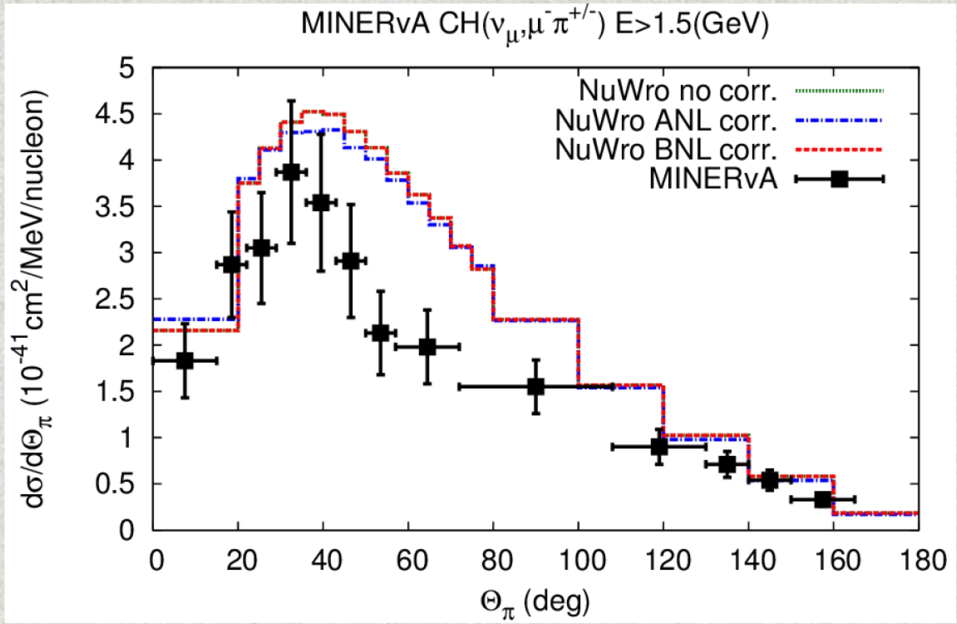
NuWRO Developments

Figures: J. Zmuda



Coherent Pion production

- Have implemented the Berger-Sehgal model for NC and CC channels.
- A joint project with Paul Martins working on behalf of NEUT.



Pion Angular Distribution from Delta Decay

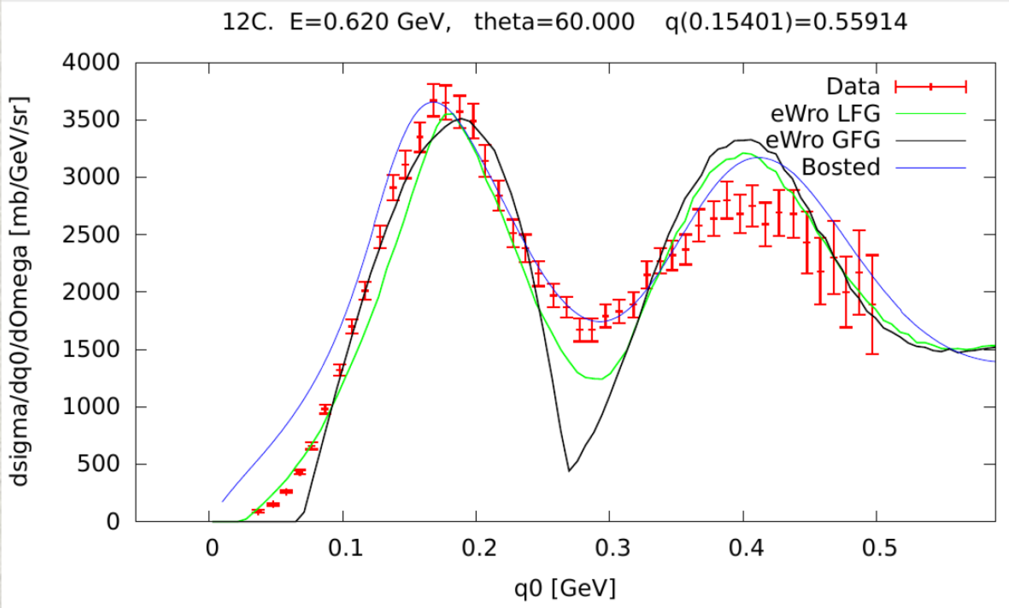
- Before: uniform in Delta rest frame
- Now: Based on measurements from ANL/BNL bubble chamber experiments.

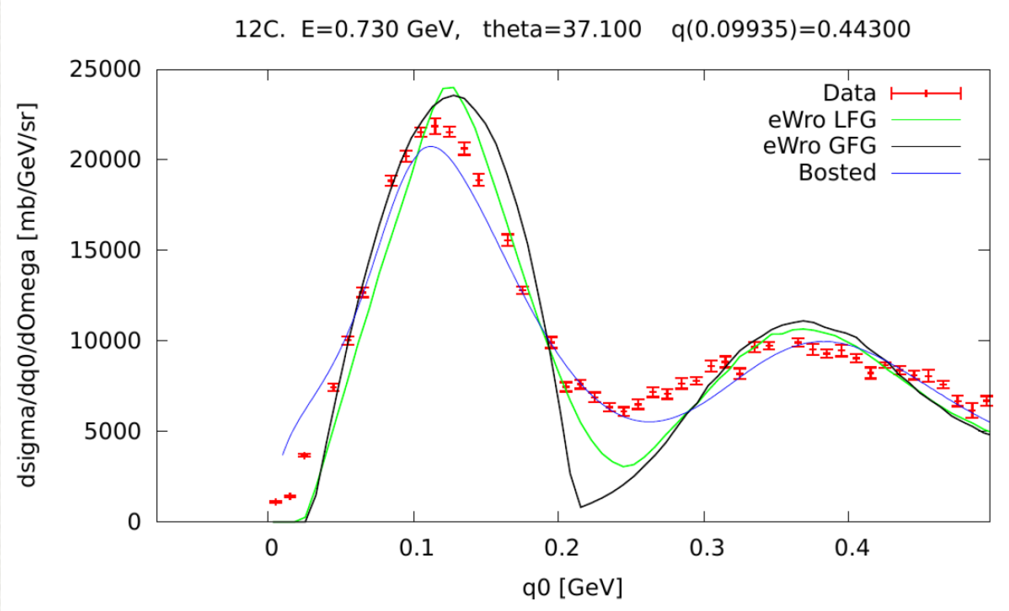
NuWRO Developments

Figures: Cezary Juszczak

EWro: Electron Scattering Mode

- A work in progress, much remains to be done, but preliminary results are promising.





NEUT

Initially developed for Kamiokande, used by SuperKamiokande, K2K, T2K, HyperK, SciBooNE. Model selection and update policy: Satisfy the requirements of SK and T2K.

See tomorrow's talk (WG2, 15:00) by Dr. Tom Feusels

CCQE / NCEL

- Relativistic Fermi Gas model (Smith - Moniz)
- Spectral function (Benhar - Ankowski)

Multi-Nucleon CCQE-like interaction

- Nieves et al.

Resonance 1 π / meson production

- Rein-Sehgal (as appeared in the paper)
- Rein-Sehgal with Graczyk – Sobczyk Form Factor

Current "default"

Coherent 1π production

- Rein-Sehgal (as appeared in the paper)

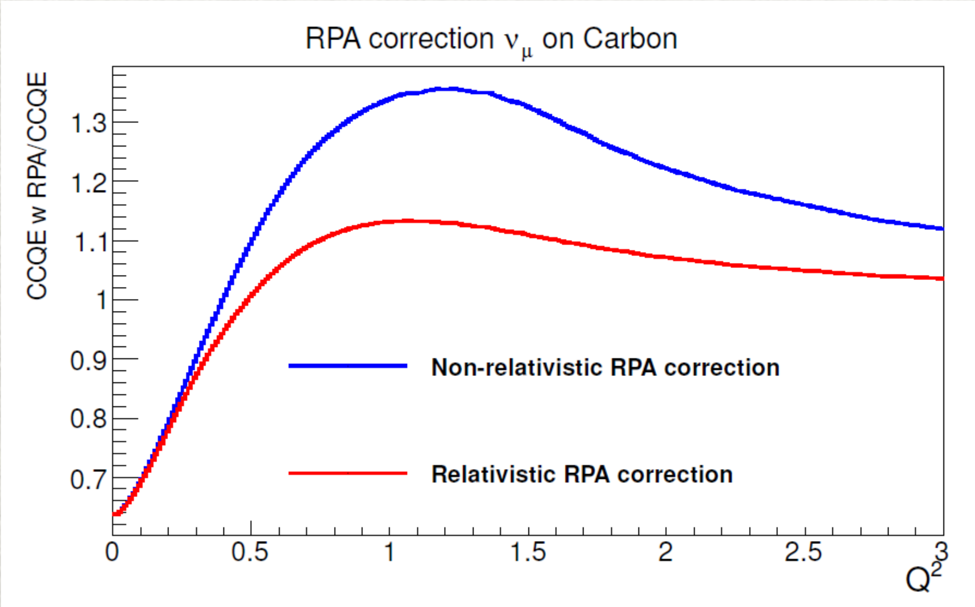
DIS

- Custom module (KNO Scaling) + PYTHIA
- GRV98 (+ Bodek-Yang correction)

NEUT

RPA: Medium correction on CCQE

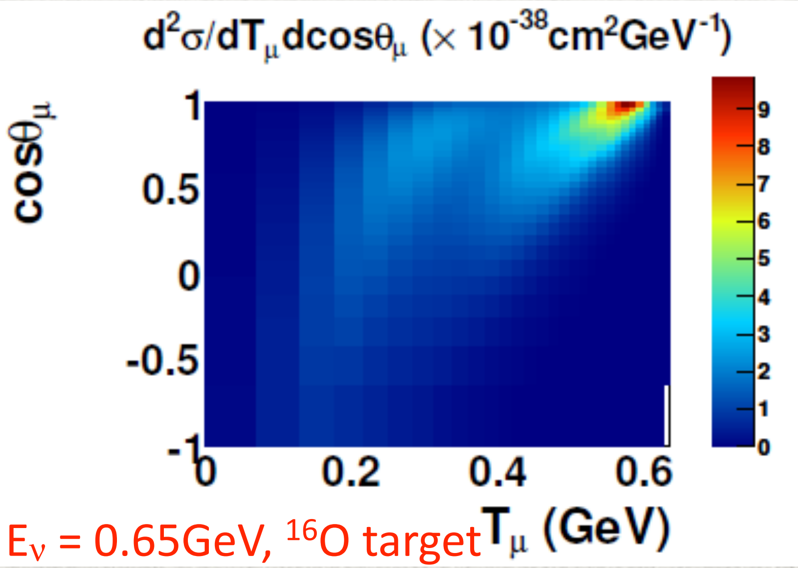
J. Nieves, J. E. Amaro, and M. Valverde. Phys. Rev. C, 70:055503, 2004

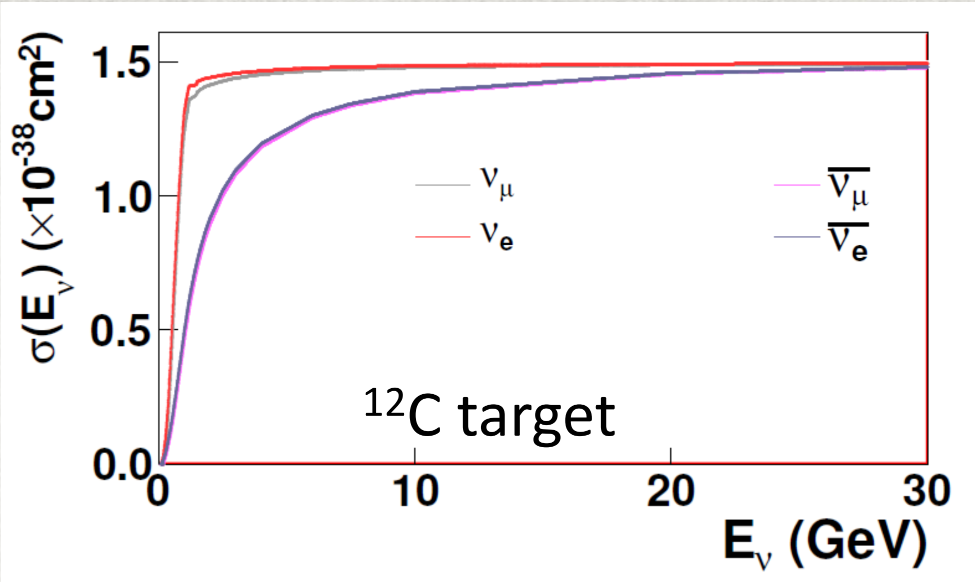


A. Radji, C. Wilkinson with F.Sanchez, R. Gran

Multi-nucleon CCQE-like interaction

J. Nieves, I. Ruiz Simo, and M Vicente Vacas. Phys.Rev. C83 (2011) 045501.





A. Redij, J. Schwehr, P. Sinclair, P. Stamoulis, R. Terri, and C. Wilkinson

NEUT

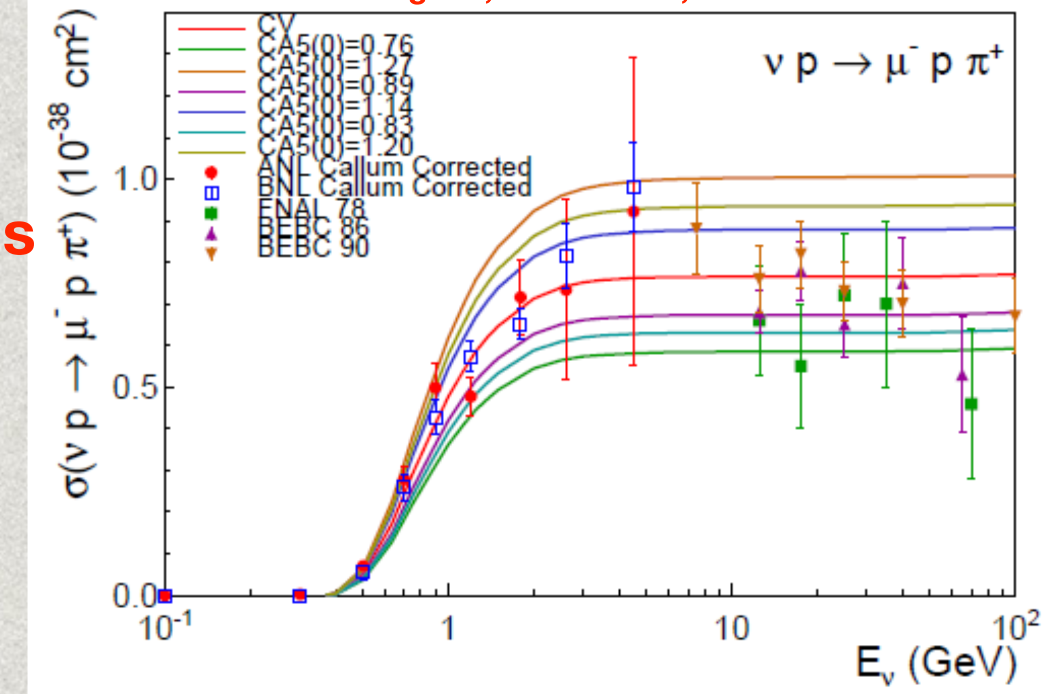
See tomorrow's talk (WG2, 15:00) by Dr. Tom Feusels

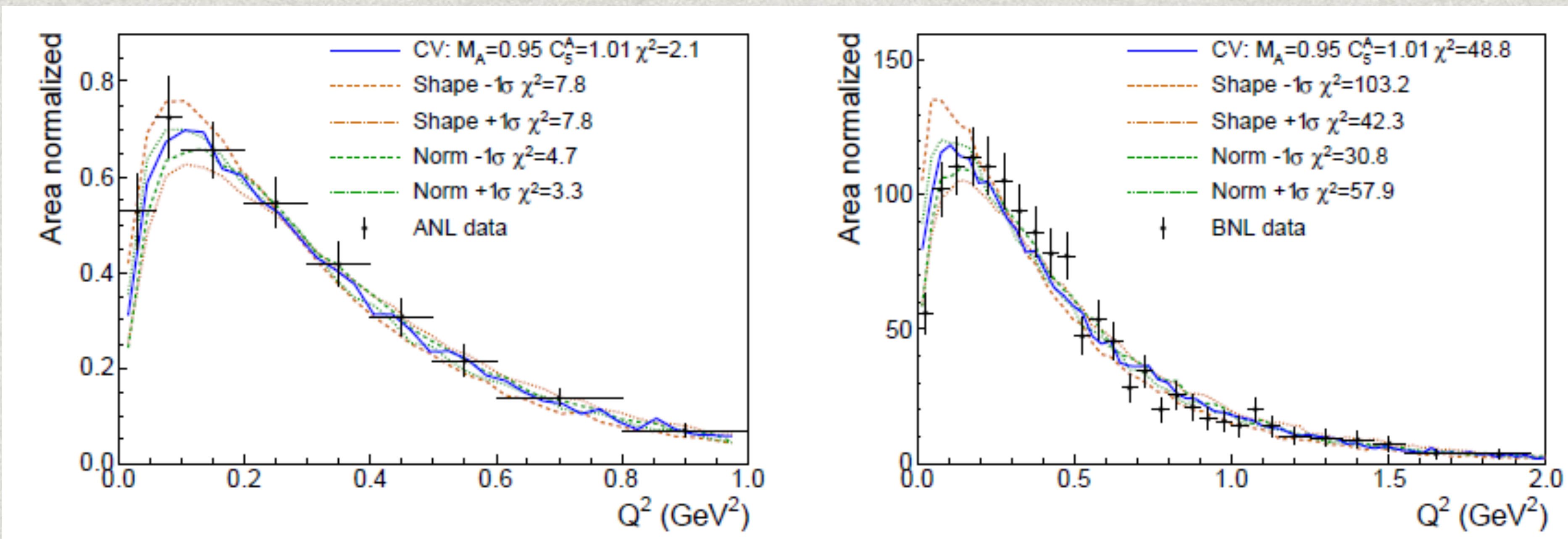
Tuning of resonance π production

Rein-Sehgal / FKR model
with Graczyk – Sobczyk Form Factor

M_A, C^A_5 and background fraction
were tuned using ANL & BNL data

P. Rodrigues, A. Bercellie, K. McFarland





NEUT

Radiative CCQE

Photon emission together with lepton is now implemented.

(K. Iwamoto, K. McFarland)

π multiplicity tuning (on-going work)

Fit bubble chamber data to tune the multiplicity of π

Especially for low W region (1.4 GeV/c^2< W < several GeV/c^2)

(C. Bronner et al.)

CCQE model by Nieves at al. (on-going work)

Local Fermi Gas with appropriate nuclear medium effect

(F. Sanchez et al.)

Coherent π production (on-going work)

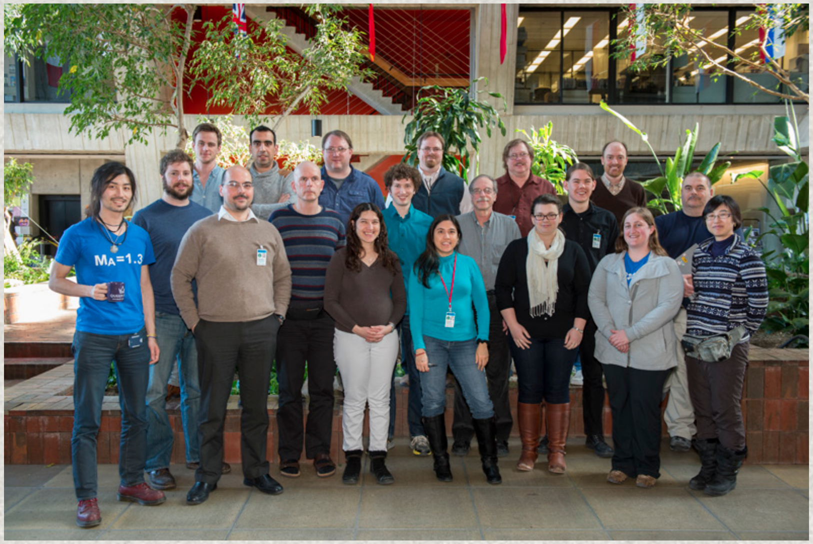
Berger-Sehgal model implementation

(P. Martins et al.)

GENIE

New organization structure to accommodate growth and more community involvement.

FNAL Developer's Workshop (Mar 2014)



Significant involvement from FNAL in GENIE development and supporting the large GENIE user base at the lab. Vision of Fermilab as a 'hub' for GENIE development.

Latest production release is 2.8.6, released 14 November, 2014. New release candidate 2.9.0 (beta) will graduate into production release 2.10.

Release numbers: Major-Minor-Patch

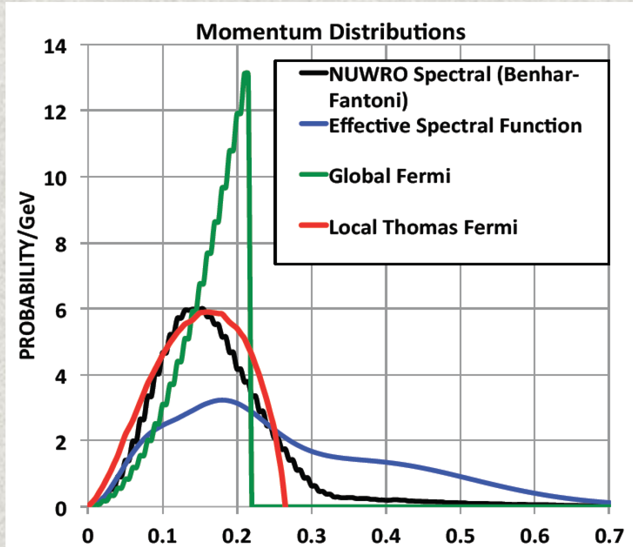
- Going forward, Major will denote a new default global physics model.
- Odd Minor numbers are release candidates ("betas").
- Even Minor numbers are production releases.

Working towards **GENIE 3.0** - 2016: New default physics tune incorporating all of the recently added models and new neutrino-nucleus cross section data, plus many tuning and data comparison tools.

GENIE - Developments

Effective Spectral Function: **B. Coopersmith**

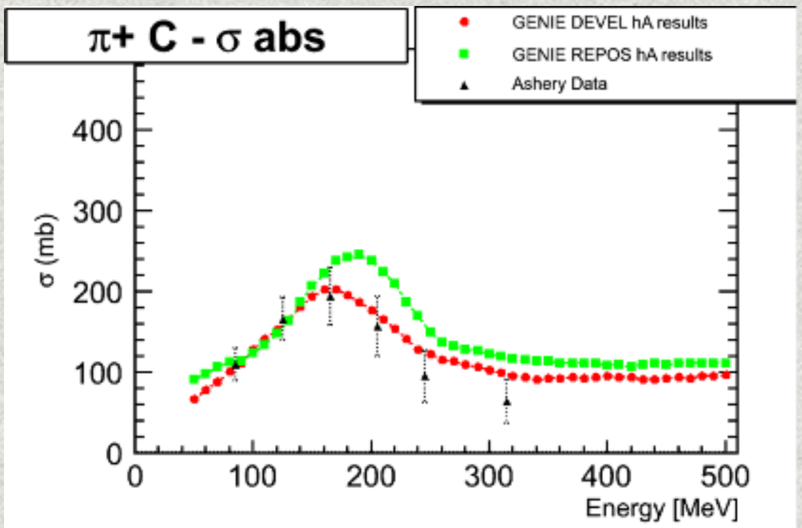
- Combines a superscaling formalism together with hadronic energy sharing prescription to form a complete QE model.
- An eight parameter spectral function is fit to the superscaling function extracted from electron scattering data (plus two parameters for binding energy and 2p2h fraction).



Bodek, Christy, Coopersmith
EPJ C (2014) 74:3091

Improved hA model **N. Geary and S. Dytman**

- In hA mode we parameterize a cascade with one effective (reweightable) interaction. Used data on iron and $A^{2/3}$ scaling for other nuclei.
- Now absorption scales as $A^{2/3+0.18}$, charge exchange as $A^{2/3}$, elastic as $A^{2/3+0.25}$, inelastic like $A^{2/3}$, pion production as $A^{2/3}$, total cross section as $A^{2/3}$.

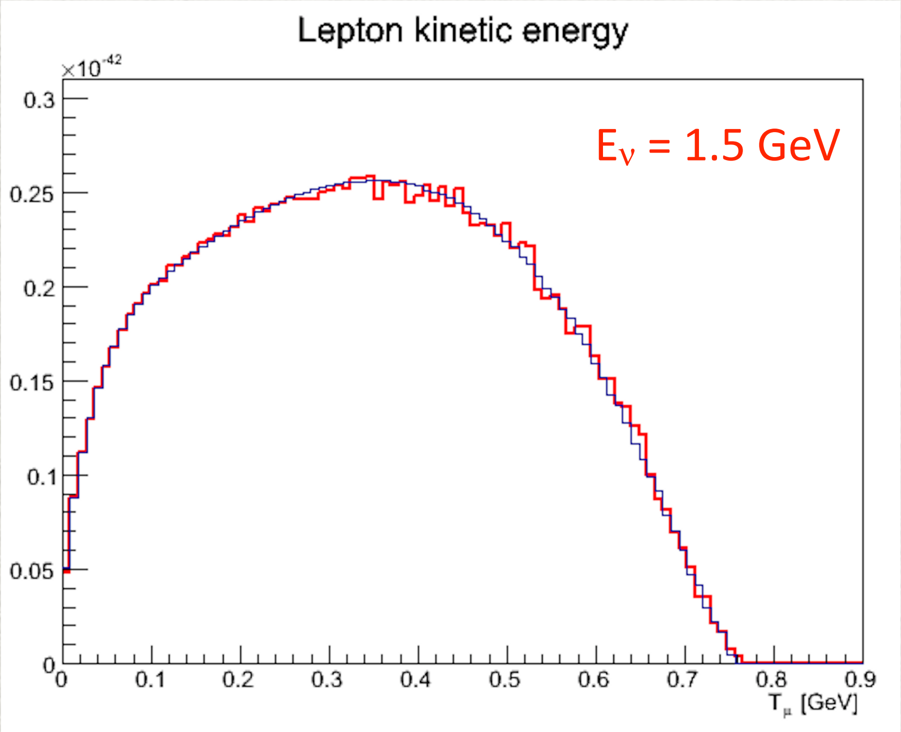


GENIE - Developments

Single Kaon Production:

Single Kaon production model by Alam, Simo, Athar, and Vacas (PRD 82, 033001 (2010)).

C. Marshall and M. Nirkko



Also:

- Very-High Energy extension (5 TeV, working toward PeV) (K. Hoshina)
- Inclusive Eta production. (J. Liu)
- New Berger-Sehgal resonant pion production model, tuned with MiniBooNE data by J. Nowak. Berger, Sehgal Phys. Rev. D76, 113004 (2007) & Kuzmin, Lyubushkin, Naumov Mod. Phys. Lett. A19 (2004) 2815 (J. Nowak and S. Dytman)
- Switch to gsl for numerical integration.

GENIE 2.12.0

- Berger-Sehgal coherent pion production (PRD 79, 053003 (2009)) (G. Perdue, HF, D. Cherdack)
- Local Fermi Gas & Nieves et al CCQE with RPA (J. Johnston and S. Dytman)
- Valencia Model Meson Exchange-Currents (J. Schwer and R. Gran)
- Alvarez-Ruso et al microscopic coherent pion production (PRC 75, 055501 (2007) and PRC 76, 068501 (2007)) (S. Dennis and S. Boyd)
- Oset FSI model (T. Golan)
- Kaon FSI (F. de Maria Blaszczyk, S. Dytman)
- z-expansion of QEL form factor (Hill et al, PRD 84, 073006) (A. Meyer)
- Benhar Spectral Functions (C. Mariani, M. Jen, and A. Furmanski)
- QEL Lambda production (J. Poage and HG)

Public project "tracking" now available via "Incubator" pages.

See: http://genie.hepforge.org/load.php?include=incubator

GiBUU

https://gibuu.hepforge.org

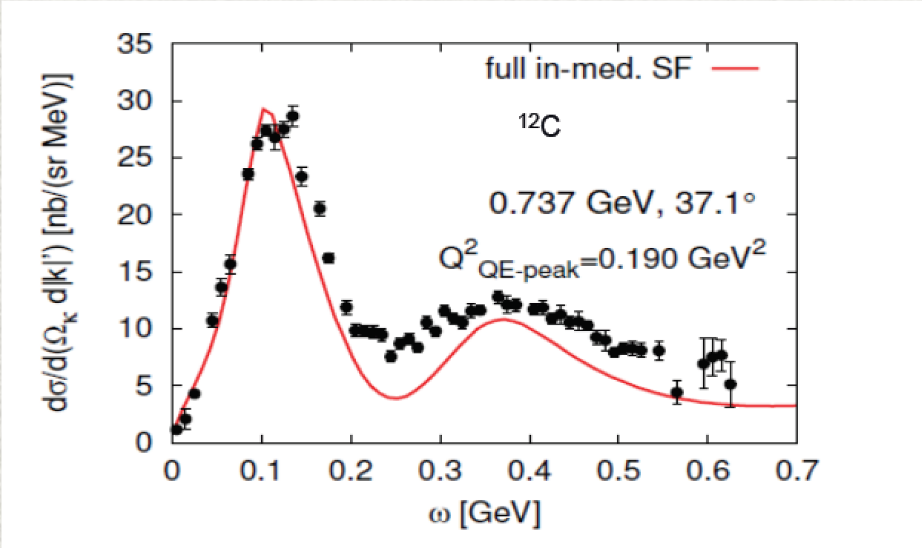
Buss et al, Phys. Rept. 512 (2012) 1- 124

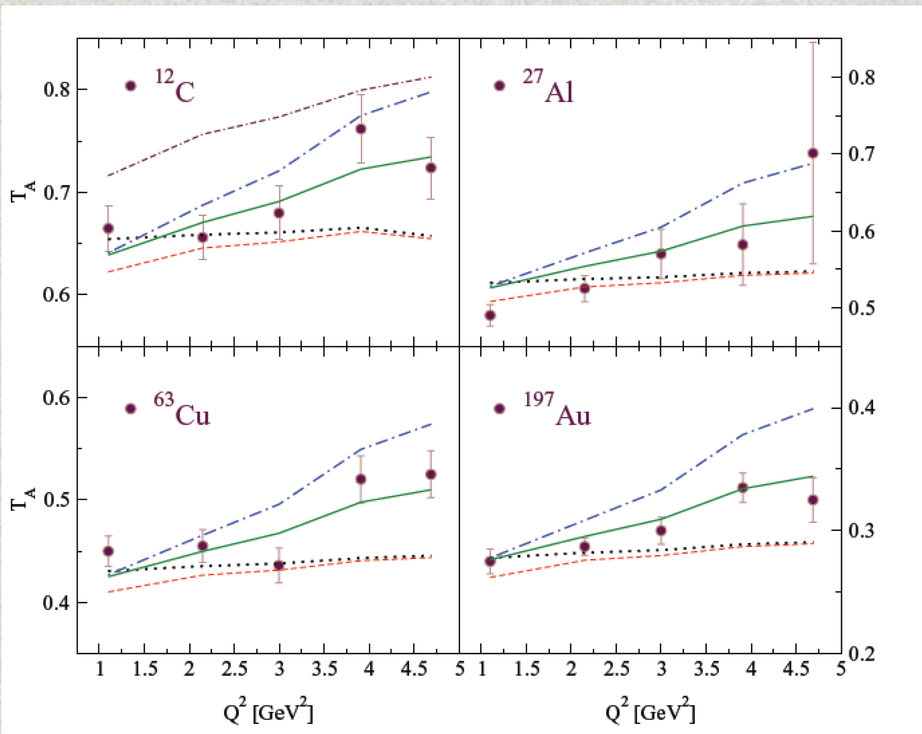
Developed by the nuclear theory group at Giessen, led by Ulrich Mosel.

Publicly available code (svn) since Release 1.6.

Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) is a semiclassical transport model in coupled channels.

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





B. Clasie et al, Phys. Rev. Lett. 99, 242502 (2007)
GiBUU: Kaskulov et al, Phys. Rev. C79 (2009) 015207.

GiBUU

K. Gallmeister et al, NP A826 (2009)

Ingredients:

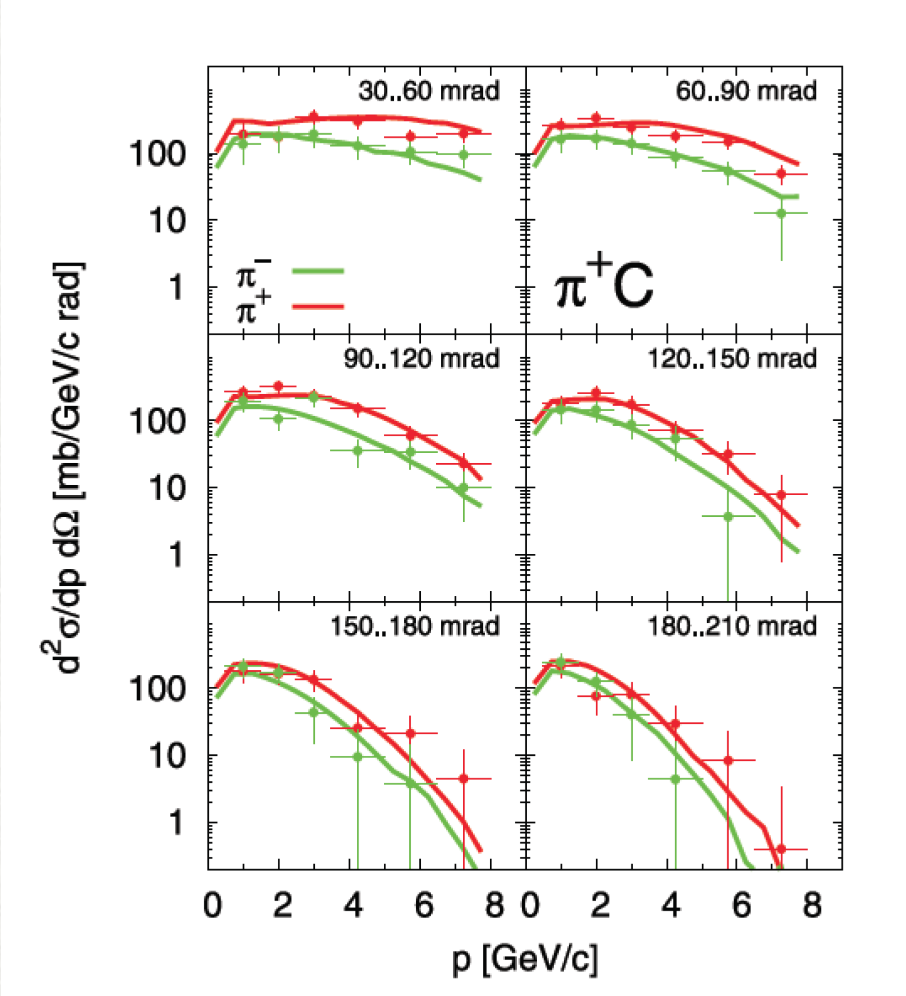
In-medium corrected primary interaction cross sections for QE, 2p2h, N* resonances, DIS, boosted to rest frame of bound nucleon, moving in bound local Fermi gas.

Includes spectral functions for baryons and mesons (binding + collision broadening).

Hadronic couplings for FSI taken from PDG.

Vector couplings taken from electro-production (MAID).

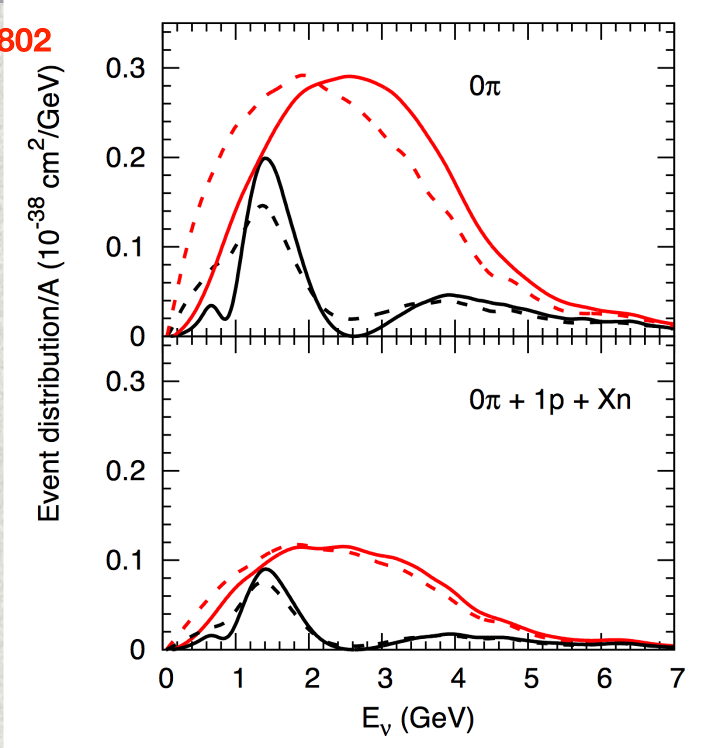
Axial couplings modeled with PCAC and dipole FF.



Extensive validation and documentation.

GiBUU

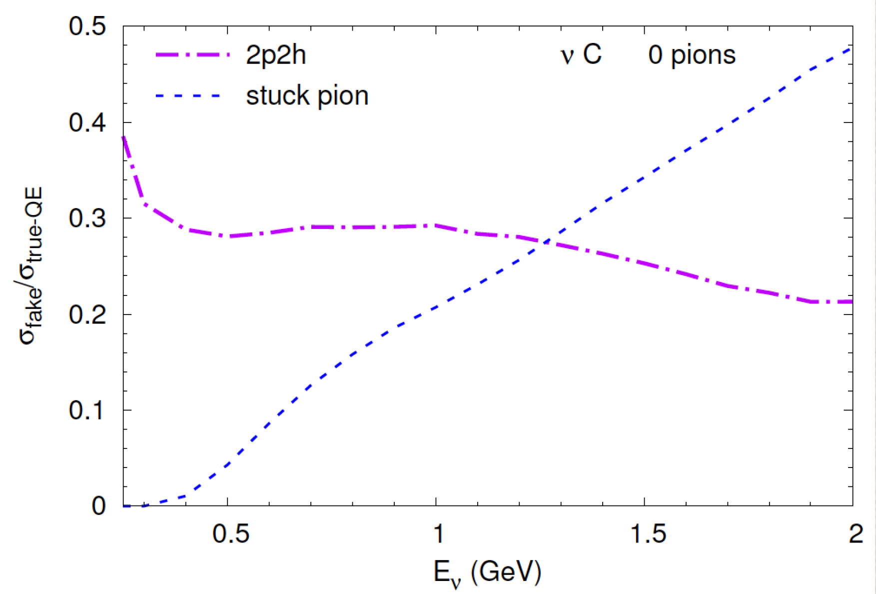
U. Mosel et al., Phys.Rev.Lett. 112 (2014) 151802



GiBUU has been used extensively over the past few years to explore important issues facing oscillation experiments.

Issues for neutrino energy reconstruction.

Effect of FSI and correlations on observable final states.

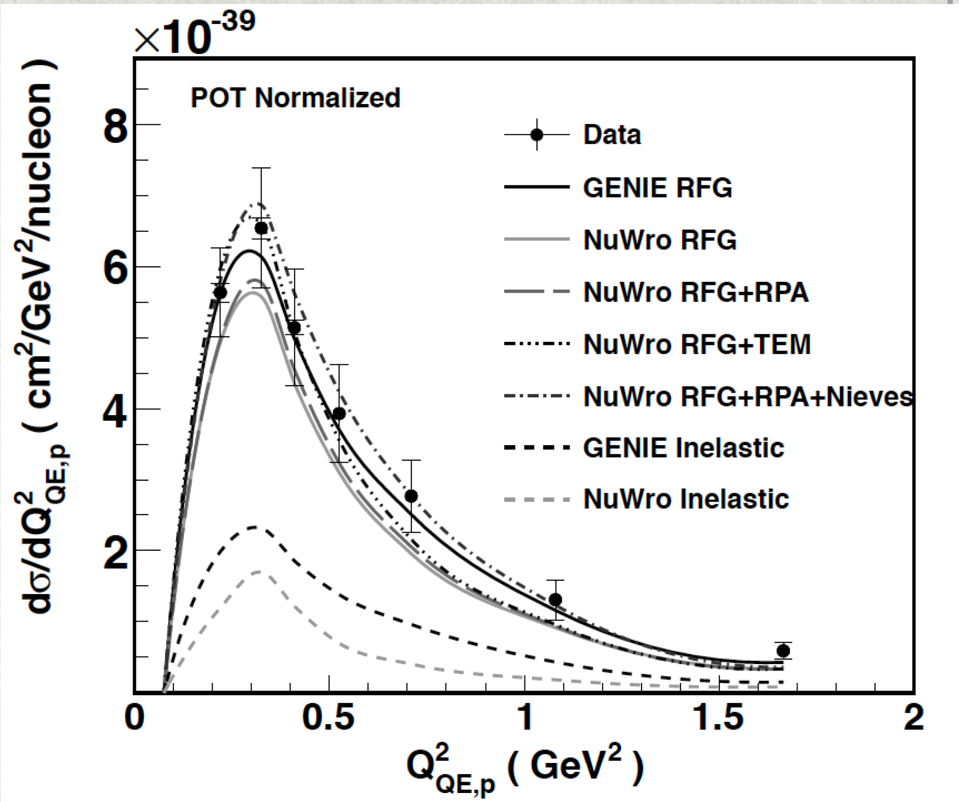


O. Lalakulich et al., Phys.Rev. C86 (2012) 054606

Generators 2015: Progress

Over the past five years there has been considerable progress in the field.

- Very active theory community.
- New model incorporation, often involving direct collaboration with theory groups (THANK YOU!).
- A move towards open source, publicly available generator codes.
- New approaches for the theory-generator interface that allow generators to incorporate more sophisticated calculations.
- More experiments are now comparing their results to multiple generators.
- A broad recognition of the importance of close experiment-theory collaboration for these efforts to succeed.



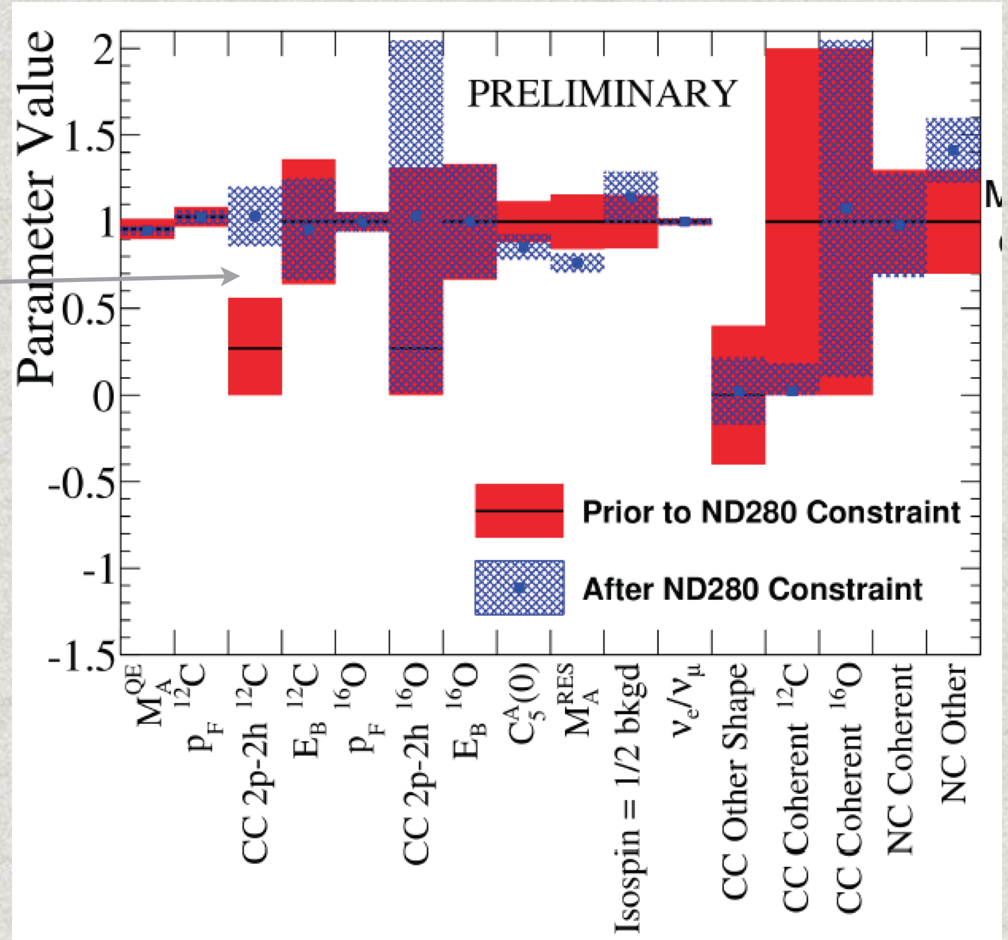
MINERvA, T. Walton et al., Phys.Rev. D91 (2015) 7, 071301

Generators 2015: Challenges

Dealing with Data!!

- *Understanding correlations in and between data sets.*
- *Fundamental limitations in models.*
- *Impossibility of fitting the world's data at present.*
- *How model-dependent are the corrections needed to prepare data for global fits?*
- *Retuning models and evaluating systematic errors requires a lot of effort.*
- *Requires close collaboration between theorists, experimentalists, and generator authors.*
- *Huge volume of data (γA, νA, eA, πA, pA) in principle involved.*

K. Mahn, NuFACT 15



One Approach (GENIE)

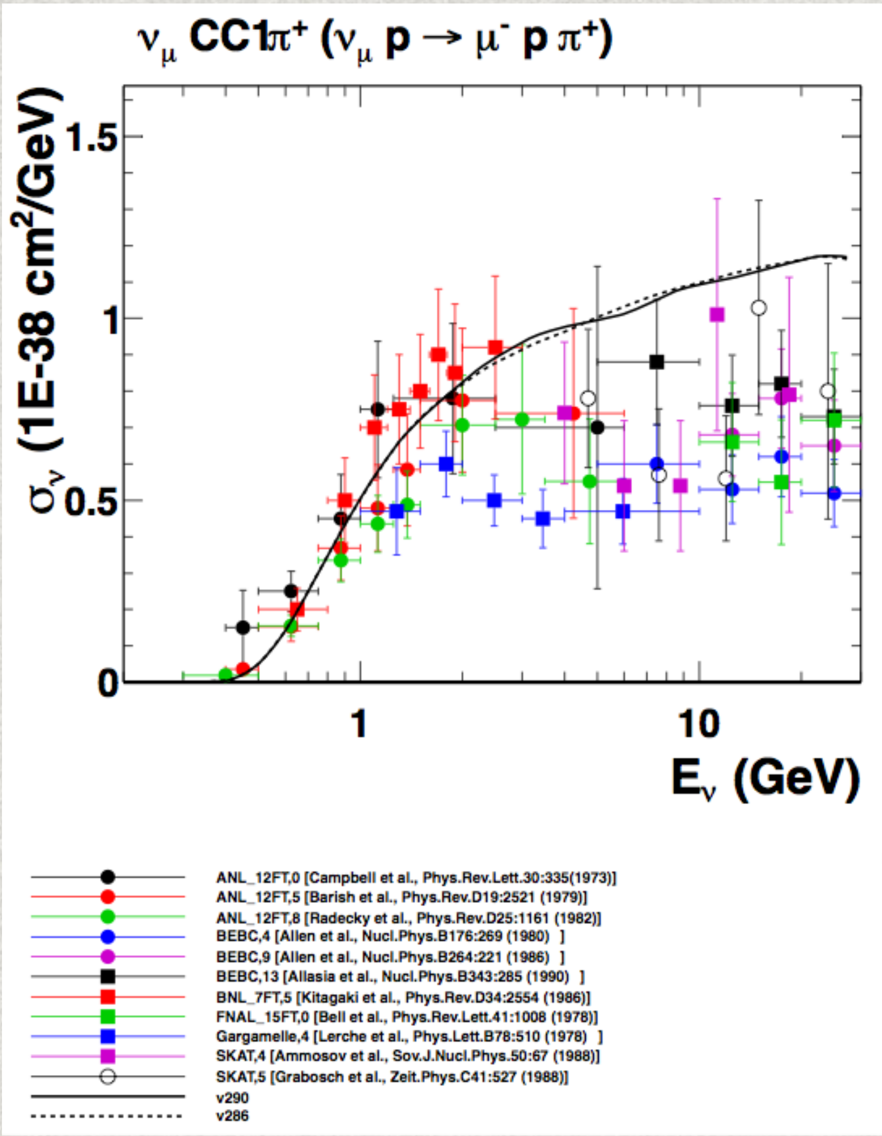
Comparisons Framework: Creates statistically rigorous generator comparisons to as much published data as is reasonable, including systematic errors. Starting with MiniBooNE and MINERvA.

Tuning Framework: Built on top of the comparisons framework and aims to provide tools for tuning the overall global physics model in GENIE.

Both frameworks are being designed to run on the OSG for large-scale statistics, etc.

Outputs from both will be published and made available for each release.

Enabled by close connections with experimental collaborations, i.e. for determination of correlated systematics.



Generators 2015: Challenges

Models/Theory:

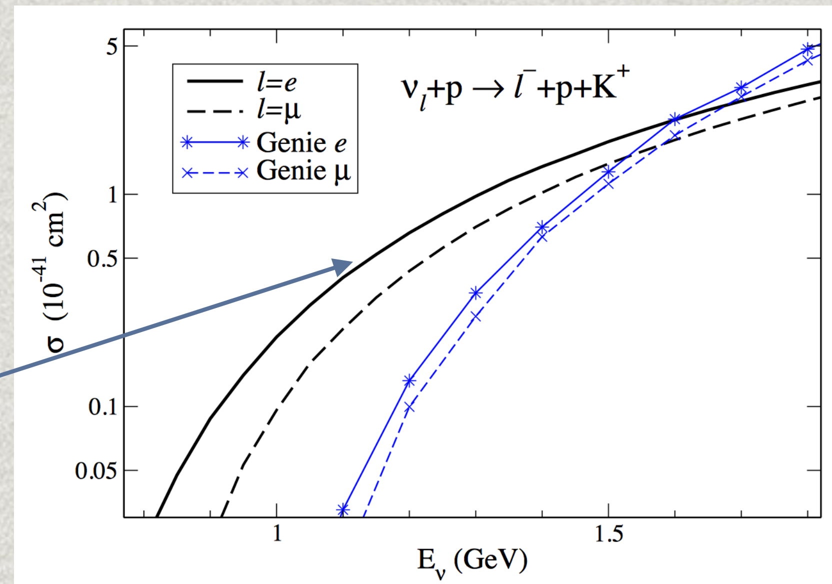
- Correctly (or effectively) incorporating sophisticated nuclear physics into a MC, in order to construct a consistent cross section model at ~1 GeV.
- Modeling of np-nh processes, *including hadrons*.
- Understanding hadronization in nuclei: formation times, coherence lengths, color transparency.

MC	QE	RES[a]	DIS
NEUT	–	SKAT	SKAT
FLUKA	Coh length	Rantf	Rantf
GENIE	–	–	Rantf-like
NUANCE	1 fm	1 fm	1 fm

T. Golan et al., Phys.Rev. C86 (2012) 015505

Bridging gaps:

- *Combining* models: np-nh, $\Delta S=1$, SIS/DIS, coherent (microscopic/ PCAC), hadronization…



Alam et al., Phys.Rev. D82 (2010) 033001

Generators 2015: Challenges

Success requires people working across boundaries.

- Geography
- Experiment / Theory
- Particle / Nuclear
- High Energy / Medium Energy
- Neutrino / Electron / Hadron scattering communities

New Initiatives (e.g. NuSTEC) are needed

Regional affiliation of speakers from NuINTs ('09,11,12)

	Americas	Europe	Asia
Experimentalists	80	20	10
Theorists	6	49	16

Generators 2015: Opinions

Experimentalists are fortunate to have access to four neutrino generators that are under active development.

- Different emphases, perspectives, priorities.

Being able to run multiple generators is a simple and (possibly) effective way to evaluate generator-related systematic errors, but ONLY when:

- They incorporate different models and/or assumptions
- They are tuned to and constrained by relevant data
- The reasons for differences between the generators are well-understood.

It should be easier for experiments to run different generators.

- Common output format (a neutrino les Houches Accordes?)

Generators 2015: Opinions

An important field-wide discussions over the coming decade will be about the assignment of generator-related systematic errors.

Particularly important for oscillation experiments…and we won't have to wait for DUNE for this to be an issue!

K. Mahn, NuFACT 15

Systematic			Without ND	With ND
Flux and Cross-section	Common to ND280/SK		9.2%	3.4%
	Super-K Only	Multi-nucleon effect on oxygen	9.5%	
		All Super-K Only	10.0%	
	All		13.0%	10.1%
Final State Interaction/Secondary Interaction at Super-K			2.1%	
Super-K Detector			3.8%	
Total			14.4%	11.6%

Conclusions

Abundance of new data and new theoretical work is starting to make its way into generators that are in use by experiments.

The underlying physics has turned out to be considerably more complex (and interesting) than we would have guessed 20 years ago!

New ideas and effort will be required in order to make the feedback loop between theory and experiment, in which generators play an important role, operate effectively.

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