Review of current neutrino simulation efforts GENIE, NEUT, NuWro

Jarek Nowak, Lancaster University

IPPP/NuSTEC topical meeting on Neutrino-Nucleus scattering

18 – 20 April 2017

Neutrino MC generators

- Monte Carlo event generators connect experiment and theory
  - Most neutrino analysis relies on MC generators
  - From neutrino beam simulations, through neutrino interactions, to detector simulations
  - Used to evaluate systematic uncertainties, backgrounds, acceptances...
- neutrino interactions:
  - GENIE (https://genie.hepforge.org)
  - GIBUU (https://gibuu.hepforge.org/trac/wiki)
  - NEUT (http://www-sk.icrr.u-tokyo.ac.jp/~hayato_s/Neut/)
  - NuWro (https://github.com/nuwro/)
  - NUANCE – currently not active

Acknowledgments

Many thanks for materials and slides

- Tomek Golan - NuWro
- Yoshinari Hayato - NEUT
- Steve Dytman - GENIE

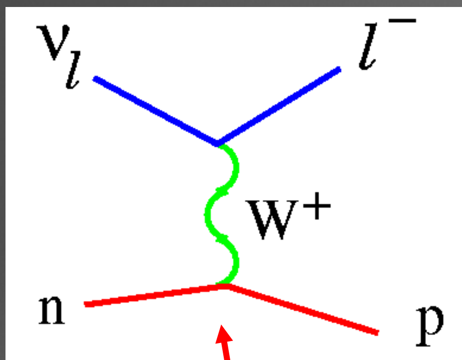
Outline

- Brief review of models implemented in GENIE, NEUT and NuWro
- Recent additions to the the GENIE, NEUT and NuWro

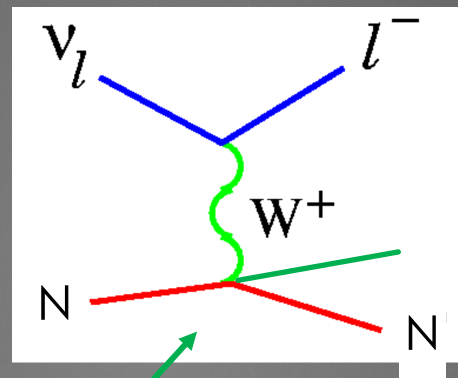
- More comparisons between MC generators will be shown by Partick Stowell
- What to do next will be discussed by Federico Sanchez
- For an example how to use the MC generator for neutrino data global fit see talk by Marco Roda

Neutrino-nucleon cross sections

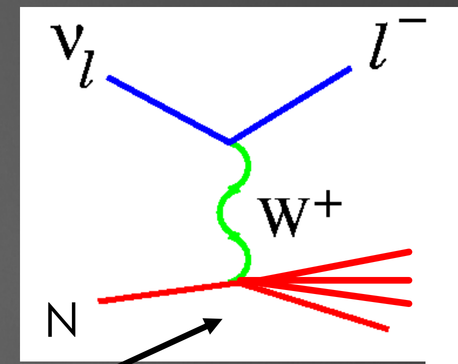
Quasi-elastic scattering CCQE

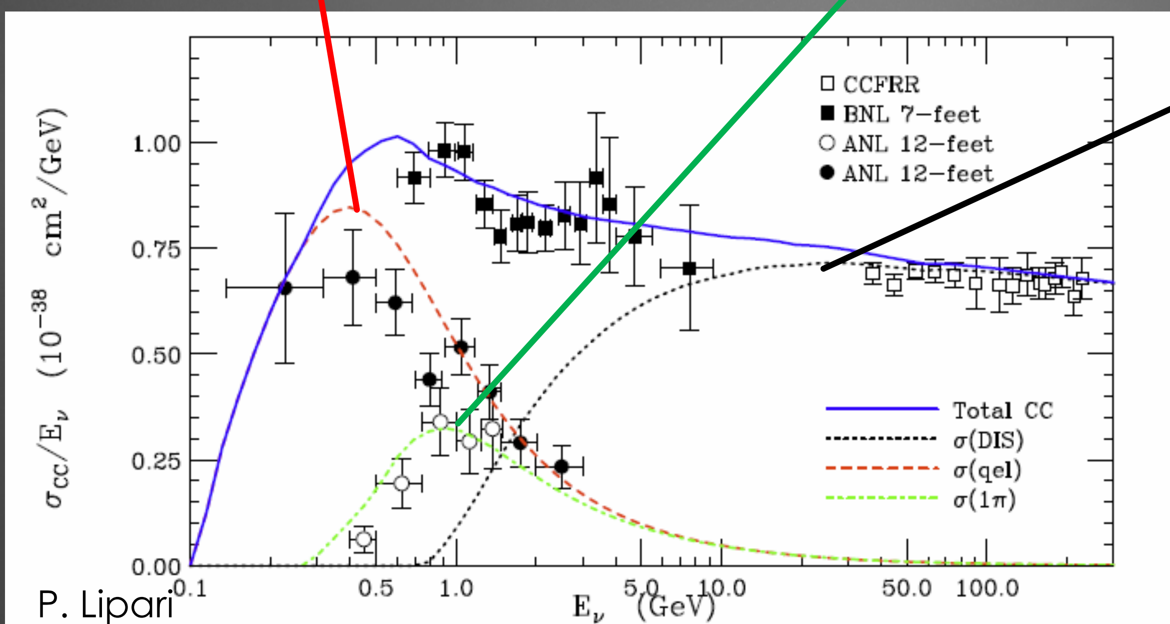


Single pion production CC1π



Deep Inelastic Scattering DIS



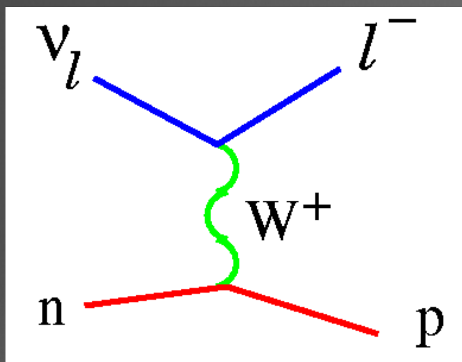


P. Lipari

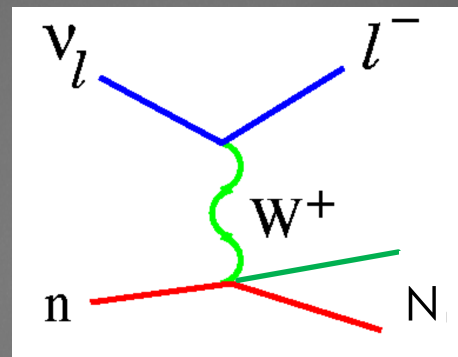
Bubble Chamber Experiments:
H_2, D_2

Neutrino-nucleus cross section

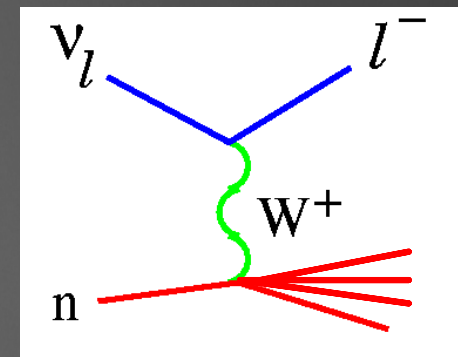
Quasi-elastic scattering
CCQE



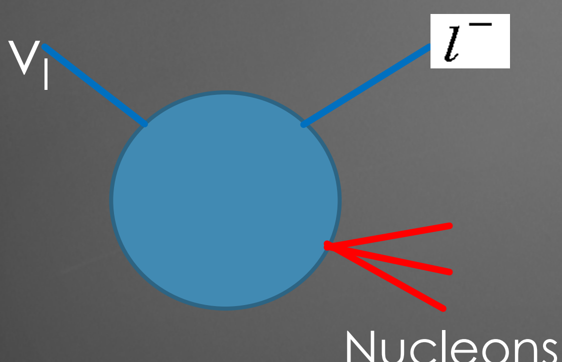
Single pion production
CC1π



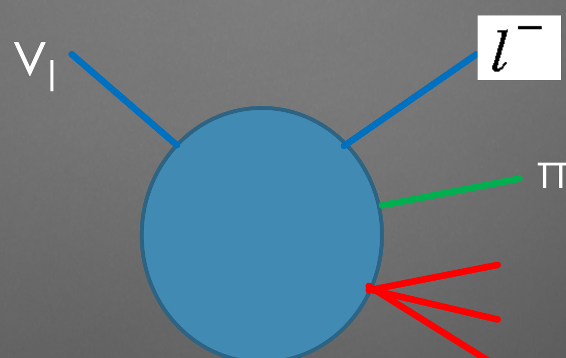
Deep Inelastic Scattering
DIS



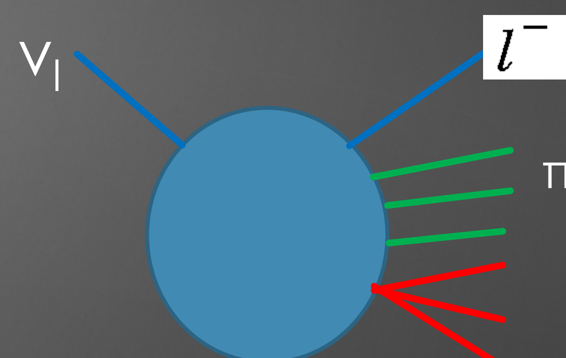
CC0π or CCQE-like
- No pions observed



CC1π or CC1π -like



CCDIS



MC ingredients

Description on the nucleon inside the nucleus (RFG, SP, LFG)

Cross section for neutrino-nucleon interaction (CCQE, 2p2h, RES, DIS, etc)

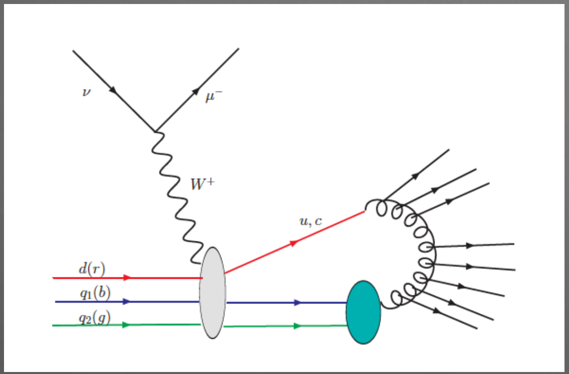
Initial Interactions

Extended Impulse Approx.

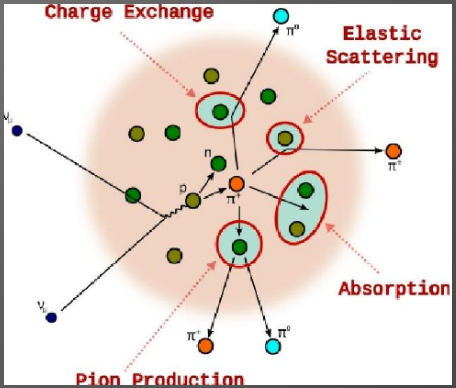
$$\frac{d\sigma^{\mathrm{IA}}_{\ell A}}{d\omega d\Omega} = \sum_N \int d^3p \, dE \; P^N_{\mathrm{hole}}(\mathbf{p}, E) \; \frac{M}{E_{\mathbf{p}}} \frac{d\sigma^{\mathrm{elem}}_{\ell N}}{d\omega d\Omega} \; P^N_{\mathrm{part}}(\mathbf{p}', \mathcal{T}')$$

Pauli Blocking- δ

Hadronization



FSI – Final State Interactions



Comparison of other generators

Model/generator	GENIE (2.14 defaul)	NuWro	NEUT
QE	Lwlyn-Smith Nieves, Eff MA	Lwlyn-Smith RPA	Lwlyn-Smith Eff RPA
Nuclear model	RFG, LFG, Effective spectral function	RFG, LFG, spectral function	RFG, LFG, spectral function
MEC	Valencia Empirical	Valencia Marteau	Valencia
Delta model	Rein-Sehgal (updated)	Home-grown, great	Rein-Sehgal (update)
Coherent	Rein-Sehgal(corrected) Berger-Sehgal	Rein-Sehgal Berger-Sehgal	Rein-Sehgal Berger-Sehgal
FSI	Schematic Cascade (med corr)	Cascade(med corr)	Cascade(med corr) **S. Dytman**

- **Differences more in detail than fundamental (physics)**

NuWro
Wroclaw Neutrino Generator

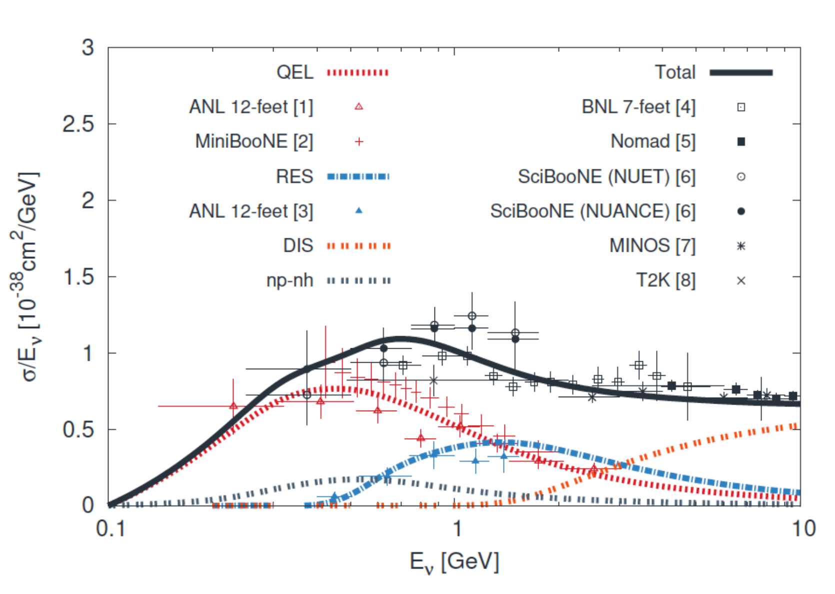
NuWro

- NuWro is not an official MC in any experiment and serves as a laboratory for new developments.
- New (or relatively new) ingredients:
  - Berger-Sehgal coherent pion production
  - π momentum distribution from Δ decay
  - effective density and momentum dependent potential for CCQE (C. Juszczak, J. Nowak, J. Sobczyk)
- eWro - electron scattering module (a work in progress) C. Juszczak, K. Graczyk, JTS, J. Zmuda
- The open source code can be downloaded from the repository: https://github.com/nuwro/
- A new userguide https://nuwro.github.io/user-guide

Implemented dynamics

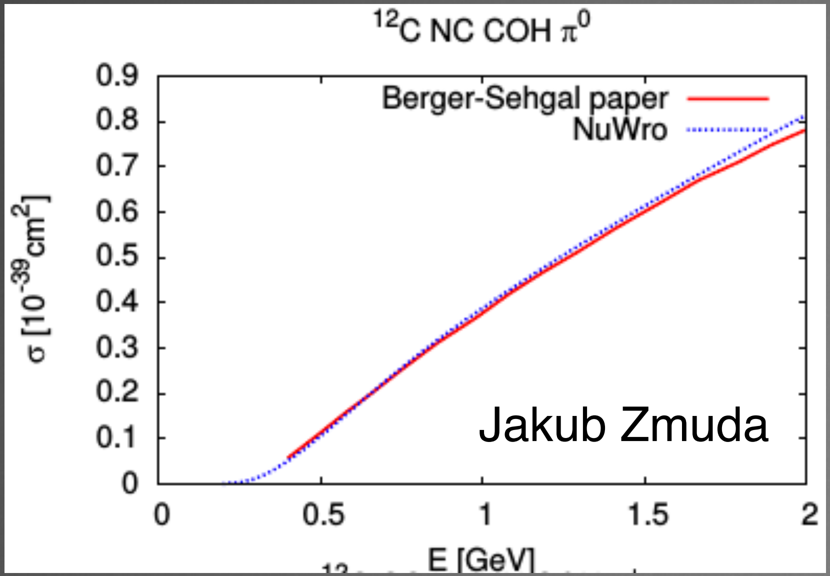
- All major interaction channels are implemented, for charged and neutral current, covering neutrino energy region from a few hundreds MeV (Impulse Approximation limit) to several TeV:

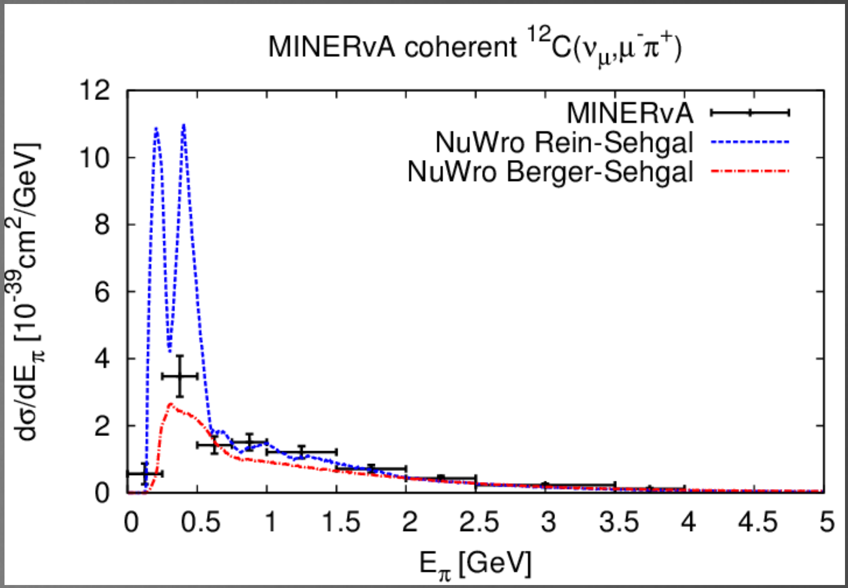
- QEL (quasi-)elastic scattering
- RES pion production through a Δ resonance excitation
- DIS more inelastic processes
- COH coherent pion production
- np-nh two body current contribution
- **Transition region treatment**: smooth transition from full RES(Δ) to full DIS starting from W=1.3 -1.6 GeV/c²



[1] PRD 19 (1979) 2521
[2] PRD 81 (2010) 092005
[3] PRD 16 (1977) 3103
[4] PRD 25 (1982) 617
[5] PLB 660 (2008) 19
[6] PRD 83 (2011) 012005
[7] PRD 81 (2011) 072002
[8] PRD 87 (2013) 092003

Berger-Sehgal model for COH

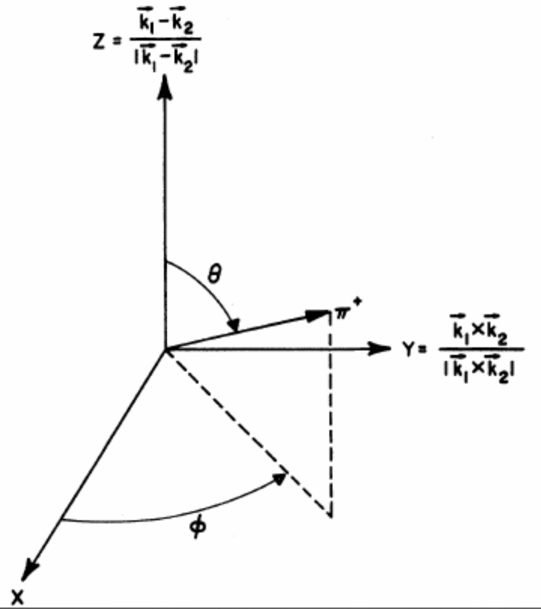




This study has been done in collaboration with Paul Martins who has been working for NEUT.

π angular distribution from Δ decay

- Events are reweighted according to how pion momentum is oriented in the Δ rest frame.
- Multiplication factor (Q^2 dependent) on the top of uniform distribution:



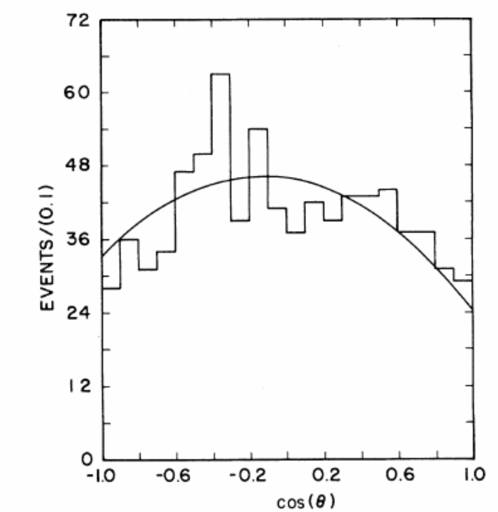


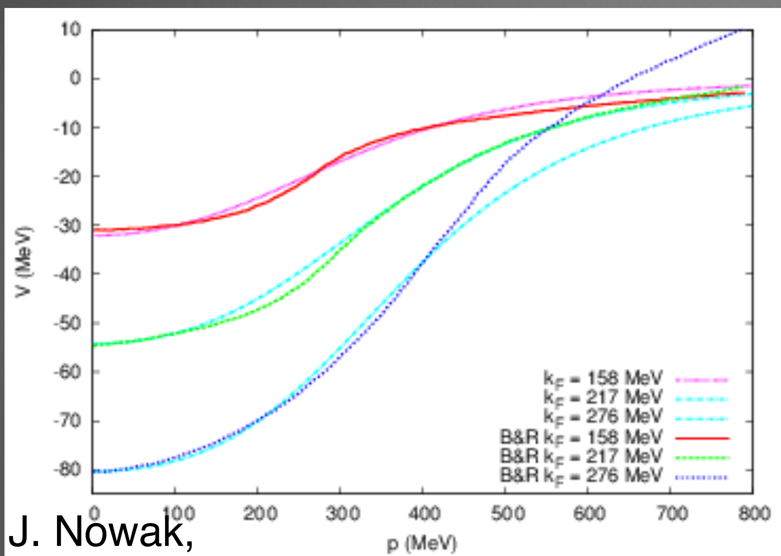
FIG. 15. Distribution of events in the pion polar angle cosθ for the final state $\mu^- p \pi^+$, with $M(p\pi^+) < 1.4$ GeV. The curve is the area-normalized prediction of the Adler model.

Radecky et al [ANL Collaboration], PRD 25 (1982) 1161.

Effective density and momentum dependent potential

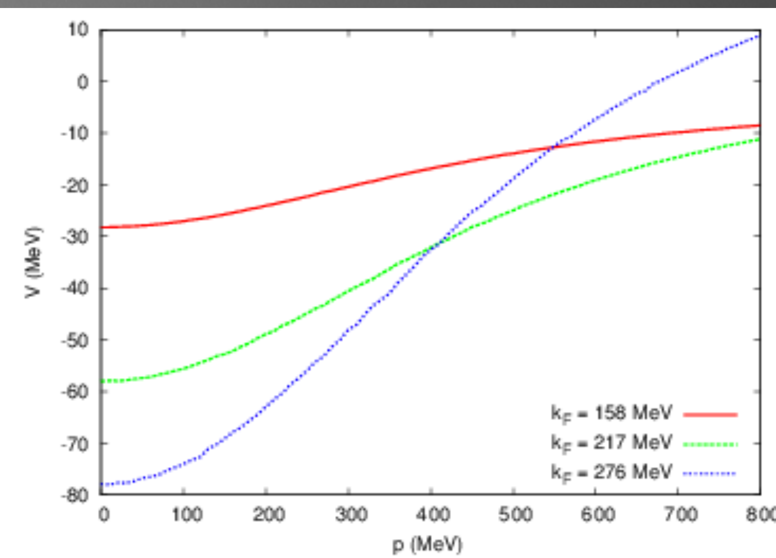
- Nucleons experience density and momentum dependent effective potential:

Brieva-Dellafiore potential and approximation used in NuWro



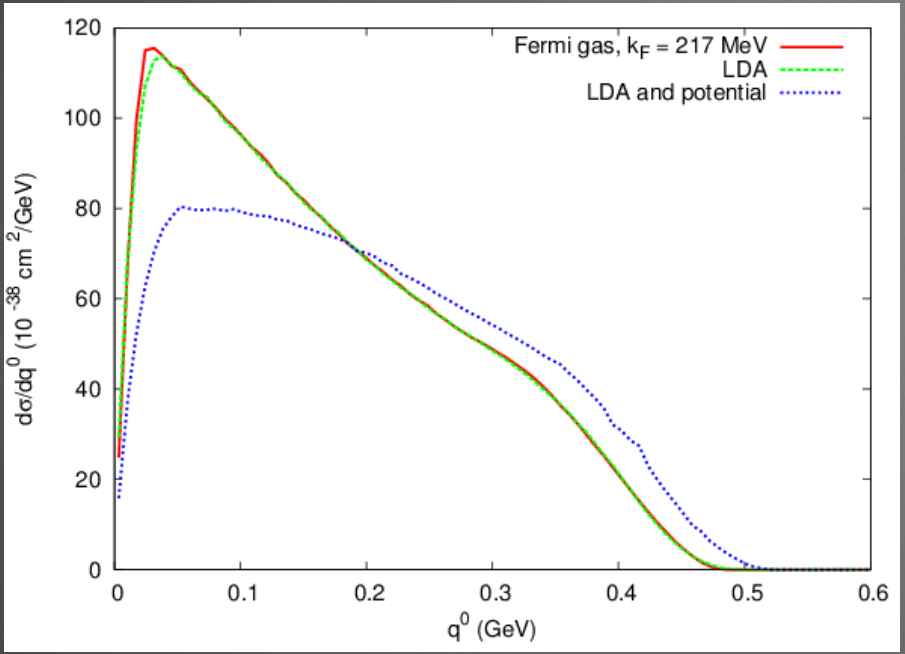
J. Nowak,

the potential used in GiBUU.



Effective density and momentum dependent potential

- The model is expected to give realistic predictions for final state muon (LDA = local density approximation). E = 600 MeV, iron target.



- reduction at lowest energy transfers q^0
- enhancement at larger q^0

The old piece of code that recently been reactivated

- works for oxygen, argon, iron
- hadronic part not yet integrated with the NuWro cascade.

C. Juszczak, J. Nowak, J. Sobczyk, Eur. Phys. J. C39 (2005) 195

EWro (work in progress)

The main idea: to test NuWro nuclear model using electron scattering data

- Fermi gas and local Fermi gas
- QE and Δ regions only
- for Δ non-resonant background after E. Hernandez, J. Nieves, M. Valverde, Phys. Rev. D76 033005 (2007)
- EM form factors from J. Zmuda, K.M. Graczyk, arXiv:1501.03086v4
- Δ self-energy following E. Oset, L.L. Salcedo, Nucl. Phys. A468 631 (1987)

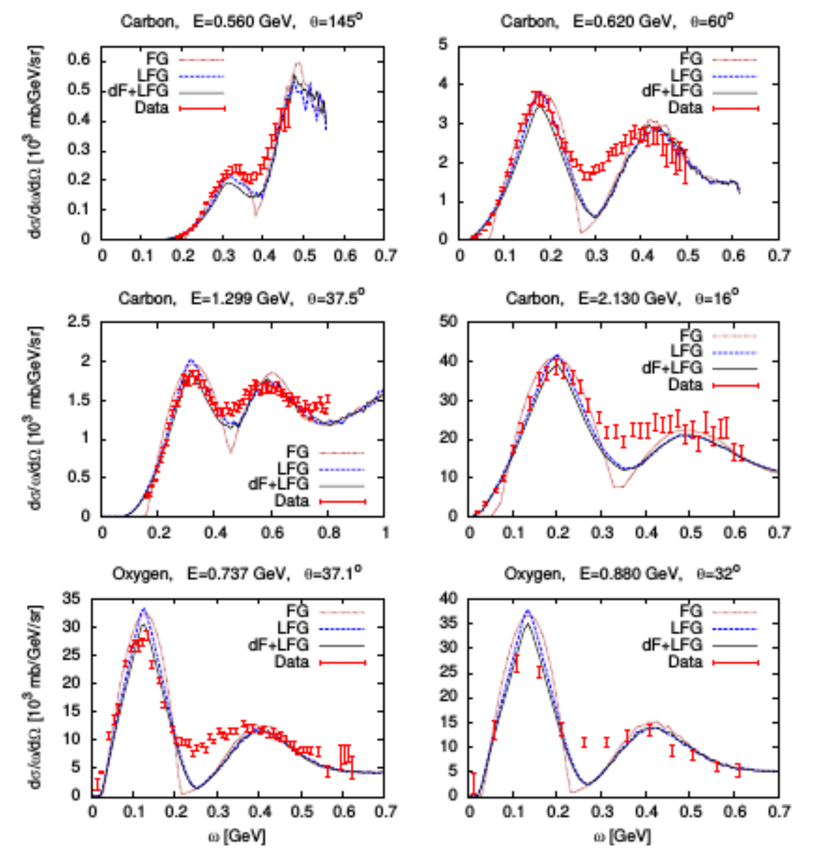


Fig. 1. Differential cross sections for electron scattering off carbon and oxygen obtained within eWro (for various beam energies, E, and scattering angles, θ).

K. Graczyk, C. Juszczak, JTS, J. Zmuda, arXiv:1510.03268

NEUT

current implementation (neut 5.3.7)

Neut - Implemented dynamics

- **CCQE**
  - Nuclear models:
    - global Fermi-Gas model,
    - relativistic Fermi-gas model (Smith and Moniz)
    - Spectral function (Benhar, Ankowski et al.)
    - RPA correction could be applied using 2D Energy-q^2 tables
  - Form factors
    - dipole, BBBA05 and BBBA07

CCQE-like multi-nucleon scattering

  - 2p2h scattering
    - meson exchange current modeled by Nieves et al.
    - Using pre-calculated cross-section tables

current implementation (neut 5.3.7)

Neut - Implemented dynamics

Resonance 1π production

- Relativistic harmonic oscillator model (Rein-Sehgal)
- Form factors
  - Original (Rein & Sehgal)
  - Improved (Graczyk-Sobczyk)

DIS

Hadronization

- Custom code for W<2GeV
- PYTHIA (in CERNLIB) for W>2GeV

PDF

- GRV98 with Bodek-Yang correction
- GRV94 with old Bodek-Yang correction
- GRV98, GRV94 and are also supported

Coherent π production

- Rein-Sehgal (as appeared in the original paper)
- Berger-Sehgal

current implementation (neut 5.3.7)

Neut: FSI

Final state interactions

- Low momentum pions
  - Delta-hole model (Oset et al.) tuned by using π scattering data.
  - Kinematics: phase shift analysis with medium correction(Seki et al.)
- High momentum pions, eta, omega and nucleon
  - Mean free path extracted from nucleon scattering data sets.
  - Kinematics - mainly, experimental data sets are used.

Neut ~ Next release (neut 5.4.x)

New release in preparation

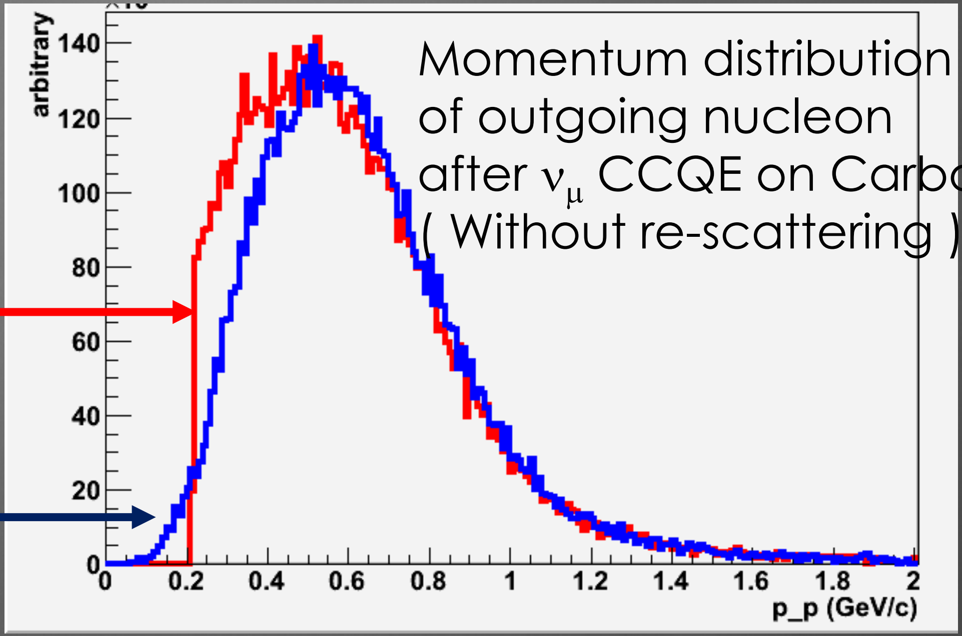
- Expected to be available in May
- a release candidate from 18/04/2017

CCQE with Local Fermi-gas model

- Based on the prescription by Nieves et al.
- Implemented by F. Sanchez et al.

Neut 5.3.7
(Global Fermi Gas
~ sharp cutoff)

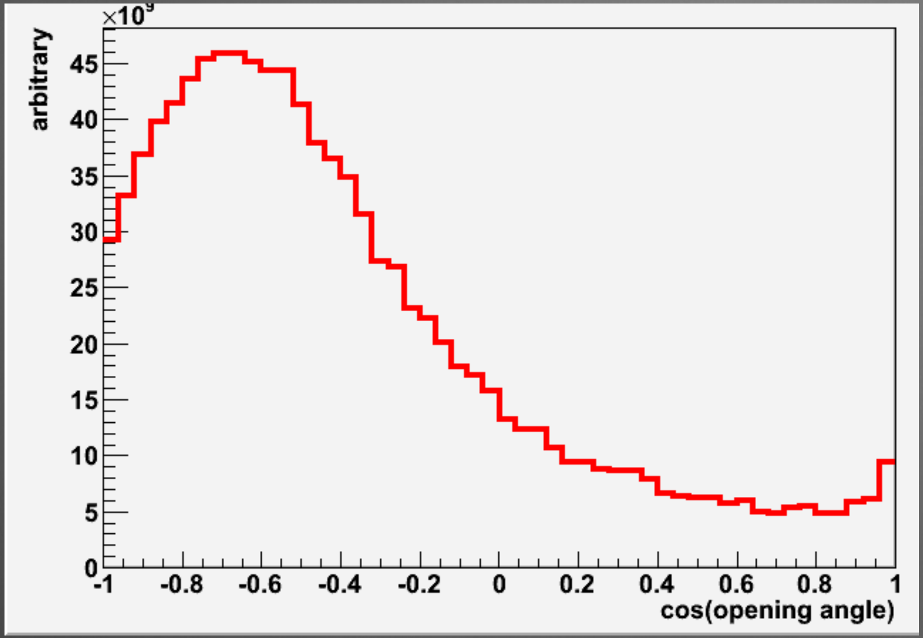
Neut 5.4.x
(Local Fermi Gas)



Neut ~ Next release (neut 5.4.x)

CCQE-like multi-nucleon scattering

- Now 2p2h scattering code uses pre-calculated hadron tensor tables instead of the cross-section tables.(Code by F. Sanchez et al.)



Opening angle of 2 outgoing nucleons

- Lab. frame
- without re-scattering
- Carbon target T2K ND280 flux

Neut ~ Next release (neut 5.4.x)

(C. Bronner)

M. Kabirnezhad & C. Wret

DIS

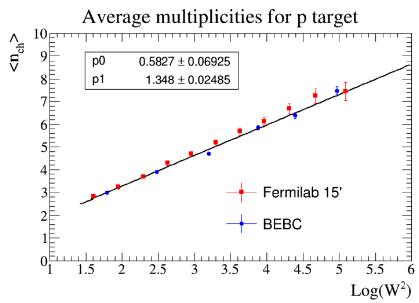
Multiplicity models

The multiplicity model gives the probability to produce a certain number of hadrons for a given value of W (invariant mass of the hadronic system)

In the new version, three hadron multiplicity models can be chosen through the variable NE-MULT:

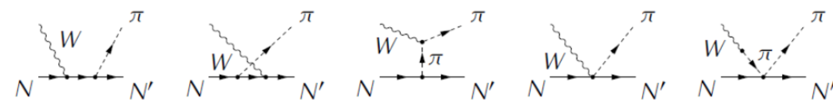
- NE-MULT=0: NEUT default (model used up to now, with a few minor changes)
- NE-MULT=1: results of my (Christophe) deuterium fits (hep-ph:1607.06558)
- NE-MULT=2: AGKY model (GENIE model, hep-ph:0904.4043)

By default model 0 is used.



Single Pion model improvement:

- **The new model covers all pions from resonant (Rein-Sehgal model) and non-resonant interactions (5 diagrams from Hernandez et.al) coherently!**



E. Hernandez, J. Nieves and M. Valverde, Phys. Rev. D **76** (2007) 033005

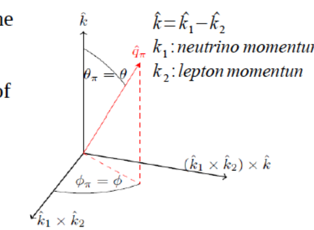
- Lepton mass is included and It is suitable for MC

  We need to define a common framework to calculate the helicity amplitudes. Isobaric system

- The main challenge is to calculate helicity amplitudes of the above diagrams in this frame

- The new model output is $d\sigma / dW\, dQ^2\, d\Omega_\pi$

  pion angles are part of cross-section!



The non-resonant bkg effects on the pion anglea due to the interference terms with resonances!

5

Diffractive pion production

- Based on the model by Rein (Implemented by R. Terri)

Refine the pion final state interaction parameters

- using the recent results from PIANO/DUET experiment(E. Pinzon et al.)

GENIE

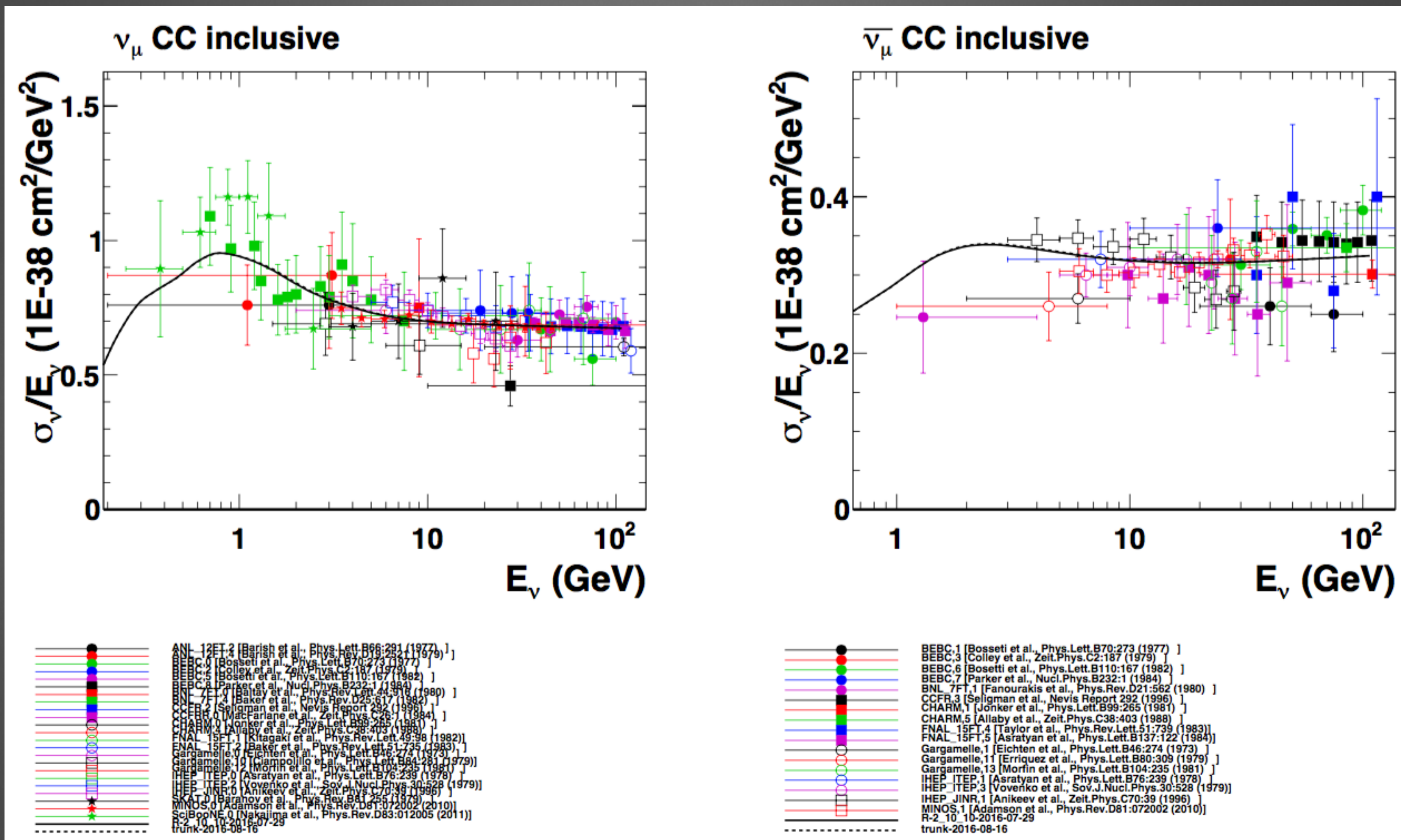
Default physics model in v2 series

Cross-section model:

- **NCEL**: Ahrens model; dipole axial form factor (MA = 0.99 GeV/c^2); strange axial contribution =0.12.
- **CCQE**: Llewellyn-Smith with BBA05 elastic f/f; pseudo-scalar form factor by PCAC; dipole axial form factor (MA = 0.99 GeV/c^2)
- **RES**: Rein-Sehgal model; 16 resonances (ignoring interference) with updated parameters at W<1.7 GeV/c^2; lepton mass only in phase space boundaries; dipole vector form factor (MA = 0.84 GeV/c2); dipole axial form factor (MA = 1.12 GeV/c^2).
- **DIS**: Bodek-Yang
- **Coherent** : Rein-Sehgal with updated PCAC formula
- Also: QE and DIS charm production, e elastic, IMD, IMD annihilation

- **Nuclear modelling**: FG with high-momentum tail. Off-shell kinematics.
- **Transition region treatment**: Non-resonance background is extrapolated Bodek-Yang model at W<1.7 GeV/c2, tuned by at to CC inclusive, CC 1π and CC 2π data.

Default physics model in v2 series

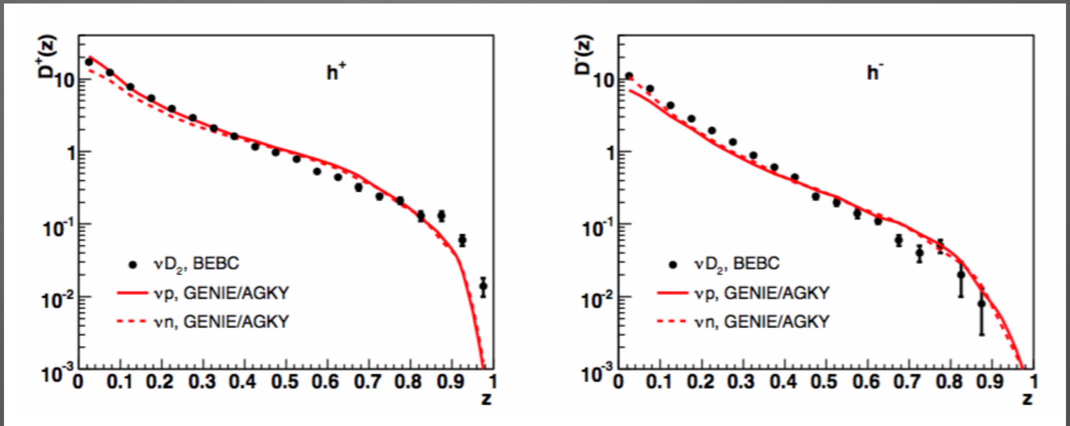


Default physics model in v2 series

Neutrino-induced hadronization

- Resonances: Phase space decay; All known decay channels included.
- DIS/SIS: Home-grown AGKY effective KNO-based "free-nucleon" hadronization at low W, anchored on many bubble chamber data; Switching gradually (W = 2.3 - 3 GeV/c2) to (tuned) PYTHIA at higher W.
- DIS charm: Home-grown model based on charm fragmentation functions and measured charm fractions, PYTHIA for non-charm system.
- In-medium effects: SKAT-type formation zone parameterization (DIS only).

Data/model comparisons of the fragmentation function for + and - charged hadrons.

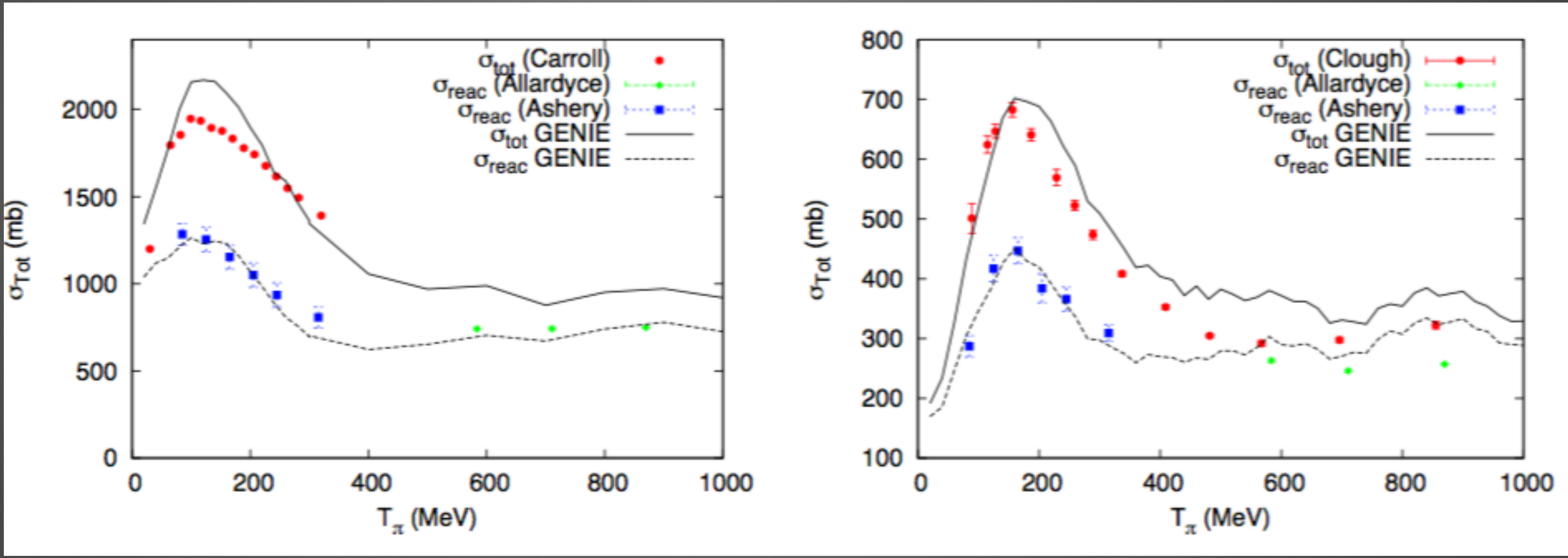


Default physics model in v2 series

Intranuclear hadron transport

- INTRANUKE/hA: Effective model anchored to selected data
- Scaled to all nuclei

Left: π^+ + Fe56. Right: π^+ + C12



Production version v2.10.0
New physics models

- Bodek-Christy-Coopersmith, spectral function (EPJC 74:3091, 2014).

B. Coopersmith and A. Bodek (Rochester)

- Very-High Energy extension (up to 5 TeV, working towards PeV scales)

K. Hoshina (Wisconsin)

- Inclusive η production. J. Liu (W&M)
- Berger-Sehgal resonance model (PRD 76, 113004, 2007)

J. Nowak (Lancaster) and S. Dytman (Pitt)

- Kuzmin-Lyubushkin-Naumov resonance model (MPL A19, 2815, 2004)

J. Nowak (Lancaster), I. Kakorin (JINR) and S. Dytman (Pitt)

- Improved INTRANUKE/hA FSI model.

S. Dytman and N. Geary (Pitt)

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

C. Marshall (Rochester) and M. Nirkko (Bern)

arXiv:1512.06882

Production version v2.12.0
New physics models

- Bhattacharya, Hill, and Paz QE Z expansion model (PRD 84:073006)

A. Meyer (Chicago)

- Local Fermi Gas & Nieves-Amaro-Valverde CCQE with RPA (Phys. Rev. C70, 055503 (2004); Phys. Rev. C72:019902, 2005) J. Johnston and S. Dytman (Pitt)
- Updates to the GENIE hown-grown empirical 2p-2h model

S.Dytman (Pitt)

- Valencia 2p-2h model (Phys.Rev. D88:113007, 2013)

J. Schwehr (CSU), D.Cherdack (CSU) and R. Gran (UMD)

- Berger-Sehgal coherent production (PRD 79:053003, 2009)

G. Perdue (Fermilab), H. Gallagher (Tufts), D. Cherdack (CSU)

- Alvarez Ruso, Geng, Hirenzaki and Vacas microscopic coherent pion production (PRC 75:055501, 2007; PRC 76:068501, 2007)

D.Scully, S. Dennis and S. Boyd (Warwick)

arXiv:1512.06882

Production version v2.12.0
New physics models

- Oset, Salcedo and Strottman FSI model (Phys. Lett. B 165:13, 1985; Nucl. Phys. A 468:631, 1987.) T. Golan (Fermilab and Rochester)
- Kaon FSI improvements F. de Maria Blaszczyk (LSU), S. Dytman (Pitt)
- Pais QE Hyperon production model (Ann. Phys. 63:361, 1971)

J. Poage and H. Gallagher (Tufts)

- Updated Rein diffractive pion model (Nucl.Phys. B278:61, 1986).

J.Wolcott (Tufts)

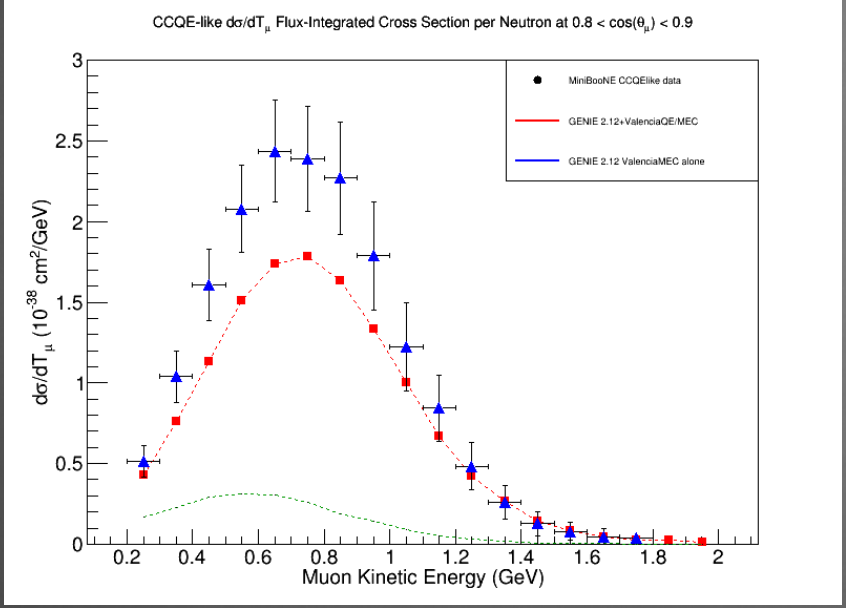
- Several resonance model updates. L.Jiang (Pittsburgh) and I.Kakorin (JINR & ITEP)
- Kuzmin, Naumov energy-dependent axial-mass model.

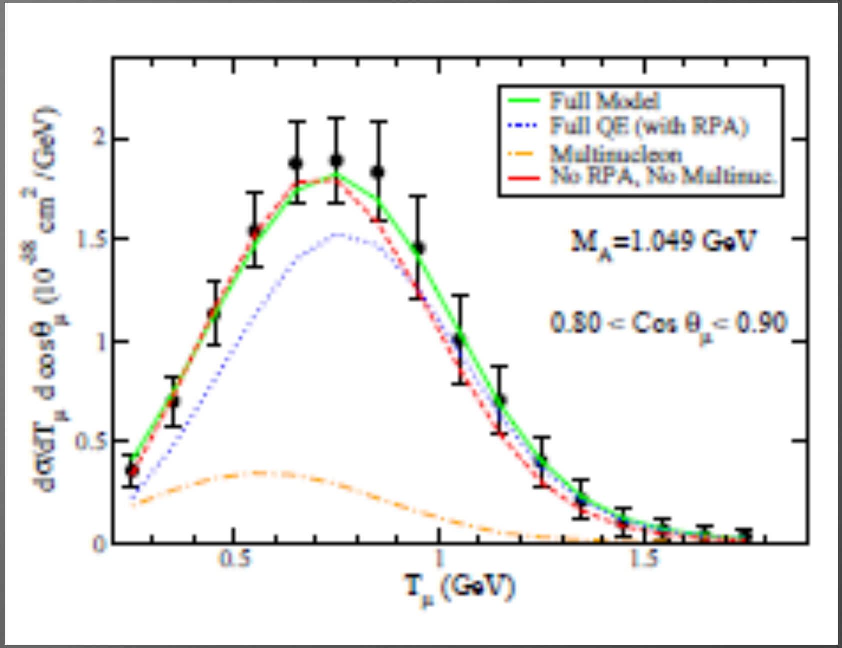
I.Kakorin (JINR & ITEP)

GENIE tests of Valencia QE+MEC

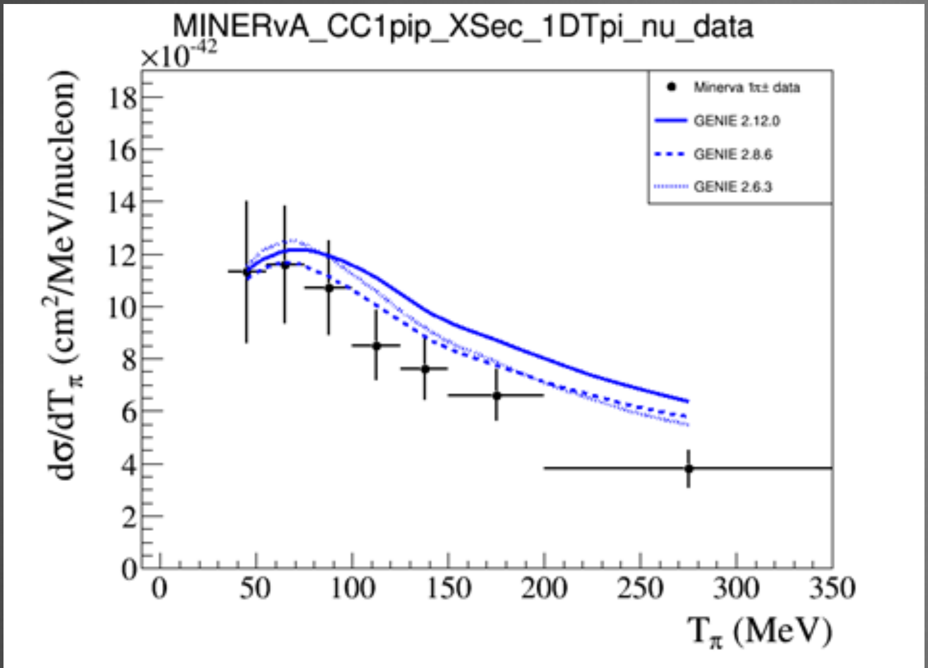
- GENIE now has complete Valencia QE model
  - QE with RPA and Coulomb corrections
  - 2p2h as in Gran paper
  - Note Valencia model is ~10% below data, renormalized in plot on right
- Left plot shows GENIE result, agrees well with Valencia QE+MEC

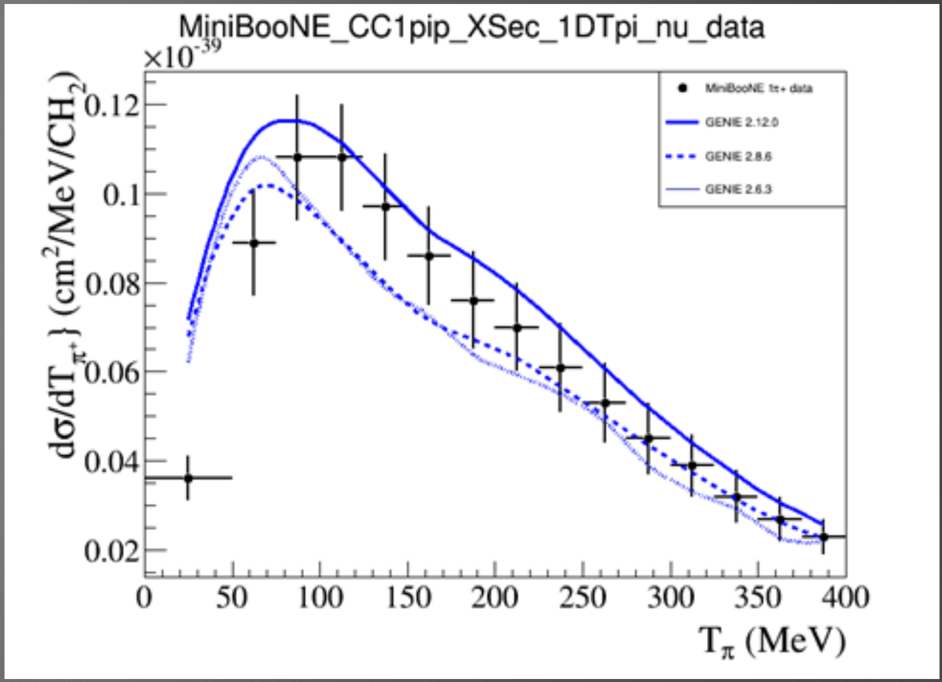
Valencia plot (Phys Lett)





MiniBooNE/MINERvA CCπ+



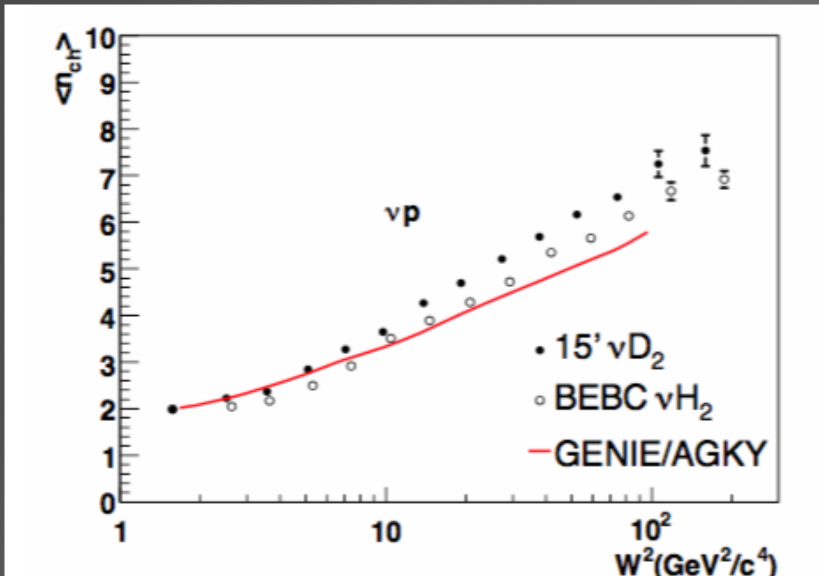


Summary

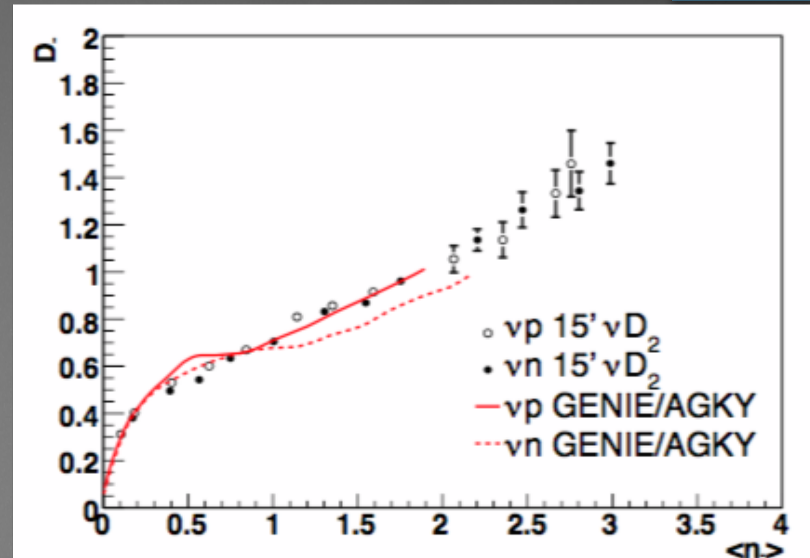
- In the past few years, the progress in the MC generators was impressive
- Cross contributions between implementations of theoretical models in the generators
- Still, there is a lot of work to do to have full validations against the electron scattering data
  - good for GiBUU and GENIE
  - needs more work for NEUT and NuWro
- How to get involved? Just download the code and start adding your model(s) or check your models.

Backup

Default physics model in v2 series



Average charged hadron multiplicity .



Negative hadron multiplicity dispersion.