Nuclear Theory and Generators: an uncertain relationship

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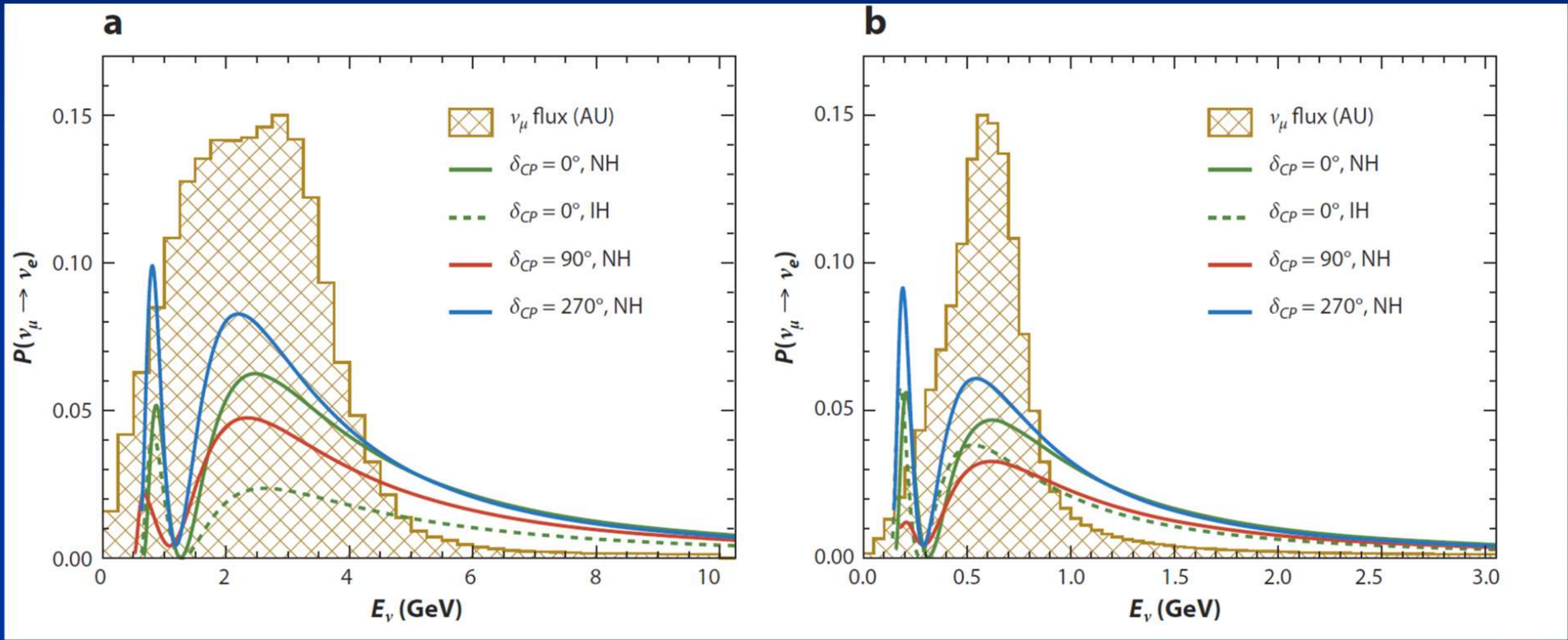
Oscillation Signals as F(E_ν)



From:
Diwan et al,
Ann. Rev.
Nucl. Part. Sci 66
(2016)

DUNE, 1300 km **HyperK (T2K) 295 km**

Energies have to be known within 100 MeV (DUNE) or 50 MeV (T2K)

Ratios of event rates to about 10%

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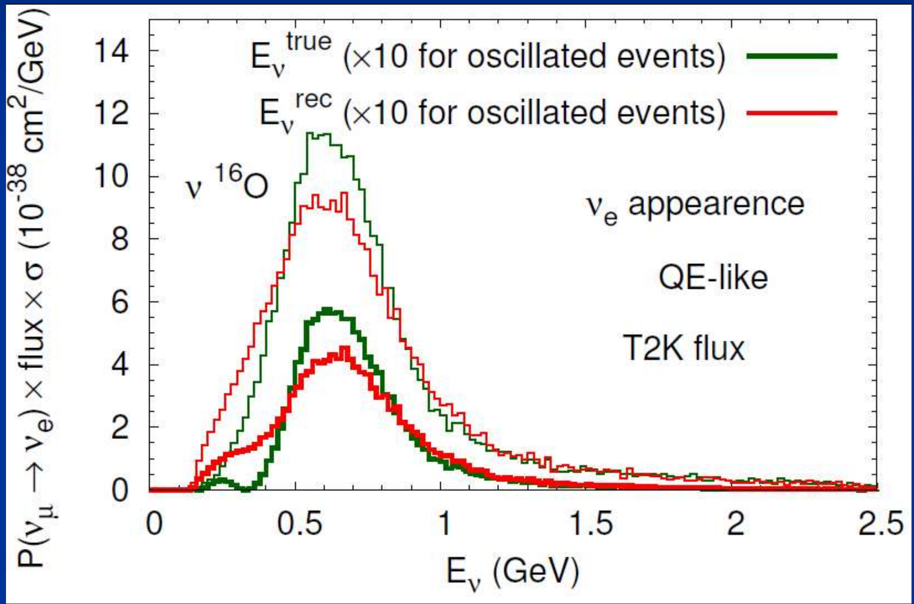
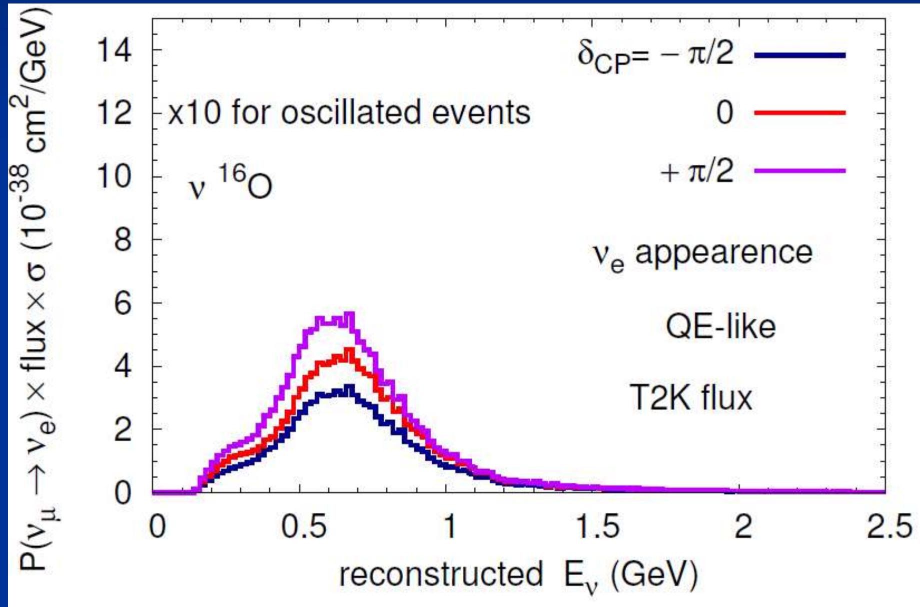
Oscillation signal in T2K

δ_{CP} sensitivity of appearance exps





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

Reconstruction error
as large as δ_{CP} dependence

Problem: Neutrino Energy

- The incoming neutrino energy on the abscissa of all such plots is not known, but must be reconstructed from an only partially observed final state (detector limitations!) ‚backwards' to the initial state

- This reconstruction requires:
  1. Knowledge of initial neutrino-nucleon -> neutrino-nucleus cross sections
     (particle or hadronphysics) (nuclear physics)
  2. Transport of initially produced hadrons through the nuclear volume, needs good knowledge of hadron-hadron FSI cross sections

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Initial State Interactions on Nucleon

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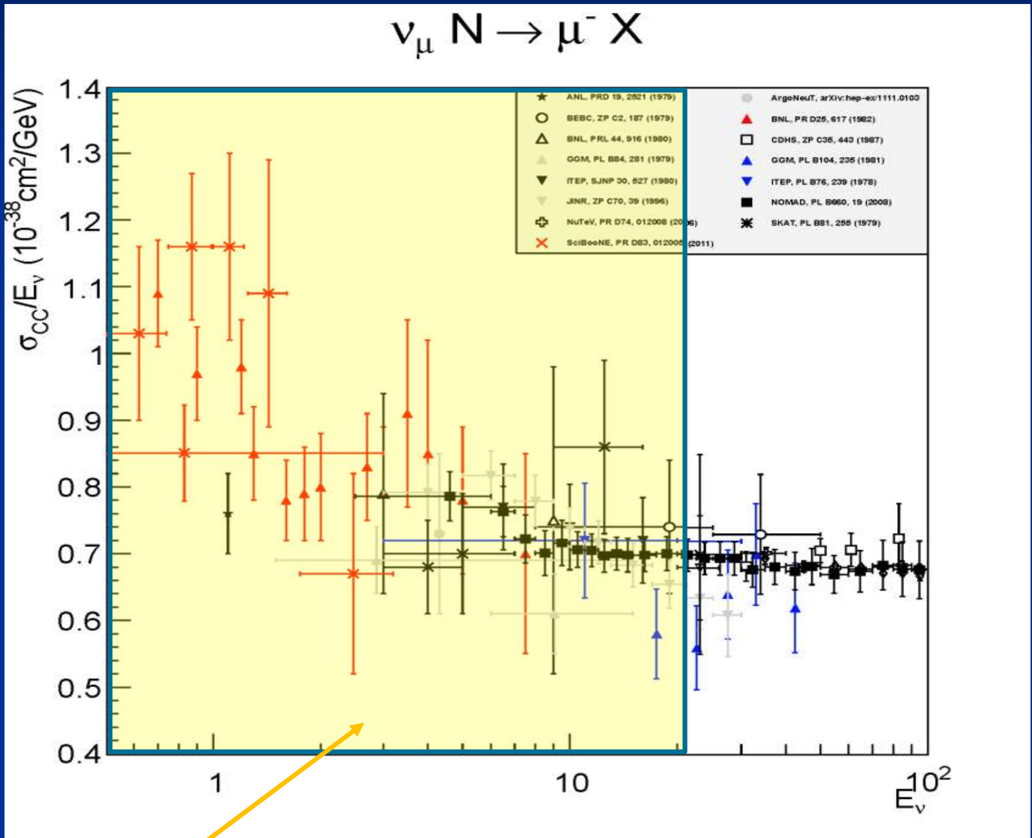
Neutrino-Nucleon Cross Sections



All modern long-baseline experiments

Experimental error-bars directly enter into neutrino-nuclear cross sections and limit accuracy of energy reconstruction, most of these data ~ 35 years old

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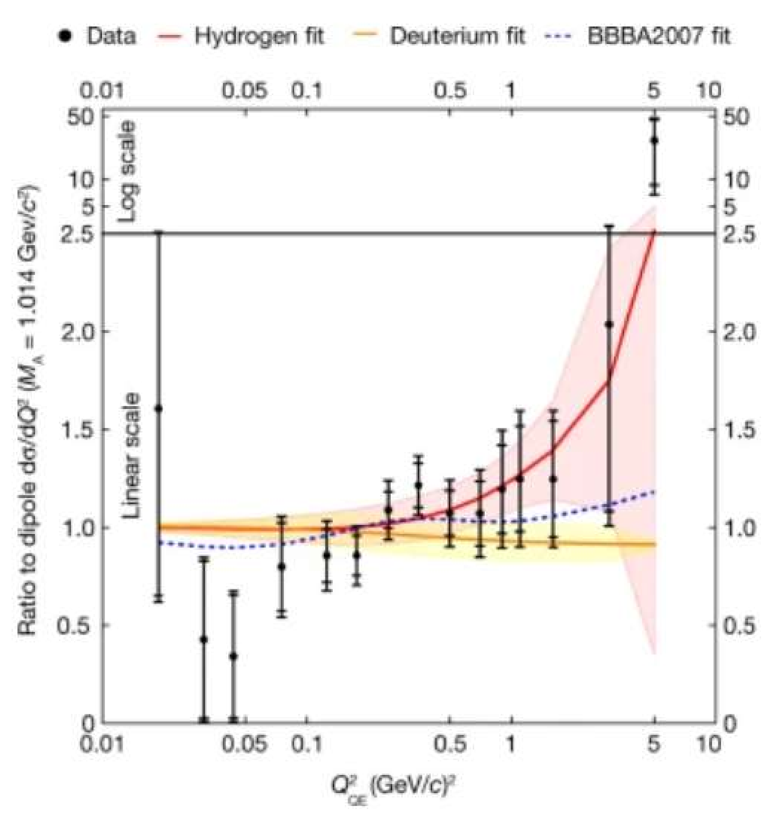
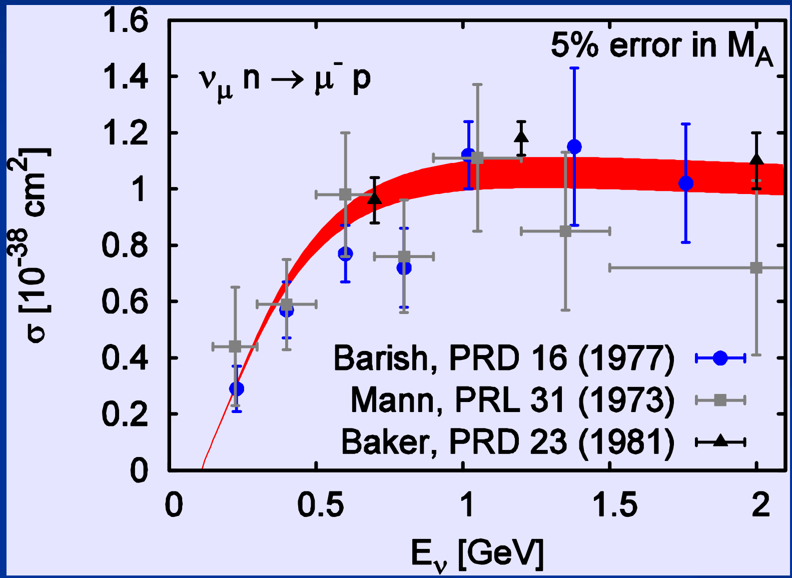
QE Scattering: Neutrinos
Axial Coupling



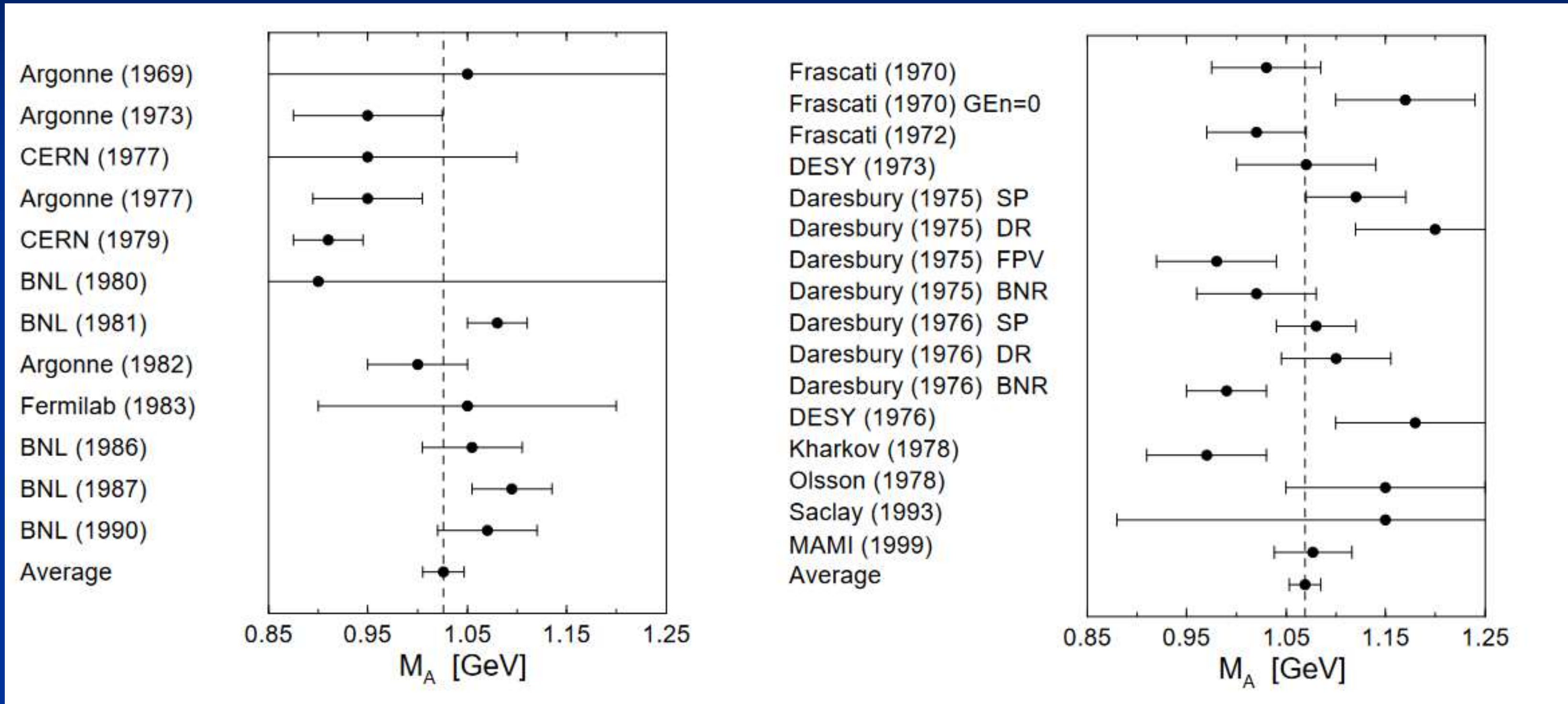
Cai et al, Nature 614, 2023



Leitner et al, 2009

All data so far compatible with dipole approx up to 1 GeV^2

World data on axial mass in 2001



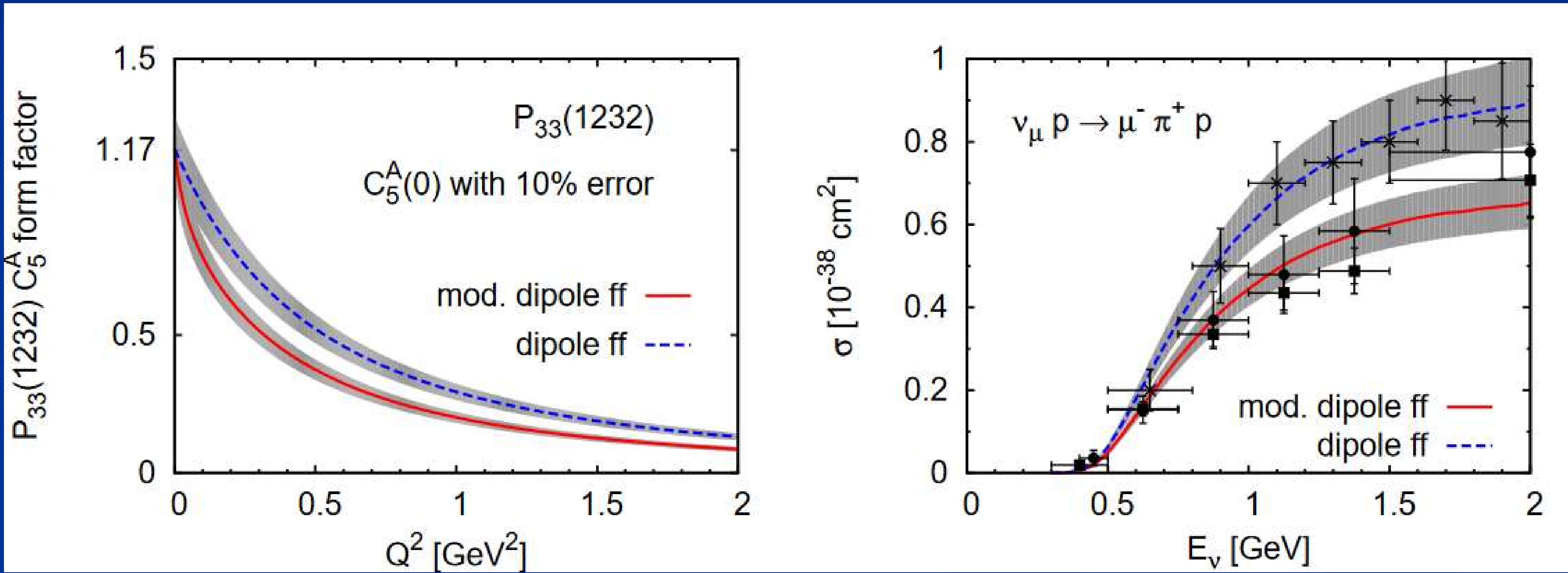
neutrinos

electrons

Dipole good up to Q^2 = 1 GeV^2

Bernard et al, 2001

Elementary Pion Data



Leitner Diss, 2009

Uncertainties in Resonances

- From Lalakulich, Paschos, Piranishvili (PR D74 (2006) 014009)
  Transition operator to spin-3/2 resonances:

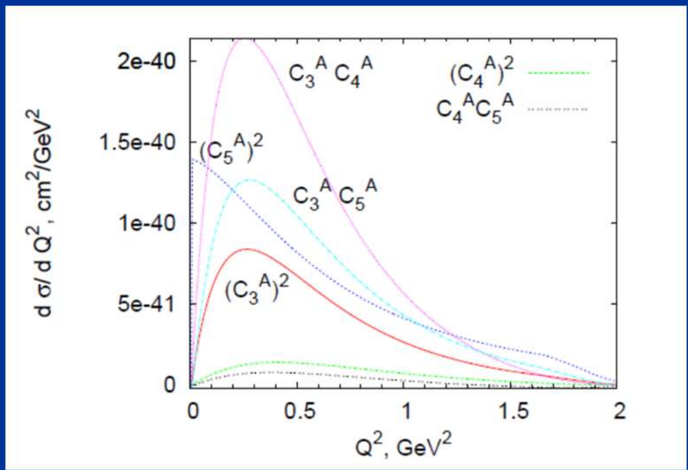
$$d^{\lambda\nu}_{D_{13}} = g^{\lambda\nu}\left[\frac{C_3^V}{m_N}\not{q} + \frac{C_4^V}{m_N^2}(p'q) + \frac{C_5^V}{m_N^2}(pq) + C_6^V\right] - q^\lambda\left[\frac{C_3^V}{m_N}\gamma^\nu + \frac{C_4^V}{m_N^2}p'^\nu + \frac{C_5^V}{m_N^2}p^\nu\right]$$

known

$$+ g^{\lambda\nu}\left[\frac{C_3^A}{m_N}\not{q} + \frac{C_4^A}{m_N^2}(p'q)\right]\gamma_5 - q^\lambda\left[\frac{C_3^A}{m_N}\gamma^\nu + \frac{C_4^A}{m_N^2}p'^\nu\right]\gamma_5 + \left[g^{\lambda\nu}C_5^A + q^\lambda q^\nu\frac{C_6^A}{m_N^2}\right]\gamma_5.$$

not known

E = 2 GeV
C3A = 1,
C4A = 1
D13(1520)



Interference terms between various axial formfactors can double the cross section!

Info obtainable from inclusive neutrino X-sections
In the range 1.2 < W < 3 GeV

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Now Nuclei

- All long-baseline experiments use nuclear targets

Neutrino Cross Sections: Nucleus

- All targets in long-baseline experiments are nuclei: C, O, Ar, Fe
- Cross sections on the *nucleon*:
  - QE + final state interactions (fsi)
  - Pion Production + fsi
  - Deep Inelastic Scattering → Pions + fsi
- Additional cross section on the *nucleus*:
  - Many-body effects, e.g., src, 2p-2h excitations
  - Coherent neutrino scattering and coh. pion production

Nuclear Physis

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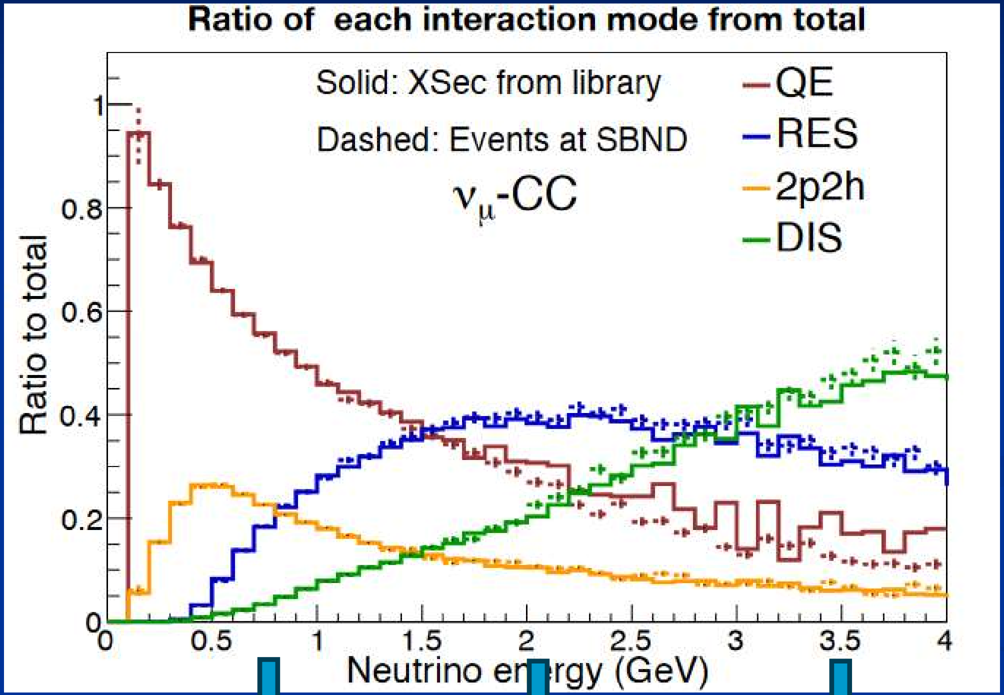
A wake-up call for the high-energy physics community:

Cartoon by S. Harris

Wake up, Dr. …., you'ʻre being transferred to low energy physics

Reaction Types (from GiBUU)



From:
Leo Aliaga

SBND

NovA

MINERvA LE

Generators describe νA interactions?

- Take your favorite neutrino generator (GENIE, …):
  „a good generator does not have to be right,
  provided it can be tuned to fit the data"
- *All* of these ‚standard' generators neglect from the outset:
  - Nuclear binding
  - Same ground states for different processes
  - Final state interactions in nuclear potential
- Generators use outdated physics: e.g.
  - Rein-Sehgal for resonances
  - hN, hA models for FSI

The Multi-Groundstate Models

- GENIE, NuWro, … :
  - QE: Fermigas or Spectral Function or SUSA, each with its own parameters
  - Pion production: Rein-Sehgal Resonance Production, background from Bodek-Yang, gs from Fermigas.
  - Pion absorption: Valencia Model (Oset et al): Local Fermi gas, no binding, no connection to production
- DANGER: inconsistent models with redundant, therefore unphysical, parameters to tune (ex: MicroBooNE g_A)

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Spectral Functions

- Spectral functions from NMBT have a problem in going beyond gs calculations:
  - Even QE is sensitive to final state potential (rediscovered by Ankowski-Benhar)
  - Potential is hidden in SF, problem for final state interactions which start in the same potential -> no factorization of ISI and FSI
  - Momentum-Dependence is hidden in SF, probably very different from ‚FSI' momentum-dependence (from p-A scattering)?
- The potential must be continuous when going from below the Fermi-surface (bound nucleons) to above the FS (outgoing nucleons)

Groundstate, Spectral Functions

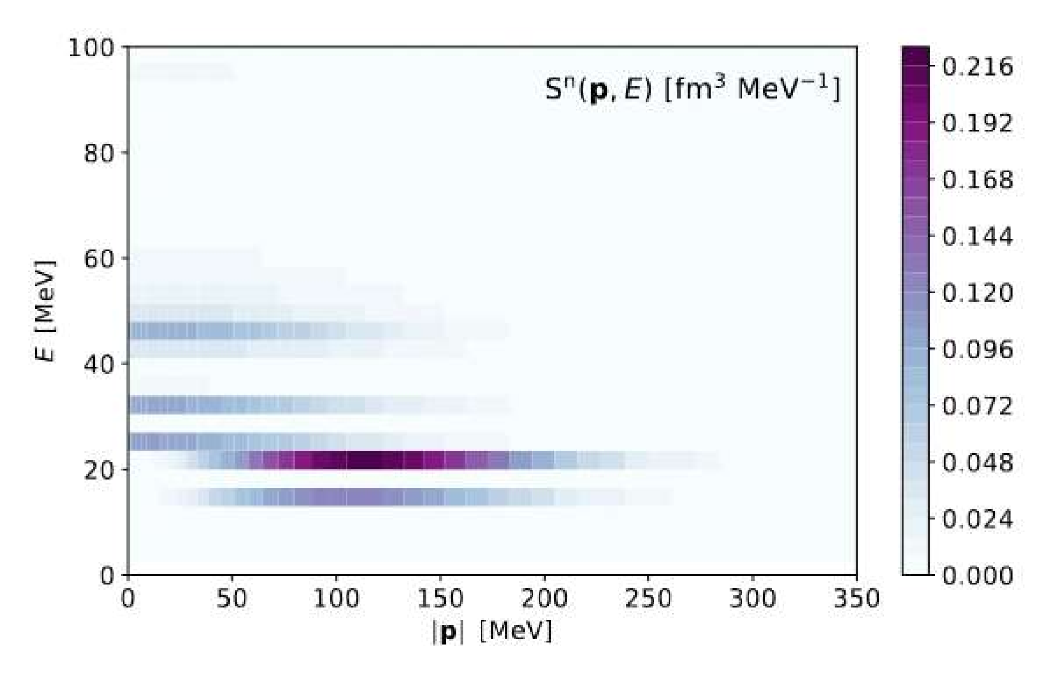
- Nuclei are bound with stable groundstate: forgotten in most generators
- GiBUU :
  - starts with nuclear energy-density functional, realistic density, determines *r*-distribution of nucleons:

$$U[\rho,p] = A\frac{\rho}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^{\tau} + 2\frac{C}{\rho_0} g \int \frac{d^3p'}{(2\pi)^3} \frac{f(\vec{r},\vec{p}')}{1+\left(\frac{\vec{p}-\vec{p}'}{\Lambda}\right)^2}$$

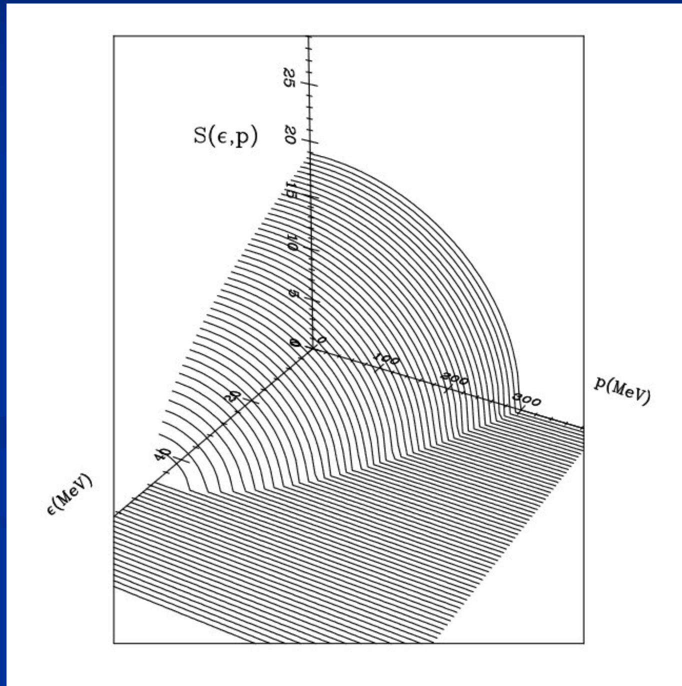
  Potential contains realistic *p*-dependence already in gs, consistent for bound and free nucleons!
  - Momentum-distribution in Local TF approximation
- Spectral Function in GiBUU NOT delta-function, but smooth, extended distribution

$$\mathcal{P}_h(\mathbf{p},E) = 2\pi g \int_{\text{nucleus}} \mathrm{d}^3x\, \Theta\left[p_{\mathrm{F}}(\mathbf{x}) - |\mathbf{p}|\right] \Theta(E)\, \delta\left(E - m + \sqrt{\mathbf{p}^2 + m^{*2}(\mathbf{x},\mathbf{p})}\right)$$

Spectral Functions



J.E. Sobczyk and S. Bacca, arXiv:2309.00355v1



W.M. Alberico et al, *Nucl.Phys.A* 634 (1998) 233-263

Electrons can resolve the shell structure,

neutrino experiments not, since they smear over energy transfers

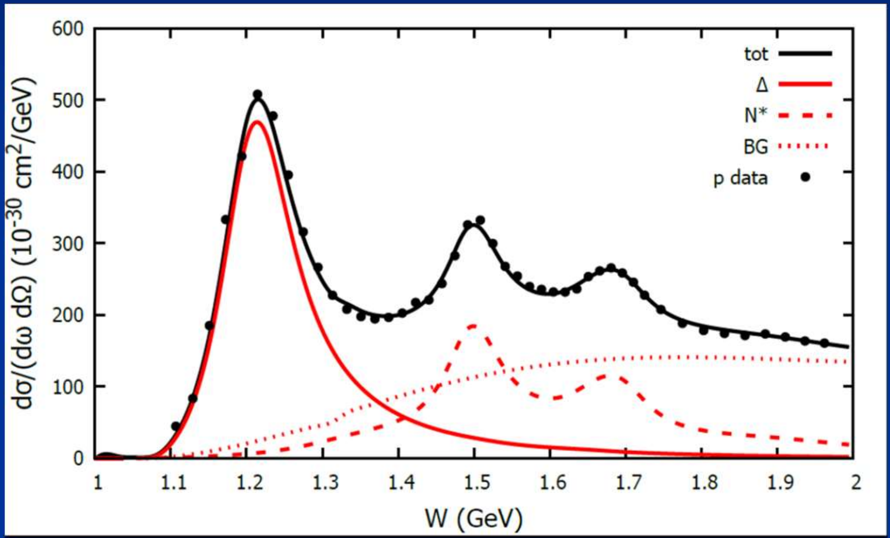
Electron-Nucleus X-sections

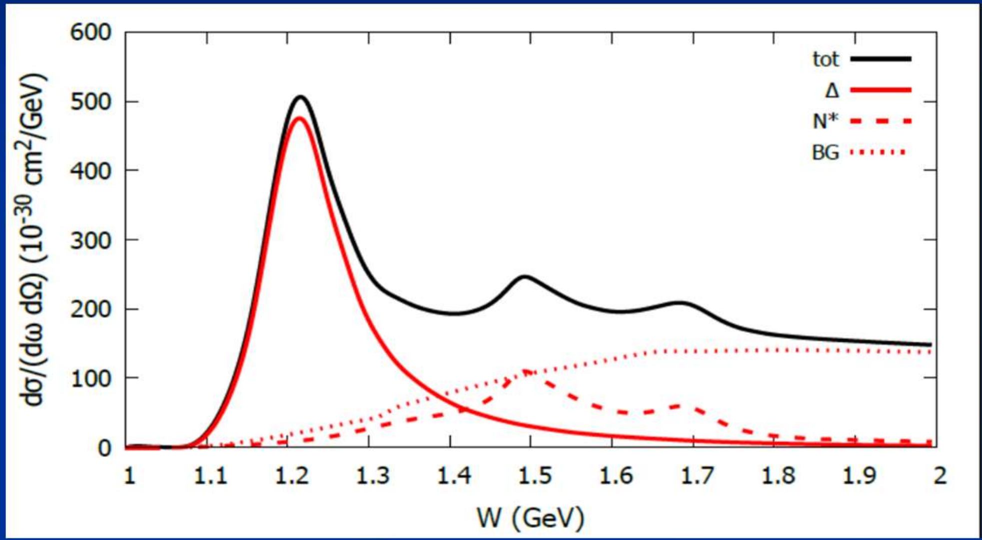
- New in GiBUU v2023:

- e-A cross sections are obtained by sampling the spectral function and then Lorentz-boost into the restframe of the nucleus.
- Then evaluate the e-N cross section in that restframe by using parametrization of e-N X-sections from Bosted-Christy
- Finally transform the X-section back to the target rest-frame.

Electrons as Test

E = 2.239 GeV, 21.95 deg





e-proton

Bosted-Christy Fit

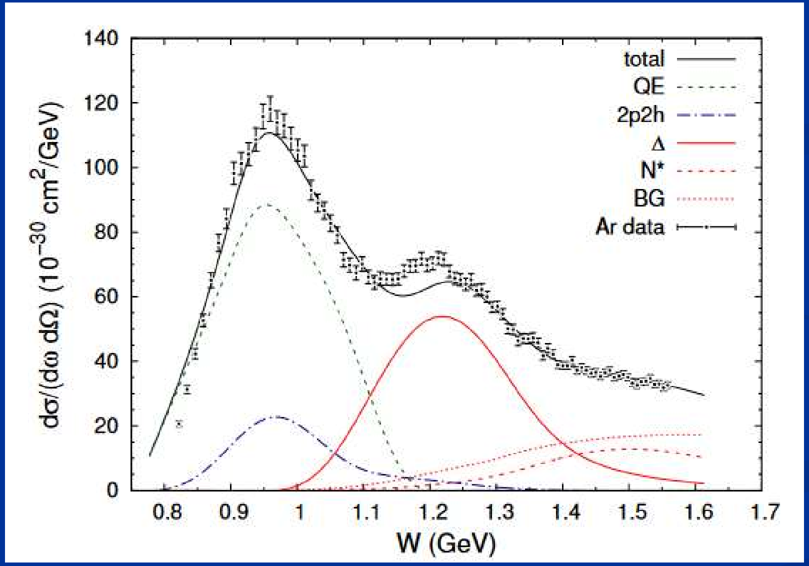
e-neutron

In both cases large non-resonant (background) contributions:

What are the final states associated with them?? How does the background decay??

QE Scattering: Electrons

- Well defined peak around nucleon mass, but not all one-particle process. Two additional overlapping contributions:
  1. 2p-2h (MEC)-excitation (in GiBUU from Bodek-Christy)
  2. Delta-excitation



e-Ar, 2.222 GeV, 15.541 deg
GiBUU, v2023

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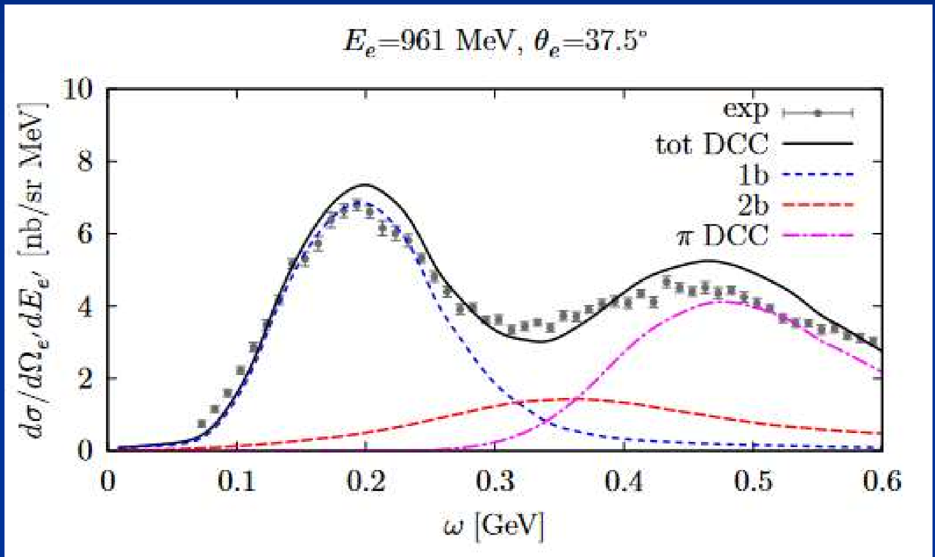
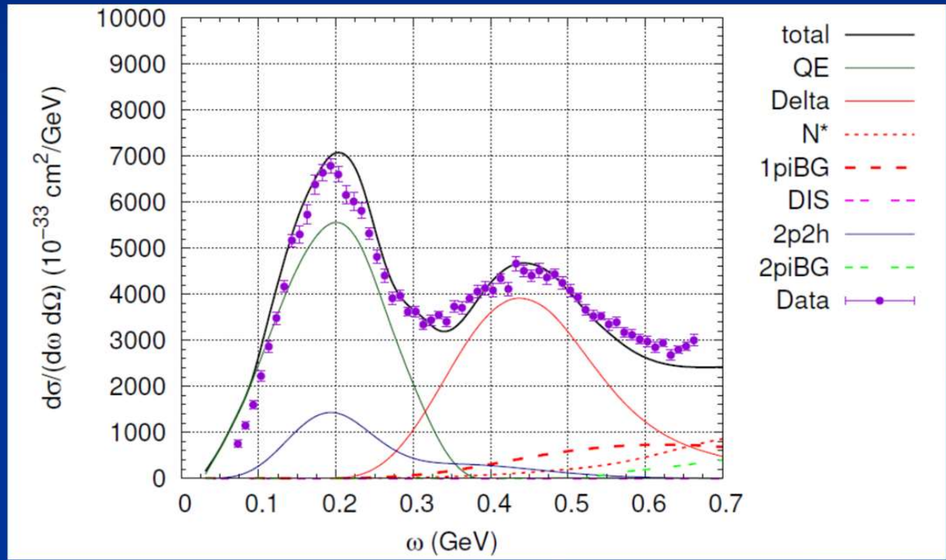
‚ab initio‘ vs quasiclassical



Rocco et al, PRC 100 (2019) 6



GiBUU

Quasiclassical models work well enough (need models for MEC contribs)

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Nucleon Resonance Problems

- There are good (and not so good) models around for resonance excitations. We know their transition currents and the vector form factors are fairly well determined from electron scattering.
- For neutrinos the additional axial form factors are less certain, but have been modeled for a long while

- Problem: How to convert the electron background cross sections into neutrino cross sections??

Electron -> Neutrino Transition

- ‚Transform‘ the structure functions:

$$W_1^\nu = \left[1 + \left(\frac{2m}{\mathbf{q}}\right)^2 \left(\frac{G_A(Q^2)}{G_M(Q^2)}\right)^2\right] 2(\mathcal{T}+1)\, W_1^e$$

$$W_3 = 2\left(\frac{2m}{\mathbf{q}}\right)^2 \frac{G_A(Q^2)}{G_M(Q^2)}\, 2(\mathcal{T}+1)\, W_1^e\,.$$

D. Walecka, 1975

$V^2 + A^2$

V A

The kinematical factor 2m/q appears in the relation between vector and axial sp current

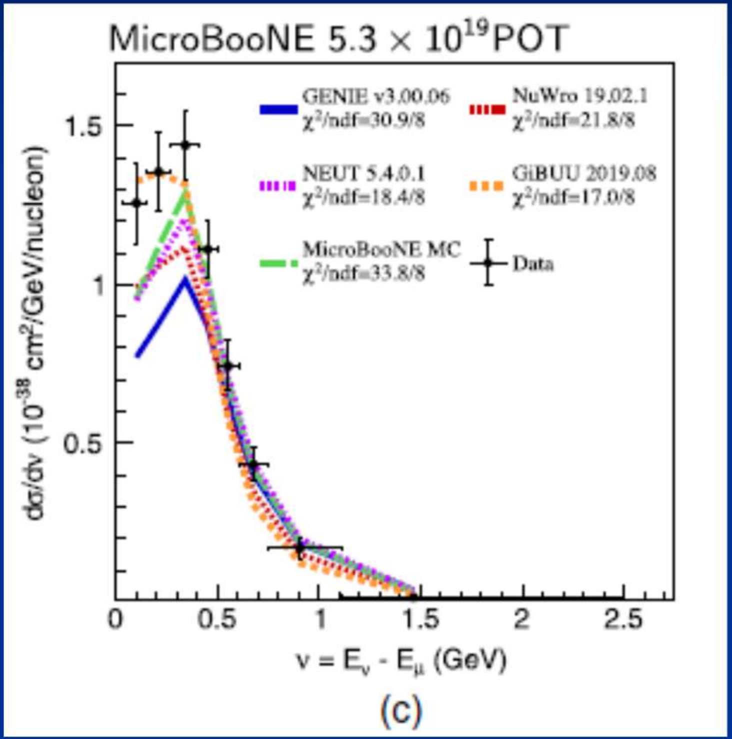
QE Scattering: Neutrinos

- BIG PROBLEM: energy transfer is experimentally not available
  → pion production (and following) reabsorption is always mixed in
  → ‚pure' QE scattering is not measurable

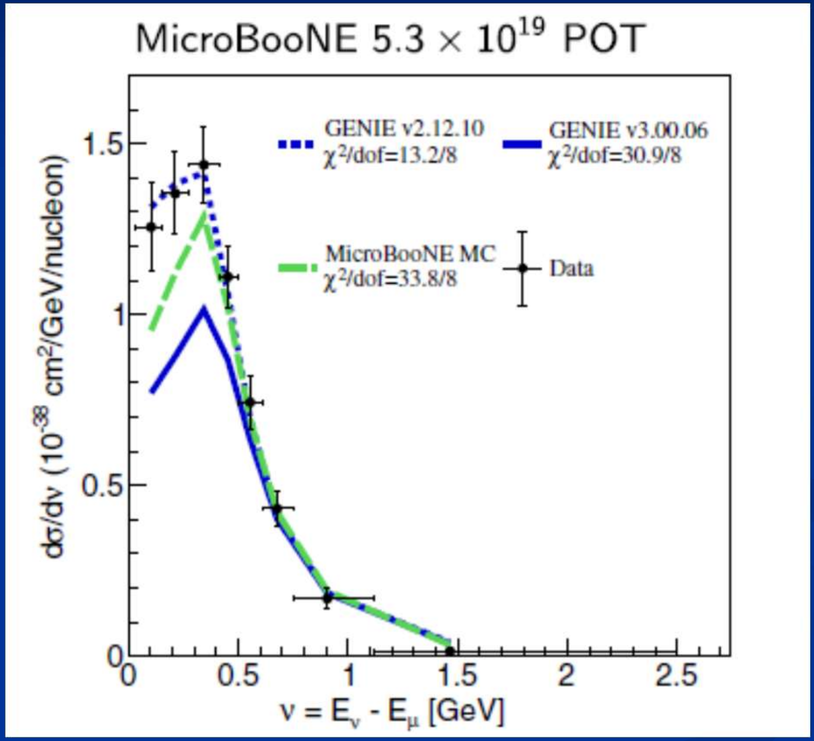
  → any comparison of QE models (NMBT, ab-initio, SUSA, ..) with inclusive neutrino data needs additional modelling of pion production (and absorption):

QE-like (1p, 0pi) is not QE

MicroBooNE comparisons



Abratenko et al, PRL 128 (2022)



Abratenko et al, PRD 105 (2022)

Nothing tuned in GiBUU

Various tunes in GENIE

Now: Exclusive

- Have to treat final state interactions

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **Giessen Model implemented in the generator GiBUU**
- **GiBUU : Quantum-Kinetic Theory and Event Generator**
  based on a BM solution of Kadanoff-Baym equations

- GiBUU propagates phase-space distributions, not particles
- Physics content and details of implementation in:
  Buss et al, Phys. Rept. 512 (2012) 1- 124
- Code from gibuu.hepforge.org, new version GiBUU 2023

Quantum-kinetic Transport Theory

On-shell drift term — BM off-shell transport term — Collision term

$$\mathcal{D}F(x,p) - \mathrm{tr}\left\{\Gamma f, \mathrm{Re}S^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}} = C(x,p)\ .$$

$$\mathcal{D}F(x,p) = \{p_0 - H, F\}_{\mathrm{PB}} = \frac{\partial(p_0 - H)}{\partial x}\frac{\partial F}{\partial p} - \frac{\partial(p_0 - H)}{\partial p}\frac{\partial F}{\partial x}$$

H contains mean-field potentials

Describes time-evolution of *F(x,p)*

$$F(x,p) = 2\pi g f(x,p)\,\mathcal{P}(x,p)$$

Spectral function

Phase space distribution

One such equation for each particle: neutrino, nucleon, resonance, meson,…
All coupled through mean field potential in *H* and collision term *C*

2-Body collision term

$$
\begin{aligned}
C^{(2)}(x,p_1) &= C^{(2)}_{\text{gain}}(x,p_1) - C^{(2)}_{\text{loss}}(x,p_1) \\
&= \frac{\mathcal{S}_{1'2'}}{2p_1^0 g_{1'} g_{2'}} \int \frac{d^4 p_2}{(2\pi)^4 2p_2^0} \int \frac{d^4 p_{1'}}{(2\pi)^4 2p_{1'}^0} \int \frac{d^4 p_{2'}}{(2\pi)^4 2p_{2'}^0} \\
&\quad \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_{1'} - p_{2'}) \overline{|\mathcal{M}_{12\to 1'2'}|^2} \\
&\quad [F_{1'}(x,p_{1'})F_{2'}(x,p_{2'})\overline{F}_1(x,p_1)\overline{F}_2(x,p_2) - F_1(x,p_1)F_2(x,p_2)\overline{F}_{1'}(x,p_{1'})\overline{F}_{2'}(x,p_{2'})] \,,
\end{aligned}
$$

$$
\overline{F}(x,p) = \begin{cases} \mathrm{i}\,\mathrm{tr}[\tilde{S}^{>}(x,p)\gamma_0] = 2\pi g A(x,p)[1 - f(x,p)] & \text{for fermions,} \\ 2p^0 \mathrm{i}\tilde{D}^{>}(x,p) = 2\pi g A(x,p)[1 + f(x,p)] & \text{for bosons.} \end{cases}
$$

Collision term in general also contains 2 <-> 1 collisions (resonance excitation and decay) and 2 <-> 3 processes. Forward and backward processes contain the same transition matrix element (time-reversal invariance). Practical consequence: Pion production and absorption must be linked by the same matrixelement, not different theories.

GiBUU

- Theory and Code for simulation of nuclear reactions
- degrees of freedom: Hadrons (Baryons, Mesons)
- propagation and collisions of particles in mean fields
- approx. Kadanoff-Baym and Boltzmann-Uehling-Uhlenbeck equations solved

HISTORY:

- A+A (~ 1990) up to 10 – 20 AGeV
- hadron+A (p+A, π+A) (~ 1995) up to 20 GeV
- γ+A (~ 1998) up to GeV
- e+A (~ 2000) up to 300 GeV
- ν+A (~ 2005 -) up to 1 TeV

FSI widely tested

Final State Interactions

- For the final state the very same potential as in the initial interaction must be present! This creates problems:
  1. Potential is *r*-dependent: trajectories between collisions (there can be many!) must be integrated numerically (no more straight line trajectories or simple mean-free-path recipes)
  2. Potential is *p*-dependent: simultaneous energy-momentum conservation at each collision is difficult: needs numerical iteration. Example: 1 + 2 -> 3 + 4
  3. Models that violate #2 violate energy conservation

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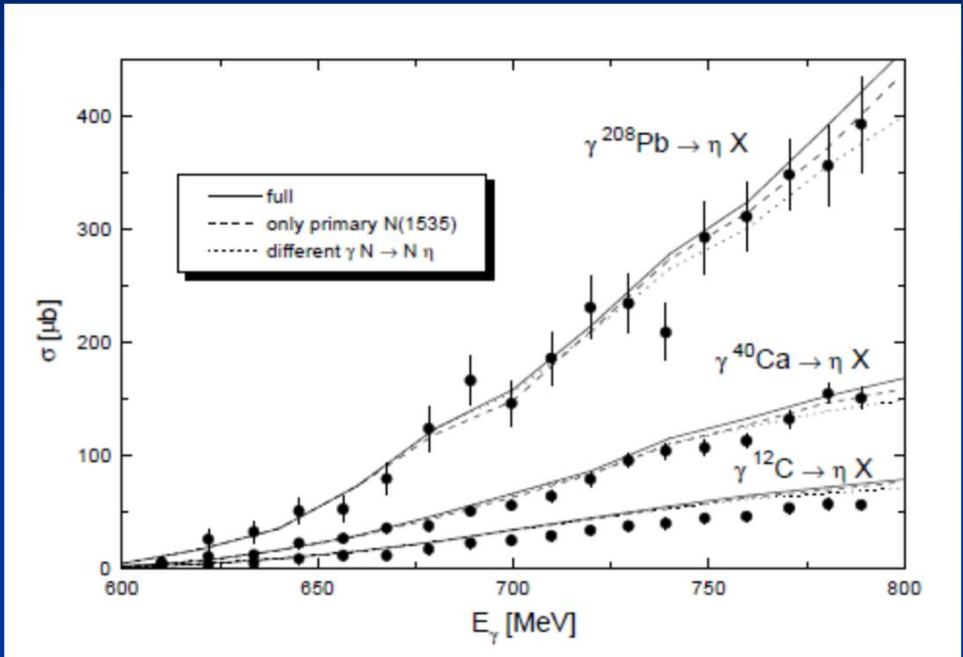
Final State Interactions

- Nuclear Physics Nogos in often used generators:
  1. Formation times, during which (after a collision) no interactions occur. Analysis of HERMES and EMC data has shown that to be incorrect.
  2. In the RES and SIS regions, formation times are determined by the widths of hadrons, they are not free parameters! Example: Deltas, created in pi + N, collide during their lifetime with another nucleon -> main mechanism of pion reabsorption.
  3. Cascades lead to ‚avalanches' of particles, so that many particles have to be followed, with many subsequent collisions.

Electromagnetic Processes



Theory: Effenberger et al, 1997
Data: Metag et al, TAPS

γA

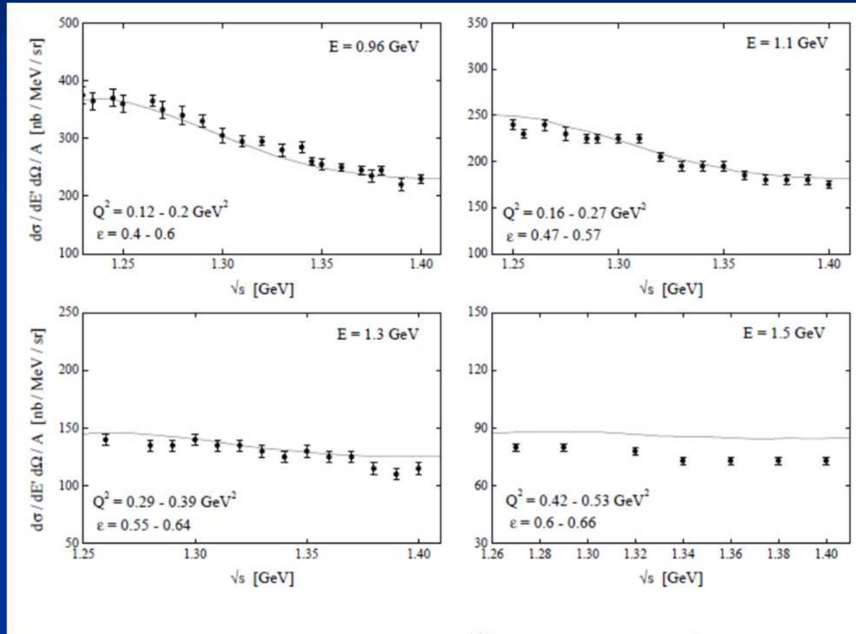


Figure 8: Cross section of the reaction $e^{12}C \to e'X$ measured at $\vartheta = 37.5°$

Theory: Lehr et al, 1999
Data: Sealock et al

eA

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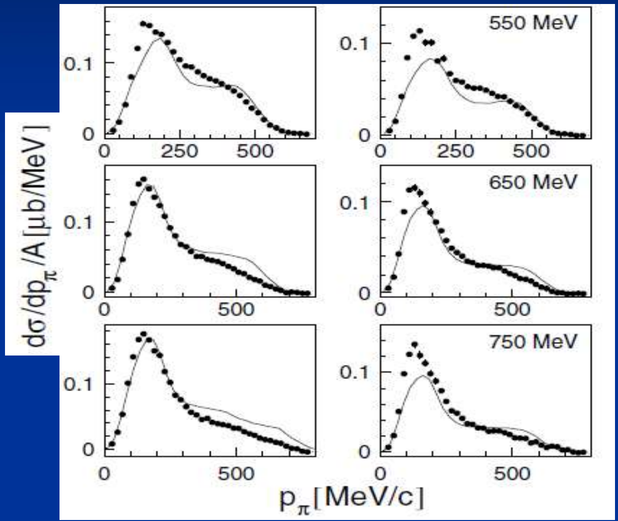
Check: pions, protons

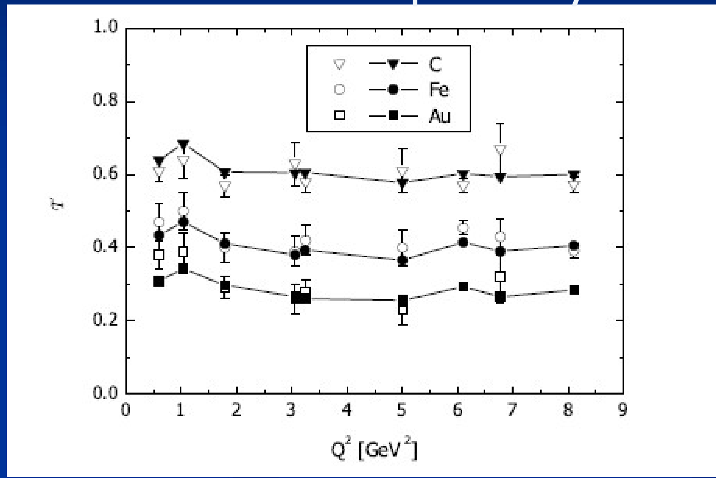
(Leitner et al, https://inspirehep.net/literature/819969 (2009))

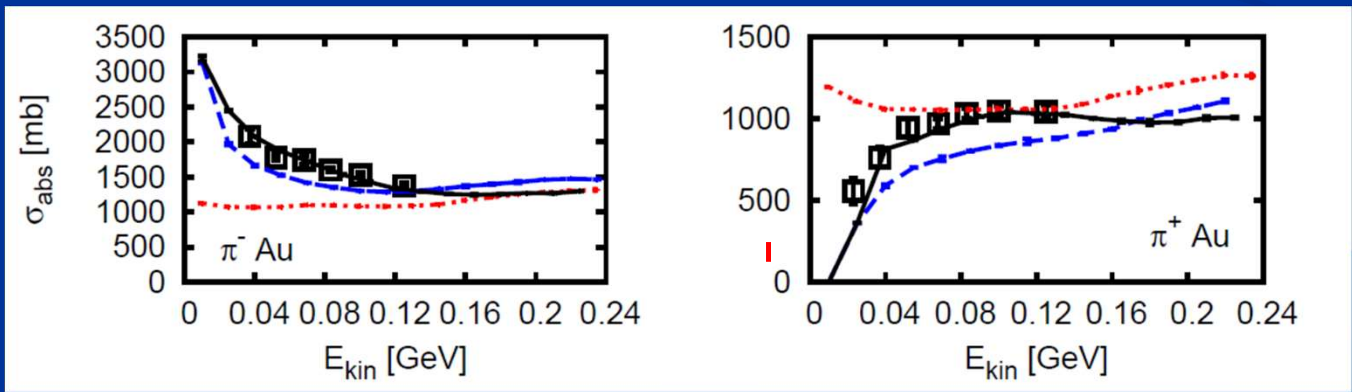
$\gamma \rightarrow \pi^0$ on Ca   Pb



1999

Proton transparency



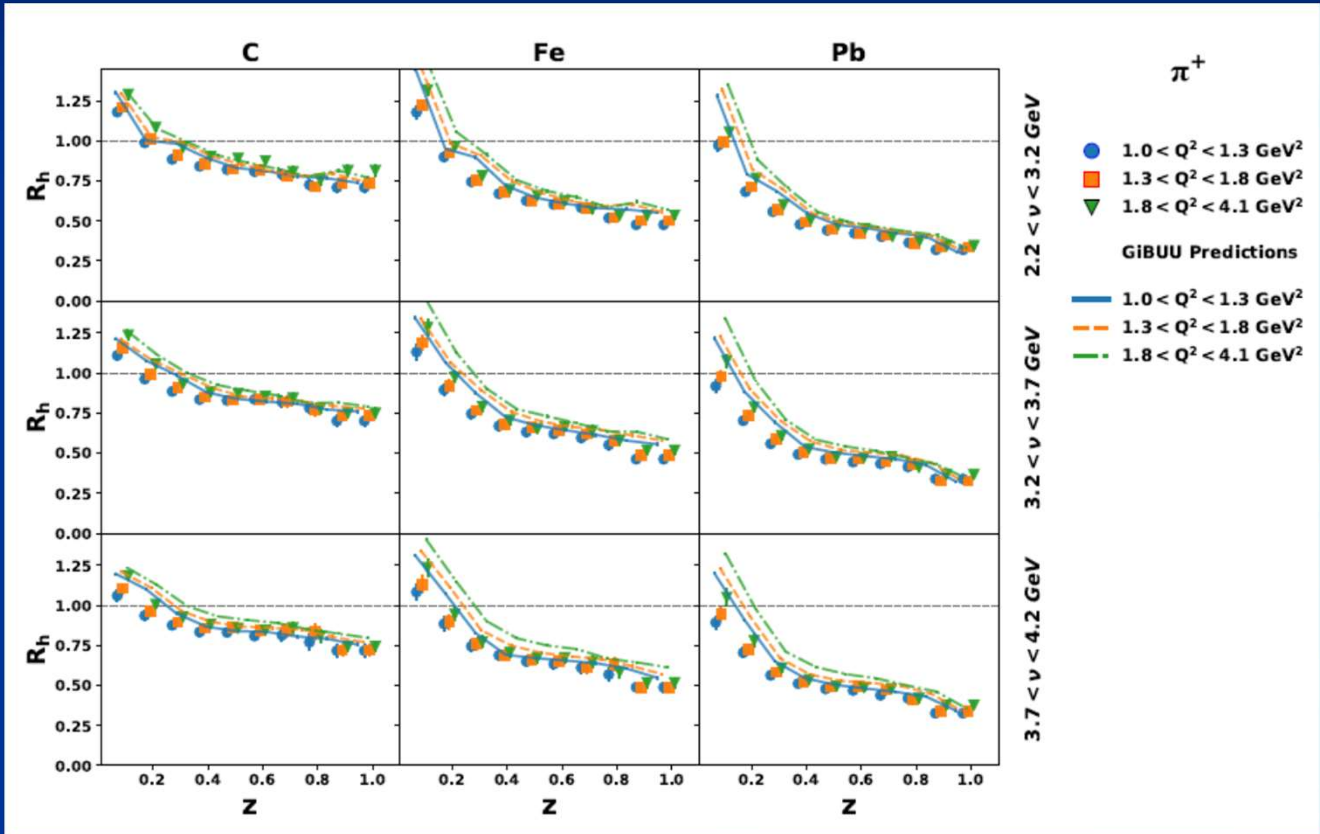


Pion reaction Xsect.
--- no potential
--- Coulomb only
--- Coulomb + nuclear

2006

SIDIS: Pions at 5 GeV@JLAB

Attenuation ratios

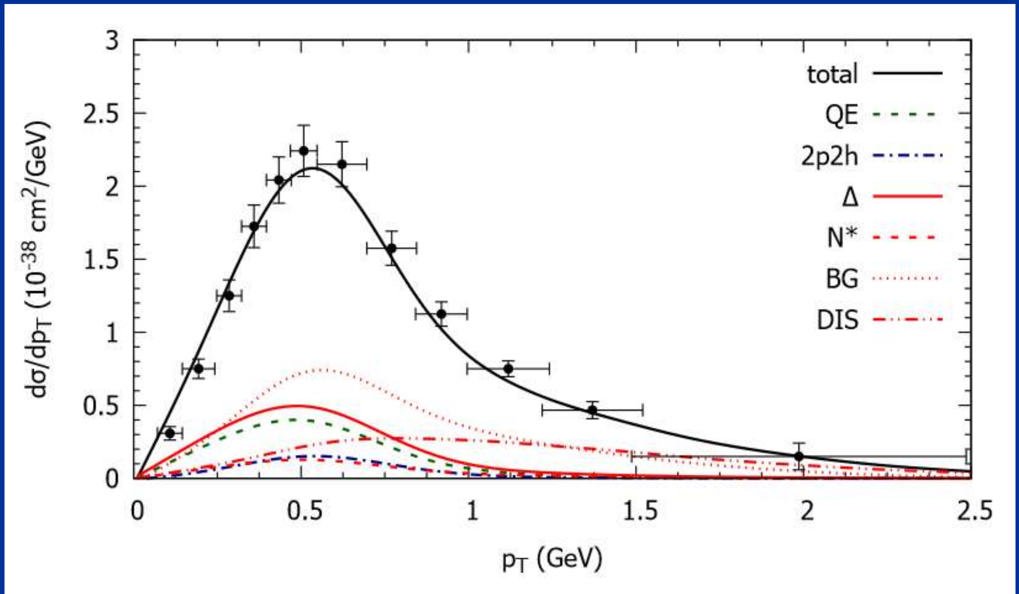


$z = E_\pi/\nu$

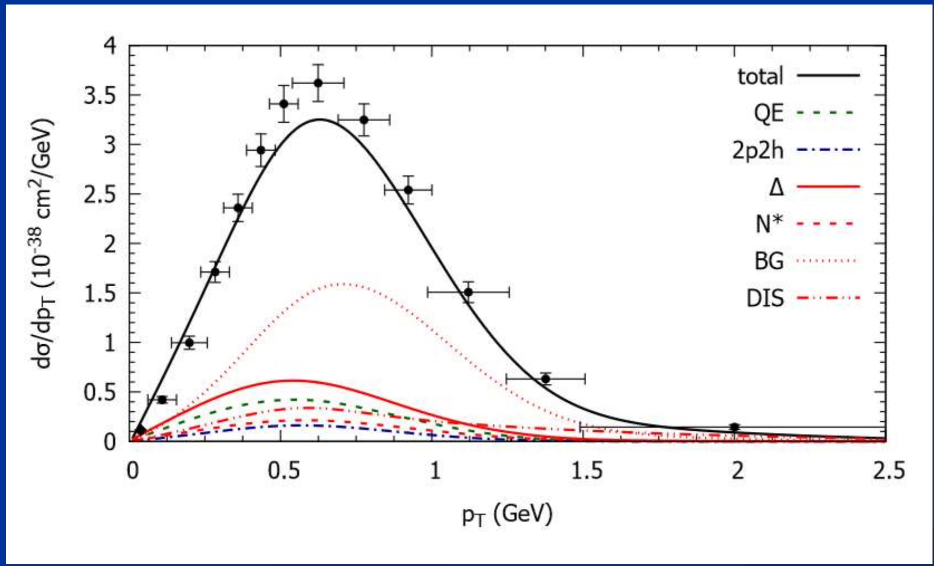
Data:
Moran et al,
Phys.Rev.C 105 (2022) 1
Theory:
GiBUU

MINERvA incl X-sections

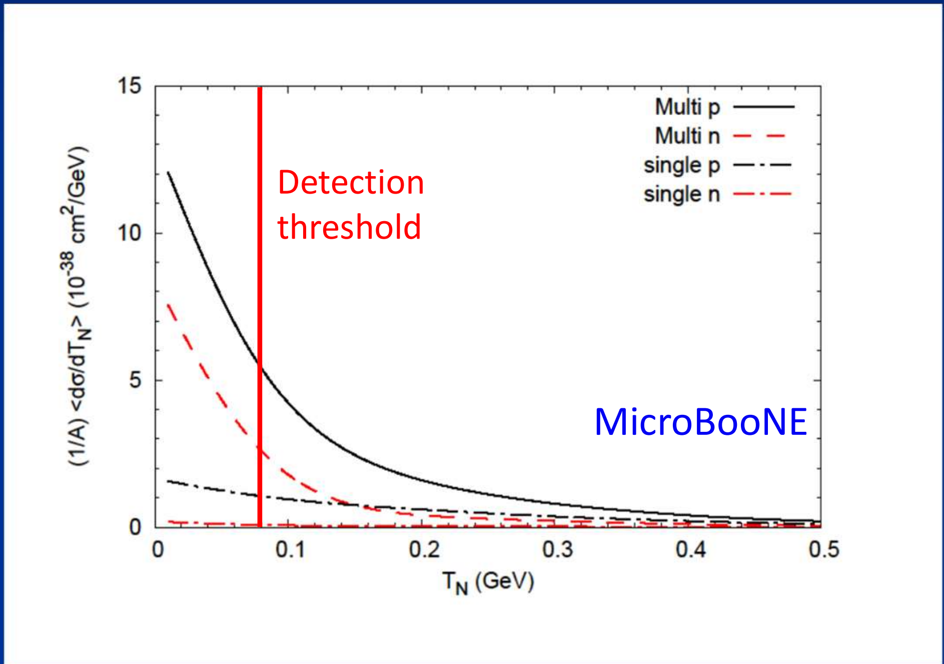
LE

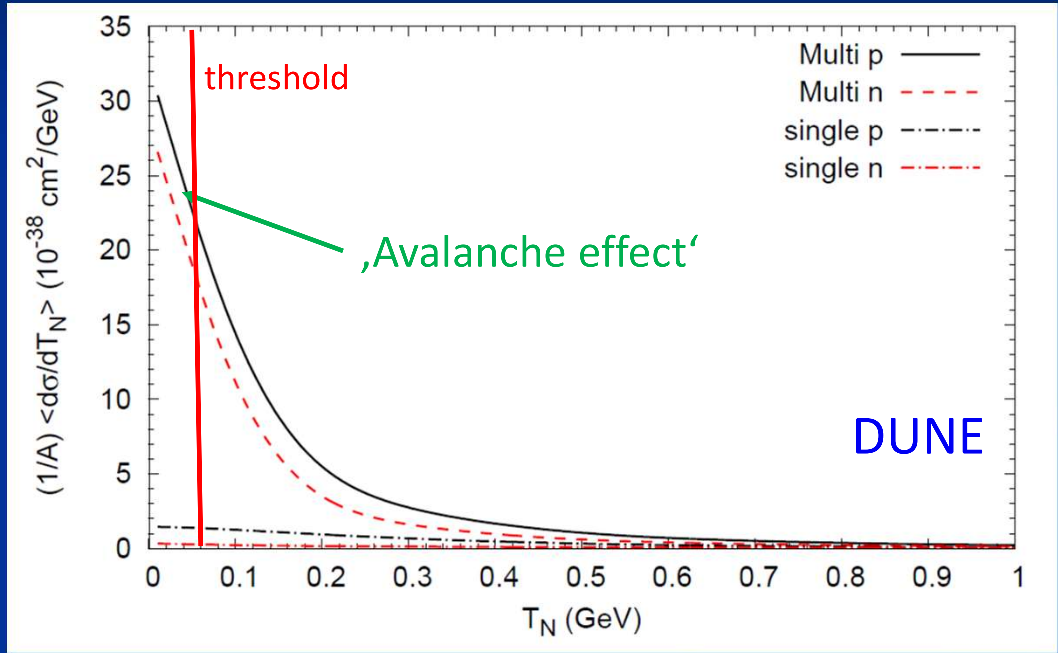


ME



Nucleon Spectra





At MB *n* < *p* , at DUNE *n* ~ *p*:
n not suppressed at DUNE because of pi-production channels

GiBUU and Neutrino Experiments

- MicroBooNE has used GiBUU in all its most recent analyses: usually works very well (see talk by Afroditi)
- A group at SBND (R. Castillo Fernandez, Leo Aliaga at UTA and Xianguo Lu, U Warwick) are working at implementing GiBUU into the LArSoft package
- Hope to see not only inclusive X-sections, but also outgoing particle spectra, first results from MicroBoone (Afroditi‘s talk)

Final State Interactions

- Theory problems:
  1. ‚Frozen density approximation' for the target may be good at MicroBooNE/T2K physics, uncertain at DUNE, clearly wrong at FASER energies (1 TeV)
  2. In-medium cross sections may be diffferent from free cross sections (work by R. Machleidt et al)
  3. Relativistic collisions are tricky: at which time do relativistic nucleons collide? The eigentimes for the two colliding nucleons are different. Relevant for DUNE/FASER energies

Summary I

- To worry about uncertainties in generators is premature
- First, worry about correctness of physics in generators, most popular generators suffer from basic physics problems
- Once the underlying physics is correct, then tune, but only within the uncertainties of input properties
- In order to learn about the underlying physics document changes from version to version in the generators. Seeing that GENIE v 3.11 tune 2 describes data better than v 3.04 tune 11 is meaningless without giving the details of what has been changed

Summary II

- It is urgent to develop a new generators that takes state-of-the-art nuclear structure, but also reaction physics into account. The initial, first interactions of the neutrino have to be calculated with the same potential in the outgoing state as in the final state.
- For the final state interactions state of the art cascades have to be employed. Quantum-kinetic transport theory with its Kadanoff-Baym equations provides a well tested treatment of the FSI. Wdely used in other fields of nuclear physics.