# GiBUU: latest Developments

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# GiBUU: History

- GiBUU was originally not meant to be a neutrino generator
- GiBUU was meant to describe the non-equilibrium development of heavy ion collisions using quantum-kinetic theory
- Later (~ 1995) GiBUU was extended first to ($\pi$ *A*) then ($\gamma$ *A*), (e *A*) to look for in-medium changes of cross sections in equilibrium nuclear targets
- Finally (~ 2005), GiBUU was extended to neutrino-*A* reactions with the same FSI machinery as in all the other reactions
- AIM: to provide a consistent set of docu and code

# GiBUU: Presence

- GiBUU is presently used to describe
  1. Dilepton and pion production in heavy-ion collisions (HADES experiment at GSI)
  2. Inelastic electron scattering at JLAB (and SLAC, MAMI)
  3. Neutrino-nucleus reactions at Fermilab, T2K and FASER
- All with the same theory input and code!
- We provide the code for download from gibuu.hepforge.org, you run it yourself (and we help if nessary and fix bugs)
- We encourage users to actively contribute to GiBUU, by theoretical input and/or actual programming



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# Groundstate, Spectral Functions

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

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

$$f(\vec{r},\vec{p}) = \Theta(|\vec{p}_F(\vec{r})| - p)$$

  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

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

$$m^* = m + U(x,p)$$



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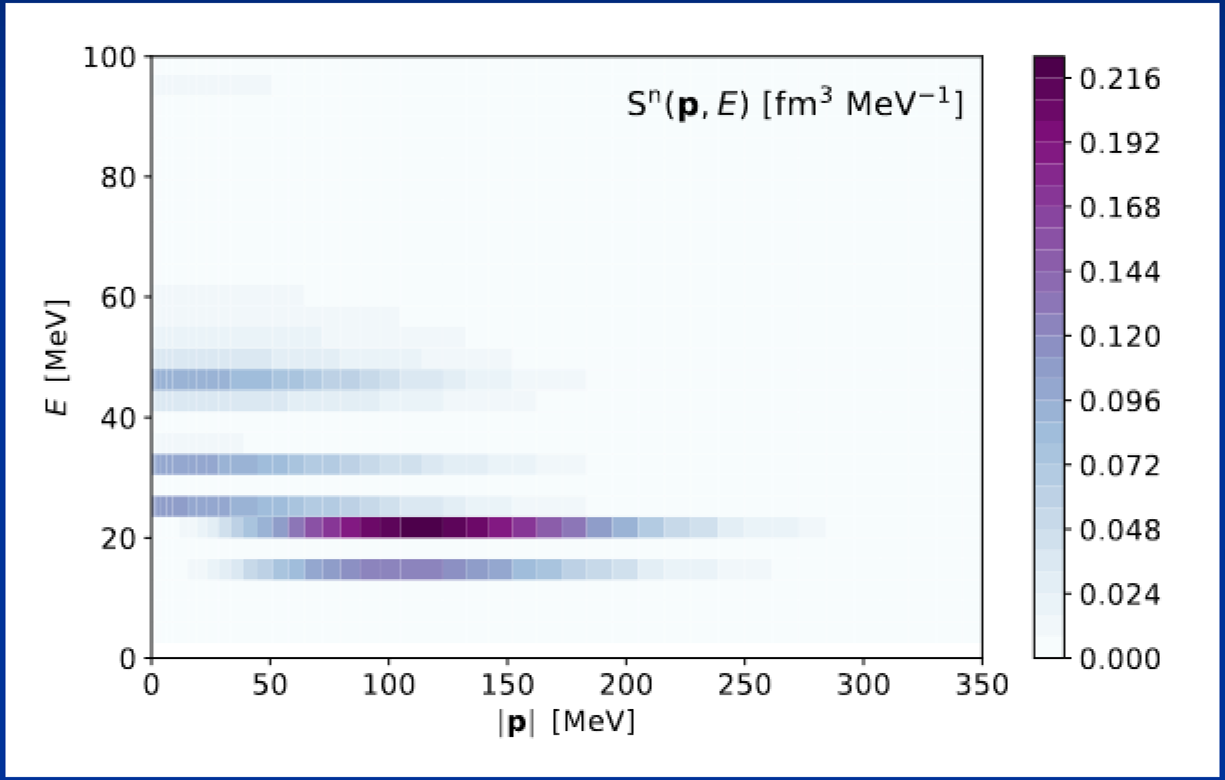
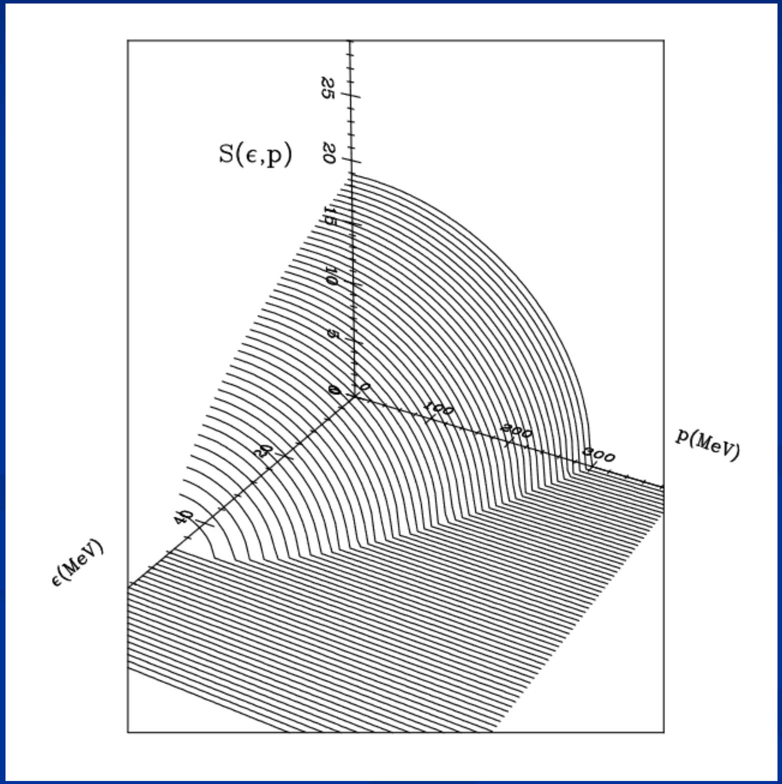
# Spectral Functions




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

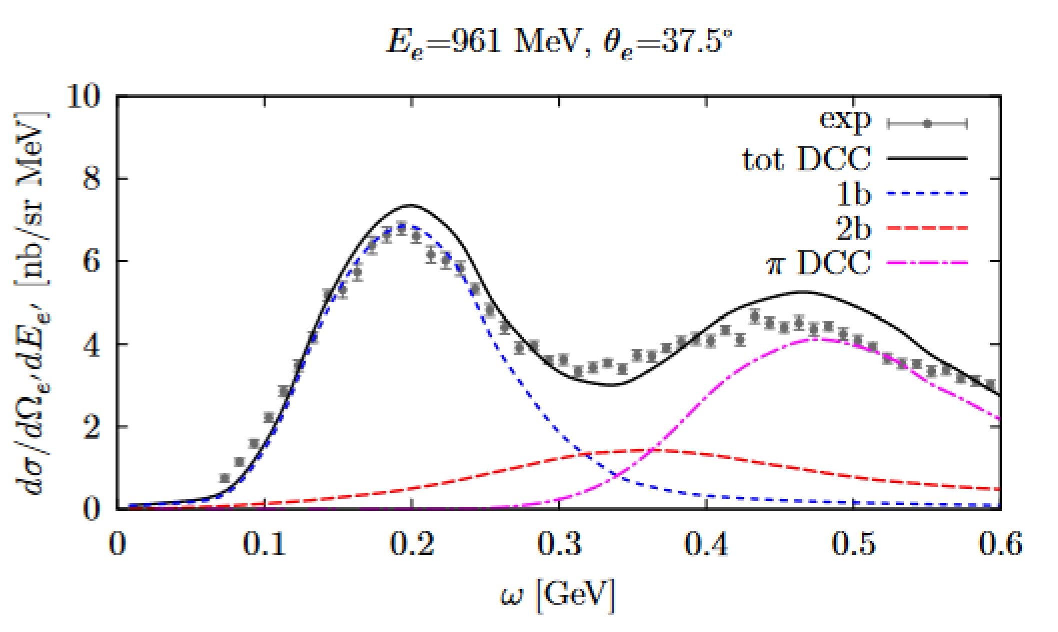
- Major new in GiBUU v2023:
- eA cross sections:

1. Sample nucleon spectral function for points (***p***, *E*) of bound nucleon
2. Lorentz-transform photon to nucleon restframe

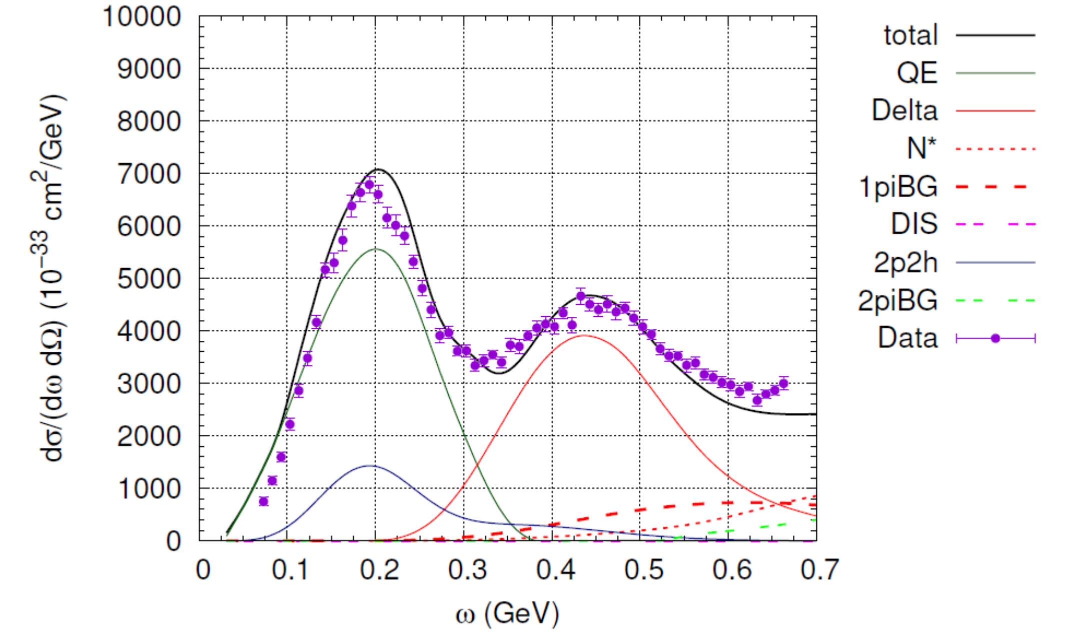
   $(\mathbf{p}, E) \rightarrow (\mathbf{0}, m+U) \rightarrow (\mathbf{q}, \omega) \rightarrow (\mathbf{q}', \omega')$ *with* $Q^2$ *conserved!*

1. Evaluate cross section for nucleon at rest from Bosted-Christy parametrization, neglect binding of nucleon
2. Lorentz boost cross section back to Lab frame
3. MEC contribution taken from Bodek-Christy (2023)

# ‚ab initio‘ vs quasiclassical




Rocco et al, PRC 100 (2019) 6




GiBUU

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



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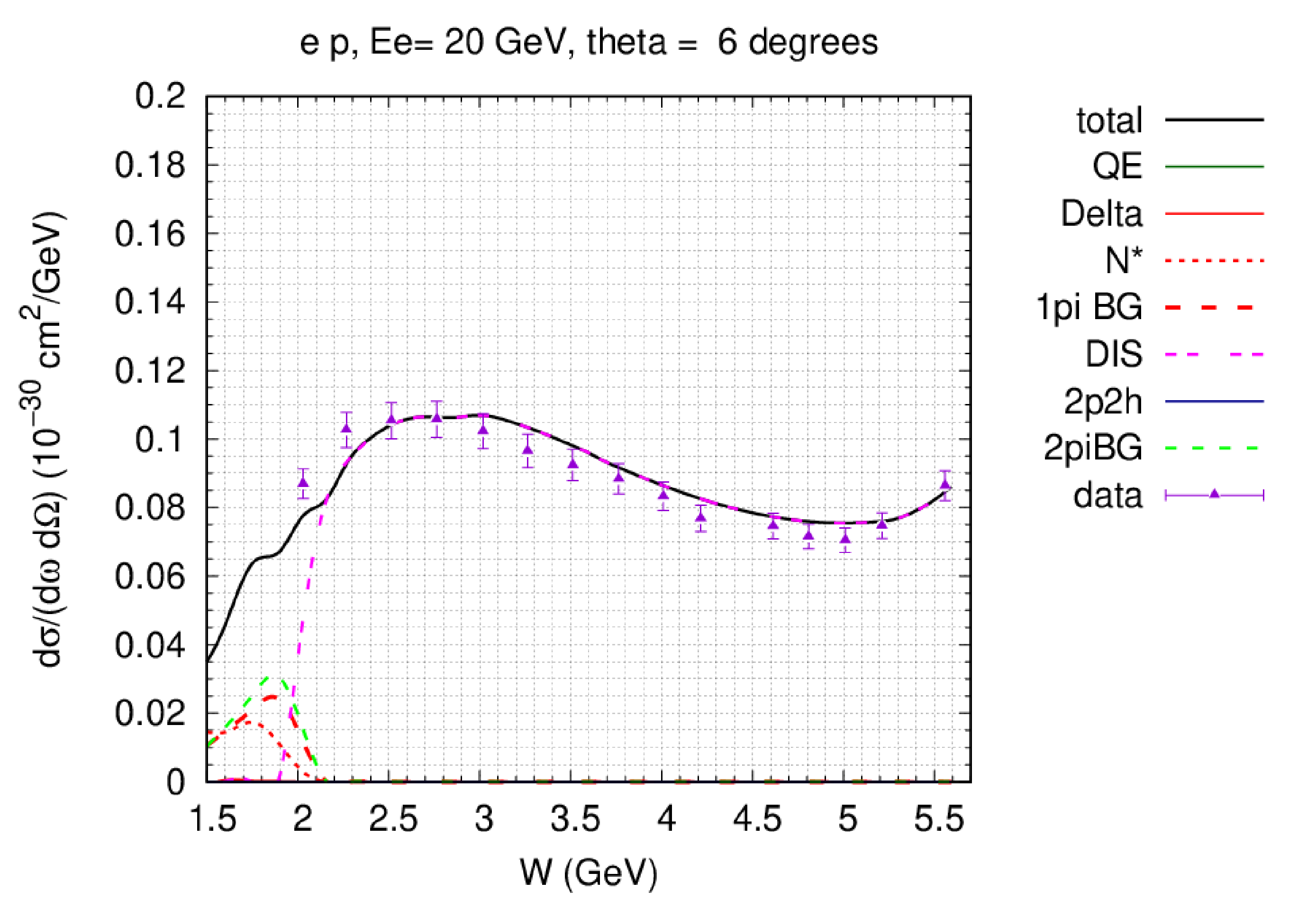
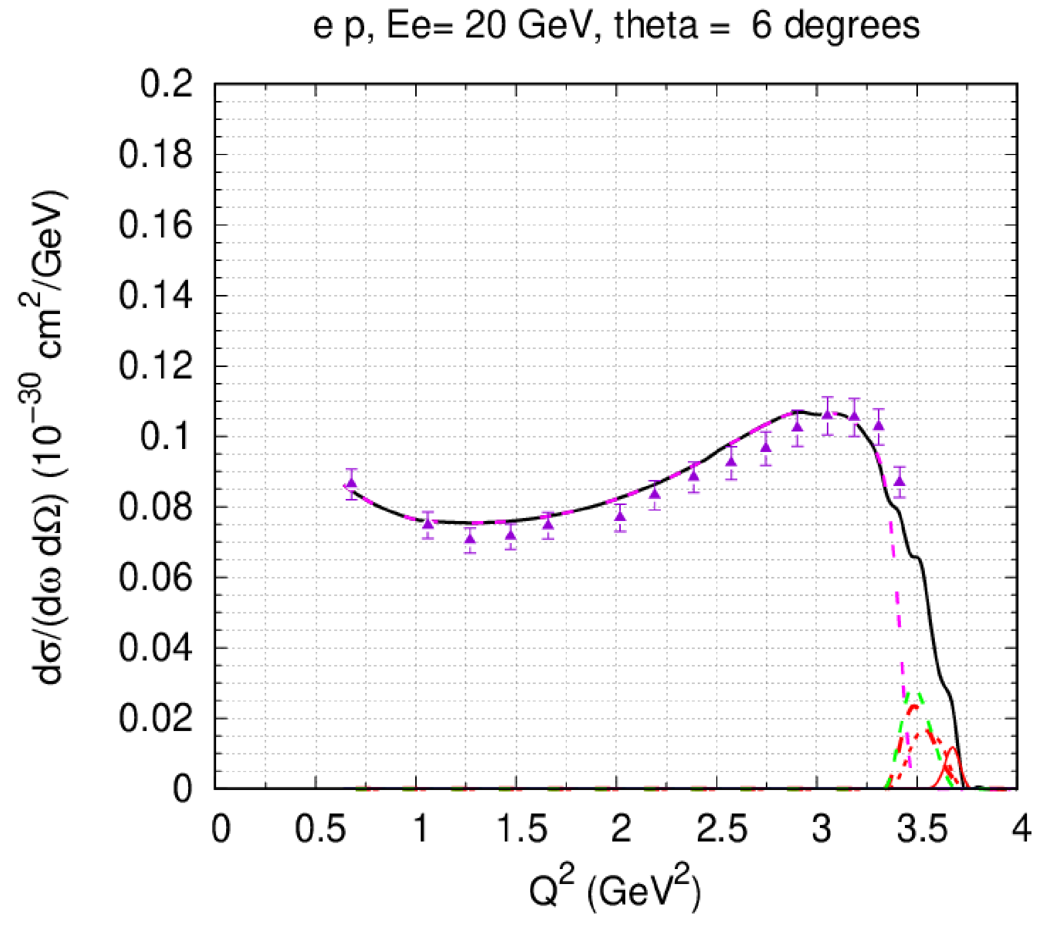
# Electrons: DIS (via PYTHIA)




SLAC Data



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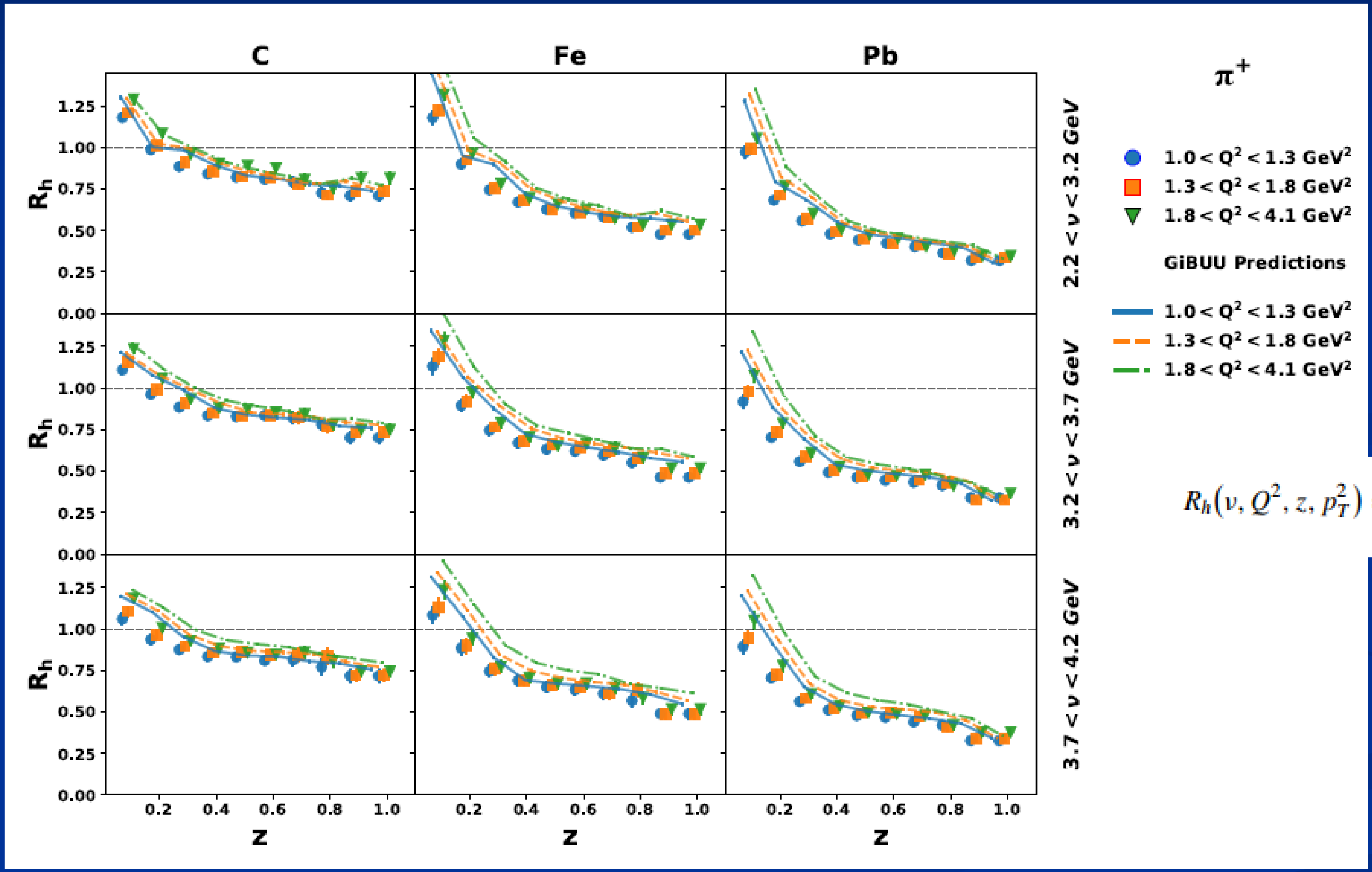
# SIDIS: Pions at 5 GeV@JLAB

Attenuation ratios

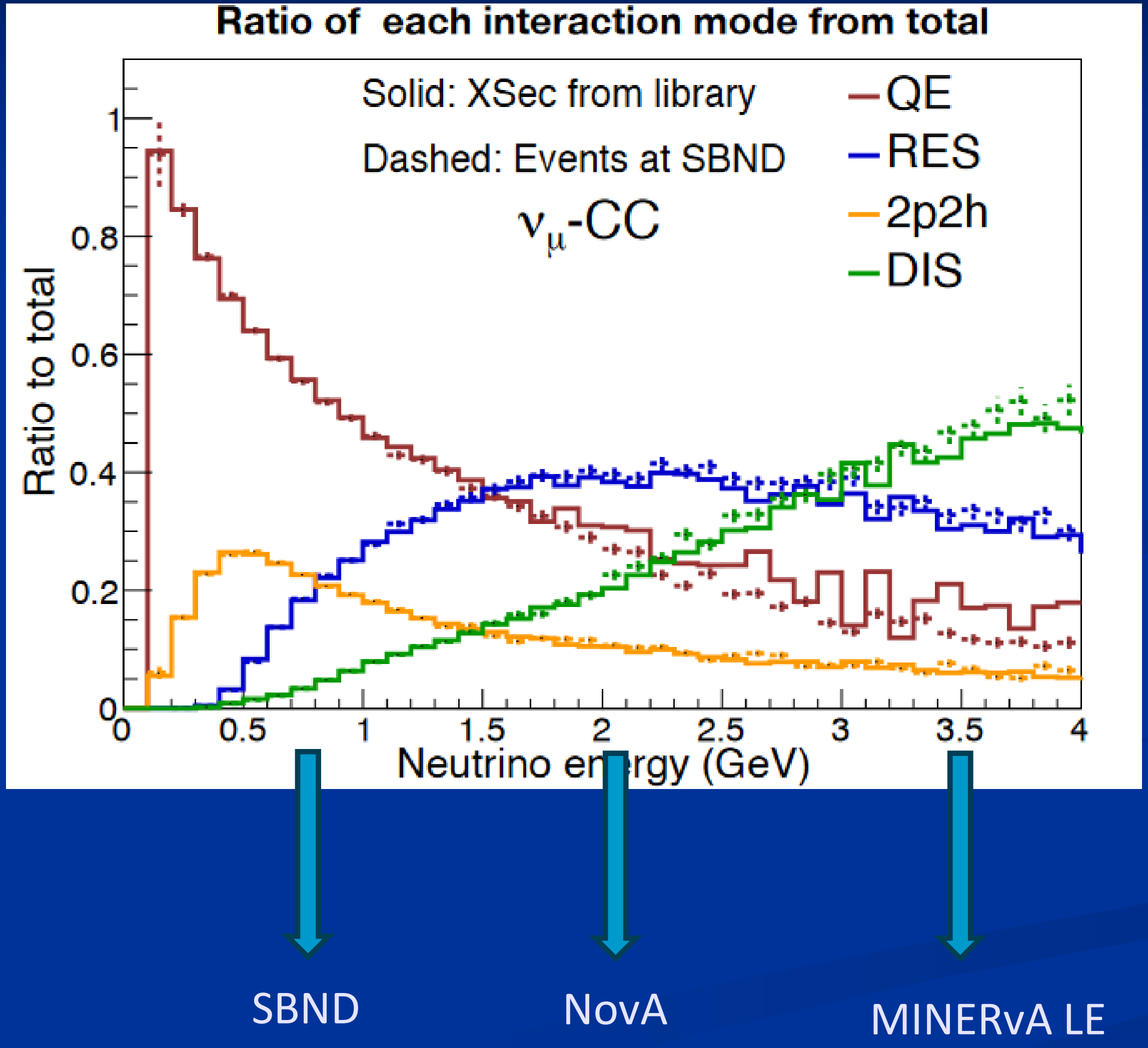



Data:
Moran et al,
*Phys.Rev.C* 105 (2022) 1
Theory:
GiBUU

$$R_h(\nu, Q^2, z, p_T^2) = \frac{N_h^A(\nu, Q^2, z, p_T^2)/N_e^A(\nu, Q^2)}{N_h^D(\nu, Q^2, z, p_T^2)/N_e^D(\nu, Q^2)}.$$

$z = E_\pi/\nu$

# Neutrino Reaction Types (from GiBUU)




From:
Leo Aliaga

# Electron -> Neutrino Transition

- ‚Transform' the structure functions:

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

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

$V^2 + A^2$

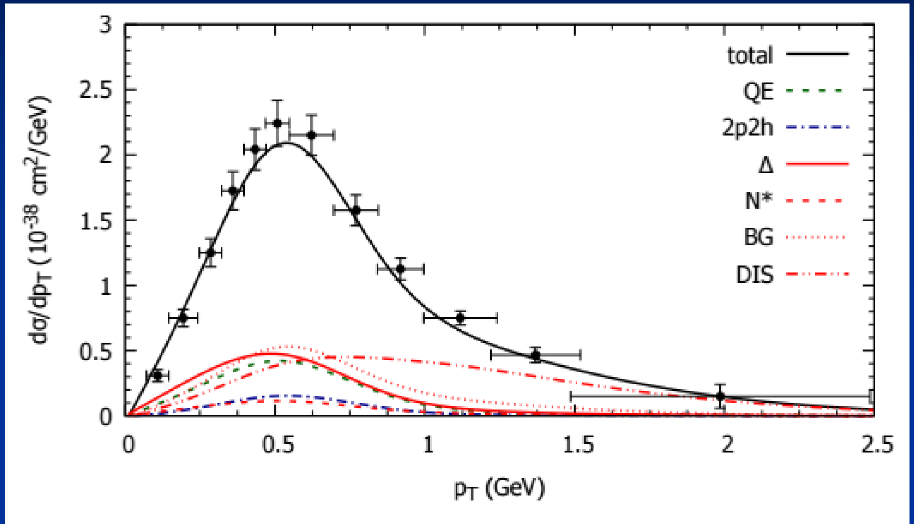
V A

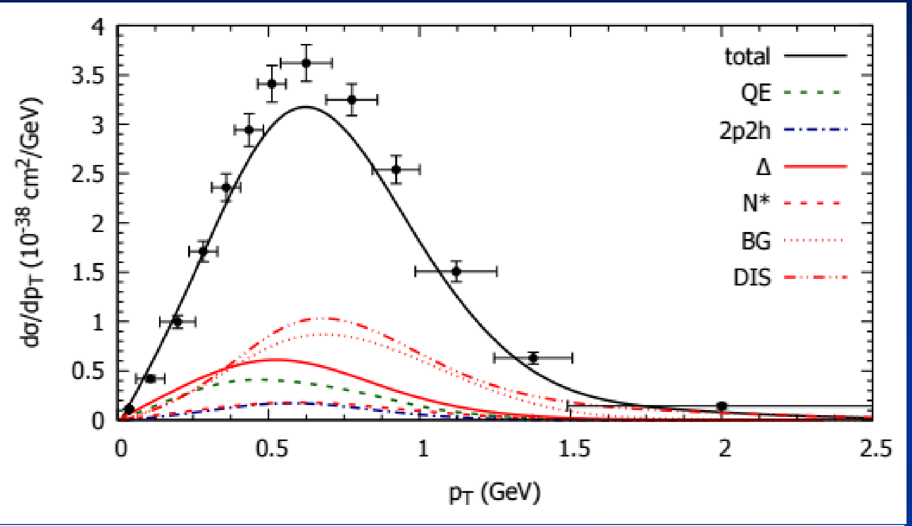
D. Walecka, 1975

The kinematical factor *2m/q* appears in the relation between vector and axial sp current
Relations derived for single particle model, assume to be good in general
Note: W3 is determined by W_1 → neutrino vs antineutrino X-section provides crucial test

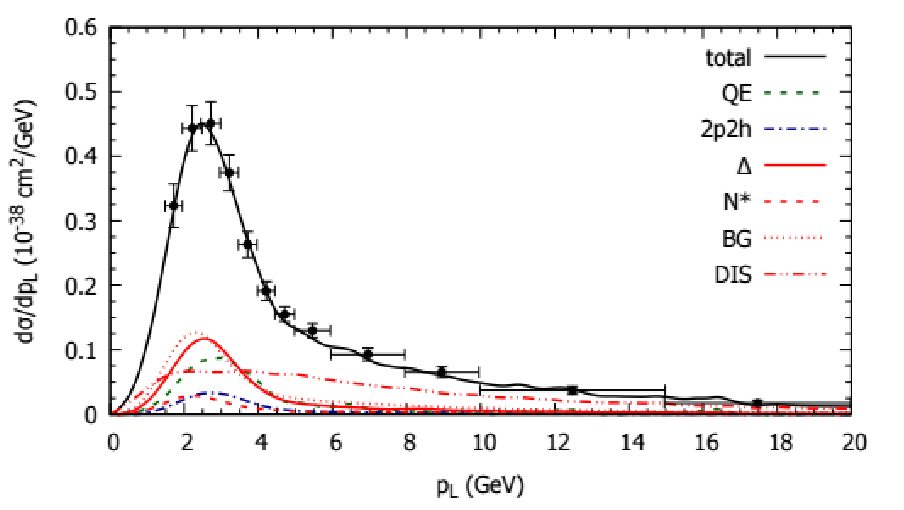
# MINERvA incl X-sections

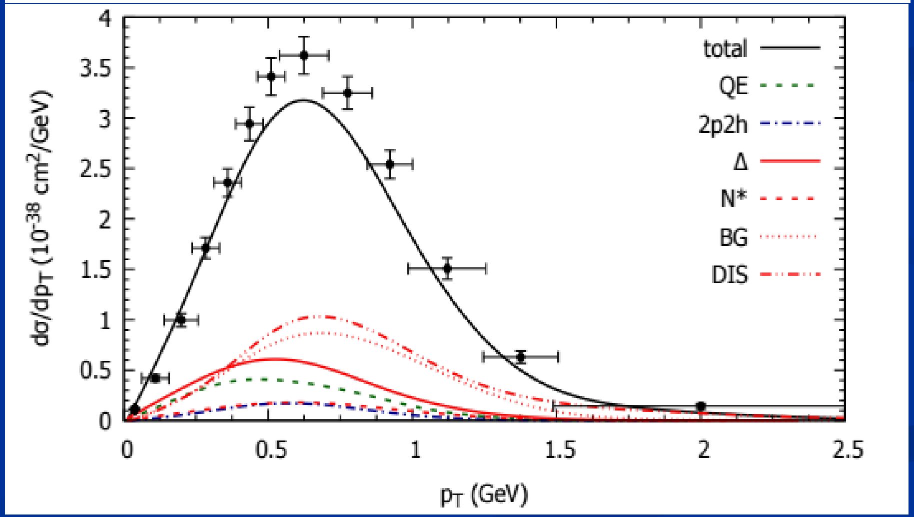
LE



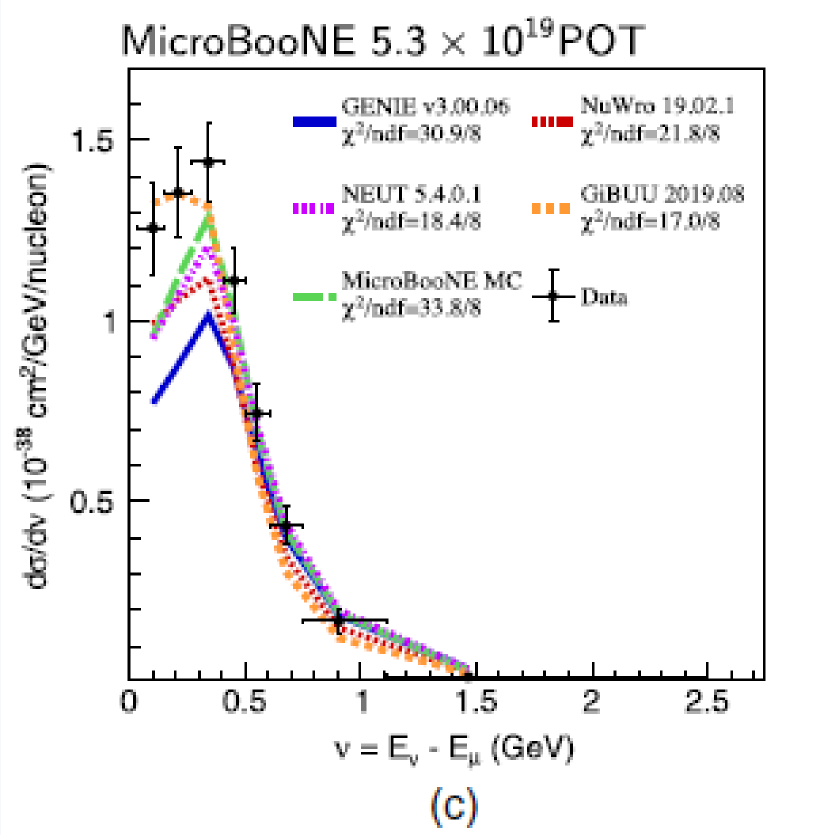




ME

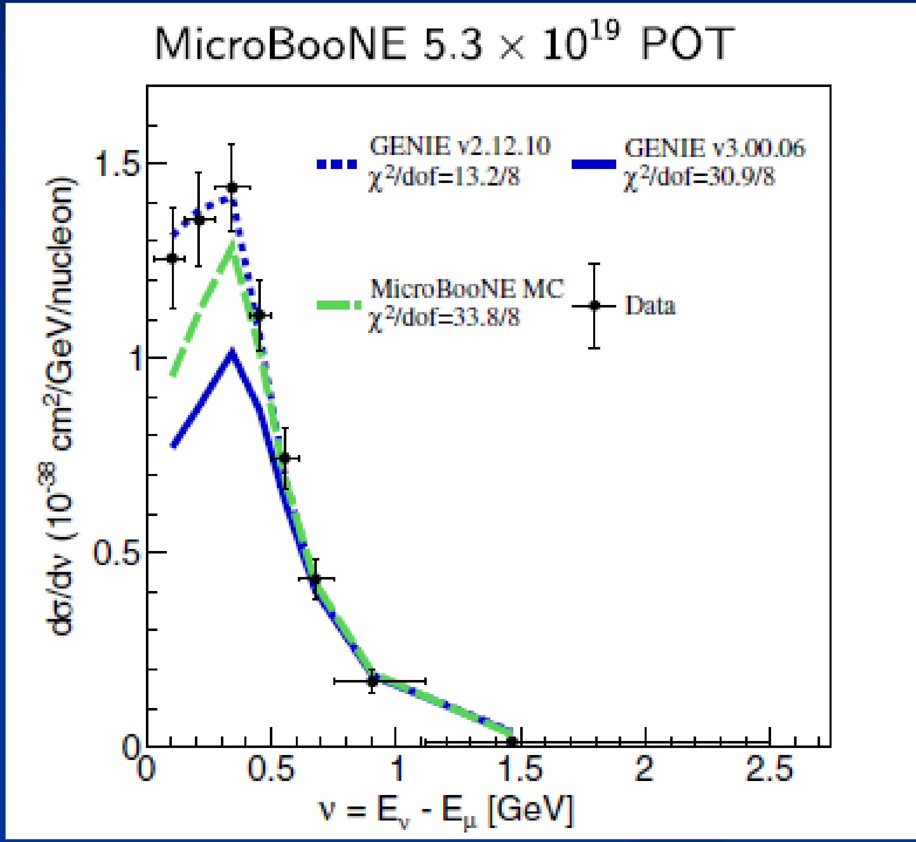


# MicroBooNE comparisons: inclusive




Abratenko et al, PRL 128 (2022)

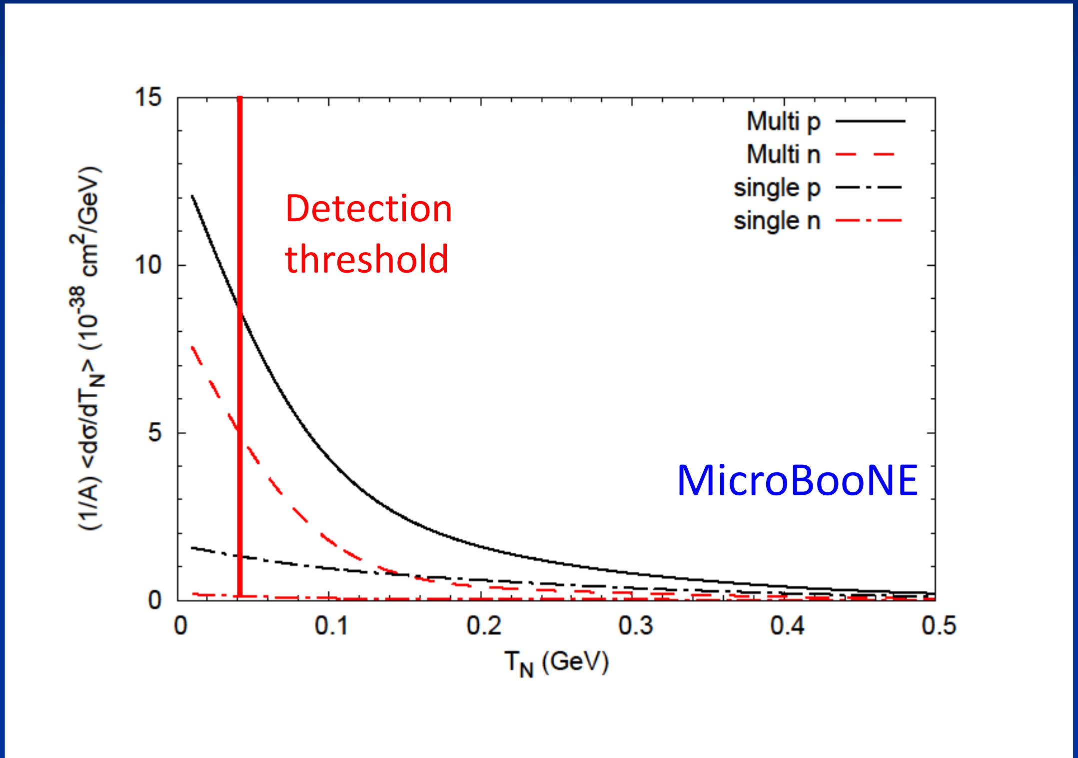


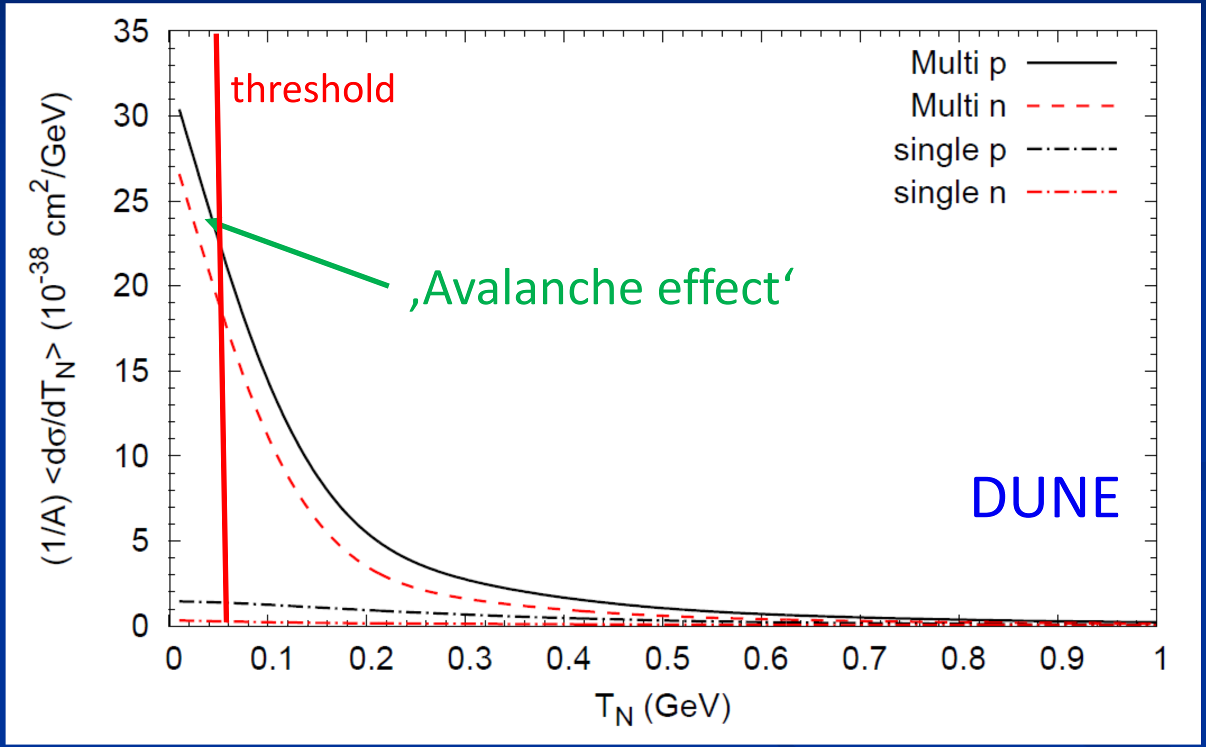

Abratenko et al, PRD 105 (2022)

Nothing tuned in GiBUU

Various tunes in GENIE

# Nucleon Spectra




At MB *n* < *p* , at DUNE *n* ~ *p*:

*n* not suppressed at DUNE because of pi-production channels



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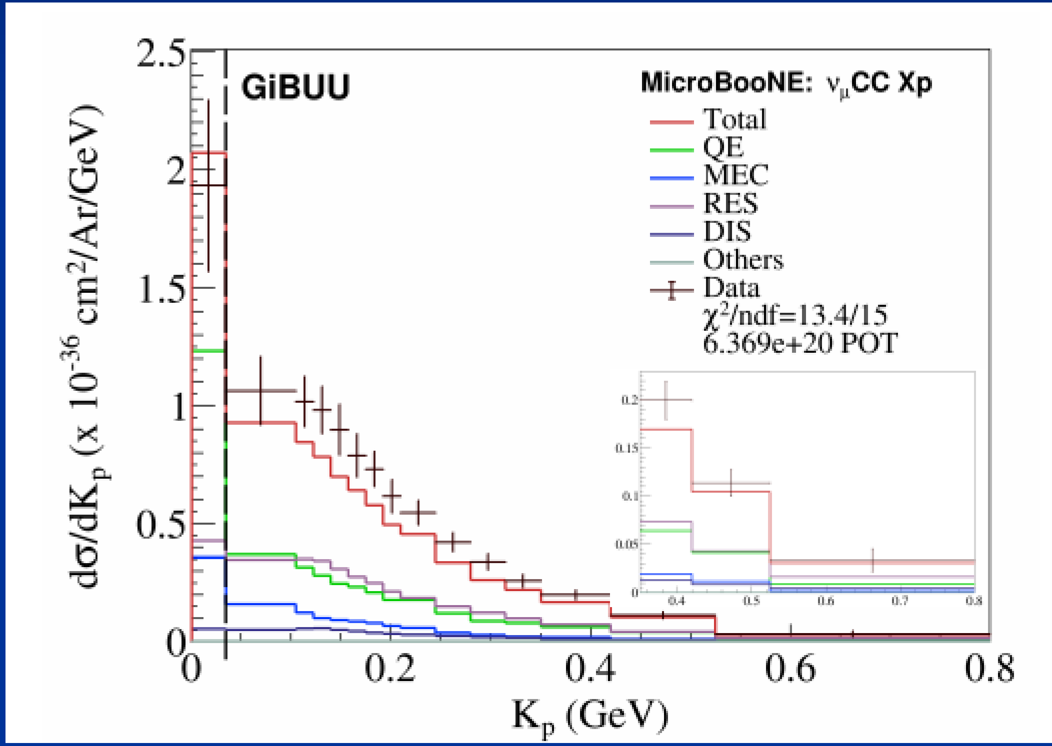
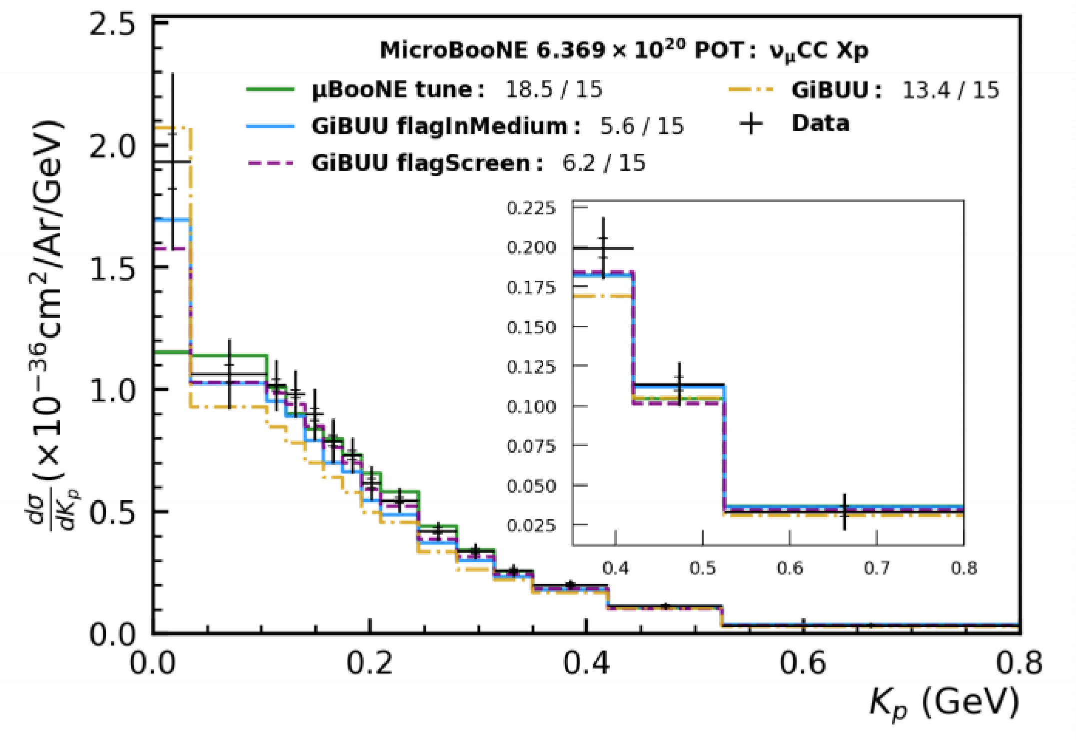
# MicroBooNE comparisons: exclusive

Abratenko et al, arXiv:2402.1216 (2024)




Free NN X-sections

From: Benjamin Bogart, U Mich




In-medium NN X-sections from relativistic Brueckner HF, Li and Machleidt and Song and Ko

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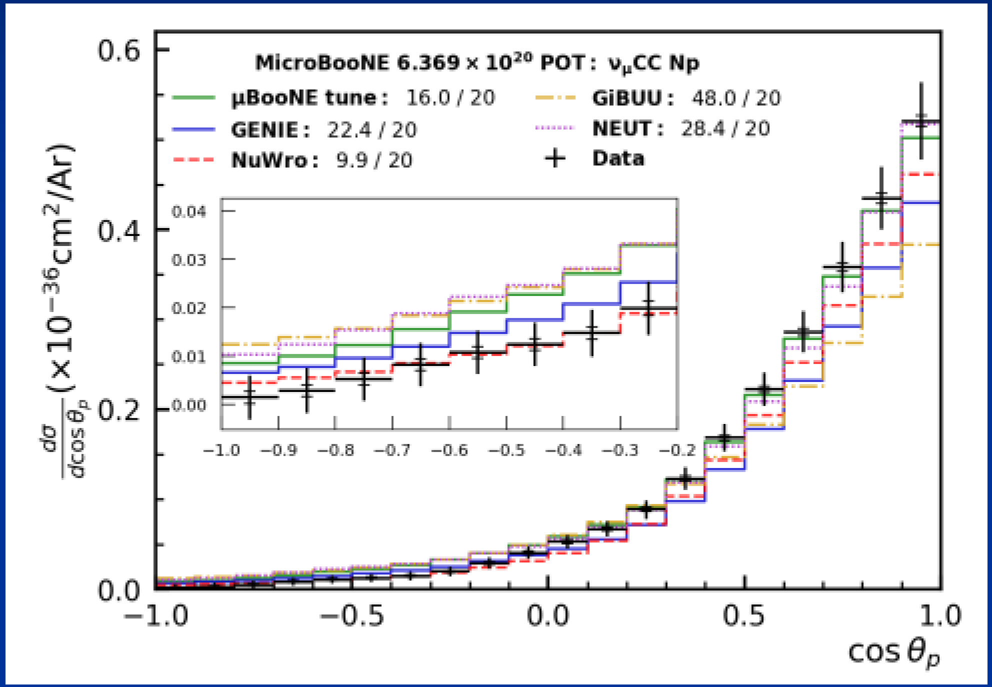
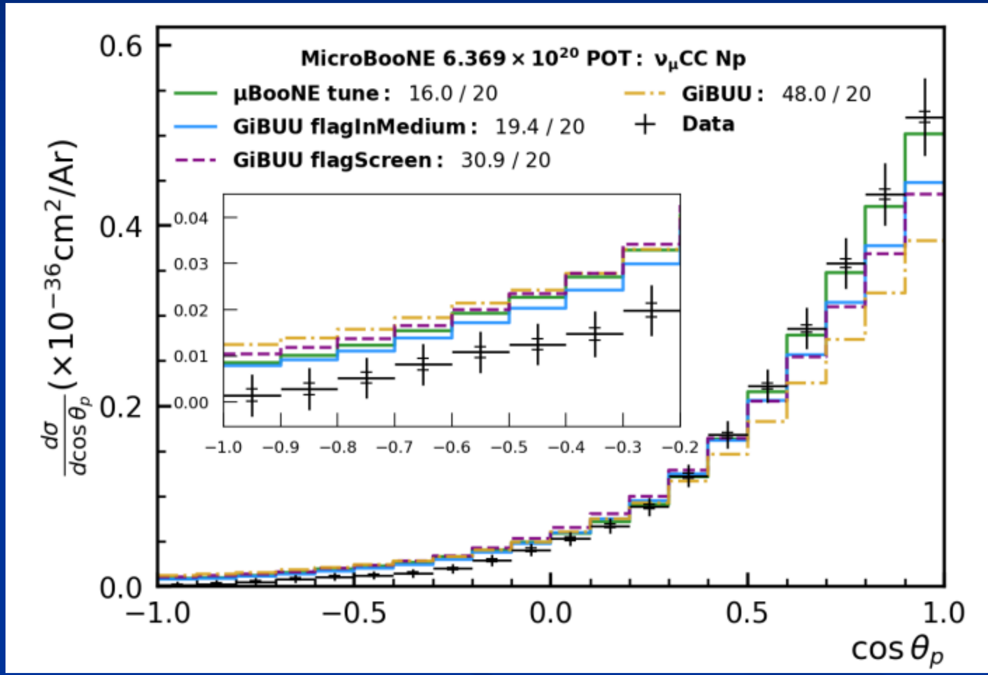
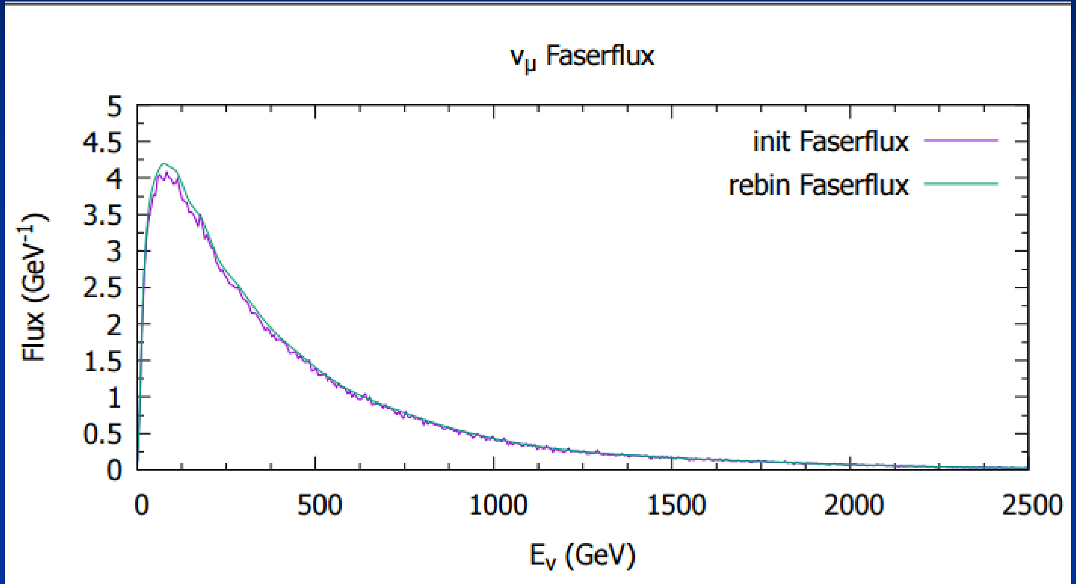


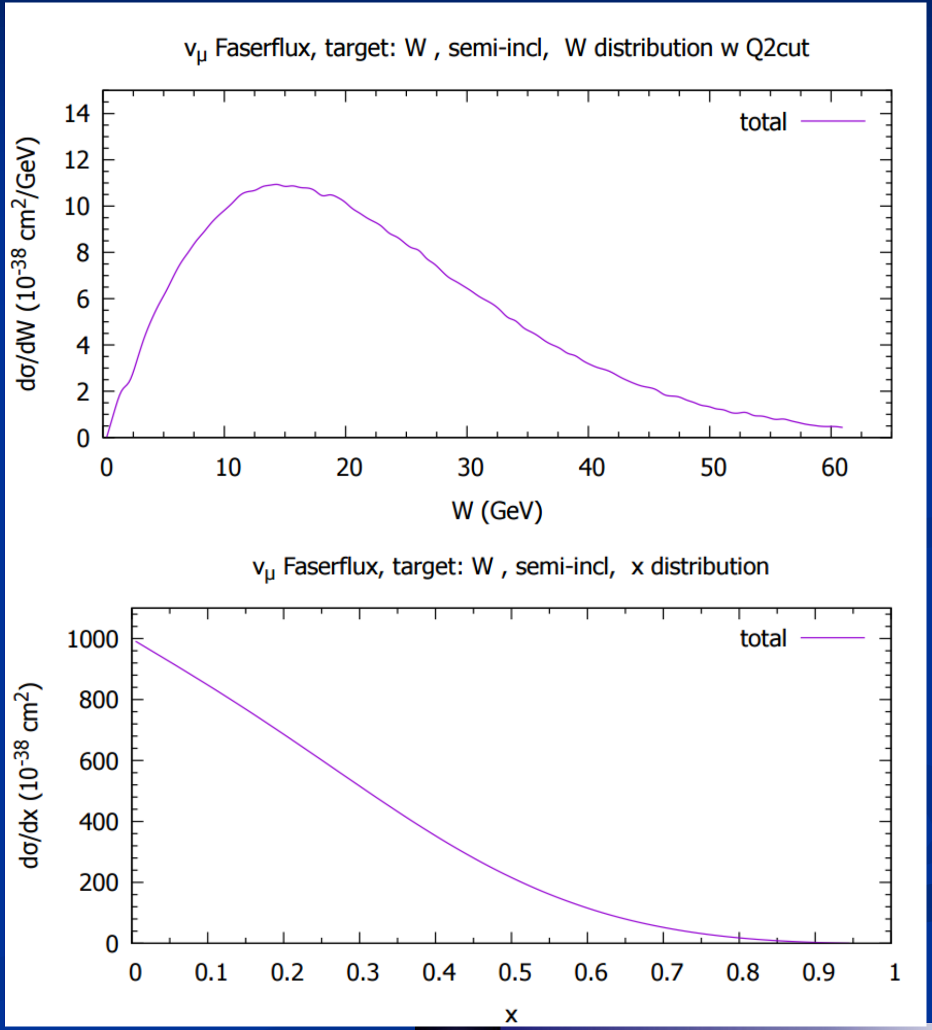

Free NN X-sections




In-medium NN X-sections from relativistic Brueckner HF, Li and Machleidt and Song and Ko

# FASER@CERN

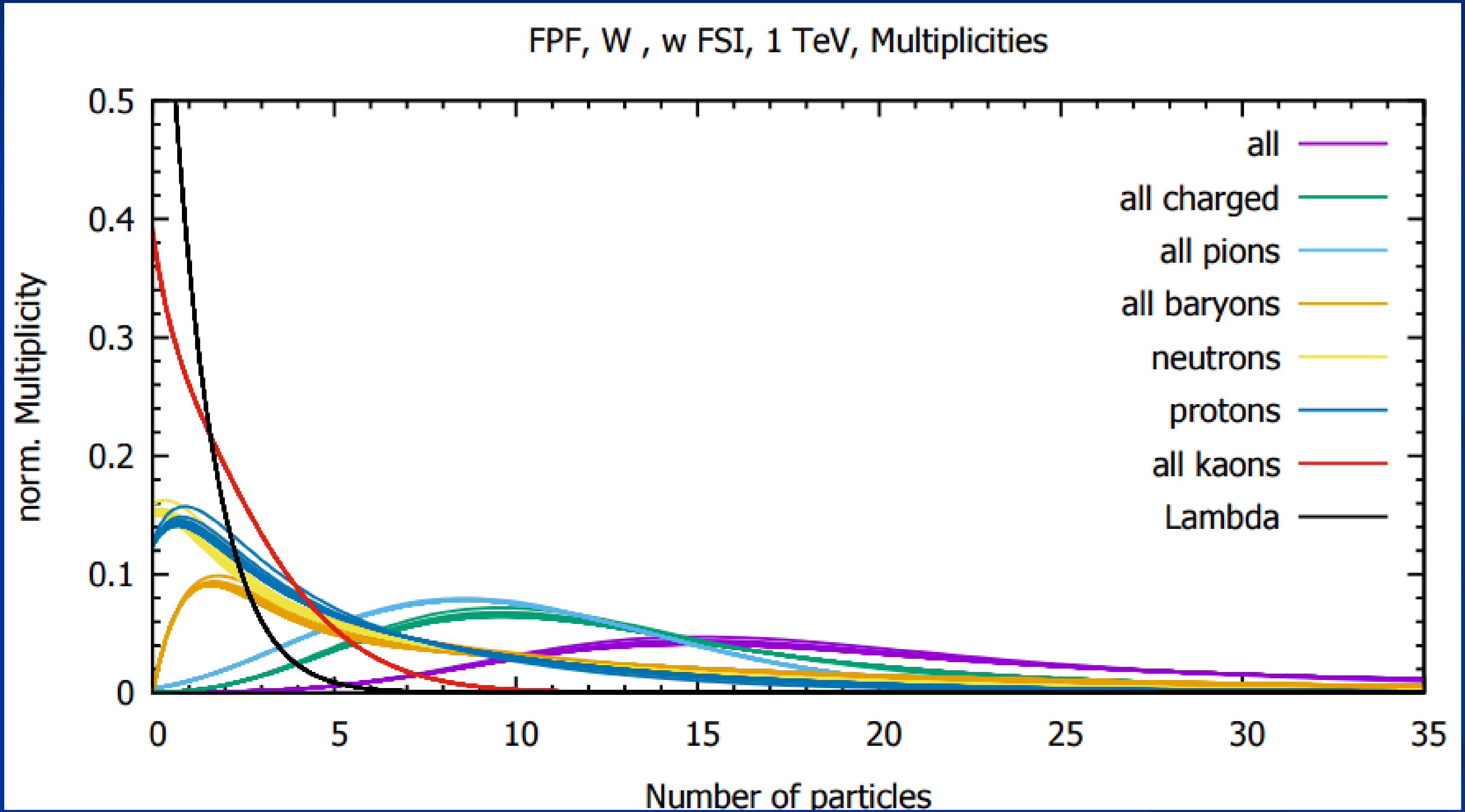



Problem at FASER/FPF energies: very large energy transfer to nucleus, large enough to destroy it

→ standard FSI treatment with fixed target no longer good, GiBUU has that built in (but so far never tested for neutrinos).

# Particle Multiplicities at 1 TeV



# Summary

- Treatment of (e, A) reactions has undergone a major reformulation, new method conserves $Q^2$ → Transition to real photons now ok.
- Neutrino background terms directly linked to electron background
- Methods works for electrons, neutrinos over a wide range of kinematics
- Now need more data on semi-exclusive final states
  → quantum-kinetic transport theory is THE method of choice.

# Supplemental Material

# GiBUU Documentation

- Mandatory Reading:
  - T. Leitner, U of Giessen thesis, 2009, https://inspirehep.net/literature/849921
  - O. Buss et al., https://inspirehep.net/literature/912923
  - K. Gallmeister et al, https://inspirehep.net/literature/1466434
  - U. Mosel et al, https://inspirehep.net/literature/2691872
- Plus:
  - Extended infos on gibuu.hepforge.org

# Generators describe $\nu$A 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



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# 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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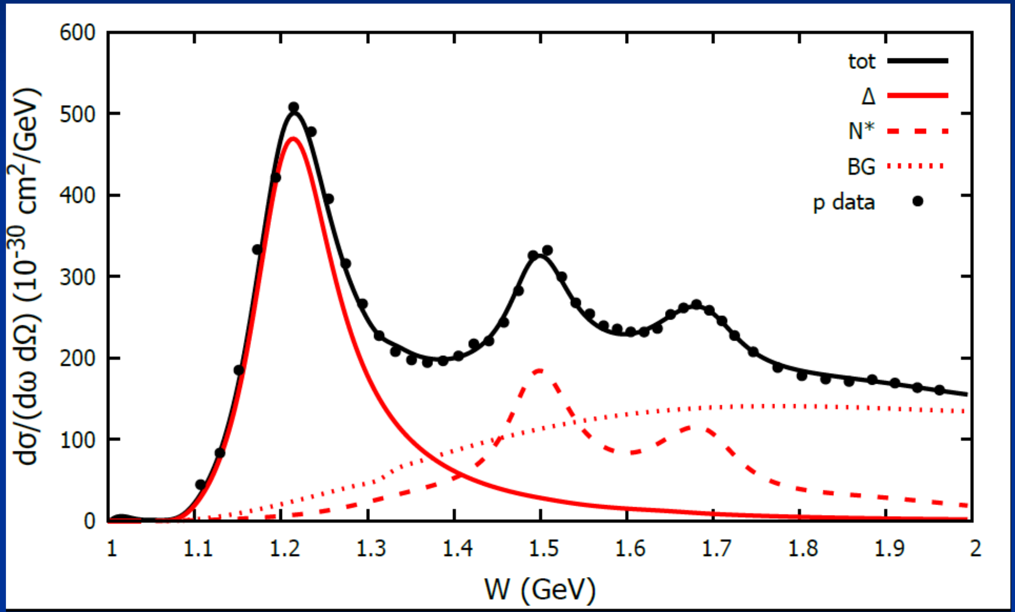
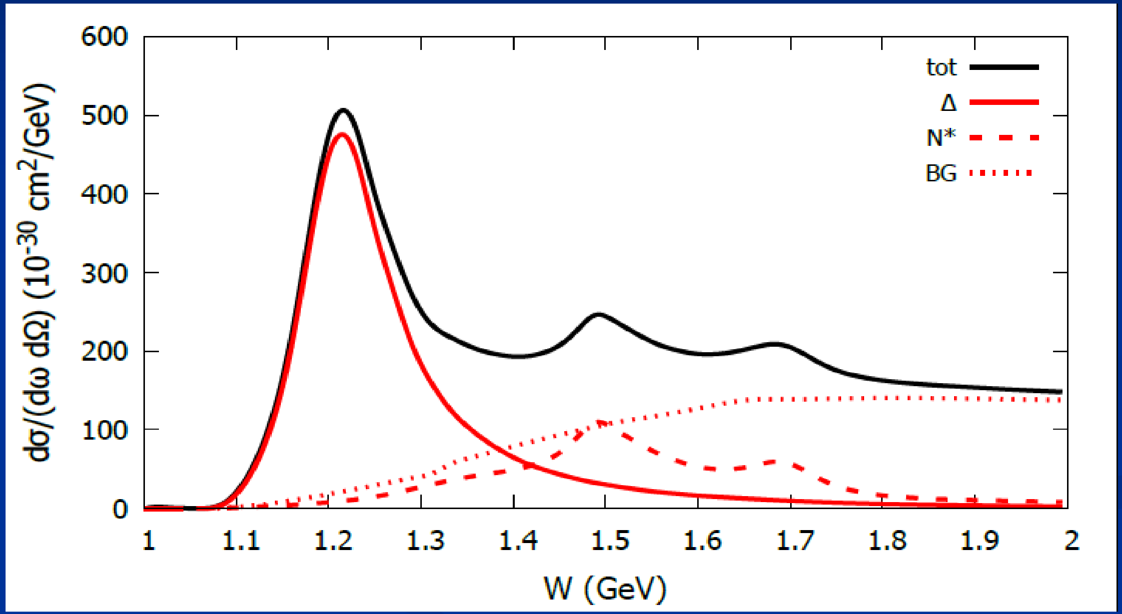
# Electrons as Test

E = 2.239 GeV, 21.95 deg




e-proton




e-neutron

Bosted-Christy Fit

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

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

GiBUU: only 1 pi and 2 pi final channels for W < 2 GeV

# Spectral Functions

- Spectral functions from NMBT have a problem in applications beyond gs calculations:
  - Even QE is sensitive to final state potential (Rosenfelder (1980), 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)

# 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*

# 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 skip #2 (e.g. Achilles, …) violate energy conservation!

# 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.



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# 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

# Uncertainty Remarks

- 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.