GiBUU: Theory and Generator

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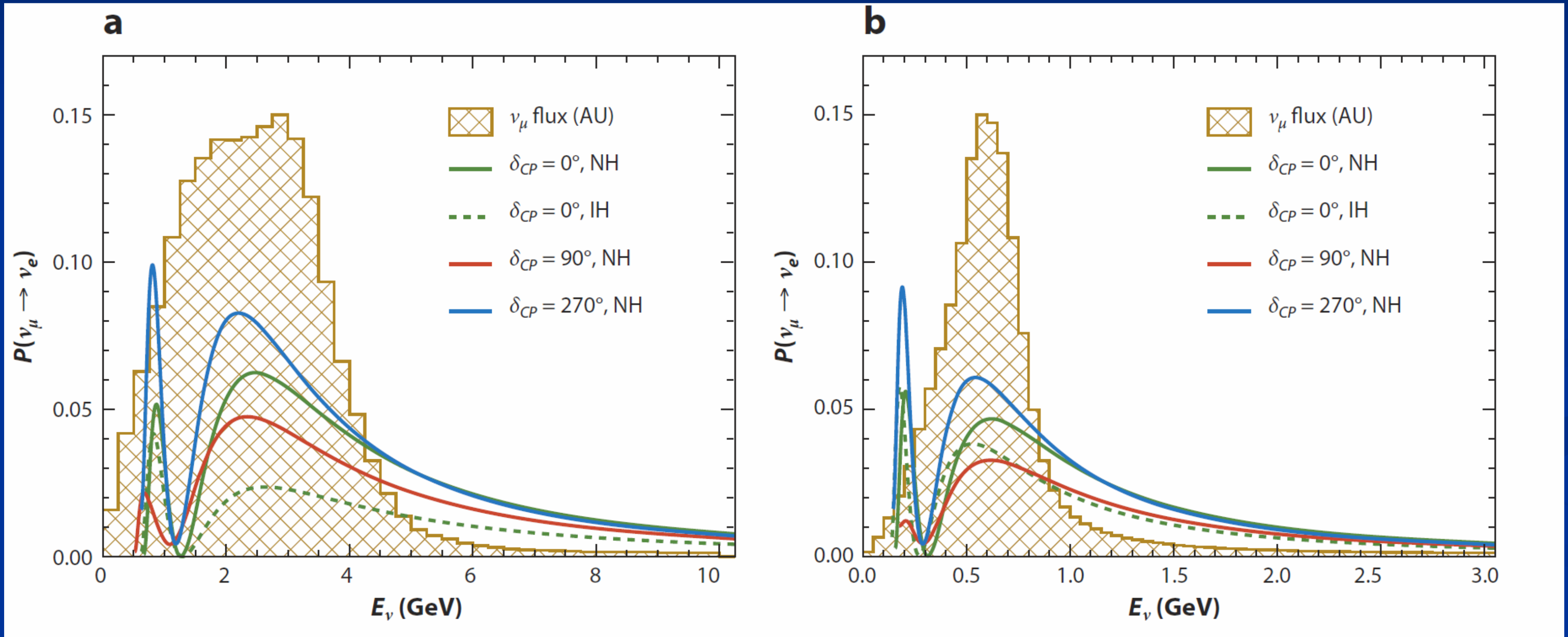
KIT 11/2023

Oscillation Signals as F(E_ν)



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

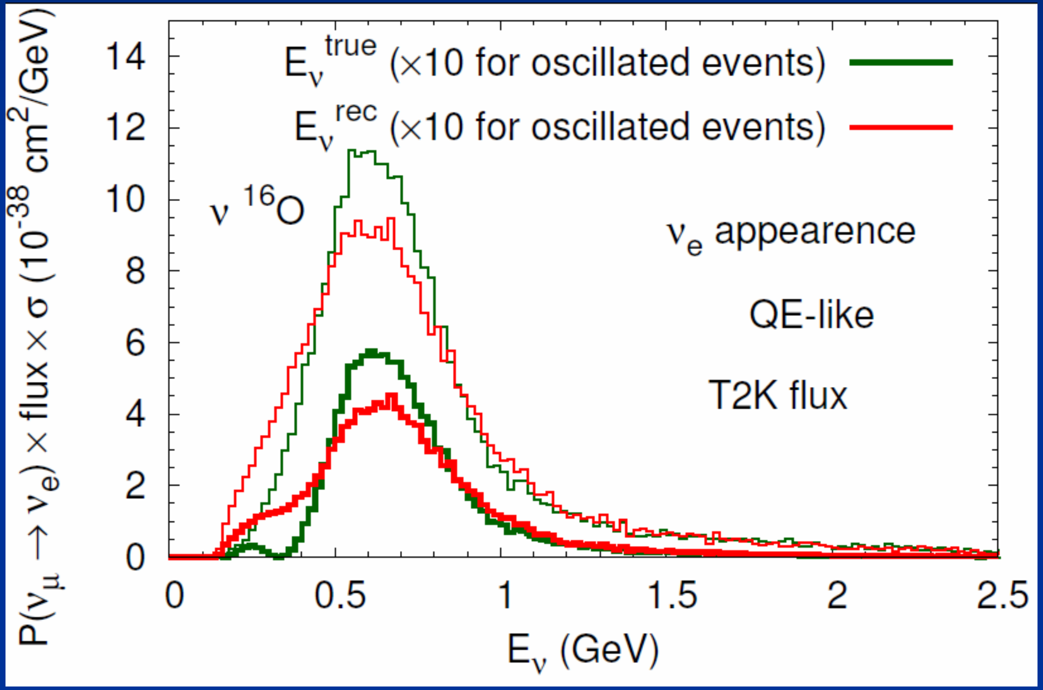
DUNE, 1300 km **HyperK (T2K) 295 km**

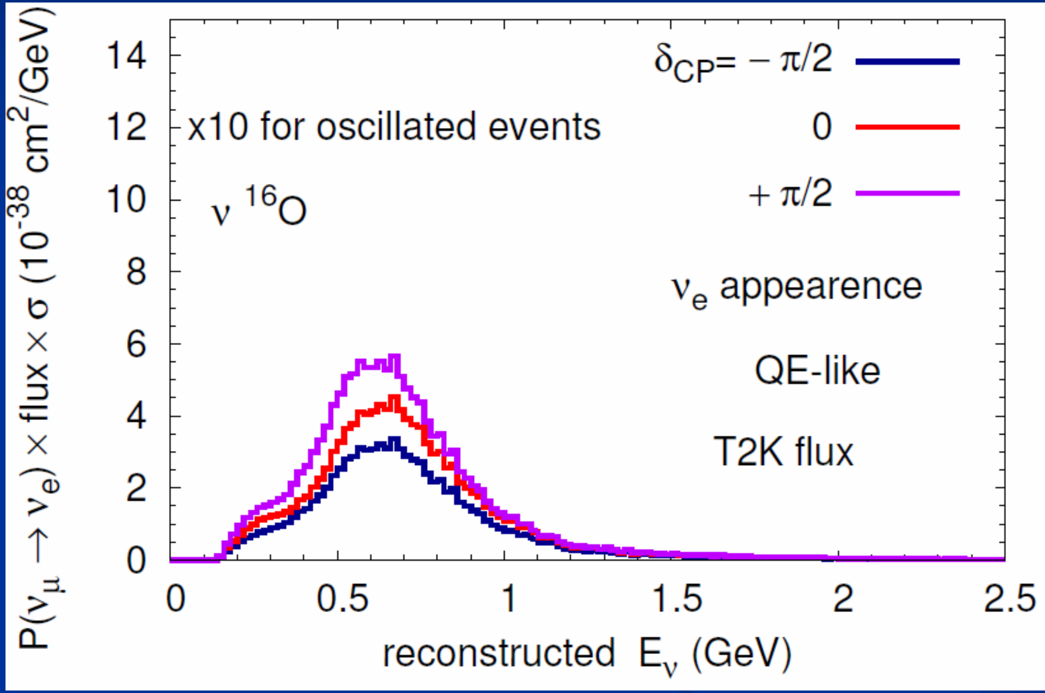
Energies have to be known within 100 MeV (DUNE) or 50 MeV (T2K)

Ratios of event rates to about 10%

Oscillation signal in T2K

δ_{CP} sensitivity of appearance exps





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

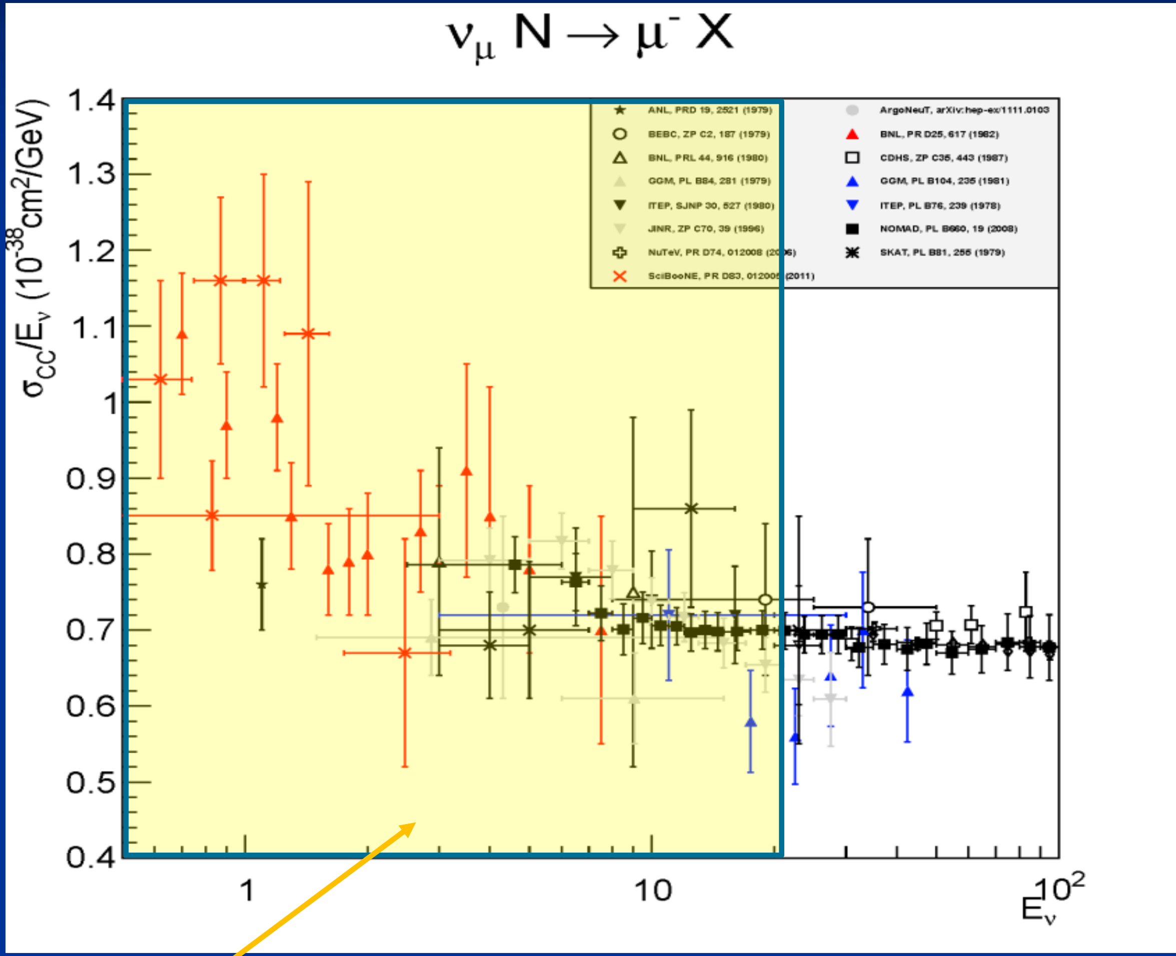
Reconstruction error
as large as δ_{CP} dependence

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 (**targets are nuclei**):
  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

Neutrino-Nucleon Cross Sections



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

All modern long-baseline experiments

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- Generators use outdated physics: e.g.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

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νA reaction needs reliable FSI description

Simplicity

- Kadanoff-Baym equation (1960s)
  - full equation not (yet) feasible for real world problems
- Boltzmann-Uehling-Uhlenbeck (BUU) models (1990): GiBUU
  - Boltzmann equation as gradient expansion of Kadanoff-Baym equations, in Botermans-Malfliet representation (1990s) with off-shell transport
- Cascade models (1970 ->)
  (typical event generators, GENIE, NEUT, NuWro, …)
  - Nuclei not bound, no mean-fields, primary interactions and FSI not consistent, frozen nuclear configuration, ….
- Purely absorptive Cascade: Glauber

Correctness

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Institut für Theoretische Physik, JLU Giessen

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 available from gibuu.hepforge.org, new version GiBUU 2023

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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*

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

- *Code Applications:*
  - A+A (~ 1990) up to 10 – 20 AGeV
  - hadron+A (p+A, π+A) (~ 1995) up to 20 GeV
  - γ+A (~ 1998) up to 1 GeV
  - e+A (~ 2000 -) up to 300 GeV (energy transfer > 50 MeV)
  - ν+A (~ 2005 -) up to 1 TeV (energy transfer > 50 MeV)

Widely tested

Giessen Model: Theory and Generator

- Initial State Interactions
  - Nucleons are bound in a momentum-dep mean-field potential
  - Treats all ISI processes: QE, RES, 2p2h, DIS
    (switch to DIS = PYTHIA at W ~ 2 - 3 GeV)
  - Contains large number of explicit N* resonances and mesons, up to charm

- Final State Interactions
  - Contains elastic and inelastic FSI, tries to respect time-reversal invariance
  - Fully relativistic transport in potential, trajectories numerically integrated
  - Relativistically correct collision criteria for FSI
  - Allows for off-shell transport of broad spectral functions
  - Contains modeling of color transparency, formation times
- ISI and FSI are both parts of the transport theory!!

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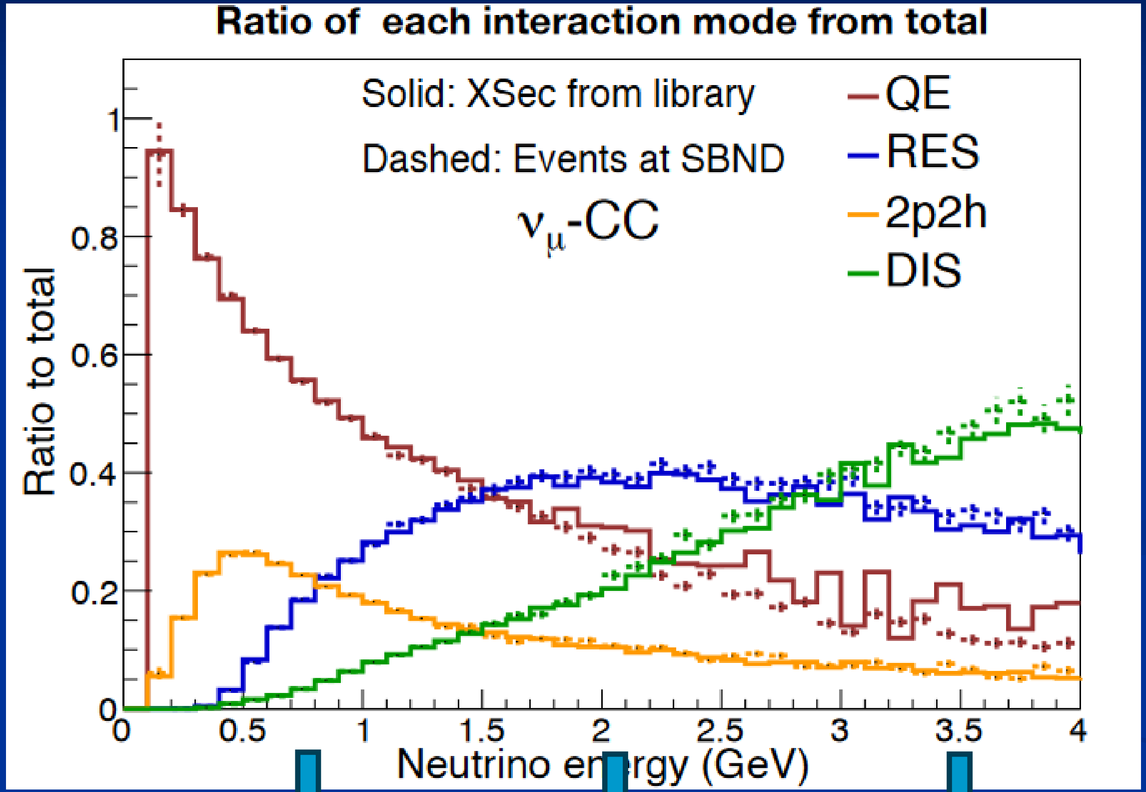
Reaction Types (from GiBUU)



From:
Leo Aliaga
(UT Arlington

SBND

NovA

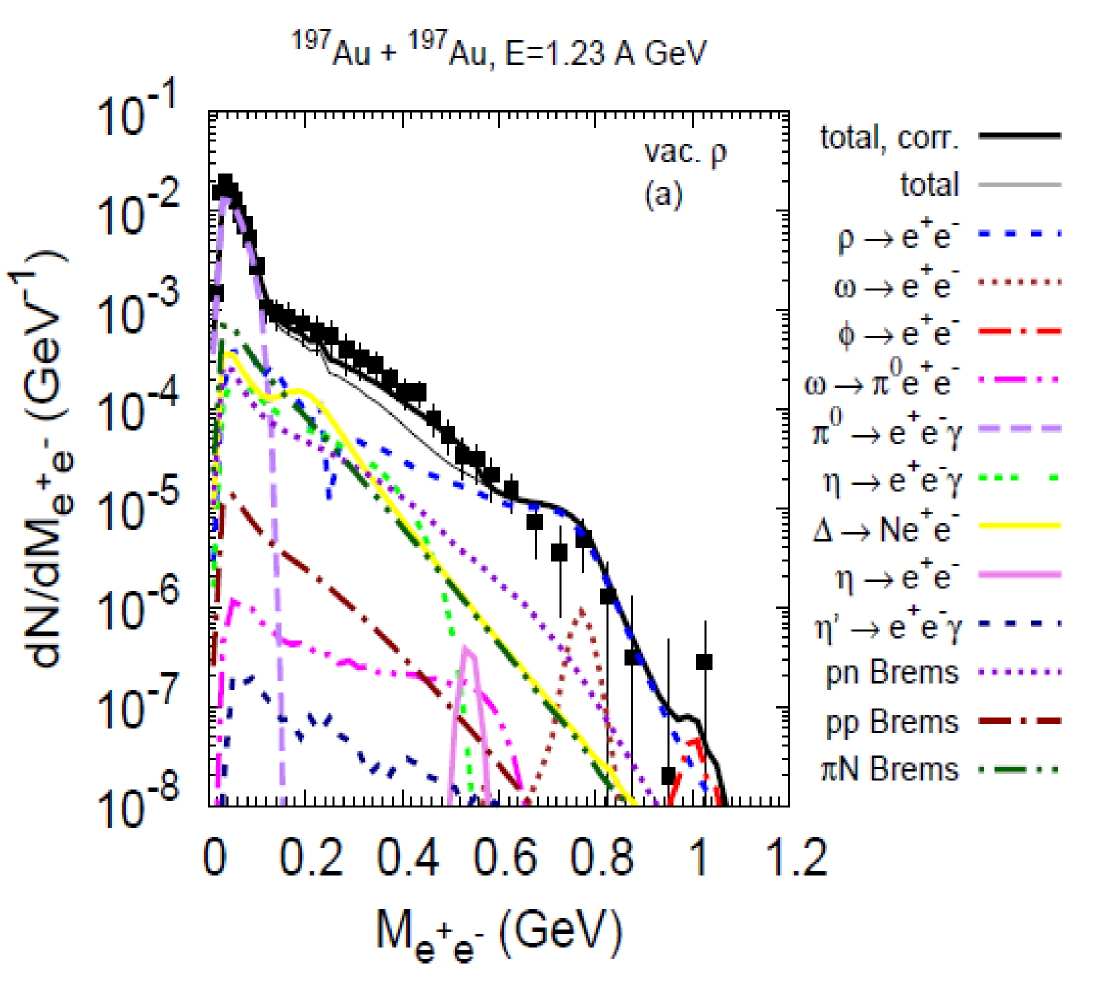
MiNERvA LE

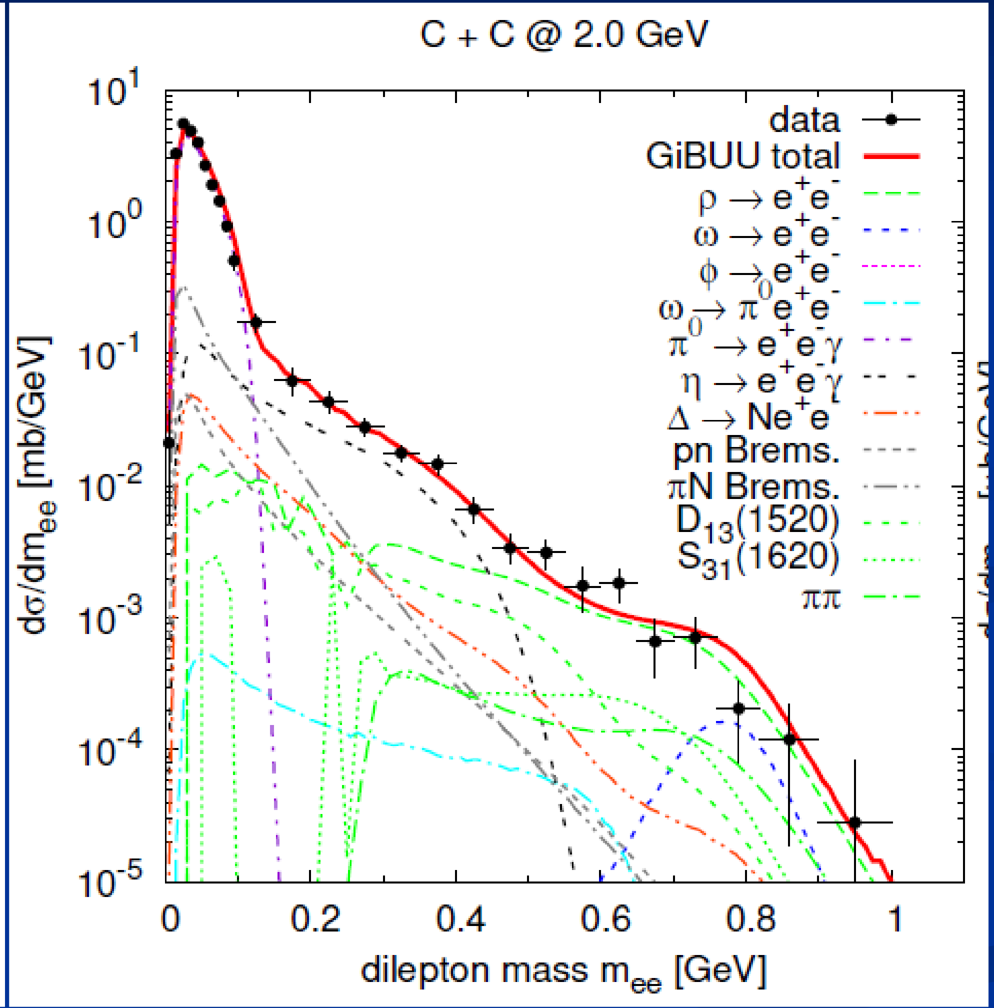
A wake-up call for the high-energy physics community:

Cartoon by S. Harris

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

Timelike photon (= dilepton) production



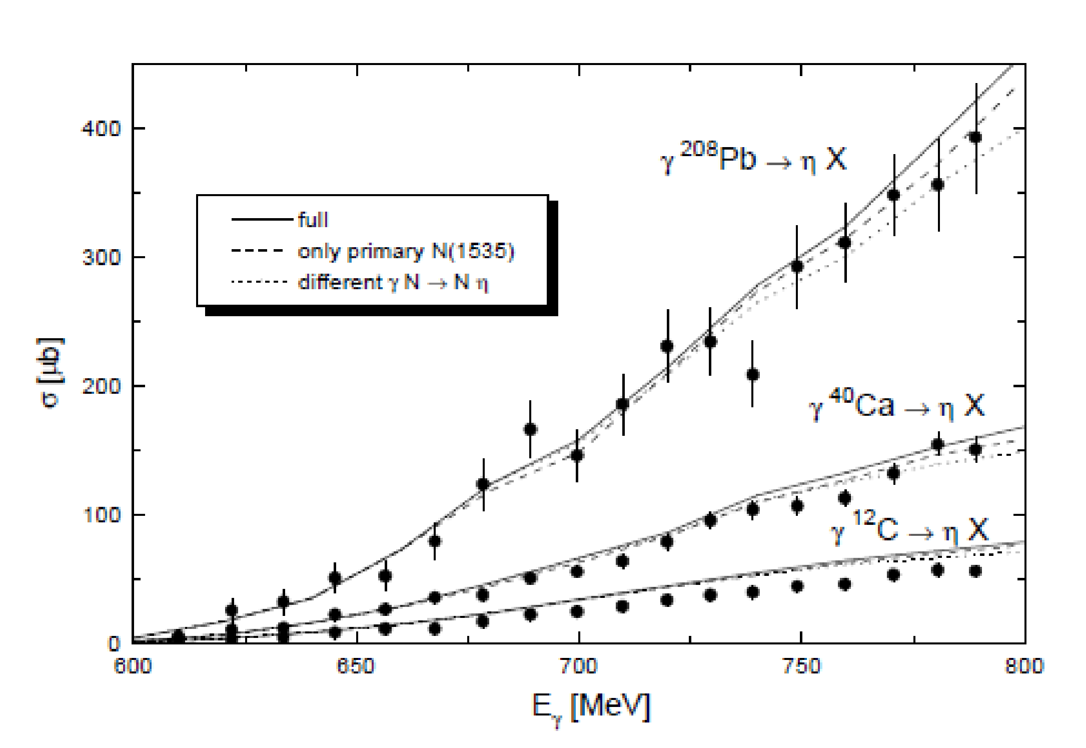


Data: HADES,
Theory:
Larionov et al, 2021

Many very different sources of dileptons, a multitude of elementary processes, described by GiBUU

Dilepton spectrum in the HADES experiment: Test for many final state processes

Electromagnetic Processes



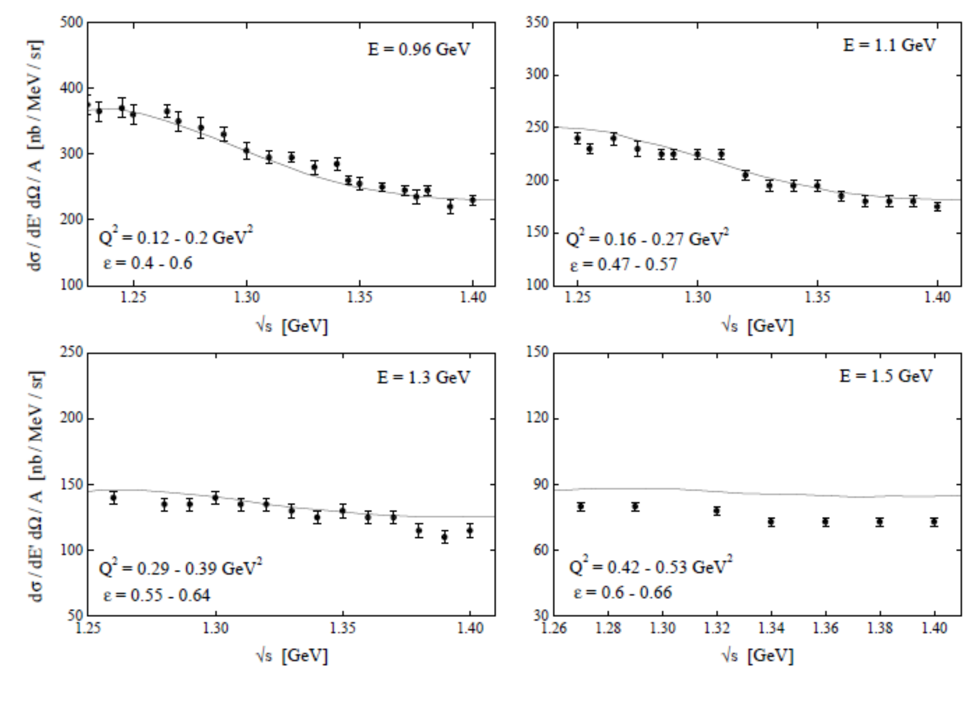


Figure 8: Cross section of the reaction $e^{12}C \to e'X$ measured at $\vartheta = 37.5°$

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

γA

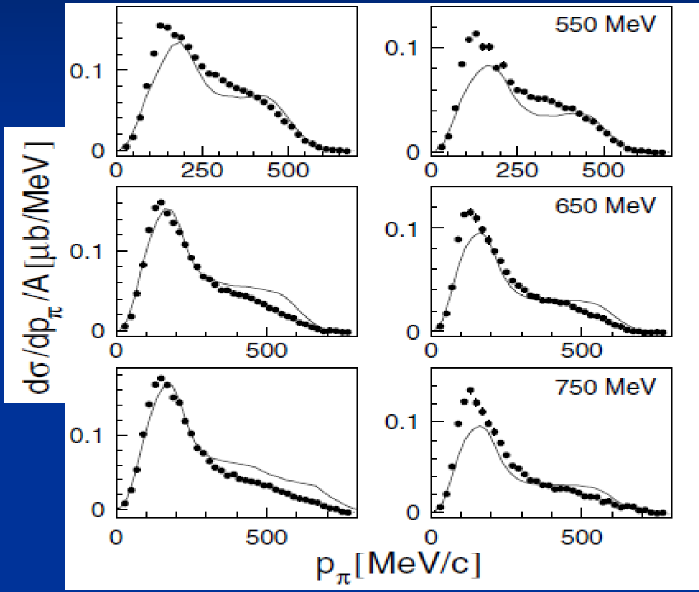
Theory: Lehr et al, 1999
Data: Sealock et al

eA

Check: pions, protons

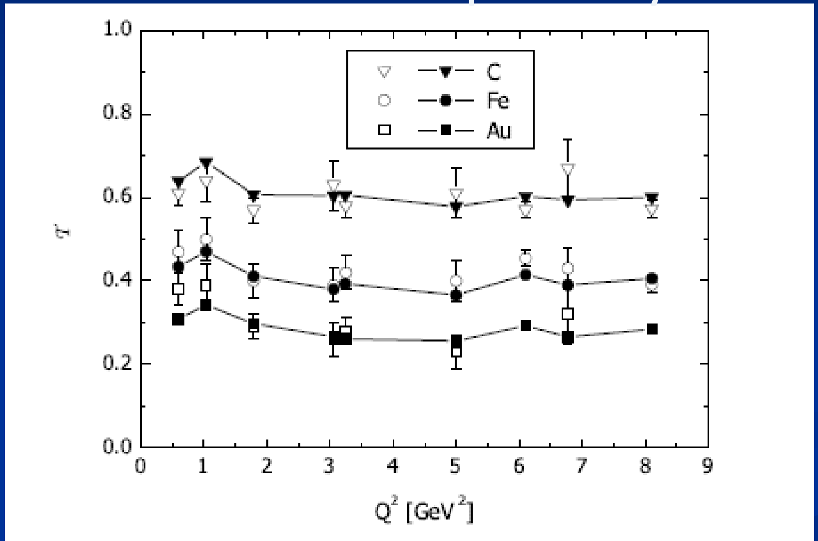
(Leitner et al, https://inspirehep.net/literature/819969 (2009))

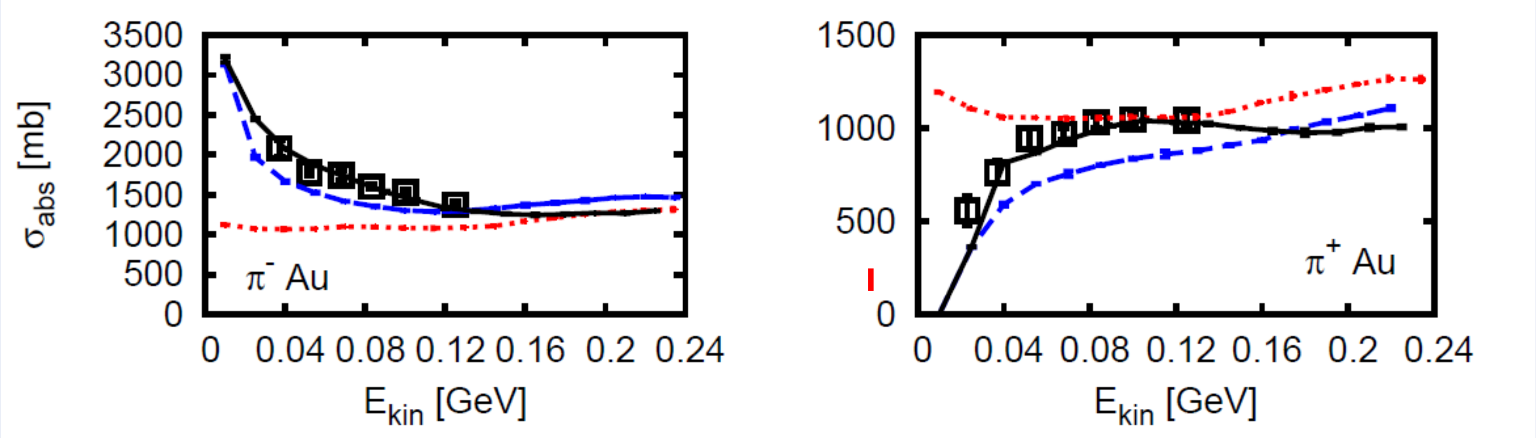
γ –>π^0 on Ca Pb



1999

Proton transparency





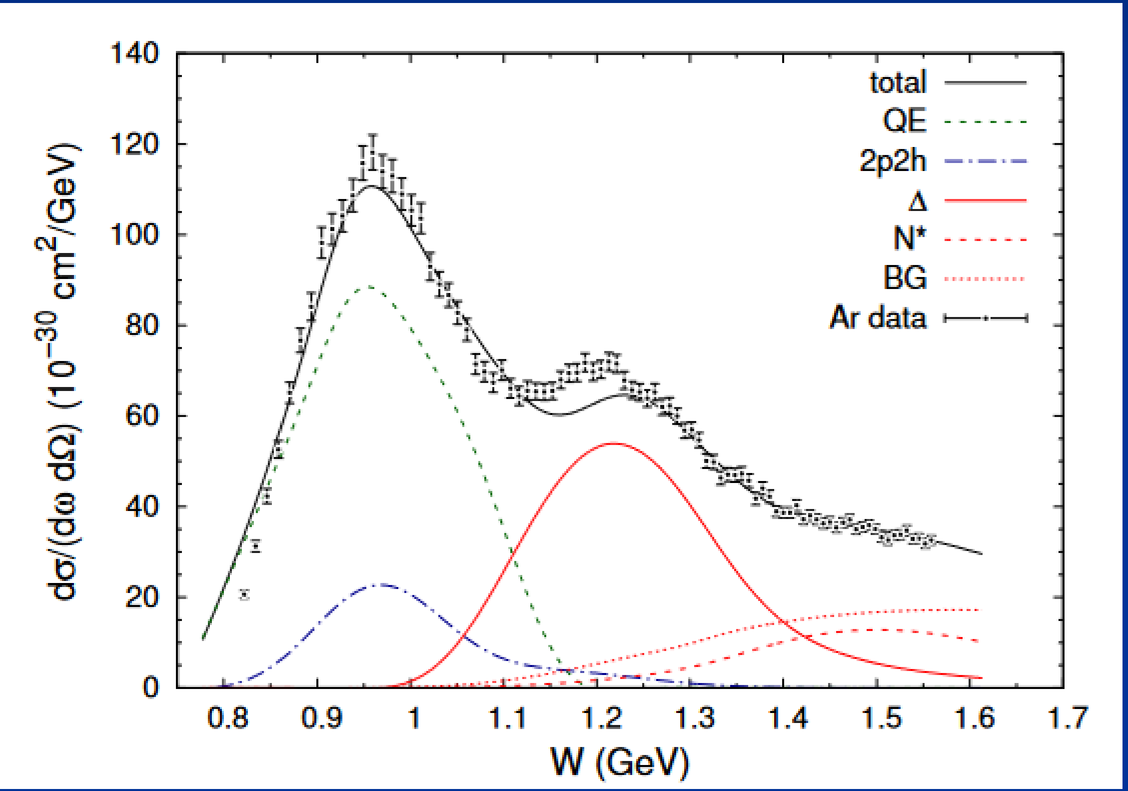
Pion reaction Xsect.
--- no potential
--- Coulomb only
--- Coulomb + nuclear

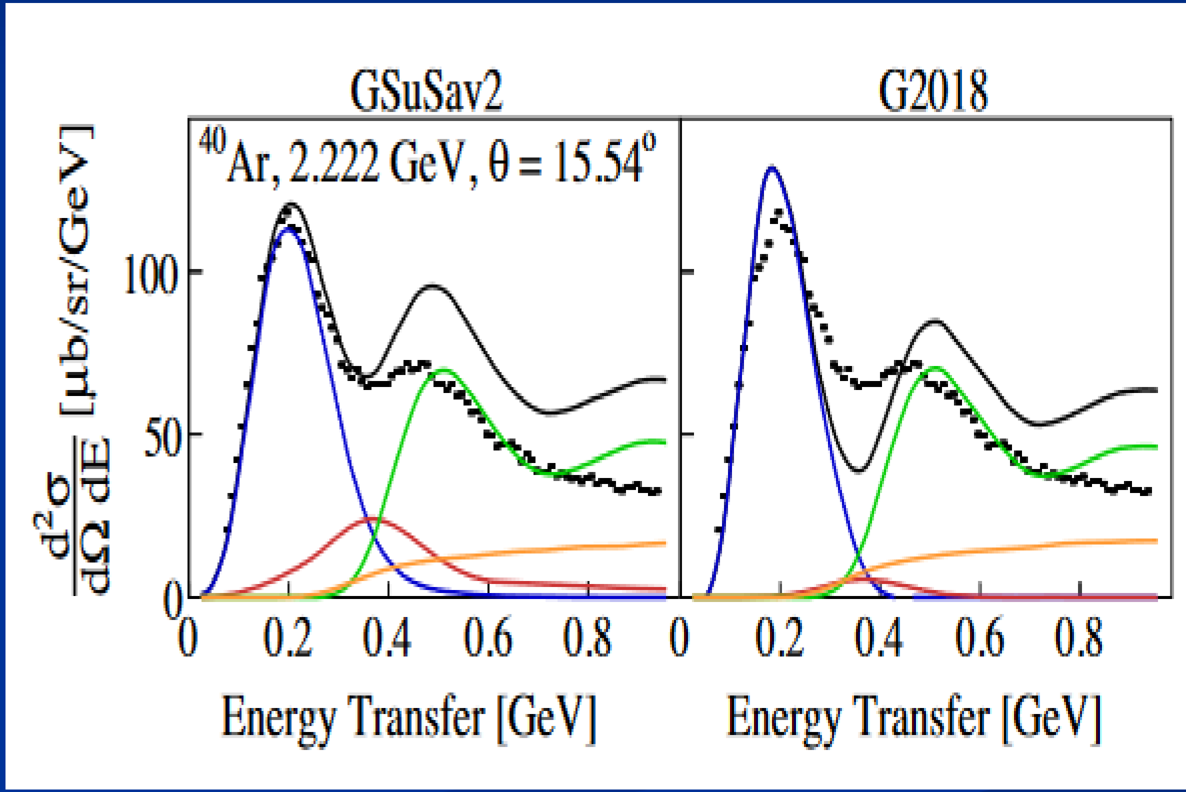
2006

Electron-Nucleus X-sections

- Electron-nucleus reactions necessary test
- *New in GiBUU v2023:*
  e-A cross sections obtained by sampling the spectral function and then Lorentz-boost into the restframe of the nucleon.
- 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 (nucleus) rest-frame.

GiBUU vs GENIE



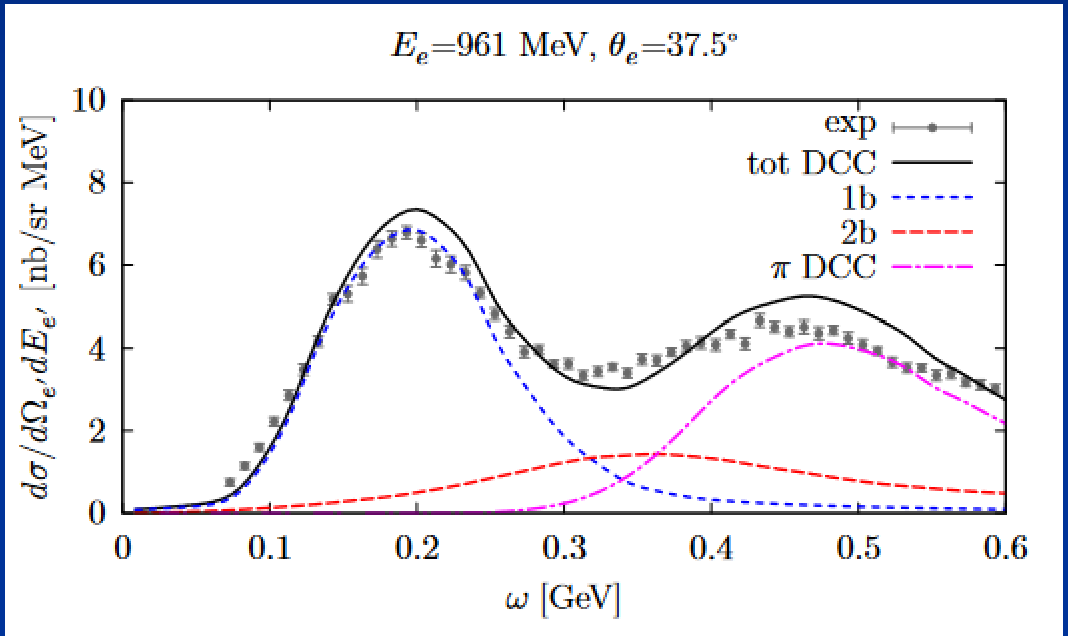


GiBUU

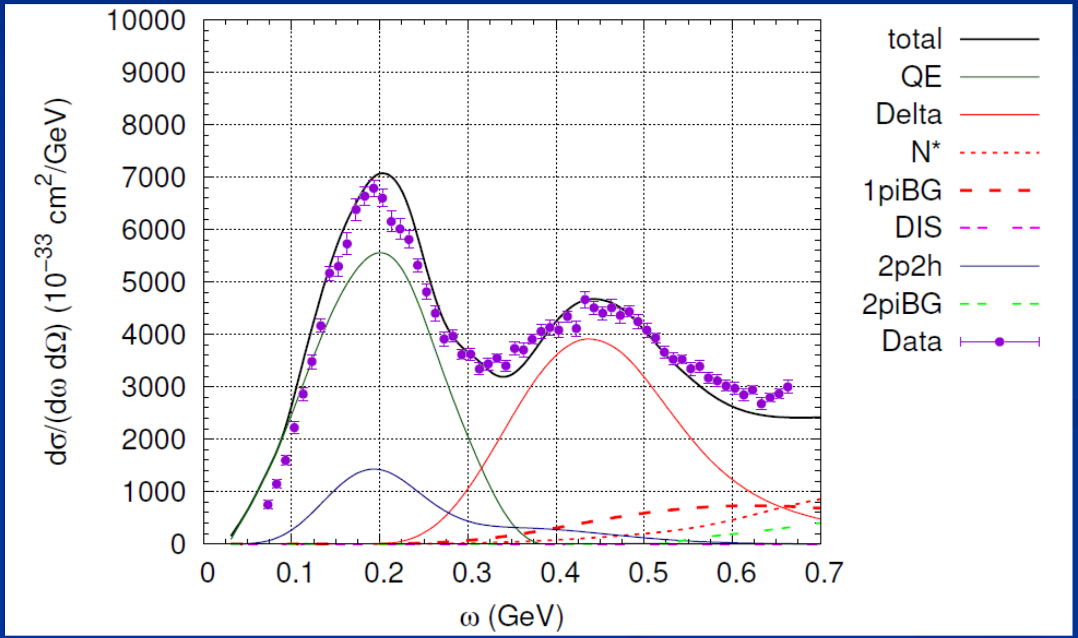
GENIE

PHYS. REV. D 103, 113003 (2021)

‚ab initio' vs quasiclassical



Rocco et al, PRC 100 (2019) 6



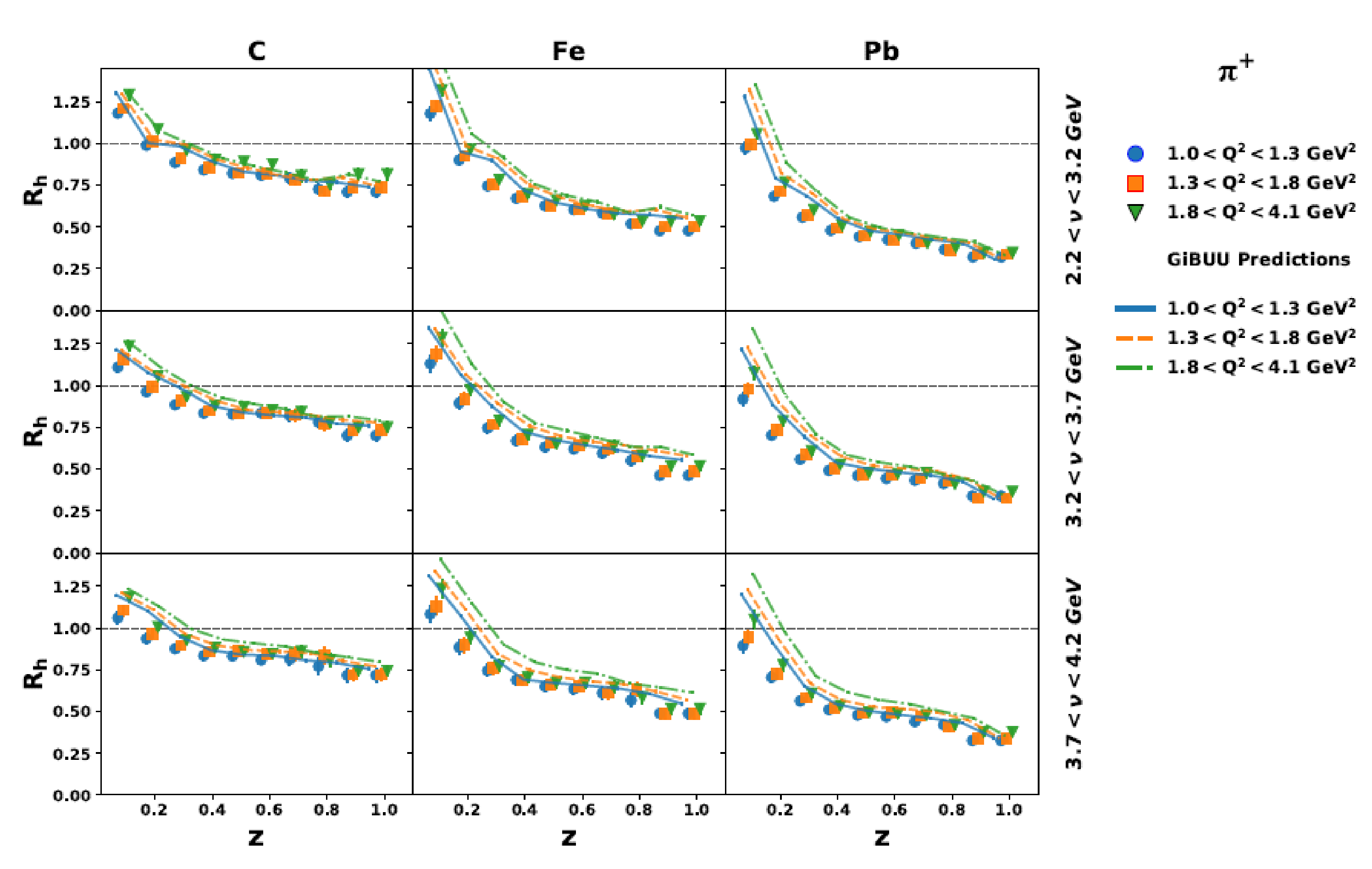
GiBUU

eC

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

SIDIS: Pions at 5 GeV@JLAB

Attenuation ratios



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

$z = E_\pi/\nu$

Electron -> Neutrino Transition

- ‚Transform' the structure functions from electrons to neutrinos:

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

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

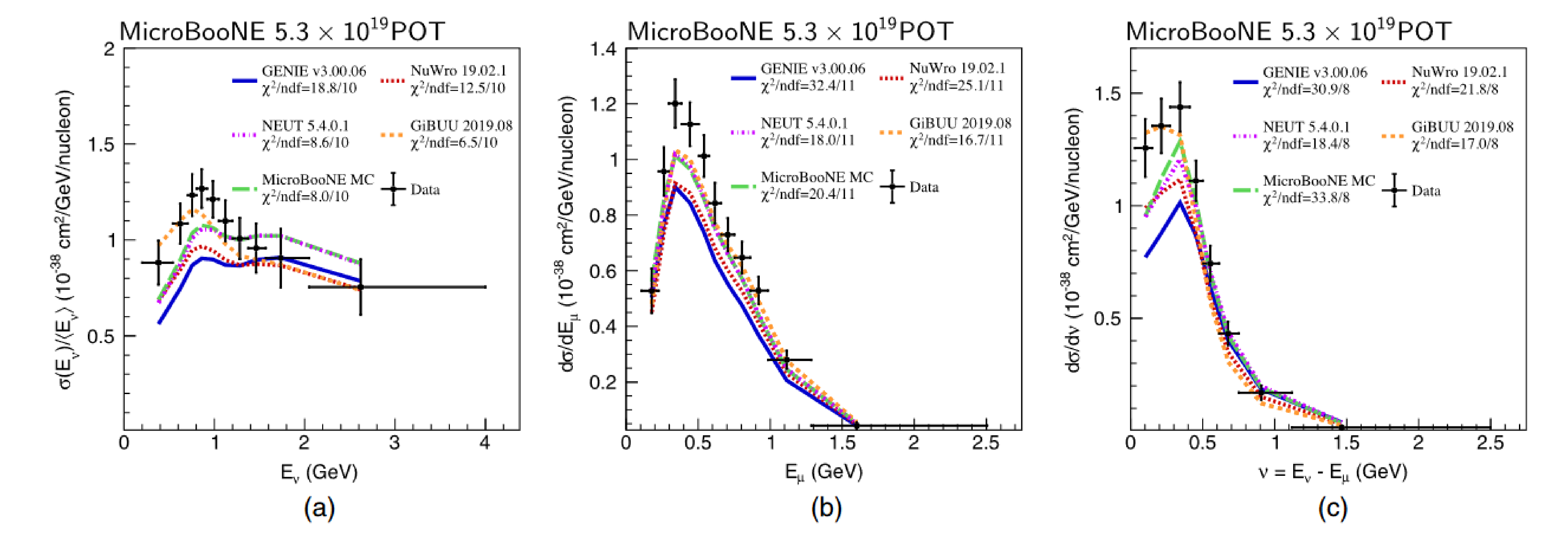
$V^2 + A^2$

V A

D. Walecka, 1975

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

MicroBooNE



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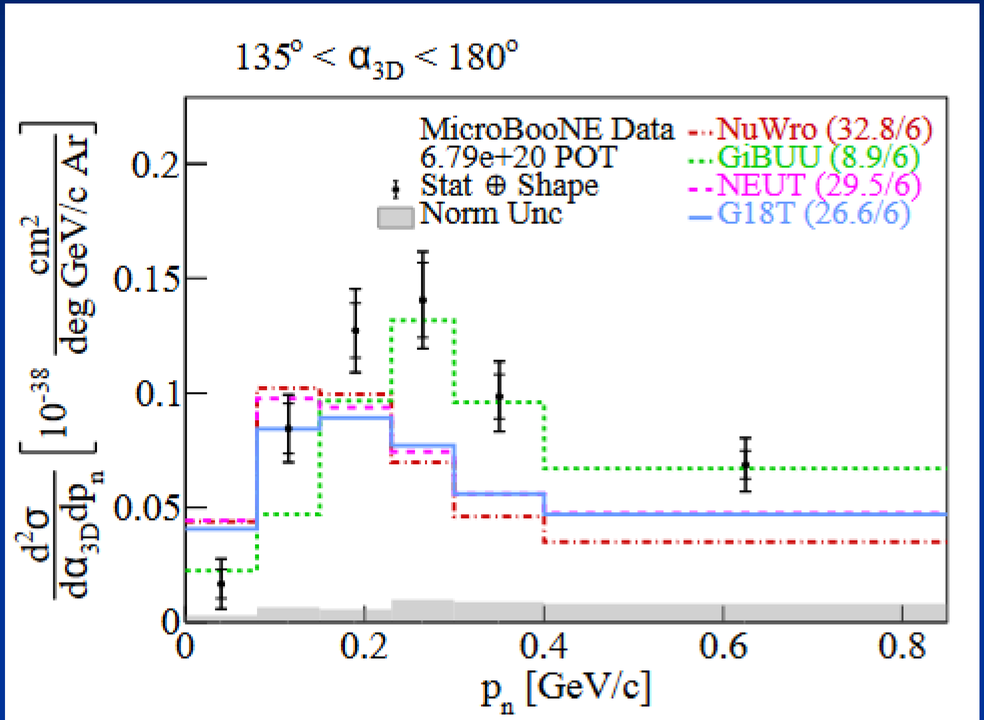
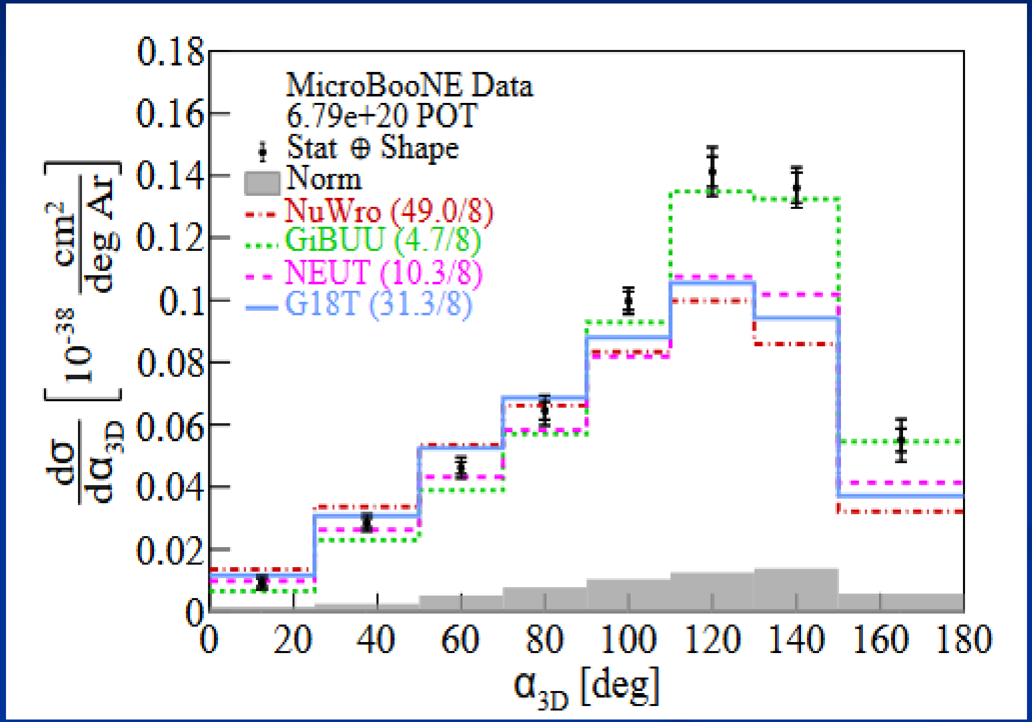
MicroBooNE

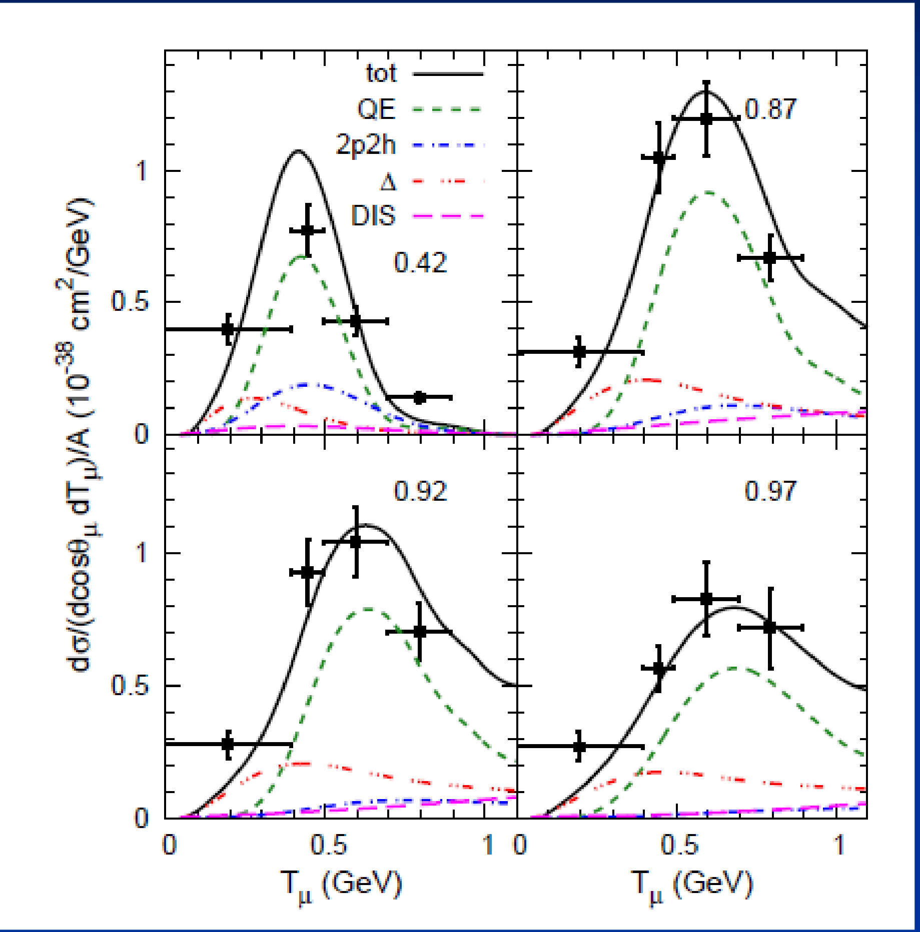




arXiv:2310.06082 [nucl-ex]

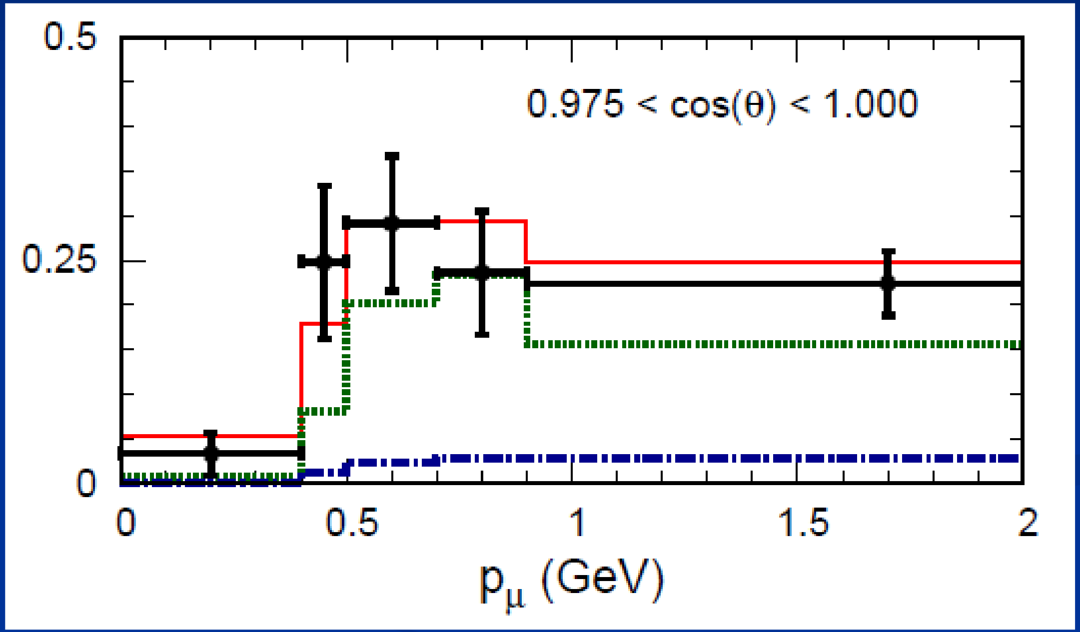
Kinematic imbalance variables

T2K Inclusives and 0π X-sections



Gallmeister et al, Phys.Rev.C 94 (2016) 3, 035502

incl



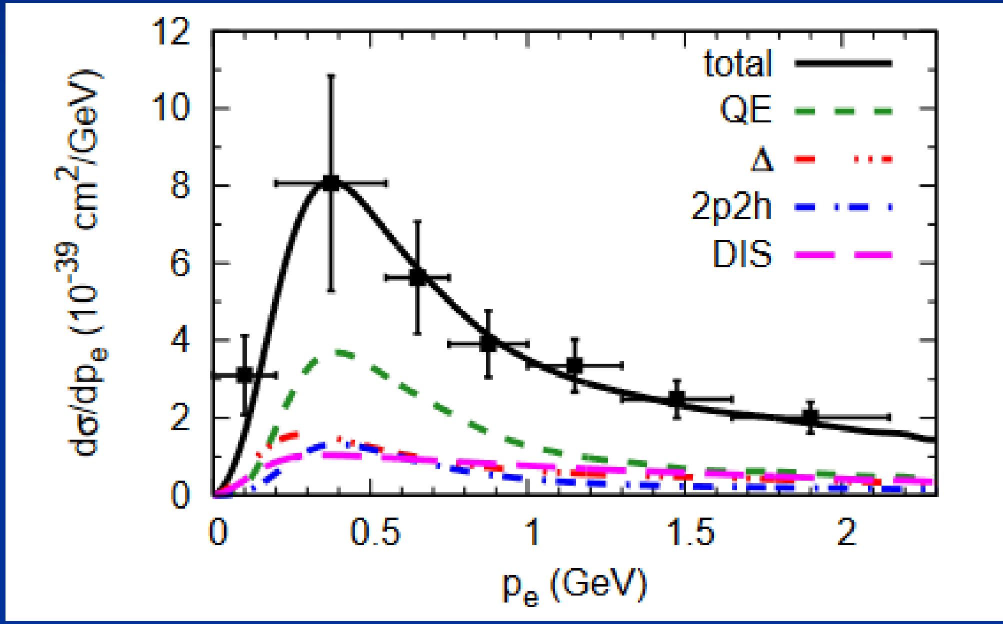
0π incl

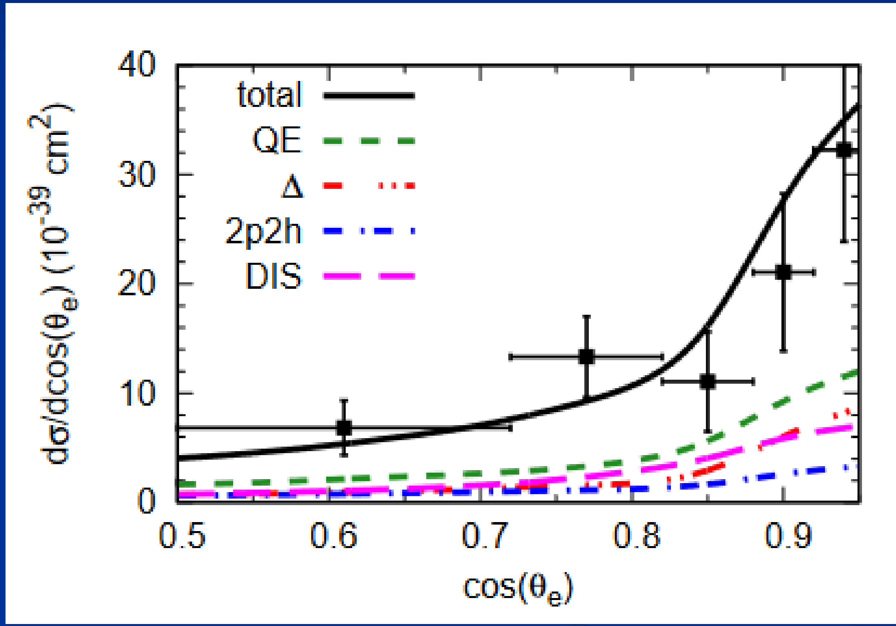
Green : QE+2p2h

Red: 0π from QE + 2p2h + π prod + π abs

T2K

Electron Neutrinos

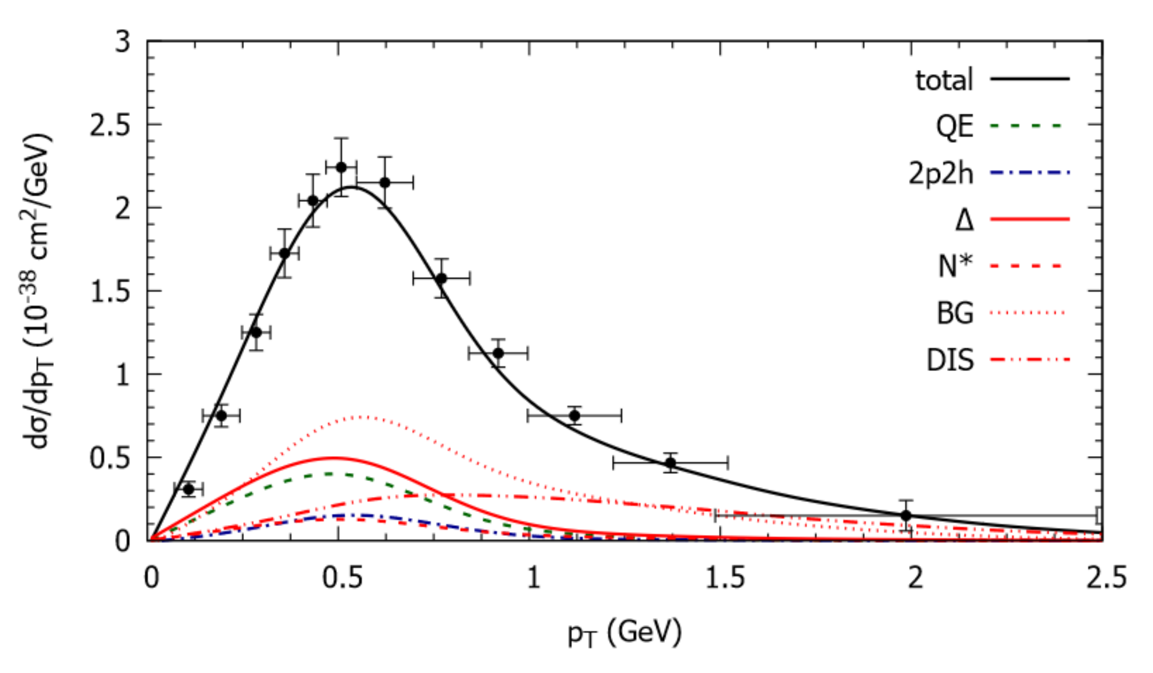




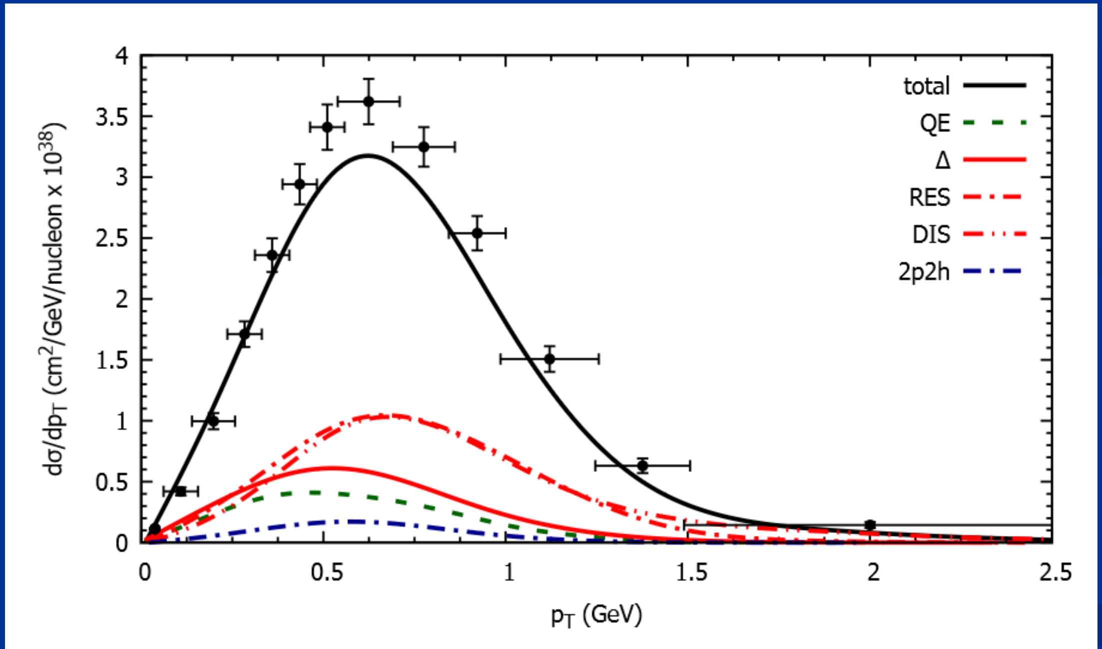
Gallmeister et al, Phys.Rev.C 94 (2016) 3, 035502

MINERvA incl X-sections

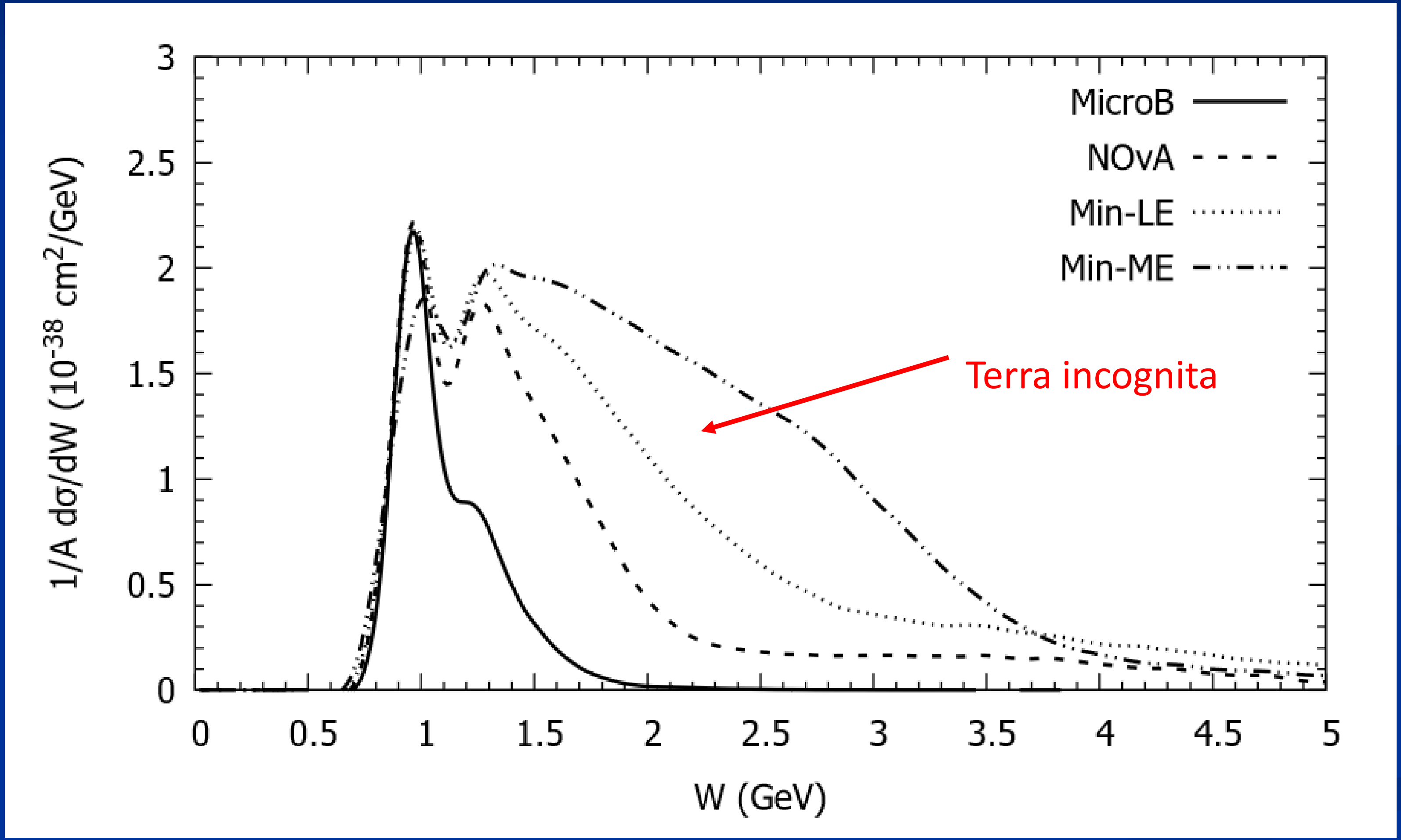
LE <E> = 3.5 GeV



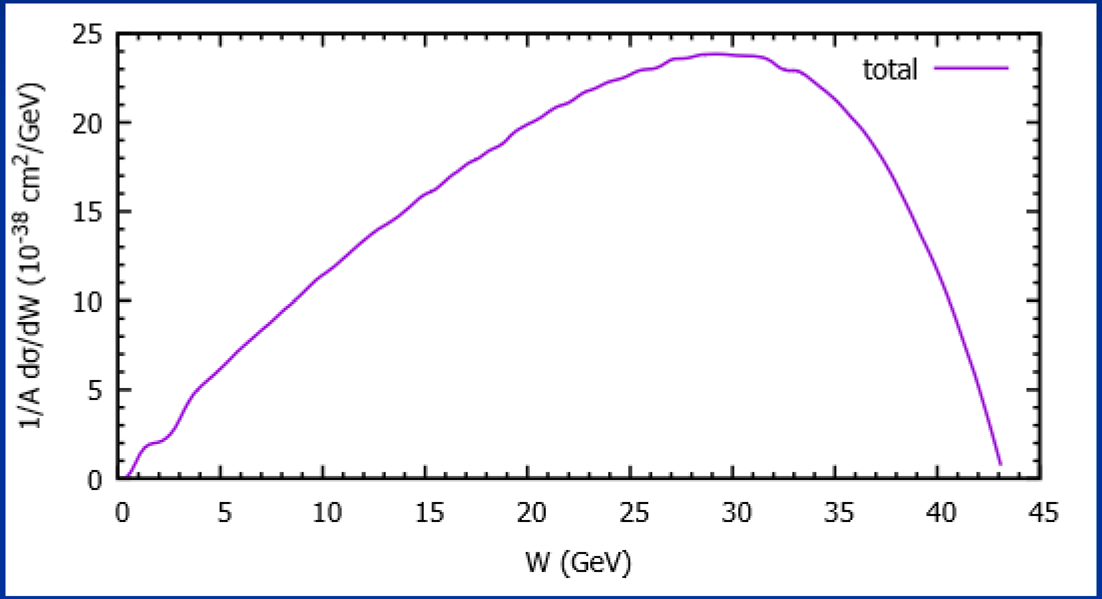
ME <E> = 6 GeV

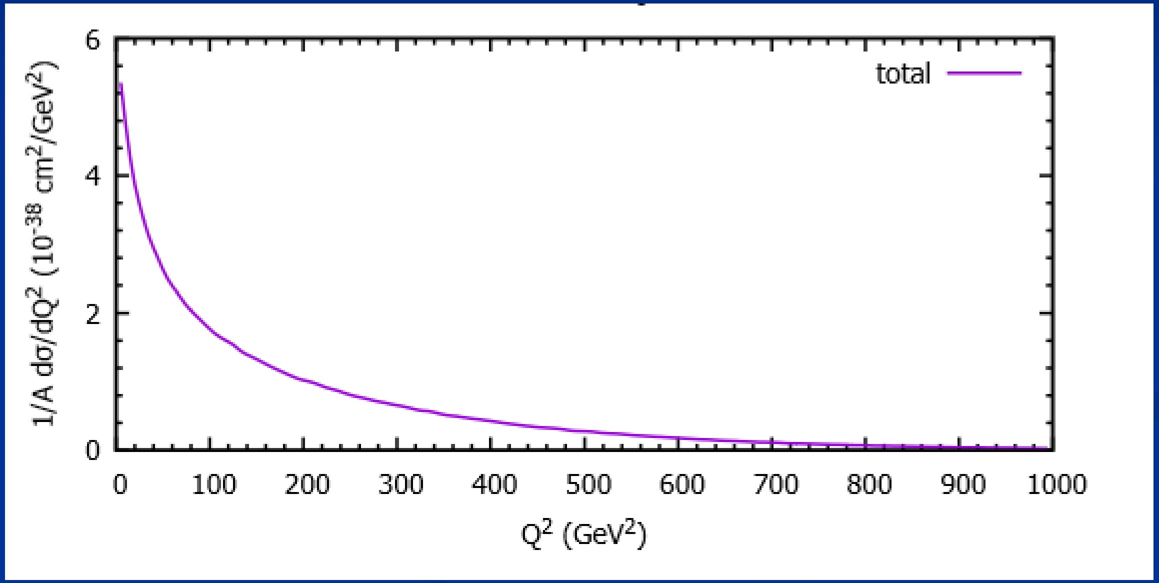


W-distributions



FASERν: 1 TeV neutrinos





arXiv:2201.04008v1 [hep-ph]

First neutrinos seen at CERN in 2023

DIS process is dominant. Experiments with nuclear targets may clarify problem with neutrino EMC effect.

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Summary

- GiBUU is a generator for many different reaction types, from heavy-ion collisions to neutrino-nucleus interactions
- GiBUU source code is freely available from gibuu.hepforge.org
- GiBUU tries to implement consistent nuclear theory descriptions for all the primary interactions (not so in GENIE, …)
- GiBUU is unique in its description of final state interactions, widely tested in different reaction types and energy regimes
- Version 2023 was released a few months ago, a first patch will appear within the next ~ 10 days.

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