The Giessen Model for νA reactions

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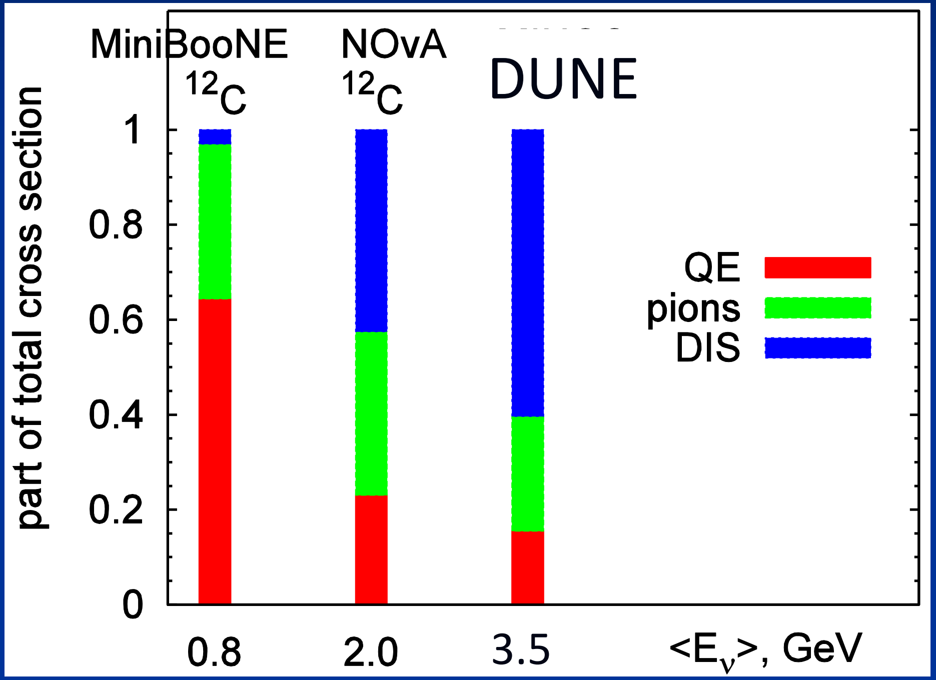
Intro

- Neutrino oscillation parameters require a reconstruction of the incoming neutrino energy
- Energy reconstruction requires generators
- The quality of the ultimate physics result (oscillation parameters, phases, neutrino mass ordering) depends on quality of the generator
- The generator must be as much state-of-the-art as the experimental equipment
- This talk concentrates on problems related to energy reconstruction and generators.

ν-A Processes



All these processes are entangled, cannot be separated experimentally.

For Mini/MicroBooNE,T2K:
physics is reasonably well described by QE and Δ resonance excitation
Both are entangled; pion reabsorption essential

For DUNE:
Must have explicit inelastic excitations and DIS
➔ Need full final state, semi-inclusive

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)
  - The low-energy part similar to Valencia model, but binds nuclei
  - Contains large number of N* resonances and mesons, up to charm
  - Not restricted to the low energies of Valencia model

- Final State Interactions: quantum-kinetic transport theory
  - 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 modelling of color transparency, formation times

Giessen model ingredients

- Baryon Resonances up to $W \sim 2$ GeV transported explicitly, with properties from PDG, *lifetime determined by widths*

- DIS Processes ($W > 2$ GeV) described by string fragmentation (PYTHIA), *lifetime determined by fragmentation time-scale*, no external `formation times`:

K. Gallmeister, U. Mosel
``Time Dependent Hadronization via HERMES and EMC Data Consistency''
Nucl. Phys. A **801**(2008) 68

K. Gallmeister, T. Falter
``Space-time picture of fragmentation in PYTHIA/JETSET for HERMES and RHIC''
Phys. Lett. B **630** (2005) 40

- Problem: Cross section development during these `formation times`, often taken to be *0* , e.g. GENIE: no interactions within *0.342* fm/c ! Contradicts experiments!

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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 2021, soon v 2022

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CT identification needs reliable FSI description

Simplicity

- Kadanoff-Baym equation (1960s)
  - full equation not (yet) feasible for real world problems
- Boltzmann-Uehling-Uhlenbeck (BUU) models: GiBUU
  - Boltzmann equation as gradient expansion of Kadanoff-Baym equations, in Botermans-Malfliet representation (1990s) with off-shell transport
- Cascade models
  (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

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

KB equations with BM offshell term

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GiBUU Tests

- Widely tested on
  - heavy-ion reactions (< 20 AGeV), p + A, π + A
    - mainly FSI tests
  - (e, A) reactions (JLAB: E < 6 GeV, HERMES: 28 GeV, EMC: 230 GeV)
  - (ν, A) reactions (MiniBooNE, MicroBooNE, T2K, MINERvA)

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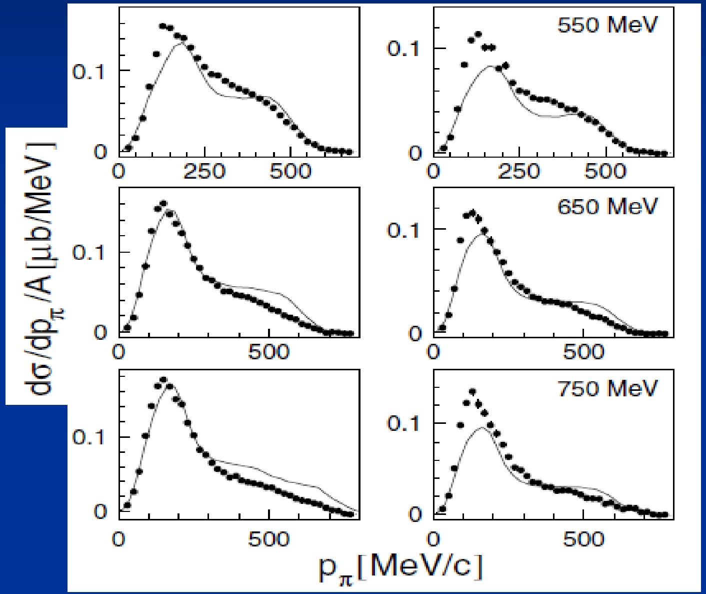
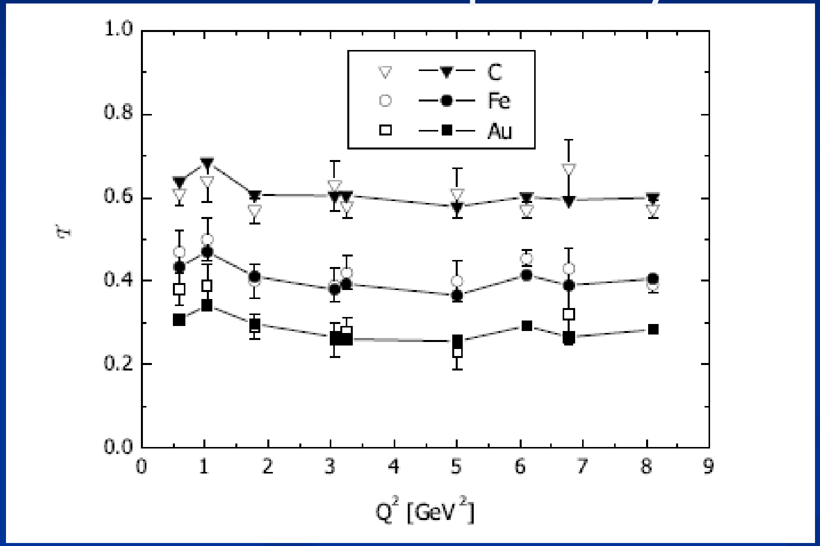
Check: pions, protons

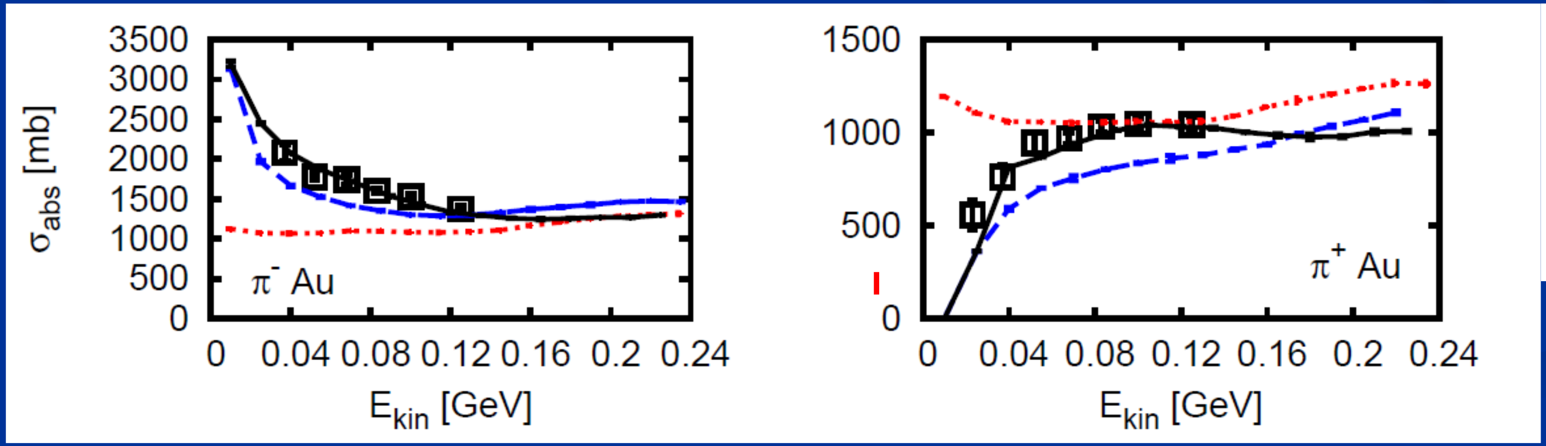
(Leitner et al, https://inspirehep.net/literature/819969 (2009))

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



Proton transparency





Pion reaction Xsect.

--- no potential

--- Coulomb only

--- Coulomb + nuclear

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Inclusive Electron X-Sections

- Necessary (vector couplings), but not sufficient (axial couplings) test
- Only indirect, weak test for FSI
- Not sufficient for energy-reconstruction

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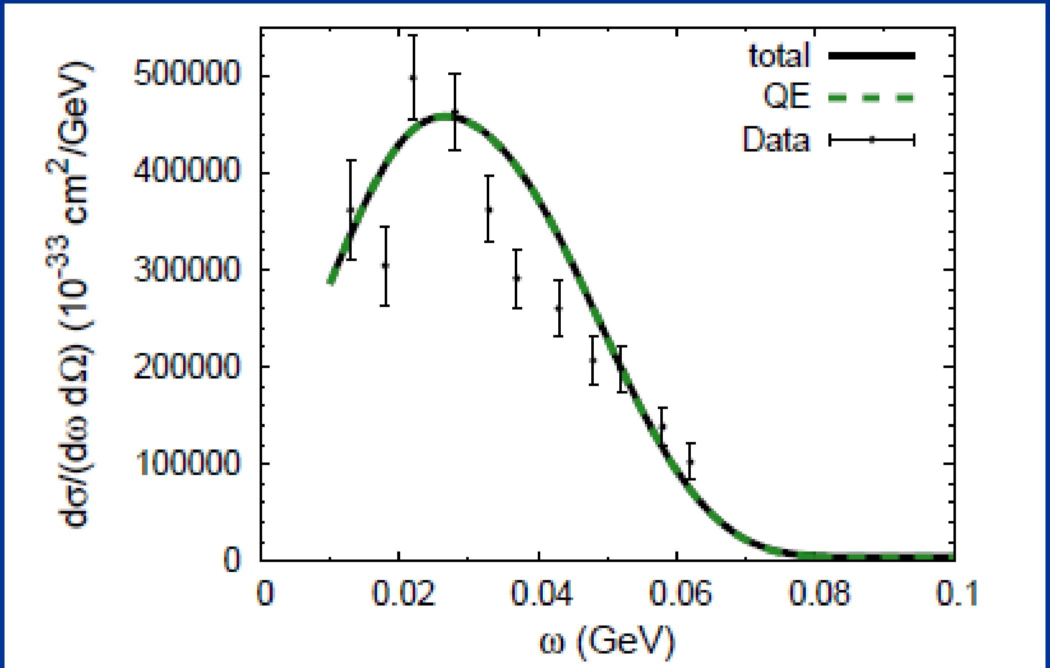
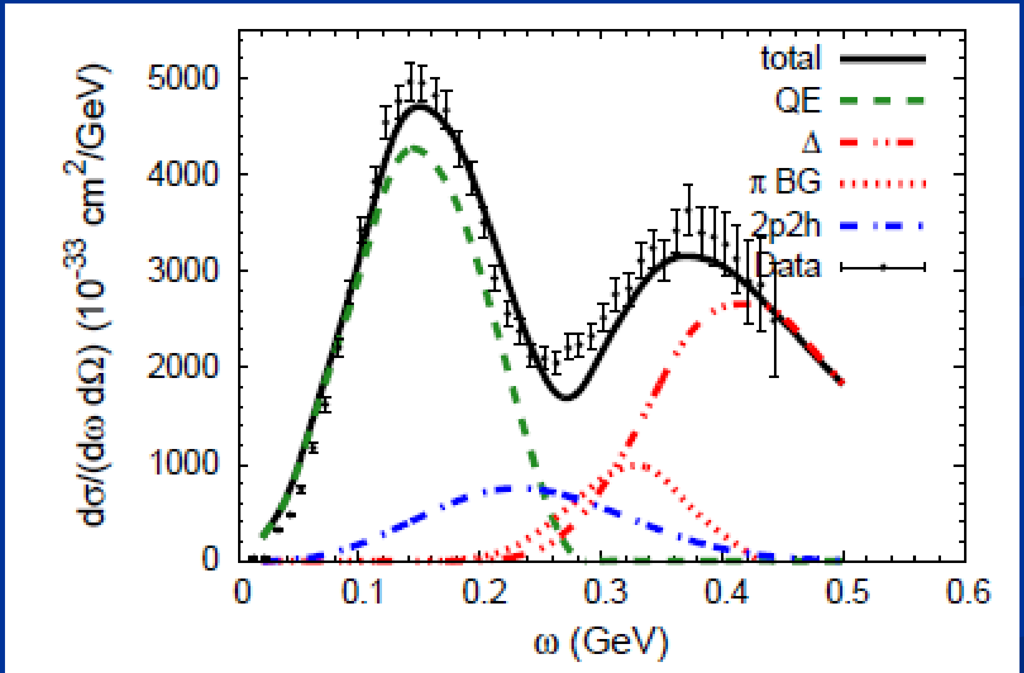
Inclusive QE Electron Scattering

- a **necessary check** for any generator development



0.24 GeV, 36 deg, $Q^2 = 0.02$ GeV^2



0.56 GeV, 60 deg, $Q^2 = 0.24$ GeV^2

Target: C

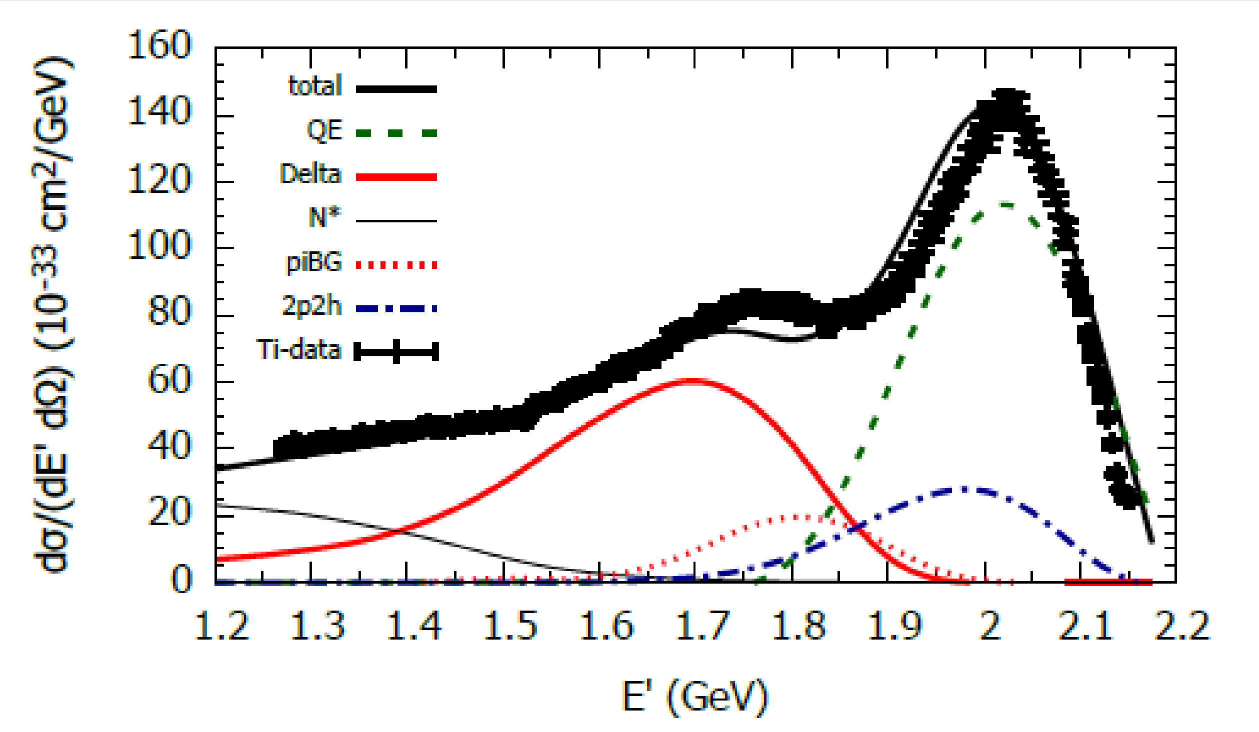
Uncertainties at lower energies

- At T2K, MicroBooNE energies:
  - Theory of QE and 2p2h reasonably well under control
  - Δ resonance can be pinned down by simultaneous analysis of incl. X-sections and π-production

  Problem is energy reconstruction via QE-like processes, because QE and pion production with subsequent pion absorption are entangled:

  exp 1p0π is not QE!!! Problem for e4nu, SUSA
- Tuning generator to e-data (e-GENIE) does not help, entanglement is physics, not generator problem, need to describe consistently QE, 2p2h and Δ resonance excitation

Inclusive Electron X-section



E = 2.22 GeV, θ= 15.5 deg

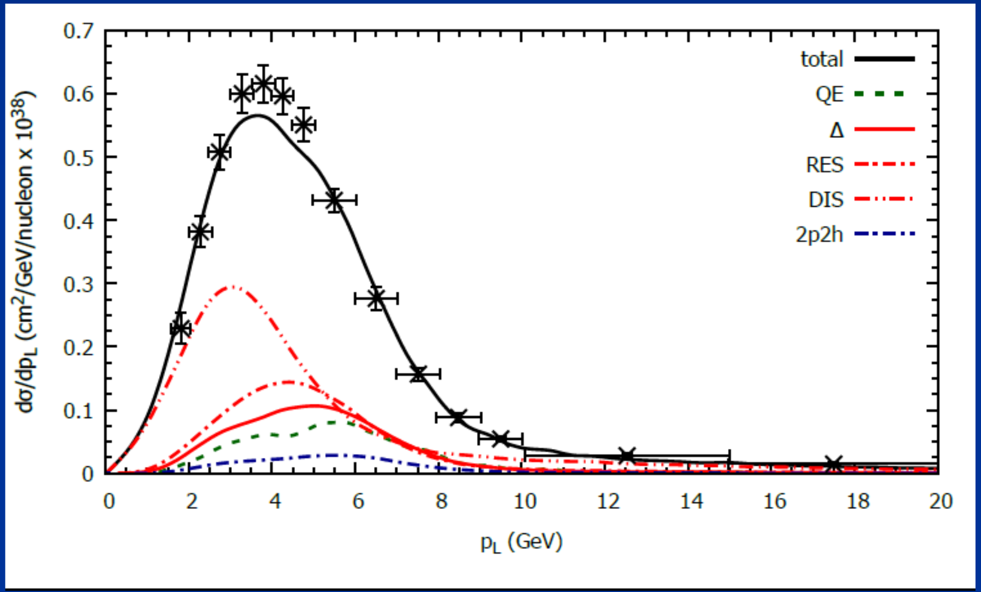
Data: Dai et al,
PRC98 (2018) 014617

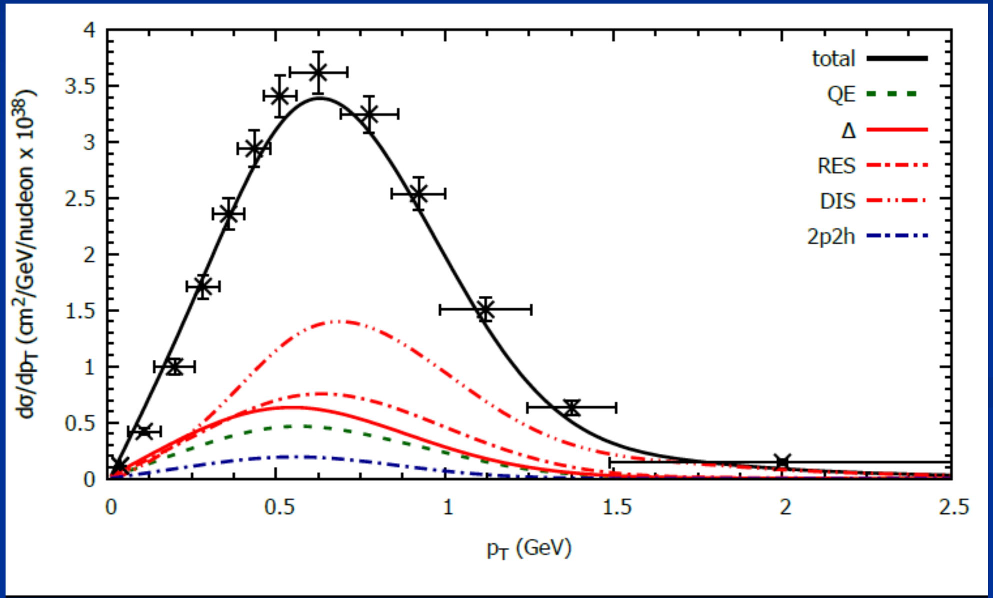
GiBUU theory:
Mosel et al, PRC 99 (2019) 6

Inclusive ν X-section at $E_\nu \sim 6$ GeV

Data: MINERvA ME, Ruterbories et al, PRC 104 (2021) 9

GiBUU preliminary





DIS and RES dominate:
DIS is uncertain at these (for pQCD) relatively low energies
RES is uncertain because of axial couplings to resonances

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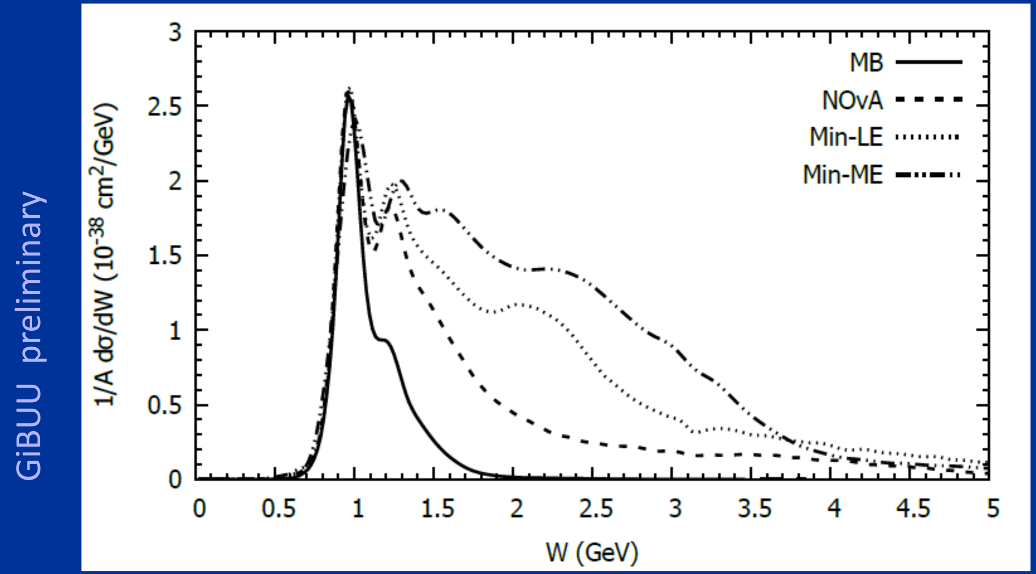
Uncertainties at higher energies (SIS)

- At NOvA, MINERvA and DUNE energies:
  - Higher resonances (> Δ, SIS region) explored by present experiments



No info from e-A reactions
axial coupling to resonances is uncertain

Axial coupling of spin 3/2 resonances:
Up to 100% uncertainty in X-section
(Lalakulich and Paschos, PR D74 (2006) 014009

Difference of MINERvA and NOvA is nearly pure RES and SIS

Neutrinos: Uncertainties in SIS

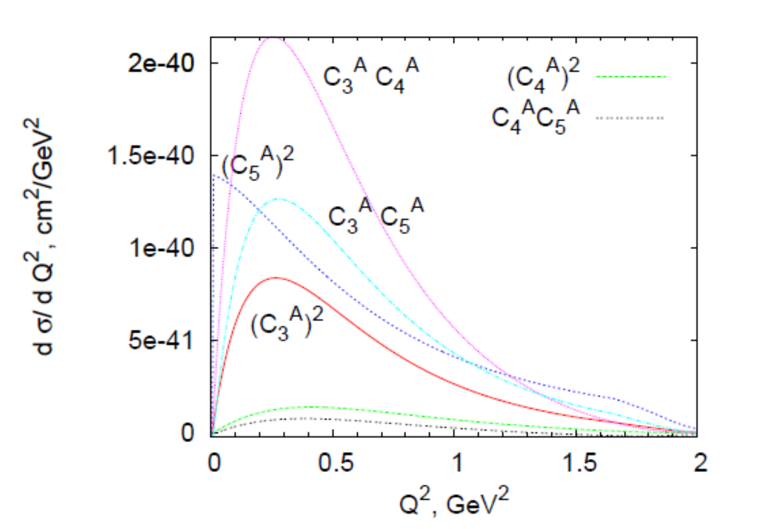
- From Lalakulich, Paschos, Piranishvili (PR D74 (2006) 014009
  Transition operator to spin-3/2 resonances:

$$
\begin{aligned}
d^{\lambda\nu}_{D_{13}} = {} & g^{\lambda\nu}\left[\frac{C_3^V}{m_N}\not{q} + \frac{C_4^V}{m_N^2}(p'q) + \frac{C_5^V}{m_N^2}(pq) + C_6^V\right] - q^\lambda\left[\frac{C_3^V}{m_N}\gamma^\nu + \frac{C_4^V}{m_N^2}p'^\nu + \frac{C_5^V}{m_N^2}p^\nu\right] \\
& + g^{\lambda\nu}\left[\frac{C_3^A}{m_N}\not{q} + \frac{C_4^A}{m_N^2}(p'q)\right]\gamma_5 - q^\lambda\left[\frac{C_3^A}{m_N}\gamma^\nu + \frac{C_4^A}{m_N^2}p'^\nu\right]\gamma_5 + \left[g^{\lambda\nu}C_5^A + q^\lambda q^\nu \frac{C_6^A}{m_N^2}\right]\gamma_5 .
\end{aligned}
$$

known

not known

E = 2 GeV
C3A = 1,
C4A = 1



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

Info obtainable only from inclusive neutrino X-sections

Energy Reconstruction at Higher Energies

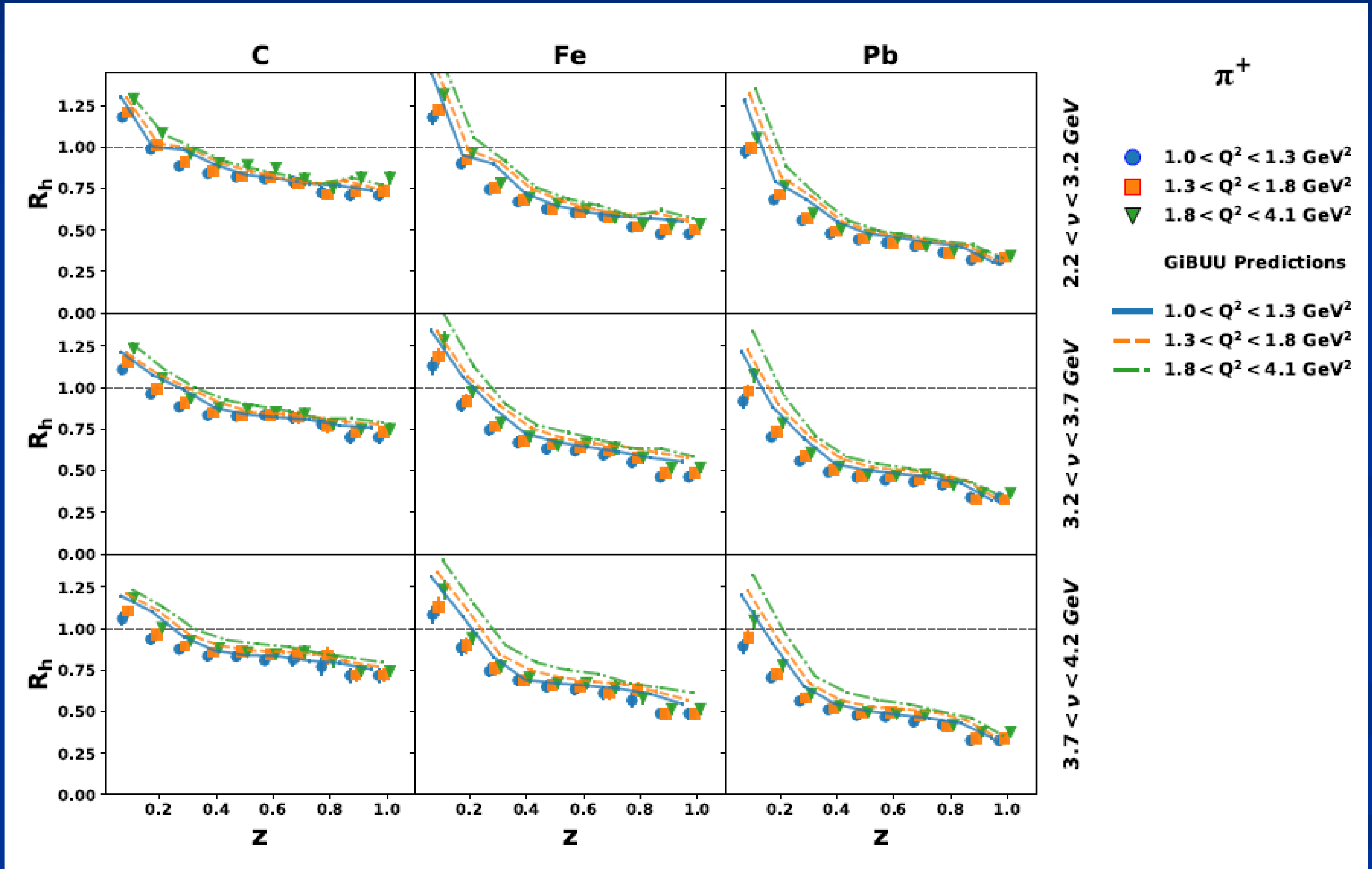
- At NOvA, MINERvA and DUNE need calorimetric method to reconstruct incoming energy → need full final state information, inclusive is not enough!

- Final State Interactions are identical for electrons and neutrinos:
final state particles do not remember how they were initially produced
→ no uncertainty stemming from axial coupling
→ semi-inclusive electron data can give relevant (and necessary) info on FSI

- Baryon spectra and multiplicities to fix and check FSI treatment are needed, for NOvA, MINERvA, DUNE semi-inclusive DIS (SIDIS) is relevant

SIDIS: Pions at 5 GeV@JLAB

Attenuation ratios

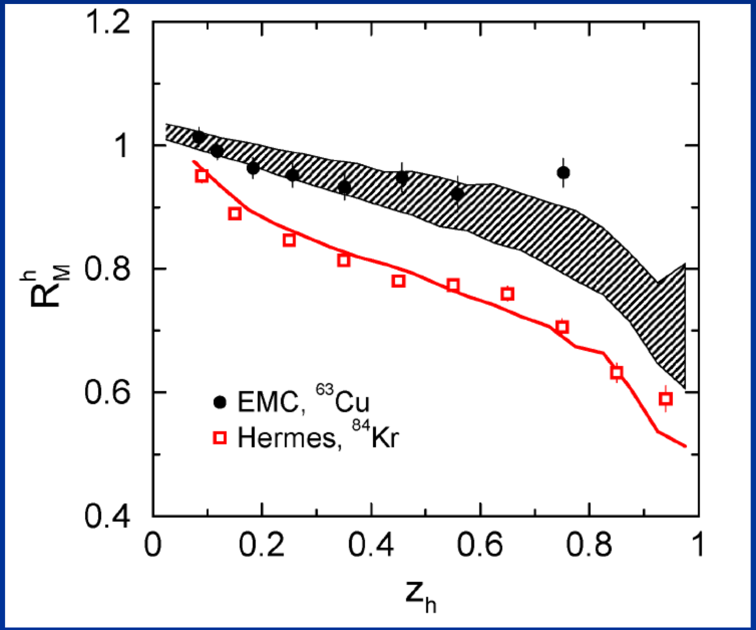


Data:
Moran et al,
Phys.Rev.C 105 (2022) 1
Theory:
GiBUU

$z = E_\pi/\nu$

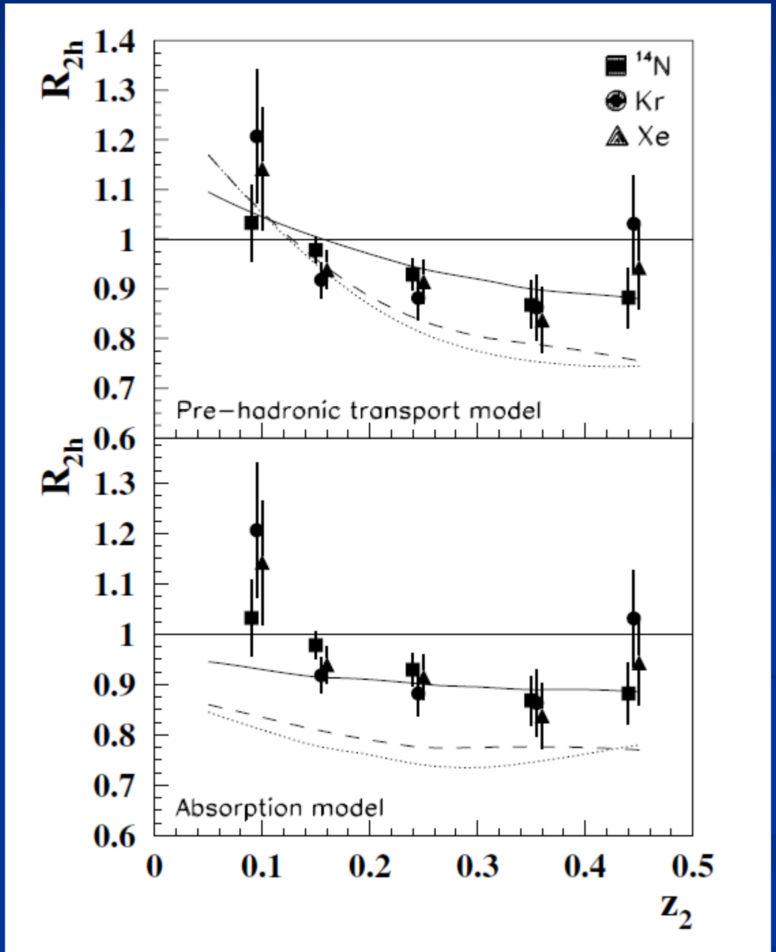
SIDIS at higher energies

All hadron attenuation



K. Gallmeister, U.M.
Nucl.Phys.A 801 (2008) 68-79

N. Bianchi / Nuclear Physics A 783 (2007) 93c–100c



HERMES Experiment:
28 GeV positrons or electrons,
2N attenuation

Curves: GiBUU

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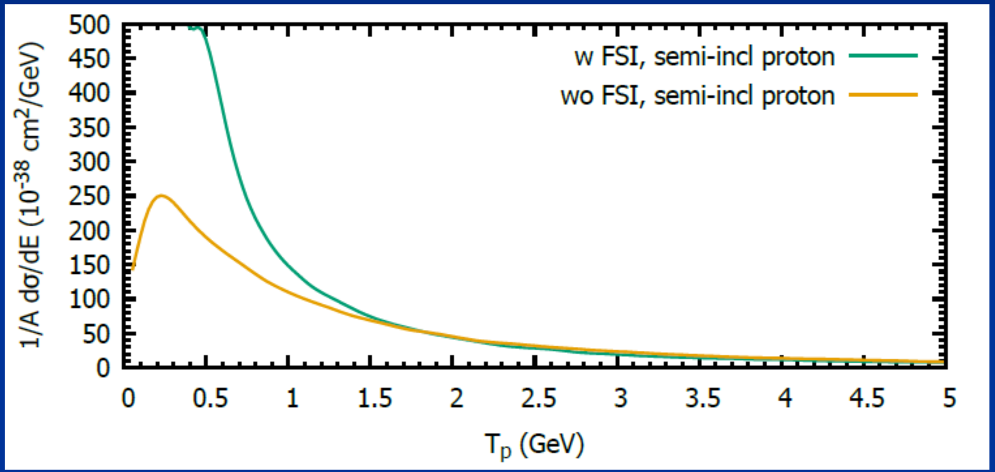
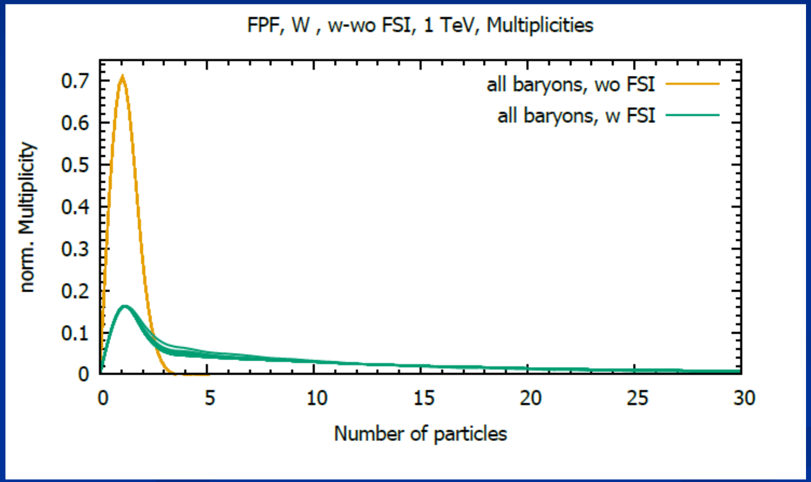
FSI effects in energy spectra





Strong avalanche effect: pileup of baryons at low energies

strong rise sets in below ~1.5 GeV kinetic energy,
reflects strong rise of NN X-sections at this energy

Target: W, 1 TeV
for FPF project

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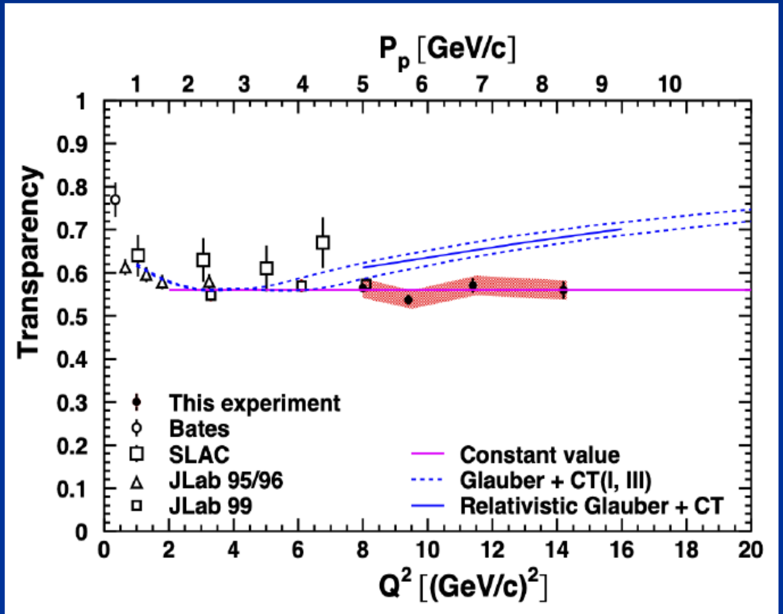
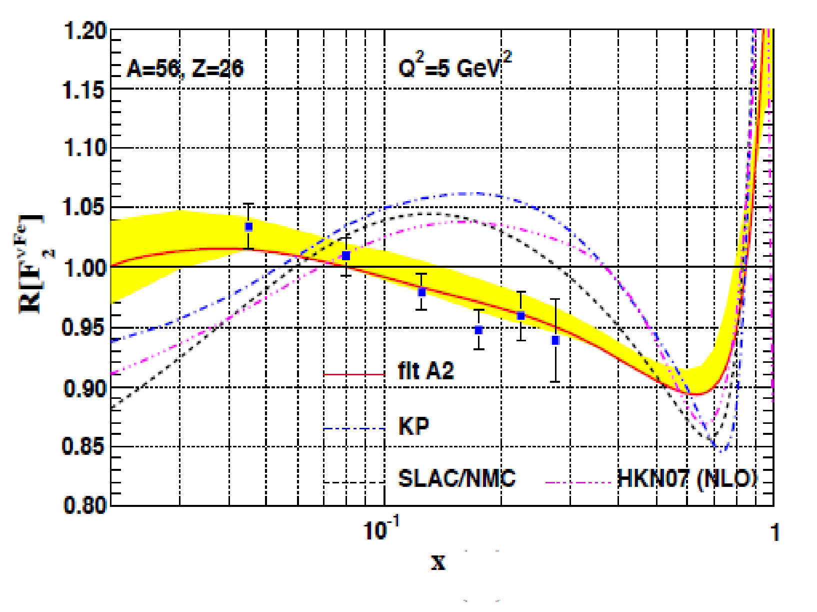
Fundamental open problems

JLAB 2021



Where isColor Transparency ???
Needs generator to follow struck
hadrons through nuclear target



EMC effect for neutrinos,
tension with electrons:
needs generator to reconstruct Bjorken x

Summary

- ‚Low-energy' experiments are dominated by QE, 2p2h, Δ. Energy reconstruction can rely on QE-like processes, but needs generator to separate out true QE. Even there the generator must go beyond models for inclusive Xsections (also for experimental analyses of semi-inclusive electron data).
- ‚High-energy' experiments have large contributions from SIS and DIS. Energy reconstruction needs calorimetric method and needs reliable generators for semi-inclusive X-sections in SIS/DIS regime
  - Axial properties of N* resonances are quite uncertain, inclusive X-sections can give info on SIS region.
  - Semi-inclusive electron data are dominated by FSI, i.e. independent of axial uncertainties -> crucial tests for generators are final state particle spectra and multiplicities. Few electron-SIDIS data are available in the DUNE energy regime (few GeV) and so far no neutrino data.

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Fundamental open problems

- Construct a generator that is theoretically as much state-of-the-art as the experimental equipment.
- Use state-of-the-art nuclear structure and reaction theory to get away from tuning unphysical parameters.
- Ultimate problem: obtain sufficient funding (and long-range jobs for younger scientists) for such a development which has to start now to be ready for the start of DUNE
  One possible solution: bring generator-theory into the CERN neutrino platform, needs transatlantic funding scheme between CERN and FNAL

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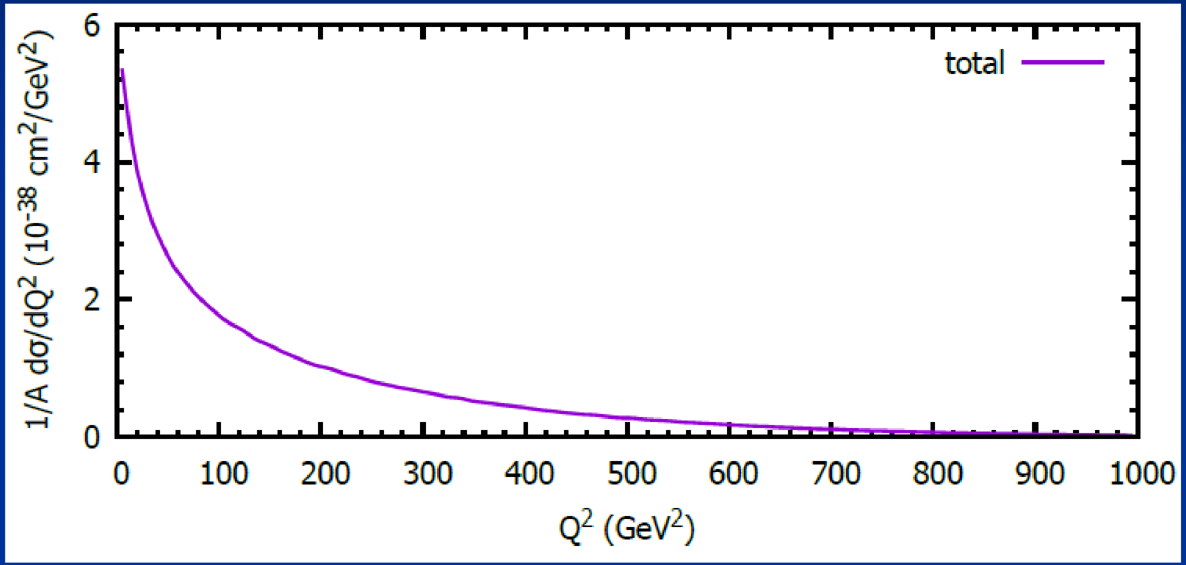
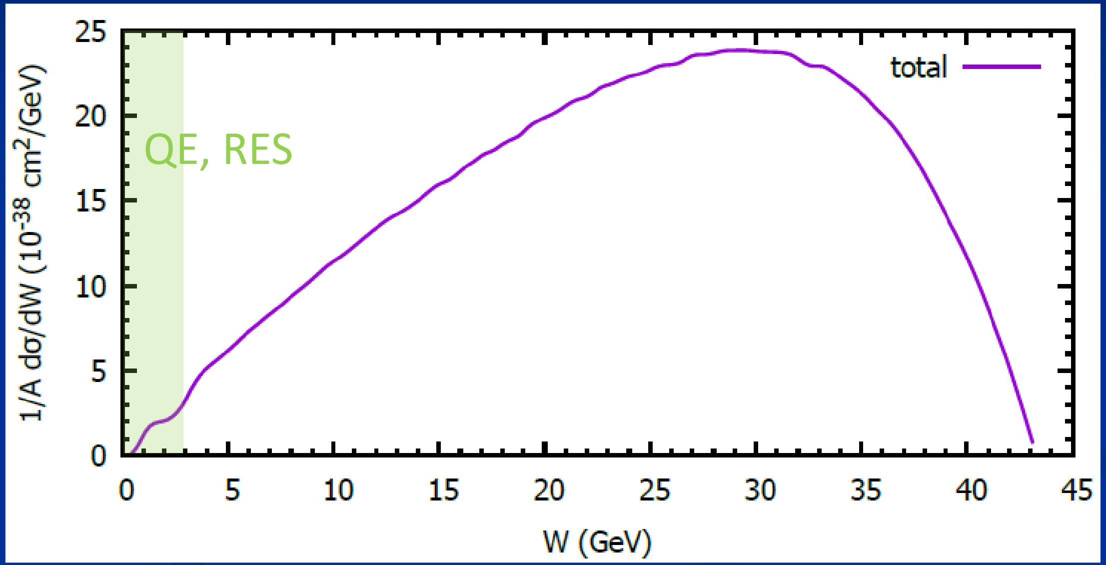
Time Course of a (γ,ν) *A* Reaction

- First, initial state (IS) interaction of incoming boson (γ, *W*, *Z*) with Fermi-moving nucleon bound in a groundstate potential
  -> initially produced *final state hadrons are affected by that potential*
- Initial starting points for hadron FS transport are anywhere within the nuclear volume; photons and neutrinos illuminate the whole nucleus.
- Second, *final state (FS) interaction of the produced hadrons in that same potential*, move out through the nucleus to detector

- ➔ IS and FS do not factorize!

FPF, 1 TeV, incl. distributions





Dominated by DIS , have to worry about Color Transparency in FSI:

$$\frac{\sigma^*(t)}{\sigma} = X_0 + (1 - X_0) \cdot \left(\frac{t - t_P}{t_F - t_P} \right), \quad X_0 = r_{\text{lead}} \frac{\text{const}}{Q^2},$$

Farrar, Strikman et al

describes JLAB and HERMES hadronization data, also EMC

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