Physics of ν-A

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A Wake-up Call

"Wake up, Dr. Erskine—you're being transferred to low energy physics."

GiBUU

- Essential References:
  1. Buss et al, Phys. Rept. 512 (2012) 1
     contains both the theory and the practical implementation of transport theory
  2. Gallmeister et al., Phys.Rev. C94 (2016), 035502
     contains the latest changes in GiBUU2016
  3. Mosel, Ann. Rev. Nucl. Part. Sci. 66 (2016) 171
     short review, contains some discussion of generators

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νA Reaction

- General structure: **approximately** factorizes

full event (four-vectors of all particles in final state)

$\cong$

initial interaction *x* final state interaction

Determines inclusive X-section

Determines the final state particles

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A theory-based generator

- Aim: to construct the best possible consistent theory framework for inclusive reactions *and* full event simulations (NOT exclusive 1particle out or coherent).
  Requirements:
  - Relativistically correct (Skyrme-like or RMF) momentum-dependent potentials, nuclear binding, approximately correct handling of collision terms
  - Same potentials in initial state and final state interactions
  - Final state interactions testable in many different reactions, such as p+A, pi+A, A+A, e+A, gamma+A

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The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** : **Quantum-Kinetic Theory and Event Generator** based on a BM solution of Kadanoff-Baym equations
- Physics content and details of implementation in:
  Buss et al, Phys. Rept. 512 (2012) 1- 124
  Mine of information on theoretical treatment of potentials, collision terms, spectral functions and cross sections, useful for any generator
- Code from gibuu.hepforge.org, new version GiBUU 2016
  Details in Gallmeister et al, Phys.Rev. C94 (2016) no.3, 035502

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The Giessen Boltzmann-Uehling-Uhlenbeck Project

- *Initial interaction:* can be any sophisticated model → inclusive cross sections
- *Final state interaction:* propagates these outgoing particles through the nucleus using quantum-kinetic transport theory, fully relativistic → full event, four-vectors of all particles
- Initial and final interactions come from the same Hamiltonian: CONSISTENCY of inclusive and semi-inclusive X-sections

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The Giessen Boltzmann-Uehling-Uhlenbeck Project

- The same groundstate for all processes!
  - Different from GENIE (NEUT), where different processes (QE, 2p2h, …) are calculated within different models.
- Bound groundstate
  - Different from all generators, also from Nieves, Martini
- New in GiBUU 2016:
  - Better ground state: constant Fermi surface enforced, - 8 MeV binding for all nuclei, not tuned
  - new treatment of 2p2h, consistent with e-scattering

Inclusive and Exclusive Modelling

- In quantum-kinetic theory the inclusive X-section emerges as time = 0 step for the time-development of the one-body phase-space distribution of all particles involved:

$$f(\mathbf{x},0,\mathbf{p}) = \frac{1}{(2\pi)^3}\int \mathrm{d}\mathbf{s}\, e^{-i\mathbf{p}\cdot\mathbf{s}} \rho\left(\mathbf{x}-\frac{\mathbf{s}}{2},\mathbf{x}+\frac{\mathbf{s}}{2}\right)$$

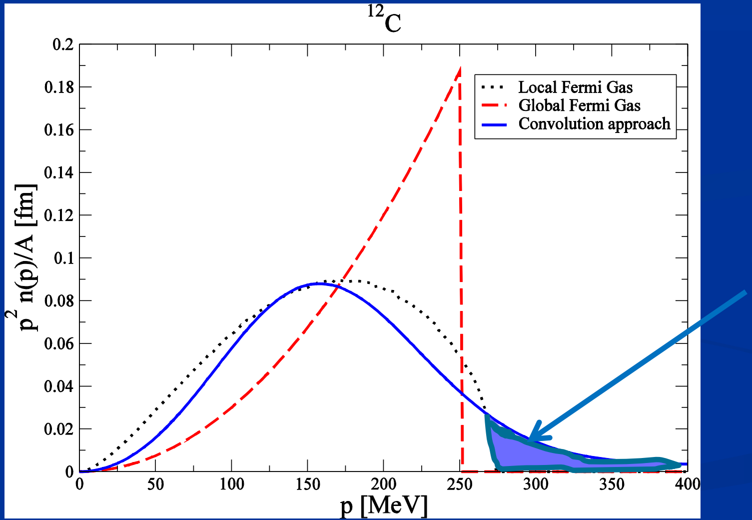
$$\mathcal{P}_h(\mathbf{p},E) = g \int_{\text{nucleus}} \mathrm{d}^3x\, f(\mathbf{x},0,\mathbf{p})\Theta(E)\,\delta\left(E - m^*(\mathbf{x},\mathbf{p}) + \sqrt{\mathbf{p}^2 + m^{*2}(\mathbf{x},\mathbf{p})}\right)$$

$$\mathrm{d}\sigma_{\mathrm{QE}}^{\nu A} = \int \frac{\mathrm{d}^3p}{(2\pi)^3}\mathrm{d}E\,\mathcal{P}_h(\mathbf{p},E) f_{\mathrm{corr}}\, \mathrm{d}\sigma_{\mathrm{QE}}^{\mathrm{med}}\, P_{\mathrm{PB}}(\mathbf{x},\mathbf{p})\ .$$

Initial State Correlations

- GiBUU ground state: nucleons bound in momentum-dependent potential, obtained from EFT, momentum given by local Ferm gas, potential RMF or Skyrme

Energy-distribution smooth because of x-dependent Potential --> spectral function close to realistic, but no shell-effects



Alvarez-Ruso, Hayato, Nieves

True src contribution
Very small effect on
Inclusive cross sections

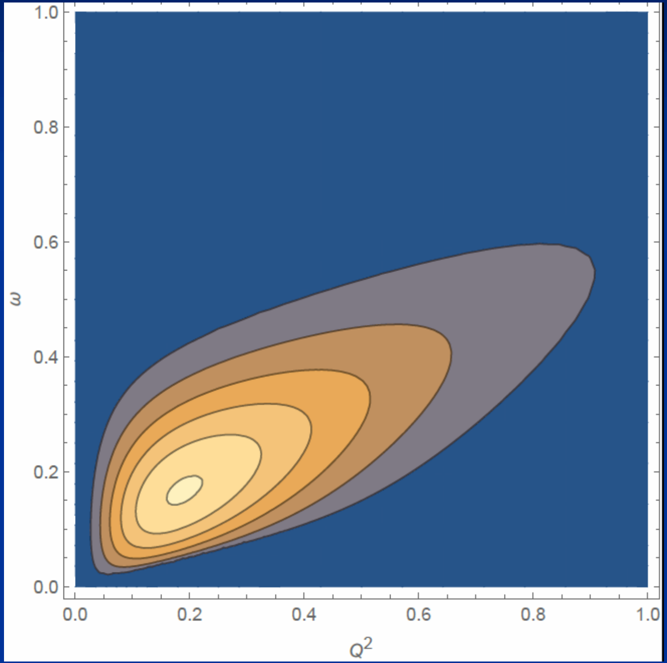
GiBUU Ingredients: 2p-2h

- **Assume**: 2p2h transverse, structure function W_1 for electrons from experimental fit of MEC contribution by Bosted and Mamyan (arXiv:1203.2262) and Christy (priv. comm.) to world data for $0 < W < 3.2$ GeV and $0.2 < Q^2 < 5$ GeV^2

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2}{Q^4} E'^2 2 \left(\frac{Q^2}{2\vec{q}^{\,2}} \cos^2\frac{\theta}{2} + \sin^2\frac{\theta}{2} \right) W_1(Q^2,\omega)$$

- Transverse assumption established around 1990, Ericsson, Marteau

2p2h Q^2-ω Distribution for 2p2h

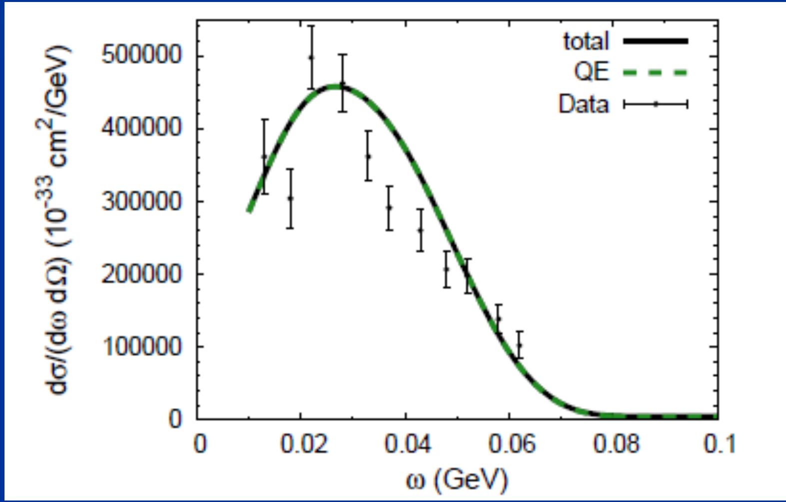


W_1

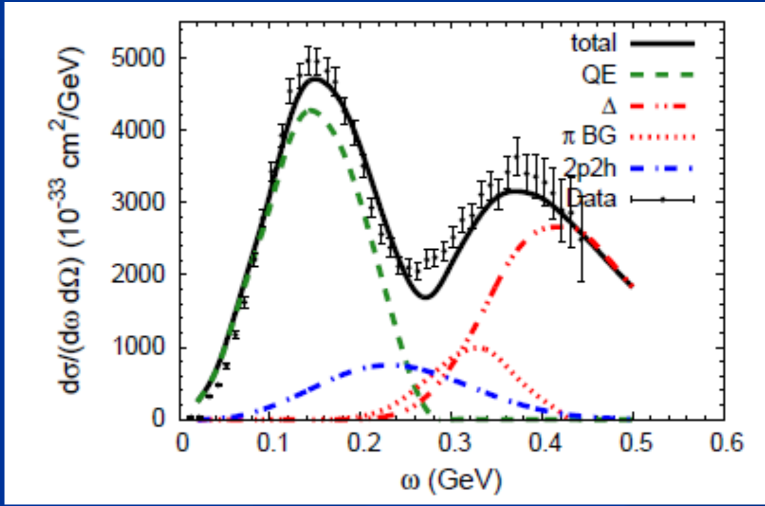
From:
Bosted and Mamyan,
Christy

Semi-inclusive QE Electron Scattering

- a necessary check for any generator development

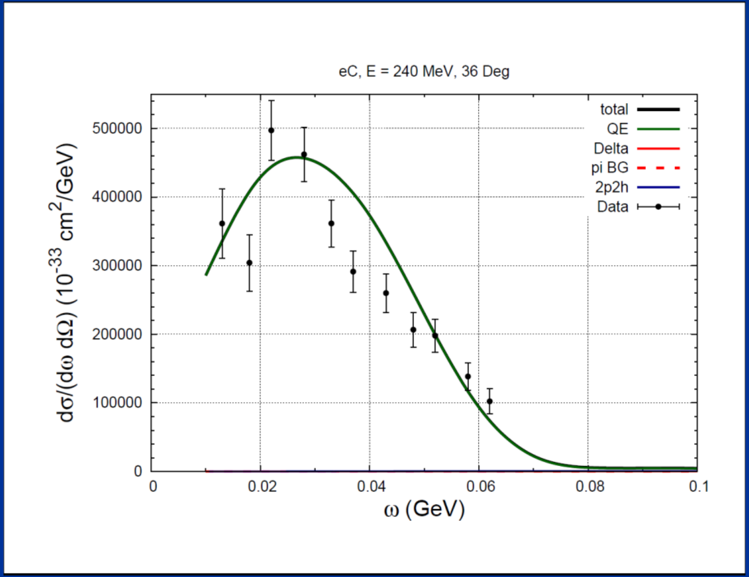


0.24 GeV, 36 deg, $Q^2 = 0.02$ GeV^2



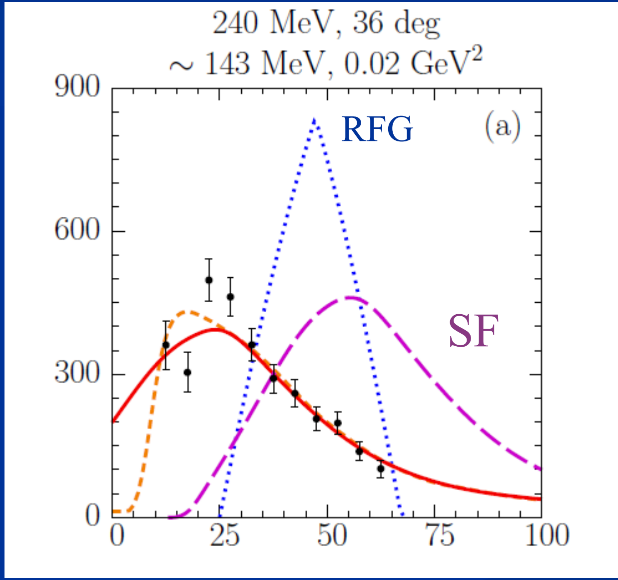
0.56 GeV, 60 deg, $Q^2 = 0.24$ GeV^2

Test with Electron Data



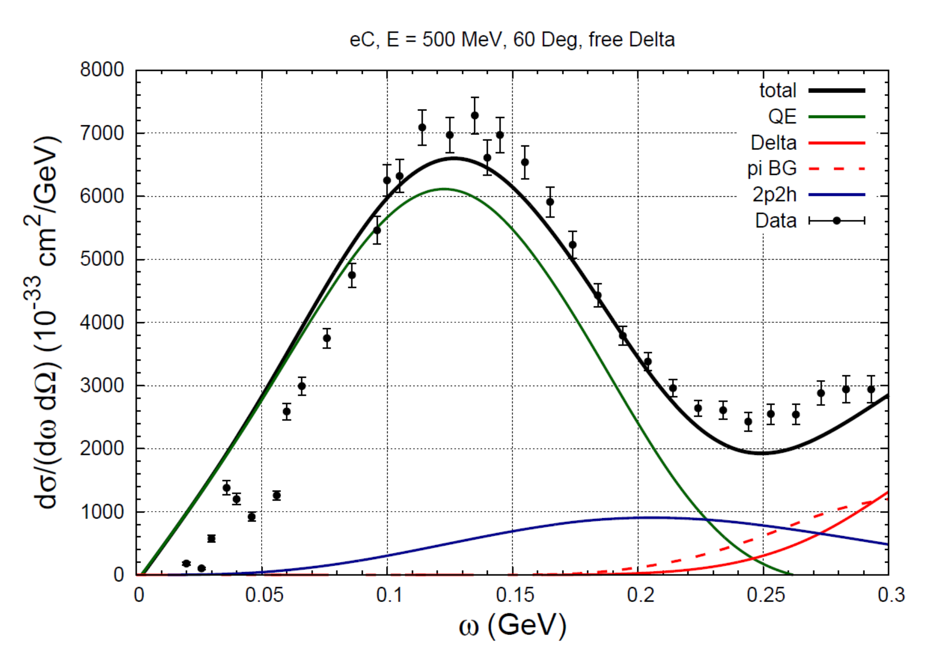
GiBUU

Dramatic influence of fsi

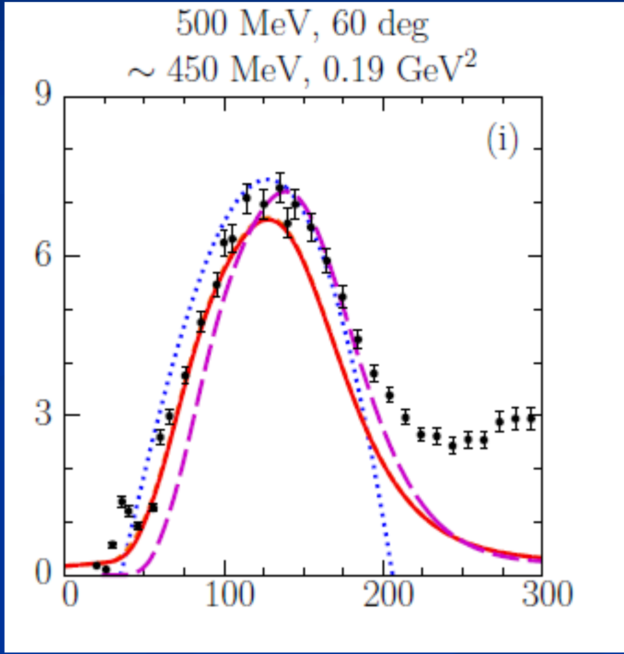


Ankowski, Benhar, Sakuda, PR D91 (2015) 03305

Test with Electron Data

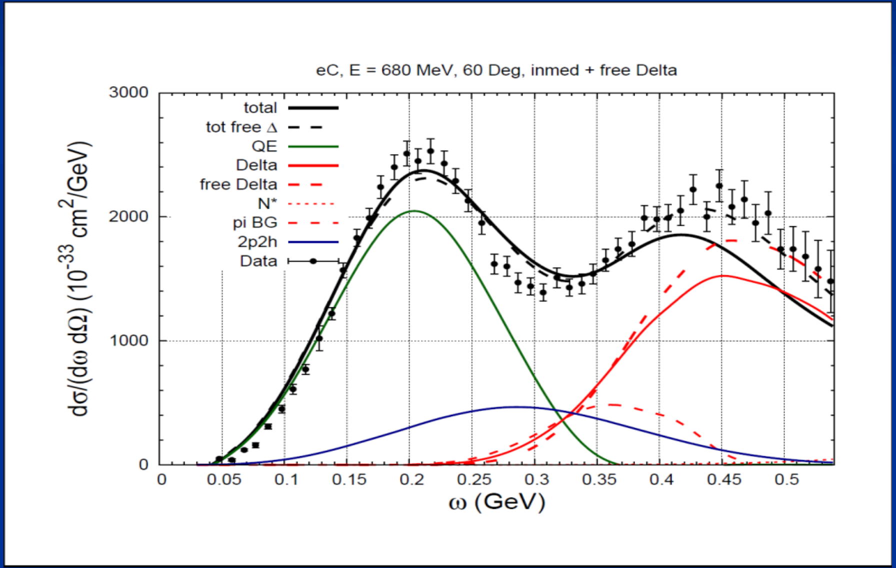


GiBUU 2016

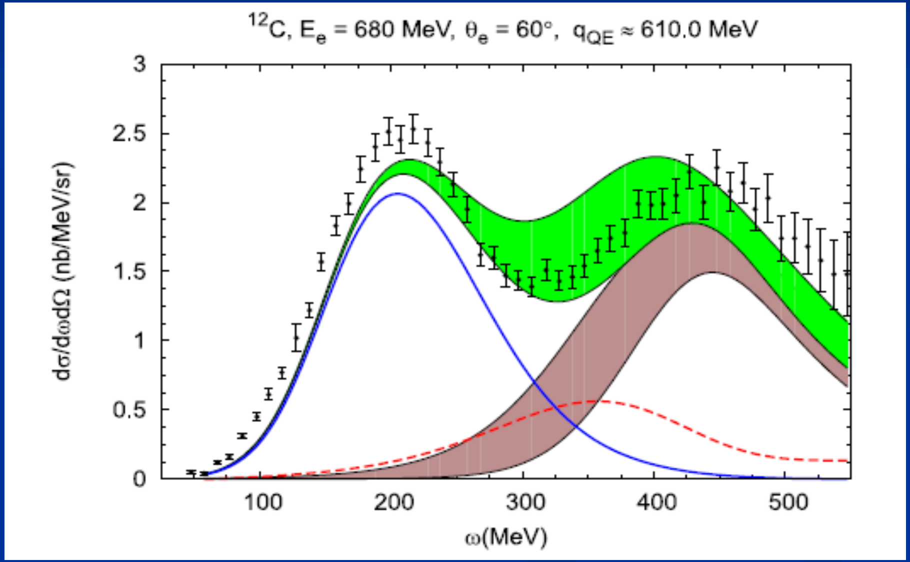


Ankowski. Benhar, Sakuta

Test with Electron Data



GiBUU



M.V. Ivanov et al, J.Phys. G43 (2016) 045101, Scaling

Agreement with data, without explicit RPA or src!

Now to (Anti-) Neutrinos

- QE, pion production, DIS straightforward
- 2p2h: purely transverse, use response from e

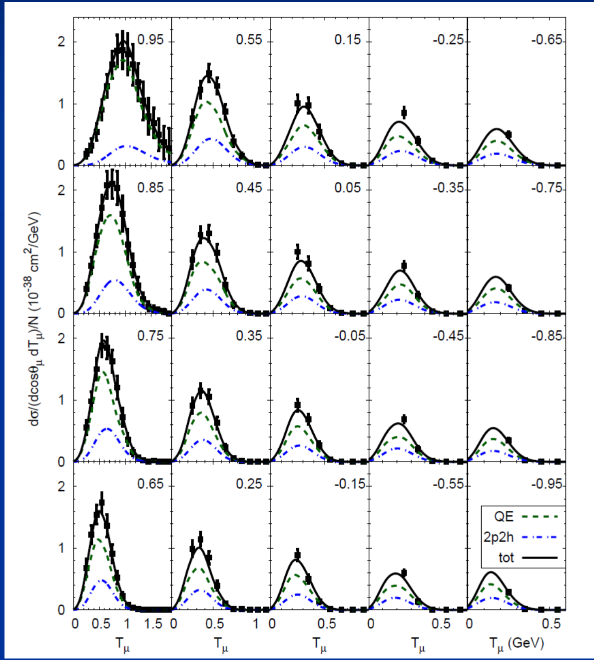
$$\frac{d\sigma}{d\Omega dE'} = \frac{G^2}{2\pi^2}E'^2\left[\frac{Q^2}{\vec{q}^{\,2}}\left(G_M^2\frac{\omega^2}{\vec{q}^{\,2}}+G_A^2\right)R_{\sigma\tau}(T)\cos^2\frac{\theta}{2}\right.$$
$$+2\left(G_M^2\frac{\omega^2}{\vec{q}^{\,2}}+G_A^2\right)R_{\sigma\tau}(T)\sin^2\frac{\theta}{2}$$
$$\left.\pm 2\frac{E+E'}{M}G_A G_M R_{\sigma\tau}(T)\sin^2\frac{\theta}{2}\right]$$

from: Martini et al.

$R_{\sigma\tau} \sim W_1$ from electron scattering

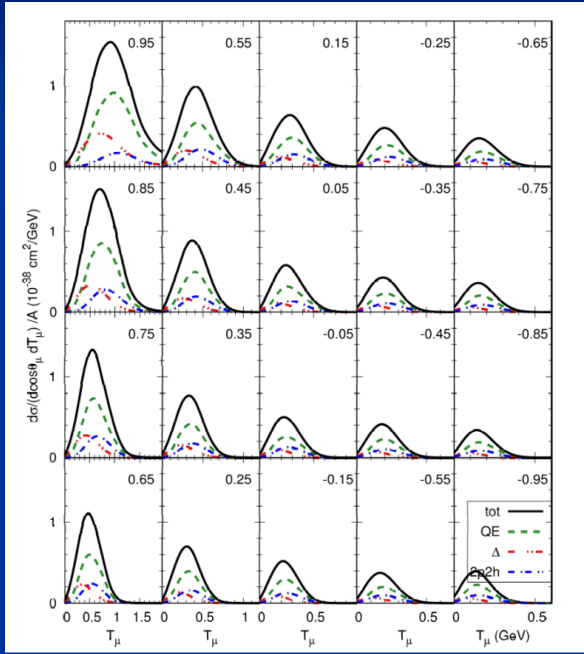
Same Response in V + A as in V · A ~ W_1 from Walecka 1975

Inclusive Lepton Kinematics



MiniBooNE C12 (QE + 2p2h)

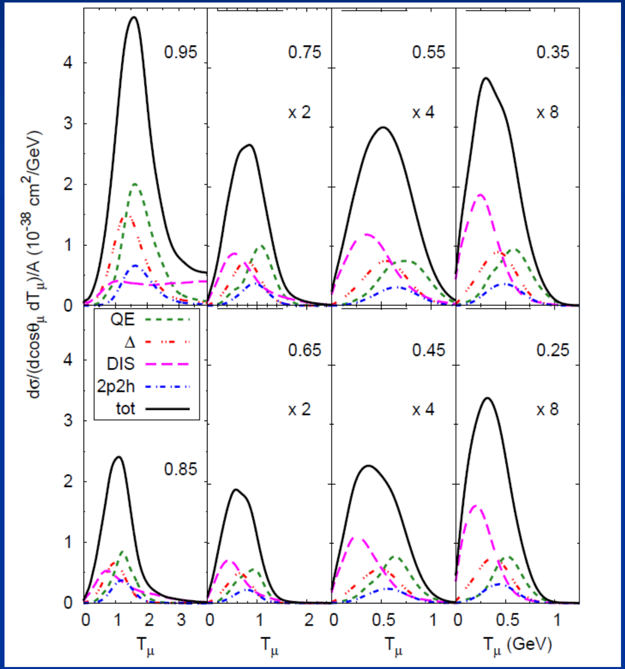
Gallmeister et al.
Phys.Rev. C94 (2016) no.3, 035502



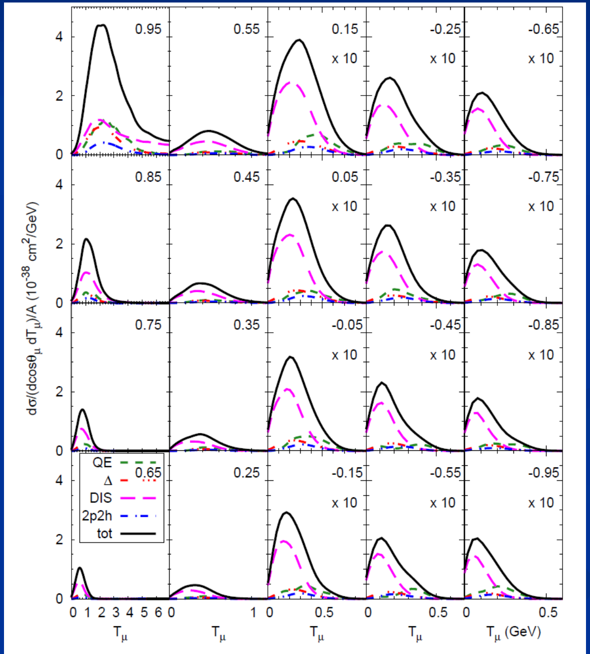
MicroBooNE Ar40 (fully inclusive)

2p2h ~ Δ

Inclusive Lepton Kinematics



NOvA C12



DUNE/LBNF Ar40

Gallmeister et al.
Phys.Rev. C94 (2016) no.3, 035502

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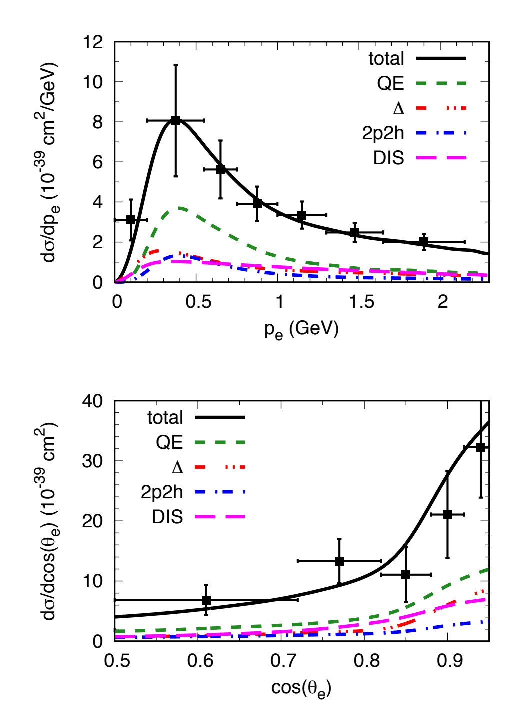
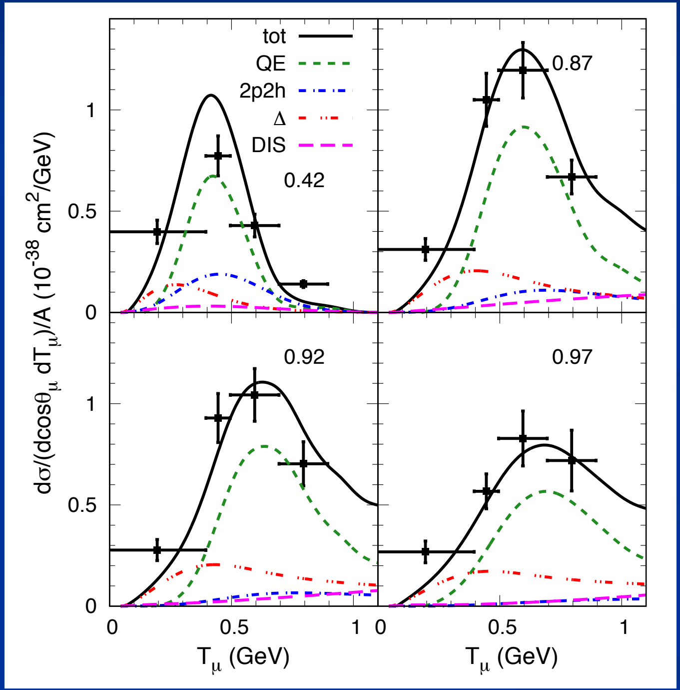
Comparison with T2K Data



T2K, ν_e



T2K, ν_μ

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Now to Final State Interactions

- Quantum-kinetic Transport Theory (Kadanoff-Baym, 60s, Botermans-Malfliet 90s))
- Basic object: not particle (as in MC generators), but single particle density matrix:

$$f(\mathrm{x},0,\mathrm{p}) = \frac{1}{(2\pi)^3} \int \mathrm{ds}\, e^{-i\mathrm{p}\cdot\mathrm{s}} \rho\left(\mathrm{x}-\frac{\mathrm{s}}{2}, \mathrm{x}+\frac{\mathrm{s}}{2}\right)$$

Here, for simplicity, given for on-shell particle, at time 0

Quantum-kinetic Transport Theory

On-shell drift term — 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

Inclusive and Exclusive Modelling

- GiBUU takes the final state of the first, initial lepton-nucleus interactions and propagates it (i.e. all particles in it) through the nuclear volume.

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

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

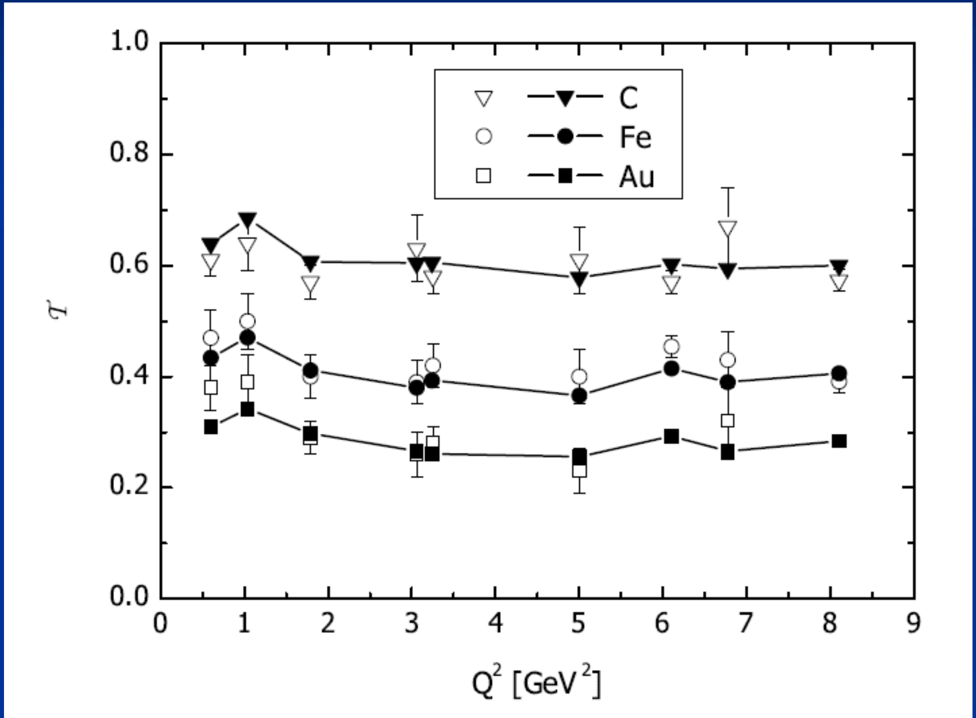
Transparency

- Transparency: integral measure of in-medium initial and final state effects
- Basic Definition:

$$T = 1/A * \sigma(A)/\sigma(N)$$

widely used in electron-A interaction physics and in in-medium physics

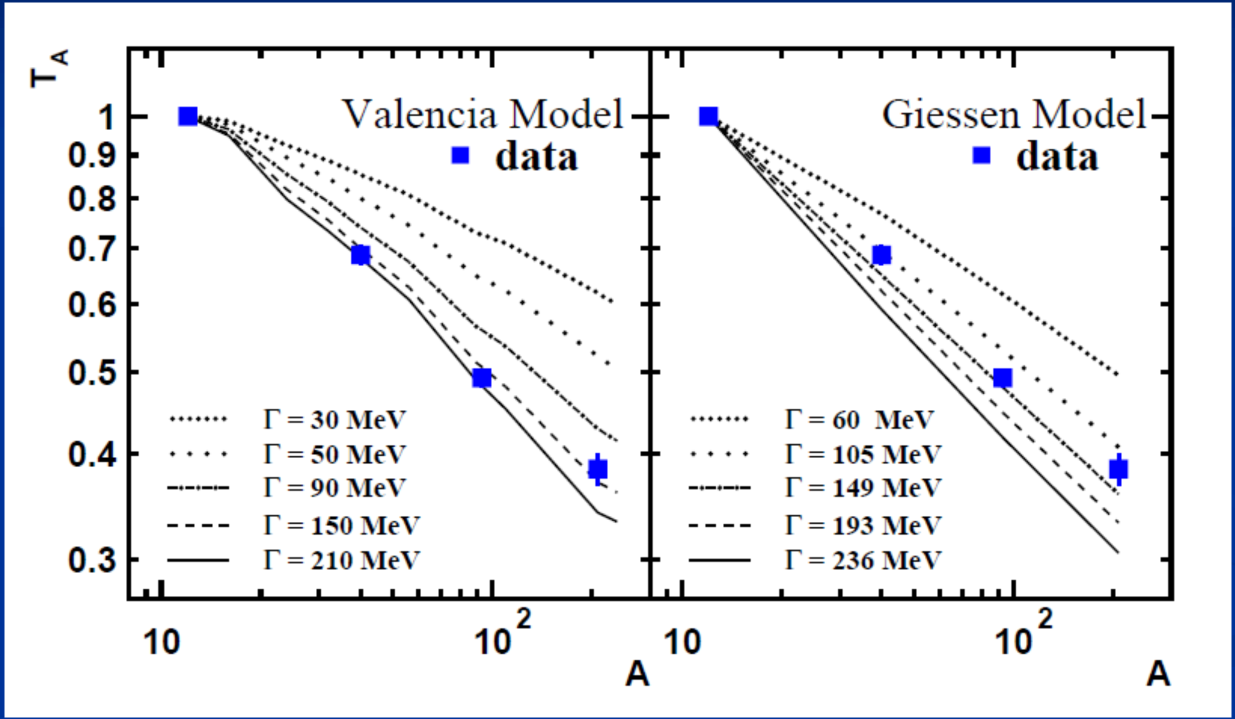
Proton Transparency



GiBUU: full symbols
Data: open symbols
JLAB, SLAC

from: J. Lehr, Giessen thesis, 2003

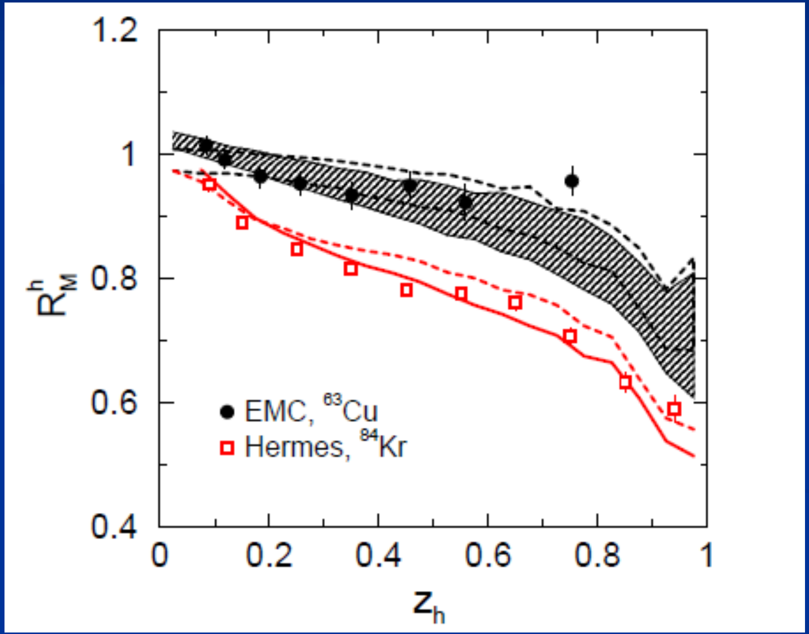
ω Meson Transparency



Transparency *T* gives integral information on in-medium width *Γ*

Kotulla et al, Phys.Rev.Lett. 100 (2008) 192302

Hadron Transparency

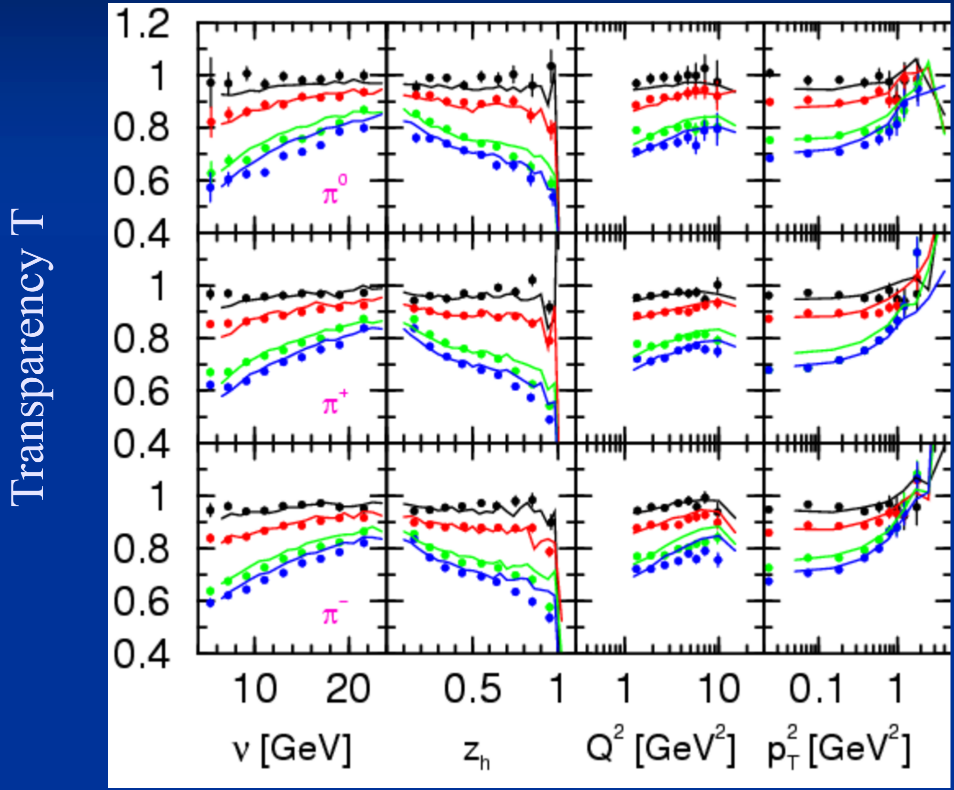


EMC: 200, 280 GeV leptons
Hermes: 28 GeV

$Z_h = E_h/\nu$

Distribution contains
Info on hadron formation
times

Hermes@27: A.Airapetian et al., NPB780(2007)1



$^{2}d_{1}$
$^{4}He_{2}$
$^{20}Ne_{10}$
$^{84}Kr_{36}$
$^{131}Xe_{54}$

For neutrinos:
get T distributions for
$T(E_h)$ and $T(p_T^2)$
Possible without reconstruction

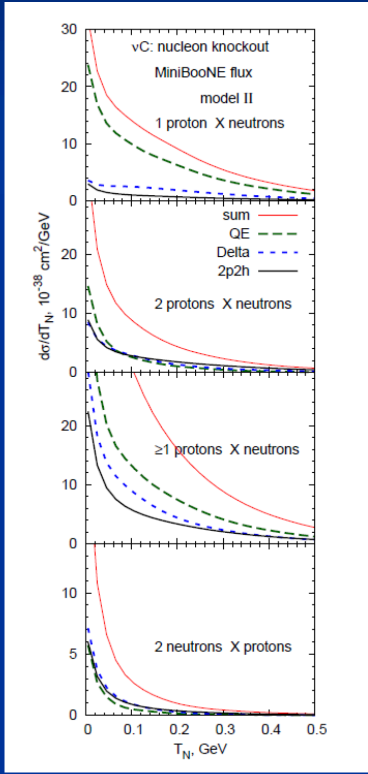
Proton Tagging and Multi-Nucleons

- FSI cause ‚avalanche effect‘ : one nucleon kicks out other nucleons and looses energy

  → 2 outgoing particles can come also from true, one-body QE (and $\Delta N \rightarrow NN$, pion absorption)

Proton Tagging and Multi-Nucleons

Lalakulich et al., Phys.Rev. C86 (2012) no.1, 014614



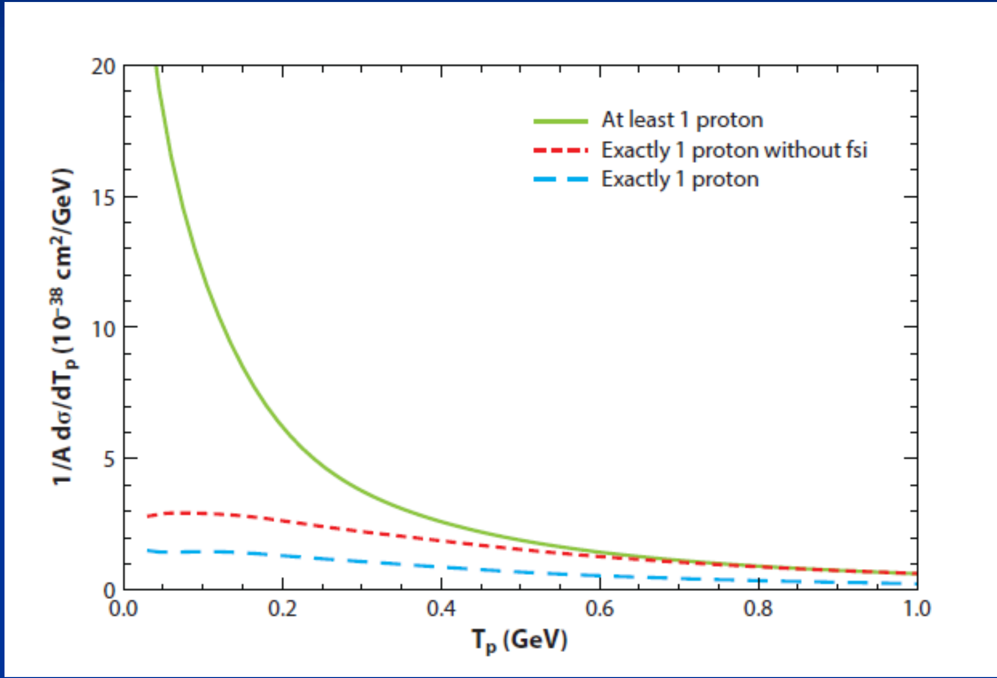
FSI cause ‚avalanche effect' : one nucleon kicks out other nucleons and looses energy

→ 2 outgoing particles can come also from true, one-body QE (and ΔN → NN, pion absorption)

HOWEVER:

events with one nucleon out can come only from true QE

Proton Spectrum



Transparencies contain integral Info on imaginary parts of self-energies
Loss of flux only, no info on where the flux goes.

Spectra give the full story, essential for influence of experimental acceptance cuts

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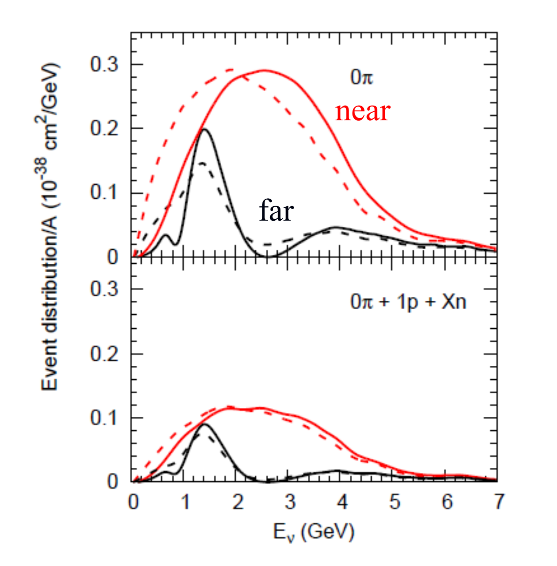
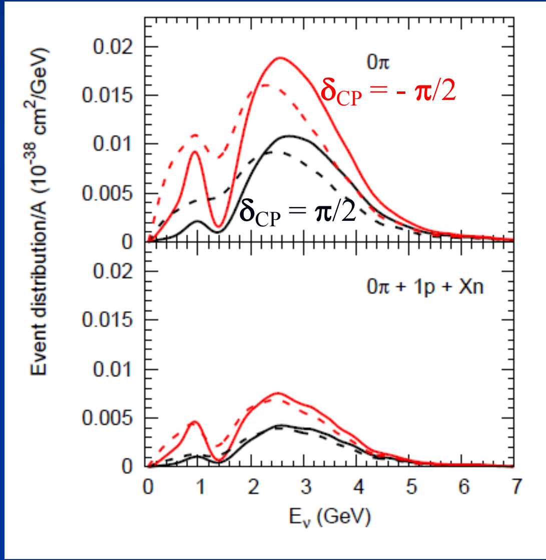
Proton Tagging and Multi-Nucleons



Event rates at near (LBNF) and far detector (DUNE)



δ_{CP} sensitivity at DUNE

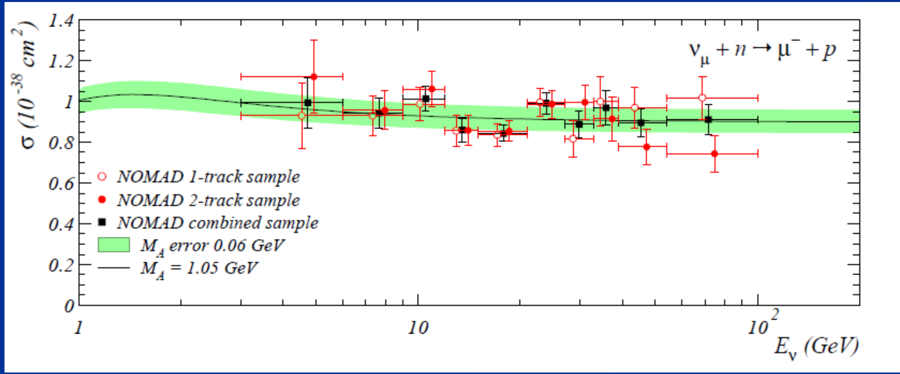
Mosel et al, Phys.Rev.Lett. 112 (2014) 151802

Solid: true E

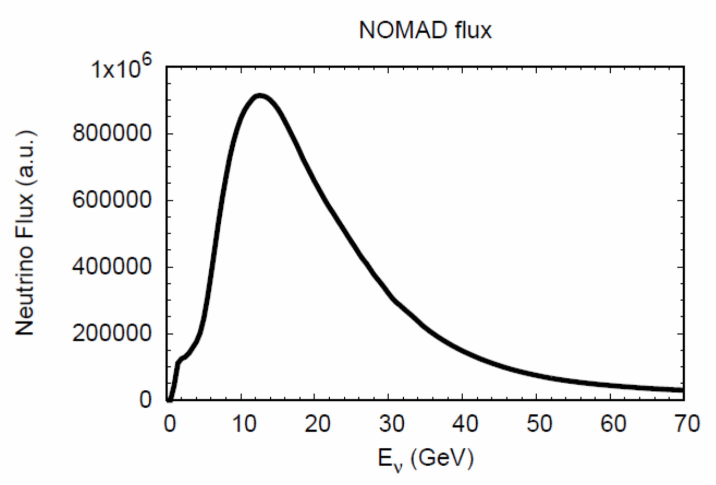
Dashed: reconstructed E

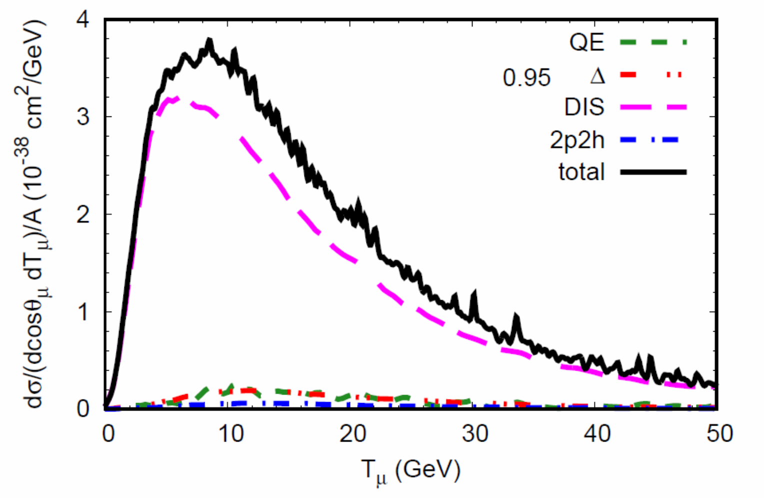
CCQE in MiniBooNE and NOMAD

- Different Event Selection
  - MiniBooNE: 1μ,0π
  - NOMAD: 1μ,0π (1track) + 1μ,0π,1p (two-track)



NOMAD Event-Rates





QE and 2p2h are very small parts of the total interaction

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Summary I

- Theory:
  - State-of-the-art calculations of inclusive cross sections provide a necessary (but not sufficient) check for a full description of νA reactions
  - Free-Space Monte Carlo Simulations miss the most important aspect of nuclei: potentials and binding!
  - Quantum-kinetic Transport Theory is the (well established, and – in other fields of physics - widely used) method to deal with potentials and binding in non-equilibrium processes, allows for off-shell transport

Summary II

- Experiment:
  - Give data with as little generator contamination as possible. No-go is, e.g., flux cuts to mimick lepton acceptance
  - QE-events are experimentally indistinguishable from ‚stuck-pion‘ events -> give your cross section for these reabsorption events (as MB did!). Aim for consistency: use the same theory to calculate both the explicit and the reabsorbed pion events
  - At DUNE (and MINERvA) DIS dominates the total event rate. It should give interesting info on W_3 in medium (EMC effect for neutrinos)