Neutrino Interactions with Nucleons and Nuclei

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Based on work with
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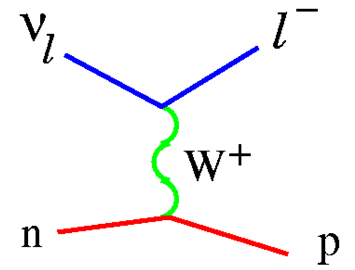
Motivation

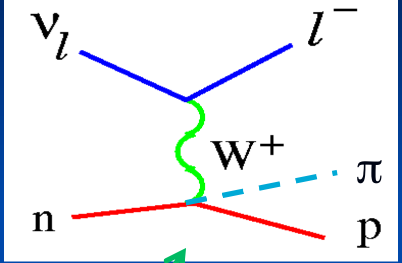
- Neutrino properties can be extracted from Long Baseline Experiments only if energy is known
- Both calorimetry and QE-based energy reconstruction methods require understanding of the full event
- Theory has to be able to describe the full final states of all particles, inclusive X-sections are not sufficient

Neutrino-nucleon cross section

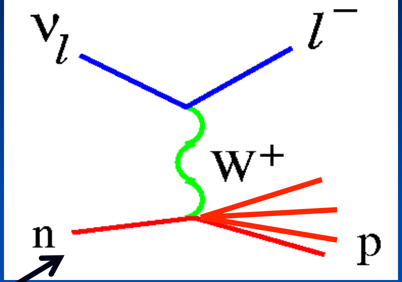
CCQE

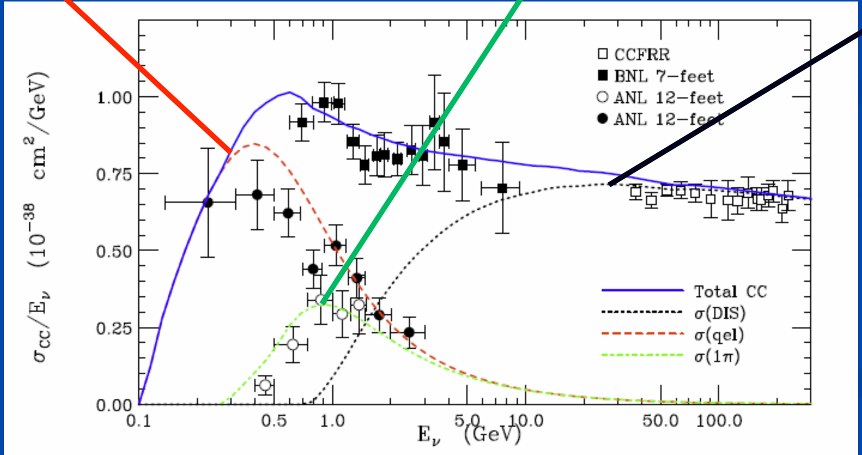


1π



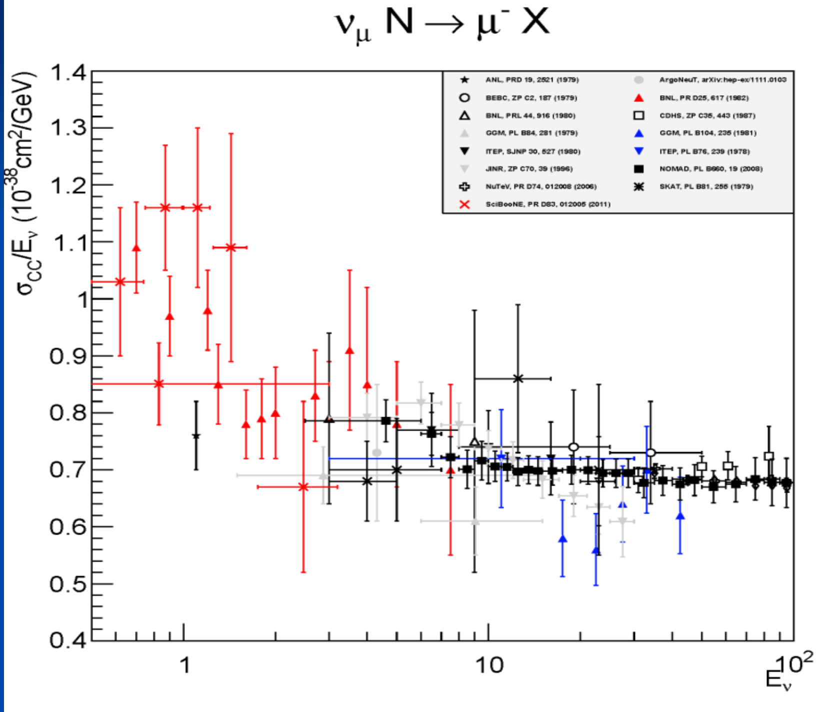
DIS





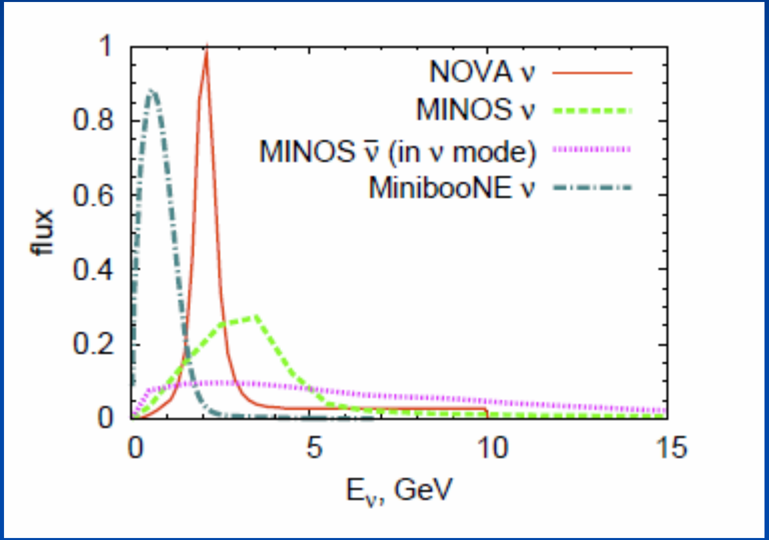
note:
10^{-38} cm² = 10^{-11} mb

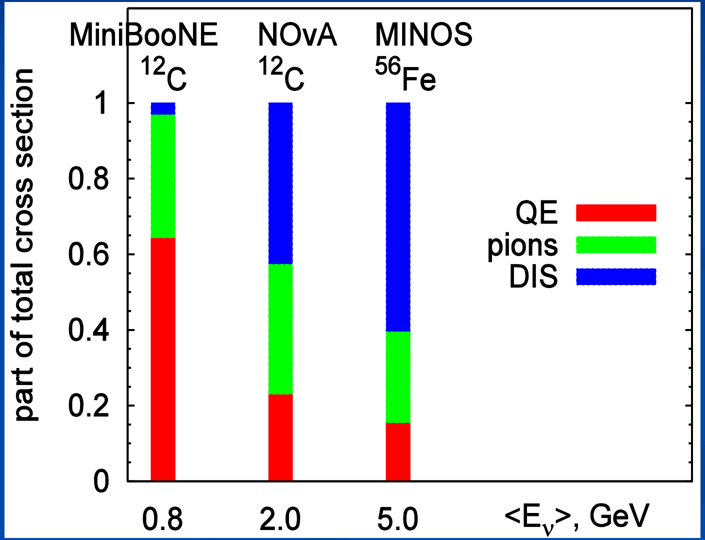
Neutrino-Nucleon Cross Sections



Neutrino Beams

- Neutrinos do not have fixed energy:

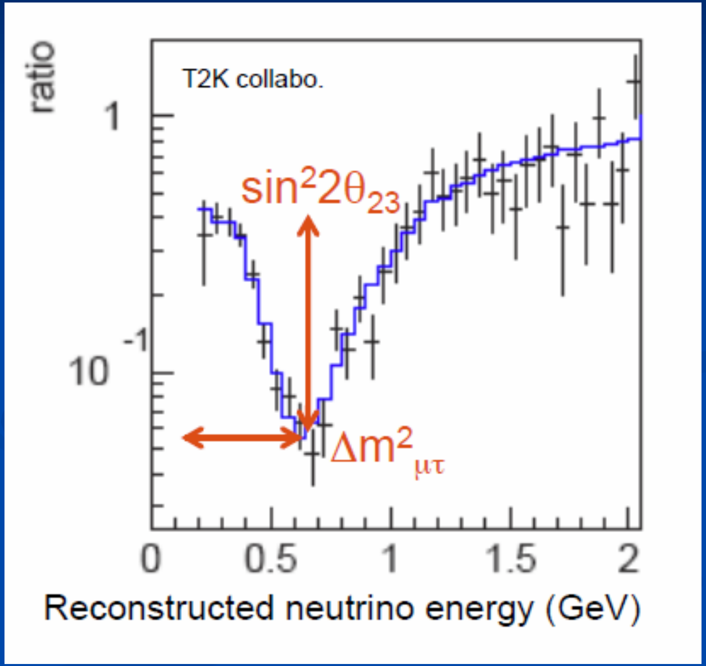




Have to reconstruct energy from final state of reaction

Observable Oscillation Parameters

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$



Neutrino Oscillations

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;\simeq\;& \sin^2 2\theta_{13}\, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
-\;& \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+\;& \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+\;& \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \\
\equiv\;& O_1 \;+\; O_2(\delta) \;+\; O_3(\delta) \;+\; O_4 \;.
\end{aligned}
$$

$$\Delta = \frac{\Delta m^2_{21} L}{4E} \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \xi = \cos\theta_{13}\, \sin(2\theta_{12})\, \sin(2\theta_{23})$$

$$\hat{A} = \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}} \qquad \delta = \text{CP violating phase}$$

appearance probability

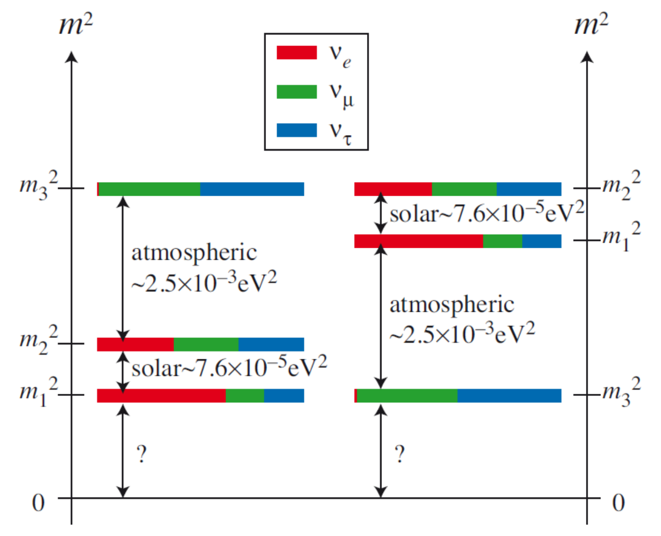
Vacuum oscillation

Matter effects,
n_e = electron density
Depends on sign of Δ_{31}

Oscillation depends on difference of (squared) masses only

Oscillation Signal

Dependence on Hierarchy and Mixing Angle



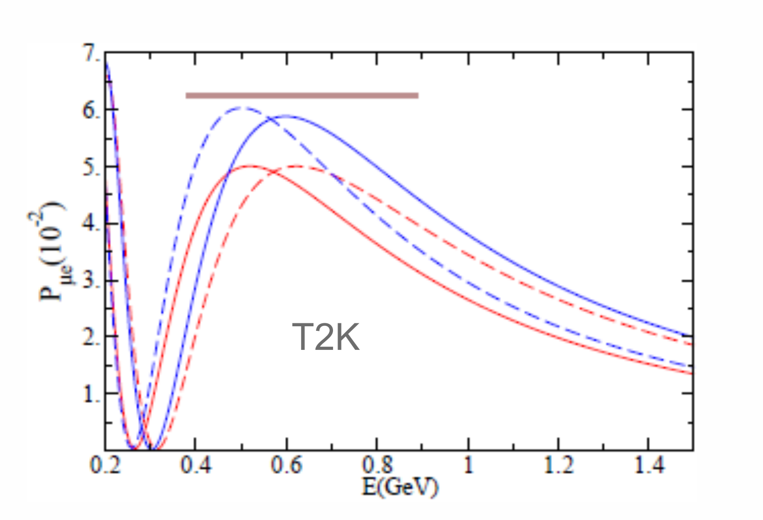


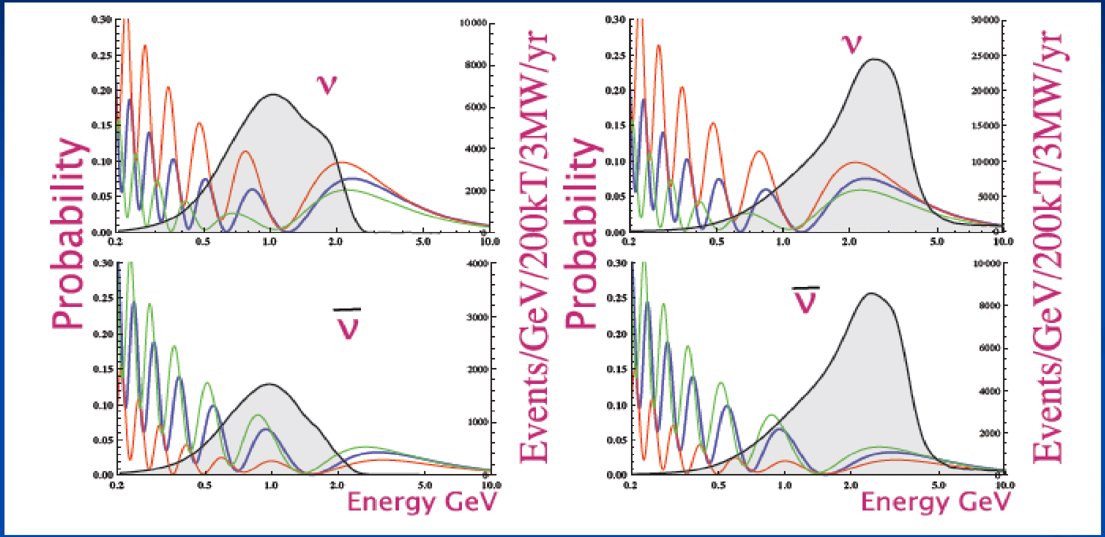
Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

D.J. Ernst et al., arXiv:1303.4790 [nucl-th]

- Energy has to be known better than 50 MeV
Shape sensitive to hierarchy and sign of mixing angle

LBNE, δ_{CP} sensitivity

From: Bishai et al., hep-ex 12034090



8 GeV

60 GeV

proton energy

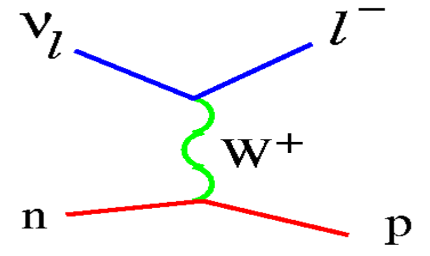
From:
Bishai et al
arXiv:1203.409

$\delta_{CP} = 0$
$\delta_{CP} = \pi/2$
$\delta_{CP} = -\pi/2$

Need energy within 100 MeV to distinguish between different δ_{CP}

Energy Reconstruction by QE

- In QE scattering on nucleon at rest, only *l* +*p*, *0* π, is outgoing. lepton determines neutrino energy:

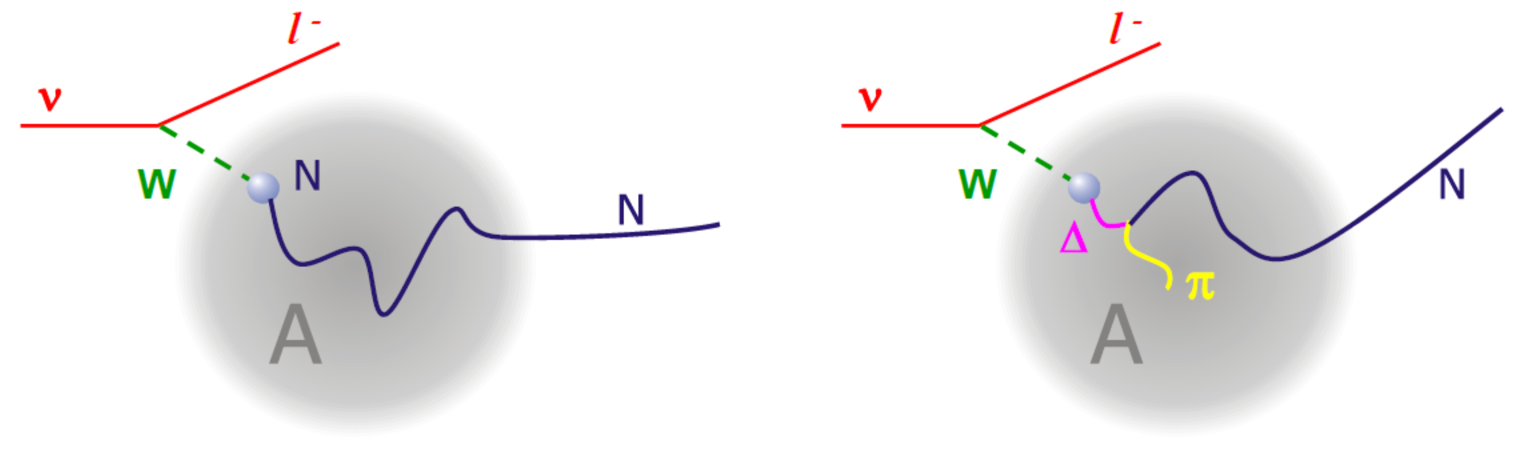


$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

- Trouble: all presently running exps use nuclear targets

1. Nucleons are Fermi-moving
2. Final state interactions may hinder correct event identification

FSI in Nuclear Targets



Complication to identify QE, entangled with π production

Both must be treated at the same time

Nuclear Targets (K2K, MiniBooNE, T2K, MINOS, Minerva,LBNE)

Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU** : **Theory and Event Simulator**
  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
  Code available from **gibuu.hepforge.org**

  Mine of information on theoretical treatment of potentials, collision terms, spectral functions and cross sections, useful for any generator

Transport Equation

- Kadanoff-Baym equation for space-time development of one particle spectral phase space density *F (Wigner Function)* after gradient expansion

$$\mathcal{D}F(x,p) + \mathrm{tr}\left\{\mathrm{Re}\tilde{S}^{\mathrm{ret}}(x,p), -\mathrm{i}\tilde{\Sigma}^{<}(x,p)\right\}_{\mathrm{pb}} = C(x,p).$$

F = spectral phase-space density: $F(x,p) = -2f(x,p)\mathrm{tr}[\mathrm{Im}\,(\tilde{S}^{\mathrm{ret}}(x,p))\gamma^0],$

$$\mathcal{D}F = \{p_0 - H, F\}_{\mathrm{pb}} \quad \text{with } H = E^*(x,p) - \mathrm{Re}\tilde{\Sigma}^0_V(x,p).$$

Transport Equation

Collision term

$$\mathcal{D}F(x,p) + \mathrm{tr}\left\{\mathrm{Re}\tilde{S}^{\mathrm{ret}}(x,p), -\mathrm{i}\tilde{\Sigma}^{<}(x,p)\right\}_{\mathrm{pb}} = C(x,p).$$

Drift term

$$\left[\left(1-\frac{\partial H}{\partial p_0}\right)\frac{\partial}{\partial t} + \frac{\partial H}{\partial \mathbf{p}}\frac{\partial}{\partial \mathbf{x}} - \frac{\partial H}{\partial \mathbf{x}}\frac{\partial}{\partial \mathbf{p}} + \frac{\partial H}{\partial t}\frac{\partial}{\partial p^0} + \text{KB term}\right] F(x,p)$$

$$= \text{- loss term} + \text{gain term}$$

Kadanoff-Baym equation

- LHS: drift term + backflow (KB) terms
- RHS: collision term = - loss + gain terms

Collision term

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

with

$$\begin{aligned}
F(x,p) \quad &= \quad 2\pi g A(x,p) f(x,p) \\
\bar{F}(x,p) \quad &= \quad 2\pi g A(x,p) \left[1 - f(x,p)\right]
\end{aligned}$$

More complicated expressions for 3-body interactions (e.g. pion absorption)

BM Simplification

Problem: ‚backflow‘ term does not directly depend on *F*

Botermans-Malfliet simplification for equilibrium, correction terms are of higher order in gradients

$$\tilde{\Sigma}^{<}_{\mathrm{eq}}(x,p) = \mathrm{i}\Gamma_{\mathrm{eq}}(x,p) f_{\mathrm{eq}}(x,p),$$
$$\tilde{\Sigma}^{>}_{\mathrm{eq}}(x,p) = -\mathrm{i}\Gamma_{\mathrm{eq}}(x,p)[1 - f_{\mathrm{eq}}(x,p)]$$

$$\Gamma(x,p) = -2\mathrm{Im}\tilde{\Sigma}^{ret}(x,p)$$

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

BM term now ~ Γ, controls off-shell transport

Spectral Function

$$F(x,p) = -2f(x,p)\,\mathrm{tr}[\mathrm{Im}\,(\tilde{S}^{\mathrm{ret}}(x,p))\gamma^0],$$

$$A(x,p) := \frac{1}{g}\mathrm{tr}[\hat{A}(x,p)\gamma^0] = -\frac{1}{g\pi}\mathrm{tr}[\mathrm{Im}\,(\tilde{S}^{\mathrm{ret}}(x,p))\gamma^0],$$

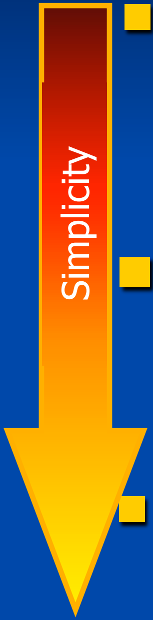
$$F(x,p) = 2\pi g f(x,p) A(x,p).$$

„Spectral Phase Space Density“
= Product of phase-space density *f* and spectral function *A*

GiBUU and MC Event Generators

- Phase-space distribution *f* is solved by a testparticle method, well known in numerical fluid dynamics
- Care is taken to respect relativity and detailed balance
- GiBUU reduces to MC event generators if
  - All particles on shell
  - No potentials present
  - No in-medium effects

Theoretical Basis of GiBUU



- Kadanoff-Baym equation (1960s)
  - full equation can not be solved yet
    - not (yet) feasible for real world problems
- Boltzmann-Uehling-Uhlenbeck (BUU) models
  - Boltzmann equation as gradient expansion of Kadanoff-Baym equations, in Botermans-Malfliet representation (1990s): **GiBUU**
- Cascade models (typical event generators, NUANCE, GENIE, NEUT,..)
  - no mean-fields, primary interactions and FSI not consistent

Practical Basis: GiBUU

- one transport equation for each particle species (61 baryons, 21 mesons)
- coupled through the potential in *H* and the collision integral *C*
- W < 2.5 GeV: Cross sections from resonance model (PDG and MAID couplings), consistent with electronuclear physics
- W > 2.5 GeV: particle production through string fragmentation (PYTHIA), with smoothened transition

- **GiBUU**: Only \`Neutrino Event Generator´ that has widely been tested with various hadronic and em reactions, **NO TUNING to nuclear data (except 2p2h)**

GiBUU Ingredients: ISI

- In-medium corrected primary interaction cross sections, boosted to rest frame of moving bound nucleon in local Fermigas
- Includes spectral functions for baryons and mesons (binding + collision broadening)
- *Hadronic* couplings for FSI taken from PDG (Manley anal.)
- *Vector* couplings taken from electro-production (MAID)
- *Axial* couplings modeled with PCAC

Reaction Types

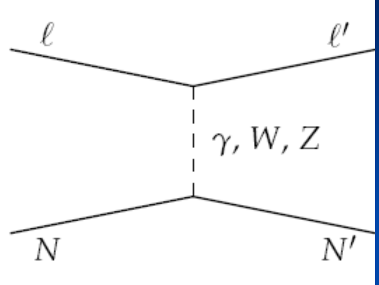
- 2 major reaction types relevant:

1. QE scattering
   1. true QE (single particle interaction)
   2. many-particle interactions (RPA + 2p2h + spectral functions)
2. Pion production
   1. through nucleon resonances (W < 2 GeV)
   2. through DIS (W > 2 GeV)

- All reaction types are entangled:
  final states may look the same

QE Scattering

Quasielastic Scattering



$$J^{\mu}_{QE} = \left(\gamma^{\mu} - \frac{\not{q}\, q^{\mu}}{q^2}\right) F_1^V + \frac{i}{2M_N}\sigma^{\mu\alpha} q_{\alpha} F_2^V + \gamma^{\mu}\gamma_5 F_A + \frac{q^{\mu}\gamma_5}{M_N} F_P$$

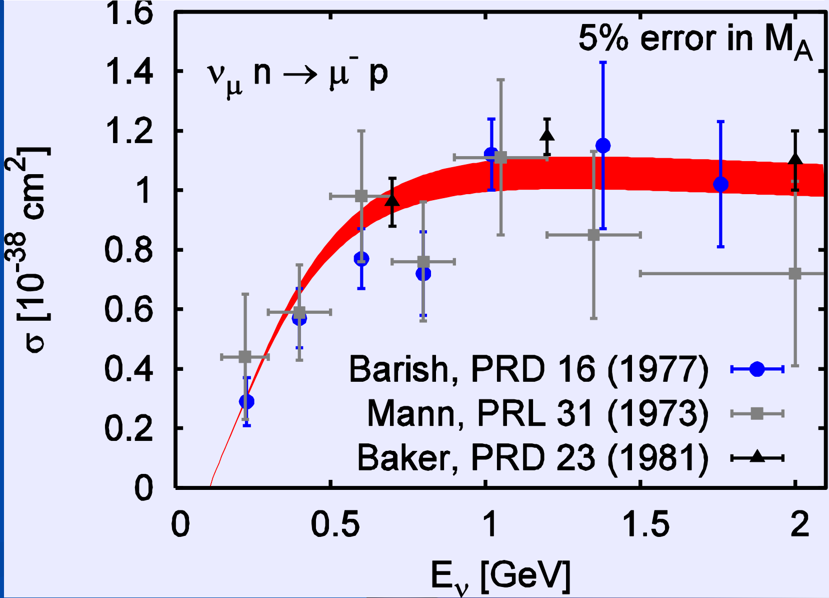
- Vector form factors from *e* –scattering
- axial form factors

  $F_A \Leftrightarrow F_P$ and $F_A(0)$ via **PCAC**

  dipole ansatz for F_A with

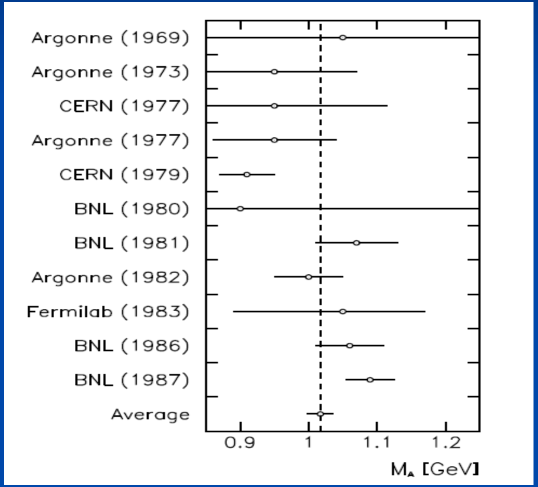
  M_A= 1 GeV**:**

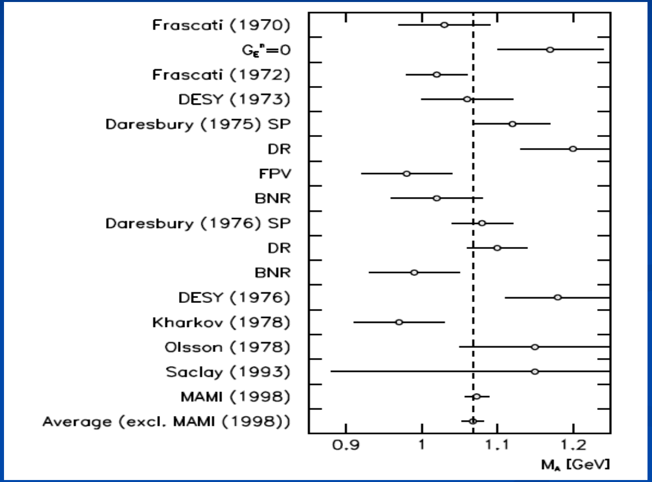
$$F_A(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{M_A^2}\right)^2}$$



Axial Formfactor of the Nucleon

- neutrino data agree with electro-pion production data





$M_A \cong 1.02$ GeV world average

$M_A \cong 1.07$ GeV world average

Dipole ansatz is simplification, not good for vector FF

Spectral Functions

- Single particle spectral functions absorb effects of interactions in particle properties
- Free Fermi gas (in generators):

  $$P_h(\mathbf{p},E) = \Theta(\mathbf{p_F} - \mathbf{p})\,\delta(E+T_p)$$

  spiky E-dep. leads to artifacts in response
- Now: dress particle with interactions, mean field and/or additional interactions → quasiparticles

Spectral Function in GiBUU

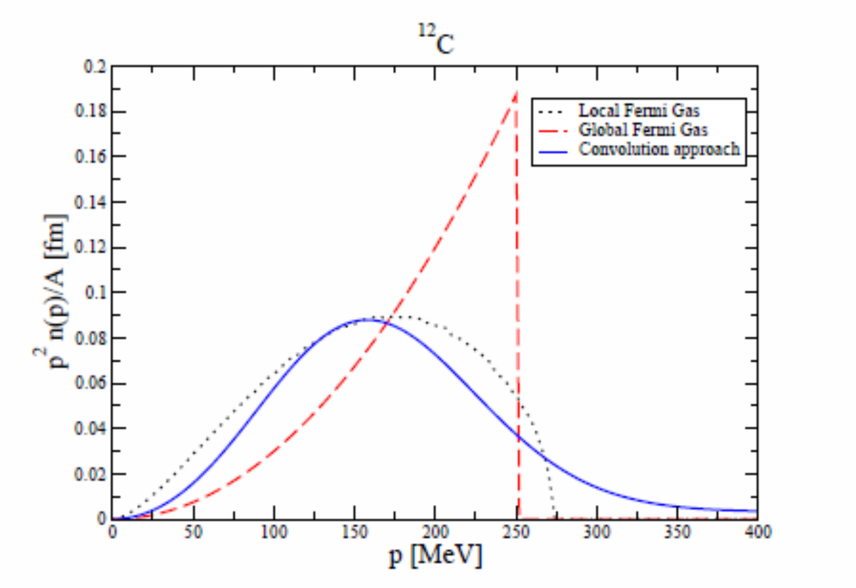
$$P_h(\mathbf{p}, E) = \int_{NV} \mathrm{d}^3x \left[\Theta(p_F(\mathbf{x}) - \mathbf{p})\, \delta\left(E + T_p + V(\mathbf{x}, \mathbf{p})\right)\right]$$

Two essential features:

1. Local TF momentum distribution removes artifacts of sharp cut at p_F
2. Particles bound in momentum- and coordinate-dependent potential, integration removes delta-function spikes in energy

Spectral function in GiBUU contains interactions in mean field

Nuclear Groundstate the same for all processes!



From:
Alvarez-Ruso, Hayato, Nieves

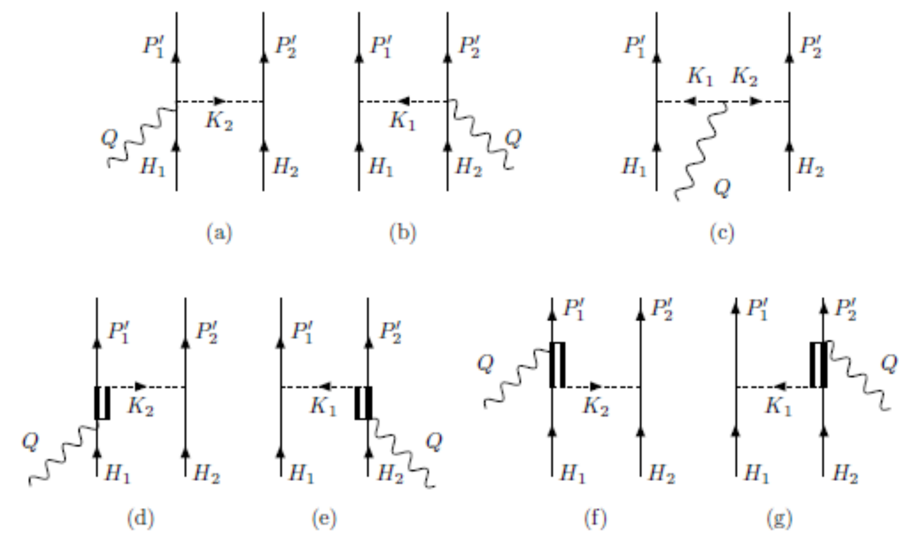
Also *E*-dependence is different from Global Fermi Gas: momentum and x-dependent otential leads to smooth behavior

GiBUU uses Local Fermi Gas + Nukleon mean field potential

2p-2h in Generators

- Mandatory: same nuclear ground state for 1p-1h and 2p-2h processes
  - Generators: free Fermi gas
  - Nieves 2p-2h model: dressed Fermi gas in mean field potential
- Nieves model cannot be simply added to simple generators: inconsistent → inconclusive

2p-2h and spectral functions



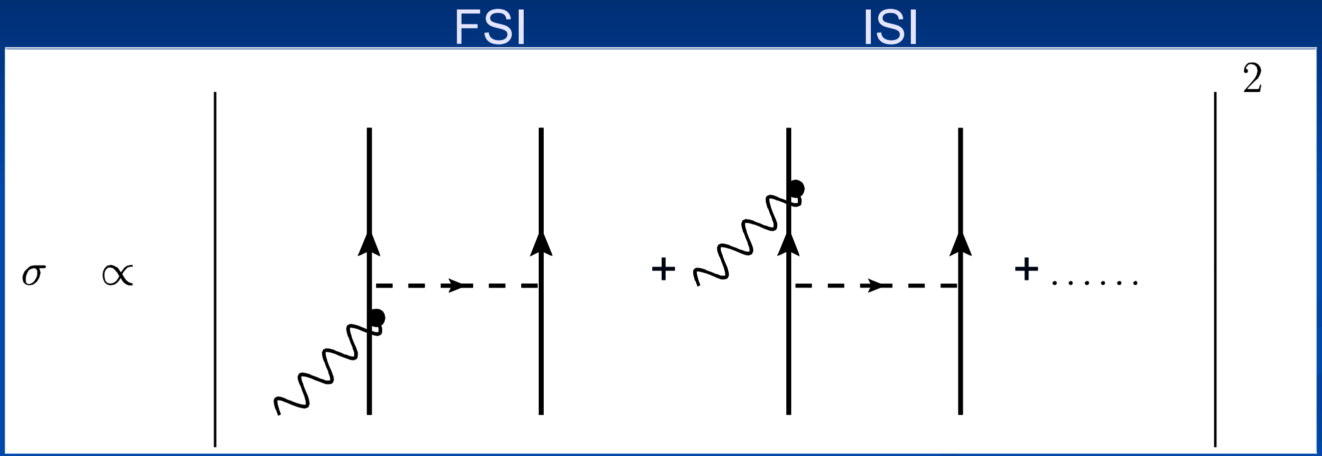
M.B. Barbaro et al, 2011

Cross section= sum over amplitudes squared

2p-2h and spectral functions

- Part of 2p-2h interactions is contained in spectral function
- Another part is missing!

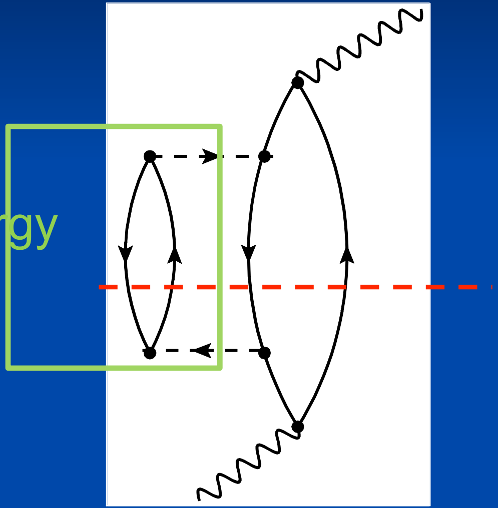
2p-2p excitations and spectral functions



Can also be obtained by cutting selfenergy diagrams (Optical Theorem, Cutkosky rules)

2p-2p excitations and spectral functions

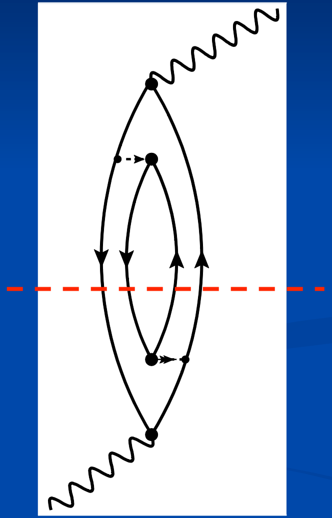
2nd ampl. squared



Hole Spectral Function

$$\mathcal{A}(x,p) = \frac{1}{\pi} \frac{\sqrt{p^{*2}}\,\Gamma_{\mathrm{med}}}{[p^{*2} - m^{*2}]^2 + p^{*2}\Gamma_{\mathrm{med}}^2}$$

Interference term squared

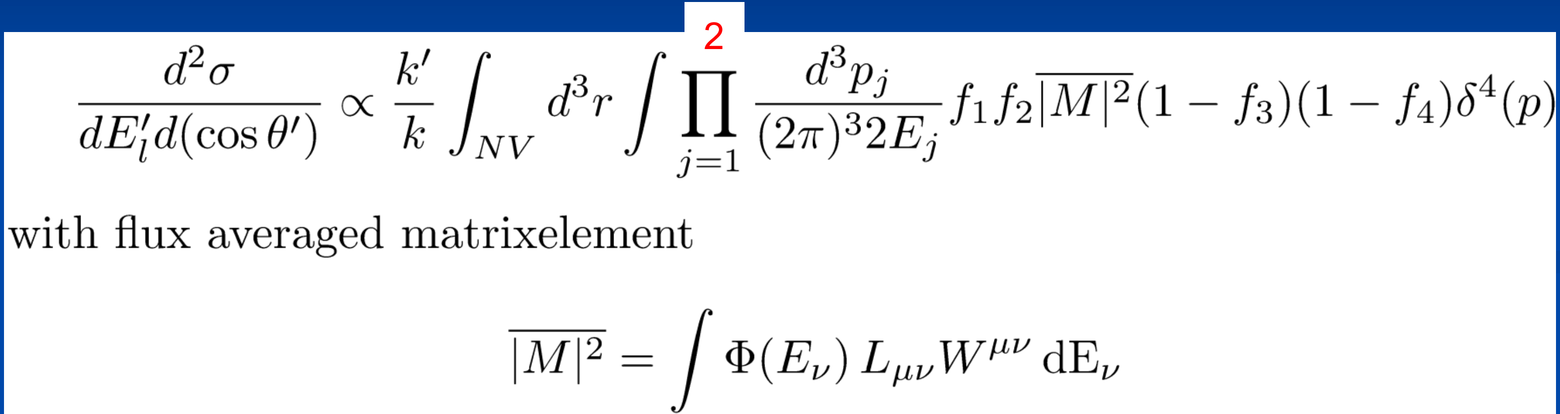


No selfenergy,
Vertex correction,
not included in spectral
function

Interference of ISI and FSI

GiBUU 2p2h

- Model for $\nu + p_1 + p_2 \rightarrow p_3 + p_4 + \mu$ (no recoil)



$$\frac{d^2\sigma}{dE_l' \, d(\cos\theta')} \propto \frac{k'}{k} \int_{NV} d^3r \int \prod_{j=1}^{2} \frac{d^3p_j}{(2\pi)^3 2E_j} f_1 f_2 \overline{|M|^2} (1-f_3)(1-f_4)\delta^4(p)$$

with flux averaged matrixelement

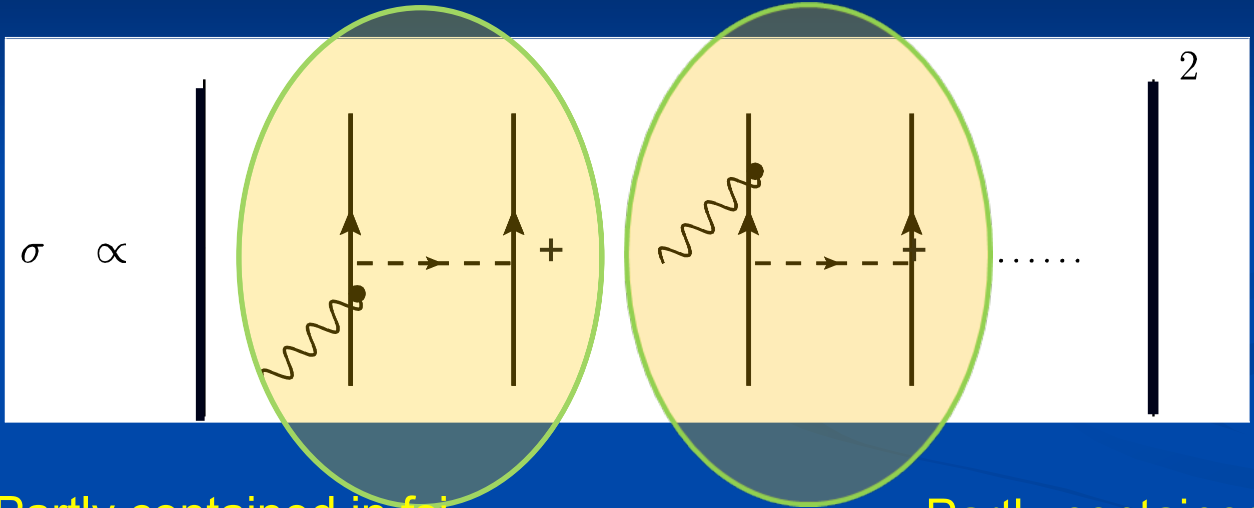
$$\overline{|M|^2} = \int \Phi(E_\nu)\, L_{\mu\nu} W^{\mu\nu} \, \mathrm{dE}_\nu$$

Flux smears out details in hadron tensor *W*
W contains 2p-2h and poss. RPA effects

GiBUU 2p2h

- $W^{\mu\nu} = F(Q^2)\, P^{\mu\nu}_T\,(q)$
- Integration over initial states; final state phase space not integrated,
- Final state phase space calculated in 2p cm-system, then Lorentz-boosted to lab and Pauli-blocking applied

2p-2h Problems



Partly contained in fsi

Partly contained in SF

Double Counting Problem for 2p2h Implementation in Generators

Only adhoc ‚tune‘ in GiBUU

- Educated guess for 2p2h in GiBUU with tuned strength
- Big open question: up to which neutrino energies (or Q^2, ν) are models good?
- Compare with Lightbody-Bosted analysis

Pions

Pion Production

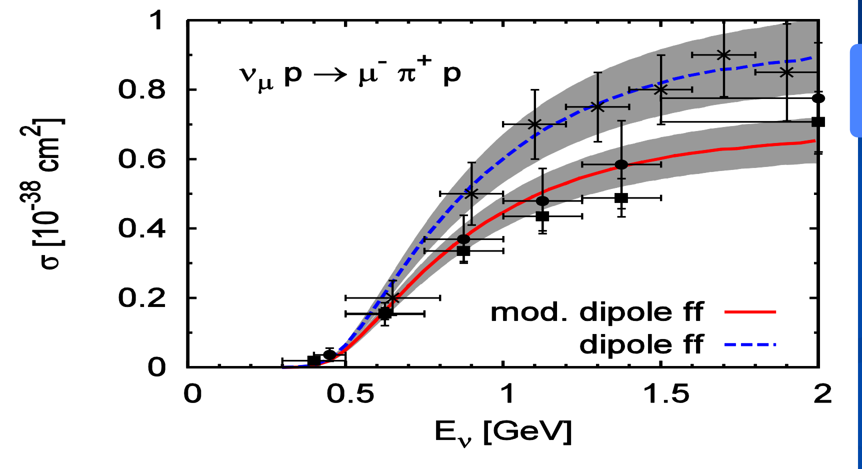
$$J_{\Delta}^{\alpha\mu} = \left[\frac{C_3^V}{M_N}\left(g^{\alpha\mu}\not{q} - q^{\alpha}\gamma^{\mu}\right) + \frac{C_4^V}{M_N^2}\left(g^{\alpha\mu} q \cdot p' - q^{\alpha} p'^{\mu}\right) + \frac{C_5^V}{M_N^2}\left(g^{\alpha\mu} q \cdot p - q^{\alpha} p^{\mu}\right)\right]\gamma_5 + \frac{C_3^A}{M_N}\left(g^{\alpha\mu}\not{q} - q^{\alpha}\gamma^{\mu}\right) + \frac{C_4^A}{M_N^2}\left(g^{\alpha\mu} q \cdot p' - q^{\alpha} p'^{\mu}\right) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M_N^2} q^{\alpha} q^{\mu}$$

- 13 resonances with W < 2 GeV, non-resonant single-pion background, DIS
- pion production dominated by **P_{33}(1232) resonance**:
- C^V from electron data (MAID analysis with CVC)
- C^A from fit to neutrino data (experiments on hydrogen/deuterium),
  so far only C^A_5 determined, for other axial FFs only educated guesses

Pions

- Pion production amplitude
  = resonance contrib + background (Born-terms)
- Resonance contrib
- *V* determined from e-scattering (MAID)
- *A* from PCAC ansatz
- Background:
  - Up to about Δ obtained from effective field theory
  - Beyond Δ unknown
  - 2 pi BG totally unknown

Pion Production

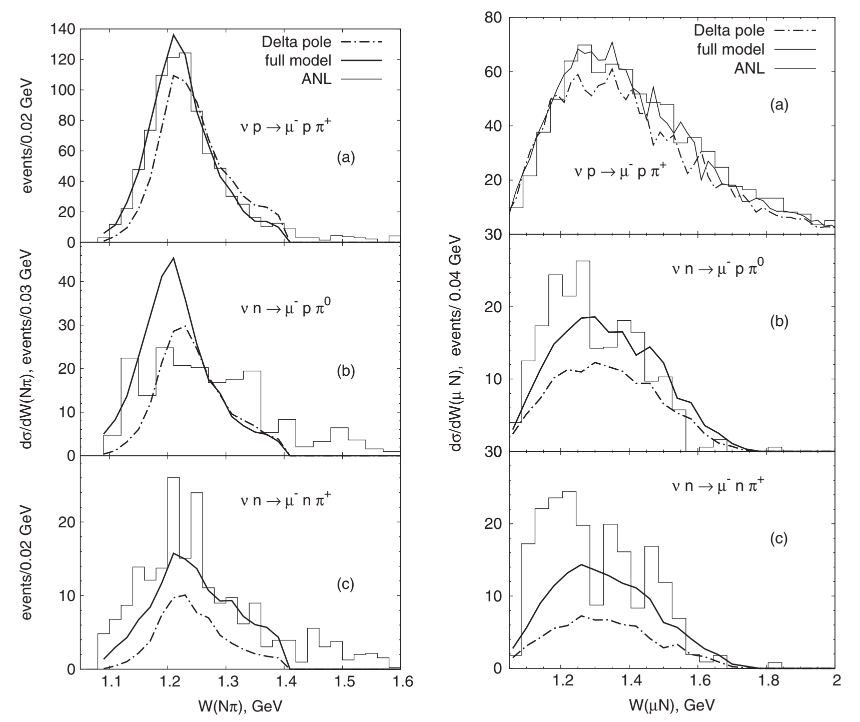


10 % error in $C_5^A(0)$

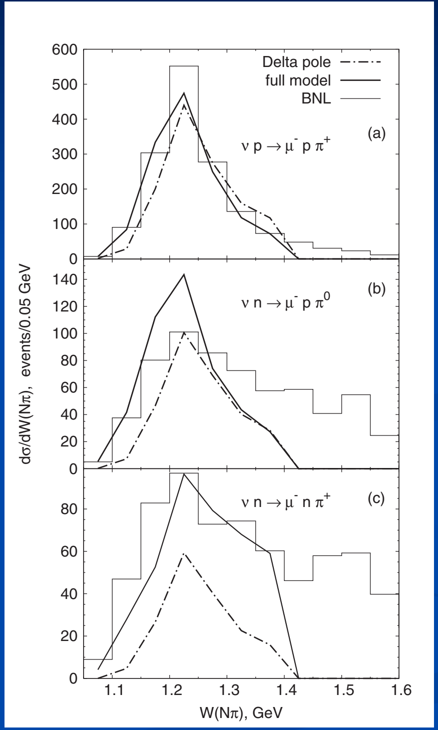
data:
PRD 25, 1161 (1982), PRD 34, 2554 (1986)

discrepancy between elementary data sets
→impossible to determine 3 axial formfactors

π-N inv. Mass Distributions



ANL data



BNL data

Lalakulich et al.,
Phys. Rev. D 82,
093001 (2010)

Hadronization

Observables, Experiments

multiplicity ratio

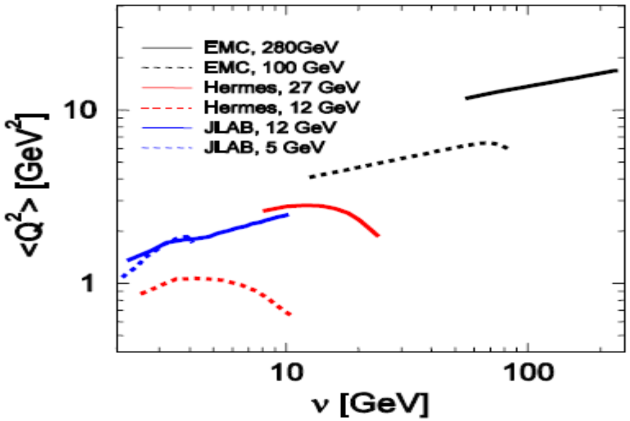
$$R_M^h(z_h,\ldots) = \frac{\left(\frac{N_h(z_h,\ldots)}{N_e(\ldots)}\right)_A}{\left(\frac{N_h(z_h,\ldots)}{N_e(\ldots)}\right)_D}$$

- hadronic: $z_h = \frac{E_h}{\nu}\ ,\ p_\perp\ ,\ \ldots$
- photonic: $\nu,\ Q^2,\ W,\ x_B,\ \ldots$

Experiments

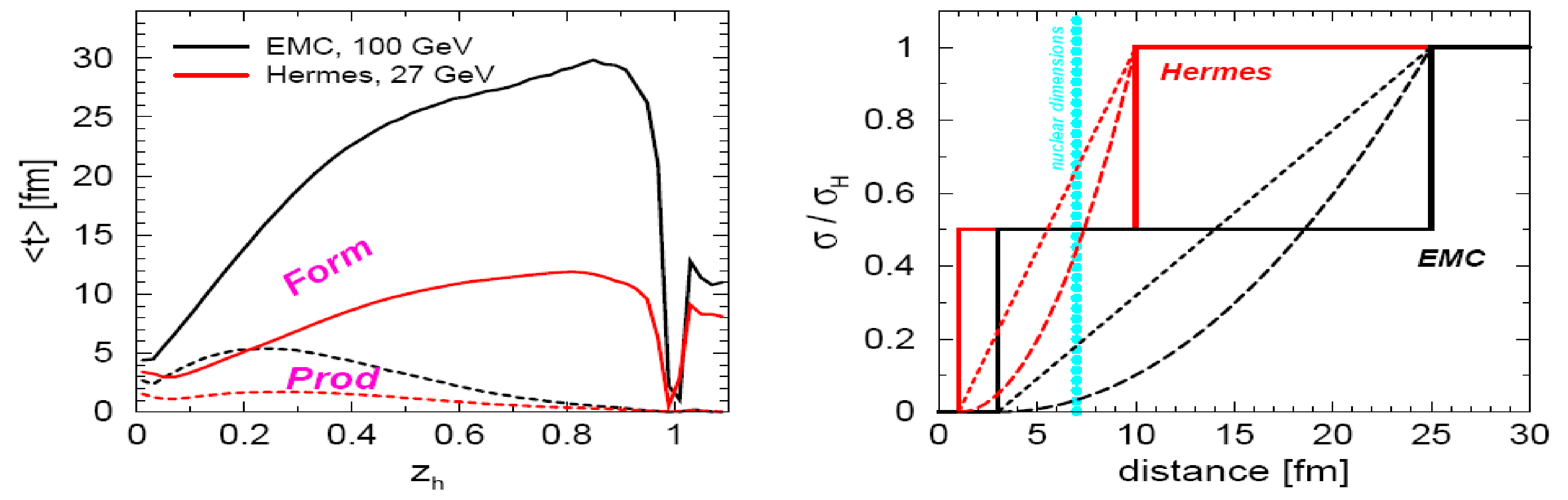
	E_{lepton} =
EMC	100…280 GeV
Hermes	27 GeV
Hermes	12 GeV
CLAS	12 GeV
CLAS	5 GeV

…multiple combinations of targets



Production and Formation Times from PYTHIA

$z_h = E_h/\nu$



All times in lab (nucleus) frame, from **Falter & Gallmeister**, **Phys.Lett.B630:40-48,2005**

Times at low (< 1 GeV) energies

- Physics dominated by isolated nucleon resonances, e.g.:

  $(e, \nu) + N \rightarrow \Delta \rightarrow \pi + N$

- Lifetime of Δ determines production time of pion, formation time is zero (because hadrons,are produced in their gs, due to phase-space limitation)

Times at Low Energies

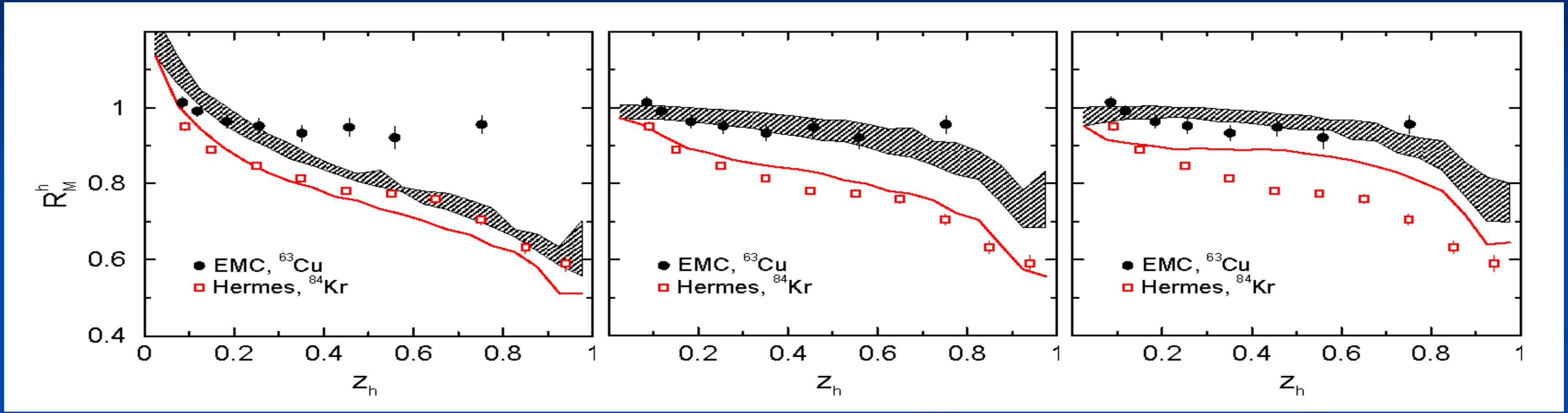
- Naive guess for production time:

$\tau_p = 1/\Gamma_0$ (Γ_0 = free resonance width)

- Educated guess:

$\tau_\mathbf{p} = 1/(\Gamma_0 + \Gamma_{\mathrm{coll}})$ with $\Gamma_{\mathrm{coll}} = \rho\, v\, \sigma$

Attenuation: EMC and HERMES



σ_{pre} = const (0.5) linear quadratic

Attenuation Data are sensitive to details of prehadronic interactions!

Prehadronic Cross Section

- From now on quantum diffusion model (Farrar et al.)

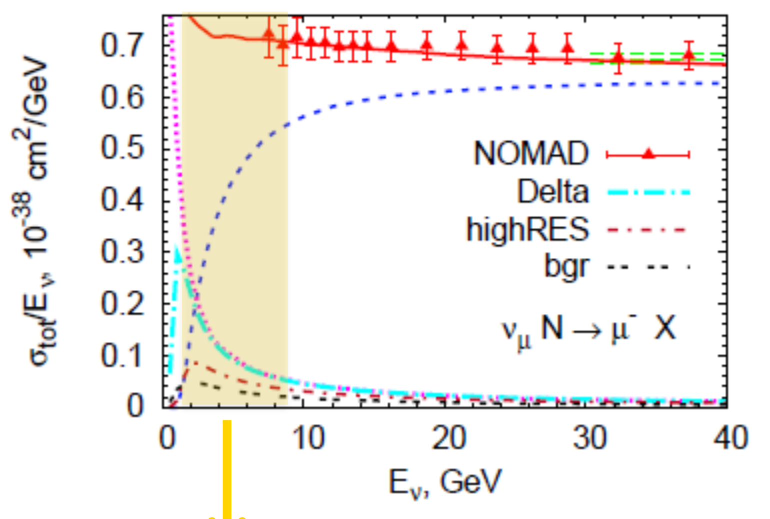
$$\sigma_{\mathrm{eff}} = \sigma_{\mathrm{hN}} \left[\left(\left(\frac{\#}{Q^2}\right)\left(1 - \frac{t}{t_f}\right) + \frac{t}{t_f} \right) \Theta(t_f - t) + \Theta(t - t_f) \right]$$

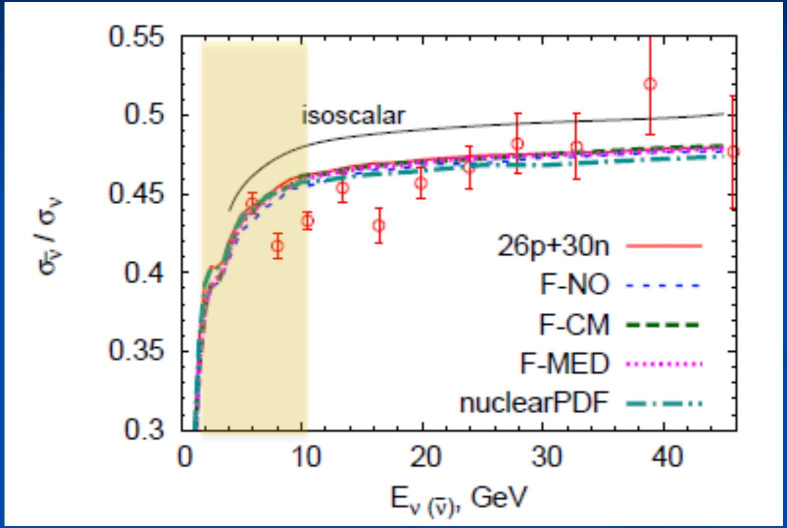
- 1/Q² dependence not essential, linear dependence on time is essential

Summary of Formation Times

- Times
  - At low energies, resonance regime:
    t_f = lifetime of resonance → *N* + hadron
  - At high energies, QCD regime,
    t_f from string-fragmentation
- Interactions
  - At low energies: collisional broadening of resonances
    → cross sections are density dependent!
  - At high energies: nuclear attenuation

SIS – DIS by PYTHIA

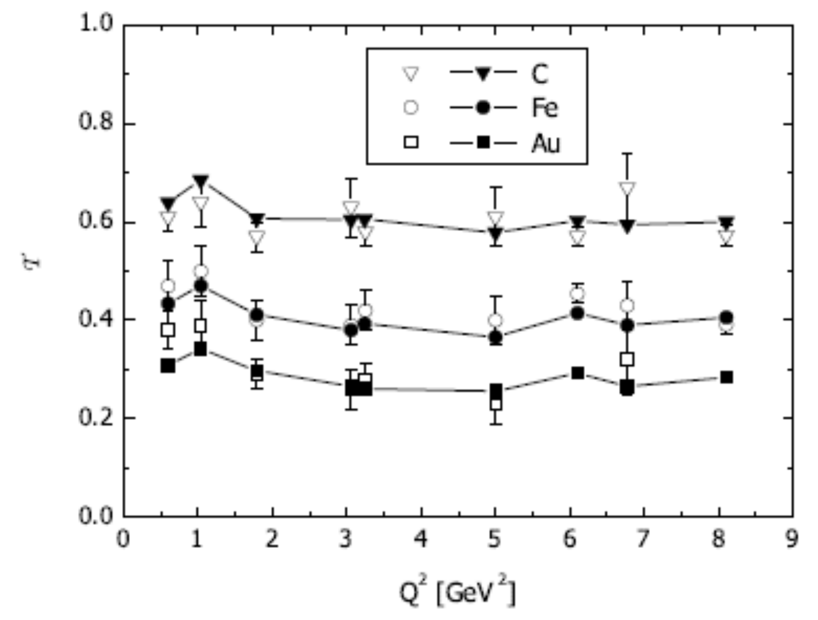




Shallow Inelastic Scattering,
interplay of different reaction mechanisms
→ Ambiguity to switch from one mechanism to the other

Code and Theory Checks

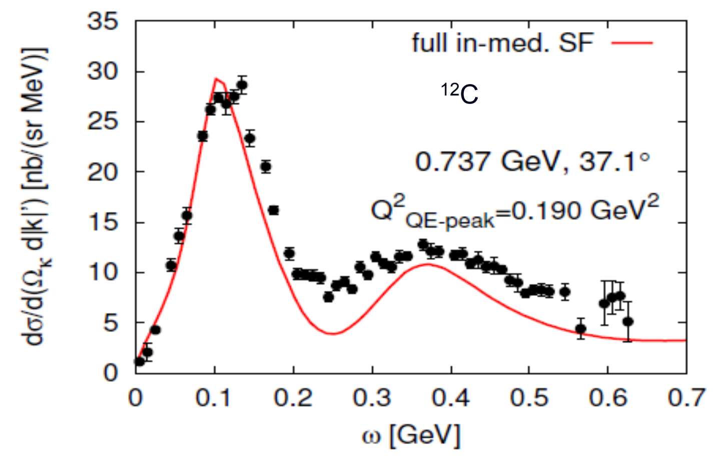
Check: protons

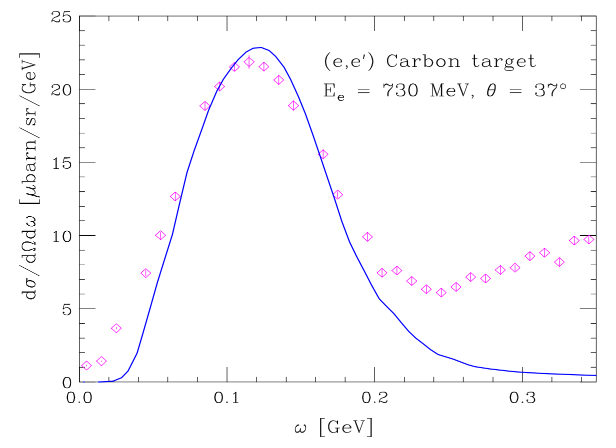


Curves: GiBUU

Proton transparency

Electrons as Benchmark for GiBUU

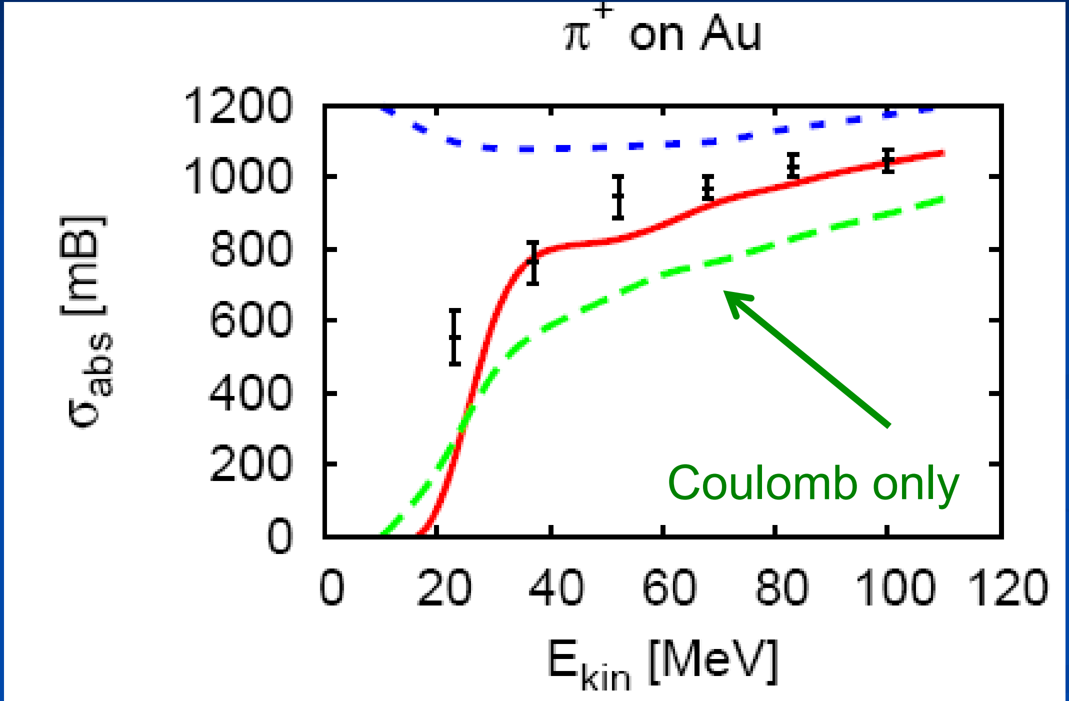




No free parameters!
no 2p-2h, contributes
in dip region and under Δ

O. Benhar, spectral fctn

Check: Pion Absorption



Pion potential essential, as well as Coulomb

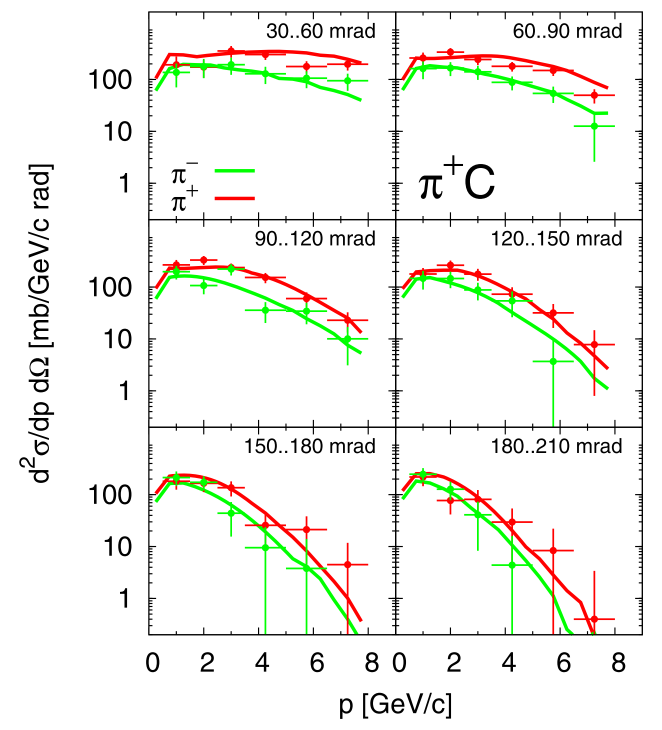
Note: Pion absorption does not provide a sensitive test for fsi with nucleons

Check: pions in HARP

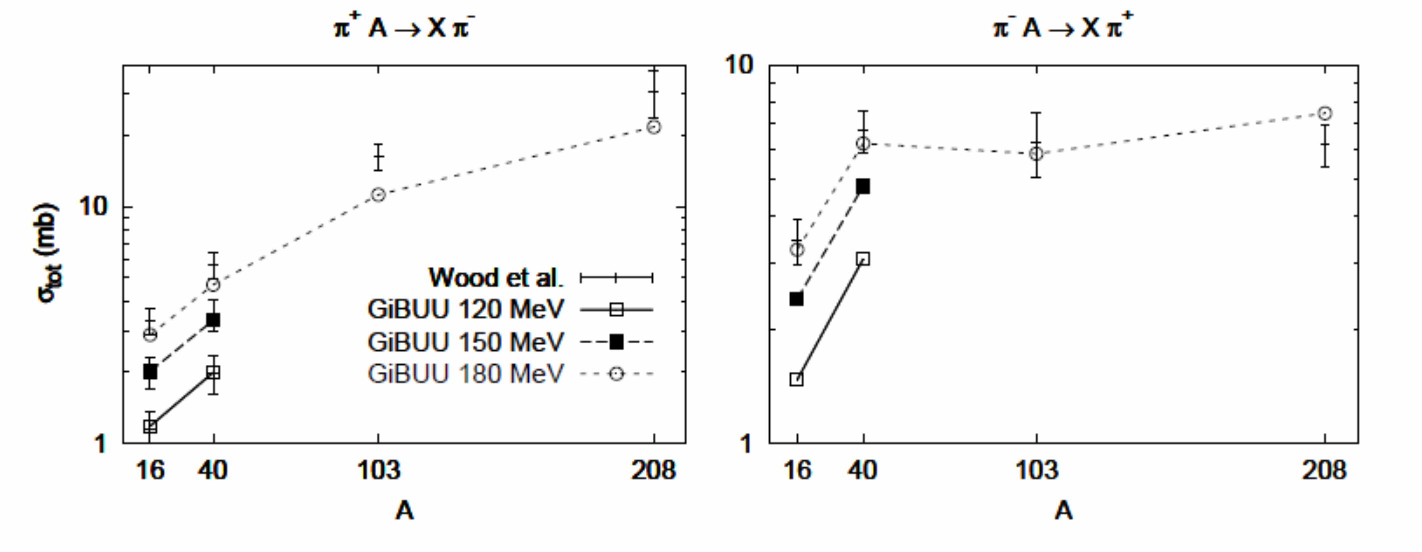
HARP small angle analysis
12 GeV protons

Curves: GiBUU

K. Gallmeister et al, NP A826 (2009)



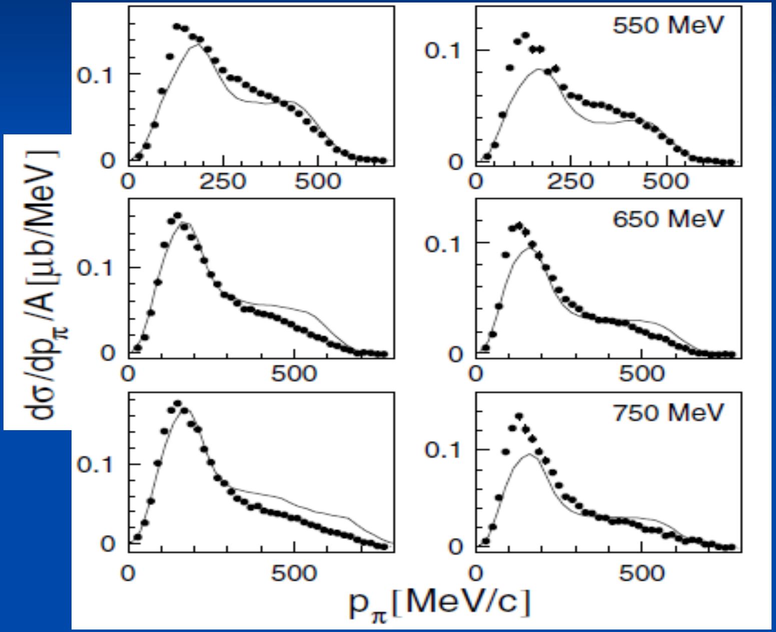
Check: Pion DCE



Data: Wood et al, GiBUU: Buss et al, **Phys.Rev. C74 (2006) 044610**

Check: Pions in Nuclei

$\gamma \to \pi^0$ on Pb

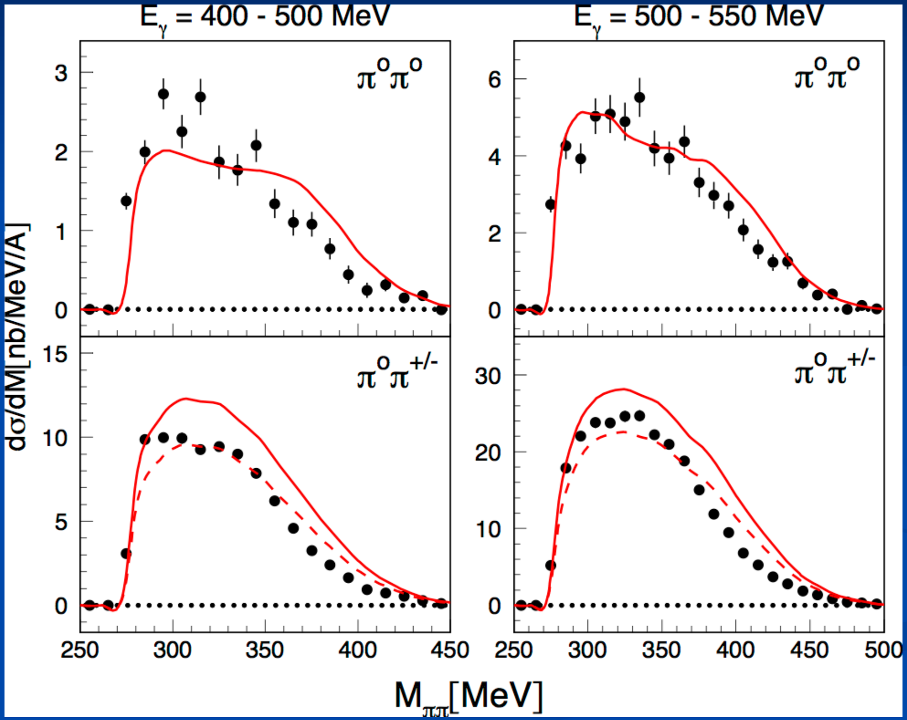


Photons illuminate the whole nucleus, test various pion mean free paths

Data: TAPS, Krusche et al

As in neutrino-induced reactions pions are produced inside the nucleus, more sensitive than pion absorption checks

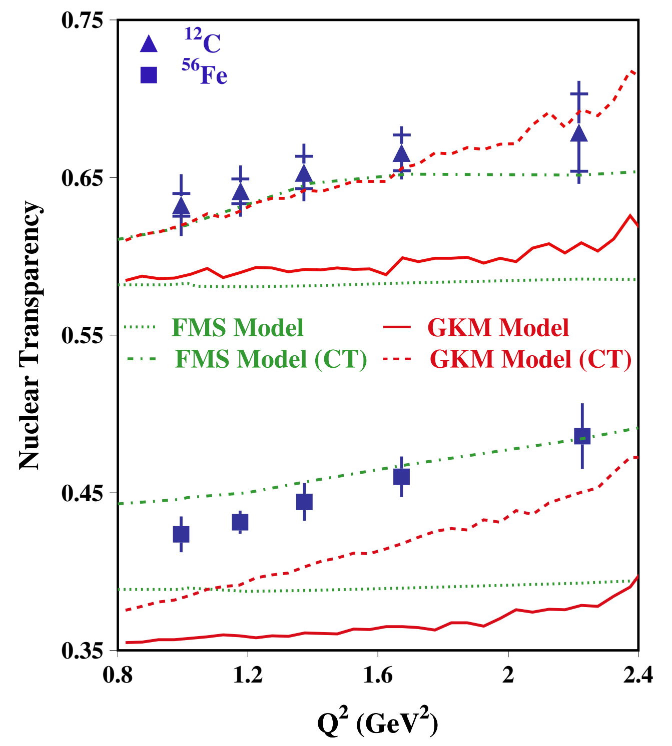
Check: Pions in Nuclei



Data:
TAPS
Krusche et al

Target: Ca

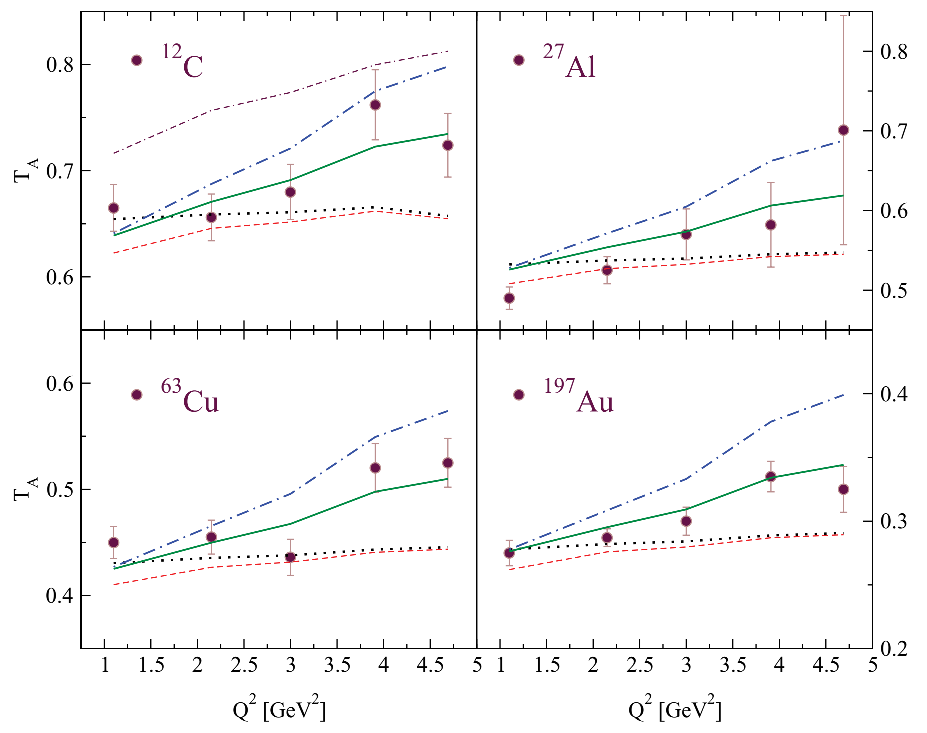
JLAB ρ Production



Exp: Hafidi et al, Hall B
Phys.Lett. B712 (2012) 326-330

GiBUU: Gallmeister et al.
Phys.Rev. C83 (2011)

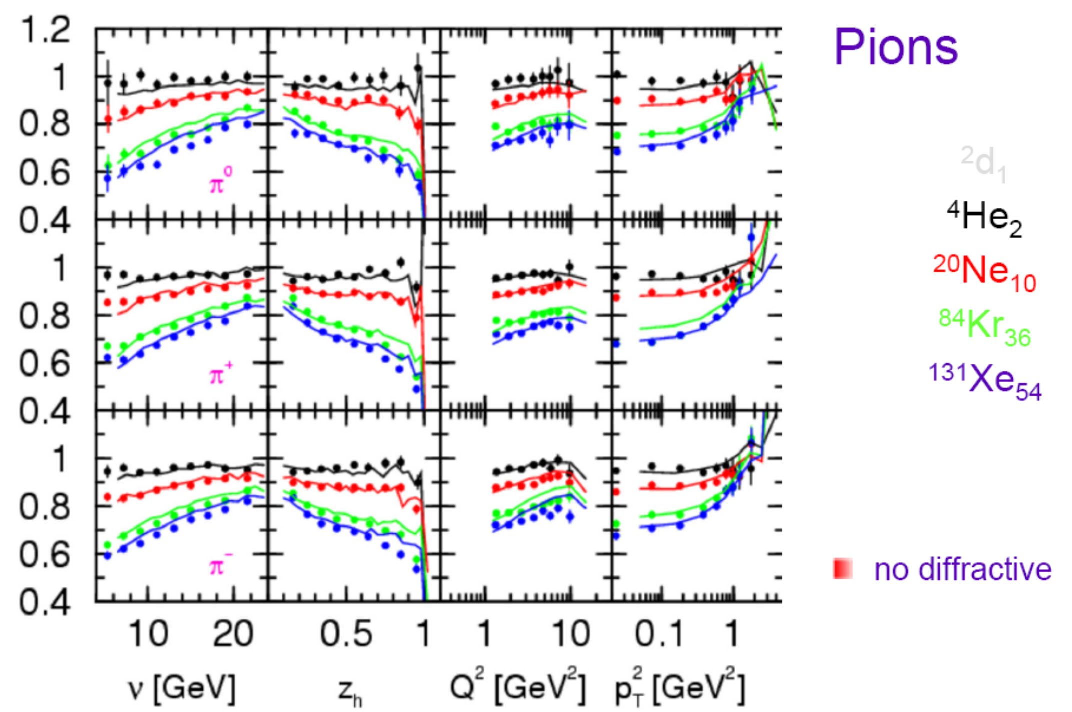
Pion Production at JLAB



Exp: B. Clasie et al.,Hall C
Phys. Rev. Lett. 99, 242502 (2007).

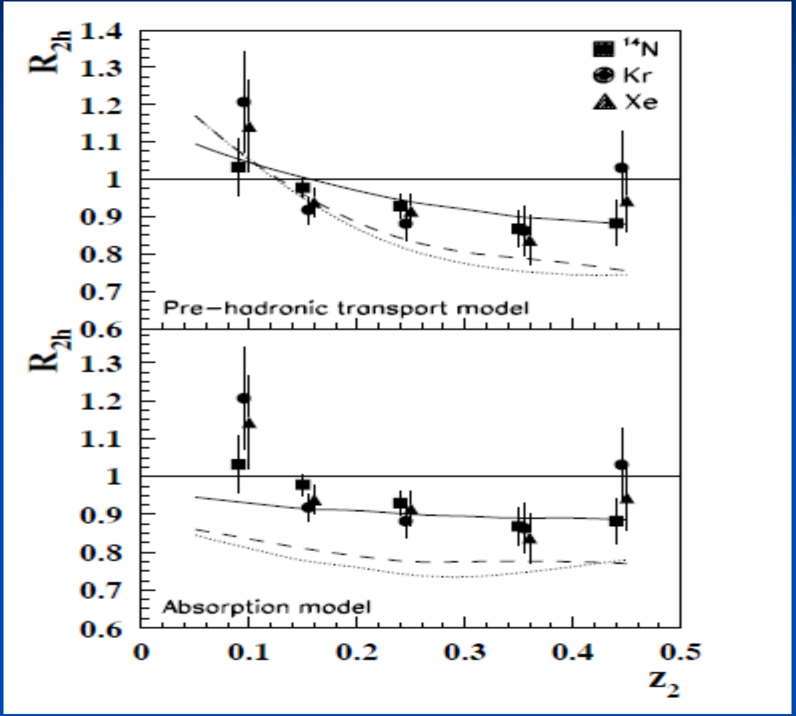
GiBUU: Kaskulov et al,
Phys.Rev. C79 (2009) 015207

Pions from HERMES at 27 GeV



Data:
Airapetian et al
Curves: GiBUU
Nucl.Phys. A801
 (2008) 68-79

Double Hadron Attenuation

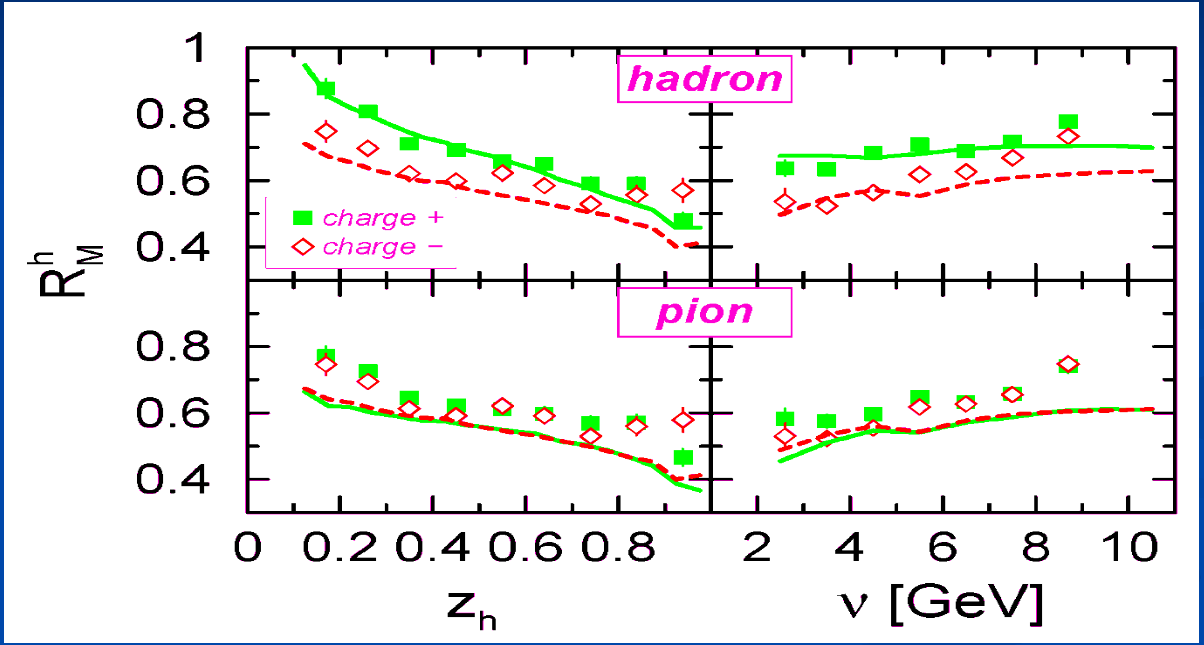


Glauber: fails at low $z_{2.}$

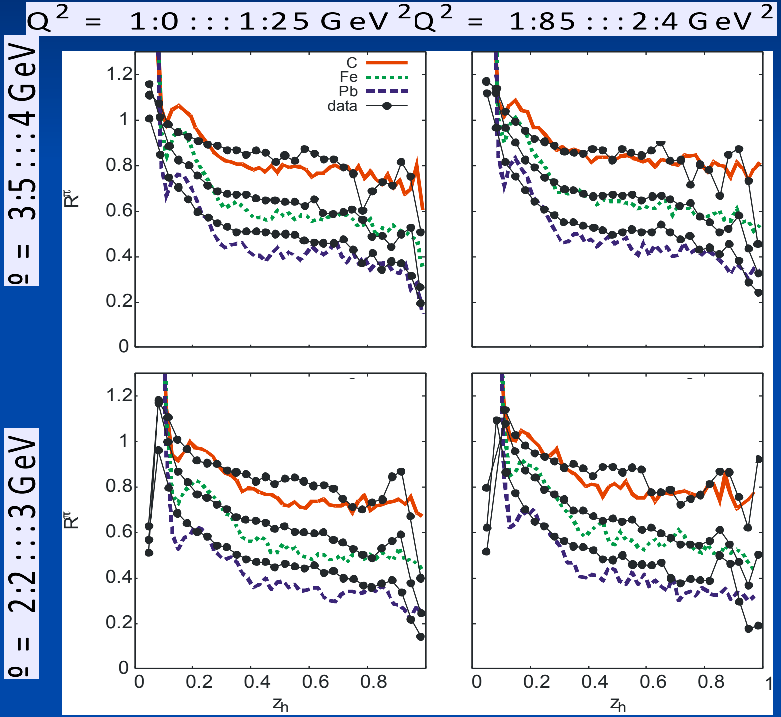
Low z hadrons show pile-up through final state interactions

Implication for (e,e‘2p)?

HERMES@12 GeV



JLAB π^+ production



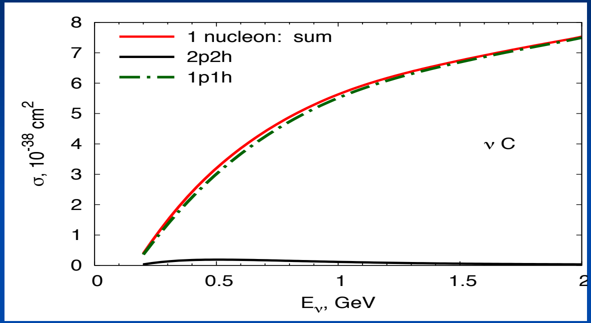
Data: W. Brooks et al., JLAB

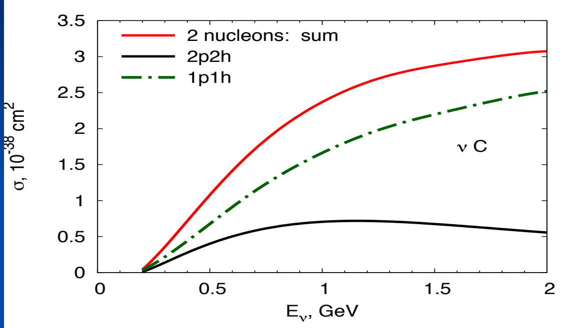
Same parameters as for HERMES

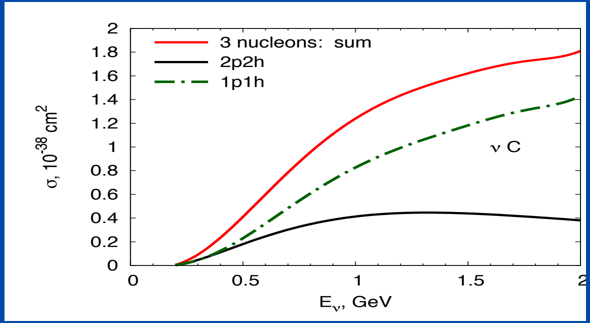
Now to Neutrinos

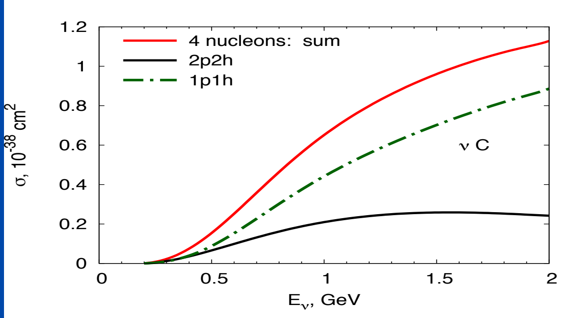
Experimental Verification of 2p2h

Nucleon Knock-Out for various processes





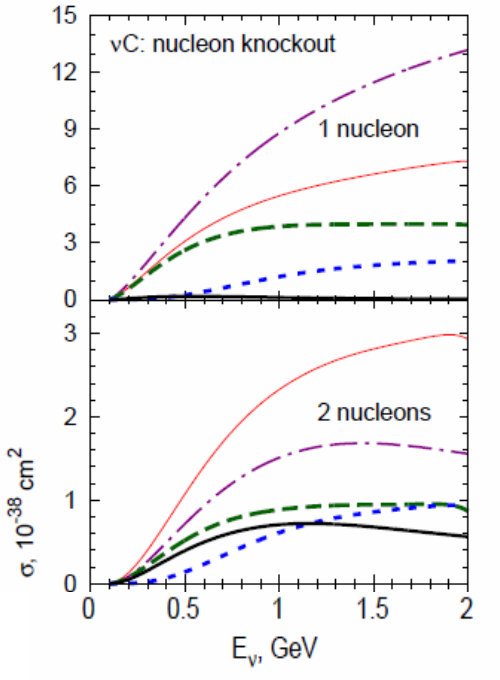


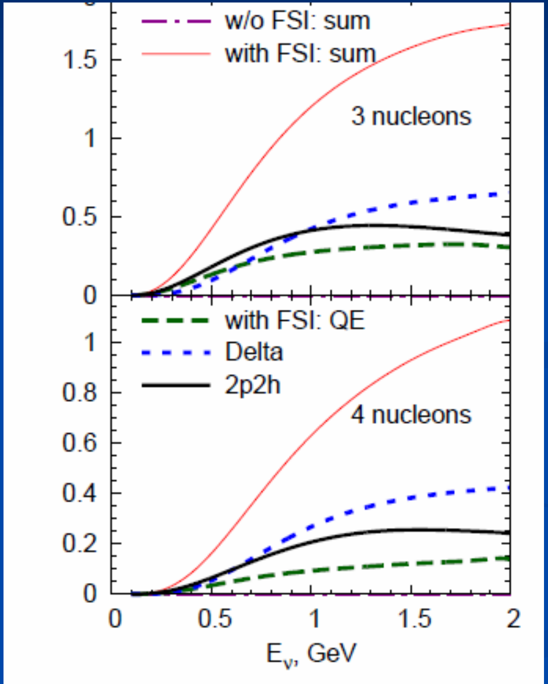


Only true QE
can be identified

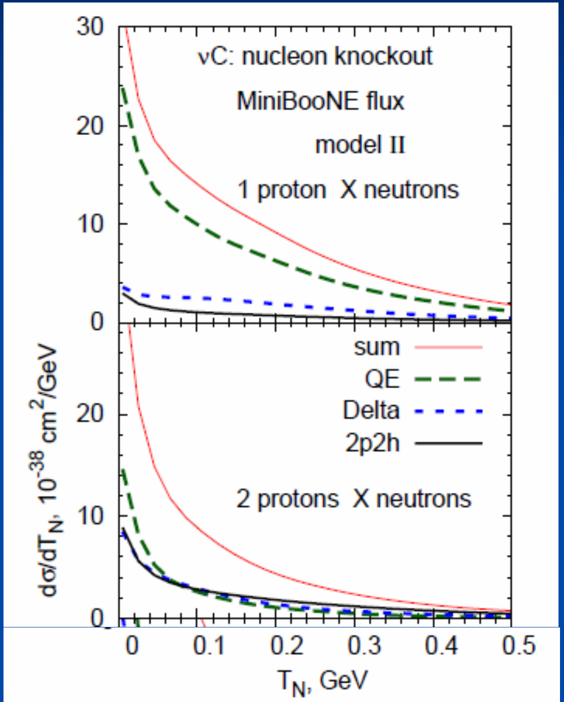
Avalanching shadows
Initial reaction

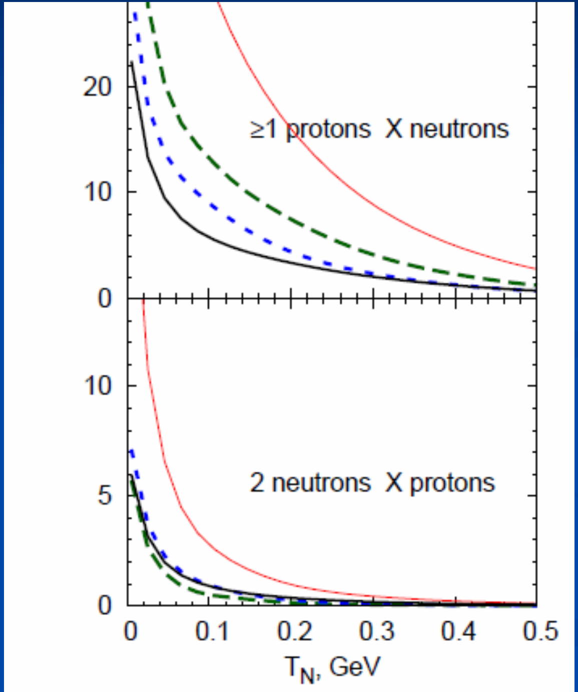
Nucleon Knock-out and 2p-2h





Nucleon Knock-out and 2p-2h

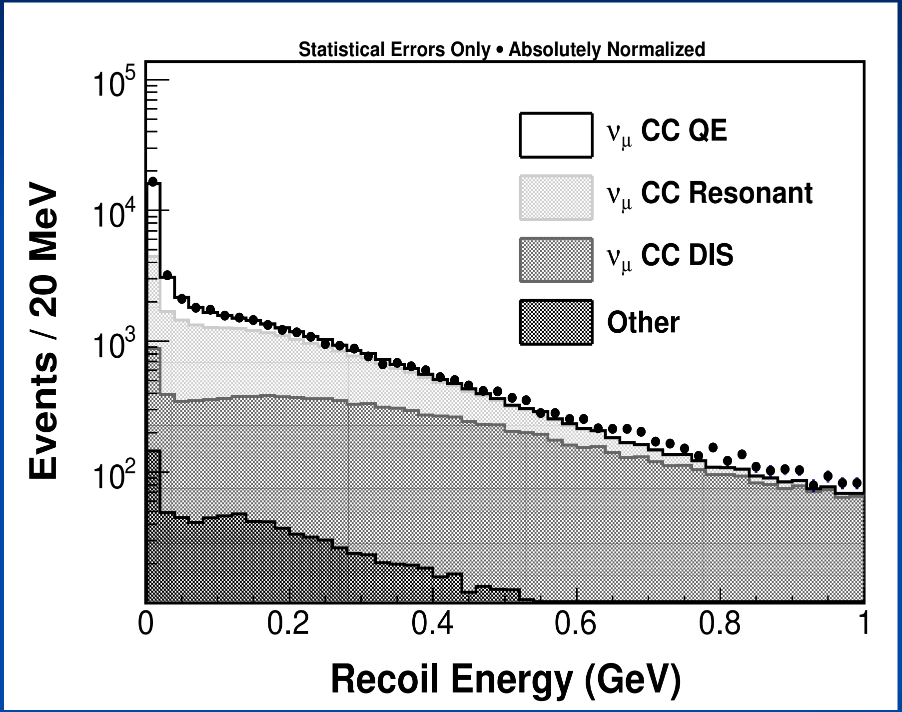




MB flux

Only 1pXn channel is reasonably close to true QE

MINERvA QE Analysis



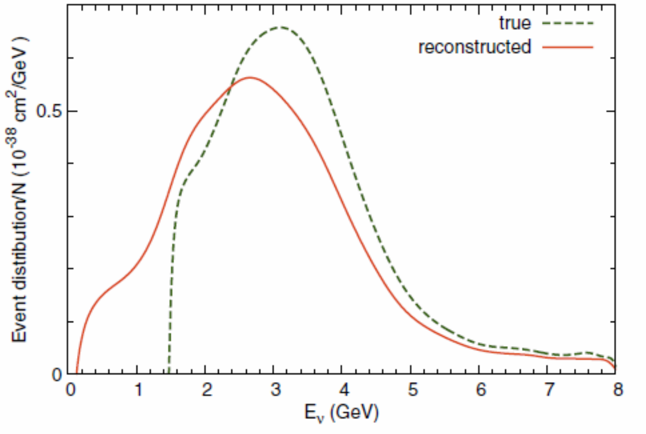
QE is a small part of the X-section over a large X-section

Background identification depends on generator

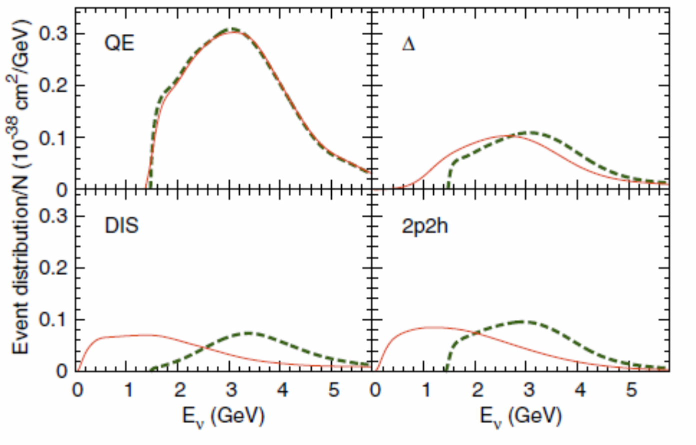
➔

QE signal generator-dependent

MINERvA Analysis



only 0-pion events

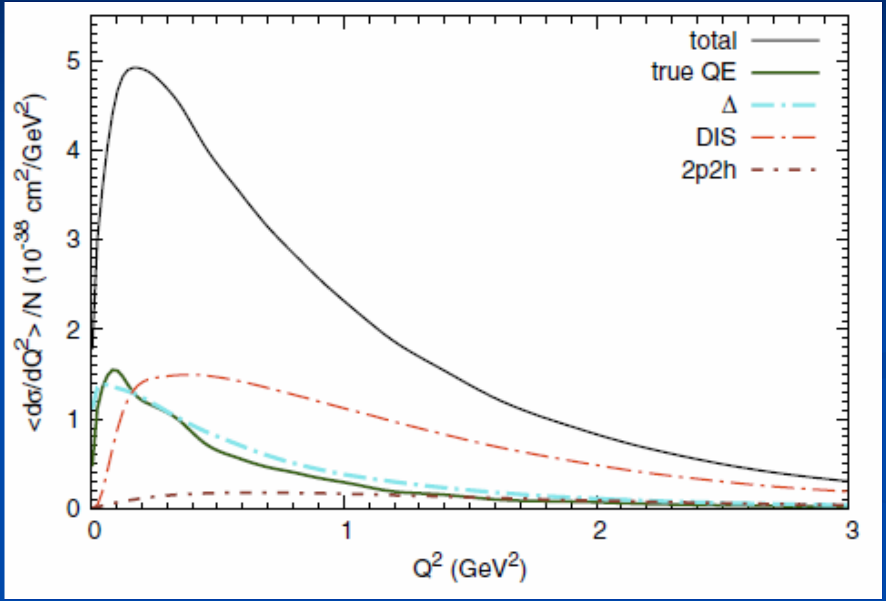


Mosel et al.,
PR D89 (2014) 093003

Flux cuts are dangerous:
distort true distribution!
Minerva cuts out (too?) large part

Energy reconstruction
strongly affected by
all channels, not just 2p2h!

Minerva Q^2 Reconstruction



True Q^2 distribution, *all* events

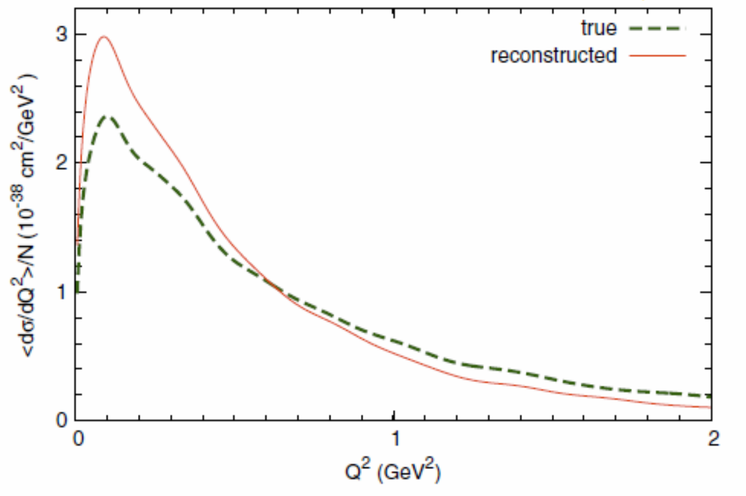
Dominant:
QE, DIS, Δ

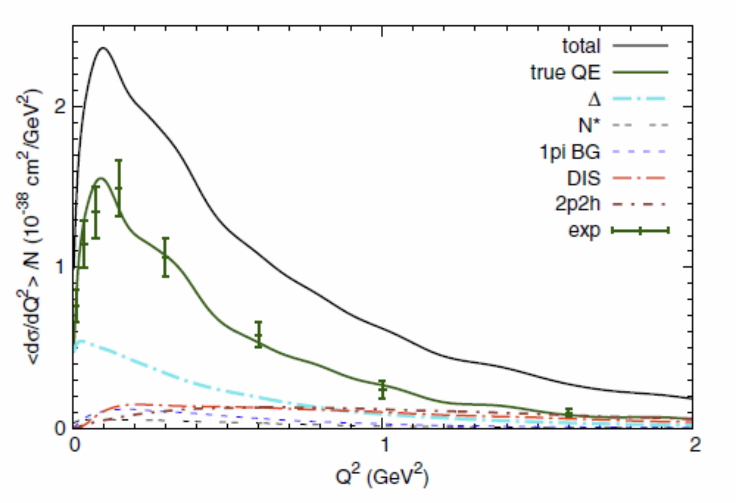
Δ and true QE very similar,
difficult to separate

Mosel et al.,
PR D89 (2014) 093003

MINERvA Q^2 Reconstruction

Only 0-pion events



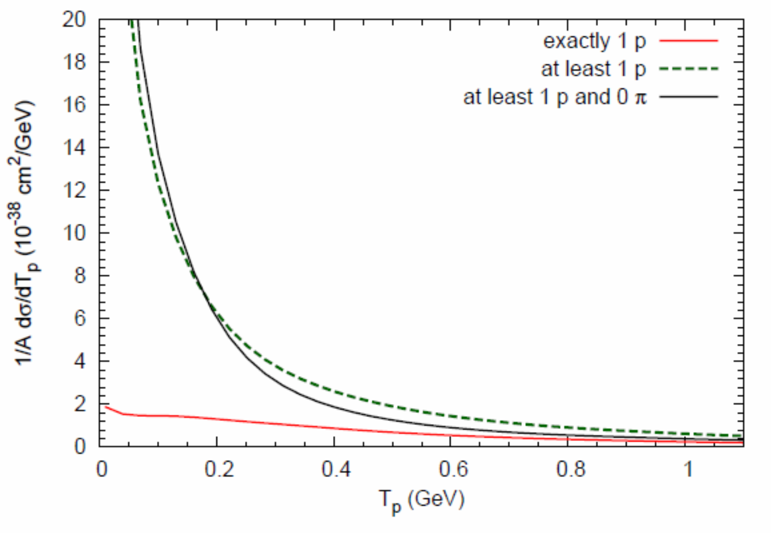


Dramatic sensitivity to reconstruction in peak area:can be removed with generator,

But: how good is your generator? accuracy of ‚data'??

Mosel et al.,
PR D89 (2014) 093003

Nucleon Knock-out at MINERvA



Extremely strong fsi:
fast initial proton becomes many low-energy nucleons

Pion Production

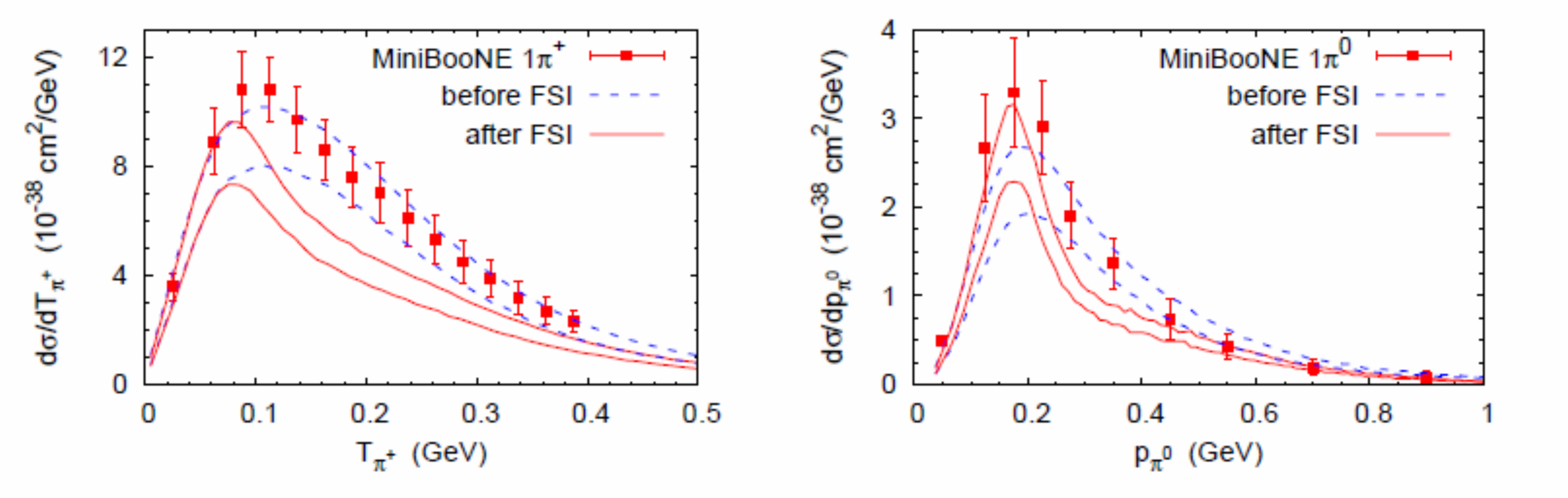
from: Phys.Rev. C87 (2013) 014602

1p-1h-1π X-section:

$$\mathrm{d}\sigma^{\nu A\to\ell' X\pi} = \int \mathrm{d}E \int \frac{\mathrm{d}^3p}{(2\pi)^3} P(\mathbf{p},E) f_{\mathrm{corr}}\, \mathrm{d}\sigma^{\mathrm{med}}\, P_{\mathrm{PB}}(\mathbf{r},\mathbf{p}) F_\pi(\mathbf{q}_\pi,\mathbf{r}) \;.$$

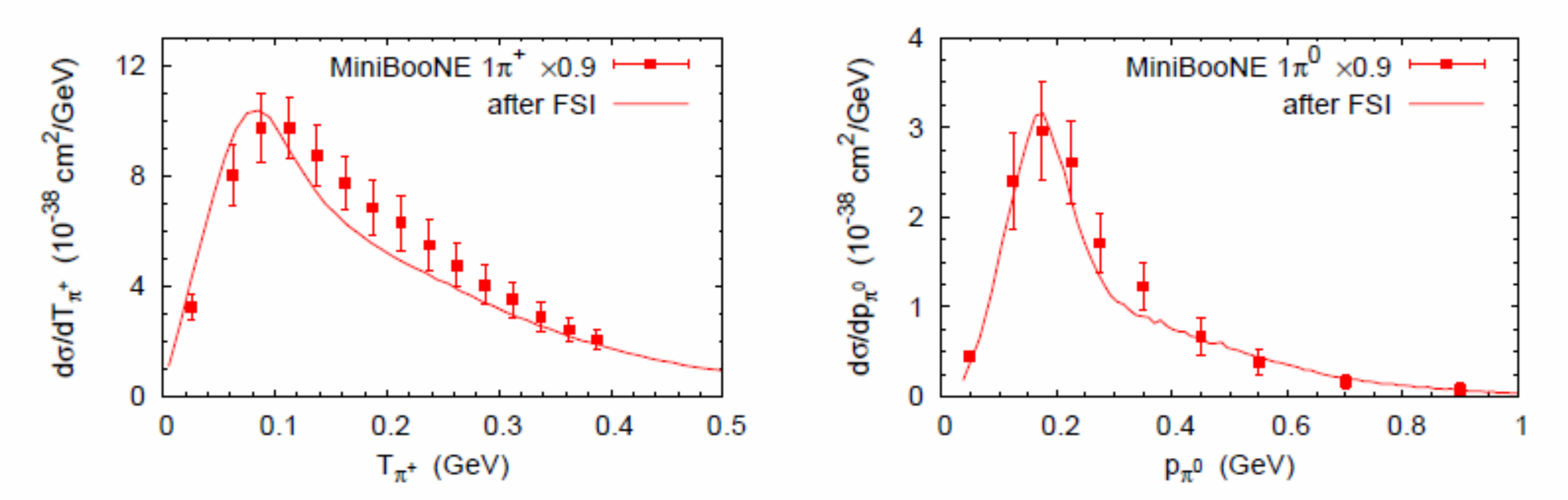
Pion fsi (scattering, absorption, charge exchange) handled by transport,
Includes Δ transport, consisent width description

Pion Production in MB



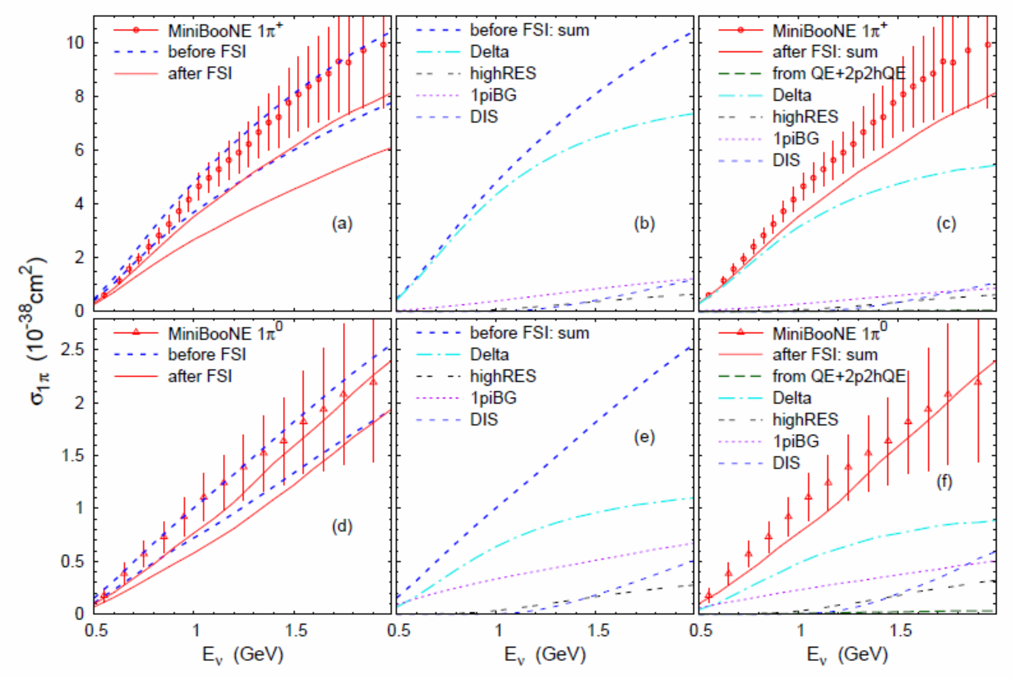
Spectral shape determined by pi-N-Delta dynamics in nuclei,
spectral disagreement due to choice of Bayes prior distributions???

Pion Production in MB



Flux renormalization (data x 0.9 (cf. Nieves QE analysis))

Pion Production



Upper line: BNL input
Lower line: ANL input

Tendency for theory too low, more so for π+, at E > 1 GeV

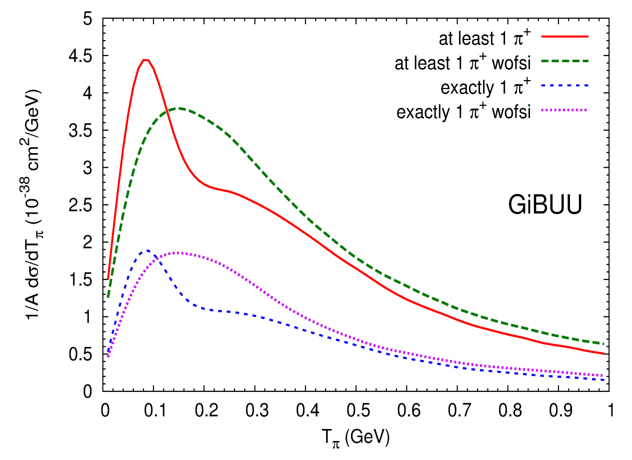
DIS and higher resonances contribute for E > 1 GeV

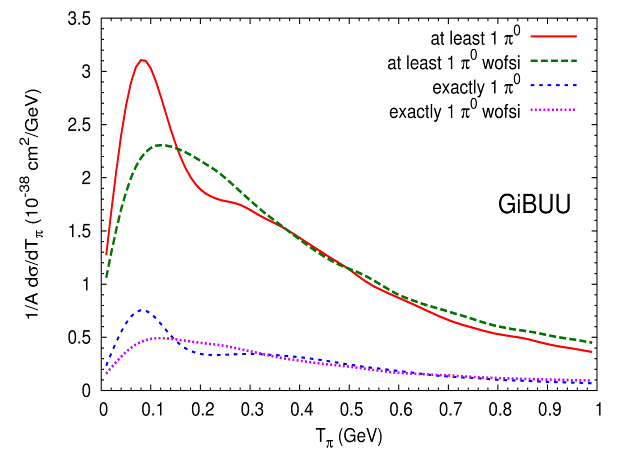
Discrepancy mainly in tail of flux distributions (large uncertainty)

Pions at MB

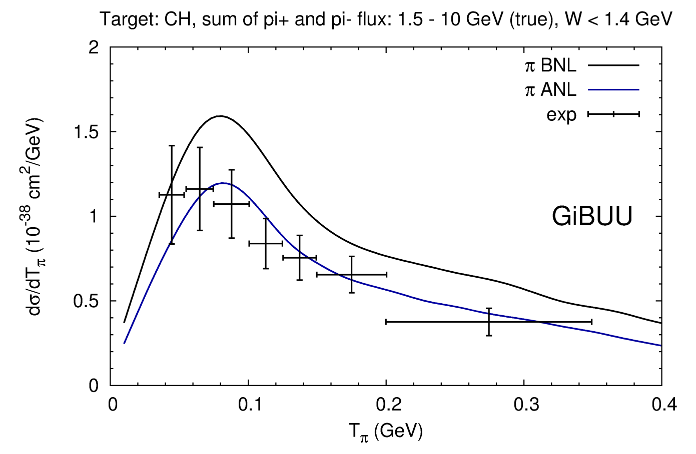
- Pions at MiniBooNE are compatible only with the (higher) BNL input

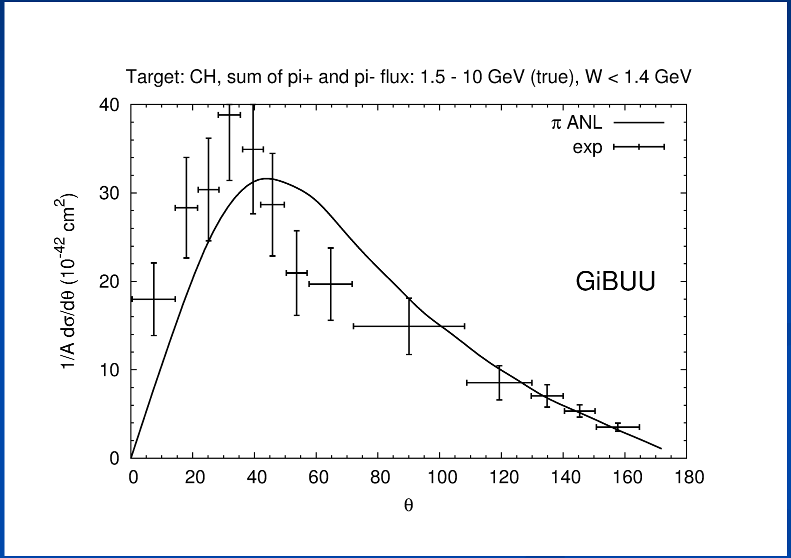
Pion FSI at MINERvA





MINERvA Pions





Data: Eberly et al

GiBUU preliminary

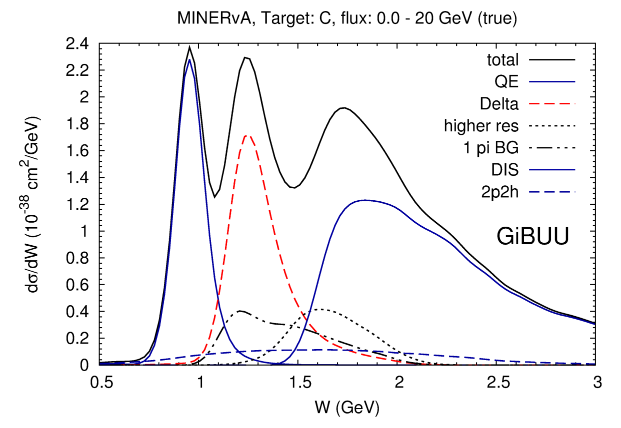
Pions at MINERvA compatible only with lower ANL data

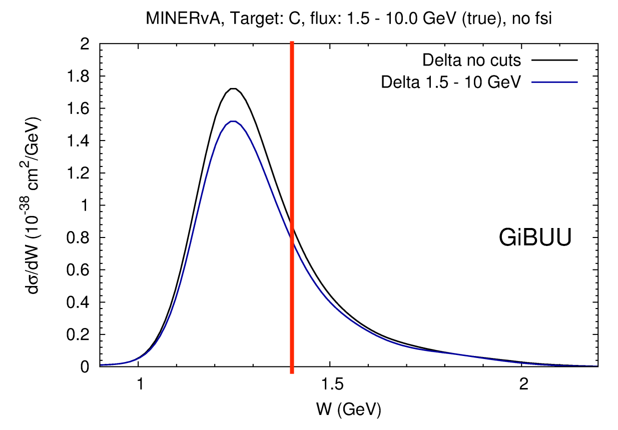
MINERvA Pions

- MINERvA cuts flux from 1.5 – 10 GeV
  → Generator Dependence

- MINERvA cuts invariant mass W > 1.4 GeV
  → Generator Dependence

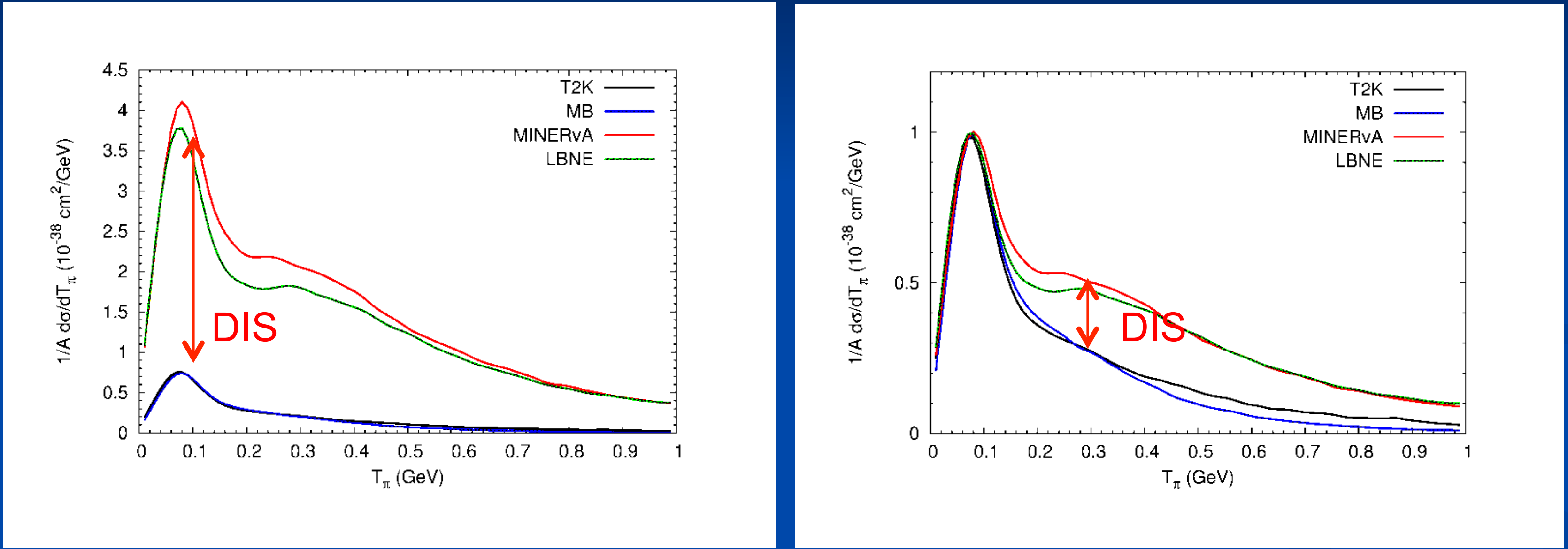
Effects of cuts





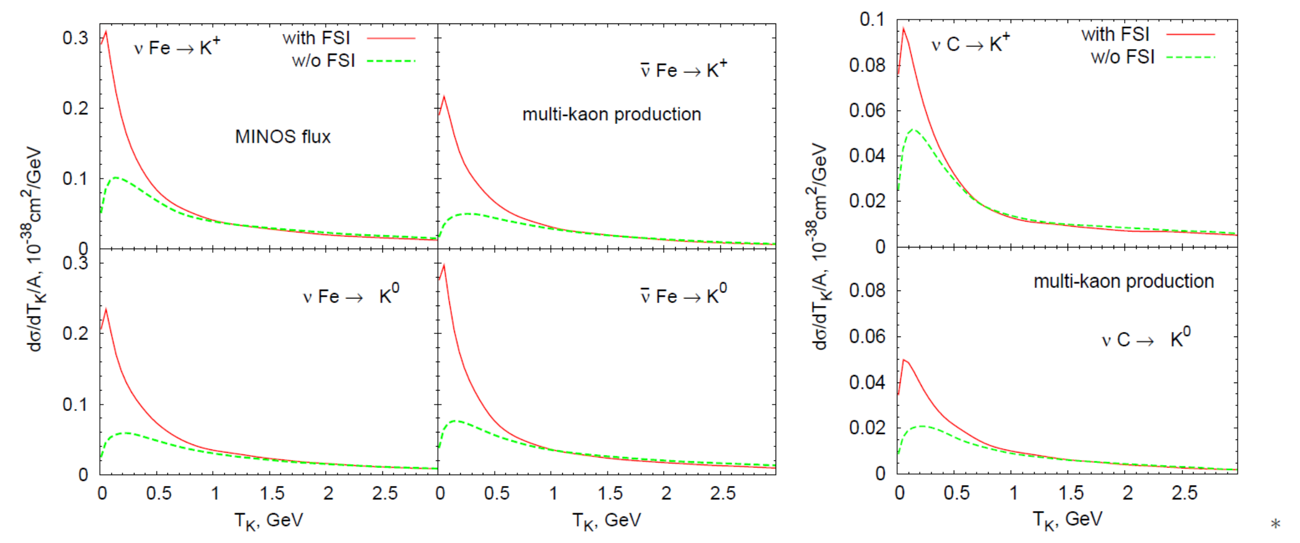
W distribution for Δ is significantly broadened due to Fermi-motion,
Cut at 1.4 GeV cuts away 25% of total strength
Note: $W^2 = M^2 + 2 M \nu - Q^2$ *.ne.* $(p + q)^2$

Pions at various experiments



Multi π^+, target: C for MB, T2K and MINERvA, Ar for LBNE

Kaons at MINOS and NOvA



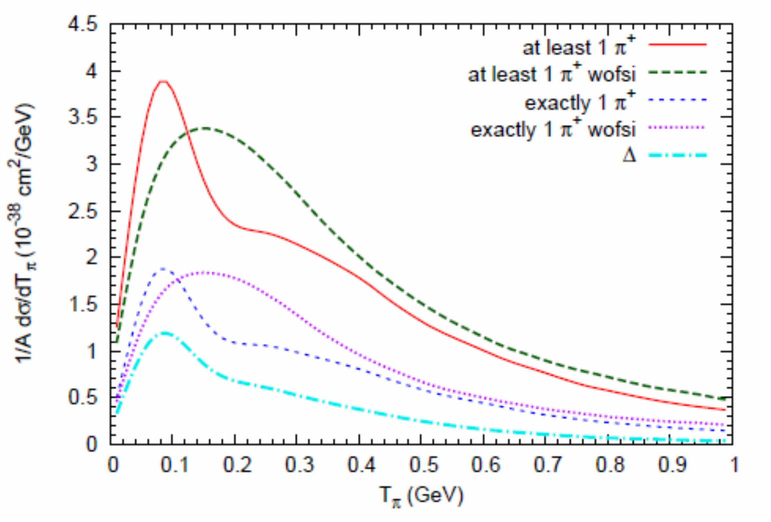
Lalakulich et al,
PR D86, 014607
(2012)

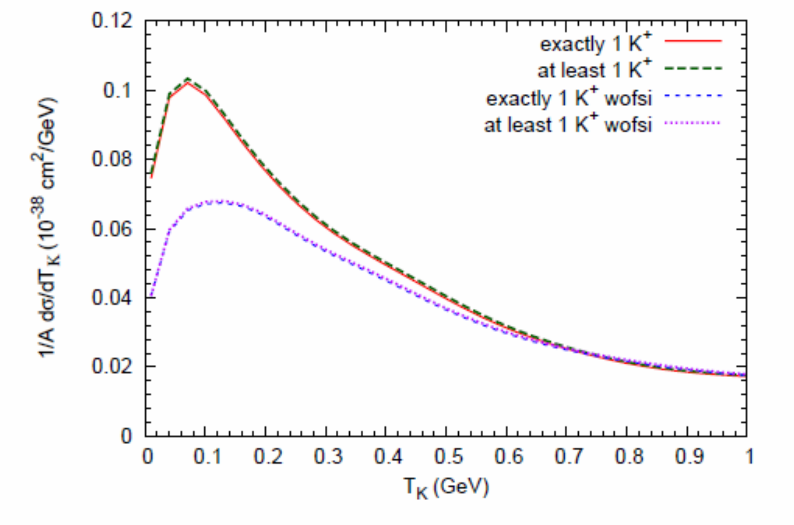
FSI increase the cross section!

Semi-inclusive X-sections much larger than exclusive ones

(1 order of magnitude, cf. Athar, Alvarez-Ruso)

MINERvA





Fsi are most important, but different, for pions and kaons
Elementary kaon vertices ‚shielded‘ by secondary production:

$$\pi + N \rightarrow K + \Lambda$$

Coherent Pion Production

- ***Coherent pion production***:
  not really part of a MC generator, since coherent process.

  Nakamura, Sato and Lee (PRC81 (2010) 035502) have given (nearly) correct theory. Supersedes oversimplified earlier models, but nowhere used. WHY???

Conclusions

- Elementary pion data still uncertain, MiniBooNE and MINERvA data show tension
- Kaons at higher energies are dominantly produced in DIS events, together with pions. Secondary kaon production large → elementary kaon production difficult in MINERvA
- A plea to the experimentalists: show data with as little model (generator) dependence as possible. Flux cuts and *W* cuts introduce generator dependence into data.

Importance of Generators

- A good generator does not have to fit the data, provided it is right (meaning: theoretically correct and consistent)
- A good generator does not have to be right, provided it fits the data
- Let us strive for the right generator that is as much state-of-the-art as the experimental equipment!