Particle Production from MiniBooNE and T2K to MINERvA and LBNE

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with

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Neutrino GiBUU Publications since NUINT2012

1. **"Reaction Mechanisms at MINERνA"**
   U. Mosel, O. Lalakulich and K. Gallmeister.
   arXiv:1402.0297 [nucl-th]
   10.1103/PhysRevD.89.093003
   Phys. Rev. D **89**, 093003 (2014)

2. **"Energy reconstruction in the Long-Baseline Neutrino Experiment"**
   U. Mosel, O. Lalakulich and K. Gallmeister.
   arXiv:1311.7288 [nucl-th]
   10.1103/PhysRevLett.112.151802
   Phys. Rev. Lett. **112**, 151802 (2014)

3. **"Pion production in the T2K experiment"**
   O. Lalakulich and U. Mosel.
   arXiv:1305.3861 [nucl-th]
   10.1103/PhysRevC.88.017601
   Phys. Rev. C **88**, no. 1, 017601 (2013)

4. **"Pion production in the MiniBooNE experiment"**
   O. Lalakulich and U. Mosel.
   arXiv:1210.4717 [nucl-th]
   10.1103/PhysRevC.87.014602
   Phys. Rev. C **87**, 014602 (2013)

5. **"Energy reconstruction in quasielastic scattering in the MiniBooNE and T2K experiments"**
   O. Lalakulich, U. Mosel and K. Gallmeister.
   arXiv:1208.3678 [nucl-th]
   10.1103/PhysRevC.86.054606
   Phys. Rev. C **86**, 054606 (2012)

6. **"Neutrino- and antineutrino-induced reactions with nuclei between 1 and 50 GeV"**
   O. Lalakulich, K. Gallmeister and U. Mosel.
   arXiv:1205.1061 [nucl-th]
   10.1103/PhysRevC.86.014607
   Phys. Rev. C **86**, 014607 (2012)

7. **"Many-Body Interactions of Neutrinos with Nuclei - Observables"**
   O. Lalakulich, K. Gallmeister and U. Mosel.
   arXiv:1203.2935 [nucl-th]
   10.1103/PhysRevC.86.014614
   Phys. Rev. C **86**, 014614 (2012)

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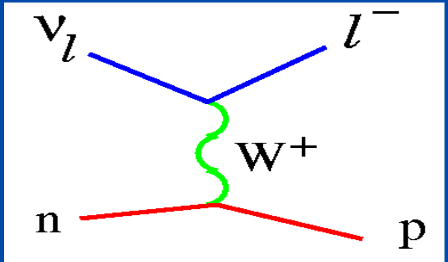
Motivation and Contents

- Determination of neutrino oscillation parameters and axial properties of nucleons and resonances requires knowledge of neutrino energy and momentum transfer
- Neutrino beams are broad in energy
- Modern experiments use nuclear targets
- Nuclear effects affect event characterization, cross section measurements, neutrino energy reconstruction and, consequently, oscillation parameters

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

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GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : 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
  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

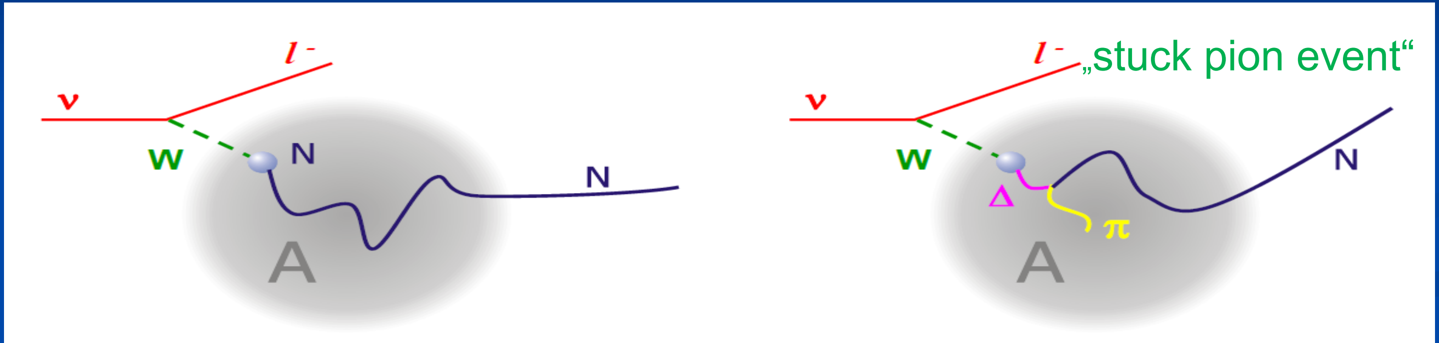
Reaction Types

- 2 major reaction types relevant:

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

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

Final State Interactions in Nuclear Targets



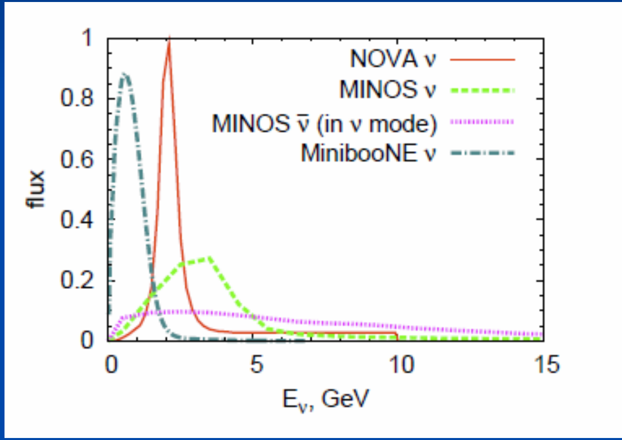
Complication to identify QE, entangled with π production

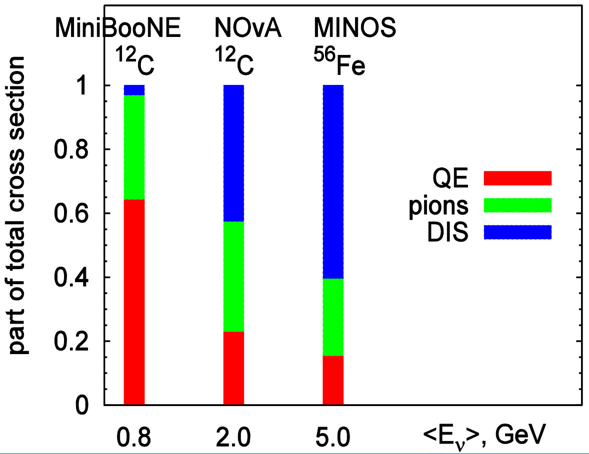
Both must be treated at the same time!

Nuclear Targets (K2K, MiniBooNE, T2K, MINOS, Minerva, ….)

Neutrino Beams

- Neutrinos do not have fixed energy nor just one reaction mechanism

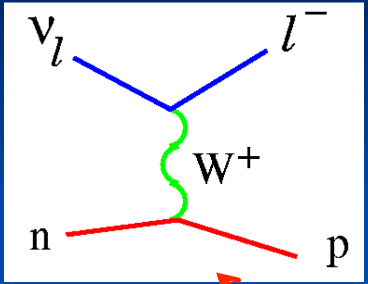




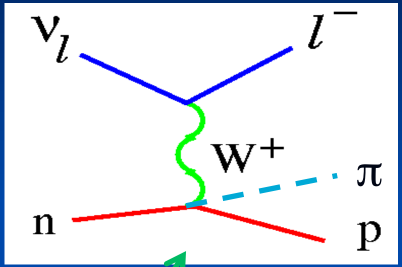
Have to reconstruct energy from final state of reaction
Different processes are entangled

Neutrino-nucleon cross section

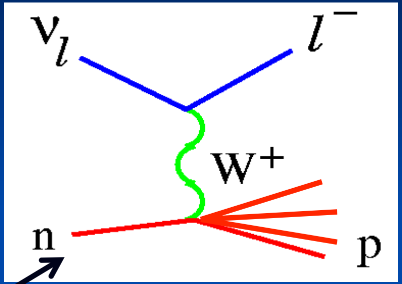
CCQE

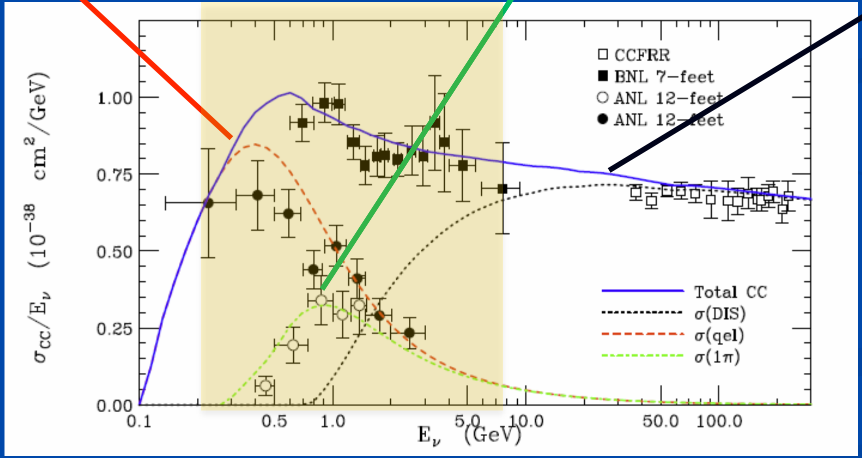


1π



DIS





NUINT 2014

note:
10^{-38} cm² = 10^{-11} mb

In the region of modern experiments (0.5 – 10 GeV) all 3 mechanisms overlap

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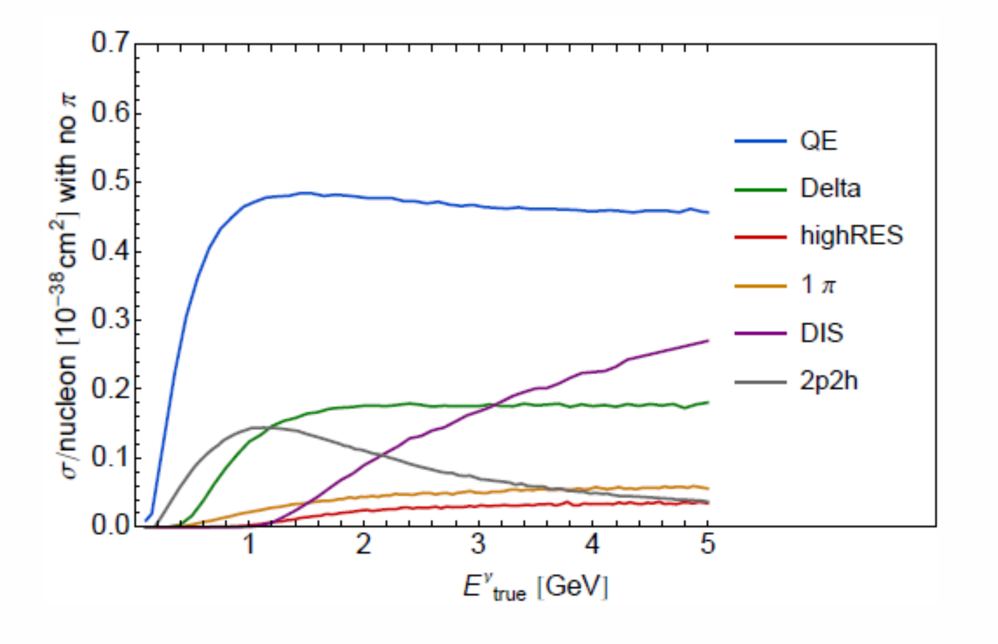
0 Pion Events from GiBUU

From Coloma & Huber: arXiv:1307.1243v1



Pion Production

- Pion production dominated by **P_{33}(1232) resonance (not just a heavier nucleon)**

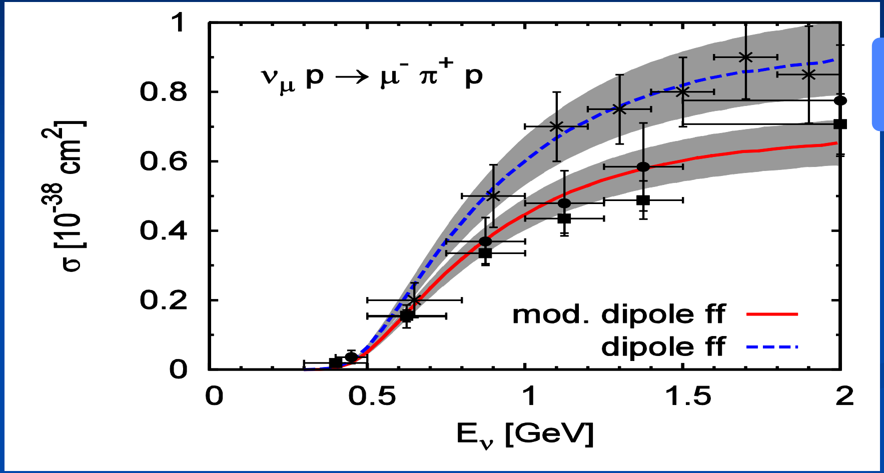
$$J^{\alpha\mu}_{\Delta} = \left[\frac{C_3^V}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu) + \frac{C_4^V}{M_N^2}(g^{\alpha\mu}q\cdot p' - q^\alpha p'^\mu) + \frac{C_5^V}{M_N^2}(g^{\alpha\mu}q\cdot p - q^\alpha p^\mu)\right]\gamma_5$$
$$+\frac{C_3^A}{M_N}(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu)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

- ***$C^V(Q^2)$*** from electron data (MAID analysis with CVC
- ***$C^A(Q^2)$*** from fit to neutrino data (experiments on hydrogen/deuterium), so far only C^A_5 determined, for other axial FFs only educated guesses

Pion Production

- 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

New pion data on elementary target desparately needed!

Pion Production

from: Phys.Rev. C87 (2013) 014602

1p-1h-1π X-section:

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

Hole spectral function

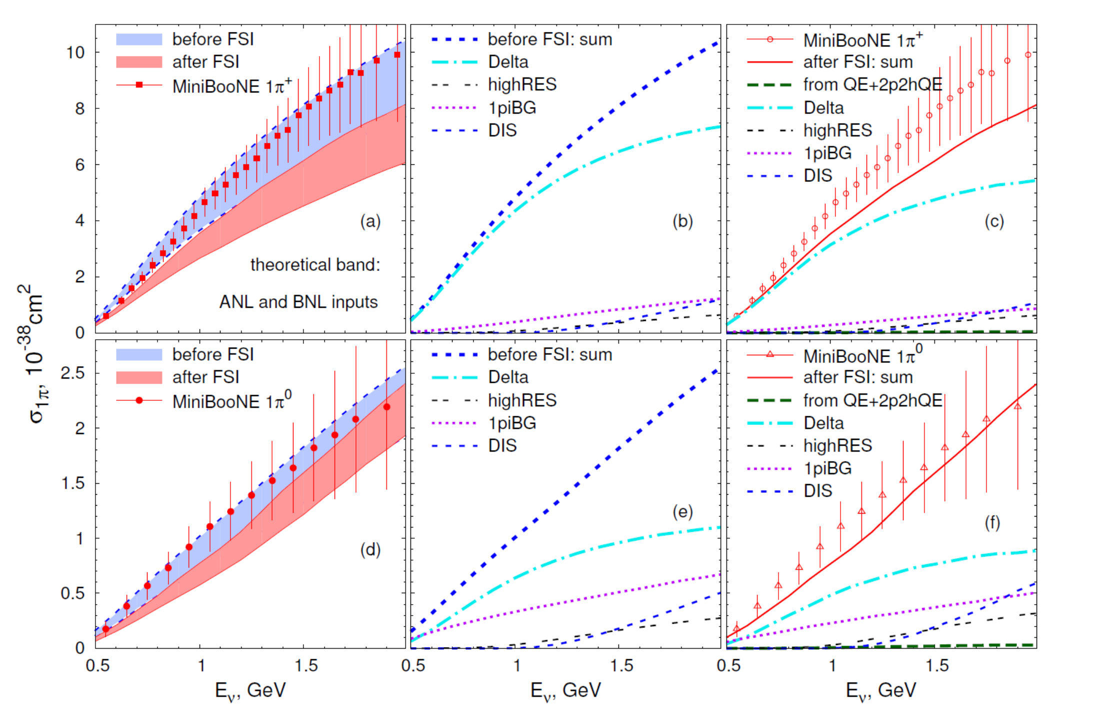
$$P(\mathbf{p},E) = g \int_{\mathrm{nucleus}} \mathrm{d}^3r\, \Theta\left[p_{\mathrm{F}}(\mathbf{r}) - |\mathbf{p}|\right] \Theta(E) \delta\left(E - m^* + \sqrt{\mathbf{p}^2 + m^{*2}}\right)$$

Pion fsi (scattering, absorption, charge exchange) handled by transport,
Includes Δ transport, consistent width description of Delta spectral function, detailed balance

Pion Production

- In-medium self-energy of Delta from Oset et al.
- In-medium self-energy consistent with collision terms in cascade (2 and 3 body coll)
- Calculations include on top of resonance 1-pi decays also 2pi decay channels and semi-inclusive production through DIS

Pions in MiniBooNE



Only BNL input comes close to data

Δ dominant only up to about 0.8 GeV

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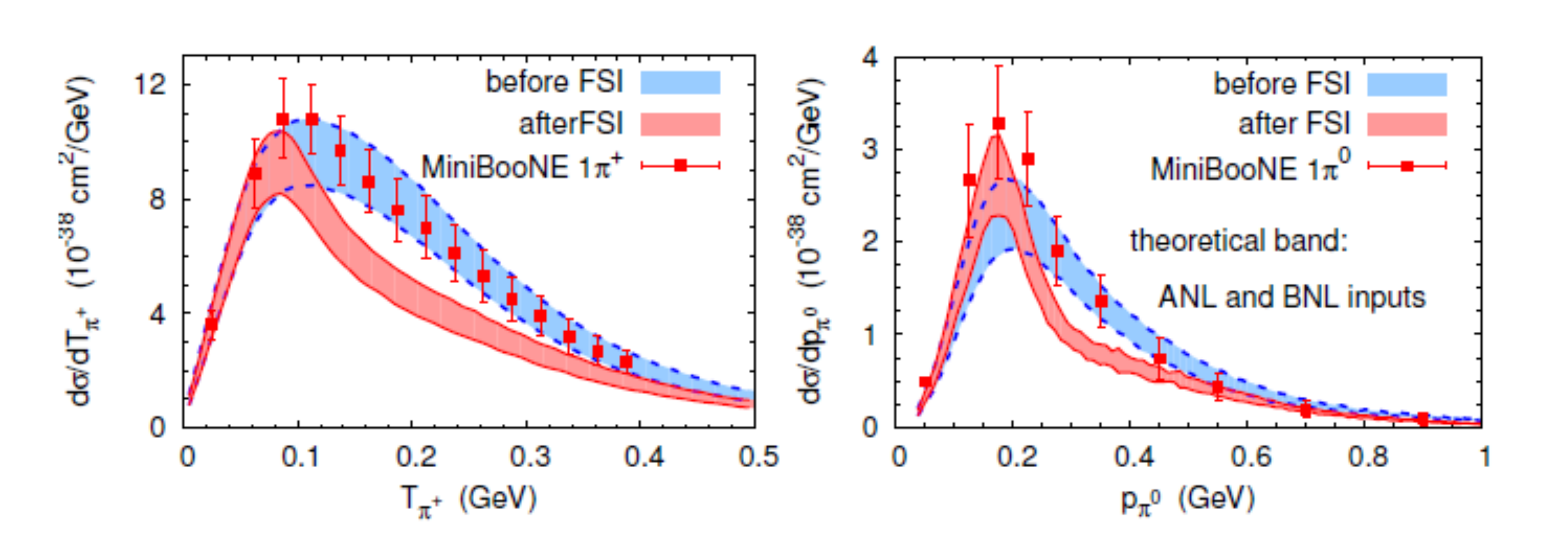
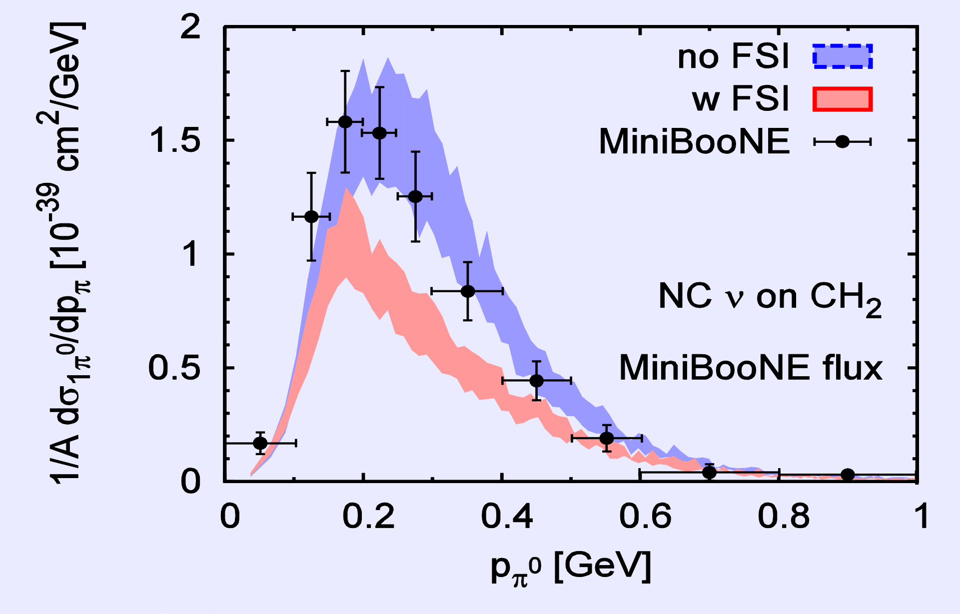
Pion Spectra in MB



GiBUU results confirmed by Hernandez & Nieves

MiniBooNE NC $1\pi^0$



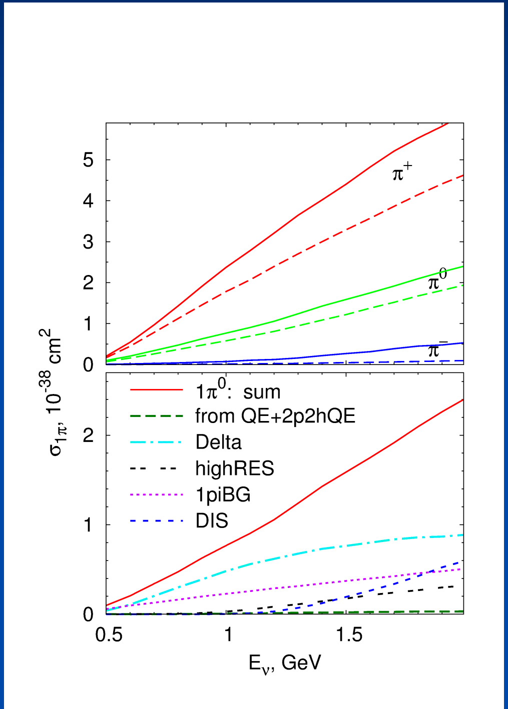
arXiv:0910.2835

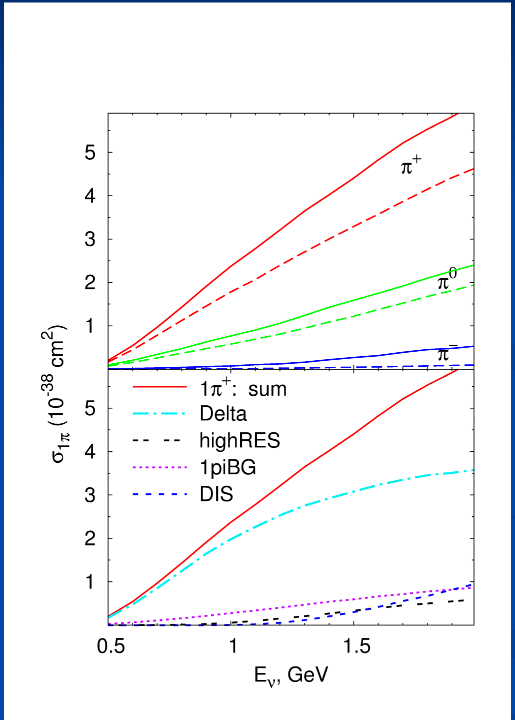
data: C. Anderson, NUINT09

Hard to understand:
pion data agree with Fermi-motion folded free cross cection, but fsi must be there

bands:
uncertainty of axial form factor

Pion Production in T2K

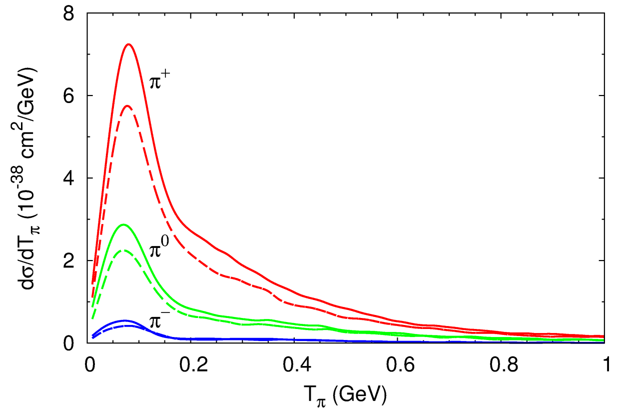


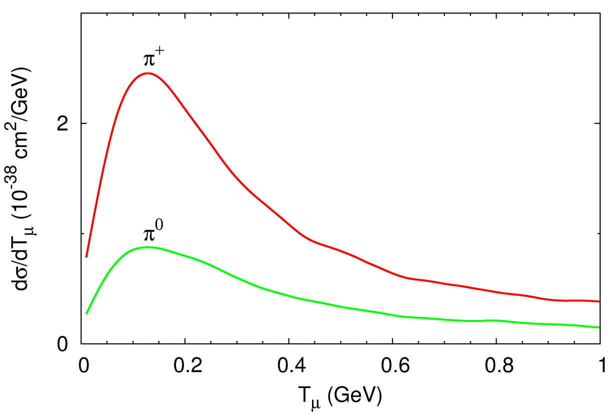


Δ dominant only up to 0.8 GeV

Measurement of pion production between about 0.5 and 0.8 GeV would be clean probe of Δ dynamics.

Pion Production in T2K





T2K pion data may help to distinguish between ANL and BNL input

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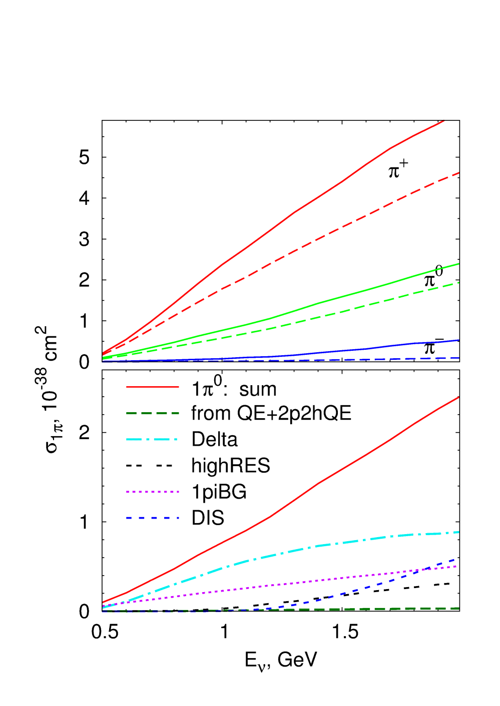
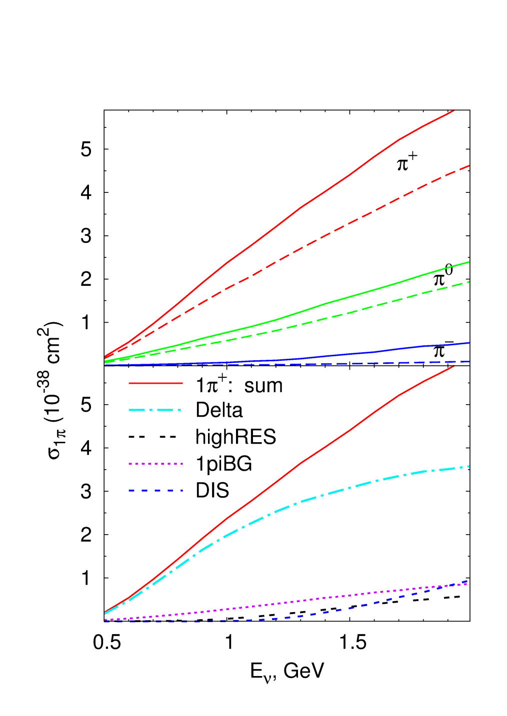
Pion Production in T2K





Δ dominant only up to 0.8 GeV

Measurement of π^+ production between about 0.5 and 0.8 GeV would be clean probe of Δ dynamics.

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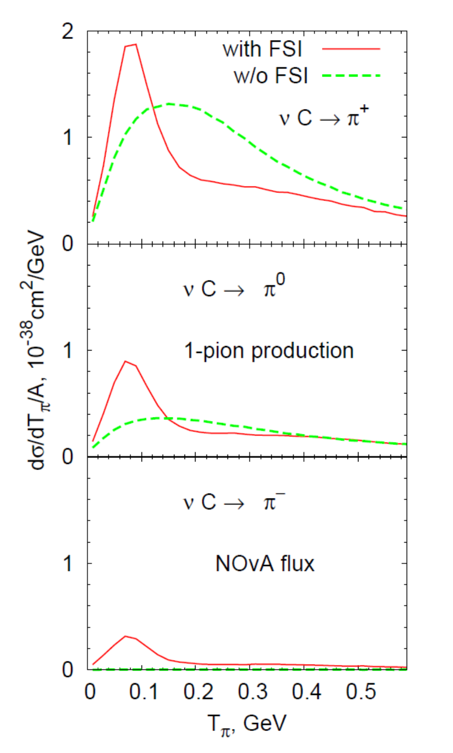
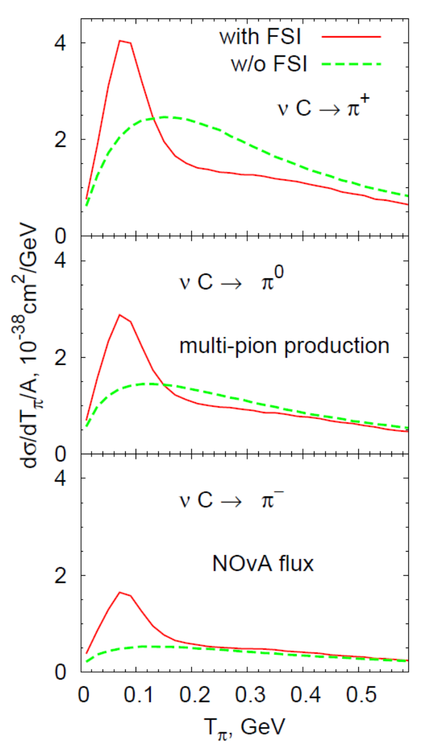
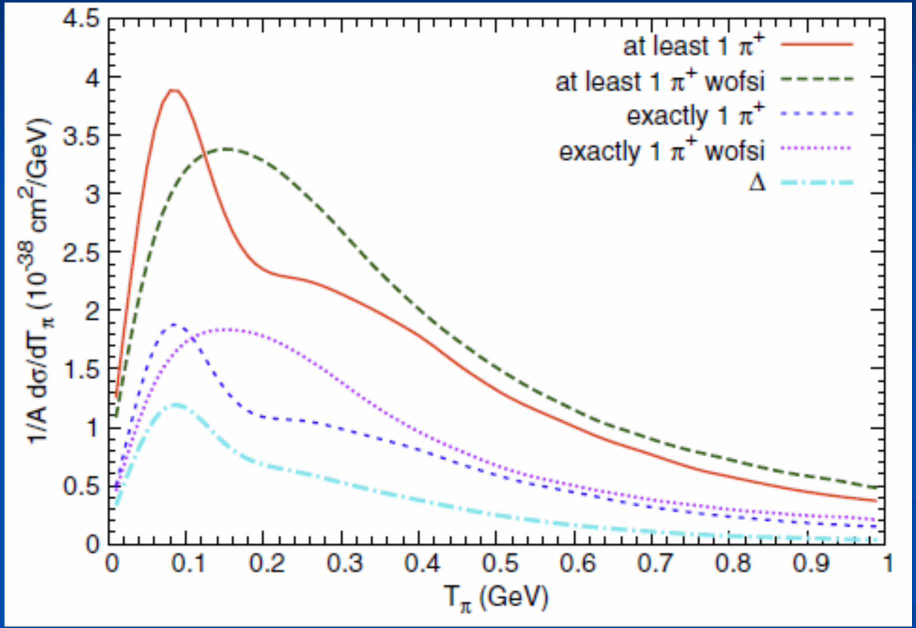
Pions at NOvA





Lalakulich et al, PR D86, 014607 (2012)

Pions at MINERvA



1.5 – 10 GeV
no *W* cut

Δ dominance
because of fsi

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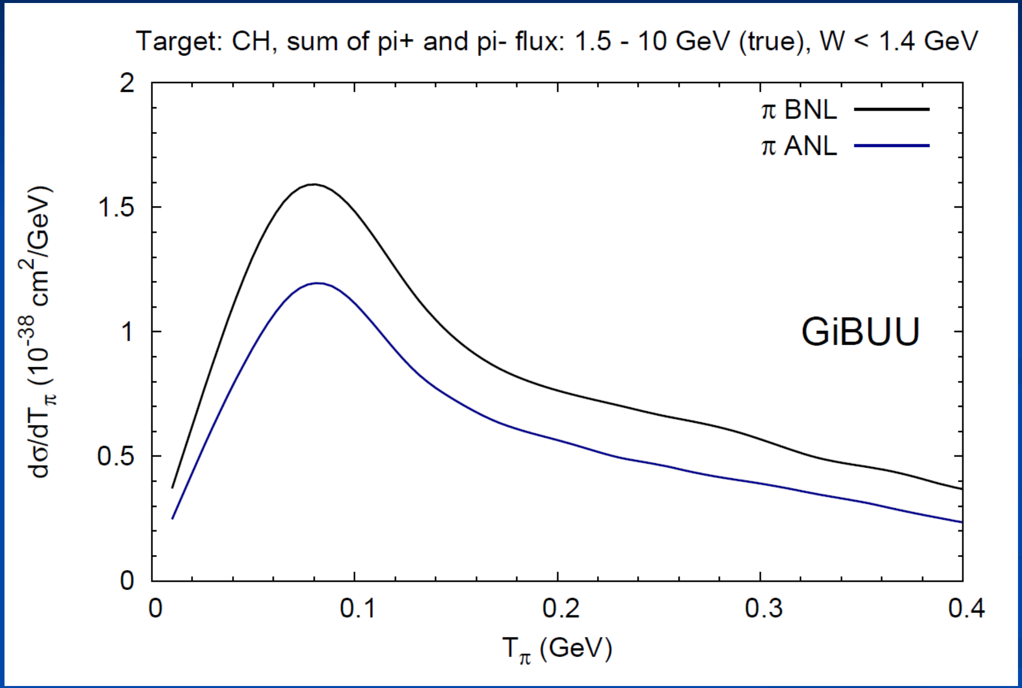
Pions at MINERvA



Cut on $W_{\pi N}$

Influence of elementary cross section

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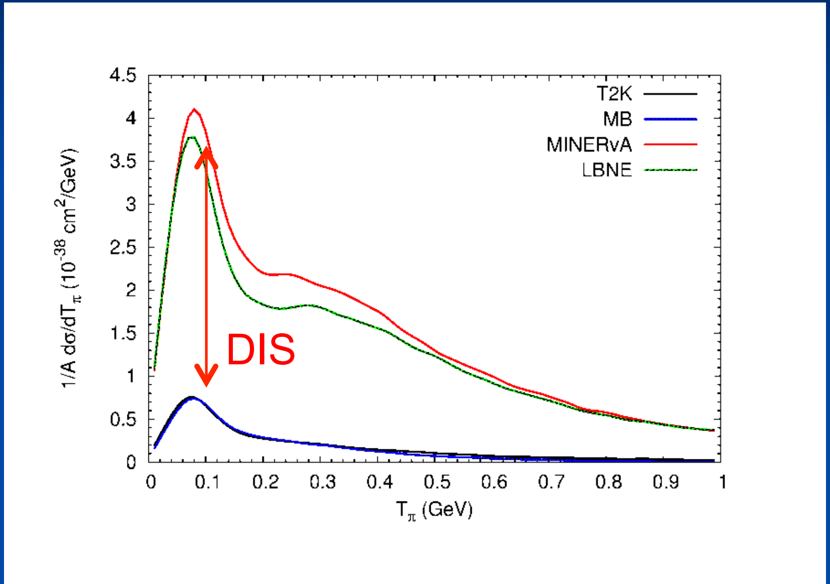
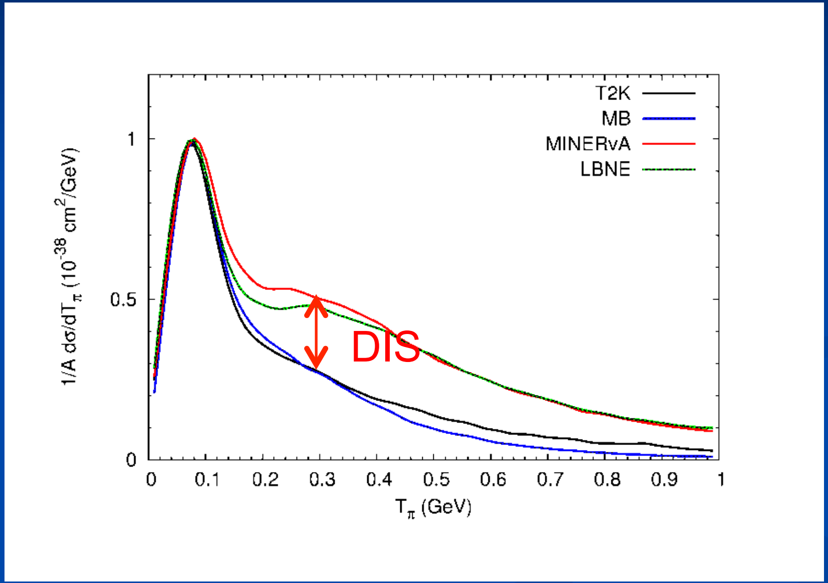
Pions at various experiments





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

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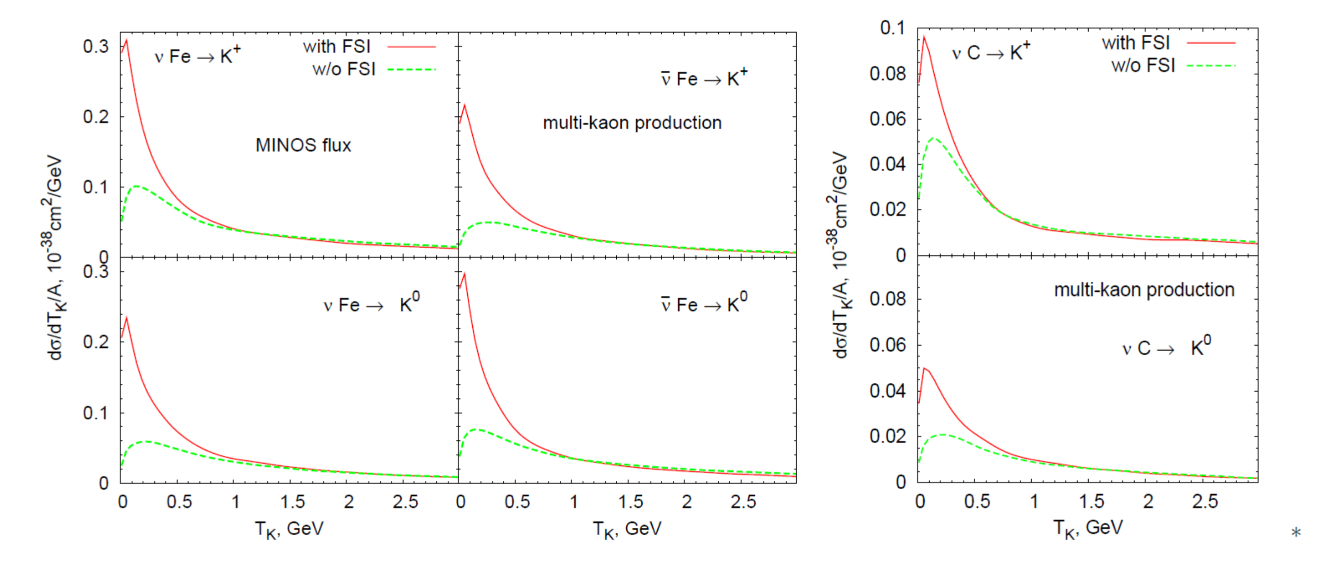
Kaons at MINOS and NOvA



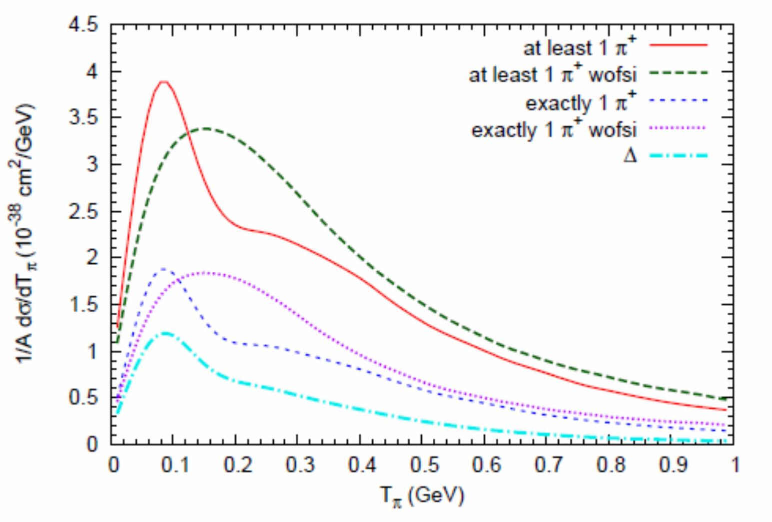
Lalakulich et al, PR D86, 014607 (2012)

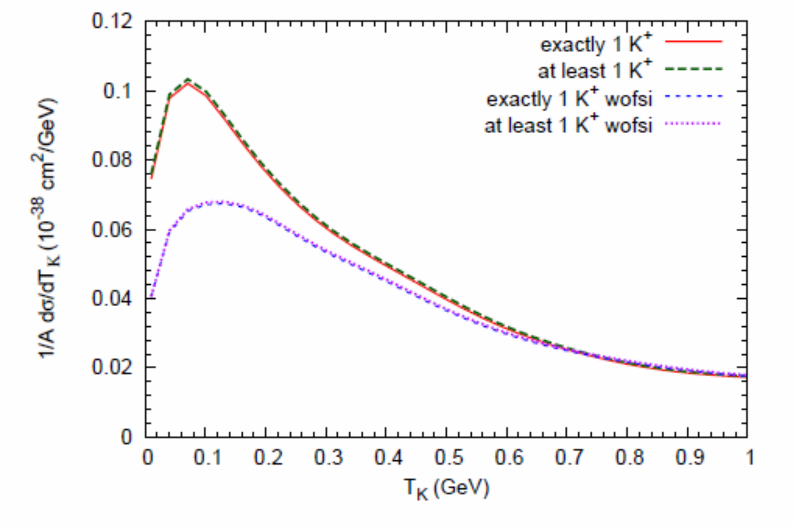
FSI increase the cross section!

Semi-inclusive X-sections much larger than exclusive ones

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

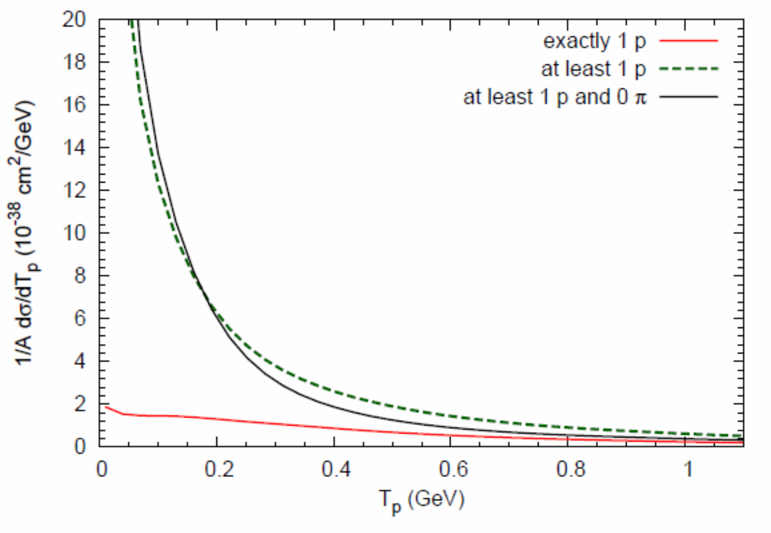
MINERvA





Fsi are most important, but different, for pions and kaons
Elementary kaon vertices ‚shielded‘ by secondary production:
$\pi + N \rightarrow K + \Lambda$

Nucleon Knock-out at MINERvA



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

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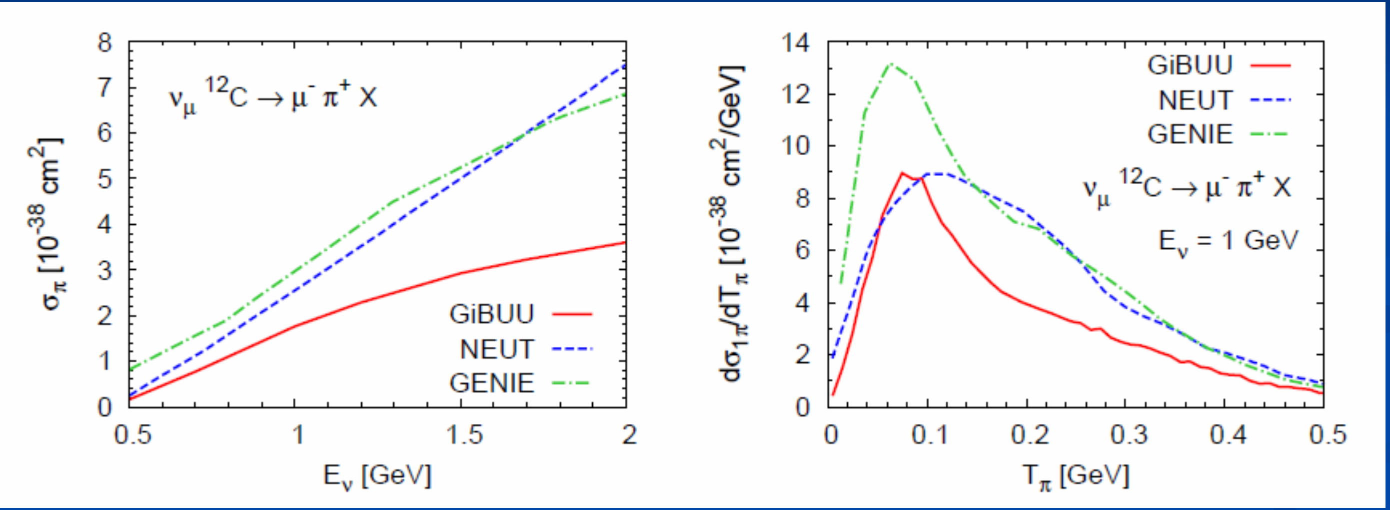
Summary

- Pions from resonance decay and DIS are large background contribution to QE
- Pions have to be well under control for QE studies; hindered by uncertainties in elementary X-sections
- Pions up to 800 MeV offer possibility to explore the axial coupling to the Delta
- Kaons are produced enhanced by fsi; makes it very different to isolate elementary kaon prod. X-sections

Comparison with other generators NUINT 2009



What causes all these significant differences??