# Giessen Model of Pion Production Theory and Generator

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U. Mosel, J. Phys. G 46, no 11 (2019):
https://dx.doi.org/10.1088/1361-6471/ab3830
general review of neutrino generators, incl pion production

# Giessen Model and GiBUU Generator

1. Theoretical Basis
   1. Elementary $\nu N$
   2. Nuclear $\nu A$
2. Application: Comparison with data
   1. MiniBooNE
   2. T2K
   3. MINERvA
3. Predictions:
   1. NOvA
   2. DUNE
4. Summary and Conclusions



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# The Giessen Model

For a more detailed description of theory and numerical implementation see:

O. Buss et al.:

„Transport-theoretical Description of Nuclear Reactions"

**Phys.Rept. 512 (2012) 1-124**

DOI: 10.1016/j.physrep.2011.12.001

Code from gibuu.hepforge.org, present version GiBUU 2019



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# Elementary Cross section

- Pion production has resonance and background amplitudes

$$\sigma \propto |A_R + A_{BG}|^2 = |A_R|^2 + |A_{BG}|^2 + interference$$

For electrons we obtain both from MAID2007 analysis for W < 2 GeV of electron- and photon-induced pion production on the nucleon

Electron cross section on *nucleon* is correct by construction

→ Vector part of Neutrino cross section on *nucleon* correct by construction!

- Higher excitations with W > 2 are handled by DIS processes through PYTHIA with smooth transition



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# Resonance Cross Section

- Calculated with standard $\Delta$ propagator,
  no extension as in Hernandez, Nieves et al.

Hadron tensor

$$H^{\mu\nu} = \frac{1}{2}\mathrm{Tr}\left[\not{p} + M)\Gamma^{\alpha\mu}\Lambda_{\alpha\beta}\Gamma^{\beta\nu}\right]$$

Vertex factor

$$\Gamma^{\alpha\mu} = \left(V^{\alpha\mu} - A^{\alpha\mu}\right)\gamma^5$$

Spin-3/2 projector

$$\Lambda_{\rho\sigma} = -\left(\not{p}' + \sqrt{p'^2}\right)\left(g_{\rho\sigma} - \frac{2}{3}\frac{p'_\rho p'_\sigma}{p'^2} + \frac{1}{3}\frac{p'_\rho\gamma_\sigma - p'_\sigma\gamma_\rho}{\sqrt{p'^2}} - \frac{1}{3}\gamma_\rho\gamma_\sigma\right)$$

Contract lepton tensor with hadron tensor gives the resonance production cross section:

$$\frac{\mathrm{d}\sigma^{\mathrm{med}}}{\mathrm{d}\omega\mathrm{d}\Omega'} = \frac{|\mathbf{k}'|}{32\pi^2}\frac{\mathcal{P}^{\mathrm{med}}(p')}{[(k\cdot p)^2 - m_\ell^2 M^2]^{1/2}}|\mathcal{M}_R|^2$$

Resonance spectral function

# Resonance Cross Section

$$d\sigma(\nu p \to \ell^- p \pi^+) = \sum_{\substack{I=3/2 \\ \text{resonances}}} b_i \, d\sigma_{R_i^{++}},$$

$$d\sigma(\nu n \to \ell^- n \pi^+) = \frac{1}{3} \sum_{\substack{I=3/2 \\ \text{resonances}}} b_i \, d\sigma_{R_i^{+}} + \frac{2}{3} \sum_{\substack{I=1/2 \\ \text{resonances}}} b_i \, d\sigma_{R_i^{+}} \, ,$$

$$d\sigma(\nu n \to \ell^- p \pi^0) = \frac{2}{3} \sum_{\substack{I=3/2 \\ \text{resonances}}} b_i \, d\sigma_{R_i^{+}} + \frac{1}{3} \sum_{\substack{I=1/2 \\ \text{resonances}}} b_i \, d\sigma_{R_i^{+}} \, ,$$

branching ratios $b_i = \Gamma_{\pi N} / \Gamma_{\text{tot}}$

In the vector sector data are described because we use MAID07 analysis
Also $2\pi$ resonance decays considered (W > 1520 MeV)



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# Background Cross Section

- Practical treatment:

$$\sigma \propto |A_R + A_{BG}|^2 = |A_R|^2 + |A_{BG}|^2 + interference$$

$$\sigma \propto= |A_R|^2 + BGterms$$

BG + Interference

- BG is obtained from
  - for electrons from MAID

$$\sigma_{1p1h\,1\pi} = \sigma_R \frac{\Gamma_\pi}{\Gamma_{\rm tot}} + \sigma_{\rm BG}$$

  - effective field theory
    (Nieves et al, restricted to $\Delta$, cannot be used for MINERvA, NOvA, DUNE!)
  - Fit to elementary data (default)

$$\mathrm{d}\sigma_{\rm BG} = (1 + b^{N\pi})\,\mathrm{d}\sigma^V_{\rm BG}$$



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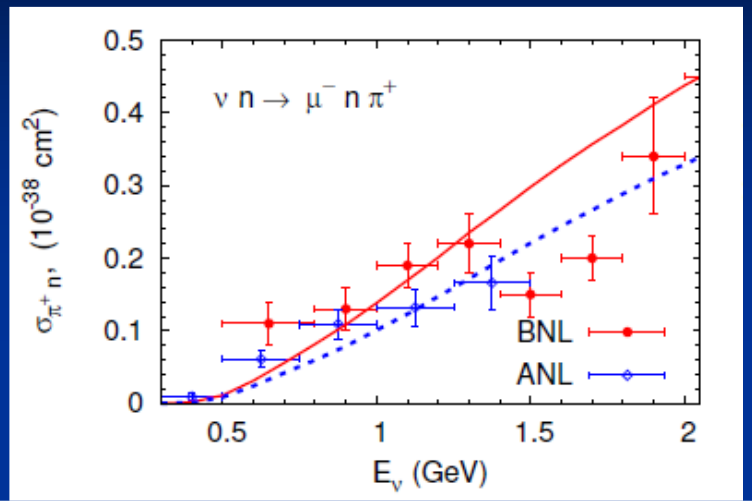
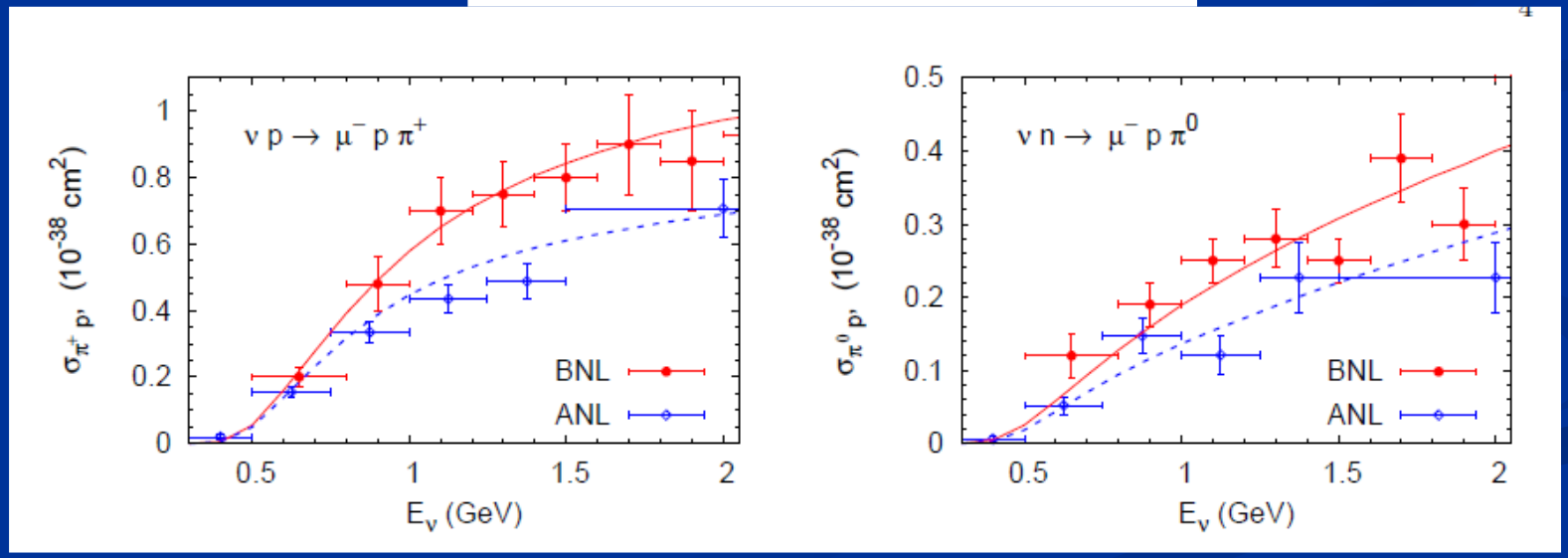
# Elementary Cross Sections




ANL
is now default,
No masscut



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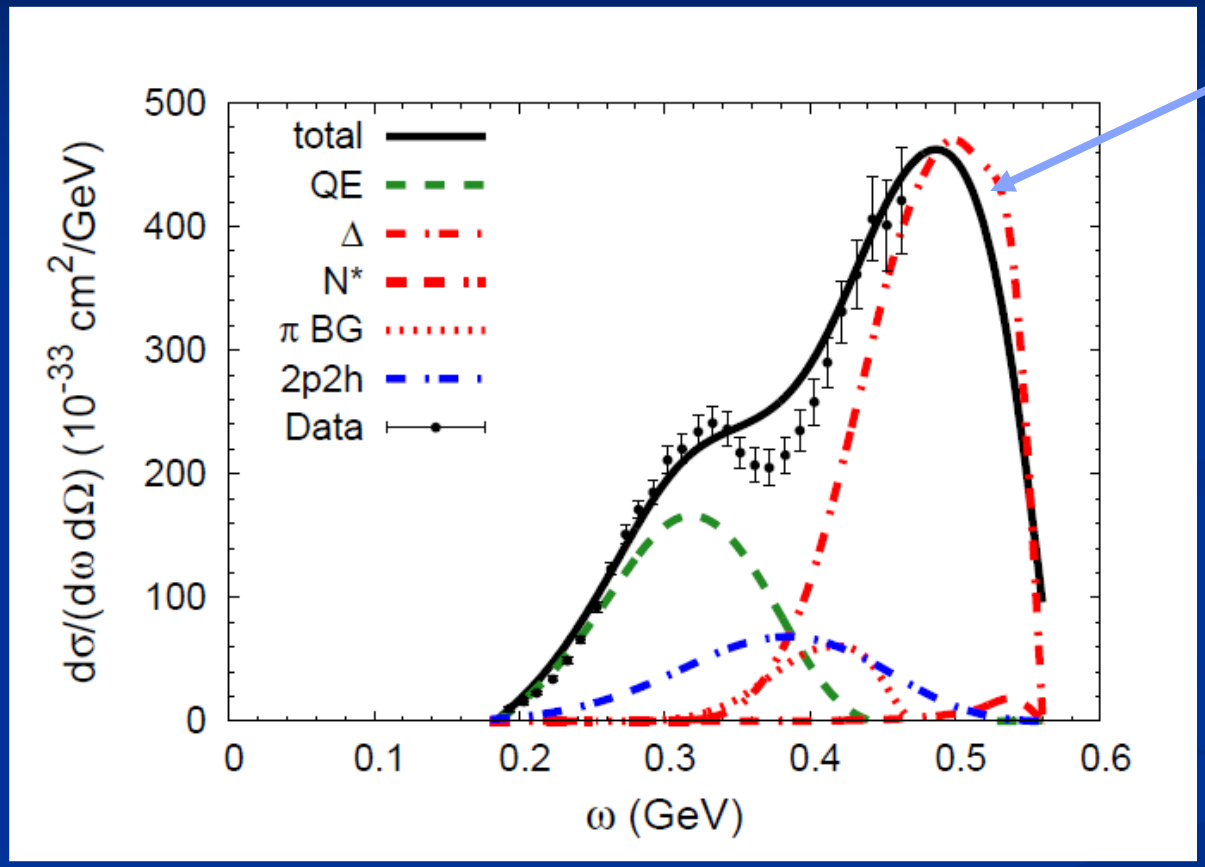
# Resonance-Background Interference




Interference terms can be negative!

GiBUU has Res-BG interference



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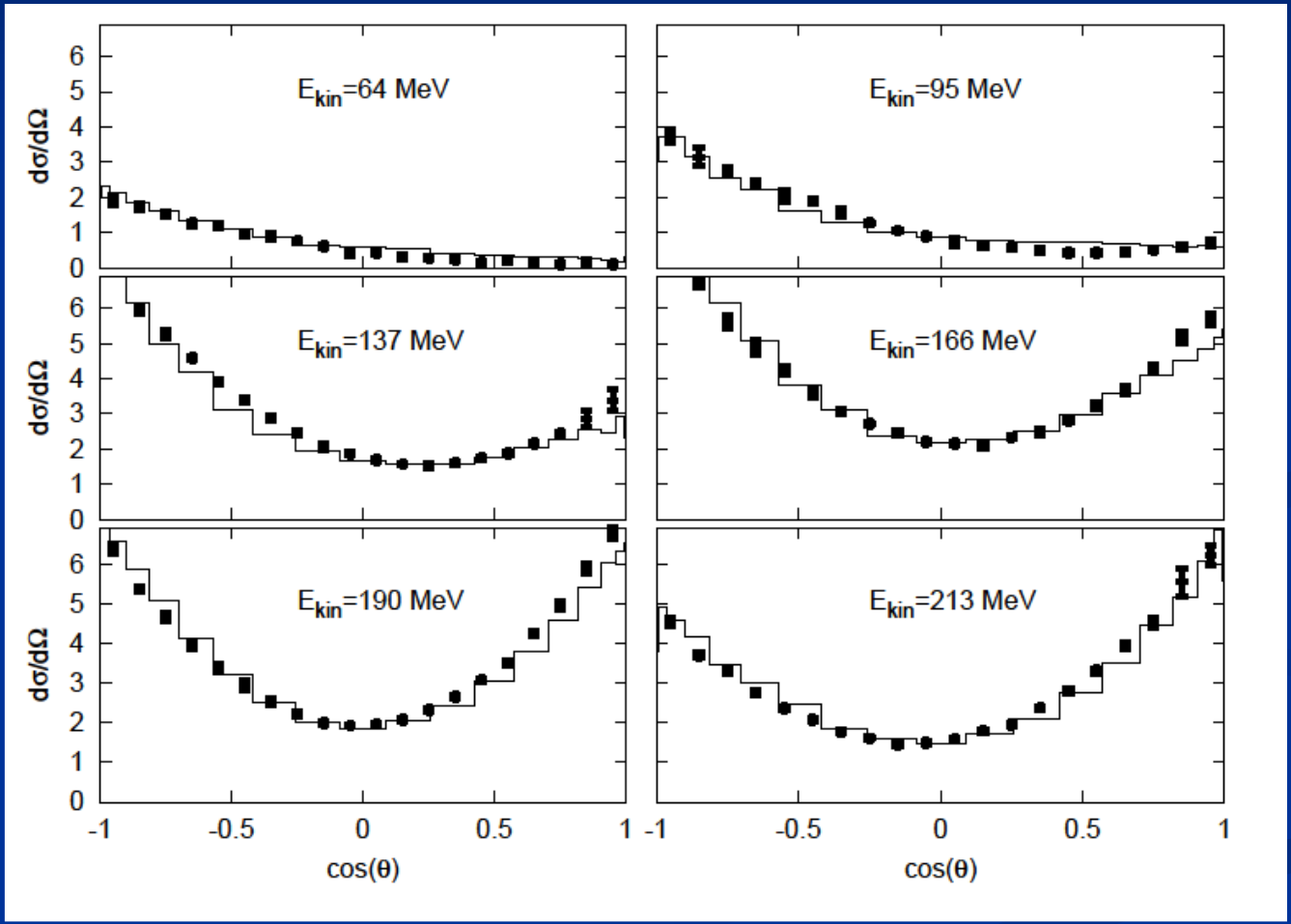
# $\pi^- p \rightarrow \pi^0 n$ angular distributions



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# Formalism on Nucleus

Integrate the nucleon cross sections over the Fermi-sea of bound nucleons

$$d\sigma_\pi^{\nu A} = \int \frac{d^3p}{(2\pi)^3}\frac{dE}{2\pi}\mathcal{P}_h(\mathbf{p},E) f_{\text{corr}}\, d\sigma_\pi^{\nu N}(E_\nu, E, Q^2, \omega)\,\mathcal{F}(E_\nu, \mathbf{p}, E)$$

Hole spectral function

Final state transport by KB equations

Resonances and nucleons bound in mean-field potential, Delta potential is weaker than nucleon potential (~ 2/3)

Hole spectral function of groundstate (LTF):

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

Potental in here



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# GiBUU Generator

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Quantum-Kinetic Theory and Event Generator** based on a BM solution of Kadanoff-Baym (KB) equations
- describes **non-equilibrium** processes, **no coherent** ones, add your favorite model for coherent production!
- GiBUU is a semi-classical theory, propagates 8-dimensional relativistic (off-shell) Wigner transform *F(x,p)*
- GiBUU propagates phase-space distributions, not particles
- The code runs for νA, eA, γA, πA, pA, AA, same physics and code, no special modules for FSI, FSI extensively tested with γA, πA, pA, AA
- Code works for energy transfers ≈> 50 MeV

# The GiBUU Generator

- Model and numerical algorithms well documented: *Buss et al, Phys. Rept. 2012*
- Code written in modern Fortran 2003, open source, well commented throughout: *gibuu.hepforge.org*
- Produces millions of events on ‚normal' PC, within a day of running time
- Gives result file with four-vectors of all final state particles on event-by-event basis, plus other relevant information, such as history-info on primary reaction mechanism (QE, DIS, Res,… )
- Event output file is either .txt or root format
- Allows for reweighting of events because of history info



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# $\pi N\Delta$ in Nuclei

- Nucleons are bound in a mean field
- The mean field is *r*- and *p*-dependent
- Ejected nucleons feel the same potential, at different momentum (less attractive)
- Coulomb-potential for charged hadrons
- Delta-Potential $\cong$ 2/3 nucleon potential



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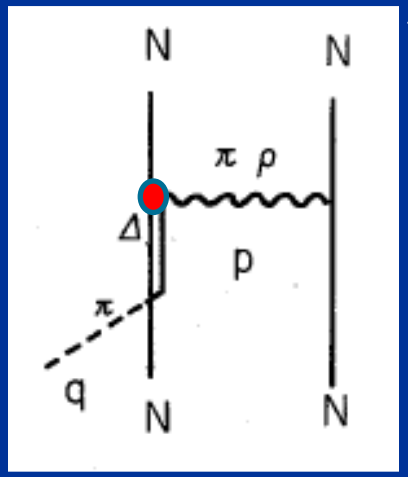
# Absorption of Pions

- Two-body $\pi$ absorption through
  $\pi + N \rightarrow \Delta$, $\Delta + N \rightarrow NN$

$\Delta$ in medium shifted and broadened




$$\Gamma_{N_A N_B \pi \to N_a N_b} = \Gamma^{\mathrm{BG}}_{N_A N_B \pi \to N_a N_b} + \Gamma^{\text{resonance contribution}}_{N_A N_B \pi \to N_a N_b}$$

The vertex ● is the same for pion production and absorption:

Detailed balance

violated if you use e.g. RS for production and Valencia code for absorption (GENIE, NuWro,…)



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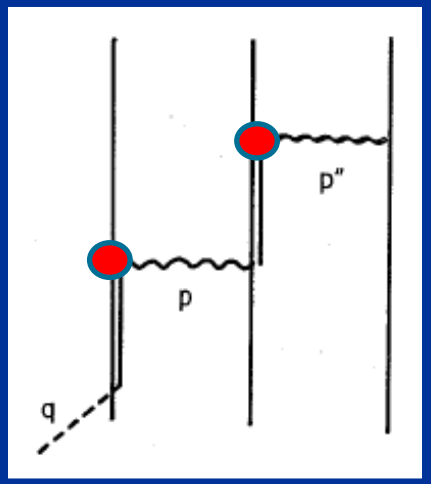
# Absorption of Pions

- Three-body pi absorption




$$\Gamma^{\mathrm{BG}}_{N_A N_B \pi \to N_a N_b} \sim \sigma^{\mathrm{BG}}_{NN \to NN\pi}$$

$$\Gamma^{\mathrm{resonance\ contribution}}_{N_A N_B \pi \to N_a N_b} \sim \sigma^{\mathrm{resonance\ contribution}}_{NN \to NN\pi}$$

As large as two-body
(Oset, Toki,~ 1986)
not contained in your favorite generator,
but in GiBUU



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# Checks of Code



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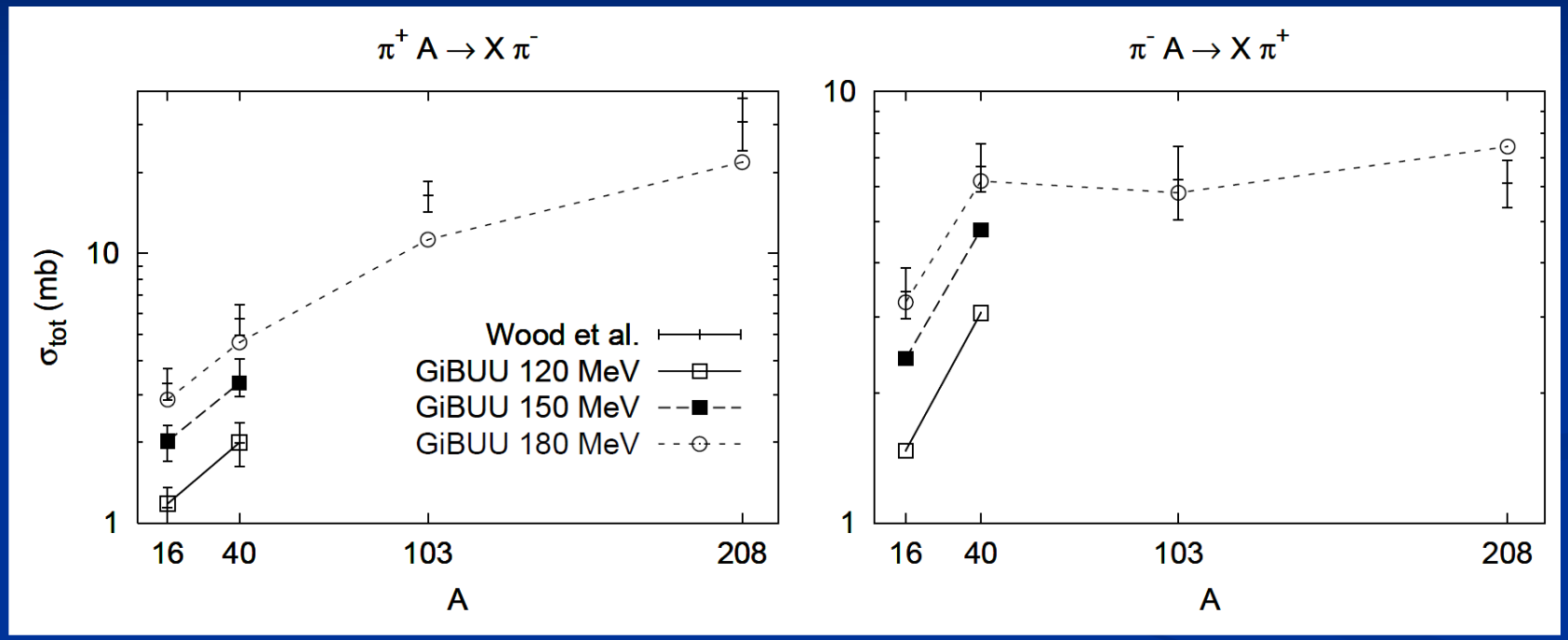
# DCX at $T_\pi$ = 180 MeV




Data: Wood et al, Phys. Rev. C46, 1903 (1992), Theory: Buss et al, Phys. Rev. C74 (2006) 044610



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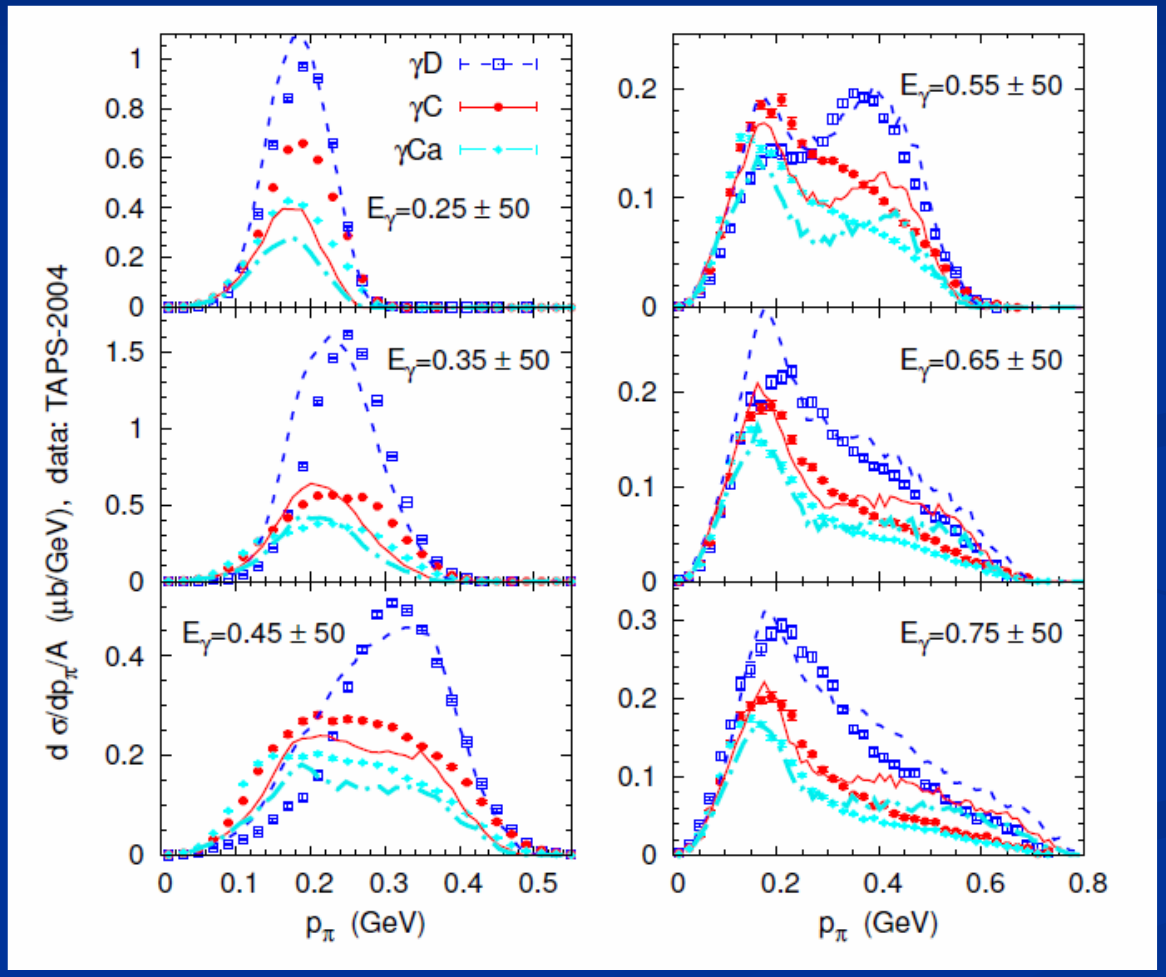
# Test with $\gamma A \rightarrow \pi^0$

- TAPS data




Targets:
D
C
Ca

Lalakulich et al,
AIP Conf.Proc.
1663 (2015) 040004



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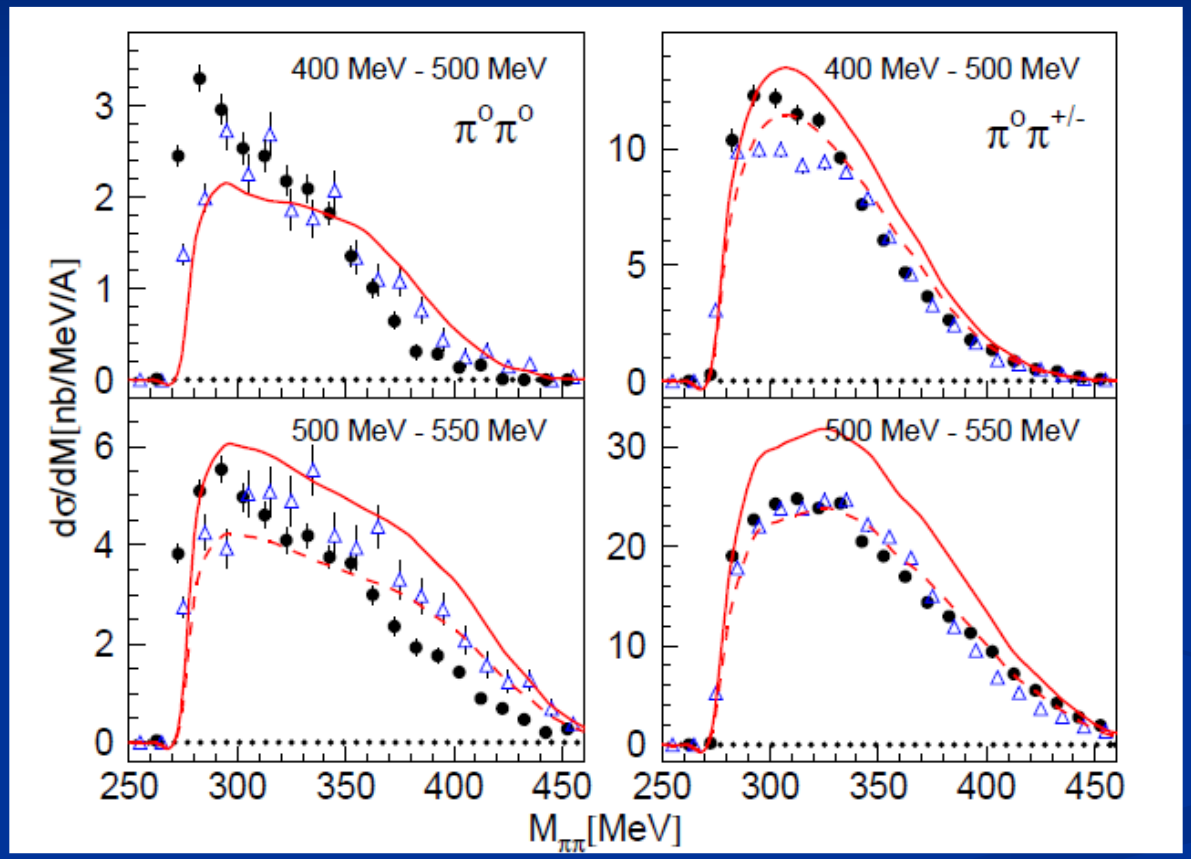
# Test with γA → 2π




TAPS data

Eγ = 400 – 500 MeV

TAPS data

Eγ = 500 – 550 MeV



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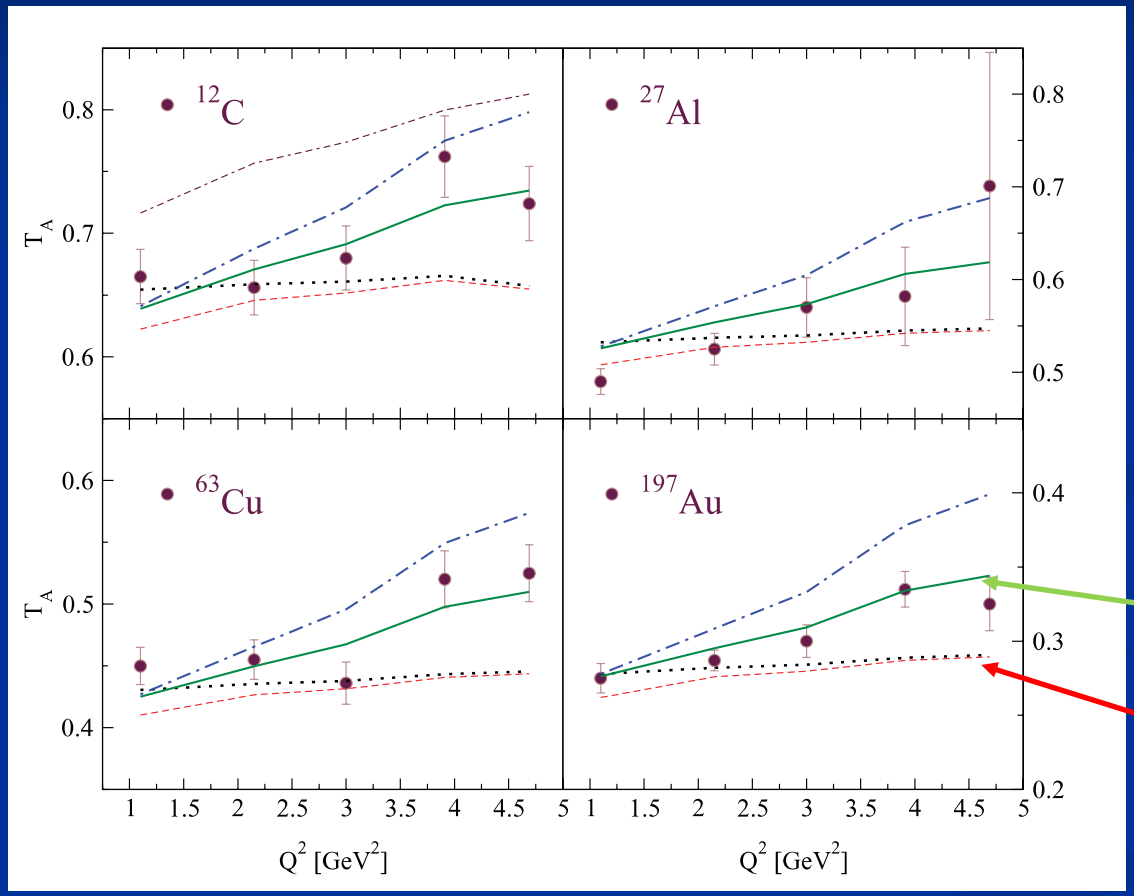
# Test with eA→ π + X (such data do exist!)




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

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

Pion Transparency

CT

No CT



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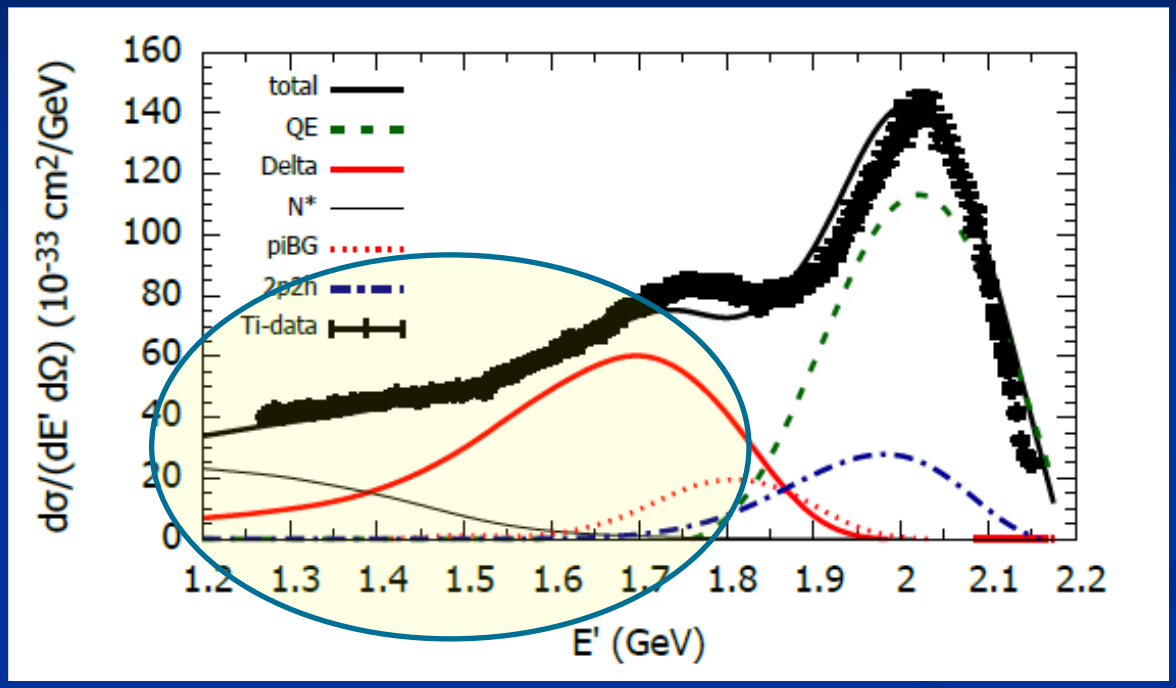
# Test with eA incl




JLAB data $(e,{}^{48}\mathrm{Ti})$ at 2.222 GeV



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# Neutrino Pion Production



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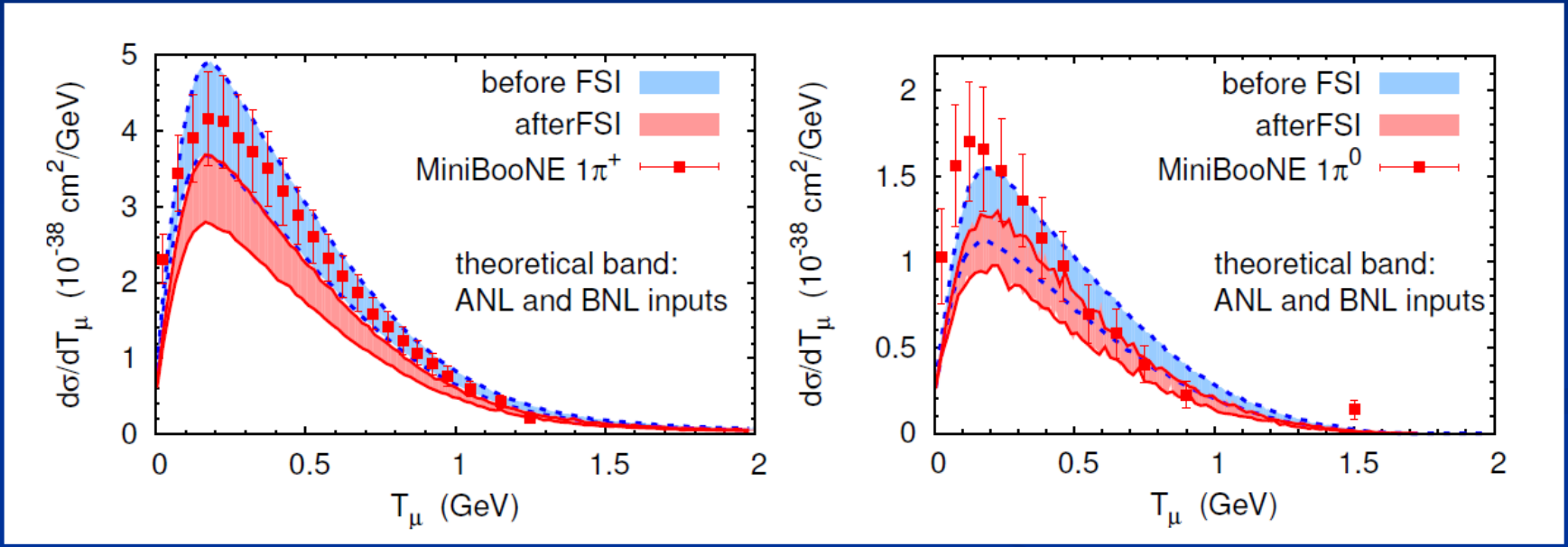
# MiniBooNE Pion Puzzle




Calculated with nominal flux

Remember: Nieves et al increased flux by factor 0.89 to fit dd X-section

➔ Use same flux for QE-like and pion production



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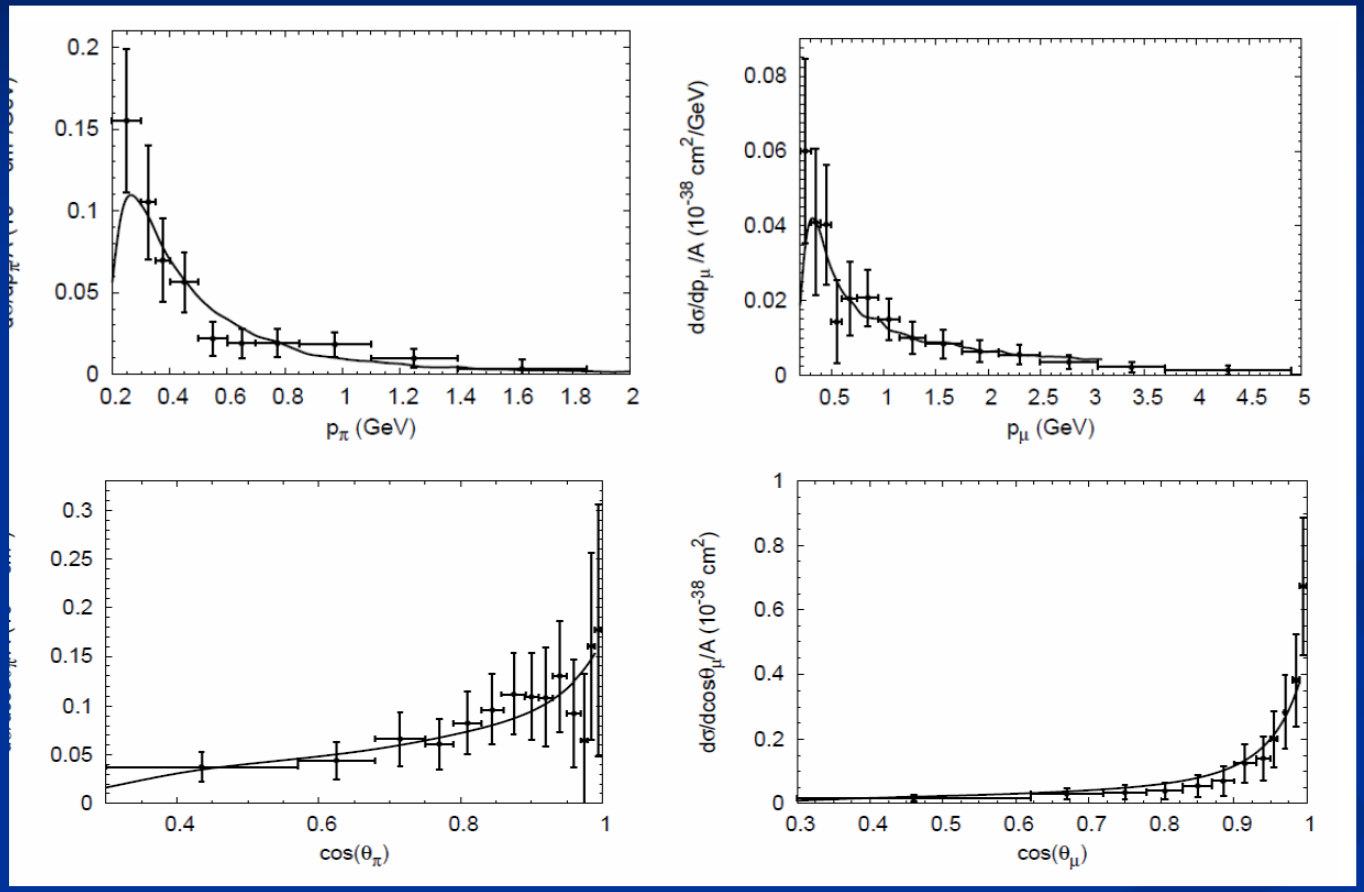
# T2K pions on $H_2O$




Mosel, Gallmeister: Phys.Rev. C96 (2017) 015503

T2K has flux similar to MiniBooNE



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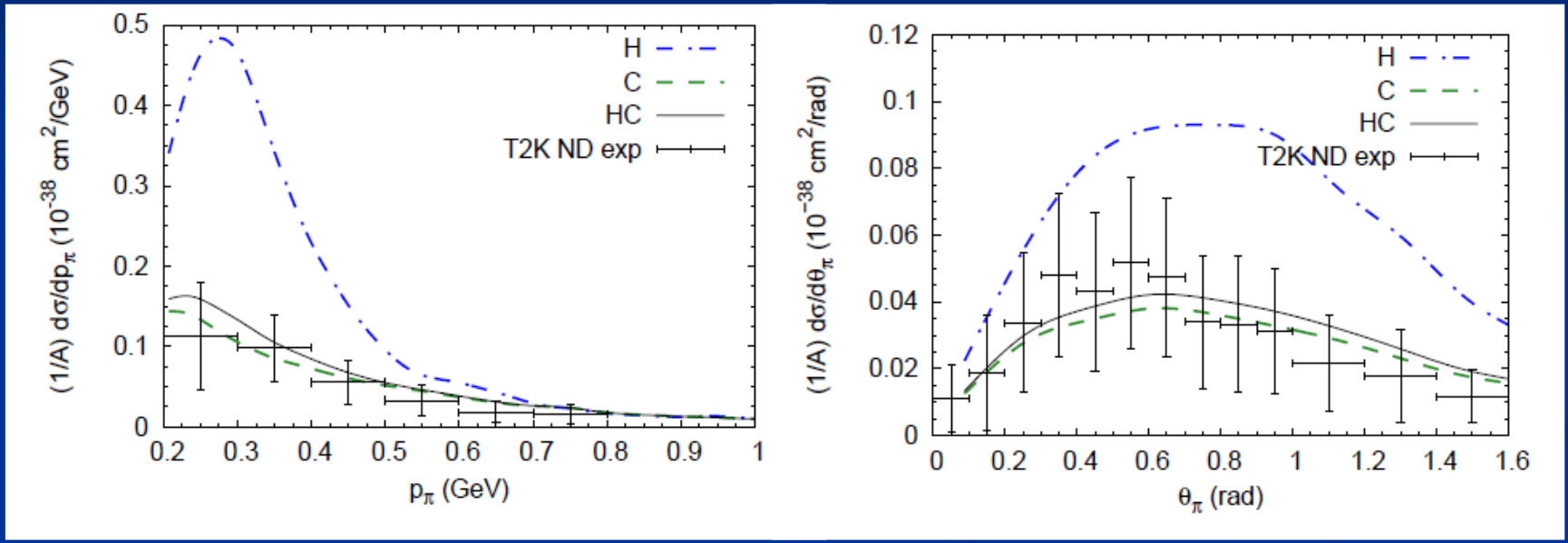
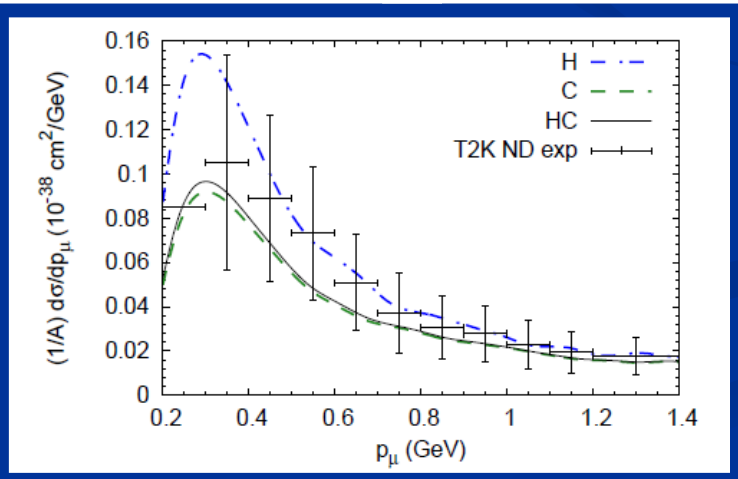
# T2K pions on CH




Data: Abe et al
arXiv:1909.03936
Calc: Mosel et al
PR C99 (2019) 035502




T2K: energy similar to MiniBooNE

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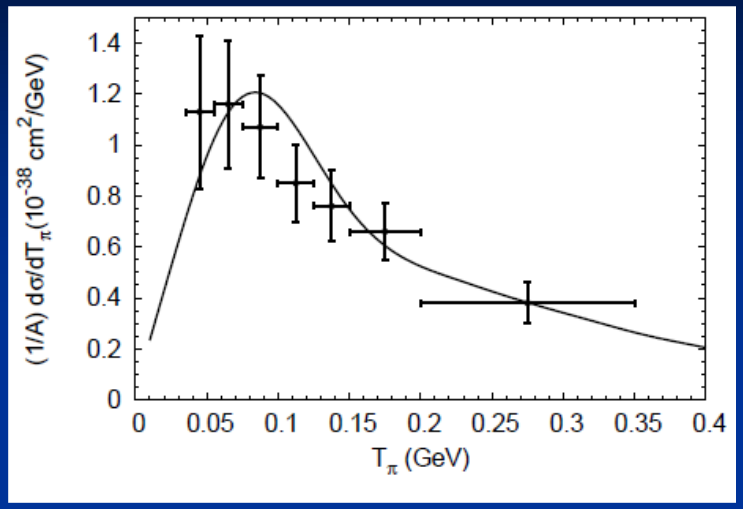
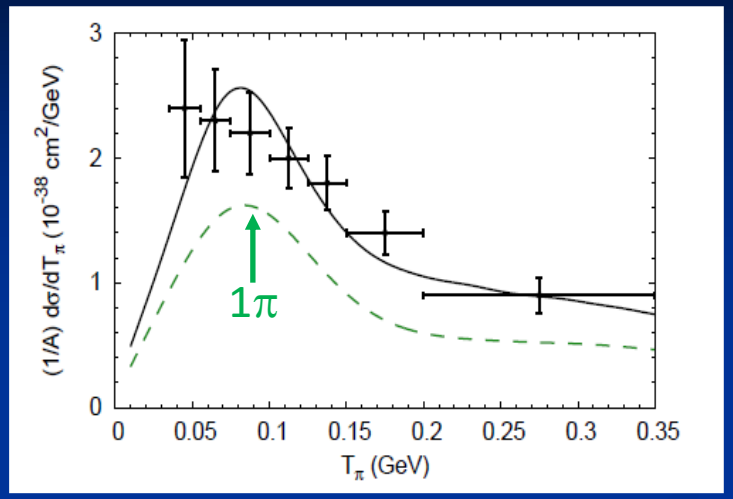
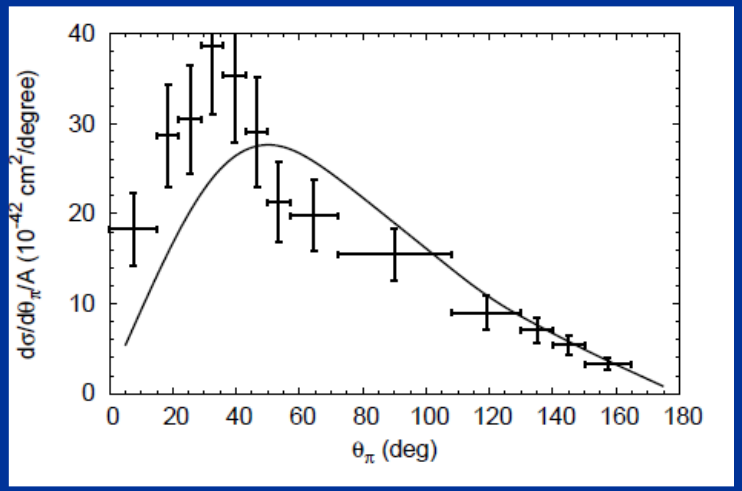
# MINERvA Charged Pion Data

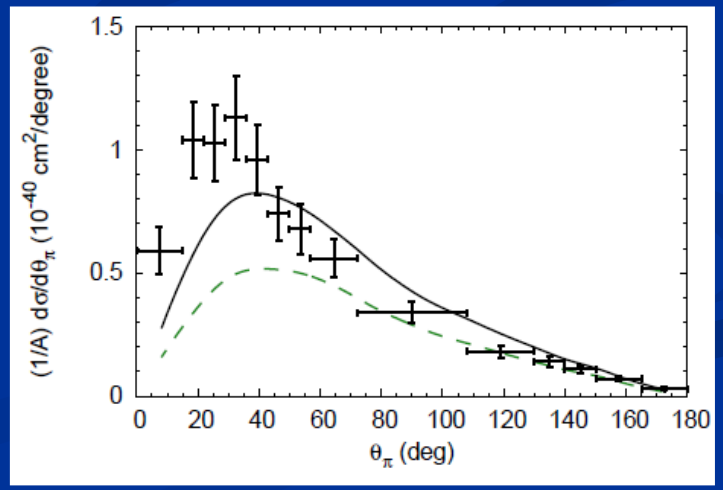



Single pi, W < 1.4 GeV

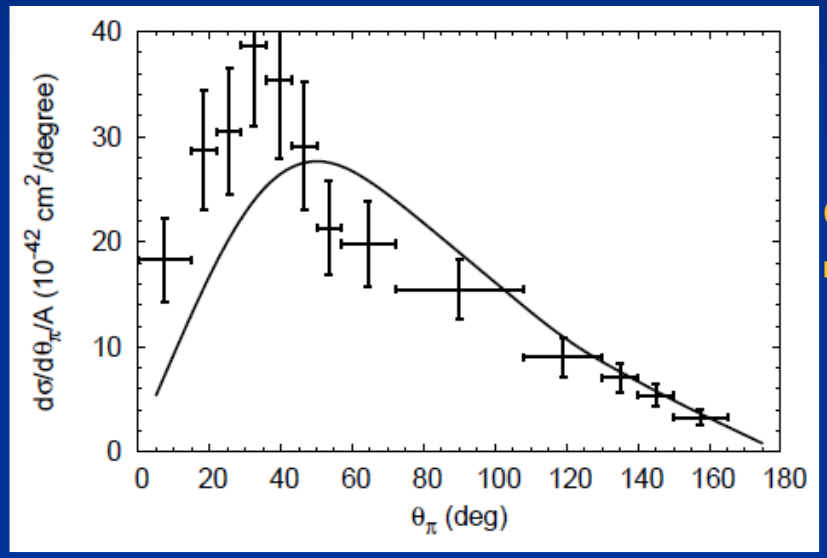



Multiple pi, W < 1.8 GeV



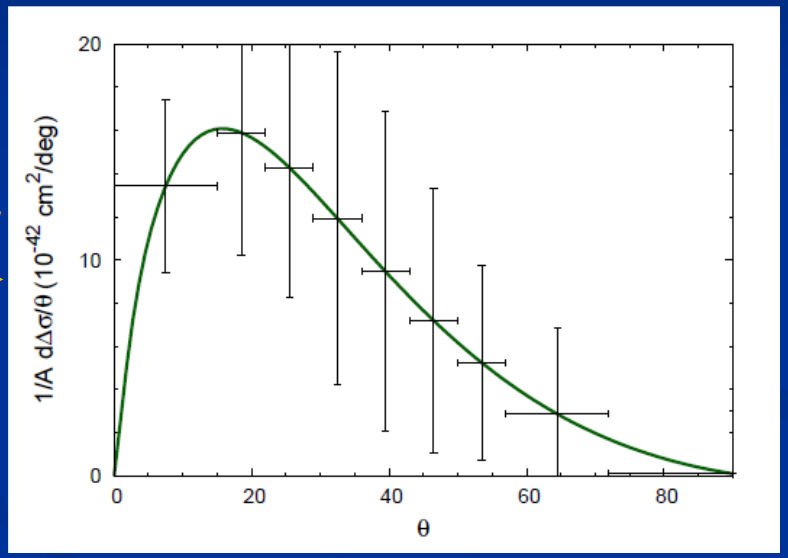

Mosel, Gallmeister:Phys.Rev. C96(2017) 015503

# MINERvA data, W < 1.4 GeV




discrepancy

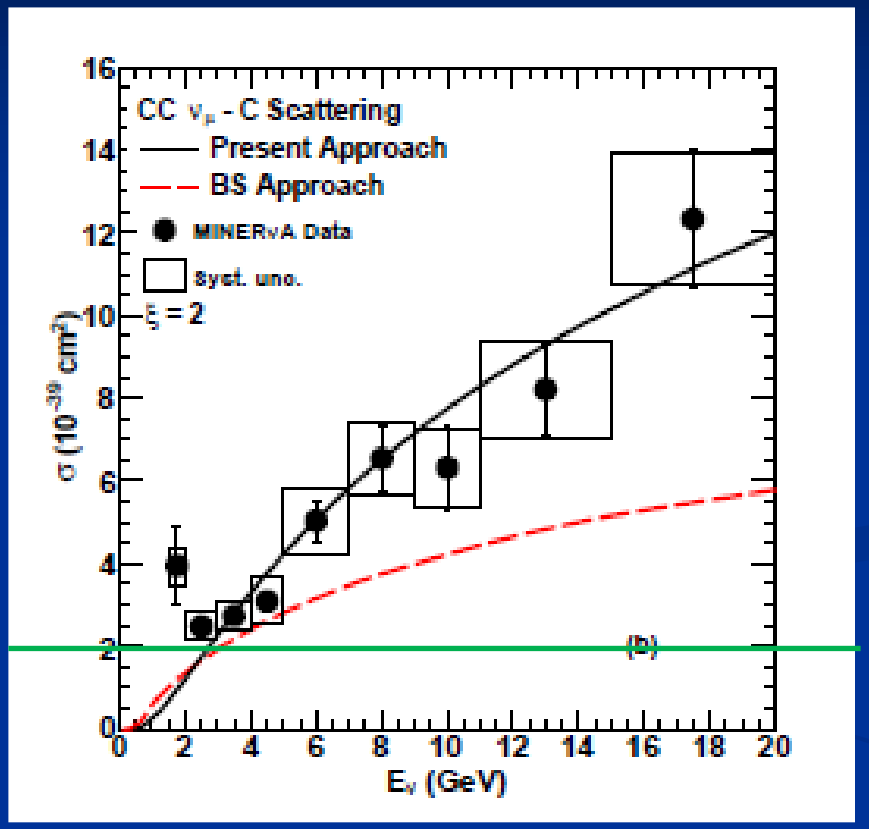
Difference: data – GiBUU theory




Forward discrepancy gives very small contribution to total cross section because of Jacobian sinθ

Integrated difference : ~ 2 • $10^{-39}$ $cm^2$

# Coherent Pion Production




K. Saraswat et al,
Phys.Rev. C93 (2016) 035504

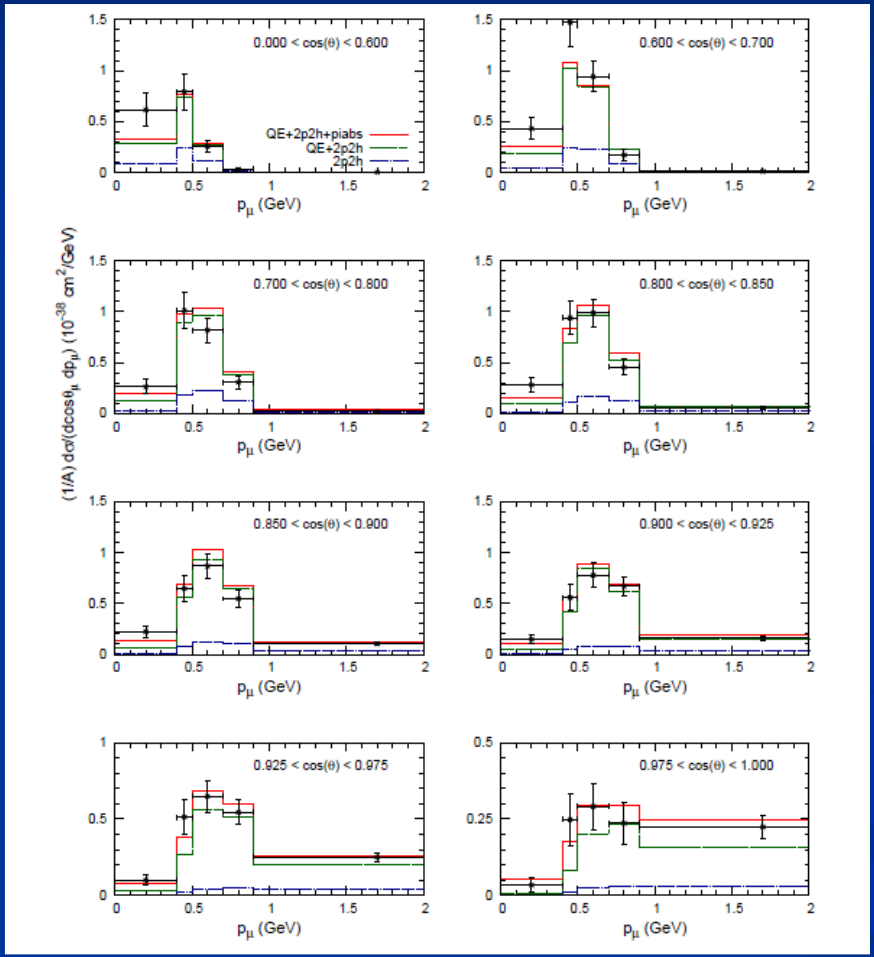
Difference between exp and GiBUU X-section
→ Consistent with coherent Production

Coherent X-section increases by about a factor of 6 between MiniBooNE/T2K energy and MINERvA energy

➔

Discrepancy at small angles and small energies is coherent production

# 0-pion events, sensitive to pion production and absorption




Data: T2K
Target H2O

Difference between green and red curves: reabsorbed pions



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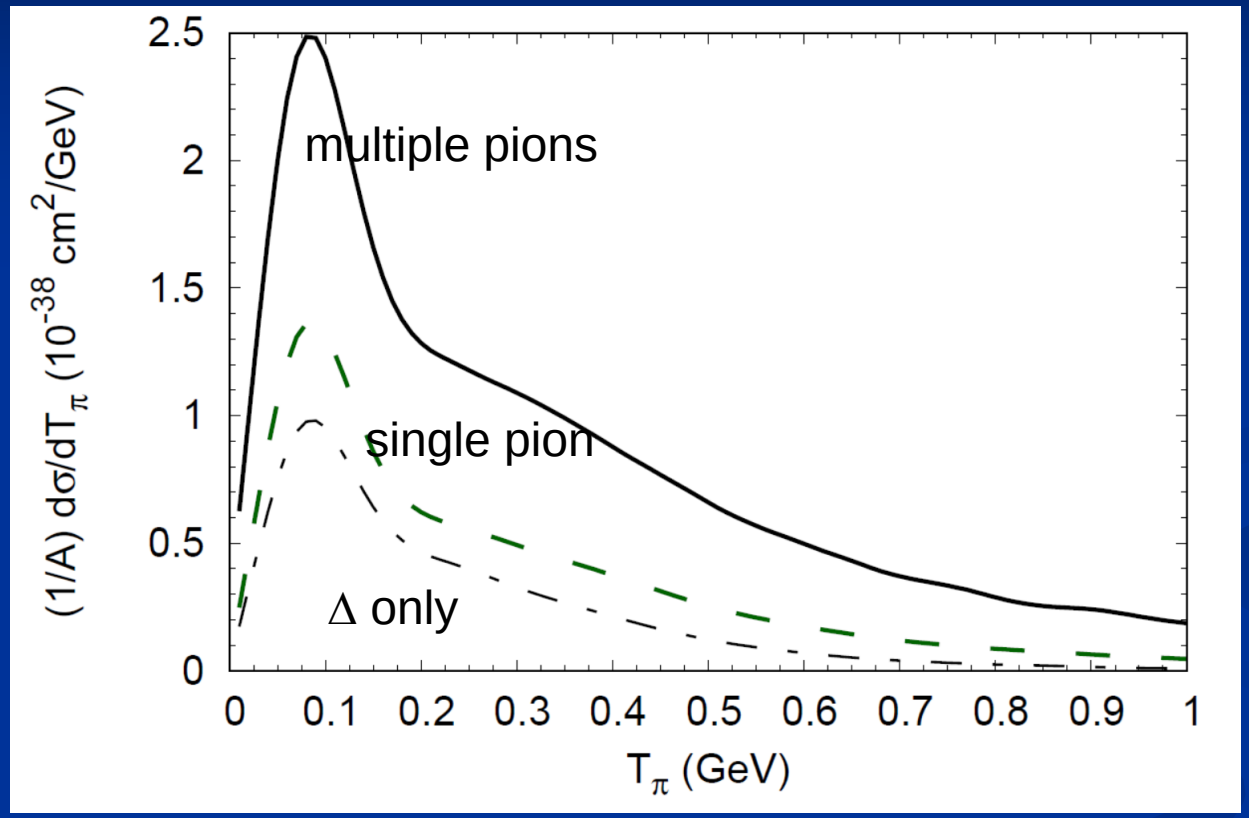
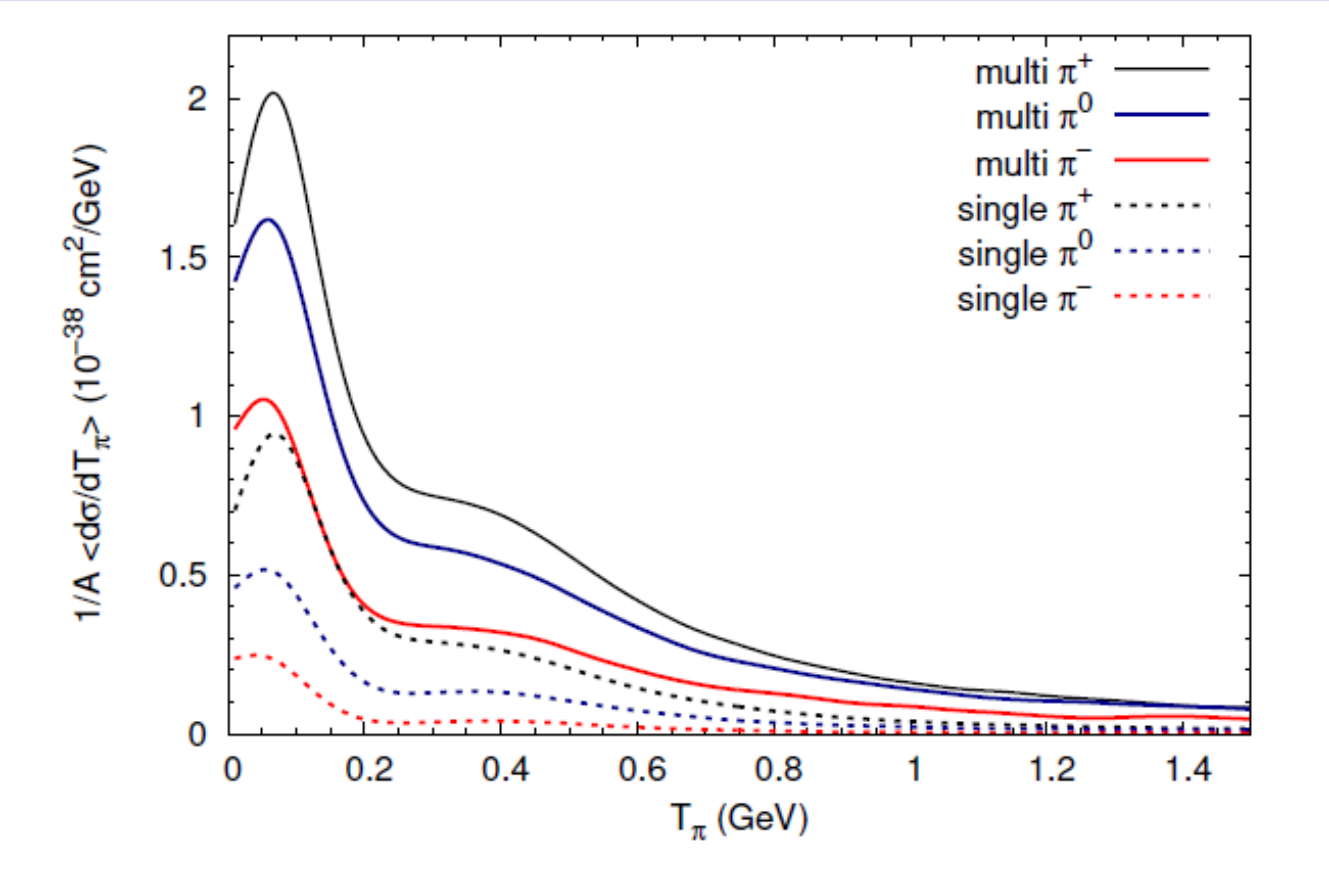
# Pions at NOvA




No longer Δ dominated,
Multipion events from higher resonances and DIS prevail

# Pions at DUNE



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# Conclusion: Pion Production is understood and under control

Mosel, Gallmeister, Phys. Rev. C98 (2017)

We have shown that the T2K ND data on a water target agree quite well with the GiBUU calculations, both in absolute magnitude and in shape. The T2K experiment works with a neutrino flux that is centered around the same energy as in the MiniBooNE. We, therefore, conclude that the latter data are too high and that the shape of the pion kinetic energy distribution determined by MiniBooNE is not correct. This conclusion receives additional support from the observation that all the MINERvA pion data, both the single pion data with a $W < 1.4$ GeV cut and the more recent multiple pion data with a $W < 1.8$ GeV cut, are described very well by the present GiBUU calculations. The remaining discrepancies, mainly at the lowest pion energies and the lowest angles, are compatible with a coherent contribution in the data, which is not contained in the present calculations.



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# Summary

- *GiBUU Theory* uses the standard resonance propagators, no special tune or special terms invented!
  Consistent with ~ 35 years old, classical $\pi N\Delta$ physics.
- The *GiBUU Generator* has been checked against a large set of pion photo- and electronproduction data,
  works without any special tune!
- Pion data from T2K and MINERvA are consistent, both described well by GiBUU
  → MiniBooNE data most likely incorrect (flux norm ?)
- Any theoretical description of data at MINERvA, NOvA, DUNE needs to take higher resonances + DIS into account



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# Outlook

- Pion production data often suffer from a generator ‚contamination' through flux cuts and W-cuts
- Need these data without these constraints, only with ‚physical cuts' on outgoing lepton → reanalysis of MINERvA data! T2K data do not suffer from these contaminations
- NOvA data are an important further test for pion production at higher energies, without generator-generated cuts
- GiBUU is a mature code, based on consistent nuclear theory, as far as possible, no need for major new developments

This talk is based on work with:
Kai Gallmeister



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