Pion Production

In GiBUU

With

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Elementary Cross section

Pion production has resonance and background amplitudes

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

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

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

We propagate the resonances; the BG terms can be < 0!

Pion production on the nucleon

Transition currents to resonances:

$$V^{\alpha\mu}_{3/2} = \frac{C_3^V}{M}\left(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu\right) + \frac{C_4^V}{M^2}\left(g^\alpha \mu q\cdot p - q^\alpha p\mu\right) + \frac{C_5^V)}{M^2}\left(g^{\alpha\mu} q\cdot p - q^\alpha p^\mu\right) + g^{\alpha\mu}C_6^V$$

$$A^{\alpha\mu}_{3/2} = -\left[\frac{C_3^A}{M}\left(g^{\alpha\mu}\not{q} - q^\alpha\gamma^\mu\right) + \frac{C_4^A}{M^2}\left(g^{\alpha\mu} q\cdot p - q^\alpha p^\mu\right) + C_5^A g^{\alpha\mu} + \frac{C_6^A}{M^2} q^\alpha q^\mu\right]\gamma^5 .$$

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

Vertex factor

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

Hadron tensor

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

Contract lepton tensor with hadron tensor gives the resonance productioncross section:

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

Formalism on Nucleon

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

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

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

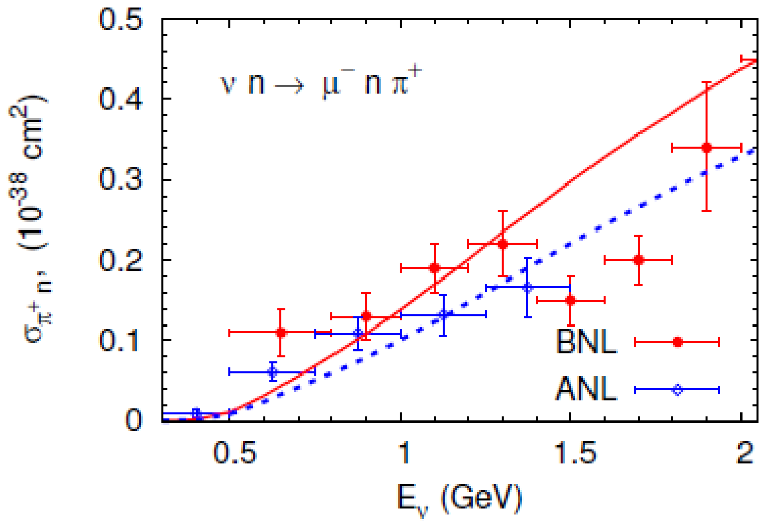
branching ratios $b_i = \Gamma_{\pi N} / \Gamma_{\text{tot}}$

In the vector sector data are described because we use MAID07 analysis
Higher excitations with W > 2 are handled by DIS processes through PYTHIA

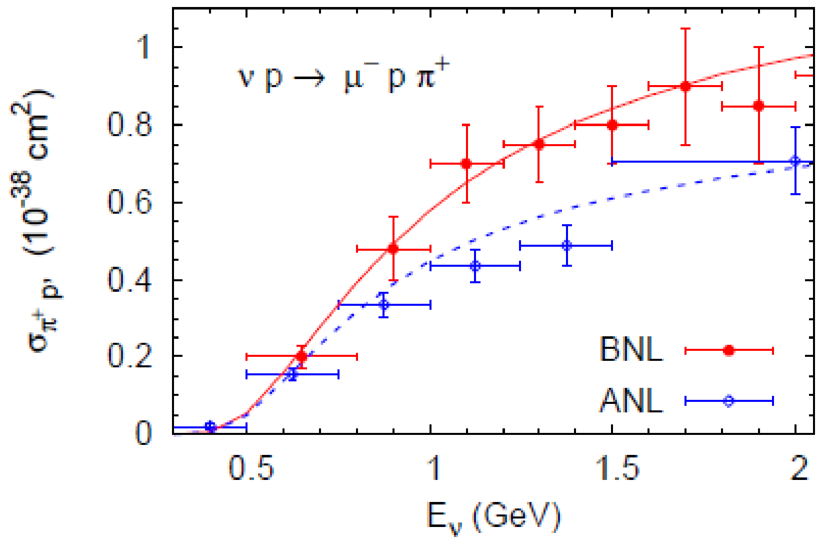
BG parameters:

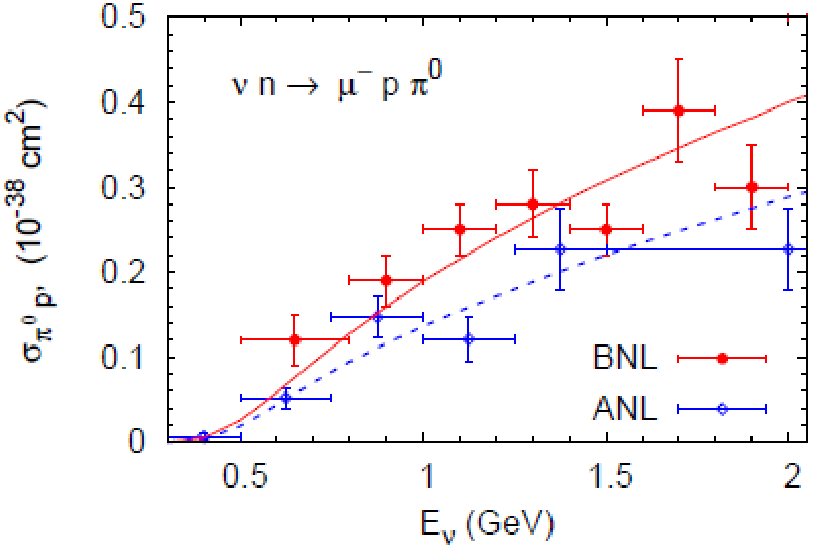
- for electrons from MAID analysis
- for neutrinos are obtained by fit to nucleon data

Elementary Cross Sections



ANL
is now default





Formalism on Nucleus

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

$$d\sigma^A = \int \frac{d^3p}{(2\pi)^3} dE\, P_h(p,E)\, d\sigma^N P_{PB}$$

Hole spectral function

Pauli blocking

Resonances and nucleons sit in potential,
Delta potential is weaker than nucleon potential (~ 2/3)

Final State Interactions of Pions

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

- Three-body pi absorption:

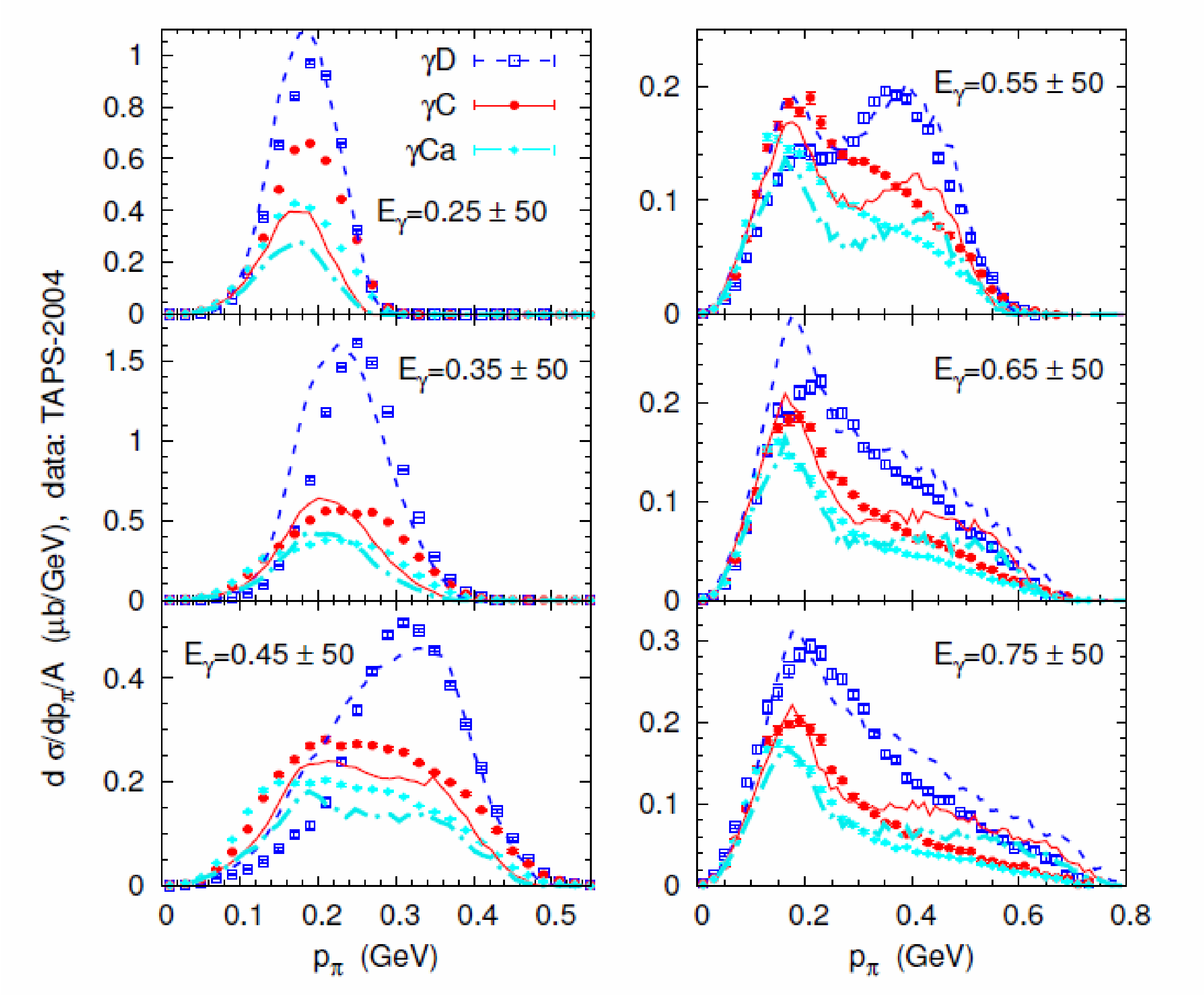
$$\Gamma_{N_A N_B \pi \rightarrow N_a N_b} = \Gamma^{\mathrm{BG}}_{N_A N_B \pi \rightarrow N_a N_b} + \Gamma^{\mathrm{resonance\ contribution}}_{N_A N_B \pi \rightarrow N_a N_b}$$

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

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

Test with γA

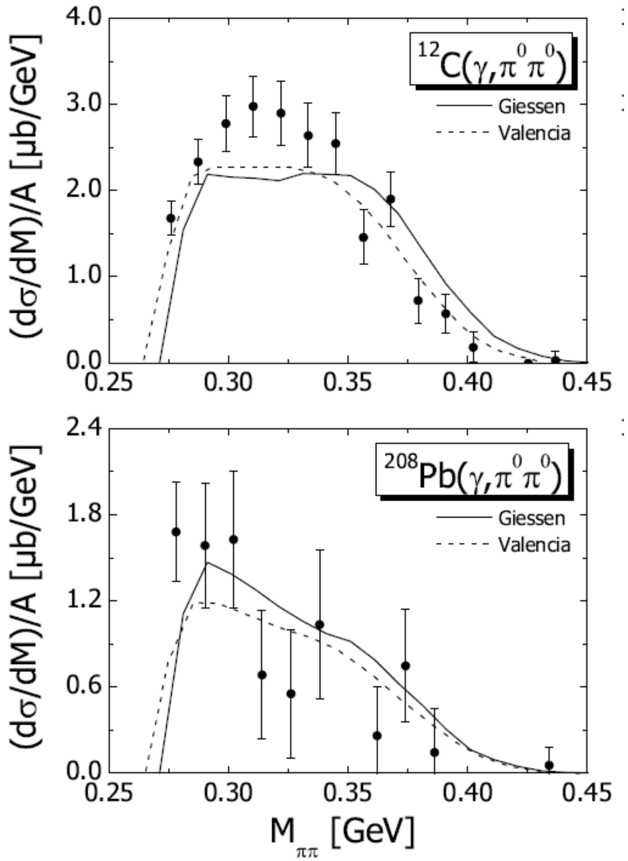
- $\gamma A \rightarrow \pi^0$ TAPS data



Targets:
D
C
Ca

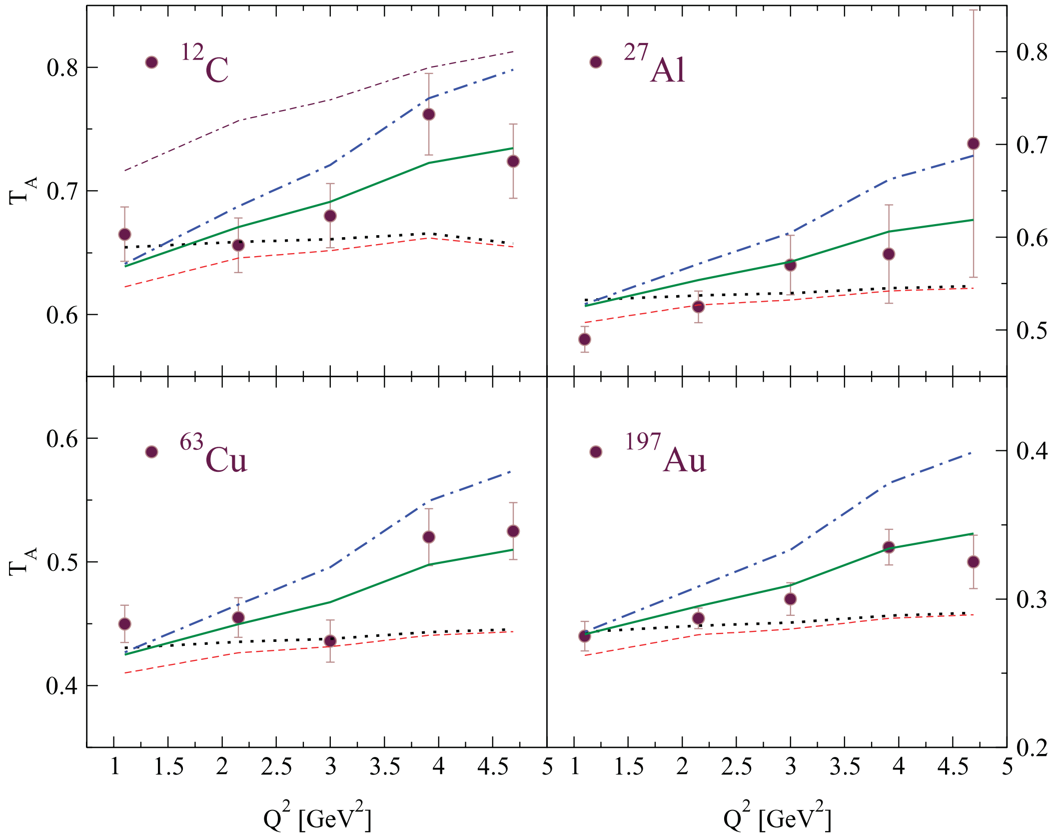
Lalakulich et al,
AIP Conf.Proc.
1663 (2015) 040004

2pi Photoproduction



Test with eA

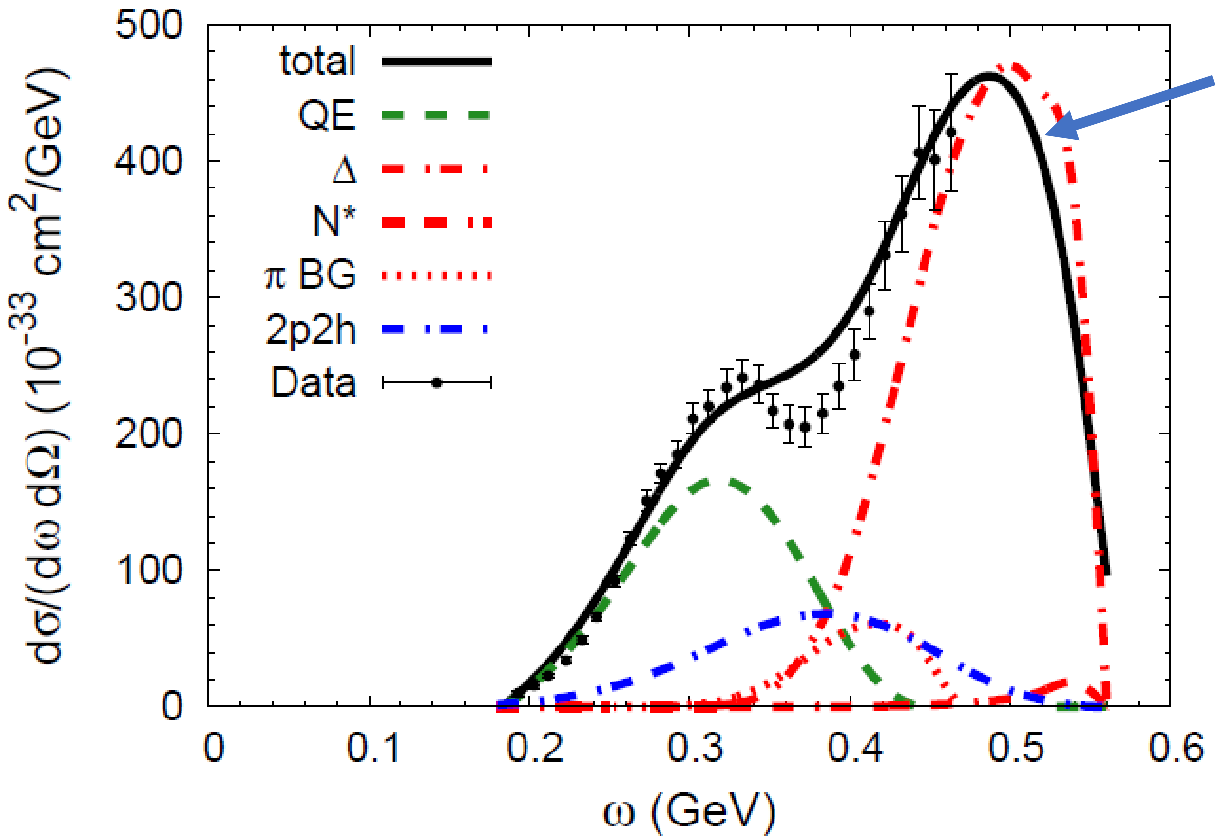
- π+ JLAB data



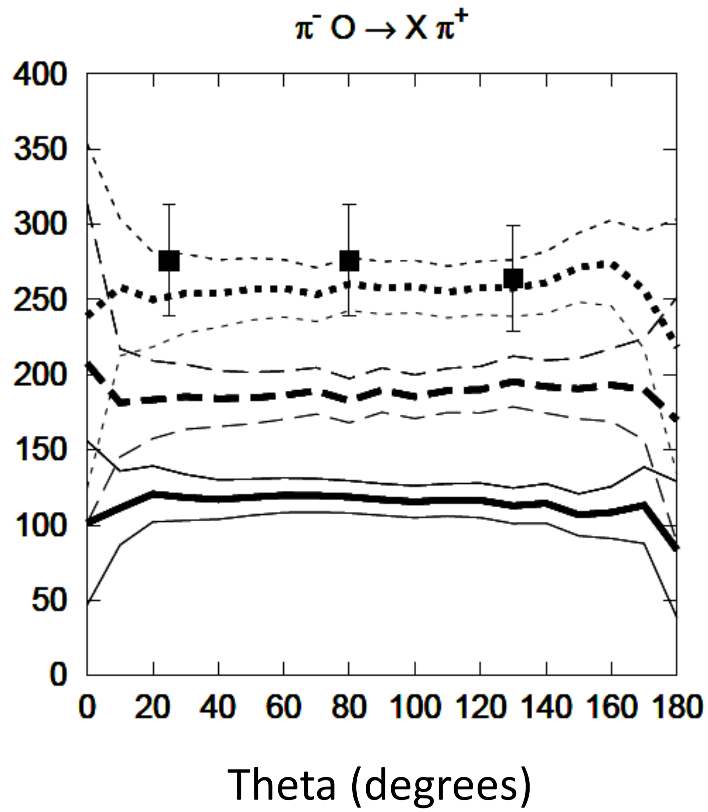
Exp: B. Clasie et al.
Phys. Rev. Lett. 99, 242502 (2007).

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

Resonance-Background Interference



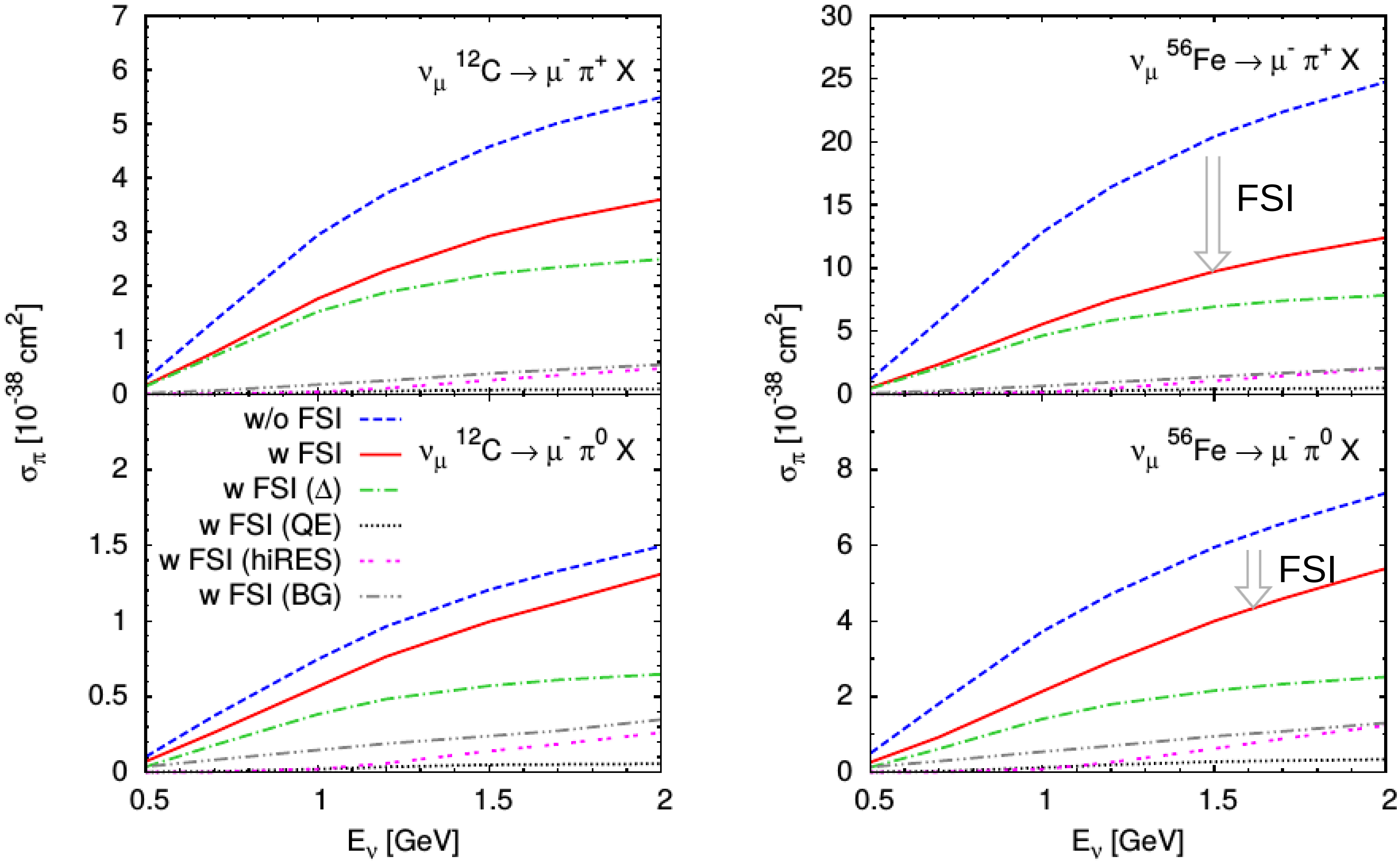
Double Charge Exchange



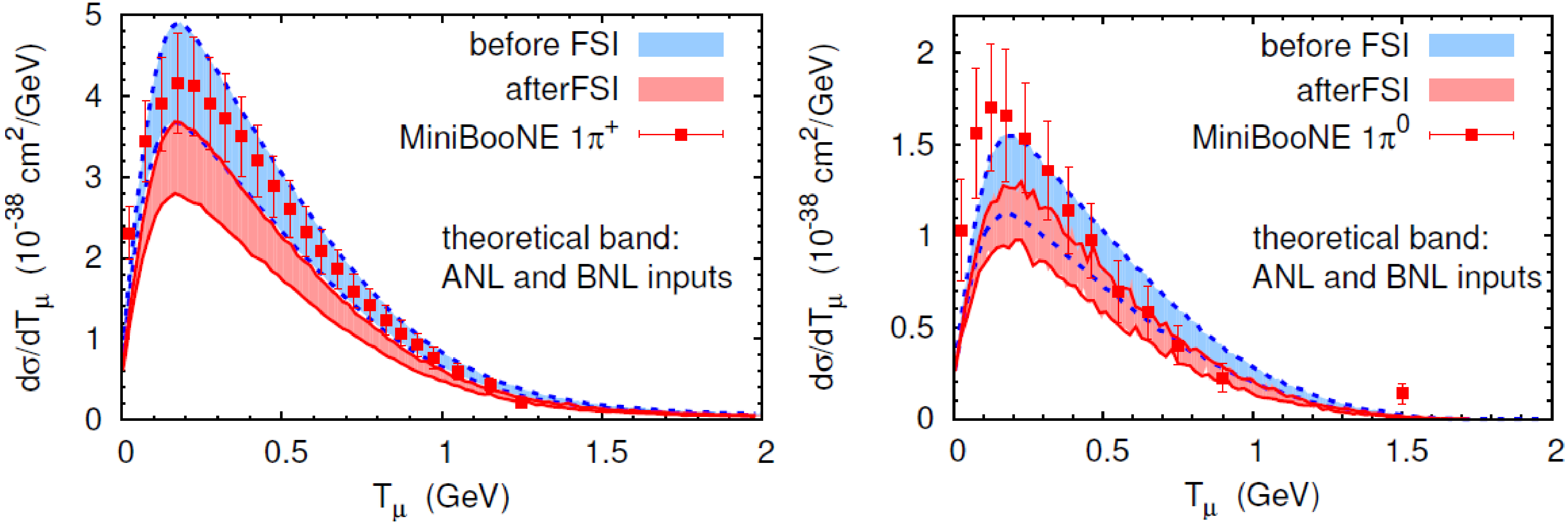
neutrino induced

- CC: π^+ and π^0 production

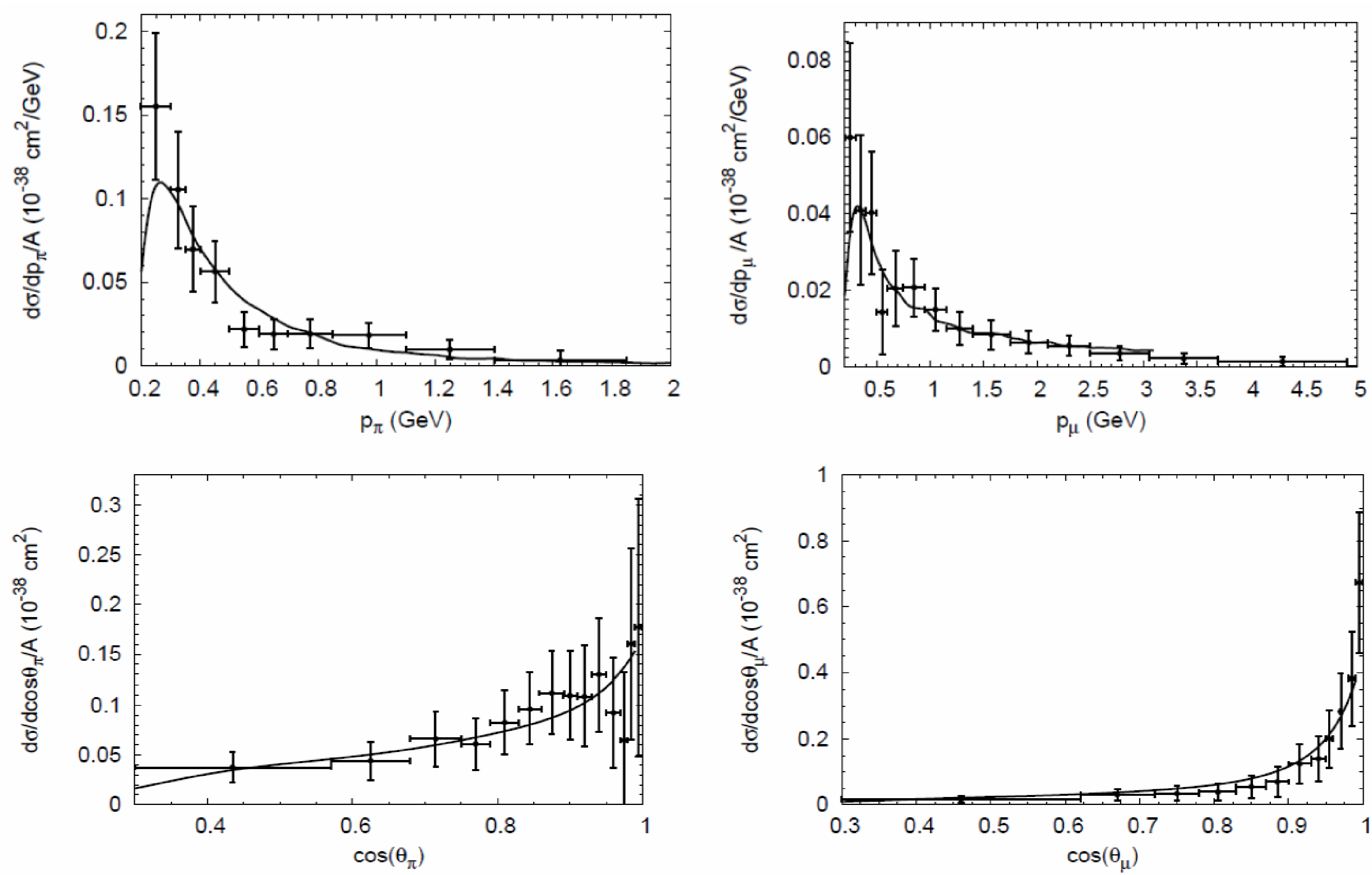
T.Leitner, PhD thesis, 2009



The MiniBooNE Puzzle



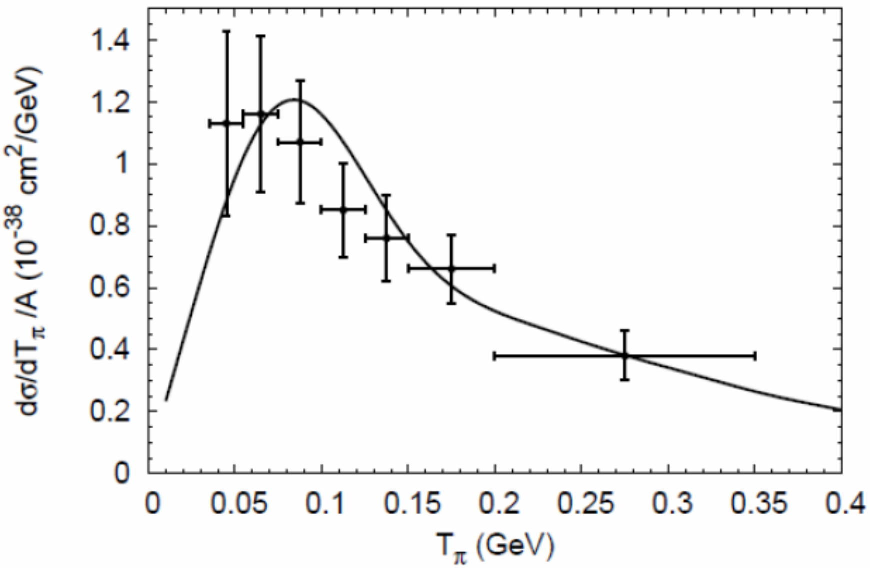
T2K ND280 pions on water



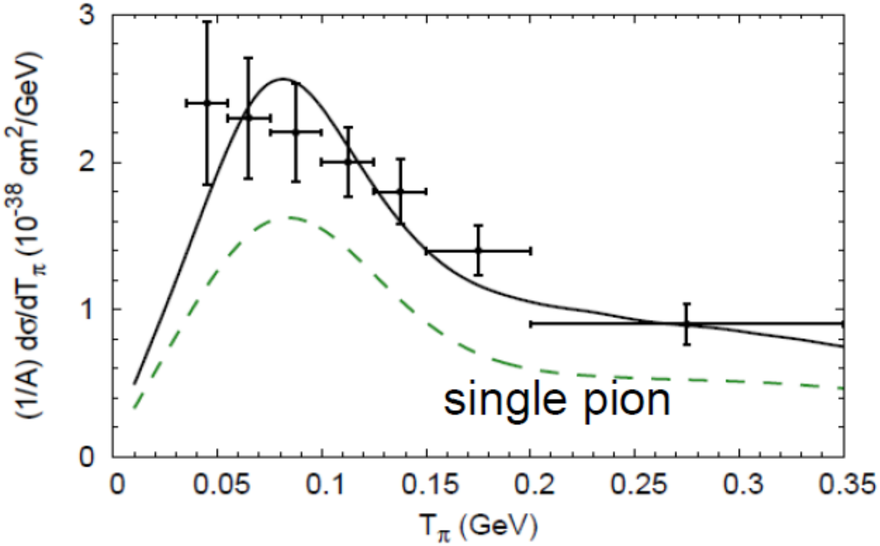
Data: T2K ND280
Phys.Rev. D95 (2017) 012010

MINERvA pions

- CC charged pions



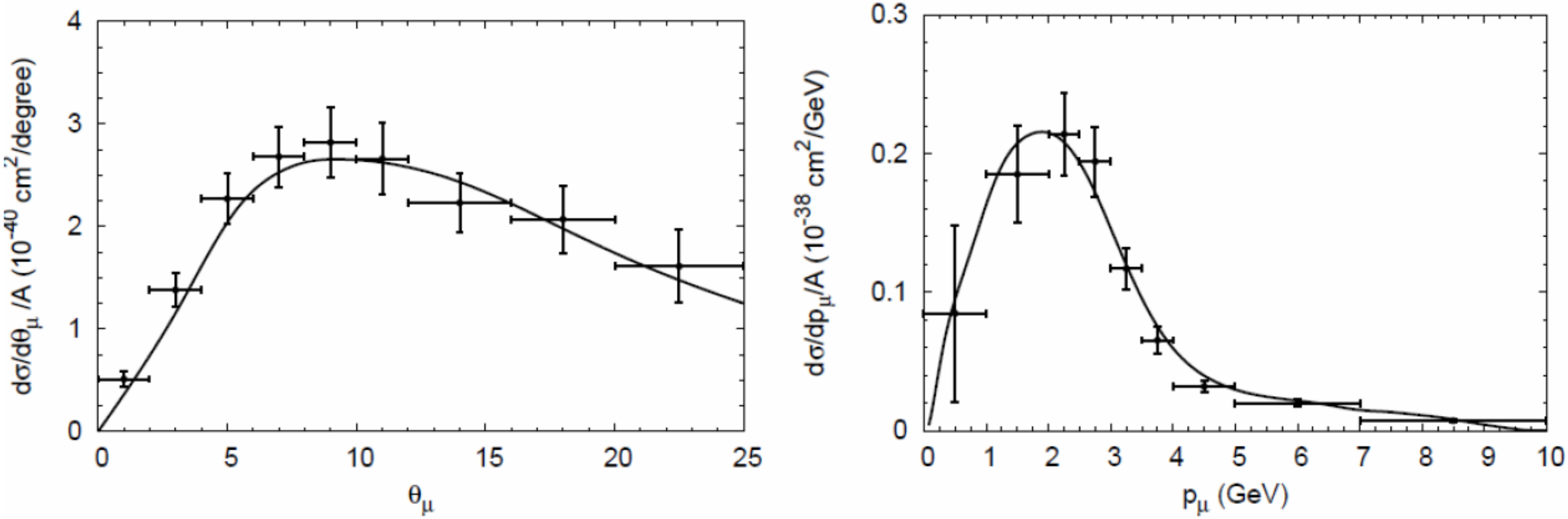
W < 1.4 GeV



W < 1.8 GeV, multiple pions

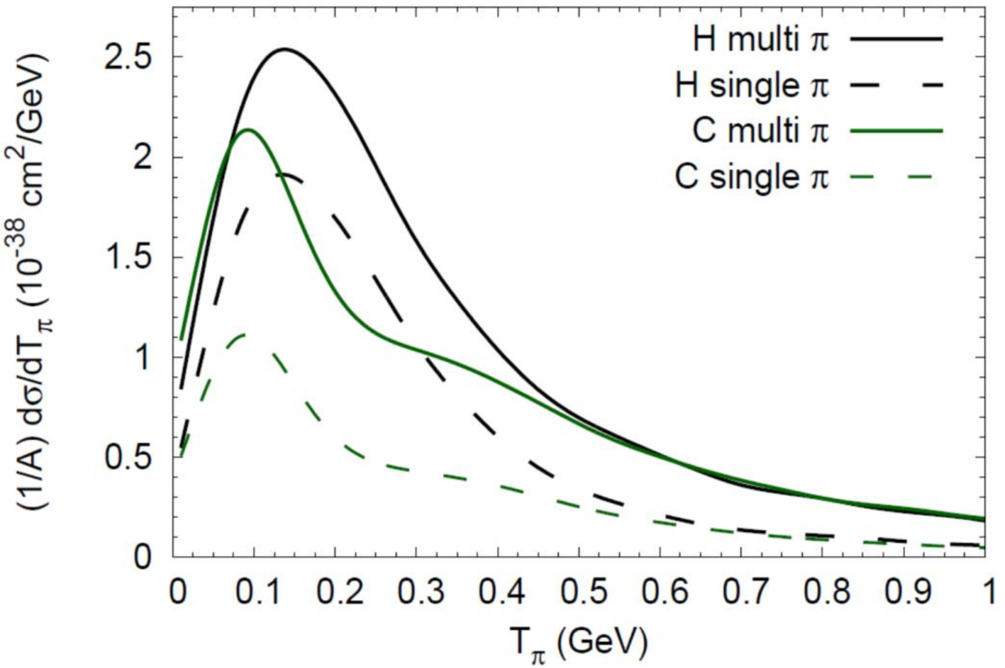
MINERvA pions

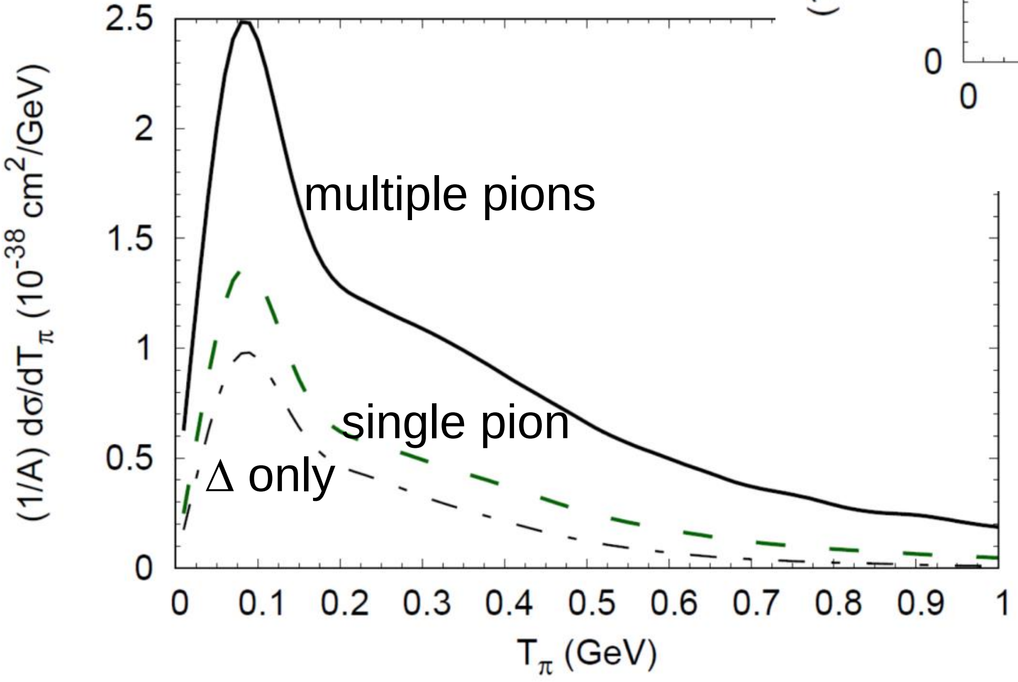
- CC charged pions



W < 1.8 GeV

Pions at NOvA





Conclusions

- The GiBUU generator has been checked against a large set of pion photo- and electronproduction data.

One and the same consistent model describes all the CC charged pion data from T2K and MINERvA without any special tune.