# Quo vadis NuInt?

L. Alvarez-Ruso

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# Outline

- QE scattering
- $1\pi$ production
- Other inelastic processes
- Shallow inelastic scattering
- Deep inelastic scattering

# QE scattering

- Recent $M_A$ "measurements":
  - K2K on $H_2O$ : $M_A = 1.20 \pm 0.12$
  - MiniBooNE on $CH_2$ : $M_A = 1.35 \pm 0.17$ GeV
  - MINOS on Fe : $M_A = 1.26\,^{+0.12}_{-0.10}\,^{+0.08}_{-0.12}$ GeV

- Previously:
  - $M_A = 1.016 \pm 0.026$ GeV $(\nu d\,, \bar{\nu} p)$ Bodek et al., EPJC 53 (2008)

moreover

  - $M_A^{ep} = 1.069 \pm 0.016$ GeV from $\pi$ electroproduction on p

    Liesenfeld et al., PLB 468 (1999) 20

and after hadronic corrections (ChPT) Bernard et al., PRL 69 (1992) 1877

  - $\Rightarrow M_A^{ep} = 1.014 \pm$ GeV at least at low $Q^2$

# QE scattering

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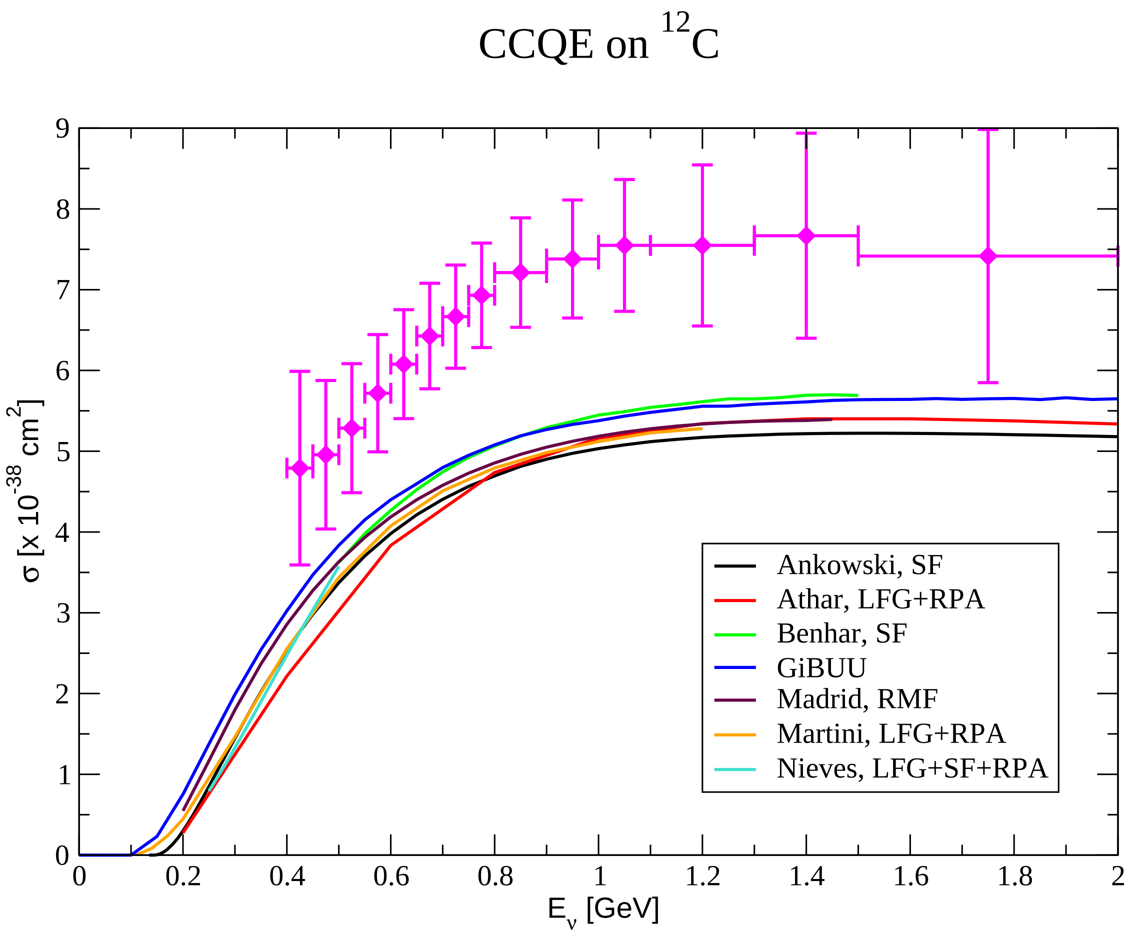
- Have these experiments really measured $M_A$ ?
  - No, what has been measured is a parameter $M_A^{eff}$
    - Specific for the Relativistic Global Fermi Gas model
    - Target dependent
    - Flux dependent

# QE scattering

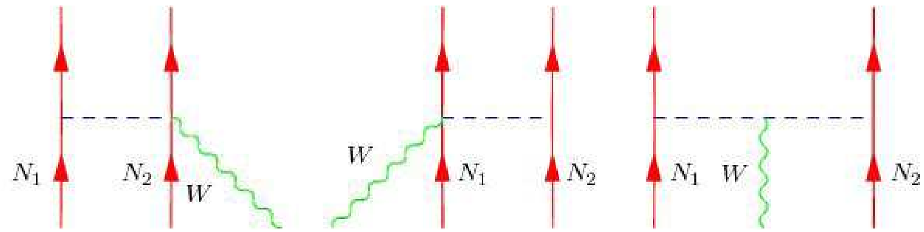
- The problem:



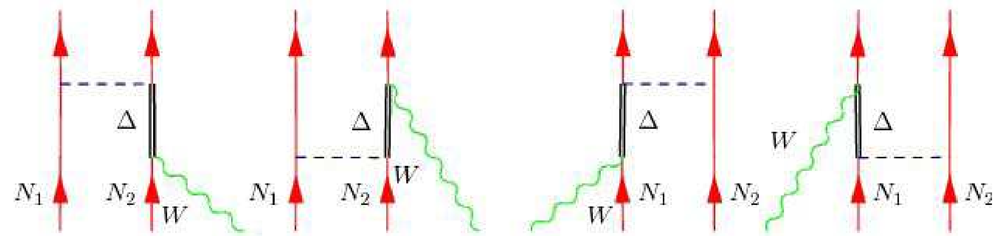

Source: Boyd et al., AIP Conf. Proc. 1189
Data: MiniBooNE, PRD 81, 092005 (2009)

# QE scattering

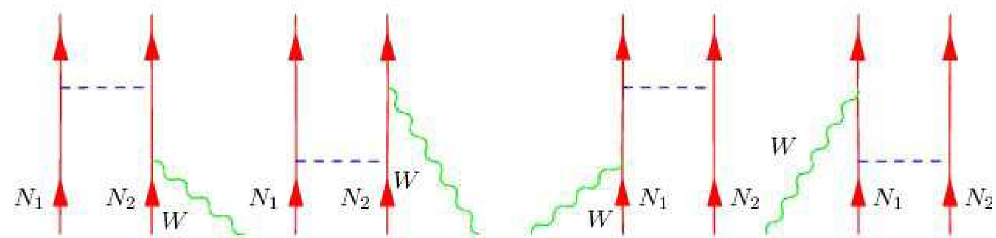
- The solution:
- multinucleon (2p2h) contributions
  - Martini et al., PRC 80 (2009)
  - Nieves et al., PRC 83 (2011)
  - Amaro et al., PLB 696 (2011)
- + RPA (important at low $Q^2$)




Contact and *pion-in-flight* diagrams




Δ-Meson Exchange Current diagrams

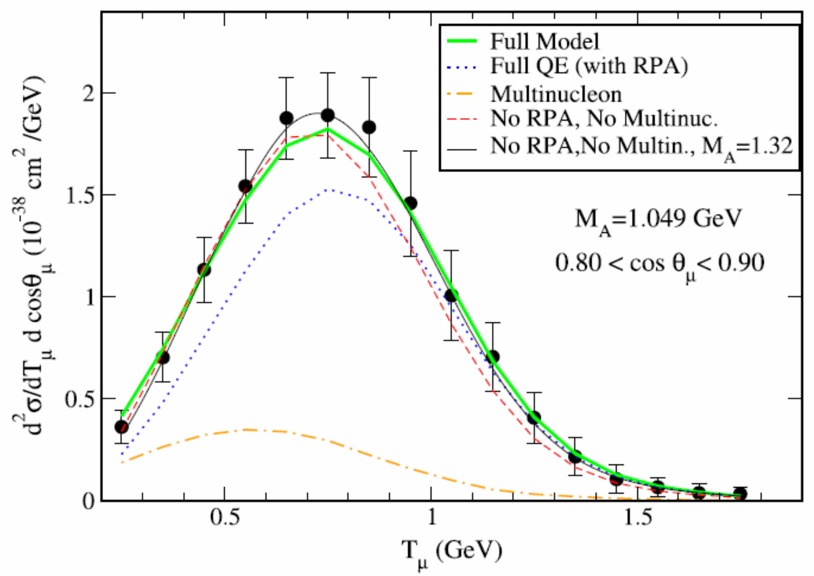



Correlation diagrams

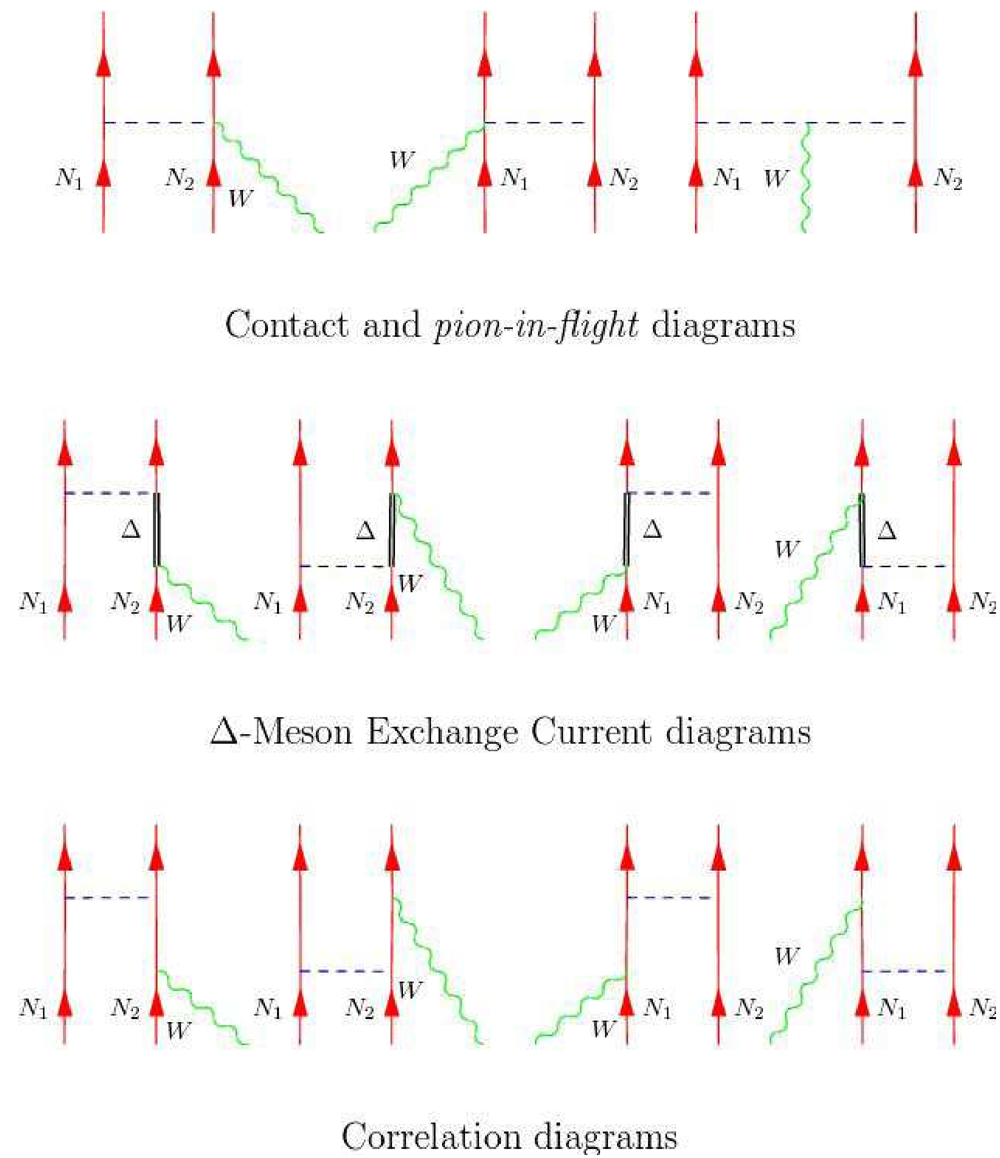
J. Sobczyk @ NuFact12

# QE scattering

- The solution:
- multinucleon (2p2h) contributions
  - Martini et al., PRC 80 (2009)
  - Nieves et al., PRC 83 (2011)
  - Amaro et al.,
- + RPA (important at low $Q^2$)
- Good agreement with MiniBooNE 2-D c.s. with $M_A \sim 1$ GeV




Nieves @ NuInt12




Sobczyk @ NuFact12

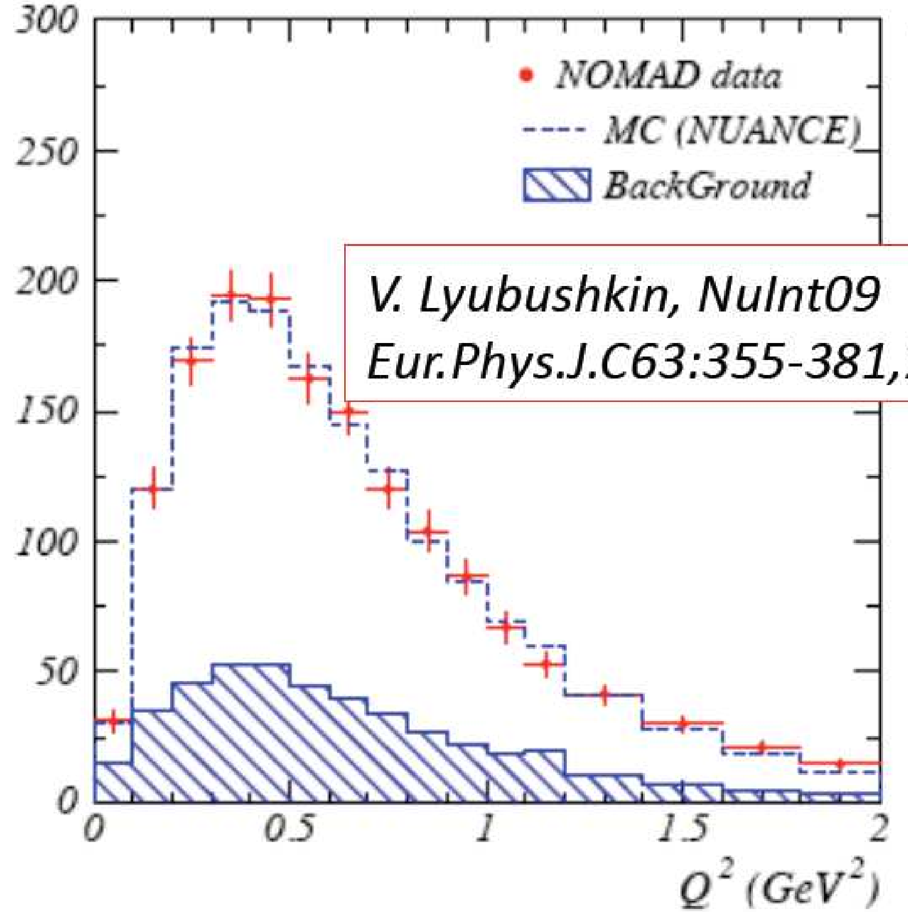
# QE scattering

- Has NOMAD measured $M_A$?

$$M_A = [1.05 \pm 0.02(stat) \pm 0.06(syst)]\ \text{GeV}$$

"Our measured $M_A$ is found to be in good agreement with the world average value obtained in previous deuterium filled bubble chamber experiments"

K. Mahn @ NuInt12




V. Lyubushkin, NuInt09
Eur.Phys.J.C63:355-381,2009

- Are T2K, MINER$\nu$A, ArgoNeut, … measuring (or going to measure) $M_A$?

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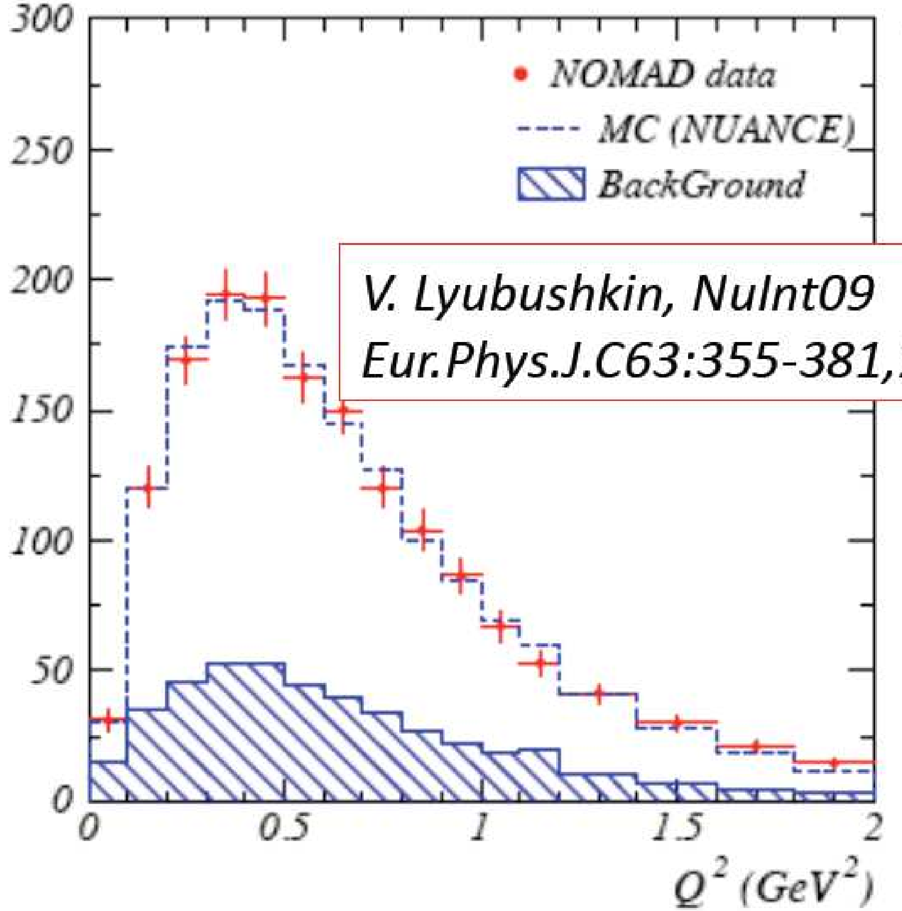


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- Are T2K, MINER$\nu$A, ArgoNeut, … measuring (or going to measure) $M_A$?

- My answer: A priory not
  - Unless kinematics, cuts, etc suppress 2p2h contribution
  - Perhaps 2-track analyses help…

# QE scattering

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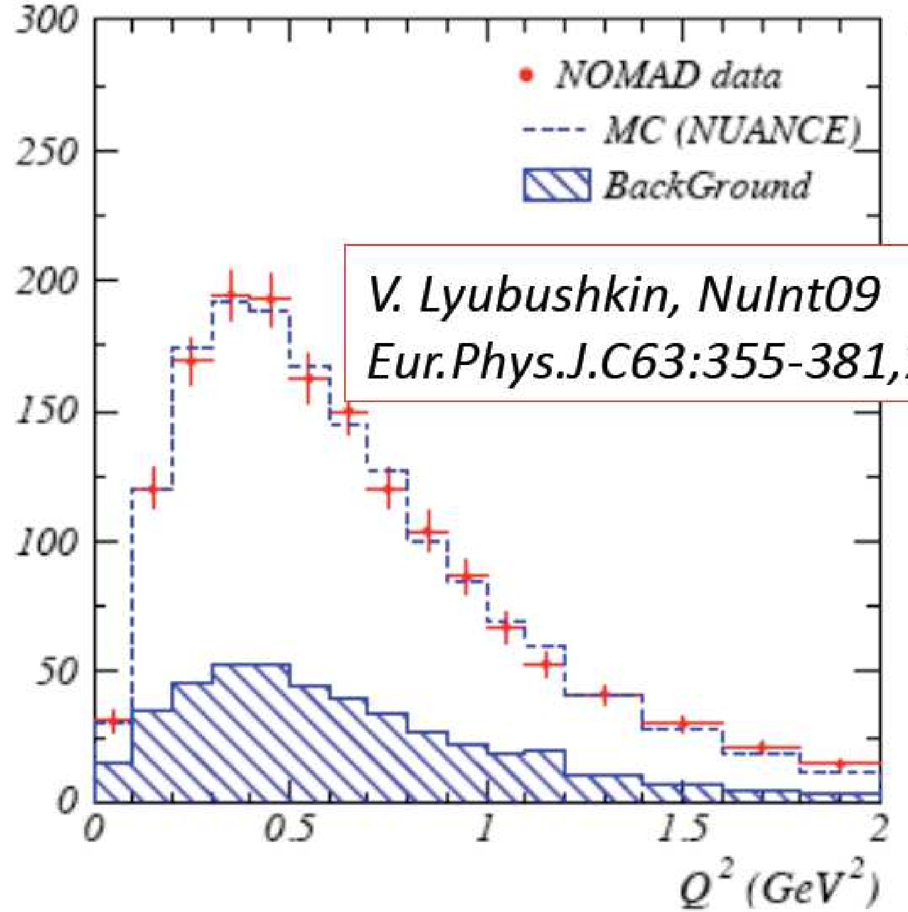


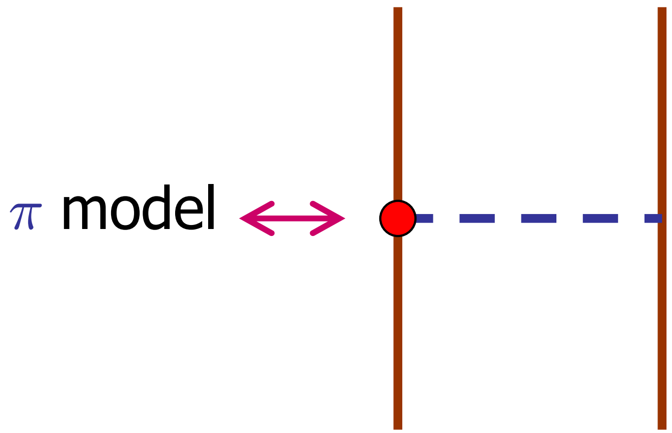

- Are T2K, MINER$\nu$A, ArgoNeut, … measuring (or going to measure) $M_A$?

- My answer: MINER$\nu$A with a H target ← YES
  MINER$\nu$A with a D target ← yes

"Even in a dilute system like deuterium MEC are important" Schiavilla@NuInt12

# QE scattering

- Implementing 2p2h models in MC generators
  - Difficult (but not impossible) task
  - Existing theoretical models are (almost) directly applicable to T2K
  - Much harder for MINER$\nu$A:
    - Present models are not directly applicable
    - High energy extensions are uncertain
    - Minimal requirement: realistic $\pi$ production model throughout the resonance region

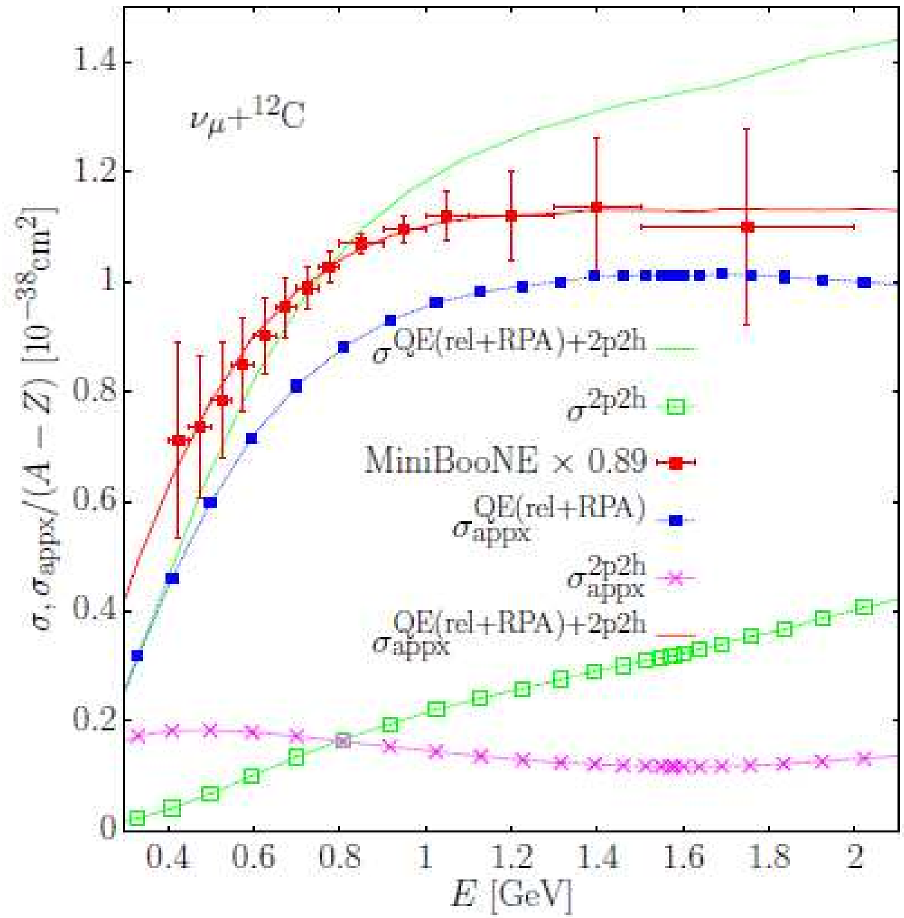


# QE scattering

- Implementing 2p2h models in MC generators
  - First steps: toy models
    - GiBUU $\leftrightarrow$ constant matrix element
    - NuWro $\leftrightarrow$ Bodek
    - GENIE $\leftrightarrow$ Katori@NuInt12
  - Problems with toy models
    - Cannot be applied to different processes (e, photon, anti-$\nu$)
    - Once in, they will stay…

# QE scattering

- Why bother? (Let's "measure" $M_A$ in the ND)
  - Such a CCQE model based in RFG with an effective $M_A$ is wrong
  - Not accurate flavor ($\mu \to e$) extrapolation Morfin@NuInt12
  - 2p2h contributions lead to incorrect $\nu$ energy determination




Nieves @ NuInt12

# QE scattering

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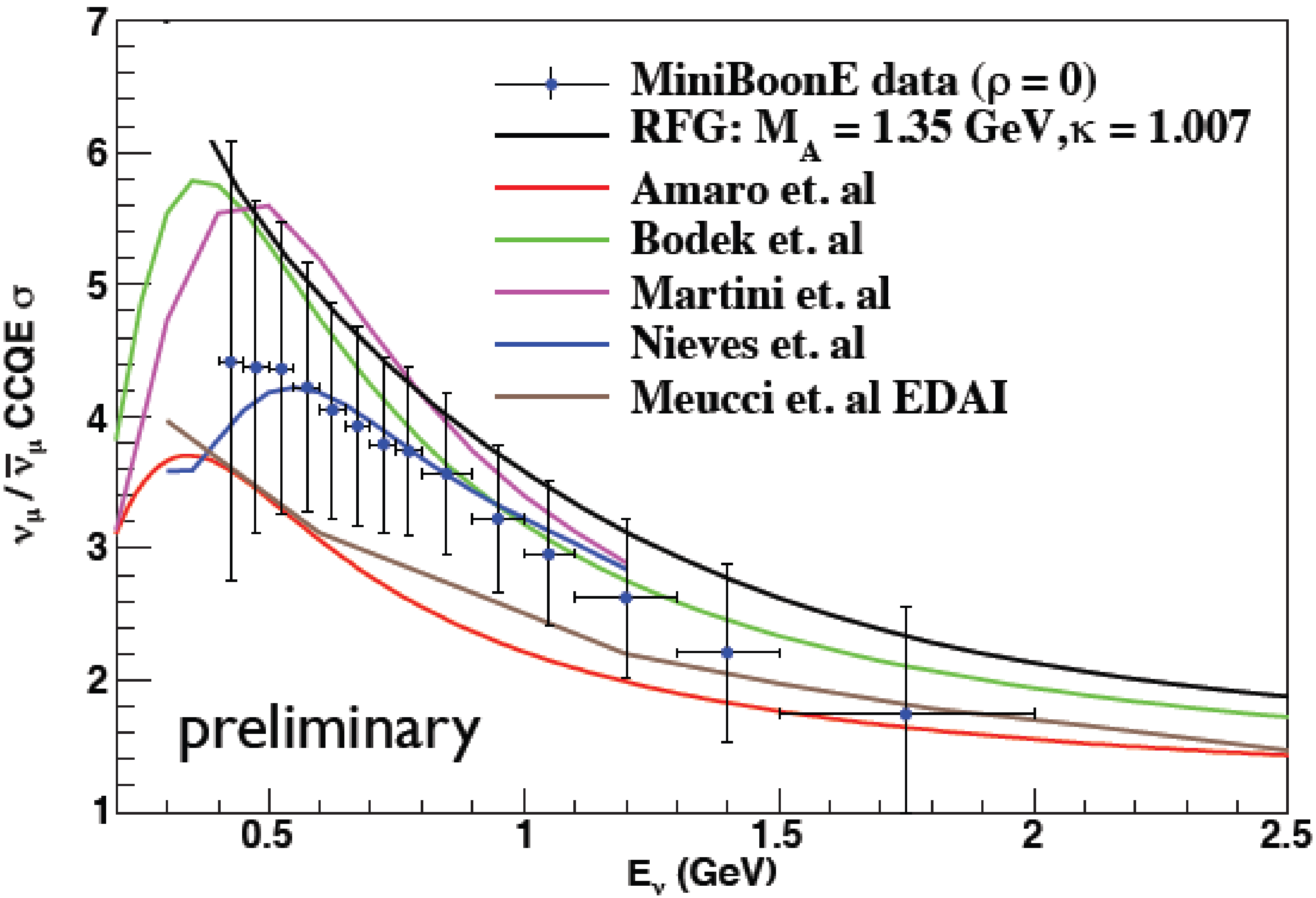
  - 2p2h contributions lead to incorrect $\nu$ energy determination
  - Different cross sections have an impact in the achievable precision of oscillation parameters Meloni

# QE scattering

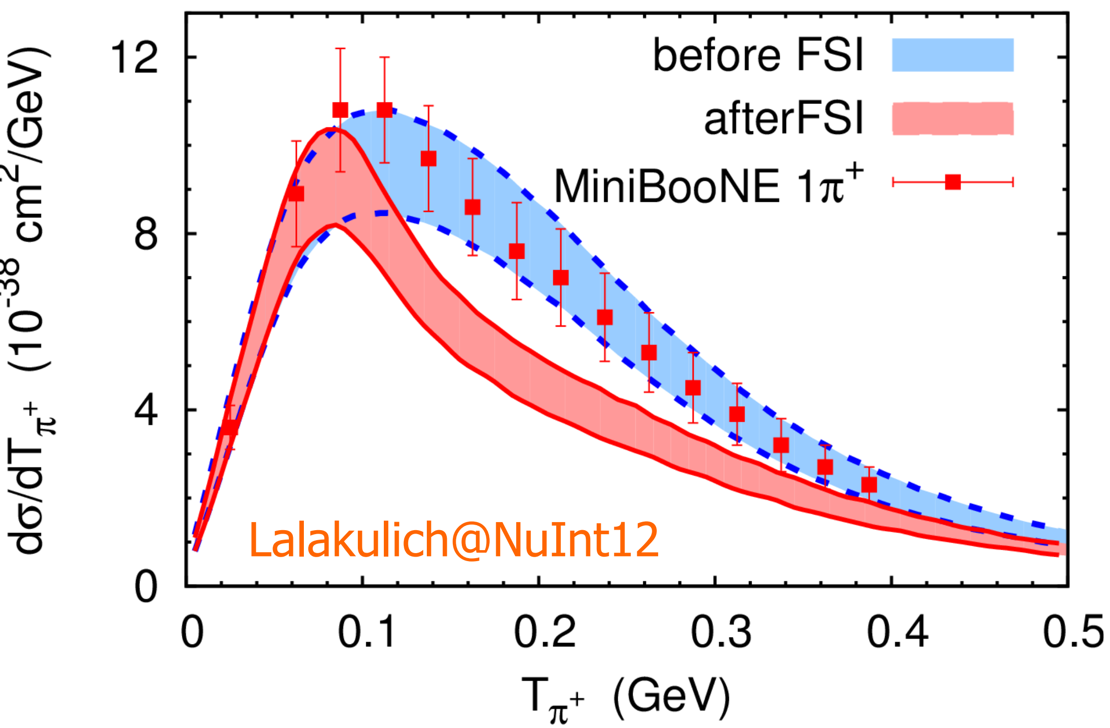
- Model discrimination at work!

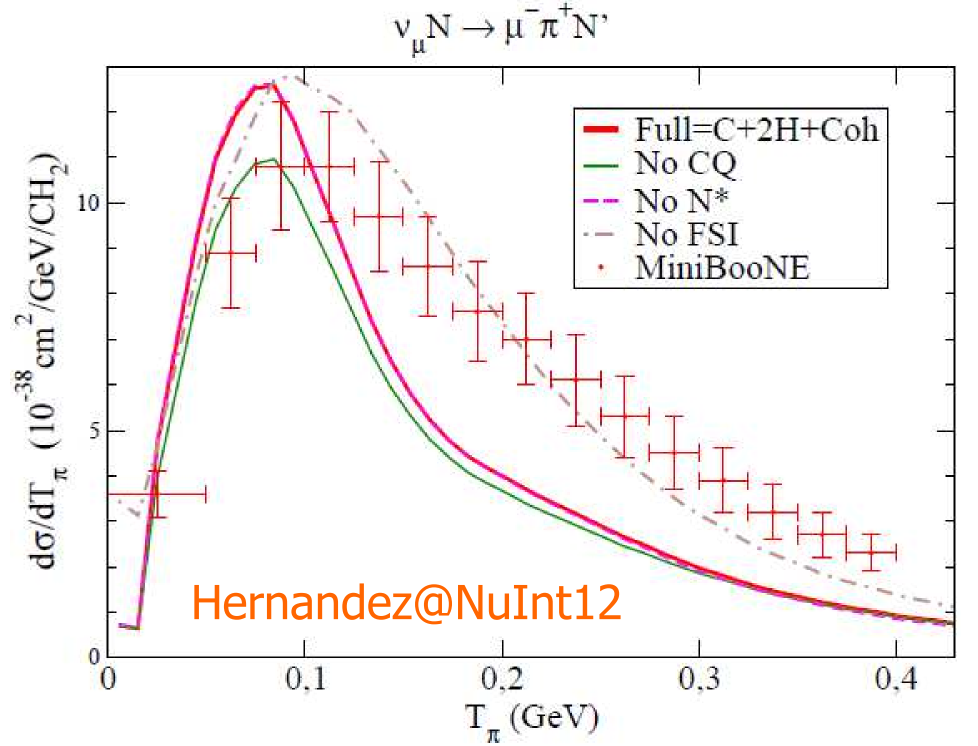



Grange @ NuInt12

# $\pi$ production

- State of the art calculations describe better the data without FSI




- Transport
- 13 resonances
- Resonance propagation
- contribution from DIS

- Cascade
- 2 resonances
- No resonance propagation
- No DIS

# $\pi$ production

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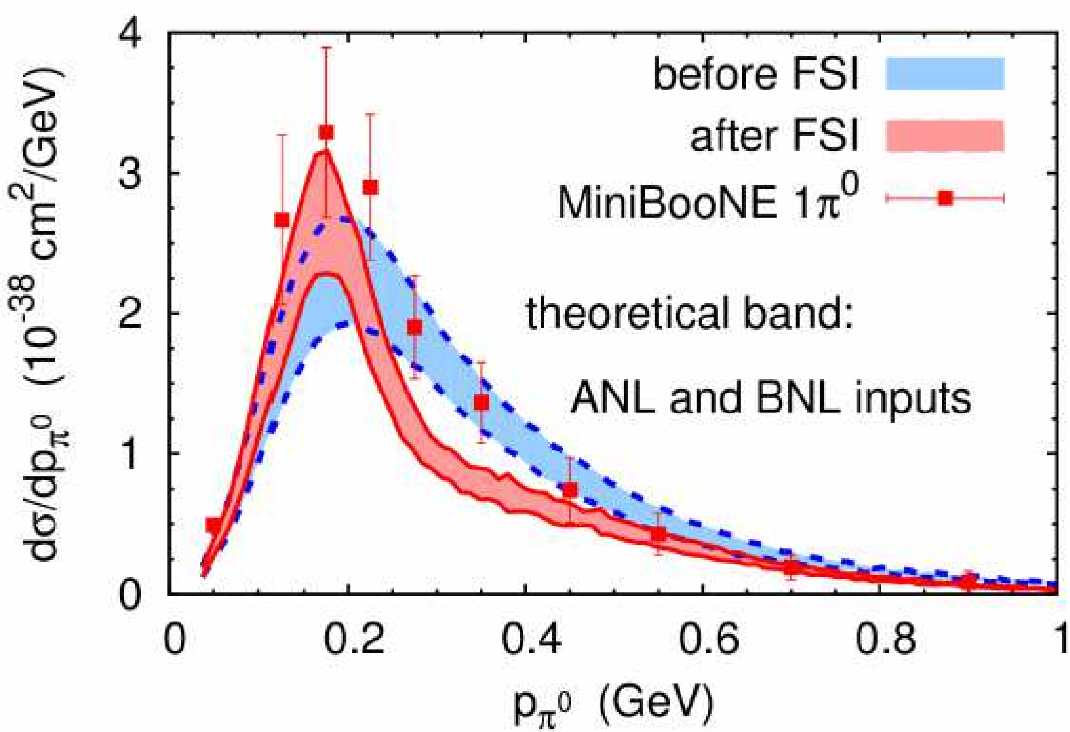
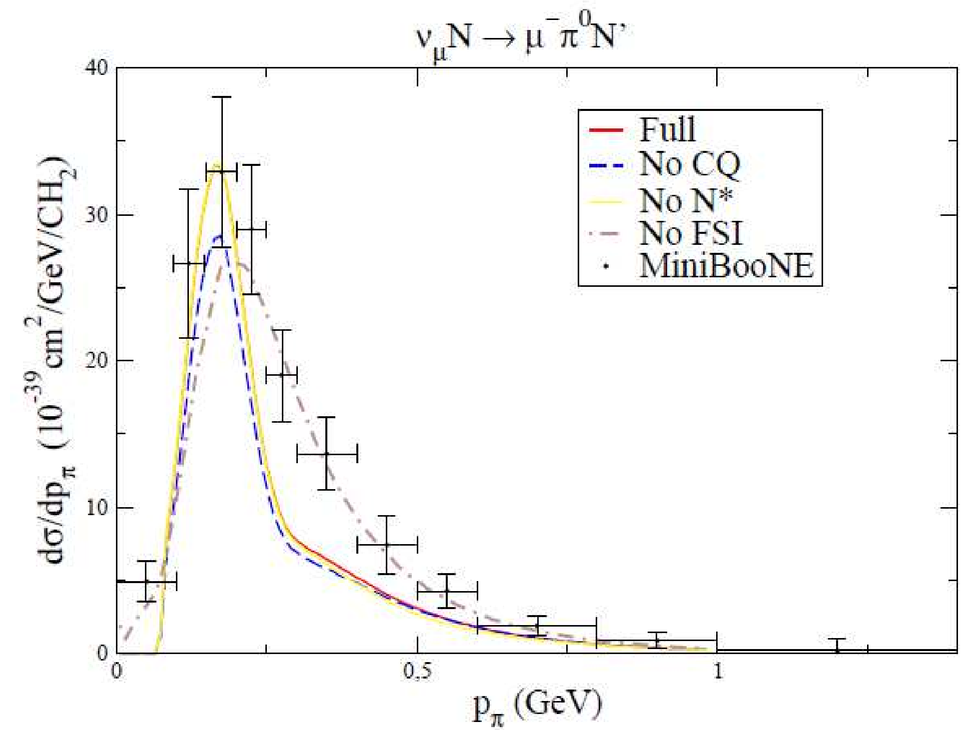



Lalakulich@NuInt12

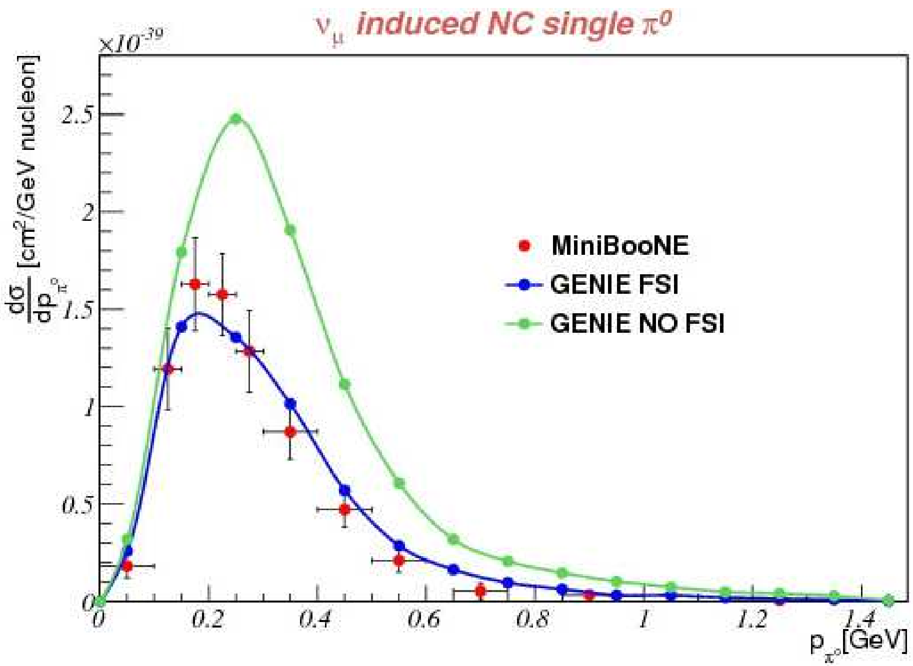


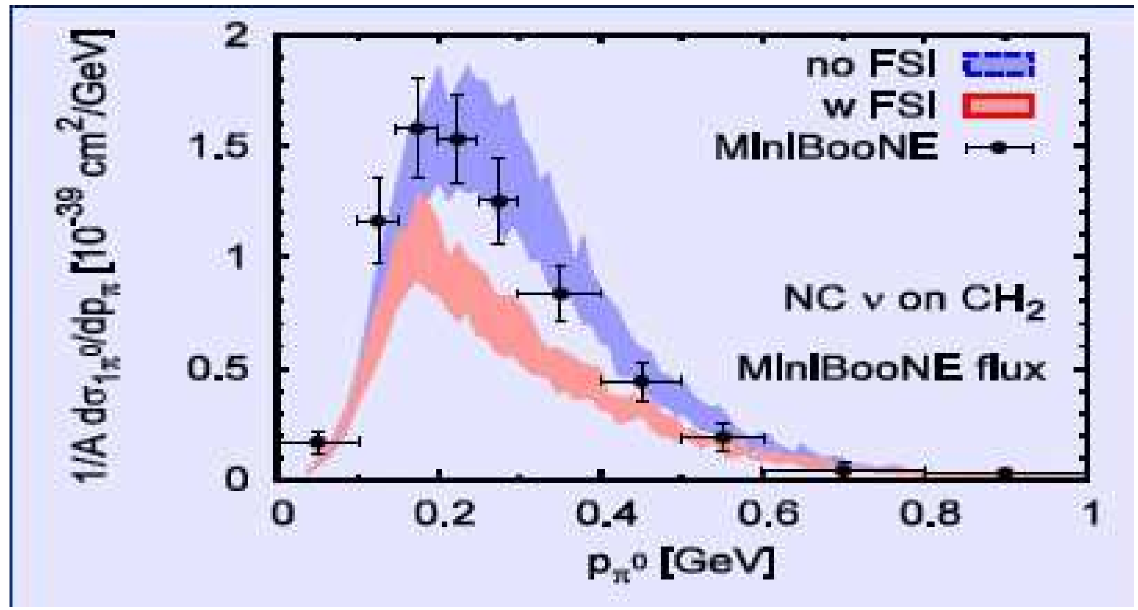

Hernandez@NuInt12

- Possible problems in:
  - $\pi$ production model on the nucleon
  - medium modifications of amplitudes
  - FSI

# $\pi$ production

- GENIE vs GiBUU NC$\pi^0$



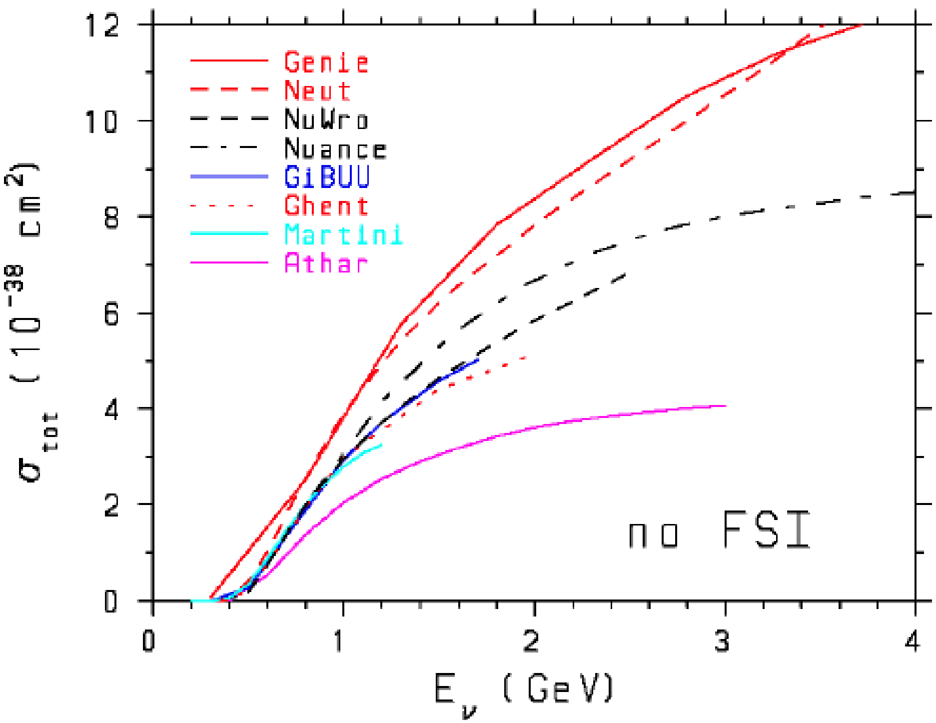




Dytman@NuInt12

- Largest discrepancies seem to be in the cross sections before FSI
- At the nucleon level, both compatible with ANL/BNL data!

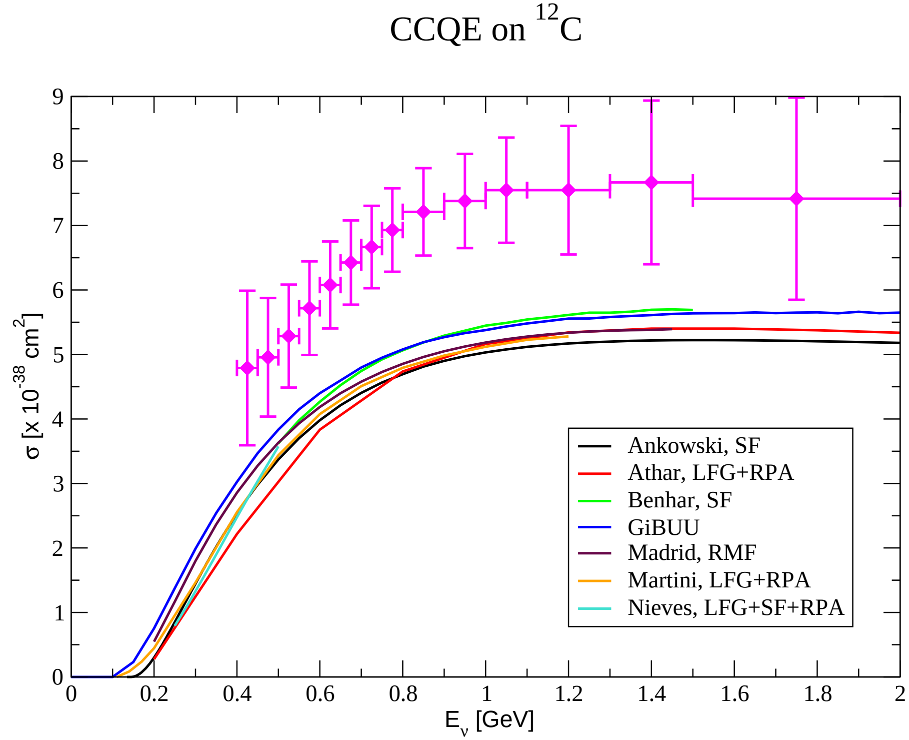
# $\pi$ production

- Large discrepancies even before FSI




Boyd et al., AIP Conf. Proc. 1189

compare to CCQE

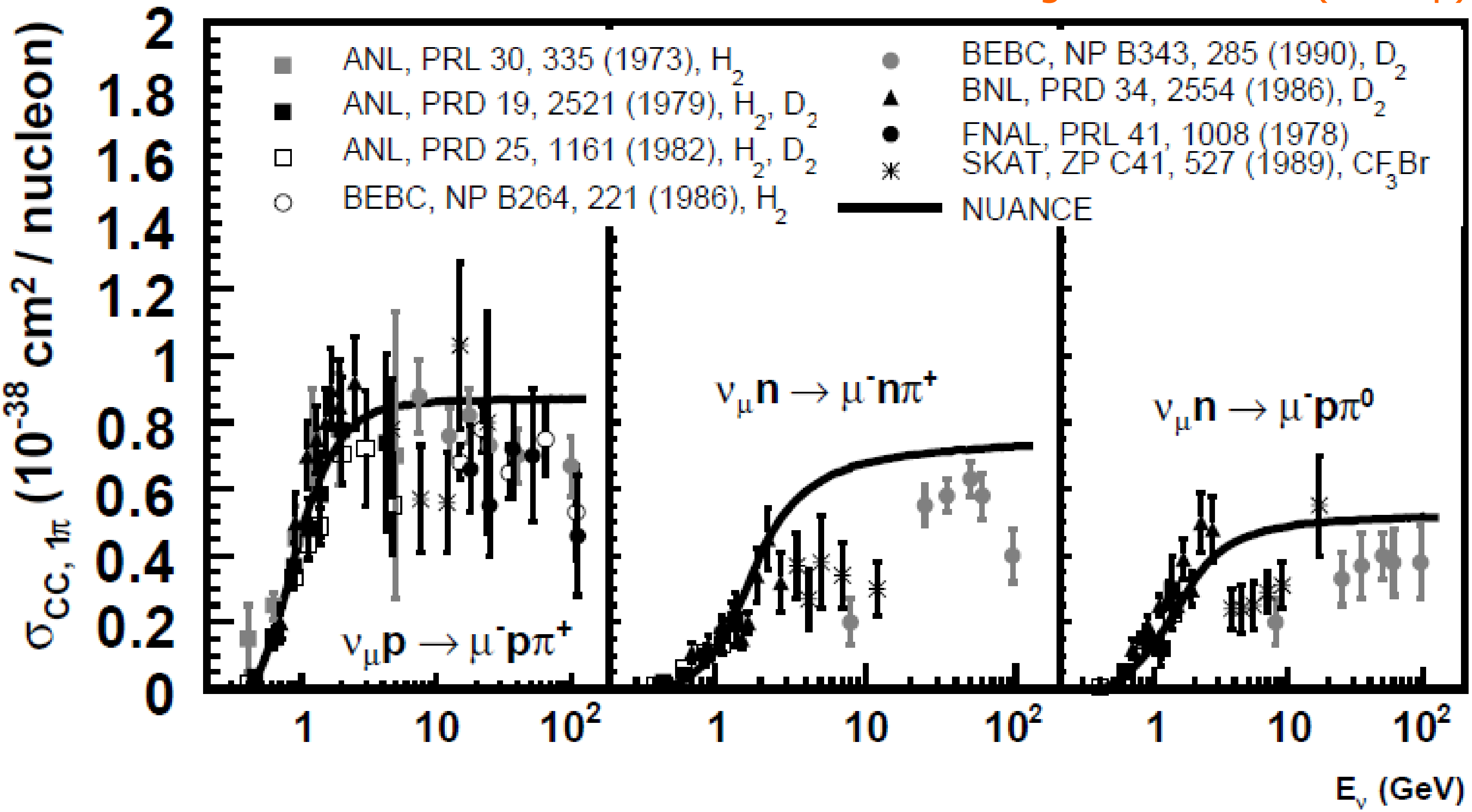



- Large differences at the nucleon level
  - non-resonant background
  - N-Resonance transition form factors (vector and axial)

# $\pi$ production

- Large discrepancies even before FSI

Rodrigues@NuInt12 (backup)




- non-resonant background
- N-Resonance transition form factors (vector and axial)
- ANL/BNL data not particularly helpful…

# $\pi$ production

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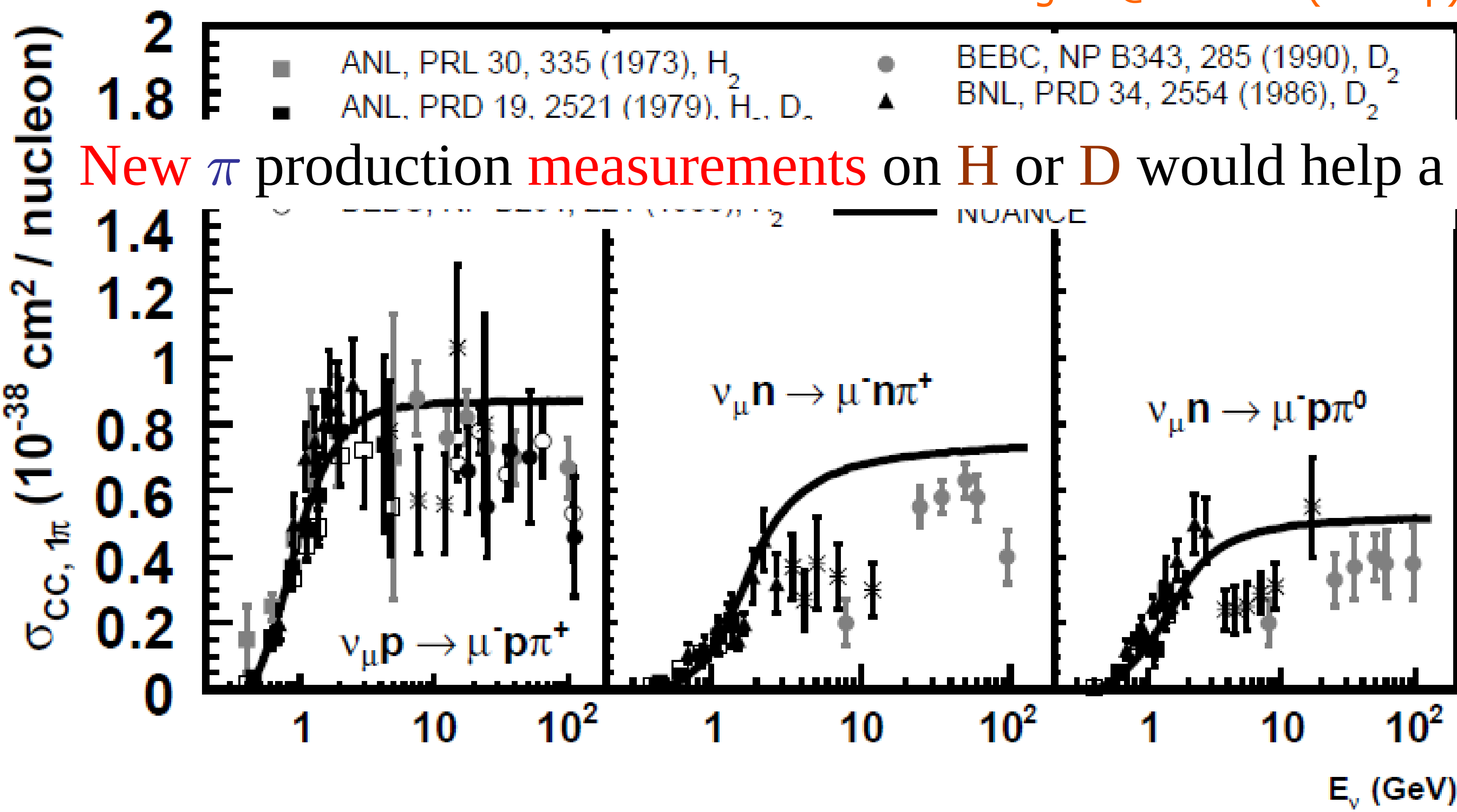
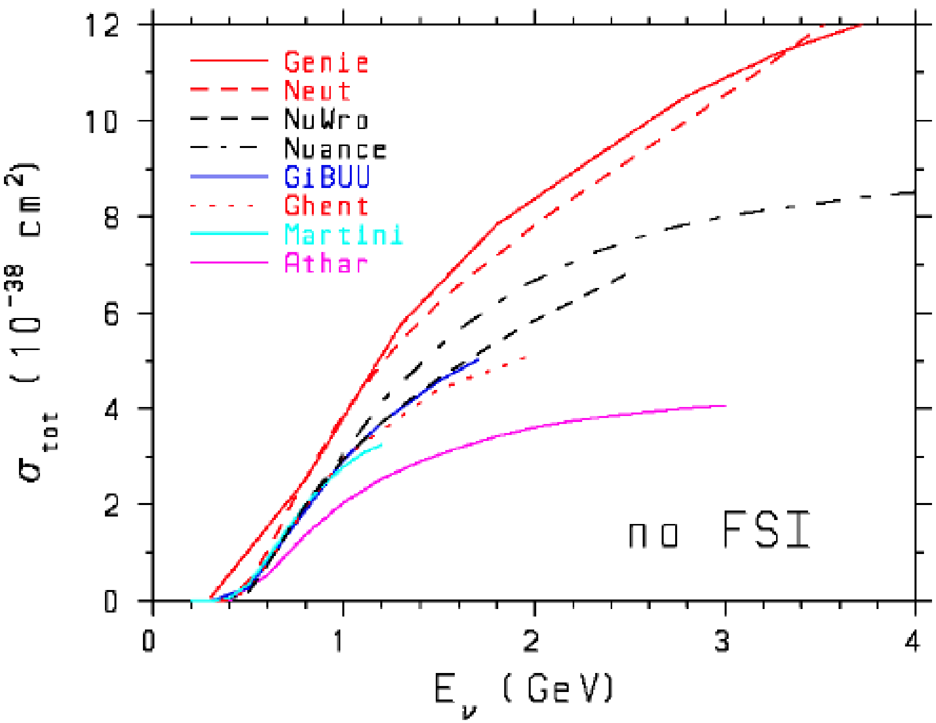



New $\pi$ production measurements on H or D would help a lot

- non-resonant background
- N-Resonance transition form factors (vector and axial)
- ANL/BNL data not particularly helpful…

- Large discrepancies even before FSI




Boyd et al., AIP Conf. Proc. 1189

- Large differences at the nucleon level
  - non-resonant background
  - N-Resonance transition form factors (vector and axial)
  - $\Delta(1232)$ in medium modification

# $\pi$ production

- For $\pi$ production in nucleons: theoretical models (including MC) should (al least) agree on:
  - Threshold behavior (dictated by chiral symmetry of QCD)
  - Electromagnetic N-Resonance transition properties (helicity amplitudes or form factors) $\leftarrow$ data and analyses available from photon, electron scattering

- Dynamical coupled channel (DCC) Nakamura@NuInt12
  - Starting point: very accurate description (based on data) of $\gamma N, \pi N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$

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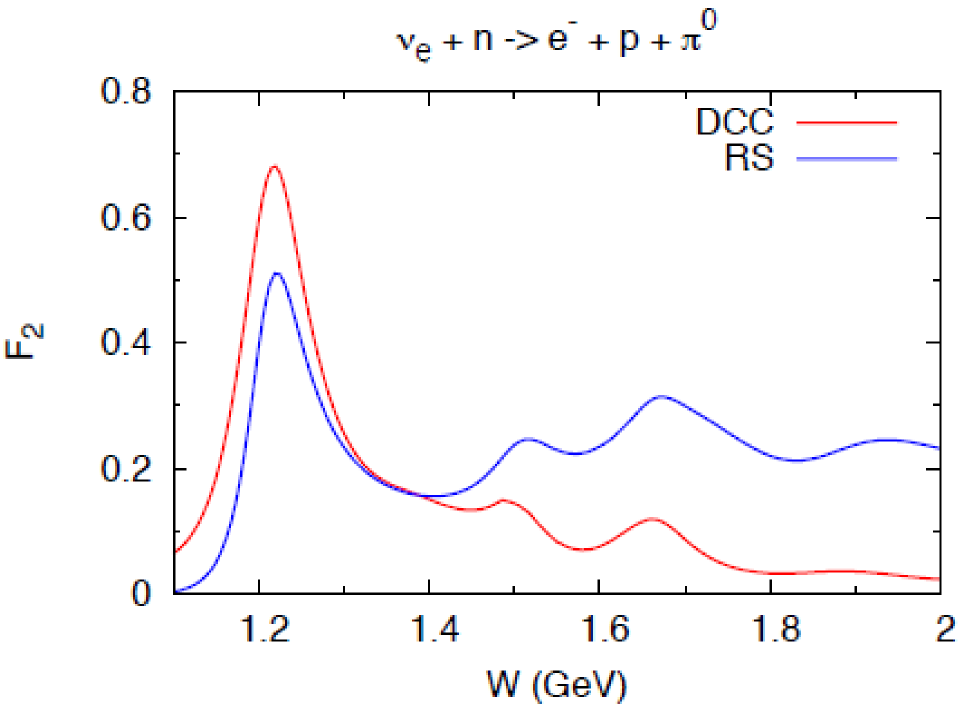


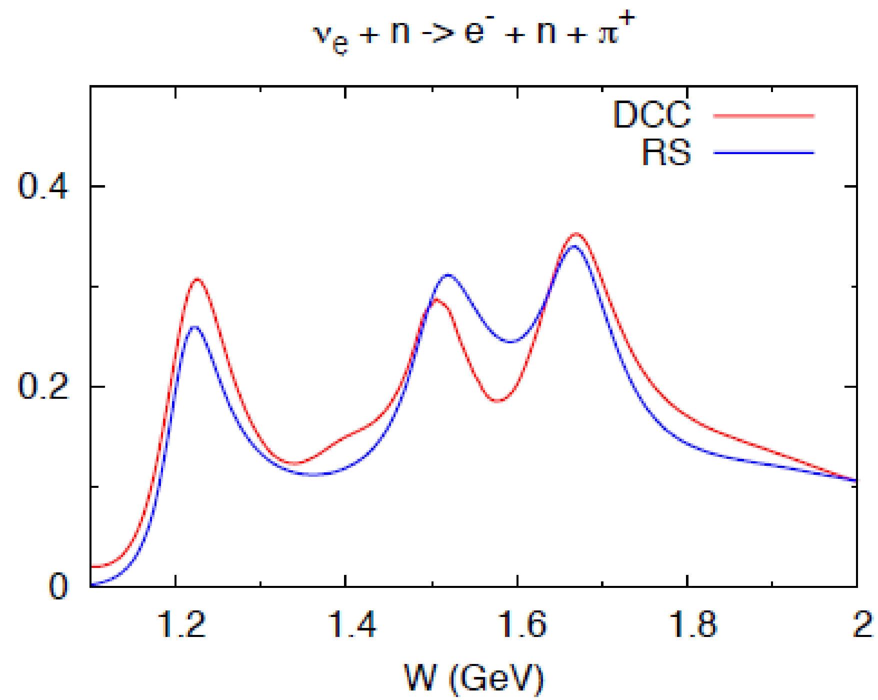


- using PCAC (at $Q^2 \to 0$):
  - another indication that R&S is not realistic

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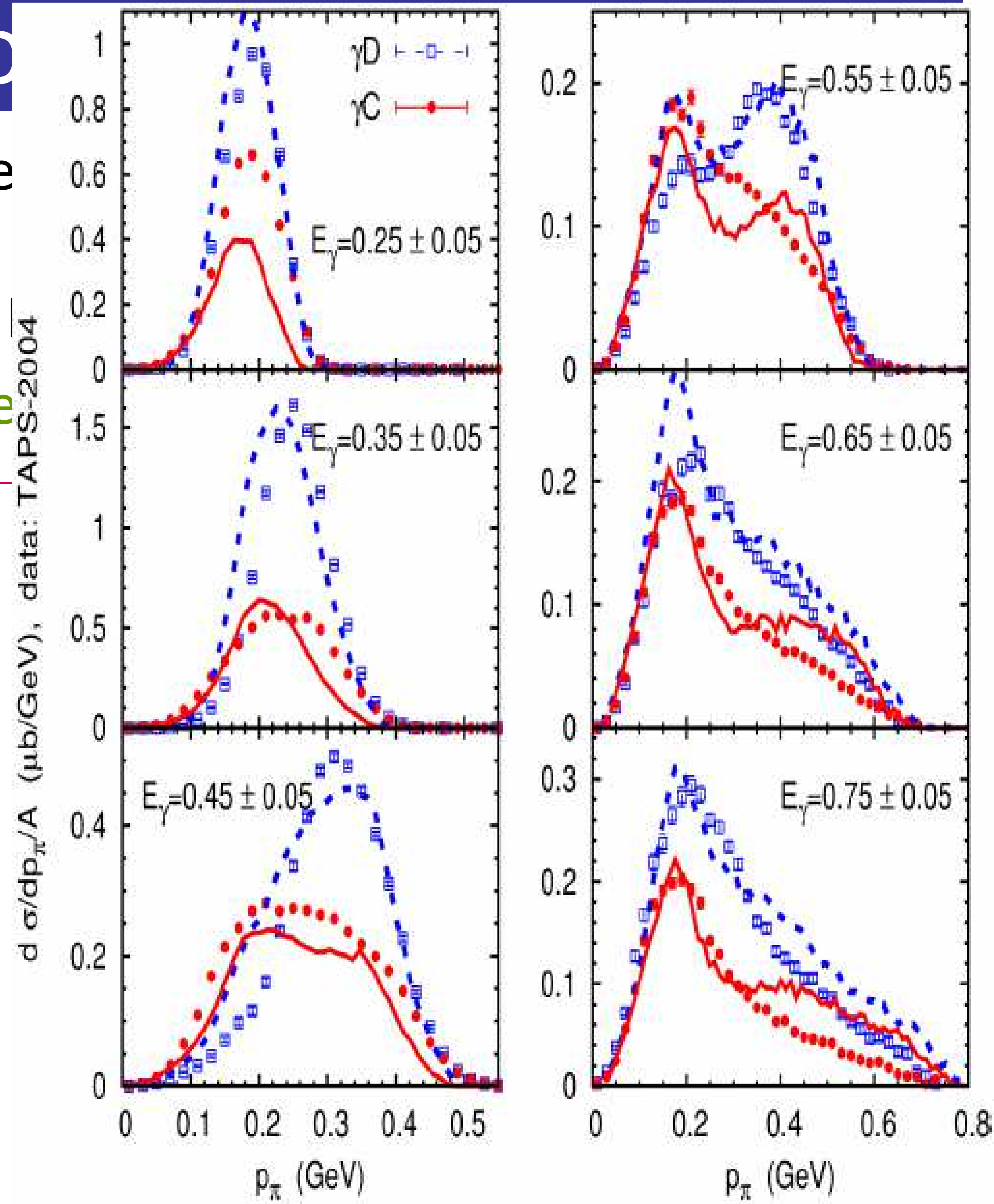
    $\gamma N, \pi N \rightarrow \pi N, \pi\pi N, \eta N, K\Lambda, K\Sigma$
  - using PCAC (at $Q^2 \to 0$):
  - beyond PCAC: resonance axial properties are unknown

# $\pi$ pro

- For $\pi$ production in nucleons: the
  least) agree on:
  - Threshold behavior (dictated |
  - Electromagnetic N-Resonance
    amplitudes or form factors) ←
    photon, electron scattering

- FSI model comparison to
  $\pi$ photoproduction




Lalakulich@NuInt12

# Other inelastic channels

- Photon emission in NC interactions:

$$\nu(\bar{\nu})\, N \to \nu(\bar{\nu})\, \gamma\, N$$
$$\nu(\bar{\nu})\, A \to \nu(\bar{\nu})\, \gamma\, X$$

  - Easier than $\pi$ production (no FSI)
  - Carries all uncertainties present in N-R axial transitions
  - Benefits from any improvement in $\pi$ production on the nucleon

# Other inelastic channels

- Singe K production Athar@NuInt12

$$\nu_l + p \to l^- + K^+ + p \qquad \bar{\nu}_l + p \to l^+ + K^- + p$$
$$\nu_l + n \to l^- + K^0 + p \qquad \bar{\nu}_l + p \to l^+ + \bar{K}^0 + n$$
$$\nu_l + n \to l^- + K^+ + n \qquad \bar{\nu}_l + n \to l^+ + K^- + n$$

- Associated strangeness production

$$\nu_l n \longrightarrow l^- K^0 \Sigma^+$$
$$\nu_l n \longrightarrow l^- K^+ \Lambda^0$$
$$\nu_l n \longrightarrow l^- K^+ \Sigma^0$$
$$\nu_l p \longrightarrow l^- K^+ \Sigma^+$$

$$\bar{\nu}_l p \longrightarrow l^+ \Sigma^- K^+$$
$$\bar{\nu}_l p \longrightarrow l^+ \Lambda^0 K^0$$
$$\bar{\nu}_l p \longrightarrow l^+ \Sigma^0 K^0$$
$$\bar{\nu}_l n \longrightarrow l^+ \Sigma^0 K^-$$

- Eta production:

$$\nu_e(k) + N(p) \to e^-(k') + N'(p') + \eta(p_\eta)$$
$$\bar{\nu}_e(k) + N(p) \to e^+(k') + N'(p') + \eta(p_\eta)$$

# Other inelastic channels

- Single K, associated strangeness, single eta production Athar@NuInt12
  - Advanced calculations close to threshold
  - Chiral amplitudes + resonances
- Nakamura et al. will also study these processes

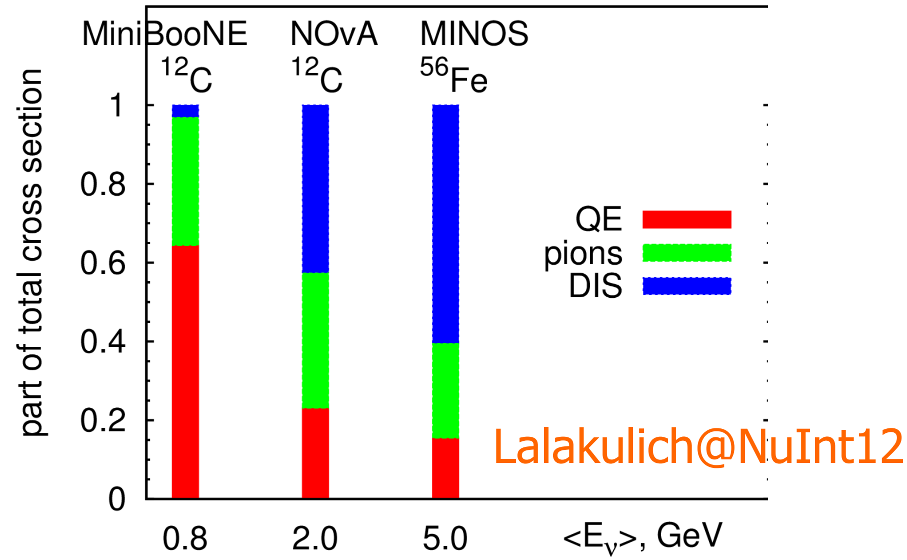
However:

- Will these reactions be really analyzed at Minerva ?
- Would it be possible to investigate the axial structure of the hadrons involved?
- FSI could obscure substantially the results

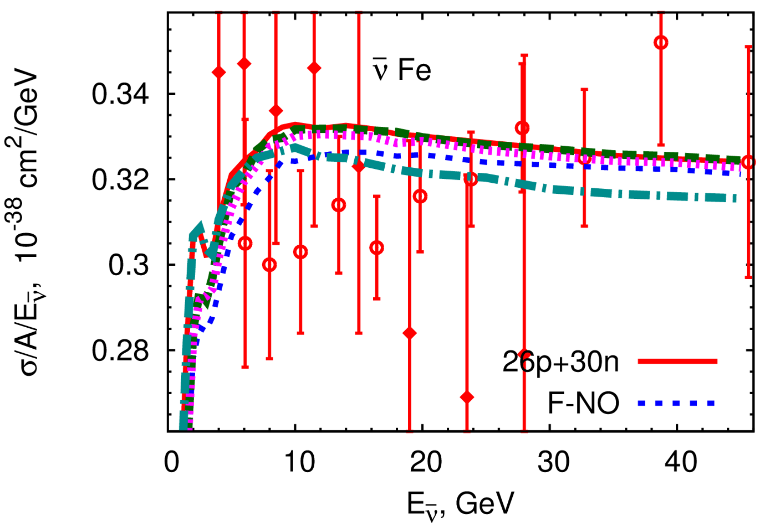
"strangeness changing events are clearly outnumbered by kaons produced through DIS" Lalakulich et al., PRC86

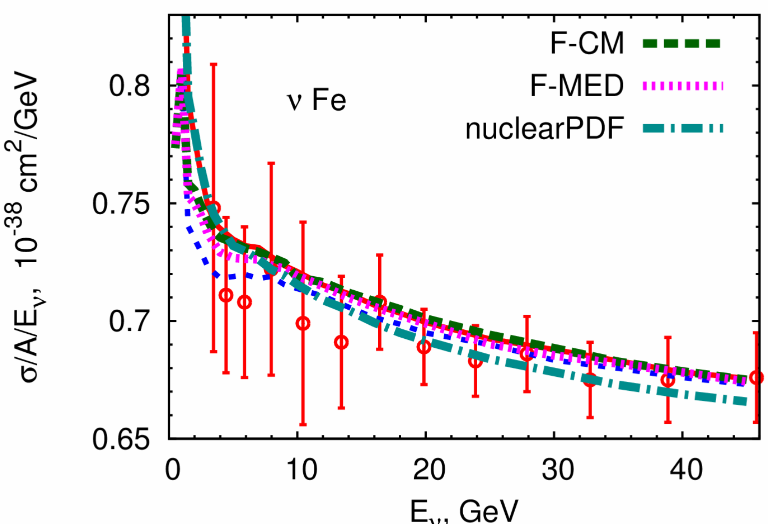
# Shallow inelastic scattering

- Several experiments (Minerva, NOvA, MINOS, ArgoNeut) (will be) running in this energy range
- Complex dynamics:
  - Many mechanisms contribute
  - Non-resonant terms unknown
  - Nontrivial interplay between resonances and DIS




- Surprisingly good agreement with inclusive MINOS data




- It will be worse in exclusive channels

# Deep inelastic scattering

- Ongoing effort to extract PDF from eN, eA, $\nu$ N, $\nu$A in different kinematic regions: large x has large uncertainties
- The best way to look at d/u is with (anti)$\nu$
- Nuclear effects can be encoded in the PDF
- Finding: Nuclear effects at the parton level are different for $\nu$A and $l^{\pm}$A
  - Due to presence of the axial current?
- Systematic experimental study is needed: Minerva

# Conclusion

There is work to be done