NuInt15

Present status of single pion production in neutrino-nucleus reactions

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Introduction

- Why π production?

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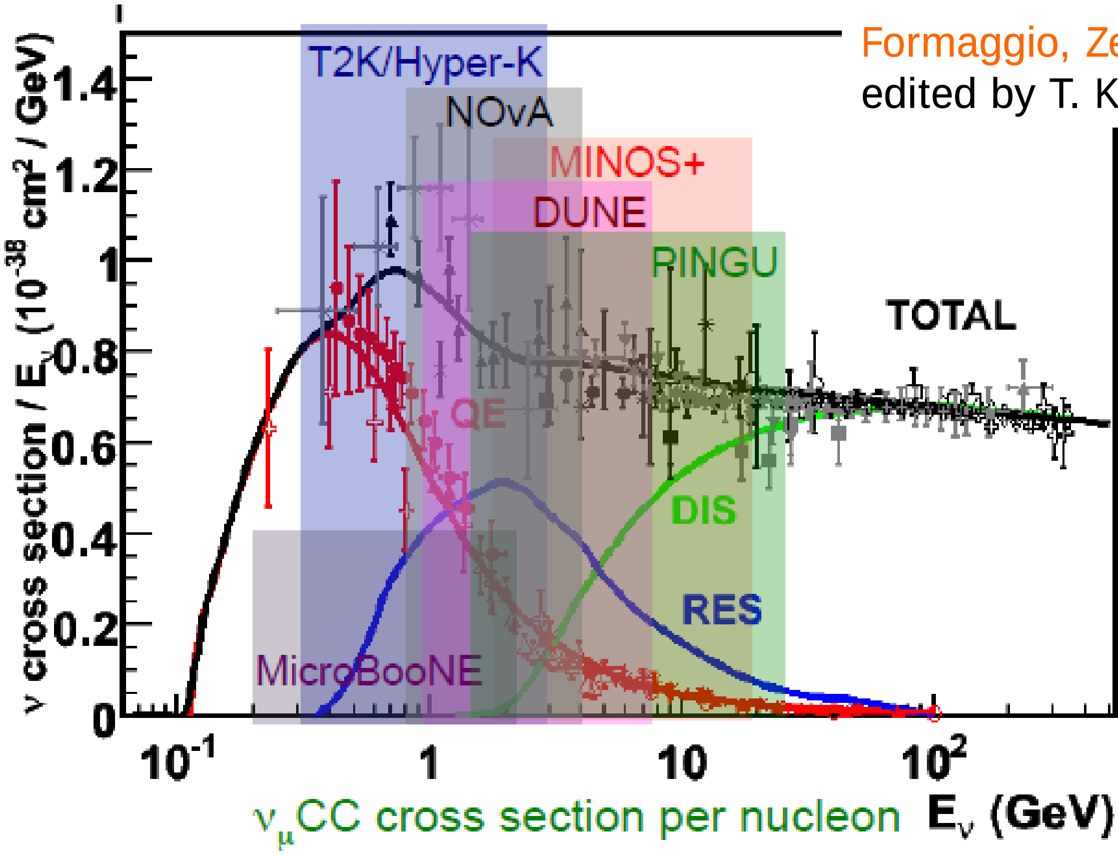
  - Important contribution to the inclusive νA cross section



Formaggio, Zeller, Rev. Mod. Phys. (2012)
edited by T. Katori

  - RES = predominantly $\Delta(1232)$ excitation $\Rightarrow \Delta \to N\,\pi$

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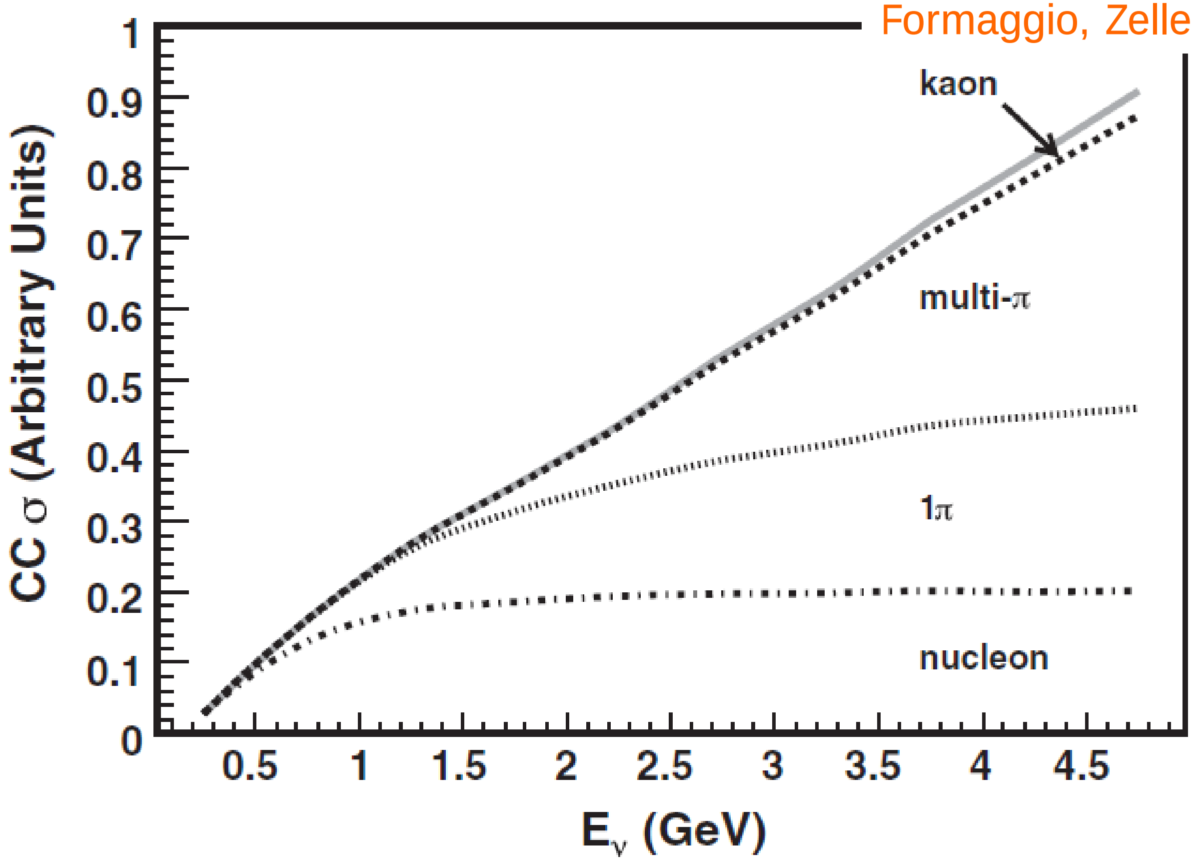

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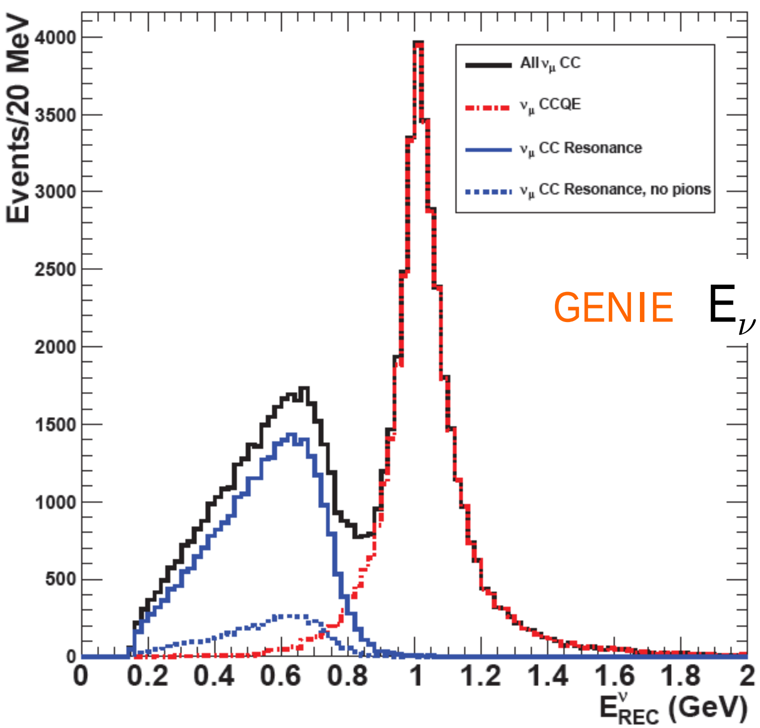
  - CC: $\nu_l \, N \to l^- \, \pi \, N'$
    - source of CCQE-like events (in nuclei)
    - needs to be subtracted for a good E_ν reconstruction



GENIE E_ν = 1 GeV

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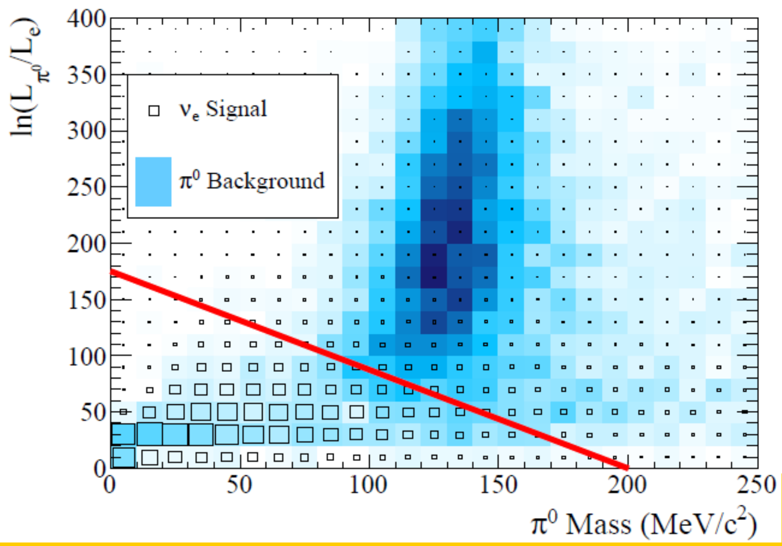
  - NC: $\nu_l \, N \rightarrow \nu_l \, \pi \, N'$
    - π^o: e-like background to $\nu_\mu \rightarrow \nu_e$ searches
    - improved at T2K with a π^o rejection cut



Abe et al, PRL 112 (2014) 061802

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  - NC: $\nu_l \, N \rightarrow \nu_l \, \pi \, N'$
    - π^0: e-like background to $\nu_\mu \rightarrow \nu_e$ searches
  - Interesting for hadronic physics
    - Nucleon-Resonance (N-Δ, N-N*) axial form factors
  - Key ingredient for 2p2h models

1π production on nucleons

$$\nu_l\, N \to l\, \pi\, N'$$

- CC: $\nu_\mu\, p \to \mu^-\, p\, \pi^+, \qquad \overline{\nu}_\mu\, p \to \mu^+\, p\, \pi^-$

  $\nu_\mu\, n \to \mu^-\, p\, \pi^0, \qquad \overline{\nu}_\mu\, p \to \mu^+\, n\, \pi^0$

  $\nu_\mu\, n \to \mu^-\, n\, \pi^+, \qquad \overline{\nu}_\mu\, n \to \mu^+\, n\, \pi^-$

- NC: $\nu_\mu\, p \to \nu_\mu\, p\, \pi^0, \qquad \overline{\nu}_\mu\, p \to \overline{\nu}_\mu\, p\, \pi^0$

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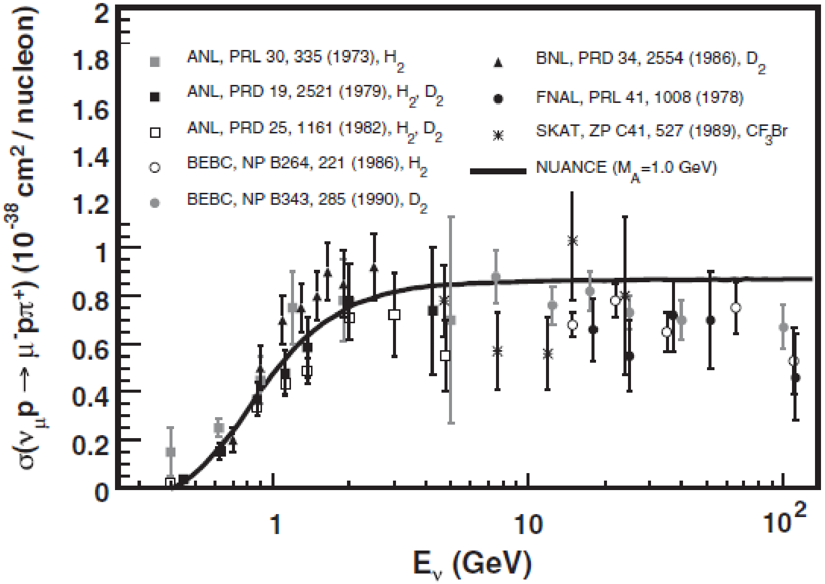
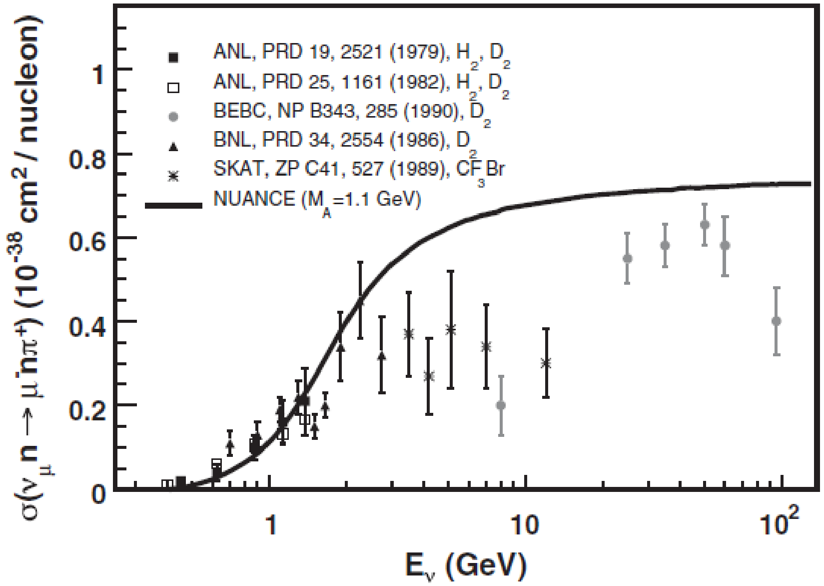
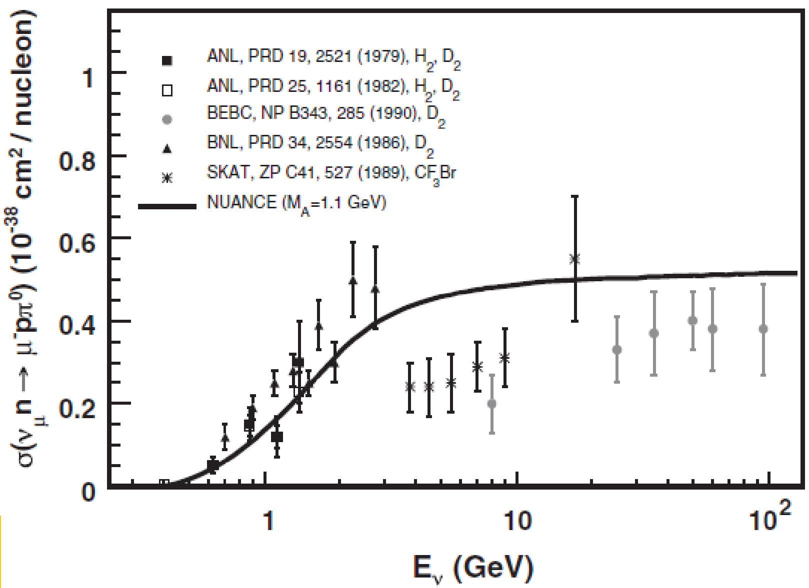
  $\nu_\mu\, n \to \nu_\mu\, p\, \pi^-, \qquad \overline{\nu}_\mu\, n \to \overline{\nu}_\mu\, p\, \pi^-$

1π production on nucleons

- CC data



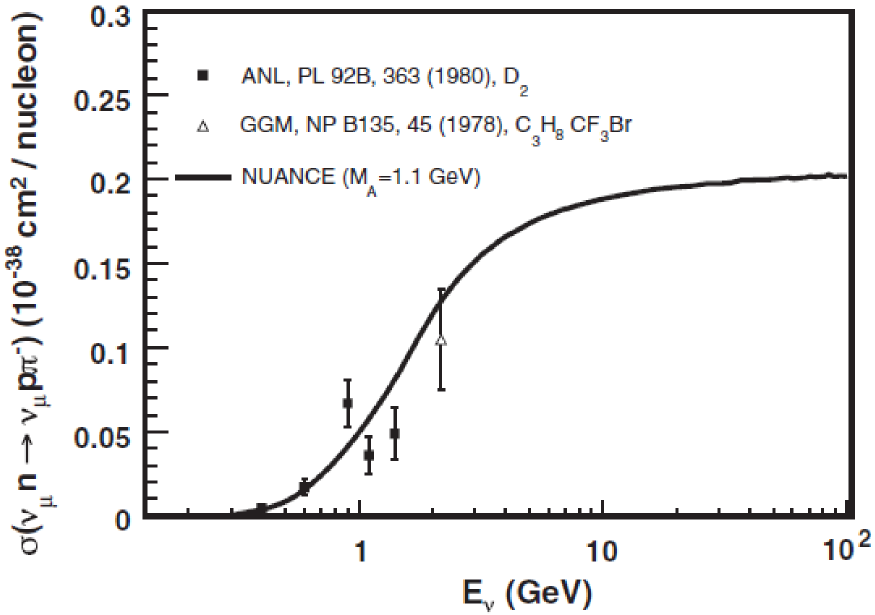


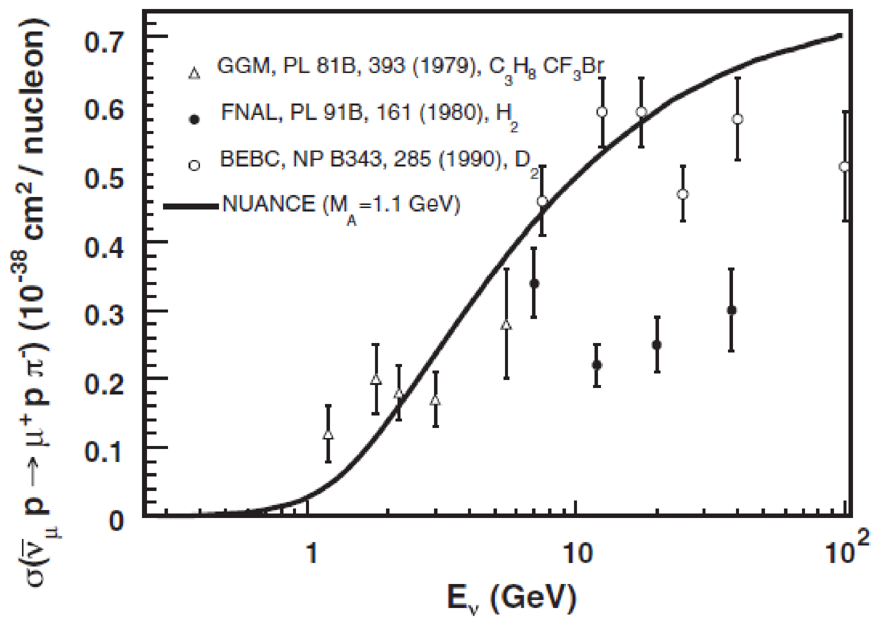


Formaggio, Zeller, Rev. Mod. Phys. (2012)

1π production on nucleons

- NC data





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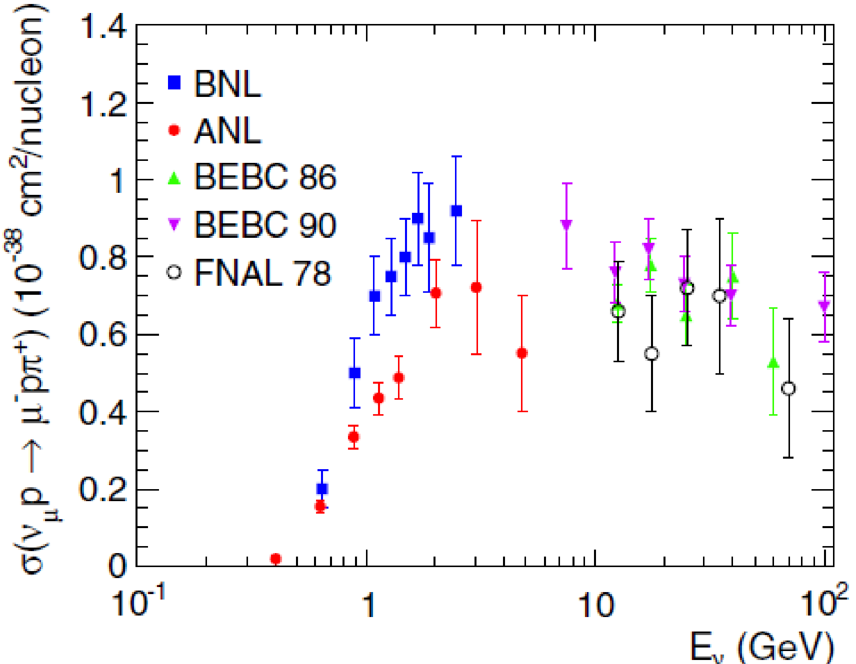
1π production on nucleons

- Discrepancies between ANL and BNL datasets

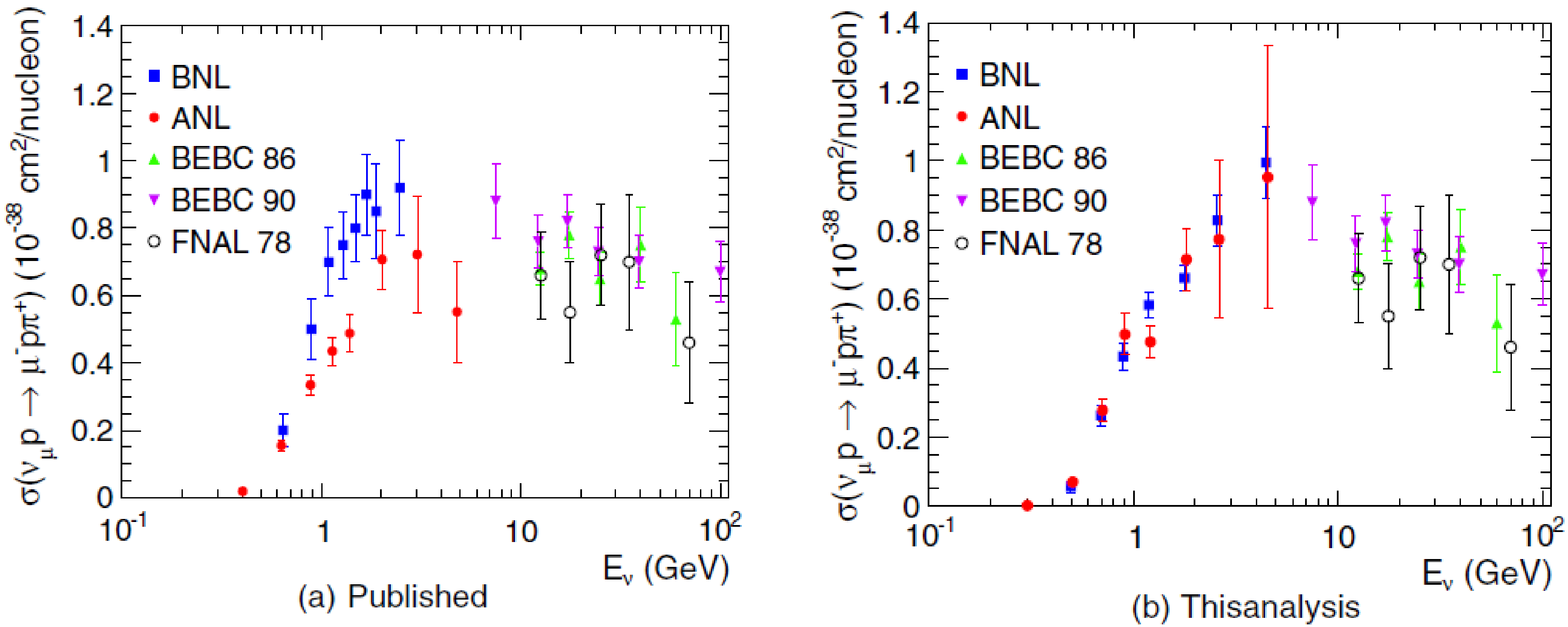


(a) Published

- Reanalysis by Wilkinson et al., PRD90 (2014)
  - Flux normalization independent ratios: CC1π^+/ CCQE
  - Good agreement for ratios
  - Better understood CCQE cross section used to obtain the CC1π^+ one

1π production on nucleons

- Discrepancies between ANL and BNL datasets



- Reanalysis by Wilkinson et al., PRD90 (2014)
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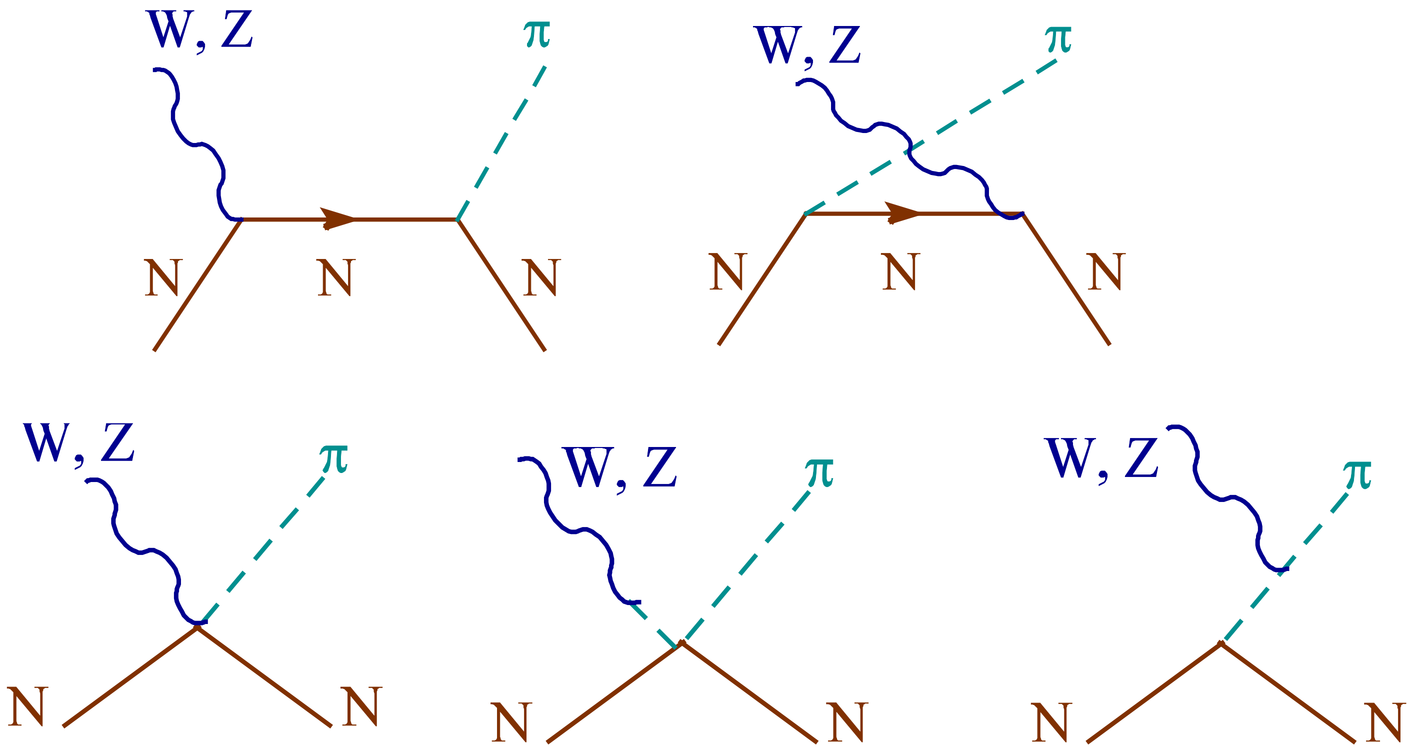
1π production on nucleons

$$\nu_l \, N \rightarrow l \, \pi \, N'$$

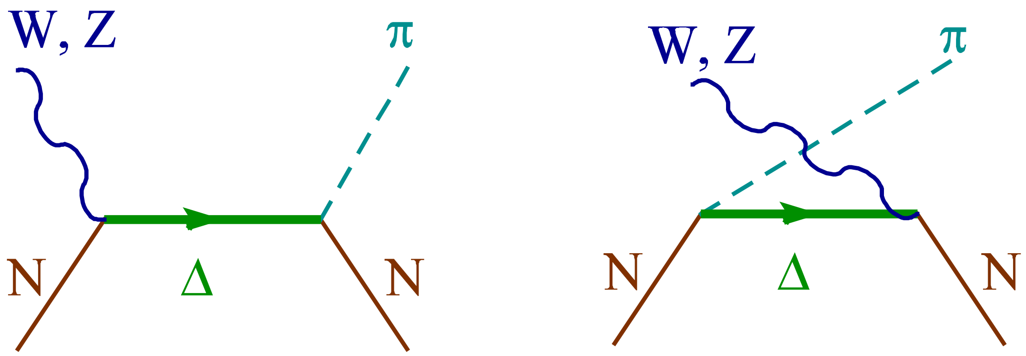
- From Chiral symmetry:



Hernandez et al., Phys.Rev. D76 (2007) 033005

1π production on nucleons

- Δ (1232) excitation:



- N-Δ transition current:

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

- Vector form factors ⇔ Helicity amplitudes

1π production on nucleons

- N-Δ transition current

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- Helicity amplitudes can be extracted from data on π photo- and electro-production

$$A_{1/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^+ J^\mu_{\mathrm{EM}} \right| N, J_z = -1/2 \right\rangle \zeta$$

$$A_{3/2} = \sqrt{\frac{2\pi\alpha}{k_R}} \left\langle R, J_z = 3/2 \left| \epsilon_\mu^+ J^\mu_{\mathrm{EM}} \right| N, J_z = 1/2 \right\rangle \zeta$$

$$S_{1/2} = -\sqrt{\frac{2\pi\alpha}{k_R}} \frac{|\mathbf{q}|}{\sqrt{Q^2}} \left\langle R, J_z = 1/2 \left| \epsilon_\mu^0 J^\mu_{\mathrm{EM}} \right| N, J_z = 1/2 \right\rangle \zeta$$

1π production on nucleons

- N-Δ transition current

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

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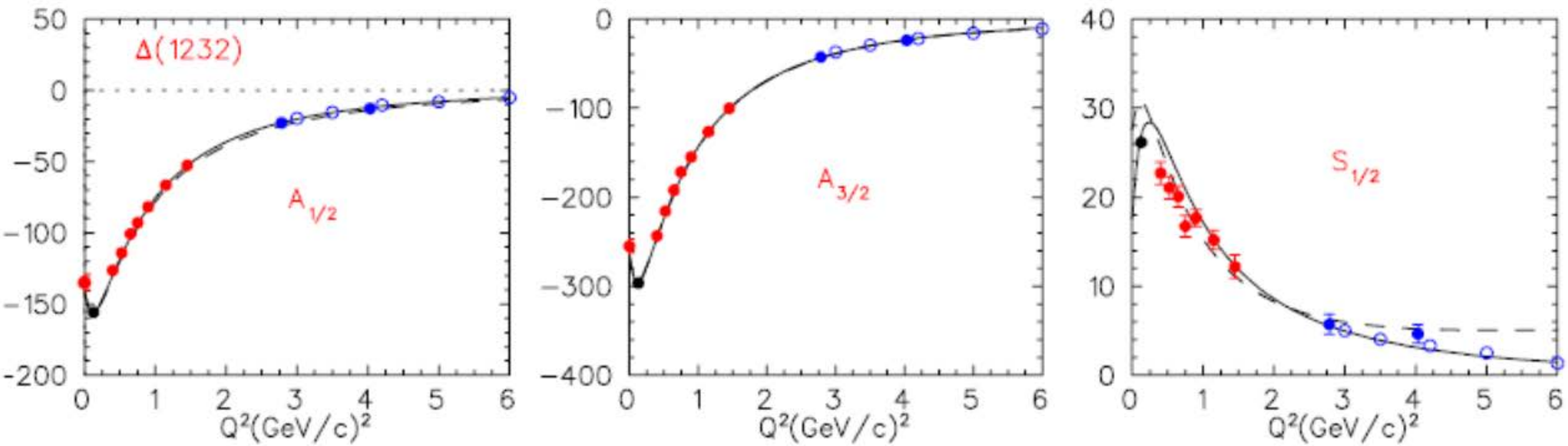

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  - Axial form factors

$$C_6^A = C_5^A \frac{M^2}{m_\pi^2 + Q^2} \leftarrow \text{PCAC}$$

$$C_5^A = C_5^A(0) \left(1 + \frac{Q^2}{M_{A\Delta}^2} \right)^{-2}$$

  - Constraints from ANL and BNL data on $\nu_\mu \, d \rightarrow \mu^- \, \pi^+ \, p \, n$
    - with large normalization (flux) uncertainties
  - ANL and BNL data do not constrain $C^A_{3,4}$: consistent with zero

    Hernandez et al., PRD81(2010)

1π production on nucleons

- N-Δ axial form factors: determination of $C^A_5(0)$ and $M_{A\Delta}$
- $$C_5^A = C_5^A(0)\left(1+\frac{Q^2}{M_{A\Delta}^2}\right)^{-2}$$
- From ANL and BNL data on $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$

- Graczyk et al., PRD 80 (2009)
  - Deuteron effects
  - Non-resonant background absent
  - $C^A_5(0) = 1.19 \pm 0.08$, $M_{A\Delta} = 0.94 \pm 0.03$ GeV

- Hernandez et al., PRD 81 (2010)
  - Deuteron effects
  - $C^A_5(0) = 1.00 \pm 0.11$, $M_{A\Delta} = 0.93 \pm 0.07$ GeV
  - 20% reduction of the GT relation $C_5^A(0) = 1.15 - 1.2$

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- Alam et al., arXiv:1509.08622 & R. Alam @ NuInt15
  - Deuteron effects
  - N* resonances: $P_{11}(1440)$, $S_{11}(1535)$, $D_{13}(1520)$, $S_{11}(1650)$, $P_{13}(1720)$.
  - $C^A_5(0) = 1.00$, $M_{A\Delta} = 1.026$ GeV
  - 20% reduction of the GT relation $C_5^A(0) = 1.15 - 1.2$

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- N-Δ axial form factors: determination of $C^A_5(0)$ and $M_{A\,\Delta}$
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- From ANL and BNL data on $\nu_\mu\, d \to \mu^-\, \pi^+\, p\, n$

- Graczyk et al., PRD 90 (2014)
  - Deuteron effects
  - Non-resonant background present
  - N-Δ e.m. form factors fitted to F_2 data (e-p scattering)
  - $C_5^A(0) = 1.10^{+0.15}_{-0.14}$, $M_{A\Delta} = 0.85^{+0.09}_{-0.08}$ GeV

1π production on nucleons

- Watson's theorem LAR, E. Hernandez, J. Nieves, M. J. Vicente Vacas, arXiv:1510.06266
  - Unitarity
  - Time reversal invariance

$$\sum_M \langle M|T|F\rangle^* \langle M|T|I\rangle = -2\mathrm{Im}\langle F|T|I\rangle \in \mathbb{R}$$

- For W N $\rightarrow$ π N
  - assuming that |M⟩ = |F⟩ = |π N⟩
  - schematically:

$$\langle \pi N|T|\pi N\rangle^* \langle \pi N|T|W N\rangle = -2\mathrm{Im}\langle \pi N|T|W N\rangle \in \mathbb{R}$$

$$\langle \pi N|T|\pi N\rangle \approx \langle \pi N|T_{\mathrm{strong}}|\pi N\rangle$$

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- For W N $\to$ π N

$$\sum_\rho \sum_L \frac{2L+1}{2J+1} (L,1/2,J;0,-\lambda')(L,1/2,J;0,-\rho)\langle J,M;L,1/2|T_{\rm str}|J,M;L,1/2\rangle^* \langle J,M;0,\rho|T|0,0;r,\lambda\rangle \in \mathbb{R}.$$

- For the dominant J=3/2, I=3/2, L=1 $\Leftrightarrow$ P_{33} partial wave

$$\left[\sum_\rho (1,1/2,3/2;0,-\rho)\,(1,1/2,3/2;0,-\rho)\,\langle 3/2,M;0,\rho|T|0,0;r,\lambda\rangle\right] e^{-i\delta_{P_{33}}} \in \mathbb{R}$$

writing $T = T_\Delta + T_B e^{-i\delta(W,q^2)}$ we impose Watson's theorem.

- This approach has been applied for π photo and electroproduction

Olsson, NPB78 (1974)
Carrasco, Oset, NPA536 (1992)
Gil, Nieves, Oset, NPA627 (1997)

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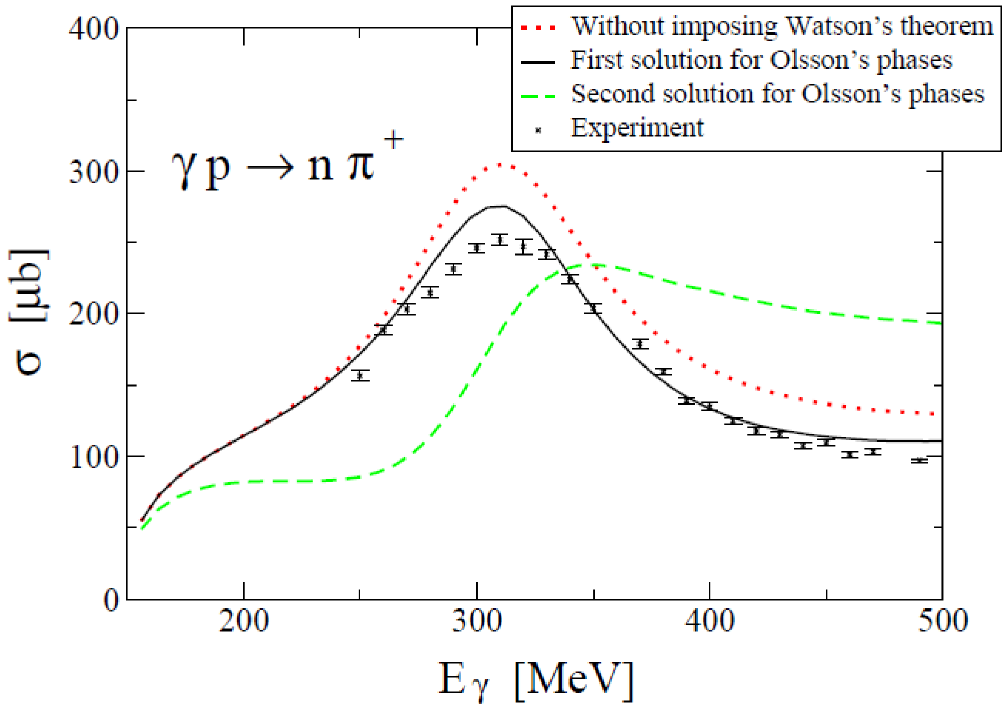

- For W

$$\sum_\rho \sum_L \frac{2L+1}{2J+1}(\quad , 1/2\rangle^* \langle J, M; 0, \rho | T | 0, 0; r, \lambda\rangle \in \mathbb{R}.$$

- For the ... wave

$$\left[\sum_\rho (1, 1/2 \quad T|0, 0; r, \lambda\rangle\right] e^{-i\delta_{P_{33}}} \in \mathbb{R}$$

writing T ... s theorem.

- This approach has been applied for π photo and electroproduction

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- For the dominant J=3/2, I=3/2, L=1 $\Leftrightarrow$ P_{33} partial wave

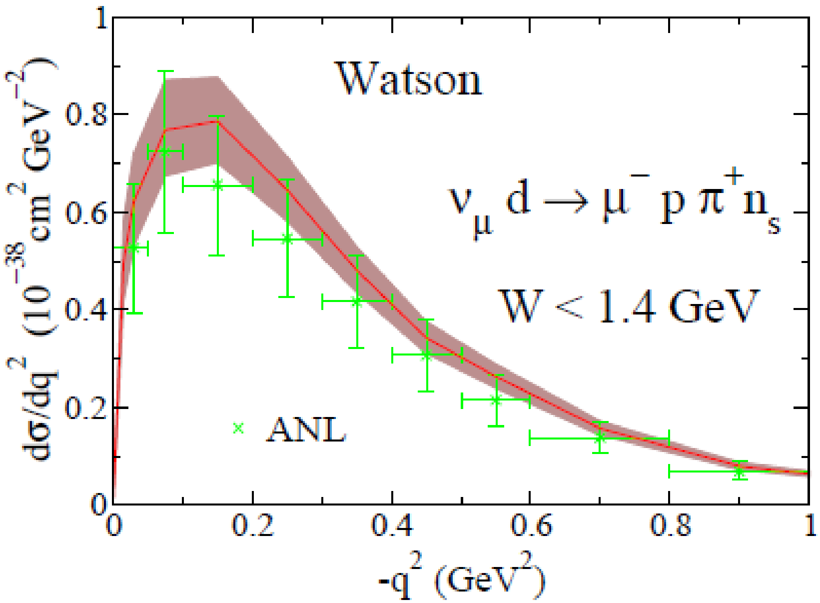
$$\left[\sum_\rho (1,1/2,3/2;0,-\rho)\,(1,1/2,3/2;0,-\rho)\,\langle 3/2,M;0,\rho|T|0,0;r,\lambda\rangle\right] e^{-i\delta_{P_{33}}} \in \mathbb{R}$$

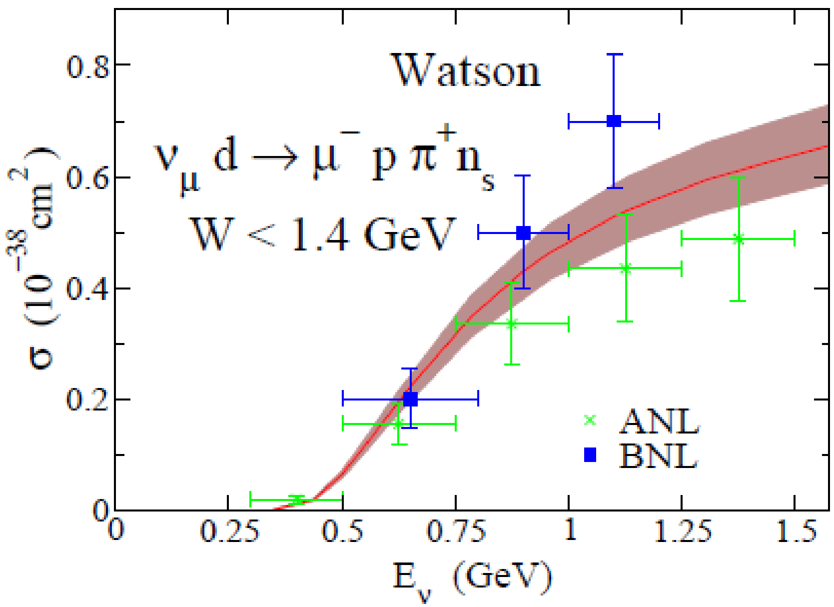
writing $T = T_\Delta + T_B e^{-i\delta(W,q^2)}$ we impose Watson's theorem.

- This approach has been applied for π photo and electroproduction
- In weak production two phases δ_V and δ_A are needed

1π production on nucleons

- Watson's theorem LAR, E. Hernandez, J. Nieves, M. J. Vicente Vacas, arXiv:1510.0626
- Fit to ANL and BNL data with W < 1.4 GeV

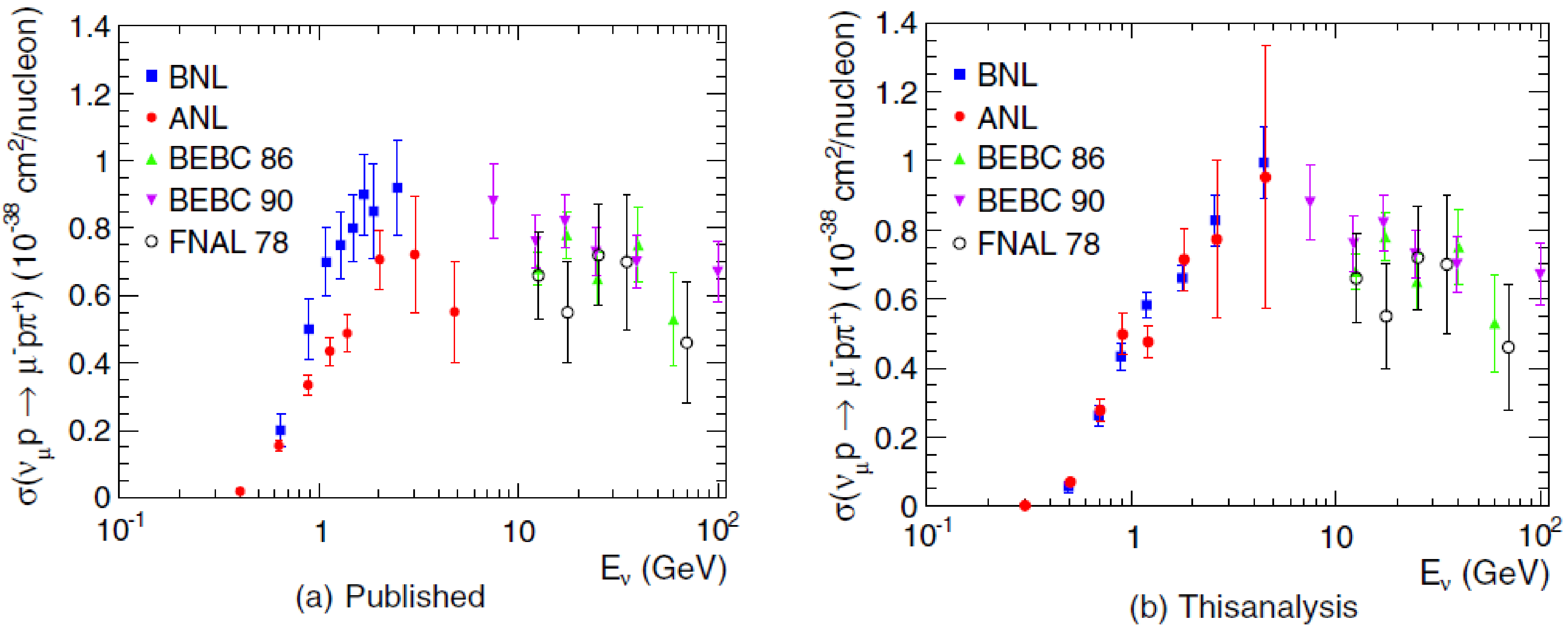




- $C^A_5(0)$ =1.12 ± 0.11, $M_{A\Delta}$ = 0.95 ± 0.06 GeV
- Consistent with the off-diagonal GT relation $C_5^A(0) = 1.15 - 1.2$

1π production on nucleons

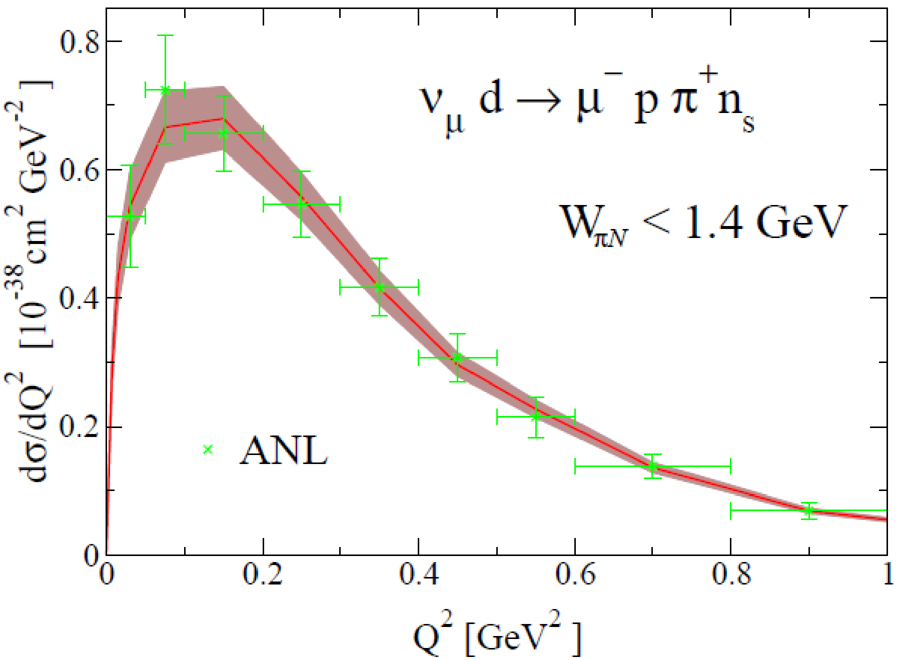
- Discrepancies between ANL and BNL datasets

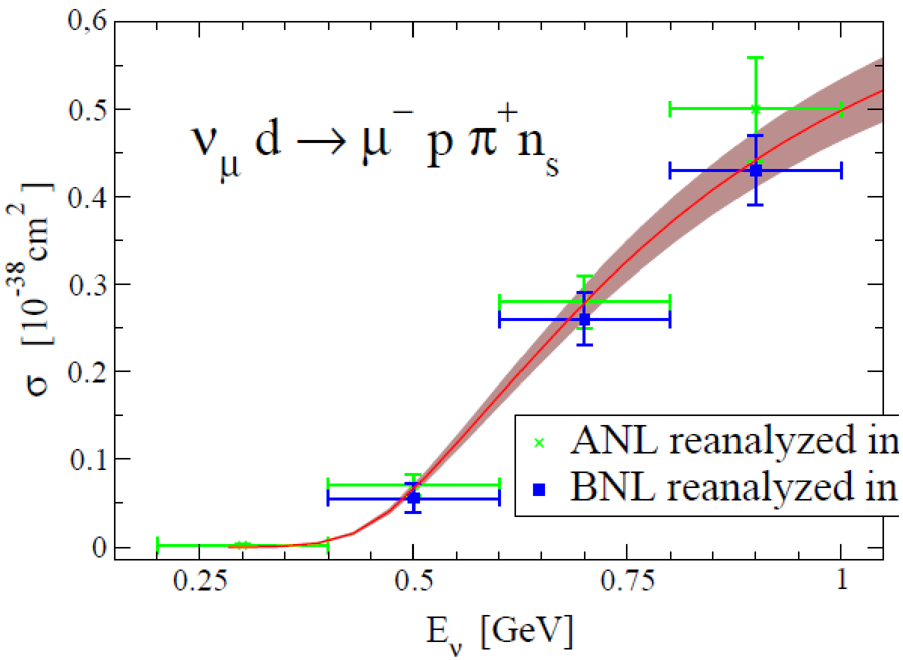


- Reanalysis by Wilkinson et al., PRD90 (2014)
  - Flux normalization independent ratios: $CC1\pi^+$/ CCQE
  - Good agreement for ratios
  - Better understood CCQE cross section used to obtain the $CC1\pi^+$ one

1π production on nucleons

- New fit to ANL and BNL data
  - Shape from original ANL $d\sigma/dQ^2$
  - Integrated σ from Wilkinson et al.: points with E_ν < 1 GeV





- $C^A_5(0) = 1.14 \pm 0.07$, $M_{A\Delta} = 0.96 \pm 0.07$ GeV
- $C^A_5(0) = 1.12 \pm 0.11$, $M_{A\Delta} = 0.95 \pm 0.06$ GeV $\leftarrow$ former fit
- $C^A_5(0) = 1.15 – 1.20$ $\leftarrow$ GT

1π production on nucleons

- Fits to ANL and BNL data
  - $C^A_5(0) = 1.12 \pm 0.11$, $M_{A\,\Delta} = 0.95 \pm 0.06$ GeV $\leftarrow$ original data (A)
  - $C^A_5(0) = 1.14 \pm 0.07$, $M_{A\,\Delta} = 0.96 \pm 0.07$ GeV $\leftarrow$ reanalysis (B)
- Relative error: $r_A = 10\ \% \Rightarrow r_B = 6\ \%$
- Is this precision enough?

1π production on nucleons

- NN final state interactions: d target
  - Wu, Sato and Lee, PRC 91 (2015) and H. Lee @ NuInt15
  - Reduce the cross section for pn final states but not for pp
  - Cuts in the actual measurements should be considered

- Dynamical model Sato, Uno, Lee, PRC67 (2003)
  - Lippmann-Schwinger equation in coupled channels $\Rightarrow$ unitarity
  - Watson's theorem exactly fulfilled
- Extended (DCC) to other meson production channels
  Nakamura et al, PRD92 (2015)

1π production on nuclei

- (Modern) cross section measurements:

- MiniBooNE: on CH_2 at <E_ν> $\sim$ 1 GeV
  - ν_μ $\bar{\nu}_\mu$ NCπ^0 Aguilar Arevalo et al., PRD81 (2010)
  - ν_μ CCπ^+ Aguilar Arevalo et al., PRD83 (2011)
  - ν_μ CCπ^0 Aguilar Arevalo et al., PRD83 (2011)

- MINERvA: on CH at <E_ν> $\sim$ 4 GeV
  - ν_μ CC$\pi^\pm$ Eberly et al., arXiv:1406.6415
  - $\bar{\nu}_\mu$ CCπ^0 Le et al., PLB749 (2015)

- ArgoNeuT: on Ar at <E_ν> $\sim$ 9.6 GeV (ν_μ) and 3.6 GeV ($\bar{\nu}_\mu$)
  - ν_μ $\bar{\nu}_\mu$ NCπ^0 Acciarri et al., arXiv:1511.00941

1π production on nuclei

- Incoherent 1π production in nuclei

$$\nu_l \, A \rightarrow l \, \pi \, X$$

  - Fermi motion, or more realistic SF, and Pauli blocking
  - Modification of the $\Delta(1232)$ properties in the medium

$$D_\Delta \Rightarrow \tilde{D}_\Delta(r) = \frac{1}{(W + M_\Delta)(W - M_\Delta - \mathrm{Re}\Sigma_\Delta(\rho) + i\tilde{\Gamma}_\Delta/2 - i\mathrm{Im}\Sigma_\Delta(\rho))}$$

$\tilde{\Gamma}_\Delta \leftarrow$ Free width $\Delta \rightarrow N\,\pi$ modified by Pauli blocking

$$\mathrm{Re}\Sigma_\Delta(\rho) \approx 40\mathrm{MeV}\frac{\rho}{\rho_0}$$

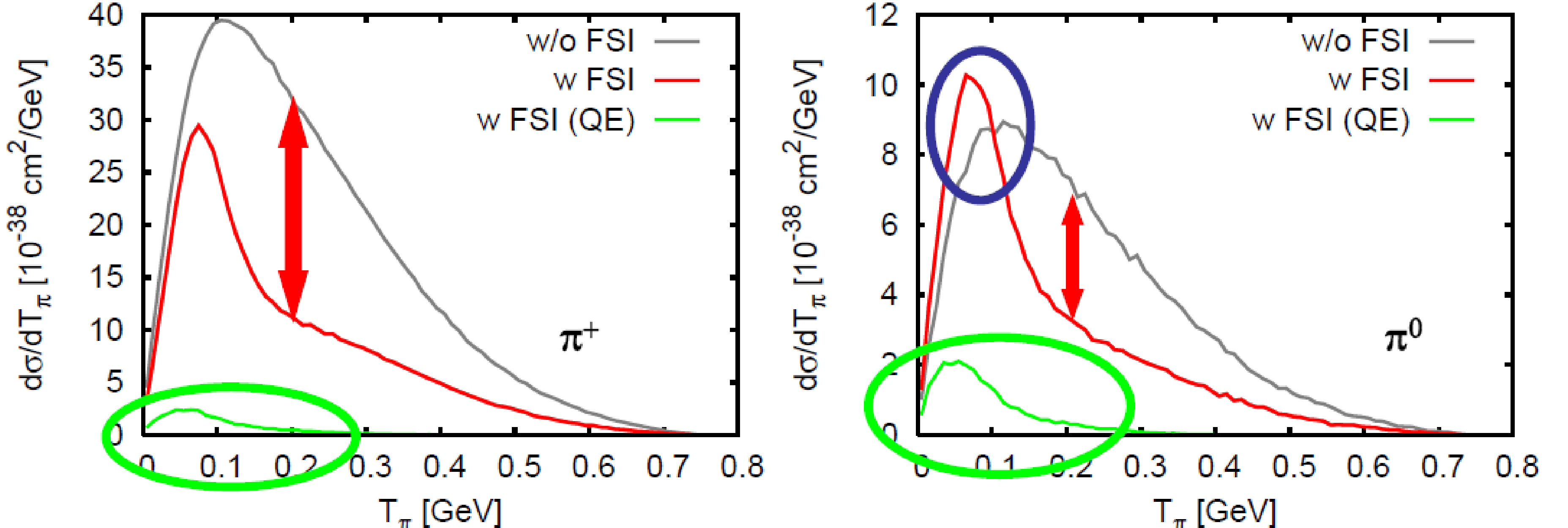
$\mathrm{Im}\Sigma_\Delta(\rho) \leftarrow$

- $\Delta\, N \rightarrow N\, N$
- $\Delta\, N \rightarrow N\, N\, \pi$
- $\Delta\, N\, N \rightarrow N\, N\, N$

  - π propagation (scattering, charge exchange), absorption (FSI)
    - semiclassical cascade, transport models

1π production on nuclei

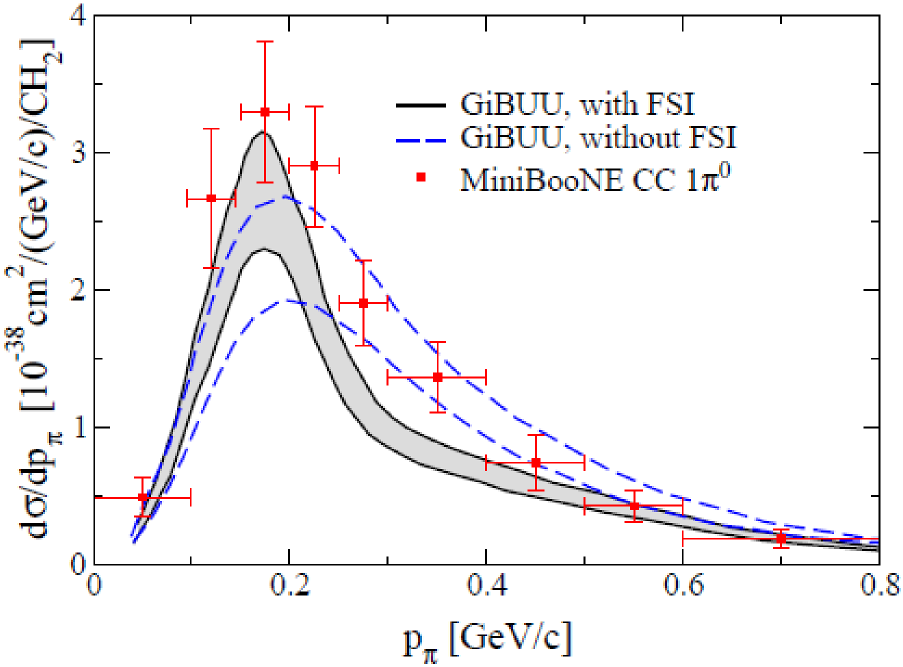
- GiBUU Leitner, LAR, Mosel, PRC 73 (2006)
  - Effects of FSI on pion kinetic energy spectra
    - strong absorption in Δ region
    - side-feeding from dominant π^+ into π^o channel
    - secondary pions through FSI of initial QE protons



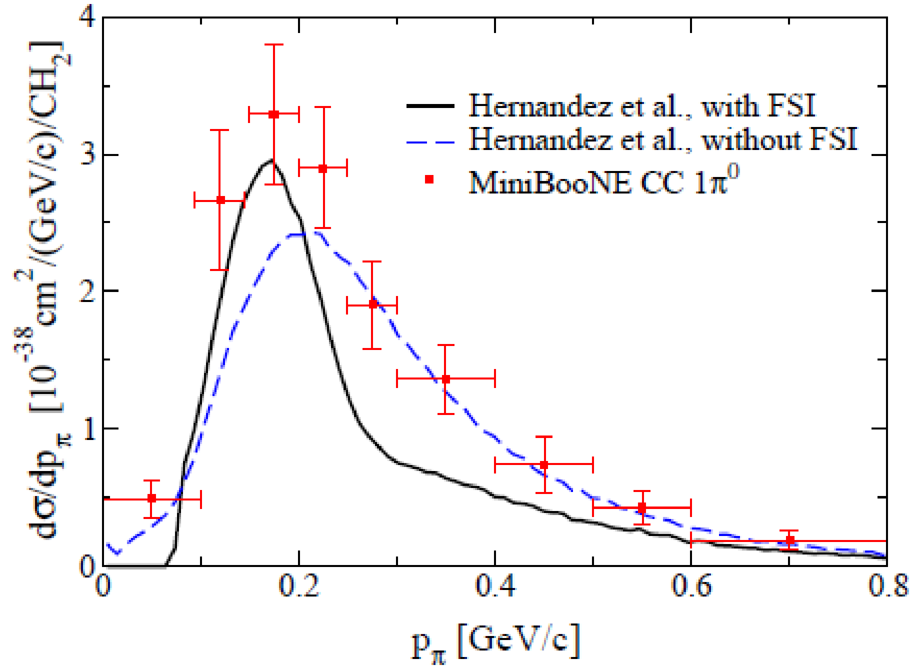
$$\nu_\mu + {}^{56}Fe \rightarrow \mu^- \, \pi \, X \quad E_\nu = 1\ \mathrm{GeV}$$

1π production on nuclei

- Comparison to MiniBooNE: CC1π^0 Aguilar-Arevalo, PRD83 (2011)



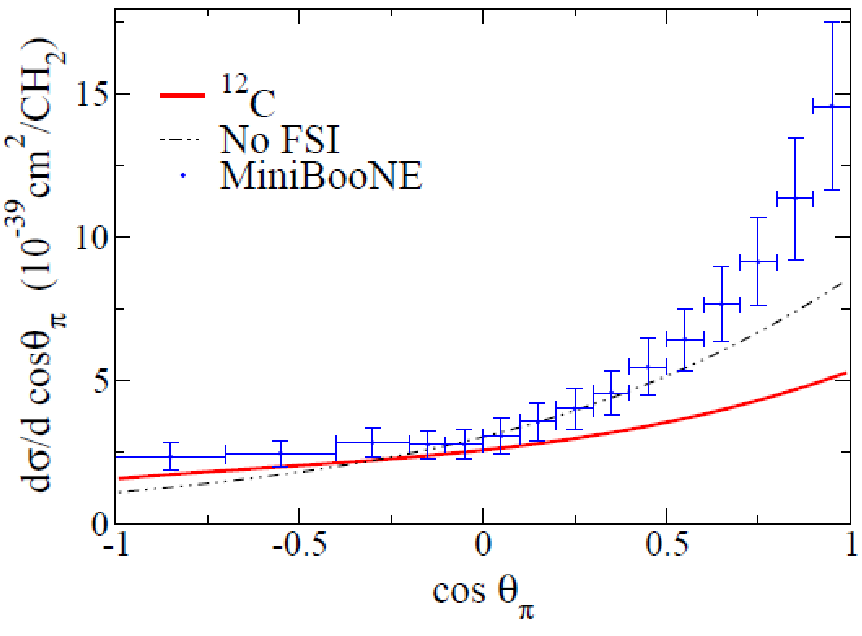
Hernandez et al., PRD87 (2013)



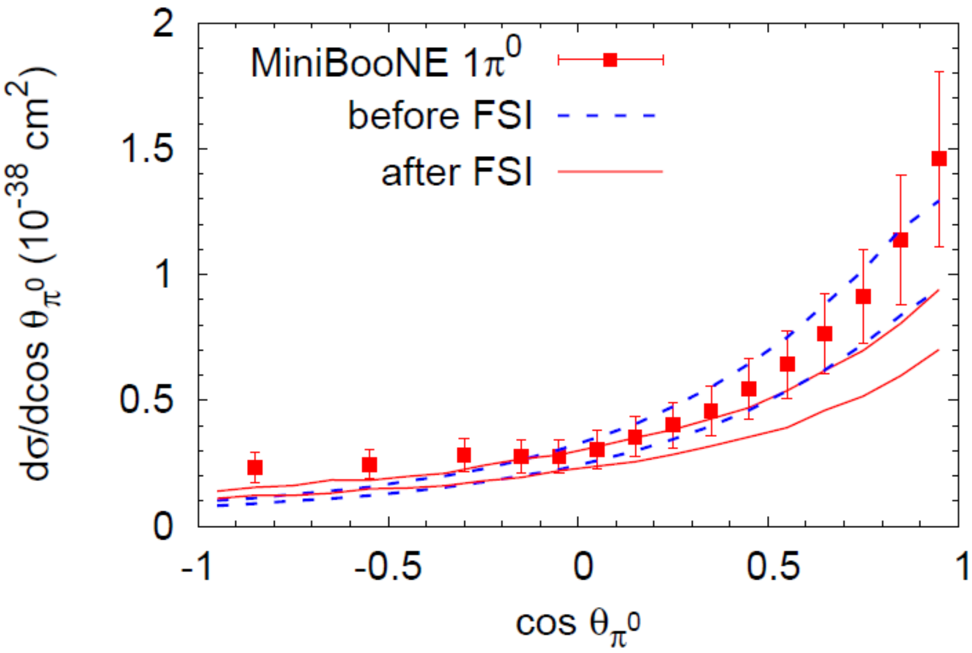
Lalakulich, Mosel, PRC87 (2013)

1π production on nuclei

- Comparison to MiniBooNE: CC$1\pi^0$ Aguilar-Arevalo, PRD83 (2011)



Hernandez et al., PRD87 (2013)

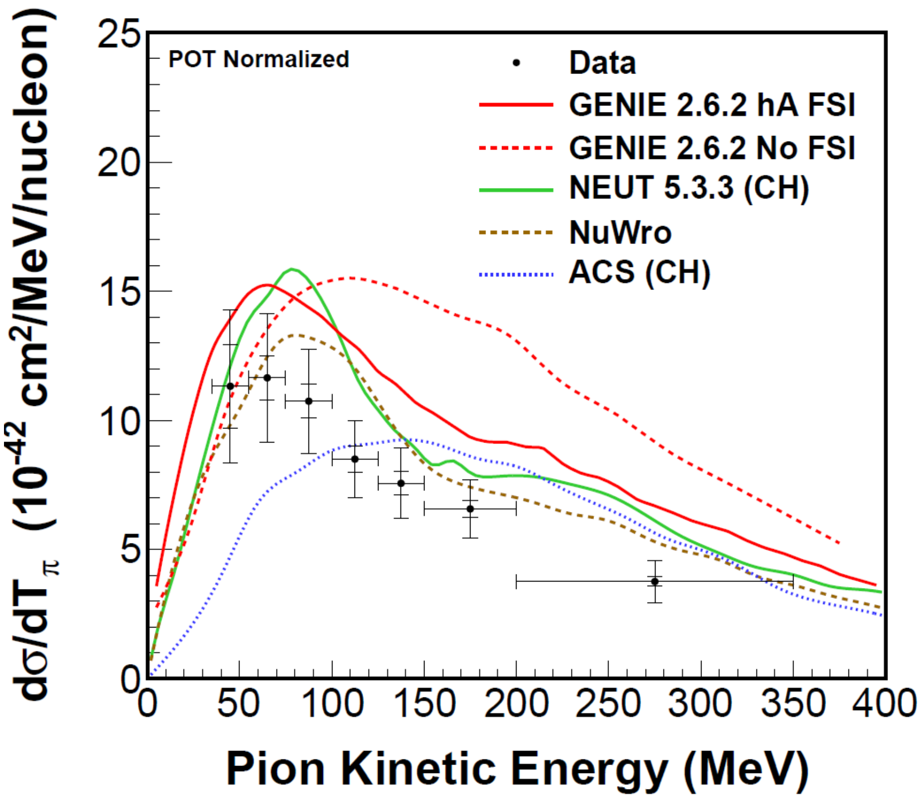


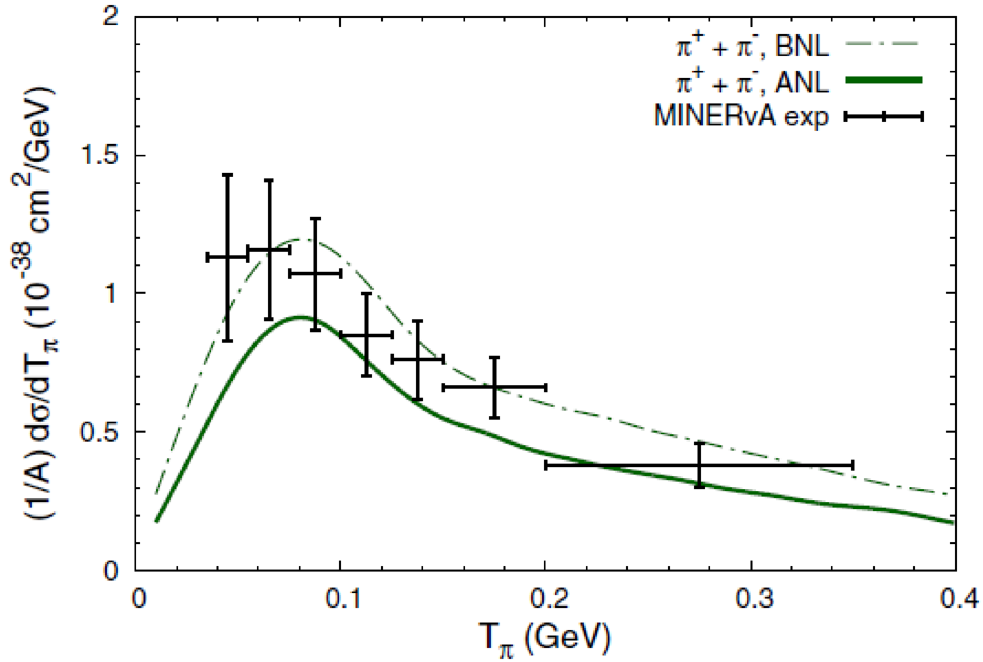
Lalakulich, Mosel, PRC87 (2013)

- Deficit at forward π^0 angles
- Two-nucleon mechanisms (?)

1π production on nuclei

- Comparison to MINERvA: CC$\pi^{\pm}$ Eberly et al., arXiv:1406.6415



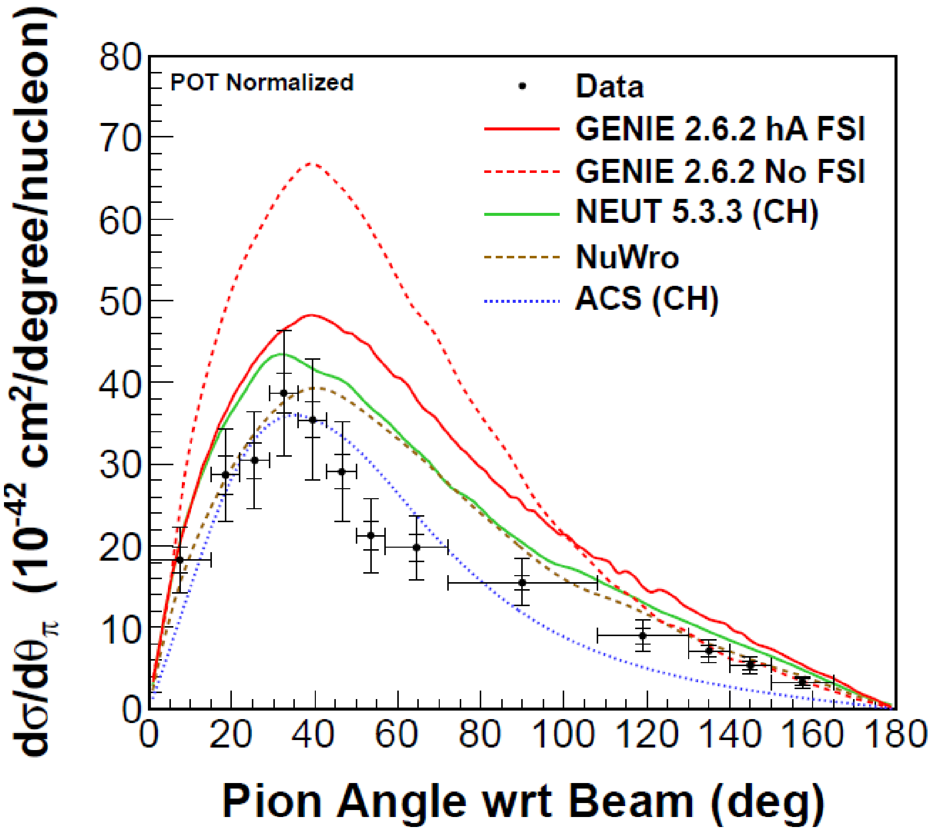


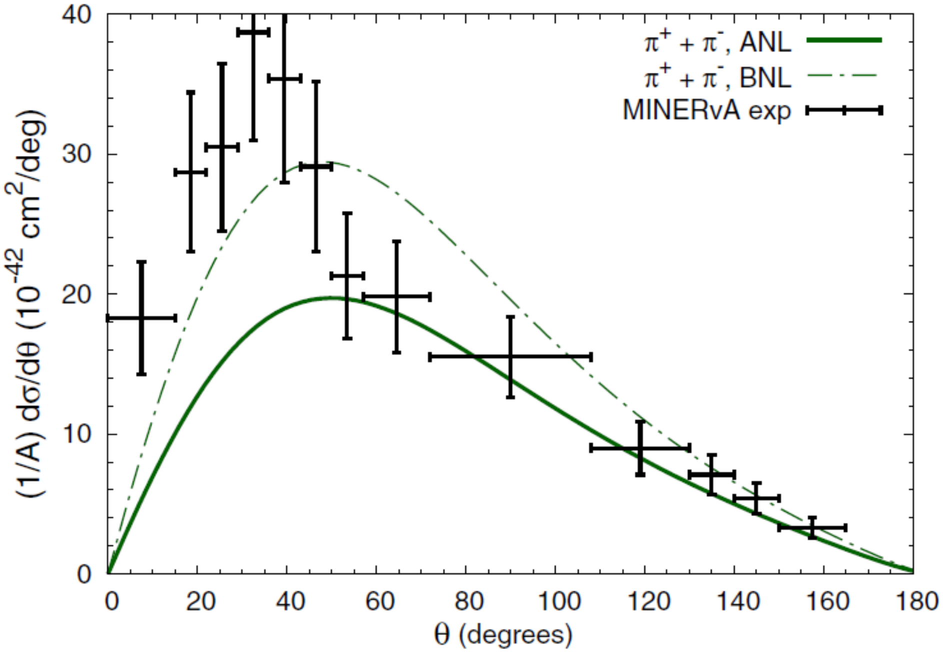
Mosel, PRC91 (2015)

- GiBUU: deficit of $\pi^{\pm}$

1π production on nuclei

- Comparison to MINERvA: CC$\pi^{\pm}$ Eberly et al., arXiv:1406.6415



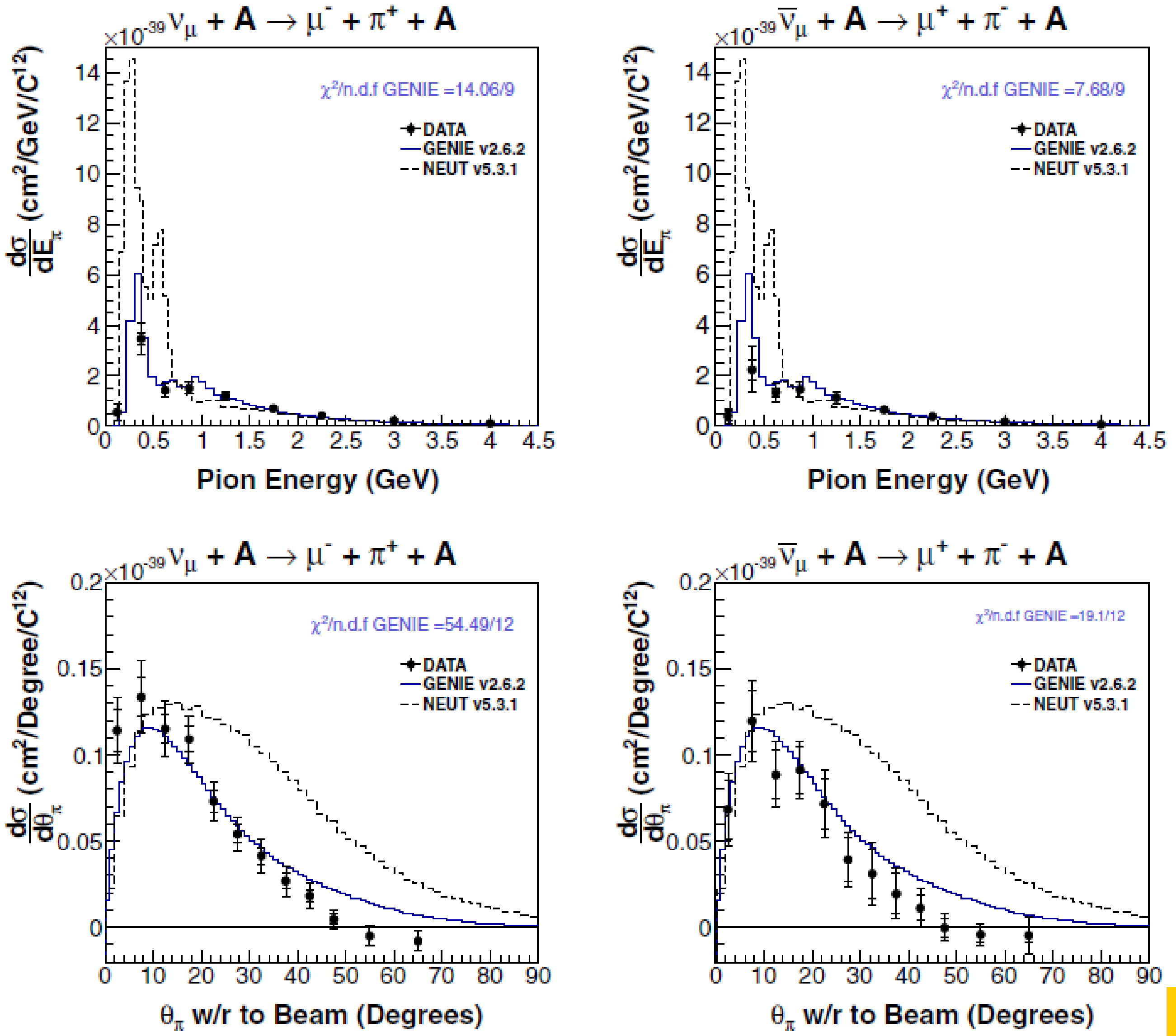


Mosel, PRC91 (2015)

- GiBUU: deficit of $\pi^{\pm}$ at forward angles

Coherent Pion Production

- MINERvA measurement Higuera et al., PRL 113 (2014)



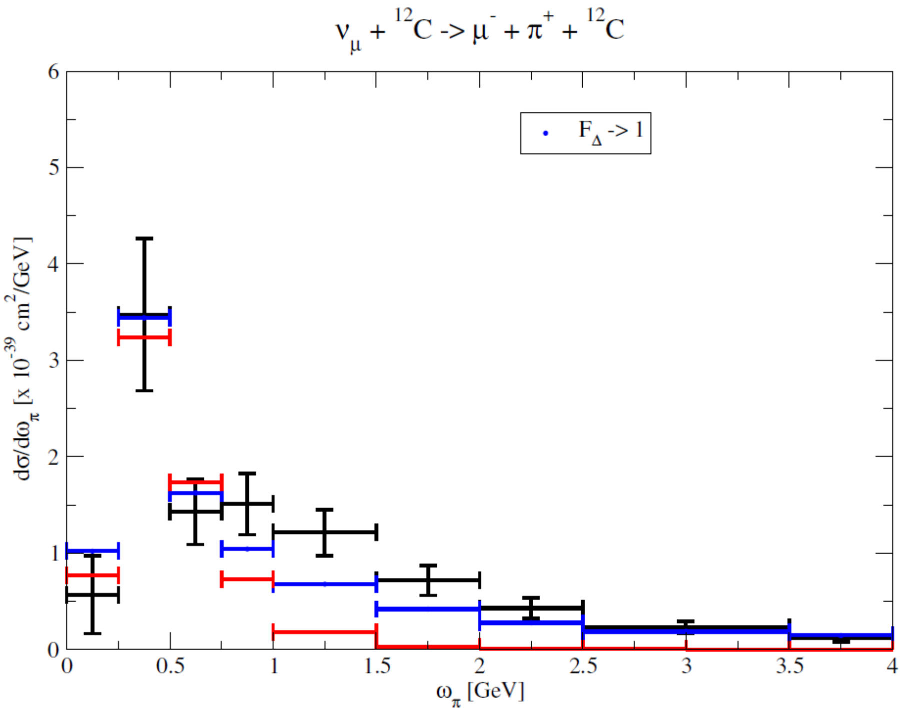
Coherent Pion Production

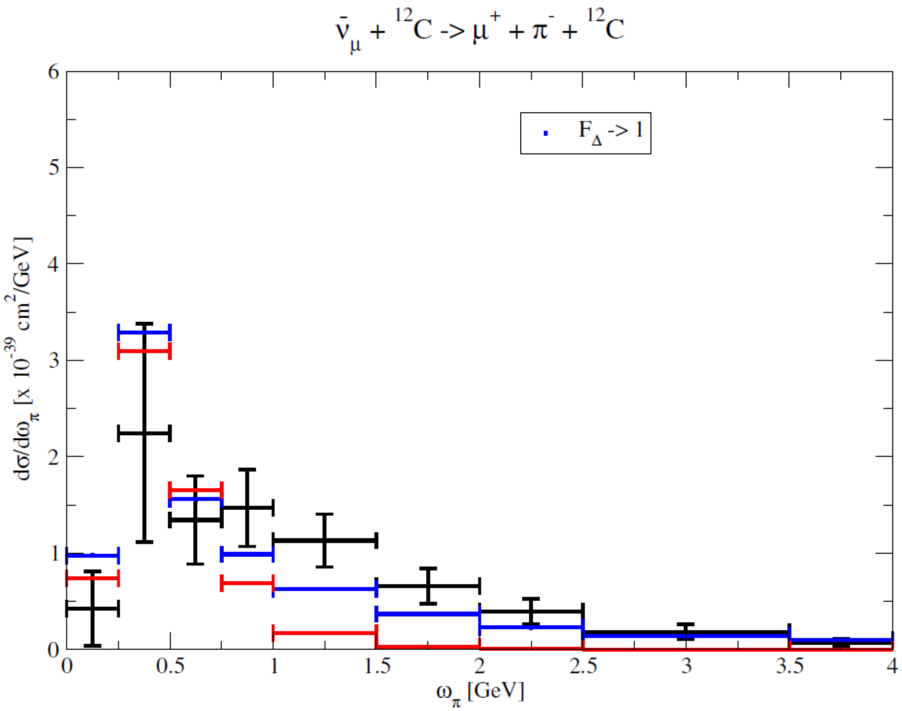
- PCAC models Rein & Sehgal, NPB 223 (1983), Kartavtsev et al., PRD 74 (2006), Berger & Sehgal, PRD 79 (2009), Paschos & Schalla, PRD 80 (2009)
  - In the $q^2=0$ limit, PCAC is used to relate ν induced coherent pion production to πA elastic scattering
  - $q^2=0$ approximation neglects important angular dependence at low energies and for light nuclei
  - πA elastic not realistic $\Rightarrow$ experimental πA cross section

- Microscopic models Kelkar et al., PRC55 (1997); Singh et al., PRL 96 (2006); LAR et al., PRC 75, 76 (2007); Amaro et al., PRD 79 (2009), Nakamura et al, PRC 81 (2010), Zhang et al. PRC 86 (2012)
  - Same hadronic/nuclear input as for the incoherent(resonant) channel
  - Can be applied/validated in other reactions (γ, e, π, ...)
  - Limited to the Δ region and below
  - Technically more complex and harder to implement than PCAC models

Coherent Pion Production

- Microscopic model: comparison to MINERvA data, LAR, preliminary

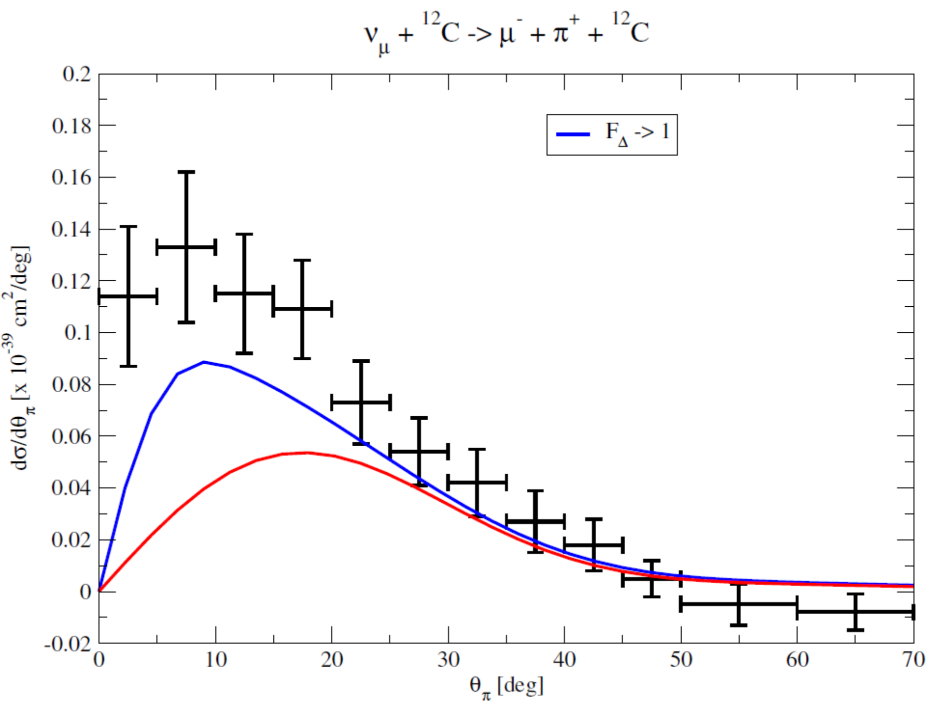


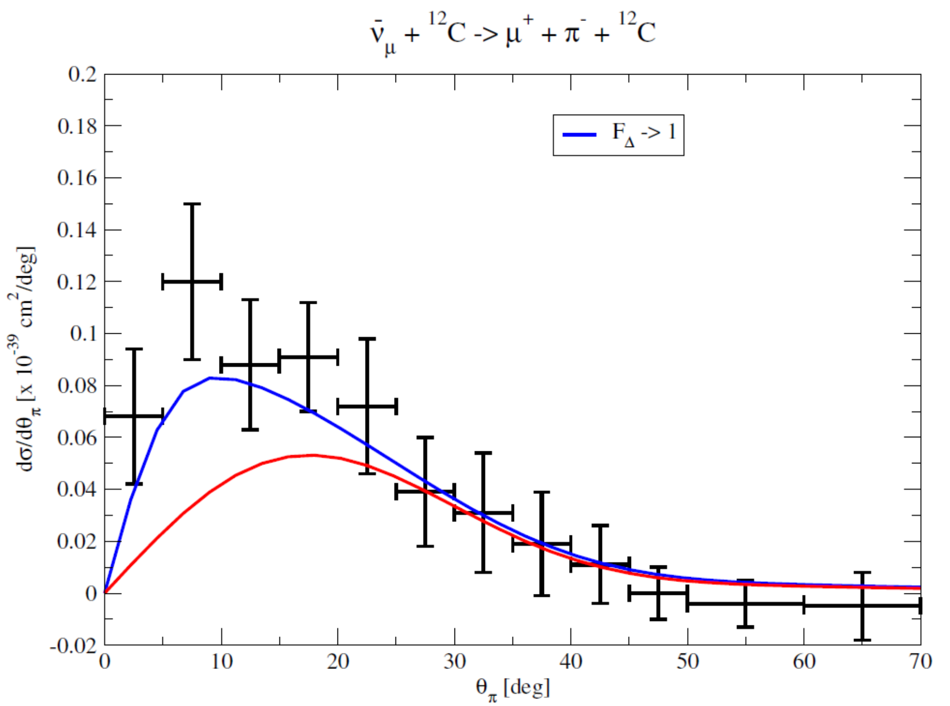


- Good agreement at the Delta(1232) peak

Coherent Pion Production

- Microscopic model: comparison to MINERvA data, LAR, preliminary

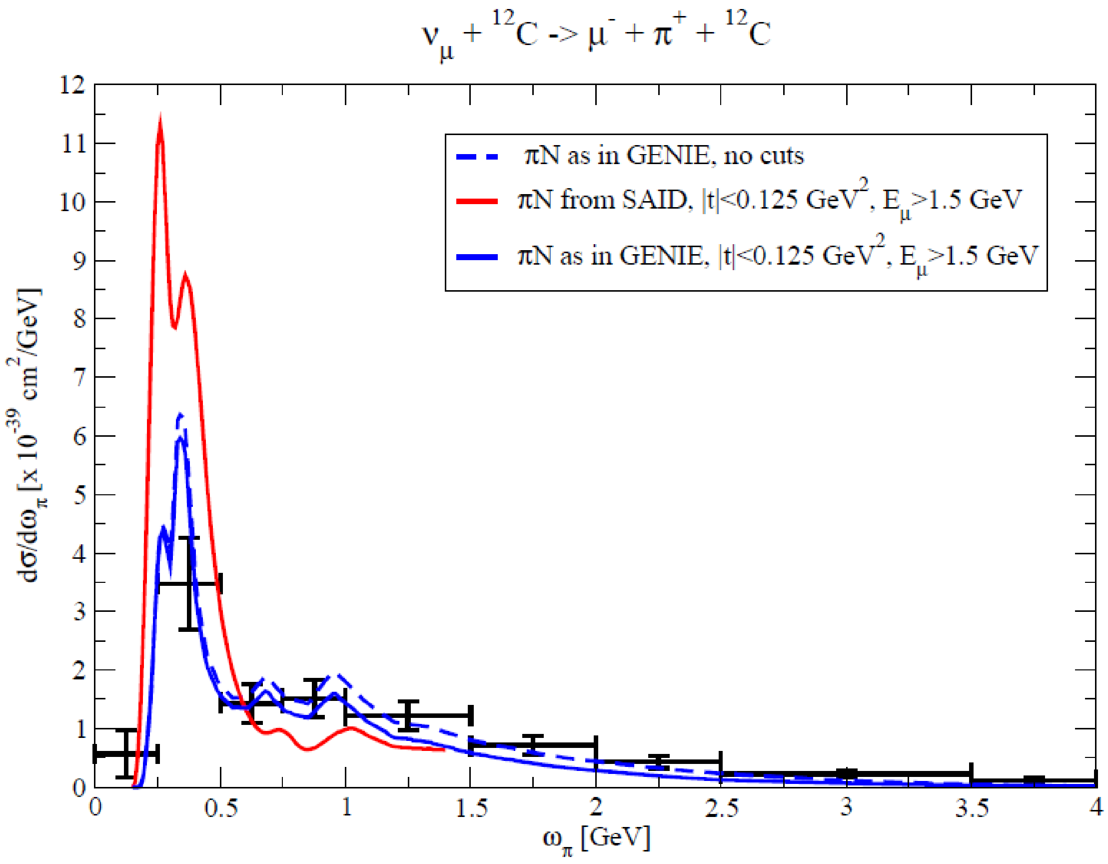




- Δ(1232) contribution is less forward peaked than data

Coherent Pion Production

- PCAC models: comparison to MINERvA data, LAR, preliminary



- Improvement in πN $\Rightarrow$ disagreement with data !?!

Conclusions

- ν-induced pion production on nucleons and nuclei is relevant for oscillation studies and interesting for hadron physics
- Consistency with the off-diagonal G-T relation for the N-Δ transition is restored by imposing the Watson's theorem
- Proper understanding of ν-induced pion production on nuclei still missing
- Coherent pion production
  - Microscopic description OK at the Delta(1232) peak
  - Are PCAC models realistic at MINERvA energies?