Uniwersytet Wrocławski

1π Production Induced by ν-nucleon Interactions

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NuWro

Wrocław Neutrino Event Generator

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- Motivation
- Short review of phenomenological models
- Problems and results
- Summary

* based on the works with: J. Sobczyk, J. Zmuda, C. Juszczak, B. Kowal

Physics of long- and short- baseline neutrino oscillation experiments

→ Neutrino oscillations, *CP* violation in lepton sector, mass hierarchy problem... (T2K, MINOS,...)

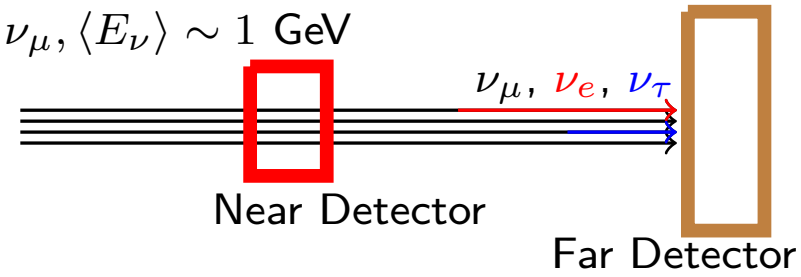
- Accelerator neutrinos:

→ interactions of 1 GeV neutrinos with light nuclei (Oxygen, Carbon,...)

- a progress requires precision knowledge of ν-nuclei, ν-nucleon scattering cross sections

→ experimental and theoretical effort: Minerνa Experiment,... progress in investigation of νN and νA scattering

- To have realistic model for 1π ν-Nucleus one needs to control 1π ν-Nucleon interactions



1π in NuWro

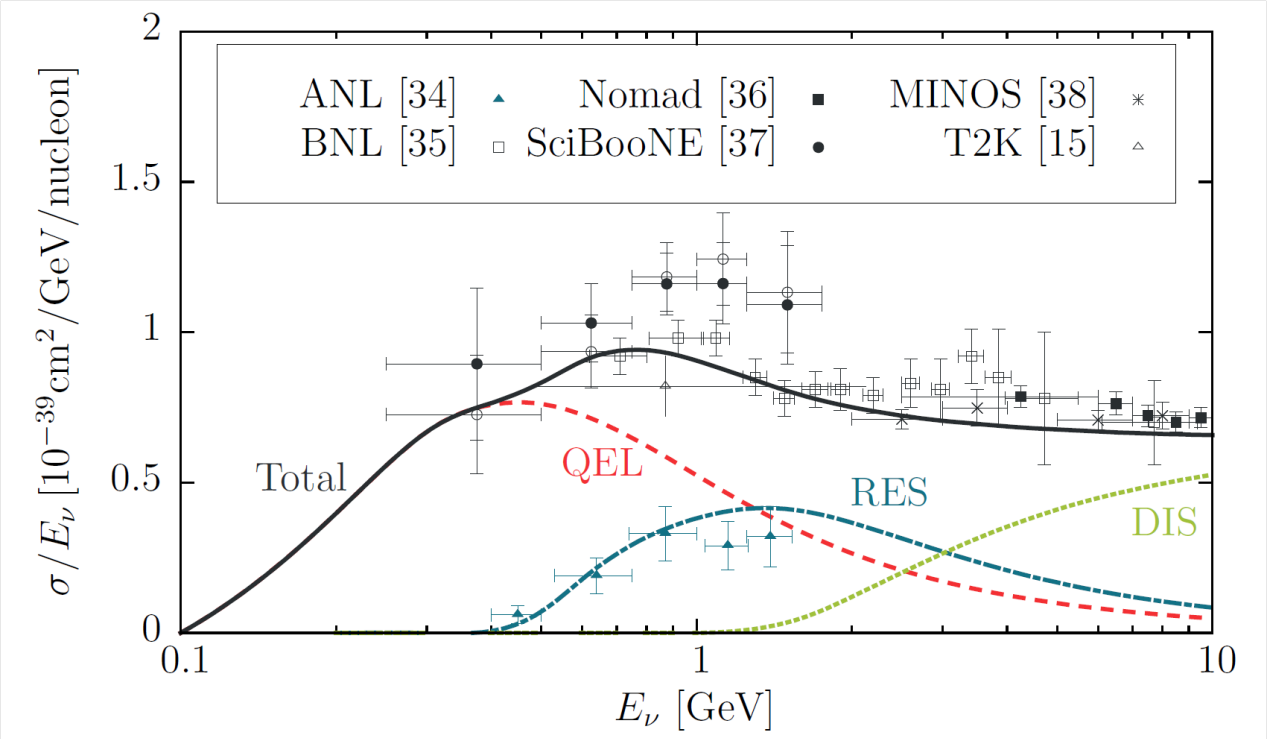
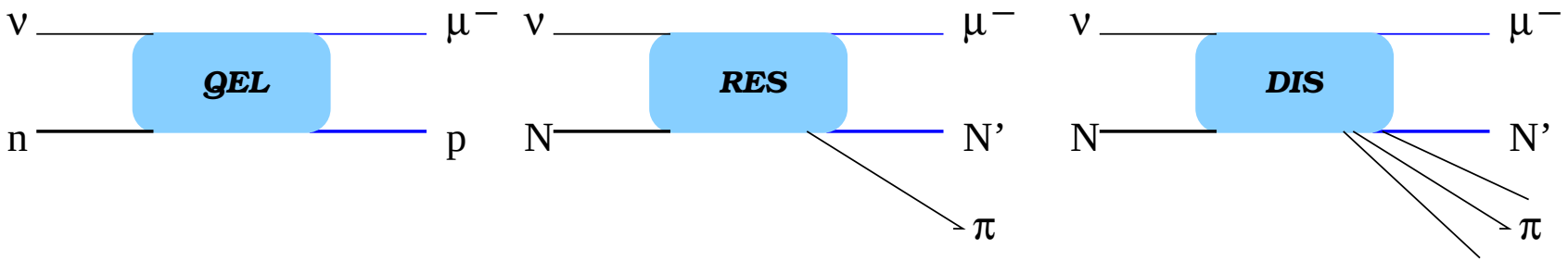


fig from T. Golan PhD thesis;

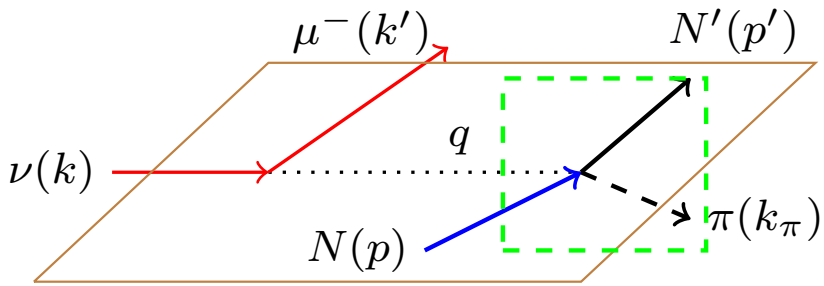
1π-like events:

- disappearance:
  $\nu_\mu \to \nu_\tau$
  – (from QE)
- appearance:
  $\nu_\mu \to \nu_e$
  – (ν_e detection)



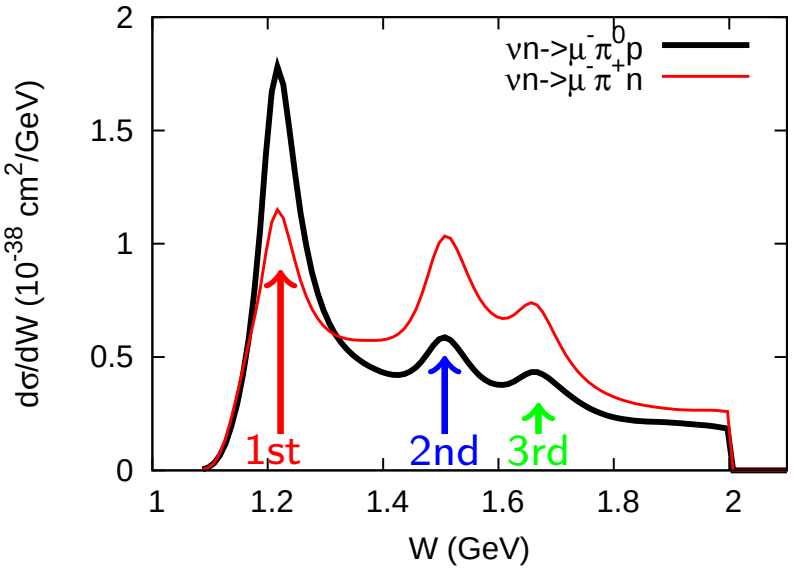
1π in charged current νN interactions

$$\begin{aligned} \nu + p &\rightarrow \mu^- + \pi^+ + p \\ \nu + n &\rightarrow \mu^- + \pi^0 + p \\ \nu + n &\rightarrow \mu^- + \pi^+ + n \end{aligned}$$

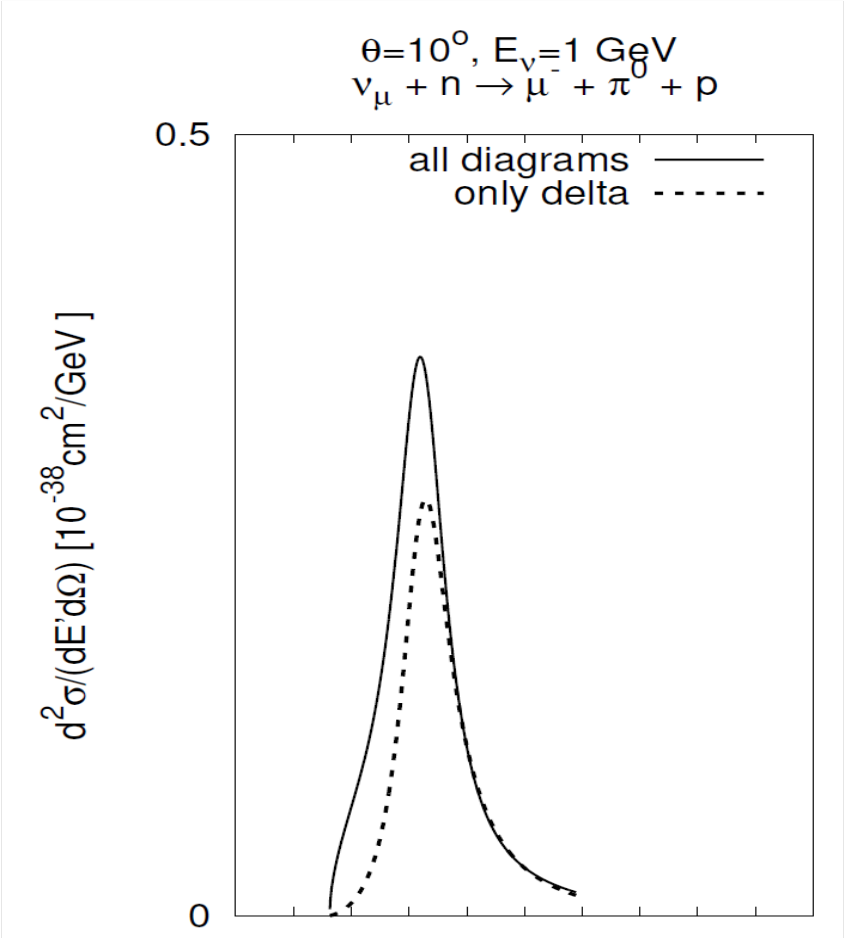


$$\begin{aligned} q^\mu &= k^\mu - k'^\mu = (\omega, \mathbf{q}) \\ Q^2 &= -q^2 = -(k-k')^2 \\ W^2 &= (p+q)^2 \end{aligned}$$

,



- studies of the weak $N \rightarrow N^*$ transition
- $\Delta(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$, $S_{31}(1620)$, $S_{11}(1650)$,...
- in νA resonance structure smeared out by Fermi motion



energy transfer

$$\nu + N \quad \rightarrow \quad \mu^- + N^*(\rightarrow N'\pi) : \text{resonant}$$
$$\rightarrow \quad \mu^- + \pi + N' : \text{nonresonant}$$

Experimental analyses:

- usually Rein-Seghal model (improved in K.M.G, Sobczyk PRD77, 053001)

$$d\sigma \sim d\sigma(N \rightarrow N^*) + d\sigma(background))$$

- very effective description of nonresonant background...

Phenomenological

- Adler model, Fogli-Narduli, Rein-Seghal model with Adler background terms (by Rein), Sato-Lee model, HNV model (Nieves, Hernandez), and many others....
- Hadron degrees of freedom: N, π, $\Delta(1232)$, ...

Constructing Nonresonant background: an example

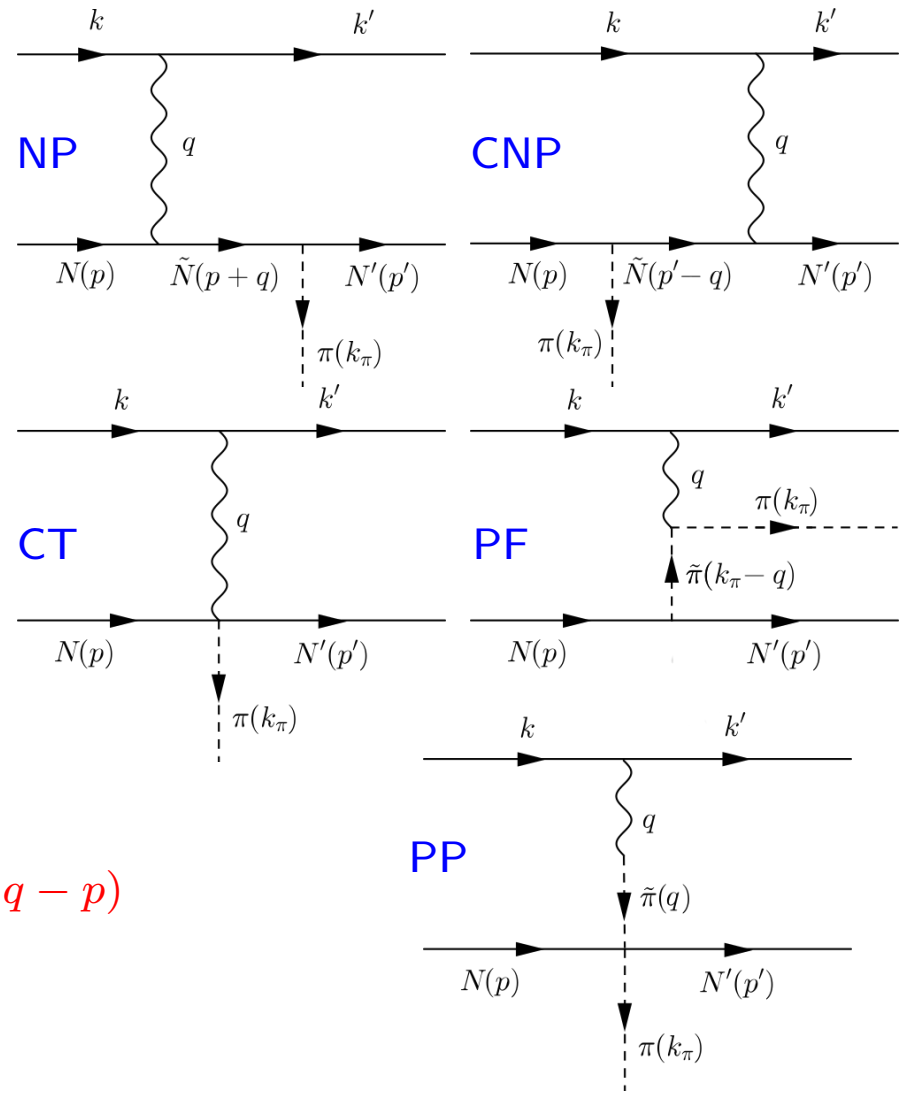
- nonlinear σ model πN (on the tree level)
- phenomenological vertices ($\rightarrow$ the form factors)

* HNV: Hernandez, Nieves, Valverde, PRD76 033005

$$\frac{d\sigma}{d^2 E_{k'} d\Omega} \sim L_{\mu\nu}(k', k') W_{\mu\nu}$$

Hadron tensor

$$W_{\mu\nu} \sim \overline{\sum_{spin}} \int \frac{d^3\mathbf{k}_\pi}{E_\pi} \frac{d^3\mathbf{p'}}{E_{p'}} J^\mu J^{\nu *} \delta^{(4)}(p' + k_\pi - q - p)$$



$$J^\mu = \langle \pi(\mathbf{k}_\pi), N'(\mathbf{p}') | \mathcal{J}^\mu | N(\mathbf{p}) \rangle, \quad J^\mu = \sum_{k \in \mathcal{D}} C^k J^\mu_k$$

C^k Clebsch-Gordan coefficient

$\Delta(1232)$ resonance

- $P_{33}(1232)$: spin $\frac{3}{2}^+$, isospin $3/2$
- Positive parity
- Rarita-Schwinger field Ψ_μ:

$$u_\mu(\mathbf{p},s) = \sum_{\lambda,r} \langle 1\lambda, \frac{1}{2}r | \frac{3}{2}s\rangle \underbrace{\epsilon_\mu(\mathbf{p},\lambda)}_{spin\,1} \underbrace{u(\mathbf{p},r)}_{spin\,1/2}$$

$$\begin{aligned} 0 &= (i\partial\!\!\!/ - M_\Delta)\Psi_\mu \\ 0 &= \partial^\mu \Psi_\mu = \gamma^\mu \Psi_\mu \end{aligned}$$

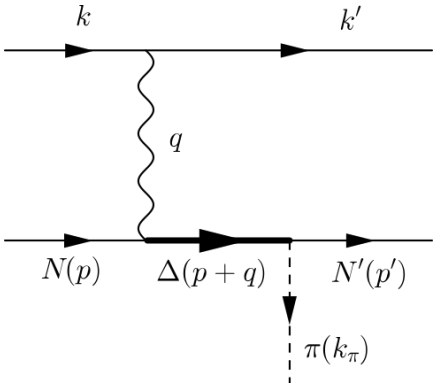
Propagator

$$\mathcal{P}_{\alpha\beta}(p) = -\frac{(p\!\!\!/ + M_\Delta)}{p^2 - M_\Delta^2 + iM_\Delta\Gamma_\Delta(p)} \left(g_{\alpha\beta} - \frac{1}{3}\gamma_\alpha\gamma_\beta - \frac{2}{3}\frac{p_\alpha p_\beta}{M_\Delta^2} + \frac{1}{3}\frac{p_\alpha\gamma_\beta - \gamma_\alpha p_\beta}{M_\Delta} \right)$$

$\Gamma_\Delta(p)$ calculated from

$$H_{\Delta N\pi} = \frac{f^*}{m_\pi}\overline{\Delta}_\mu \mathbf{T}^\dagger \partial^\mu \phi N + h.c.$$

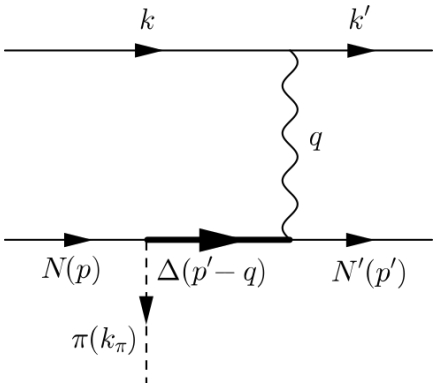
$\Delta(1232)$ resonance amplitudes



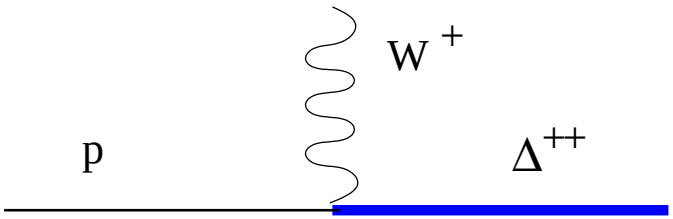
$$J^{\mu}_{\Delta P} = i\sqrt{3}\bar{u}(p')k^{\alpha}_{\pi}\mathcal{P}_{\alpha\beta}(p+q)\Gamma^{\beta\mu}(p,q)u(p)$$

$$J^{\mu}_{C\Delta P} = i\frac{1}{\sqrt{3}}\bar{u}(p')\widetilde{\Gamma}^{\mu\alpha}(p',q)k^{\beta}_{\pi}\mathcal{P}_{\alpha\beta}(p'-q)u(p)$$

$$\widetilde{\Gamma}^{\mu\alpha}(p',q) = \gamma^0[\Gamma^{\alpha\mu}(p',-q)]^{\dagger}\gamma^0$$



$N \to \Delta$ weak transition



$$\langle \Delta(p' = p + q) | \mathcal{J}_\mu | N(p) \rangle = \overline{\Psi}^\lambda(p') \Gamma_{\lambda\mu}(p,q) u(p)$$

$$\Gamma_{\lambda\mu} \equiv \Gamma^V_{\lambda\mu}\gamma_5 + \Gamma^A_{\lambda\mu}.$$

$$\Gamma^{V,\lambda}_\mu = g^\lambda_{\ \mu}\left(\frac{C_3^V}{M}\gamma_\nu + \frac{C_4^V}{M^2}p'_\nu + \frac{C_5^V}{M^2}p_\nu\right)q^\nu - q^\lambda\left(\frac{C_3^V}{M}\gamma_\mu + \frac{C_4^V}{M^2}p'_\mu + \frac{C_5^V}{M^2}p_\mu\right)$$

3 vector form factors: from electroproduction

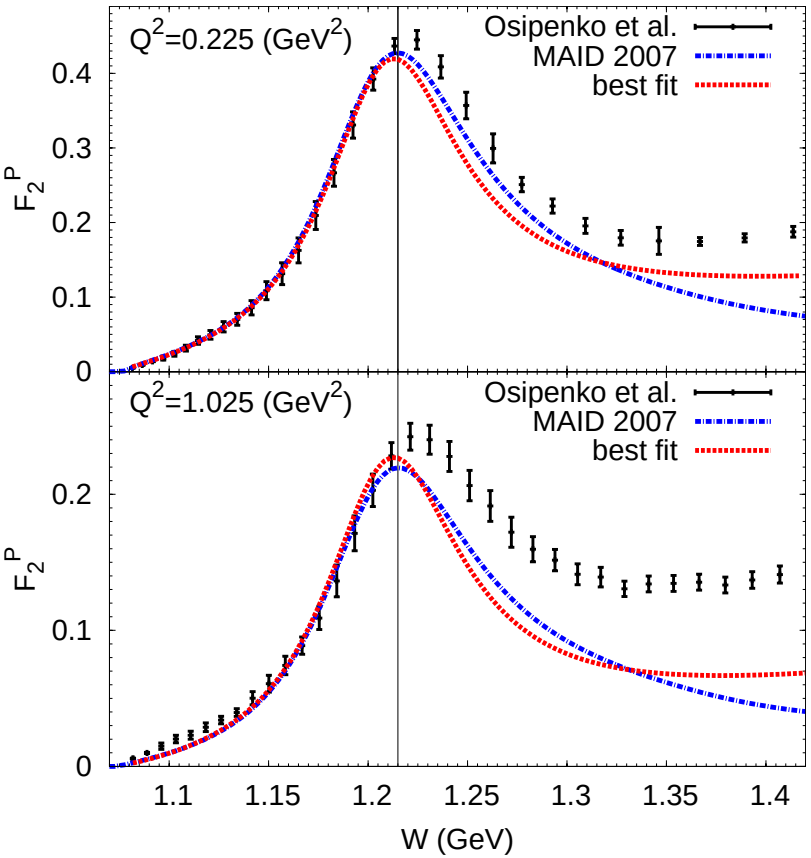
$$\Gamma^{A,\lambda}_\mu = g^\lambda_\mu\left(\gamma_\nu\frac{C_3^A}{M} + \frac{C_4^A}{M^2}p'_\nu\right)q^\nu - q^\lambda\left(\frac{C_3^A}{M}\gamma_\mu + \frac{C_4^A}{M^2}p'_\mu\right) + g^\lambda_{\ \mu}C_5^A + \frac{q^\lambda q_\mu}{M^2}C_6^A$$

4 axial form factors: from neutrinoproduction

Fixing Vector Contribution for $N \to \Delta(1232)$

- inclusive ep scattering CLAS data: arXiv:hep-ex/0309052:
- 32 series of measurements for $Q^2 \in (0.225, 2.025)$ GeV^2
- cuts: $W < M + 2\pi$
- data for $A_{1/2}$, $A_{3/2}$ and $S_{1/2}$ helicity amplitudes included
- **8 parameters fit:**

$$C_5^V(Q^2) = \frac{C_5^V(0)}{\left(1 + D\frac{Q^2}{M_V^2}\right)^2}$$

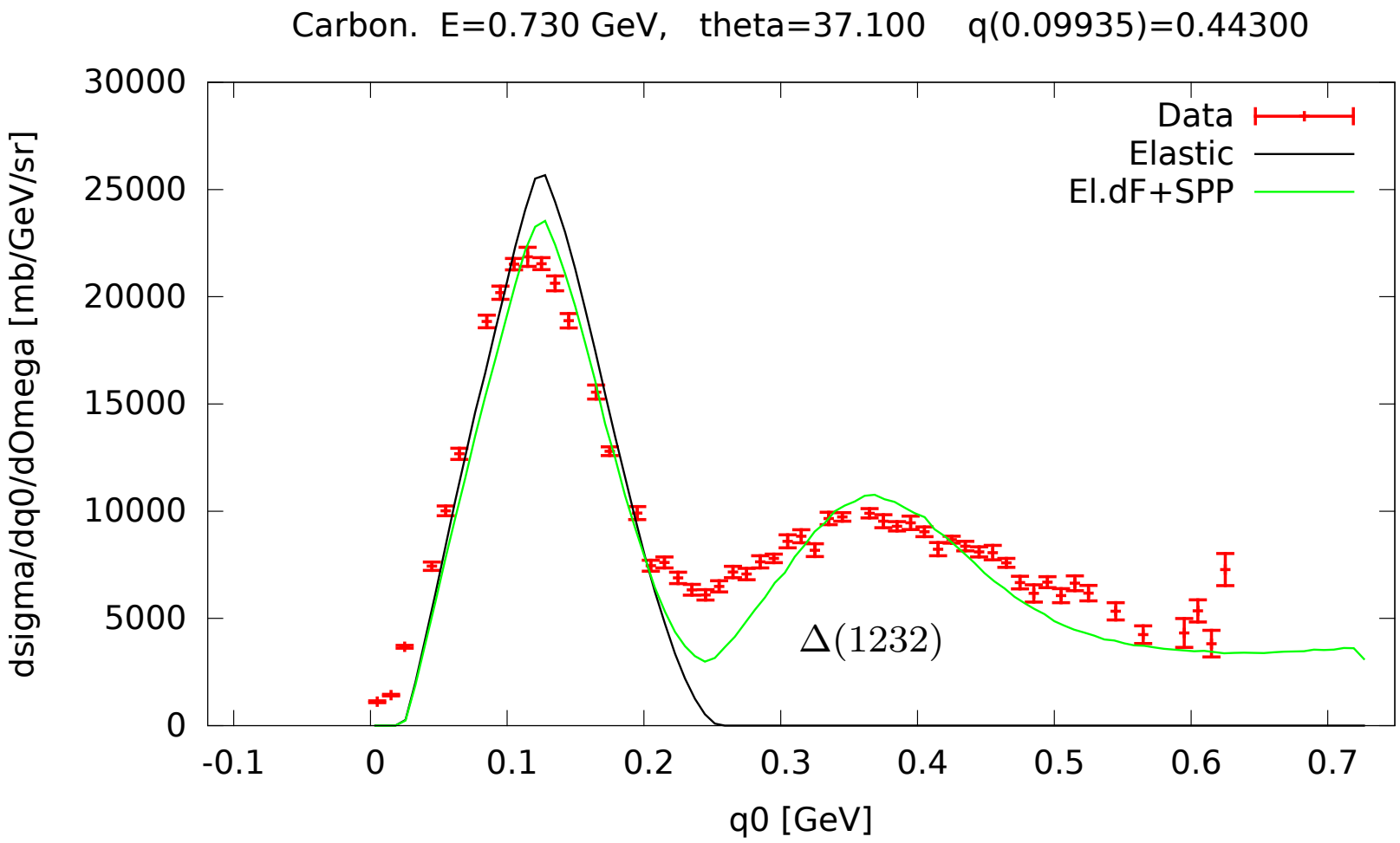


KMG, Żmuda, Sobczyk, PRD90, 093001

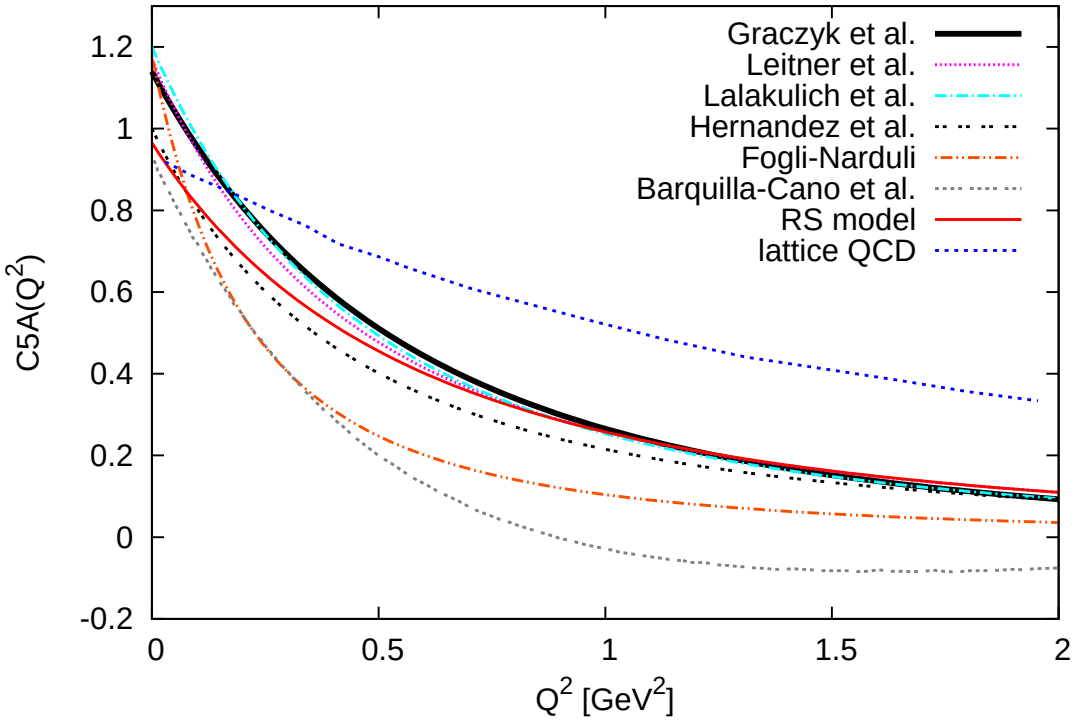
$$C_3^V(Q^2) = \frac{C_3^V(0)}{1 + AQ^2 + BQ^4 + CQ^6} \cdot (1 + K_1 Q^2)$$

$$C_4^V(Q^2) = -\frac{M}{W} C_3^V(Q^2) \frac{1 + K_2 Q^2}{1 + K_1 Q^2},$$

eWro: elctron-nucleus Monte Carlo generator



data not included in the fit



Axial transition form factors

- **Lack of informative data**
- in $SU(6)$ symmetry limit $C_3^A(Q^2) = 0$
- Adler relation (dispersion analysis) $C_4^A(Q^2) = -C_5^A(Q^2)/4$
- from PCAC

$$C_6^A(Q^2) = \frac{M^2}{m_\pi^2 + Q^2} C_5^A(Q^2)$$

- $C_5^A(0)$ from the off-diagonal Goldberger-Treiman relation

$$C_5^A(0) = \frac{g_{\pi N \Delta} f_\pi}{\sqrt{6} M} = 1.15 \pm 0.01,$$

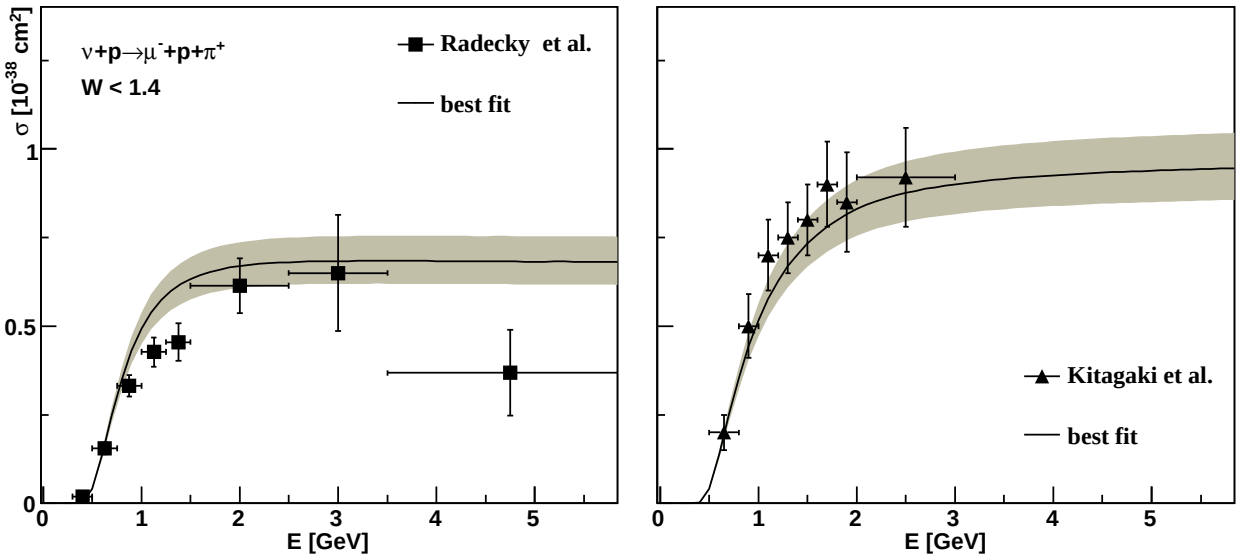
$\rightarrow$ **only**

$$C_5^A(Q^2) = \frac{C_5^A(0)}{(1 + Q^2/{M_A}^2)^2}$$

- at low-Q^2: $d\sigma \sim [C_5^A(Q^2)]^2$

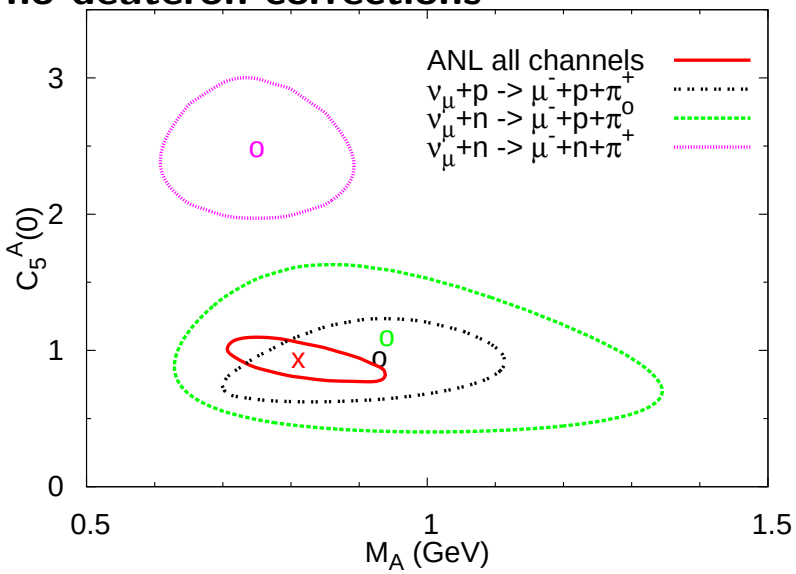
Fixing C_5^A Axial Form Factors

- Data ν-nucleon from bubble chamber νD scattering data
- ANL: Radecky et al., PRD 25 (1982) 1161
- BNL: Kitagaki et al., PRD 42 (1990) 1331
- **ANL and BNL puzzle**
- Statistical agreement between data for $\nu + p \to \mu^- + \pi^+ + p$: shown in K.M.G. D. Kiełczewska, P. Przewłocki, J. T. Sobczyk, PRD80 093001

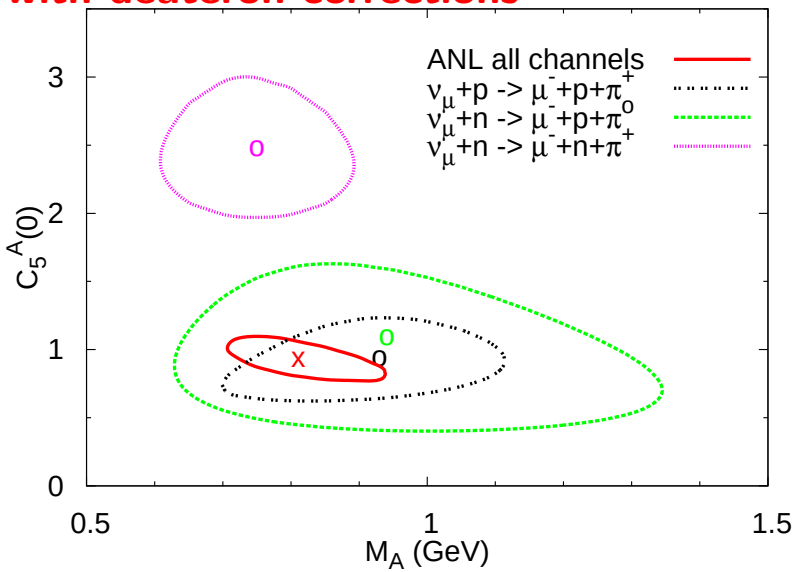


to constrain nonresonant background information from other channels necessary!

no deuteron corrections



with deuteron corrections



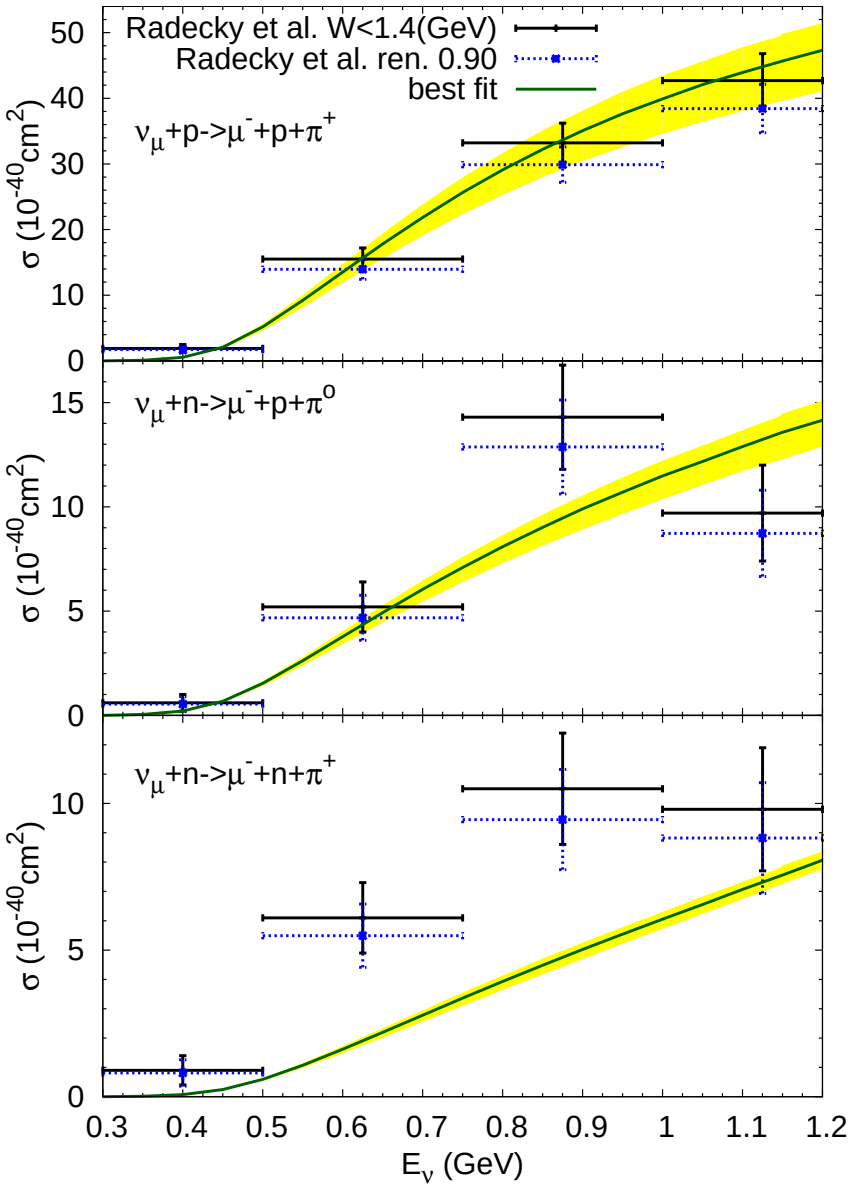
K.M.G. J.T. Sobczyk, J. Zmuda, PRD90, 093001

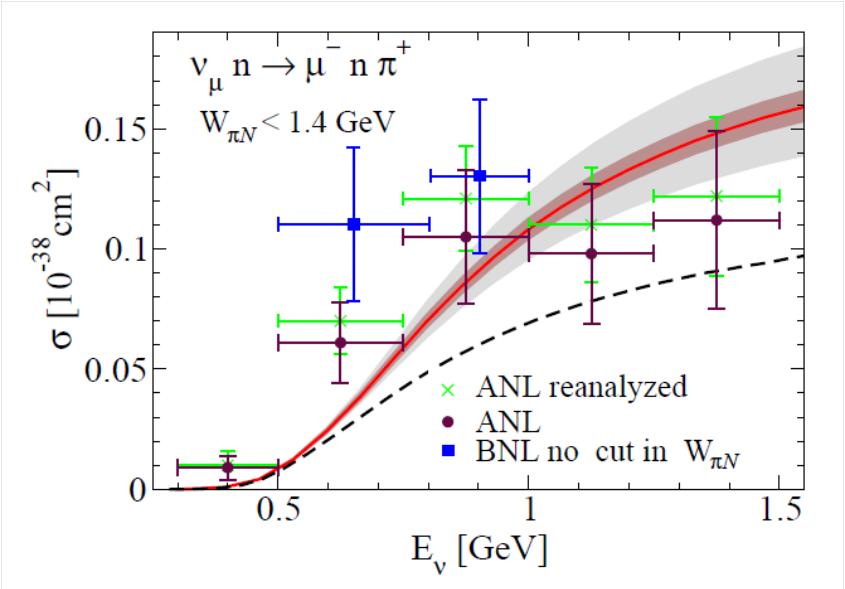
$\nu n \to \mu^- n \pi^+$ puzzle

- ANL $\nu D \to \mu^- N N' \pi$ scattering data for 3 channels
- two-parameter-fit

$$C_5^A(Q^2) = \frac{C_5^A(0)}{(1 + Q^2/{M_A}^2)^2}$$

- simple model of deuteron (De Forest like): binding energy, momentum distribution
- disagreement: between data from different channels
- Final State Interaction corrections (J-J Wu, Sato, Lee, PRC91 (2015) 035203) – still channel $n\pi^+$ out of others





- Heranandez and Nieves, PRD95, 053007

→ spin $1/2$ allowed by gauge invariance terms?

- Need of new data for $\nu - H$ and $\nu - D$...
- New observables containing signal from non-resonant background

Final Lepton Polarization

$\nu_l(k)+N(p) \to \vec{l}^-(k',\xi)+N'(p')+\pi(k_\pi$

where

$$\xi^\mu = \xi^\mu_L + \xi^\mu_N + \xi^\mu_T$$

$\boldsymbol{\xi}_L \sim \mathbf{k}', \;\; \boldsymbol{\xi}_N = \mathbf{k}\times\mathbf{q}, \;\; \boldsymbol{\xi}_T \sim \mathbf{k}'\times(\mathbf{k}\times\mathbf{q}$

Polarization four-vector

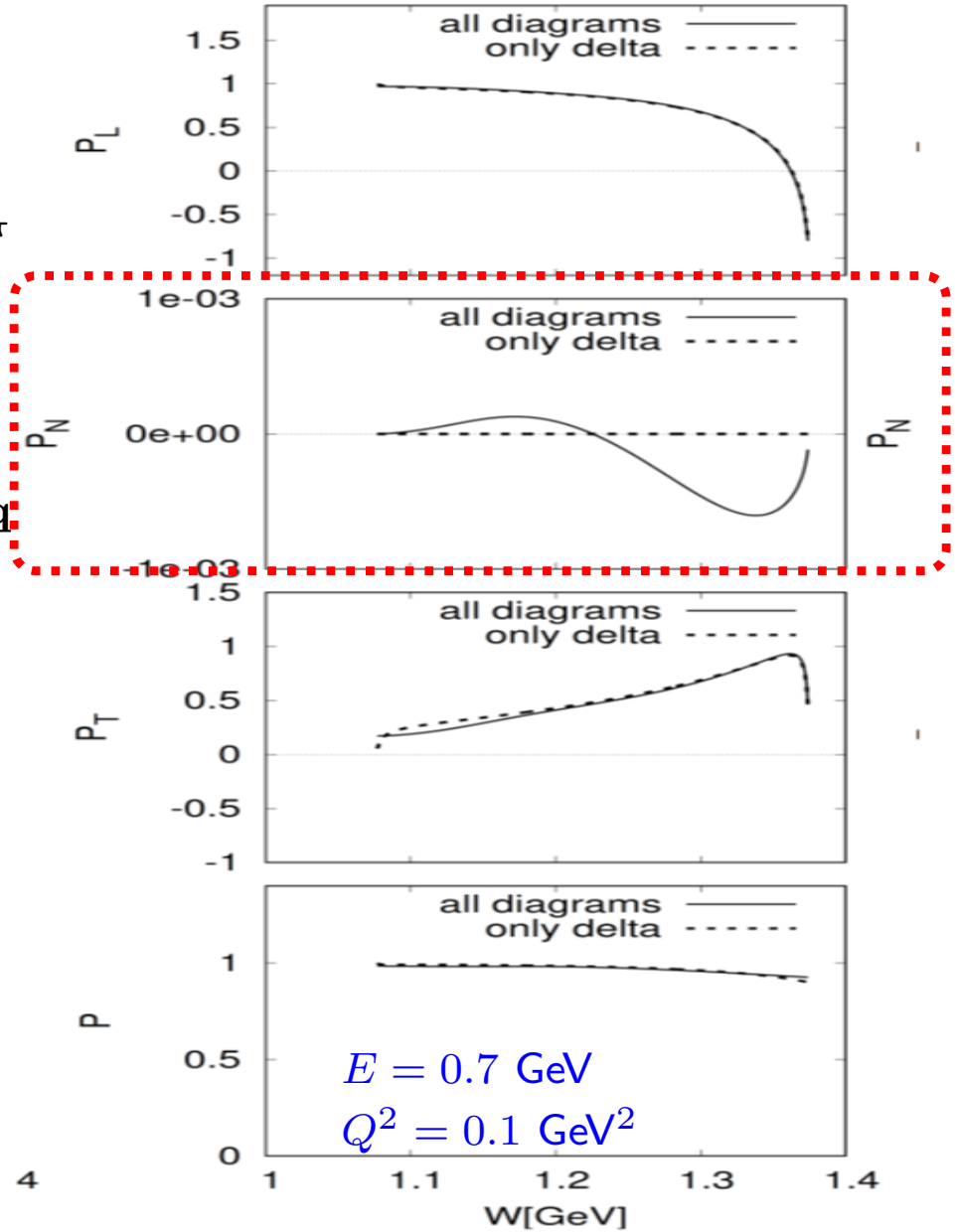
$$\mathcal{P}^\mu_\xi = \mathcal{P}^L_\xi \xi^\mu_L + \mathcal{P}^N_\xi \xi^\mu_N + \mathcal{P}^T_\xi \xi^\mu_T$$

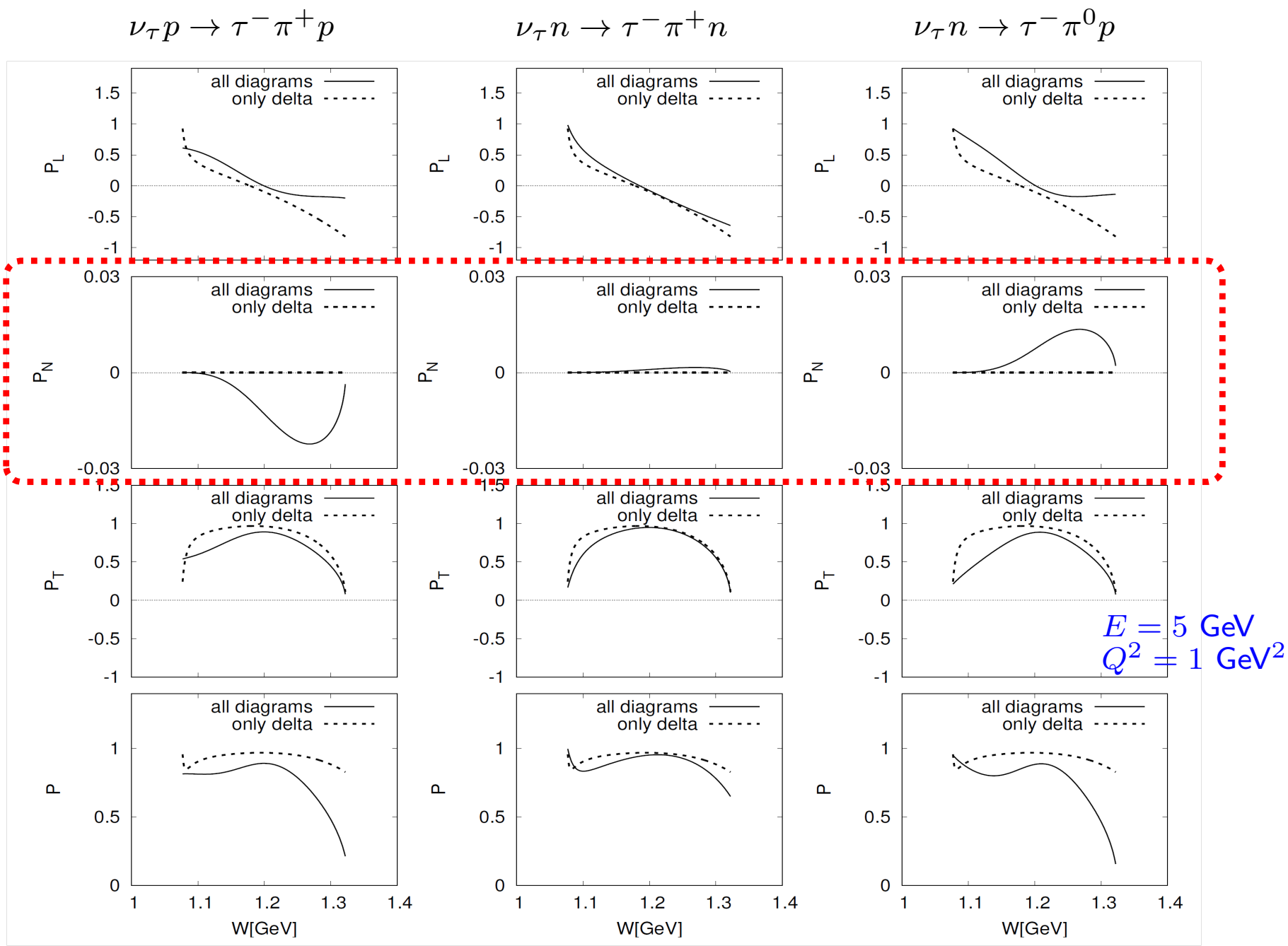
The degree of polarization:

$$\mathcal{P}_\xi = \sqrt{-\mathcal{P}^\mu_\xi \mathcal{P}_{\xi\mu}}$$

$\mathcal{P}_N \sim \Re(J_\Delta J^*(background))!$

$\nu_\mu n \to \mu^- \pi^+ n$




$\nu_\tau p \to \tau^- \pi^+ p$
$\nu_\tau n \to \tau^- \pi^+ n$
$\nu_\tau n \to \tau^- \pi^0 p$
all diagrams
only delta
P_L
P_N
P_T
P
W[GeV]
$E = 5$ GeV
$Q^2 = 1$ GeV^2

Final Nucleon Polarization

$$\nu_l(k)+N(p) \to l^-(k')+\vec{N}'(p',\zeta)+\pi(k_\pi),$$

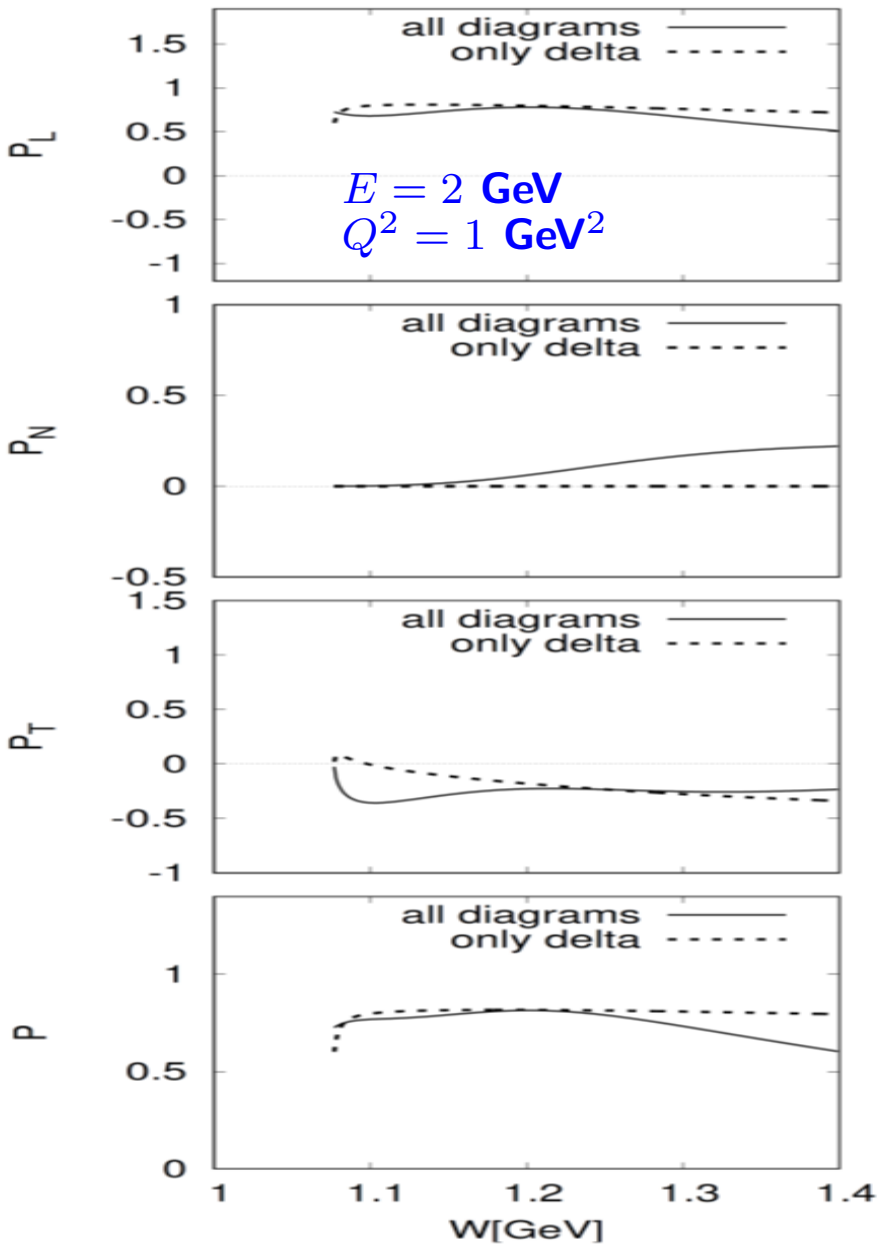
$$\begin{aligned} \zeta_L \quad &\sim \quad \mathbf{p}', \quad \zeta_N \sim \mathbf{p}' \times \mathbf{k}_\pi, \\ \zeta_T, \quad &\sim \quad \mathbf{p}' \times (\mathbf{p}' \times \mathbf{k}_\pi) \end{aligned}$$

Polarization

$$\mathcal{P}^\mu_\zeta = \mathcal{P}^L_\zeta \zeta^\mu_L + \mathcal{P}^N_\zeta \zeta^\mu_N + \mathcal{P}^T_\zeta \zeta^\mu_T$$

$$\mathcal{P}_\zeta = \sqrt{-\mathcal{P}^\mu_\zeta \mathcal{P}_{\zeta\mu}}$$

$\nu_\mu n \to \mu^- \pi^0 p$



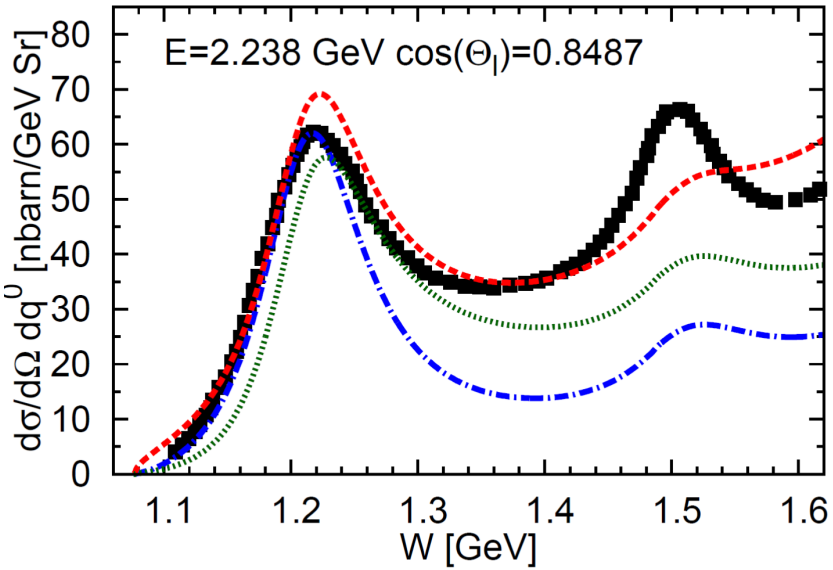
Remarks on second resonance region

- Positive parity spin-$1/2$, isospin-$1/2$: $P_{11}(1440)$
- Negative parity spin-$1/2$, isospin-$1/2$: $S_{11}(1535)$

$$J^\mu = e^{i\phi_{N^*}} \left\{ \left(F^V_{1N^*}(q^\mu \not{q} - q^2\gamma^\mu) + iF^V_{2N^*}\sigma^{\mu\nu}q_\nu \right) \begin{pmatrix} 1 \\ \gamma_5 \end{pmatrix} - (G^{N^*}_A \gamma^\mu + G^{N^*}_P q^\mu \not{q}) \begin{pmatrix} \gamma_5 \\ 1 \end{pmatrix} \right\}$$

at least 3 form factors for each resonance...and one phase factor

- Negative parity spin-$3/2$, isospin-$1/2$: $D_{13}(1520)$
  $\rightarrow$ analogical transition current structure as $\Delta(1232)$: 7 additional form factors and phase factor: C^V_{3R}, C^V_{4R}, C^V_{5R}, C^A_{3R}, C^A_{4R}, C^A_{5R}, C^A_{6R}



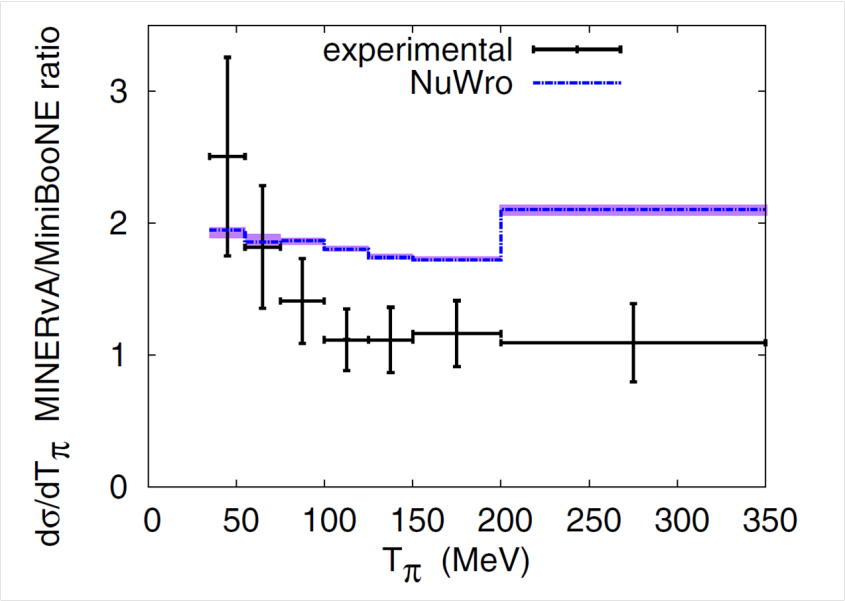
- HNV
- HNV: flipped sign between Δ - background
- Fogli-Narduli

Fig. from Jakub Żmuda PhD thesis (2014)

Final Remarks

- MiniBoooNE vs. Minerva
- Final State Interactions ?
- Resonance propagation in nuclear matter...
- $1\pi^0$ distribution in Minerva – reduction of the non-resonant background: arXiv:1708.03723 ?
- New measurements of νH and νD necessary
- Measurement of new observables to constrain models

Tension between Minerνa and MiniBooNE measurements (ν-Carbon interaction)



Sobczyk, Żmuda, PRC91 (2015), 045501