Neutrino-nucleon/nucleus interactions

in 1 GeV energy range

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Why we study neutrino interactions with nucleons and nuclei?

Study fundamental neutrino properties

- oscillation parameters, $\mathcal{CP}$ violation phase, mass hierarchy problem etc.

→ Goal: neutrino physics "a precision science"

→→ P5 report*: 3σ sensitivity for measuring CP violation effect requires a reduction of the systemic cross section for signal and background on the level 1% and 5% respectively.

* S. Ritz, et al *Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context*, HEPAP Subcommittee (2014).

- A need for precise theoretical predictions of neutrino-nucleon/nuclei scattering cross sections
- Experiment Minerνa, project NuStorm dedicated to measure ν cross sections

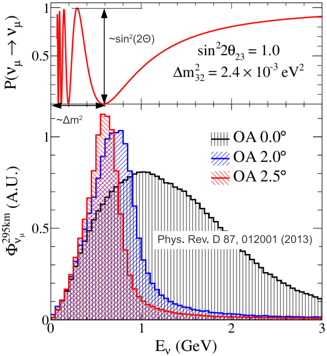
Investigation of hadronic and nuclear structure within neutrino-nucleon/nuclei interactions

- axial hadronic structure, transition form factors, electroweak nucleon-resonance excitation
- structure of the nucleus, **correlations**

Neutrino interactions in Wrocław (group of J. Sobczyk)

- investigation of interactions of 1 GeV neutrinos with nucleons and nuclei

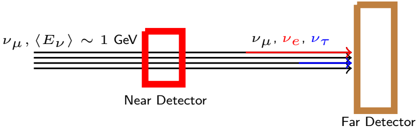
* close collaboration with polish experimental neutrino groups and T2K and Minerνa experiment `http://wng.ift.uni.wroc.pl`

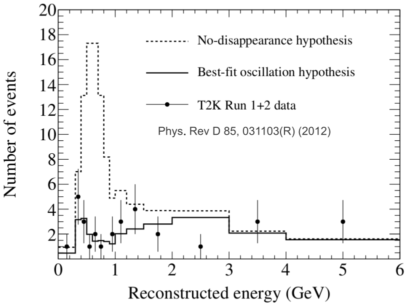


- accelerator source of neutrinos $\to E_\nu \sim 1$ GeV but neutrino energy not monochromatic: only energy spectrum known with some precision
- neutrinos weakly interact $\to$ heavy targets like water (oxygen), liquid argon etc...

ν-A Interactions

T2K experiment, but also MINOS and others





energy spectrum reconstructed from QE events

- QuasiElastic (QE) scattering: only final charged lepton is visible
- but primary interaction would be inelastic $\rightarrow$ important role of FSI (final state interaction)
- energy reconstruction based on Monte Carlo. What you put is what you get $\rightarrow$ **dependency on theoretical lepton-nucleus interaction models**.
- imprecise knowledge of nuclear effects results in large systematic uncertainty for CP violation phase and mixing parameters Coloma and Huber, PRL 111, 221802 (2013)

Monte Carlo Generator

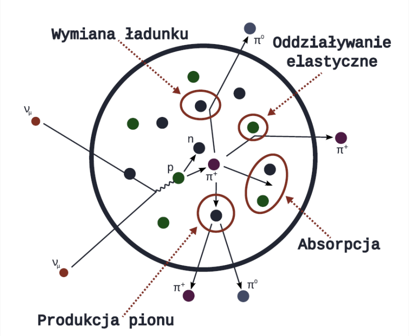
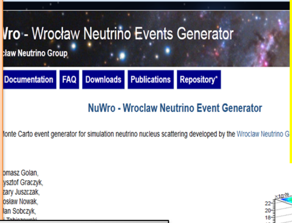


Fig. from Golan

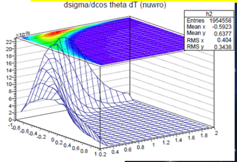
- Monte Carlo event generator: a bridge which connects experiment with theory

NuWro (Neutrino-Wrocław) Monte Carlo Generator

- **Authors:**
- **J.Sobczyk**
- C. Juszczak
- J. Nowak
- T. Golan
- K. Graczyk
- J. Żmuda
- M. Tabiszewski
- **Autor Honoris Causa D. Kiełczewska**



Selected papers:
- Żmuda, Sobczyk Phys.Rev. C91 (2015) 4, 045501
- Golan, Graczyk, Juszczak, Sobczyk, Phys.Rev. C88 (2013) 024612
- Golan, Juszczak, Sobczyk, Phys. Rev. C86 (2012) 015505
- Juszczak , Sobczyk, Żmuda, Phys. Rev. C82 (2010) 045502
- Juszczak, Acta Phys.Polon. B40 (2009) 2507
- Juszczak, Nowak, Nucl. Phys. Proc. Suppl. 159 (2006) 211

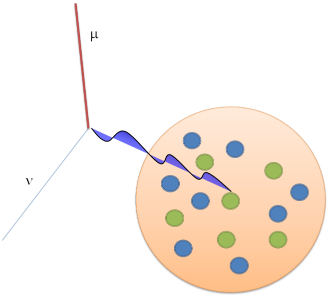


- ❑All major neutrino-nucleus interaction channels (QEL, DIS, RES and COH)
- ❑Covers ν energies from MeV to TeV
- ❑density profiles and binding energies for most of nuclei
- ❑Local Fermi Gas and Spectral Function models of nucleus.
- ❑Intra-Nuclear cascade with pion-nucleon and nucleon-nucleon scattering.
- ❑scattering of **complex neutrino beams** on real **detector** geometries
- ❑the detector geometry is read from a data file (NuWro can be used by many different experiments)
- ❑The object oriented data analysis –compatible with root CERN frametool.

- NuWro is the firts MC generator to
  - include such dynamical effects like spectral function and Meson Exchange Current.
  - has an online interface http:/nuwro.ift.uni.wroc.pl
  - It is a probably the fastest event generation, compared to other codes.

ν @ IFT @

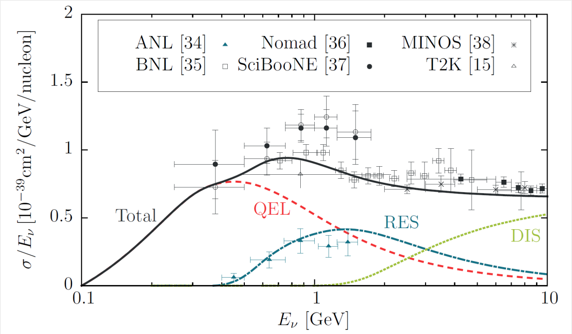
Modelling interactions of "1 GeV" neutrinos with nucleons and nuclei



- Q^2 the relevant four-momentum transfer below 1 GeV^2
- mesons (πs, ...) and hadrons (n, p, $\Delta(1232)$,...) , but also nuclei (coherent π production) as effective degrees of freedom

Impuls Approximation (IA):

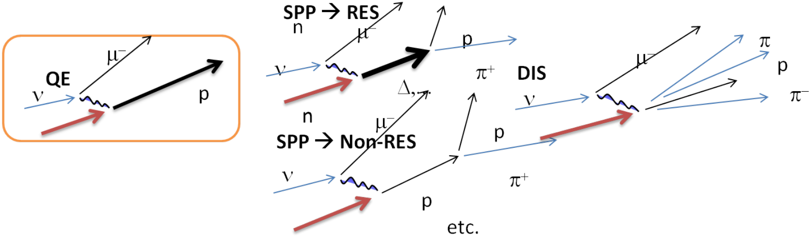
- it is assumed that the primary vertex of interaction is given by ν-free nucleon vertex (with nucleon transition form factors)
- effectively neutrino interacts only with one single nucleon inside nucleus
- many body current (describing the interaction) is replaced by sum of one body currents
- the nucleus is treated as set of non-interacting nucleons
- works well for momentum transfer $|\mathbf{q}| > 400$ MeV



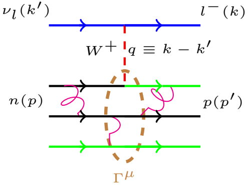
Charged Current (**CC**) processes:

- CCQE: $\nu_l + n \to l^- + p$
- RES (SPP): $\nu_l + N \to l^- + N' + \pi$
- DIS: $\nu_l + N \to l^- + N' + \pi + \ldots$

Data vs. NuWro simulations: Fig. from Golan, PhD thesis (2014)



- **C**harged **C**urrent **Q**uasi **E**lastic
  ν-Nucleon interaction



$$\approx \frac{G_F}{\sqrt{2}} \overline{u}(k')\gamma_\mu(1-\gamma_5)u(k) \underbrace{\overline{u}(p')\boldsymbol{\Gamma}^{\boldsymbol{\mu}}(\mathbf{q})u(p)}_{Hadronic}$$

$$\nu_l + N \to \nu_l + N$$

$$\boldsymbol{\Gamma}_{\boldsymbol{N}}^{\boldsymbol{\mu}} \quad = \quad \gamma^\mu \underbrace{F_1^V(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M}F_2^V(q^2)}_{Vector} - \underbrace{\gamma_\mu\gamma_5 F_A(q^2) - \frac{q^\mu\gamma_5}{2M}F_P(q^2)}_{Axial},$$

- Vector form factors taken from elastic ep scattering (from Conserved Vector Current CVC)
- Partially Conserved Axial Current (PCAC) $\rightarrow$

$$F_P = \frac{4M^2 F_A}{m_\pi^2 - q^2}$$

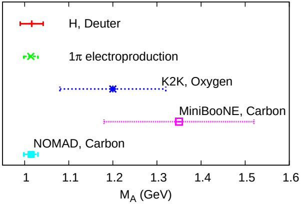
- dipole parametrization

$$F_A = \frac{g_A}{(1 - q^2/M_A^2)^2}$$

$g_A = 1.267$ from β-decay

- M_A obtained from analysis of νN scattering data
- $\langle r_A^2 \rangle$ can be extracted from single pion electro-production data

$$\langle r_A^2 \rangle = \frac{6}{F_A(0)} \left. \frac{dF_A}{dq^2} \right|_{q^2=0} = \frac{12}{M_A^2}$$



large M_A mass puzzle

- Inconsistency between M_A from $\nu - H$, $-D$ and $\nu - C$ scattering data (2007)?

→ Break down of impulse approximation? Let's go beyond the Fermi gas model

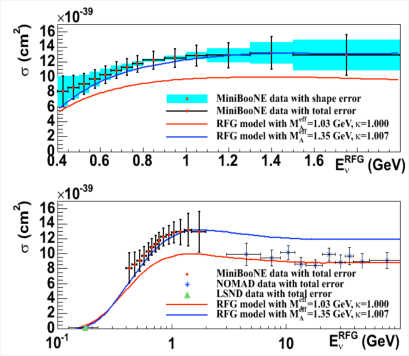


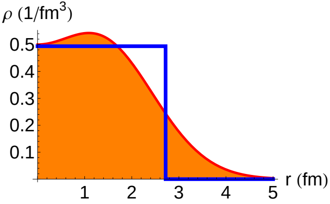
Fig. from Katori, Neutrino Division Seminar, Wrocław 11/30/2009

Relativistic Fermi Gas (RFG) model

- system of non-interacting nucleons;
- the ground state $\mid \Psi_0 \rangle$ contains positive-energy baryon levels filled to some wave number k_F and no antiparticles i.e.

$$
\begin{aligned}
a_{\mathbf{p},s} \mid \Psi_0 \rangle &= 0, \quad |\mathbf{p}| > k_F, \\
a^{\dagger}_{\mathbf{p},s} \mid \Psi_0 \rangle &= 0, \quad |\mathbf{p}| < k_F, \\
b_{\mathbf{p},s} |\Psi_0 \rangle &= 0, \quad \text{dla } \forall\ \mathbf{p},
\end{aligned}
$$

baryon density $\rho_B = 2k_F^3/3\pi^2$.



charge (proton) distribution insiede Oxygen, $\langle k_F \rangle = 199$ MeV

Quantum Hadrodynamics, Walecka, Serot

- Relativistic many body theory
- Nucleons, σ, ω, ρ and π mesons, $\Delta(1232)$
- Mean Field approximation,
- Hartree and Hartree-Fock approximmations

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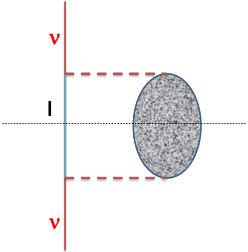

QE scattering

- $\nu_l + A[N,Z] \rightarrow$
  $l^- + (A-1)[N-1,Z] + p$
- ν-RFG scattering , 1p-1h excitation

$$\frac{d^2\sigma}{d\Omega_{k'}dE_l} = -\frac{G^2\cos^2\theta_c|\mathbf{q}|}{64\rho_B\pi^3E}\mathrm{Im}\left(L_{\mu\nu}\Pi^{\mu\nu}\right).$$

$\rho_B = k_F^3/3\pi^2$ – Baryon density

$$\mathrm{i}\Pi^{\mu\nu}_{RFG}(q) = \int d^4x e^{\mathrm{i}q\cdot x}\langle\Psi_0 \mid \mathrm{T}\left(\mathcal{J}^{\mu\dagger}(x)\mathcal{J}^{\nu}(0)\right) \mid \Psi_0\rangle$$

$$= \int \frac{d^4p}{(2\pi)^4}\mathrm{Tr}\left(G(p+q)\Gamma^{\mu}(q)G(p)\Gamma^{\nu}(-q)\right)$$

$$G(p) = (\gamma^{\mu}p_{\mu}+M)\left(\frac{1}{p^2-M^2+\mathrm{i}\epsilon}+\frac{\mathrm{i}\pi}{E_p}\delta(p_0-E_p)\theta(k_F-|\mathbf{p}|)\right)$$

Notice that $J_\mu \sim a^\dagger(p)a(p)$.

Long range correlations

IA breaks down below $|\mathbf{q}| < 400$ MeV. We need to enrich description by correlations e.g. collective excitations $\rightarrow$ RPA.

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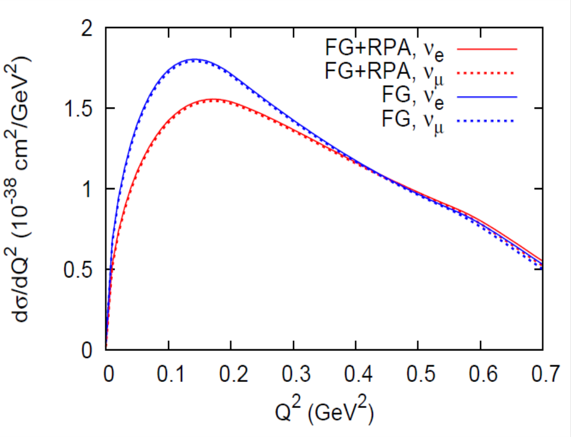
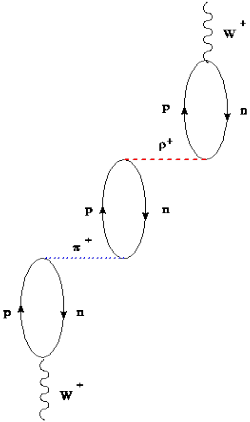
$$\Pi^{\mu\nu} = \Pi^{\mu\nu}_{FG} + \Delta\Pi^{\mu\nu}_{RPA},$$

- Ring Random Phase approximation: collective excitations $\to$ renormalization of different components of hadronic tensor, see e.g. Graczyk, Sobczyk, EPJ C31, 177 (2003); Graczyk, NPA748, 313 (2005).

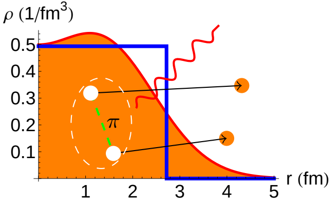


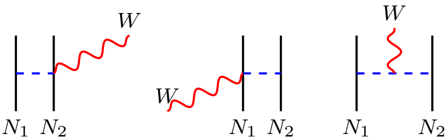


But inclusion RPA do not allow to resolve axial mass problem!Let's go beyond one body current approximation

Meson Exchange Currents: Two-body current contribution:

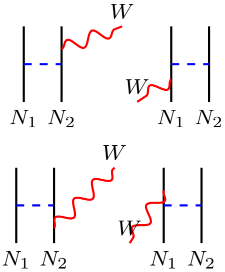
- Neutrino interacts at once with two correlated nucleons





Two body current:

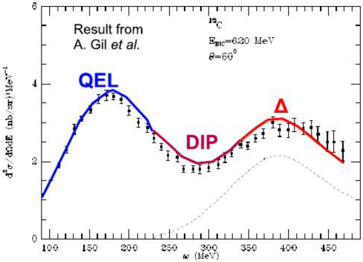
- $$J_\alpha^{2p2h} \sim a^\dagger(p'_1)a^\dagger(p'_1)a(p_1)a(p_1)$$
- annihilates (removes from the Fermi sea, producing a hole) two nucleons with momentum p_1 and p_2
- creates (above the Fermi level) two nucleons with momentum p'_1 and p'_2
- transferred energy and momentum are shared between two nucleons



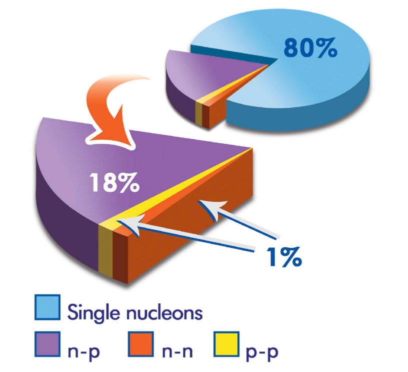
etc.

Correlations in electron scattering

- the problem studied over 40 years
- in electron experiments one knows exactly energy and momentum transfer
- QE and $\Delta(1232)$ peak regions can be studied independently
- MEC has relatively large contribution in DIP region



from A. Gil, J. Nieves and E. Oset, Nucl. Phys. A 627 (1997) 543;



electron scattering: CLAS experiment, Science 320 1476 (2008)

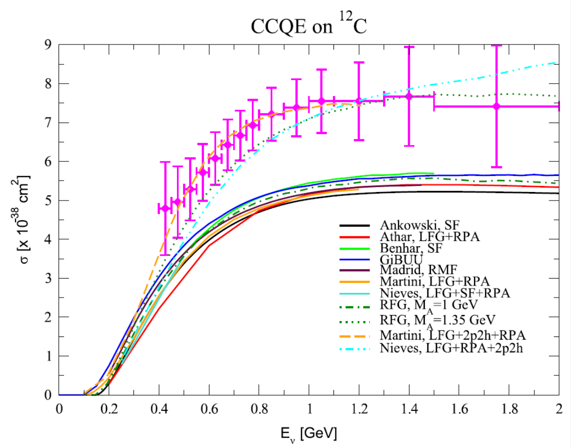


Fig. from Alvarez-Ruso, Hayato, Nieves, New Journal of Physics **16**, 075015 (2014)

- Martini et al.: inclusion 2p2h in the analysis of MiniBooNE data resolves partially the problem of large axial mass! $M_A \sim 1$ GeV

Correlations in neutrino scattering, theoretical models:

- M. Martini et al.
- Valencia group (J. Nieves et al.) a consistent theoretical scheme describing CCQE, 1π production and two body current contributions
- superscaling approach (Donnelly et al.)
- transverse enhancement (A. Bodek et al.) based on electron scattering data
- state of art many body theory computations (J. Carlson, R. Schiavilla, A. Lovato et al) provides a clear theoretical picture, constrained to light nuclei and difficult to translate into direct observable.

Experimental investigations: Minerνa, ArgoNeuT,... and others

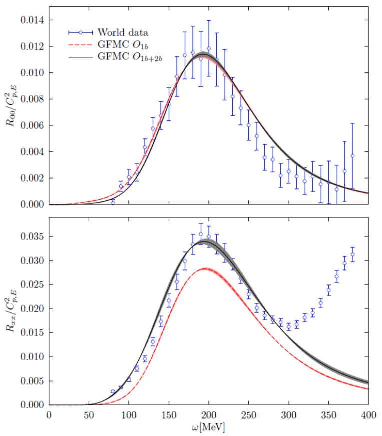


FIG. 3. (Color online) Electromagnetic longitudinal (top panel) and transverse (lower panel) response functions of ^{4}He at $q = 600$ MeV. Experimental data are from Ref. [10].

Lovato et al. arXiv:1501.01981

Transverse enhancement!

1π production (SPP)

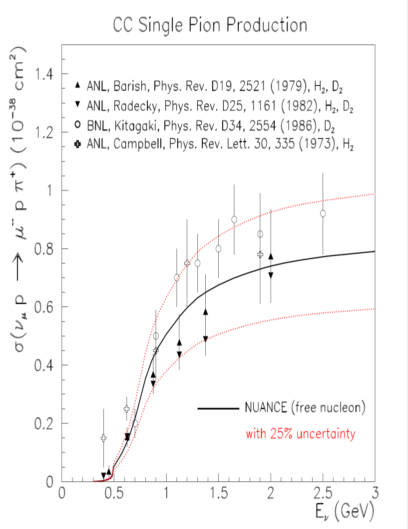


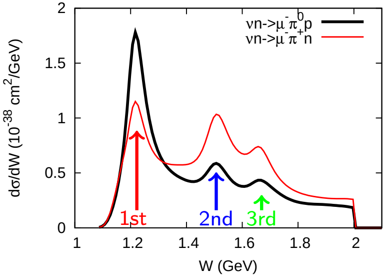
Fig. from Wascko, NuInt05

$$\nu + p \rightarrow \mu^- + \pi^+ + p$$
$$\nu + n \rightarrow \mu^- + \pi^0 + p$$
$$\nu + n \rightarrow \mu^- + \pi^+ + n$$

- theoretical (phenomenological) models vs. data
  - ANL and BNL ν-Deuteron scattering data
  - ANL and BNL total and differential cross sections consistent for SPP in νp, Graczyk et al. 2009, Hernandez et al. 2010, Wilkinson et al. 2015
- ~ 1 GeV neutrinos dominant contribution from $N \rightarrow \Delta(1232) \rightarrow \pi N'$

* $\Delta(1232)$ first exited state of the nucleon, $3/2$ spin, $3/2$ isospin,...

- investigation of axial structure of the $\Delta(1232)$ resonance



Data analysis $\rightarrow$ MC (Nuance, Neut, Genie but not NuWro) $\rightarrow$ Rein-Seghal model

- relativistic quark model for neutrinoproduction of resonances
- effectiv nonresonant contribution
- only two form factors, 18 resonances ($W < 2$ GeV)
- improvements: Graczyk, Sobczyk, PRD77 (2008) 053001, PRD77 (2008) 053003, see also V. Naumov et al. **But this model should be replaced by more consistent description!**

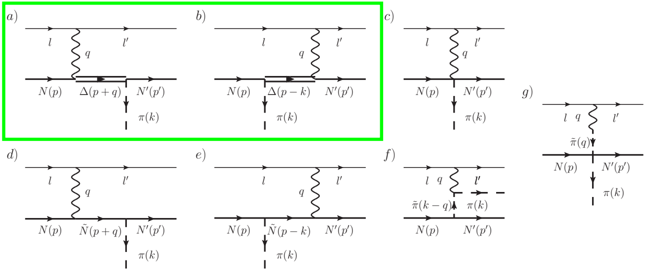
Other theoretical approaches:

- Sato-Lee model: dynamical model i.e. Hamiltonian of ΔN coupling obtained with constituent quark model, T-matrix obtained by solving Lippmann-Schwinger equation in coupled channels.
- Isobar models: Giessen group, NuWro, Serot and Zhang, Fogli and Narduli, etc.
- ChiFT: IFIC group, Barbero and Mariano, ...

Problems

- with reproduction of old νD data **and** recent experimental measurements of Minerνa and MiniBooNE
- imprecise knowledge of axial resonance form factors
- with consistent inclusion of heavier resonances and more inelastic contribution

Hernandez et al. latter Lalakulich et al. Wrocław group



$$\langle \Delta(p'=p+q) \mid \mathcal{J}^{CC}_{\mu} \mid N(p)\rangle = \bar{\Psi}^{\lambda}(p')\Gamma^{CC}_{\lambda\mu}u(p), \quad \Gamma^{CC}_{\lambda\mu} = \Gamma^{V}_{\lambda\mu} + \Gamma^{A}_{\lambda\mu}.$$

$$\Gamma^{V,\lambda}_{\mu} = \left[g^{\lambda}{}_{\mu} \left(\frac{C_3^V}{M}\gamma_\nu + \frac{C_4^V}{M^2}p'_\nu + \frac{C_5^V}{M^2}p_\nu \right) q^\nu - q^\lambda \left(\frac{C_3^V}{M}\gamma_\mu + \frac{C_4^V}{M^2}p'_\mu + \frac{C_5^V}{M^2}p_\mu \right) \right] \gamma_5,$$

vector form factors are obtained from electroproduction:

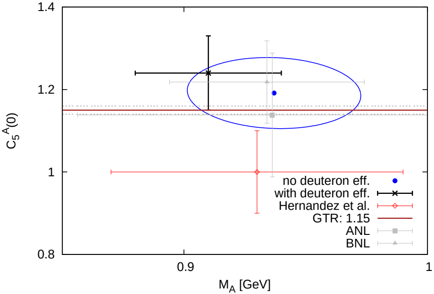
$$\Gamma^{A,\lambda}_{\mu} = g^{\lambda}_{\mu} \left(\gamma_\nu \frac{C_3^A}{M} + \frac{C_4^A}{M^2}p'_\nu \right) q^\nu - q^\lambda \left(\frac{C_3^A}{M}\gamma_\mu + \frac{C_4^A}{M^2}p'_\mu \right) + g^{\lambda}{}_{\mu} C_5^A + \frac{q^\lambda q_\mu}{M^2} C_6^A$$

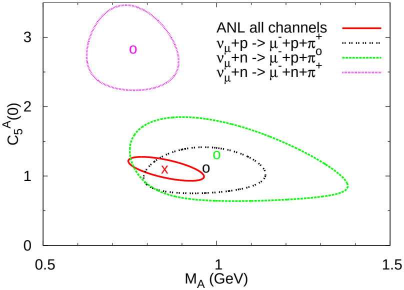
axial form factors are obtained from neutrinoproduction but one needs to reduce # independent form factor to C_5^A (it is model dependent procedure)

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

$C_5^A(0) \approx 1.15$ related with strong $g_{\pi N \Delta}$ coupling constant (PCAC and Goldberger-Treiman off diagonal Relation – GTR)

- full model with non-resonant contribution $C_5^A \approx 1.0$!in disagreement with GTR value!$\rightarrow$ lack of unitarity of the model (Hernandez et al. (2010))
- inconsistency between different channels of ANL data! (Graczyk et al. 2014, but also U. Mosel et al. 2011) – nonresonant background not properly described? or/and the problems with FSI effects? J.J. Wu et al.





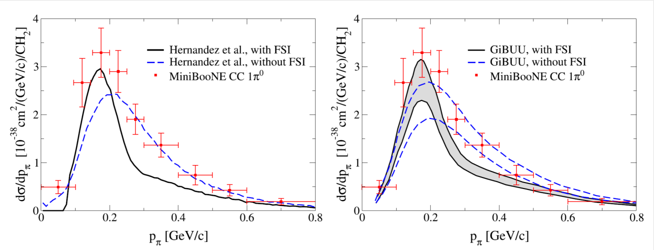
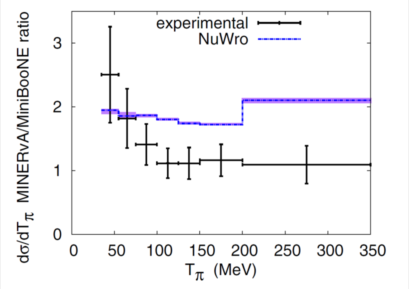


Fig. from Alvarez-Ruso, Hayato, Nieves, New Journal of Physics **16**, 075015 (2014)

ν-Carbon scattering

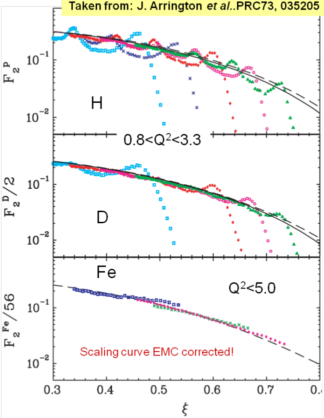
- MiniBooNE puzzle
- final state interaction, propagation of $\Delta(1232)$ in nuclear medium ...
- data are better described by the model without FSI effects? Mosel et al. Hernandez et al.
- tension between Minerνa and MiniBooNE measurements Sobczyk, Żmuda PRC91 (2015), 045501



SPP and more inelastic channels for $W > 1.4$ GeV?

- include resonances from 2nd and 3d regions $\rightarrow$ # of unknown axial form factors increases! Problems with nonresonant contribution...
- Quark-hadron duality $\rightarrow$ Bloom-Gilman duality in eN, eA scattering (PRL25 (1970) 1140, th. De Rujula et al., Ann. Phys. 103, (1976) 315,)
  $\rightarrow$ RESonance region data (i) oscillate around the scaling curve; (ii) are on average equivalent to the scaling curve (iii) "slide" along the deep inelastic curve with increasing Q2.
- Fermi motion smears the resonance structure $\rightarrow$ duality even better!
- RES structure function $\rightarrow$ DIS structure function inelastic νA cross sections (idea of A. Bodek), used in NuWro
- BG duality for isoscalar target in νN Graczyk, Juszczak, Sobczyk A781 (2007) 227, Lalakulich, Melnitchouk, Paschos, PRC75 (2007) 015202

Taken from: J. Arrington *et al.*.PRC73, 035205

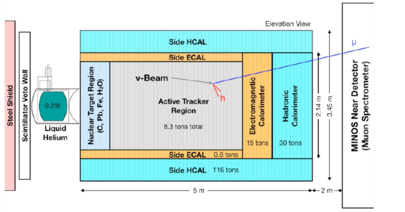


Summary

- Neutrino interactions with nucleons/nuclei are intensively studied experimentally and theoretically.
- New neutrino results stimulates electron scattering community.
- **All theoretical models discussed in this talk are implemented in NuWro Monte Carlo generator, which is currently used in analysis of experiments: Minerνa, T2K.**

ν interactions in Minerνa:

A unique role of the MINERvA experiment



- a dedicated experiment to study ν interaction cross sections and to understand better nuclear effects

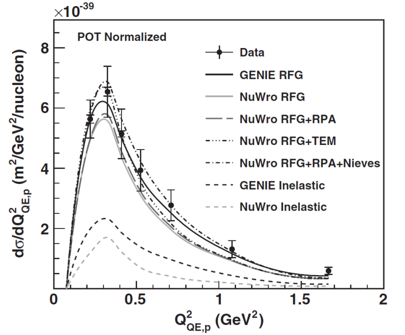


Fig. from Minerva experiment, Phys.Rev. D91 (2015) 7, 071301.

- Neutrino cross section models must be confronted with electron scattering data, eWro electron Monte Carlo generator

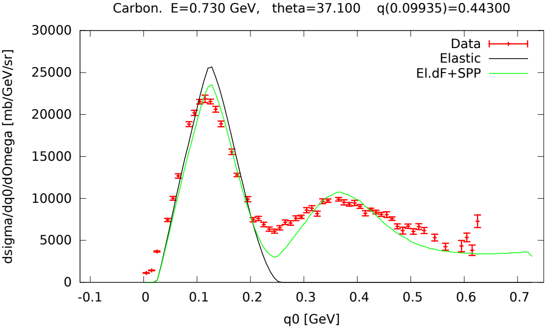


Fig. from C. Juszczak