Theoretical challenges in neutrino cross-sections

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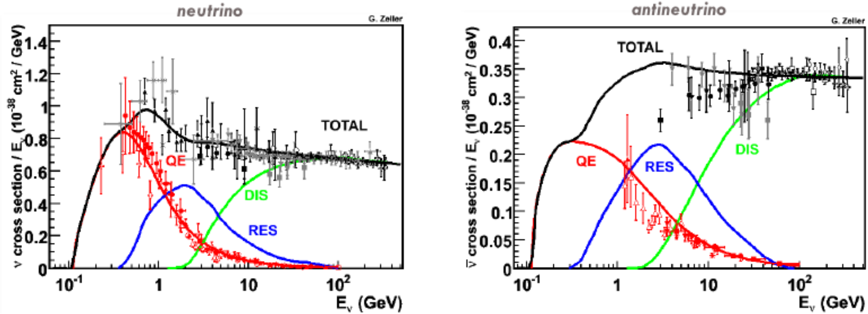
Outline:

- Introduction and general remarks.
- Challenge # 1: understanding CCQE peak.
- Challenge # 2: a size and characteristics of 2p-2h contribution.
- Challenge # 3: understanding π production in the Δ region on nuclear targets.
- Conclusions.



(from Sam Zeller; based on P. Lipari et al, Phys. Rev. Lett. 74 (1995) 4384)

CCQE is $\nu_\mu\ n \to \mu^-\ p$, or $\bar{\nu}_\mu\ p \to \mu^+\ n$.

RES stands for resonance region e.g. $\nu_\mu\ p \to \mu^-\ \Delta^{++} \to \mu^-\ p\ \pi^+$;
one often speaks about SPP - single pion production

DIS stands for: more inelastic than RES.

In case of nucleus target scattering one must consider also COH (coherent pion production) and MEC (2p-2h).

General remarks

- Motivation: reconstruction of ν energy based on detected final state particles
  - a pattern of ν oscillations is energy dependent
- A general picture: impulse approximation
  - interaction is a two step process: scattering on a bound nucleon (CCQE , RES or DIS) followed by final state interactions
  - IA has its own limitations: momentum transfer should be large enough
- Challenges are related both with primary interaction and nuclear effects.
- Typically, challenges have both "theoretical" and "experimental" aspects
  - E.g. for CCQE it would be nice to calculate axial form factor with lattice QCD, but also it would be great to have new measurements in hydrogen/deuterium bubble chamber experiments.

Challenge # 1. Understanding CCQE/QE peak region.

In a few GeV region CCQE is most important to understand properly.

- CCQE is analogous to $eN \to eN$ scattering.
- Nuclear effects in electron and neutrino nucleus scattering are similar: mean-free path of virtual photon and W/Z boson are much larger than nucleus size.
- We can use information gathered in electron scattering studies.
- It is necessary to include MEC contribution.

Challenge # 1. (cont.)

In the case of ν scattering we know the story:

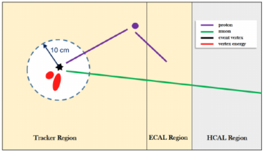
- MiniBooNE large CCQE M_A measurement.
- Marteau-Martini-Chanfray-Ericson theoretical explanation in terms of a large MEC contribution.
- Nieves et al computations implemented in MC generators.
- MiniBooNE CCQE $\bar{\nu}_\mu$ measurement.
- MINERvA CCQE ν_μ and $\bar{\nu}_\mu$ measurements.
- Problems with reproducing all the data with a single model.

Challenge # 1. (cont.)

Important question related with the MINERvA measurement: Is Monte Carlo (GENIE) bias fully understood?

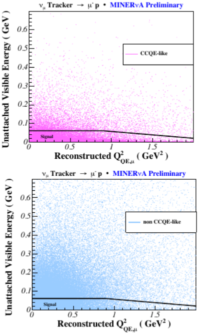
Removing Background Events

- Large amounts of extra energy, not associated with the muon or proton, usually come from untracked particles
- Define an unattached visible energy, energy outside 10 cm



- Requires the unattached energy versus the 4-momentum transfer QE scattering using the muon kinematics

$$Q^2_{QE} = 2E_{\nu,QE}(E_\mu - p_\mu cos\theta_\mu) - m^2_\mu$$

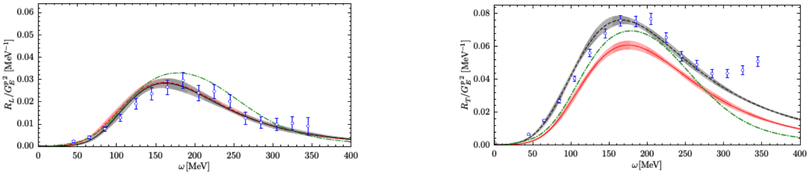


Betancourt, NuInt15

How well MC (here GENIE) reproduces distribution of hadronic energy?

Challenge # 1. (cont.)

Ab initio Green function Monte Carlo (GFMC) computations (electron scattering) show that there is a significant 2-body current (MEC) contribution in the QE peak region (below results for $|\vec{q}| = 570$ MeV/c):



Lovato et al, PRL 117 (2016) 082501

O_{1b+2b} is needed to reproduce QE peak in R_T ($2b$ is 2p-2h).

PWIA - plane wave impulse approximation – e.g. Fermi gas model

O_{1b} - one body operator

O_{1b+2b} - one body and two body operator

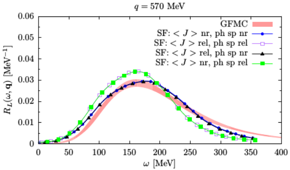
Challenge # 1. (cont.)

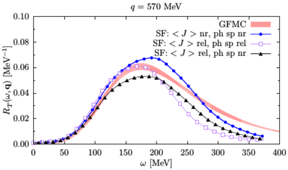
Ab initio computations have important limitations

- light nuclei (numerical complexity and nuclear structure)
- restricted kinematical region (nonrelativistic regime, no pion production)

They may be used to benchmark effective models in kinematical region where both are reliable

- this is challenging because GFMC is most reliable at low $|\vec{q}|$ when IA cannot be fully trusted.

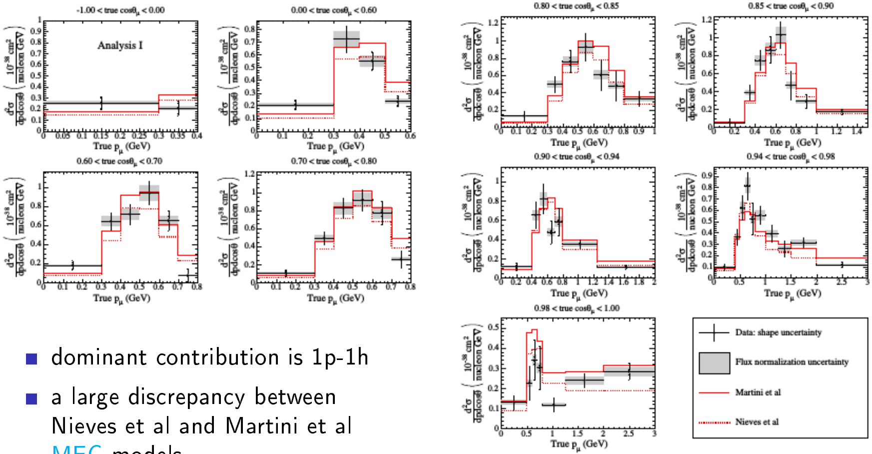




Rocco, Lovato, Benhar, arXiv:1610.06081 [nucl-th]

Challenge # 2. A size and characteristics of MEC contribution.

T2K results for CC0π: Phys.Rev. D93 (2016) 112012



- dominant contribution is 1p-1h
- a large discrepancy between Nieves et al and Martini et al MEC models.

Challenge # 2. A size and characteristics of MEC contribution.

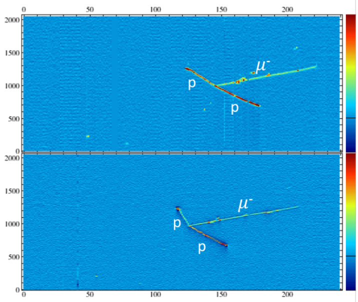
Investigation of more exclusive channels like $1\mu 0\pi 1p$, $1\mu 0\pi 2p$ can be very useful.

Two motivations:

- ν_μ energy reconstruction is better.
- Measurement of MEC can hopefully be done.

Transverse kinematics studies:

Lu et al Phys.Rev. C94 (2016) 015503; Lu, Betancourt (for the MINERvA Collaboration), arXiv:1608.04655 [hep-ex]; Dolan, Lu, Pickering, Vladisavljevic, Weber (for the T2K collaboration) arXiv:1610.05077 [hep-ex]



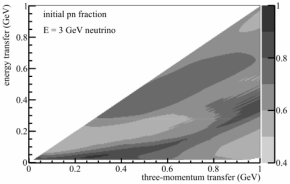
Acciarri et al., PRD90 (2014) 012008

ArgoNeuT hammer events.

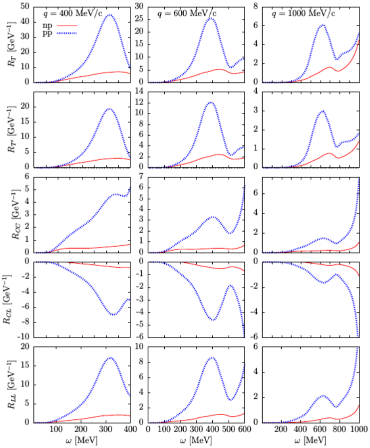
Challenge # 2. A size and characteristics of MEC contribution.

Investigation of more exclusive channels like $1\mu 1p$, $1\mu 2p$.

- We need reliable predictions for final state nucleons from of MEC events
  - isospin composition of NN pairs
  - sharing of momentum transfer $\vec{q}$



Gran, Nieves, Sanchez, Vicente Vacas, PRD88 (2013) 113007



Ruiz-Simo et al, PLB762 (2016) 124-130

Challenge # 2. A size and characteristics of MEC contribution.

A possible goal is to identify true CCQE in CC0π sample of events. Remaining are MEC and RES with π absorption.

- For $1\mu 1p0\pi$ events under CCQE hypothesis using energy and momentum conservation one can reconstruct ν and neutron momentum vectors.
- p_T is unbalanced transverse momentum (transverse relative to neutrino momentum)

$$p_L = \frac{(M_A + k'_L + p'_L - E' - E_{p'})^2 - p_T^2 - {M^*_{A-1}}^2}{2(M_A + k'_L + p'_L - E' - E_{p'})},$$

$$p_{neutron} = \sqrt{\vec{p}_T^{\,2} + p_L^2}.$$

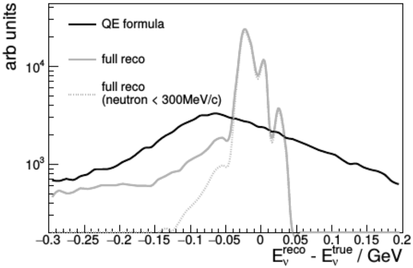
M_A target mass, E', k'_L muon energy and longitudinal momentum, $E_{p'}$, p'_L proton energy and longitudinal momentum, M^*_{A-1} remnant nucleus mass.

$$E_\nu = k'_L + p'_L - p_L.$$

If FSI effects are under control one can arrive at very good seperation of CCQE from RES and MEC with an excellent E_ν reconstruction of CCQE enhanced sample. Details: back-up slides.

Challenge # 2. A size and characteristics of MEC contribution.

One gets high purity CCQE sample of events ($\sim 95\%$) with a very good ν_μ energy reconstruction:



Furmanski, JTS, arXiv:1609.03530 [hep-ex].

- Black solid line: traditional CCQE E_{rec} formula.
- Grey solid line: our E_ν formula without a cut on neutron momentum.
- Grey dotted line: our E_ν formula without a cut on neutron momentum.

Peaks come from argon shell structure!

WARNING: details depend on the quality of MC FSI models.

Challenge # 3. Understanding π production in the Δ region on nuclear targets.

There are several ingredients of theoretical computations

- $N \to \Delta$ transition matrix element (in terms of form factors)
- a model of non-resonant background
- Δ self-energy in nuclear matter
- π final state interactions effects (absorption, charge exchange).

Challenge # 3 (cont.)

$N \to \Delta$ transition matrix elements, a lot of hard work to extract information form old ANL and BNL deuterium bubble target experiments:

- an apparent cross section normalization tension understood in terms of flux errors

  Graczyk, JTS, et al, PRD80 (2009) 093001; Rodrigues et al, Eur.Phys.J. C76 (2016) 474

- inclusion of non-resonant background has impact on extracted values of M_A^{res} and $C_A^5(0)$

  Hernandez, Nieves, Valverde, PRD76 (2007) 033005

- most of studies focus on $\nu_\mu p \to \mu^- p \pi^+$ channel but there seem to be a tension with other two channels

  Graczyk, Żmuda, JTS, PRD90 (2014) 093001

- deuteron effects are surprisingly large

  Wu, Sato, Lee, PRC91 (2015) 035203

Challenge # 3. (cont.)

MiniBooNE

- target is CH_2
- flux peaks at 600 MeV, without high energy tail $\Rightarrow$ the relevant dynamics is in the Δ region
- coherent π^+ production is a part of the signal
- signal is defined as $1\pi^+$ and no other pions in the final state.

Aguilar-Arevalo et al. [MiniBooNE Collaboration], PRD83 052007 (2011).

MINERvA

- target is CH
- NuMi flux $(1.5 - 10)$ GeV with $< E_\nu > \sim 4$ GeV
- a cut $W < 1.4$ GeV
- as a result, the Δ region is investigated, like in the MiniBooNE experiment
- coherent π^+ production is a part of the signal
- signal is defined as $1\pi^+$ and no other $\pi^\pm$ in the final state
  - contrary to MiniBooNE there can be arbitrary number of π^0s in the final state
  - due to W cut there is no phase space for many π^0s though

Eberly et al, [MINERvA Collaboration], PRD92 (2015) 092008

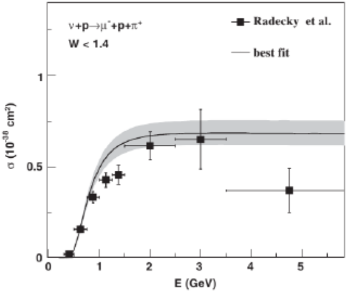
Challenge # 3. (cont.)

Does it make sense to compare MiniBooNE and MINERvA results?

- very different energies

But...

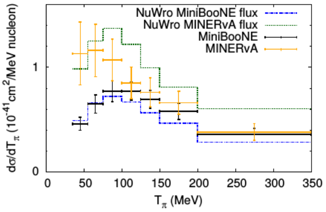
- the same Δ mechanism

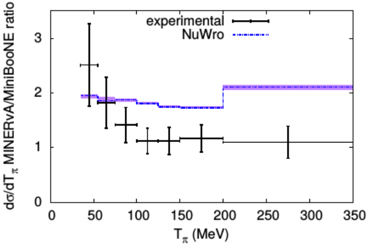


- the only major difference is coming from ν energy is normalization
- π^+ production cross section at 4 GeV is $\sim$ twice that at 700 MeV
- less important: slightly different definitions of the signal.

K. Graczyk, D. Kiełczewska, P. Przewłocki, JTS, PRD80 (2009) 093001

Challenge # 3. (cont.)





- the ratio is expected to be quite flat
- there is a worrying data/MC normalization dicrepancy, more than 40%

The actual normalization discrepancy is smaller because MINERvA made better estimate of the flux and all the older cross section must be increased by 10-15% (no official data available yet).

NuWro is not perfect but the ratio result seems to be mostly independent on the model details. The only really important input is Δ excitation cross section.

Conclusions

- There is a lot of experimental and theoretical activities focused on ν cross sections.
- There is a lot of progress,

but ... much is left to be done.

My feeling is that further progress depend on precise cross section measurements (experimental challenges)

- π production – to resolve MiniBooNE/MINERvA tension.
- CCQE peak – to estimate a size of MEC contribution.

and on (theoretical challenges)

- ability to explore information contained in hadronic final state (FSI effects for π and nucleons, reliable models of hadronic final state from MEC events).

Back-up slides

Challenge # 2. A size and characteristics of MEC contribution.

M^*_{A-1} can be estimated using information about argon shell model structure:

Subshell	E_α [MeV]	σ_α [MeV]	# neutrons n_α
$1s_{1/2}$	62	6.25	2
$1p_{3/2}$	40	3.75	4
$1p_{1/2}$	35	3.75	2
$1d_{5/2}$	18	1.25	6
$2s_{1/2}$	13.15	1	2
$1d_{3/2}$	11.45	0.75	4
$1f_{7/2}$	5.56	0.75	2

Ankowski, JTS, Phys.Rev. C77 (2008) 044311

where E_α is energy level and σ_α is its width.

One gets probability distribution for separation energy:

$$P(E) = \frac{1}{N}\sum_\alpha n_\alpha G(E - E_\alpha, \sigma_\alpha)$$

(G is Gaussian distribution, N number of neutrons) and

$$M_A = 22M_n + 18M_p - 343.81 \text{ MeV},$$

$$M^*_{A-1} = M_A - M_n + E.$$

Challenge # 2. A size and characteristics of MEC contribution.

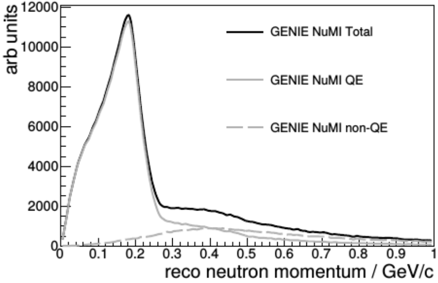
Selection: $1\mu 1p0\pi$ with some proton reconstruction threshold p_{thr}?

When reconstructed neutron momentum has very large value (wrt Fermi momentum)?

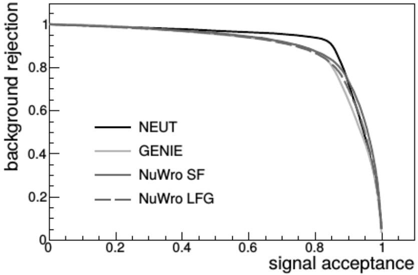
- Event was MEC. Second proton momentum is below threshold.
- Event was RES with π being absorbed.
- Event was CCQE with proton suffering from severe FSI effects.

Challenge # 2. A size and characteristics of MEC contribution.

Typical distribution of reconstructed neutron momentum:



One can try to optimize reconstructed neutron momentum cut:



Furmanski, JTS, arXiv:1609.03530 [hep-ex].

Optimal cut is $p_{cut} \approx 300$ MeV/c.

A sample that are rejected contains many MEC events!.

Challenge # 3. (cont.)

Composition of signal in two experiments according to NuWro

MiniBooNE

- RES: 87.1%
- COH: 6.7%
- DIS: 3.6%
- CCQE and MEC: 2.7%

MINERvA

- RES: 84.7%
- COH: 10.7%
- CCQE and MEC: 4.6%

Challenge # 3. (cont.)

The only relevant difference is in normalization: at MINERvA energies cross section is larger by a factor of ~ 2!

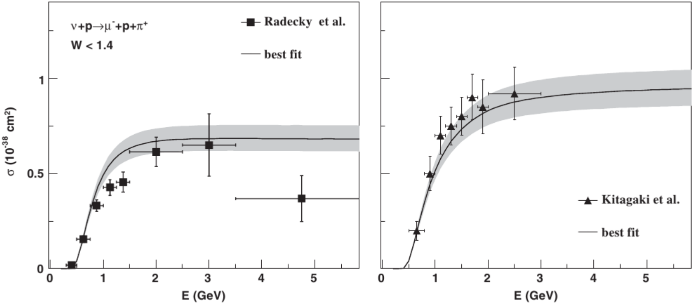


FIG. 5. Total cross section for $\nu + p \rightarrow \mu^- + p + \pi^+$. In the left panel the ANL data [5] with the cut $W = 1.4$ are shown (black squares), while the right panel presents the BNL data [42] (without cuts in W)—black triangles. The overall normalization error is not plotted. The best fit curves were obtained with a corresponding cut in W. The theoretical curves were obtained with dipole parametrization Eq. (32) with $M_A = 0.94$ GeV and $C_5^A(0) = 1.19$. The shaded areas denote the 1σ uncertainties of the best fit. The theoretical curves are not modified by the deuteron correction effect.

Graczyk, Kiełczewska, Przewłocki, JTS, PRD80 093001 (2009).