Monte Carlo studies of exclusive final states

Jan T. Sobczyk

Wrocław University

INT Workshop, Seattle, December 5-9, 2016

Organisers requests

- How well do models of semi-inclusive quasielastic electron scattering account for experimental observation?
- How are initial state correlations taken into account?
- How definitive and powerful can the inclusive lepton kinematics be in disentangling various nuclear effects given the breadth and uncertainties in the neutrino flux?
- What is the definition of transparency? Is it helpful? Are the effects of *transparency* accounted for in most models?
- What role can proton tagging/kinematics have in probing the multi-nucleon effects in pionless neutrino interactions?
- How would you compare the CCQE measurements of MiniBooNE and NOMAD?
- How can we reconcile/interface inclusive and semi-inclusive/exclusive modelling?

Marked in green will be addressed.

Outline

- NuWro project.
- Can we learn about 2p-2h from inclusive studies?
- ArgoNeuT *hammer* events.
- Investigation of $1\mu 1p0\pi$ events.
- Nucleon transparency.

Monte Carlo event generators *by construction* provide all the exclusive cross sections.

Two main questions are:

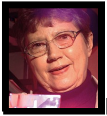
- How useful they can be? (the main topic in this talk)
- How reliable they are?

NuWro project

NuWro team (people who contributed significantly).

From the left: T. Golan, K. Graczyk, C. Juszczak, J. Nowak, JTS, J. Żmuda.

The project started ∼ 2005; idea put forward by:


Danka Kiełczewska (Warsaw)

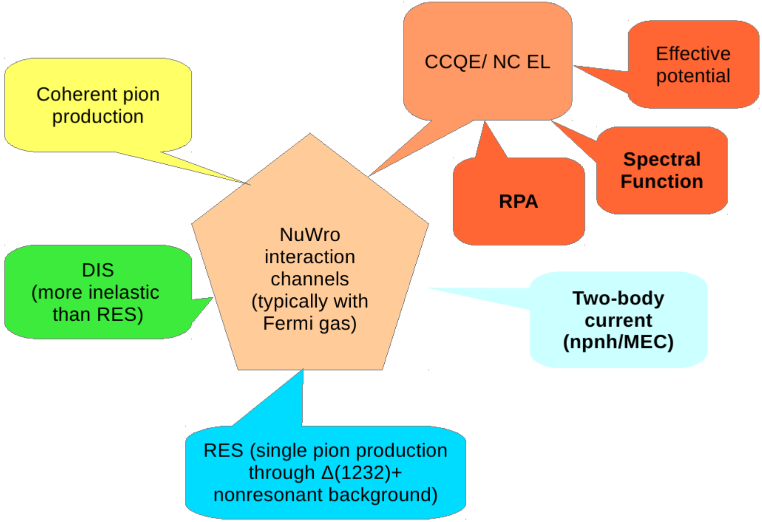
(passed away last February)

NuWro activities in T2K:


Paweł Przewłocki (Warsaw)

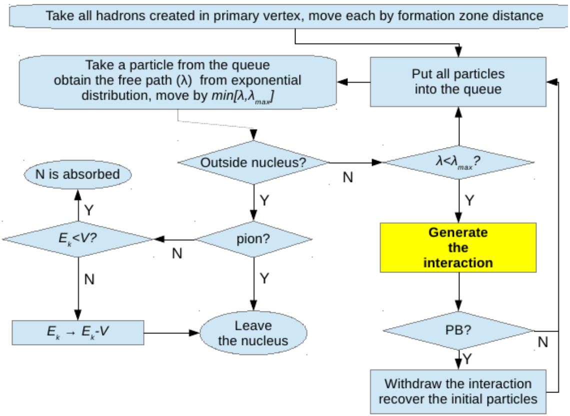
- the code is written in C++,
- can handle various targets, fluxes, has a detector interface,
- open source project: http://borg.ift.uni.wroc.pl/nuwro/
- recently event reweighting tools

NuWro interaction modes



from Jakub Żmuda

NuWro cascade model

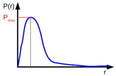


Impulse approximation.

Sampling interaction points:

- To sample vertex position: find maximum probability P_{max} (efficiency/speed tip: do it only once, when your nucleus gets generated for the first time!)

$$P(r)=\frac{4\pi}{A}r^2\rho(r), \int P(r)\,dr=1$$



- Each distance → $P=P(r)/P_{max}$.
- Choose proton (P=p/(p+n)) or neutron (P=n/(p+n)). Special case: CCQE: always neutron (neutrinos) or always proton (anti-neutrinos).

NuWro cascade model – nucleons

- Critical in all exclusive studies.
- Starting point: free nucleon-nucleon cross sections.
- Improvement: effective (strongly reduced) density dependent nucleon-nucleon cross sections.

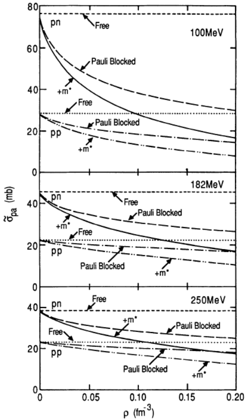


FIG. 2. The effective cross sections $\tilde{\sigma}_{pn}$ and $\tilde{\sigma}_{pp}$ for $E_{\rm lab}=100$, 182, and 250 MeV as a function of symmetric nuclear matter density. The curves labeled $+m^*$ include both Pauli blocking and the effective-mass corrections.

Pandharipande, Pieper, PRC45 (1992) 791

NuWro cascade model – pions;

Based on microscopic model

L. L. Salcedo, E. Oset, M. J. Vicente-Vacas, and C. Garcia-Recio, Nucl. Phys. A484 (1988) 557

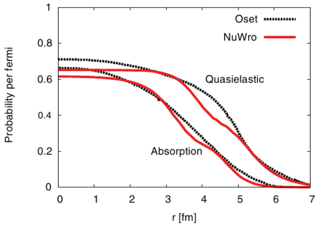


FIG. 6. (Color online) Probability (per fermi) of microscopic pion-nucleon interactions in iron as a function of distance from the nucleus center. Pion kinetic energy $T_k = 165$ MeV. The Oset model results are taken from [10].

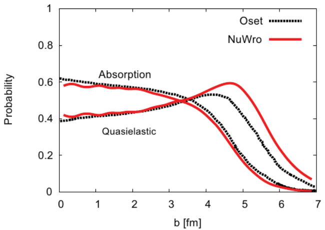


FIG. 7. (Color online) Probability of macroscopic quasielastic or absorption interactions as a function of an impact parameter b for π^{+40}Ca scattering with pion kinetic energy $T_k = 180$ MeV. The Oset model results are taken from [10].

TABLE I. Probabilities that macroscopic quasi-elastic process proceeds through n microscopic collisions. Oset model results are taken from [10].

	$T_\pi = 85$ MeV			$T_\pi = 245$ MeV			
	$n = 1$	$n = 2$	$n = 3$	$n = 1$	$n = 2$	$n = 3$	$n = 4$
Oset	0.90	0.09	0.01	0.69	0.25	0.05	0.01
NuWro	0.89	0.10	0.01	0.67	0.24	0.07	0.02

TABLE II. Probabilities that pion absorption occurs after n quasi-elastic microscopic scatterings. Oset model results are taken from [10].

	$T_\pi = 85$ MeV			$T_\pi = 245$ MeV			
	$n = 0$	$n = 1$	$n = 2$	$n = 0$	$n = 1$	$n = 2$	$n = 3$
Oset	0.81	0.17	0.02	0.37	0.41	0.17	0.04
NuWro	0.87	0.12	0.01	0.41	0.37	0.16	0.05

NuWro cascade model – pion absorption final states (LADS data)

charge multiplicity (in %)	1C	2C	3C	$\geq$ 4C
argon 118 MeV (LADS)	34.3	56.6	8.8	0.3
argon 118 MeV (NuWro)	36.6	54.7	8.2	0.5
argon 239 MeV (LADS)	18.2	53.8	24	3.9
argon 239 MeV (NuWro)	25.5	50	20.5	4
nitrogen 118 MeV (LADS)	22.8	63.3	13.2	0.8
nitrogen 118 MeV (NuWro)	25.2	63.3	10.6	0.9
nitrogen 239 MeV (LADS)	10.2	53.4	29.9	6.5
nitrogen 239 MeV (NuWro)	16.9	52.6	25.2	5.3

LADS data from Rowntree et al, PRC60 (1999) 054610

- LADS seperates protons and deuterons; in NuWro only protons
- in NuWro momentum cut 200 MeV/c is imposed. Energy threshold for proton detection in LADS is 16 – 22 MeV i.e. 175 – 200 MeV/c.

LADS paper: "*[limitations of the detector] most commonly cause high final state multplicities to be understated and also lower multiplicities to be overstated [...] Rudimentary estimates indicate that in severe cases (e.g. a three nucleon final state at 118 MeV) roughly 70% of actual strength is observed.*"

Information from inclusive data only

Exploring only inclusive data

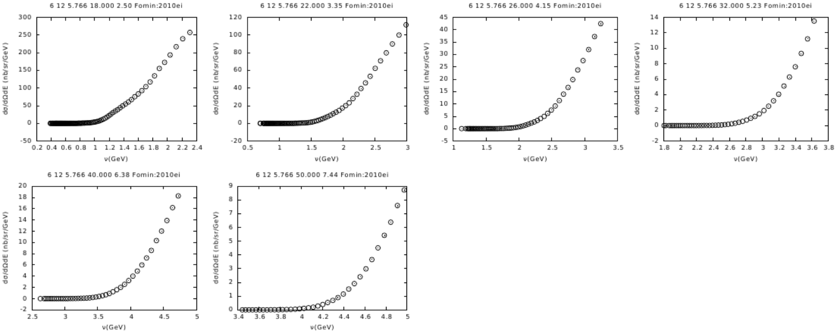
For electrons one can study two-body mechanism in the inclusive data. The strategy

- identify kinematical region (e.g. in q and q^0, or in Q^2 and x_B) where one-body mechanism is suppressed.
  - Consider Fermi motion and binding energy B
  - Cross section suppression for events $W \geq M$ with one outgoing nucleon.
  - Cross section dominated by events with $W \geq 2M$ with two outgoing nucleons.
- Look for non-zero cross section in this region.
  - One can *see* 2p-2h events in the inclusive data.
  - One can count NN SRC pairs.

Exploring only inclusive data

How to *see* 2p-2h events in the inclusive data?

A sample of electron ^{12}C scattering data:



http://faculty.virginia.edu/qes-archive/index.html

Exploring only inclusive data

This data is used to count correlated pairs.

$$x_B > 1.5$$

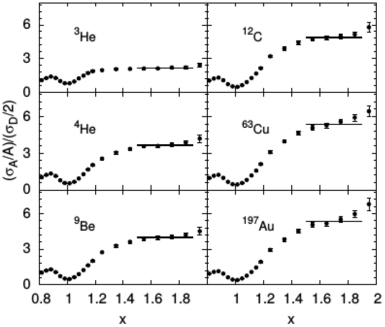
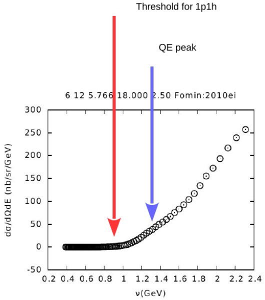


FIG. 2: Per-nucleon cross section ratios vs x at θ_e=18°.

Fomin et al

Exploring only inclusive data

How to *see* two-body current mechanism in the inclusive data?



E [GeV]	Θ (deg)	QE peak (GeV)	thr 1-body (GeV)	data (GeV)
5.766	50	3.96	3.53	≥ 3.44
5.766	40	3.4	2.92	≥ 2.63
5.766	32	2.78	2.28	≥ 1.8
5.766	26	2.21	1.72	≥ 1.13
5.766	22	1.78	1.32	≥ 0.7
5.766	18	1.33	0.925	≥ 0.39

The numbers in in last three columns are values of energy transfer.

On the left from the red arrow scattering on correlated pairs; the cross section is low but not zero!

Exploring only inclusive data

Can we do something similar for neutrinos?

- The problem is that neutrino beam is wide band.

$\cos\theta_\mu$ \ T_μ(GeV)	0.2,0.3	0.3,0.4	0.4,0.5	0.5,0.6	0.6,0.7	0.7,0.8	0.8,0.9	0.9,1.0	1.0,1.1	1.1,1.2	1.2,1.3	1.3,1.4	1.4,1.5	1.5,1.6	1.6,1.7	1.7,1.8	1.8,1.9	1.9,2.0
+0.9,+1.0	190.0	326.5	539.2	901.8	1288	1633	1857	1874	1803	1636	1354	1047	794.0	687.9	494.3	372.5	278.3	227.4
+0.8,+0.9	401.9	780.6	1258	1714	2084	2100	2035	1620	1118	783.6	451.9	239.4	116.4	73.07	41.67	36.55	—	—
+0.7,+0.8	553.6	981.1	1501	1884	1847	1629	1203	723.8	359.8	156.2	66.90	26.87	1.527	19.50	—	—	—	—
+0.6,+0.7	681.9	1222	1546	1738	1365	909.6	526.7	222.8	81.65	35.61	11.36	0.131	—	—	—	—	—	—
+0.5,+0.6	765.6	1233	1495	1289	872.2	392.3	157.5	49.23	9.241	1.229	4.162	—	—	—	—	—	—	—
+0.4,+0.5	871.9	1279	1301	989.9	469.1	147.4	45.02	12.44	1.012	—	—	—	—	—	—	—	—	—
+0.3,+0.4	910.2	1157	1054	628.8	231.0	57.95	10.69	—	—	—	—	—	—	—	—	—	—	—
+0.2,+0.3	992.3	1148	850.0	394.4	105.0	16.96	10.93	—	—	—	—	—	—	—	—	—	—	—
+0.1,+0.2	1007	970.2	547.9	201.5	36.51	0.844	—	—	—	—	—	—	—	—	—	—	—	—
0.0,+0.1	1003	813.1	404.9	92.93	11.63	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.1, 0.0	919.3	686.6	272.3	40.63	2.176	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.2,-0.1	891.8	503.3	134.7	10.92	0.071	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.3,-0.2	857.5	401.6	79.10	1.947	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.4,-0.3	778.1	292.1	33.69	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.5,-0.4	692.3	202.2	17.42	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.6,-0.5	600.2	135.2	3.624	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.7,-0.6	497.6	85.80	0.164	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.8,-0.7	418.3	44.84	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.9,-0.8	348.7	25.82	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-1.0,-0.9	289.2	15.18	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

TABLE VI: The MiniBooNE ν_μ CCQE flux-integrated double differential cross section in units of 10^{-41} cm^2/GeV in 0.1 GeV bins of T_μ (columns) and 0.1 bins of $\cos\theta_\mu$ (rows).

Which bins are kinematically suppressed for 1p-1h mechanism for neutrinos in the energy range from 500-3000 MeV?

Exploring only inclusive data

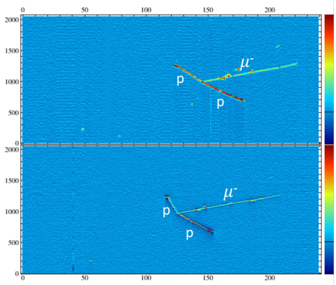
$\cos\theta_\mu$ \ T_μ (GeV)	0.2,0.3	0.3,0.4	0.4,0.5	0.5,0.6	0.6,0.7	0.7,0.8	0.8,0.9	0.9,1.0	1.0,1.1	1.1,1.2	1.2,1.3	1.3,1.4	1.4,1.5	1.5,1.6	1.6,1.7	1.7,1.8	1.8,1.9	1.9,2.0
+0.9,+1.0	190.0	326.5	539.2	901.8	1288	1633	1857	1874	1803	1636	1354	1047	794.0	687.9	494.3	372.5	278.3	227.4
+0.8,+0.9	401.9	780.6	1258	1714	2084	2100	2035	1620	1118	783.6	451.9	239.4	116.4	73.07	41.67	36.55	—	—
+0.7,+0.8	553.6	981.1	1501	1884	1847	1629	1203	723.8	359.8	156.2	66.90	26.87	1.527	19.50	—	—	—	
+0.6,+0.7	681.9	1222	1546	1738	1365	909.6	526.7	222.8	81.65	35.61	11.36	0.131	—	—				—
+0.5,+0.6	765.6	1233	1495	1289	872.2	392.3	157.5	49.23	9.241	1.229	4.162	—			—	—	—	—
+0.4,+0.5	871.9	1279	1301	989.9	469.1	147.4	45.02	12.44	1.012	—	—		—	—	—	—	—	—
+0.3,+0.4	910.2	1157	1054	628.8	231.0	57.95	10.69	—	—			—	—	—	—	—	—	—
+0.2,+0.3	992.3	1148	850.0	394.4	105.0	16.96	10.93	—		—	—	—	—	—	—	—	—	—
+0.1,+0.2	1007	970.2	547.9	201.5	36.51	0.844	—		—	—	—	—	—	—	—	—	—	—
0.0,+0.1	1003	813.1	404.9	92.93	11.63	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.1, 0.0	919.3	686.6	272.3	40.63	2.176	—		—	—	—	—	—	—	—	—	—	—	—
-0.2,-0.1	891.8	503.3	134.7	10.92	0.071		—	—	—	—	—	—	—	—	—	—	—	—
-0.3,-0.2	857.5	401.6	79.10	1.947	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.4,-0.3	778.1	292.1	33.69	—		—	—	—	—	—	—	—	—	—	—	—	—	—
-0.5,-0.4	692.3	202.2	17.42	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.6,-0.5	600.2	135.2	3.624	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.7,-0.6	497.6	85.80	0.164		—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.8,-0.7	418.3	44.84	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-0.9,-0.8	348.7	25.82	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
-1.0,-0.9	289.2	15.18	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

The suppressed bins are far away from those with measured non-zero cross section.

ArgoNeut hammer events

Two-proton events in the ArgoNeut experiment

R. Acciarri, et al [ArgoNeuT], Phys. Rev. D90 (2014) 012008



- Motivation: search for SRC nucleon pairs.
- Very low proton reconstruction threshold $P_{thr} \sim 200$ MeV/c, below Fermi momentum.
- Two hints of existence of SRC pairs.
- Four *hammer* events in the LAB frame with almost back-to-back momenta.
- Attempt to reproduce initial two nucleon state (if there is one).
- An access of reconstructed pairs in back-to-back state.

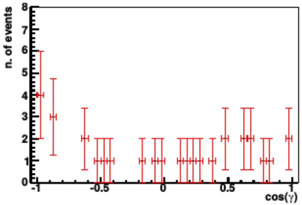
Two recent studies

K. Niewczas, JTS, Phys. Rev. C93 (2016) 035502

L.B. Weinstein, O. Hen, E. Piasetzky, Phys.Rev. C94 (2016) 045501

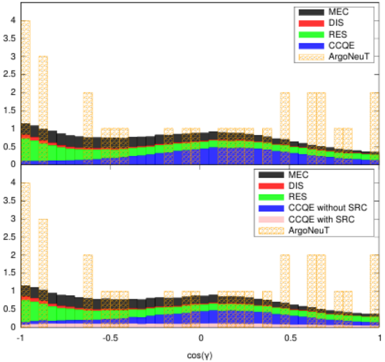
Two-proton events in the ArgoNeut experiment

Results for 30 LAB two proton events with four *hammer* events ($\cos\gamma < -0.95$).



NuWro results used as the probability distribution. We calculate probability to have at least 4 events in the first bin.

- $P(4+) = 2.9\%$ for the LFG model,
- $P(4+) = 3.0\%$ for the SF approach.



At $\cos\gamma \sim -1$ RES dominates, as suggested by ArgoNeuT.

NuWro predicts too few hammer events.

Two-proton events in the ArgoNeut experiment

NuWro followed exactly the procedure adopted by the ArgoNeuT.

- the idea: look for a hypothetical initial two-nucleon SRC state
- need to *reconstruct* events kinematics
- $\vec{p}^{\,T}_{miss} = \vec{p}^{\,T}_{\mu} + \vec{p}^{\,T}_{1} + \vec{p}^{\,T}_{2}$
- $E_\nu \approx E_\mu + T_{p1} + T_{p2} + T_{A-2} + E_{miss}$
- $T_{A-2} \approx (p^T_{miss})^2/2M_{A-2}, \quad E_{miss} = 30$ MeV
- momentum transfer $\vec{q}$ can be calculated
- $\vec{q}$ absorbed by more energetic proton
- both protons did not suffer from FSI.

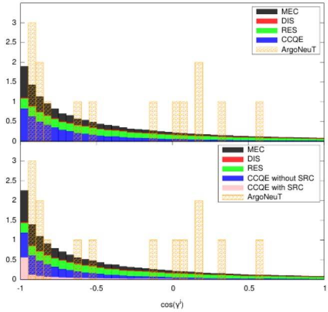
The procedure may be not very precise but it defines an observable.

Two-proton events in the ArgoNeut experiment

Results for 15 *reconstructed* events (hammers excluded as most likely coming from RES).

The *effect* is kinematical in nature and tells nothing about SRC pairs.

- neglecting invisible neutrons $\vec{q} \approx \vec{p}_1 + \vec{p}_2$
- $\vec{q}_{rec} \approx \vec{q}$
- $\vec{p}_{1\ rec} = \vec{p}_1 - \vec{q}_{rec} \approx -\vec{p}_2$ i.e. *back-to-back configuration* is the preferred one
- FSI (mostly neutrons) introduce a lot of smearing,
- the argument does not depend on the interaction mechanism.



NuWro results used as the probability distribution.

	$\cos\gamma^{i} \leq -0.9$	$\cos\gamma^{i} \leq -0.8$
NuWro: LFG	$P(3+) = 64.5\%$	$P(6+) = 45.4\%$
NuWro: SF	$P(3+) = 70.5\%$	$P(6+) = 49.6\%$

One muon and one proton sample of events

$1\mu 1p 0\pi$ sample of events

Two motivations:

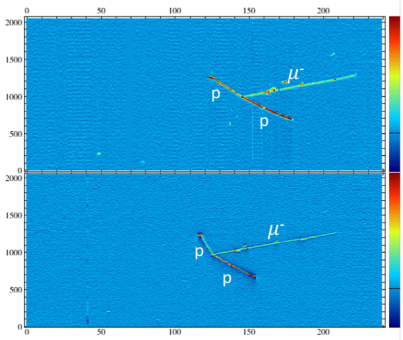
- ν_μ energy reconstruction is better.

  Mosel

- Information about 2p-2h can hopefully be obtained.

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]



$1\mu 1p0\pi$ sample of events

In the transverse kinematics studies momentum conservation in the transverse plane is explored.

- For CCQE events without Fermi motion and FSI effects transverse momentum components of muon and proton must be opposite.

One can go a step forward and explore information in the longitudinal components.

- Using only energy and momentum conservation one can reconstruct kinematics of the CCQE event completely.
- Neutrino energy and neutron momentum can be calculated.
- A caveat is that one must make an assumption about excitation of remnant nucleus.
    - A reasonable model is proposed.

How to use this study?

- One can select a high purity CCQE sample with excellent E_ν reconstruction.
- Rejected events are 2p-2h enhanced :).

$1\mu 1p0\pi$ sample of events

$$\vec{k} = \vec{k}' + \vec{p}' + \vec{p}_R$$
$$E_\nu + M_A = E' + E_{p'} + E_{A-1}.$$

where $\vec{k}$ and E_ν refer to neutrino, $\vec{k}'$ and E' - to muon, $\vec{p}'$ and $E_{p'}$ - final state proton, $\vec{p}_R$, E_{A-1} refer to remnent nucleus with $A-1$ nucleons.
In the plane wave impulse approximation we interpret this reaction as

$$\vec{k} + \vec{p} = \vec{k}' + \vec{p}',$$

$$E_\nu + E_p - B = E' + E_{p'}.$$

where $\vec{p}$ and E_p are target neutron momentum and energy. It follows that $\vec{p}_R = -\vec{p}$ and the binding energy B can be expressed as

$$B = E_p + E_{A-1} - M_A$$

and is neutron momentum dependent, $E_{A-1} = \sqrt{{M^*_{A-1}}^2 + \vec{p}^2}$ with M^*_{A-1} a mass of remnant nucleus in general in excited state.
Separating momenta vectors into longitudinal and transverse components we obtain:

$$\vec{p}_T = \vec{p}'_T + \vec{k}'_T$$
$$E_\nu + p_L = k'_L + p'_L$$
$$E_\nu + E_p - B = E' + E_{p'}.$$

We assume that $\vec{p}'_T$, $\vec{k}'_T$, k'_L, p'_L are directly measured. Thus $\vec{p}_T$ is automatically known and we arrive at two equations for E_ν and p_L. All that provided that we know the value of M^*_{A-1}.

$1\mu 1p0\pi$ sample of events

Solutions are:

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

$$p_{neutron} = \sqrt{\vec{p}_T^2 + p_L^2}, \qquad E_\nu = k'_L + p'_L - p_L.$$

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

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

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

$1\mu 1p0\pi$ sample of events

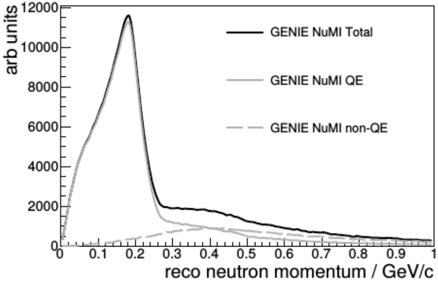
Selection: $1\mu 1p0\pi$ with only one proton above a reconstruction threshold p_{thr}.

What can be said if the reconstructed neutron momentum has very large value (wrt Fermi momentum)?

- Event was 2p-2h. Second nucleon is either neutron or proton with momentum below the threshold.
- Event was RES with π absorption.
- Event was CCQE with proton that suffered from severe FSI effects.

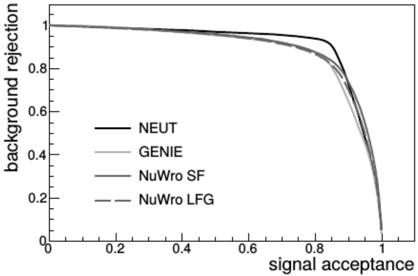
$1\mu 1p0\pi$ sample of events

Typical distribution of reconstructed neutron momentum:



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

One can try to optimize reconstructed neutron momentum cut:



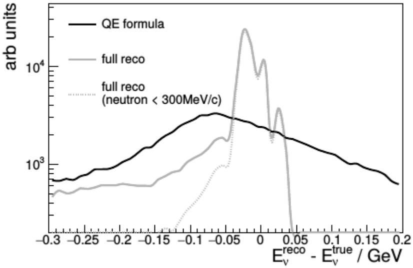
Points along the lines correspond to different values of $p_t hr$.

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

A sample that are rejected contains many 2p-2h events!.

$1\mu 1p0\pi$ sample of events

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 with a cut on neutron momentum.

Peaks come from argon shell structure!

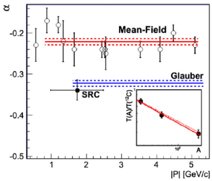
Rejected events are 2p-2h enhanced!

Nucleon transparency

Nucleon transparency

The simplest observable characterizing nucleon FSI effects is nucleon (proton) transparency.

- Defined as a probability for a proton to leave nucleus without significant reinteractions after QE interaction.
- Many experimental and theoretical studies.
- Intriguing discrepancy between mean-field and correlated nucleons transparency.
  - Hen et al. studied transparency of nucleons from SRC pairs.



Hen et al [CLAS], PLB722 (2013) 63

$T(A) \sim A^{\alpha}$.

Nucleon transparency

In the MC studies two options:

- Use true information if proton interacted or not.
  - Natural from the MC point of view.
  - Unclear how to treat soft interactions.
- Try to reproduce what was actually measured.
- In experimental studies there is some model dependence
  - One cannot measure cross section with FSI switched off.
  - More technical issue: correction for spectroscopic factors.

In what follows, MC truth studies results are shown.

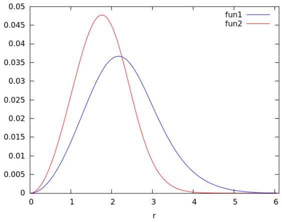
We allow protons to change its momentum direction by $\leq 5^\circ$.

Nucleon transparency

Hypothesis: a disrepancy between old and Hen et al results comes from distribution of interaction points in both cases.

Currently NuWro selects interaction point using $\rho(\vec{r})$ as probability distribution.

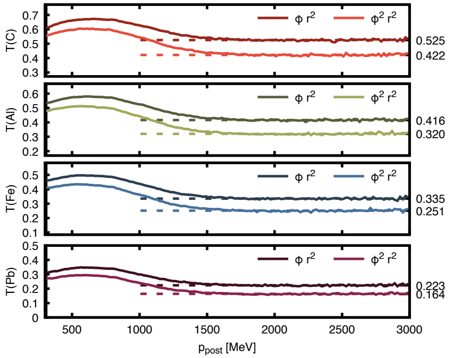
- what is a difference between $\rho(\vec{r})$ and $\rho^2(\vec{r})$?



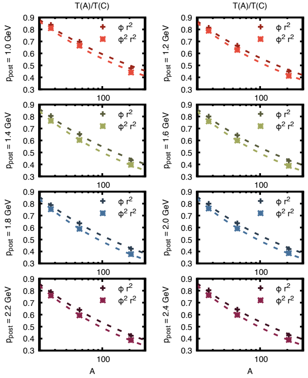
Above a comparison of $r^2\rho(r)$ (blue) and $r^2\rho^2(r)$ (red) (properly normalized) for carbon.

- With $\sim \rho^2$ distribution nucleons are more strongly affected by FSI effects.
- Transparency should be suppressed.

Nucleon transparency



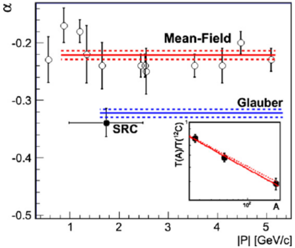
A dependence:



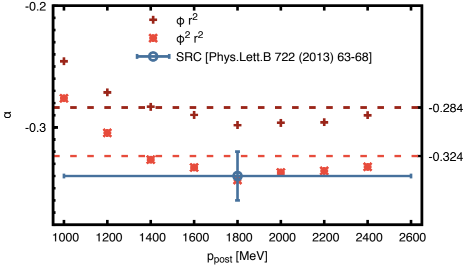
Transparency suppression is clearly seen.

Nucleon transparency

A fit to $T(A) = A^{\alpha}$ is done. The same set of point as in the Hen et al paper.



Hen et al [CLAS], PLB722 (2013) 63



Kajetan Niewczas, JTS

We reproduce the effect reported by Hen et al. In our study α becomes smaller (reduction from -0.284 to -0.324).

In neutrino 2p-2h studies it is better to select interaction points using ρ^2 and not ρ.

Conclusion:

- MC studies allow for various studies involving hadrons in the final state.