2p-2h excitations in NuWro

Jan T. Sobczyk

Wrocław University

Two-body current ..., Saclay, April 18-20, 2016

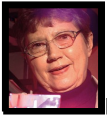
Outline:

- NuWro project
- motivation for MC studies
  - why do we need hadronic model
- NuWro 2p-2h models
  - Nieves et al model
  - transverse enhancement (TE) model
- options for the hadronic model
- example: proton pairs with momenta above certain threshold
- applications
  - looking for promising observables
  - analysis of ArgoNeuT data
- summary

NuWro team (people who contributed significantly during 10 years).

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)

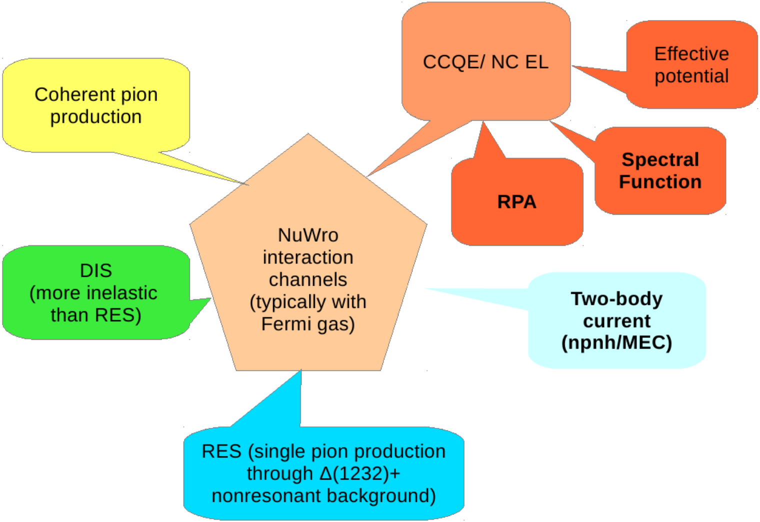
(passed away last February)

NuWro activities in T2K:

PawełPrzewłocki (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

Motivation and challenges

- it is important to know the size of 2p-2h contribution
- it is not enough to have predictions for the final state muon only
    - in electron scattering energy and momentum transfers are known and one can select a kinematical region where one-body mechanism is impossible
- several attempts to look for the 2p-2h hadronic final states

  L. Fields et al [MINERvA Collaboration], Phys. Rev. Lett. 111 (2013) 022501;

  G.A. Fiorentini et al. [MINERvA Collaboration] Phys. Rev. Lett. 111 (2013) 022502;

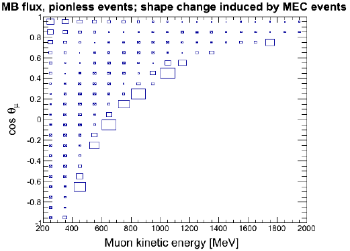
  P.A. Rodrigues et al [MINERvA Collaboration], Phys. Rev. Lett. 116 (2016) 071802;
- background from π production and absorption
- needs a reliable model for final state interactions (FSI).

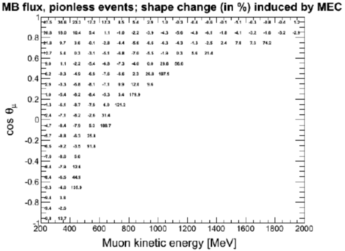
Motivation and challenges (2)

Look for shape modifications in 2D differential cross section introduced by two body current events:

$$\frac{\frac{d^2\sigma^{with\ \ 2body}}{d\cos\theta_\mu dT_\mu} - \frac{d^2\sigma^{without\ \ 2body}}{d\cos\theta_\mu dT_\mu}}{\frac{d^2\sigma^{without\ \ 2body}}{d\cos\theta_\mu dT_\mu}}$$

with both $\sigma^{with\ \ 2body}$ and $\sigma^{without\ \ 2body}$ normalized to the same value.





NuWro simulations with Nieves et al model

The effect is large only in very low statistics bins

Motivation and challenges (2)

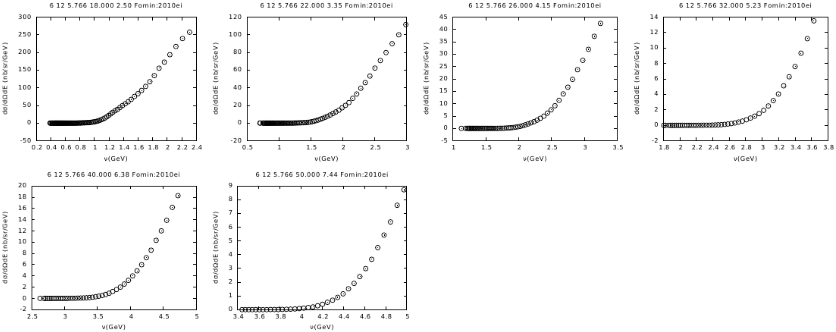
For electrons one can study two-body mechanism in the inclusive data. The strategy

- identify kinematical region (e.g. in q and q^0, or in Q^2 and x_B) where one-body mechanism is forbidden
  - consider Fermi motion and binding energy B
  - it is impossible to get $W \geq M$ with one outgoing nucleon
  - it is possible to get $W \geq 2M$ with two outgoing nucleons
- look for non-zero cross section in this region.

Motivation and challenges (3)

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

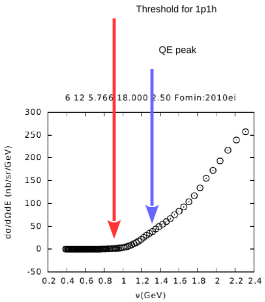
A sample of electron scattering data:



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

Motivation and challenges (4)

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!

Motivation and challenges (5)

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 forbidden for 1p-1h for neutrino in the energy range from 500-3000 MeV?

Motivation and challenges (6)

$\cos\theta_\mu$ \ 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
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+0.4,+0.5	871.9	1279	1301	989.9	469.1	147.4	45.02	12.44	1.012	—	—		—	—	—	—	—	—
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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	—		—	—	—	—	—	—	—	—	—	—	—
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-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	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

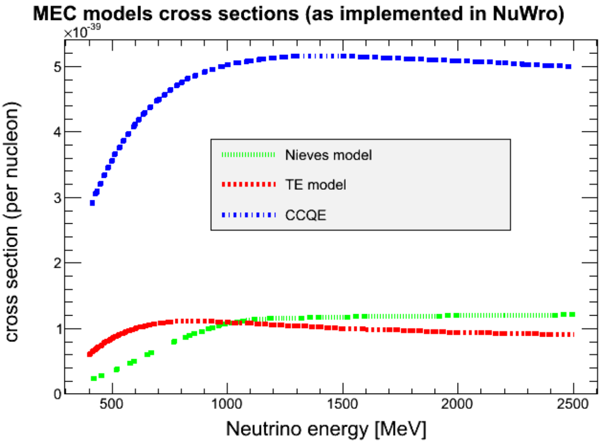
Unfortunately, the forbidden bins are far away from those with non-zero cross section.

2p-2h final states

In NuWro two sources of 2p-2h states (before FSI)

- spectral function as an option in the QE dynamics
  - Omar Benhar approach
  - FSIs affected final state lepton are not implemented
  - carbon, oxygen, iron; Artur Ankowski approximation for argon
- MEC
  - added incoherently
  - contribution to lepton inclusive cross section from Arie Bodek TE and Juan Nieves et al models
  - in the past also Jacques Marteau model; no longer supported
  - final state nucleons described with the same model.

NuWro 2p-2h models cross sections (carbon target)



NuWro implementation of the Nieves model (1)

- original paper:

  J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas, Phys. Rev. C83 (2011) 045501
- implementation based on the formalism of response functions
  - for a given target the complete information about inclusive cross section contained in five functions of two variables, e.g. energy and momentum transfer q^0, q
  - the same set of functions describes both electron and muon and also both neutrino and antineutrino cases

NuWro implementation of the Nieves model (2)

$$
\begin{aligned}
\frac{d\sigma}{dE'd\Omega} &= \frac{|k'|E'M_T G_F^2}{\pi^2}\Big\{2W_1(q^0,|q|)\sin^2\frac{\Theta}{2}+W_2(q^0,|q|)\cos^2\frac{\Theta}{2}+\\
&\mp W_3(q^0,|q|)\frac{E+E'}{M_T}\sin^2\frac{\Theta}{2}+\\
&+\frac{m_l^2}{E'(E'+|k'|)}\Big[(W_1(q^0,|q|)-W_2(q^0,|q|)/2)\cos\Theta+\\
&\pm\frac{W_3(q^0,|q|)}{2M_T}(E'+|k'|-(E+E')\cos\Theta)+\frac{W_4(q^0,|q|)}{2M_T^2}(m_l^2\cos\Theta+\\
&+2E(E'+|k'|)\sin^2\Theta)\frac{W_5(q^0,|q|)}{2M_T}(E'+|k'|)\Big]\Big\}. \qquad (1)
\end{aligned}
$$

where E' and $|k'|$ are energy and momentum of the outgoing lepton, Θ is the lepton scattering angle and M_T-target nucleus mass.

- for electron neutrino $m_l \approx 0$ and only three response functions contribute.

NuWro implementation of the Nieves model (3)

- fortran code to calculate five nuclear response functions was obtained from Nieves and Vicente-Vacas
- a uniform grid of points in energy q^0 and momentum transfer $|q|$ with $q^0 \leq |q|$ has been created for ^{12}C, ^{16}O and ^{40}Ca targets separately
- in this approach it is easy to add a constraint $q^0 < |q| < 1.2$ GeV as proposed in

  R. Gran, J. Nieves, F. Sanchez, and M.J. Vicente Vacas, Phys. Rev. D88 (2013) 113007
- many comparisons with NEUT implementation of the same model were done within the T2K neutrino interactions working group (NIWG)

NuWro implementation of the TE model

A. Bodek, H.S. Budd, and M.E. Christy, Eur. Phys. J. C71 (2011) 1726

- very easy to implement
- modification of the vector magnetic form factor

$$G_M^{p,n}(Q^2) \rightarrow \tilde{G}_M^{p,n}(Q^2) = \sqrt{1 + AQ^2 \exp(-\frac{Q^2}{B})} G_M^{p,n}(Q^2)$$

where $G_M^{p,n}(Q^2)$ are electromagnetic form-factors, $A = 6$ GeV^{-2} and $B = 0.34$ GeV^2.

- assuming no interference 2p-2h contribution can be extracted as

$$\frac{d^2\sigma^{TEM}}{dqd\omega} = \frac{d^2\sigma^{CCQE}}{dqd\omega}(\tilde{G}_M^{p,n}) - \frac{d^2\sigma^{CCQE}}{dqd\omega}(G_M^{p,n}).$$

- TE model can be applied to NC reactions as well

  T. Golan, K.M. Graczyk, C. Juszczak, and JTS, Phys. Rev. C88 (2013) 024612

NuWro 2p-2h implementation:

Basic algorithm

1. q^0 and q are selected; probability distribution is given by double differential cross section (either TE or Nieves model)
2. two initial state nucleons are found based on some assumptions (to be discussed later)
3. hadronic system (both nucleons and 4-momentum transfer) is boosted to its rest frame
4. final state nucleons momenta are selected
5. nucleons are boosted back to the laboratory frame
   - if Pauli blocking condition is imposed the steps (4, 5) are repeated until a configuration is found with both nucleons above the Fermi level
6. both nucleons propagate through nucleus.

JTS, Phys. Rev. C86 (2012) 015504

NuWro 2p-2h implementation:

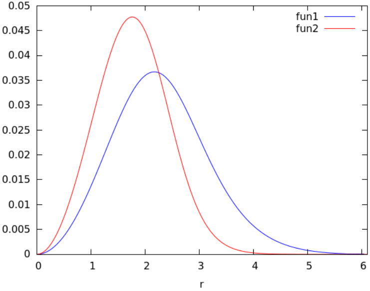
Decisions to be taken

- interaction point
  - currently sampled according to density profile $\rho(r)$, but perhaps $\rho^2(r)$ more appropriate?
- initial configuration - isospin
  - governed by a free parameter
- initial configuration - momenta
  - various options
- final state nucleons
  - phase space model or its modification.

Interaction points

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

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



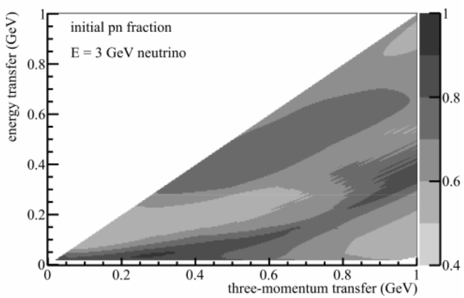
Above a comparison of $r^2\rho(r)$ (blue) and $r^2\rho^2(r)$ (red) (properly normalized) for carbon.

- with $\sim \rho^2$ distribution nucleons are more strongly affected by FSI effects.

Initial configuration - isospin

Governed by the parameter **mec_ratio_pp**

- for neutrino scattering it tells how often np pair is selected
- default value is 0.9
  - suggested by the mechanism of creation of SRC pairs
  - not taken from the Nieves et al model



R. Gran, J. Nieves, F. Sanchez, and M.J. Vicente Vacas, Phys. Rev. D88 (2013) 113007

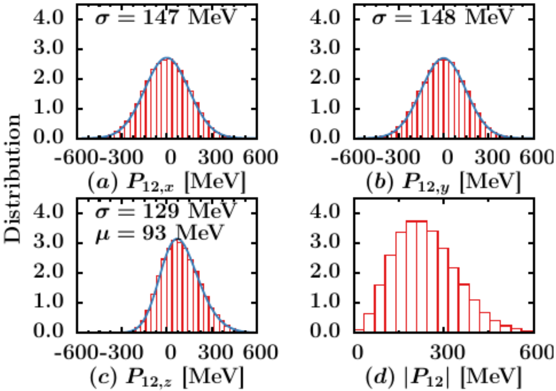
Fraction of pn pairs in the initial state in the Nieves et al model

Initial configuration - momentum

NuWro offers several options

- basically two nucleons are in the back to back configuration
- momentum distribution with a large momentum tail (taken from NuWro SF implementation)
- a new option is center of mass momentum of NN pairs
  - CM momentum assumed to follow gaussian distribution
  - governed by the parameter **mec_central_motion**
- if CM motion is neglected it is possible to introduce a gaussian smearing of exactly back to back configuration
  - the relevant parameter is **mec_back_to_back_smearing**

Initial configuration - momentum



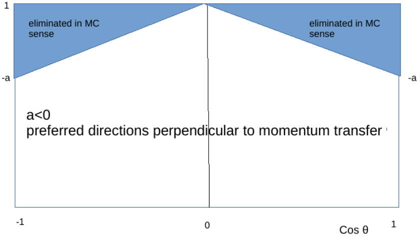
C. Colle, W. Cosyn, J. Ryckebusch, and M. Vanhalst, Phys. Rev. C89 (2014) 024603

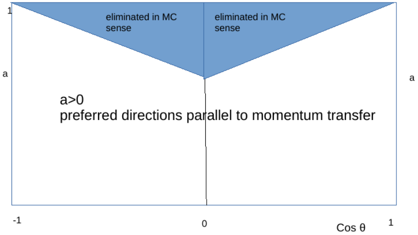
Total (bottom right) and directional distributions of NN pairs.

Final state configuration

- both nucleons must be eventually on shell and it is difficult to achieve it not using center of mass frame
- in the simplest version the nucleon CM distribution is uniform
- this can be modified by introducing some CM selection criteria
- in NuWro a new parameter **MEC_cm_direction**
  - a distinguished direction is that of the momentum transfer $\vec{q}$

Final state configuration





By setting **MEC_cm_direction** (in the figures above denoted as a) $\neq 0$ it is possible to select directions on avarage more parallel or more perpendicular to $\vec{q}$.

CC events with no π and proton pair

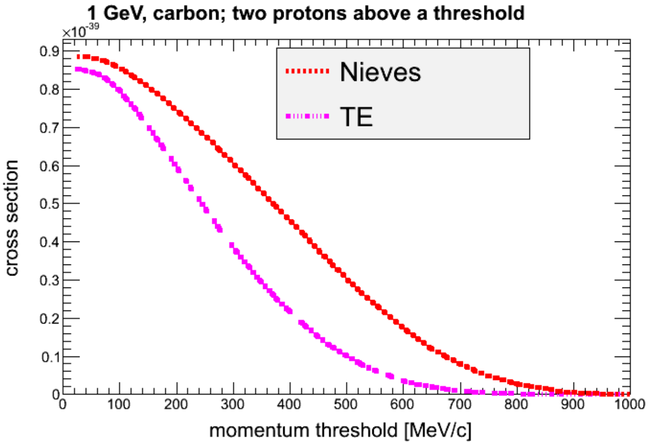
Three sources:

- genuine 2p-2h events
- π production and absorption
- FSI effects following CCQE.

Question: how many events with second (less energetic) proton above given threshold?

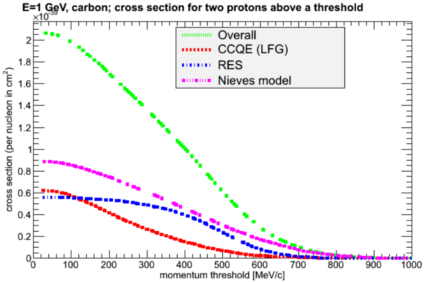
CC events with no π and proton pair

NuWro 2p-2h models

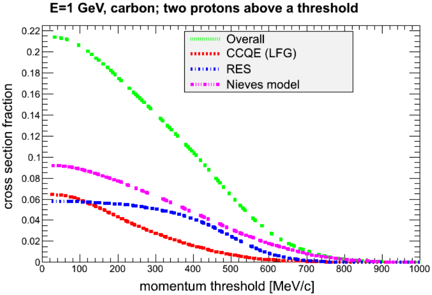


From now on we focus on the Nieves model.

CC events with no π and proton pair



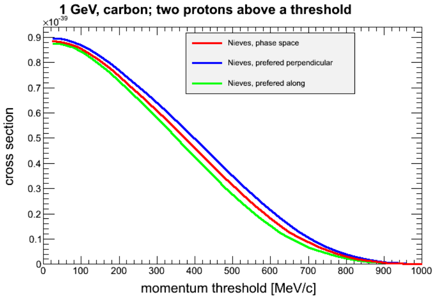
Absolute cross section (per nucleon)



Fractions of the total cross section

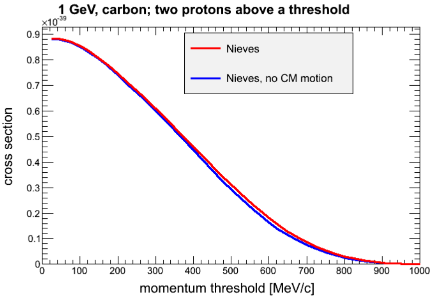
CC events with no π and proton pair

Examples of the impact of NuWro hadronic model uncertainties



Impact of modification of uniform phase space model.

For a threshold of $\sim$ 500 MeV/c it is quite large.



Impact of CM motion.

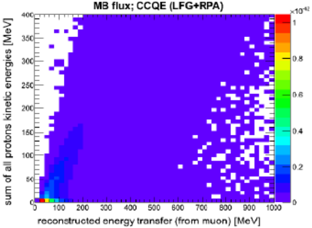
Negligable.

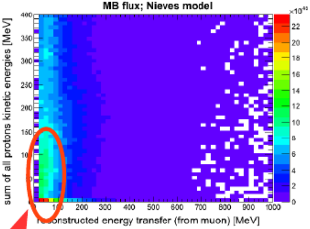
Application of MC 2p-2h models

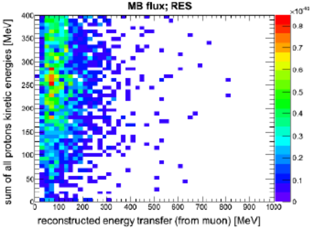
1. looking for potentialy promising observables
2. analyzing existing experimental data

Looking for potentially promising observables - example

Muon and proton information put together



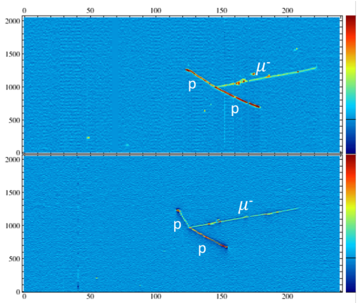




- there is a kinematical region where two body current may dominate
- seems to be a promising observable, but the cross section may be too low.

Application: 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!
- four *hammer* events in LAB with almost back-to-back momenta
- attempt to reproduce initial two nucleon state (if there is one)
- SRC pairs ?!

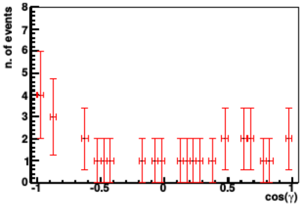
Two recent studies

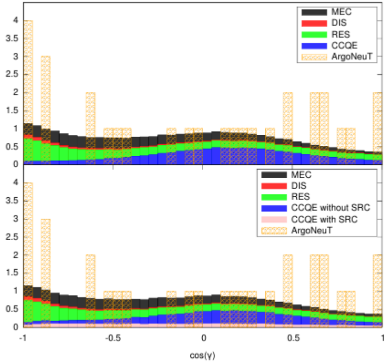
K. Niewczas, JTS, Phys. Rev. C93 (2016) 035502

L.B. Weinstein, O. Hen, E. Piasetzky, *Hammer events, neutrino energies, and nucleon-nucleon correlations*, arXiv:1604.02482 [hep-ex]

ArgoNeuT – NuWro simulations

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





NuWro results used as the probability distribution:

- $P(4+) = 2.9\%$ 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.

ArgoNeuT – NuWro simulations

NuWro followed exactly the procedure adopted by the ArgoNeuT.

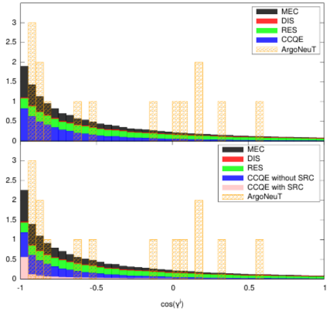
- the idea: look for a hypothetical initial two-nucleon SRC state
- need to *reconstruct* events kinematics
- $\vec{p}^T_{miss} = \vec{p}^T_\mu + \vec{p}^T_1 + \vec{p}^T_2$
- $E_\nu \approx E_\mu + T_{p1} + T_{p2} + T_{A-2} + E_{miss}$
- $T_{A-2} \approx (p^T_{miss})^2/2M_{A-2}, \quad E_{miss} = 30$ MeV
- momentum transfer $\vec{q}$ can be calculated
- $\vec{q}$ absorbed by more energetic proton
- both protons did not suffer from FSI.

ArgoNeuT – NuWro simulations

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

The *effect* is kinematical in nature

- 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	$P(3+) = 70.5\%$	$P(6+) = 49.6\%$

Summary

- NuWro offers many options in modeling 2p-2h contribution to the neutrino cross section
- plans
  - implement better theoretical model of the QE peak region (1-body 2-body interference effects etc)
  - improve FSI model
  - develop eWro – electron scattering module