Developments in NuWro

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NuInt15 Osaka, November 20, 2015

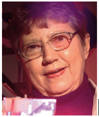
Outline:

- Part I
  - NuWro project,
  - recent upgrades,
- Part II
  - applications in physics studies,
- NuWro future.

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 $\sim$ 2005; important encouragment:


Danka Kiełczewska (Warsaw)

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/
- documentation is poor but many people say it is user's friendly :)

NuWro

NuWro is not an official MC in any experiment and serves as a laboratory for new developments.

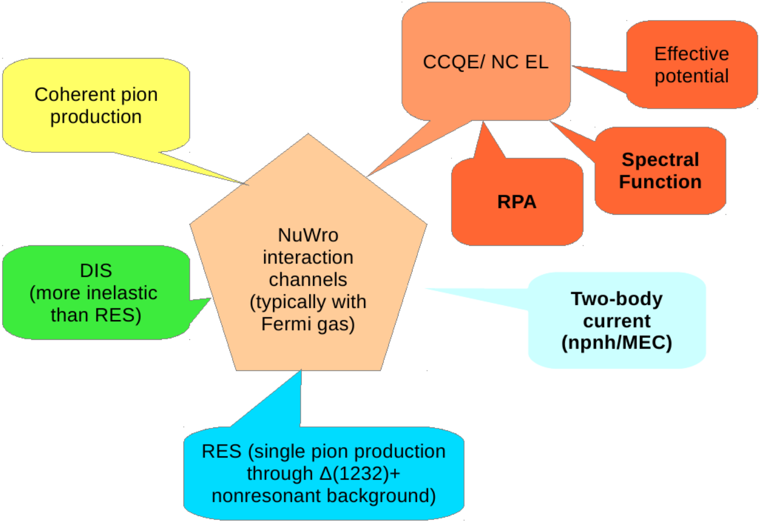
New (or relatively new) ingredients:

- Berger-Sehgal coherent pion production
- distribution of π's from Δ decay
- effective density and momentum dependent potential for CCQE

  C. Juszczak, J. Nowak, JTS
- eWro - electron scattering module (a work in progress)

  C. Juszczak, K. Graczyk, JTS, J. Żmuda

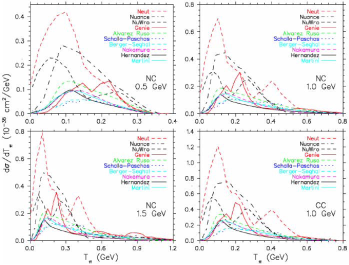
NuWro interaction modes



from Jakub Żmuda

Berger-Sehgal model for COH

Motivation:

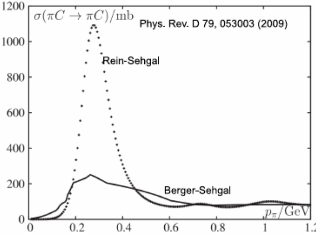


(Disaster) comparison of coherent pion production models

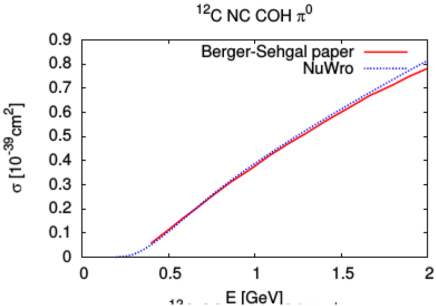
S. Boyd, S. Dytman, et al, NuInt09

Rein-Sehgal COH model based on PCAC argument

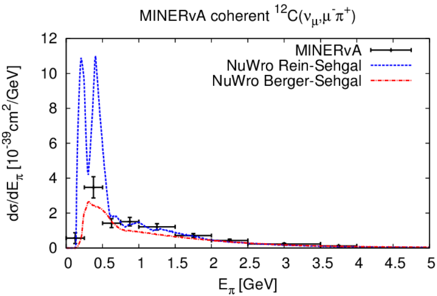
- COH cross section expressed in terms of π^{12}C elastic cross section
- Berger and Sehgal took this cross section directly from experiment



Berger-Sehgal model for COH



from Jakub Żmuda

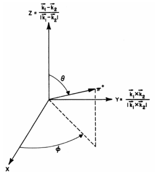


This study has been done in collaboration with Paul Martins who has been working for NEUT.

π angular distribution from Δ decay

Events are reweighted according to how pion momentum is oriented in the Δ rest frame.

Multiplication factor (Q^2 dependent) on the top of uniform distribution:



$$(1-(\tilde{\rho}_{33}-1/2)*(3*cos(\theta_\pi)^2-1)-\sqrt{3}*(2*\tilde{\rho}_{31}*sin(\theta_\pi)*cos(\theta_\pi)*cos(\phi_\pi)+\tilde{\rho}_{3-1}*sin^2(\theta_\pi)*(2*cos^2(\phi_\pi)-1))).$$

TABLE V. $\Delta^{++}(1232)$ density matrix elements.

Angular or Q^2 range	$\tilde{\rho}_{33}$	$\tilde{\rho}_{31}$	$\tilde{\rho}_{3-1}$	Events
$-1.0 \le \cos\theta^* \le 1.0$	0.661 ± 0.036	-0.107 ± 0.040	-0.088 ± 0.042	805
$-1.0 \le \cos\theta^* < -0.4$	0.582 ± 0.095	0.003 ± 0.101	-0.144 ± 0.102	125
$-0.4 \le \cos\theta^* < 0.0$	0.768 ± 0.084	-0.049 ± 0.095	-0.073 ± 0.107	141
$0.0 \le \cos\theta^* < 0.4$	0.722 ± 0.073	-0.011 ± 0.087	-0.160 ± 0.097	159
$0.4 \le \cos\theta^* < 0.8$	0.704 ± 0.064	-0.169 ± 0.074	0.035 ± 0.081	235
$0.8 \le \cos\theta^* \le 1.0$	0.488 ± 0.090	-0.266 ± 0.095	-0.176 ± 0.090	145
$0.0 \le Q^2 < 0.10$ (GeV/c)^2	0.523 ± 0.086	-0.322 ± 0.096	-0.138 ± 0.093	145
$0.10 \le Q^2 < 0.30$ (GeV/c)^2	0.649 ± 0.061	-0.128 ± 0.064	0.034 ± 0.071	292
$0.30 \le Q^2 < 0.50$ (GeV/c)^2	0.674 ± 0.079	-0.017 ± 0.088	-0.203 ± 0.090	172
$0.50 \le Q^2 < 1.00$ (GeV/c)^2	0.748 ± 0.079	0.041 ± 0.090	-0.162 ± 0.098	160

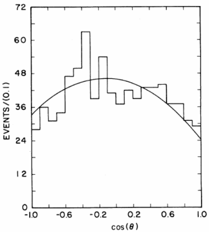
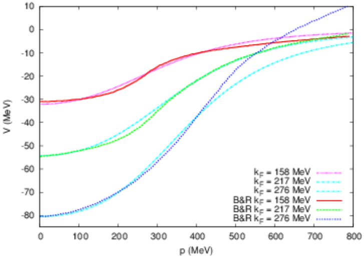


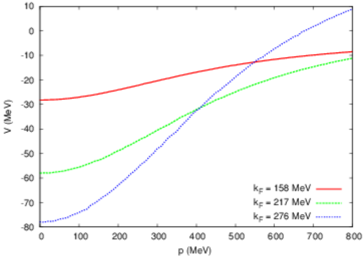
FIG. 15. Distribution of events in the pion polar angle $\cos\theta$ for the final state $\mu^- p \pi^+$, with $M(p\pi^+) < 1.4$ GeV. The curve is the area-normalized prediction of the Adler model.

Radecky et al [ANL Collaboration], PRD 25 (1982) 1161.

Effective density and momentum dependent potential

Nucleons experience density and momentum dependent effective potential:





J. Nowak, PhD thesis

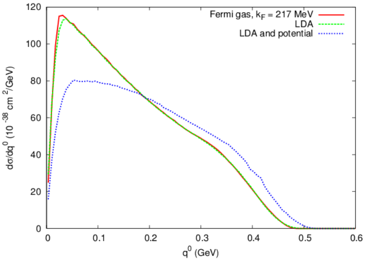
On the left: Brieva-Dellafiore potential and approximation used in NuWro.

On the right: the potential used in GiBUU.

Effective density and momentum dependent potential

The model is expected to give realistic predictions for final state muon (LDA = local density approximation).

$E_\nu = 600$ MeV, iron target.



C. Juszczak, J. Nowak, JTS, Eur. Phys. J. C39 (2005) 195

Interesting:

- reduction at lowest energy transfers q^0
- enhancement at larger q^0

The old piece of code that recently been reactivated

- works for oxygen, argon, iron
- hadronic part not yet integrated with the NuWro cascade.

Ewro (work in progress)

The main idea: to test NuWro nuclear model using precise electron scattering data

- Fermi gas and local Fermi gas
- QE and Δ regions only
- for Δ non-resonant background after E. Hernandez, J. Nieves, M. Valverde, Phys. Rev. D76 033005 (2007)
- EM form factors from J. Żmuda, K.M. Graczyk, arXiv:1501.03086v4
- Δ self-energy following E. Oset, L.L. Salcedo, Nucl. Phys. A468 631 (1987)

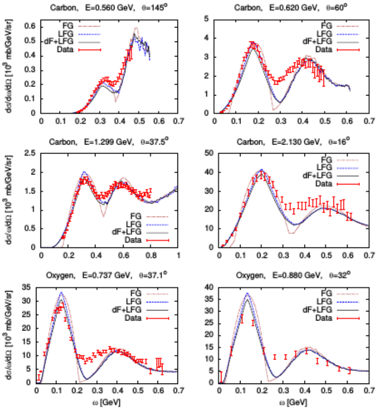


Fig. 1. Differential cross sections for electron scattering off carbon and oxygen obtained within eWro (for various beam energies, E, and scattering angles, θ).

K. Graczyk, C. Juszczak, JTS, J. Żmuda, arXiv:1510.03268

Applications

Most of recent ν cross section measurements/studies are inclusive ones.

- several dynamical mechanisms contributed
- important role of FSI effects
- in order to understand the results completely it is preferable to use MC.

Two examples:

π^+ production measurements of MiniBooNE and MINERvA

JTS, J. Żmuda, Phys. Rev. C91 (2015) 4, 045501

ArgoNeuT study of two proton final states

K. Niewczas, JTS, arXiv:1511.02502

Application 1: π^+ production on (mostly) carbon target

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.

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 not much phase space for many π^0s

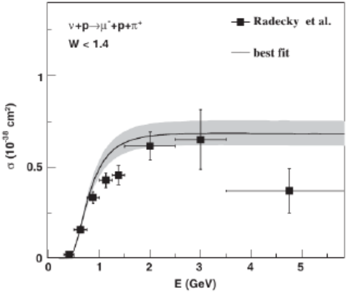
MinoBooNE and MINERvA

Does it make sense to compare MiniBooNE and MINERvA results?

- very different energies

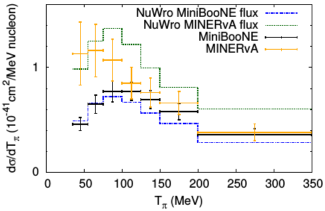
But...

- the same Δ mechanism

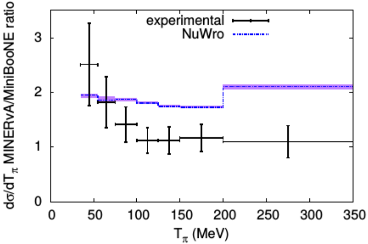


- the only major difference is coming from ν energy is normalization
- π^+ production cross section at 4 GeV is $\sim$ twice that at 700 MeV
- less important: slightly different definitions of the signal.

MinoBooNE and MINERvA

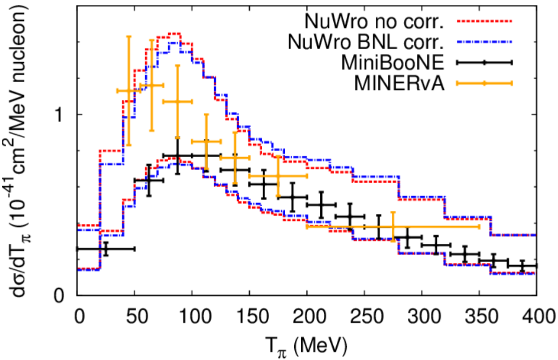


- the ratio is expected to be quite flat
- there is a worrying data/MC normalization dicrepancy, more than 40%



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.

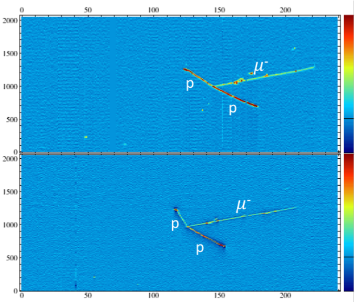
π angular distribution from Δ decay - effect



The shape is slightly changed. The effect is a few %. No impact on the conclusions.

Application 2: two-proton events in 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 ?!

ArgoNeuT – NuWro simulations

	ν-mode		$\bar{\nu}$-mode		2p events	
	(% of sample of 2p events)				(% of total)	
ArgoNeuT	11	(37%)	19	(63%)	30	(3.4%)
NuWro: LFG	60680	(22.3%)	211346	(77.7%)	272026	(1.5%)
NuWro: SF	64558	(22.5%)	222402	(77.5%)	286960	(1.6%)

Proton momentum $\Leftrightarrow$ track length

$$T(R) = \frac{A}{b+1} R^{b+1},$$

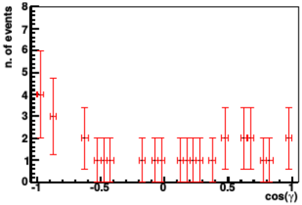
$A = 17$ in the units of MeV/cm$^{(1+b)}$, $b = -0.42$.

Protons with momentum 500 MeV/c travel average distance of 12.2 cm.

- ν_μ interactions from ν_μ and $\bar{\nu}_\mu$ beams
- normalization according to numbers of efficiency corrected CC events (729+3759)
- proton tracks must be fully contained in the detector 47x40x90 cm^3
- two NuWro modes; one with spectral function for CCQE (some events occur on back-to-back neutron-proton SRC pairs)
- hole SF and Nieves MEC are combined together; inconsistent but both are sources of events on correlated nucleon pairs.

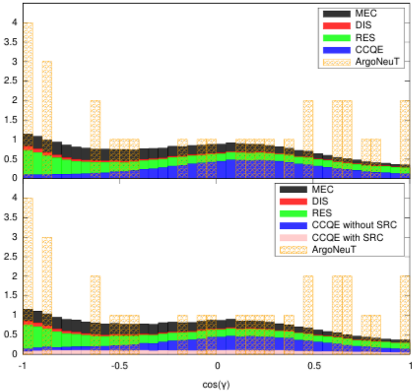
ArgoNeuT – NuWro simulations

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



NuWro results used as the probability distribution:

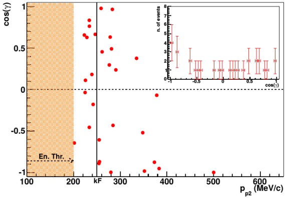
- $P(4+) = 2.9\%$ for the LFG model,
- $P(4+) = 3.0\%$ for the SF approach.



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

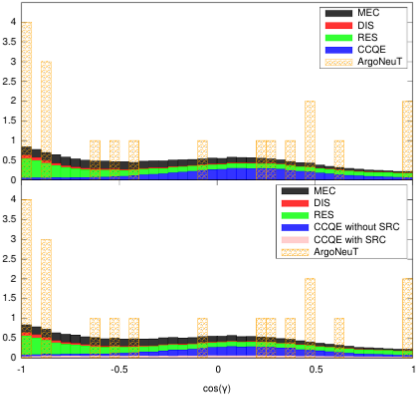
ArgoNeuT – NuWro simulations

A restricted subset of 19 events.



Extra condition:
$p1, p2 > 250$ MeV/c.

- $P(4+) = 1.1\%$ for the LFG model,
- $P(4+) = 1.1\%$ for the SF approach.



NuWro predicts too few hammer events.

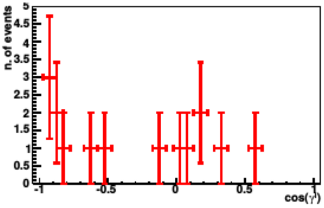
ArgoNeuT – NuWro simulations

Results for reconstructed events.

- 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.

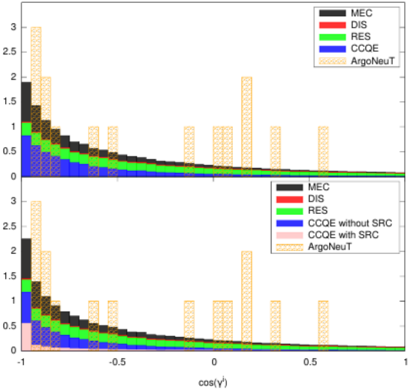
ArgoNeuT – NuWro simulations

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



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

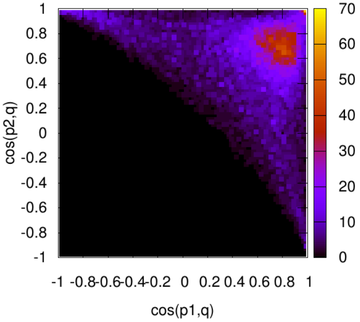


In the SF mode many SRC pairs populate region $\cos\gamma^i \sim -1$.

Many *reconstructed* back-to-back initial pairs originate from CCQE or RES.

ArgoNeuT – NuWro simulations

The preference of back-to-back *reconstructed configurations* is kinematical in origin.



Despite FSI there is a lot of correlation between $\vec{q}_{rec}$ and $\vec{p}_1$, $\vec{p}_2$ (on the top).

- 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.

Conclusions

- NuWro is doing well, though ...

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  - ... we suffer from a severe lack of **active** manpower
  - anybody interested to join the NuWro team as overtime job?...

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Main plans:

- eWro
- event reweighting tools
- improvements in the cascade model
- a service to the community.