NuWro and eWro

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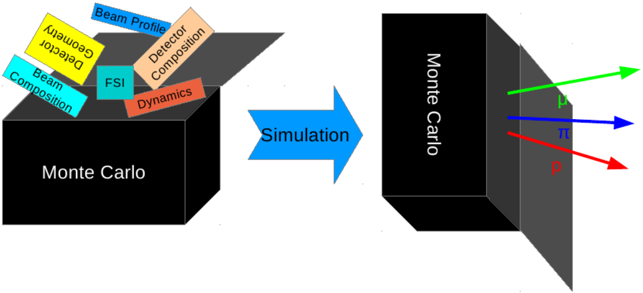
Outline:



- NuWro.
- A few data/MC comparisons.
- eWro.

NuWro – basic information

- Monte Carlo generator of neutrino interactions
- begining ∼ 2005 at Wrocław University,
- basic motivation: investigation of an impact of differences between nuclear models on observables
- optimized for ∼ 1 GeV neutrinos
- can handle all kind of targets, neutrino fluxes, equipped with detector interface
- used by many experimental groups (T2K, MINERvA, MicroBooNE, ...)
- written in C++
- output files in ROOT format
- PYTHIA is used for hadronization in DIS
- open source code, repository: https://github.com/NuWro/nuwro
  - the most recent version is 21.09

NuWro project

A major part of NuWro physics models were investigated and implemented by PhD students: Jarosław Nowak (2006), Tomasz Golan (2014), Kajetan Niewczas (2022?).

The structure of the code was constructed by Cezary Juszczak.

Important contributions were done by Jakub Żmuda, Krzysztof Graczyk, Artur Ankowski.

Reweighting tools were implemented by Luke Pickering and Patrick Stowell.

Basic references:

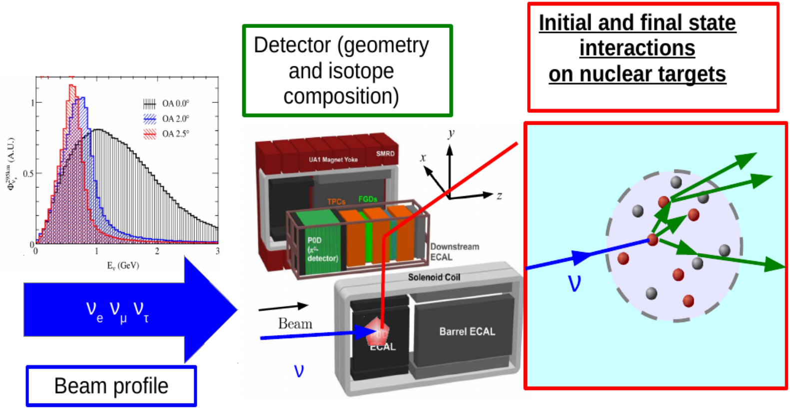
C. Juszczak, J.A. Nowak, and J.T. Sobczyk, *Simulations from a new neutrino event*, Nucl.Phys.B Proc.Suppl. 159 (2006) 211-216.

T. Golan, C. Juszczak, J.T. Sobczyk, *Final State Interactions Effects in Neutrino-Nucleus Interactions*, Phys.Rev.C 86 (2012) 015505.

NuWro Neutrino Monte Carlo Generator: Physics, Design and Usage (in preparation)

PhD thesis of J. Nowak (in Polish) and T. Golan.

NuWro functionalities



NuWro running

NuWro needs for every run:

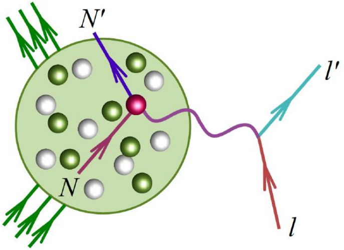
- information about neutrino flux
  - energy spectrum? flavor composition?
- information about the target
  - free nucleon? nucleus? compoud target?
- physics model configuration (defined in the file `params.txt`);

In cross section studies NuWro provides two pieces of information:

- the average cross section (which translates into the overall expected number of events if flux (POT) and detector size are known)
  - NuWro does not use tabularized cross sections; all the cross sections are calculated in real time
- samples of equal weight events
  - alternatively weighted events can also be produced.

Nuclear effects - a big picture.

In the 1 GeV region nuclear effects are treated in the impulse approximation–IA scheme: neutrinos interact with individual bound nucleons or correlated pairs of nucleons.



A. Ankowski

Within IA one needs a joint probability distribution of momenta and binding energies of target nucleons.

Any ν nucleus interaction is viewed as a two-step process: a primary interaction is followed by final state interactions (FSI): before leaving nucleus hadrons undergo reinteractions.

- In some models de Forest prescription for off-shell matrix elements is applied.

NuWro does not model nucleus de-excitation and typically nucleus is left in an excited state.

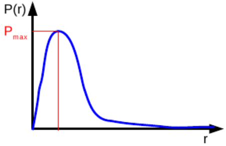
Impulse approximation

In impulse approximation interaction point is selected at random using nucleus density as probability density

- this information is used in NuWro FSI model
- spherical symmetry is assumed
- NuWro has density profiles of practically all isotopes
- in local Fermi gas model nucleon momentum is selected in the next step

- 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!)

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

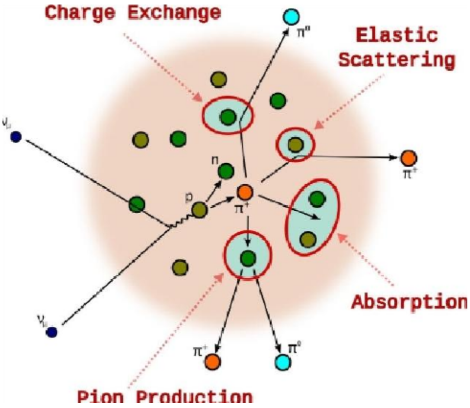


- Each distance → $P=P(r)/P_{max}$.
- Choose proton (P=p/(p+n)) or neutron (P=n/(p+n)). Special case: CCQE: always neutron (neutrinos) or always proton (anti-neutrinos).

from J. Żmuda

Final state interactions:

What is observed are particles in the final state.



T. Golan

Pions...

- can be absorbed
- can be scattered elastically
- (if energetically enough) can produce new pions
- can exchange electic charge with nucleons

A similar picture can be drawn for nucleons.

Basic interaction modes – neutrino-nucleon scattering

NuWro distinguishes several *dynamics* for neutrino-nucleon scattering.

i) quasi-elastic (QEL)

$$\nu_l \; n \rightarrow l^- \; p, \quad \bar{\nu}_l \; p \rightarrow l^+ \; n$$

and its neutral current counterpart:

$$\nu \; N \rightarrow \nu \; N$$

ii) resonance excitation (RES) defined by $W \leq 1.6$ GeV; for example

$$\nu_\mu \; p \rightarrow \mu^- \; \Delta^{++} \rightarrow \mu^- \; p \; \pi^+$$

iii) “deep inelastic scattering” (DIS) defined by $W > 1.6$ GeV

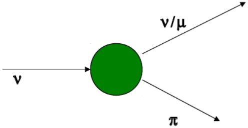
iv) quasi-elastic hyperon production (HYP)

$$\bar{\nu}_l + p \rightarrow l^+ + \Lambda, \quad \bar{\nu}_l + p \rightarrow l^+ + \Sigma^0, \quad \bar{\nu}_l + n \rightarrow l^+ + \Sigma^-$$

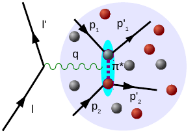
Basic interaction modes – neutrino-nucleus scattering

In the case of nucleus target there are two other "basic" dynamics:

v) (COH) coherent pion production



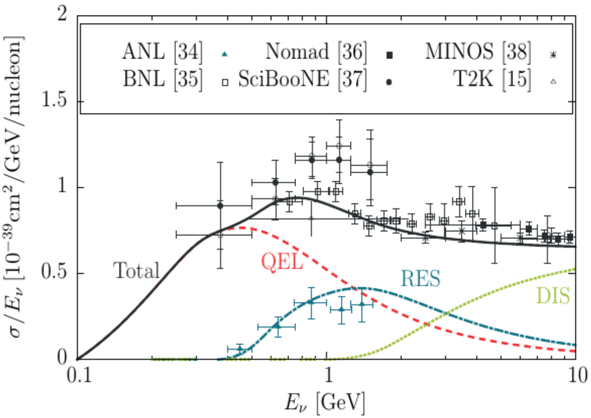
vi) (MEC) two body current



from J. Żmuda

Neutrino-electron interactions (LEP) are also included:

$$\nu_l \ e \to \nu_l \ e, \quad \nu_l \ e \to \nu_e \ l, \quad \bar{\nu}_l \ e \to \bar{\nu}_l \ e, \quad \bar{\nu}_e \ e \to \bar{\nu}_l \ l.$$



T. Golan, PhD thesis

Black line shows NuWro results.

Example: proton observables

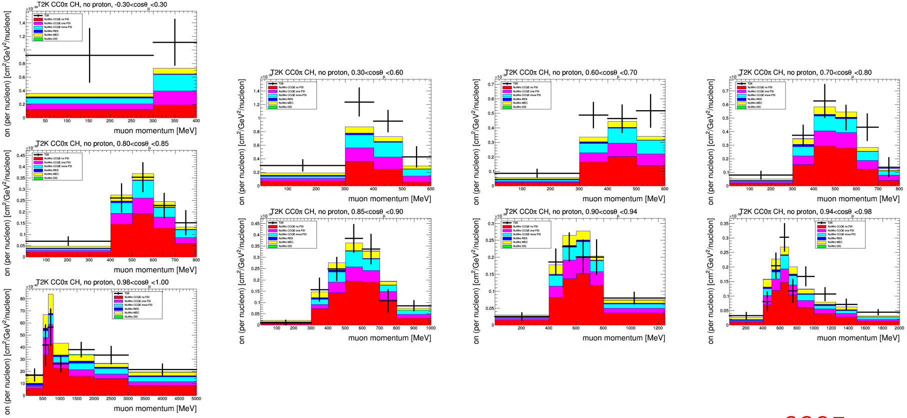
Motivation: it order to resolve contributions to CCQE it is necessary to study final state protons.

Typical configuration in data/MC comparisons

- LFG+RPA for QEL
- Valencia model for MEC

T2K CC0π with no detected proton

Phys.Rev. D98 (2018) 032003



Individual contributions from particular interaction modes are shown, as modeled by NuWro: CCQE with no FSI, CCQE with one FSI, CCQE with more FSI, RES, MEC, DIS.

- A lot of sensitivity to proton FSI.

T2K proton data – “inferred kinematics”

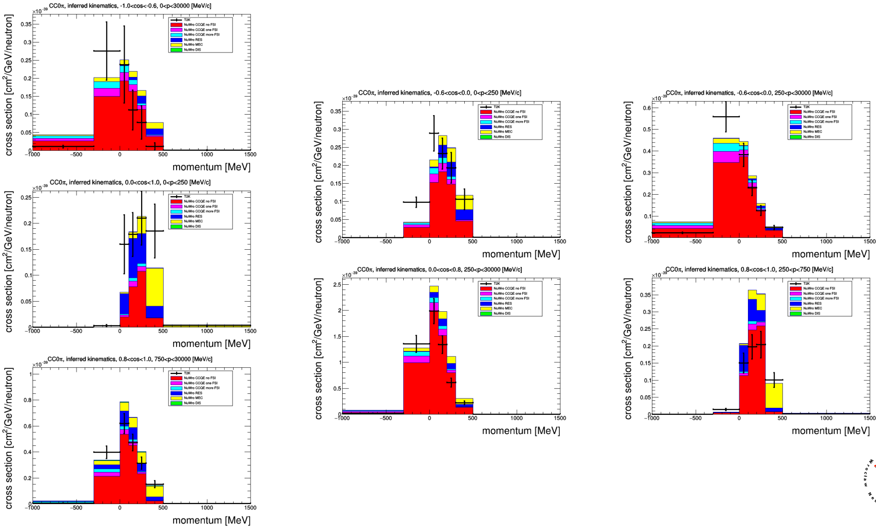
Phys.Rev. D98 (2018) 032003

- Starting point: assumption that interaction was CCQE and occured on a bound neutron at rest.
- FSI are neglected.
- From energy and momentum conservation one can calculate expected momentum of knocked-out proton $\vec{p}^{inferred}$
- A difference with respect to what is observed $\vec{p}^{observed}$ will be shown on the next slide.
- On the horizontal axis the variable is $|\vec{p}^{observed}| - |\vec{p}^{inferred}|$

It is an alternative to better known approach of *transverse kinematics imbalance* proposed by Xianguo Lu.

T2K proton data – “inferred kinematics”

Phys.Rev. D98 (2018) 032003



eWro

eWro

- NuWro framework is applied to electron scattering.
- As much as possible is left untouched
  - procedures to select initial nucleon, generatoe events etc
  - FSI is exactly the same.

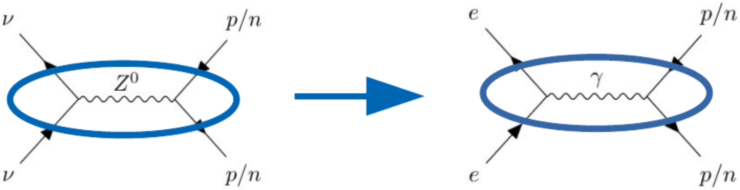
A general idea is to use electron scattering data to test implemented models.

eWro

- For a moment eWro is available for QE dynamics only
- available nuclear models:
  - local Fermi gas
  - global Fermi gas
  - Bodek-Ritchie
  - hole spectral function
  - effective momentum and density dependent potential

eWro

- Vertices, boson propagator, vector form-factors are amended accordingly; axial contribution is removed.

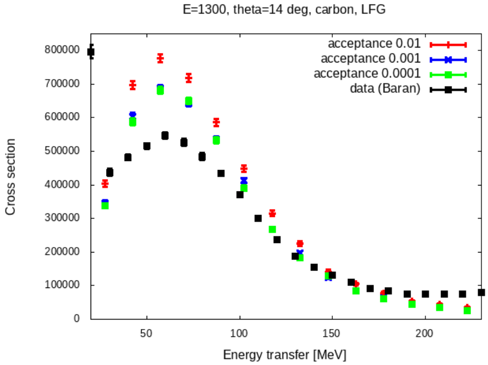


eWro

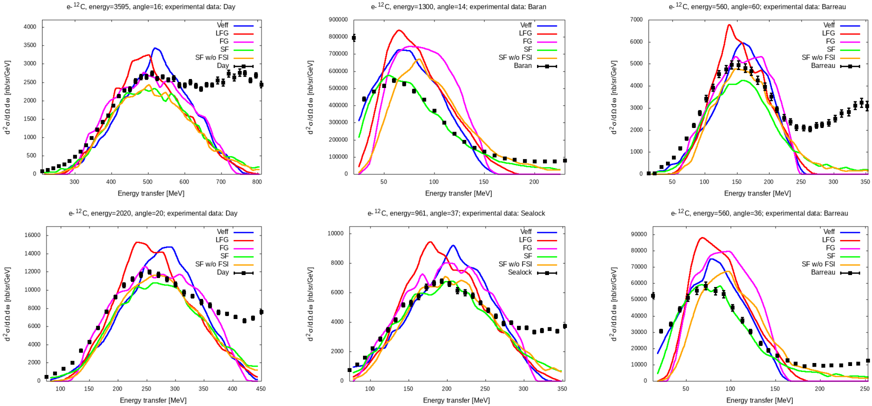
A few technicalities

- one must set dyn_qel_el $= 1$
- one must define a spherical cone from which events are collected with two parameters:
  - el_costh_lab (central value)
  - el_costh_del so that electrons are accepted from the region (el_costh_lab - el_costh_del, el_costh_lab + el_costh_del)
- normalization is such that the output in $\frac{d\sigma}{d\cos\theta}[\mathrm{cm}^2/\mathrm{nucleon}]$

It is important to adjust properly acceptance (smaller acceptance results in much larger execution time)



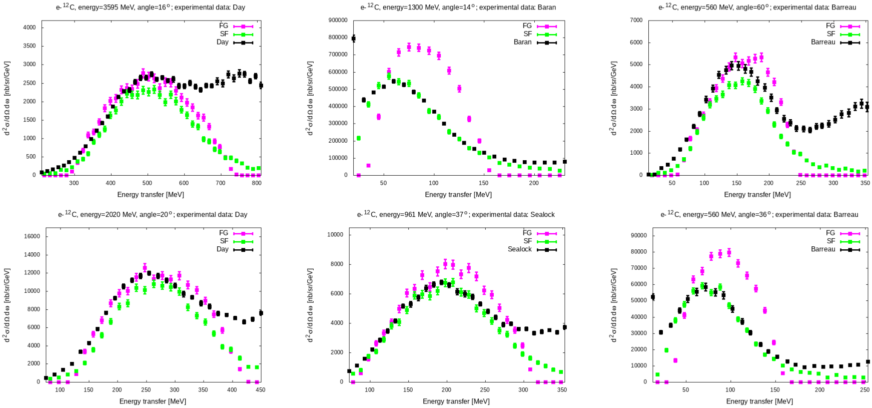
eWro



Results from 5 available CCQE models.

On the next slide global Fermi gas and hole spectral function (with FSI).

eWro



Work in progress (unfortunately not yet finished): a comparison to the data published in Nature 599 (2021) 7886, 565-570

Conclusion

eWro is under development, giving a possibility to test nuclear model implemented in NuWro.