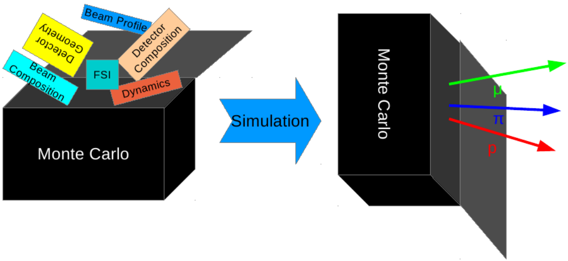
NuWro – status and plans

Jan T. Sobczyk

Wrocław University

Workshop on Neutrino Event Generators, Fermilab, March 15-17, 2023



Outline (following Steven's request)

- General information.
- Recent and exciting developments, priorities.
- New theory calculations, BSM, compatibility of languages.
- Flux and geometry.
- Information which is stored.
- Systematic uncertainties.
- Interest in defining standards.

NuWro – general information

- Monte Carlo generator of neutrino interactions
- begining $\sim$ 2005 at Wrocław University,
- basic motivation: investigation of an impact of alternative choices of nuclear models on observables
- optimized for $\sim$ 1 GeV neutrinos
- 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 – general information (2)

A major part of NuWro physics models were investigated and implemented by PhD students: Jarosław Nowak (2006), Tomasz Golan (2014), Kajetan Niewczas (2023?).

The structure of the code was constructed by Cezary Juszczak.

Important contributions from Jakub Żmuda, Krzysztof Graczyk, Artur Ankowski.

Reweighting tools added 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 (in English).

NuWro – genaral information (3)

NuWro distinguishes several *dynamics* for neutrino–free target scattering.

i) quasi-elastic (QEL)

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

and its neutral current counterpart:

$$\nu\ N \to \nu\ N$$

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

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

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

iv) quasi-elastic hyperon production (HYP)

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

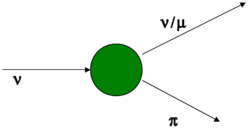
v) neutrino-electron scattering (LEP)

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

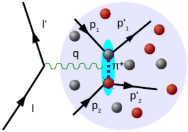
NuWro - general information (4)

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

vi) (COH) coherent pion production



vii (MEC) two body current



from J. Żmuda

eWro

- NuWro framework is applied to electron scattering.
- As much as possible is left untouched, in particular
  - procedures to select initial nucleon, generatate events, assign kinematics
  - FSI.

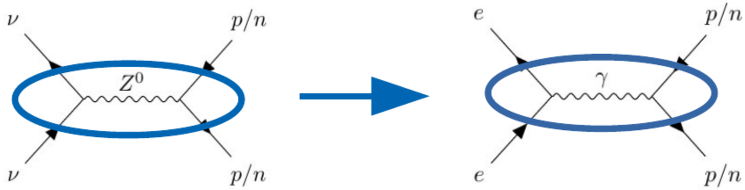
A general idea is to use electron scattering data to test implemented models.

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 modified accordingly; axial contribution is removed.



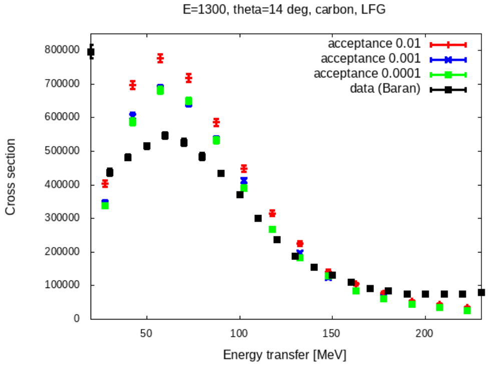
eWro

A few technicalities

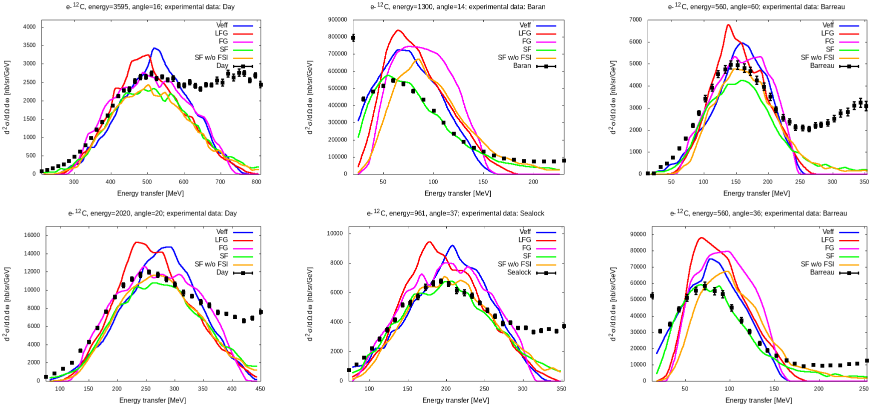
- one must set dyn_qel_el $= 1$
- one must define a spherical cone from which events are collected with two parameters:
  - el_costh_lab (central value)
  - el_costh_del so that electrons are accepted from the region (el_costh_lab - el_costh_del, el_costh_lab + el_costh_del)
- normalization is such that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

It is important to adjust properly acceptance.

- smaller acceptance leads to better precision at a cost of larger execution time;
- a reasonable compromise must be found.



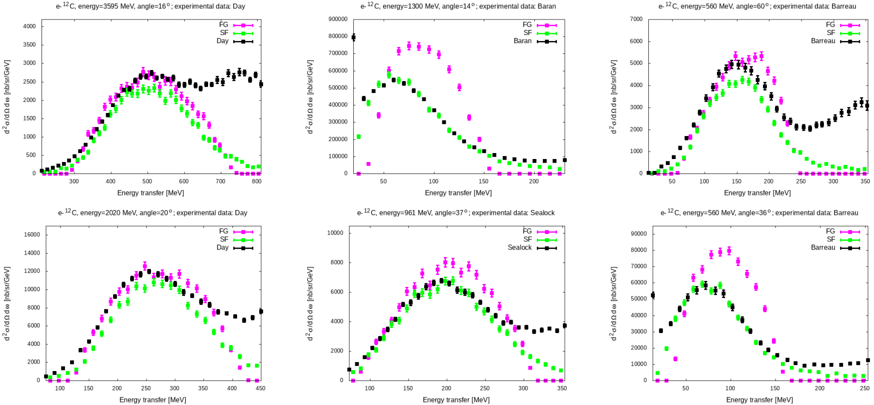
eWro



Results from 5 available CCQE models.

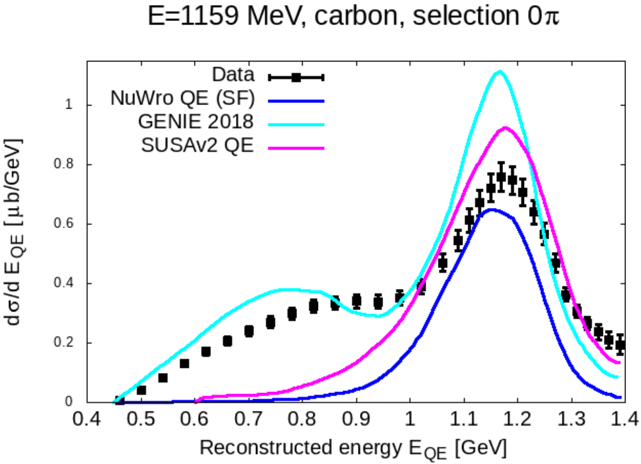
On the next slide global Fermi gas and hole spectral function (with FSI).

eWro


e- 12C, energy=3595 MeV, angle=16°; experimental data: Day
FG
SF
Day
d2σ/dΩdω [nb/sr/GeV]
Energy transfer [MeV]
e- 12C, energy=1300 MeV, angle=14°; experimental data: Baran
FG
SF
Baran
d2σ/dΩdω [nb/sr/GeV]
Energy transfer [MeV]
e- 12C, energy=560 MeV, angle=60°; experimental data: Barreau
FG
SF
Barreau
d2σ/dΩdω [nb/sr/GeV]
Energy transfer [MeV]
e- 12C, energy=2020 MeV, angle=20°; experimental data: Day
FG
SF
Day
d2σ/dΩdω [nb/sr/GeV]
Energy transfer [MeV]
e- 12C, energy=961 MeV, angle=37°; experimental data: Sealock
FG
SF
Sealock
d2σ/dΩdω [nb/sr/GeV]
Energy transfer [MeV]
e- 12C, energy=560 MeV, angle=36°; experimental data: Barreau
FG
SF
Barreau
d2σ/dΩdω [nb/sr/GeV]
Energy transfer [MeV]

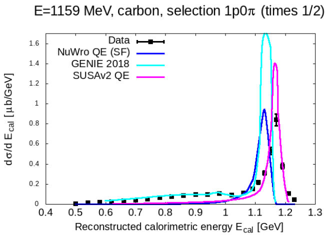
Comparison to the data published in Nature 599 (2021) 7886, 565-570

The first selection is 0π.



Comparison to the data published in Nature 599 (2021) 7886, 565-570

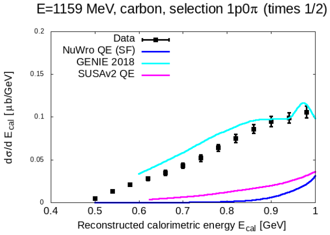
For most results the selection is $1p0\pi$.

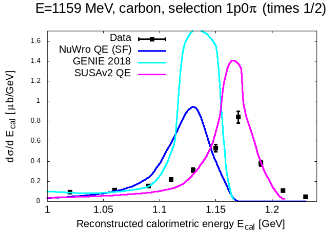


Problems with the energy scale.

- $E_{rec} = \sum_j E_j + \epsilon_j$, for protons $\epsilon_j = 21$ MeV (info from Adi)
- Here the data peak exceeds $E_{electron}$ by ~ 10 MeV
- From the paper: "We adjusted $\Delta\epsilon$ so that the peaks in the Ecal spectrum for low-PT events reconstructed to the correct beam energy."

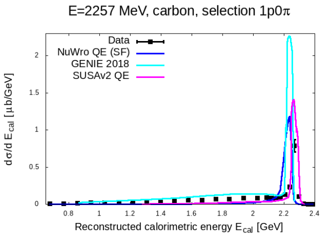
Below, in more detail.





Comparison to the data published in Nature 599 (2021) 7886, 565-570

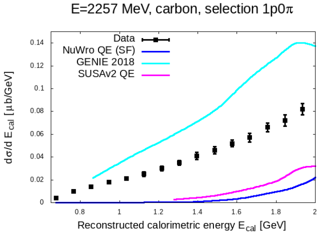
For most results the selection is $1p0\pi$.

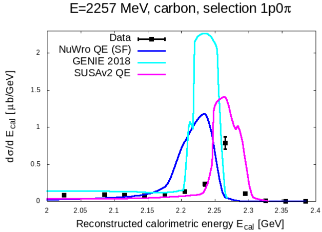


Problems with the energy scale.

- $E_{rec} = \sum_j E_j + \epsilon_j$, for protons $\epsilon_j = 21$ MeV (info from Adi)
- Here the data peak exceeds $E_{electron}$ by $\sim$ 10 MeV
- From the paper: "We adjusted $\Delta\epsilon$ so that the peaks in the Ecal spectrum for low-PT events reconstructed to the correct beam energy."

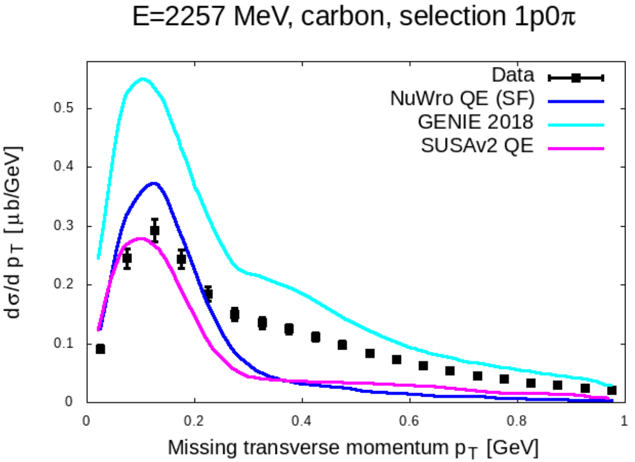
Below, in more detail.



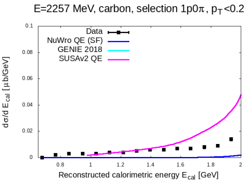


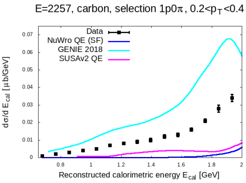
Comparison to the data published in Nature 599 (2021) 7886, 565-570

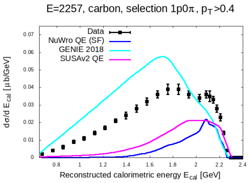
For the selection is $1p0\pi$ transverse kinematic variables were studied and then used in more detail analysis of E_{rec}.

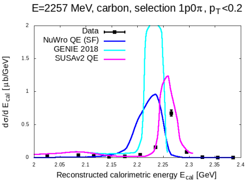


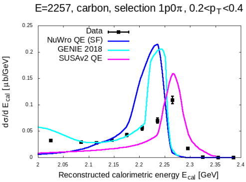
Comparison to the data published in Nature 599 (2021) 7886, 565-570











Reconstructed calorimetric energy - slices in missing transverse momentum.

In the slice $p_T < 0.2$ GeV the maximum is located in the bin $(2.22, 2.25)$ i.e. slightly below $E_{electron}$.

Current activities/plans for the future

- New single pion production model employing theoretical computations of the Ghent group

  R. Gonzalez-Jimenez, K. Niewczas, N. Jachowicz, Phys.Rev.D 97 (2018) 1, 013004

  K. Niewczas, A. Nikolakopoulos, J.T. Sobczyk, N. Jachowicz, R. Gonzalez-Jimenez, Phys.Rev.D 103 (2021) 5, 053003

- MEC Ghent model

  K. Niewczas, in preparation

- Nuclear de-excitation model

  KamLAND Collaboration, S. Abe, et al., e-Print: 2211.13911 [hep-ex]

  A. Ershova, S. Bolognesi, et al., Phys.Rev.D 106 (2022) 3, 032009

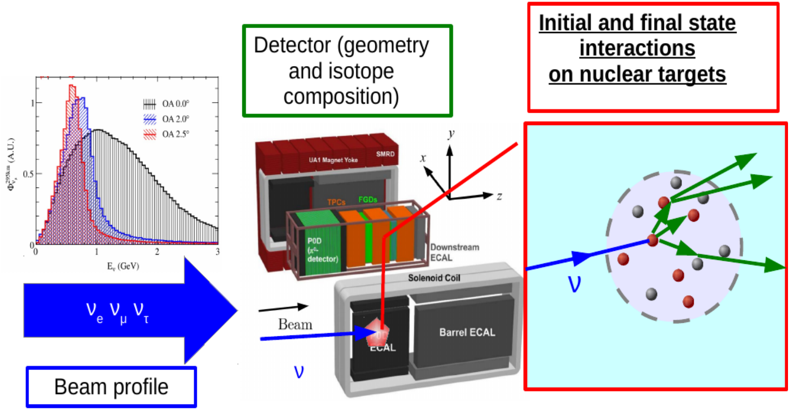
- Argon spectral function

  Jefferson Lab Hall A Collaboration, L. Jiang, et al., Phys.Rev.D 105 (2022) 11, 112002, Phys.Rev.D 107 (2023) 1, 012005.

New theory calculations etc

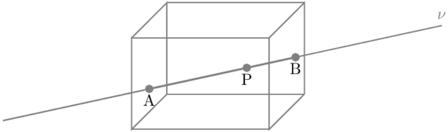
- We have been thinking about BSM for some time...
- The problem is manpower...

NuWro – flux and geometry



NuWro – flux and geometry (2)

- Detector geometry should be described with GEANT4.
- For fluxes an algorithm proposed by Cezary Juszczak to deal with non-uniform beams is employed.



Read all neutrinos into memory discarding (but calculating their percentage) all ν not crossing the box of interest. Then repeat:

1. Get ν from the beam (with probability proportional to its norm).
2. Find entry/exit points A/B and calculate $l =$ length of $\overline{AB}$
3. Take random $P \in \overline{AB}$
4. Calculate $d =$ density of matter at P.
5. Take random $x \in [0, d_{\max} \cdot l_{\max}]$ and go to 1. if $x > d \cdot l$.
6. Get isotope A according its mass share in matter at P.
7. Enter properties of A (p, n, k_F, E_b) in `params` structure.
8. Simulate event for isotope A and decrease its weight by percentage of discarded neutrinos.

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.

Event reweighting tools

- For some parameters **reweight-to** reads events from the output root file and re-calculates the cross sections for the new values of parameters, keeping the kinematics and the event topology unchanged.
- Two options for storing the effect od reweighting: either a new root file with modified weights, or a file containing array with new weights
- A list of available reweighting includes: C_5^A, M_A and non-resonant background for pion production, M_A for CCQE and NC elastic, z-expansion parameters, overall normalization of individual dynamics.

Interest in defining standards

YES!

- To avoid repeating the same work many times.
- Perhaps an initial step in unification?