NuWro - neutrino event generator

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Overview

- Main features
- Probabilistic scheme and assumptions
- Efficiency considerations
- Beam types and implementation details
- Target types
- Detector geometry implementation
- Impulse approximation
- Primary vertex
- QEL, RES, DIS, COH, MEC interaction channels
- FSI - intranuclear cascade
- Outlook

Main features

Developed in Wrocław since about 2002 (encouraged by late D. Kiełczewska) by: J.Sobczyk, J.Nowak, T.Golan. J.Żmuda, C.J., (important contributions from K. Graczyk, A. Ankowski, ...)

- Fast and easy to use
- Arbitrary Beam and Detector Geometry (defined in external files)
- Realistic density profiles for all nuclei automatically used for reaction probability LDA and FSI
- First MC to include Spectral Function, MEC,
- root output file contains a tree of event objects
- Online interface exists.

Probabilistic scheme – assumptions

- Original (in memory) events are **weighted**
- $mean(weight)$ = cross section per nucleon.
- Output (in file) events are (by default) **unweighted**
- the probability of accepting event $= weight/max(weight)$.
- efficiency $= mean(weight)/max(weight)$.
- peeks in the event weight destroy efficiency.
- to prevent peeks many techniques are used.

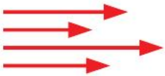
Efficiency tricks - identify event clases

Ideal - efficiency = 100% when all events have the same weight.
Practical - generate in one go only events with similar weight.

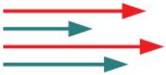
- NuWro generates events of certain classes separately:
  - Test run - calculate mean(weight), max(weight) and desired number of events for each dynamical channel.
  - Real run - generate desired number events for each channel separately.
  - Copy generated events to one file in random order.
- In Nuwro there are 10 classes of events. Five dynamical channels: QEL, RES, DIS, COH, MEC. Each divided into CC and NC events.
- For mixed (neatrino/antineutrino) beams it could be benefitial to separete neutrino and antineutrino events (easy but not done).
- One could go even further and divide events according to neutrino energy if beam is not monoenergetic.

Nuwro generates **unweighted** neutrinos according to energy profile or neutrino list read from MC data files.
Three options:

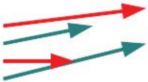
- one flavour neutrinos, fixed direction, an arbitrary energy distribution



- a mixture of flavours, each one with its own energy distribution but same direction



- neutrinos retrieved from data files (arbitrary flavours, directions, energies)



Beam efficiency - integrate energy profile

Effective creation of **unweighted** neutrinos:

- w_i - array of energy profile bin heights or neutrino weights.
- partial sums $s_i = w_1 + ... + w_i$ satisfy $0 = s_0 \leq s_1 \leq ... \leq s_n$
- bisection can be used to find which interval $[s_{i-1}, s_i)$ contains random $x \in [0, s_n)$ and create neutrino of corresponding energy $E \in [E_{i-1}, E_i)$ or just i-th neutrino.
- when detector geometry is used the neutrinos missing the region of interest are discarded upon reading from file (but accounted for in the POT calculations).
- due to logarithmic performance of bisection the ND280 neutrino beam ($\sim$ 60 million neutrinos) is hardly slower than the mono-energetic beam.

Biased beam for DIS and RES

In these channels the cross section is proportional to energy at hight E so there is no upper limit on $max(weight)$.

Even one high energy tail neutrino can destroy efficiency.

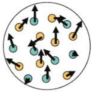
Therefore in NuWro each beam has two copies of weight arrays:

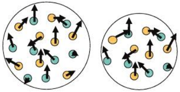
- basic version with weights w_i generates unweighted neutrinos.
- for DIS and RES interaction channels weights $w_i' = E_i w_i$ are used instead of w_i so more high energy neutrinos are produced but the events obtain initial weight factor $\sim 1/E$ which cancels the cross section divergence at high E.
- this approach could in principle be generalized so that for every interaction there is an energy dependant bias proportional to the total cross section. However, significant efficiency improvements for other channels are unlikely.

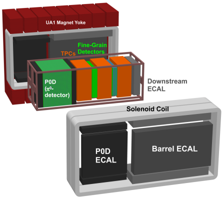
Target

The target class is responsible for selecting nucleus on which the interaction is to take place. There are three options:

- a single isotope model (including also a single nucleon mode)
- a mixture of isotopes (composition defined by relative weights)
- detector's geometry given as a root Geometry object.
  - geometry is read from a file containing the detector's definition
  - region of interest can be limited to a box by specifying its center and halfsize vectors.







Detector target

- Detector's geometry is generated by the GEANT4 software.
- full agreement with the detector MC.
- no need to track neutrino through the detector.
  - for spatially uniform beams, **random point inside the region of interest** is accepted according to material density at that point.
  - for beams of neutrinos with given trajectories, **random point on neutrino trajectory's intersection with the region of interest** is accepted according to material density multiplied by the intersection length.
- for each try a new neutrino is taken from the beam until some point of interaction is accepted.
- if material at the interaction point is a mixture the concrete isotope is chosen based on its mass share in the mixture.
- the scheme is simple, fast, and no additional weighting factors appear.

Interactions - basic assumptions

At this point the event generator knows neutrino flavour, momentum and the target isotope.

- Impulse Approximation - nucleus is composed of quasi-free nucleons.
- primary interaction (with a single nucleon) is followed by Final State Interactions
- the FSI do not affect the final lepton, or the event weight.
- FSI effects are modelled within a semiclassical intranuclear cascade model - point particles (pions and nucleons) moving on strait lines between collisions with nuclear matter.
- cross sections of nucleons and pions with nuclear matter are assumed the same as with free nucleons.

Dynamical Channels

In all but the coherent channel the event is split into to phases:

- the primary interaction and
- FSI - implemented as intranuclear cascade.

The primary interaction is one of:

- QEL - quasi elastic scattering (cc/nc)
- RES - resonance region (cc/nc)
- DIS - deep inelastic scattering
- COH - coherent scattering
- MEC - meson exchange current

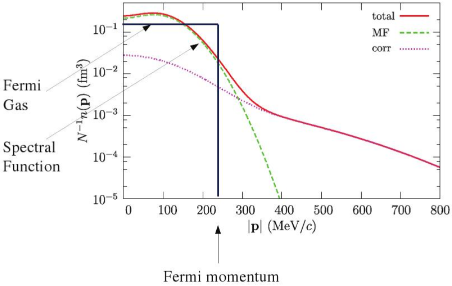
each mode can be separately switched on and off.

The primary interaction involves concrete nucleon (in MEC nucleon pair)

Primary interaction

In each (but the coherent) case a particular nucleon is selected with nuclear matter density used as the probability density.
Its momentum is chosen:

- from a ball with the radius set to Fermi momentum
- as a draw from the Spectral Function.



Kinematics is usually solved in the CMS frame (of the nucleon and neutrino pair) where every scattering angle is possible. Particles in the final state are boosted back to the LAB frame.

QEL - Quasielastic interaction

The standard Llewellyn Smith formula, with many vector form factors sets: dipole, BBA03, BBBA05, Alberico, Graczyk et al.

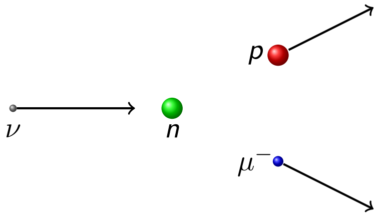
Options for kinematics and nuclear effects:

- global or local Fermi Gas from realistic density profiles for all nuclei.
- Spectral Function (Carbon, Oxygen, Iron, Calcium and Argon)
    - for Carbon, Oxygen and Iron tables obtained from Omar Benhar
    - for Calcium and Argon the approximate model [A.M. Ankowski, JTS, Phys. Rev. C**77** 044311 (2008)]
    - De Forest prescription for off-shell matrix elements..
- momentum dependent nuclear potential (Brieva, DellaFiore) [C. Juszczak, J.A. Nowak, and JTS, Eur. J. Phys. C**39** (2005) 195]
- RPA corrections by K. Graczyk (option)

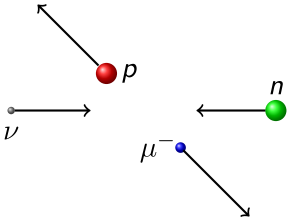
Quasielastic reaction on free nucleon target

$$\nu_l + n \to l^- + p,$$

$$\bar{\nu}_l + p \to l^+ + n.$$



QEL scattering in LAB frame
$\cos\theta_{lab} \in [??, 1]$.



QEL scattering in CMS frame
$\cos\theta_{cms} \in [-1, 1]$

QEL - kinematics improvement

The differential cross section $d\sigma/d\cos\theta_{CMS}$ is very convenient to use in event generation. In many cases (QEL and COH are examples) this cross section has peak in the forward direction.

- The simplest way to remove this peak is to change the integral

$$\sigma = 2\pi \int_{-1}^{1} f(x)\, dx$$

where $x = \cos\theta_{cms}$, using the substitution $x = 1 - 2y^2$, into

$$\sigma = 2\pi \int_{0}^{1} f(1-2y^2) 4y\, dy$$

- random $x \in [-1, 1]$ is replaced with random $y \in [0, 1]$.
- for neutrino energies around 1 GeV the increase in efficiency is from about 15% to about 40%.
- this can be generalized to any positive power of y but in most cases $n = 2$ is just good enough.

Resonance (Δ) production

- defined by $W < 1.6$ GeV
- only Δ treated explicitly
- **no** Rein-Sehgal model
  - quark-hadron duality,
  - heavier resonances not seen in reactions on nuclear targets
  - our hadronization model works well for low W
- non-resonant background is approximated as a fraction of the DIS contribution
- smooth (linear) transition to pure DIS for $W \in (1.3, 1.6)$ GeV

Vector current:

$$\langle \Delta^{++}(p') | \mathcal{J}^V_\mu | N(p) \rangle = \sqrt{3} \bar{\Psi}_\lambda(p')$$

$$\times \left[g^\lambda_{\ \mu} \left(\frac{C_3^V}{M} \gamma_\nu + \frac{C_4^V}{M^2} p'_{\ \nu} + \frac{C_5^V}{M^2} p_\nu \right) q^\nu \right.$$

$$\left. - q^\lambda \left(\frac{C_3^V}{M} \gamma_\mu + \frac{C_4^V}{M^2} p'_\mu + \frac{C_5^V}{M^2} p_\mu \right) \right] \gamma_5 u(p),$$

M - nucleon mass, $\Psi_\mu(p')$ - Rarita-Schwinger field for Δ, $u(p)$ - Dirac spinor for N, $q^\mu = p'^\mu - p^\mu$.

Axial current:

$$\left\langle \Delta^{++}(p') \right| \mathcal{J}_{\mu}^{A} \left| N(p) \right\rangle = \sqrt{3}\bar{\Psi}_{\lambda}(p')$$

$$\times \left[g^{\lambda}_{\ \mu} \left(\gamma_{\nu} \frac{C_3^A}{M} + \frac{C_4^A}{M^2} p'_{\ \nu} \right) q^{\nu} - q^{\lambda} \left(\frac{C_3^A}{M} \gamma_{\mu} + \frac{C_4^A}{M^2} p'_{\ \mu} \right) \right.$$

$$\left. + g^{\lambda}_{\ \mu} C_5^A + \frac{q^{\lambda} q_{\mu}}{M^2} C_6^A \right] u(p).$$

There are altogether 7 form-factors.

Axial FF

[K.M. Graczyk, D. Kiełczewska, P. Przewłocki, and JTS, Phys. Rev. D**80** (2009) 093001]

- typically one sets $C_3^A(Q^2) = 0$;
- the Adler model suggests $C_4^A(Q^2) = -C_5^A(Q^2)/4$,
- the PCAC hypothesis implies $C_6^A(Q^2) = \frac{M^2}{m_\pi^2+Q^2} C_5^A(Q^2)$, m_π is the pion mass;
- $C_5^A(0)$ from the off-diagonal Goldberger-Treiman relation: $C_5^A(0) = \frac{g_{\pi N\Delta} f_\pi}{\sqrt{6}M} = 1.15 \pm 0.01$,
- one of two analyzed functional forms is:

$$C_5^A(Q^2) = \frac{C_5^A(0)}{\left(1 + \frac{Q^2}{M_A^2}\right)^2},$$

We fit either only M_A or both M_A and $C_5^A(0)$.

Fitting procedure

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{\sigma_{th}^{diff}(Q_i^2) - p\sigma_{ex}^{diff}(Q_i^2)}{p\Delta\sigma_i} \right)^2 + \left(\frac{p-1}{\Delta p} \right)^2,$$

p accounts for the overall normalization.

Both ANL and BNL data are used in the simultaneous fit.

Deuterium nuclear corrections are included:

$$R(Q^2) = \frac{\left(d\sigma(\nu d \to \mu^- n\Delta^{++})/dQ^2\right)_{deuteron}}{\left(d\sigma(\nu p \to \mu^- \Delta^{++})/dQ^2\right)_{free\ target}}$$

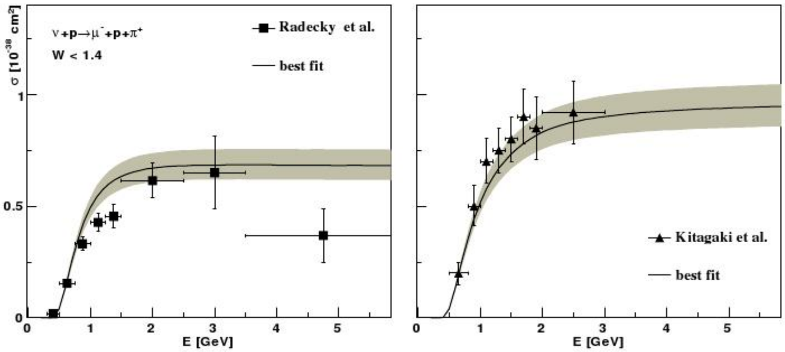
[L. Alvarez-Ruso, S. K. Singh and M. J. Vicente Vacas, Phys. Rev. C **59** (1999) 3386.
S.K. Singh, S. Ahmad, and Sajjad Athar, talk at NuInt02]

Results

	M_A (GeV)	$C_5^A(0)$	p_{ANL}	p_{BNL}	χ^2/NDF	GoF
dipole, only M_A, free target	0.95 ± 0.04		1.15 ± 0.06	0.98 ± 0.03	25.5/28	0.60
dipole, only M_A, deuteron	0.94 ± 0.04		1.04 ± 0.06	0.97 ± 0.03	24.5/28	0.65
dipole, M_A and $C_5^A(0)$, free target	0.95 ± 0.04	1.14 ± 0.08	1.15 ± 0.11	0.98 ± 0.03	25.5/27	0.54
dipole, M_A and $C_5^A(0)$, deuteron	0.94 ± 0.03	1.19 ± 0.08	1.08 ± 0.10	0.98 ± 0.03	24.3/27	0.60

Nuclear effects change $C_5^A(0)$ by 5%. Renormalization factors p_{ANL} and p_{BNL} are quite different: ANL and BNL data become compatible.

Results



The fit was done in the Δ^{++} channel in which a non-resonant background is very small. However, the background contributes significantly to other channels.

RES - more details

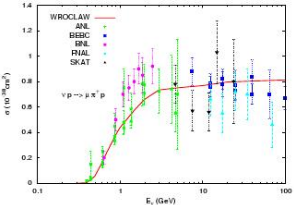
$$\frac{d\sigma^{SPP}}{dW} = \frac{d\sigma^{\Delta}}{dW}(1-\alpha(W)) + \frac{d\sigma^{DIS}}{dW}F^{SPP}(W)\alpha(W),$$

$$F^{SPP} \equiv \frac{\frac{d\sigma^{DIS,1\pi}}{dW}}{\frac{d\sigma^{DIS}}{dW}}, \qquad \alpha_0 \text{ is a free parameter}$$

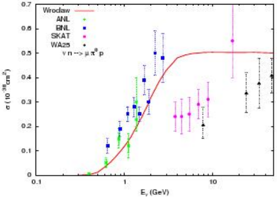
$$\alpha(W) = \Theta(W - W_{max}) + \Theta(W_{min} - W)\frac{W - W_{thr}}{W_{min} - W_{thr}}\alpha_0$$

$$+\Theta(W_{max} - W)\Theta(W - W_{min})\frac{W - W_{min} + \alpha_0(W_{max} - W)}{W_{max} - W_{min}}.$$

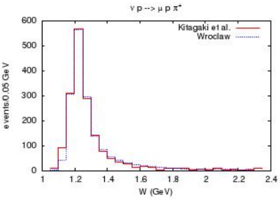
$\nu_\mu p \rightarrow \mu^- p \pi^+$

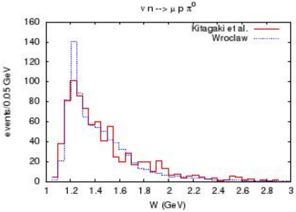


$\nu_\mu n \rightarrow \mu^- p \pi^0$



A cut $W < 2$ GeV was imposed. For the distribution of events in W we compare with the BNL data (Kitagaki et al):



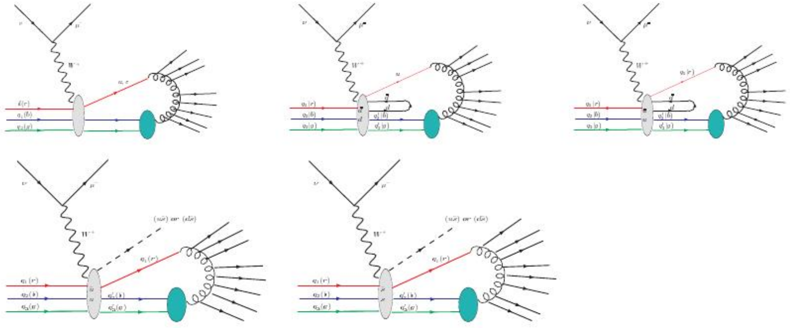


DIS - deep inelastic scattering

In NuWro DIS stands for *more inelastic channels* than RES.

- defined as $W > 1.6$ GeV
- total cross section taken from the Bodek-Yang approach
- hadronization done by a custom-made model
  - inspired by F. Sartogo PhD thesis (supervised by Paolo Lipari)
  - contributions from individual quarks
  - PYTHIA6 fragmentation routines are used
  - some parameters were fine tuned:
    - PARJ(32) = 0.1 GeV (default value: 1.0 GeV)
    - PARJ(33) = 0.5 GeV (0.8 GeV)
    - PARJ(34) = 1.0 GeV (1.5 GeV)
    - PARJ(36) = 1.0 GeV (2.0 GeV)
    - MSTJ(17) = 3 (2)

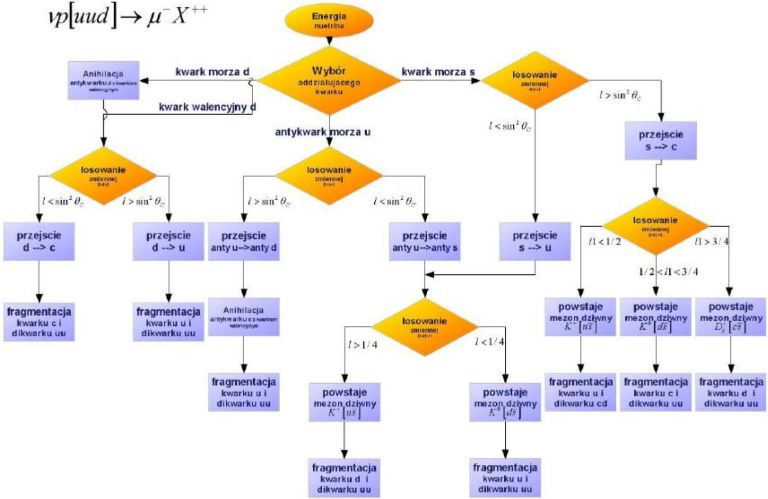
DIS - contribution from scattering on individual partons



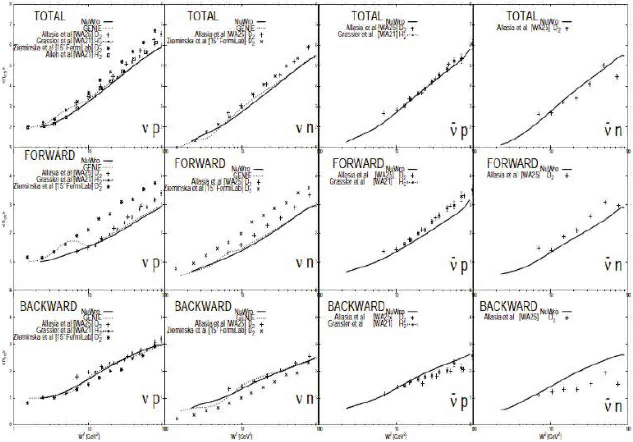
A νN CC interaction can happen on quarks $d, s, \bar{u}$.

DIS - details of particular scenarios

$\nu p[uud] \rightarrow \mu^- X^{++}$



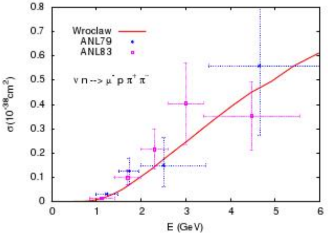
Charged hadron multiplicities in neutrino reactions: total, forward and backward hemispheres.

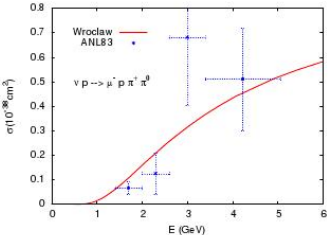


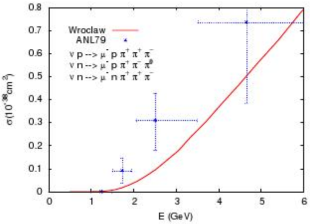
DIS - NuWro performance 2

Another interesting test: multpion production.
From top right in the clockwise direction:

1) $\nu_\mu n \to \mu^- p \pi^+ \pi^-$
2) $\nu_\mu p \to \mu^- p \pi^+ \pi^0$
3) Sum of 3π production channels







COH - coherent pion production

- Coherent pion production process leaves the nucleus in its ground state.
- In NuWro it is simulated using two phenomenological PCAC based models described in Rein-Sehgal and Berger-Sehgal papers:
  - D. Rein, L. M. Sehgal, Nucl. Phys. B 223, 29 (1983).
  - Ch. Berger, L.M. Sehgal, Phys.Rev. D79, 053003 (2009).
- the newer model seems to better reproduce MINERvA data.
- after taking the Rein Sehgal. formula "as is" the efficiency of real events generation was very poor...
- change of integration variables and gave 4 orders of magnitude improvement! Now it is about 5%.

MEC - meson exchange current

Importance of MEC was fist realized by Martini et al. in connection with MiniBooNE CCQE cross section measurement publication.

The MiniBooNE analysis gave abnormally large nucleon axial mass prediction, but it neglected the MEC contribution.

Inclusion of MEC makes it possible to reproduce standard value of M_A from the MiniBooNE data:

J. Nieves, I. Ruiz Simo, M. J. Vicente Vacas, Phys. Lett. B 707, 72 (2012).

In NuWro there are two MEC implementations available:

- the effective transverse enhancement model, which parametrizes MEC effects as an enlargement of magnetic nucleon form factors:

  H. S. Bodek, A. Budd, M. E. Christy, Eur. Phys. J. C 71, 1726 (2011).

- microscopic IFIC model (only for charge current interactions):

  J. Nieves, I. Ruiz Simo, M. J. Vicente Vacas, ibid. 83, 045501 (2011).

FSI - intranuclear cascade

Pions and nucleons after leaving the primary vertex interact with nuclear matter:

- first implemention was based on old (1956) Metropolis papers
- realistic density profiles are used for mean free path, Fermi motion, and Pali blocking (within LDA)
- particle move in steps not larger than 0.2 Fermi.
- now π cross sections in the Δ region are taken from Oset et al (like NEUT)
- πN pion production cross sections directly from the data.
- free NN cross sections are used.
- for nucleon a phenomenological approach with an effective nuclear potential is used.

Outlook

Some of our plans for near future:

- Use electron interactions to fine tune the FSI.
- Include electron interactions in the public releases.
- Add deexcitation code to FSI.
- Include reweighting code in NuWro repository.
- New interaction channels?
- Update DIS fragmentation code to PYTHIA8?
- Update/create comprehensive documentation.
- ...