NuWro: Wrocław Neutrino Event Generator

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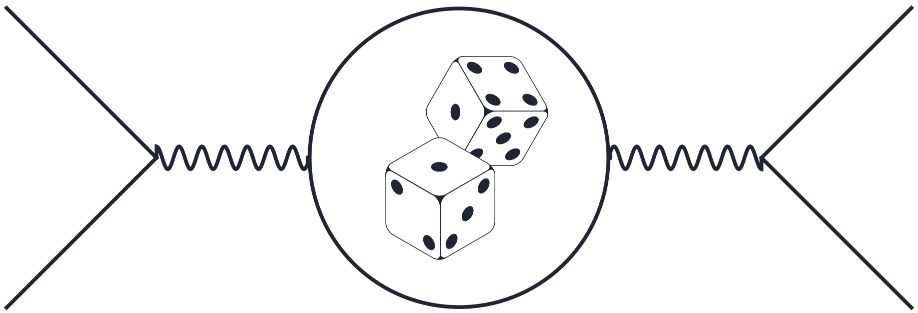
Uniwersytet Wrocławski

Introduction

General information



NuWro is a Monte Carlo neutrino event generator, which has been developed for over 9 years at the Wrocław University by:

Cezary Juszczak	*a significant contribution from:*
Jan Sobczyk	*Krzysztof Graczyk*
Jarosław Nowak	*Jakub Żmuda*
Tomasz Golan	*and others*

The authors were encouraged by Danuta Kiełczewska.

The open-source C++ code is available in the repository:

`http://borg.ift.uni.wroc.pl/gitweb/?p=nuwro`

General information

Primary interactions	
quasi-elastic scattering	*Llewellyn-Smith formalism*
$\Delta(1232) \rightarrow \pi$ production	*Adler-Rarita-Schwinger*
deep inelastic scattering	*quark-parton model*
coherent π production	*Rein-Sehgal model*
two-body current	*IFIC (Nieves et al.) model* *MEChM*-like model* *Transverse Enhancement*

**MEChM = Martini-Ericson-Chanfray-Marteau*

....

We thank Marco Martini for consultations in our implementation, but we also warn users that it is different than the original MEChM model.

We thank Juan Nieves and collaborators for providing us his original source code.

General information

Nucleus models

Fermi gas → local and "global"

Spectral function → for ^{12}C, ^{16}O, ^{40}Ar, ^{40}Ca, ^{56}Fe

Final state interactions

Intra-nuclear cascade for pion:

→ *Oset et al. model for kinetic energies up to* 350 *MeV*

→ *a phenomenological approach for higher energies*

Intra-nuclear cascade for nucleon:

→ *a phenomenological approach with an effective nuclear potential*

Other features

- ability to use a realistic beam
- ability to use a detector geometry

Multi-nucleon knockout

Two-body current

Our strategy for two-body current contribution

- It is very important for the community to have a chance to use various models.
- We are very grateful to authors of theoretical models who share with us their original codes.
- In case we do not have access to important models we are trying to develop approximate approaches.

Nieves et al. model

First approach

Tables for $^{12}C(\nu_\mu, \mu^-)$
$\rightarrow \mathrm{d}^2\sigma/\mathrm{d}T_\mu \mathrm{d}\cos\theta_\mu$

→ *40 values for E_ν from 155 MeV to 2995 MeV*

→ *for each E_ν 40x40 table for T_μ and* $\cos\theta_\mu$

Extension for higher E_ν

→ *Gran, Nieves, Sanchez, Vicente Vacas [PRD 88 (2013) 113007]*

→ *cut in momentum transfer $|\vec{q}_{max}| = 1.2$ GeV*

Note, similar approach is currently used in NEUT.

Current approach

Nucleus "knows":	It "does not know":
→ $q = (q_0, \vec{q})$	→ *lepton mass*
→ *type of int.*	→ *its energy*

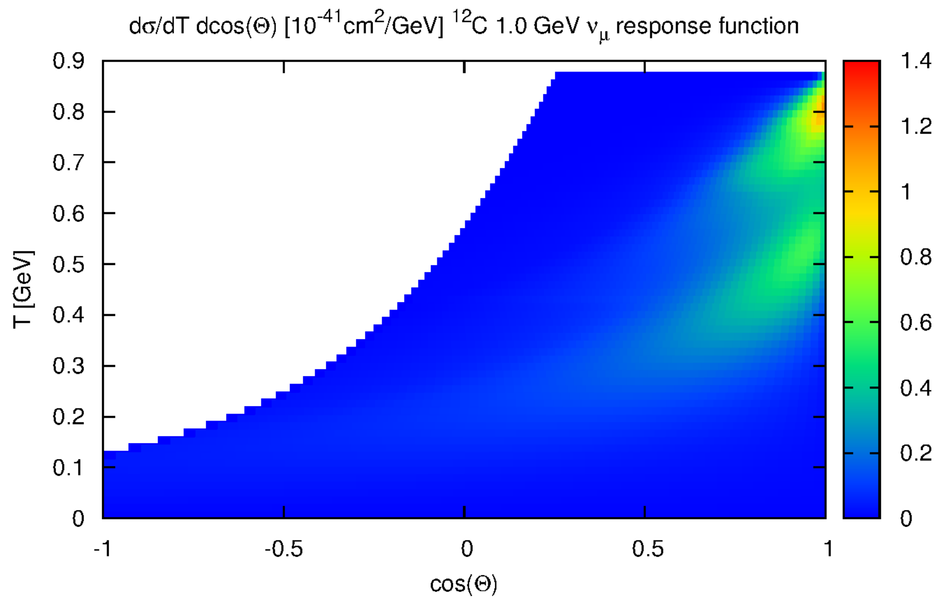
$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}\Omega' \mathrm{d}E'} \sim \sum_{i=1}^{5} W_i(q_0, \vec{q}) f_i$$

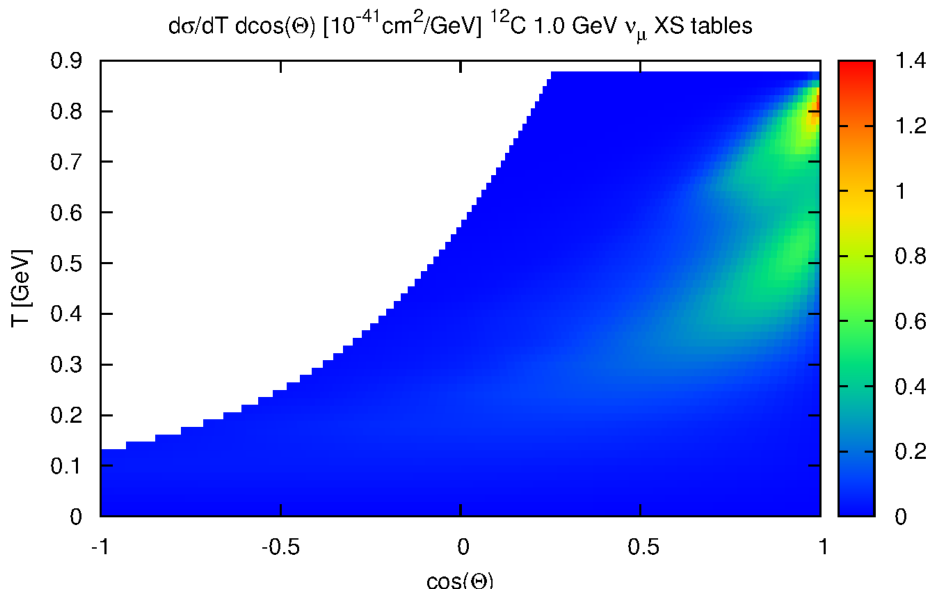
- *f_i depend on lepton kinematics*
- *W_i → response functions depend on nucleus type, channel and four-momentum transfer*

Knowing W_i one can calculate double-differential cross section for each kind of neutrino and with no energy limit.

Nieves et al. model

Both approaches give the same results.





from J. Żmuda, Vanish Valencia workshop

See J. Żmuda "Meson Exchange Currents models in NuWro Monte Carlo generator" for details.

Hadron kinematics for two-body current

All of them give predictions for lepton kinematics only!

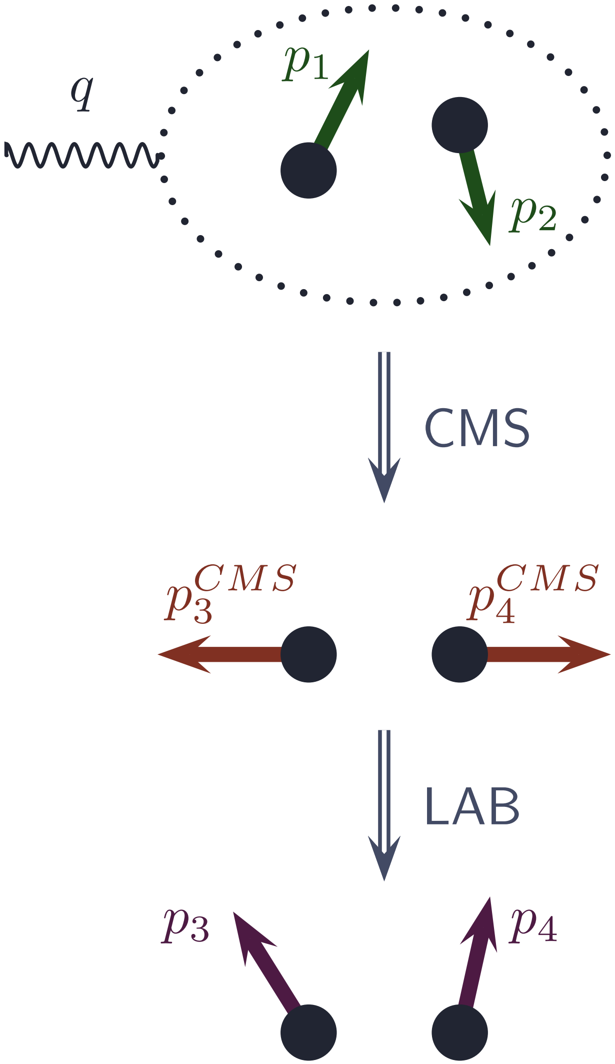
→ Four-momentum transfer q is shared by two nucleons with four-momenta p_1 and p_2.

→ In the CMS frame the direction of momentum $\vec{p}$ is selected uniformly:

$$q + p_1 + p_2 \xrightarrow{CMS} (E^{CMS}, 0)$$

$$p_3^{CMS} = (E^{CMS}/2, \vec{p})$$
$$p_4^{CMS} = (E^{CMS}/2, -\vec{p})$$

→ p_3 and p_4 are obtained by preforming boost back to the LAB frame.

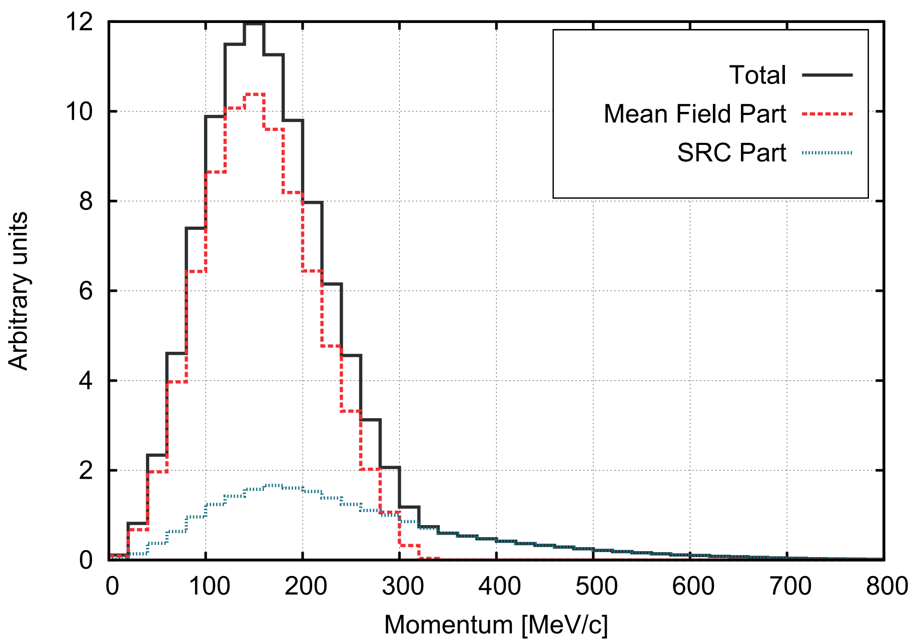


Spectral function

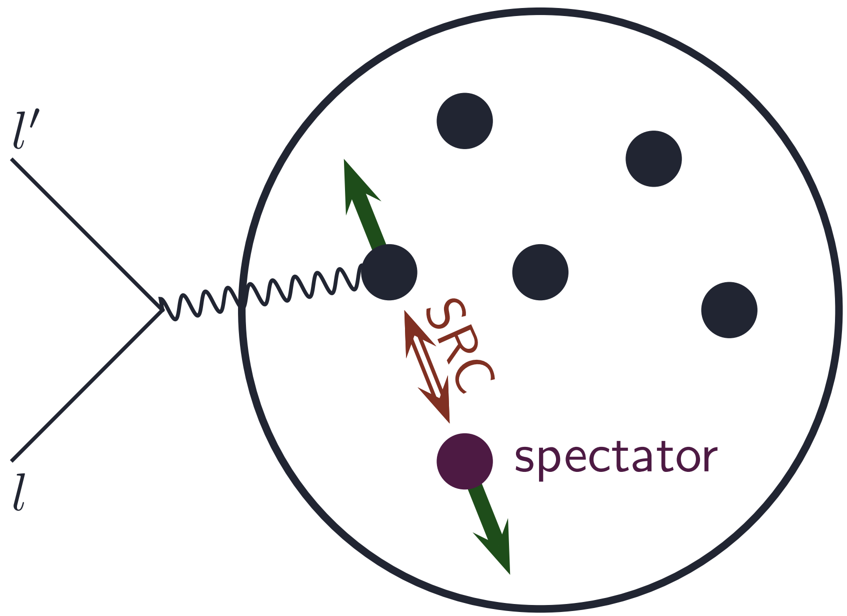
Spectral function:

$$P_{total}(\vec{p}, E) = P_{MF}(\vec{p}, E) + P_{corr}(\vec{p}, E)$$

NuWro implementation
of Benhar's spectral function



About 20% of interactions occur on a correlated nucleon.



The spectator is now also knock out in NuWro.

to be improved.

Nucleon-nucleon cross section

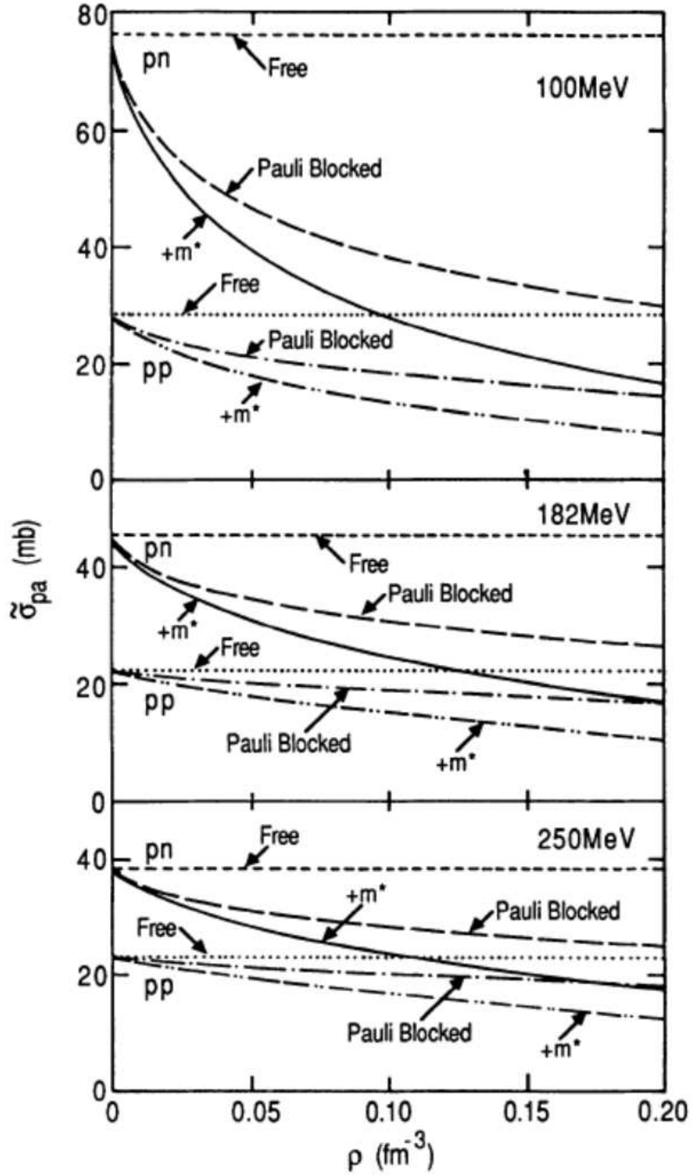
→ Usually, free nucleon-nucleus cross sections are used in nucleon cascade models.

→ Effective density dependent NN cross section:

Pandharipande, Pieper PRC45 (1992) 791

→ In medium NN cross section becomes much smaller.

Important in MEC studies!



Protons multiplicity

ArgoNeuT preliminary results

→ *K. Partyka "Exclusive 1mu+np topologies in ArgoNeuT" NuInt12*

→ *O. Palamara "QE or not QE, that is the question" INT workshop, Seattle, 2013*

Observable

→ *number of protons ($T_k \gtrsim 22$ MeV) in the final state*

→ *no pion in the final state*

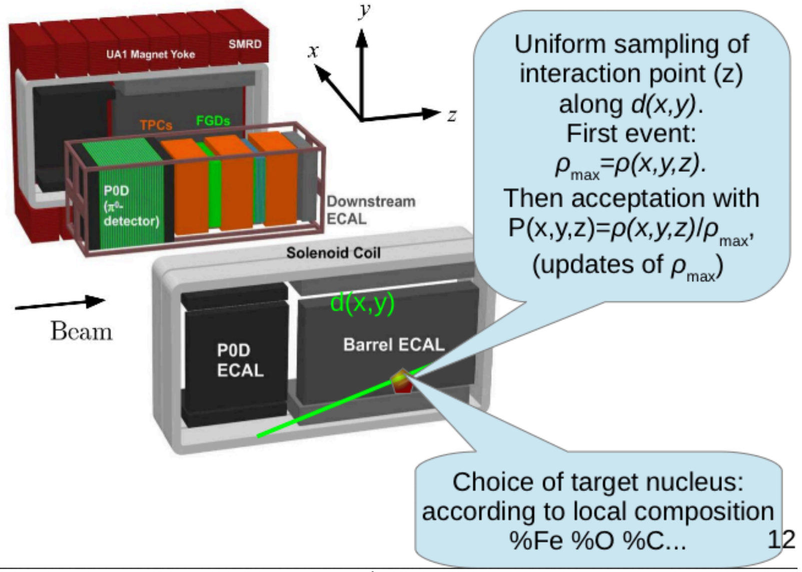
	ν mode		$\overline{\nu}$ mode	
No. of protons	Data	NuWro	Data	NuWro
0	14	15.4	67.7	64.9
1	48	50.8	23.7	22.7
2	26	17.8	6.4	8.0
3	12	9.6	1.4	2.8
more	0	6.3	1.0	1.6

errors are of the order of 20%

Detector geometry

Detector geometries and flux information in NuWro

- NuWro can now make simulations in a real detector environment
  - ROOT geometry definitions supported
    - spatial distribution of materials with given density and composition
  - extremely fast simulation code
  - vertex position/outgoing particles are saved
    - can be further used in detector simulation software
- This feature has already been used in T2K experiment (see next slide)

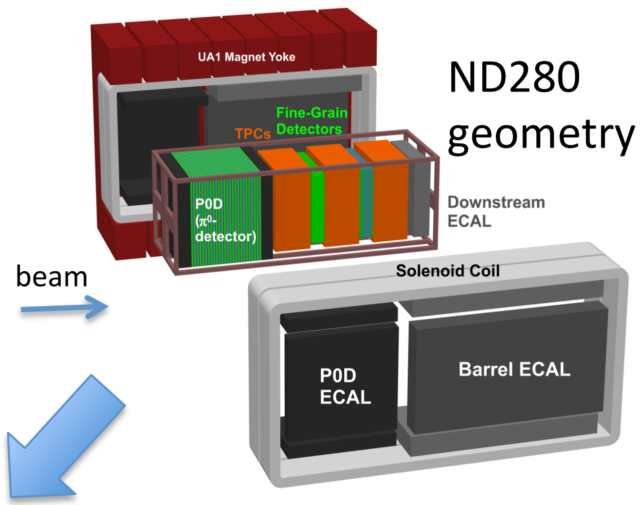


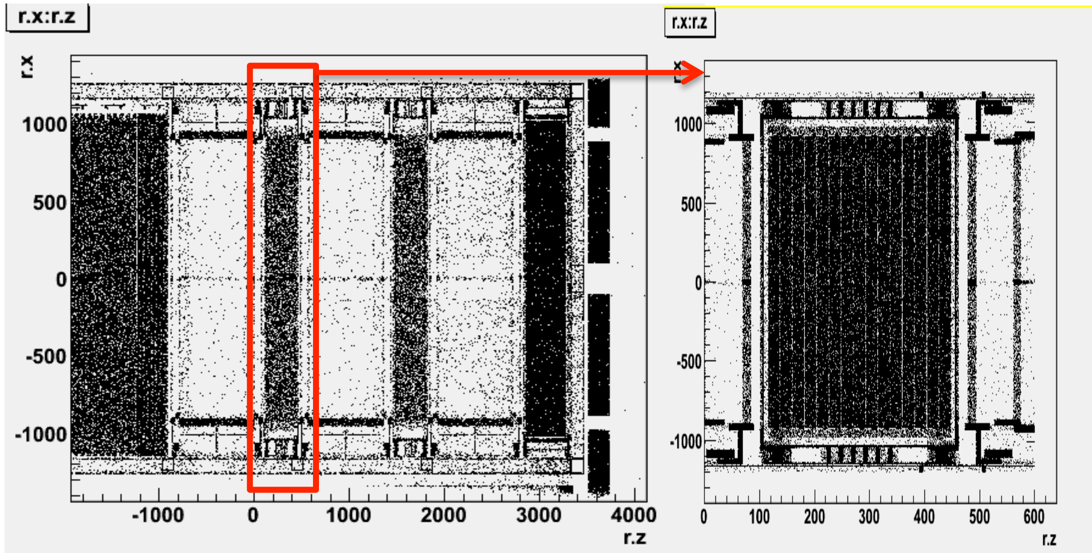
from Jakub Żmuda, Vanish 2014 Valencia workshop

- Beam flux files are supported
  - NuWro can read neutrino by neutrino from flux files generated by beam MC
  - important for off-axis experiments

Detectors in NuWro – ND280@T2K

- An example of usage: simulation for ND280 near detector of the T2K experiment
- A set of samples prepared to study possibilities of multi-nucleon (np-nh, MEC) events' selection
  - NuWro has got implementations of two multi-nucleon models: Nieves and Martini-Marteau
- Several samples generated in different regions of the detector
- and subsequently processed using full detector simulation
  - Output can be directly compared with data
  - Analysis in progress

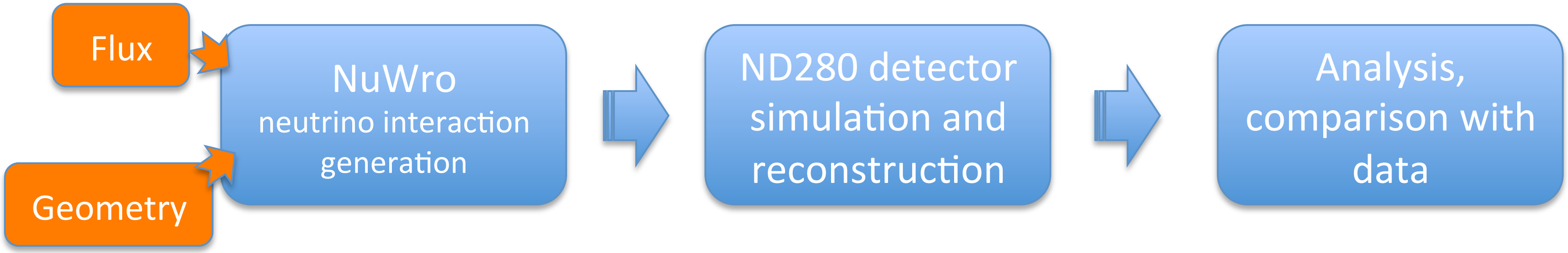




Vertex distribution (left) of NuWro simulated events using the ND280 geometry (left: full inner detector and right: FGD1 only - single scintillator bars visible). The denser parts contain more vertices

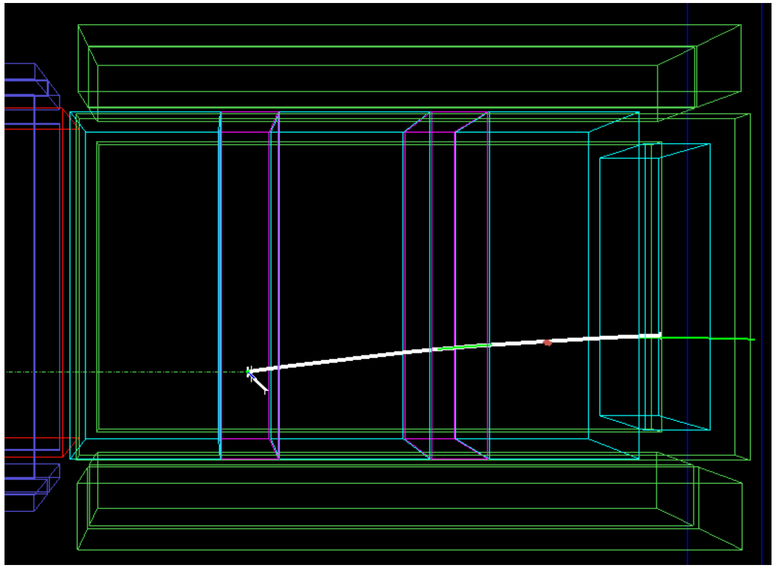
Detectors in NuWro – ND280@T2K (2)

ND280 NuWro simulation workflow

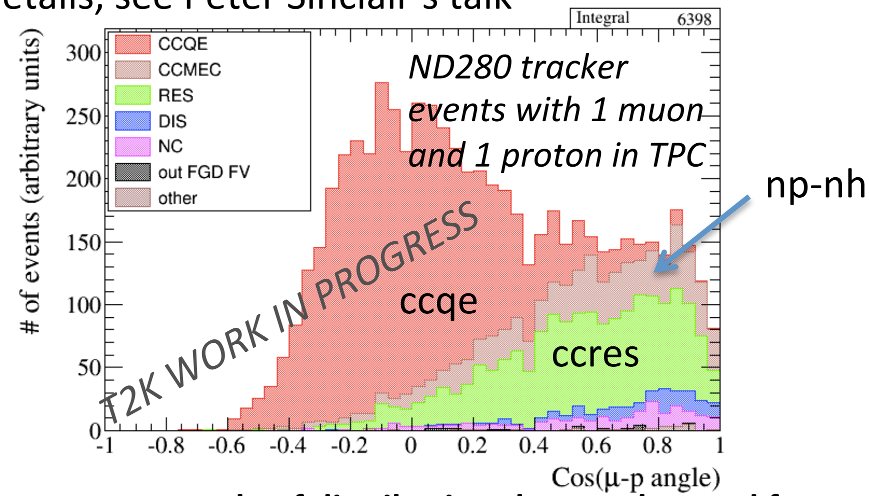


NuWro-generated samples are used in the T2K studies of **np-nh contribution** in ND280 tracker data

For details, see Peter Sinclair's talk



An example event display (above) of a NuWro generated event (CCQE), a muon and a proton are visible (both are properly reconstructed)



Above: an example of distribution that can be used for np-nh search – cosine of angle between muon and proton (visible differences between CCQE and mec events)

NuWro online

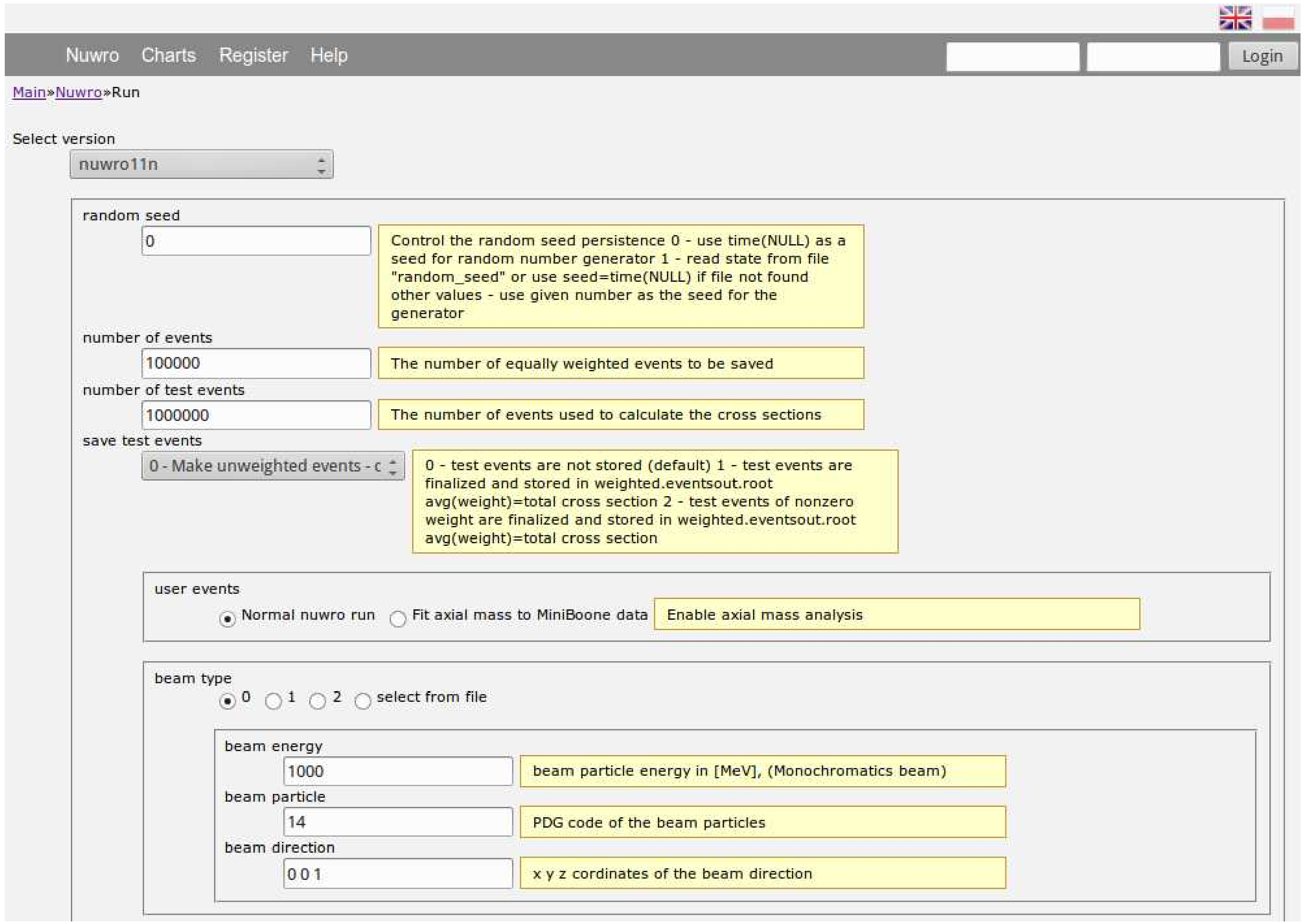
NuWro online

The on-line graphical interface for NuWro is now available:

`http://nuwro.ift.uni.wroc.pl`

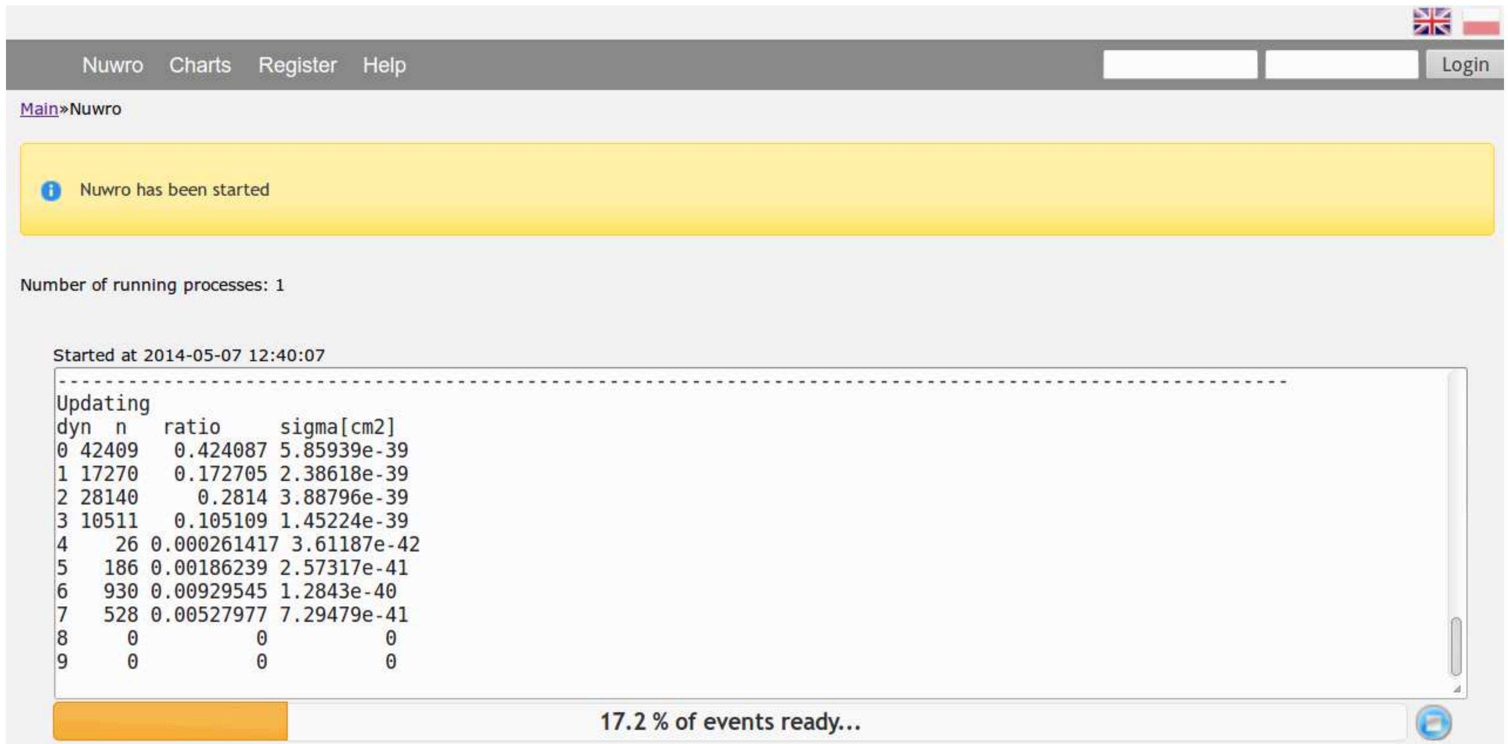
→ setting parameters
→ running simulations
→ making plots

NuWro online



NuWro online

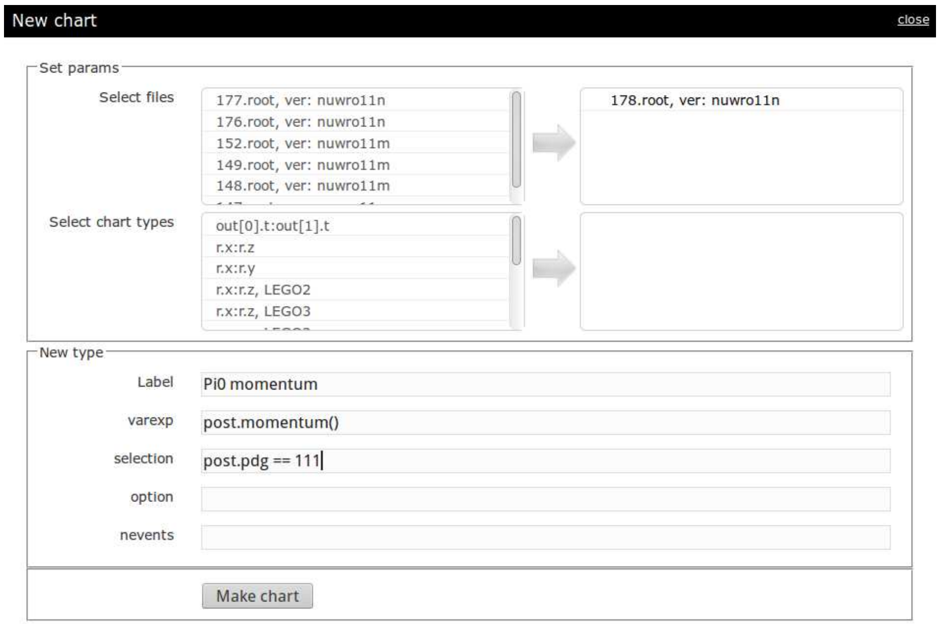
1. The simulation is done on our server

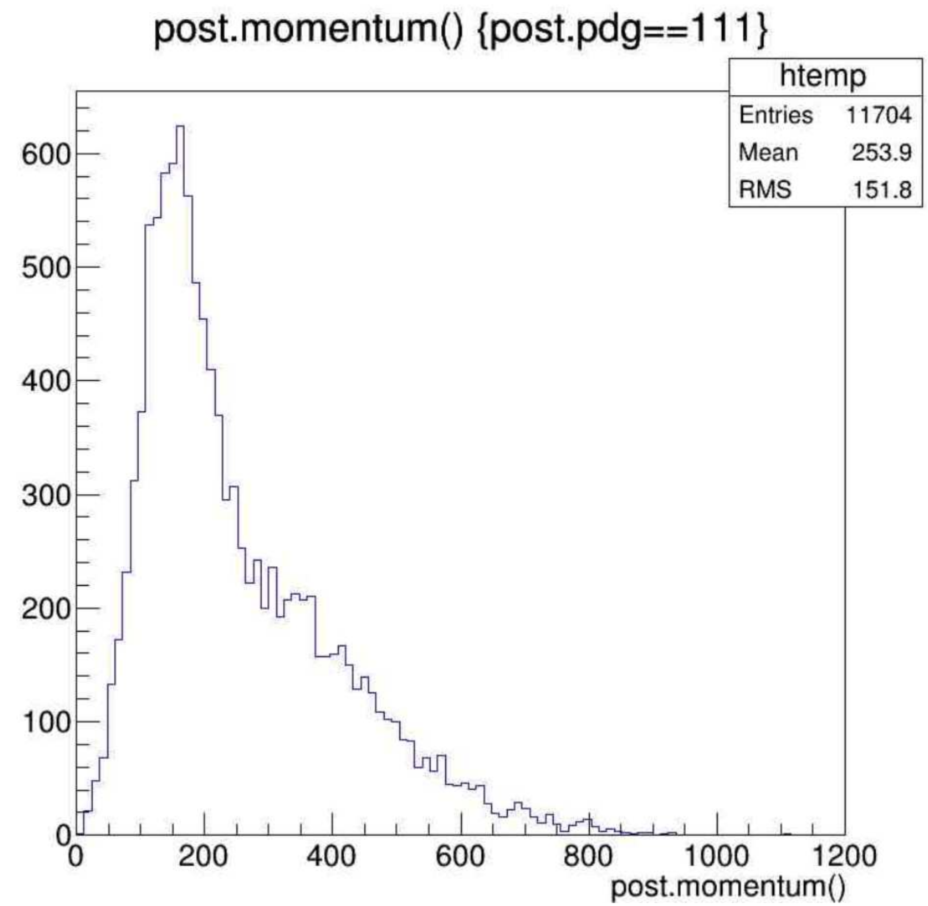


2. The output ROOT file is stored on our server, but one can download it.

NuWro online

One can use already defined types of charts or define its own





Summary

1. NuWro is a complete tool to analyze the data.
2. All major neutrino interaction types are included.
3. There are several models of two-body current contribution.
4. The realistic beam as well as detector geometry can be used.
5. There is a graphical on-line interface.