

NuWro: Wrocław Neutrino Event Generator

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Uniwersytet
Wrocławski

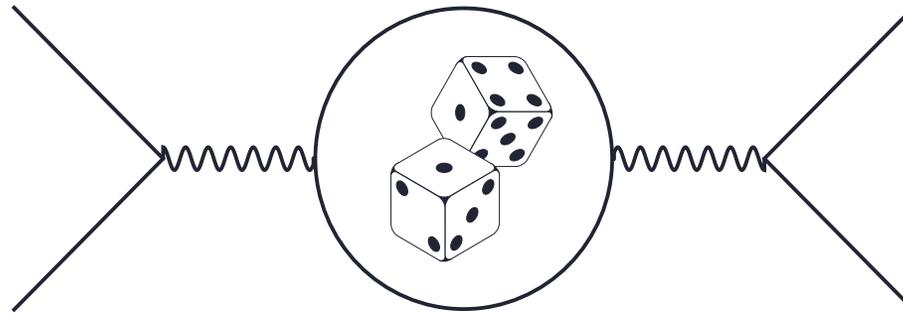
Introduction

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

*Cezary Juszczyk
Jan Sobczyk
Jarosław Nowak
Tomasz Golan*

*a significant contribution from:
Krzysztof Graczyk
Jakub Żmuda
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>

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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.

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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

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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.

FIRST APPROACH

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

\rightarrow 40 values for E_ν from 155 MeV to 2995 MeV

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

Extension for higher E_ν

\rightarrow Gran, Nieves, Sanchez, Vicente Vacas [PRD 88 (2013) 113007]

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

Note, similar approach is currently used in NEUT.

CURRENT APPROACH

Nucleus “knows”:

$\rightarrow q = (q_0, \vec{q})$

\rightarrow type of int.

It “does not know”:

\rightarrow lepton mass

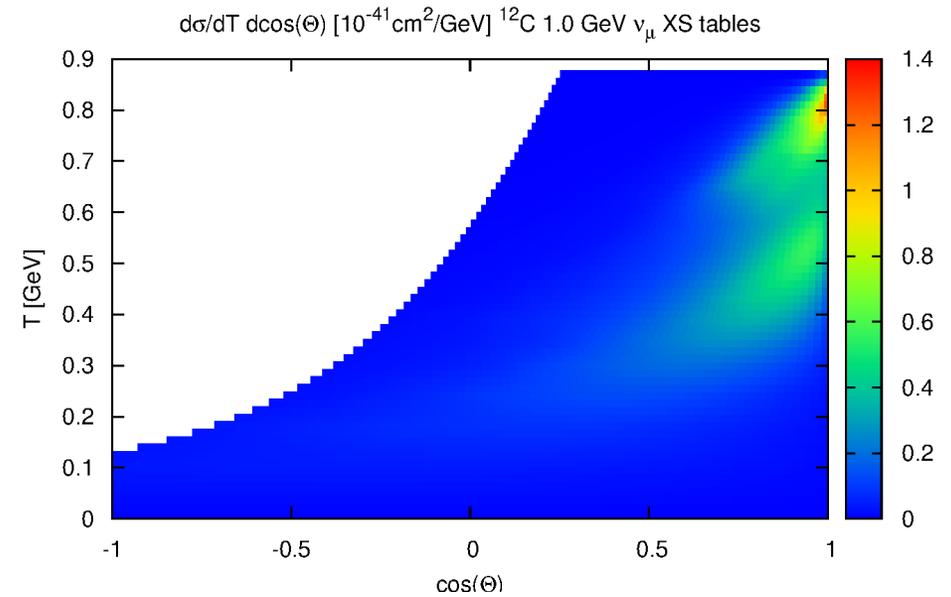
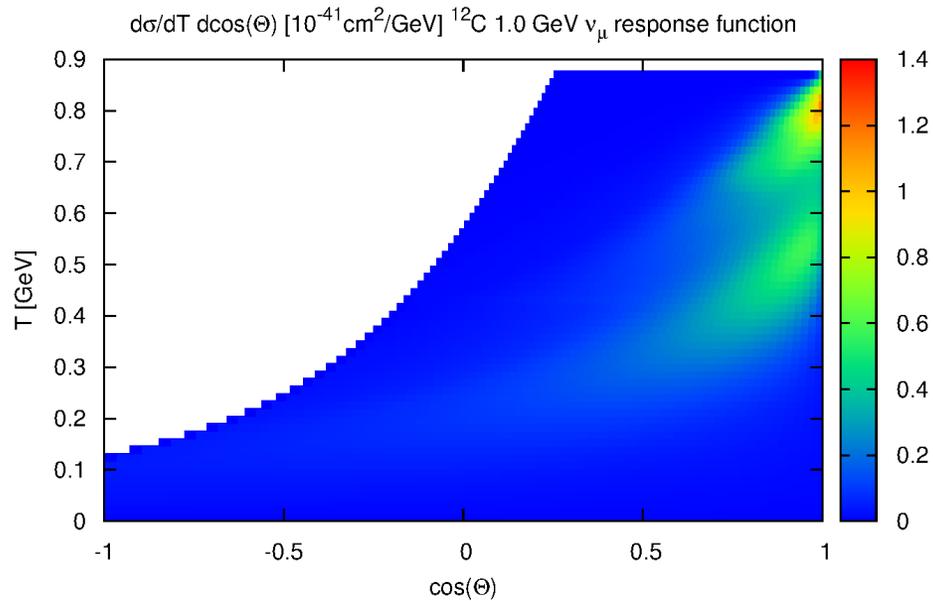
\rightarrow its energy

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

- f_i depend on lepton kinematics
- $W_i \rightarrow$ 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.

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.

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 .

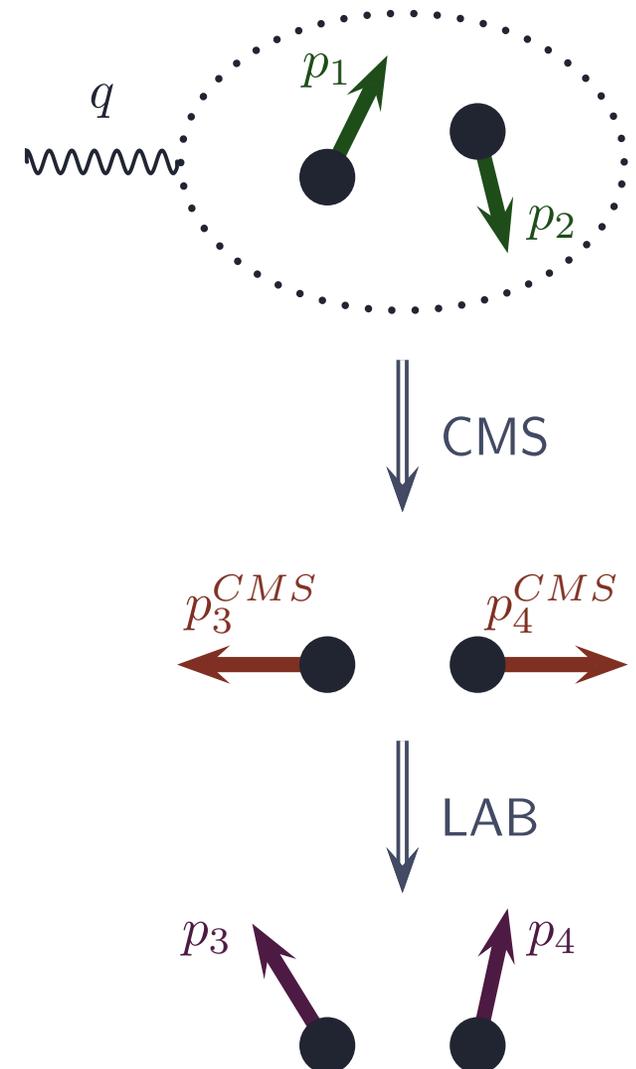
→ In the CMS frame the direction of momentum \vec{p} is selected uniformly:

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

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

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

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



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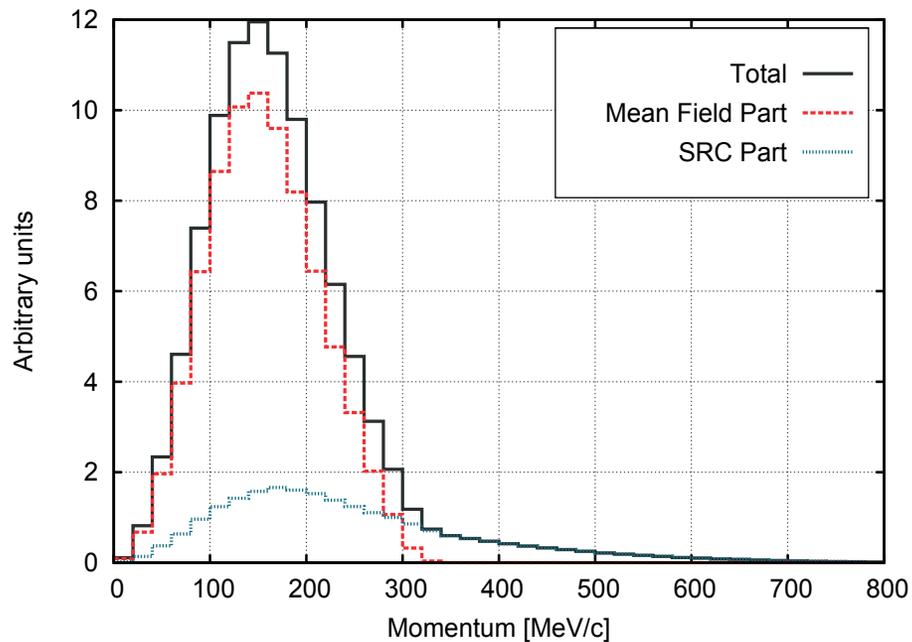
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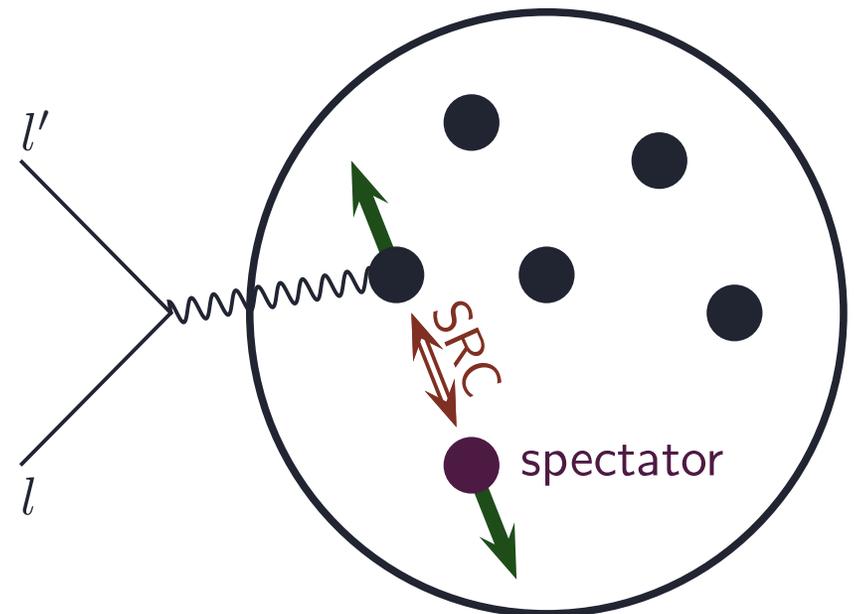
Spectral function:

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

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.

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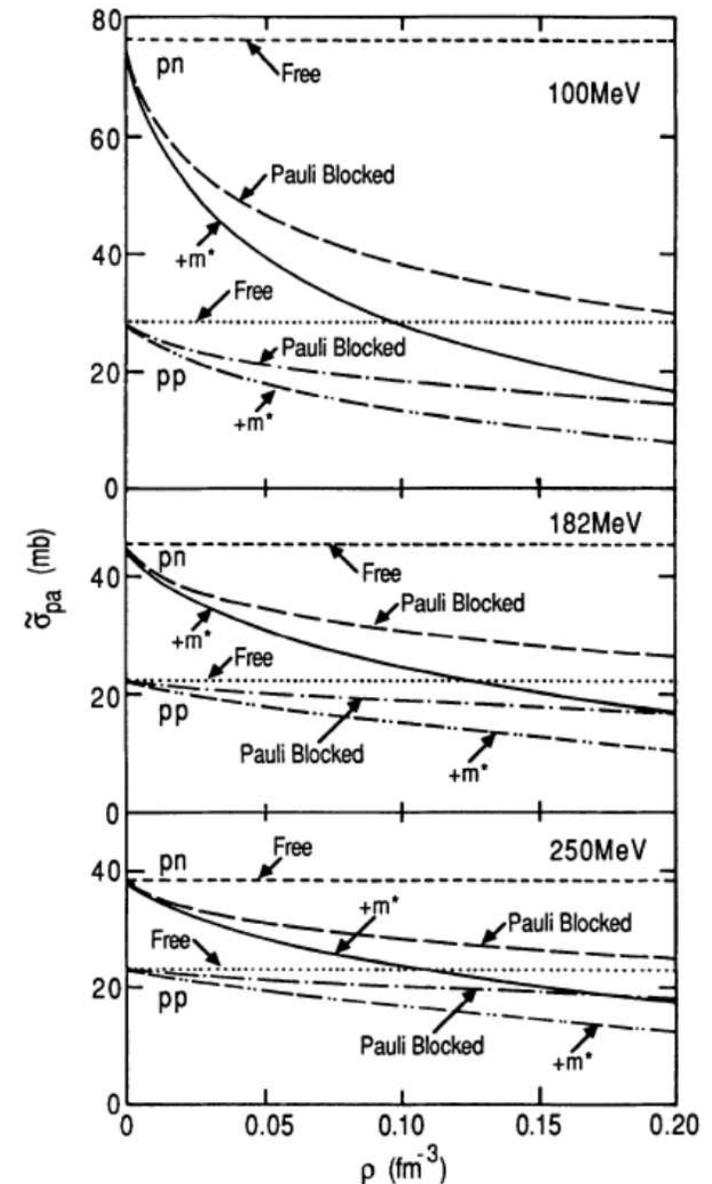
→ Usually, free nucleon-nucleus cross sections are used in nucleon cascade models.

→ Effective density dependent NN cross section:

*Pandharipande, Pieper
 PRC45 (1992) 791*

→ In medium NN cross section becomes much smaller.

Important in MEC studies!



ArgoNeuT preliminary results

- *K. Partyka "Exclusive $1\mu+np$ 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*

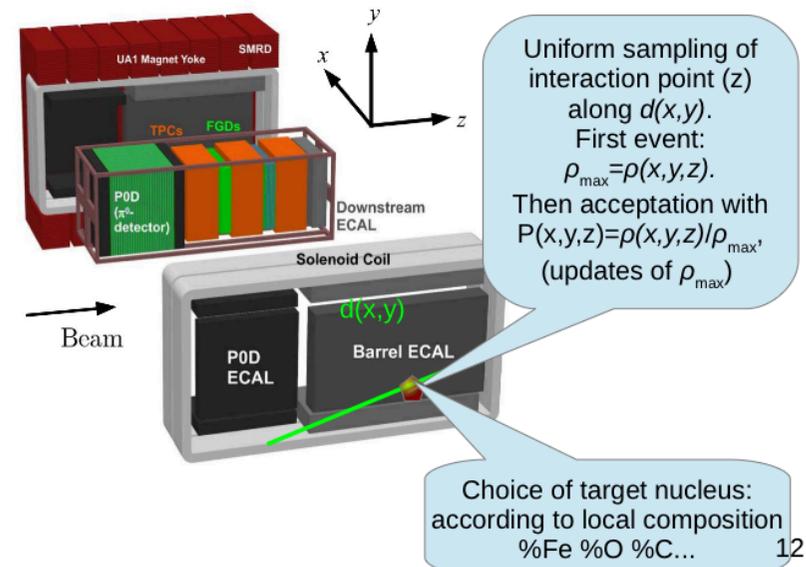
No. of protons	ν mode		$\bar{\nu}$ mode	
	Data	NuWro	Data	NuWro
0	14	15.4	67.7	64.9
1	48	50.8	23.7	22.7
2	26	17.8	6.4	8.0
3	12	9.6	1.4	2.8
more	0	6.3	1.0	1.6

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)

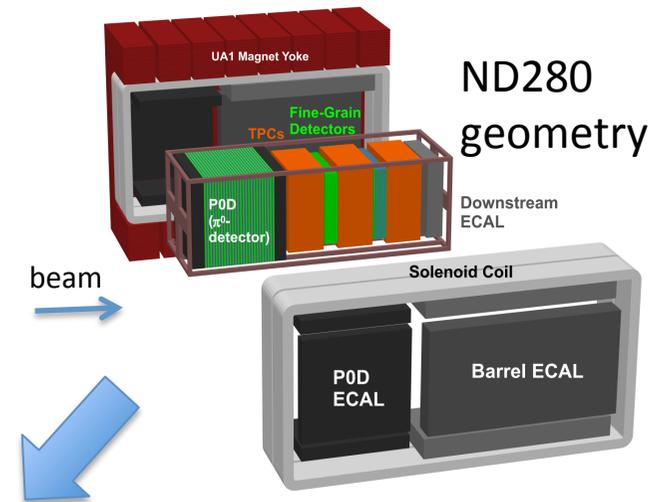


from Jakub Žmuda, Vanish 2014 Valencia workshop

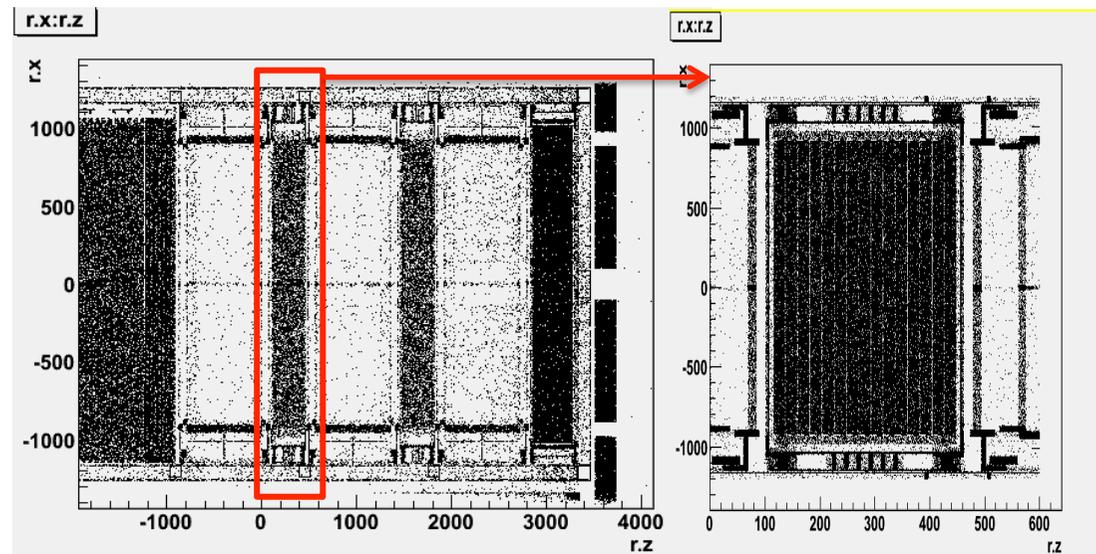
- Beam flux files are supported
 - NuWro can read neutrino by neutrino from flux files generated by beam MC
 - important for off-axis experiments

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

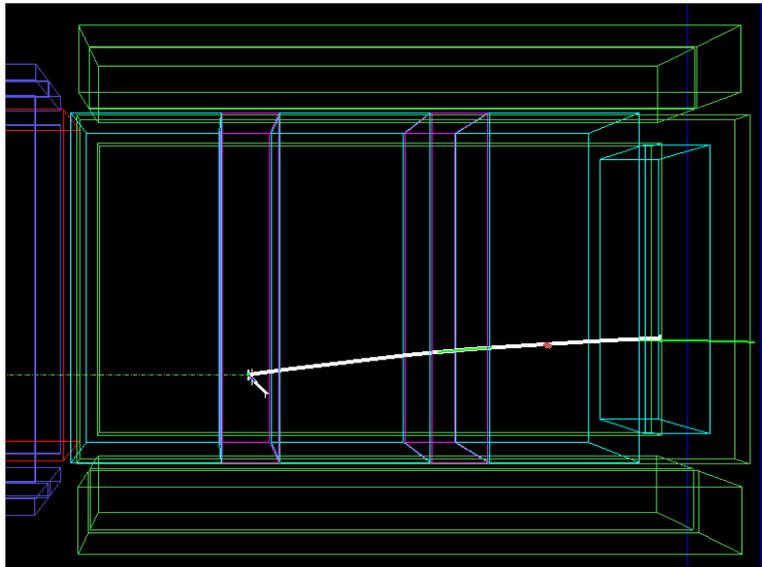


Vertex distribution (left) of NuWro simulated events using the ND280 geometry (left: full inner detector and right: FGD1 only - single scintillator bars visible). The denser parts contain more vertices



Detectors in NuWro – ND280@T2K (2)

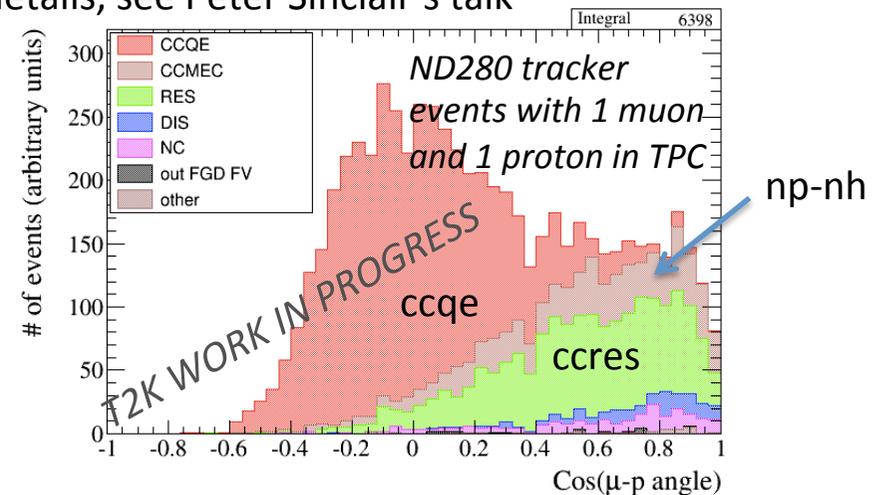
ND280 NuWro simulation workflow



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

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

For details, see Peter Sinclair's talk



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

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Summary

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

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

- setting parameters
- running simulations
- making plots

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Nuwro
Charts
Register
Help

[Main](#) » [Nuwro](#) » [Run](#)

Select version

random seed

Control the random seed persistence 0 - use time(NULL) as a seed for random number generator 1 - read state from file "random_seed" or use seed=time(NULL) if file not found other values - use given number as the seed for the generator

number of events

The number of equally weighted events to be saved

number of test events

The number of events used to calculate the cross sections

save test events

0 - test events are not stored (default) 1 - test events are finalized and stored in weighted.eventsout.root avg(weight)=total cross section 2 - test events of nonzero weight are finalized and stored in weighted.eventsout.root avg(weight)=total cross section

user events
 Normal nuwro run
 Fit axial mass to MiniBoone data
 Enable axial mass analysis

beam type
 0
 1
 2

beam energy

beam particle energy in [MeV], (Monochromatics beam)

beam particle

PDG code of the beam particles

beam direction

x y z coordinates of the beam direction

Introduction

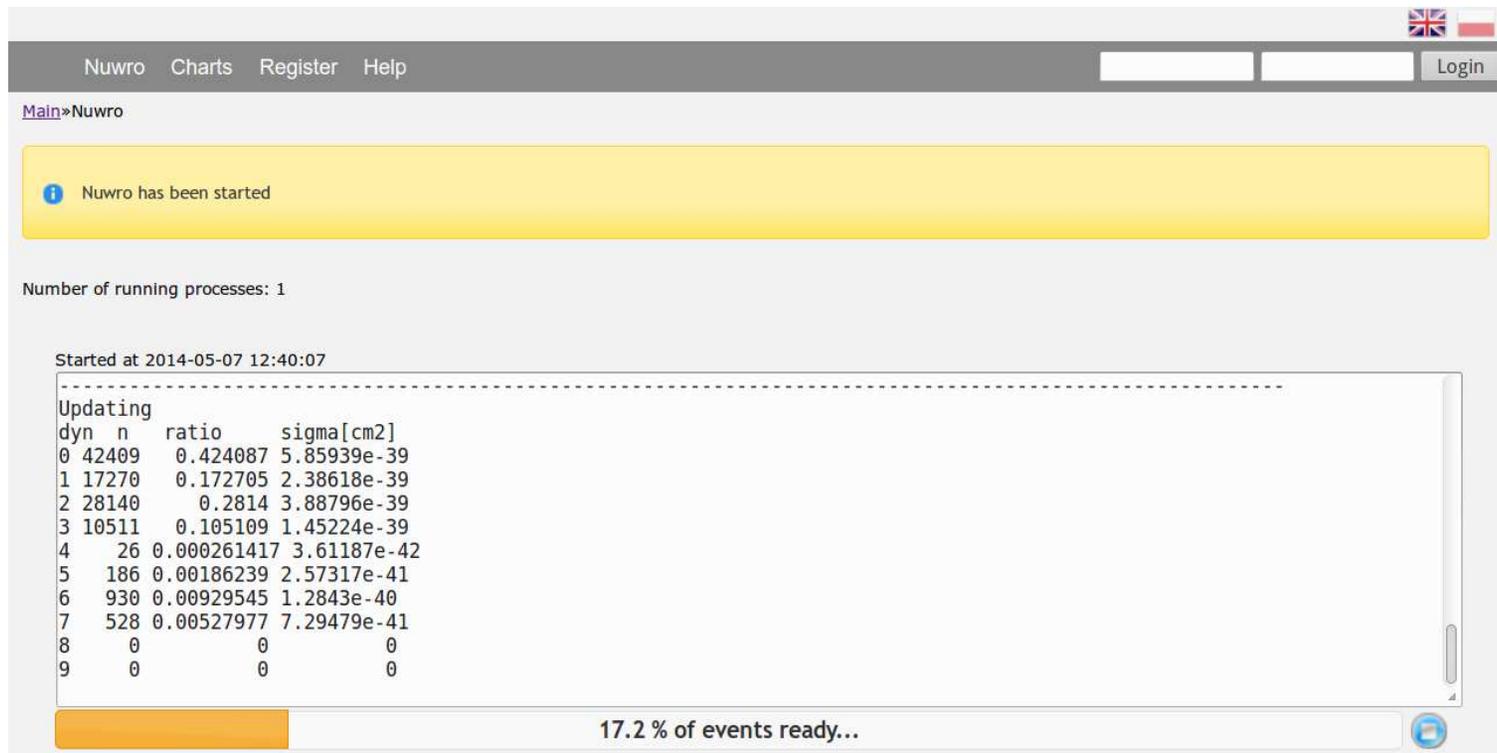
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Summary

1. The simulation is done on our server



The screenshot shows the NuWro online web interface. At the top, there are navigation links: Nuwro, Charts, Register, Help, and a Login button. A yellow notification bar states "Nuwro has been started". Below this, it indicates "Number of running processes: 1". A terminal window shows the simulation output, starting at 2014-05-07 12:40:07. The output is a table with columns: dyn, n, ratio, and sigma[cm2].

dyn	n	ratio	sigma[cm2]
0	42409	0.424087	5.85939e-39
1	17270	0.172705	2.38618e-39
2	28140	0.2814	3.88796e-39
3	10511	0.105109	1.45224e-39
4	26	0.000261417	3.61187e-42
5	186	0.00186239	2.57317e-41
6	930	0.00929545	1.2843e-40
7	528	0.00527977	7.29479e-41
8	0	0	0
9	0	0	0

At the bottom of the terminal window, a progress bar shows "17.2 % of events ready..."

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

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

New chart close

Set params

Select files

177.root, ver: nuwro11n	178.root, ver: nuwro11n
176.root, ver: nuwro11n	
152.root, ver: nuwro11m	
149.root, ver: nuwro11m	
148.root, ver: nuwro11m	

Select chart types

out[0].t:out[1].t	
r.x:r.z	
r.x:r.y	
r.x:r.z, LEGO2	
r.x:r.z, LEGO3	

New type

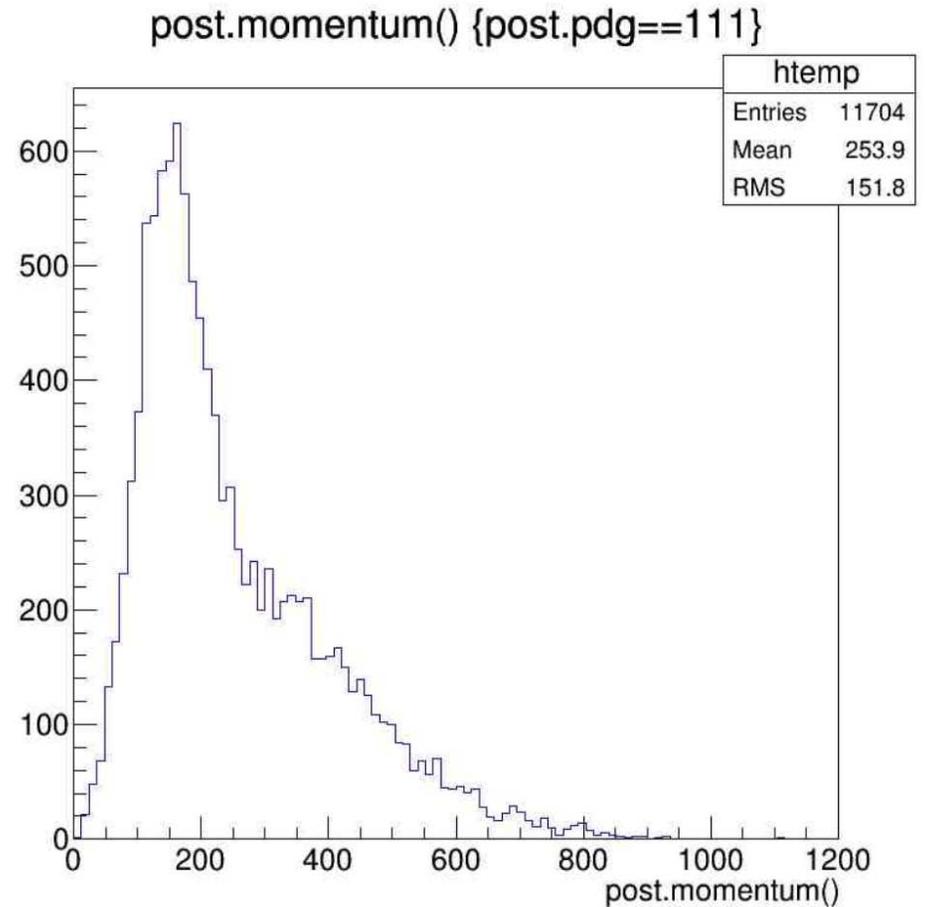
Label

varexp

selection

option

nevents



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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.