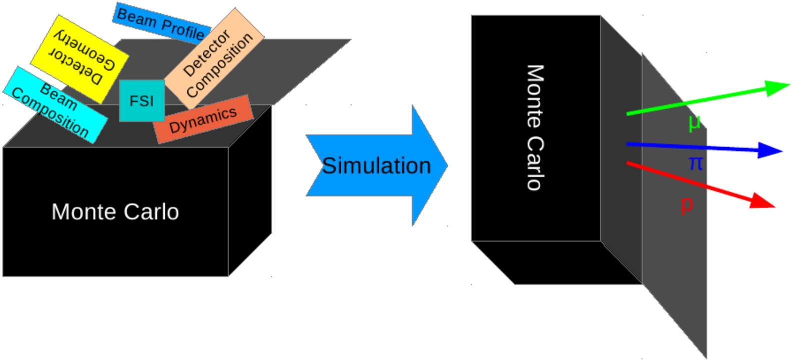
NuWro Monte Carlo event generator

Jan T. Sobczyk

Wrocław University

ECT* workshop, Trento, July 9-13, 2018

Outline:



What is there in the NuWro black box?

NuWro team

T. Golan | K. Graczyk | C. Juszczak | K. Niewczas | J. Nowak | J.T. Sobczyk | J. Żmuda

Notable supporters

Warsaw

D. Kiełczewska
(passed away in 2016)

General,
many discussions

P. Przewłocki

NuWro at T2K

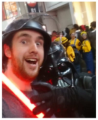
VA, U.S.

A. Ankowski

Spectral function

U.K.

L. Pickering



P. Stowell

Reweightning tools

A short history

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Nuclear Physics B (Proc. Suppl.) 139 (2005) 266–271

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WroNG – Wrocław Neutrino Generator of events for single pion production

Jan T. Sobczyk[a]* , Jarosław A. Nowak[a], Krzysztof M. Graczyk[a]

[a]Institute of Theoretical Physics, Wrocław University.
pl. M. Borna 9, 50-204 Wrocław, Poland

We constructed a new Monte Carlo generator of events for neutrino CC single pion production on free nucleon targets. The code uses dynamical models of the DIS with the PDFs modified according to the recent JLab data and of the Δ excitation. A comparison with experimental data was done in three channels for the total cross sections and for the distributions of events in invariant hadronic mass.

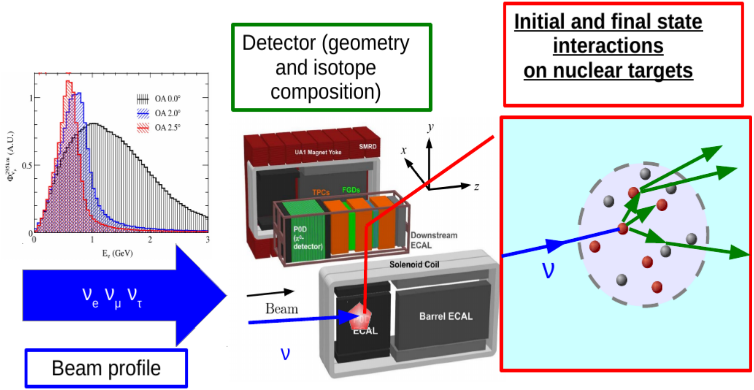
The first presentation at NuInt04 in Gran Sasso.

Since then, a long way...

NuWro – basic information

- written in C++
- output files in ROOT format
- PYTHIA is used for hadronization in DIS
- open source code, repository: https://github.com/NuWro/nuwro
- NuWro follows NEUT and GENIE in many respects.

NuWro functionalities



Events reweighting tools are under development (some are active).

Electron scattering module (eWro) is under development.

Today: focus on cross sections.

NuWro running

NuWro needs for every run:

- information about neutrino flux
  - energy spectrum? flavor composition?
- information about the target
  - free nucleon? nucleus? compoud target?

NuWro provides two pieces of information:

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

Cross section

In general several particles in the final state.

- contributions from distinct final states are added incoherently

$$\sigma(E) = \int d^3k' \sum_{\alpha} \int \prod_{j=1}^{F} d^3p_j \frac{d^{3(F+1)}\sigma}{d^3k' d^3p_1 \dots d^3p_F}.$$

α label possible final states *topologies*, each of them consisting of F hadrons, nuclei, nucleus remnants, ... with momenta $\vec{p}_1$, ..., $\vec{p}_F$ and lepton $\vec{k}'$

- spin degress of freedom are omitted for simplicity.

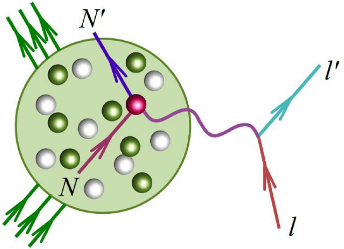
Monte Carlo event generator is basically a machine to calculate the above integral using MC algorithm.

Cross sections - general problems

- Usually a theoretical input in not in a complete form of the differential cross sections for all the exclusive channels
  - often we only know muon inclusive cross section $\frac{d\sigma}{d^3k'}$ after integrating out hadronic final states

Nuclear effects - a big picture.

In the 1 GeV region nuclear effects are treated in the impulse approximation scheme: neutrinos interact with individual bound nucleons.



A. Ankowski

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

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

- In SF mode de Forest prescription for off-shell matrix elements.
- MEC occur on nucleon pairs - departure from IA.

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

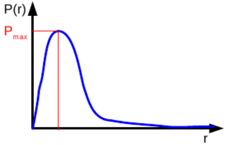
Impulse approximation

In impulse approximation interaction point is selected at random using information about nucleus density

- this information is used in NuWro FSI model
- spherical symmetry is assumed
- NuWro has density profiles of practically all isotopes
- in LFG model nucleon momentum is selected in the next step
- in events occuring on SRC pairs sampling should probably be different?

- 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

Basic interaction modes – neutrino-nucleon scattering

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

(i) quasi-elastic (QEL)

$$\nu_\mu \ n \to \mu^- \ p$$

and its neutral current counterpart:

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

(ii) resonance excitation (RES) defined by $W < 1.6$ GeV; typically

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

(iii) "deep inelastic scattering" (DIS) defined by $W \geq 1.6$ GeV

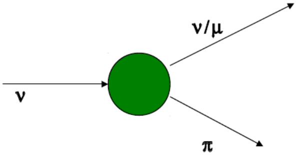
Warning: NuWro definition of RES and DIS differ from other MCs.

Neutrino-electron interactions are not included in NuWro.

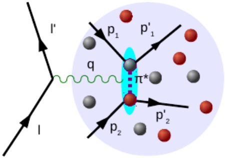
Basic interaction modes – neutrino-nucleus scattering

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

(iv) (COH) coherent pion production

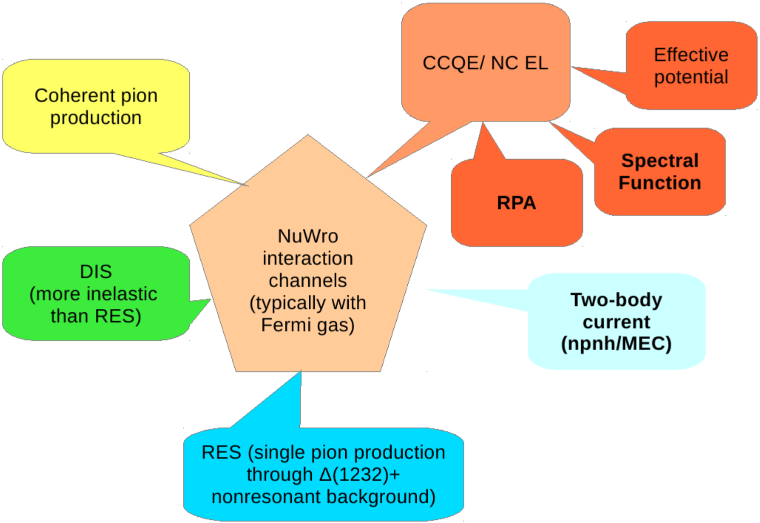


(v) (MEC) two body current



from J. Żmuda

NuWro interaction modes



NuWro – general features in generating events

- A key role of available phase space
  - phase space is used to define NuWro interaction modes (RES/DIS distinction)
- A frequent use of Lorentz boosts to center-of-mass frame and back to Lab frame.

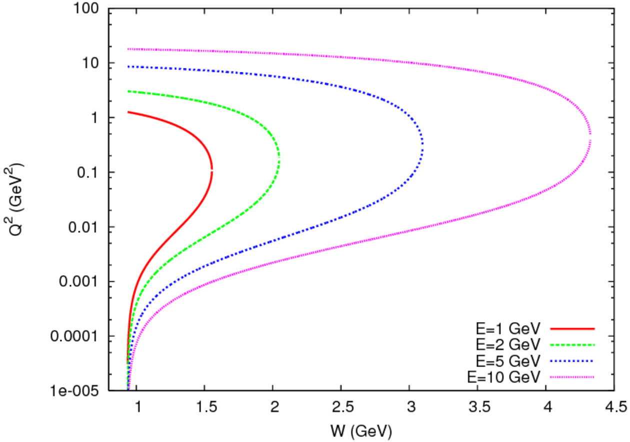
Phase space

- convenient variables: W and Q^2 (Lorentz scalars)

Which is the allowed region in W, Q^2 for muon neutrino of energy E scattering off a free nucleon at rest?

- calculate $s = (k+p)^2 = 2ME + M^2$
- in the center of mass frame (CMF) it is a square of the sum of energies of all the outgoing particles
- think about the *hadronic part* as of a *claster* with invariant mass W
- W_{max} corresponds to the situation where lepton and hadronic system do not move (in CMF) and $W_{max} + m = \sqrt{s}$.
- in CMF muon and *hadronic claster* move in back-to-back directions
- all the directions are possible
- this allows for computation of Q^2_{min} and Q^2_{max} as functions of W; available phase space is fully determined.

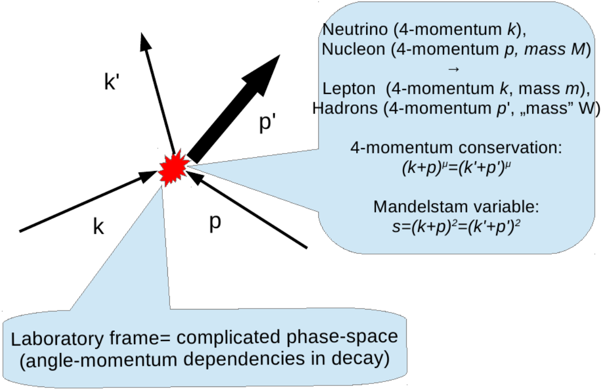
Phase space



from J. Nowak

In NuWro integration over available region in (W, Q^2) plane is typically done.

Kinematical variables



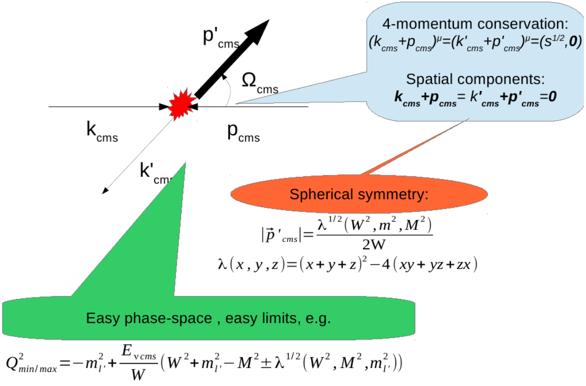
from J.Żmuda

Hadrons are put together to form a *claster* with 4-momentum p'.

$$W^2 = p'^2$$

Phase space

Kinematics is usually resolved in the center-of-mass frame.

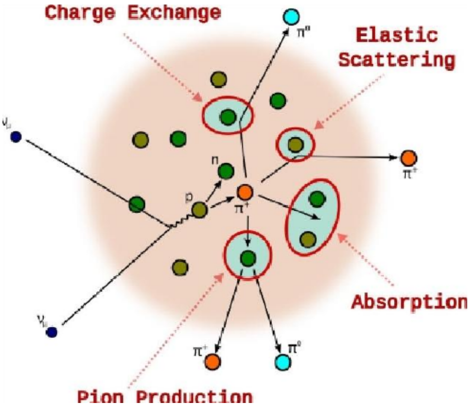


from J.Żmuda

After an event is generated all the particles are boosted back to the LAB frame.

Final state interactions:

What is observed are particles in the final state.



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.

NuWro: strategies in particular interaction modes

mode	option	cross section formula	remarks
QEL	FG, LFG	$\frac{d\sigma}{dQ^2}$	LLewellyn Smith
	+ RPA	$\frac{d^2\sigma}{d\omega dq}$	Eur.Phys.J. C31 (2003) 177
	SF	$\frac{d^2\sigma}{d\omega dq} = \int dE \int d^3p \ P(E,p)\ldots$	targets: ^{12}C, ^{16}O, ^{20}Ca, ^{56}Fe, ^{18}Ar
			from Omar Benhar and Artur Ankowski;
			de Forest prescription for off-shell matrix elements;
			approximate separation $P = P_{MF} + P_{corr}$
			and a second nucleon for P_{corr}.
	$V_{eff}(p,\rho)$		Eur.Phys.J. C39 (2005) 195
			$V_{eff}(p, k_F(\rho)) = -\frac{(ak_F)^2(k_F+b)}{f^4+d^3k_F+h^2\frac{p^2}{k_F^2}+p^4}$
			from Brieva – Della Fiore

NuWro: strategies in particular interaction modes

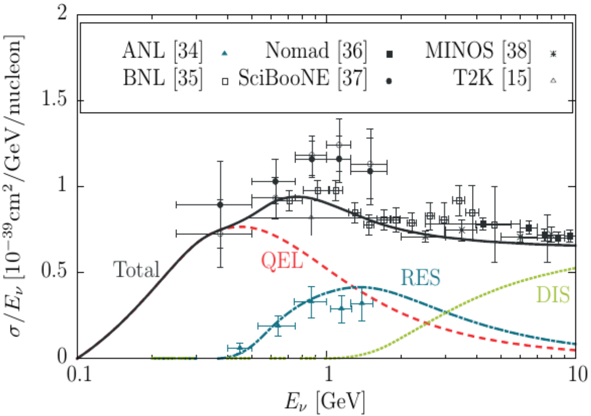
mode	option	cross section formula	remarks
MEC	Nieves (Valencia)	$\frac{d^2\sigma}{d\omega dq}$ (muon only)	only CC; hadronic information neglected
	TE (Arie Bodek)	$\frac{d^2\sigma}{d\omega dq}$ (muon only)	available for both CC and NC reactions
	Marteau	$\frac{d^2\sigma}{d\omega dq}$ (muon only)	only CC
			a universal hadronic model PRC86 (2012) 015504 for all three options; targets: ^{12}C, ^{16}O, ^{40}Ca; Rik Gran's like procedures to extrapolate to other targets based on numbers of np and nn/pp pairs (combinatorics).

NuWro: strategies in particular interaction modes

mode	option	cross section formula	remarks
DIS	Bodek-Yang	$\frac{d^2\sigma}{d\omega dq}$ (muon only)	PYTHIA used to produce final states;
			can be extrapolated down to $W = 1.1$ GeV
			no nuclear effects beyond Fermi motion.

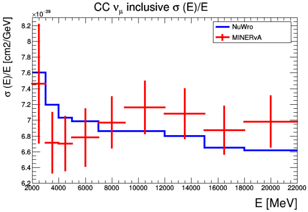
mode	option	cross section formula	remarks
RES		$\frac{d^2\sigma}{dWdQ^2}$ (muon only)	incoherent sum of Δ excitation and BKGR
			BKGR modeled as a fraction of DIS contribution;
			for SPP Δ/DIS transition region: $W \in (1.3, 1.6)$ GeV;
			2π production in $W \in (1.3, 1.6)$ GeV taken from DIS;
			Δ FFs from a fit to ANL/BNL data (PRD80 (2009) 093001);
			π angular distribution from ANL/BNL papers;
			Δ self-energy (Oset et al) - approximation
			based on PRC87 (2013) 065503.

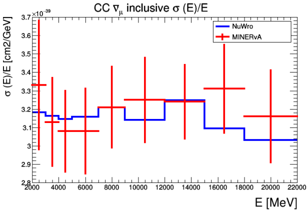
NuWro performance: Inclusive cross section

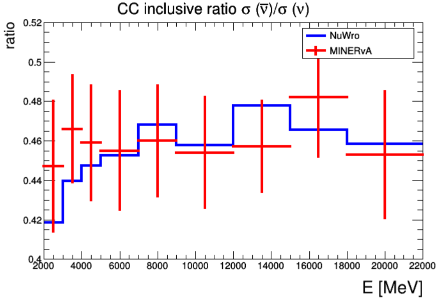


from T. Golan PhD Thesis (2014)

MINERvA inclusive ν_μ, $\overline{\nu_\mu}$, and ratio Phys.Rev. D95 (2017) 072009



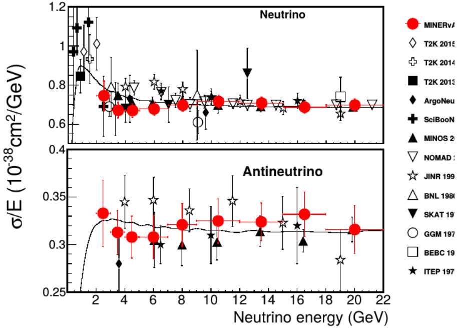


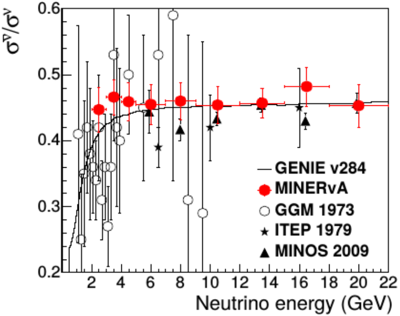


- The agreement is fair.
- MINERvA results are consistent with the previous measurements, see the next slide.

MINERvA inclusive ν_μ, $\overline{\nu_\mu}$, and ratio

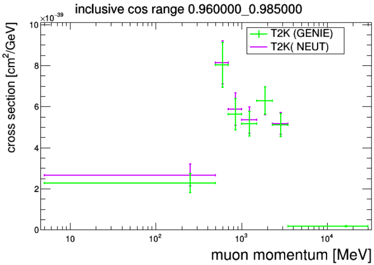
Comparison with the previous experiments

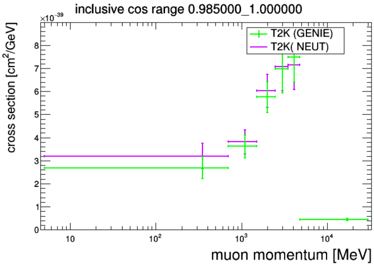




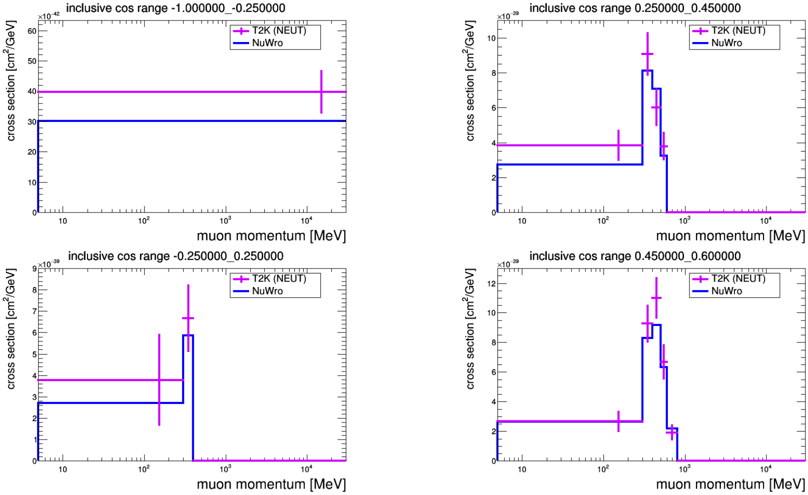
T2K CC inclusive muon double differential cross section (to be published in)

Two sets of results with different unfolding (using NEUT or GENIE). Differences are sometimes quite large. Examples:

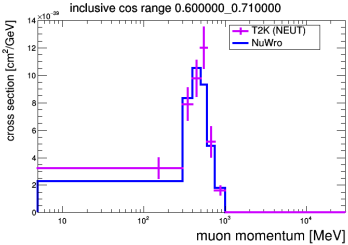


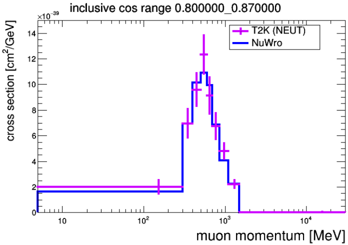


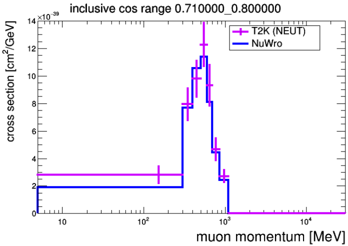
T2K CC inclusive muon double differential cross section

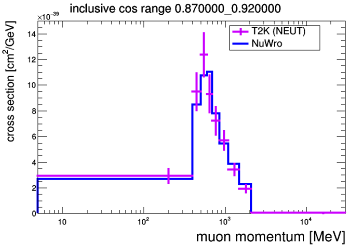


T2K CC inclusive muon double differential cross section (cont)

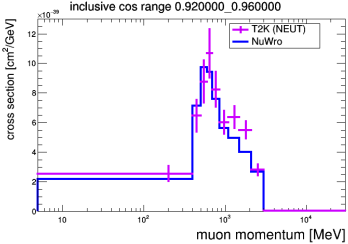


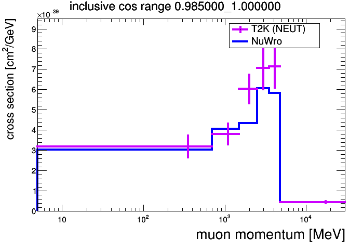


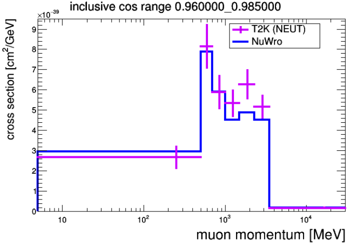


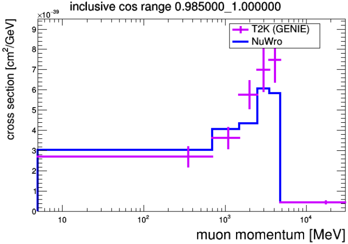


T2K CC inclusive muon double differential cross section (cont 2)









In general the agreement is good. In forward bins and large muon energies NuWro seems to underestimate cross section.

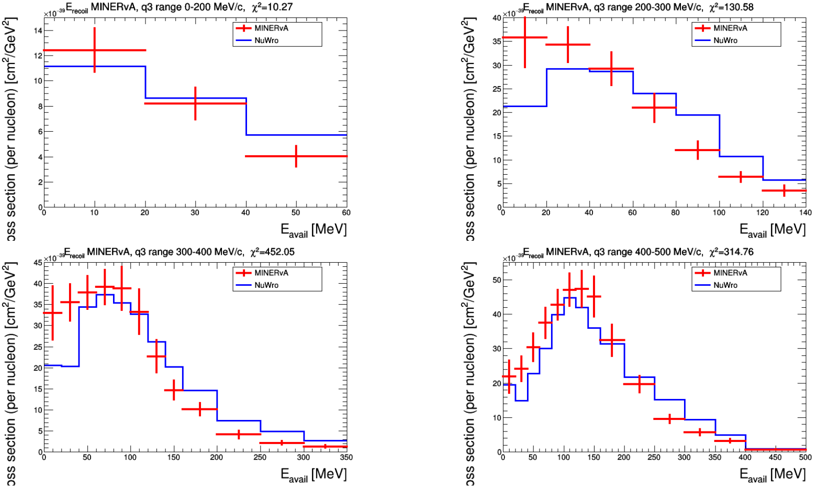
MINERvA recoil energy

An attempt to resolve kinematics completely.

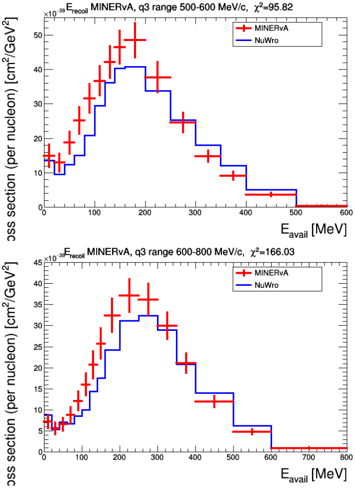
- Calorimetric measurement of hadronic energy.
- MC (GENIE) dependent estimate of energy and momentum transfer $q3$.
- Allows to single out and study region of low $q3$ and "available energy" E_{avail}
- Double differential cross section reported.

$$E_{avail} \equiv \sum_{kinetic\ \ energy} proton, \pi^{\pm} + \sum_{energy} \pi^{0}, \gamma, e^{-}.$$

MINERvA recoil energy



MINERvA recoil energy (cont)



- χ^2 values must be double checked
- NuWro results systematically shifted to the right ?

Conclusions

- NuWro black box has been opened.
- More details will follow:
  - QEL by Cezary Juszczak
  - RES – presentation prepared by Tomek Golan will be given by JS
  - 2p2h/MEC by Kajetan Niewczas
  - FSI – presentation prepared by Kajetan Niewczas will be given by JS