NuWro SIS/DIS model

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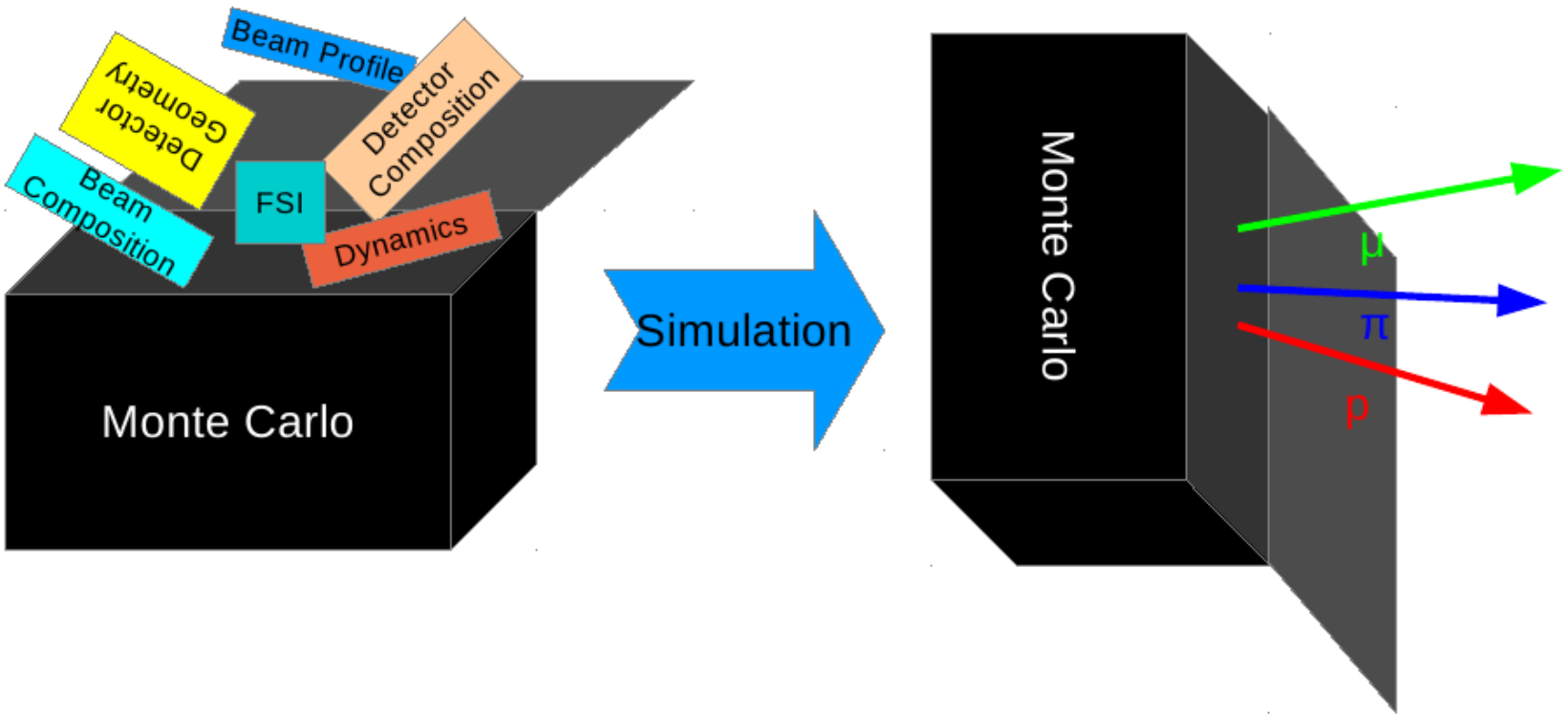
Wrocław University

SIS/DIS Workshop, L'Aquila, October 11-13, 2018

Outline:



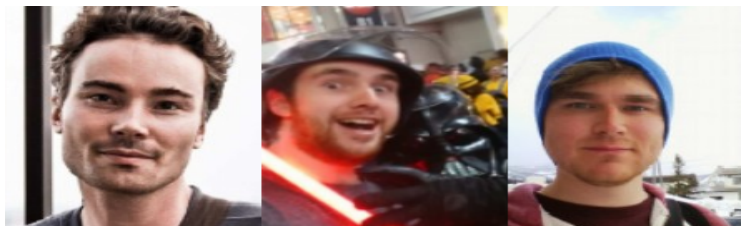
What is there in the NuWro black box as far as SIS/DIS treatment is concerned?

NuWro team

Active (but not full time :( ) developers: Cezary Juszczak, JTS, Tomasz Golan, Kajetan Niewczas

Former developers: Jarek Nowak, Krzysztof Graczyk, Artur Ankowski, Jakub Żmuda

Outside Wrocław developers/volunteers: Paweł Przewłocki, Patrick Stowell, Luke Pickering



New students: Tomasz Bonus, Michał Siemaszko

Inspiration and motivation: Danka Kiełczewska

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:

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

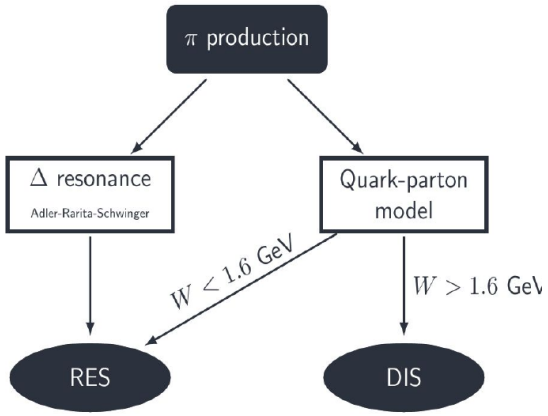
(ii) resonance excitation (RES) defined by invariant hadronic mass $W < 1.6$ GeV; most importantly through Δ excitation e.g.

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

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

NuWro definition of RES and DIS differs from other MCs. What is usually understood by SIS is contained entirely in DIS.

RES and DIS in NuWro



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

where

$$F^{SPP}(W) = \frac{d\sigma^{DIS\ 1\pi}/dW}{d\sigma^{DIS}/dW}.$$

A fraction of DIS is taken to model non-resonant background contribution (added incoherently)

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

$W_{min} = 1.3$ GeV, $W_{max} = 1.6$ GeV, $W_{thr} = M_N + m_\pi$, Θ is Heaviside step function.

$\nu_l\ p \to l^-\ \pi^+\ p \quad \hookrightarrow \quad \alpha_0 = 0.$
$\nu_l\ n \to l^-\ \pi^+\ n \quad \hookrightarrow \quad \alpha_0 = 0.2.$
$\nu_l\ n \to l^-\ \pi^0\ p \quad \hookrightarrow \quad \alpha_0 = 0.3.$

From a fit to single pion production data $\sigma(E)$ and $\frac{d\sigma}{dW}$ (Jarek Nowak PhD).

DIS in NuWro

Inclusive cross section is standard:

$$\frac{\mathrm{d}^2\sigma^{\nu/\overline{\nu}}}{\mathrm{d}x\mathrm{d}y} = \frac{G^2 M E_\nu}{\pi(1+Q^2/M_{W,z}^2)}^2 \Big[y(xy + \frac{m^2}{2E_\nu M})F_1 + (1 - y - \frac{Mxy}{2E_\nu} - \frac{m^2}{4E_\nu^2} - \frac{m^2}{2ME_\nu x})F_2 \pm (xy(1-\frac{y}{2}) - y\frac{m^2}{4ME_\nu})F_3 \Big]$$

with

$$\begin{aligned} F_1(x,Q^2) &= \sum_j (q_j(x,Q^2) + \bar{q}_j(x,Q^2)) \\ F_2(x,Q^2) &= 2xF_1(x,Q^2) \\ F_3(x,Q^2) &= 2x\sum_j (q_j(x,Q^2) - \bar{q}_j(x,Q^2)) \end{aligned}$$

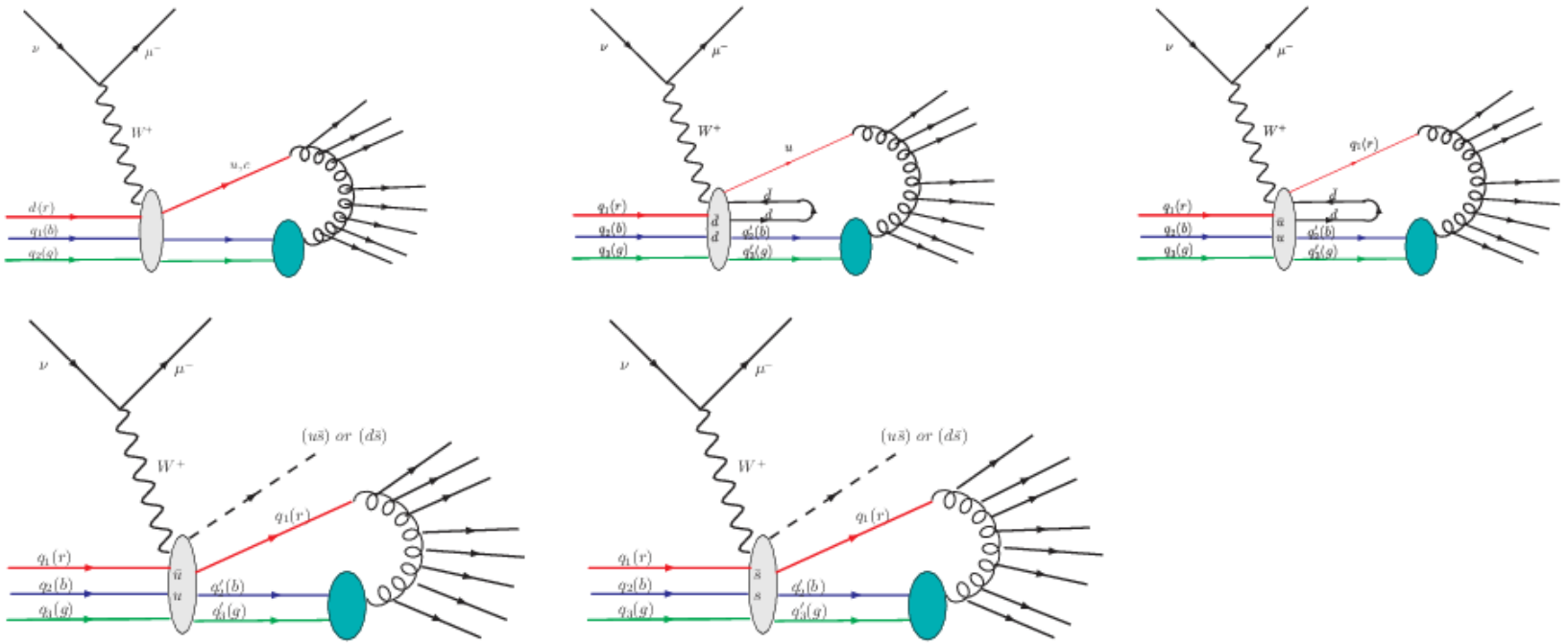
and Bodek-Yang corrections on the top of GRV94 PDFs.

Fragmentation scheme

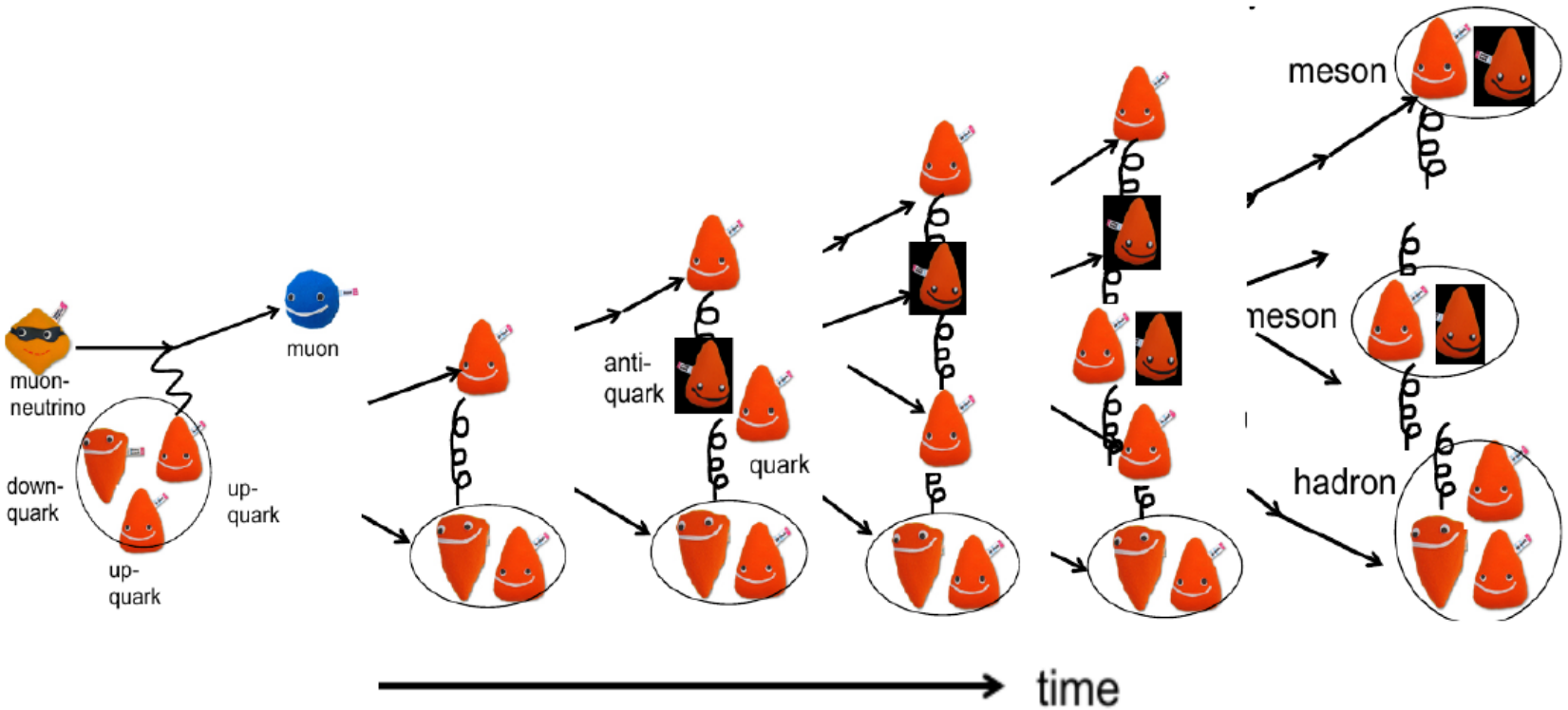
Scattering occurs on either valence or sea quark:

- For valence quark a string is created of final quark and two remaining quarks (diquark)
- For sea quark u or d, an annihilation is assumed between sea antiquark and valence quark, diquark is left as above
- For sea antiquark $\bar{u}$ or $\bar{d}$ and resulting antiquark $\bar{d}$ or $\bar{u}$, an annihilation is assumed with a valence quark.
- For sea antiquark $\bar{u}$ or $\bar{d}$ and resulting antiquark $\bar{s}$ or $\bar{c}$, a strange or charm meson is produced with remaining quark diquark string.
- For sea strange quark or antiquark, a remaining strange quark combined with a valence quark gives rise to a strange meson with remaining quark diquark string.

Fragmentation scheme



LUND model



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Charge hadron multiplicity

PYTHIA 6 optimization was done for charge hadron multiplicity. Some parameters values was modified.

- PARL(32) 1.0 GeV$\hookrightarrow$ 0.1 GeV
- PARL(33) 0.8 GeV$\hookrightarrow$ 0.5 GeV
- PARL(34) 1.5 GeV$\hookrightarrow$ 1.0 GeV
- PARL(36) 2.0 GeV$\hookrightarrow$ 1.0 GeV
- MSTJ(17) 2 $\hookrightarrow$ 3

Charge hadron multiplicity

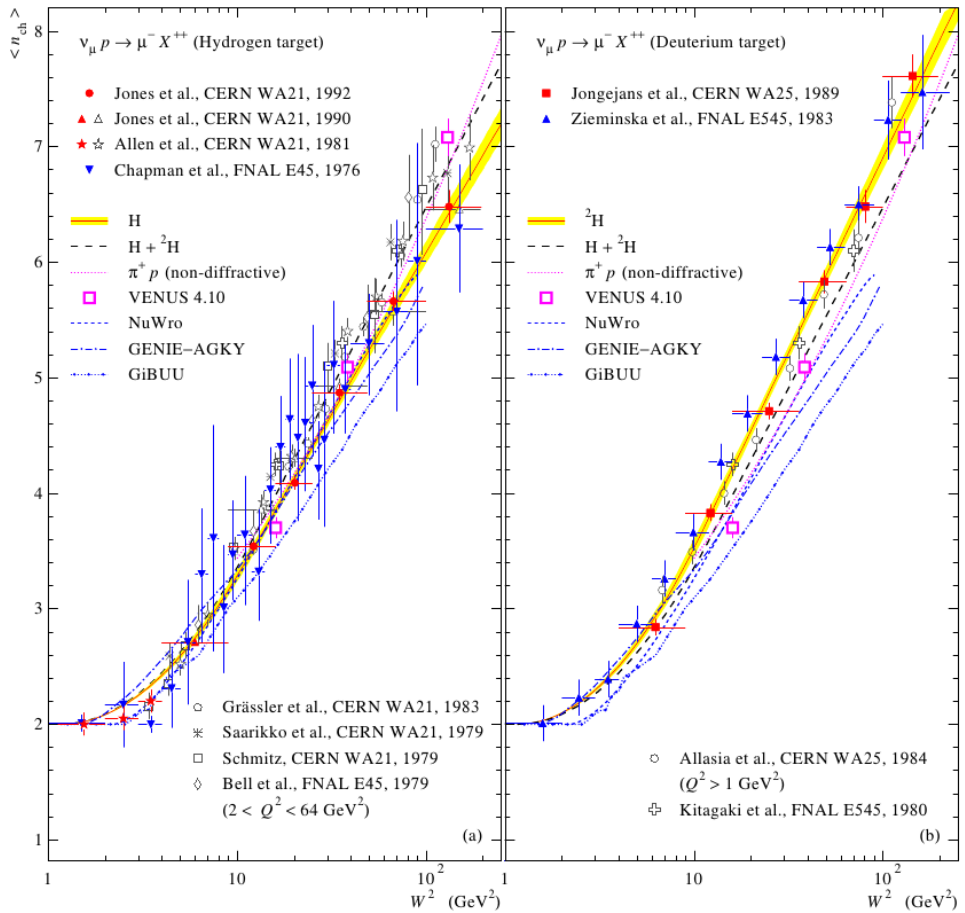


Figure 3. (Color online) A comparison between the fitted and measured charged-hadron multiplicity vs. W^2 for the reaction $\nu_\mu p \to \mu^- X^{++}$ in hydrogen (a) and deuterium (b). The data points are from the experiments FNAL E45 [22, 23], FNAL E545

Kuzmin, Naumov

NuWro strategies for RES and DIS – resumé

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.

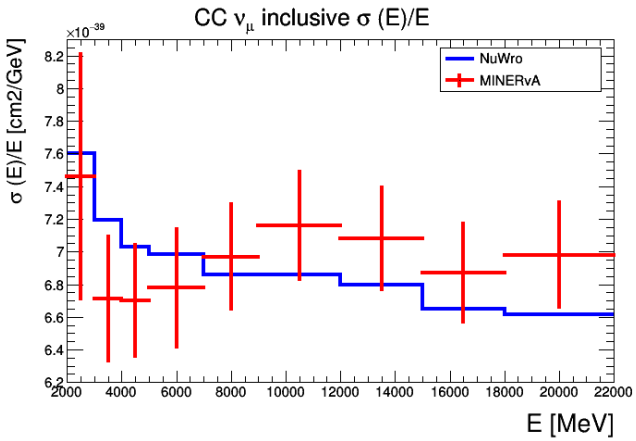
mode	option	cross section formula	remarks
RES		$\frac{d^2\sigma}{dWdQ^2}$ (muon only)	incoherent sum of Δ excitation and BKGR BKGR modeled as a fraction of DIS contribution; for SPP Δ/DIS transition region: $W \in (1.3, 1.6)$ GeV; 2π production in $W \in (1.3, 1.6)$ GeV taken from DIS; Δ FFs from a fit 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.

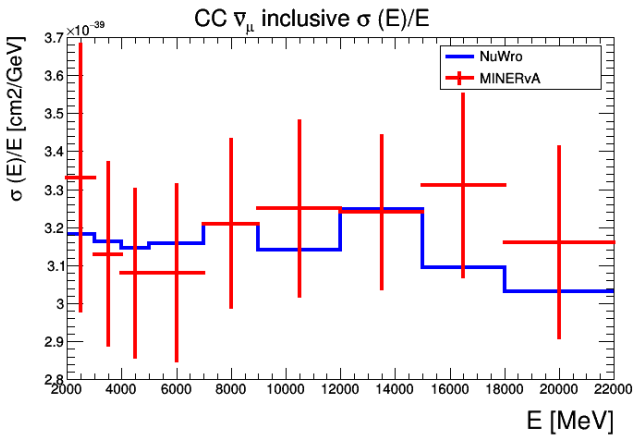
NuWro performance.

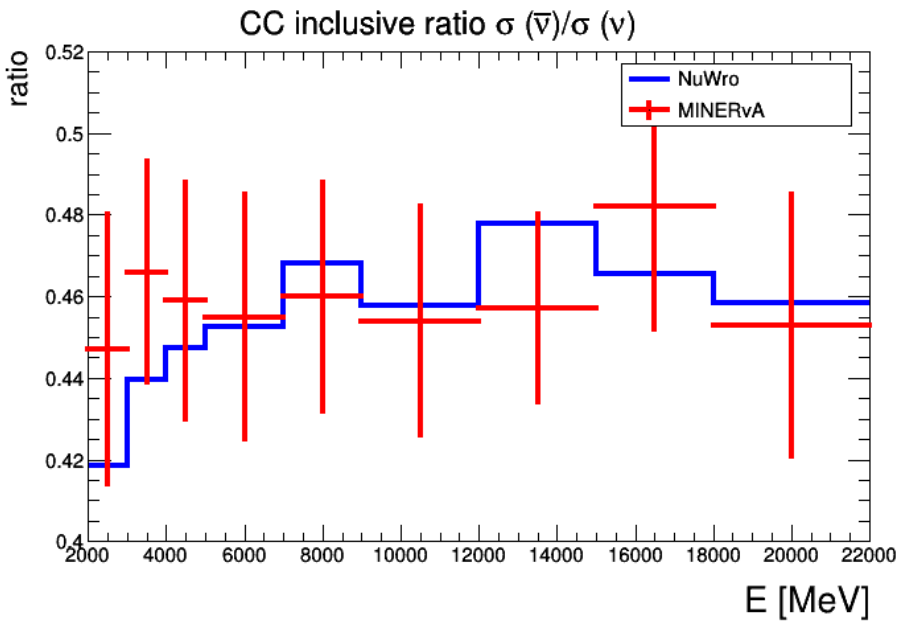
How to test SIS/DIS treatment?

- In ν interactions experiment we do not have access to exact values of W and Q^2
  - MINERvA attempt to overcome this difficulty, see below
- Inclusive cross section at low ν energies?
- Multihadron observables?

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



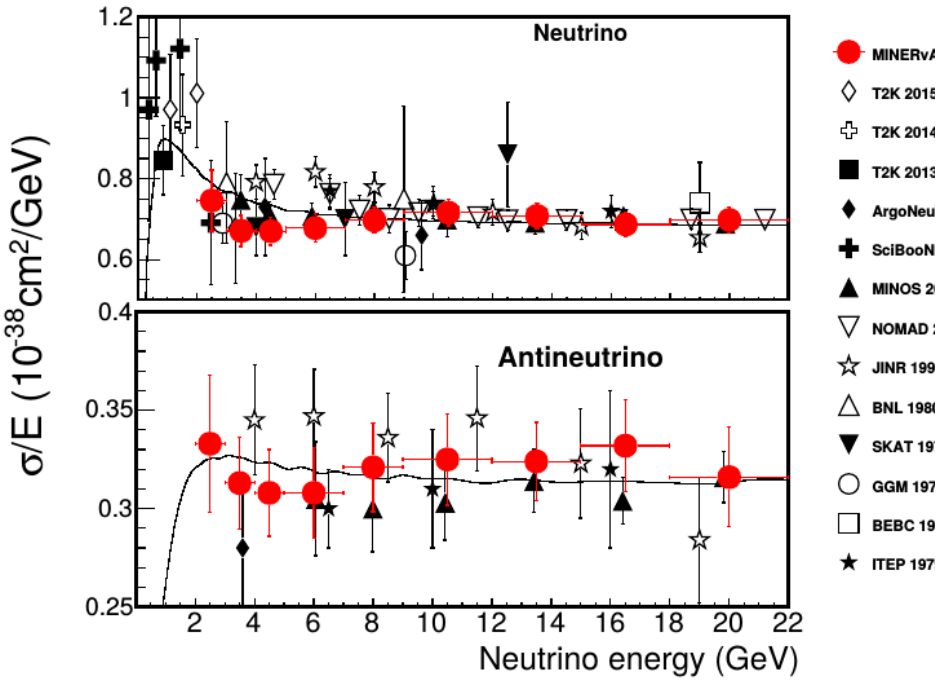


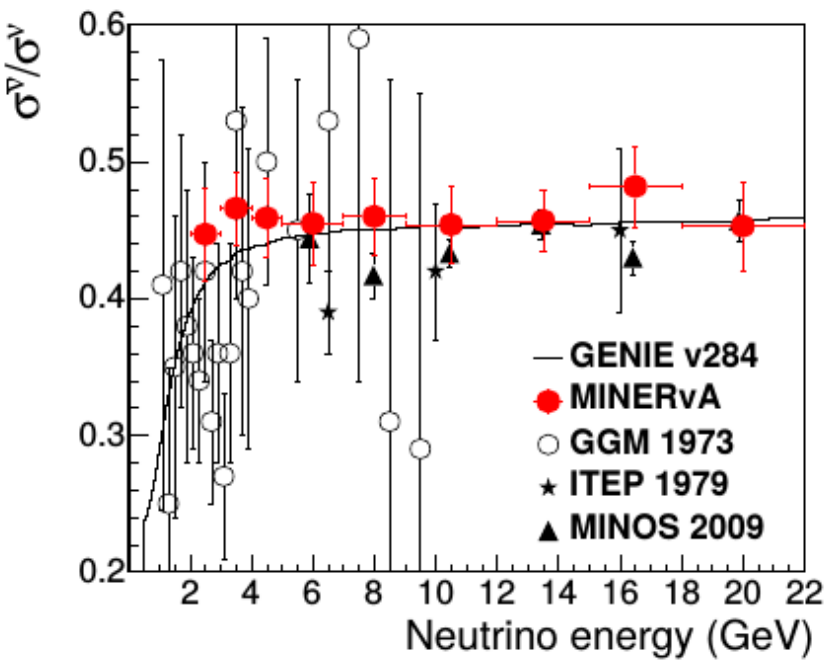


- The agreement is fair.
- MINERvA results are consistent with the previous measurements, see the next slide.

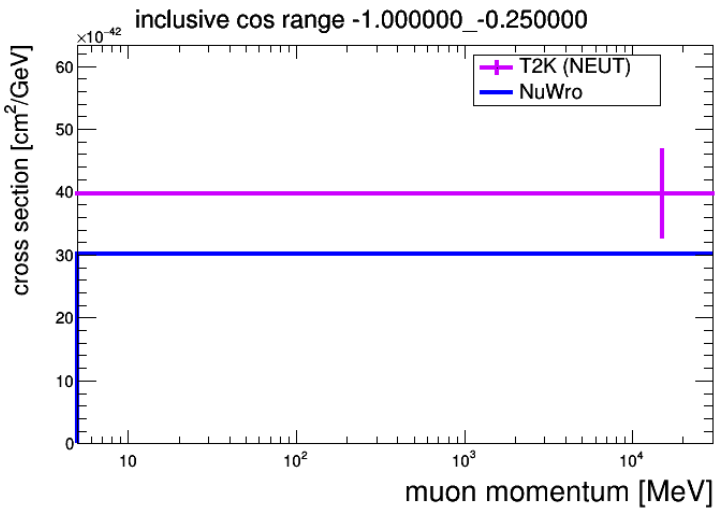
MINERvA inclusive ν_μ, $\overline{\nu_\mu}$, and ratio

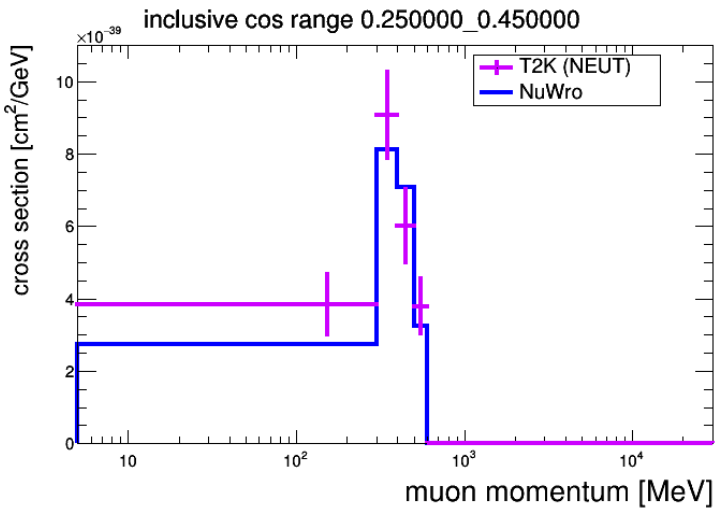
Comparison with the previous experiments

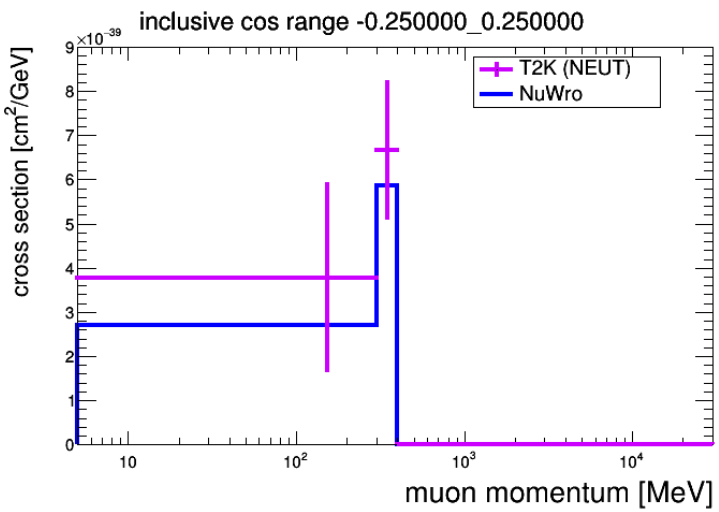


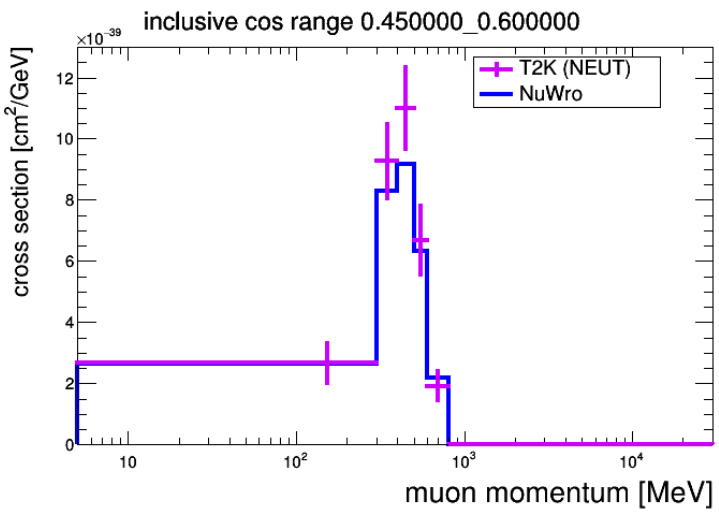


T2K CC inclusive muon double differential cross section

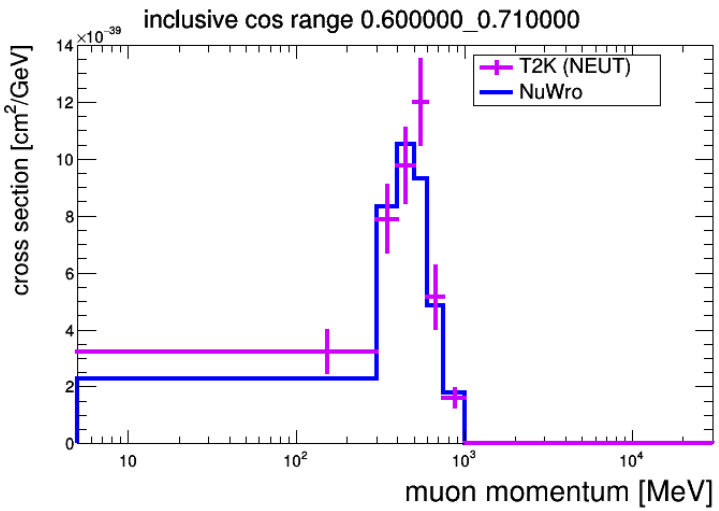


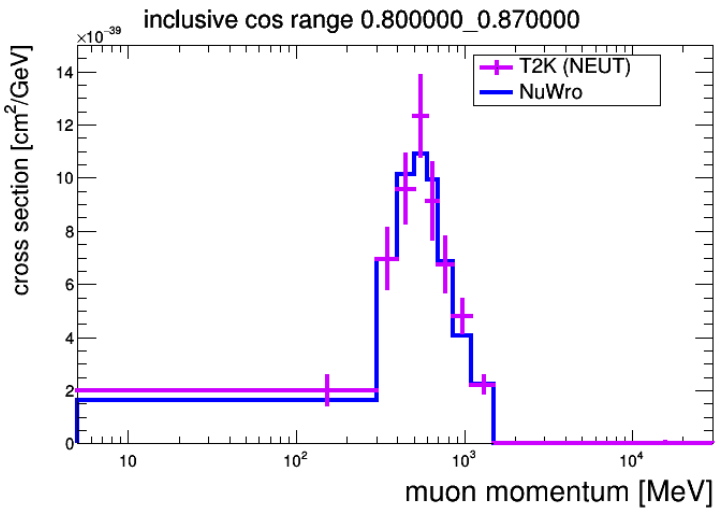


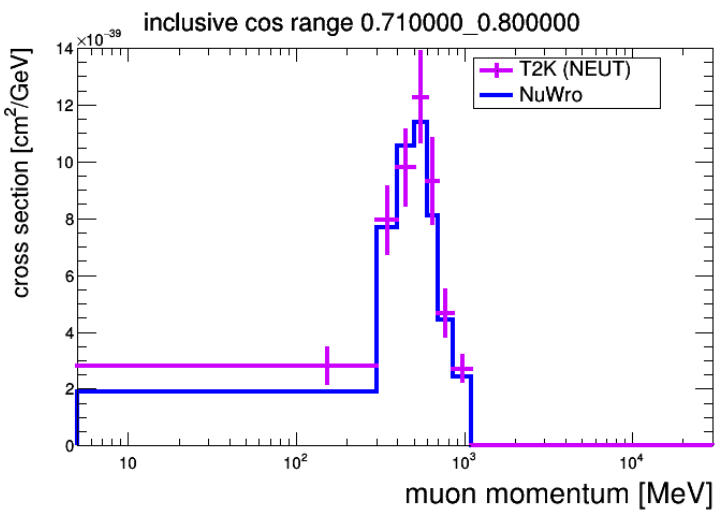


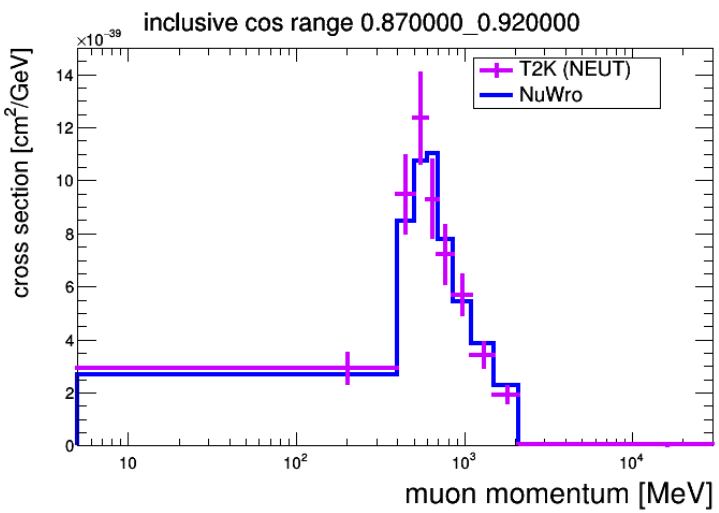


T2K CC inclusive muon double differential cross section (cont)

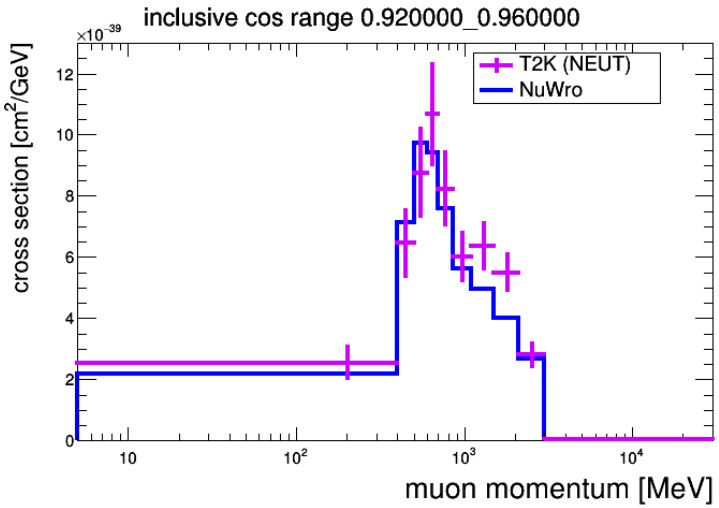


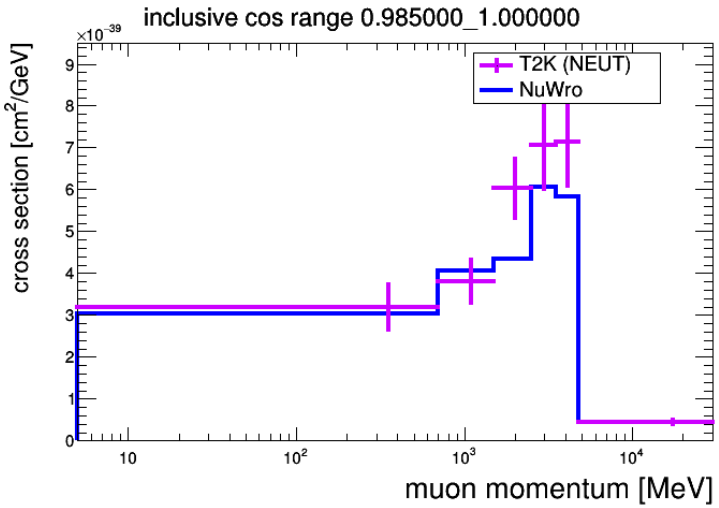


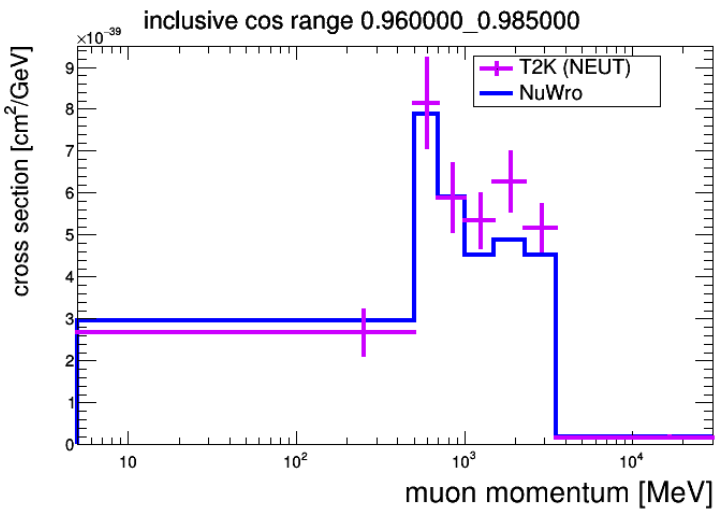


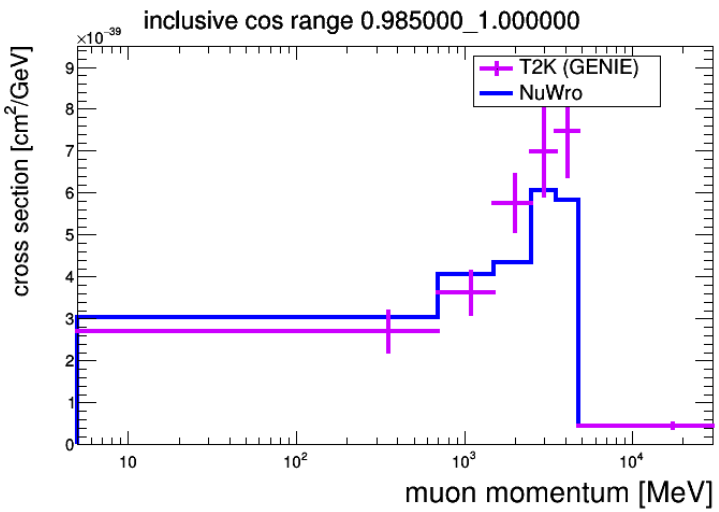


T2K CC inclusive muon double differential cross section (cont 2)









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

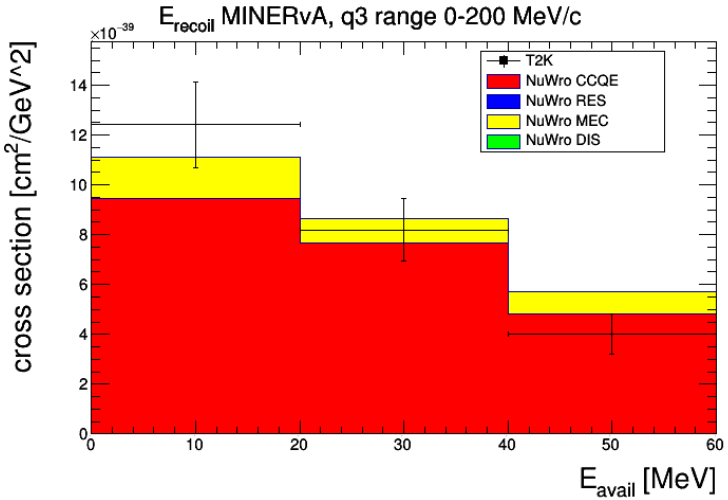
MINERvA recoil energy

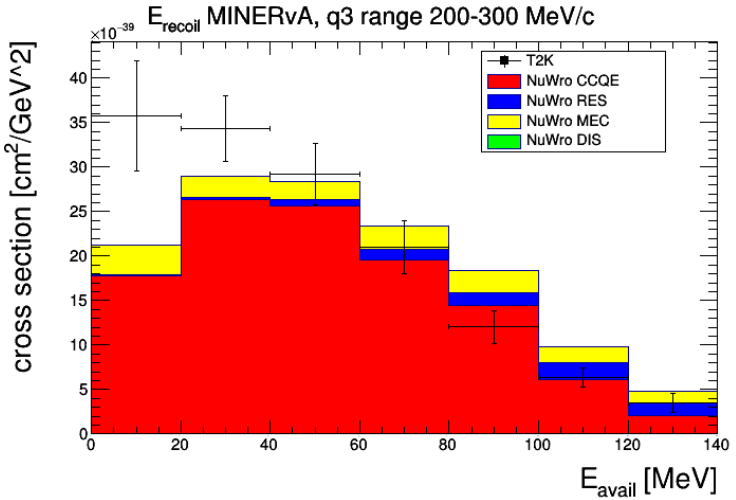
An attempt to resolve kinematics completely.

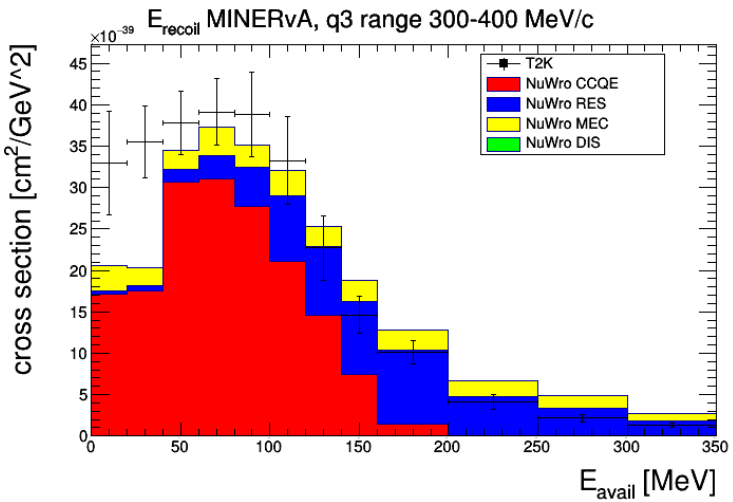
- Calorimetric measurement of hadronic energy.
- MC (GENIE) dependent estimate of energy and momentum transfer $q3$.
- Allows to single out and study region of low $q3$ and "available energy" E_{avail}
- Double differential cross section reported.

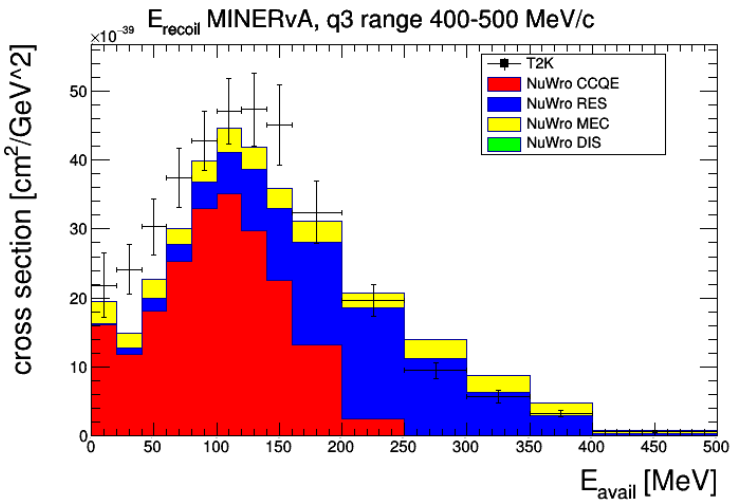
$$E_{avail} \equiv \sum_{kinetic\ \ energy} proton, \pi^{\pm} + \sum_{energy} \pi^{0}, \gamma, e^{-}.$$

MINERvA recoil energy

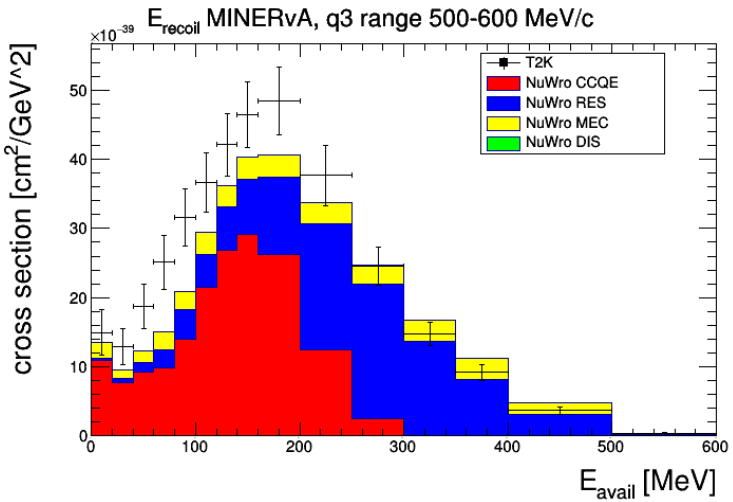


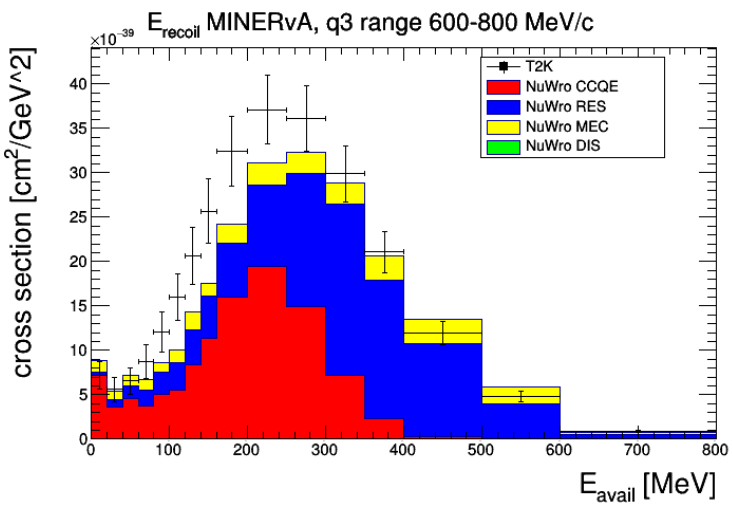






MINERvA recoil energy (cont)





- No MEC rescaling on NuWro predictions.
- NuWro results systematically shifted to the right?
- Unfortunately, no sensitivity to DIS, i.e. to "SIS/DIS"

Conclusions

- NuWro model in the SIS/DIS region is a rather simple one and goes back to Jarek Nowak PhD thesis in 2006
  - The model agrees with the pion production data surprisingly well (e.g. the most recent MINERvA data)
  - There are plans to implement Raul Gonzalez-Jimenez model.
- We need more data.