NuWro status

Jan T. Sobczyk

.

(in collaboration with Tomasz Golan and Kajetan Niewczas)

Wrocław University

NuInt Workshop, L'Aquila, October 15-19, 2018

Outline:

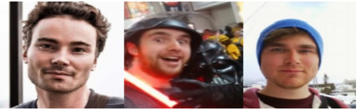
- General information
- Developments since NuInt17
    - Nucleon cascade model
    - Event reweighting
    - New MEC model
    - Validation program
- Plans for the future

NuWro team

Active (not full time, though) 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

A short history

ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT

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

NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

www.elsevierphysics.com

WroNG – Wrocław Neutrino Generator of events for single pion production

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

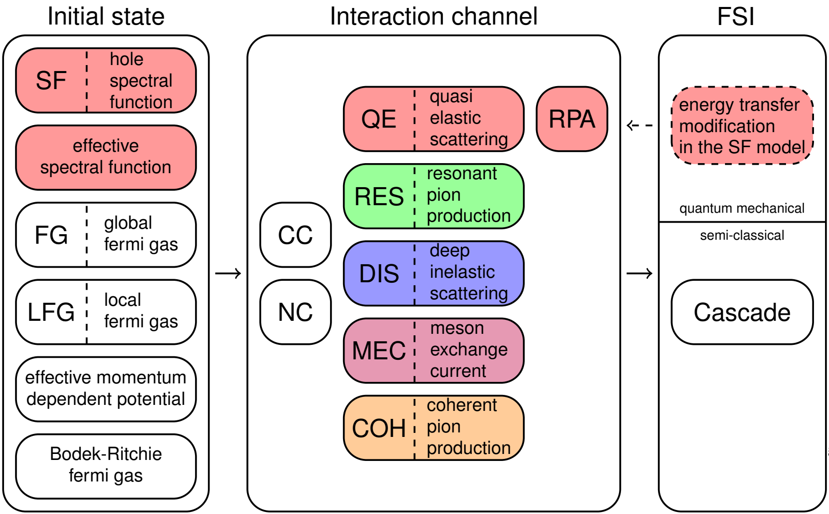
[a]Institute of Theoretical Physics, Wrocław University.
pl. M. Borna 9, 50-204 Wrocław, Poland

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 blueprint



Intranuclear cascade

Intranuclear cascade Kajetan Niewczas

- Propagates particles through the nuclear medium
- Probability of passing a distance λ:

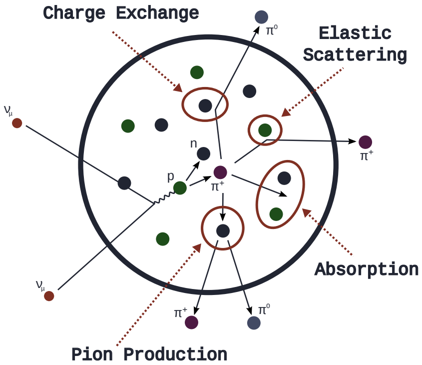
$$P(\lambda) = e^{-\lambda/\tilde{\lambda}}$$

where mean free path
$\tilde{\lambda} \equiv (\rho\sigma)^{-1}$
ρ - local density
σ - cross section

- Implemented for nucleons and pions

T. Golan, C. Juszczak, J.T. Sobczyk, Phys.Rev. C86 (2012) 015505

- Semi-classical – includes Pauli blocking, nucleon-nucleon correlation effects



from T. Golan

Nucleon cascade – technicalities

- Based on Metropolis at al. algorithm
  N. Metropolis et al., Phys. Rev. 110 (1958) 185-203 and 204-219
- Propagation and interactions of on-shell nucleons
- Nuclear potential from LFG: $V(r) = E_F(r) + E_B$ (nucleons leaving nucleus loose energy)
- Total and elastic free NN cross sections fitted to PDG2016
  M. Tanabashi et al. (Particle Data Group), Phys. Rev. D98 (2018) 030001
- Fraction of 1π production in overall cross section from Bystricky et al.
  J. Bystricky at al, J. Physique 48 (1987) 1901
- Nuclear effects on the top of all that.

Nucleon cascade – in-medium modifications

- V.R. Pandharipande, S. Pieper corrections to the elastic cross section
  - → Reduced relative nucleon velocity and available phase space
  - → Potential obtained from Urbana v_{14} + TNI Hamiltonian

  V.R. Pandharipande, S. Pieper, Phys. Rev. C45 (1992) 791-798

- Inelastic cross section modification: $\sigma^{*}_{\mathrm{NN}} = (1 - 0.2\rho/\rho_0)\sigma^{\mathrm{free}}_{\mathrm{NN}}$

  Y. Zhang, Z. Li, and P. Danielewicz, Phys. Rev. C75 (2007) 034615

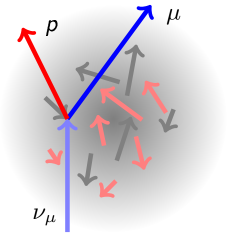
- Nucleon-nucleon correlations effects:
  - → "Effective" nuclear density due to nucleon-nucleon correlations
  - → Correlation function taken from ab initio nuclear matter calculations

Nucleon cascade – transparency

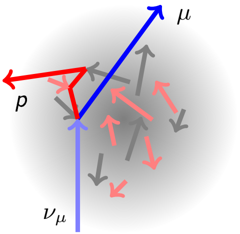
Nuclear transparency T is the probability for a knocked-out proton to escape the nucleus without significant reinteraction (soft reinteraction cannot be identified experimentally).

For Carbon experimental measurements: $\mathrm{T} \simeq 0.60$ [D. Abbott *et al.*, PRL 80 (1998), 5072]

$\sim$ 60% events without FSI



$\sim$ 40% events with FSI



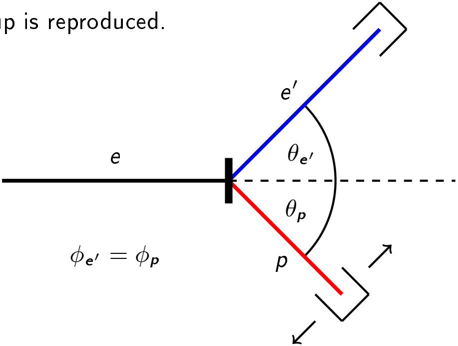
Data from $(e, e'p)$ experiments

In NuWro computations experimental setup is reproduced.

Exclusive QE proton knockout at fixed kinematics:

- beam: E_e
- electron: $E_{e'}$, $\theta_{e'}$, $\phi_{e'}$
- proton: E_p, θ_p, ϕ_p

With provided: $\frac{\Delta p}{p}$, $\Delta\theta$, $\Delta\phi$



Cuts on "missing" variables:

- energy: $E_m = \omega - T_{p'} - T_{A-1}$
- momentum: $\vec{p}_m = \vec{p}_{p'} - \vec{q}$

$$E_m < 80 \text{ MeV}, \quad |\vec{p}_m| < 300 \text{ MeV/c}$$

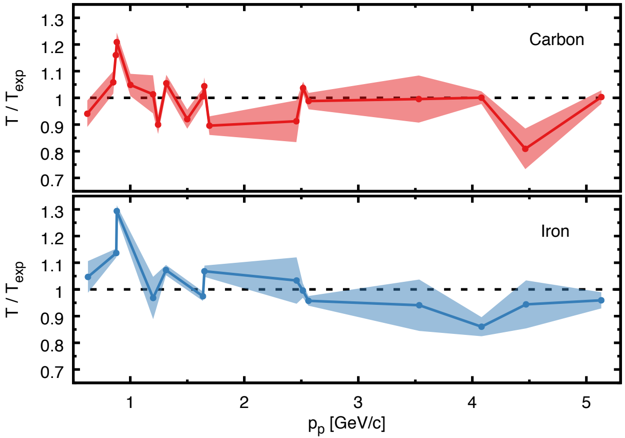
Transparency:

$$\langle T \rangle_{\theta_p} = \frac{\sigma_{\text{exp}}}{\sigma_{\text{PWIA}}} \frac{1}{c_A}$$

σ_{PWIA} - expected value without FSI (model dependent)

c_A - correlation factor

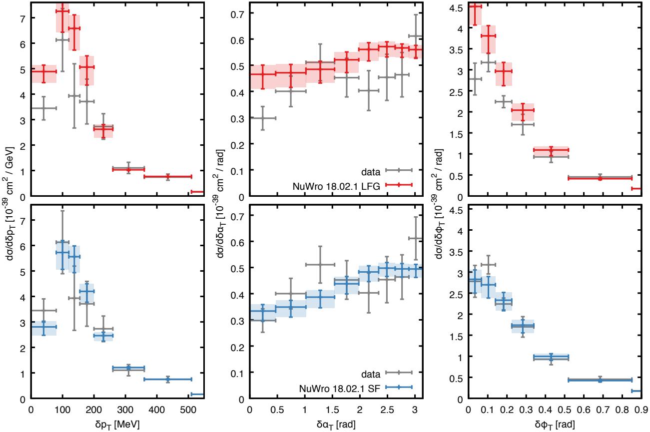
Nuclear transparency in NuWro



Simulations done for NC ν_e scattering on protons with Spectral Function.

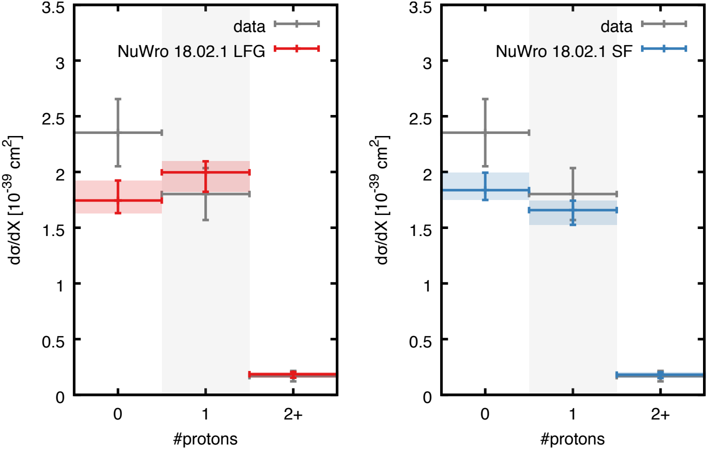
Data/MC agreement within $\sim 30\%$, typically much better

Impact of mean free path uncertainty: single transverse variables



Results from T2K experiment Phys.Rev. D98 (2018) 032003

Impact of mean free path uncertainty: proton multiplicity



Results from T2K experiment Phys.Rev. D98 (2018) 032003

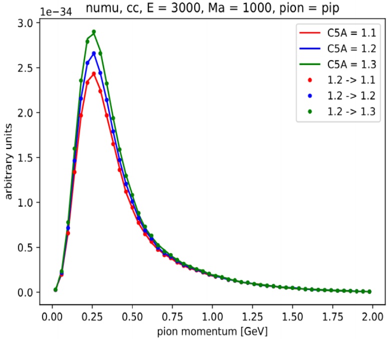
Event reweighting

Event reweighting Cezary Juszczak and Tomek Golan

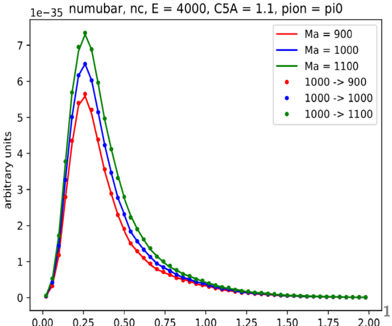
```
+-------------+       +-------------+       +-------------+
|             |       |             |       |             |
|  Neutrino   | --->  |  Detector   | --->  |   Events    |
|             |       |             |       |             |
+-------------+       +-------------+       +-------------+
                                                   |
                                                ---|---
                                                   |
+-------------+       +-------------+       +-------------+
|             |       |             |       |             |
|"new" events | <---  | Reweighting | <---  | new params  |
|             |       |             |       |             |
+-------------+       +-------------+       +-------------+
```

It is critical in time consuming detector simulations.

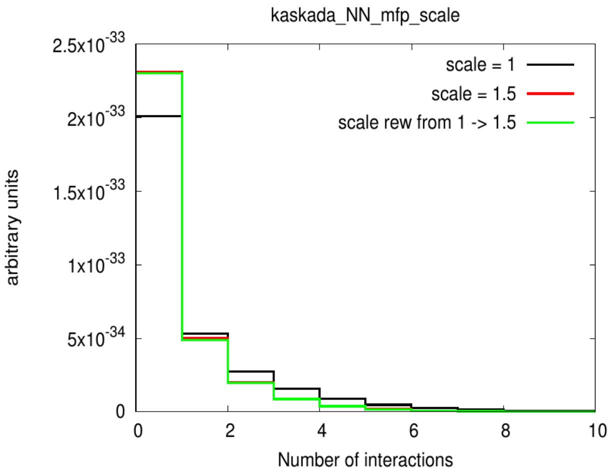
Event reweighting - RES examples



A completely new setup based on the work done by Luke Pickering and Patrick Stowell.



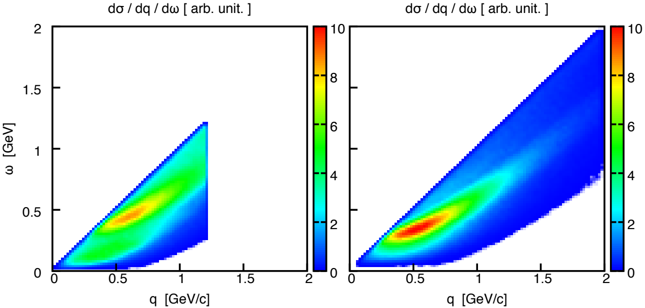
Event reweighting - nucleon FSI



Mean free path is scaled by 1.5 on every step.

New MEC model

New MEC model: SuSAv2 Kajetan Niewczas



$E_\nu = 3$ GeV, carbon target.

- Using tables from Guillermo Megias.
- Other models: Nieves, Marteau, TE.

NuWro validation

Motivation

- An ultimate goal: a complete NuWro validation tool with all relevant experimental data.
- Statistical analysis will be included.
- An attempt to identify and understand tensions in the data.
- Identification of areas of necessary/possible improvements.
- Most of work was done for the CC0π data with attempts to fit MEC contribution rescaling (motivated by GENIE MINERvA fit).

A NuWro version 17.09 is used (LFG+RPA). Future NuWro upgrades will be compared to the same data set.

Work in progress.

NuWro 17.09

CCQE

- LFG
- RPA based on K. Graczyk, JTS, Eur.Phys.J. C31 (2003) 177-185
- $M_A = 1.03$ GeV

RES

- $W < 1.6$ GeV
- Smooth (linear) transition to DIS at $W \in (1.3, 1.6)$ GeV
- LFG
- Explicit Δ plus BKGR added incoherently C. Juszczak, J. Nowak, JTS, Nucl. Phys. Proc. Suppl. 159 (2006) 211-216
- For nuclear target reactions a fraction of events is subtracted motivated by Oset et al studies JTS, J. Żmuda, Phys.Rev. C87 (2013) 065503
- π angular distribution from ANL and BNL papers.

NuWro 17.09

DIS

- $W > 1.6$ GeV
- Inclusive cross sections from Bodek-Yang model
- Hadronization with PYTHIA fragmentation functions J. Nowak, PhD thesis.
- No shadowing, anti-shadowing, EMC nuclear effects.

MEC

- Nieves et al model
- Implementation by J. Żmuda with five tabularized response function.
- Nucleons modeled with phase space model JTS, Phys.Rev. C86 (2012) 015504
  - 85% initial p-n pairs
  - Uniform distribution in nucleon CMF.

NuWro 17.09

COH

- Berger-Sehgal model.

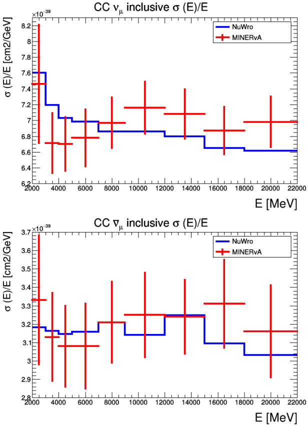
Cascade model

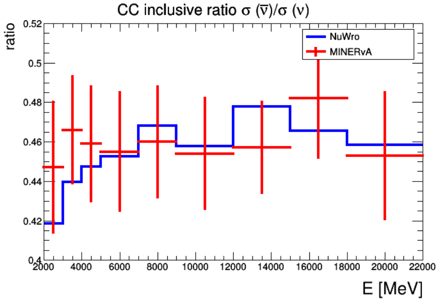
- Pions, nucleons.
- 0.2 fm steps.
- For pions Oset et al model T. Golan, C. Juszczak, JTS, Phys.Rev. C86 (2012) 015505.
- For nucleons in-medium modification of NN cross sections V.R. Pandharipande, S.C. Pieper, Phys.Rev. C45 (1992) 791-798

NuWro validation

Inclusive data

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

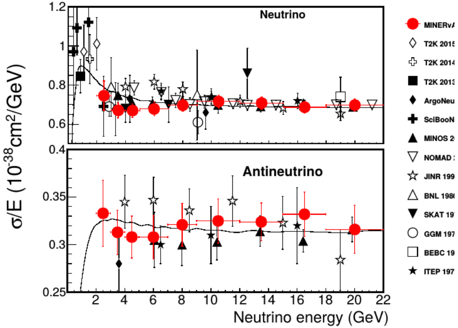


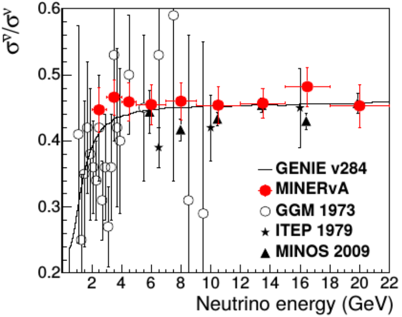


- The agreement is fair.
- MINERvA results are consistent with the previous measurements, see the next slide.

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

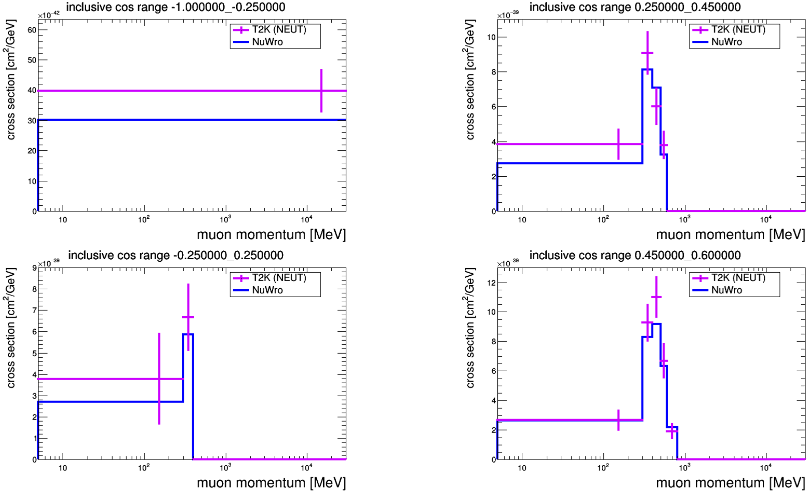
Comparison with the previous experiments



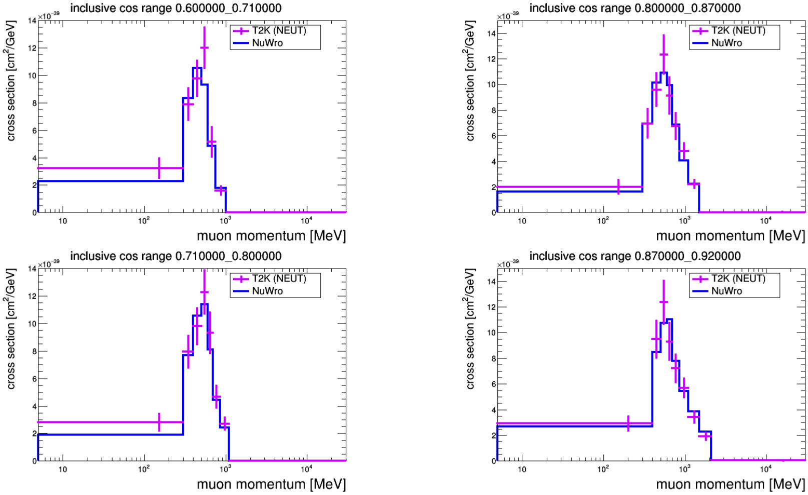


T2K CC inclusive muon double differential cross section on carbon

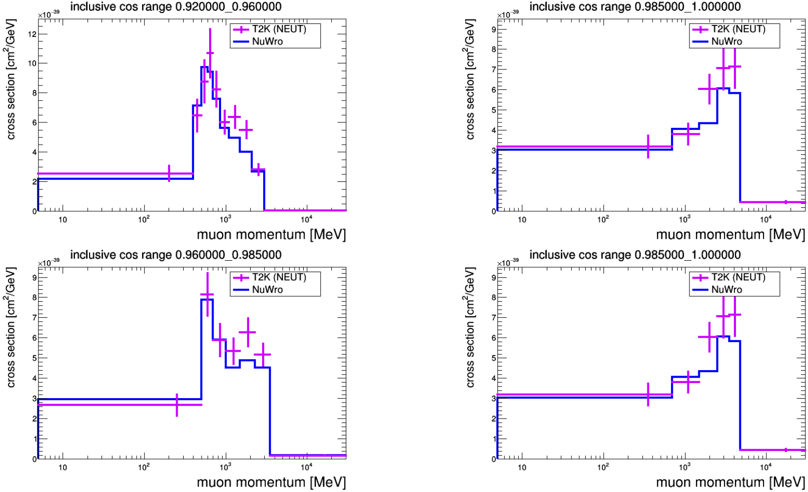
Phys. Rev. D98, 012004 (2018)



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.

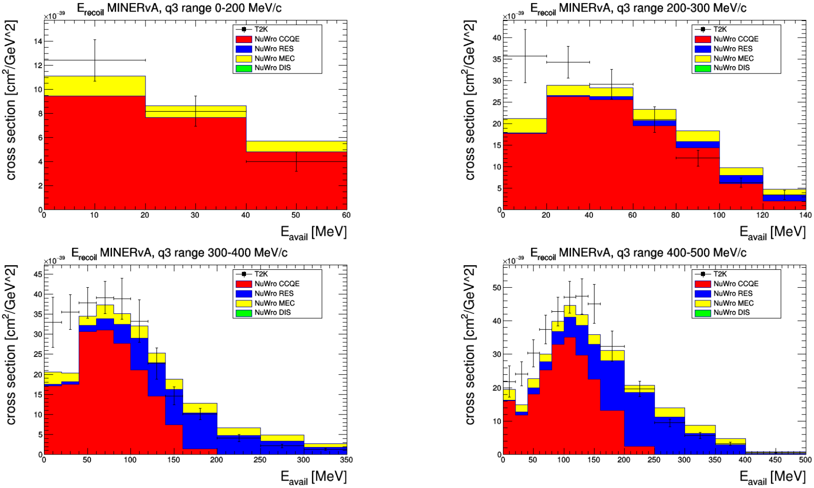
MINERvA recoil energy Phys.Rev.Lett. 116 (2016) 071802

An attempt to resolve kinematics completely.

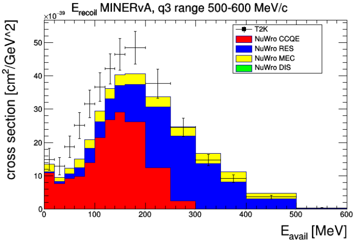
- Calorimetric measurement of hadronic energy.
- MC (GENIE) dependent estimate of energy and momentum transfers $q0$ and $q3$.
- Allows to single out and study region of low $q3$ and “available energy” E_{avail} (close to $q0$).
- Double differential cross section reported.

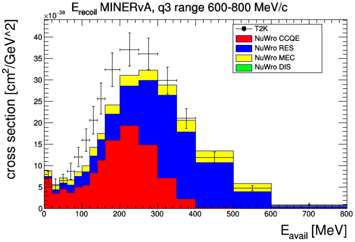
$$E_{avail} \equiv \sum_{kinetic\ \ energy} proton, \pi^{\pm} + \sum_{energy} \pi^{0}, \gamma, e^{-}.$$

MINERvA recoil energy



MINERvA recoil energy (cont)





- No MEC rescaling is adopted.
- NuWro results seems to be systematically shifted towards larger values of E_{avail}.

NuWro validation

Pion cascade

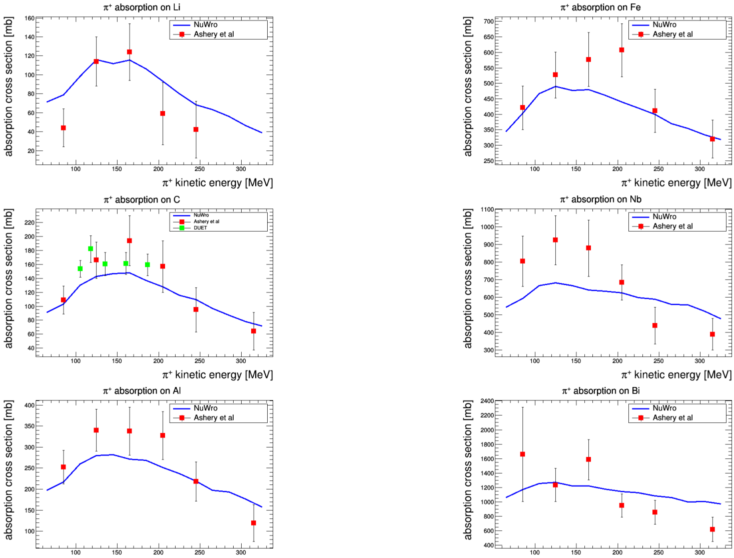
Pion cascade

NuWro cascade performance is confronted with Ashery et al (various nuclei) Phys. Rev. C23 2173 (1981) and new DUET data Phys. Rev. C95 (2017) 045203 on Carbon target only.

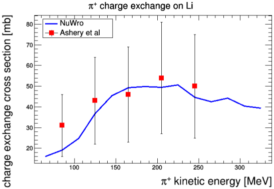
Three types of macroscopic reactions:

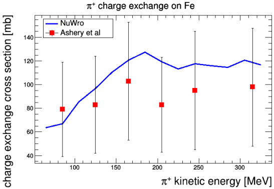
- Pion (always π^+) absorption.
- Charge exchange $\pi^+ \to \pi^0$.
- Inelastic (any other process excluding an elastic one).
  - An obvious issue: how to treat soft inelastic events?

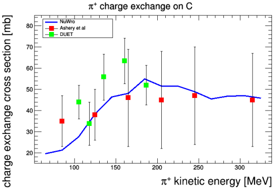
Pion cascade

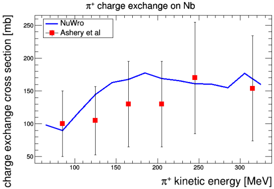


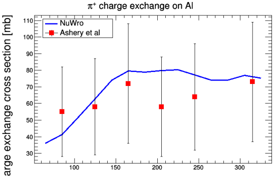
Pion cascade

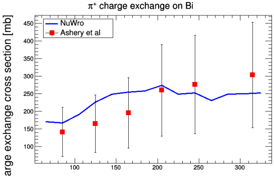








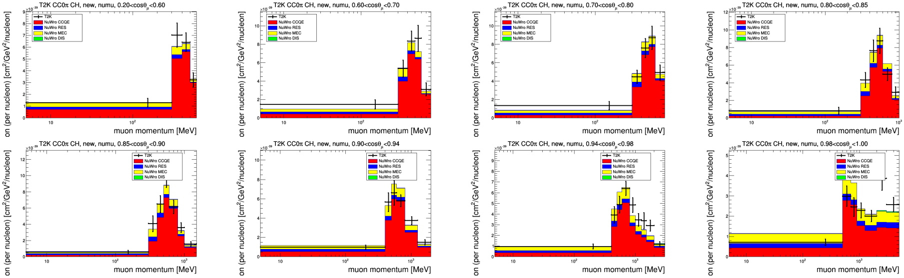




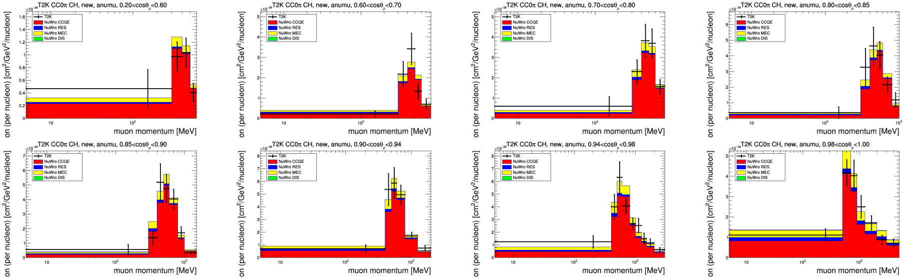
NuWro validation

CC0π/CCQE-like

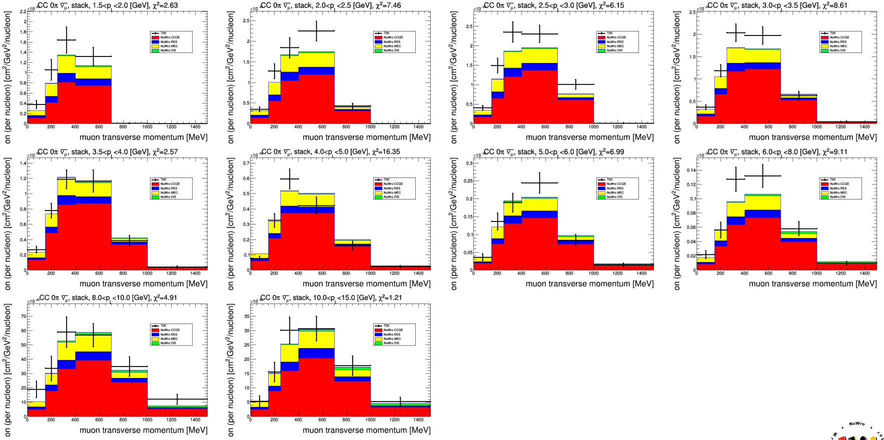
T2K ν_μ CC0π double differential cross section on CH



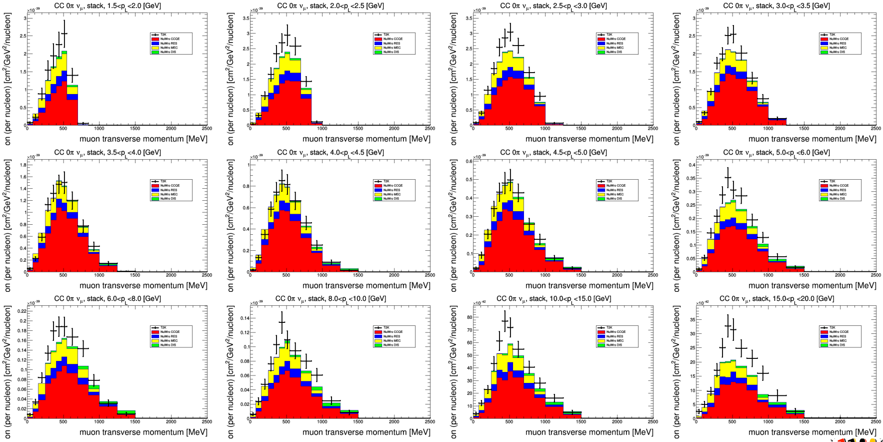
T2K $\overline{\nu_\mu}$ CC0π double differential cross section on CH



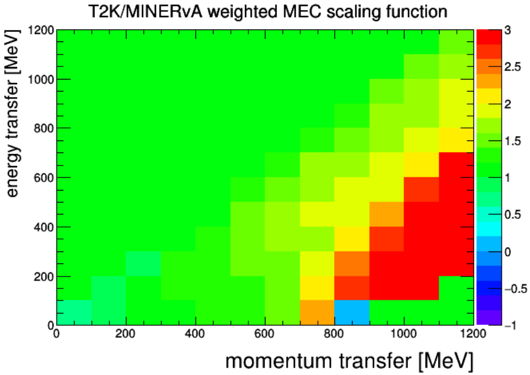
MINERvA CC0π $\overline{\nu_\mu}$ on CH in p_T, p_L variables Phys.Rev. D97 (2018) 052002



MINERvA CC0π ν_μ on CH in p_T, p_L variables



Hypothetical MEC rescaling function



- A general observation: NuWro predictions are below the data.
- One can attempt to scale MEC contribution to arrive at a better purely phenomenological model.
    - Motivation from GENIE MINERvA tune

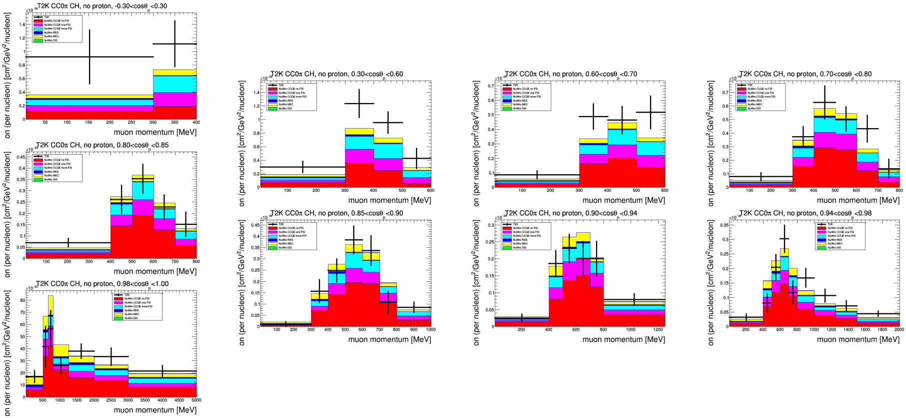
- For a moment the overall MEC scaling, all four experimental data sets are taken into account.
- Clearly can be done much better.
- Work in progress.

NuWro validation

Proton observables

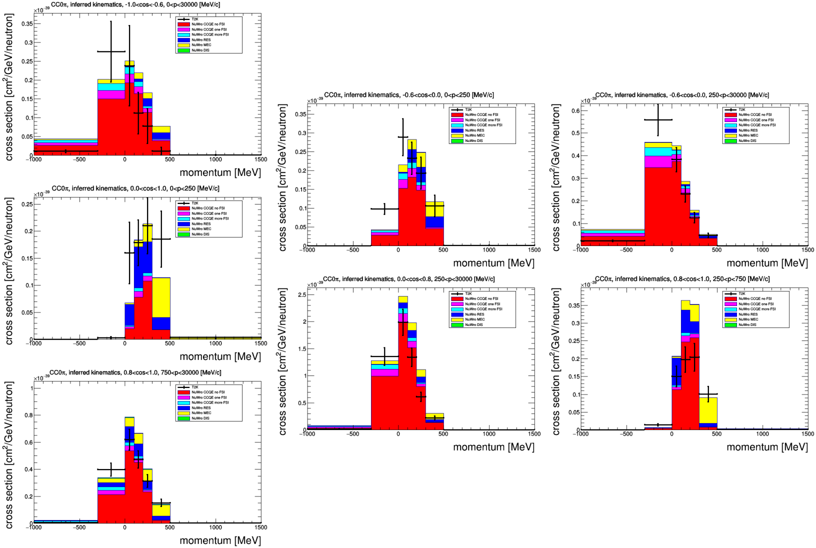
T2K proton data – no proton cross section Phys.Rev. D98 (2018) 032003

No fine tuning to experimental data was done.



- A good agreement (given a complexity of physics).
- A very little contribution from RES.
- A lot of sensitivity to proton FSI.

T2K proton data – “inferred kinematics” Phys.Rev. D98 (2018) 032003



Conclusions

Conclusions

- NuWro is under developing.
- Momentum is smaller as we lost two well trained developers.
- Future?
  - We have many ideas for a collaboration with Natalie Jachowicz' Ghent group.
  - A first NuWro workshop was organized in December 2017.

NuWro workshop 2017 (December 3-5)

	Sunday, 03.12
9:00	Welcome
9:05	*NuWro (WRONG) first years* **Jarosław Nowak**
9:30	*Discussion* **Sara Bolognesi**
10:30	Coffee break
11:00	*Discussion* **Sara Bolognesi**
12:00	*Neutrino SIS and DIS interactions* **Teppei Katori**
12:45	Lunch break
14:45	*NuWro interaction models: primary vertex* **Kajetan Niewczas**
15:30	Coffee break
16:00	*MicroBooNE* **Raquel Castillo** (remotely)

	Monday, 04.12
9:00	*Correlations in neutrino-nucleus scattering* **Natalie Jachowicz**
9:45	*Neutrino-induced pion production* **Raúl González Jiménez**
10:30	*Discussion* **Federico Sánchez**
11:30	Coffee break
12:00	*Discussion* **Federico Sánchez**
13:00	Lunch break
15:00	*NuWro — structure of the code* **Cezary Juszczak**
15:45	Coffee break
16:15	*NuWro treatment of nuclear effects* **Tomasz Golan**
17:00	*NuWro validation (part 1.)* **Jan Sobczyk**

	Tuesday, 05.12
9:00	*NUISANCE + NuWro reweighting* **Patrick Stowell** **Luke Pickering**
9:45	*Discussion* **Callum Wilkinson**
10:45	Coffee break
11:15	*Discussion* **Callum Wilkinson**
12:15	*NuWro cascade model* **Tomasz Golan**
13:00	Lunch break
15:00	*NuWro validation (part 2.)* **Jan Sobczyk**
15:45	Coffee break
16:15	*Final discussion and NuWro next steps* **Together**

- The next workshop should be organized in 2019
- We consider forming a “NuWro collaboration”.
- Any volunteers?...

Thank you!