NuWro validation & some physical considerations (2)

Jan T. Sobczyk

Wrocław University

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Motivation

- Goal: NuWro validation on recent experimental data.

  An ultimate goal: a complete NuWro validation tool with all the relevant experimental data.

- To start with: look (mostly) for measurements done after NuInt15 and before NuInt17.
- Statistical analysis included.
- An attempt to understand disagreements with the data.
- Identification of areas of necessary improvements.

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

A lot of data!

- T2K
  - CC0π muon double differential cross section on CH target [PRC93].
  - CC0π muon double differential cross section on water target [arXiv:1708.06771].
  - CC inclusive muon double differential cross section [PRD96].
  - CC differential cross section in transverse kinematics variables (one muon and $\geq$ one proton sample).
  - CC π^0 inclusive (Marcela Batkiewicz study).
- DUET π^+ absorption and charge exchange on ^{12}C.
- NOvA NC coherent π^0
- ArgoNeuT CC 1π

A lot of data!

- MINERvA
  - CC π^0 production
  - CC inclusive, ν_μ, $\overline{\nu_\mu}$, ratio (PRD94)
  - DIS ratios C, Fe, Pb wrt CH (PRC95)
  - CCQE-like $d^2\sigma/dp_L dp_T$ for ν_μ, $\overline{\nu_\mu}$
  - CC $d^2\sigma/dqdE_{avail}$ for ν_μ and $\overline{\nu_\mu}$
  - CCQE-like ratios C, Fe, Pb wrt CH (PRL119)
  - new release of CC 1π.
  - NC K^+ production (PRL119)
  - coherent K^+ production (PRL117)
  - CC K^+ production (PRD94)

Many MINERvA papers show comparisons with NuWro.

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

Including protons in the game...

CC 0π differential cross section in transverse variables

Motivation: looking for MEC events and validation of nucleon FSI.

T2K selection:

- CC0π
- muon momentum > 250 MeV/c
- cosine of muon angle > -0.6
- leading proton momentum $\in (450, 1000)$ MeV/c
- cosine of leading proton angle > 0.4.

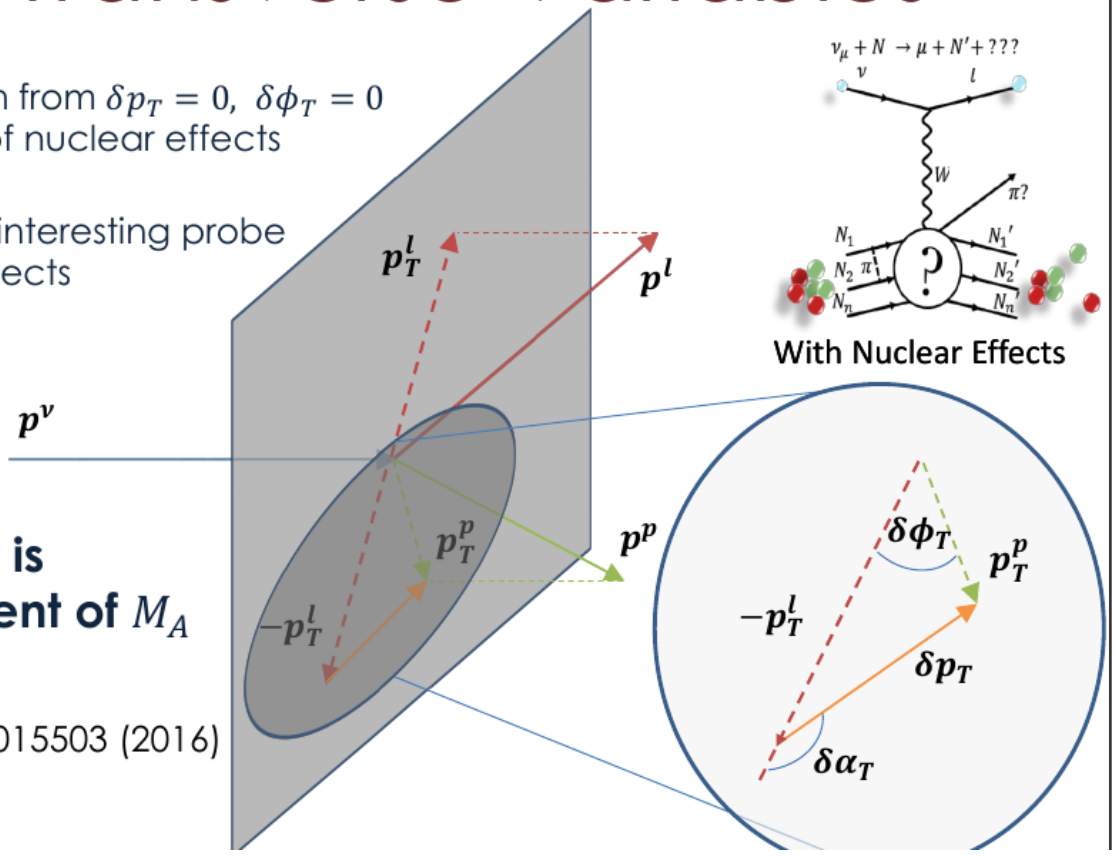
Results from Stephen Dolan presentation at NuInt17.

CC 0π differential cross section in transverse variables

Definition of transverse (wrt neutrino flux) variables.

Single Transverse Variables

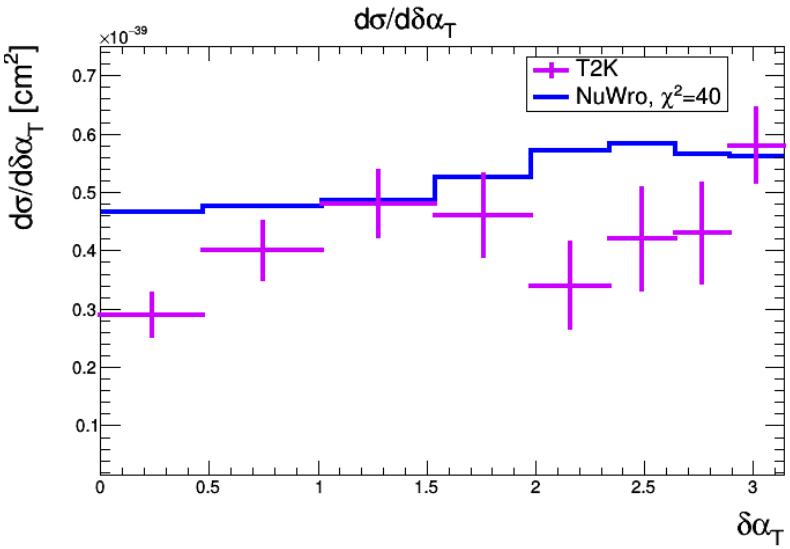
- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects
- STVs offer an interesting probe of nuclear effects
- **STV shape is independent of M_A**

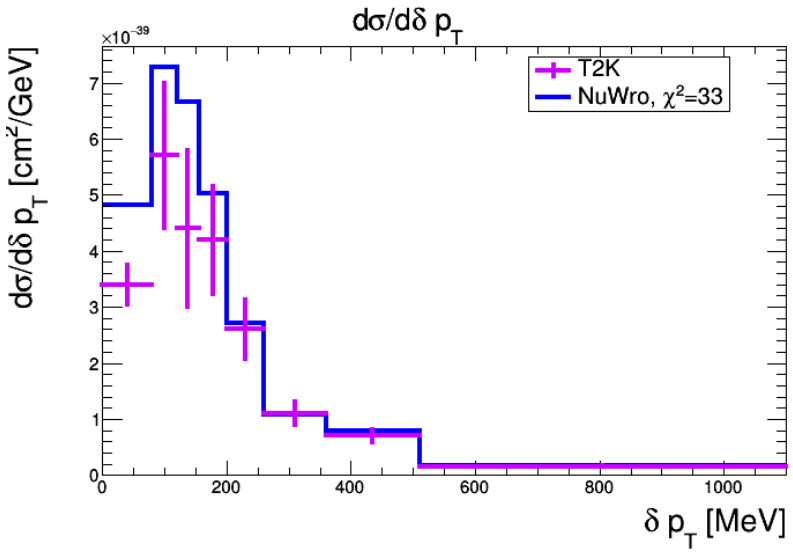


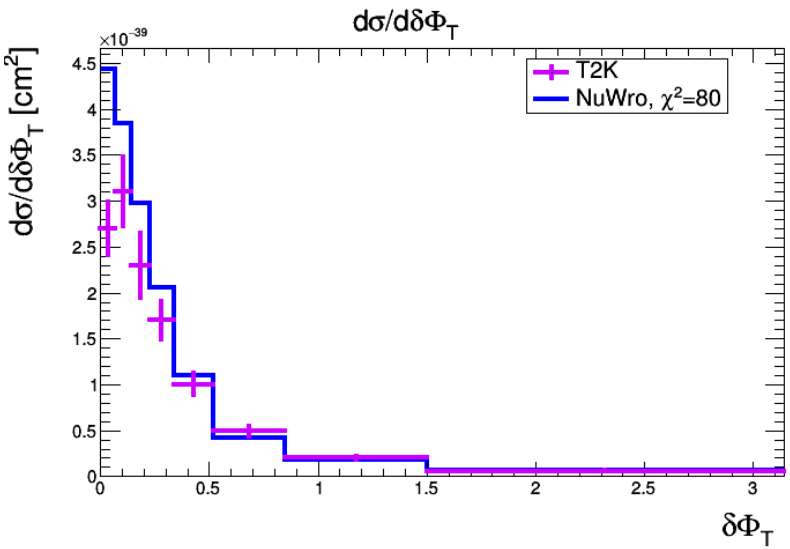
Phys. Rev. C **94**, 015503 (2016)

from Stephen Dolan presentation at NuInt17

CC 0π differential cross section in transverse variables.







- Statistics must be better.
- The current results are for 100 kiloevents.
- Stephen Dolan showed that SF leads to better agreement.

CC 0π differential cross section in transverse variables

Normalization

- NuWro is 19-24% above the data
- Too many forward moving protons
- Need more proton reinteractions?
  - NuWro proton transparency seems to be too large by $\sim 10\%$!
- Kinematical problems with RES or MEC (protons are knocked out in wrong directions)?

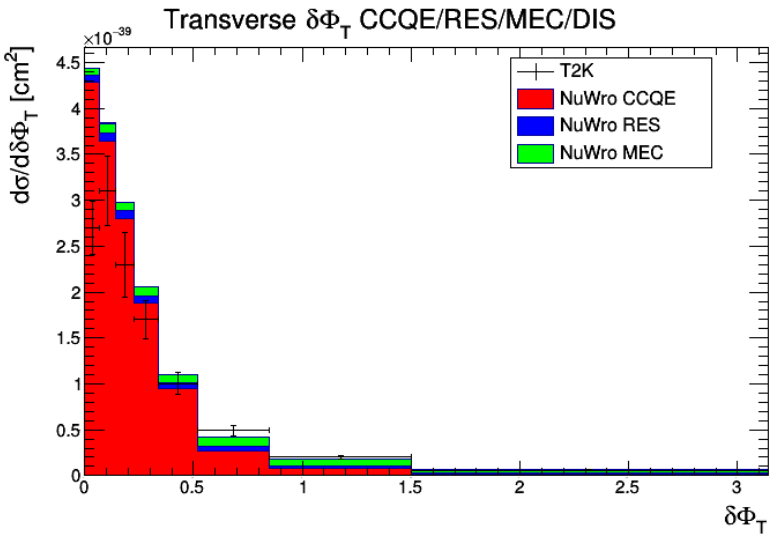
Look at $\delta\Phi_T$ distribution

- What kind of events are there in the first two bins?

Stephen, Xianguo: The most interesting variable is δp_T and not $\delta\Phi_T$.

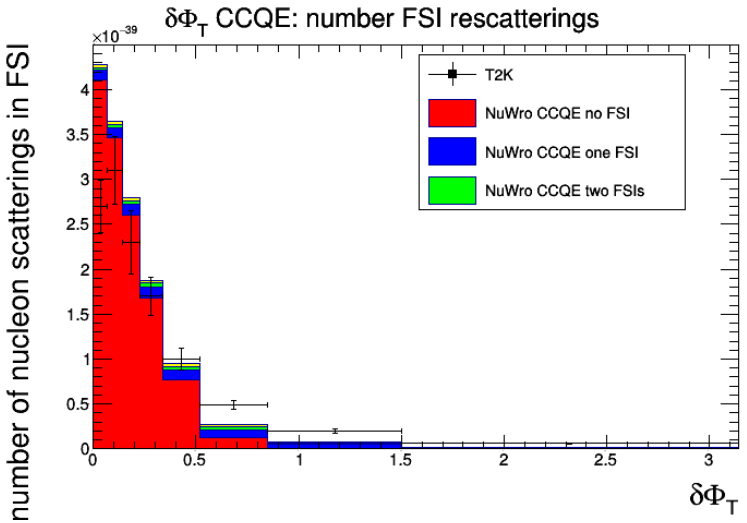
CC 0π differential cross section in transverse variables

Breakdown in interaction modes:



Almost all are CCQE (red).

How many reinteractions?

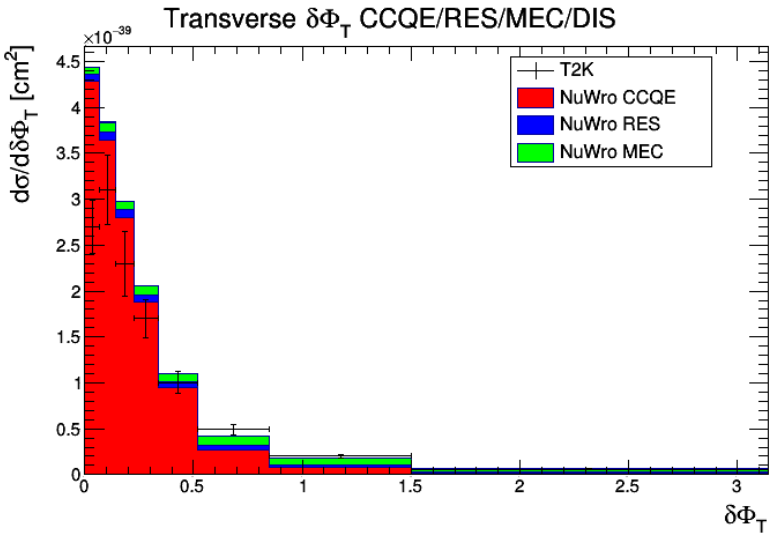


Almost all are without reinteractions (again red)!

The effect comes from the initial state CCQE.

CC 0π differential cross section in transverse variables

Breakdown in interaction modes:



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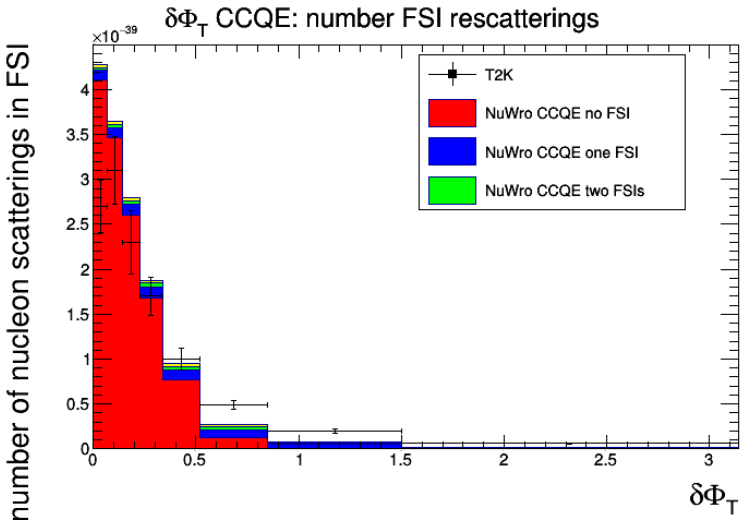
How many reinteractions?



Almost all are without reinteractions (again red)!

The effect comes from the initial state CCQE.

Stephan Dolan: I suspect the drop in the first bin of $\delta\Phi_T$ is a statistical effect. The first few bins are quite strongly anti-correlated (because of relatively small stats and substantial detector smearing) so the result is currently absolutely compatible with a monotonically decreasing dphit so long as the first two bins are fairly flat.

Reconstructed neutron momentum

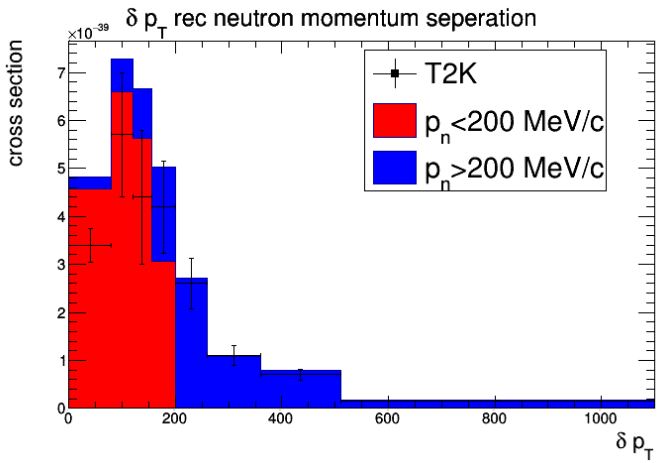
The most interesting STW is $\delta\Phi_T$, but even more interesting may be reconstructed neutron momentum introduced in A. Furmanski, JTS, Phys.Rev. C95 (2017) 065501

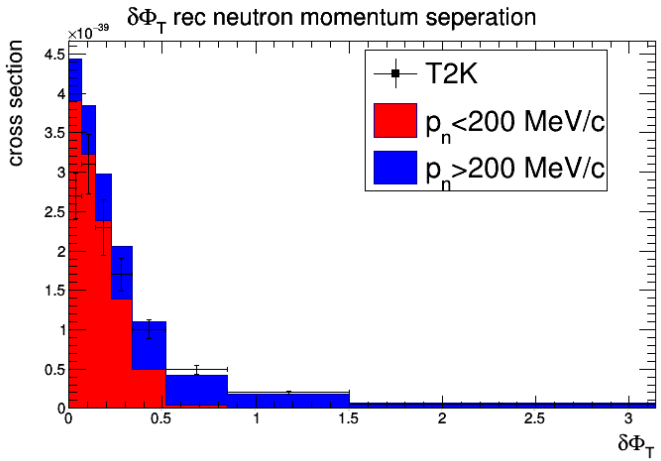
Idea: explore full information about energy and momentum observation. Not only in the transverse plane but also along neutrino beam.

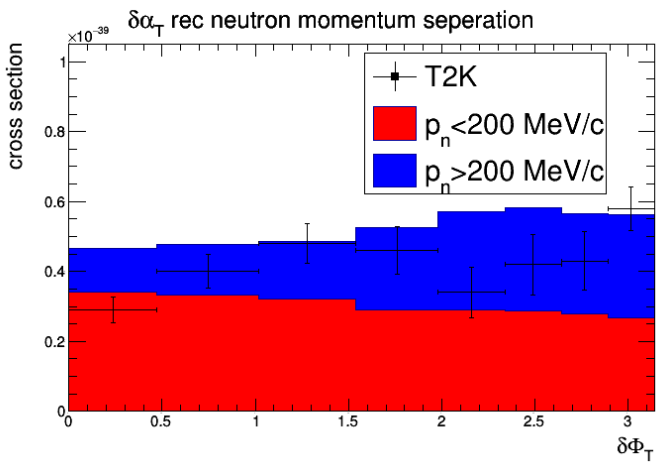
Transverse variables use information about transverse components of muon and proton, while reconstructed neutron momentum explores also information about their longitudinal components.

Reconstructed neutron momentum

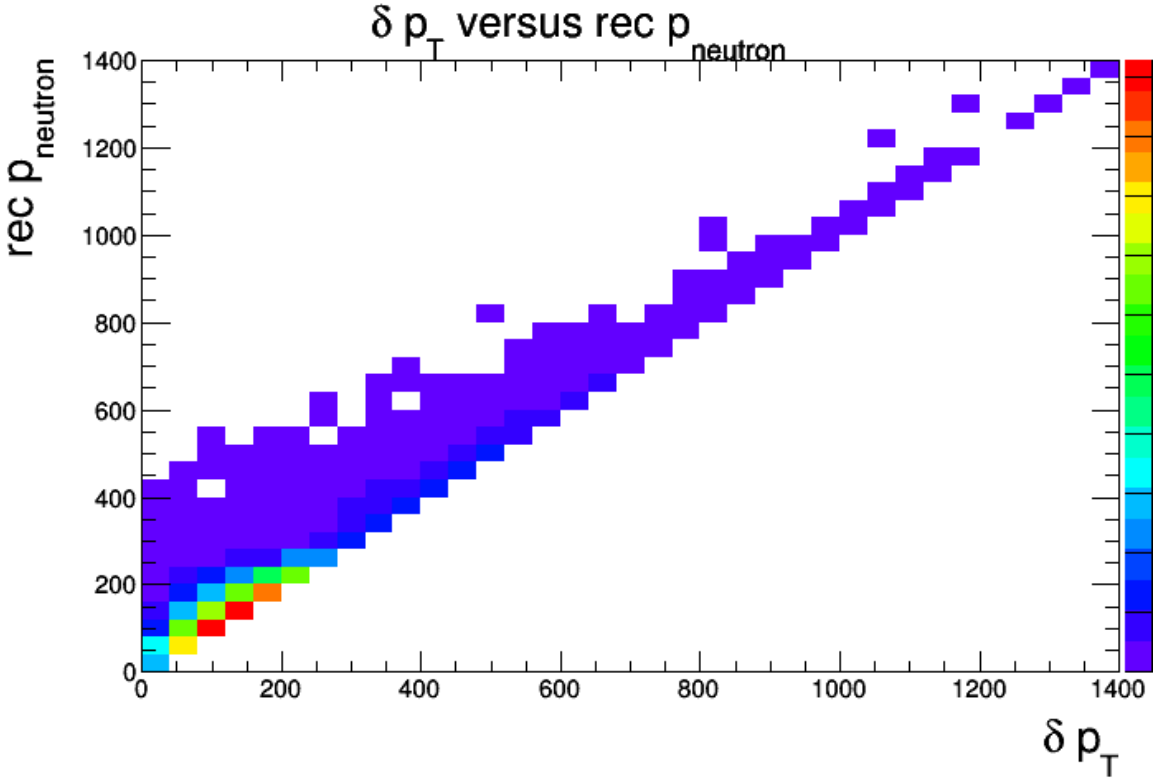
Reconstructed momentum cut in action







Reconstructed neutron momentum



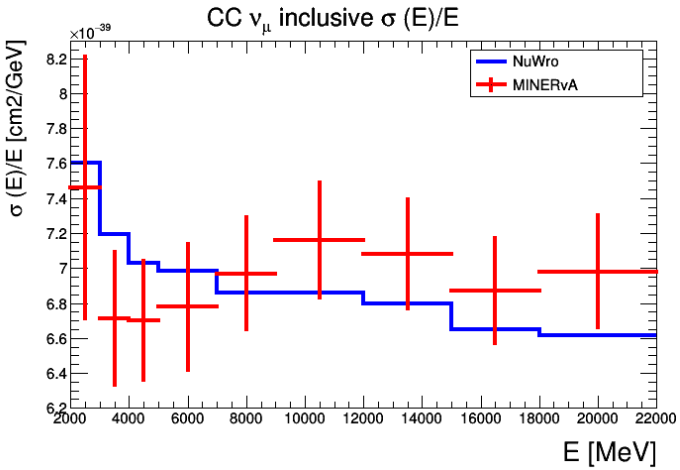
There is an obvious strong correlation.

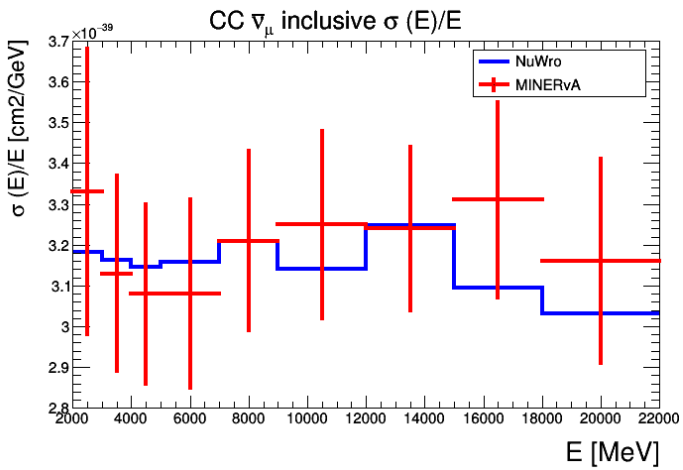
$$p_{rec} = \sqrt{(p_T)^2 + (p_L)^2} \geq p_T.$$

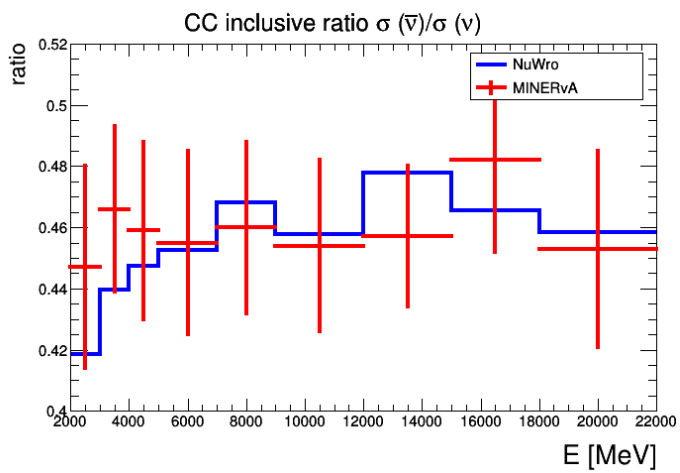
For MEC, RES events p_L is large making p_{rec} large.

Inclusive cross section

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



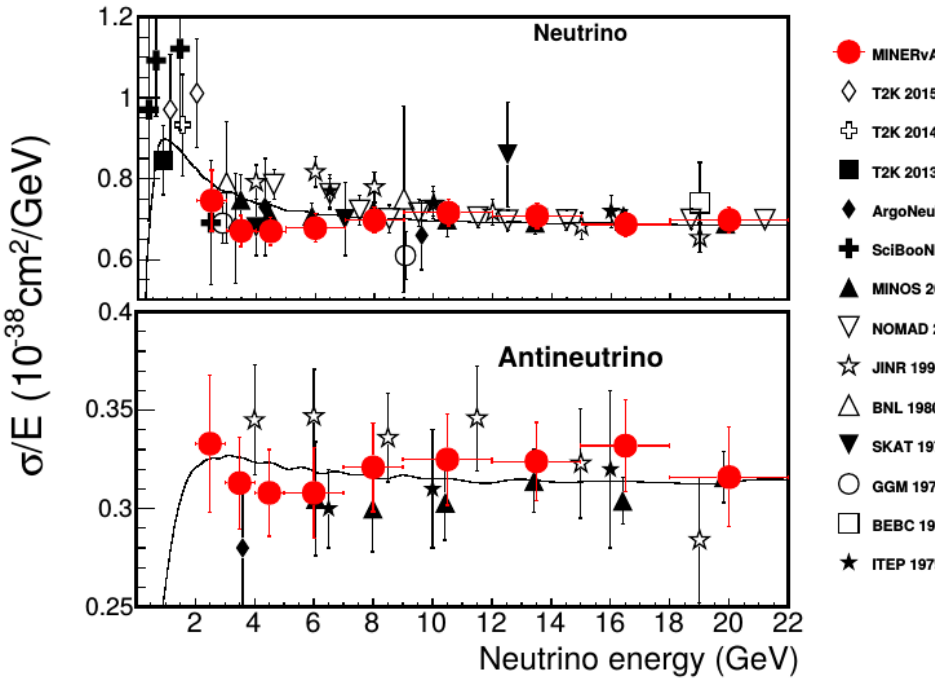


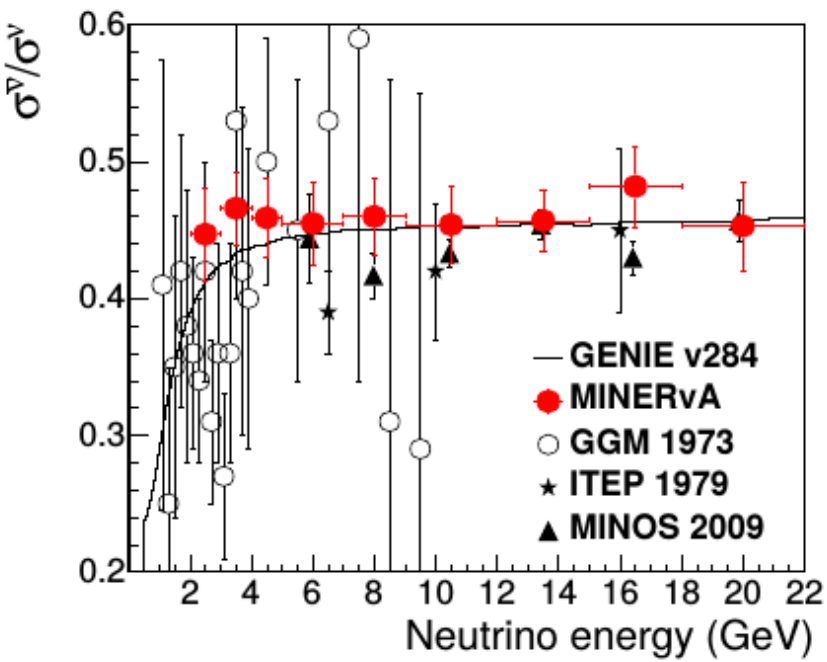


- The agreement is fair.
- Statistics must be improved.
- MINERvA is consistent with previous experiments, see the next slide.

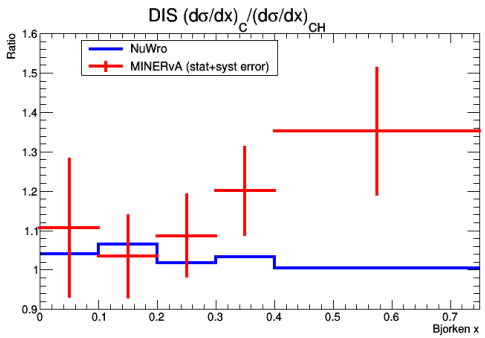
MINERvA inclusive ν_μ, $\overline{\nu_\mu}$, and ratio

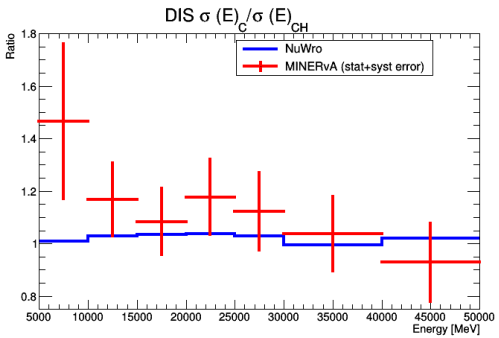
Comparison with previous experiments

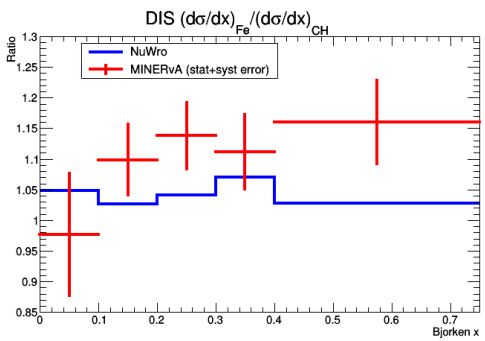


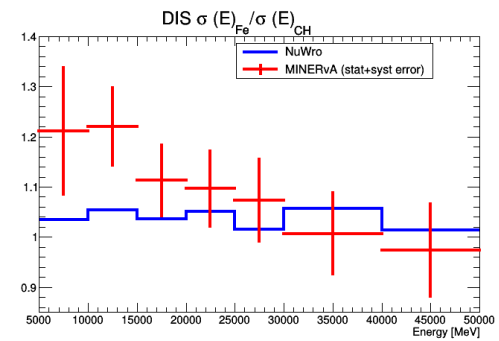


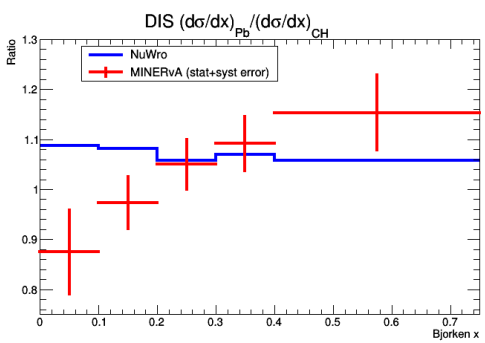
MINERvA DIS ratios C, Fe, Pb wrt CH (PRC95)

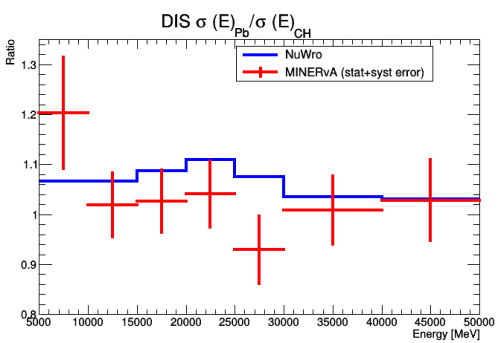








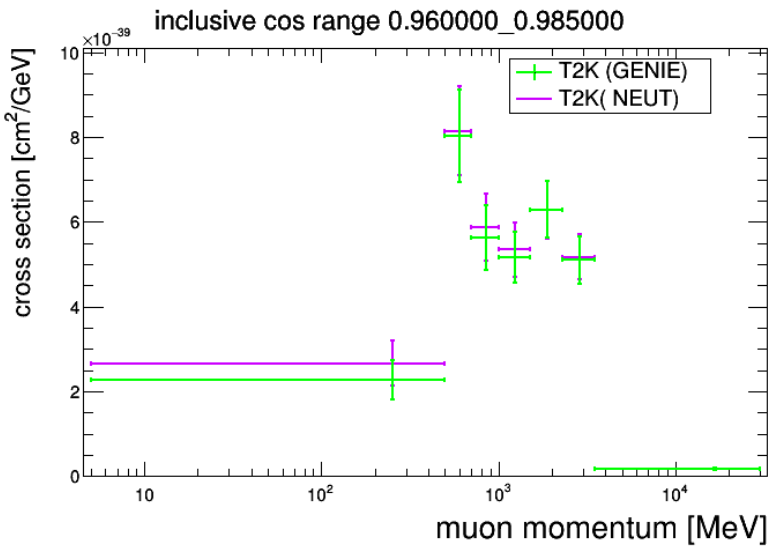


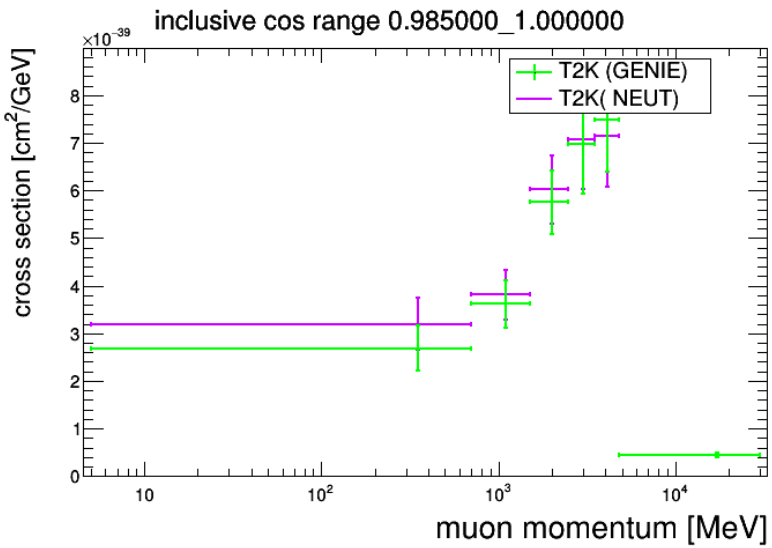


- In the data very weird CH/C disagreement at large x and "low" E.
- In NuWro DIS nuclear effects are not included (yet).
- Incorrect x dependence for Pb (Fe?), 10-15%.

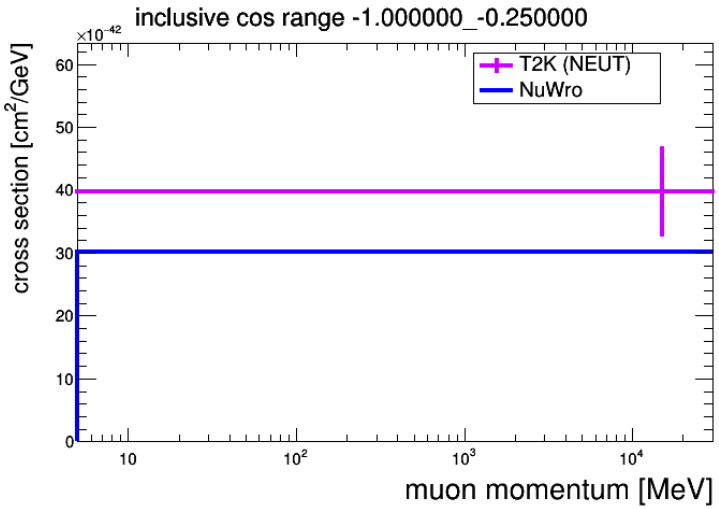
T2K CC inclusive muon double differential cross section (Alfonso Garcia, NuInt17)

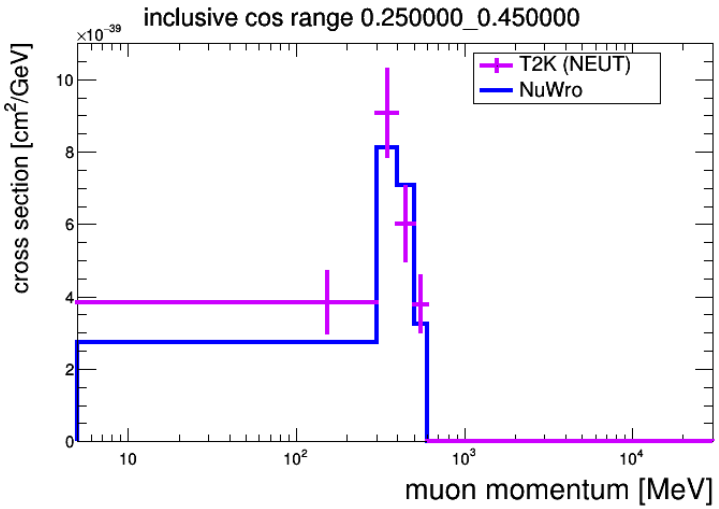
Two sets of results with different unfolding (using NEUT or GENIE). Differences are sometimes quite large. Examples:

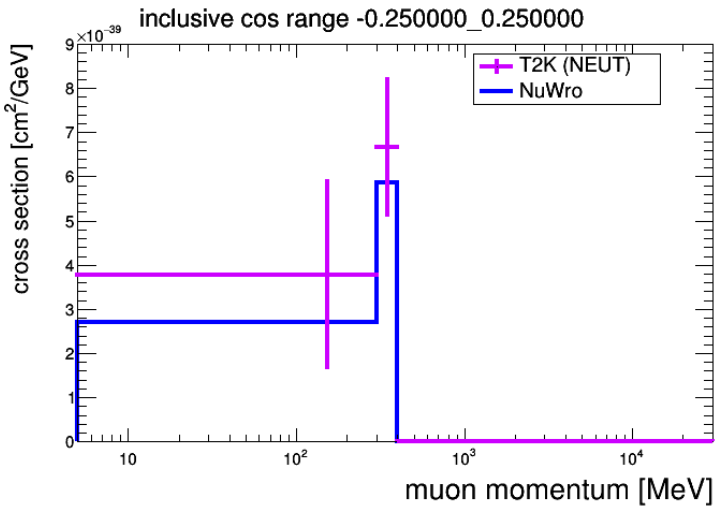


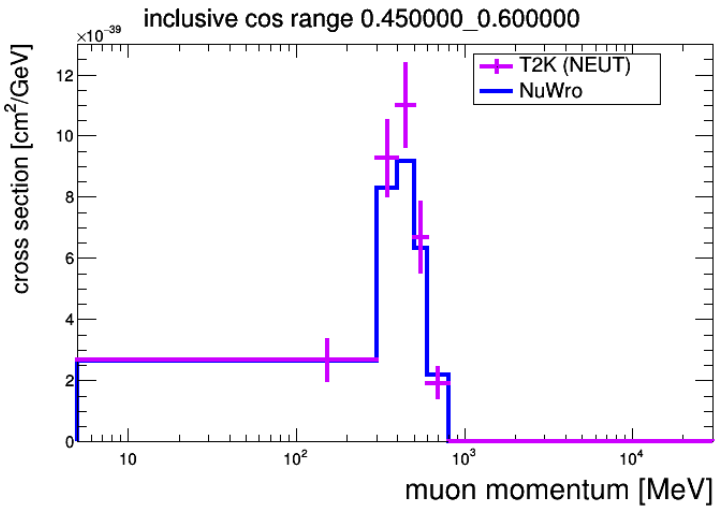


T2K CC inclusive muon double differential cross section

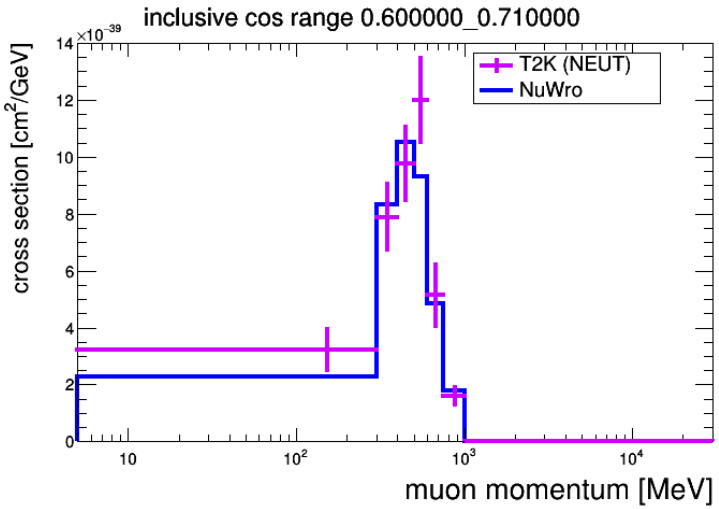


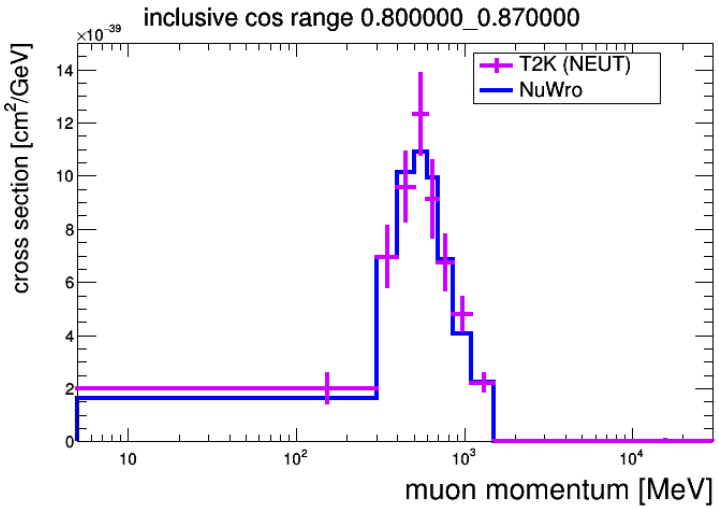


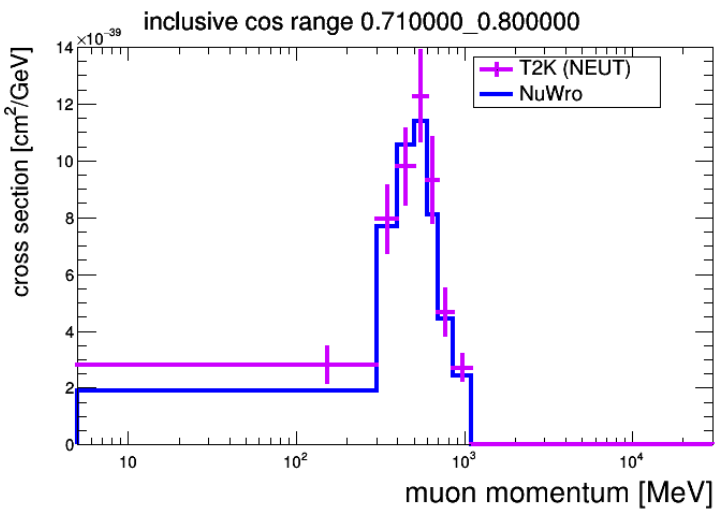


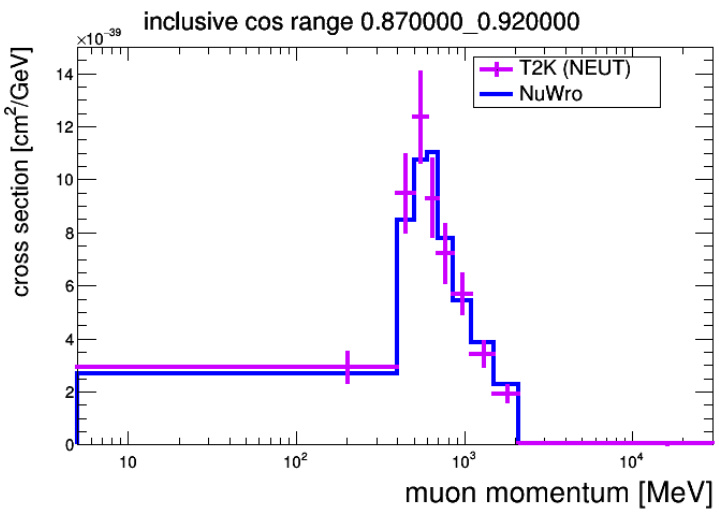


T2K CC inclusive muon double differential cross section (cont)

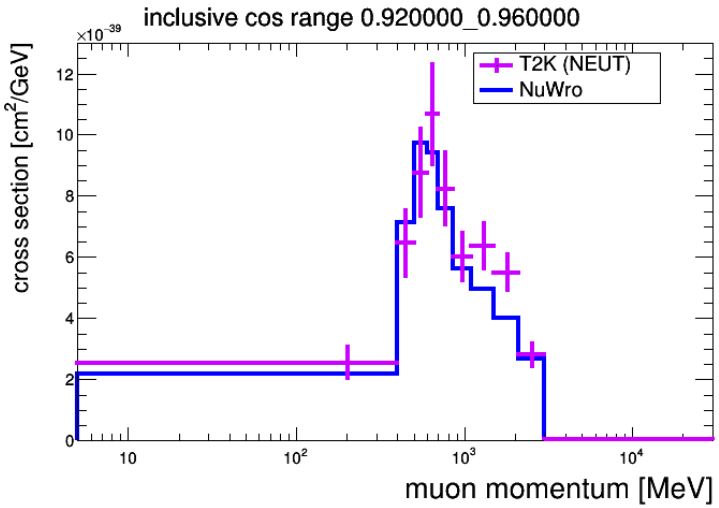


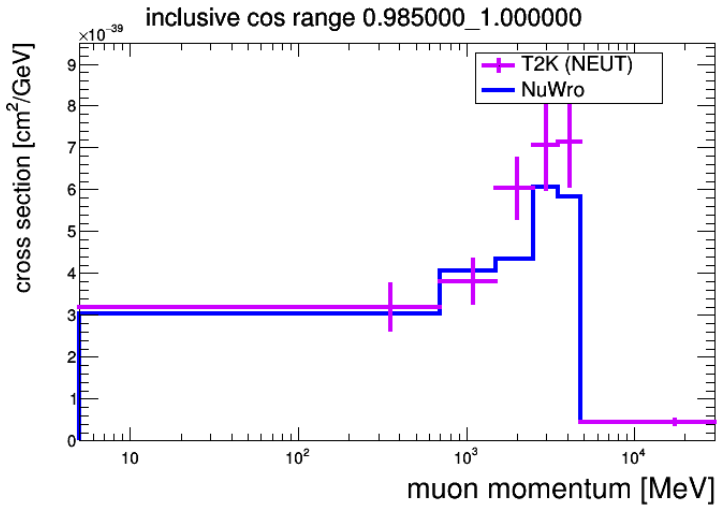


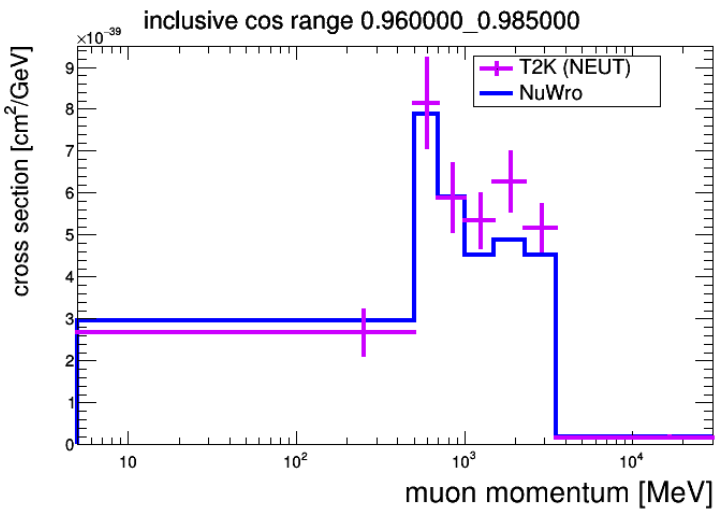


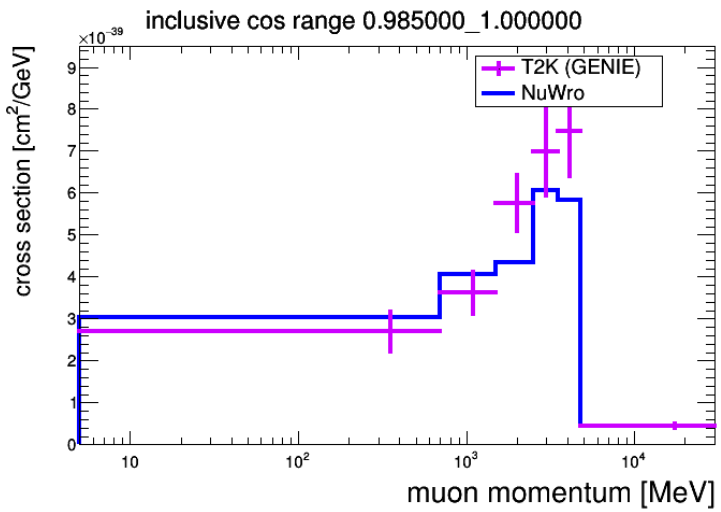


T2K CC inclusive muon double differential cross section (cont 2)









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

π production

T2K CC π^0 inclusive (Marcela study)

Presented at NuInt17

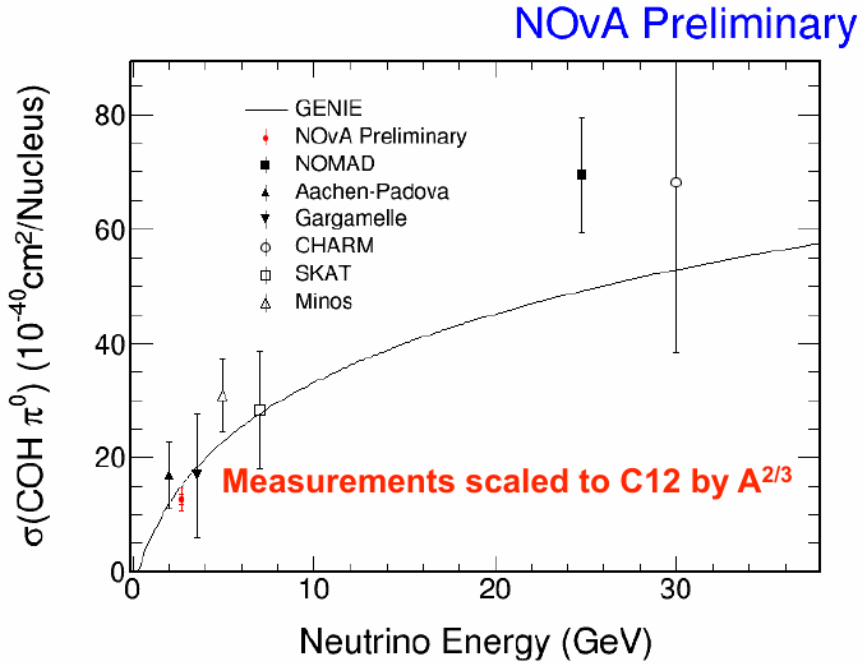
T2K $\rightarrow (1.24 \pm 0.03 \pm 0.16 \pm 0.16) \cdot 10^{-39}$ cm^2/nucleon.

NuWro $\rightarrow 0.95 \cdot 10^{-39}$ cm^2/nucleon.

There are also other indications (MINERvA) that NuWro underestimates π^0 production.

NC coherent π^0 production (NOvA study)

Presented at NuInt17



NuWro result at $E_\nu = 2.8$ GeV:

$\sigma = 11.1 \cdot 10^{-40} cm^2/nucleus.$

Must be redone with NOvA flux! (at $E_\nu = 2.9$ GeV the cross section is $\sigma = 11.4 \cdot 10^{-40} cm^2/nucleus$).

Reported value is

$\sigma = (14.0 \pm 0.9(stat.) \pm 2.1(syst.)) \cdot 10^{-40} cm^2/nucleus$

NC coherent π^0 production (MINOS study)

Another test: MINOS measurement.

- Format "per nucleus", where "nucleus" is a mixture of Fe (80%) and C(20%), i.e. it has $A = 48$ (not to be confused with Titanium!)
- More than 50% of the cross section taken from MC prediction (Berger-Sehgal, GENIE) for $E_{vis} < 1$ GeV.
- Measurement: $\sigma = (77.6 \pm 5 \pm \begin{cases} 15 \\ 16.8 \end{cases}) \cdot 10^{-40} cm^2/\text{nucleus}$.
- NuWro: $81.6 \cdot 10^{-40} cm^2/\text{nucleus}$.

Intranuclear cascade

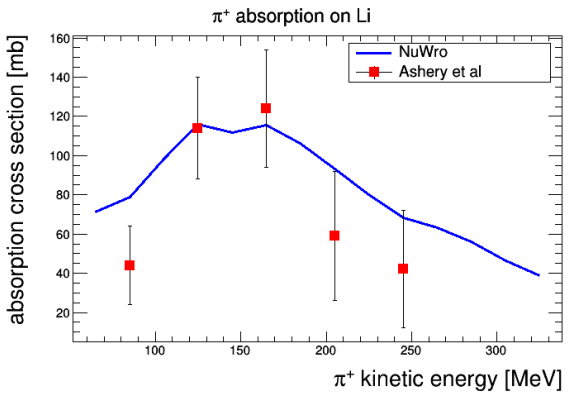
Pion cascade

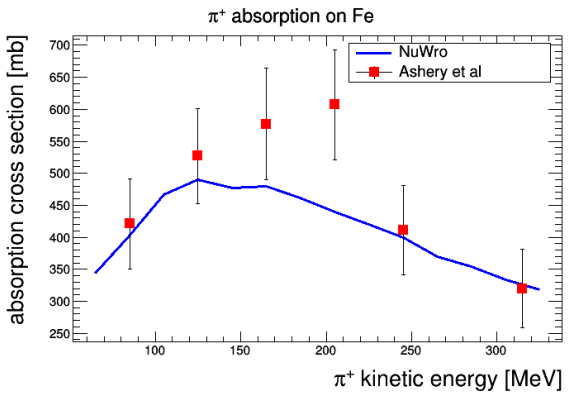
In what follows I will show NuWro cascade performance confronted with older Ashery et al (various nuclei) and new DUET data on Carbon target only.

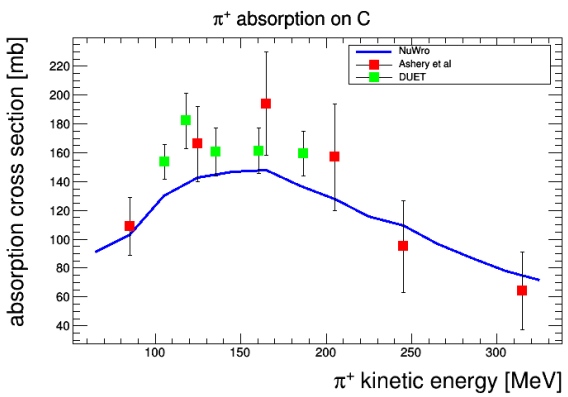
Three types of macroscopic reactions:

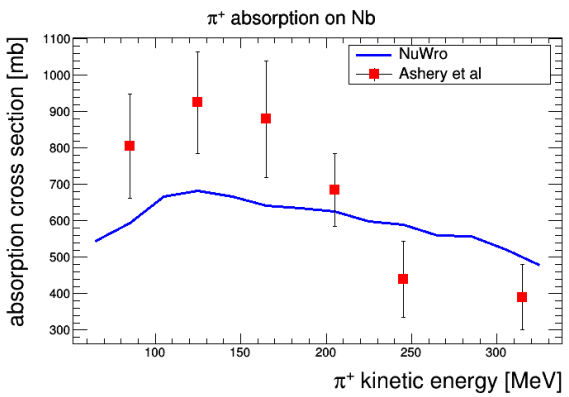
- Pion (always π^+) absorption.
- Charge exchange $\pi^+ \rightarrow \pi^0$.
- Inelastic (any other process excluding an elastic one).
  - An obvious experimental issue: how do we treat soft inelastic events?

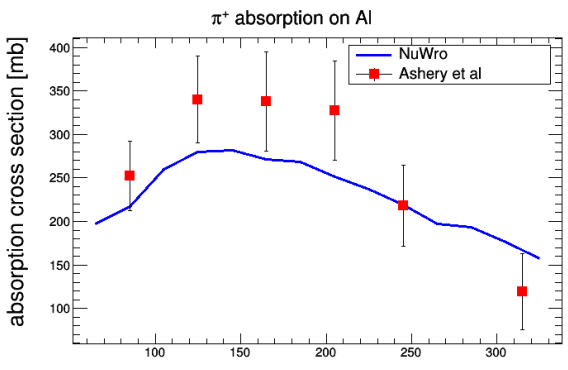
Pion cascade

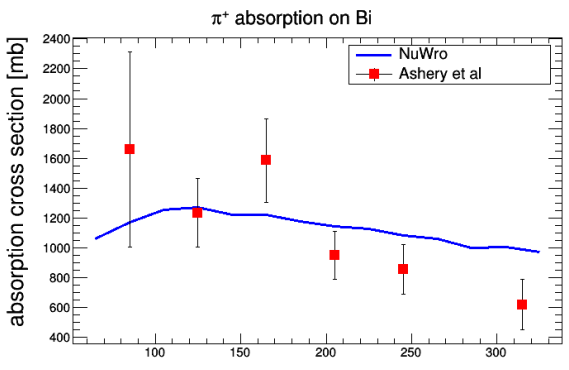




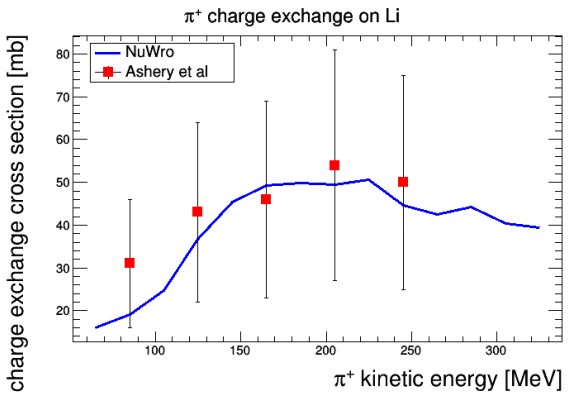


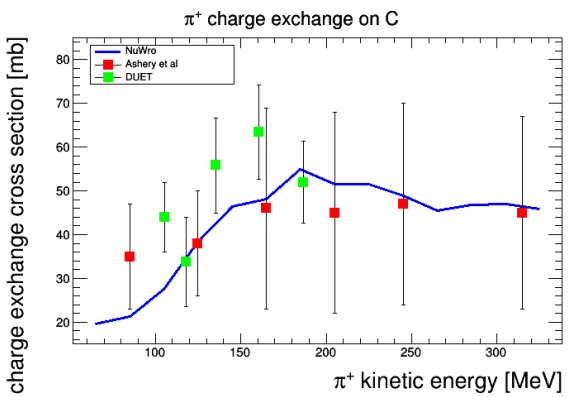


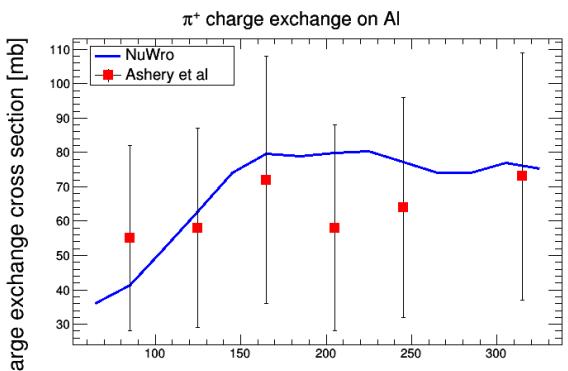


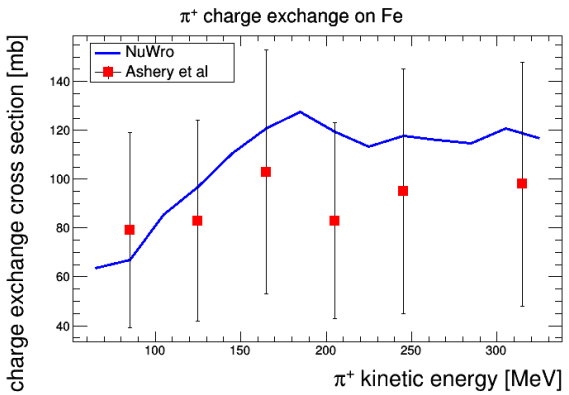


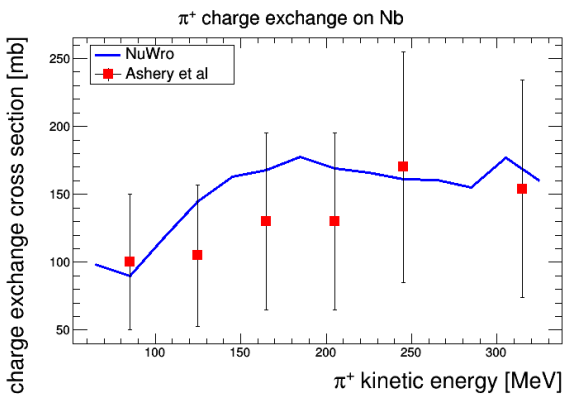
Pion cascade

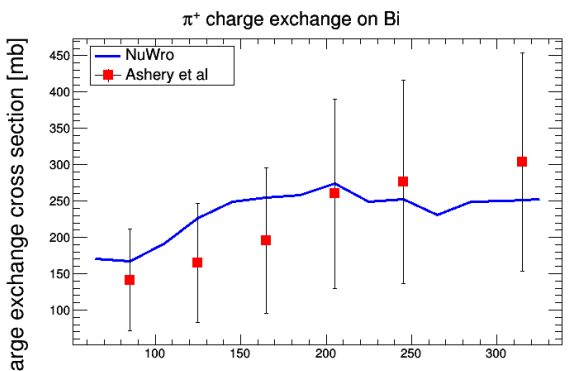












Pion cascade

There are more data to include.

What can be sais about NuWro pion cascade performance?

- Not bad!
- Absorption is OK, despite claims in the past that it was too low.
- Charge exchange seems OK.
- Inelastic (not shown) should be larger at low kinetic energies.
  - Perhaps issues with a separation of elastic component?

Summary

- More exclusive measurements are more demanding for MCs.
- How much of that is needed in the oscillation analysis.