NuWro update
(ongoing NuWro validation effort)

Jan T. Sobczyk

Wrocław University

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Motivation and outline

- Goal: NuWro validation on recent experimental data.
- The ultimate goal: NuWro validation tool with all the relevant experimental data.
- Identification of areas of necessary improvements.
- The main focus on CC0π measurements.

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

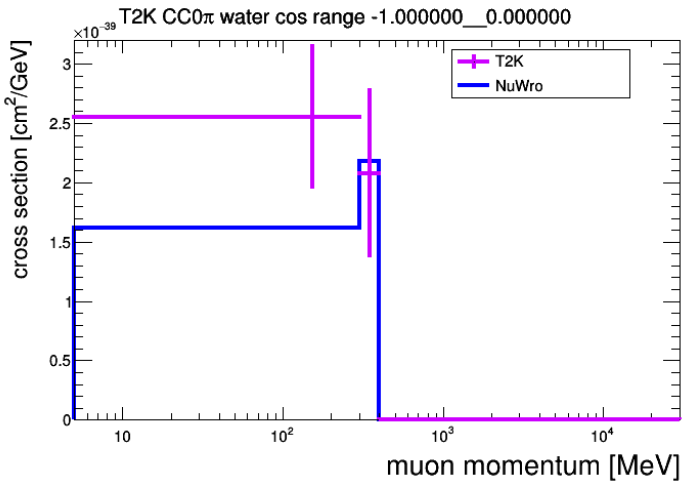
Other developments, not shown in this talk:

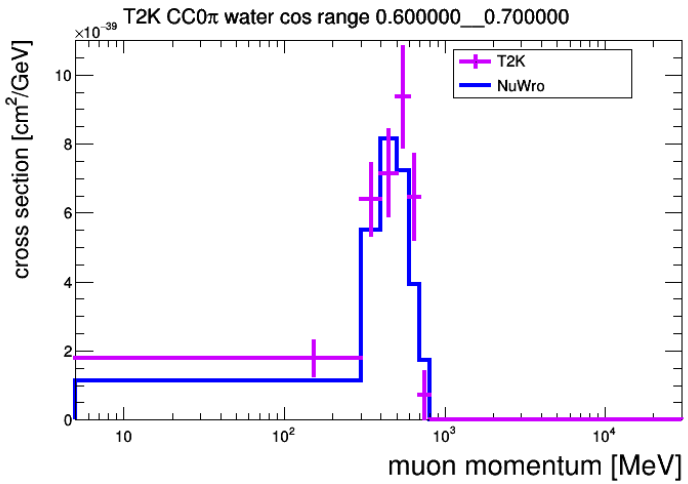
- Implementation of FSI in spectral function formalism.
- Fine tuning nucleon cascade with proton transparency data.

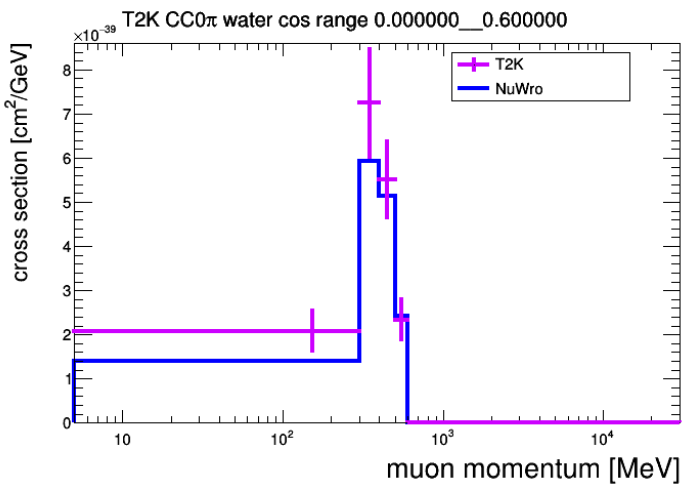
T2K CC0π double differential cross section on CH Phys.Rev. D93 (2016)

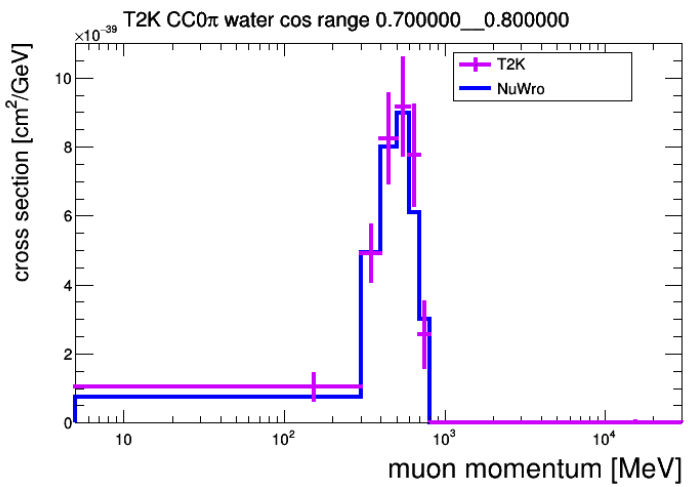
112012

Analysis I (full phase space)



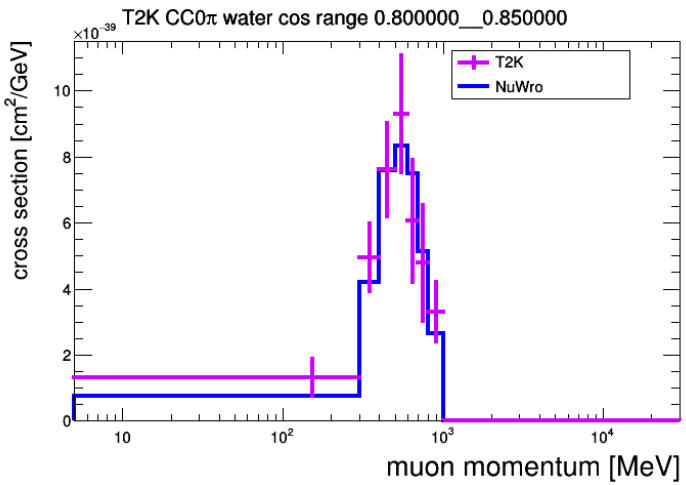


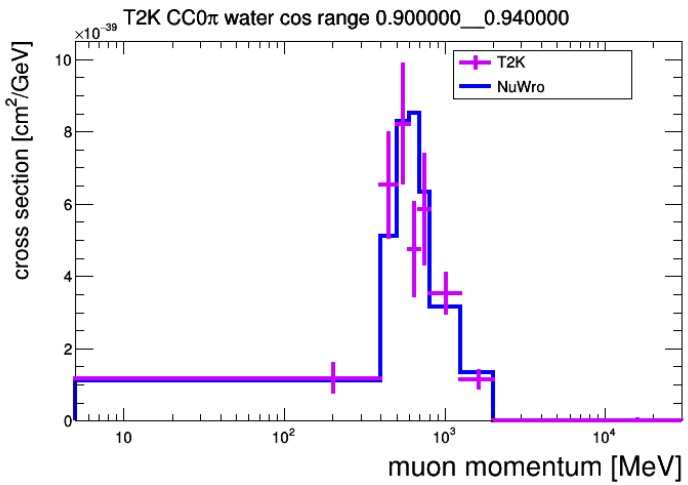


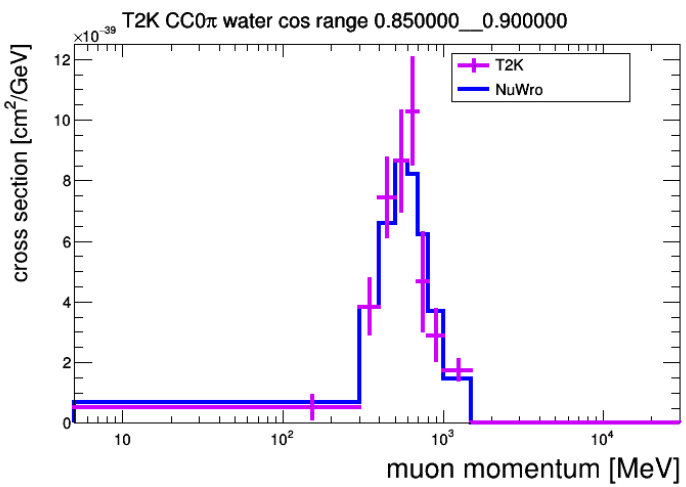


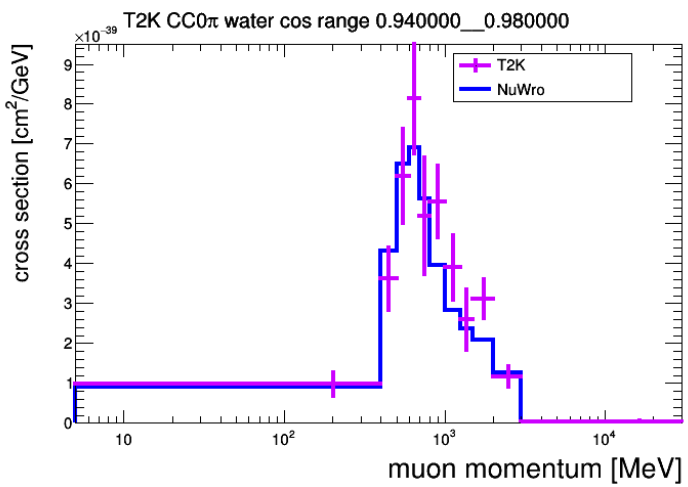
T2K CC0π double differential cross section on CH

Analysis I (full phase space)



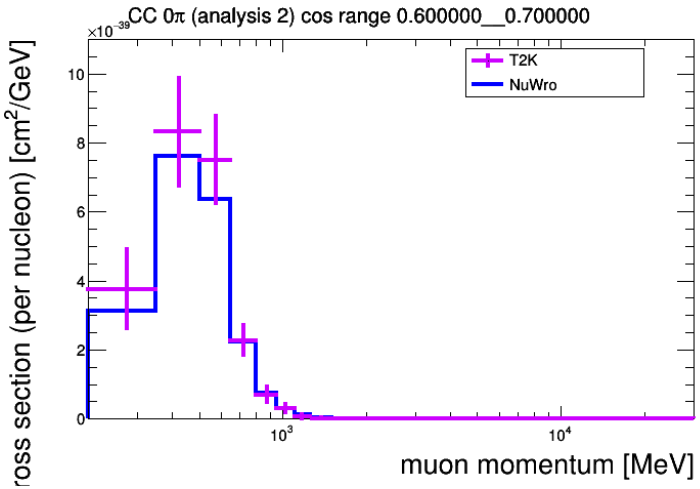


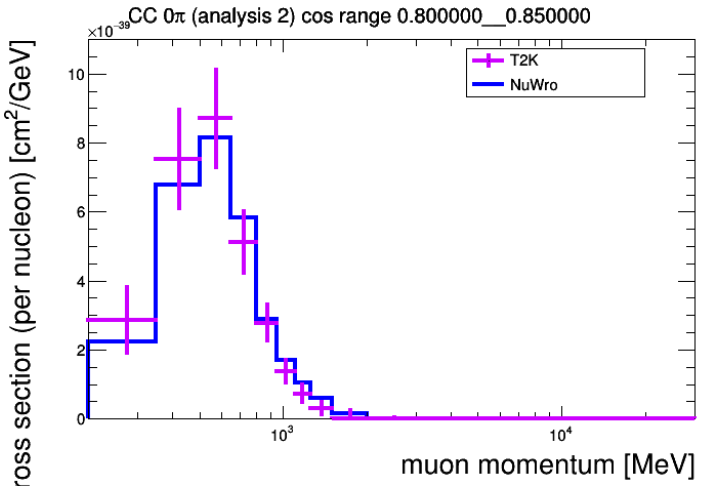


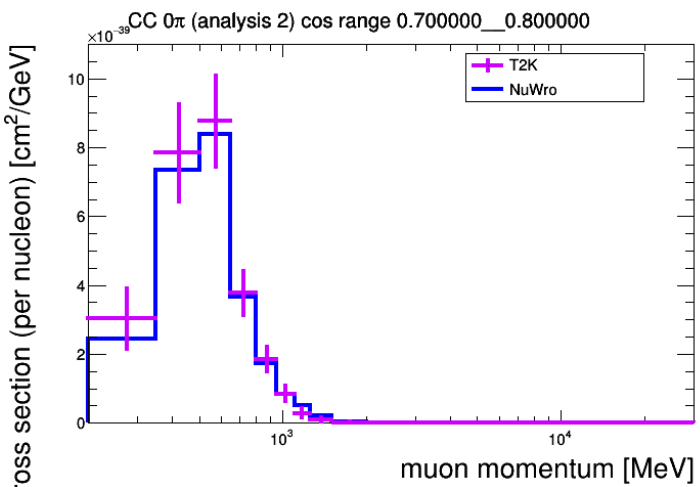


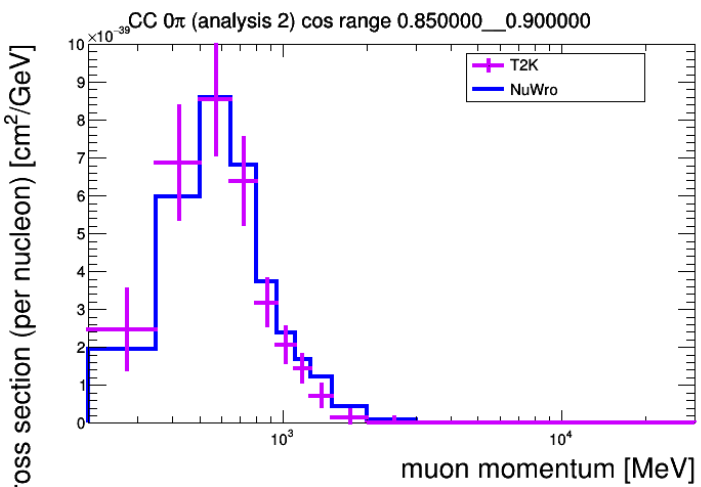
T2K CC0π double differential cross section on CH

Analysis II (restricted phase space: $\cos\theta_\mu > 0.6$, $p_\mu > 600$ MeV/c).

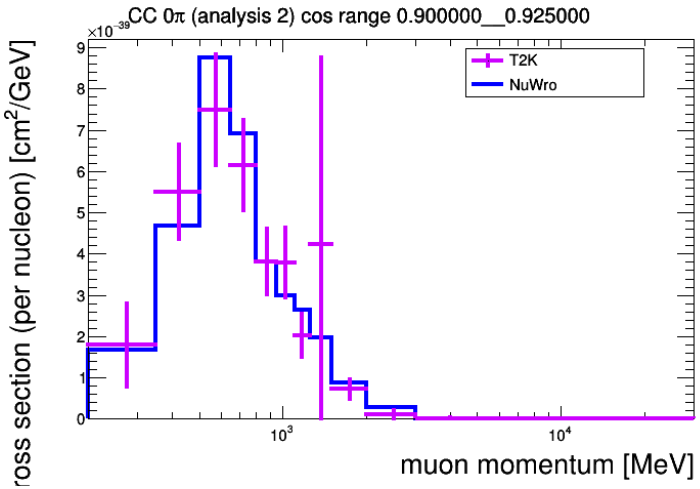


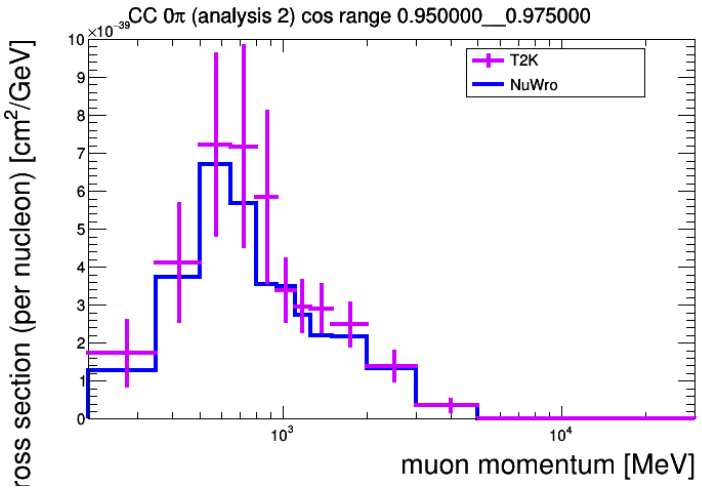


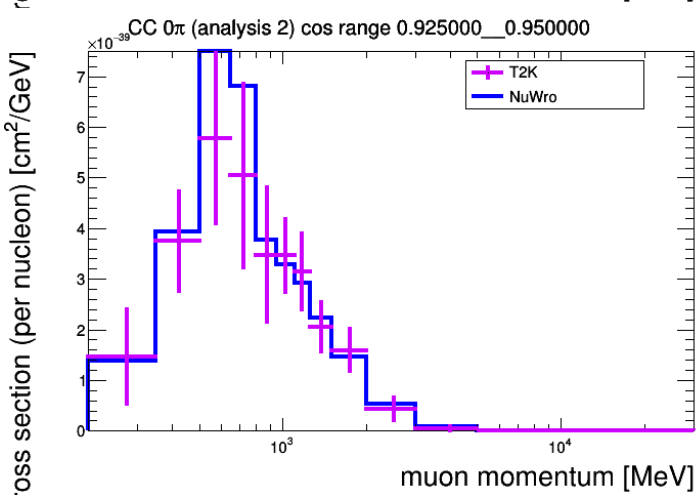


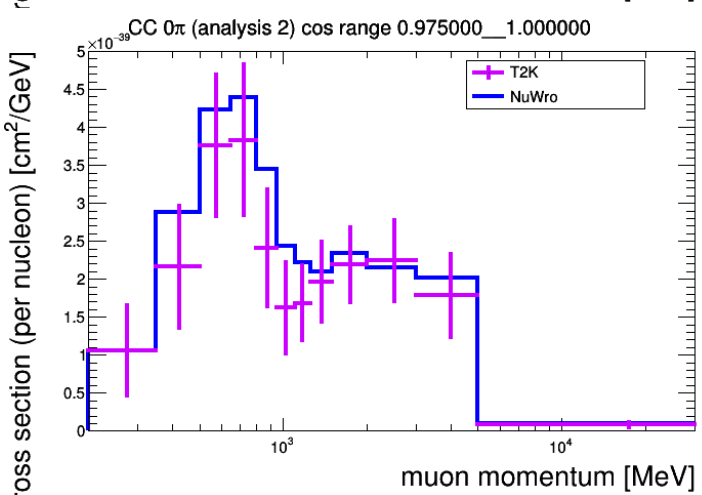


T2K CC0π double differential cross section on CH









The agreement is good.

T2K CC0π double differential cross section on CH analysis II - χ^2 study.

We add statistical tools.

- The authors provide covariance matrix M_{cov}.

$$\chi^2 = \sum_{j,k=1}^{83} (\sigma^j_{NuWro} - \sigma^j_{T2K}) M^{-1}_{cov\ jk} (\sigma^k_{NuWro} - \sigma^k_{T2K}).$$

$$\chi^2 \approx 103.2, \qquad NDF = 96$$

One can also calculate χ^2 separately for 8 cosine bins.

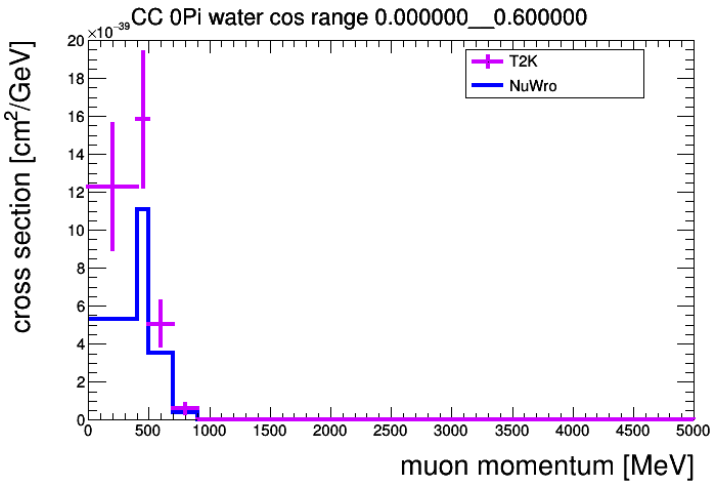
Results are: 2.8, 10.7, 12.2, 15.7, 12.0, 9.0, 6.7.

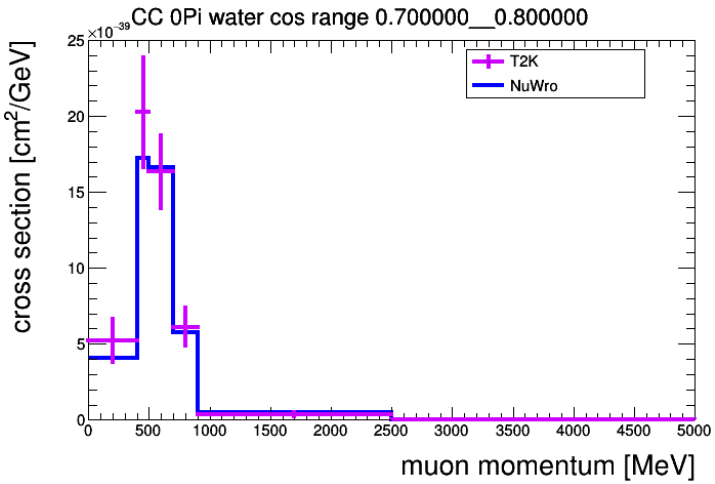
Normalization comparisons.

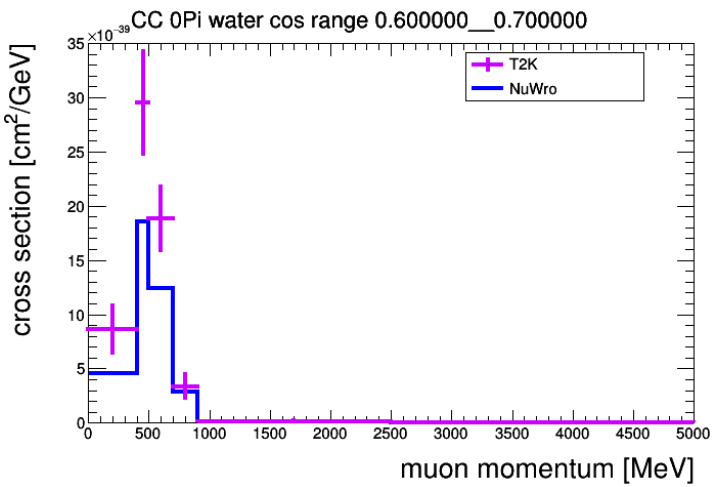
Analysis II: data $\rightarrow 2.03 \cdot 10^{-39}$; NuWro $\rightarrow 2.02 \cdot 10^{-39}$.

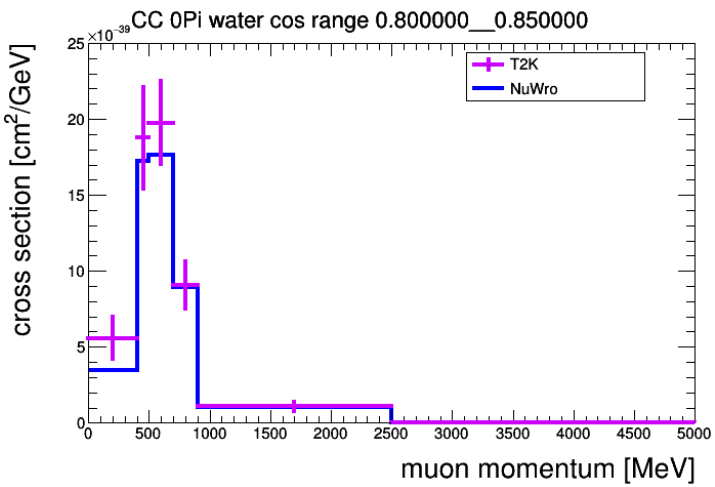
T2K CC0π double differential cross section on water arXiv:1708.06771

[hep-ex]



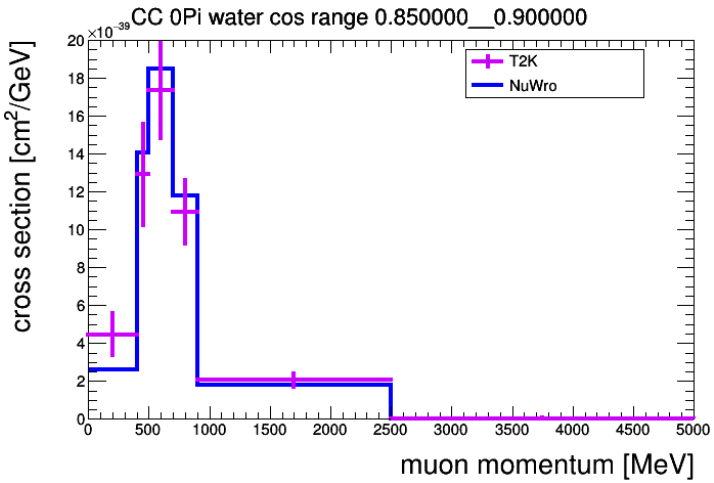


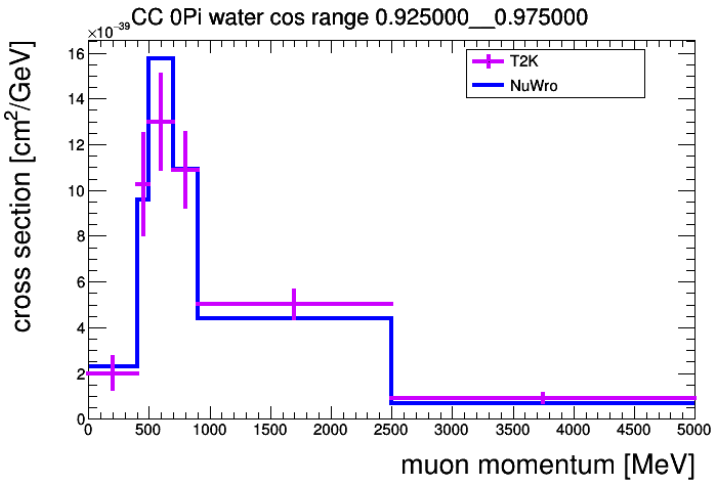


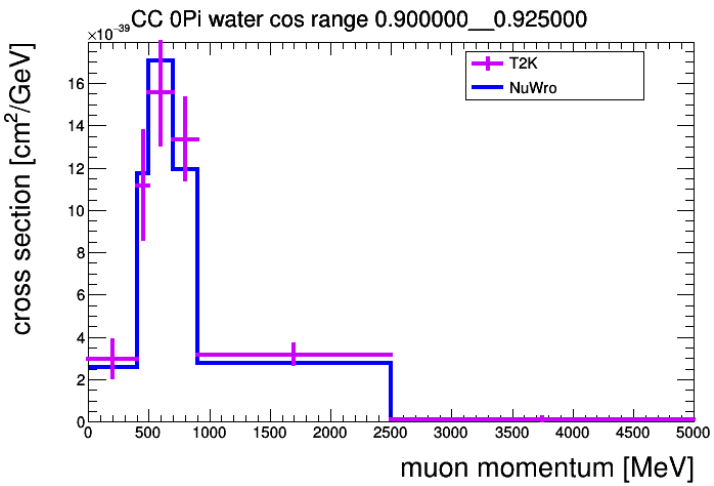


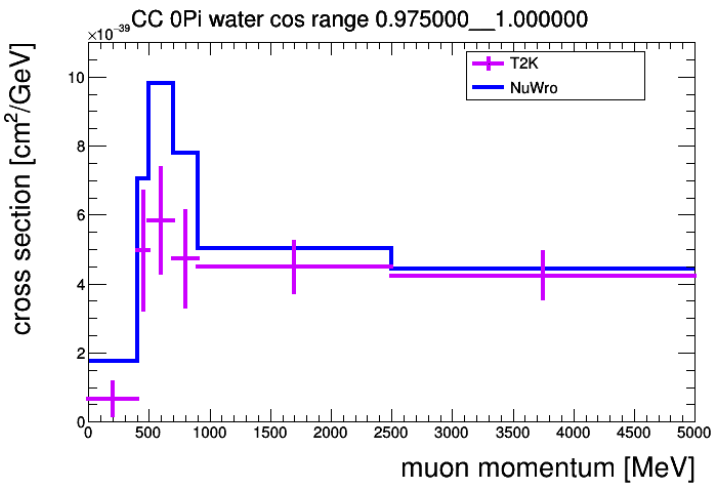
A deficit of cross section at large muon angles.

T2K CC0π double differential cross section on water (cont)



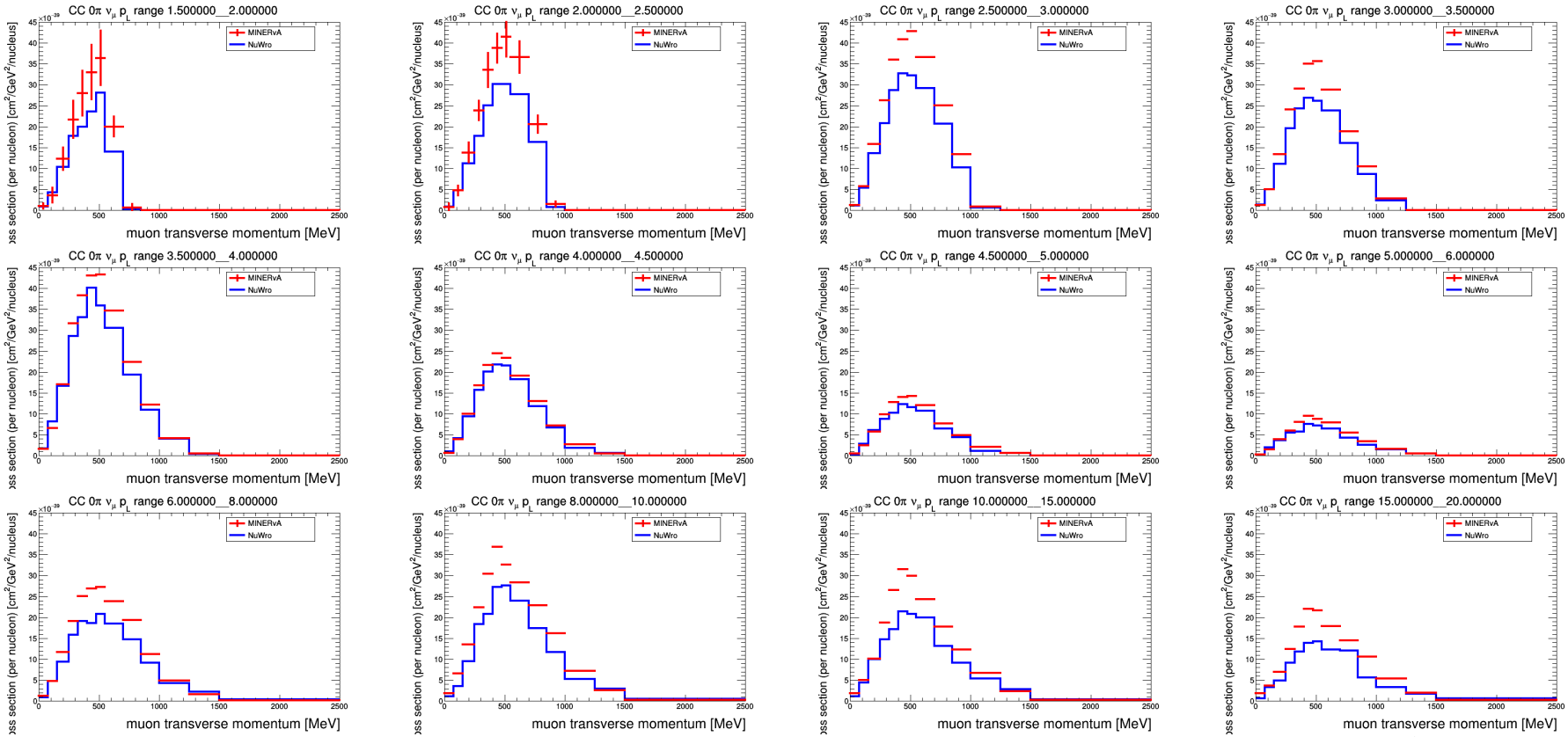






Too large cross section in the most forward bin.

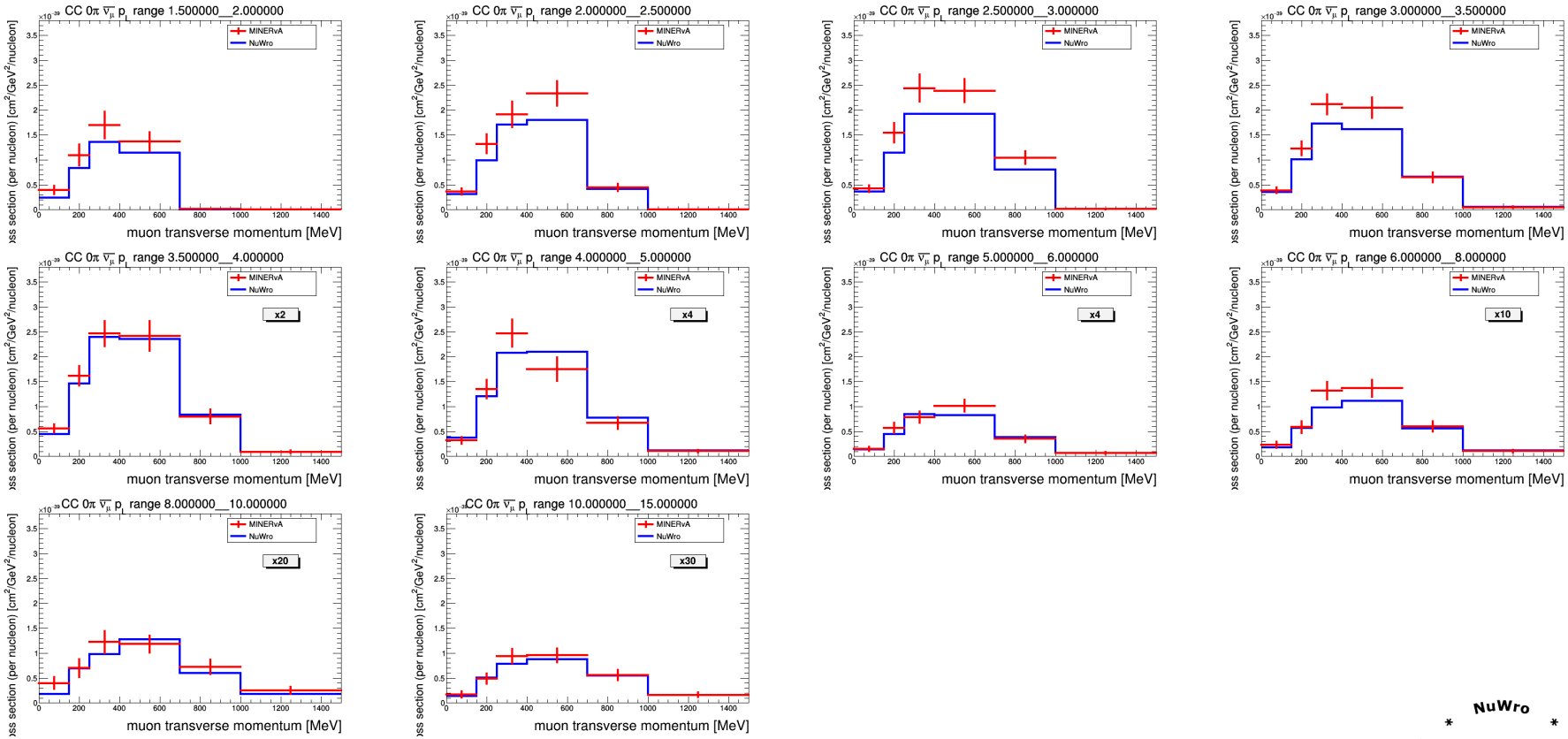
MINERvA CC0π p_T, p_L on CH ν_μ



MINERvA results are not yet published. Based on Daniel Ruterbories presentation on NuInt17.

A significant difference in normalization.

MINERvA CC0π p_T, p_L on CH $\bar{\nu}_\mu$



MINERvA results are not yet published. Based on Daniel Ruterbories presentation on NuInt17.

Much better agreement with normalization.

Including protons into the game...

CC differential cross section in transverse variables

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

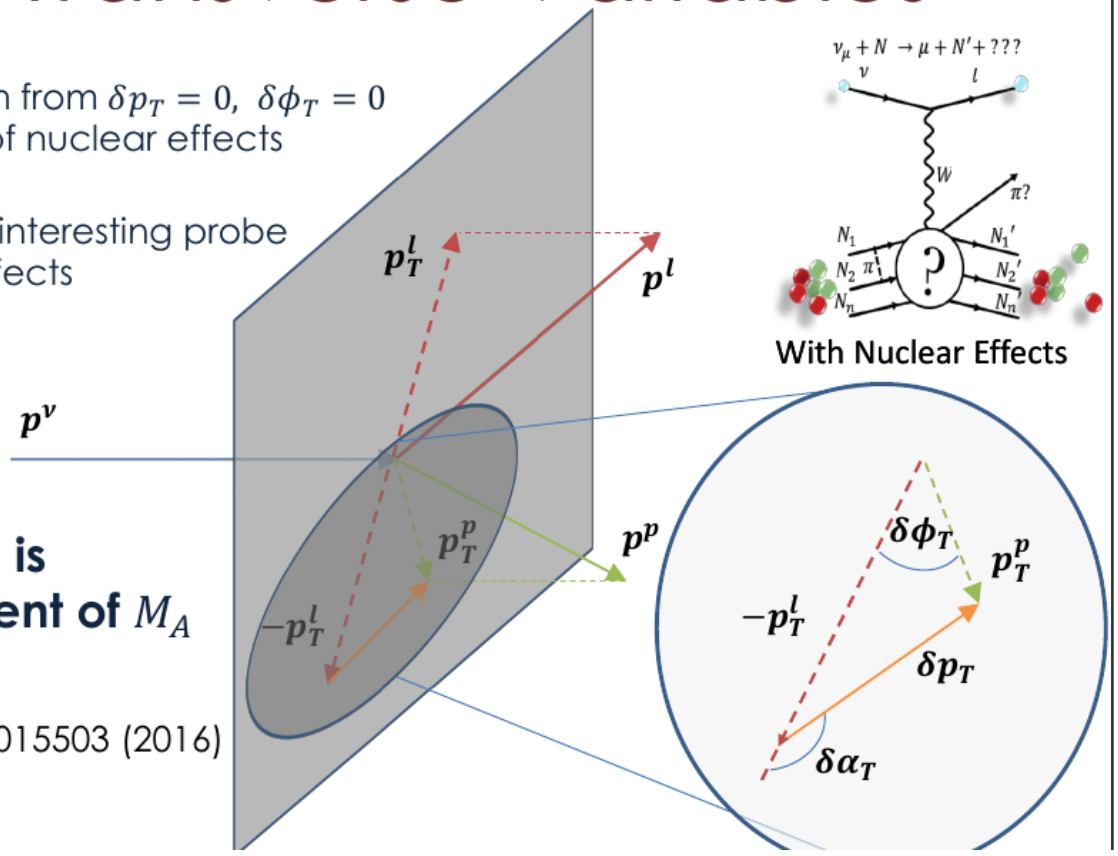
- CC0π
- muon momentum > 250 MeV/c
- cosine of muon angle > -0.6
- leading proton momentum $\in (450, 1000)$ MeV/c
- cosine of leading proton angle > 0.4.

CC 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**

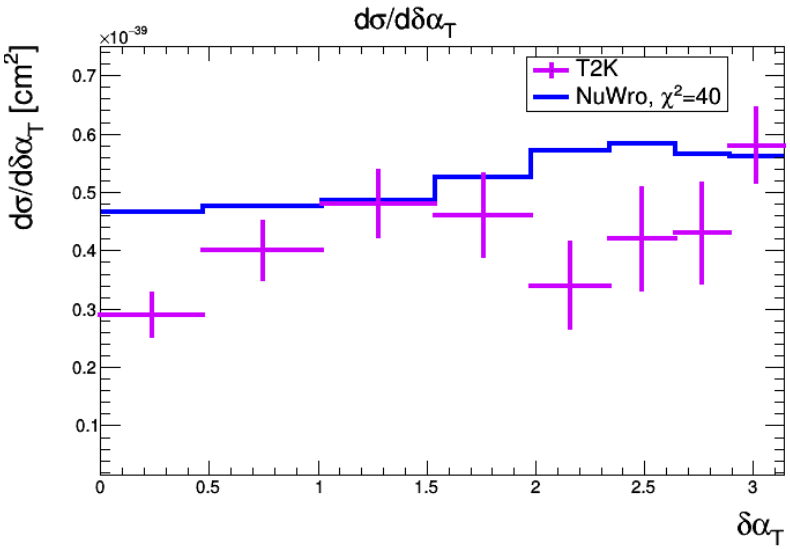


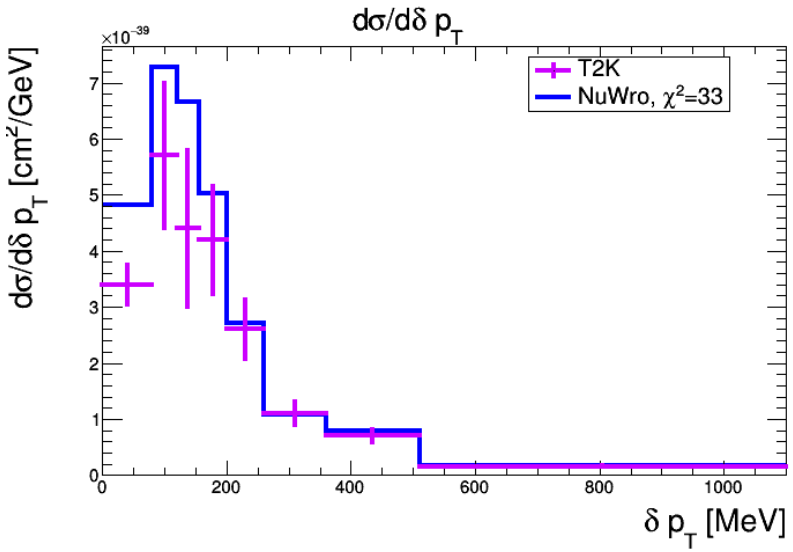
With Nuclear Effects

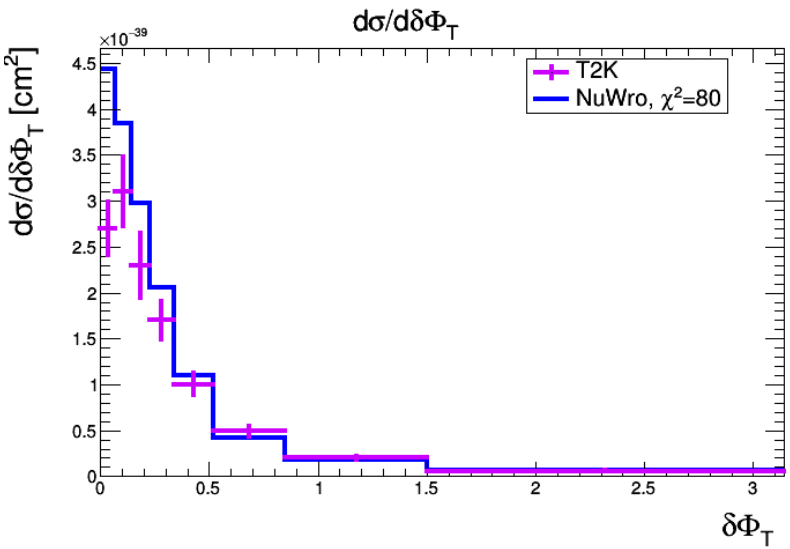
Phys. Rev. C **94**, 015503 (2016)

from Stephen Dolan presentation at NuInt17

CC differential cross section in transverse variables - χ^2

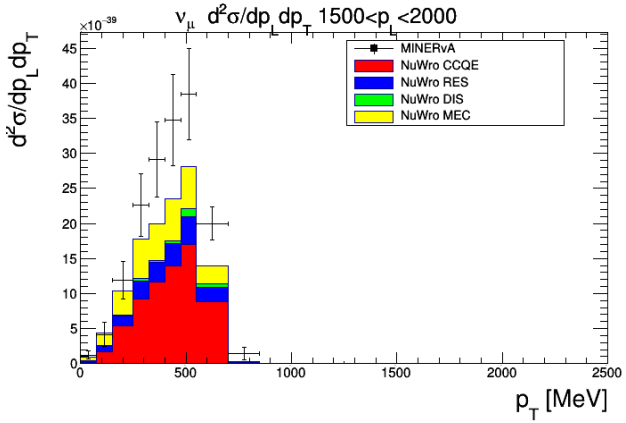


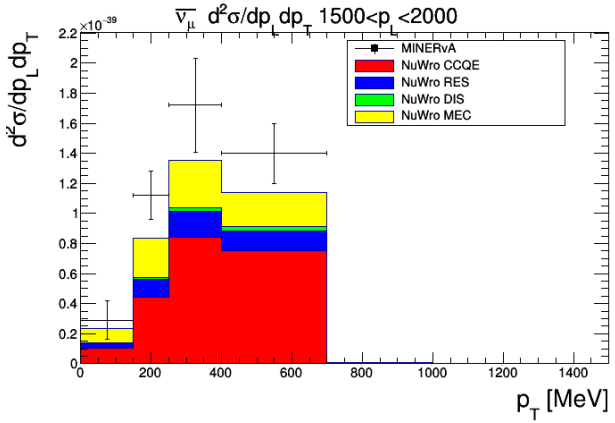


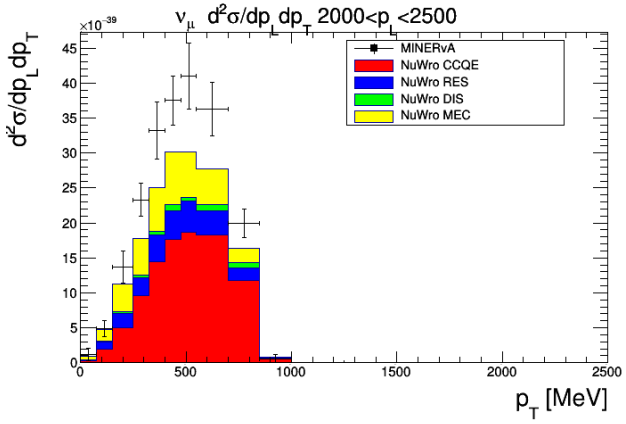


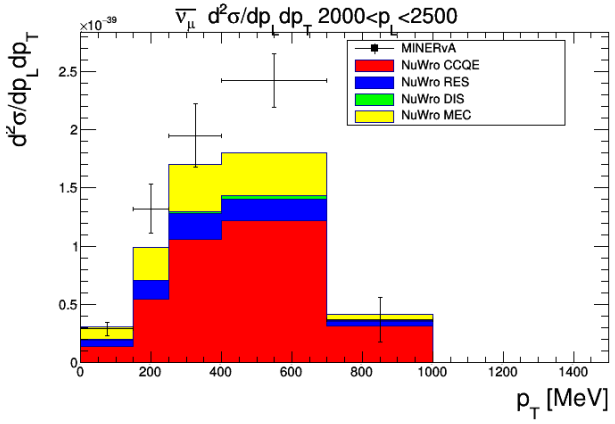
- Statistics must be better.
- The current results are for 100 kiloevents.
- With 50 kiloevents I obtained: 44, 32 and 76.
- I plan to run 500 kiloevents.

Data/MC discrepancies – MINERvA



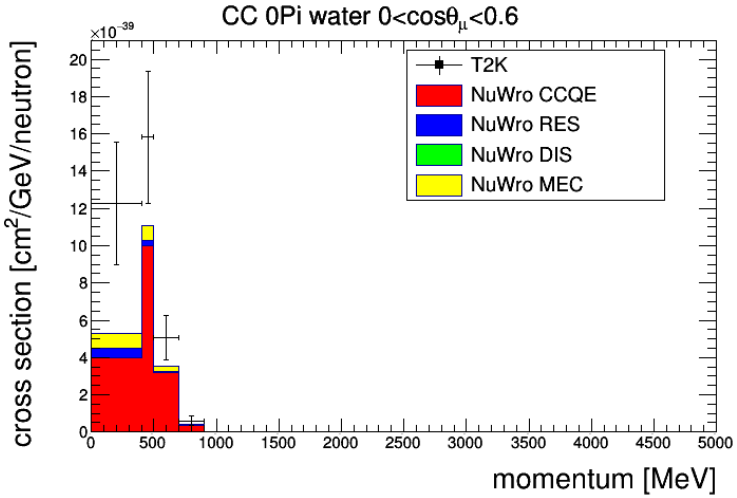


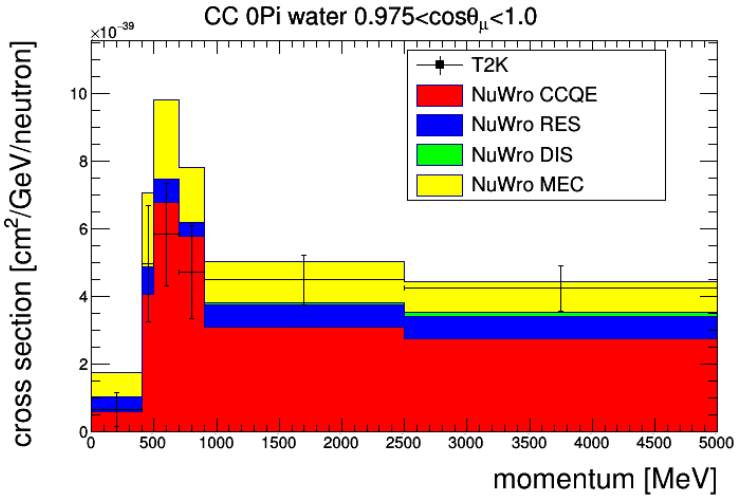


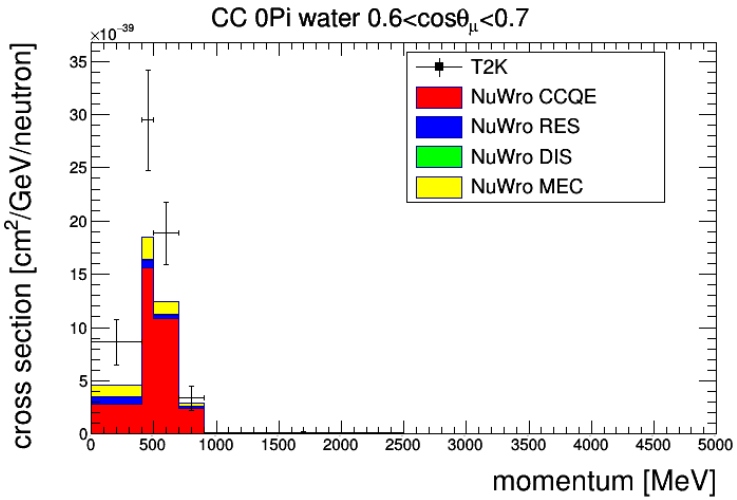


- Differences may come from CCQE or MEC; RES is unlikely to be wrong by a factor of 2, MEC is much more uncertain!
- Large MEC contributions – should be even larger?!

Data/MC discrepancies – T2K (water)







- On the left: CCQE is too small!
- On the top CCQE too large? (no room for MEC)

Examples of NuWro based studies (1)

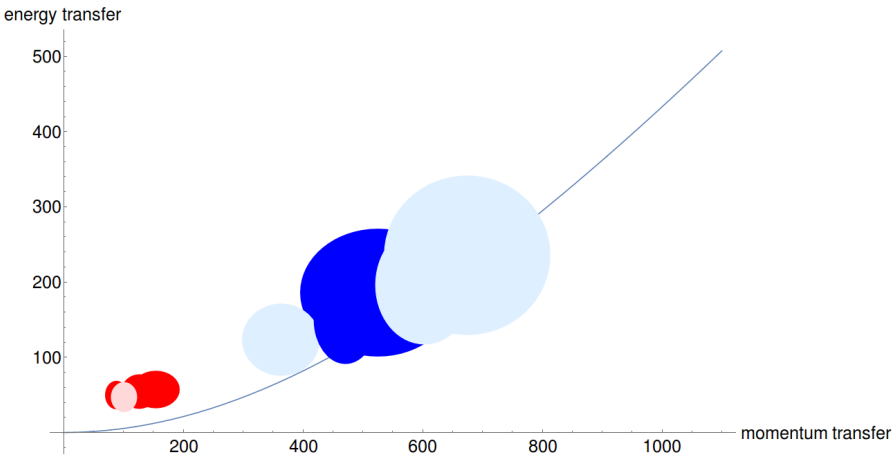
T2K CC0π double differential cross section on water

What happens in bins where data/MC tension is seen?

- With MC we easily identify kinematical characteristics of CCQE and MEC events in particular bins.
- Results are shown in (q, ω) plane.

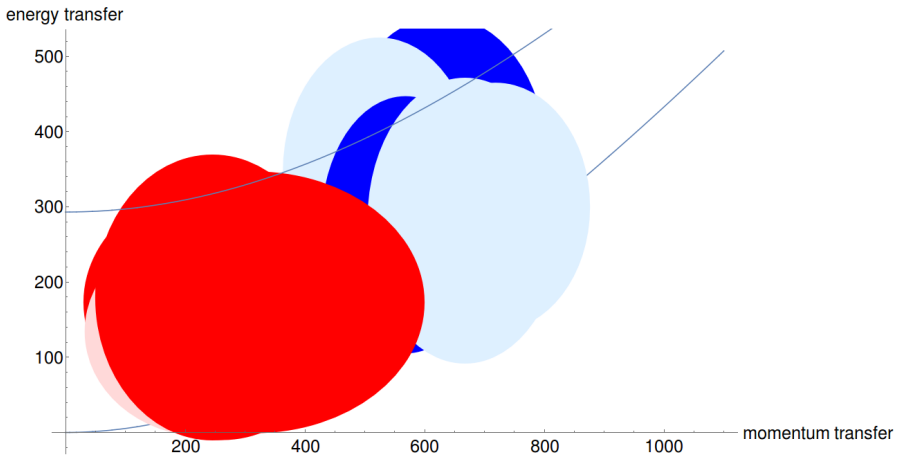
Examples of NuWro based studies (1 cont)

CCQE hypothesis



Line: QE peak.

MEC hypothesis



Lines: QE and Δ peak.

Blue: deficit of events in NuWro.

Red: excess of events in NuWro.

Examples of NuWro based studies (2)

What is a relation of transverse variables with reconstructed nucleon momentum introduced in A. Furmanski, JTS, Phys.Rev. C95 (2017) 065501?

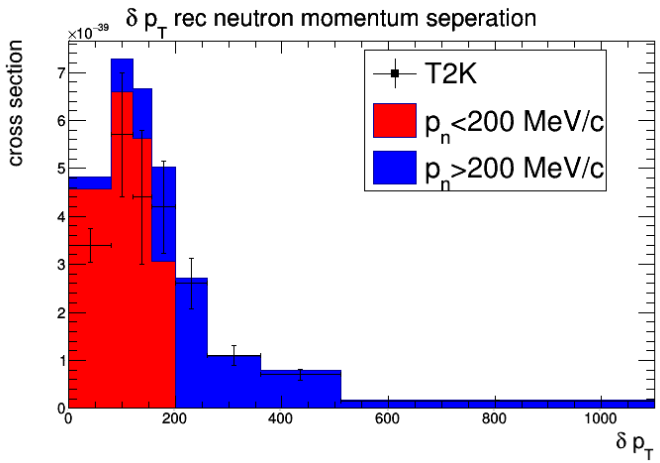
Computations done with $< B >= 27.13$ MeV.

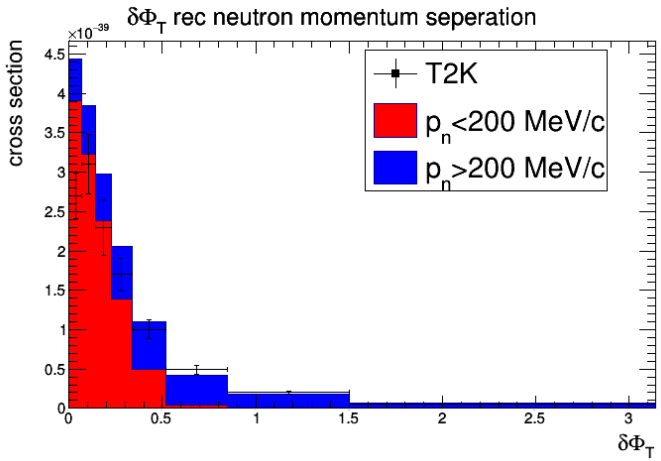
The main message from the PRC95 paper: reconstructed neutron momentum can be used to select a high purity CCQE sample of events by imposing something like $p_{rec} < 200$ MeV/c.

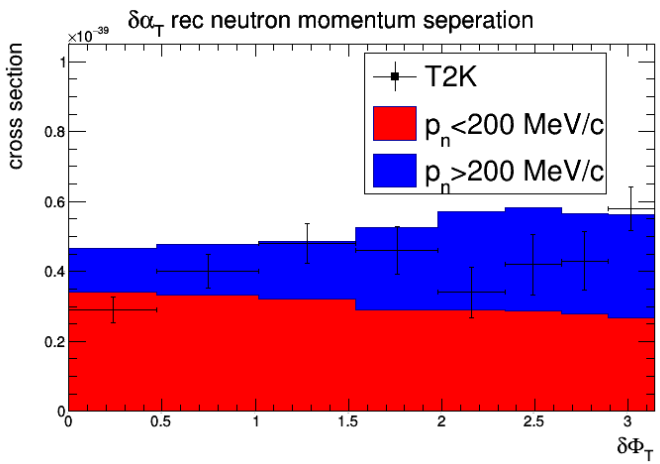
Transverse variables use information about transverse components of muon and proton, while reconstructed neutron momentum uses also information about their longitudinal components.

Examples of NuWro based studies (2 cont)

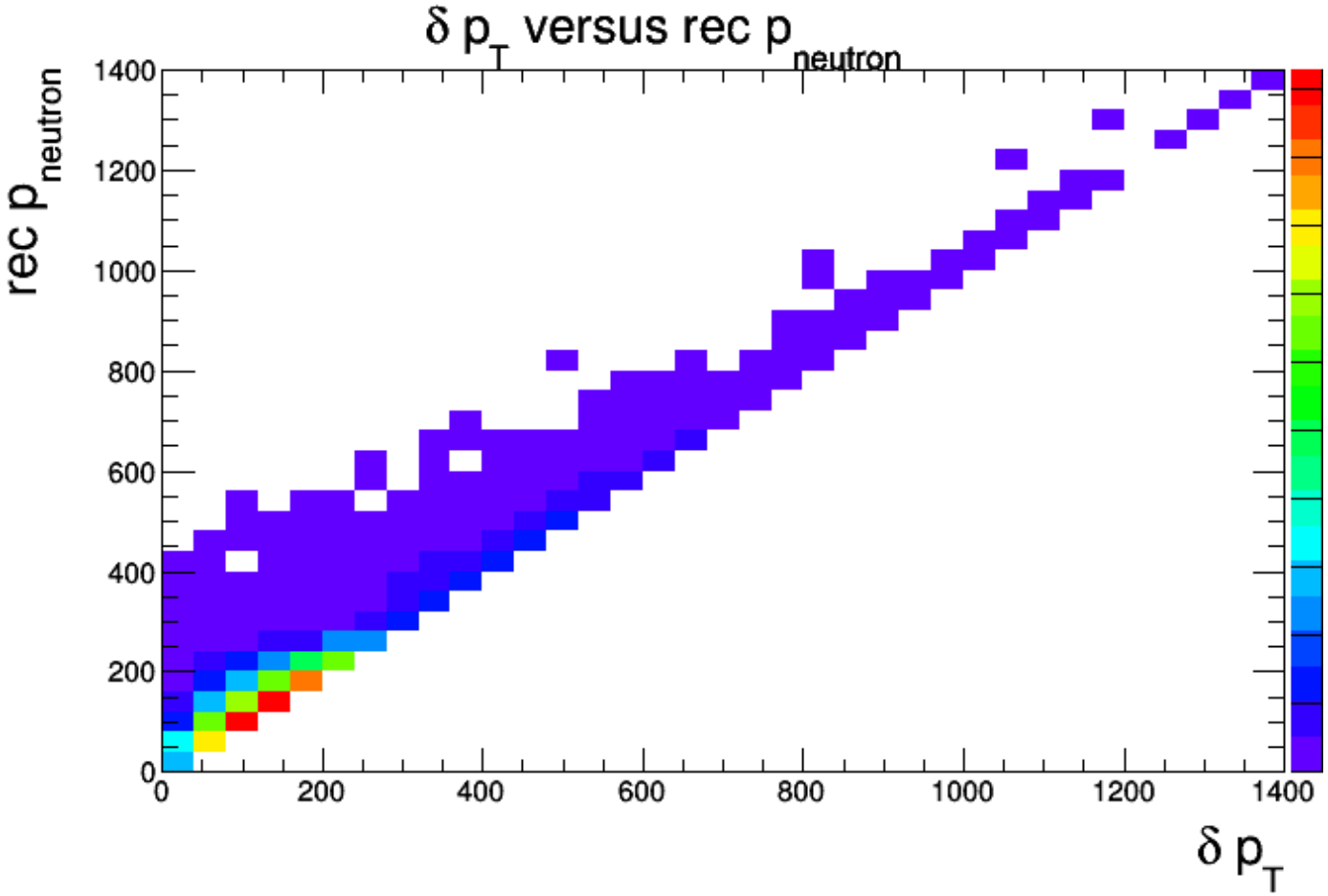
Reconstructed momentum cut in action







Examples of NuWro based studies (2 cont)



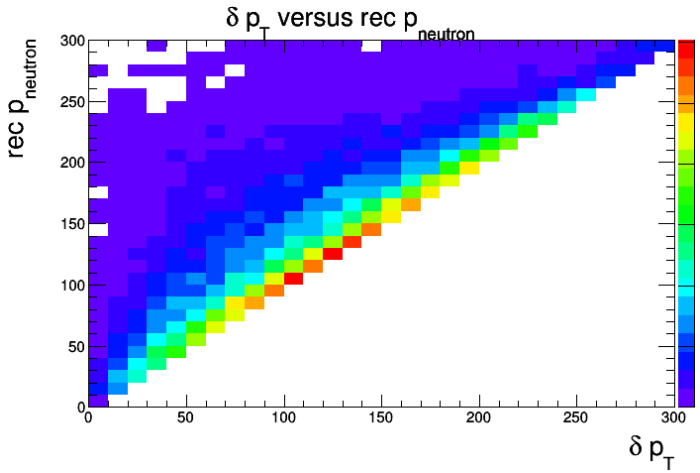
There is an apparent strong correlation.

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

Examples of NuWro based studies (2 cont)

At lower neutron momenta the correlation is kinematical in origin.

Zoom the region $p < 250$ MeV/c.



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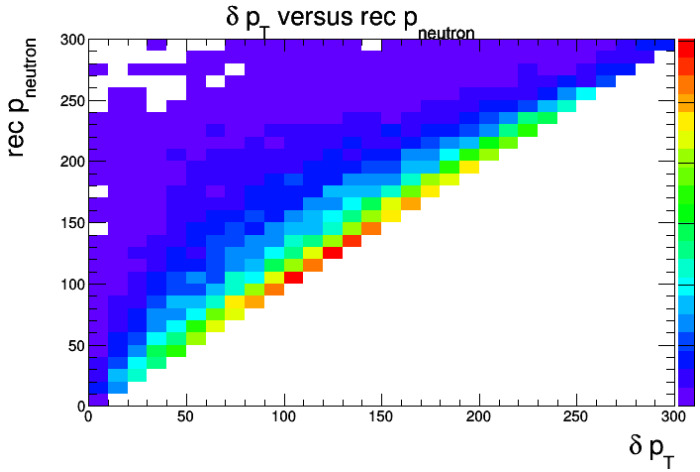
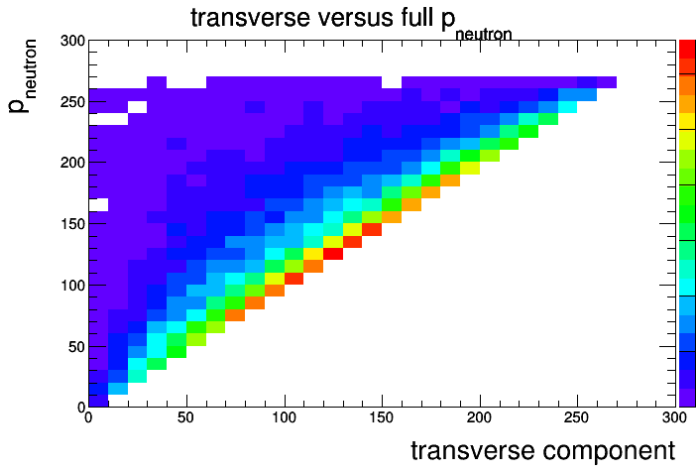


A distribution of **true** neutron momentum versus **true** transverse component.



It is a standard relation between vector and its orthogonal projection :).

For larger values of δp_T correlation is more complicated to explain.

Summary

There are many results I did not have time to show (inclusive cross section, DIS, pion absorption, ...).

A lot of work must be done...

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