Porównanie NuWro z danymi z eksperymentów T2K and MINERvA dla zdarzeń CC0π

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Zakład Fizyki Neutrin, 18 grudnia 2017 r.

NuWro validation

- On-going NuWro validation effort.
- Focus on CC0π measurements of T2K and MINERvA.
- Goal: identification of areas of necessary/possible improvements.
- For a moment NuWro scripts, in the future NUISANCE machinery will be used.

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

Everything in this talk is preliminary and should be confirmed by NUISANCE machinery!

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 0π differential cross section in transverse kinematics variables (one muon and $\geq$ one proton sample) [presented at NuInt17 by Stephen Dolan].
  - Proton multplicity [presented at NuInt17 by Stephen Dolan]
- MINERvA
  - CCQE-like $d^2\sigma/dp_L dp_T$ for ν_μ, $\overline{\nu_\mu}$ [Daniel, Heidi]
  - CC $d^2\sigma/dqdE_{avail}$ for ν_μ and $\overline{\nu_\mu}$ [PRL 116 (2016) 071802] (inclusive but very useful)
  - CCQE-like ratios C, Fe, Pb wrt CH (PRL119)

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

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.

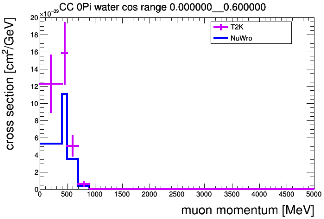
Cascade model

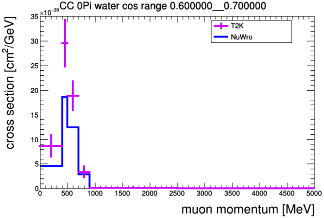
- Pions, nucleons.
- 0.2 fm steps.
- For pions Oset et al model T. Golan, C. Juszczak, JTS, Phys.Rev. C86 (2012) 015505.
- For nucleons in-medium modification of NN cross sections V.R. Pandharipande, S.C. Pieper, Phys.Rev. C45 (1992) 791-798

DIS, coherent pion production irrelevant for CC0π.

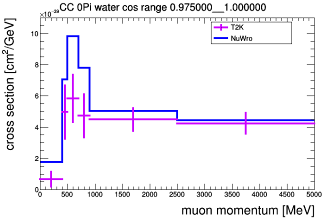
CC0π/CCQE-like

T2K CC0π double differential cross section on water arXiv:1708.06771 [hep-ex]





NuWro below the data at large muon angles.



NuWro above the data at small muon angles.

Bins where data/MC discrepancy is observed (complete results in back-up slides).

T2K CC0π double differential cross section on water (cont.)

There is also a large data/MC normalization discrepancy.

- The integration phase space: $\cos\theta_\mu > 0$, $p_{muon} < 5$ GeV/c.
- Data: $9.5 \pm 1.3 \cdot 10^{-39} cm^2$/neutron.
- NuWro: $6.78 \cdot 10^{-39} cm^2$/neutron.
  - NEUT and GENIE results very close to NuWro (6.6 or 6.8).
  - The discrepancy comes almost entirely from the most backward muon bin $\cos\theta_\mu \in (0.0, 0.6)$ where NuWro predicts 2.43 and the data is 4.59 in the units of $10^{-39} cm^2$/neutron.
  - There is also a large discrepancy in the next bin $\cos\theta_\mu \in (0.6, 0.7)$ but a contribution to the overall cross section is much smaller.

T2K CC0π double differential cross section on CH Phys.Rev. D93 (2016) 112012

There are two sets of results: full phase space ("analysis I") and restricted phase space ("analysis II").

Restricted phase space defined as: $\cos\theta_\mu > 0.6$, $p_\mu > 600$ MeV/c.

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

We add statistical tools using covariance matrix M_{cov}.

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

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

One can also calculate χ^2 separately for 8 cosine bins (all with 12 data points).

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

Normalization comparisons.

Analysis II: data $\rightarrow 2.03 \cdot 10^{-39}$ cm^2/nucleon;

NuWro $\rightarrow 2.02 \cdot 10^{-39}$cm^2/nucleon.

The agreement is very good.

A complete set of figures in back-up slides.

T2K CC0π double differential cross section on CH (analysis I)

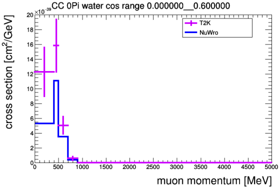
- In general, the agreement is fair, at least on eye...
- $\chi^2 = 185.6$, NDoF=67
  - Sara Bolognesi: not bad!
- Integrated cross section (per nucleon):
  - NuWro: $3.92 \cdot 10^{-39}$ cm^2/nucleon
  - Data: $4.60 \cdot 10^{-39}$ cm^2/nucleon
  - Paper: $(4.17 \pm 0.47 \pm 0.05) \cdot 10^{-39}$ cm^2/nucleon
- A significant part of normalization discrepancy comes again from the most backward bin (0.75 wrt 1.05 in the units of 10^{-39}) with a large systematic error.

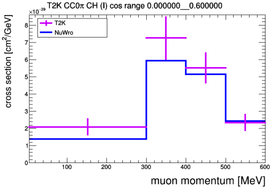
All the results on back-up slides.

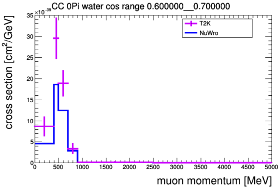
T2K CC0π oxygen wrt carbon

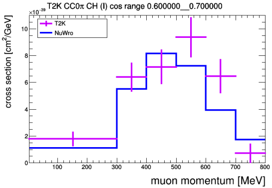
A message I from water measurement: NuWro below the data at large muon angles.

Do we see the same on carbon? Oxygen – left; carbon – right







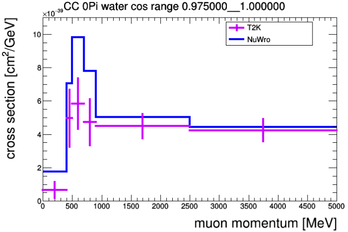


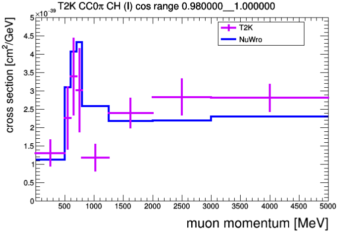
For carbon the cross section a deficit is not conclusive, but a tendency is perhaps there for lowest muon momenta?...

T2K CC0π oxygen wrt carbon

A message II from water measurement: NuWro above the data at small muon angles.

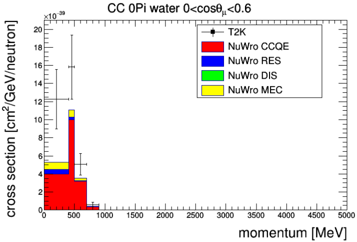
Do we see the same on carbon? Oxygen – left; carbon – right

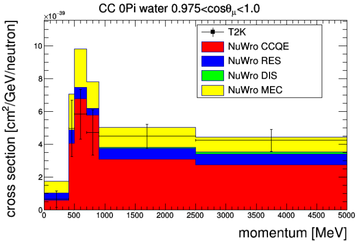


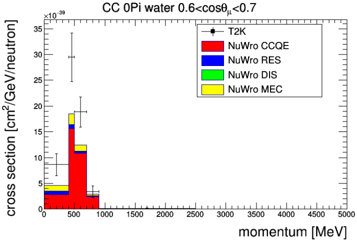


For carbon the cross section a surplus is not conclusive, but a tendency is perhaps there for muon momenta 500-1000 MeV/c?...

If a problem is there, which interaction modes are responsible?







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

A breakdown for CH results will look almost the same.

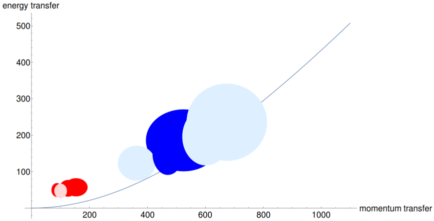
T2K 0π "suspicious bins" kinematical study

What is kinematical characteristic of bins where the data/MC tension is seen?

- We need a universal language in which tensions from distinct experiments can be discussed.
- We try to identify a region in energy and momentum transfer (q, ω) plane.
  - A limitation is that disagreement may come from either transverse or longitudinal components and their ratio depends on neutrino energy.
- With NuWro one can easily identify (q, ω) of CCQE and MEC events in particular bins.

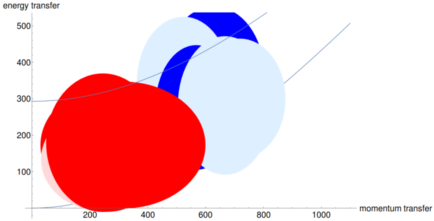
T2K 0π “suspicious bins” kinematical study (cont)

CCQE hypothesis



Line: QE peak.

MEC hypothesis



Lines: QE and Δ peak.

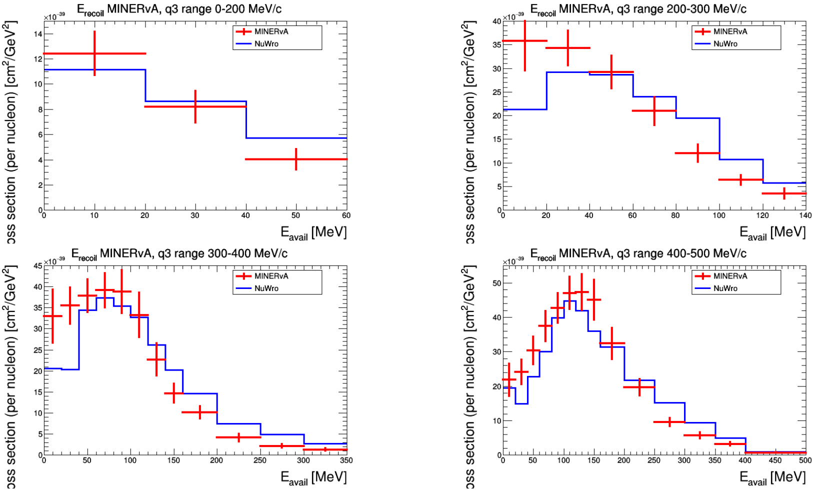
Blue: deficit of events in NuWro.

Red: excess of events in NuWro.

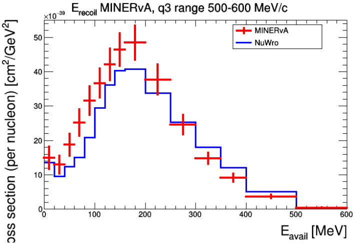
A structure is there. If the problems comes from MEC dynamics, the information less certain.

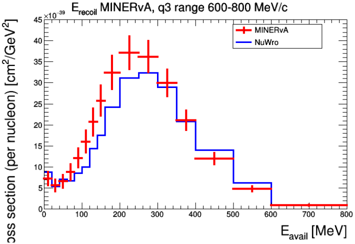
MINERvA recoil energy [PRL 116 (2016) 071802]

These are inclusive data but (hopefully) one can identify CCQE, MEC, RES regions separately.



MINERvA recoil energy (cont)





- The agreement is fair
- To be fully compared with Patrick Stowell computations (a few dfferences are there).
- NuWro is below the data at $q \in (400, 800)$ MeV/c and $E_{avail} \sim 150..200$ MeV
  - NuWro results shifted to the right? A bias in reconstruction of $q3$?
  - A deficit of events?
- NuWro is below the data $q \in (200, 400)$ MeV/c and $E_{avail} \leq 50$ MeV

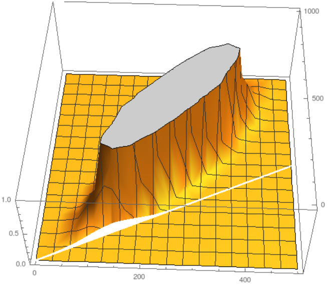
MINERvA recoil energy – my conclusions

If we treat E_{avail} as a proxy for energy transfer, the conclusions may be:

- NuWro is below the data in the region of small energy and momentum transfer: $q \in (200, 400)$ MeV/c, $\omega \leq 40$ MeV.
  - This stands in contradiction to the T2K results
- NuWro is below the data for $(q, \omega) \sim (450, 150), (550, 50 - 200), (700, 100 - 250)$.
  - This may be consistent with the T2K results!

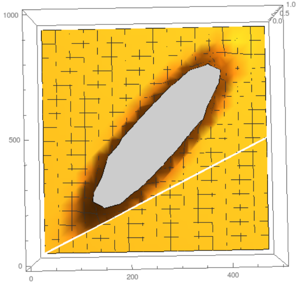
MINERvA recoil energy – GENIE fit

Based on the MINERvA results, an enhancement in MEC was proposed by Phil:



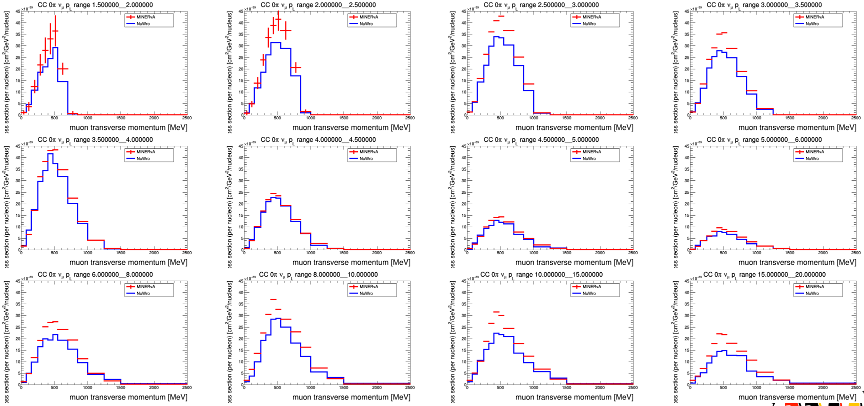
$q = 508 \pm 129$,
$\omega = 254 \pm 57$

It seems to be consistent with T2K!



The contour shows region where rescaling is $\geq 100\%$.

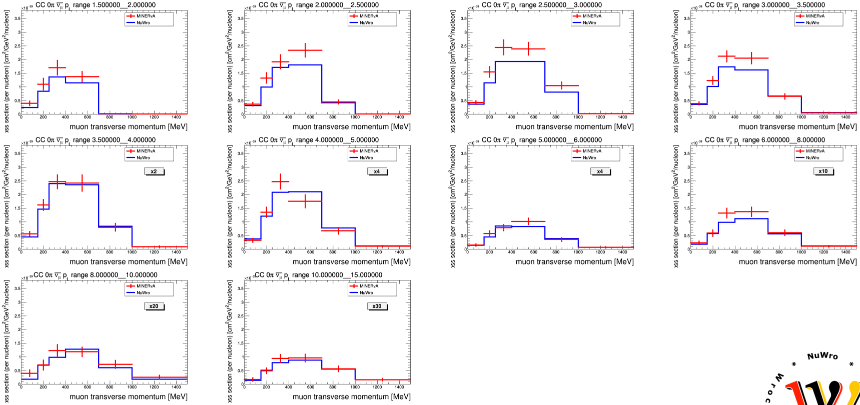
MINERvA CC0π p_T, p_L on CH ν_μ



A significant difference in normalization.

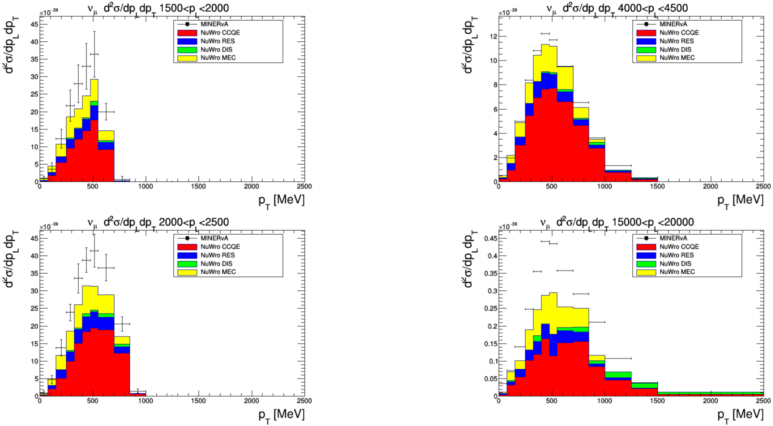
After a discussion with Daniel I applied 1.039 rescaling factor to NuWro results.

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



Much better agreement with the normalization.

Data/MC discrepancies – MINERvA



- Two major players: CCQE and MEC.
  - It is unlikely that RES is underestimated by a factor of 2.
- Always a large MEC contributions – should be even larger?!

Data/MC discrepancies – MINERvA

The first issue is normalization. NuWro is below the data in a wide kinematical region! The exception is $p_L \in (4,6)$ GeV/c. How much?

Overall rescaling factor is 1.20. In particular bins it differs from 1.42 (largest p_L) to only 1.02 (intermediate p_L).

A surprising fact: kinematical characteristics of CCQE and (to some degree) MEC events in different p_L in the p_T peak region are quite similar.

CCQE

$p_L \in (15,20)$ $p_T \in (0.4, 0.475)$ $q \sim 466 \pm 30$ MeV/c, $\omega \sim 140 \pm 50$ MeV
$p_L \in (4,4.5)$ $p_T \in (0.4, 0.475)$ $q \sim 473 \pm 32$ MeV/c, $\omega \sim 147 \pm 52$ MeV
$p_L \in (1.5,2)$ $p_T \in (0.4, 0.475)$ $q \sim 487 \pm 36$ MeV/c, $\omega \sim 156 \pm 54$ MeV

MEC

$p_L \in (15,20)$ $p_T \in (0.4, 0.475)$ $q \sim 573 \pm 126$ MeV/c, $\omega \sim 342 \pm 194$ MeV
$p_L \in (4,4.5)$ $p_T \in (0.4, 0.475)$ $q \sim 639 \pm 186$ MeV/c, $\omega \sim 403 \pm 258$ MeV
$p_L \in (1.5,2)$ $p_T \in (0.4, 0.475)$ $q \sim 735 \pm 185$ MeV/c, $\omega \sim 512 \pm 238$ MeV

Data/MC discrepancies – MINERvA

Problems with CCQE cannot explain this pattern!

If MEC enhancement stands behind the discrepancy then we need a lot of extra MEC strength at

$q \sim 573 \pm 126$ MeV/c, $\omega \sim 342 \pm 194$ MeV

and very little extra MEC strength at

$q \sim 639 \pm 186$ MeV/c, $\omega \sim 403 \pm 258$ MeV

Is that possible?!

Data/MC discrepancies – MINERvA

Events in distinct p_L bins come from mostly separated ν energies:

CCQE

$p_L \in (15, 20)$ $p_T \in (0.4, 0.475)$ $E \sim 17.2 \pm 1.2$ GeV
$p_L \in (4, 4.5)$ $p_T \in (0.4, 0.475)$ $E \sim 4.4 \pm 0.1$

MEC

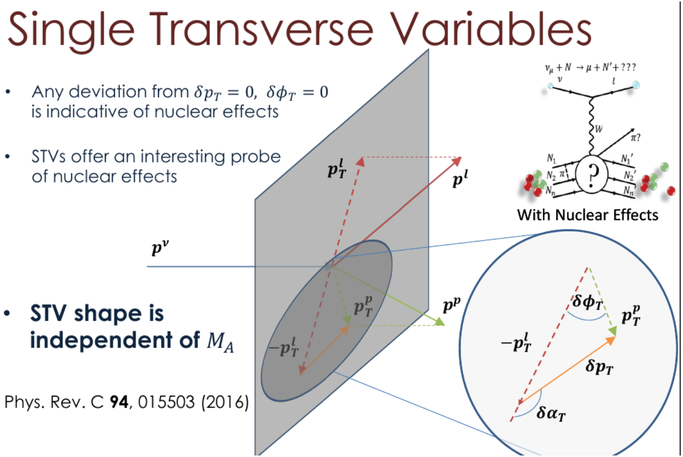
$p_L \in (15, 20)$ $p_T \in (0.4, 0.475)$ $E \sim 18.2 \pm 1.5$
$p_L \in (4, 4.5)$ $p_T \in (0.4, 0.475)$ $E \sim 4.7 \pm 0.3$

Discrepancies between various p_L bins could be easily explained by flux shape error!!!

Including protons in the game...

CC 0π differential cross section in transverse variables

Definition of transverse (wrt neutrino flux) variables.



from Stephen Dolan presentation at NuInt17

CC 0π differential cross section in transverse variables

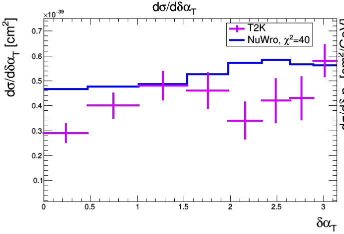
T2K selection:

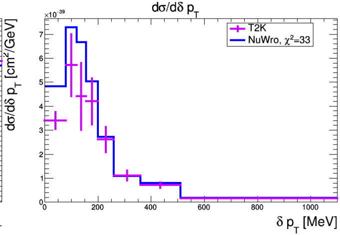
- CC0π
- muon momentum > 250 MeV/c
- cosine of muon angle > -0.6
- leading proton momentum $\in (450, 1000)$ MeV/c
- cosine of leading proton angle > 0.4.

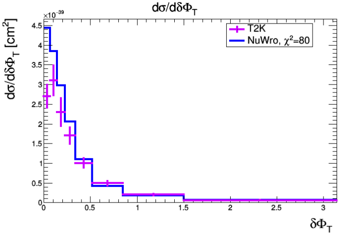
Muon selection includes a region of tha data/NuWro normalization discrepancy.

Results on the next slide from the Stephen Dolan presentation at NuInt17.

CC 0π STV – T2K.







- Stephen Dolan: SF leads to better agreement.
- NuWro is 19-24% above the data, surprising!
- Need more proton reinteractions?!
  - In fact, NuWro proton transparency seems to be too large by $\sim$ 10% (ongoing study).

Transverse variables – MINERvA

We are still checking overall normalization with Xianguo!...

Summary 1

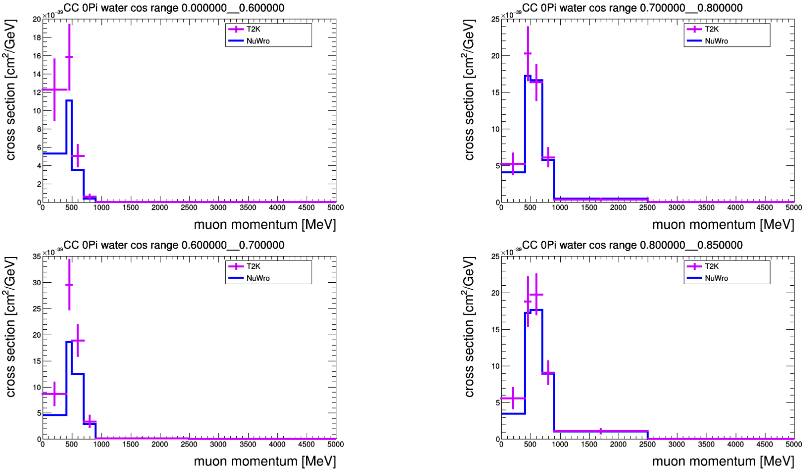
There is a lot of interesting data to be used as benchmark for MC event generators.

Summary 2

- NuWro/T2K normalization discrepancy at large muon angles.
- Some data suggest NuWro/T2K/MINERvA agreement on MEC enhancement
- Difficult to understand a pattern of NuWro/MINERvA agreement/disagreement at various p_L
- Interesting to look for NuWro/T2K/MINERvA for STV measurement/predictions (sorry, not ready yet).

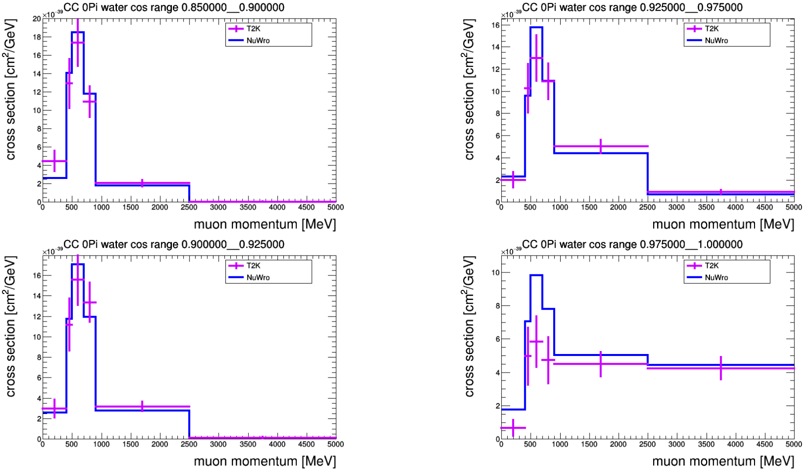
Back-up slides

T2K CC0π double differential cross section on water arXiv:1708.06771 [hep-ex]



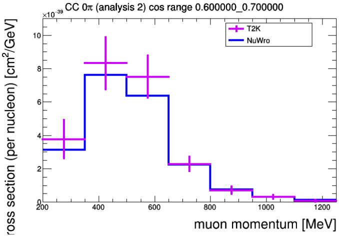
NuWro below the data at large muon angles.

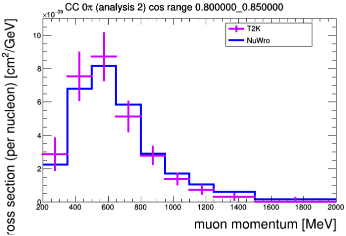
T2K CC0π double differential cross section on water (cont)

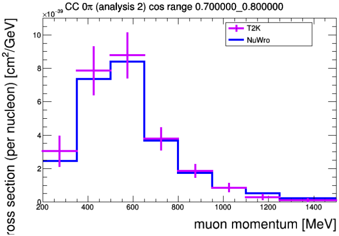


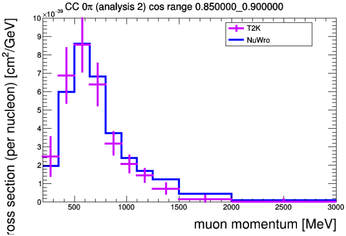
NuWro above the data at small muon angles.

T2K CC0π double differential cross section on CH (analysis II)

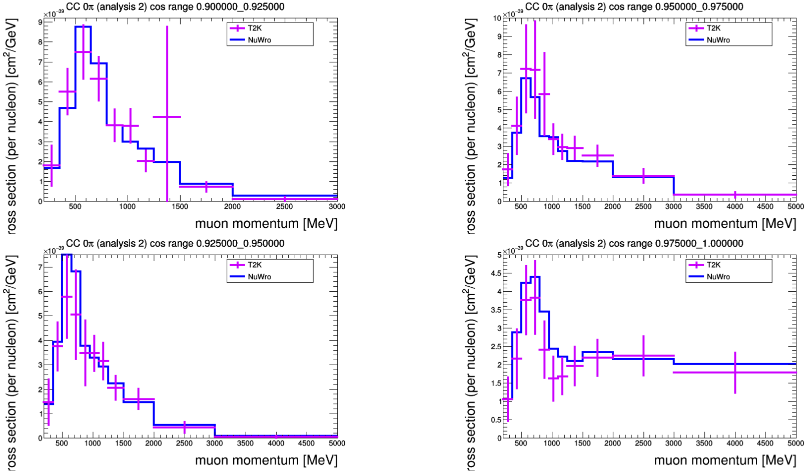






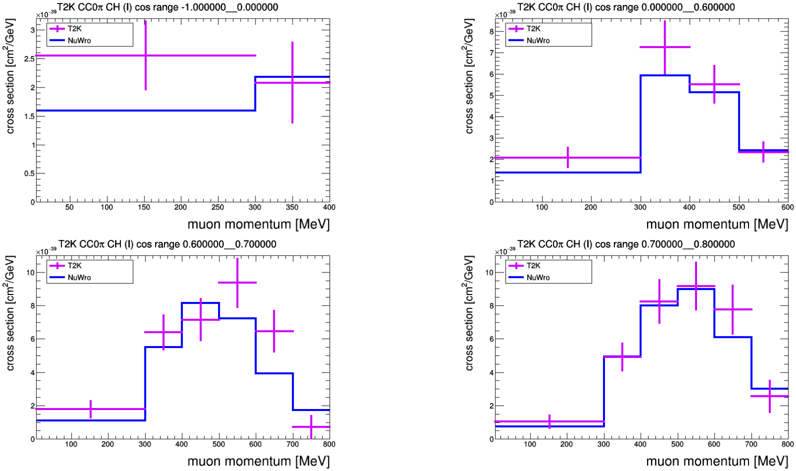


T2K CC0π double differential cross section on CH (analysis II, cont)

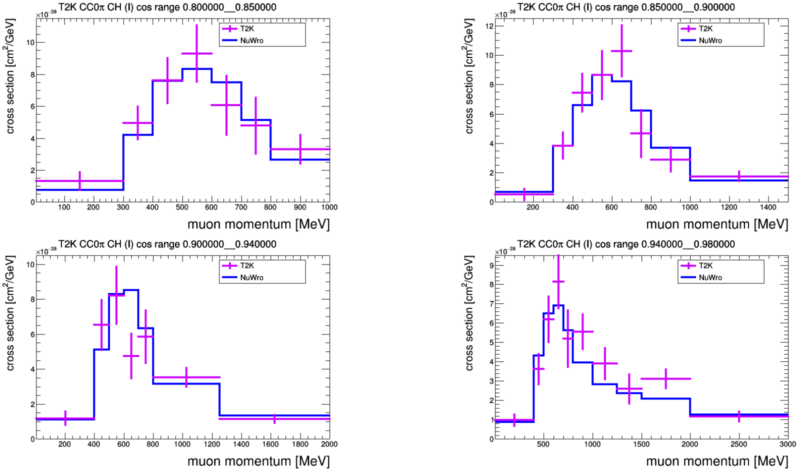


The agreement is good.

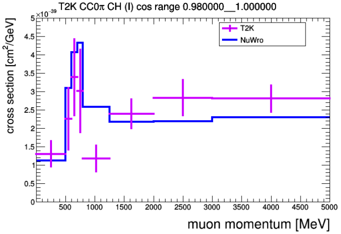
T2K CC0π double differential cross section on CH (analysis I)



T2K CC0π double differential cross section on CH (analysis I, cont)



T2K CC0π double differential cross section on CH (analysis I, cont)



- In general, the agreement is fair.

- $\chi^2 = 185.6$, NDoF=67
- Integrated cross section (per nucleon):
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- A significant part of normalization discrepancy comes from the most backward bin (0.75 wrt 1.05 in the units of 10^{-39})