NuWro validation & some physical considerations

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Motivation

- Goal: NuWro validation on recent experimental data.

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

- To start with: look (mostly) for measurements done after NuInt15 and before NuInt17.
- Statistical analysis included (a work in progress).
- An attempt to identify and understand tensions in the data.
- Identification of areas of necessary/possible improvements.

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

In the future: use NUISANCE?

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

NuWro team

T. Golan | K. Graczyk | C. Juszczak | K. Niewczas | J. Nowak | J.T. Sobczyk | J. Żmuda

Notable supporters

Warsaw

D. Kiełczewska
(passed away in 2016)

General,
many discussions

P. Przewłocki

NuWro at T2K

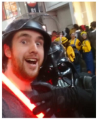
VA, U.S.

A. Ankowski

Spectral function

U.K.

L. Pickering



P. Stowell

Reweightning tools

Sorry, but...

Sorry, but...

... it is going to be a somehow boring presentation with many plots!

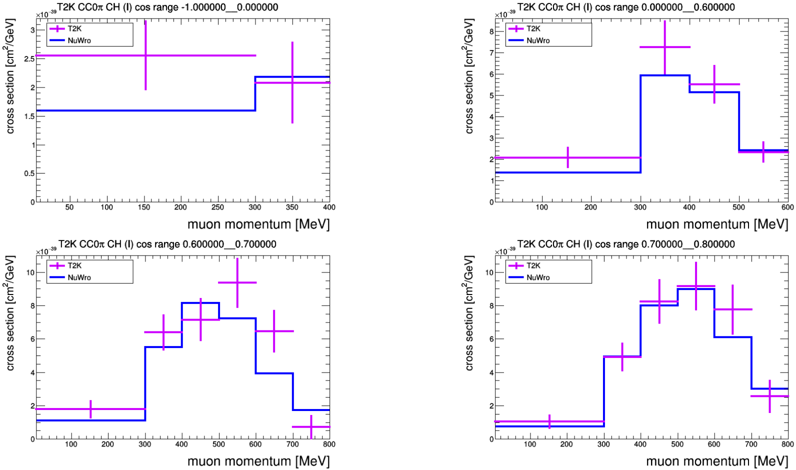
CC0π/CCQE-like

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

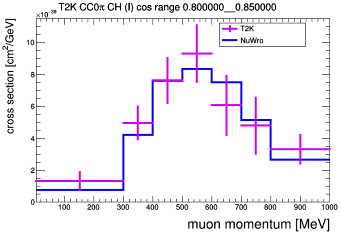
There are two sets of results: full phase space (“analysis I”) and restricted phase space (“analysis II”).

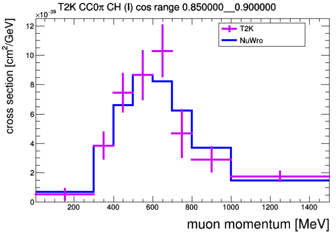
Restricted phase space defined as: $\cos\theta_\mu > 0.6$, $p_\mu > 600$ MeV/c.

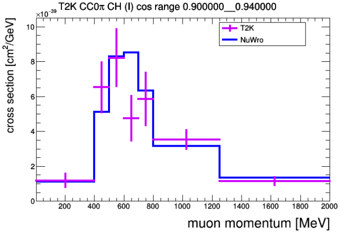
T2K CC0π double differential cross section on CH (analysis I)

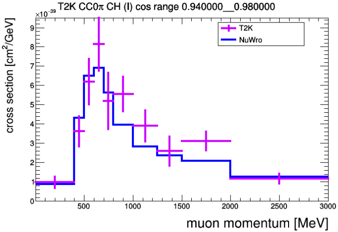


T2K CC0π double differential cross section on CH (analysis I, cont)

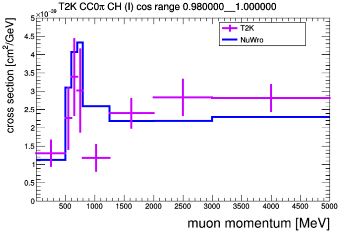








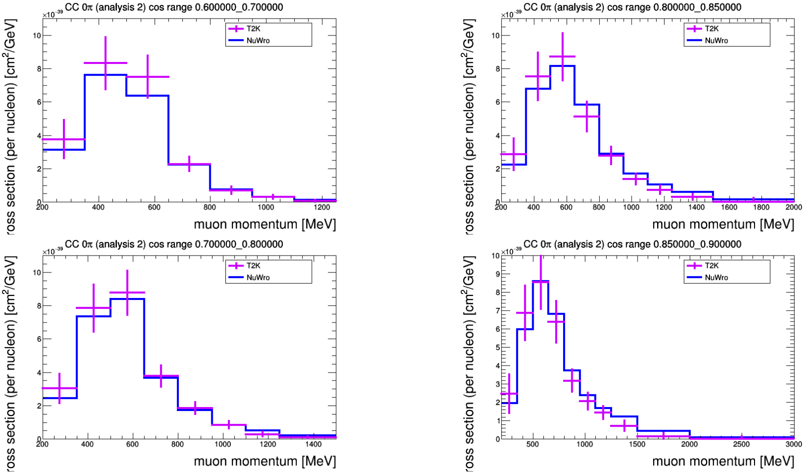
T2K CC0π double differential cross section on CH (analysis I, cont)



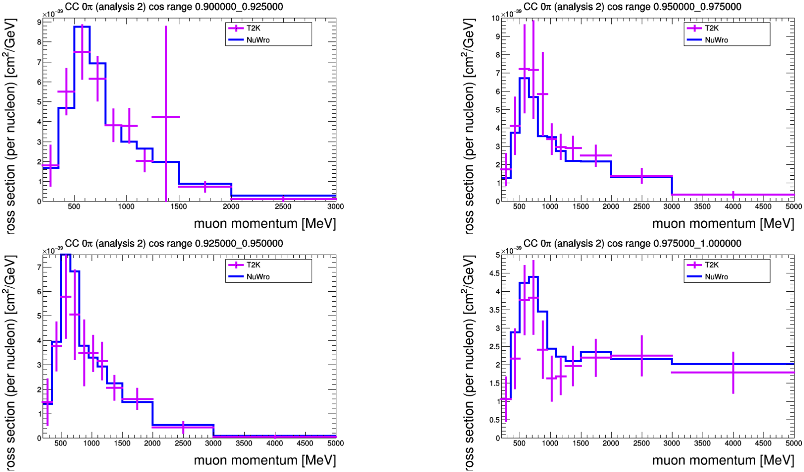
- In general, the agreement is fair.

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

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 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.

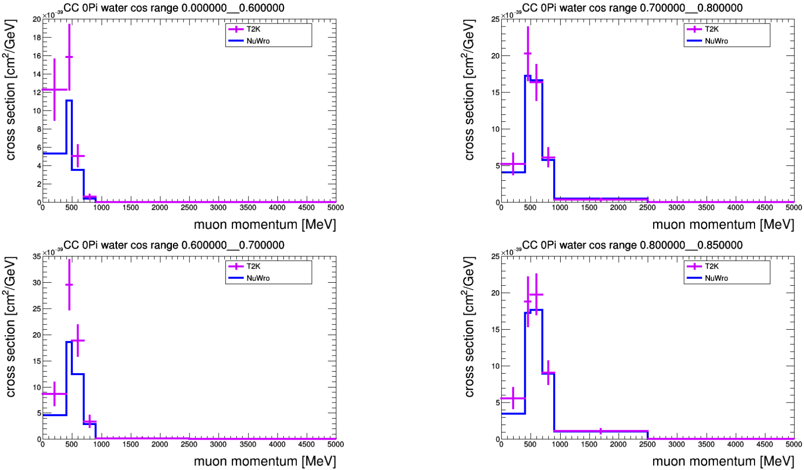
Normalization comparisons.

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

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

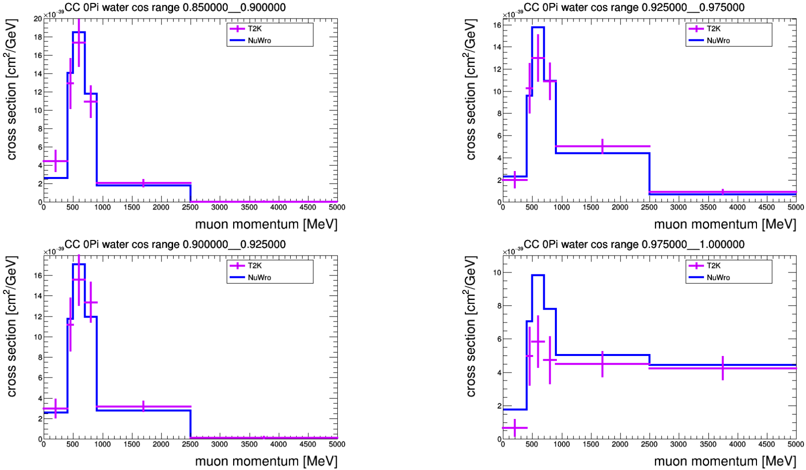
The agreement is very good.

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)

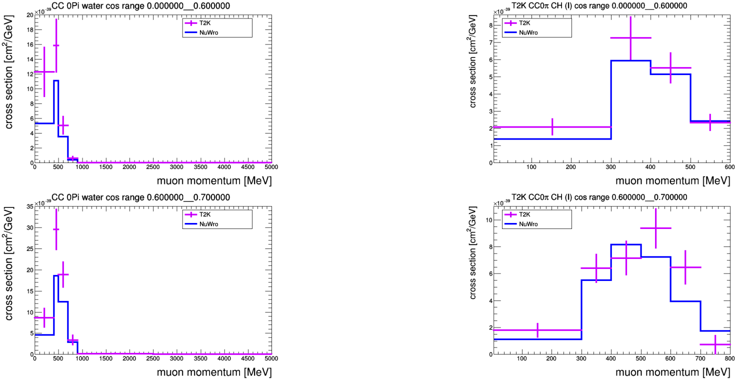


NuWro above the data at small muon angles.

T2K CC0π 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

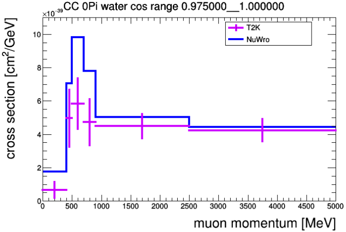


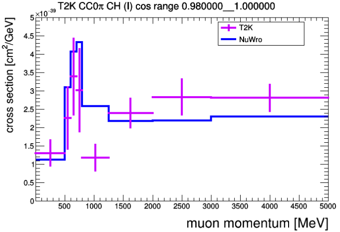
For carbon the cross section a deficit is not conclusive, but a tendency is perhaps there for lowest muon momenta?

T2K CC0π oxygen wrt carbon

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

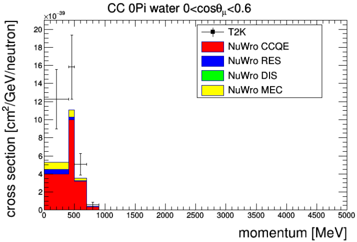
Do we see the same on carbon? Oxygen – left; carbon – right

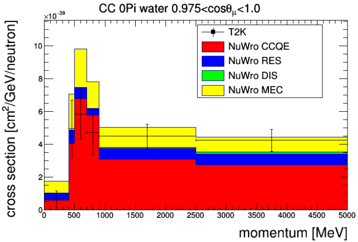


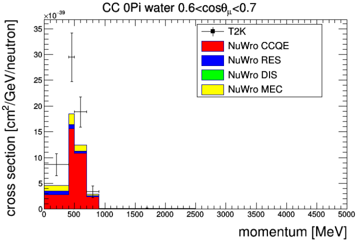


For carbon the cross section a surplus is not conclusive, but a tendency is perhaps there for muon momenta 500-1000 MeV/c?

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







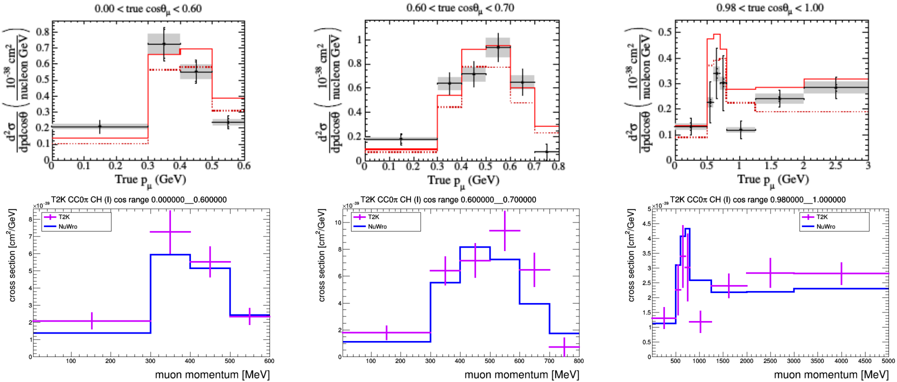
- On the left: CCQE is too small!
- On the top CCQE too large? (no room for MEC)

A breakdown for CH results will look almost the same.

Is there really a data/NuWro discrepancy?

Comparisons with other MCs/computations.

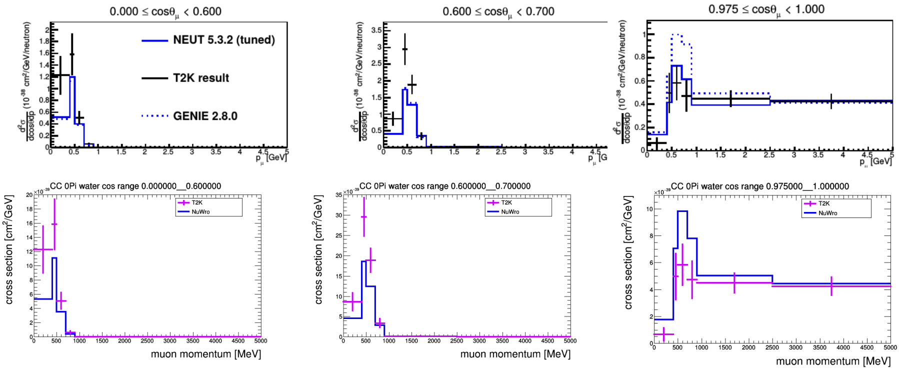
T2K 0π carbon Nieves(dotted line)/Martini(solid line)/NuWro



NuWro similar to Nieves (no surprise).

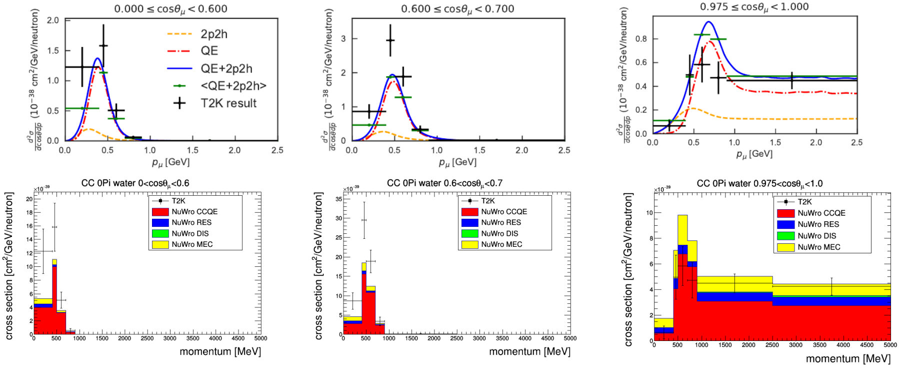
Nieves and Martini do not have pion absorption (relevant in the muon forward directions).

T2K 0π water NEUT/GENIE/NuWro



NuWro and GENIE are very similar.

T2K 0π water NuWro/other models



- The results are quite similar.
- In the SuSa2 results there is no RES contribution quite important in the forward directions.

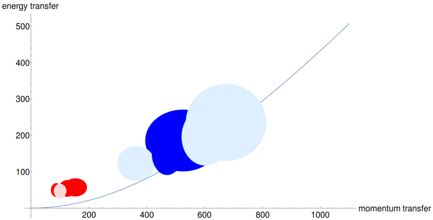
T2K 0π "suspicious bins" kinematical study

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.

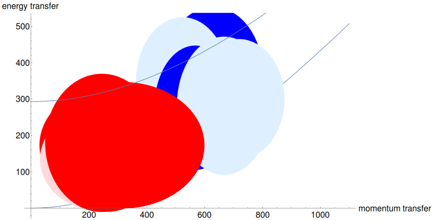
T2K 0π "suspicious bins" kinematical study (cont)

CCQE hypothesis



Line: QE peak.

MEC hypothesis



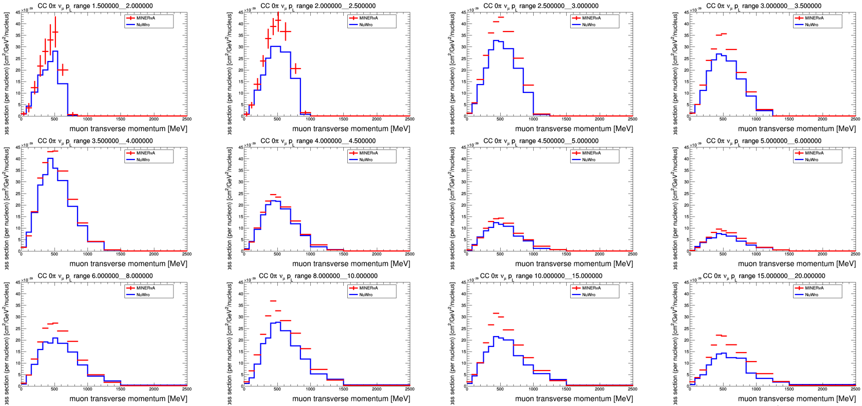
Lines: QE and Δ peak.

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 is smeared.

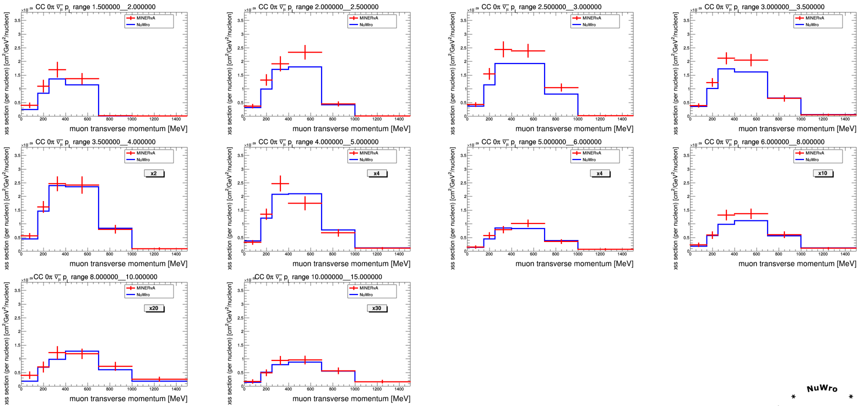
MINERvA CC0π p_T, p_L on CH ν_μ



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

A significant difference in normalization.

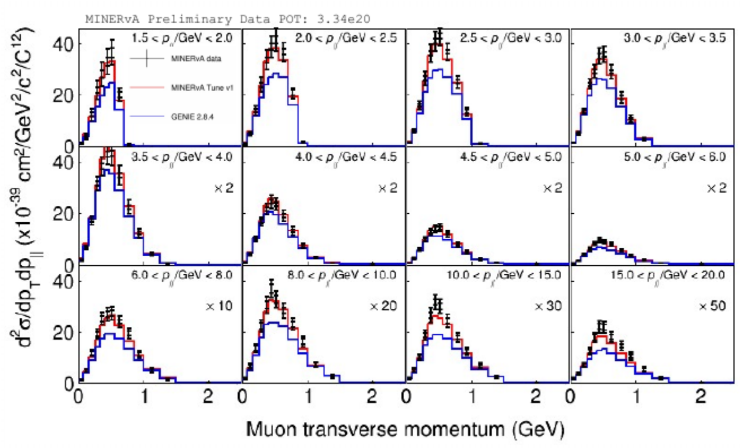
MINERvA CC0π p_T, p_L on CH $\bar{\nu}_\mu$



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

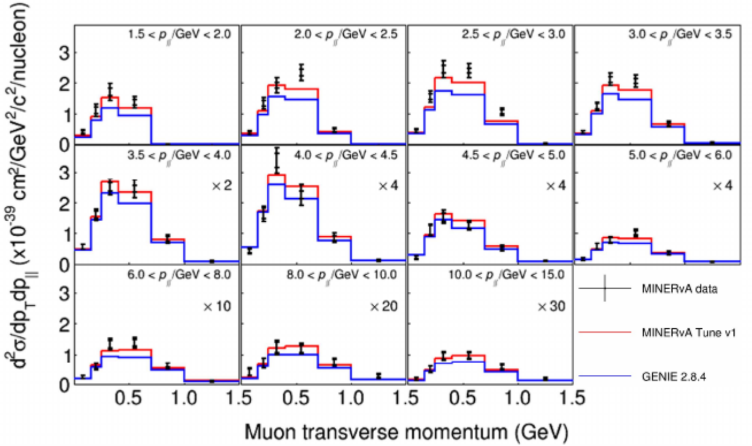
Much better agreement with normalization.

MINERvA ν_μ CC0π p_T, p_L – GENIE results

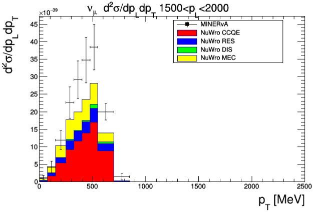


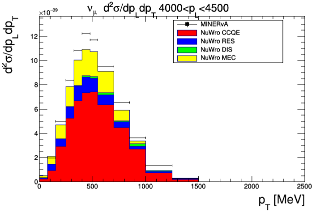
GENIE (before tuning) has very similar problems.

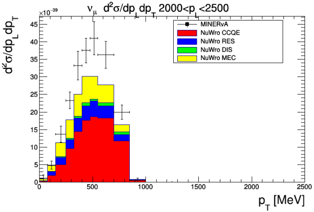
MINERvA $\bar{\nu}_\mu$ CC0π p_T, p_L – GENIE results

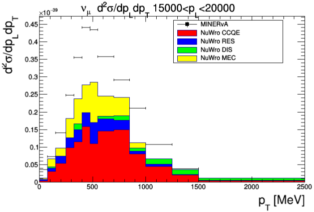


Data/MC discrepancies – MINERvA









- 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 main issue is normalization. NuWro is below the data in a vary wide kinematical region! How much?

Overall rescaling factor is 1.24. In particular bins it differs from 1.47 (largest p_L) to 1.07 (intermediate p_L).

Another puzzling fact: kinematical characteristics of CCQE and MEC events in (p_L, p_T) 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

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

Data/MC discrepancies – MINERvA

My guess: understanding of neutrino spectrum.

Why?

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

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

Relative normalization of νs in 4.5 GeV and 17.5 GeV may be different by 20-30% wrt what is expected?!

MINERvA flux normalization

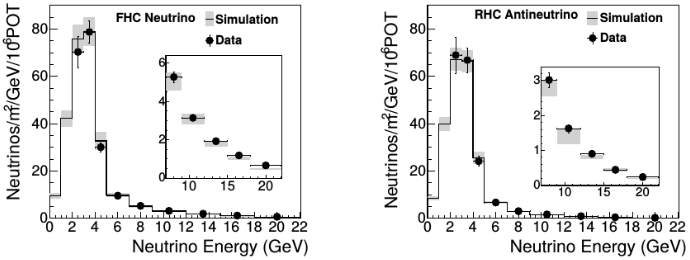


FIG. 8: Extracted low-ν flux (points) for FHC neutrino (left) and RHC antineutrino (right). The histogram shows the Monte Carlo simulated fluxes from Ref. [17] and one sigma error band (shaded bars). The insets show a zoom-in of the 9-22 GeV energy range.

Phys.Rev. D95 (2017) 072009

From Lu Ren: renormalization factors are 0.92 and 1.07.

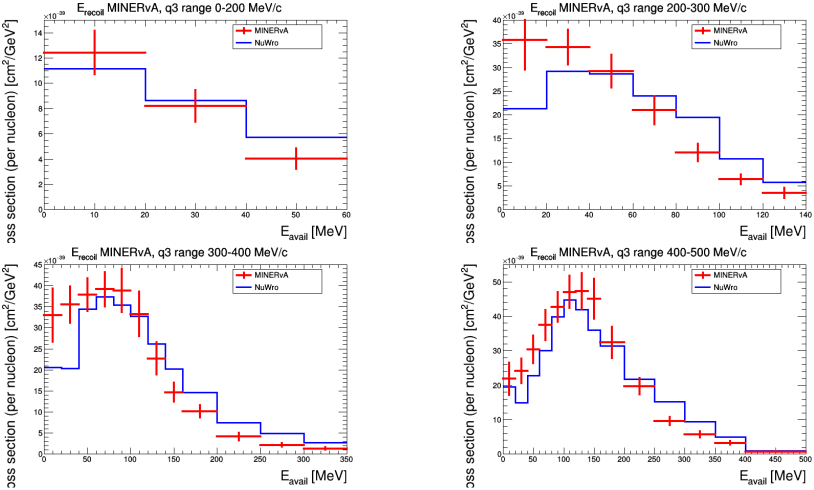
MINERvA recoil energy

An attempt to resolve kinematics completely.

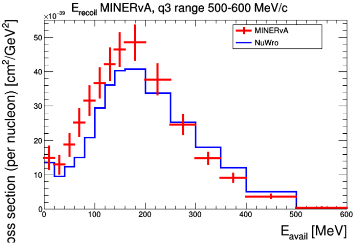
- Calorimetric measurement of hadronic energy.
- MC (GENIE) dependent estimate of energy and momentum transfer $q3$.
- Allows to single out and study region of low $q3$ and "available energy" E_{avail}
- Double differential cross section reported.

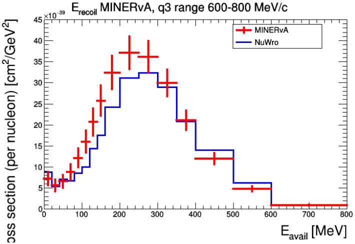
$$E_{avail} \equiv \sum_{kineticenergy} proton, \pi^{\pm} + \sum_{energy} \pi^0, \gamma, e^- .$$

MINERvA recoil energy



MINERvA recoil energy (cont)





- Surprisingly well!
- To be confirmed with Patrick computations (a few dfferences are there).
- NuWro results shifted to the right.
- A bias in reconstruction of $q3$?

MINERvA recoil energy – conclusions

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

- NuWro underestimates 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 somehow below the data for $(q, \omega) \sim (450, 150), (550, 50 - 200), (700, 100 - 250)$.
  - This may be consistent with the T2K results if the problem comes from CCQE rather than from MEC.

Tomorrow:

Including protons in the game...

Summary

- Even if NuWro 17.09 is a rather primitive model a general agreement is OK. A surprise.
- We need better data (smaller uncertainties in order to identify problems.
    - Can be on a small piece of the phase space, can be in a form of ratios, but 5% errors and not 10%!