NuWro and search for 2p2h events

Jan T. Sobczyk

(in collaboration with K. Niewczas, T. Golan, C. Juszczak)
(many discussions with Rik Gran)

Wrocław University

INT Workshop, March 5, 2018

Outline:

- Motivations.
- Attempts to estimate a size of 2p2h contributions from CC0π and CC inclusive data.
  - MINERvA/GENIE (ω, q) study.
  - ...
- NuWro CC0π studies
  - The main goals:
    - How large is 2p2h contribution?
  - Is it possible to build a phenomenological model?
- NuWro muon+proton studies.
- NuWro nuclear transparency study.
  - Proton FSI uncertainty.
- Conclusions.

NuWro version 17.09 is used (the most recent version is 18.02).

Motivations

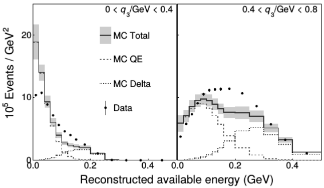
NuWro (using Nieves et al 2p2h model) is systematically below all recent CC0π experimental data.

- Before a new round of theoretical computations are available try to use the existing data to build a phenomenological model.

There is an increasing number of CC0π muon+proton measurements.

- They can be used for testing phenomenological models
- In order to explore the new data in a search for 2p2h signal it is necessary to have good control over nucleon FSI effects.

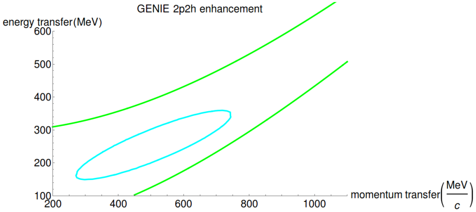
MINERvA (ω, q) measurement



PRL 116 (2016) 071802

There is need to enhance 2p2h wrt Nieves et al model in GENIE (FG+RPA) (because a strength in missing in the dip region).

Scale factors are applied to both reconstructed data and MC in a consistent way.



Green lines: QE and Δ peak.

2D Gaussian function is used.

Contour: enhancement by a factor 2 (inside the ellipsoid it is larger).

Phil Rodrigues, Rik Gran

Try to repeat the analysis based on CC0π data only.

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

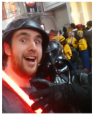
VA, U.S.

A. Ankowski

Spectral function

U.K.

L. Pickering



P. Stowell

Reweightning tools

(some info should by updated...)

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

2p2h (called on figures 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

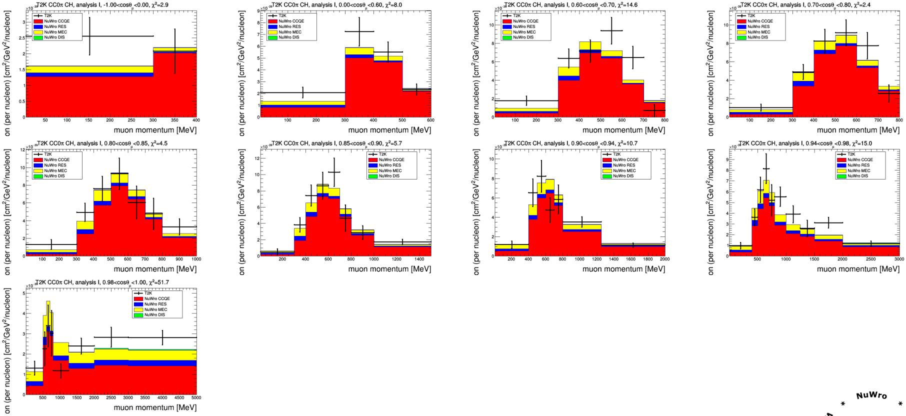
DIS is mostly irrelevant for CC0π studies.

Experimental data

- T2K
  - CC0π ν_μ muon double differential cross section on CH target [PRC93].
  - CC0π ν_μ muon double differential cross section on water target [PRD97].
  - CC0π differential cross section in transverse kinematics variables (one muon and $\geq$ one proton sample) [arXiv:1802.05078 [hep-ex]].
  - Proton inferred kinematics [arXiv:1802.05078 [hep-ex]].
  - CC0π without and with reconstructed proton [arXiv:1802.05078].
  - CC0π $\overline{\nu_\mu}$ coming soon!
- MINERvA
  - CC0π, Q^2 estimated using proton and not muon [PRD91]
  - CC0π ratios C, Fe, Pb wrt CH [PRL119].
  - CC0π $d^2\sigma/dp_L dp_T$ for $\overline{\nu_\mu}$ [arXiv:1801.01197[hep-ex]]
  - CC0π $d^2\sigma/dp_L dp_T$ for ν_μ [Daniel Ruterbories, NuInt17]
  - CC $d^2\sigma/dqdE_{avail}$ (inclusive but useful) [ν_μ Phil Rodrigues et al. PRL 116 and $\overline{\nu_\mu}$ Rik Gran, talk at NuInt17]
  - CC0π differential cross section in transverse kinematics variables and reconstructed neutron momentum [Xianguo Lu, last Friday].

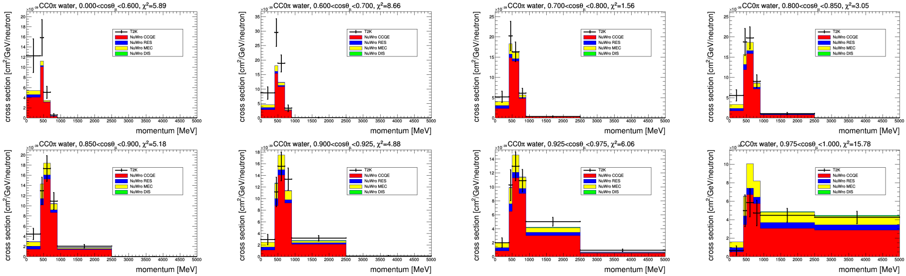
CC0π/CCQE-like

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



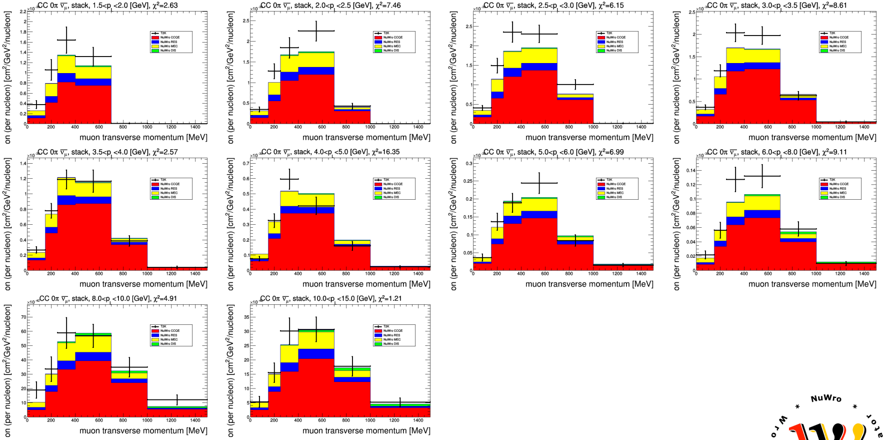
Data/MC overall normalization 4.58/3.91. In $\cos\theta_\mu$ bins: 1.04/0.75, 1.34/1.13, 0.37/0.32, 0.42/0.39, 0.24/0.23, 0.26/0.26, 0.23/0.24, 0.37/0.31, 0.31/0.28 (units 10^{-39}/nucleon).

T2K CC0π double differential cross section on water



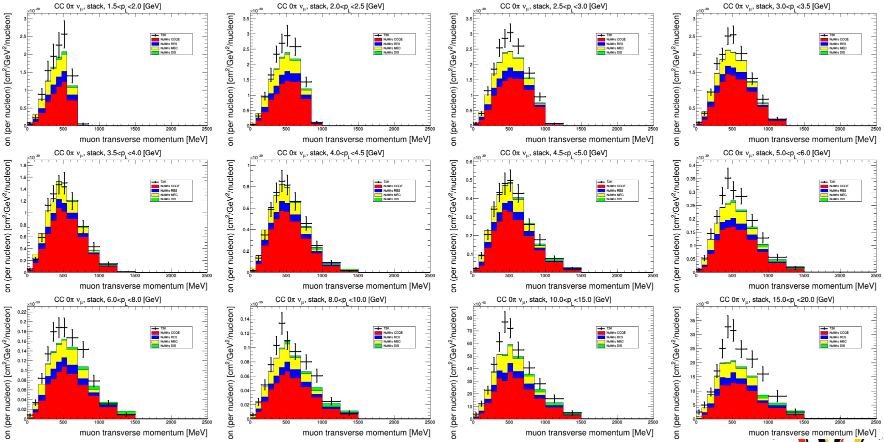
Data/MC overall normalization 9.51/6.77. In $\cos\theta_\mu$ bins: 4.59/2.46, 1.11/0.69, 0.92/0.86, 0.58/0.50, 0.60/0.57, 0.38/0.32, 0.84/0.77, 0.52/0.60 (units 10^{-39}/neutron).

MINERvA CC0π p_T, p_L on CH $\overline{\nu_\mu}$



Data/MC overall normalization 3.72/3.30. In $\cos\theta_\mu$ bins: 0.40/0.33, 0.63/0.52, 0.78/0.63, 0.64/0.57, 0.39/0.39, 0.32/0.35, 0.15/0.15, 0.18/0.15, 0.097/0.087, 0.12/0.11 (units 10^{-39}/nucleon).

MINERvA CC0π p_T, p_L on CH ν_μ



Data/MC overall normalization 4.63/4.12. In $\cos\theta_\mu$ bins: 0.48/0.40, 0.73/0.62, 0.86/0.75, 0.72/0.64, 0.44/0.44, 0.25/0.26, 0.16/0.15, 0.22/0.20, 0.26/0.24, 0.17/0.14, 0.23/0.20, 0.11/0.083 (units 10^{-39}/nucleon).

Understanding 2p2h contribution

Basic hypothesis: data/MC disagreement originates mostly from a poor understanding of 2p2h contribution.

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- NuWro 17.09 1p1h (CCQE) model is not perfect.
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- No doubt that 2p2h is most uncertain (e.g. a big difference between Nieves et al and Martini et al predictions).

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Question: how to improve (rescale?) 2p2h in order to have better agreement with the data?
A study similar in the spirit to what Phil Rodrigues and Rik Gran did for GENIE and what Patrick Stowell was doing for T2K.

We do not include MINERvA (ω, q) data as the error band includes a model uncertainty. Here we rely on the observed muon quantities only.

Understanding 2p2h contribution

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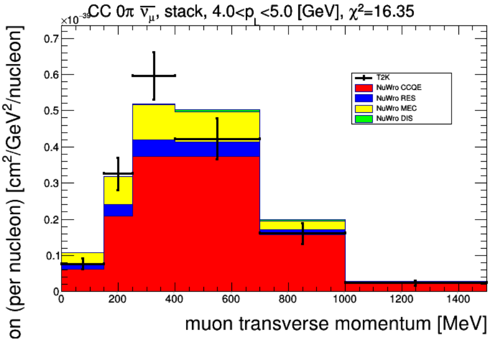
Strategy: look at all the bins if MC prediction is above/below/within error bars. Example:



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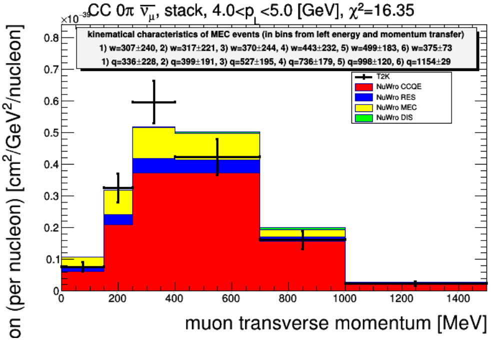
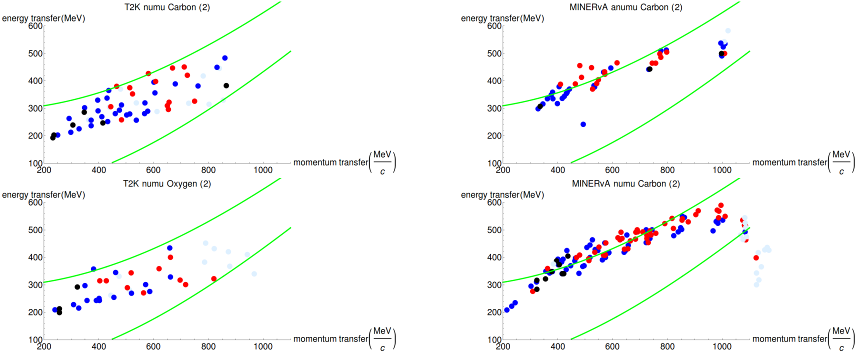
Strategy: look at values of energy and momentum transfer of 2p2h events in particular bins:

Example:



Go through all four (for a moment) data samples.

Understanding 2p2h contribution



Lines: QE and Δ peak.

Blue: data/MC agreement; not much room for significant 2p2h increase.

Red: MC below the data

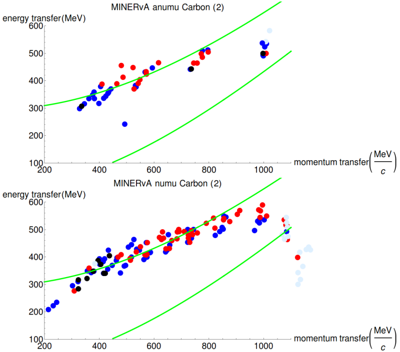
Black: MC above the data

Light blue: data/MC agreement; there is a room for significant 2p2h increase (by a factor of 2.5).

Understanding 2p2h contribution

Why for MINERvA the points lie mostly near Δ line?!

- Maybe larger energies and forward direction privilage Δ mechanism in the Nieves model?
- Rik Gran: there is a strong correlation between p_L and E_ν, and between p_T and q; we see that extra strength is needed at given q but ω remains poorly constrained.



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Understanding 2p2h contribution

Combining everything together?! Little risky...

- Combination of neutrino and antineutrino data.
- MINERvA energies are larger and extra kinematical factors may play a role.
- Rik Gran: extra kinematic factors and energy dependence plays a larger role at T2K energies.
- It is likely that more sophisticated approach is necessary.

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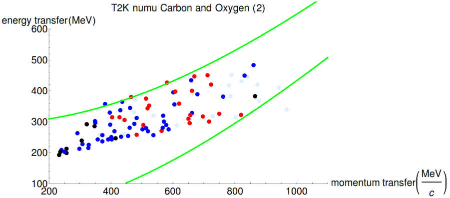

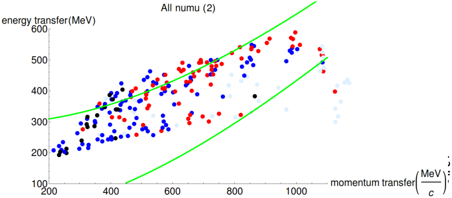

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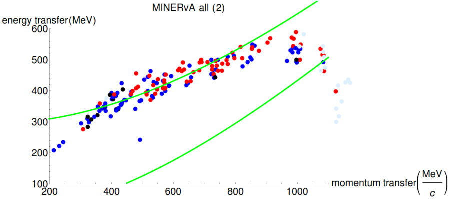
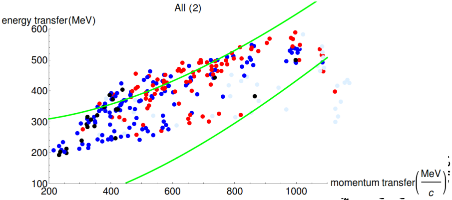
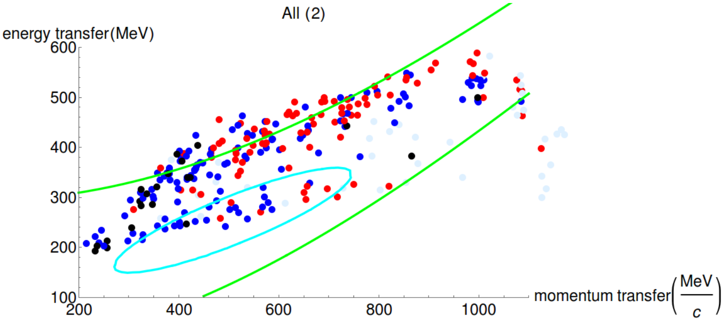




Understanding 2p2h contribution

Interesting to see a region of 2p2h enhancement found in the MINERvA (ω, q) paper (based on GENIE but the results should be universal?!).

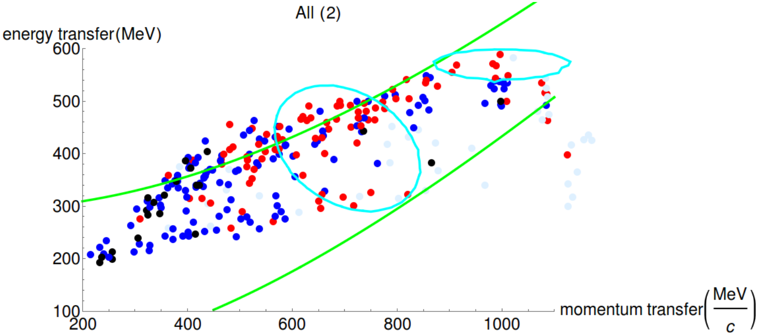
- It is not an apples to apples comparison. A deficit of events is found in the context of a particular set of models.



GENIE: 2D gaussian rescaling function by a factor of 10 at the maximum.
However, it is located in a region of low strength of the Nieves et al model.

Understanding 2p2h contribution

In the context of NuWro 17.09 the answer would look something like:



An enhancement is expected in a rather different phase space region.

Understanding 2p2h contribution

A possible strategy for the future:

Understanding 2p2h contribution

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- It may take time before complete theoretical computations are available.
  - relativistic, including Δ region

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- One can use large (and increasing) samples of CC0π data with a significant 2p2h contribution.

Understanding 2p2h contribution

A possible strategy for the future:

- It may take time before complete theoretical computations are available.
  - relativistic, including Δ region
- One can use large (and increasing) samples of CC0π data with a significant 2p2h contribution.
  - Improve statistics!
- It is preferable to start with better 1p1h (CCQE) model (by looking at the electron scattering data)
  - SF+FSI
  - Effective potential.
- Find a region of 2p2h enhancement using statistical tools.
- Double check self-consistency of the phenomenological model using the proton data (the next topic).

Including protons in the game...

T2K proton data

The first CCQE-like measurement with protons was done by MINERvA (Q^2 evaluated based on proton and not muon)

Tammy Walton et al. [MINERvA] PRD91

T2K reported very detail cross section measurements using information from muon and proton.

[arXiv:1802.05078 [hep-ex]]

- Single transverse variables.
- Proton inferred kinematics.
- No proton cross section in muon momentum and angle.
- Multidimensional differential cross section in muon and proton momenta.
- Proton multiplicity.

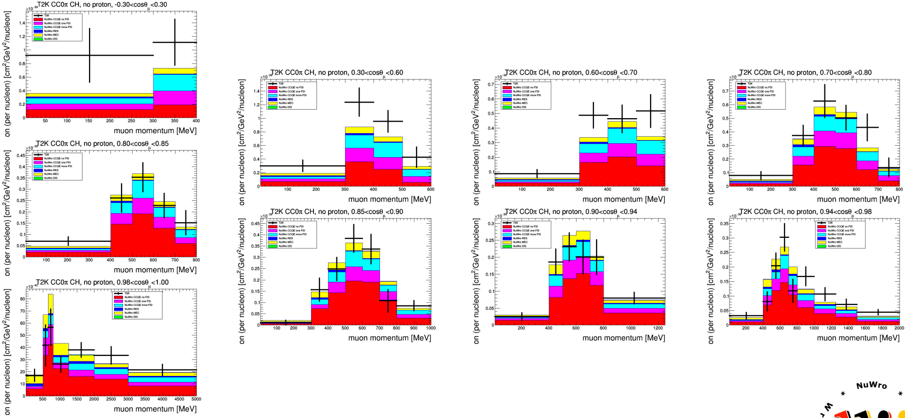
A lot of physics:

- Possibility to separate contributions from CCQE, RES and MEC.
- Possibility to investigate proton final state interactions.

Xianguo Lu [for MINERvA]: Neutrino shadow play, Fermilab *Wine and Cheese seminar*, March 2, 2018.

T2K proton data – no proton (above 450 MeV/c) cross section

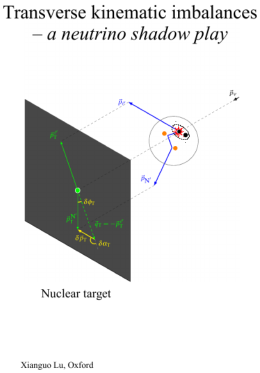
arXiv:1802.05078 [hep-ex]



- A general agreement is good.
- A very little contribution from RES (low average ν_μ energy).
- A lot of sensitivity to proton FSI (magenta and blue colors).

CC0π differential cross section in transverse variables

Definition of transverse (wrt neutrino flux) variables.



from Xianguo Lu Fermilab Wine and Cheese seminar, March 2, 2018

Transverse kinematics imbalances [XL, L. Pickering, S. Dolan et al., Phys.Rev. C94 (2016) no.1, 015503]

$\delta\phi_T$ presented in Tammy Walton et al. [MINERvA] PRD 91 071301 (2015)

CC0π differential cross section in transverse variables (STV)

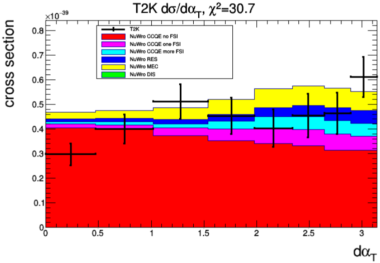
T2K selection:

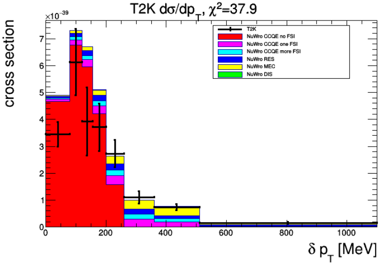
- CC0π
- muon momentum > 250 MeV/c
- cosine of muon angle > -0.6
- leading proton momentum $\in (450, 1000)$ MeV/c
- cosine of leading proton angle > 0.4.

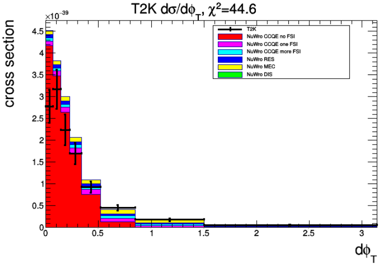
MINERvA selection

- muon momentum $\in (1.5, 10)$ GeV/c
- muon angle ≤ 20 deg
- proton momentum $\in (0.45, 1.2)$ GeV/c
- proton angle ≤ 70 deg.

T2K CC0π STV







- MEC events populate large $\delta\alpha_T$ and δp_T.
- Large δp_T region sensitive to proton FSI, 2p2h, RES.

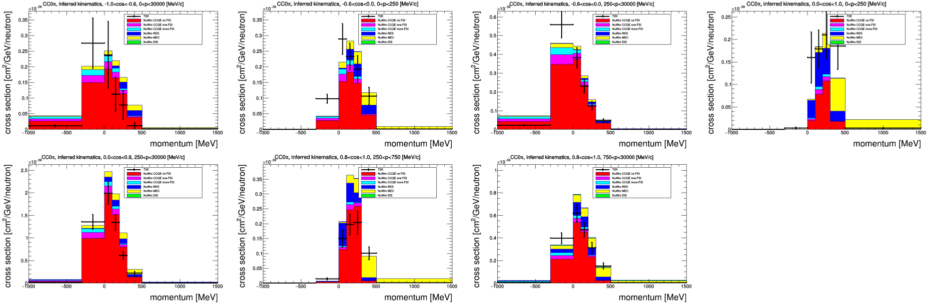
Inferred kinematics

1. Final state muon is measured
2. Assuming that target nucleon was at rest and reaction was CCQE one reconstructs neutrino energy.
3. Using energy and momentum conservation and neglecting FSI one reconstructs final state proton momentum $\vec{p}_{measured}$
4. Final state proton is measured with momentum $\vec{p}_{measured}$.

Three observables are defined:

$$\Delta p_p \equiv |\vec{p}_{measured}| - |\vec{p}_{inferred}|,$$
$$\Delta\theta_p \equiv \theta_{measured} - \theta_{inferred},$$
$$|\Delta p_p| \equiv |\vec{p}_{measured} - \vec{p}_{inferred}|.$$

Inferred kinematics Δp_p



- Given a complexity of physics, a general agreement is good.
- Some selections are dominated by RES and 2p2h!
- Some bins (large Δp_p) are dominated by 2p2h!
  - Details like proton angular distribution after rescattering may play a role.

MINERvA transverse variables (very recent results!)

Xianguo Lu "Wine and Cheese" seminar, Fermilab, March 2, 2018.

Reconstructed neutron momentum variable proposed in A. Furmanski, JTS, PRC (2017) 065501

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

It is not a shadow variable :(...

The main message from the PRC95 paper: reconstructed neutron momentum can be used to select a high purity CCQE sample of events by imposing a cut $p_n <\sim 200$ MeV/c.

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

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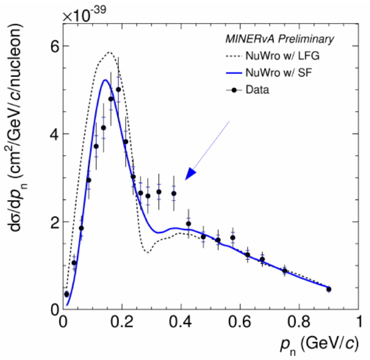
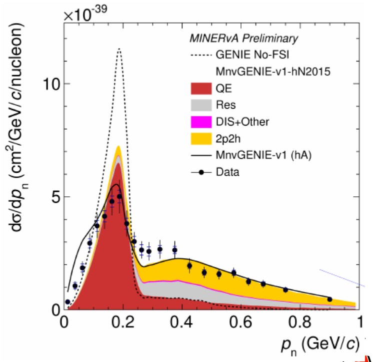
Reconstructed neutron momentum variable A. Furmanski, JTS, PRC (2017) 065501





A nice (almost) two peak structure. The first peak: CCQE, the second one: RES, 2p2h, FSI.
SF reproduces very well a shape of neutron momentum distribution.
GENIE model is Bodek-Ritchie modification of Fermi gas model.

MINERvA transverse variables (very recent results!)

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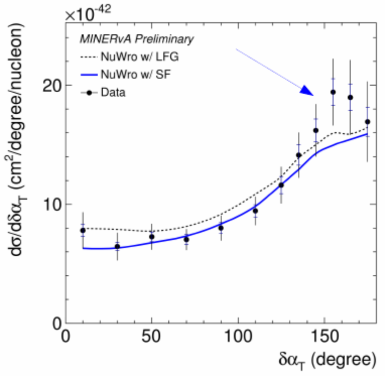
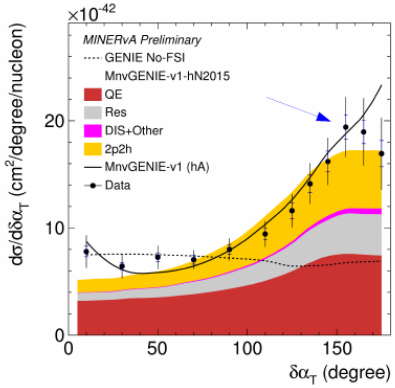




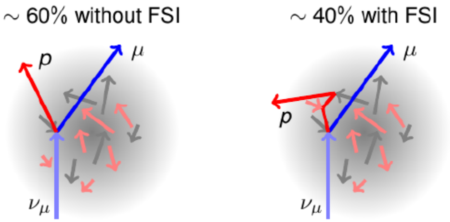
Proton final state interactions.

Nuclear transparency

Definition

Nuclear transparency is the average **probability** for a knocked-out **proton** to **escape** the nucleus **without significant reinteraction.**

e.g. measured for Carbon: $\mathrm{T} \simeq 0.60$ [D. Abbott *et al.*, PRL 80 (1998), 5072]



It is not correct to adopt Monte Carlo definition of transparency (the key word is SIGNIFICANT)

Strategy: reproduce electron scattering experiments.

How it is measured? (1)

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

Exclusive QE proton knockout at **fixed kinematics**:

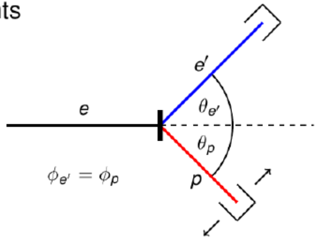
- beam: E_e
- electron: $E_{e'}$, $\theta_{e'}$, $\phi_{e'}$
- proton: E_p, θ_p, ϕ_p

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

Cuts on "missing" variables:

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

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



Transparency:

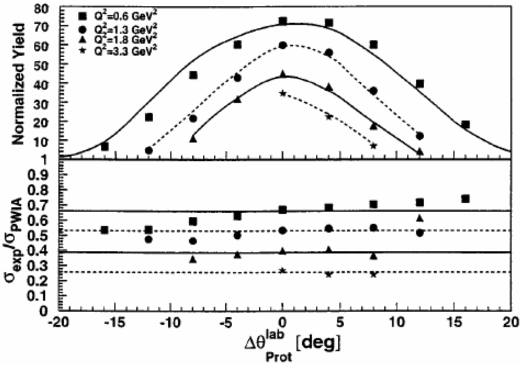
$$\langle T \rangle_{\theta_p} = \frac{\sigma_{\rm exp}}{\sigma_{\rm PWIA}} \frac{1}{c_A}$$

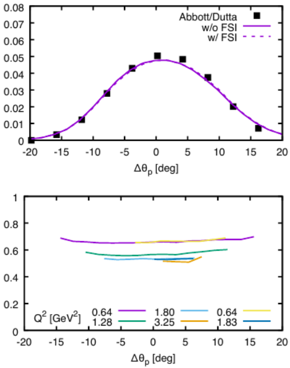
$\sigma_{\rm PWIA}$ - expected value without FSI (model dependent)

c_A - spectroscopic factor

There has been a lot of debate on c_A.

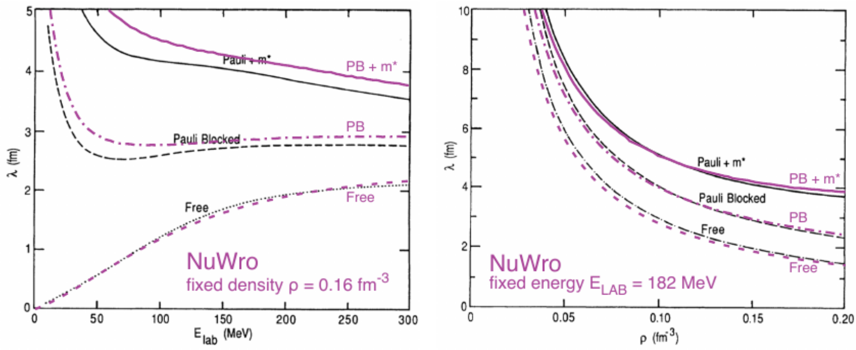
How it is measured? (2)





The shapes on the top are measured/obtained in MC simulation.
Normalization (scaling factor) defines transparency.

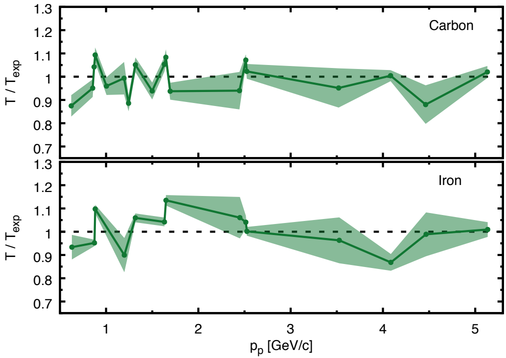
NuWro nucleon-nucleon in-medium cross sections



Pandharipande-Pieper in-medium cross sections are implemented.

Pandharipande, Pieper, Phys.Rev. C45 (1992) 791

Final comparison to the data



Experimental points do not contain shell model "correction factors":

Frankfurt, Strikman, Zhalov, PLB 503 (2001) 73

Dutta, Hafidi, Strikman, Prog. Part. Nucl. Phys. 69 (2013) 1

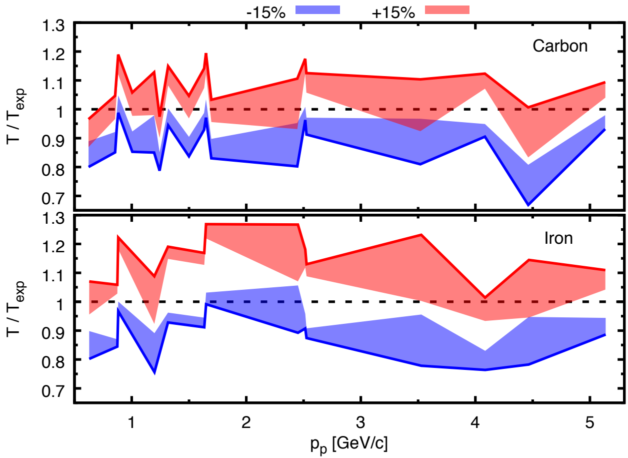
Hen et al [CLAS], PLB 722 (2013) 63

Lava, Martinez et al, PLB 595 (2004) 177

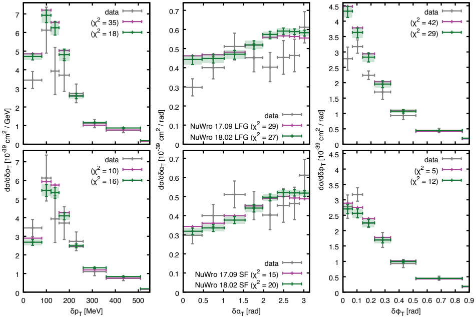
Cosyn, Ryckebusch, PRC87 (2013) 064608.

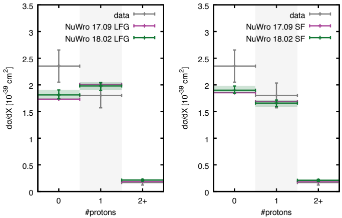
Shadow region is experimental uncertainty.

Estimation of FSI uncertainty in NuWro



Impact on proton observables T2K, arXiv:1802.05078 [hep-ex]





- SF is doing better job.
- Uncertainty is small enough to study other nuclear effects.

Conclusions

- A lot of experimental data from T2K and MINERvA to study 2p2h dynamics.
- Two kind of data:
  - $CC0\pi$ (only muon is observed)
  - Both muon and proton are observed.
- What we would like to know?
  - Does Nieves et al (or Martini) model need a data based enhancement?
  - How is energy and momentum transfer shared among both nucleons?