Neutrino-nucleus scattering: experiment overview

Daniel Ruterbories

INT Workshop 18-2a

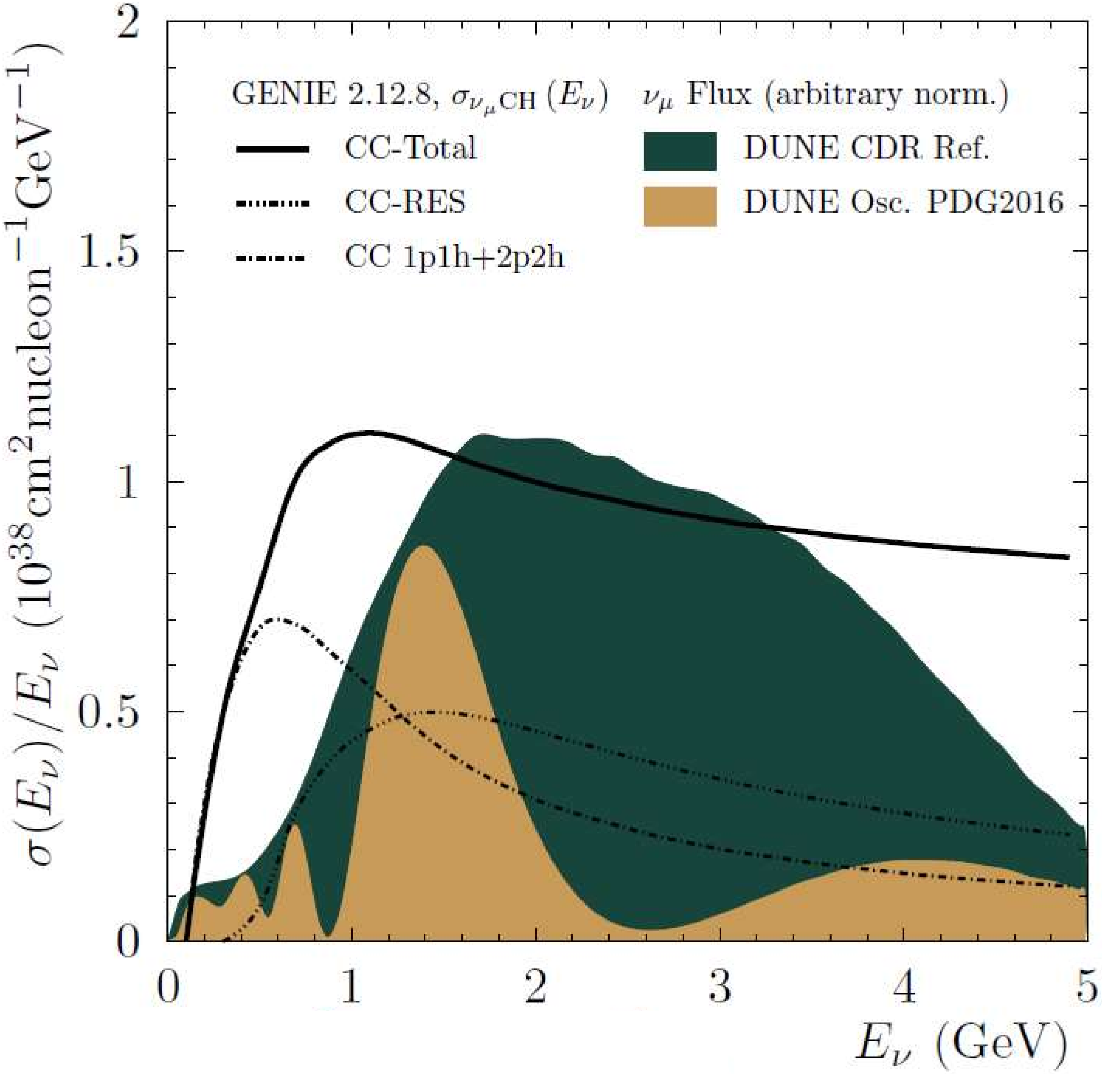
June 25th, 2018

UNIVERSITY of ROCHESTER

Roadmap

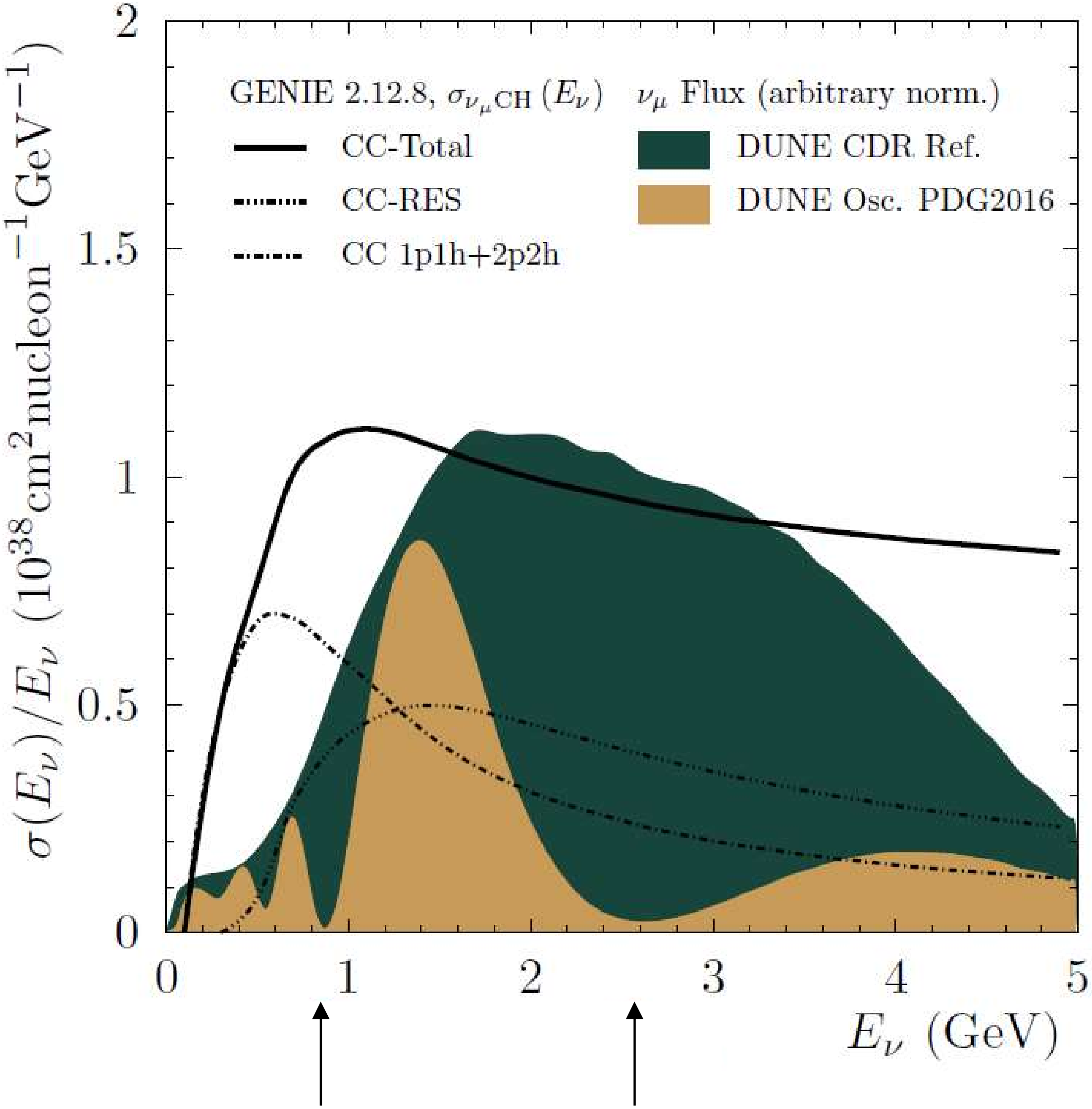
- Experimental setups
- General neutrino-nucleus scattering problems
- Experimental results
- An example of cross experiment discussion

All starts with oscillations



Credit: L. Pickering

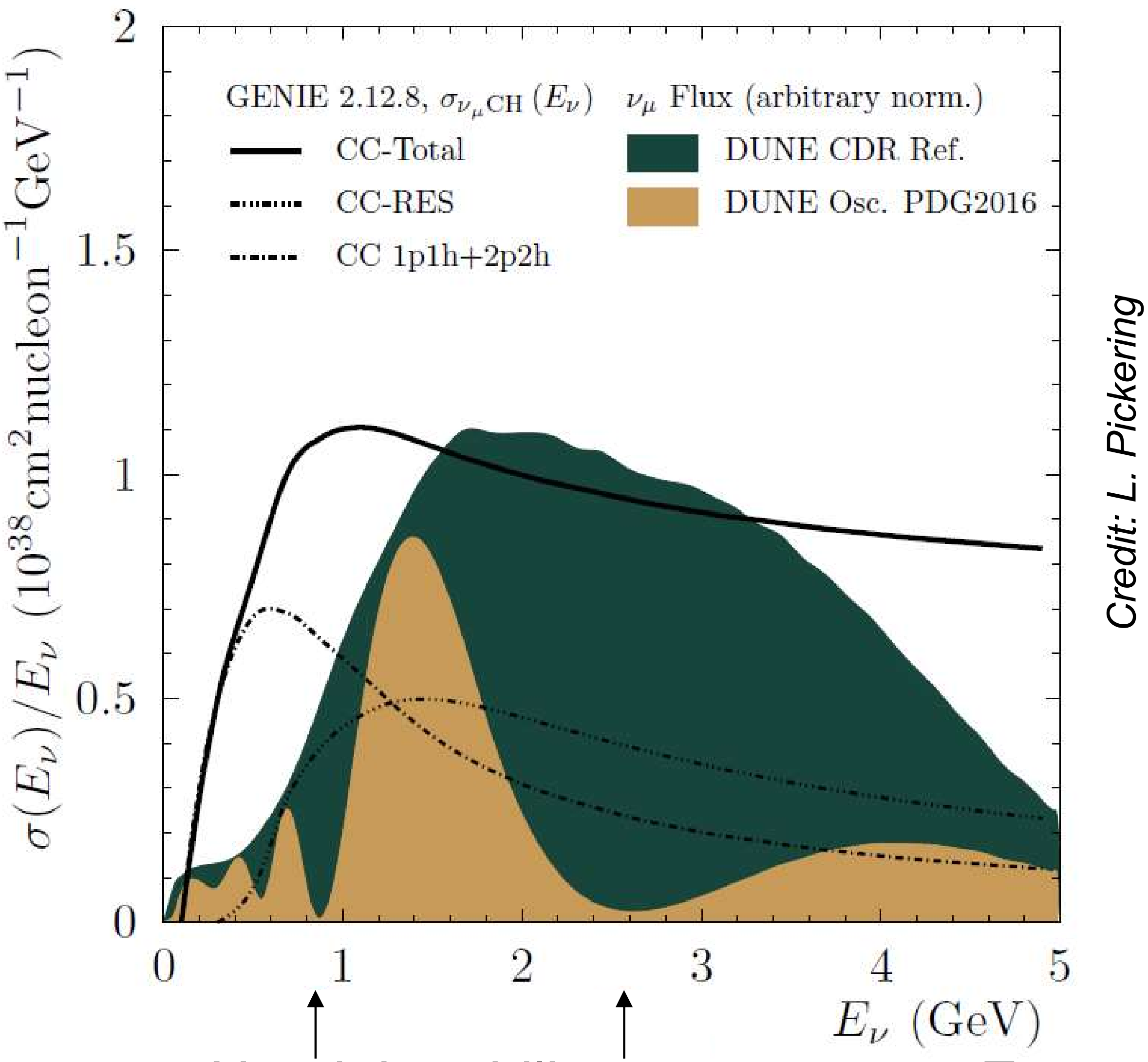
All starts with oscillations



Credit: L. Pickering

Very Interesting regions

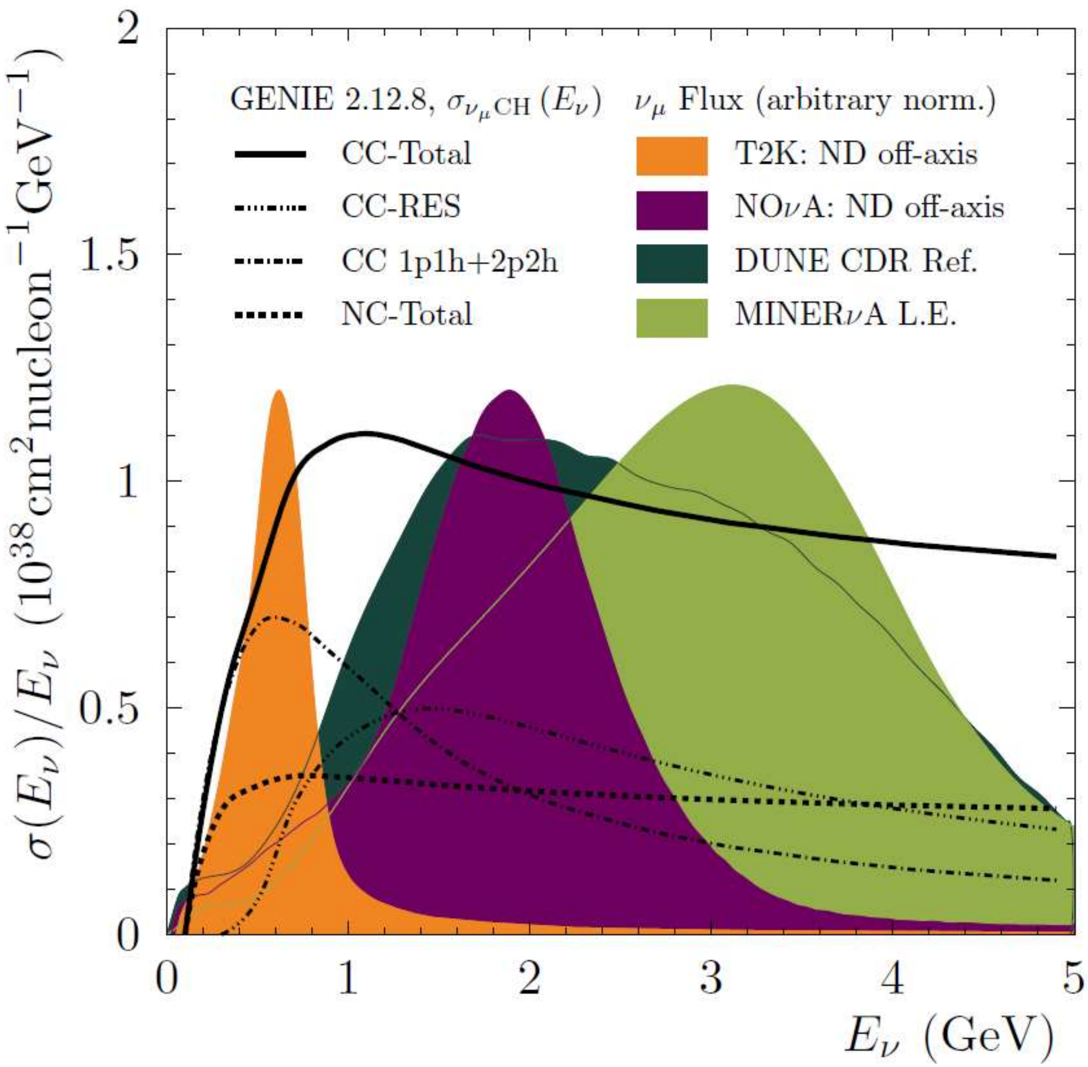
All starts with oscillations



Need the ability to reconstruct E_ν

Or correctly simulate our inability to do so

Global Effort

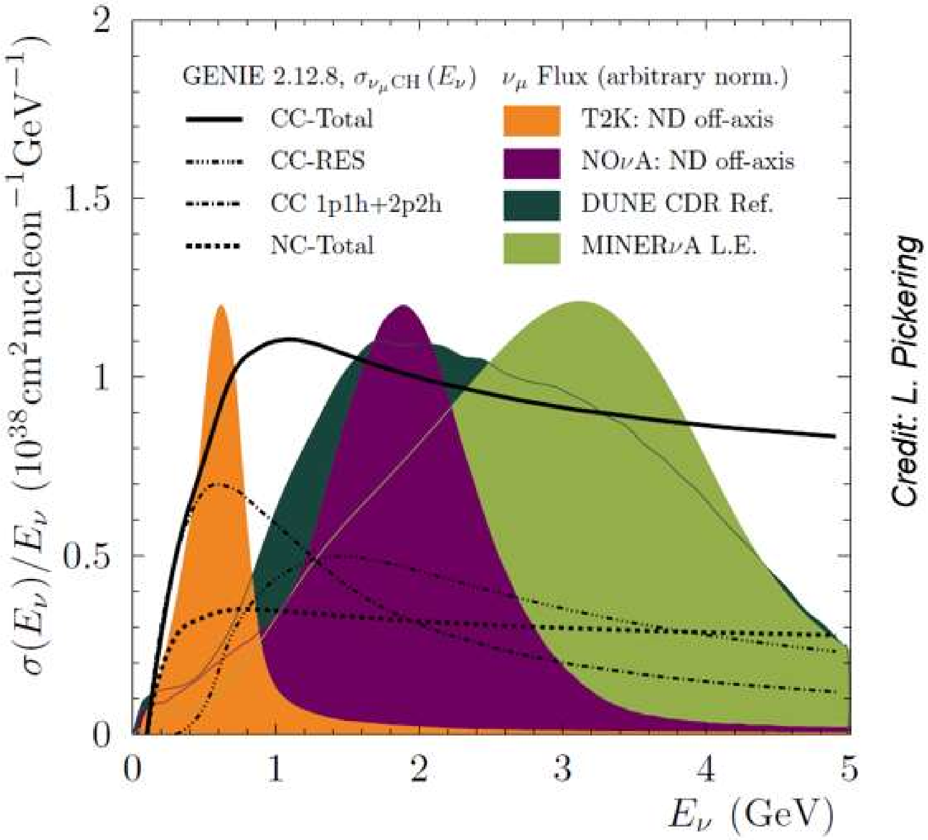


Credit: L. Pickering

MiniBooNE/MicroBooNE ~0.8

T2K on-axis ~1.2

Global Effort

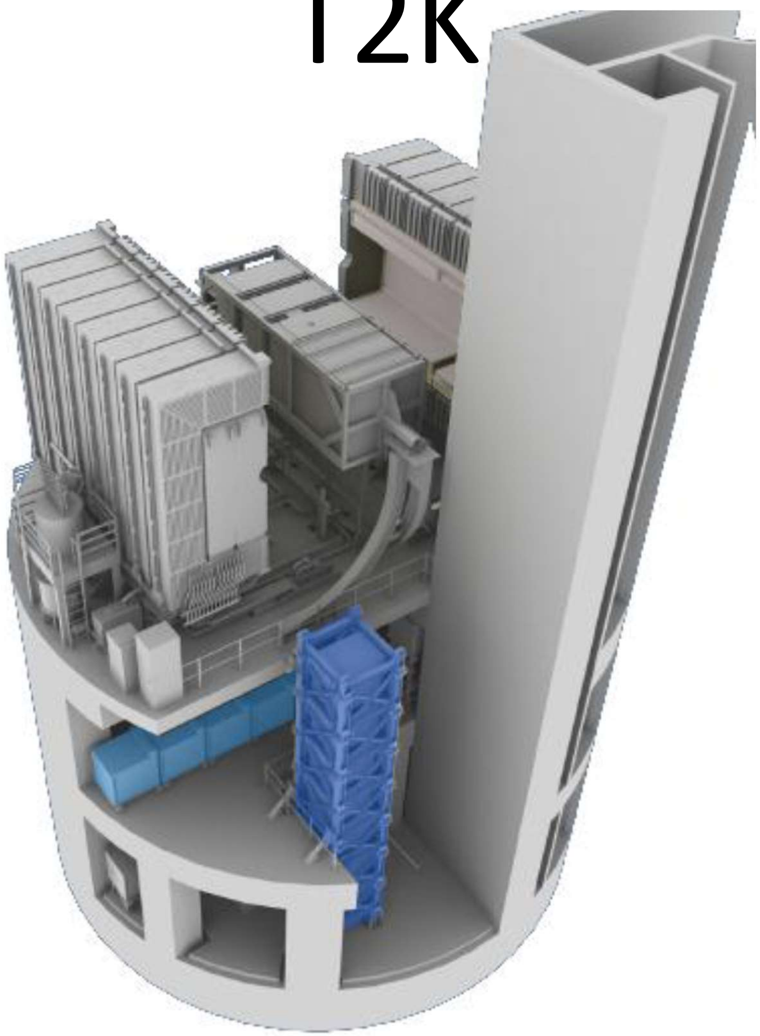


MiniBooNE/MicroBooNE ~0.8
T2K on-axis ~1.2

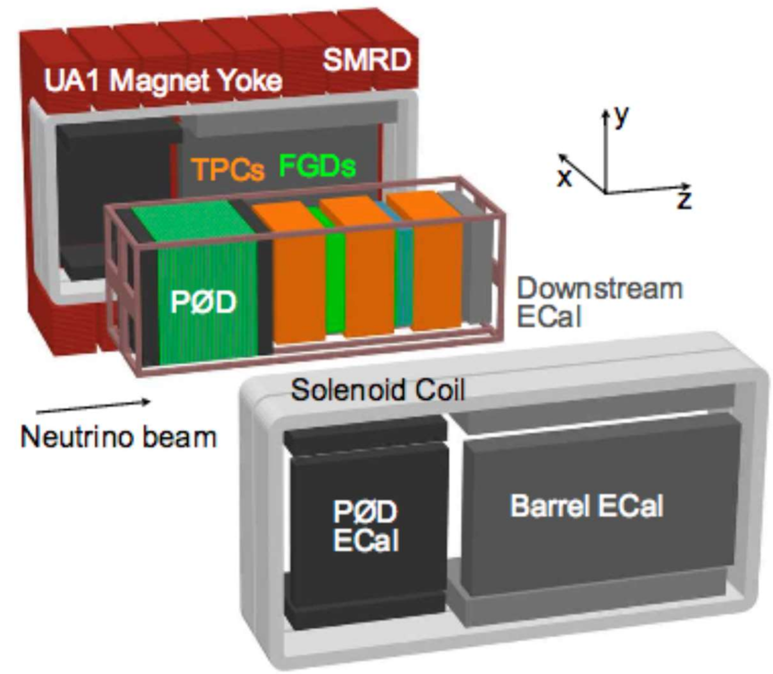
- Multiple processes with different thresholds and effects on reconstruction/detector response
- Multiple detectors with different capabilities
- Span the future oscillation program energy span (DUNE+HK)
- Critical we as a community constrain and improve modeling of this complex and rich region of neutrino-nucleus scattering

Experimental Setups

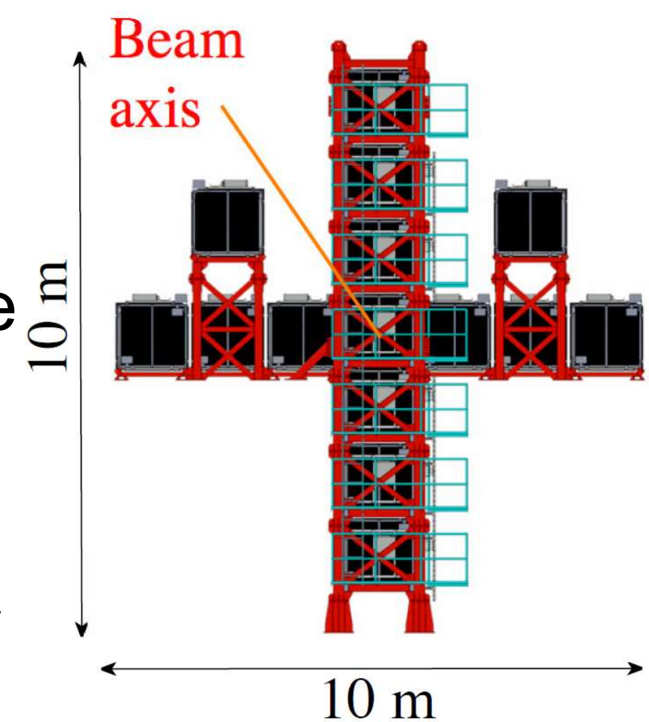
T2K



2.5 deg.
Off-axis

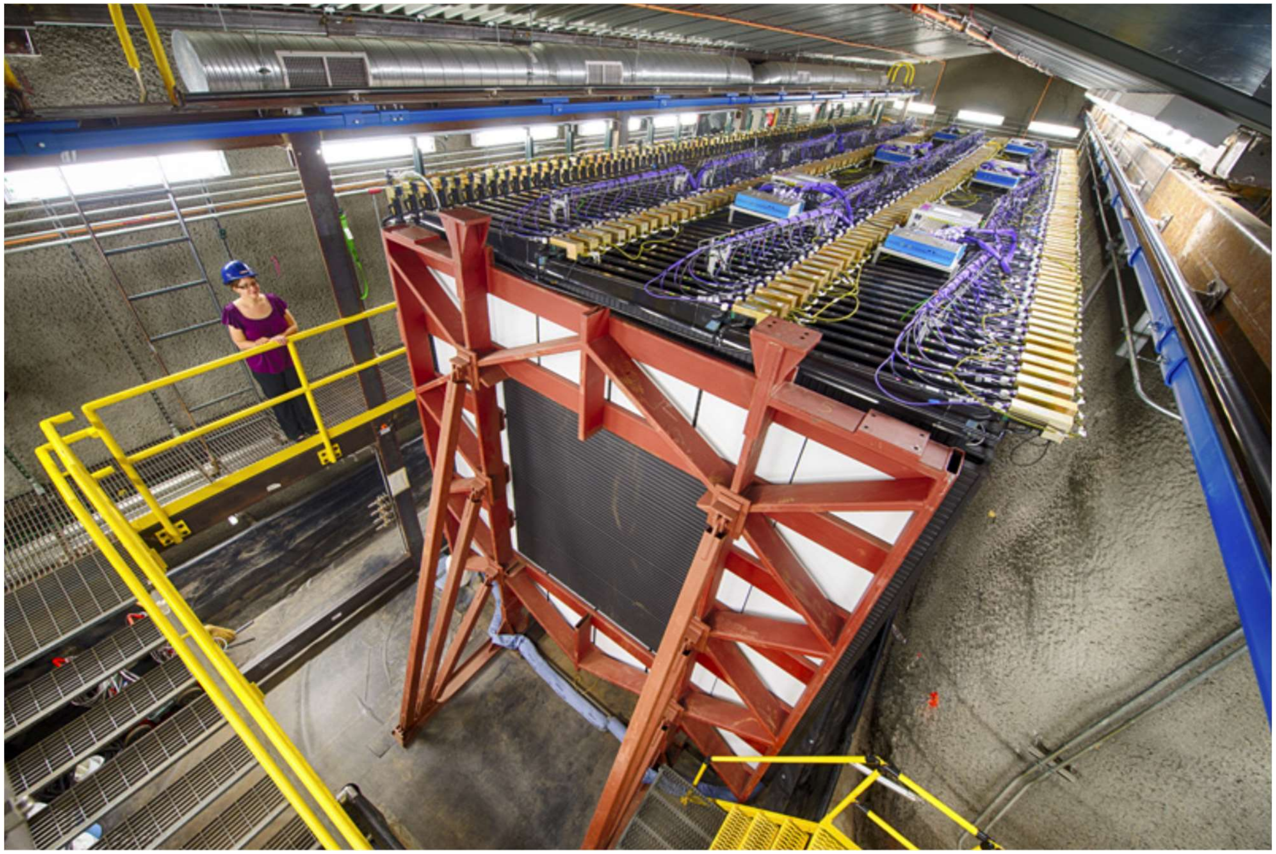


On-axis
0-1.1 deg.
acceptance



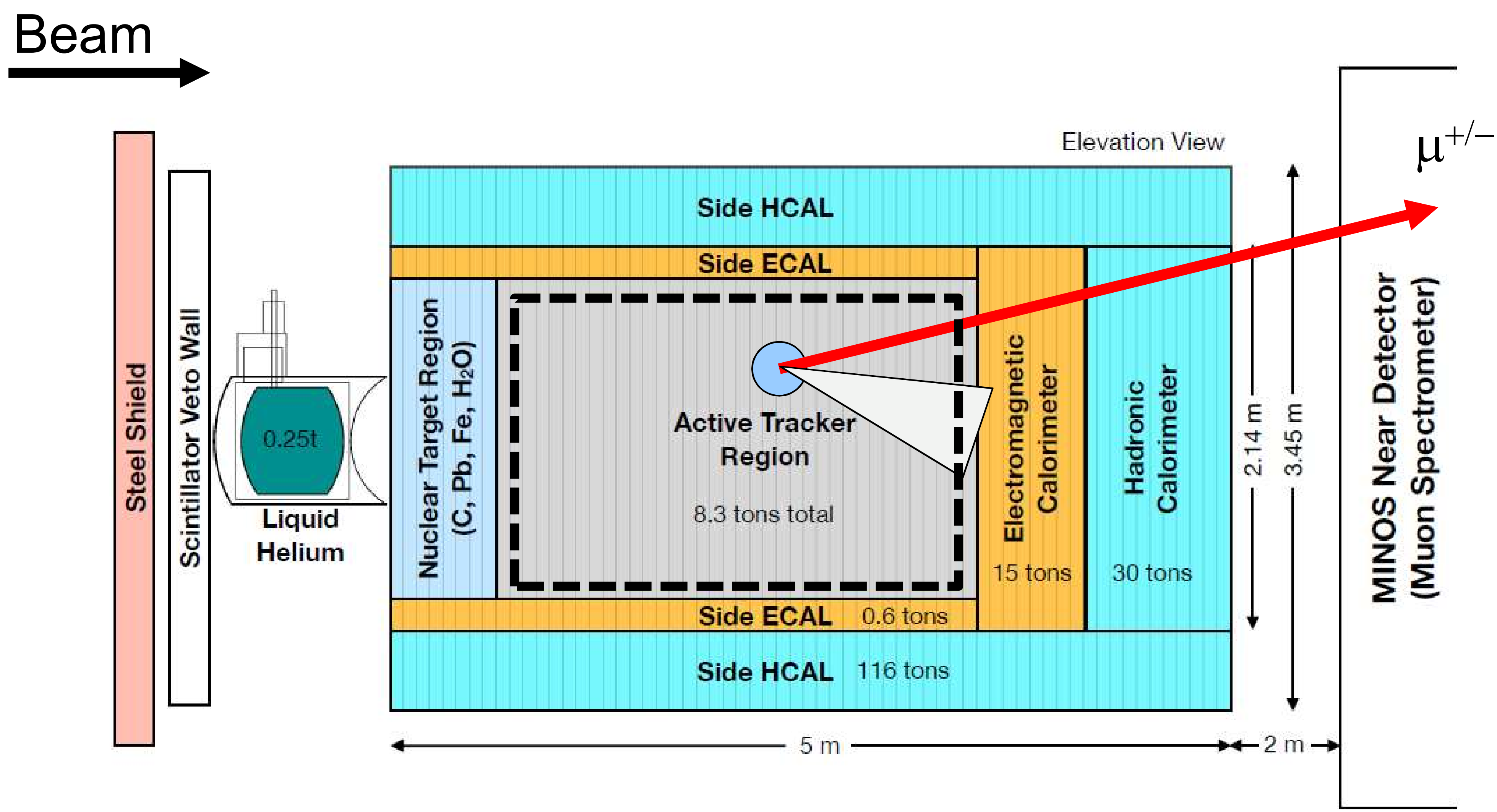
- Fine grained, small target mass
- P0D several tons with water
- FGD ~1 ton, second FGD has water
- INGRID module ~7 tons

NOvA



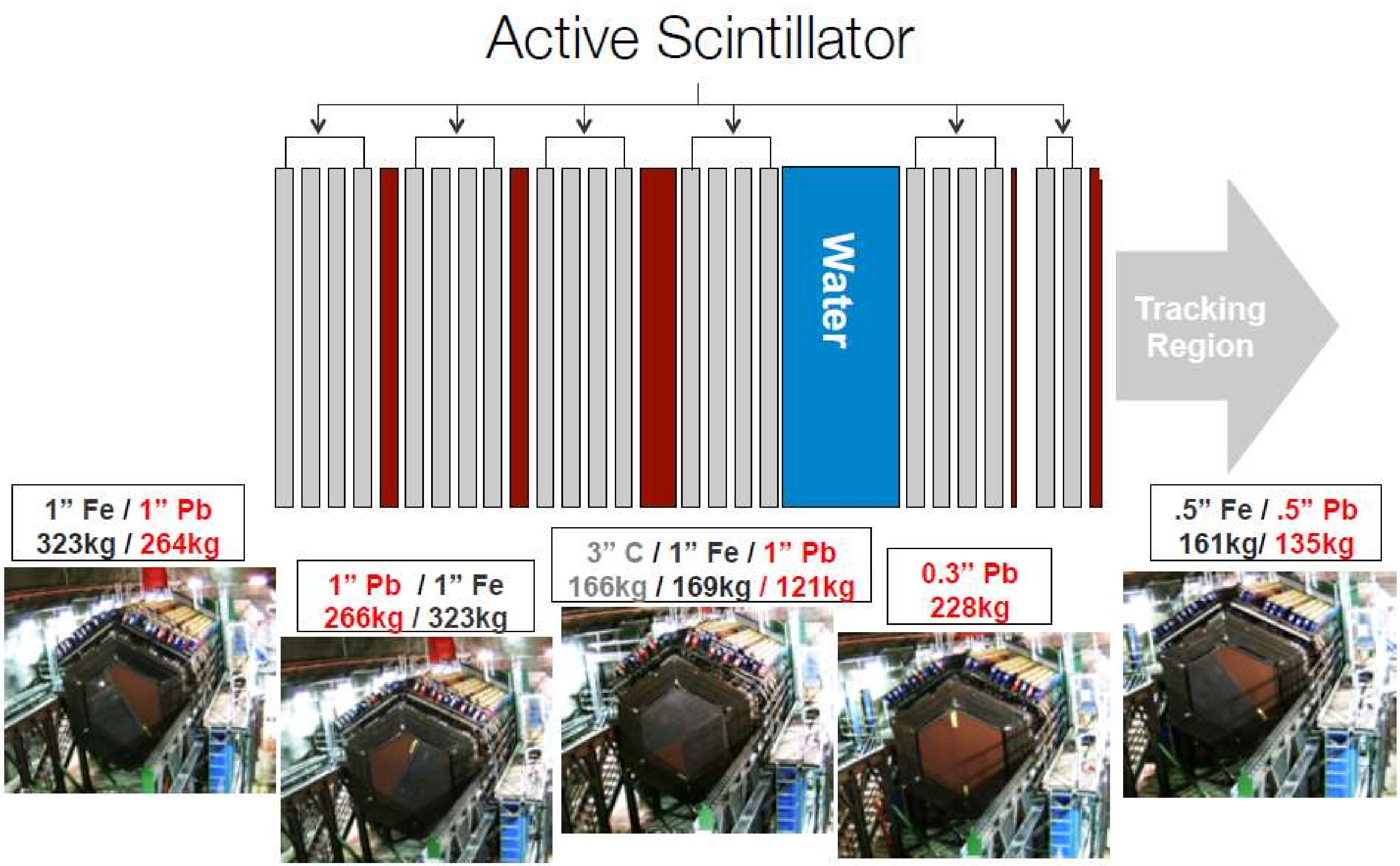
- 14mrad off-axis
- Coarser grained but massive!
- 193 tons fully active mass with a 97 ton muon catcher

The MINERvA Detector



- Moderate target mass, moderate granularity
- Nuclear targets in same detector/beam for A-dependent measurements

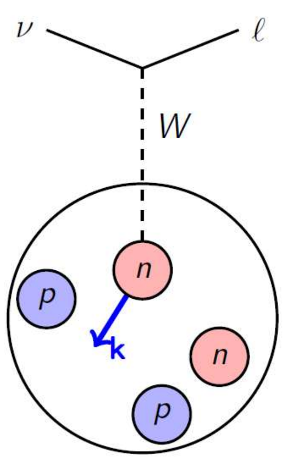
Nuclear Target Region

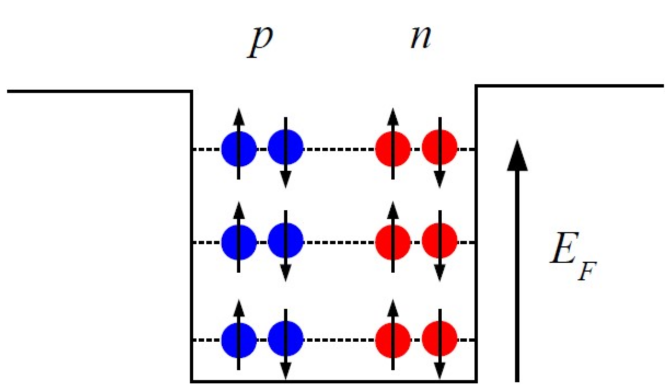


The Nucleus Is Complicated

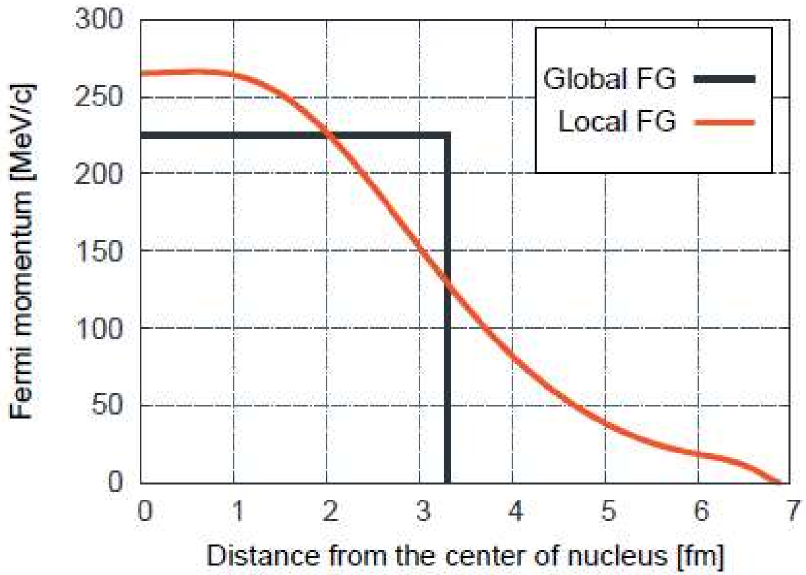
Nucleons are not free and independent particles!

- Bound and definitely not independent from their fellow nucleons
- So what… we (often) simulate the nucleons as a **R**elativistic **F**ermi **G**as (RFG)
  - Quasi-free nucleons in a mean field
  - Includes Fermi motion, binding energy, Pauli Blocking

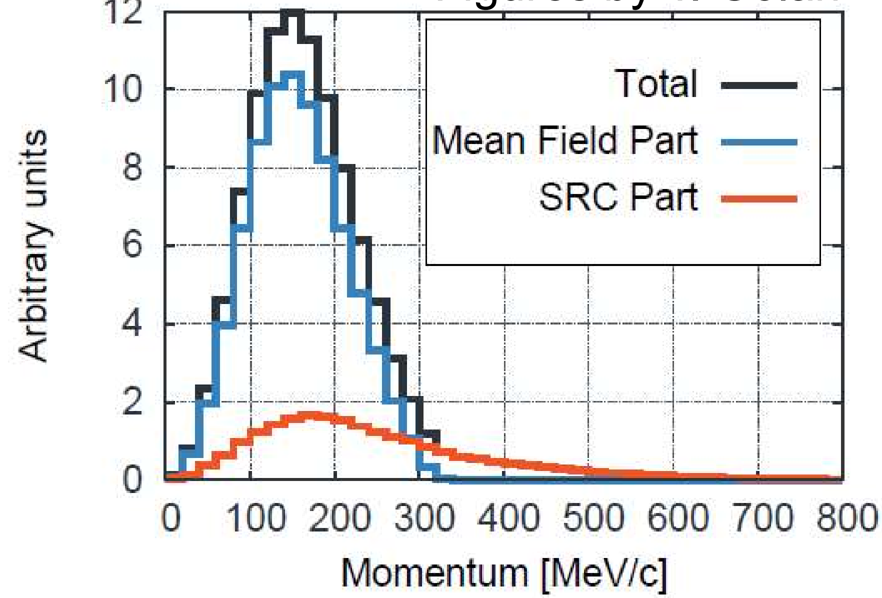


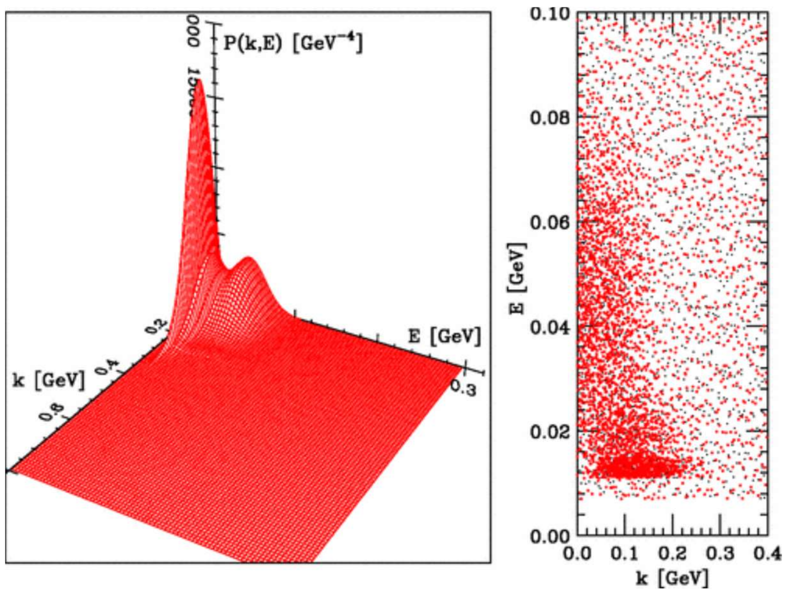


Not just GFG… LFG, SF

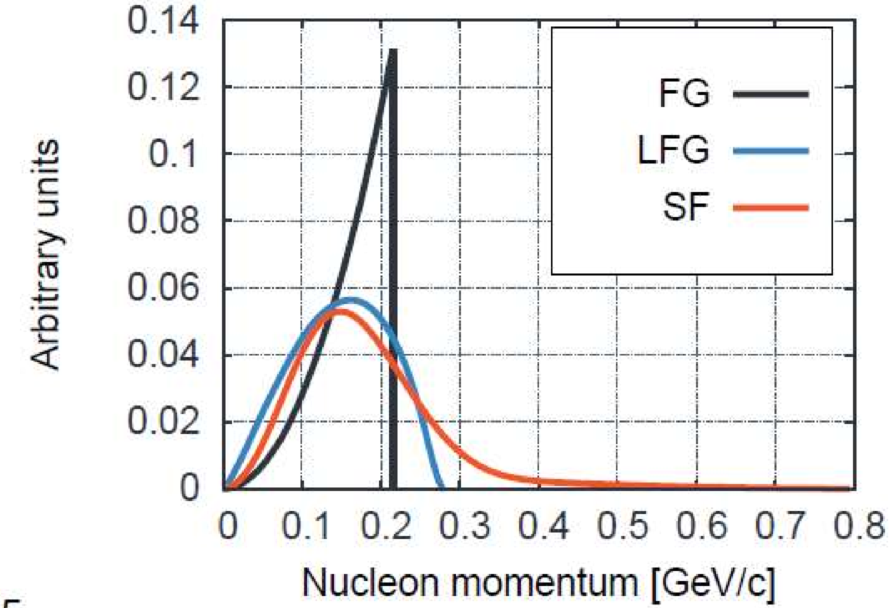


Figures by T. Golan



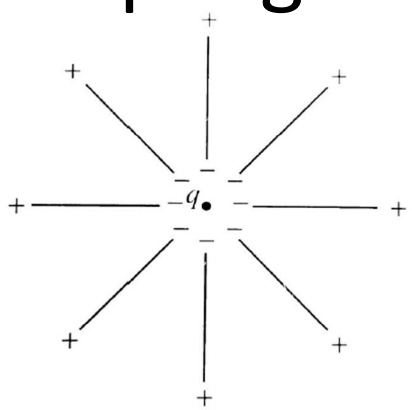


O. Benhar et al., Phys.Rev. D72 (2005) 053005

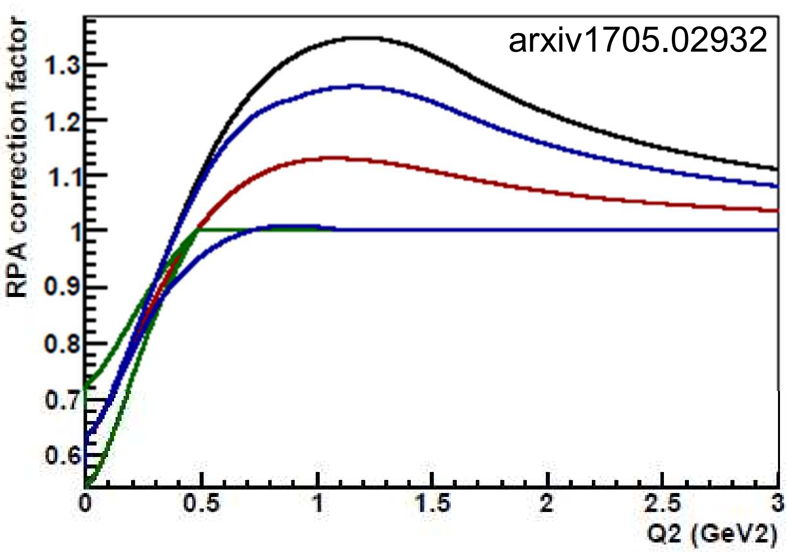


Nuclear Screening

- Polarization of the nucleus screens electroweak coupling of the W



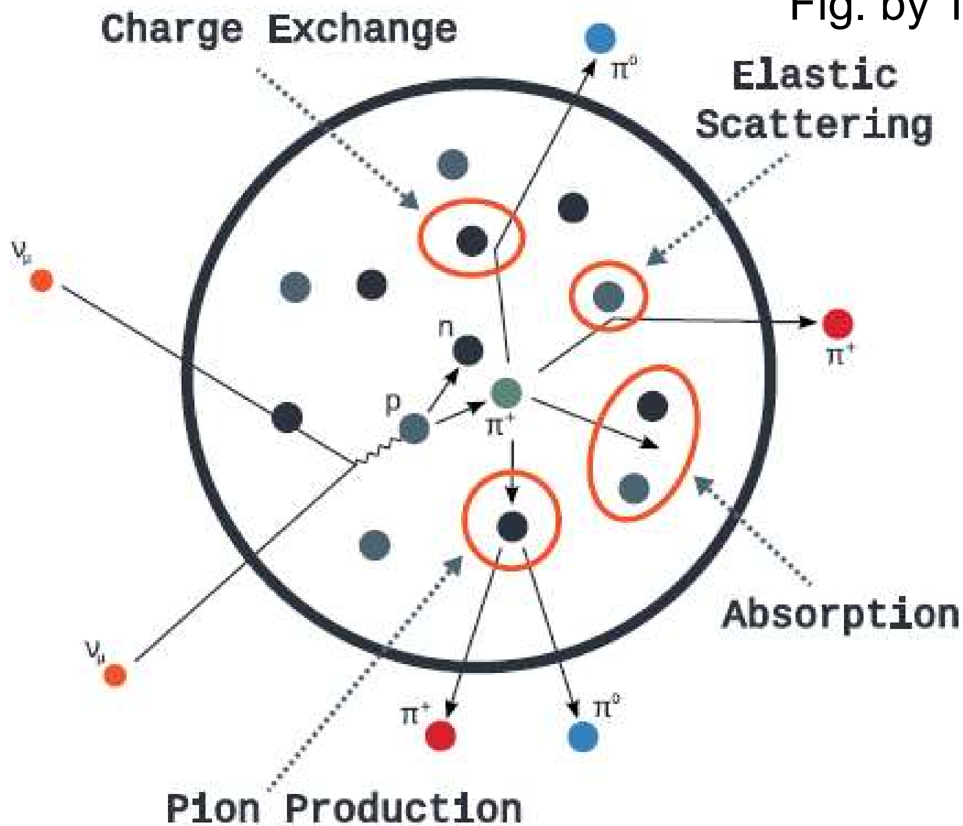
Griffiths, *Introduction to Electrodynamics*



- A common analogy is screening of electric charge in a dielectric
- Calculated using **R**andom **P**hase **A**pproximation (RPA)
- Effect on cross section: Suppression at low four momentum transfer Q^2

Final State Interactions

Fig. by T. Golan



- Signal <–> Background migrations
- Energy sharing between pions and nucleons
- Particles in the detector, and thus energy deposited, is modified

What do we measure?

- Typically (always?) flux averaged
- So-called fiducial cross section
  - Restrict phase space to what your detector/analysis can measure
- Only based on particles in the detector – what survives the FSI
- Measured variables (should) be created by kinematics of visible particles pre-FSI
  - Q^2_{QE} is an example – based on lepton(or proton) post-FSI kinematics

Inclusive Results

T2K – INGRID energy dependence [Phys. Rev. D 93, 072002 (2016)]

T2K – 4π acceptance update[arXiv:1801.05148]

MINERvA – (Anti)Neutrino low recoil analyses

[PRL 120, 221805(2018), PRL 116,071802(2016), Fit paper in prep.]

NOvA – Hadronic visible energy

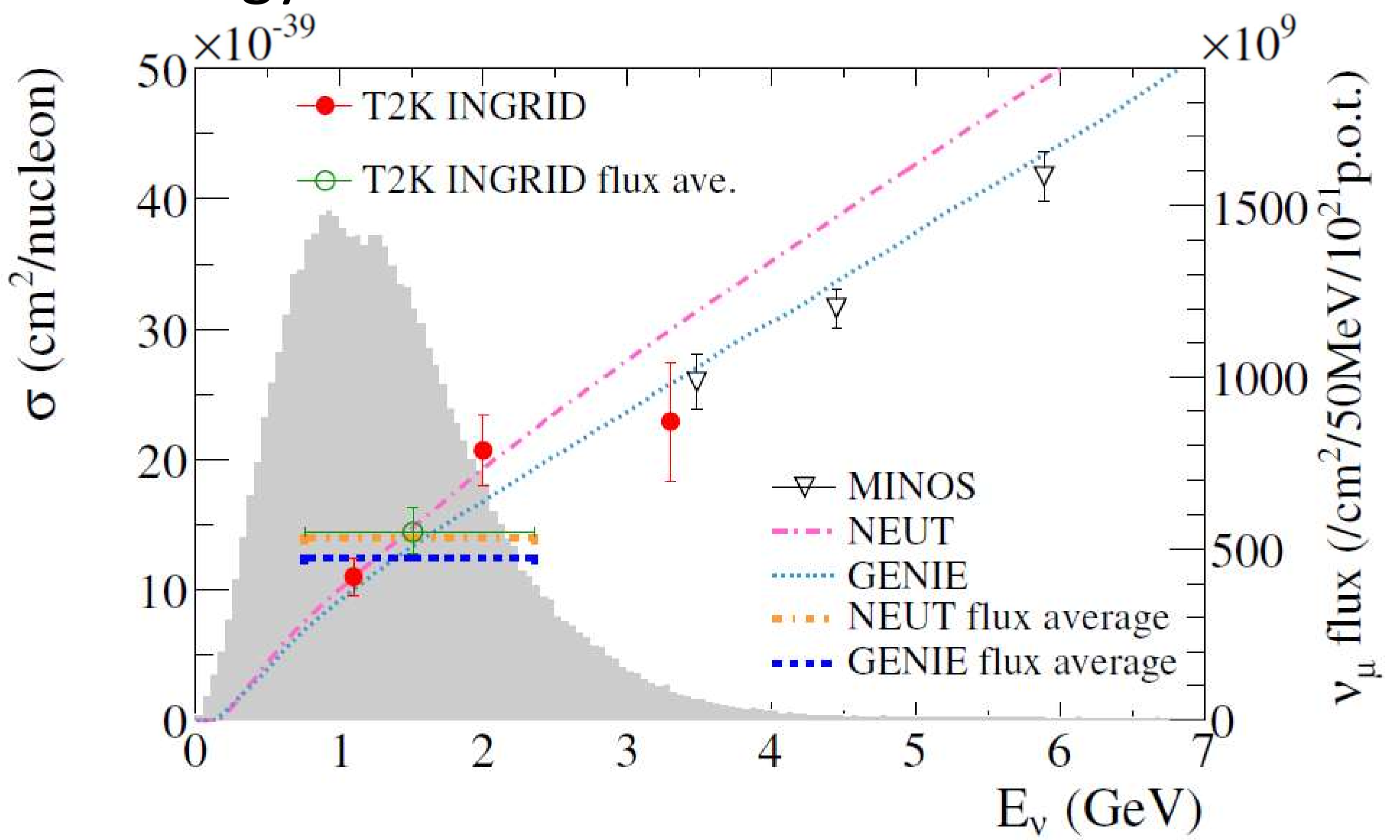
[NEUTRINO 2018, https://doi.org/10.5281/zenodo.1286758]

Extracted with
NEUT 5.1.4.2

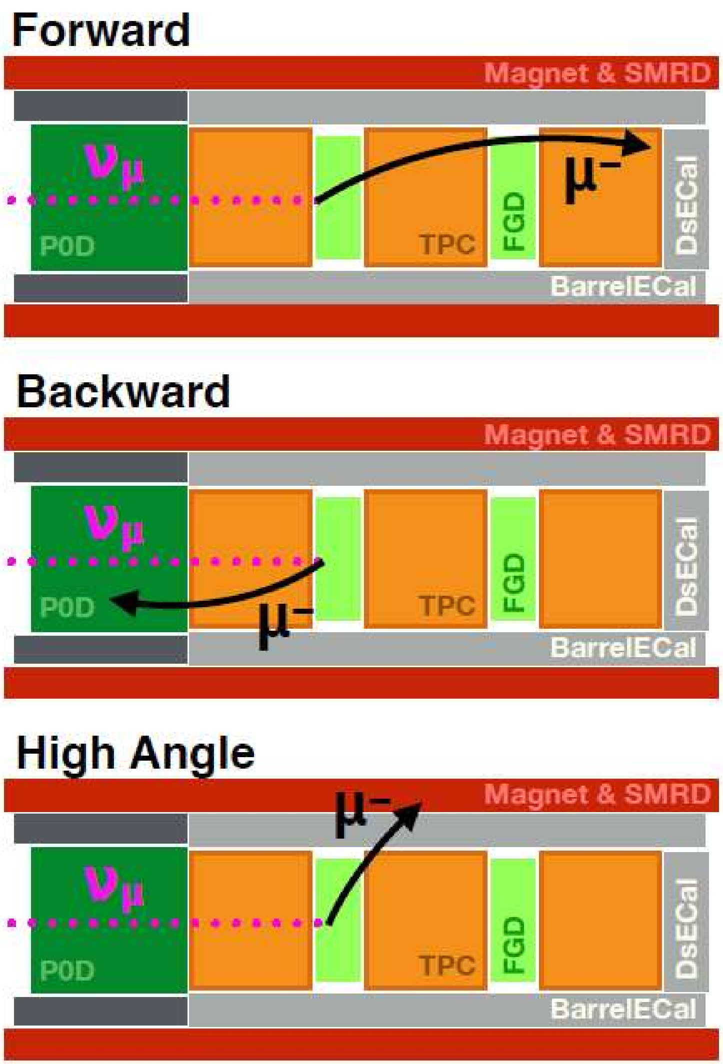
T2K-INGRID

Investigating Energy Dependence

- Uses off axis effect to sample different flux spectra via the spatial distribution of the detector
- Fit data in bins of Z-vertex and module pairs broken down by neutrino energy



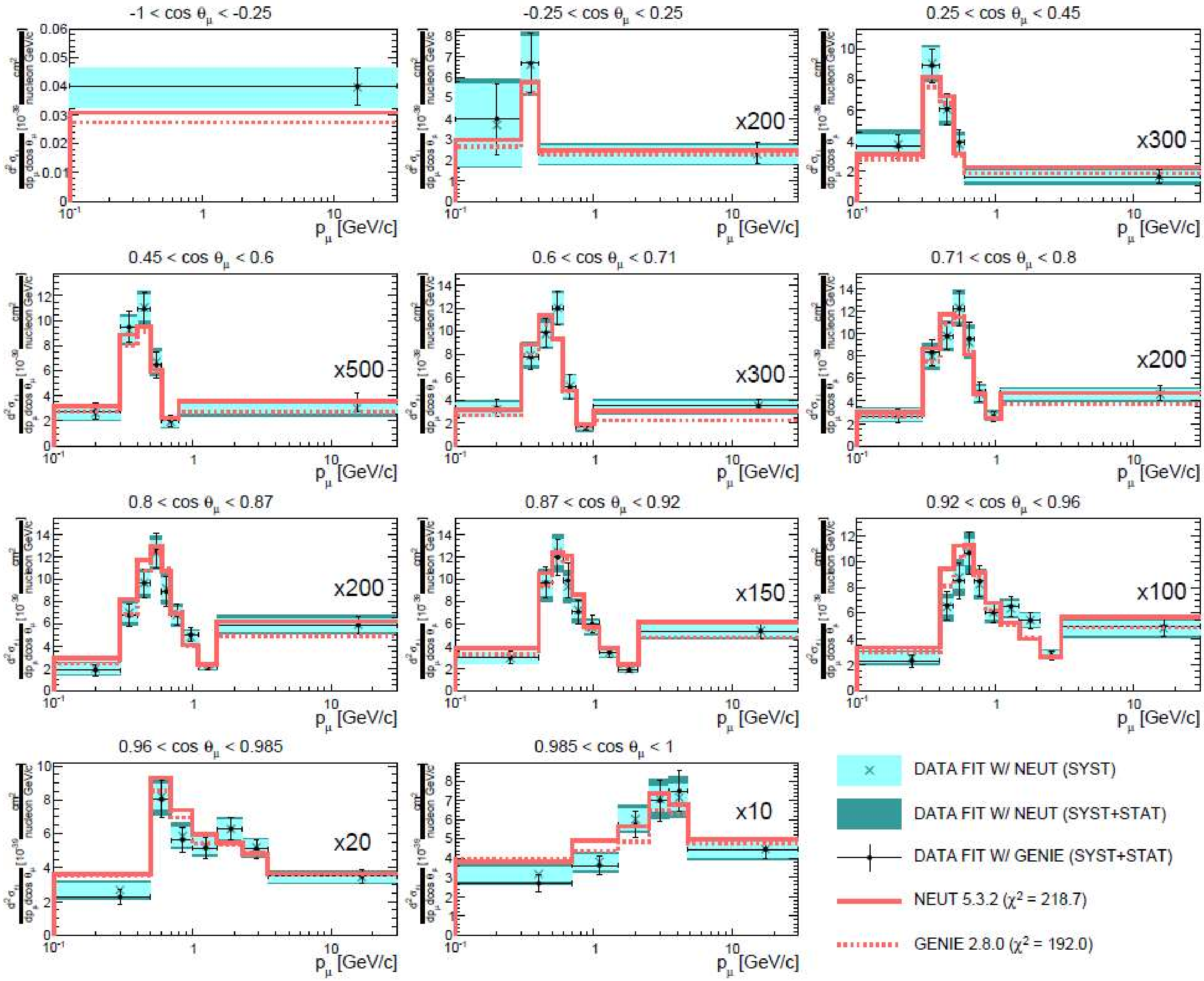
T2K-ND280
4π muon kinematics



- Improved acceptance
  - Used in future samples!
- Larger dataset
- Updated generators
- Extraction done with both
  - NEUT 5.3.2
  - GENIE 2.8.0
- Dominant uncertainties are typically flux/stat in forward region
  - Model unc. dominant in backwards region

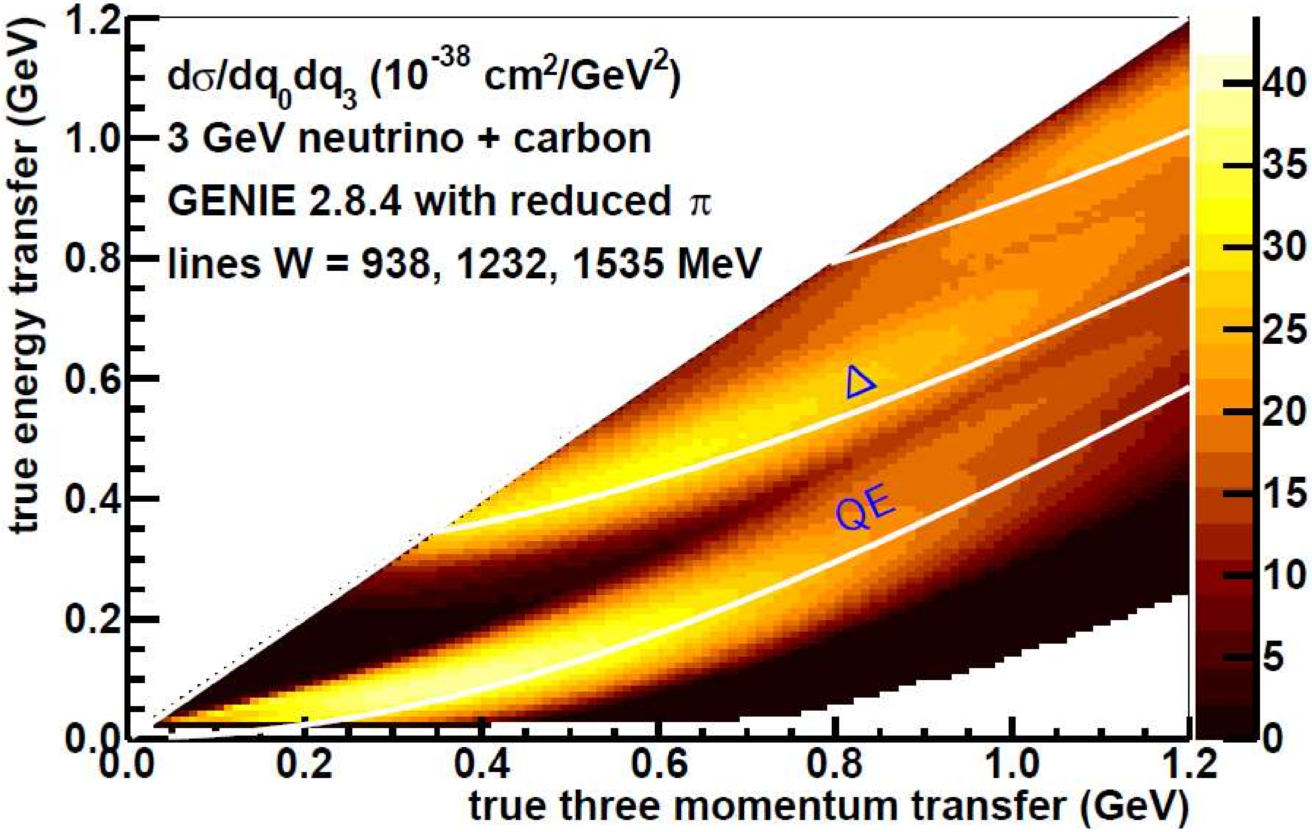
Extracted with
NEUT 5.3.2
GENIE 2.8.0

T2K-ND280
4π muon kinematics

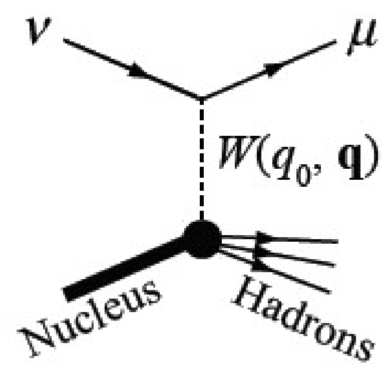


Extracted with Modified GENIE 2.8.4 (Tuned 2p2h, RPA (QE), non-resonant 1π reduction)

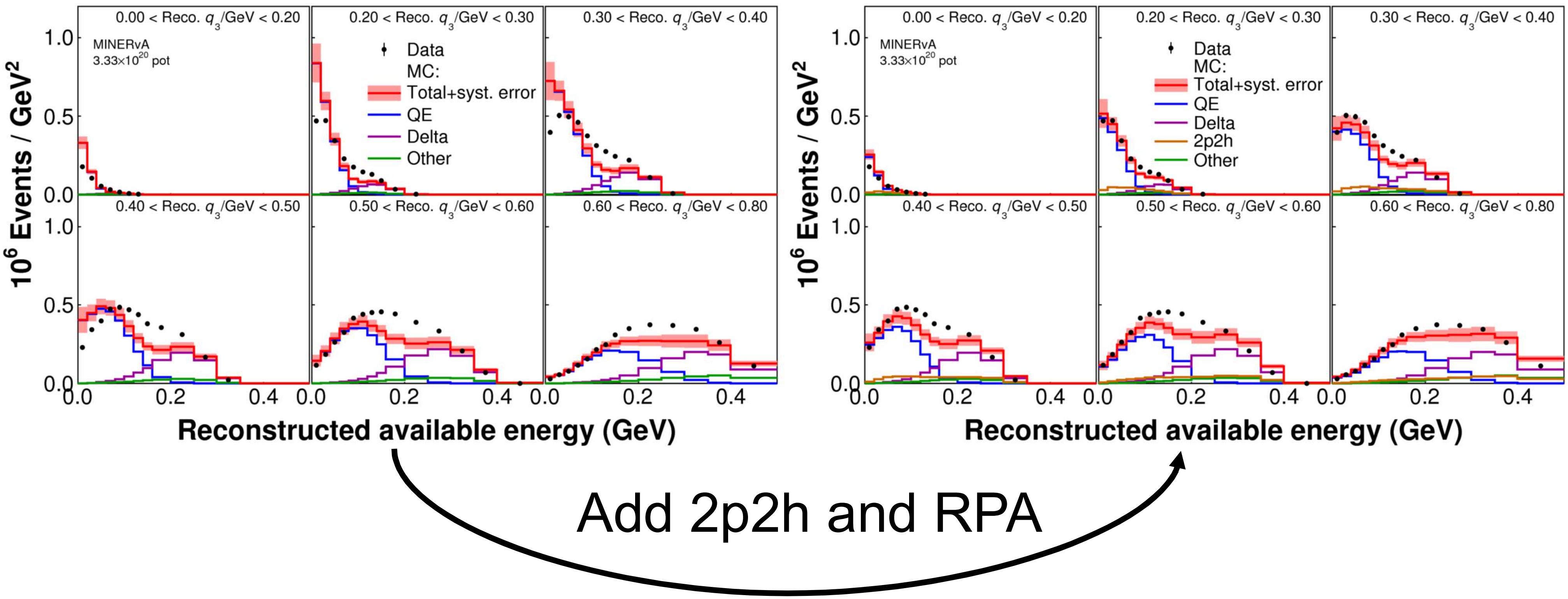
MINERvA Low Recoil Inclusive



- Same basis as theorists
- Accessible with a calorimetric detector



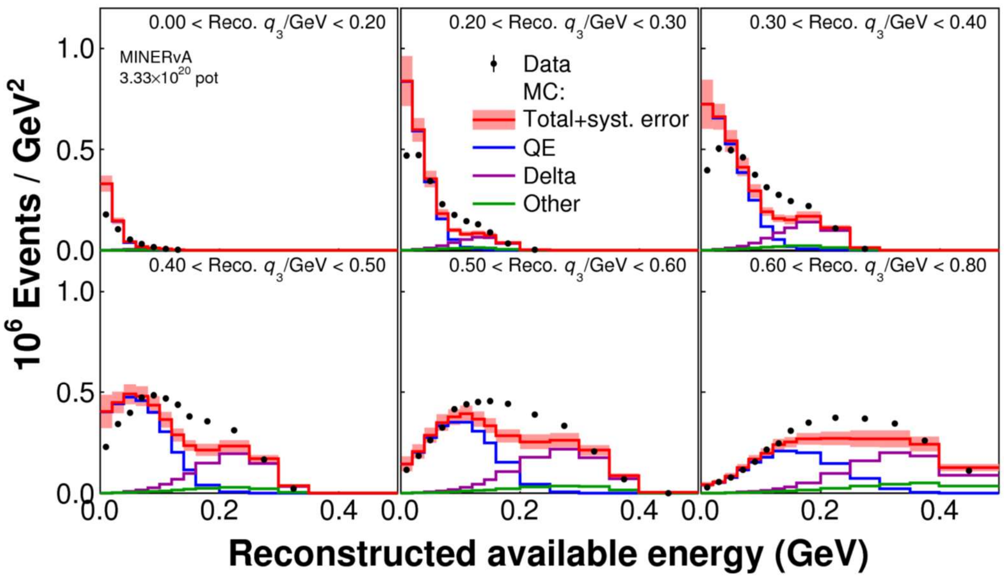
Inclusive low recoil

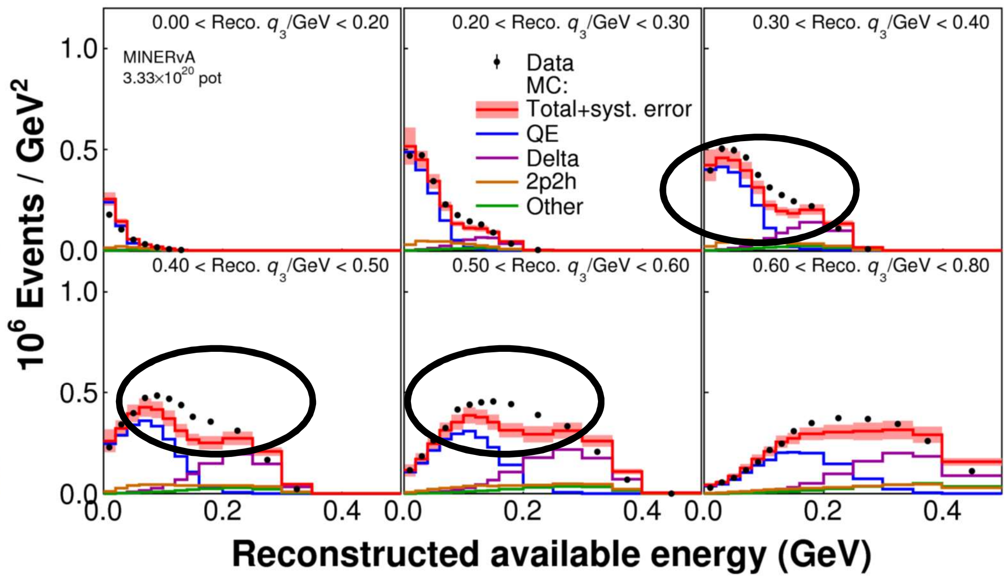


Clearly shows marked improvement when adding 2p2h and RPA

2p2h model used [PRC 83, 045501(2001),PRD 88, 113007(2013)]
RPA is application of the Valencia group via work by R.Gran (MINERvA) [https://arxiv.org/abs/1705.02932]

Inclusive low recoil

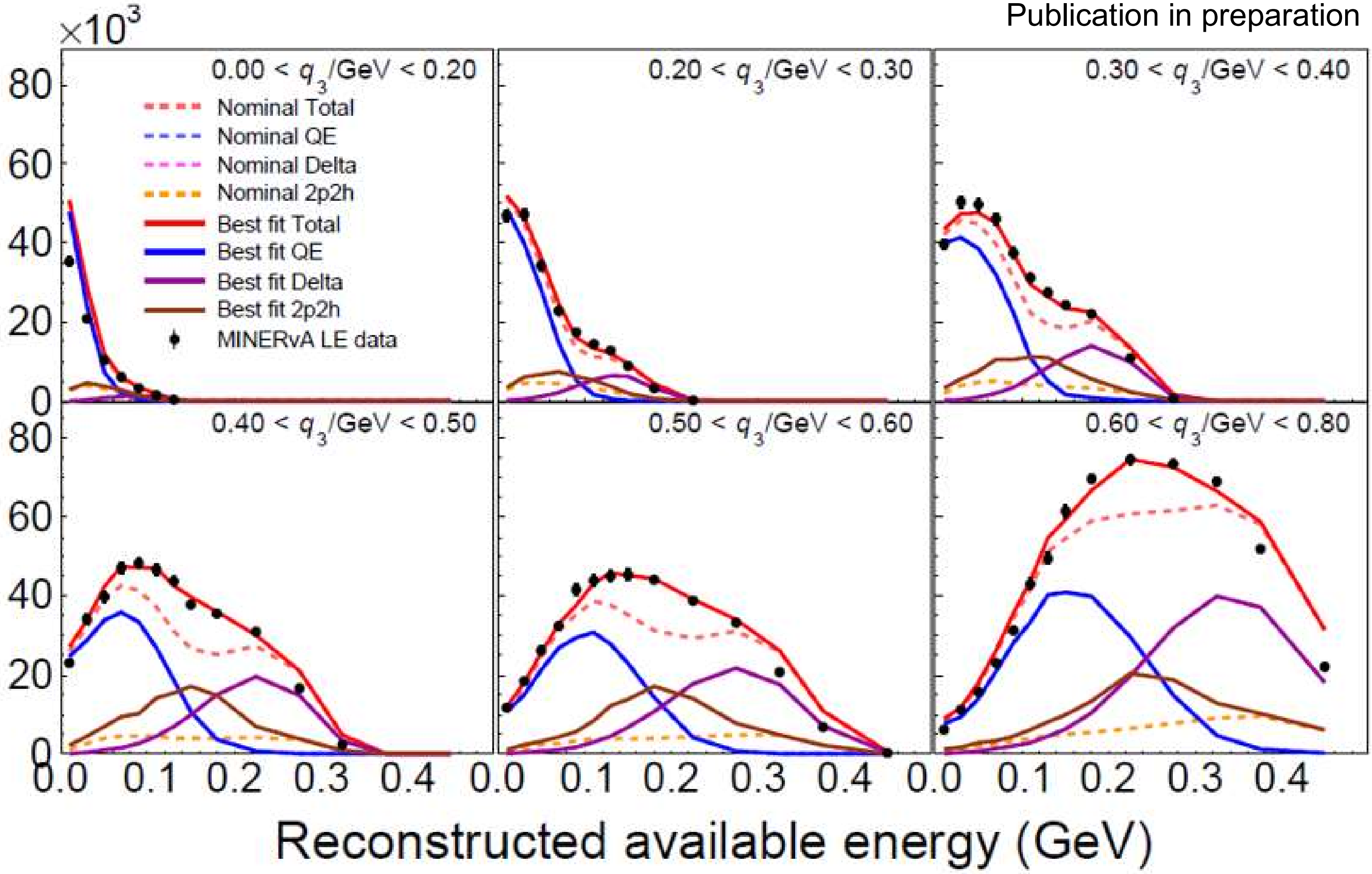




- Latest models available in simulation, but see a data excess at moderate $E_{available}$
- (*new*) Fit a 2D Gaussian in true (q_0,q_3) as a reweighting function to the 2p2h contributions to get the best agreement
  - Does not scale true QE or resonant production.

Inclusive low recoil

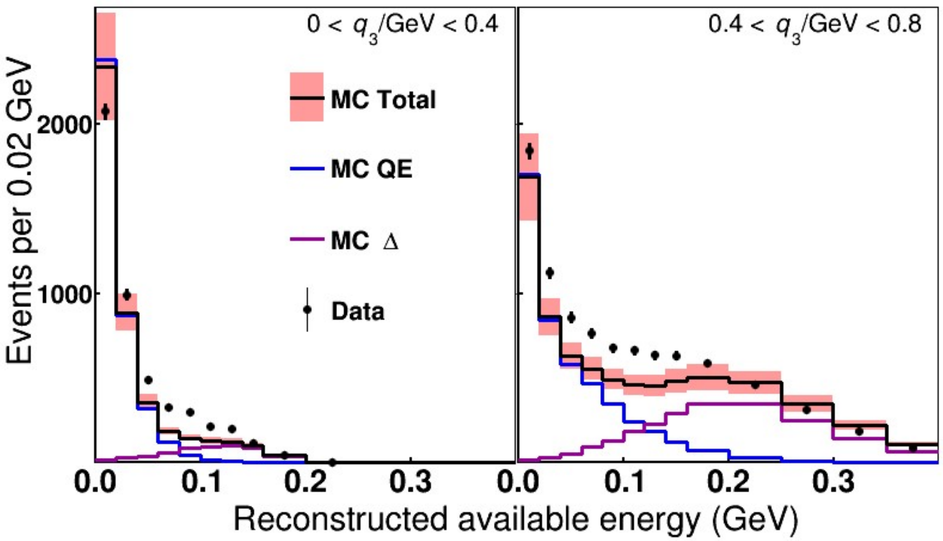
Publication in preparation



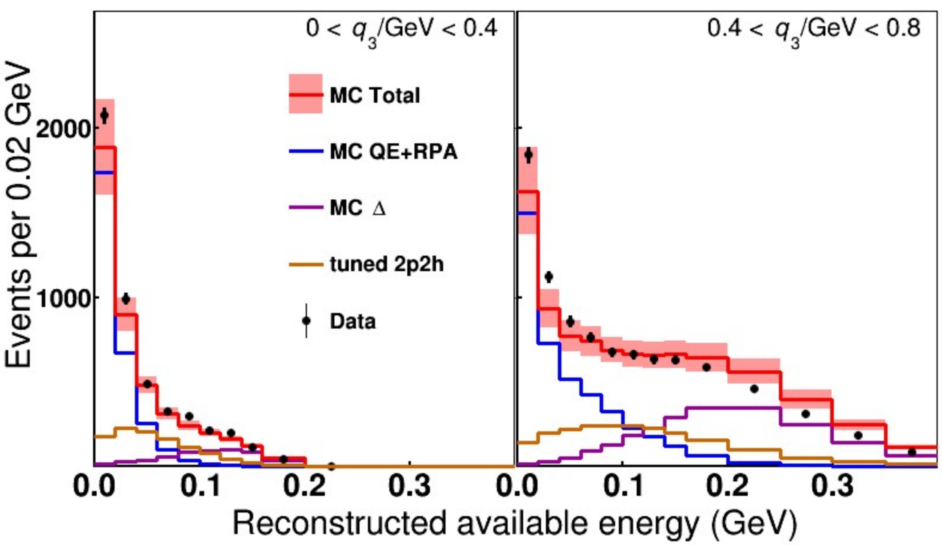
Will refer to this as the low recoil fit.
Minerva Tune (MnvGENIE) is composed of
RPA+2p2h+Low recoil fit+(non-resonant pion reduction)

Application of arXiv 1601.01888

Anti-neutrino inclusive low recoil

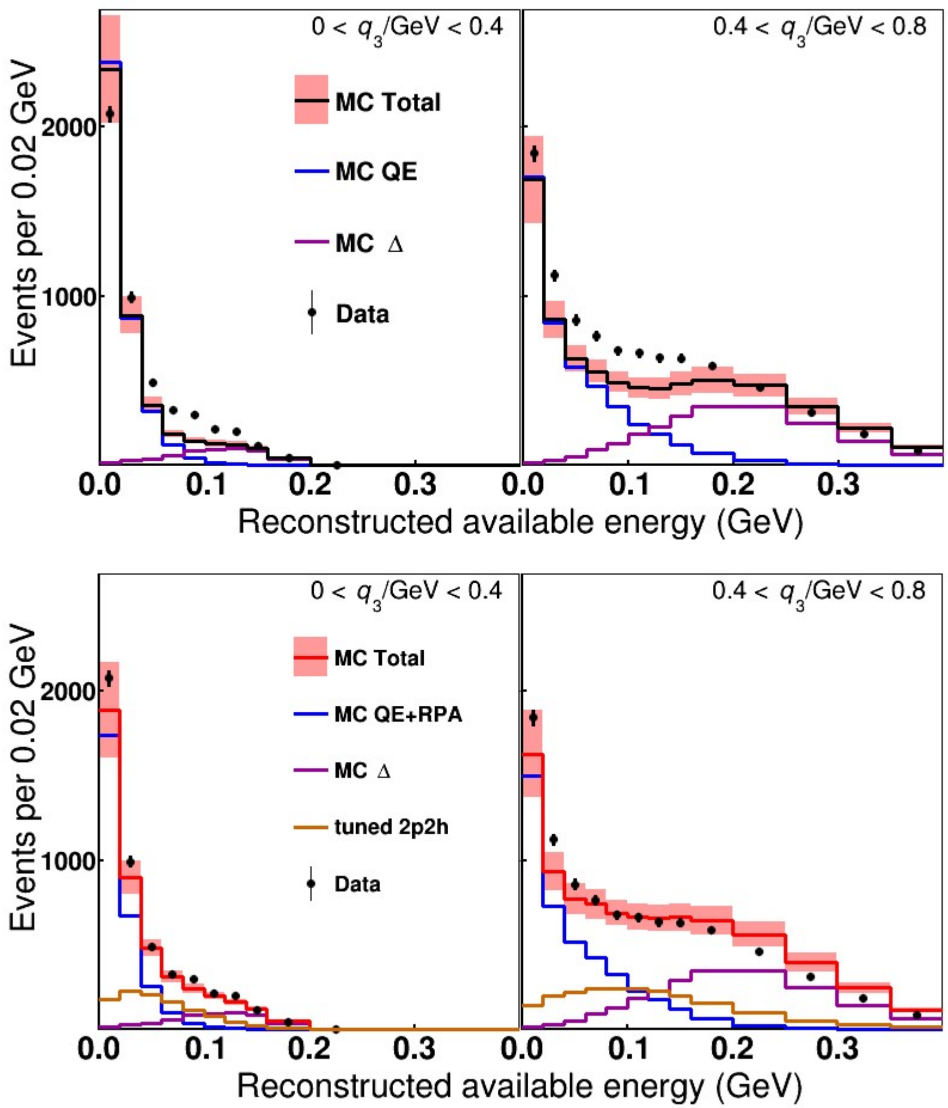


Before application of the low recoil fit



After application of the low recoil fit

Anti-neutrino inclusive low recoil

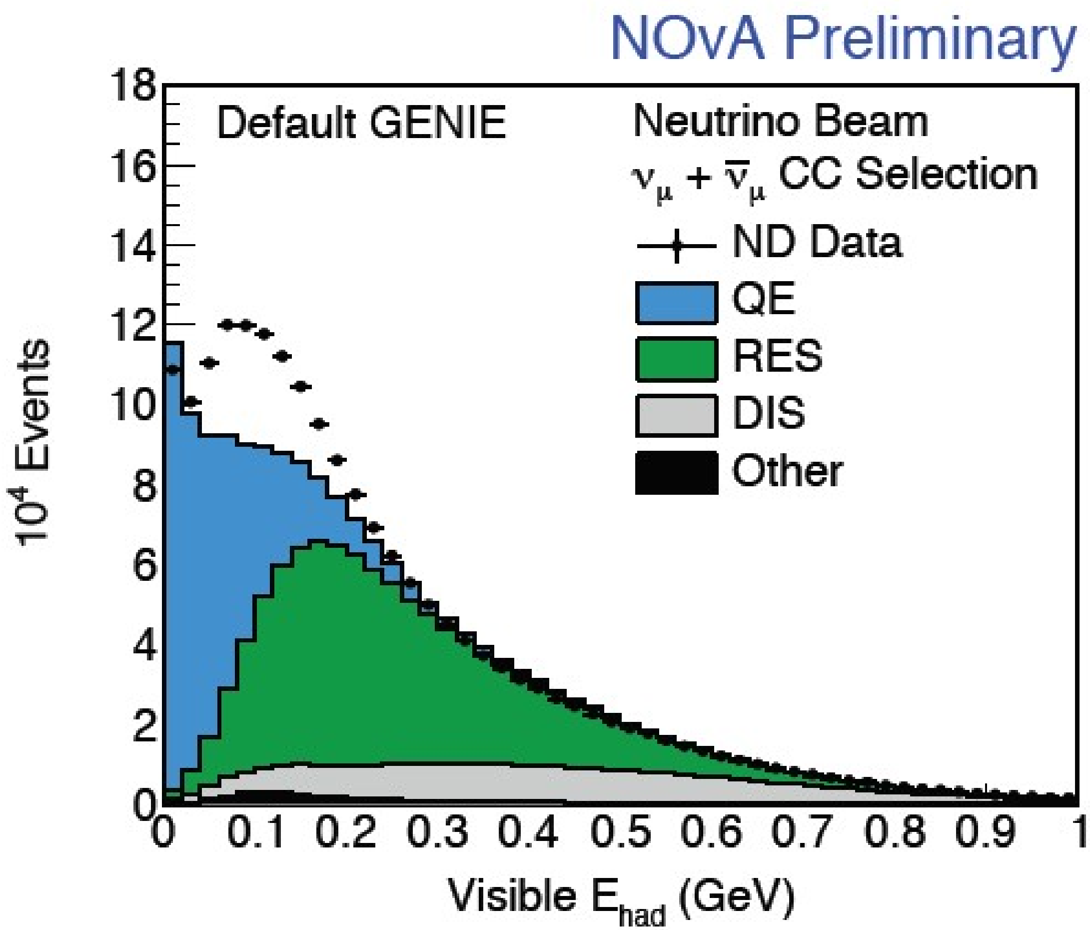


It is quite remarkable. An empirical neutrino sample based fit works well on the anti-neutrino sample!

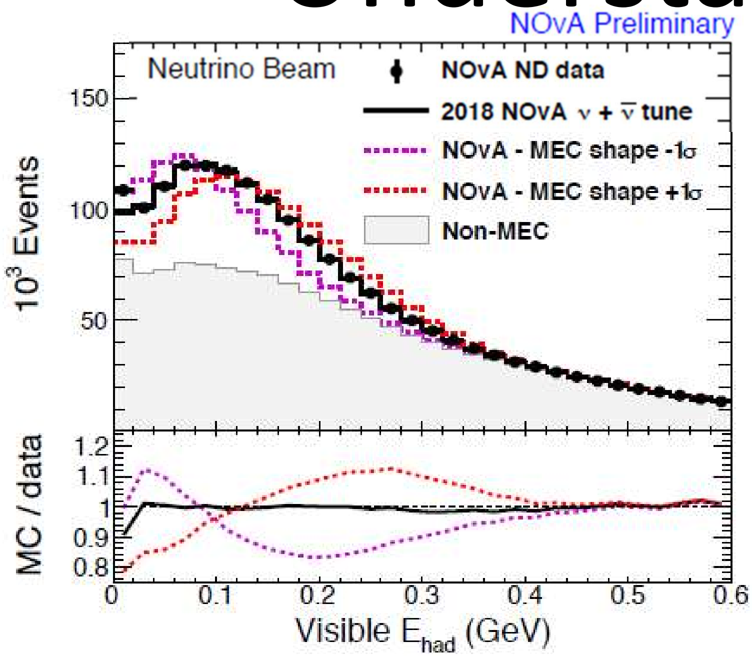
Where else might this work or not work?

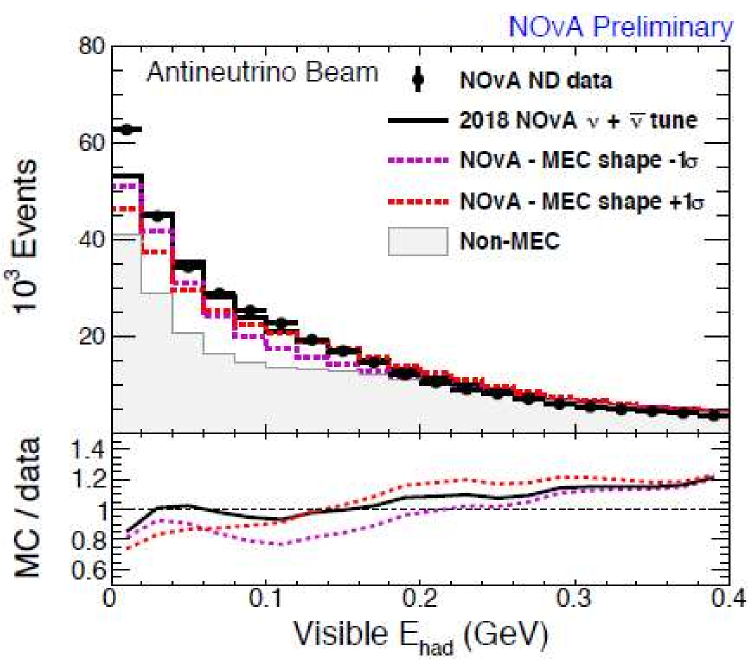
Extracted with
Modified GENIE
(tuned empirical MEC, RPA
(QE,Res), W>1.7 DIS *1.1)

NOvA
Understanding Visible Energy



NOvA
Understanding Visible Energy





- <u>Modify default GENIE</u>
  - Turn on custom "Empirical MEC"
    [T. Katori, AIP Conf. Proc.1663, 030001 (2015)]
  - Apply RPA to QE
  - Apply RPA to resonant
  - Non-resonant inelastic with $W>1.7$ GeV/c^2 increased by 10% based on NOvA data
- Modify MEC strength
  - Uncertainty established by using model variations with correlated shifts of the QE and resonant components

No pions allowed

only nucleons of some multiplicity

T2K – C_8H_8, H_2O [PRD 93, 112012(2016), PRD 97, 012001 (2018)]

MINERvA – (anti)neutrino double differentials, nuclear targets

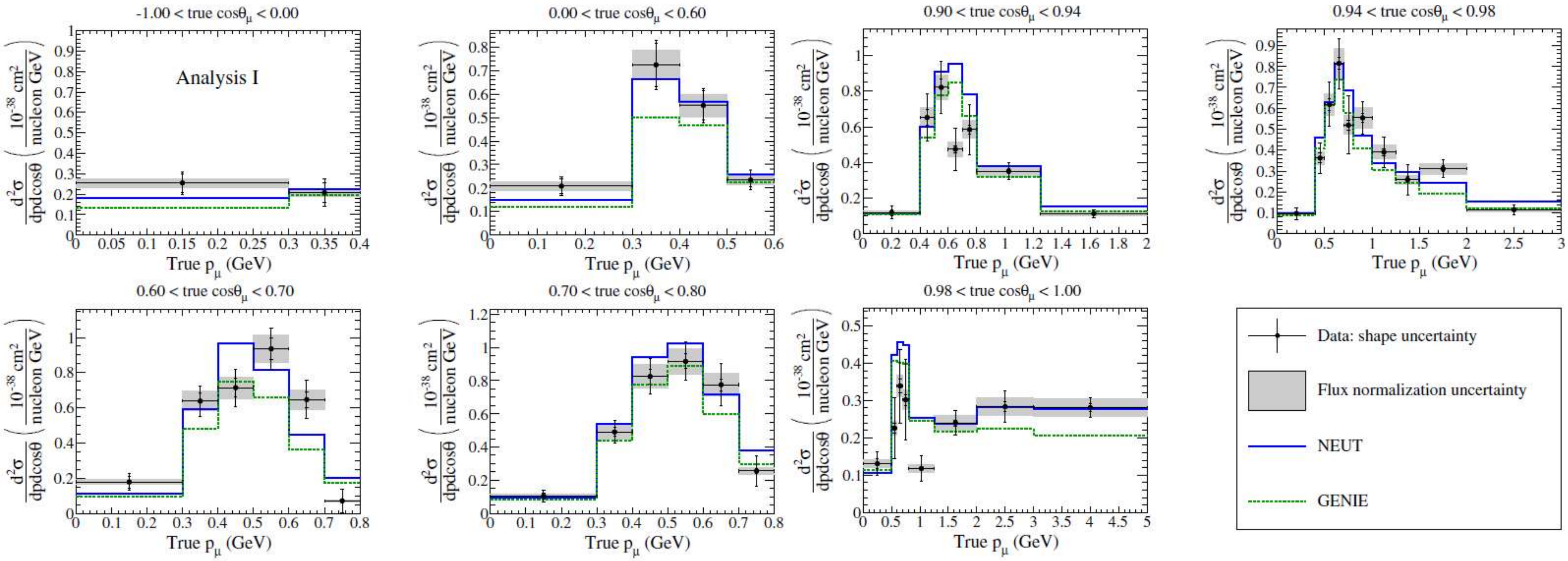
[PRD 97, 052002(2018), PRL 119,082001(2017), neutrino paper in preparation]

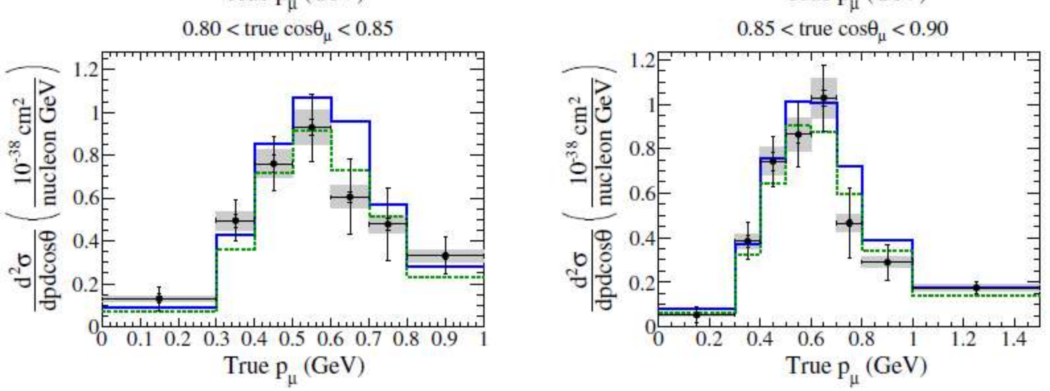
T2K
Water and carbon targets

- Carbon result uses FGD and reconstructs muons + protons.
  - Has significant acceptance to high angle and backward muons
- Water result uses the POD via water subtraction
  - Requires TPC match which limits acceptance to forward direction
  - Subtraction method results in large statistical uncertainty

Extracted with
NEUT 5.1.4.2

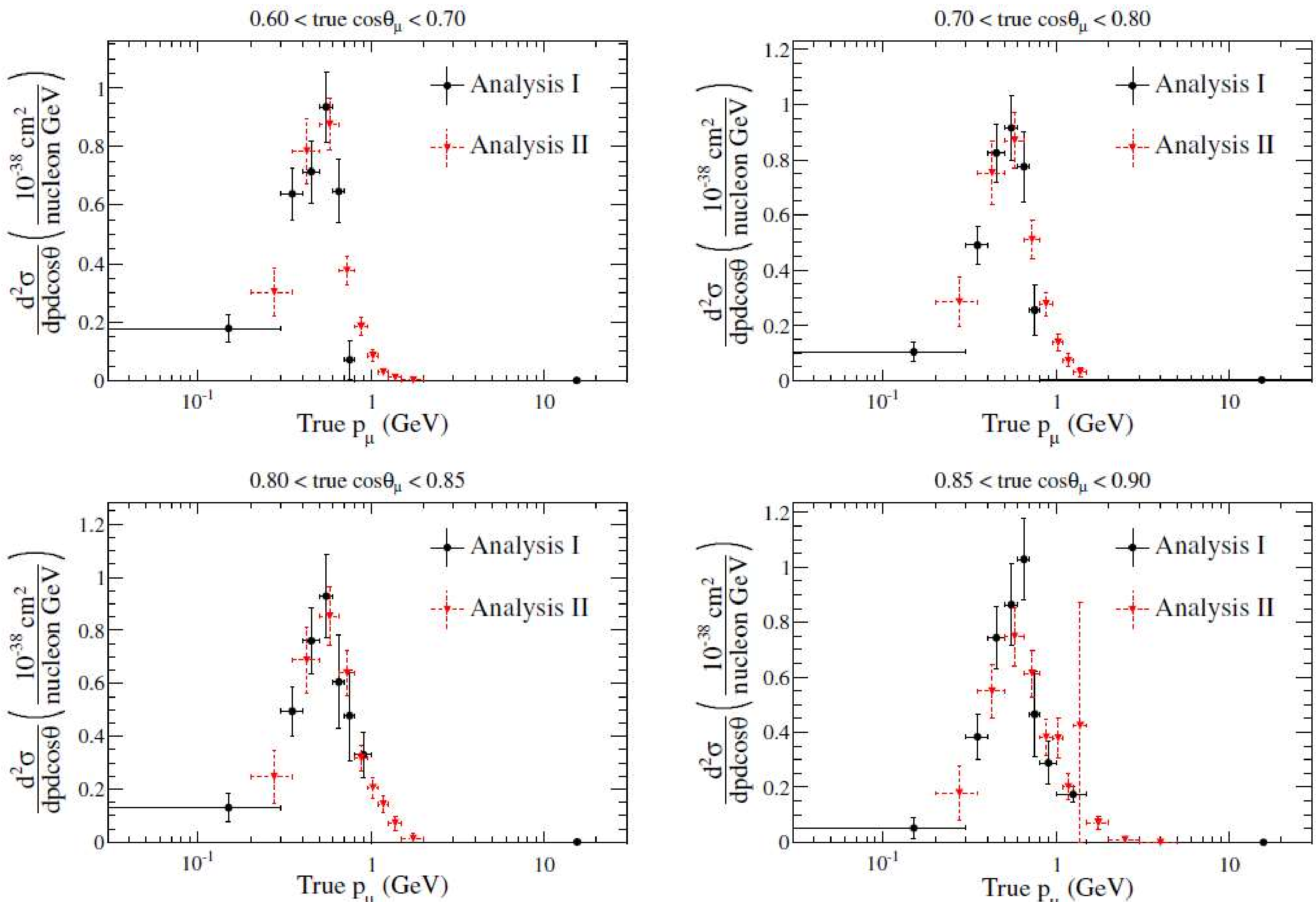
C_8H_8 Result I





- Did not use d`Agostini unfolding
- Compares to another analysis which did
  - Complicated by differing signal acceptances

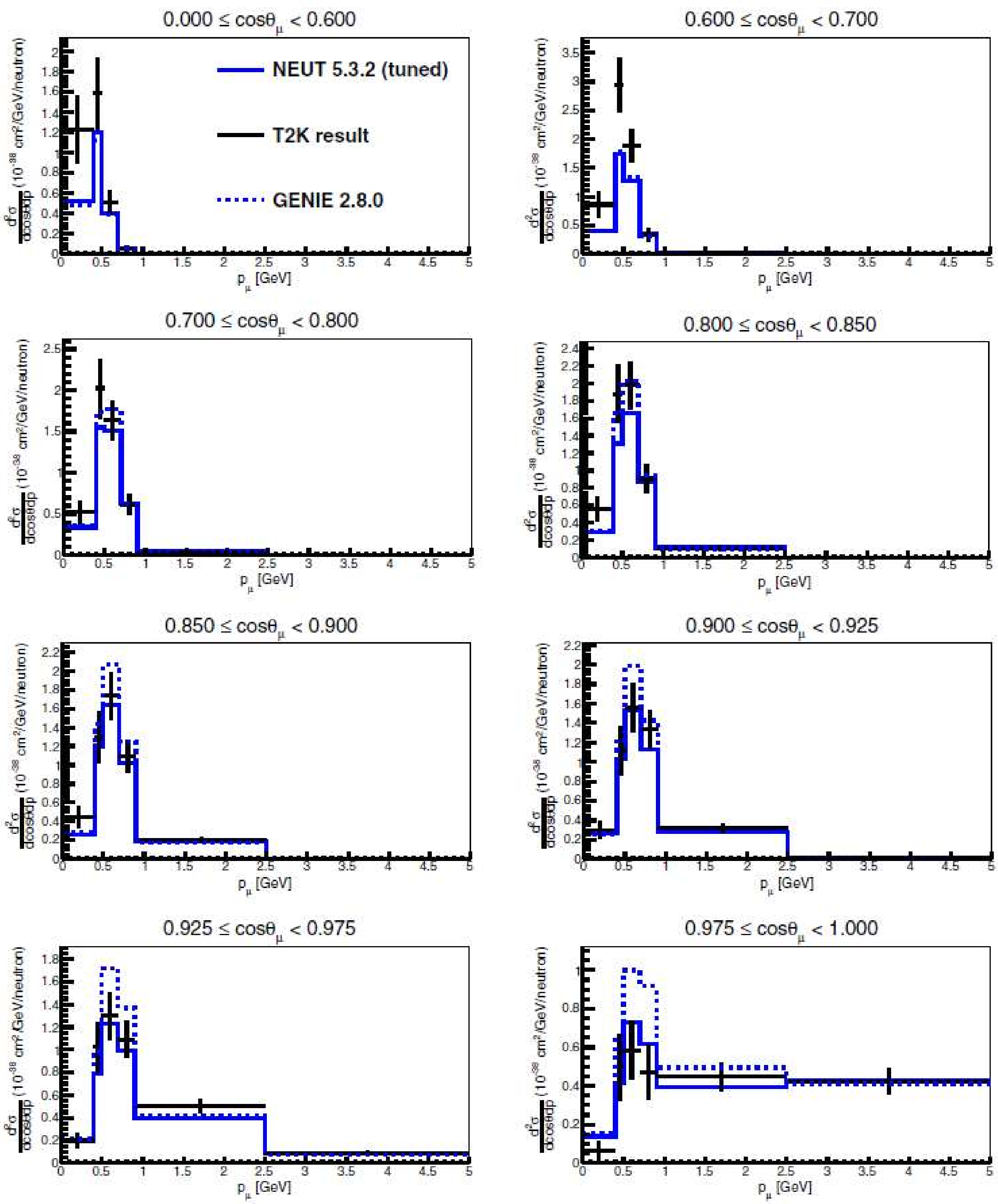
Method comparison



Analysis II has smaller acceptance

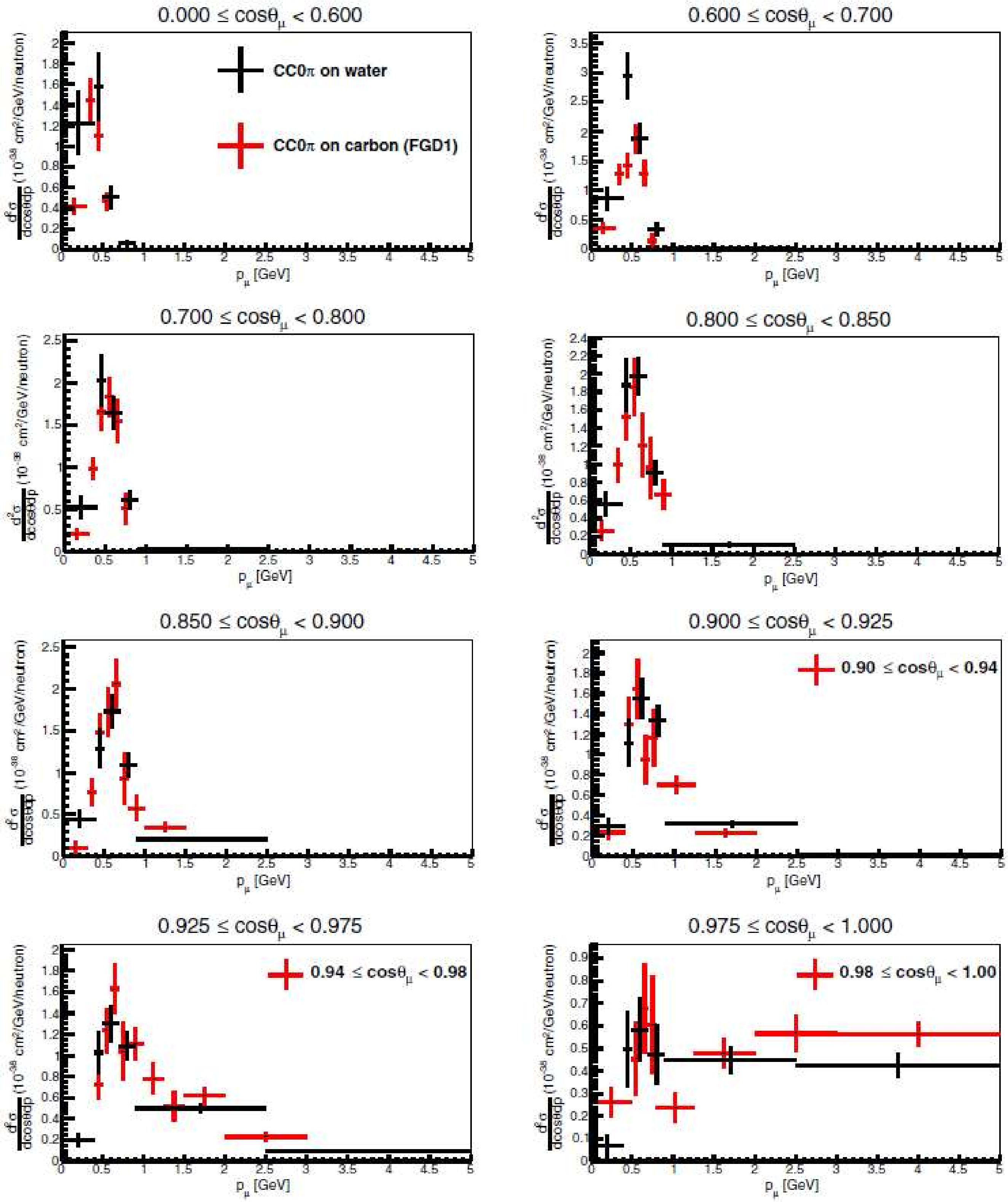
These are regions of overlap

H_2O Extracted with NEUT 5.3.2



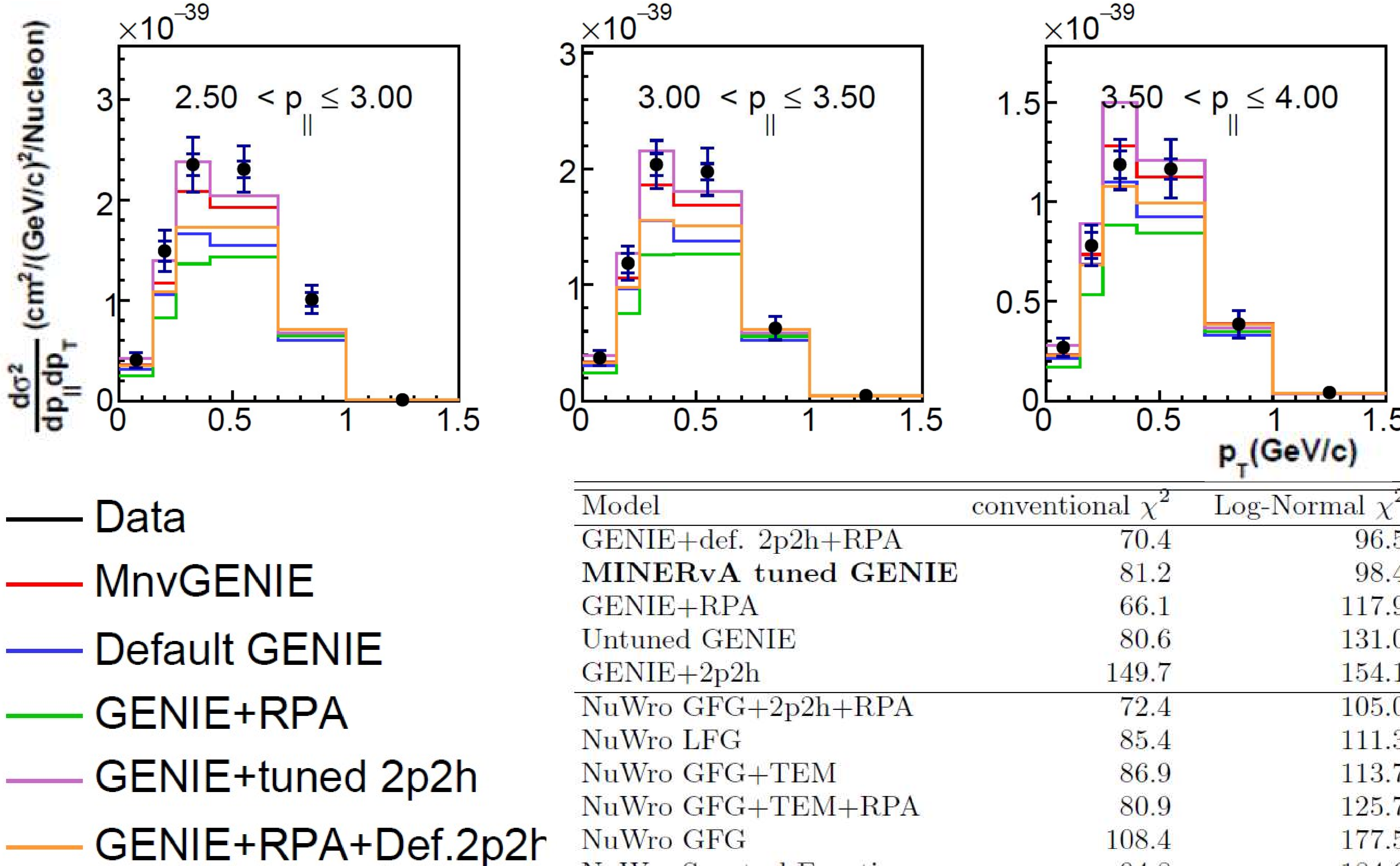
- Shows agreement in regions in the more forward direction
- Compared to Martini et. al and SuSAv2 overall the result compares better with the inclusion of 2p2h
  - Difference in forward directions
- Similar conclusion found the C_8H_8 result

C_8H_8 to H_20 Comparison



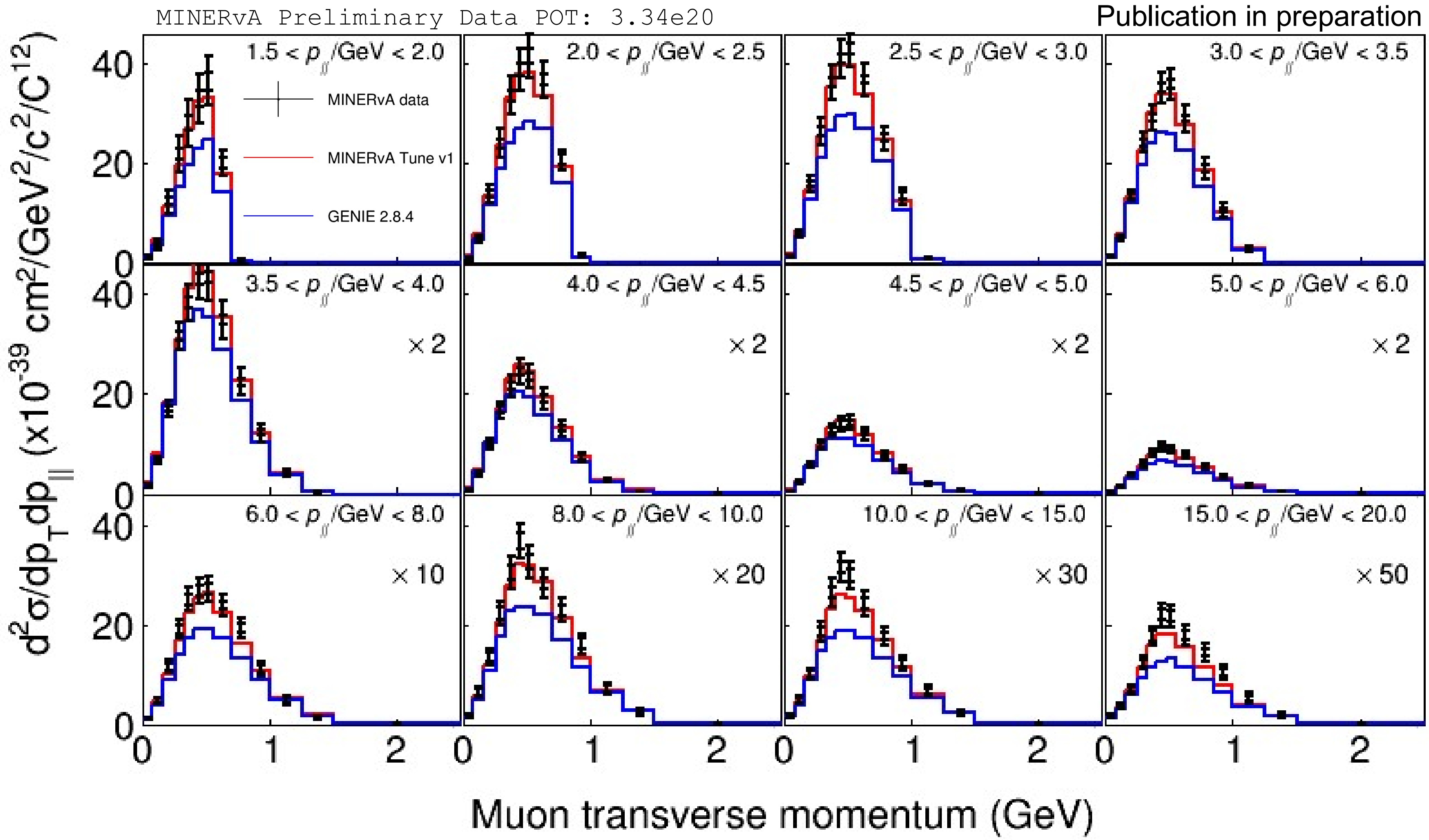
- Quite similar results
- Interesting structure in the 1+GeV forward direction region for the carbon result

MINERvA Anti-neutrino CCQE-like



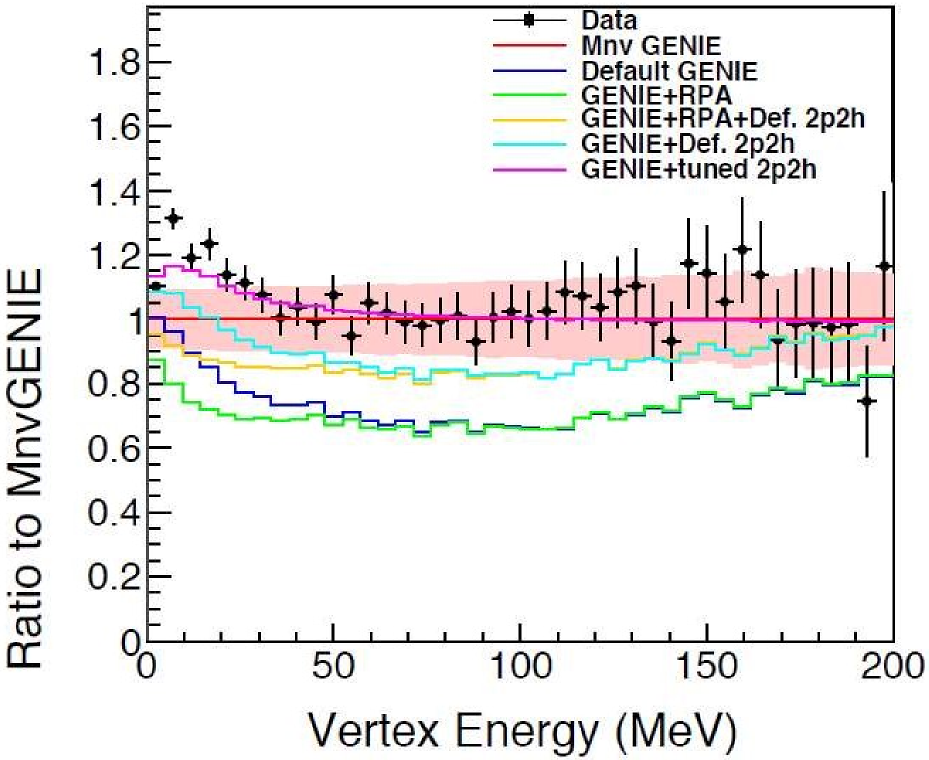
Model	conventional χ^2	Log-Normal χ^2
GENIE+def. 2p2h+RPA	70.4	96.5
MINERvA tuned GENIE	81.2	98.4
GENIE+RPA	66.1	117.9
Untuned GENIE	80.6	131.0
GENIE+2p2h	149.7	154.1
NuWro GFG+2p2h+RPA	72.4	105.0
NuWro LFG	85.4	111.3
NuWro GFG+TEM	86.9	113.7
NuWro GFG+TEM+RPA	80.9	125.7
NuWro GFG	108.4	177.5
NuWro Spectral Function	94.8	184.6
NuWro GFG+2p2h	153.7	185.9

MINERvA Neutrino CCQE-like

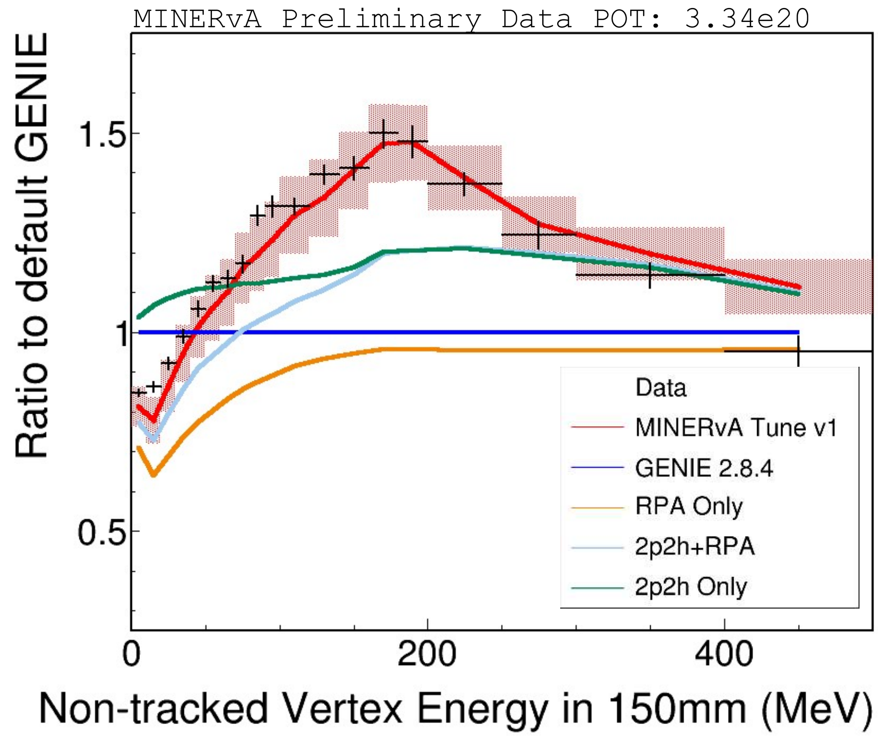


Vertex energy in QE-Like results

Phys. Rev. D 97, 052002 (2018)



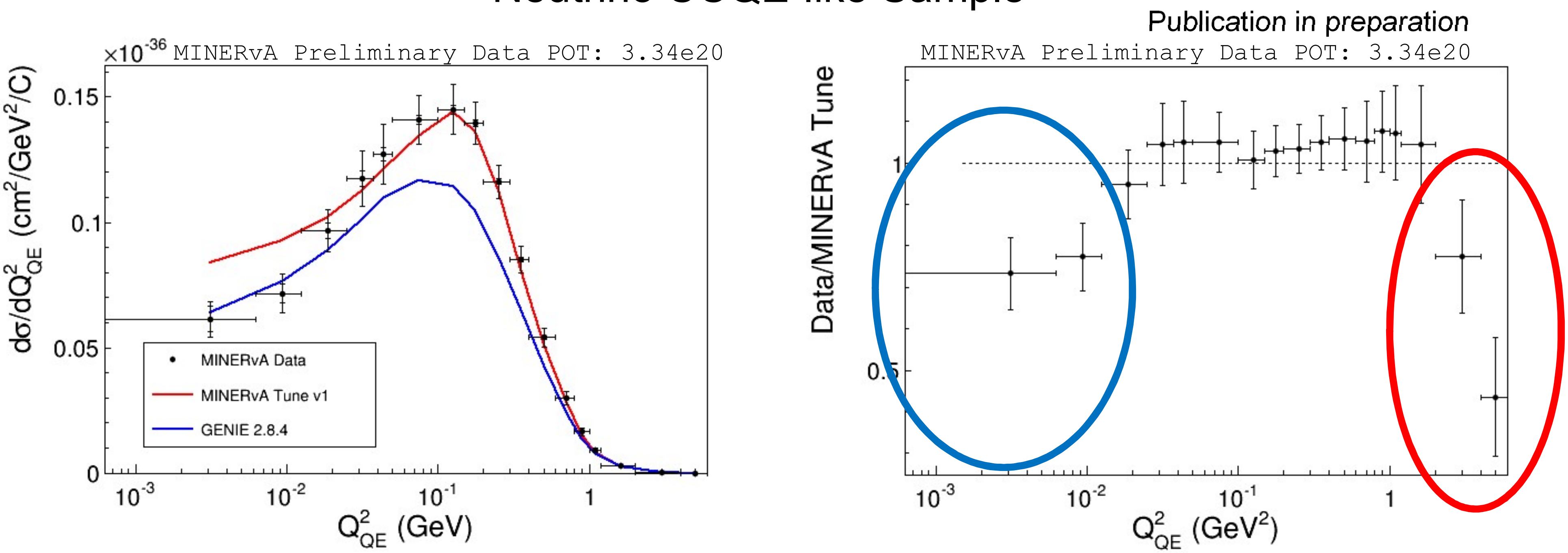
Publication in preparation



- The tune seems to enhance the events in the regions of vertex energy the data prefer!

Close, but not quite!

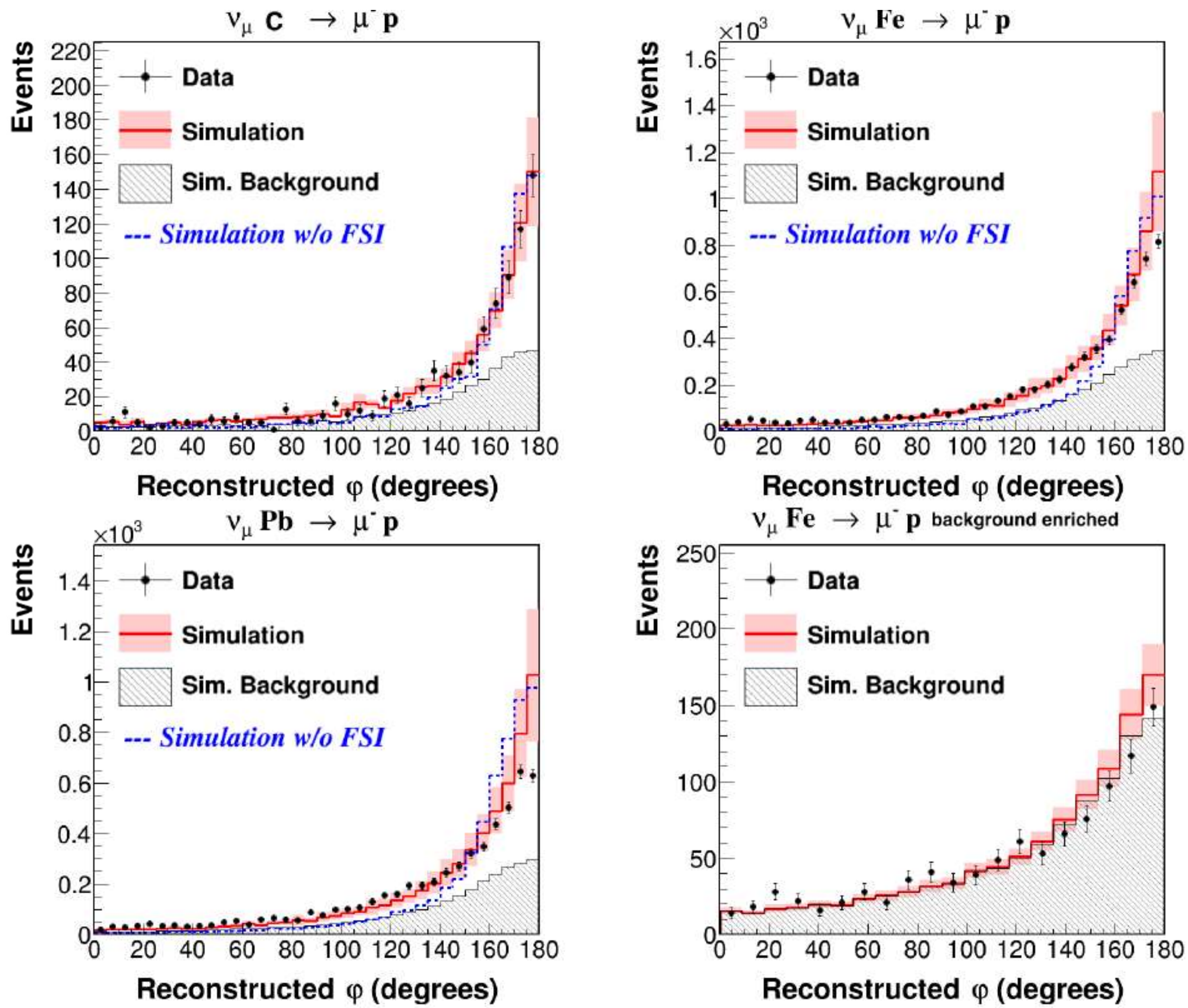
Neutrino CCQE-like Sample



- High Q^2 is a region where we are pushing the extent of the dipole approximation
- Low Q^2 is a region of phase space where the fraction of events has an increased population of resonant pion qe-like events.

Final State Effects for non-carbon targets

- A-dependence of FSI appears to not be correctly modeled
- Improvement globally with inclusion of 2p2h
- Analysis, because of proton requirement is mostly outside the regions where RPA matters
- NuWro shows better A-dependent performance



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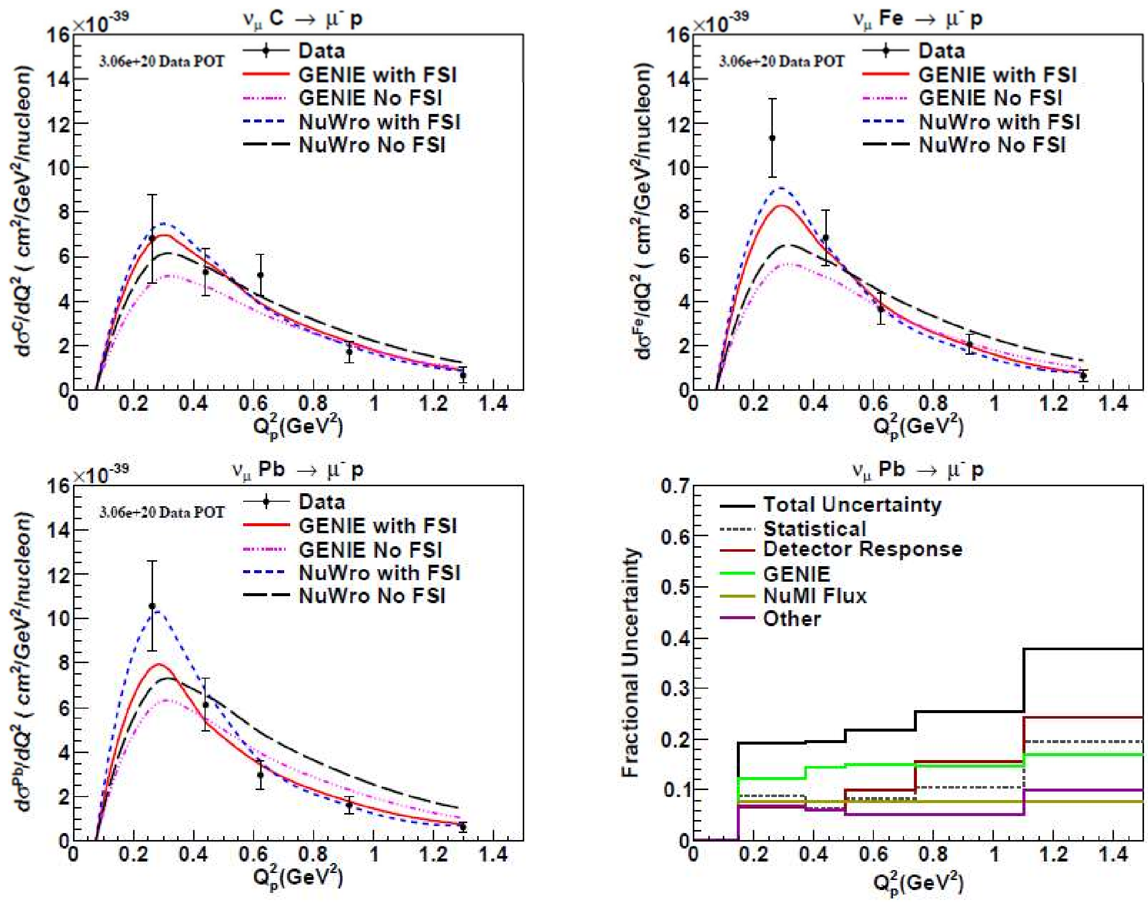


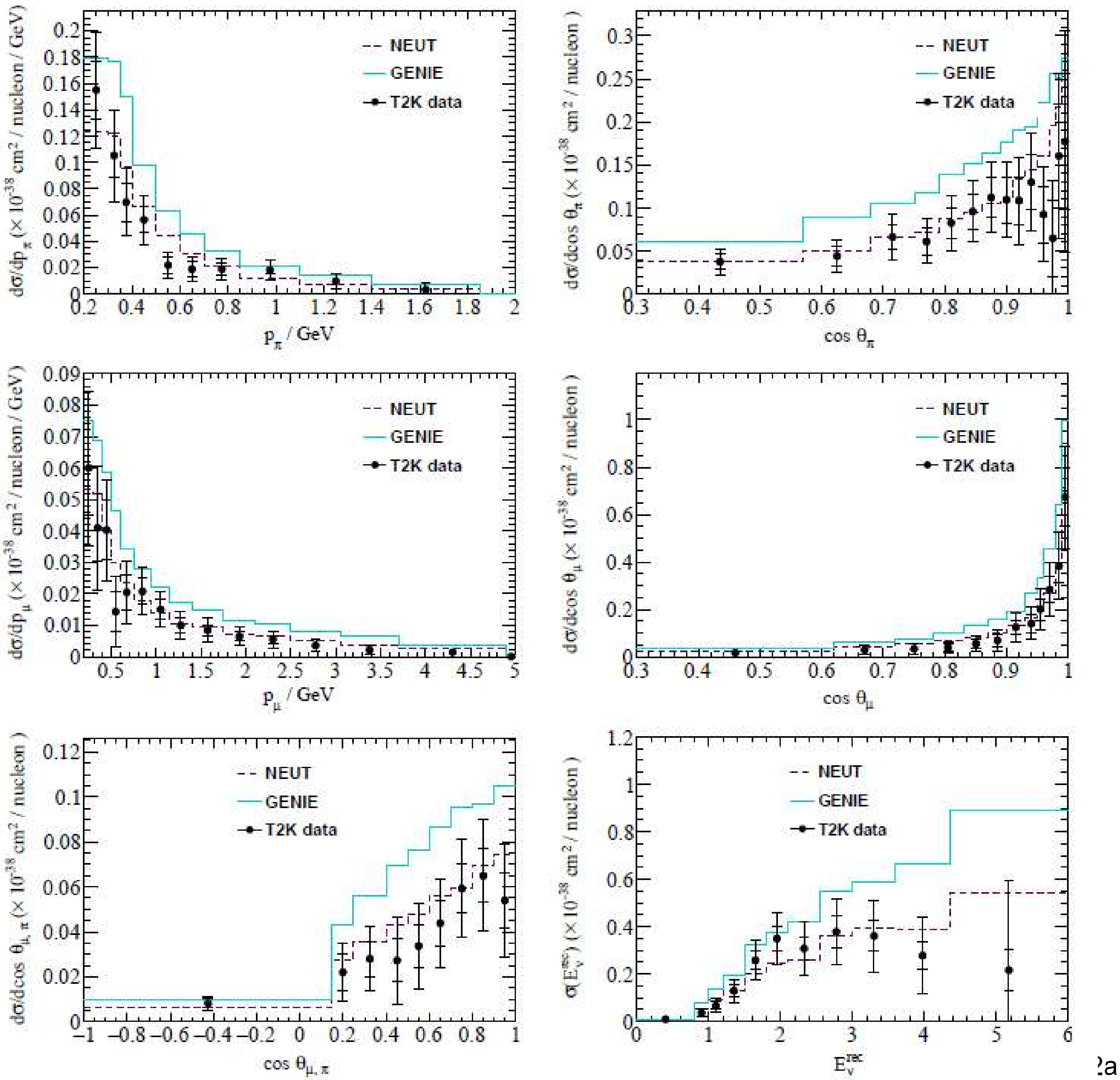
Model	Carbon	Iron	Lead
GENIE RFG	11.0	63.8	41.1
GENIE RFG + 2p2h	5.9	18.9	16.3
GENIE RFG + 2p2h + RPA	5.9	19.9	17.5
NuWro RFG + 2p2h + RPA	6.0	14.6	11.0

Charged Pion

T2K – H_20 single pion production[PRD 95, 012010(2017)]

Extracted with
NEUT 5.1.4.2

FGD charged pion



- A new pion result to add to the growing pool of pion samples
- Oxygen target
- Good agreement with NEUT
- Wants overall reduction of rate compared to GENIE

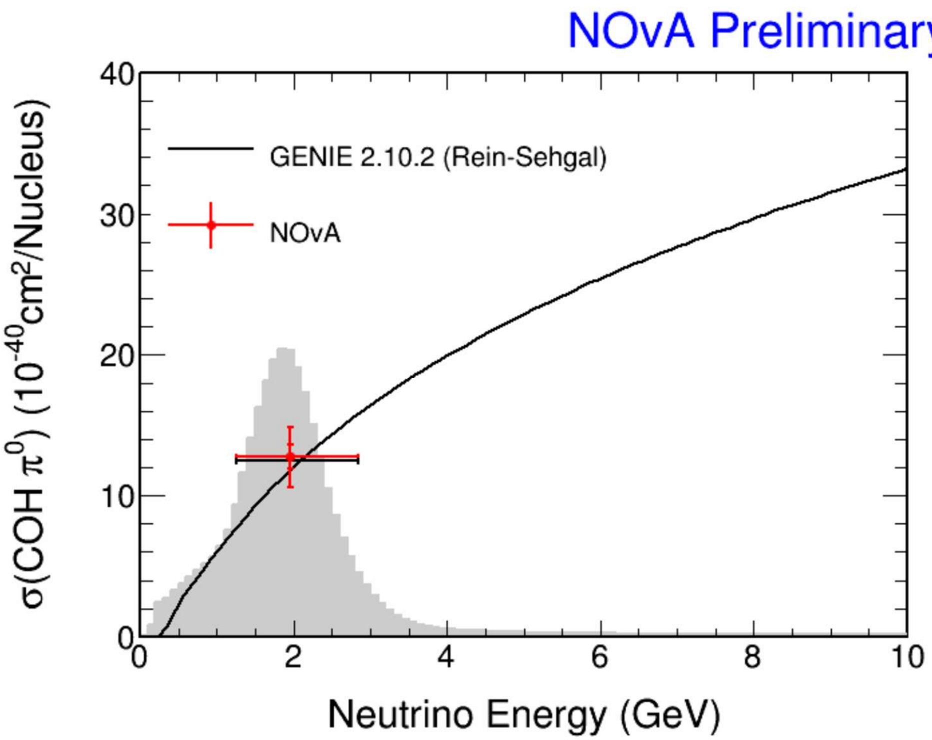
Neutral Pion

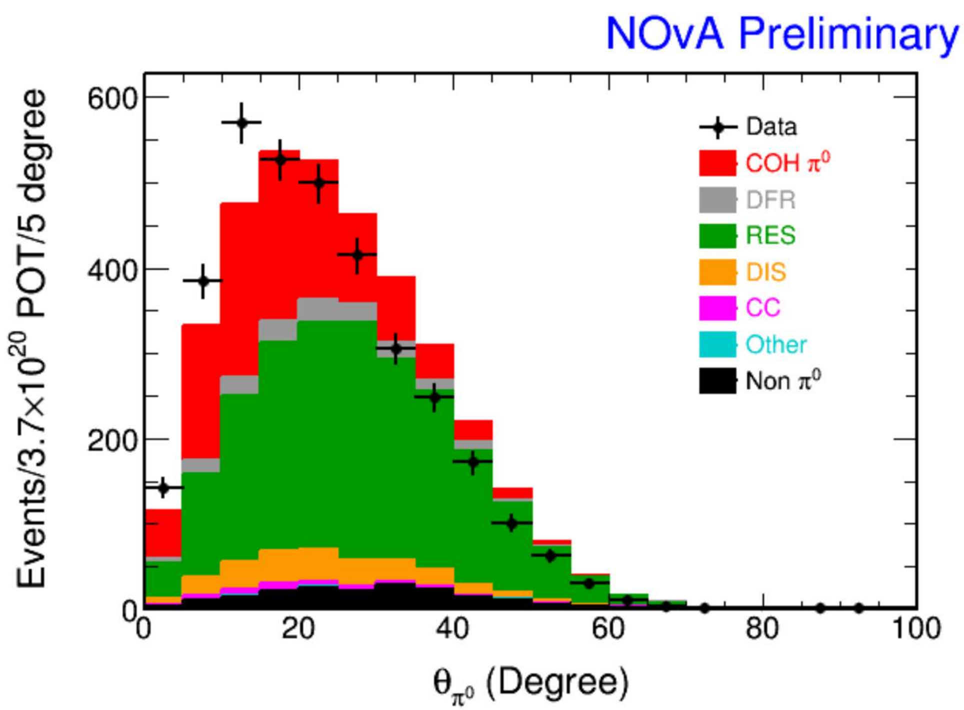
NOvA – CC and NC production JETP seminar Dec. 1st, 2017

[http://theory.fnal.gov/events/event/results-from-nova-2/]

MINERvA – CC production [PRD96,072003(2017)]

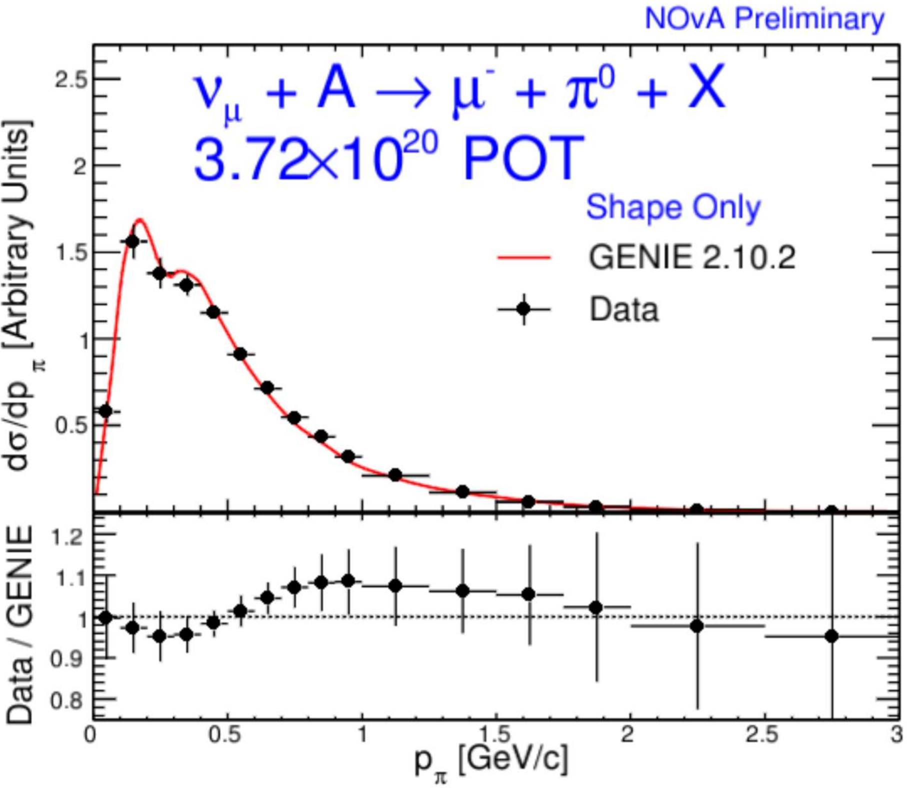
NOvA NC Coherent

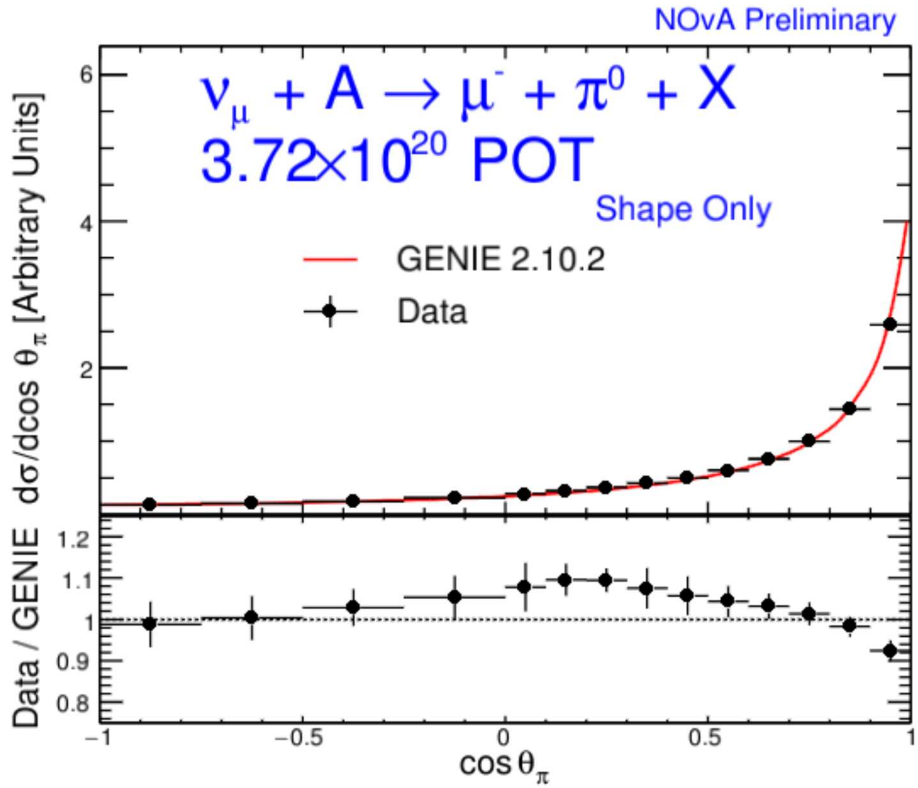




- Good agreement with other experiments with much smaller uncertainties
- Good agreement with GENIE
- Event distribution suggests a more forward going angular distribution

NOvA CCπ^0

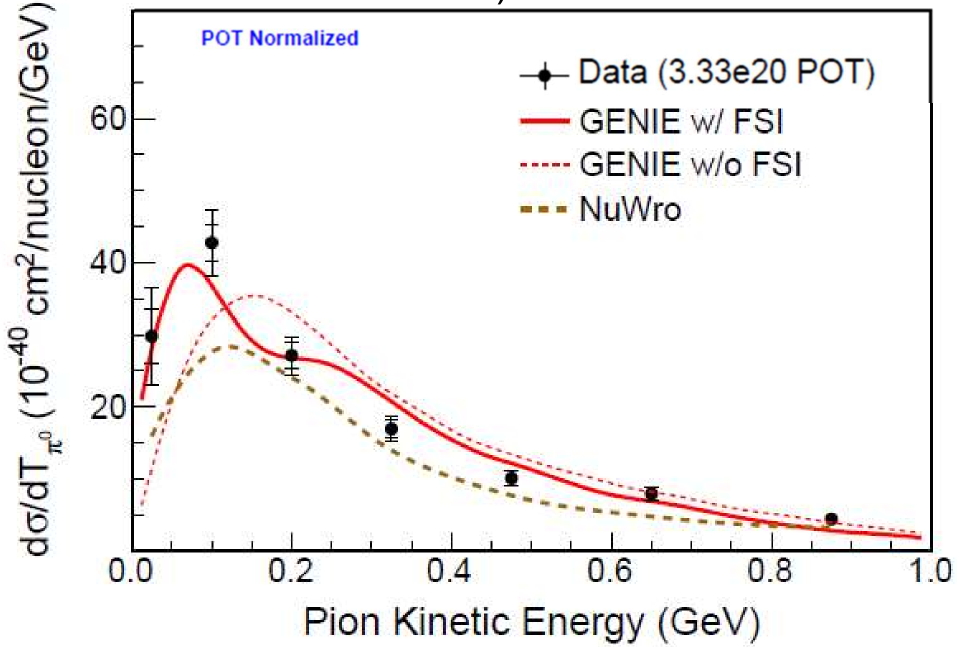


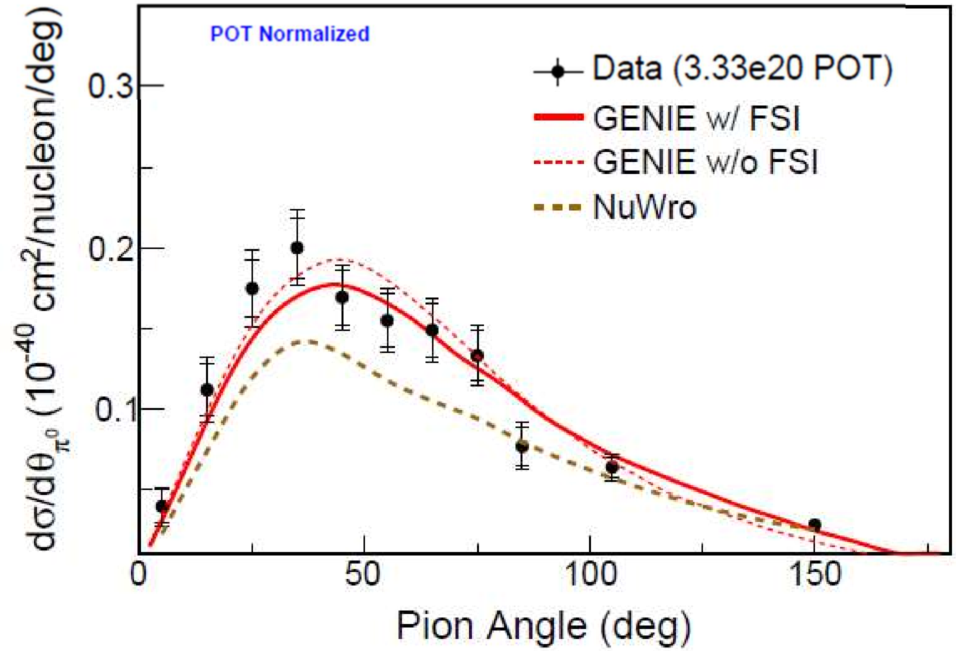


- Shape comparisons of the pion kinematics
- Desire for a harder spectrum and less forward angles?
  - Feed down effect is seen in the pion momentum
- Has complementary muon distributions

Extracted with
Modified GENIE 2.8.4
(Tuned 2p2h, RPA (QE),
non-resonant 1π reduction)

MINERvA CCπ^0

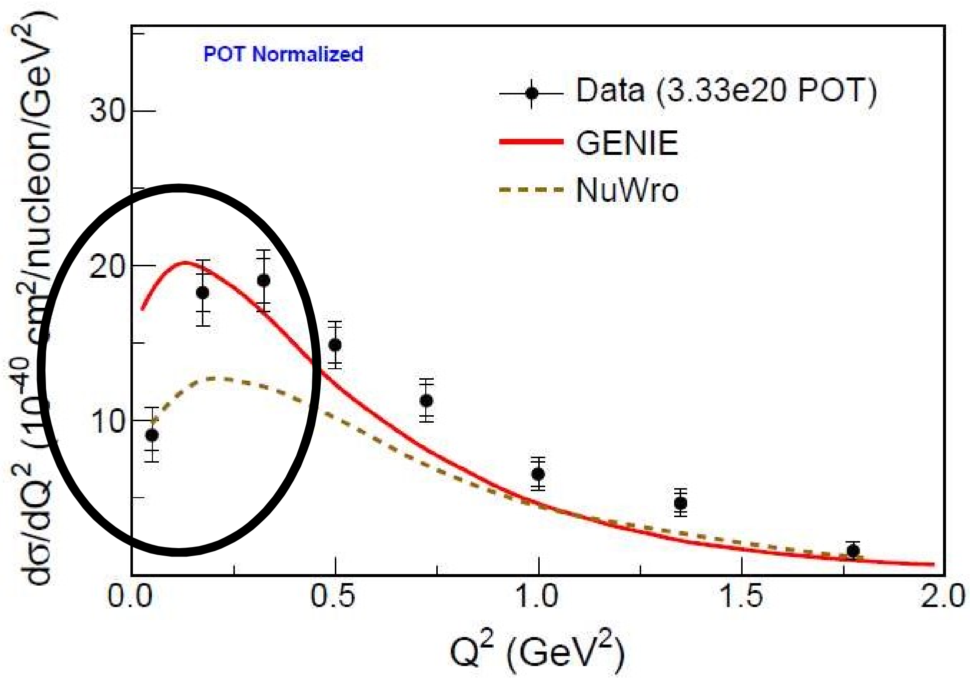


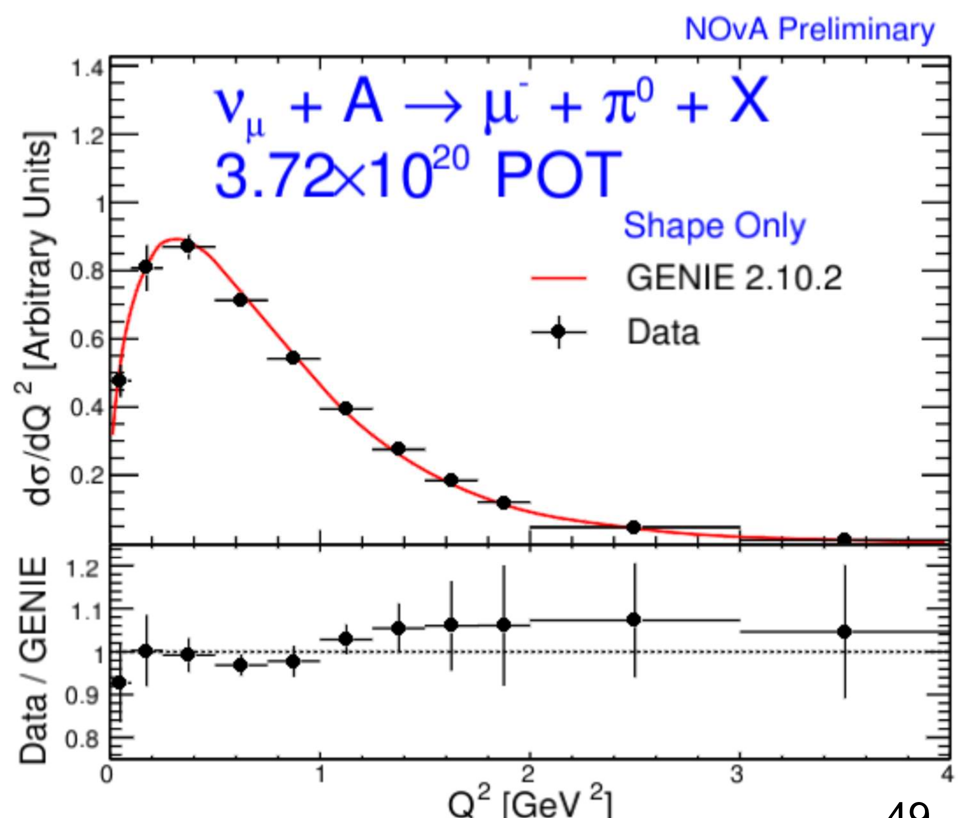


- Generally good agreement in both pion variables
- Has other results exploring polarization and pπ^0 final states

Low Q^2 reduction effect needed ?

- Recent MINERvA $CC\pi^0$ result wants a low Q^2 reduction
- So does the MINERvA anti-neutrino result $CC\pi^0$ result
- NOvA selection allows multiple π^0 in signal
  - Difference in GENIE simulations?





New Techniques

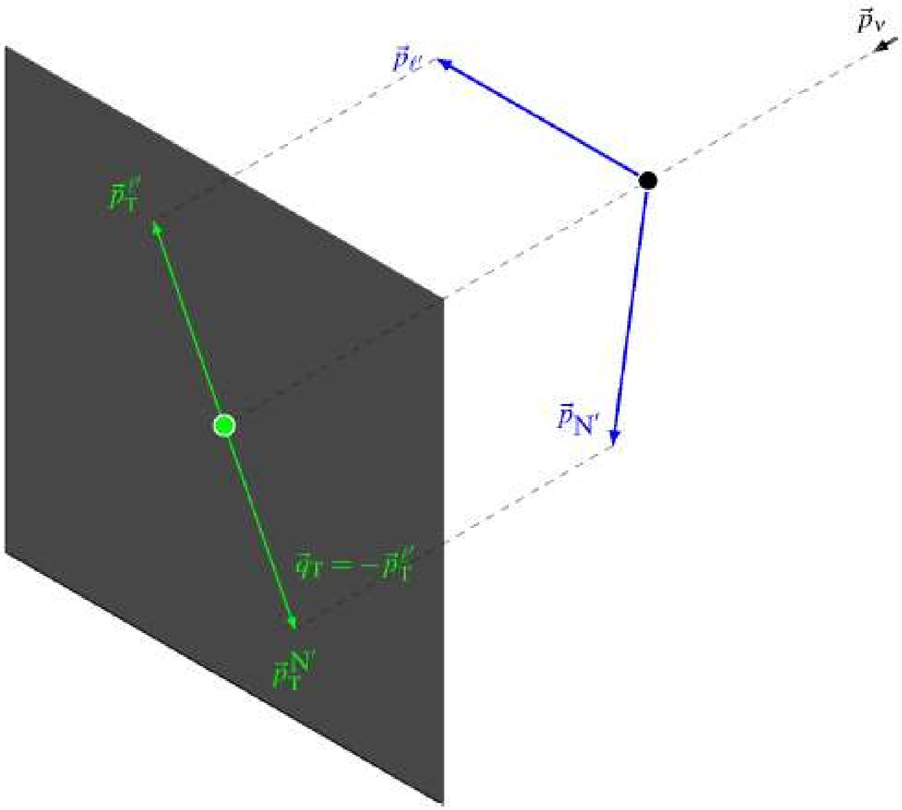
T2K – Transverse Variables, 3D muon+proton kinematics

[https://arxiv.org/abs/1802.05078]

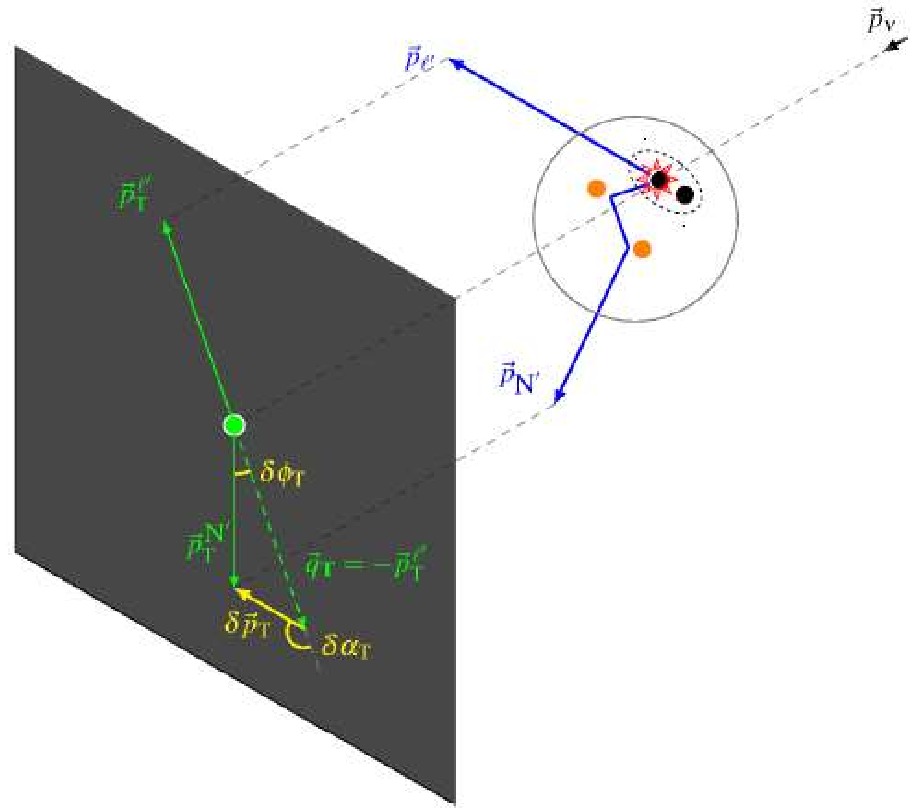
MINERvA – Transverse Variables, P_n [https://arxiv.org/abs/1805.05486]

X.-G. Lu *et al.* Phys. Rev. C 94, 015503 (2016)

New measurement variables



Static nucleon target



Nuclear target

X.-G. Lu *et al.* Phys. Rev. C 94, 015503 (2016)

New measurement variables

A more general analysis of kinematic imbalance

Transverse: $0 = \vec{p}_{\rm T}^{\,\ell'} + \vec{p}_{\rm T}^{\,\rm N'} - \delta\vec{p}_{\rm T}$

Longitudinal: $E_\nu = p_{\rm L}^{\ell'} + p_{\rm L}^{\rm N'} - \delta p_{\rm L}$

New variable: $p_{\rm n} \equiv \sqrt{\delta p_{\rm T}^2 + \delta p_{\rm L}^2}$

Neutrino energy is unknown (in the first place), equations are not closed.

Assuming exclusive μ-p-A' final states

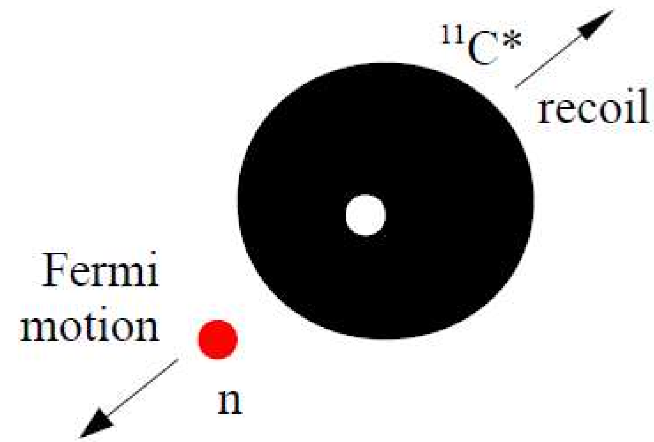
Use energy conservation to close the equations

$$E_\nu + m_{\rm A} = E_{\ell'} + E_{\rm N'} + E_{\rm A'}$$

$$E_{\rm A'} = \sqrt{m_{\rm A'}^2 + p_{\rm n}^2}$$

$p_{\rm n}$: recoil momentum of the nuclear remnant

For CCQE, A' = ^{11}C*
No more unknowns
$p_{\rm n}$: neutron Fermi motion



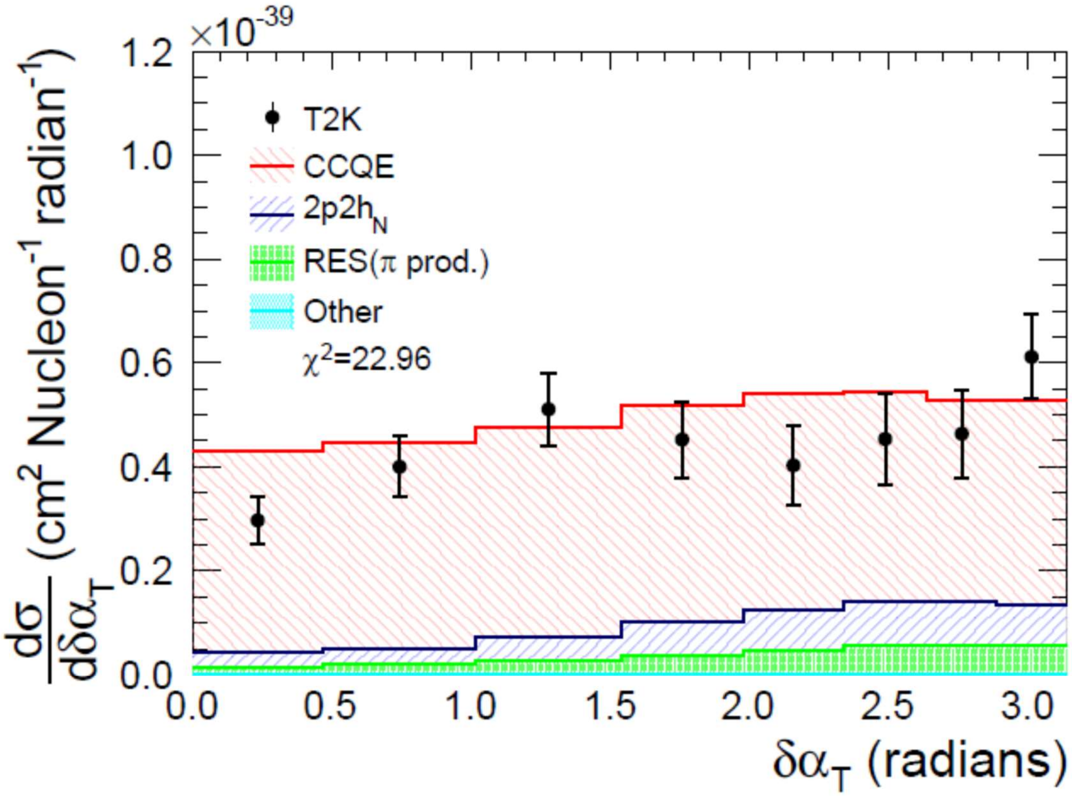
$$p_L = \frac{1}{2}(M(A) + k'_L + p'_L - E' - E_{p'}) - \frac{p_T^2 + M^*(A-1)^2}{2(M(A) + k'_L + p'_L - E' - E_{p'})}$$

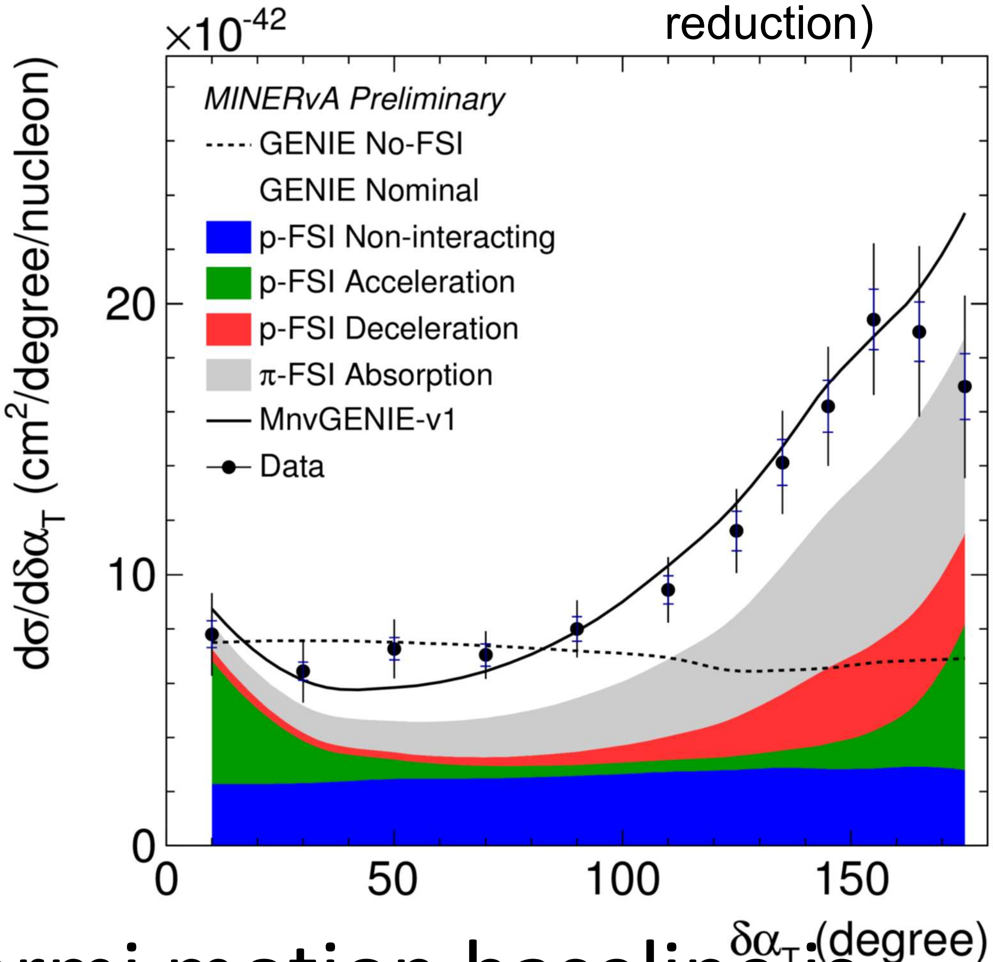
A. Furmanski, J. Sobczyk, Phys.Rev. C95 (2017) no.6, 065501

Extracted with
NEUT 5.3.2

T2K and MINERvA

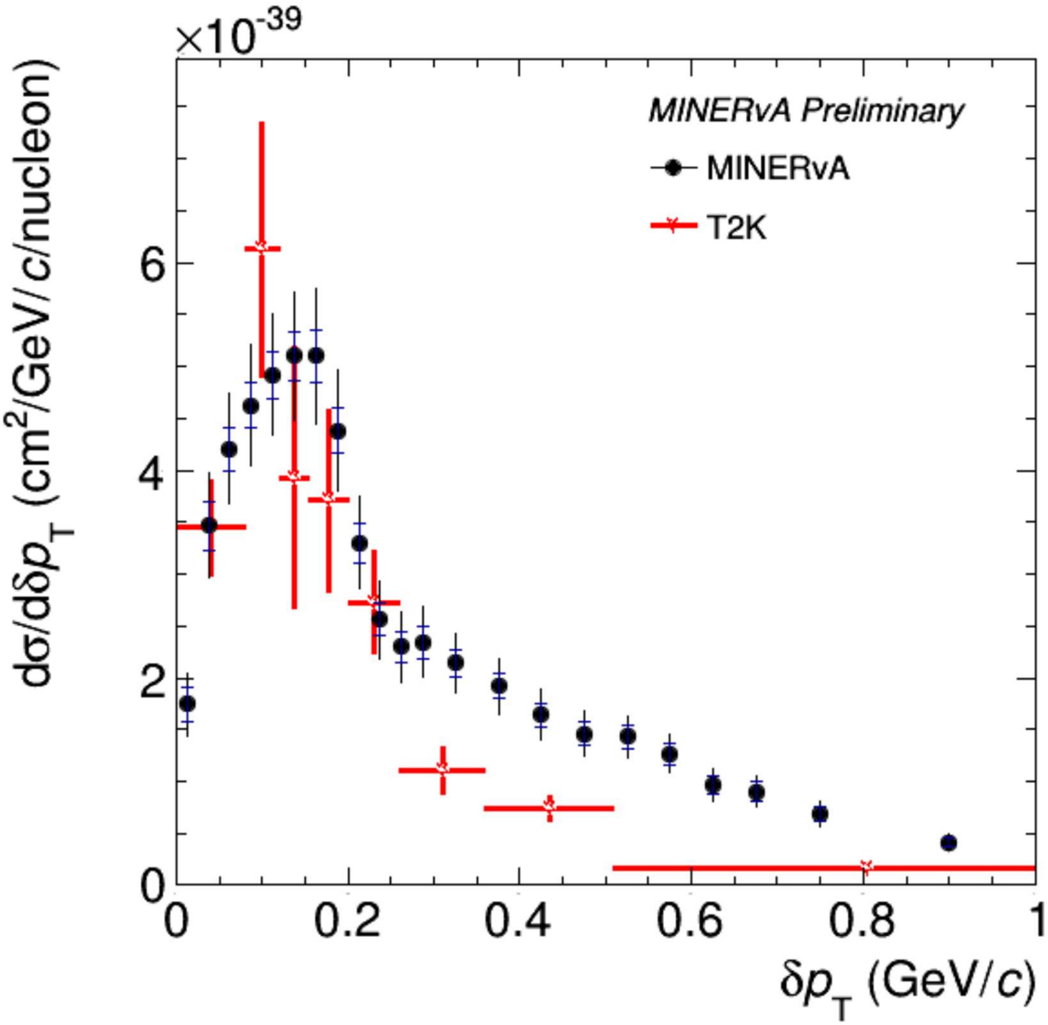
Extracted with
Modified GENIE 2.8.4
(Tuned 2p2h, RPA
(QE), non-resonant 1π
reduction)





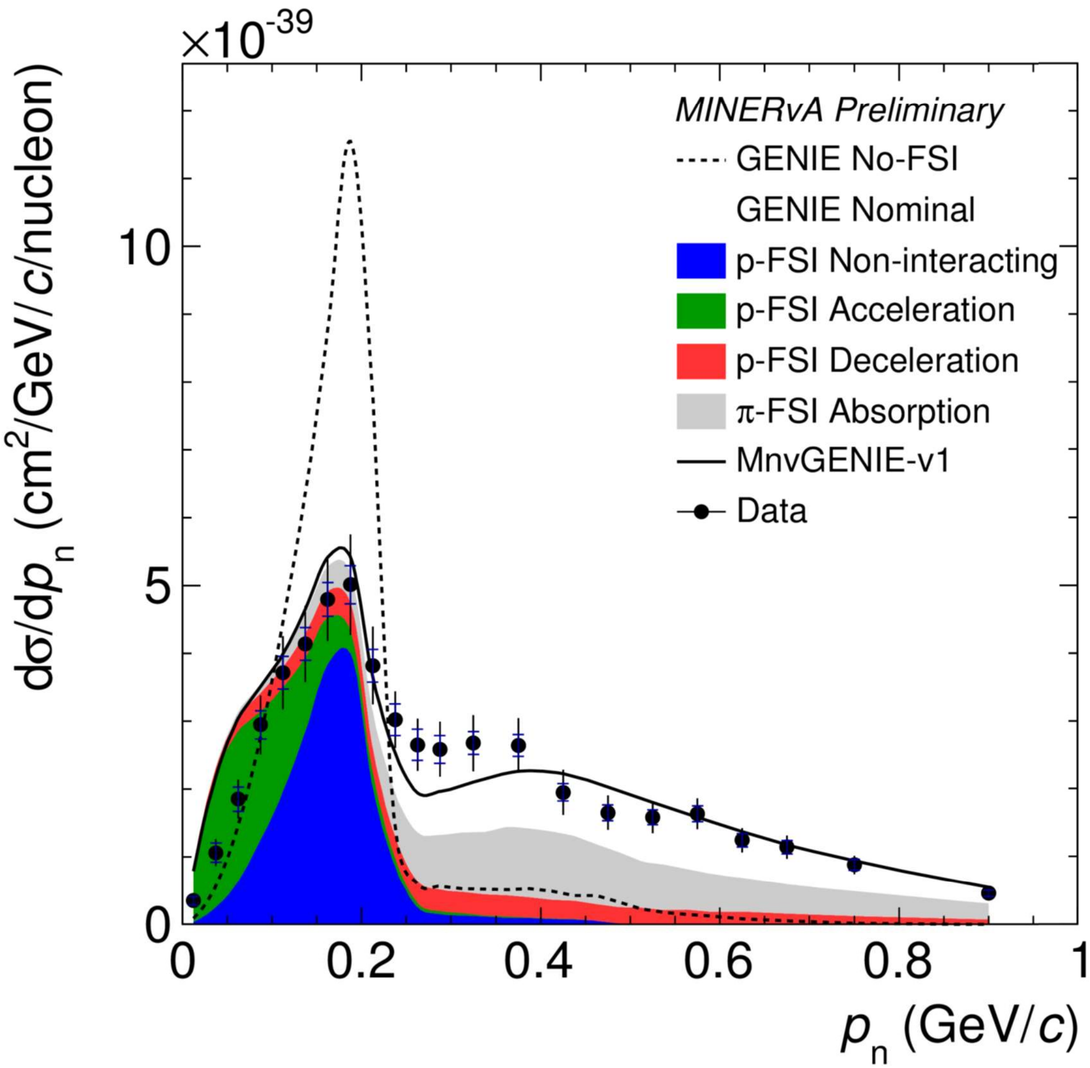
- When compared the Fermi motion baseline is consistent
- Major difference is resonant content

T2K and MINERvA



- Non-QE content is very different between experiments
  - High tails region
- QE peaks are consistent

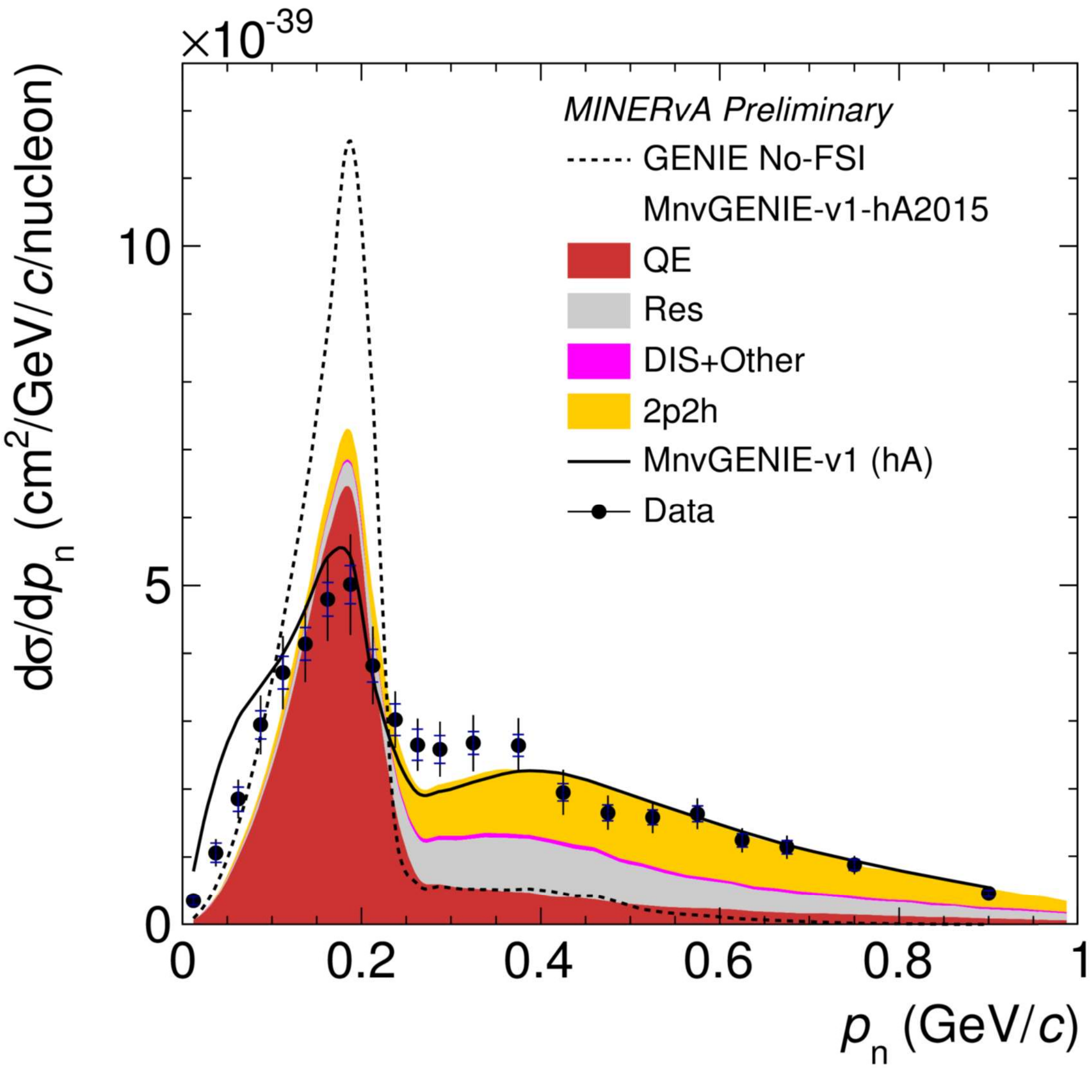
P_n, QE separator



- δp_t with longitudinal imbalance included
- Transition between QE and non-QE regions is interesting

ν

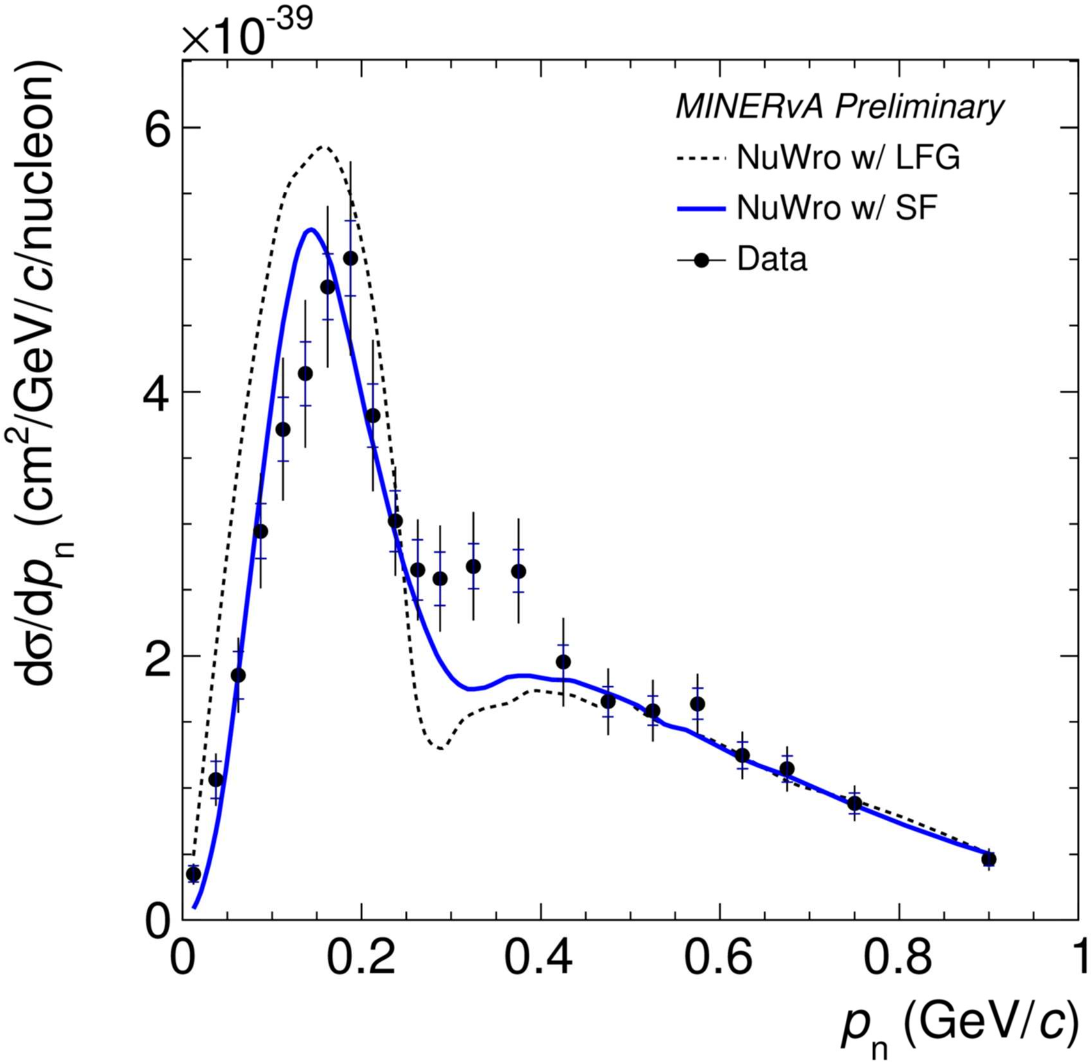
P_n, QE separator



- δp_t with longitudinal imbalance included
- Transition between QE and non-QE regions is interesting

ν

P_n, QE separator

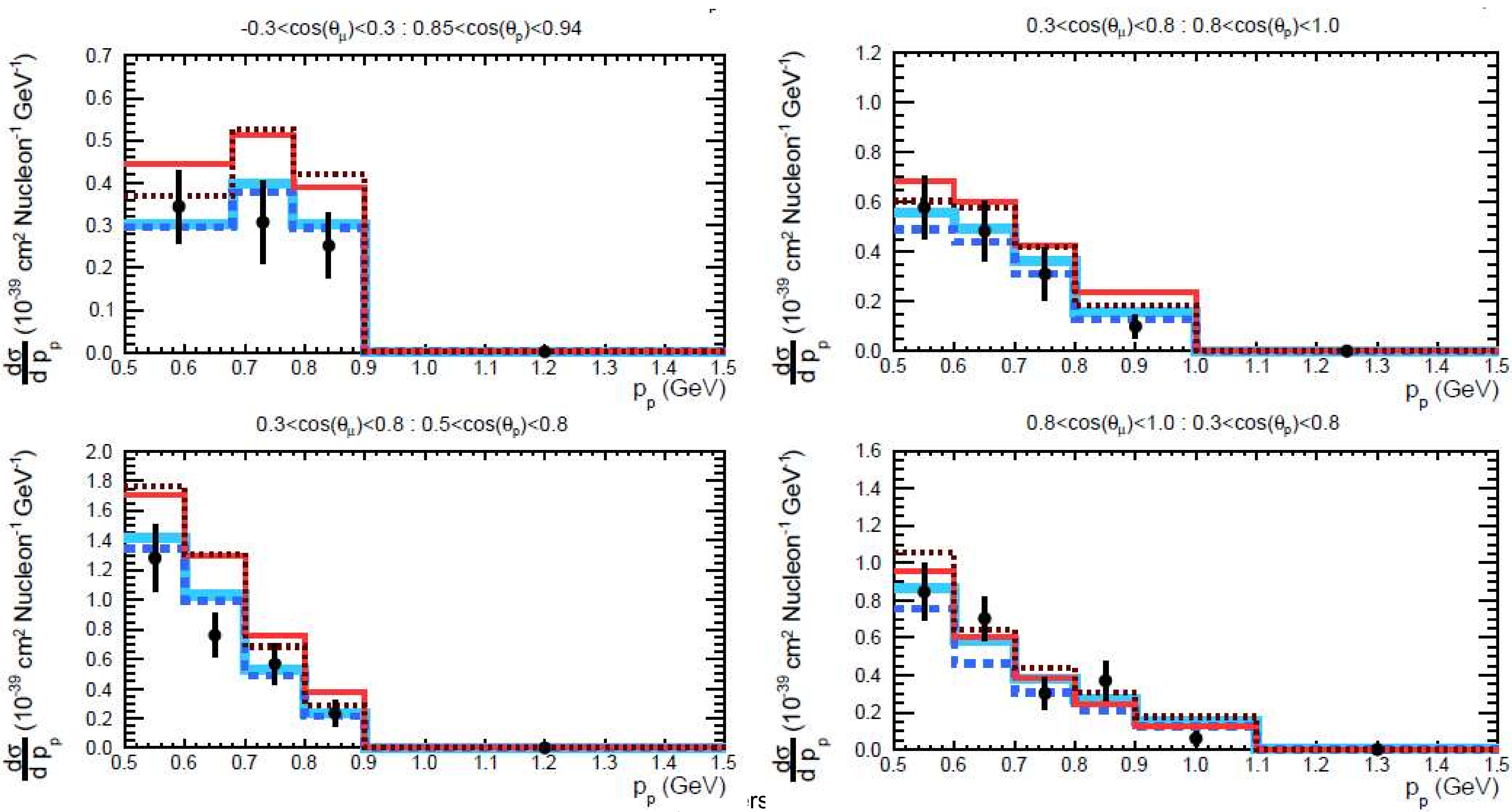


- δp_t with longitudinal imbalance included
- Transition between QE and non-QE regions is interesting

Extracted with
NEUT 5.1.4.2

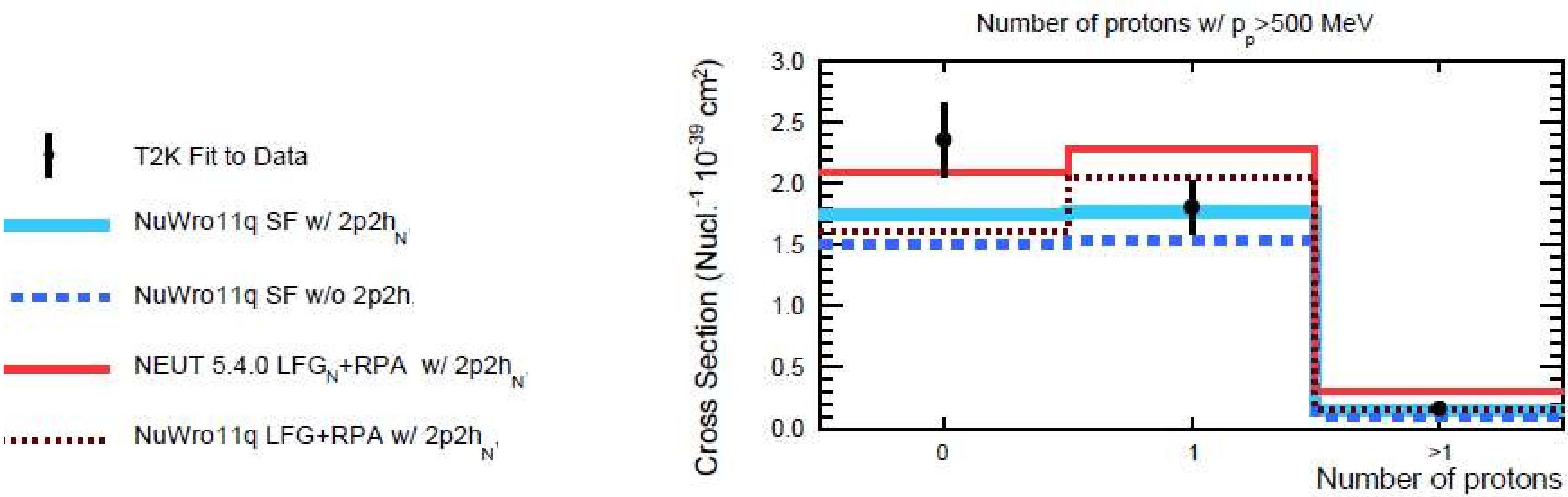
How to visualize a 3D result…

- $Cos(\theta_\mu), Cos(\theta_p), p_p$
- Threshold of proton is 500 MeV/c



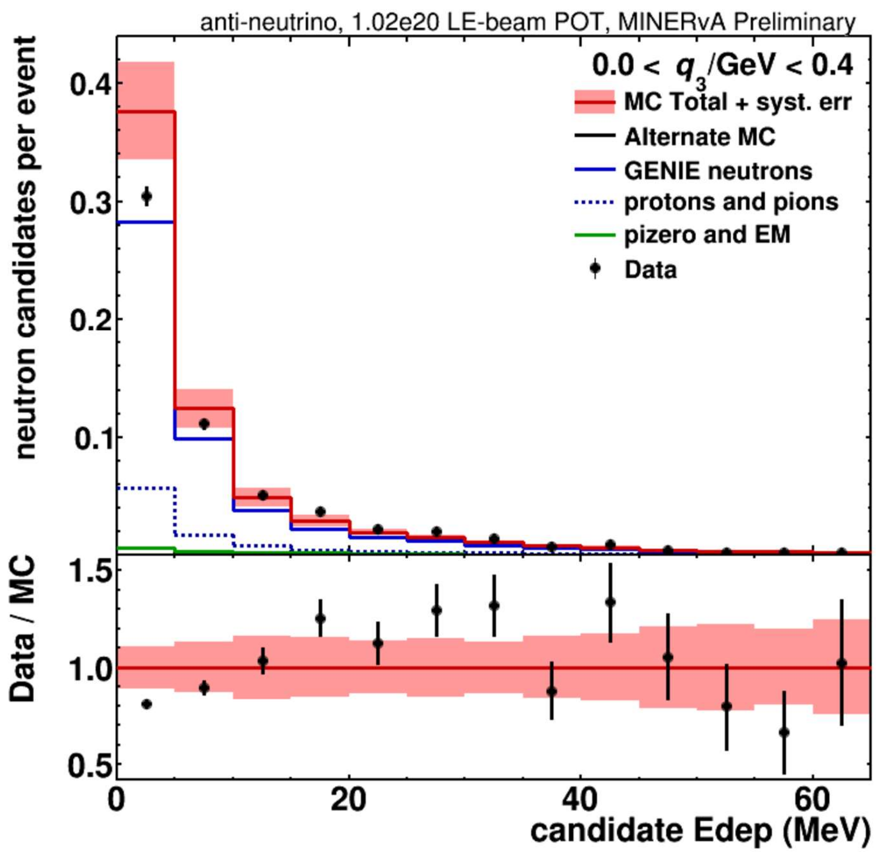
How to present said result??

- Can also extract the number of protons above threshold

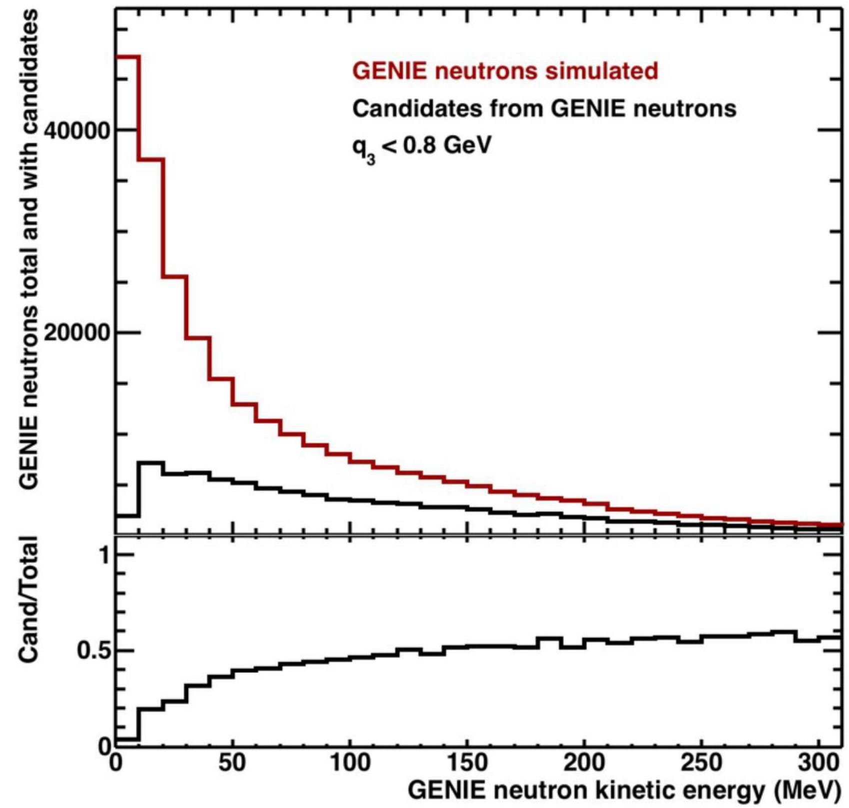


$\bar{\nu}$

Don’t forget the neutrons



Publication in preparation

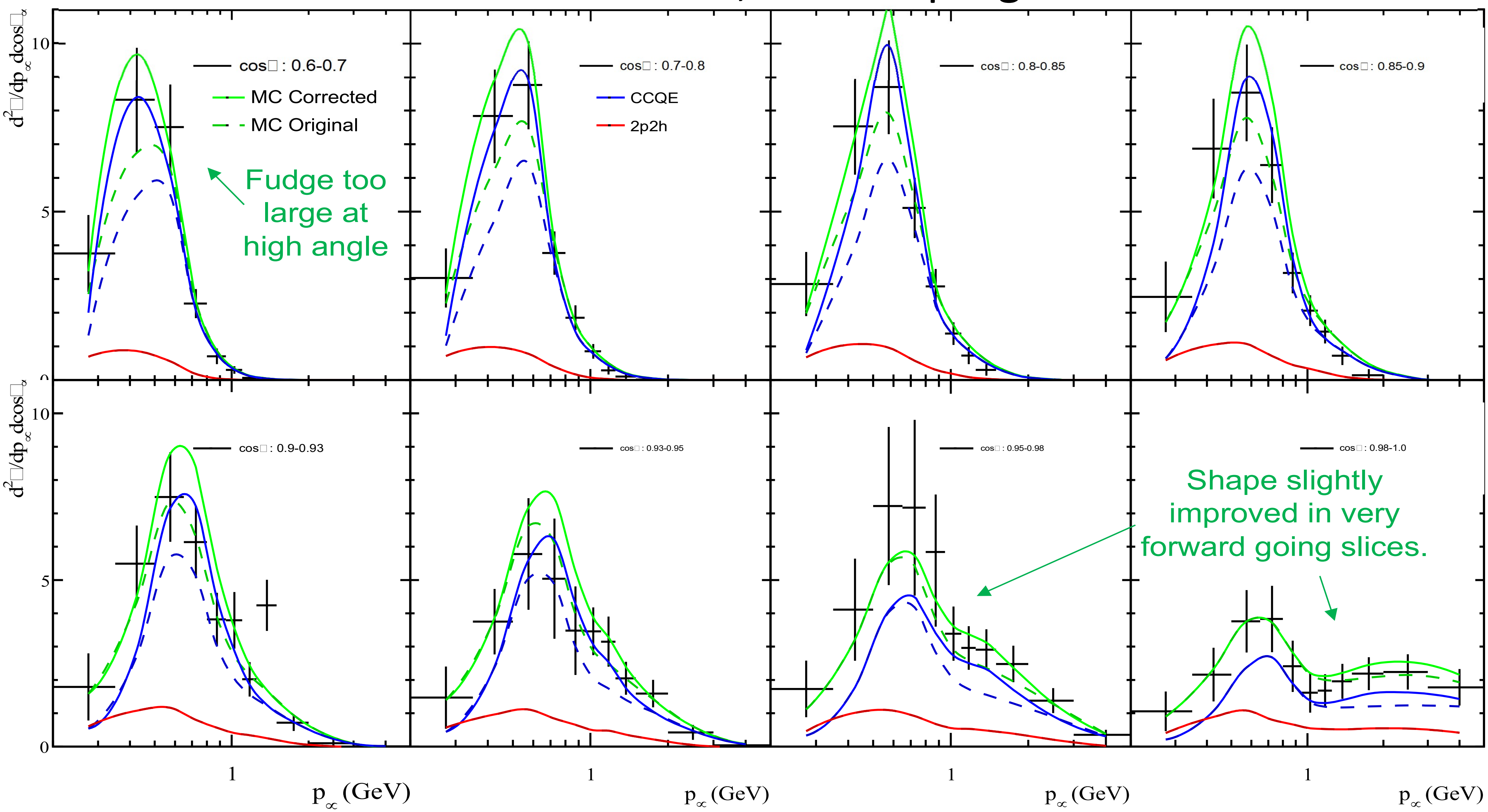


- Using the anti-neutrino low recoil sample we have started counting neutron candidates
- We can measure the time, position (2D or 3D) and energy deposited.

Example of cross experiment work

Application To T2K CC0π

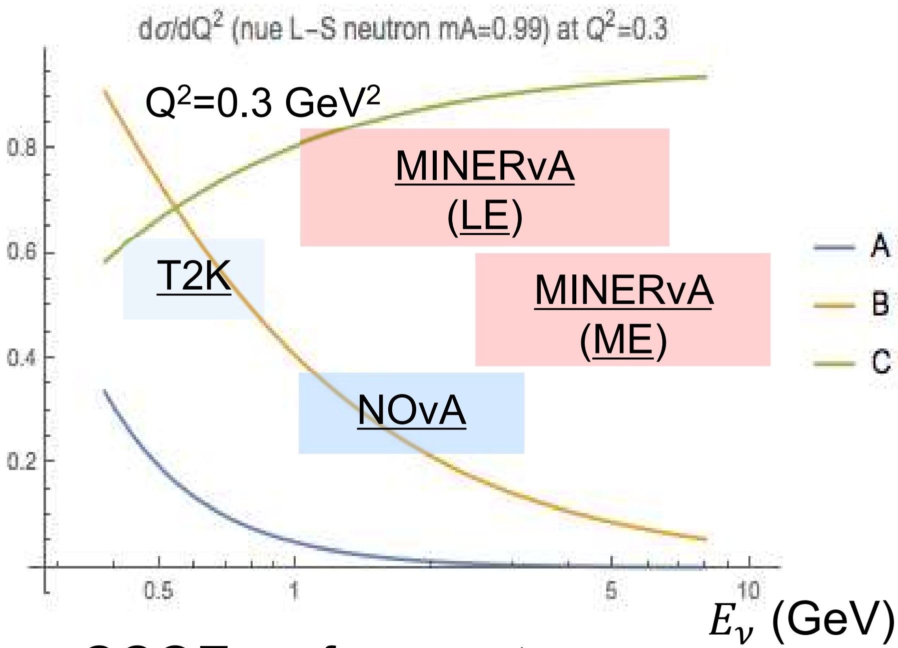
Patrick Stowell, work in progress



Phys. Rev. D93, 112012 (2016)

Could the "MINERvA tune" be Energy Dependent?

- At MINERvA energies, should we expect any? Not much. Dominated by C term



CCQE on free neutrons

- What are the A, B, C terms?

- It turns out that there is a general form for energy dependence in exclusive and inclusive reactions on nucleons

$$E_\nu^2 \frac{d\sigma}{dQ^2 d\nu} = \breve{A} + \breve{B} E_\nu + \breve{C} E_\nu^2$$

- This holds for QE, 2p2h, etc.

An expansion similar to eq. (2.5) holds for $\sum\sum m_{\mu\nu}$ in terms of k and q. Hence, whatever the explicit form of the lepton and hadron currents:

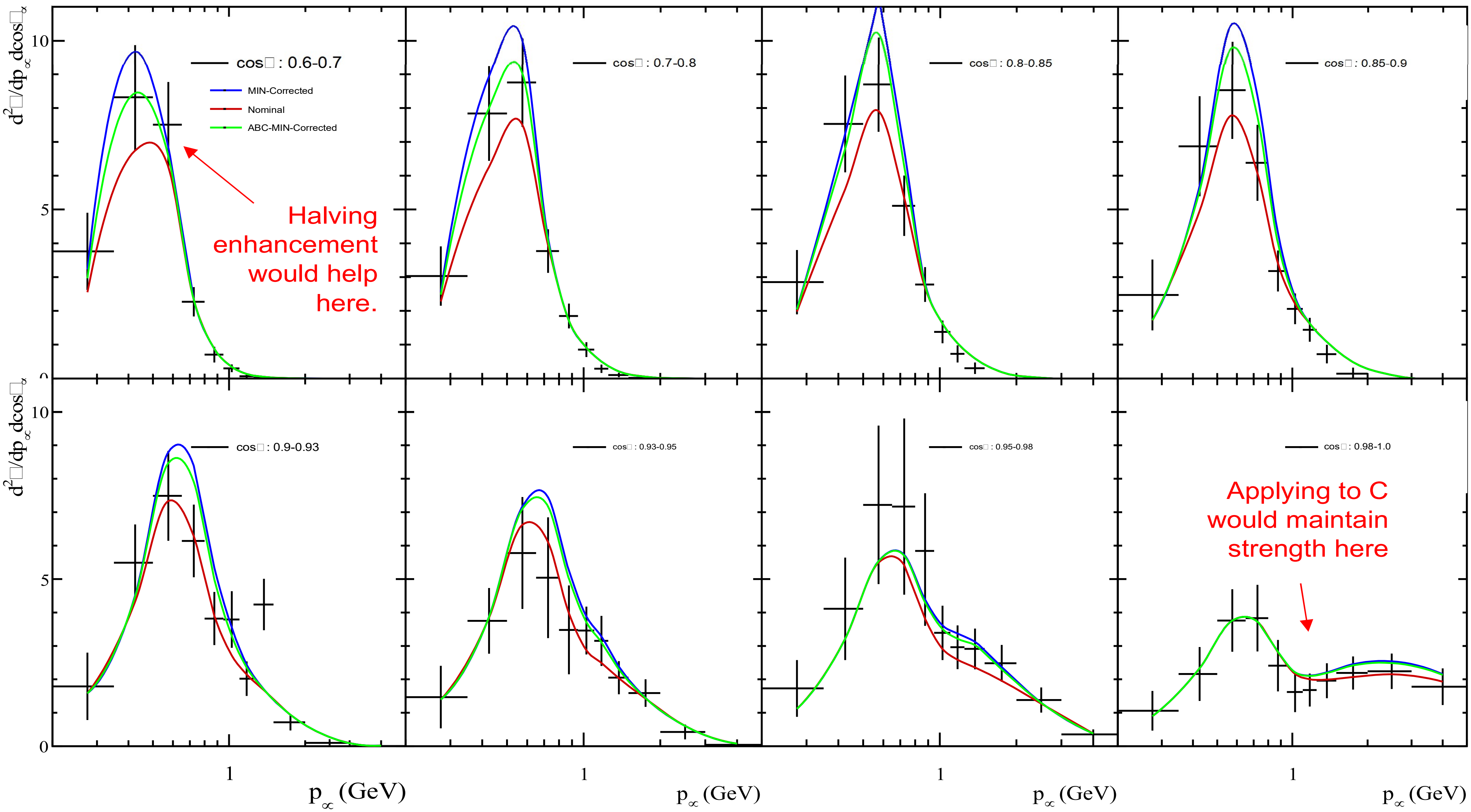
$$\overline{\sum}\sum m_{\mu\nu} \quad \overline{\sum}\sum W^{\mu\nu} = A + Bk\cdot P + C(k\cdot P)^2 , \qquad (2.7)$$

a quadratic polynomial in the laboratory energy $E_\mu = k\cdot P/M$ whose coefficients A, B and C depend on ν, q^2, and the reaction in question [L14, P2], It follows that if the interaction is of the current-current form *then* $E_\nu^2\, d^2\sigma/dq^2 d\nu$ *is a quadratic polynomical in* E_ν (cf. eqs. (2.10) and (2.11)) and therefore *only three combinations of structure functions are obtained if the final lepton polarization is not observed.* An alternative way to obtain the same result is to note that

C.H. Llewellyn Smith, Phys. Rep. 3 261-379 (1972), p. 280

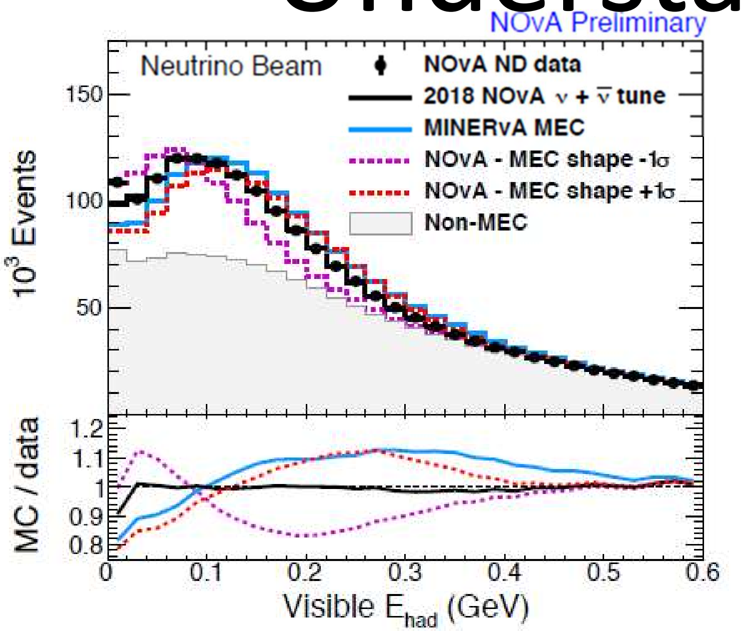
Apply to T2K C term for CC0π

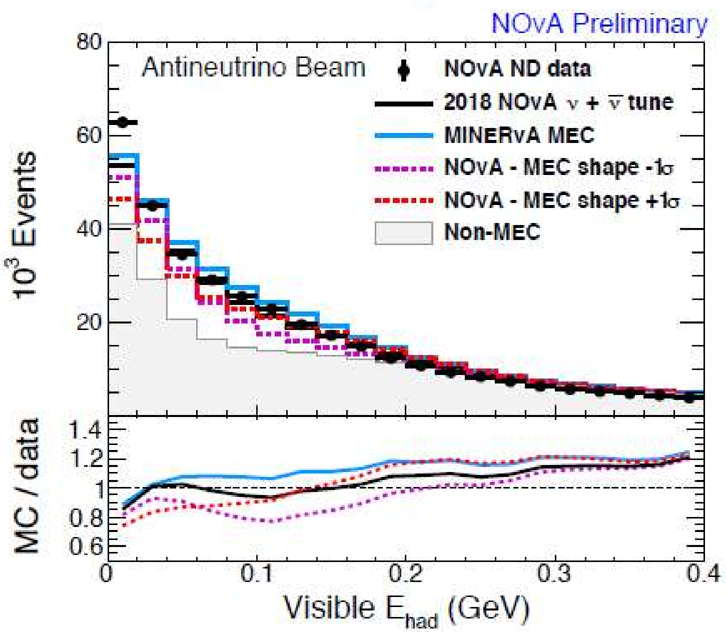
Patrick Stowell, work in progress



Phys. Rev. D93, 112012 (2016)

NOvA
Understanding Visible Energy





- <u>Modify the default GENIE</u>
  - Turn on custom "Empirical MEC"
    [T. Katori, AIP Conf. Proc.1663, 030001 (2015)]
  - Apply RPA to QE
  - Apply RPA to resonant
  - Non-resonant inelastic with $W > 1.7\ \mathrm{GeV}/c^2$ increased by 10% based on NOvA data
- Modify MEC strength
  - Uncertainty established by using model variations with correlated shifts of the QE and resonant components

Conclusions

- Volume of experimental data of neutrino-nuclei scattering is growing
  - Wide variety of energy regions
  - Varying detector capabilities – different choices of signal
- We want a “model to rule them all”.
  - This needs continued effort, communication, and development between all the experiments
    - Efforts like TENSIONS2016, NuPrint, NuSTEC are valuable!
    - NUISANCE provides a nice toolset to do this!
- We should continue to push our measurement methods and variable choices – New generation of measurements is leveraging the lepton+hadron combined measurements. Maximal model discrimination ability.