

MINER ν A Cross Section Results

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for the MINER ν A Collaboration

August 26, 2019

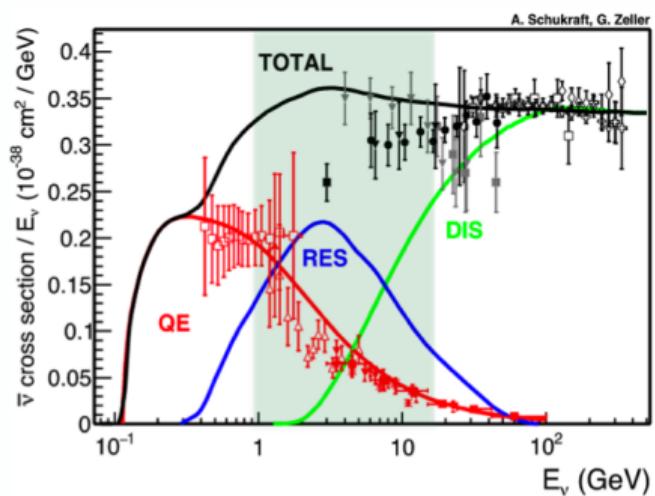
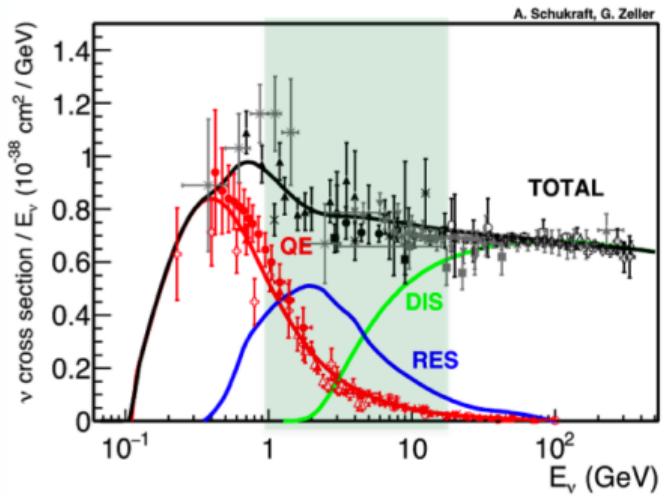
Physics Goals

Study neutrino-nucleus scattering at the few-GeV region

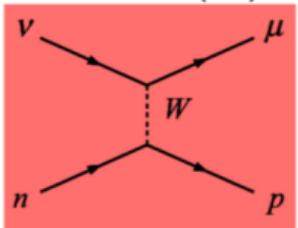
- Precision measurements on signal and background processes relevant to oscillation experiments
- Study nuclear effects to improve understanding of neutrino-nucleus cross section and modelling
- Demonstrate experimental techniques that benefit current and future oscillation experiments



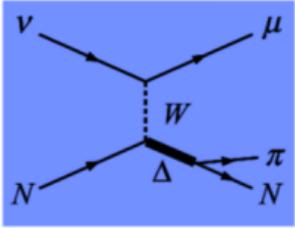
Rich Physics



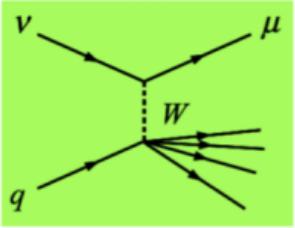
Quasielastic (QE)



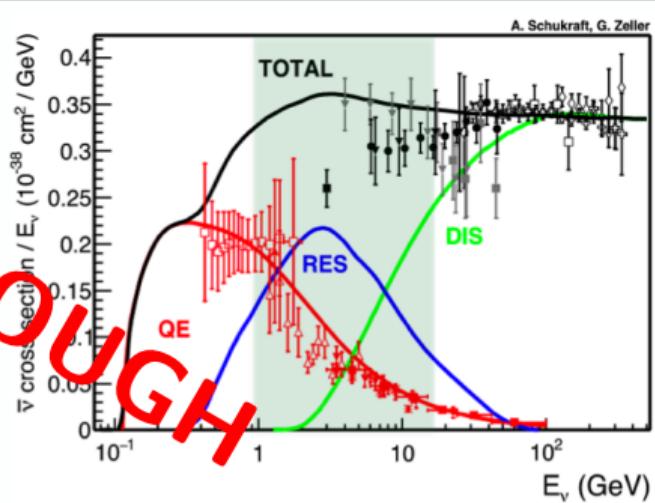
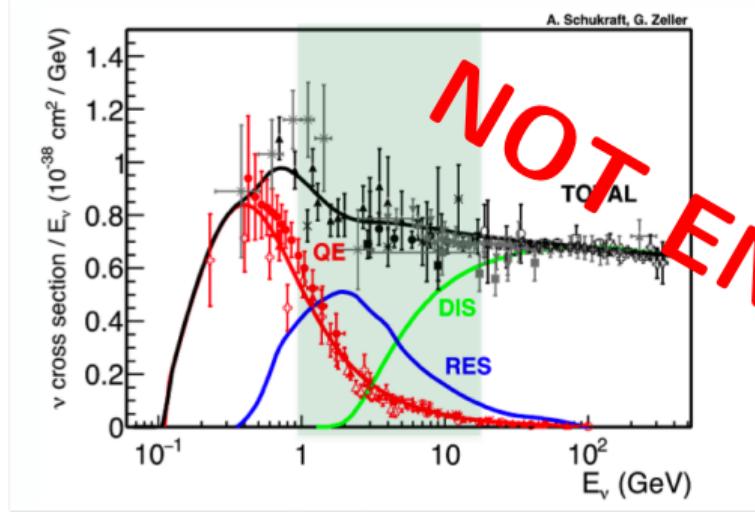
Resonance



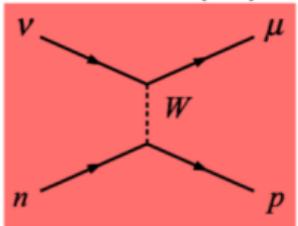
DIS



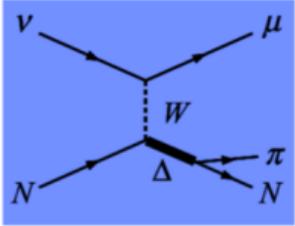
Richer than Expected!



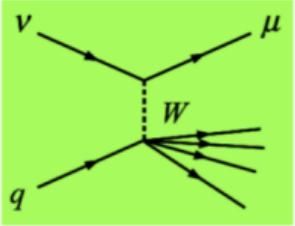
Quasielastic (QE)



Resonance

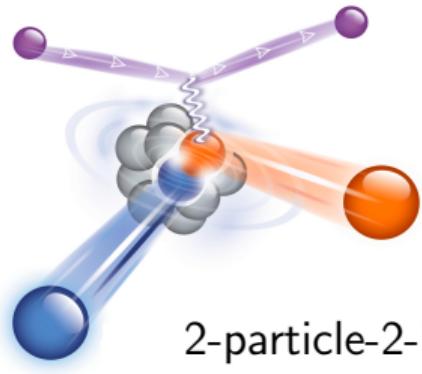


DIS

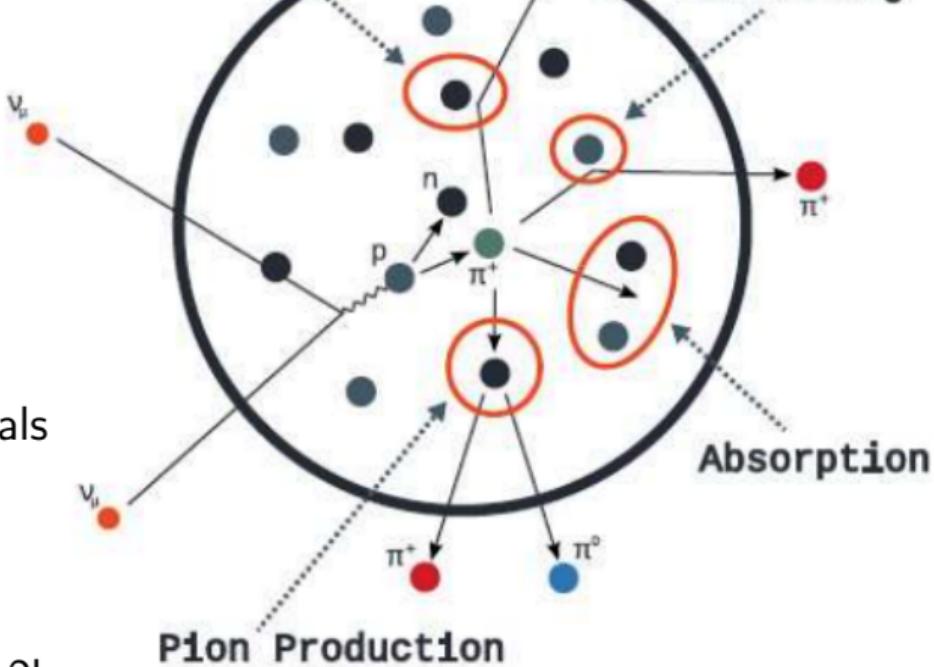


Final State Interactions,
Multinucleon effects,
Coherent ...

Nuclear Effects Affect Oscillation

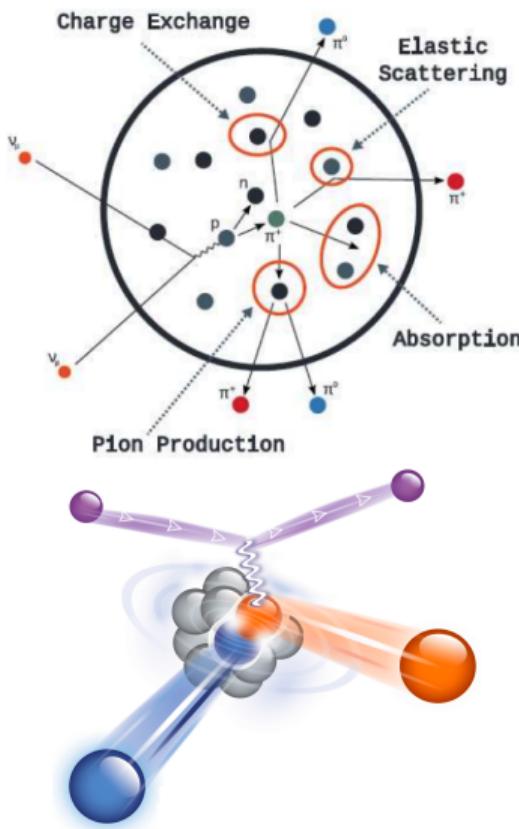


Charge Exchange



Inside nucleus:

- Initial states and nuclear potentials
- Final state interactions, i.e.
 - ▶ Pion production
 - ▶ Pion absorption
- Multi-nucleon correlation, i.e. 2p2h



Neutrino kinematics are reconstructed from the energy-depositing final states in the detectors.

Calorimetric reconstructions can go wrong:

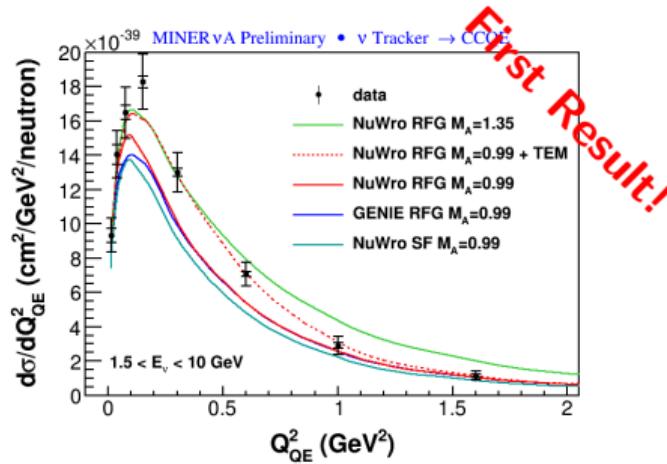
- Pion absorption mimics QE, pion production mimics RES
 - ▶ E_ν reconstructed from the respective hypotheses will be biased, and also inflate systematics
- Many pionless events involve multiple nucleons in the final states,
 - ▶ Significant energy and momentum are lost to the extra outgoing nucleon. Invisible to T2K and MINIBooNE and neutron challenging for NO ν A.

In either cases, the neutrino/anti-neutrino energy reconstruction will have bias and larger systematic uncertainties

MINER ν A aids in developing more accurate nuclear models with precision measurements and new techniques that disentangle the nuclear mess.

MINER ν A Timeline

- 2007 Begin construction
- 2009 Begin Low Energy(LE) data run
- 2012 End LE data run
first publication
- 2013 Begin Medium Energy(ME) data run
- 2019 End ME data run
33 published papers to date
more in the pipeline



Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5 \text{ GeV}$
 Phys. Rev. Lett. 111, 022502 (2013)
 Updated to reflect constrained flux

Data taking is over, but our analyses are not!

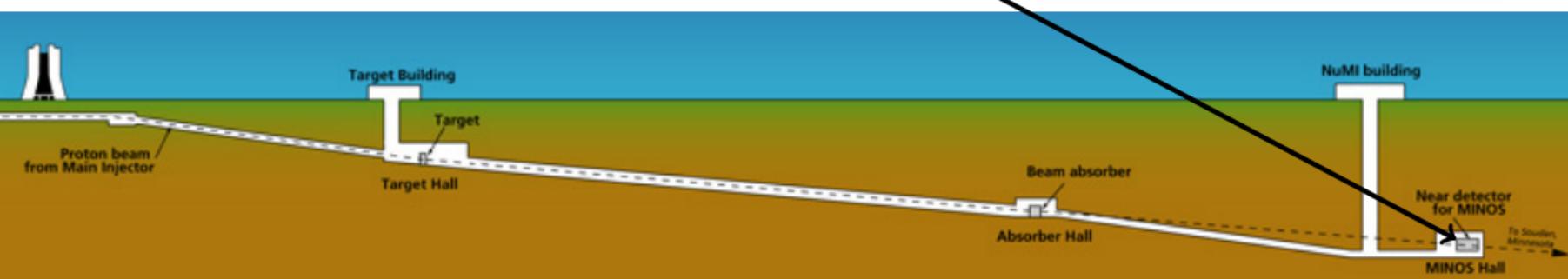
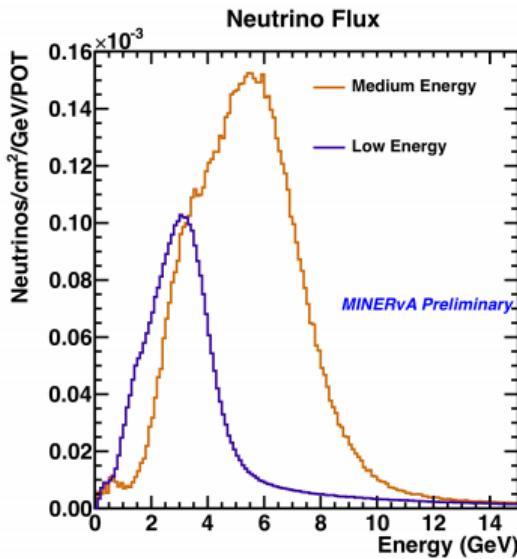
MINER ν A is on-axis in the Fermilab's NuMI beam.

LE flux overlaps with DUNE's.

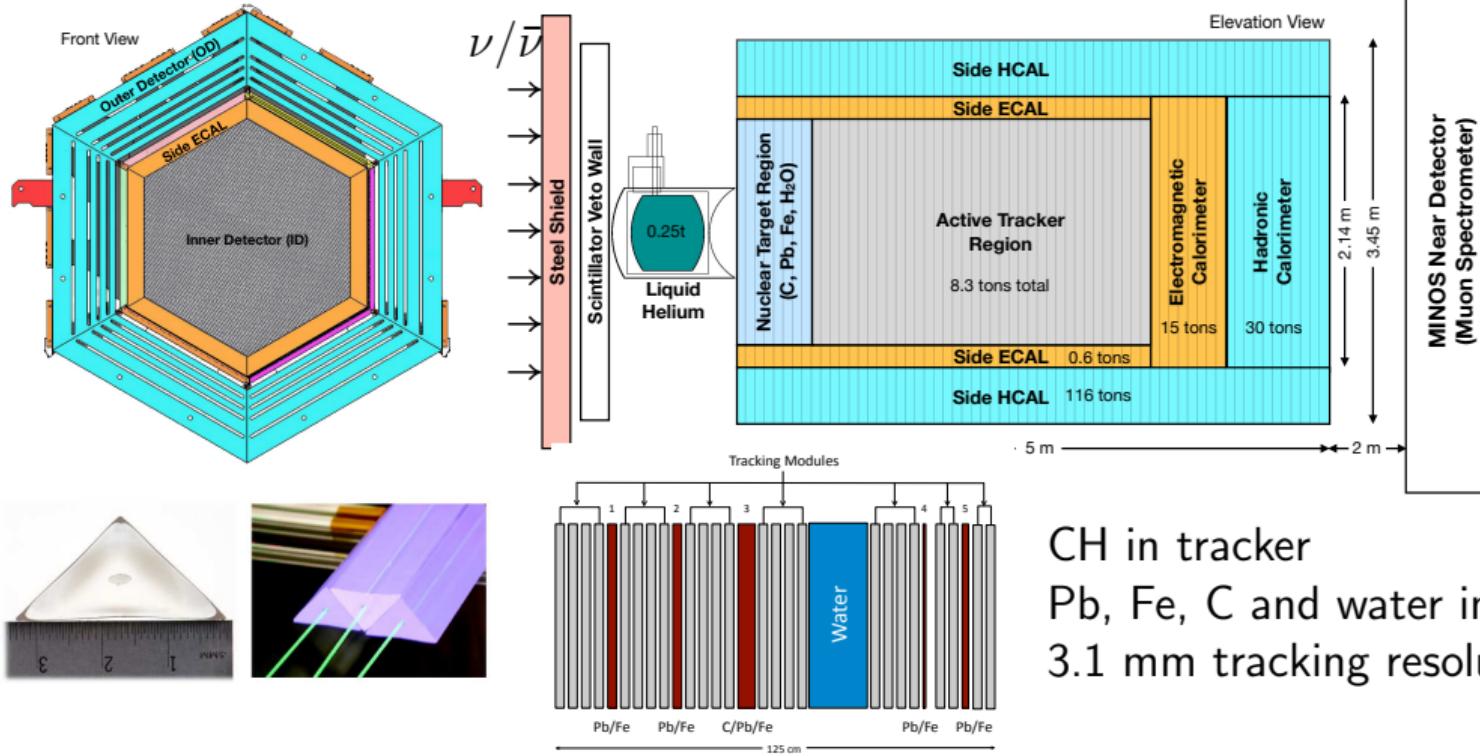
ME has higher statistics and access to expanded kinematics region.

- LE ν POT: 4.0e20
- LE $\bar{\nu}$ POT: 1.7e20
- ME ν POT: 12.1e20
- ME $\bar{\nu}$ POT: 12.4e20

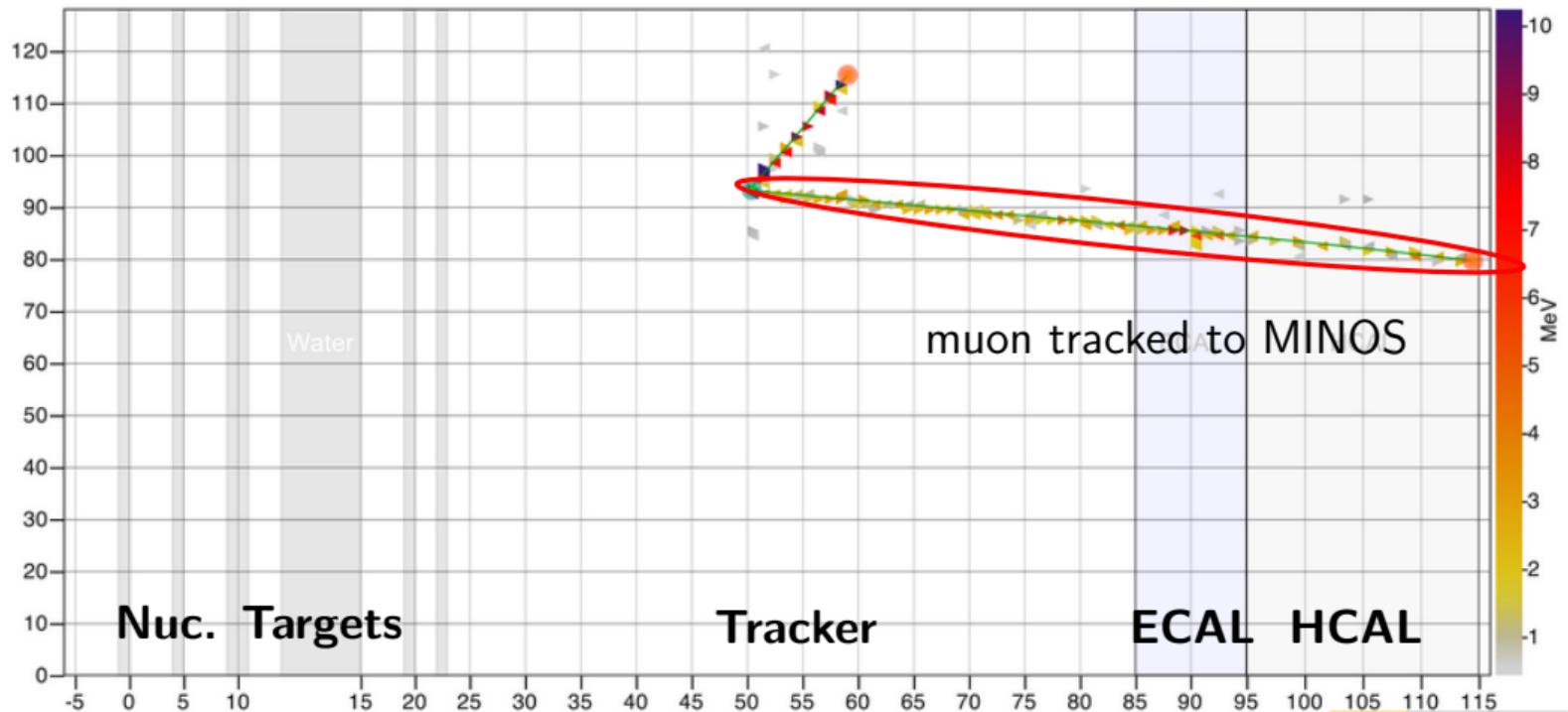
we are here!



High Resolution Scintillator(CH) Detector

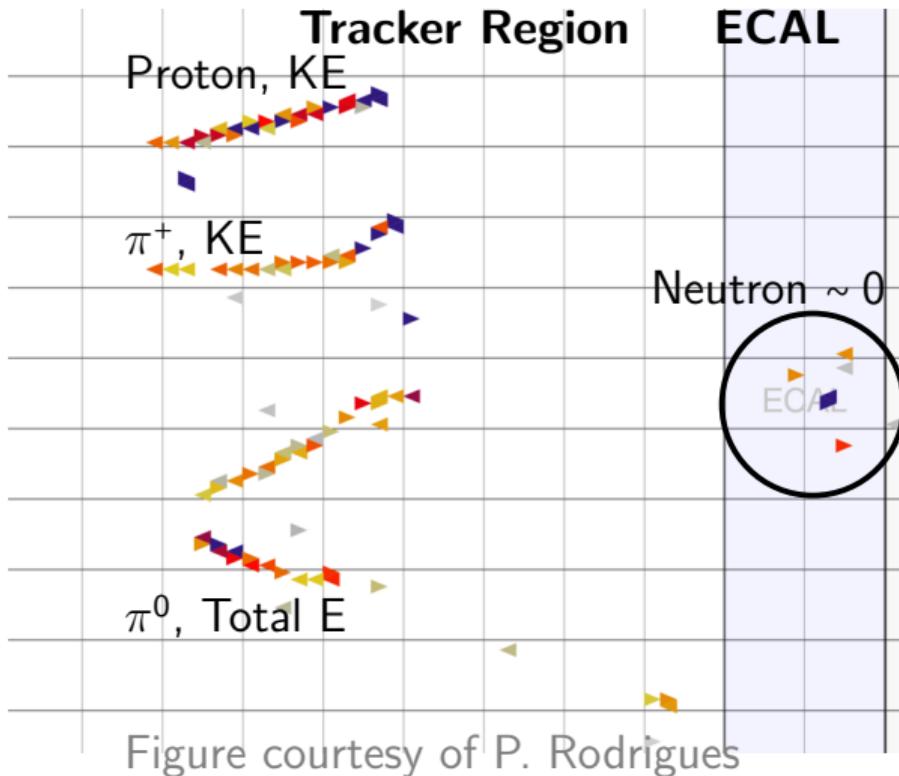


Nucl. Inst. and Meth. A743 (2014) 130.



Sensitivities to Many Final States

- MINER ν A's plastic scintillators are sensitive to small energy deposits
- Hadronic recoils are measured from calorimetry
- Tracking threshold (KE) for proton is ~ 100 MeV
- Neutrons can deposit visible energies (albeit small) after recoil inside scintillator

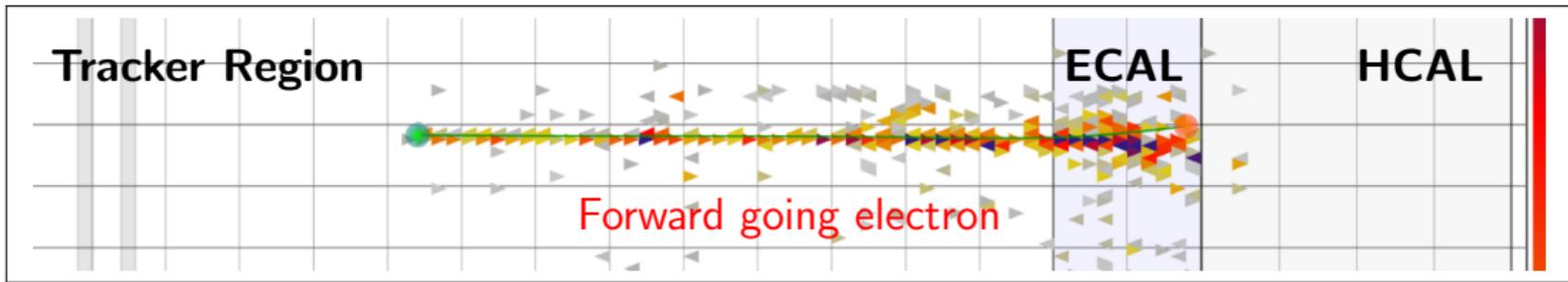


Constraining flux

Flux Normalization: $\nu - e$ Scattering

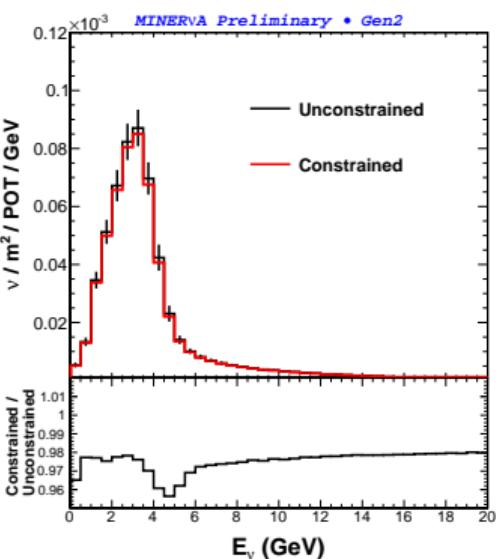
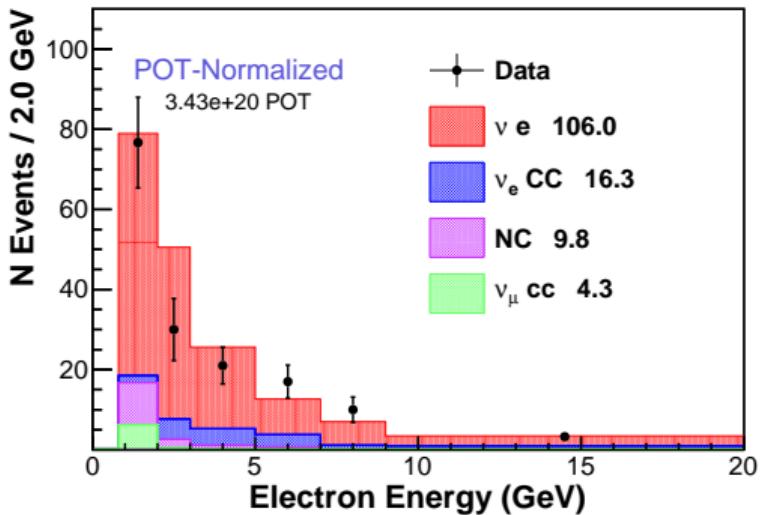
- 😊 MINER ν A pioneered the method
- 😊 $\nu - e$ is standard electroweak process with precisely predicted cross section
- 😢 2000x more rare than $\nu - A$ interactions

- Neutral current processes
 $\nu e \rightarrow \nu e$
 $\bar{\nu} e \rightarrow \bar{\nu} e$
- At $m_e \ll E_\nu$, electrons are very forward going
- The total number of $\nu - e$ events provides strong constraint on the flux normalization



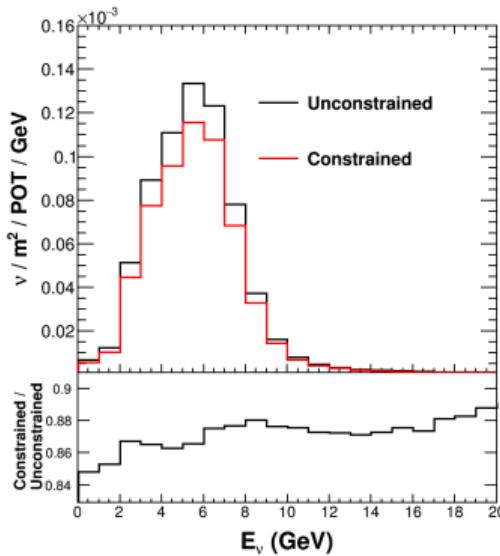
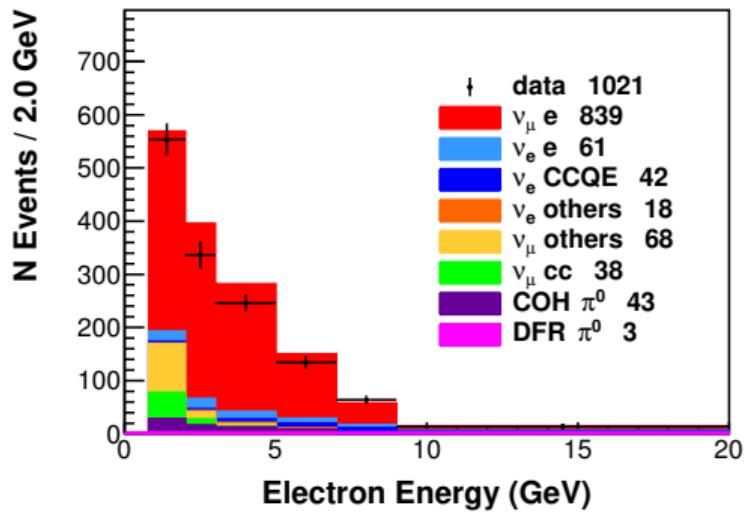
Results with NuMI Low Energy Beam

Phys. Rev. D 93, 112007 (2016)
Paper plot has been updated to reflect
our best understanding of the flux



We've performed the first in-situ flux normalizaiton measurements in the few-GeV region.

New Results with NuMI Medium Energy Beam



Reduce normalization uncertainty on integrated NuMI ν_μ flux from 7.5% to 3.9%.
8x statistics demonstrates $\nu - e$ analysis is viable for future oscillation experiments such as DUNE.

Flux Shape: the Low- ν Method for $\nu \ll E_\nu$

$$\frac{d\sigma}{d\nu} = \frac{G_F^2 M}{\pi} \int_0^1 \left(F_2 - \frac{\nu}{E_\nu} [F_2 \mp x F_3] + \frac{\nu}{2E_\nu^2} \left[\frac{Mx(1-R_L)}{1+R_L} F_2 \right] + \frac{\nu^2}{2E_\nu^2} \left[\frac{F_2}{1+R_L} \mp x F_3 \right] \right) dx \simeq \text{const}$$

and we can derive the flux for $\nu < \nu_0$:

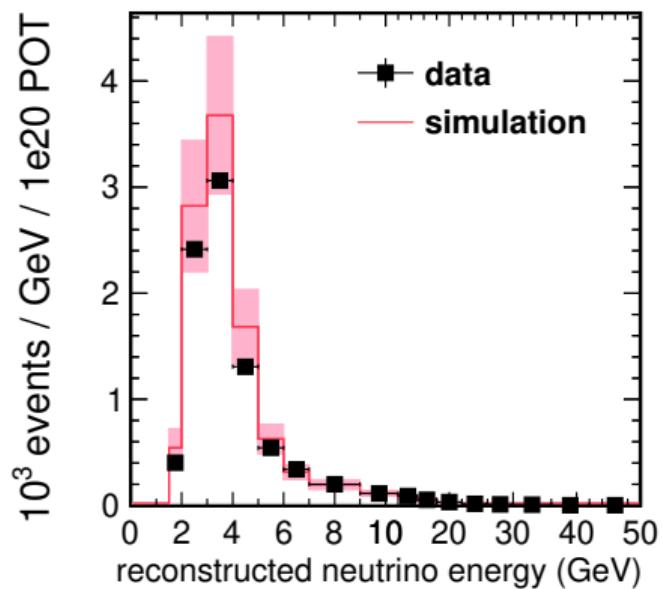
$$\Phi_\nu = \eta_\nu \frac{U_\nu (D_\nu - B_\nu)}{\epsilon_\nu \sigma_\nu^{\text{GENIE}} \# \text{target} \times \Delta E}$$

$\nu_0 = 0.3, 0.8, 2.0$ GeV

ϵ_ν : Acceptance correction

ΔE : Energy bin width

$U_\nu (D_\nu - B_\nu)$: Unfolded event rates after background subtraction



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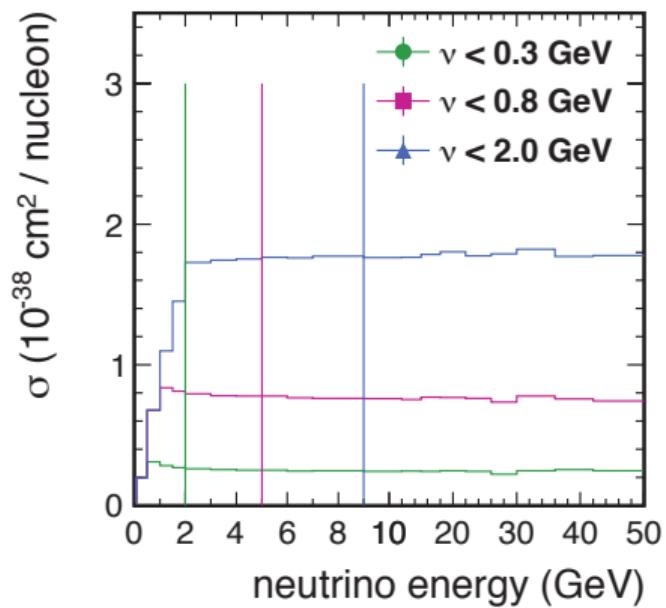
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$\sigma_\nu^{\text{GENIE}}$: $\sigma(\nu < \nu_0, E_\nu)$ from GENIE



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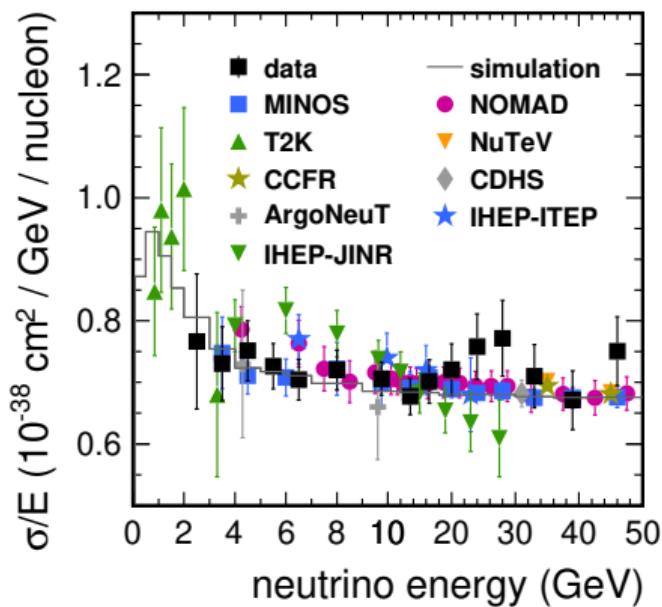
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ΔE : Energy bin width

η_ν : Normalization to $9 < E_\nu < 12$ GeV

NOMAD data



Flux Shape: the Low- ν Method for $\nu \ll E_\nu$

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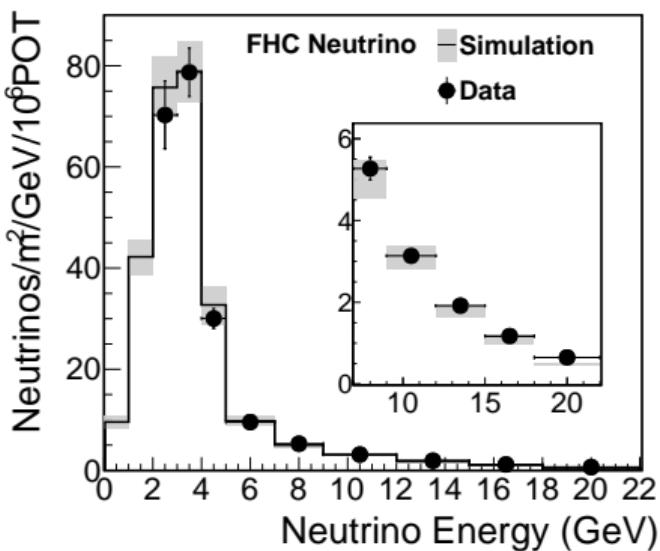
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$\nu_0 = 0.3, 0.8, 2.0$ GeV

ϵ_ν : Acceptance correction

ΔE : Energy bin width

Φ_ν : Flux shape using low- ν method



- MINER ν A has demonstrated in-situ flux constraints:
 - 1 Normalization: $\nu - e$ scattering
 - 2 Shape: low- ν method
- Low- ν method measured inclusive cross-section and provided an excellent cross check of our flux and agreement with the simulation gives us high confidence in the flux
- MINER ν A will extend the low- ν measurement to the Medium Energy
- We are working on a joint analysis between the Low Energy and Medium Energy sample to constrain the flux for a high- ν sample

Stay Tuned!

Model tuning

Glossary

GENIE: the neutrino-nucleus interaction generator used to simulate events

MnvGENIE-v1: A tuned configuration of GENIE based on our Low Energy results

- 1 Random phase approximation (RPA), the long-range correlation
Phys. Rev. D 88, 113007 (2013)
- 2 Non-resonant pion production tuned to deuterium bubble chamber data
Eur.Phys. J. C76, 474 (2016)
- 3 Valencia 2p2h model (incorporated into newer GENIE versions)
Phys. Rev. C 83, 045501 (2011)
- 4 Data-driven tune on the Valencia 2p2h model based on low recoil analysis
Phys. Rev. Lett. 116, 071802 (2016)

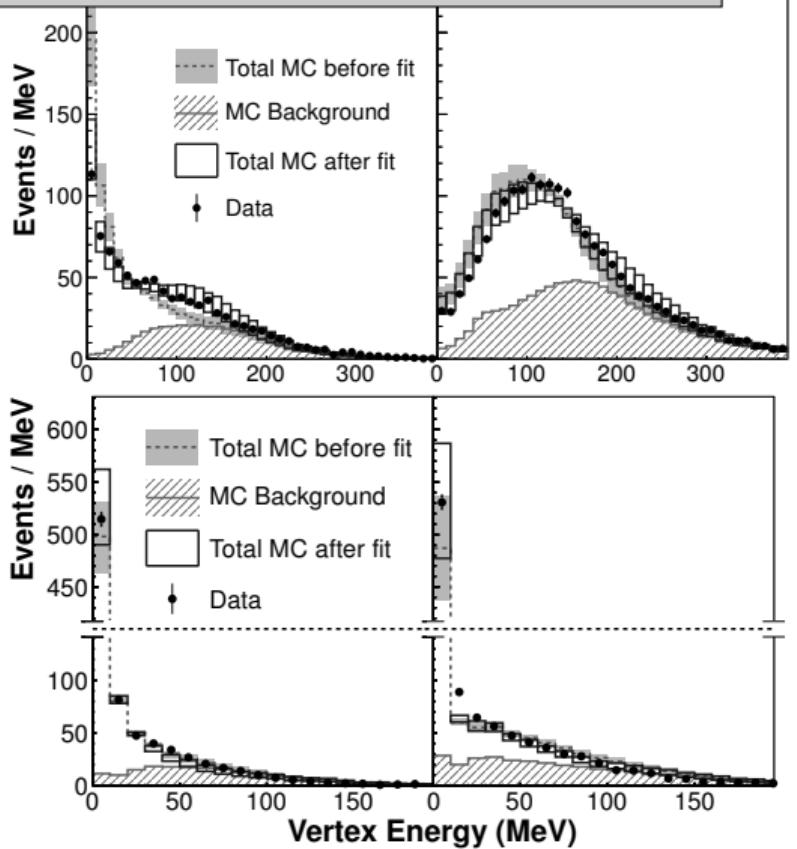
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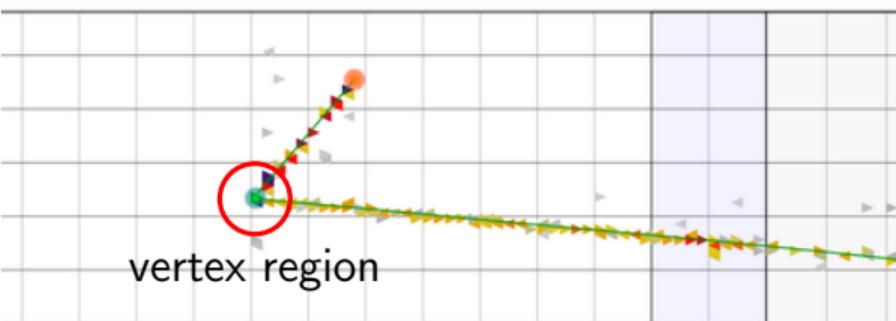
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Phys. Rev. C 83, 045501 (2011)
- 4 **Data-driven tune on the Valencia 2p2h model based on low recoil analysis**
Phys. Rev. Lett. 116, 071802 (2016)

Back to our very first CCQE results



Phys. Rev. Lett. 111, 022502 (2013)
Phys. Rev. Lett. 111, 022501 (2013)



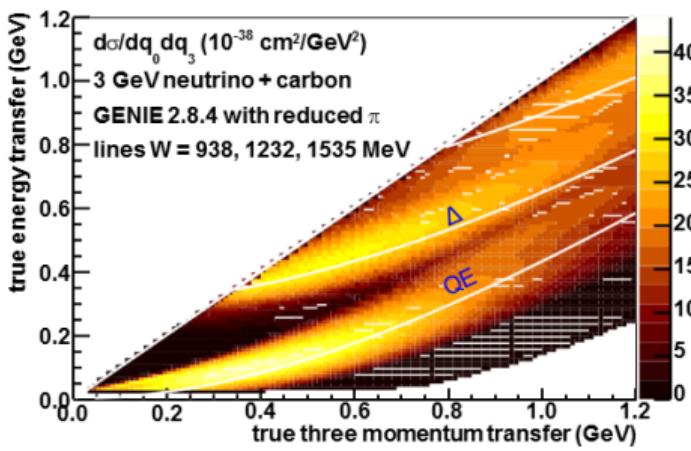
Discrepancies in vertex energy:

- prefer adding proton for ν
- does not prefer adding proton for $\bar{\nu}$
- transverse enhancement
model/2p2h needed

But how do we know it's right?

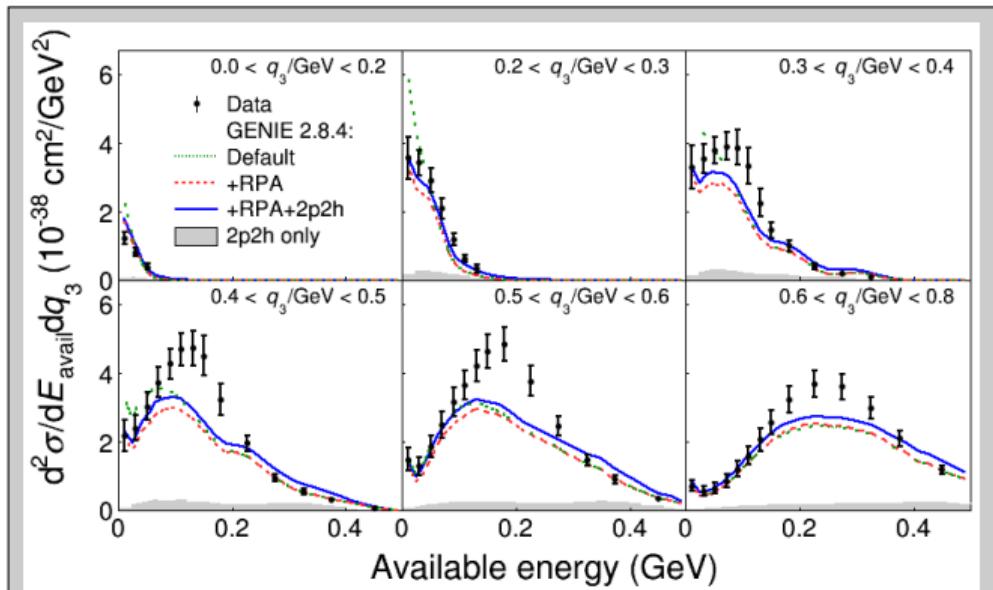
Low Recoil Analysis

MINER ν A has very good calorimetric responses, but terrible particle ID for low energy final states



Define a charged hadronic energy estimator in place of q_0 :

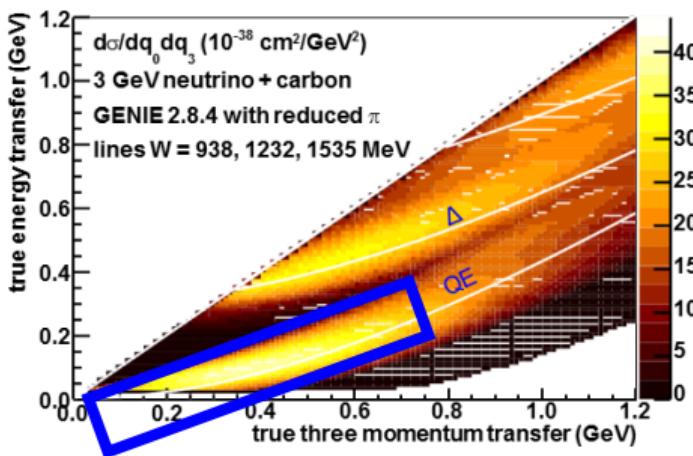
$$E_{\text{avail}} = \sum T_p + \sum T_{\pi^\pm} + E_{\text{particles other than neutrons}}$$



Phys. Rev. Lett. 116, 071802 (2016)

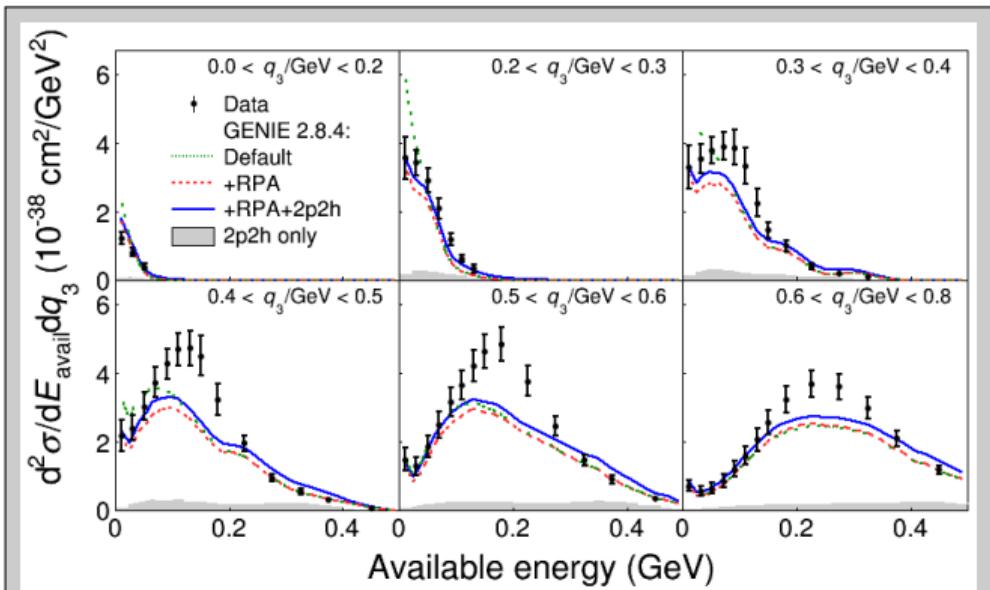
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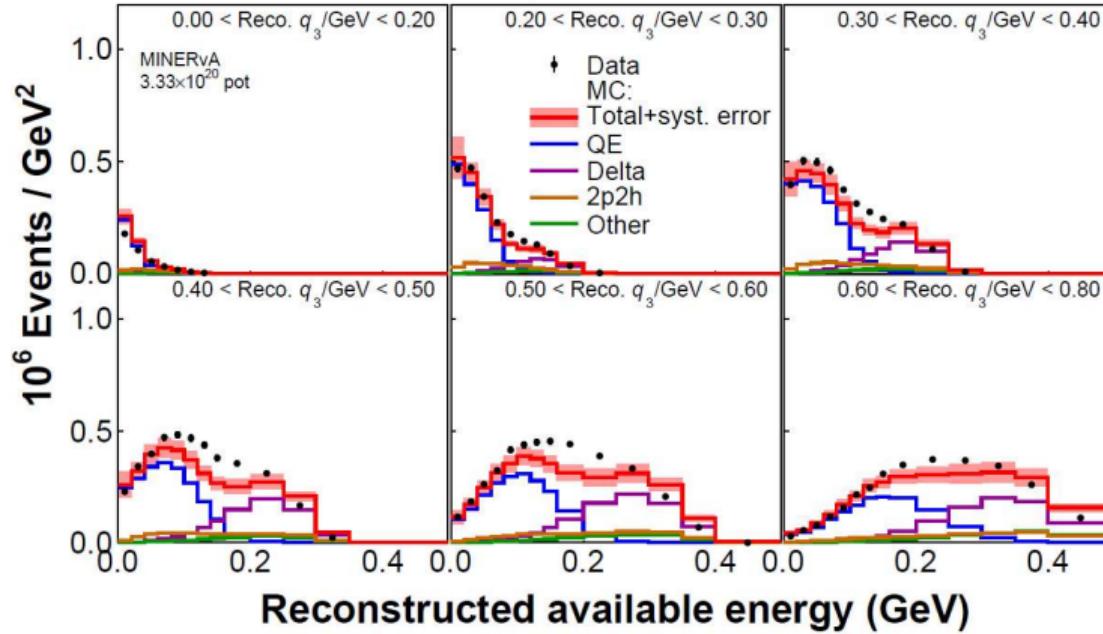
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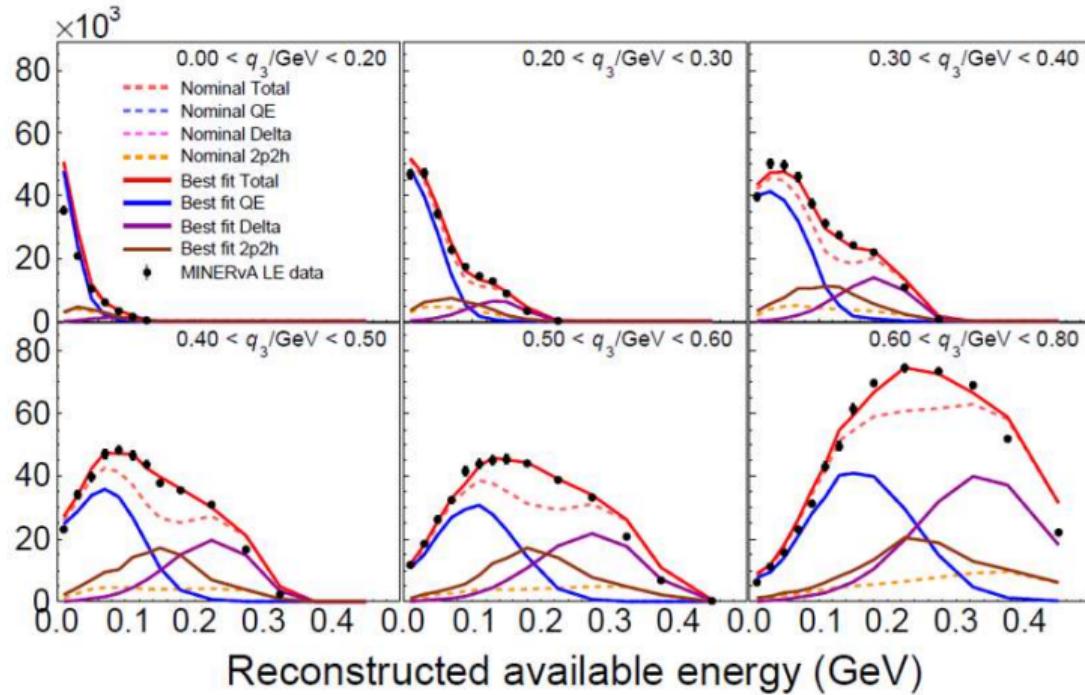


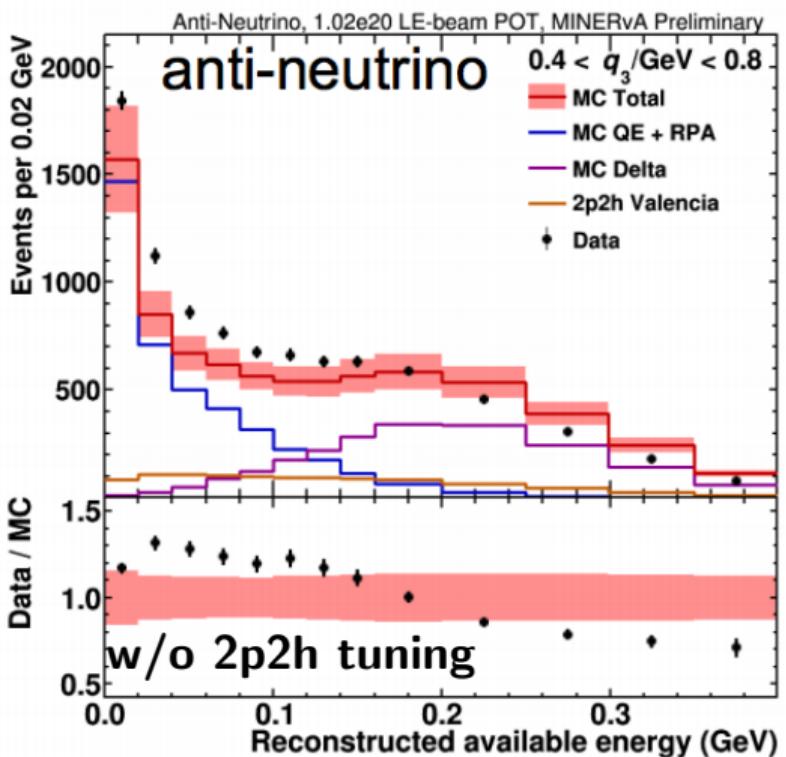
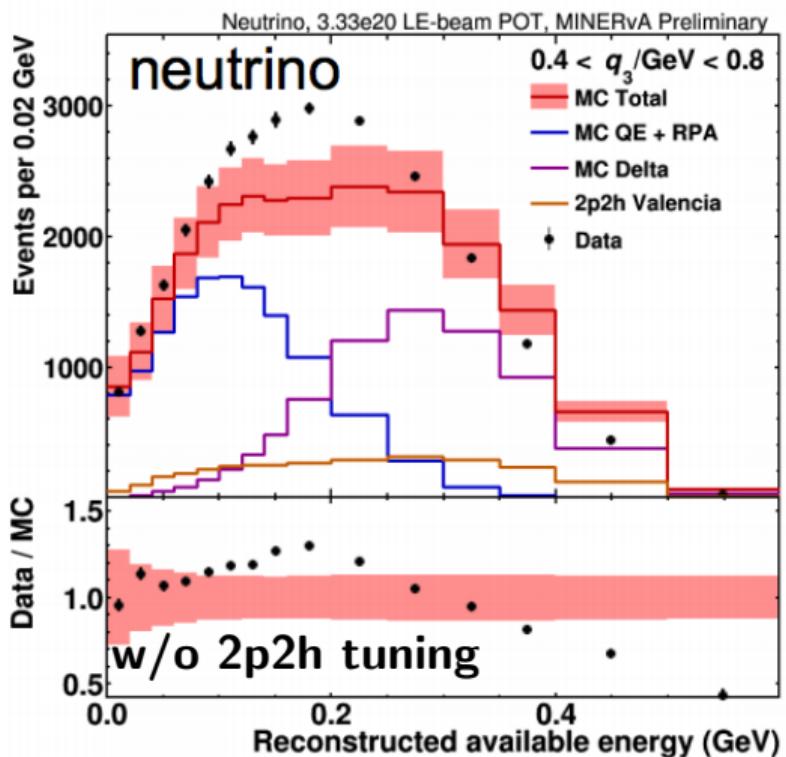
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Has all the MINER ν A tunes except 2p2h modification:

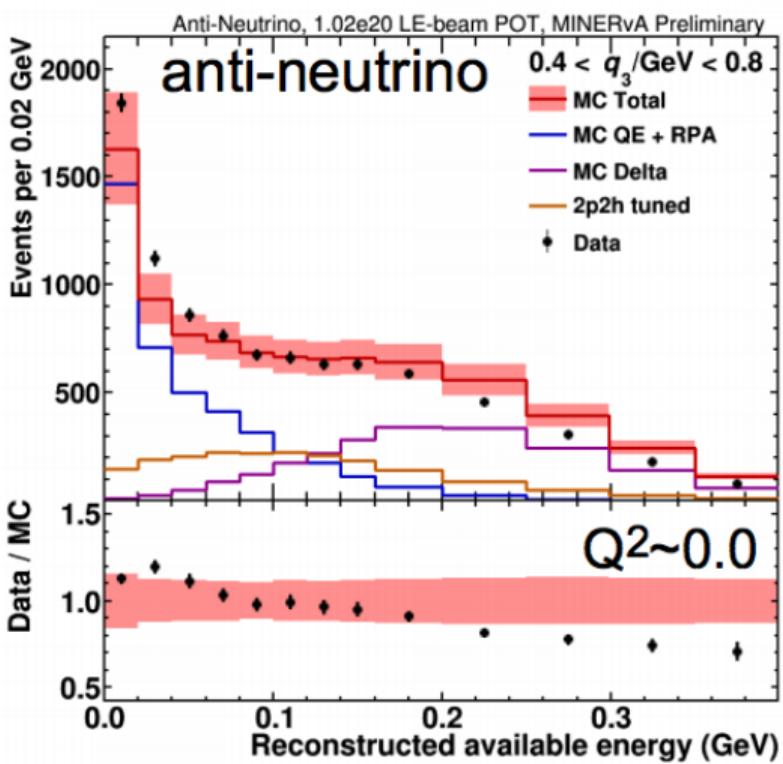
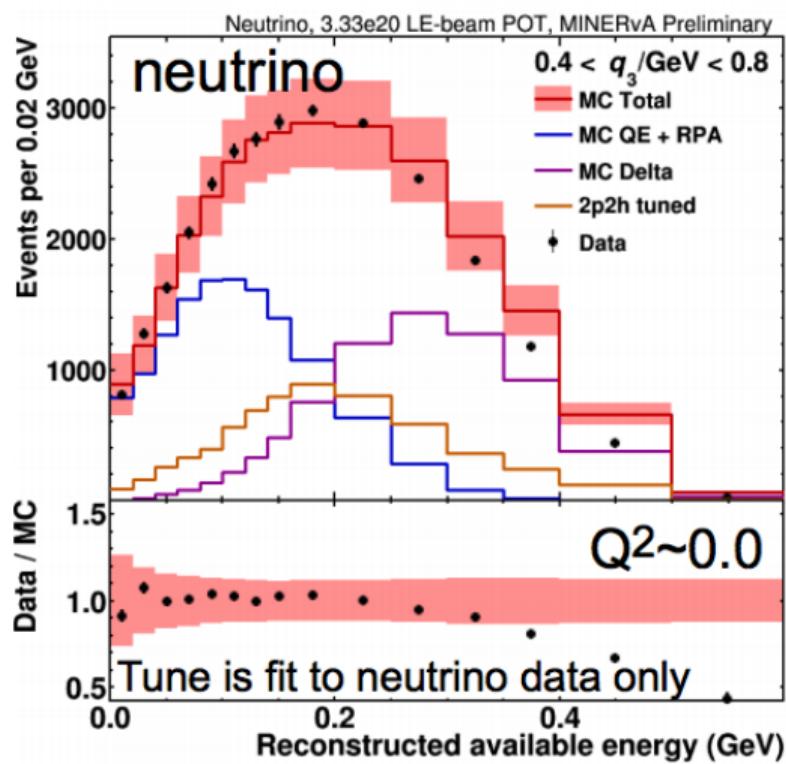


Has all the MINER ν A tunes except 2p2h modification ... not enough, we tune 2p2h to fill in the deficiencies



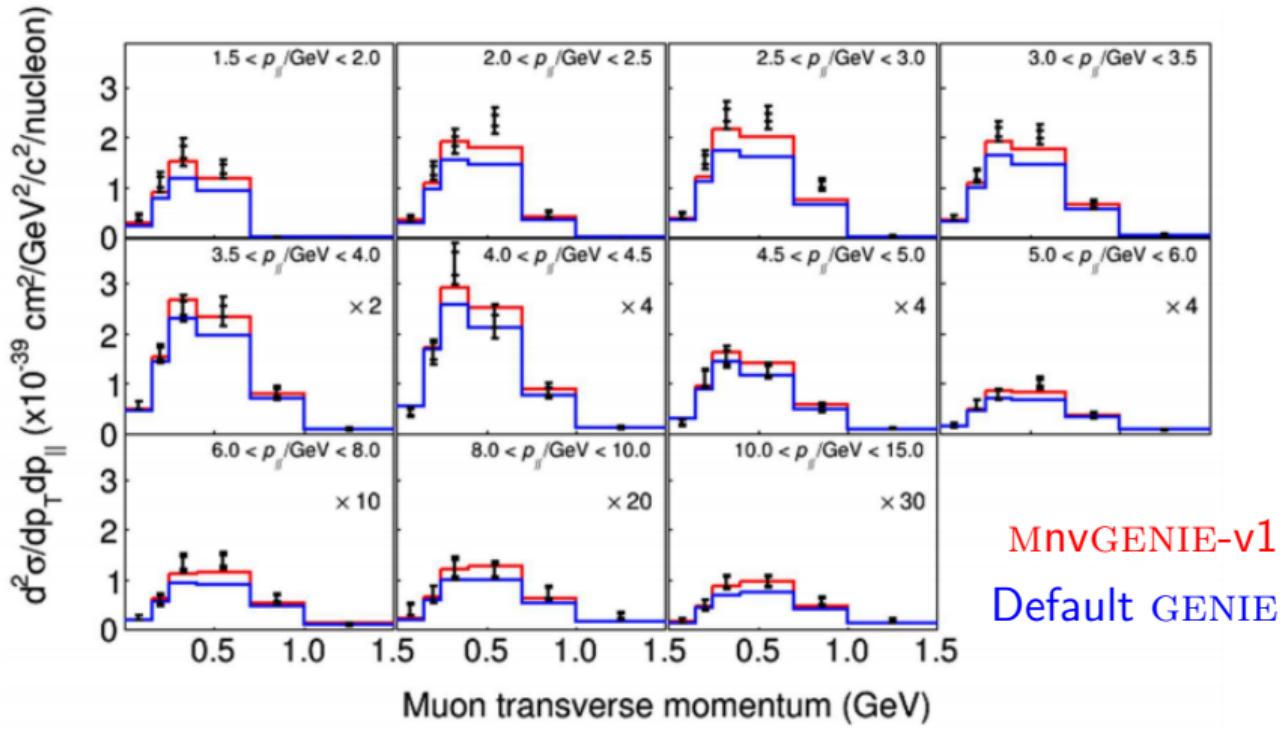


We also consider the effects on anti-neutrino.



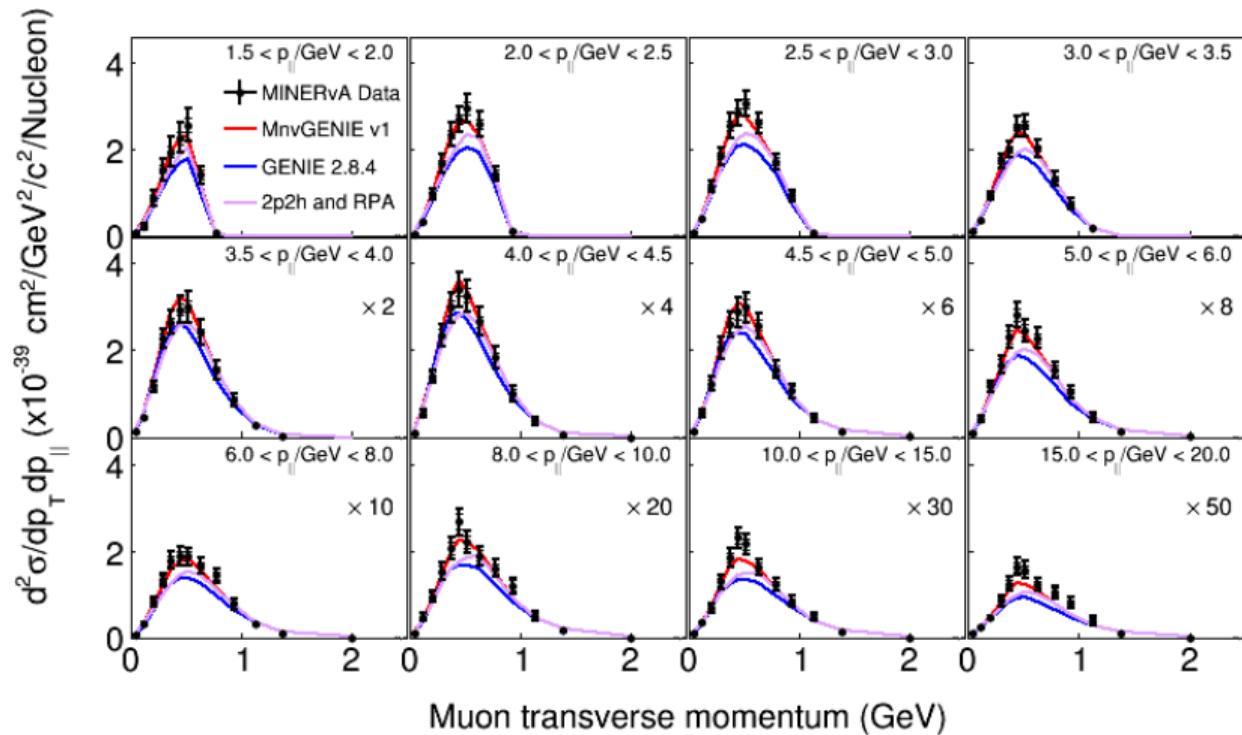
Neutrino tune works! There seems to be low Q^2 suppression

Applying tuning: QE



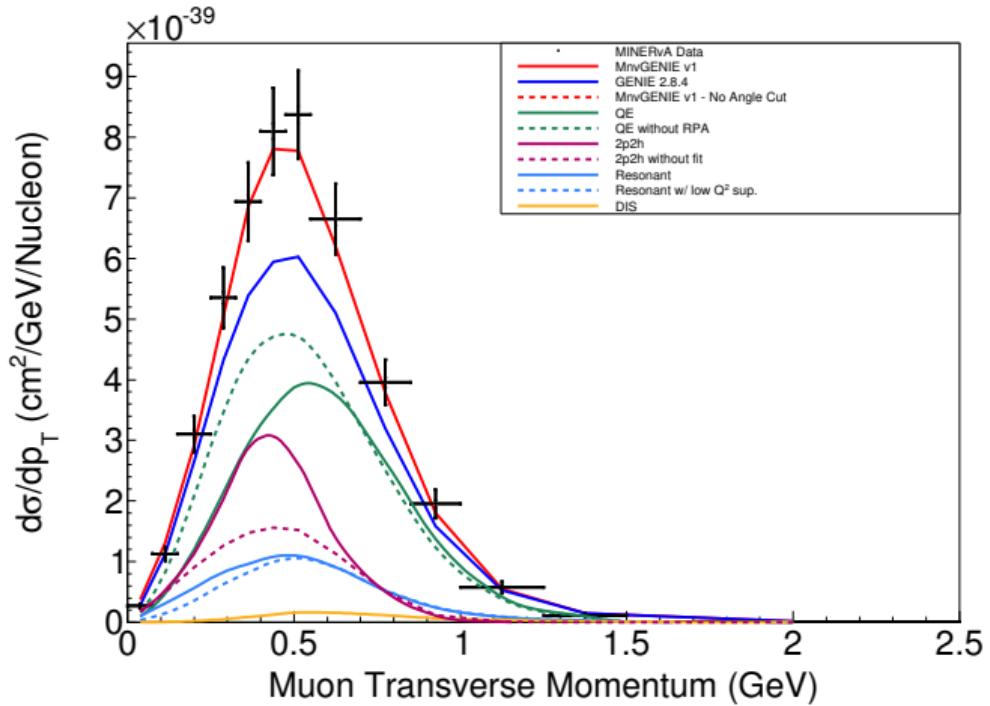
$\bar{\nu}$ double differential CCQE-Like measurements

- Better agreement between data and MC



ν double differential CCQE-Like measurements

- The tune improves agreement between data and MC

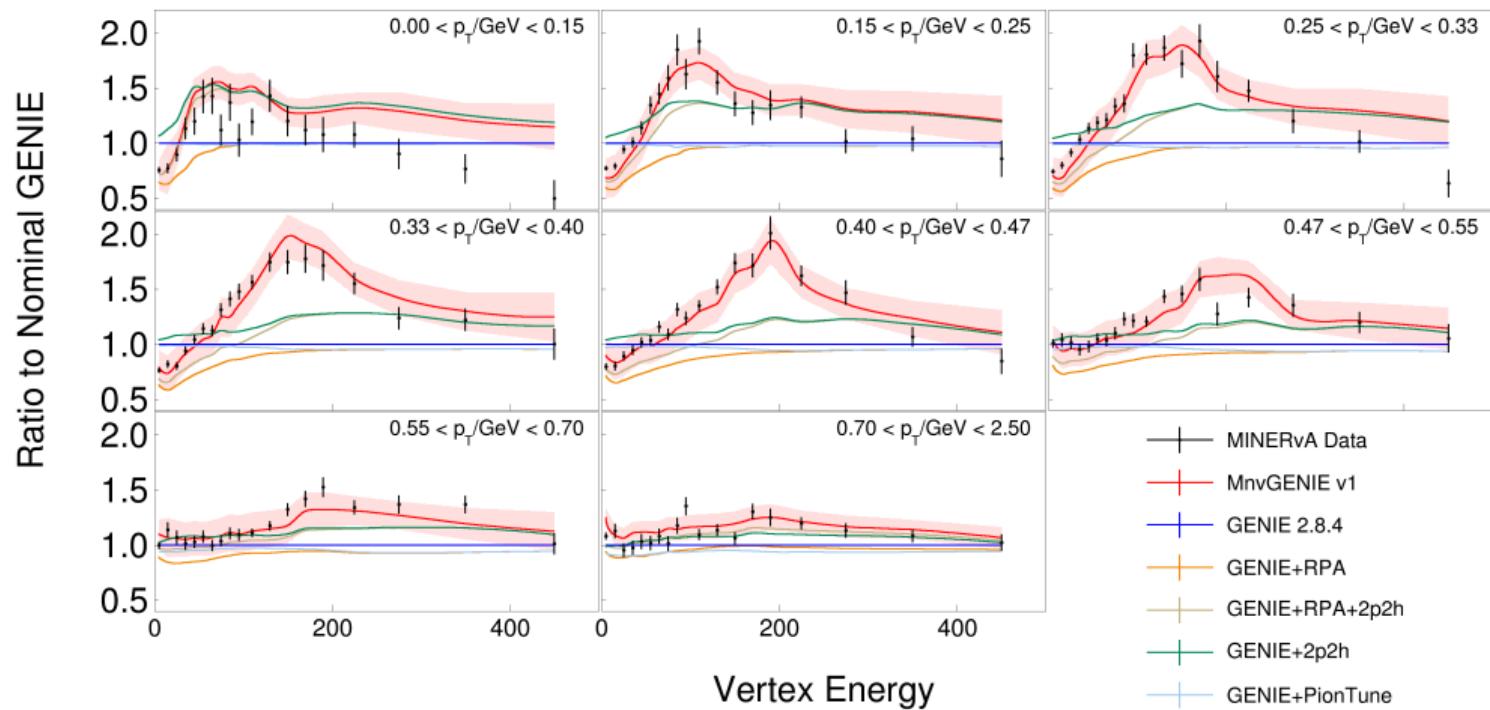


ν double differential CCQE-Like measurements

- The tune improves agreement between data and MC

Applications of MINER ν A Tunes ^{QE}

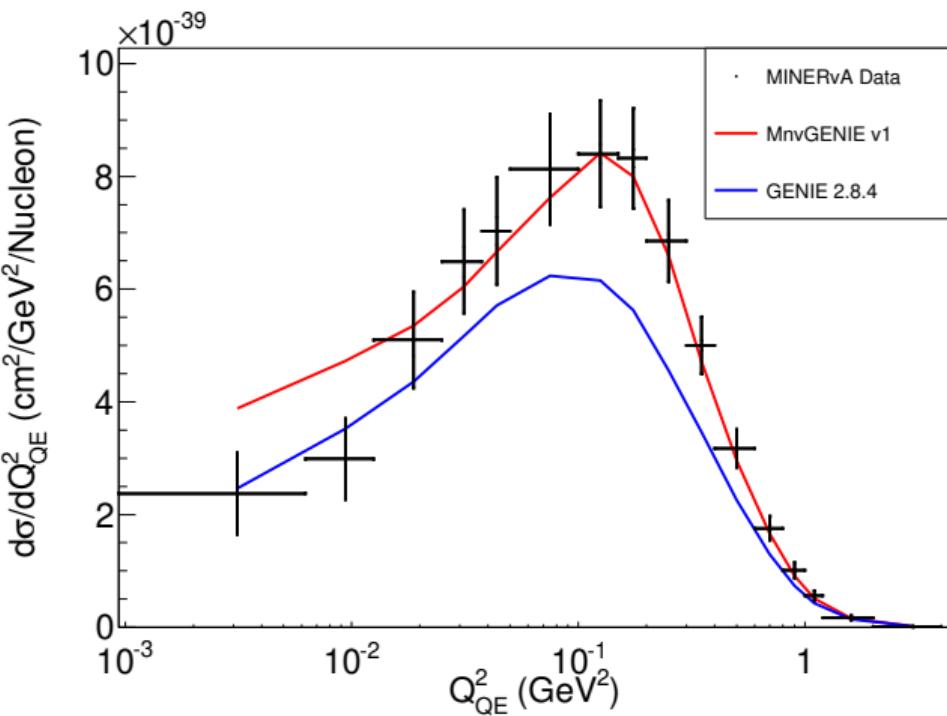
Phys. Rev. D 99, 012004 (2019)



ν double differential CCQE-Like measurements

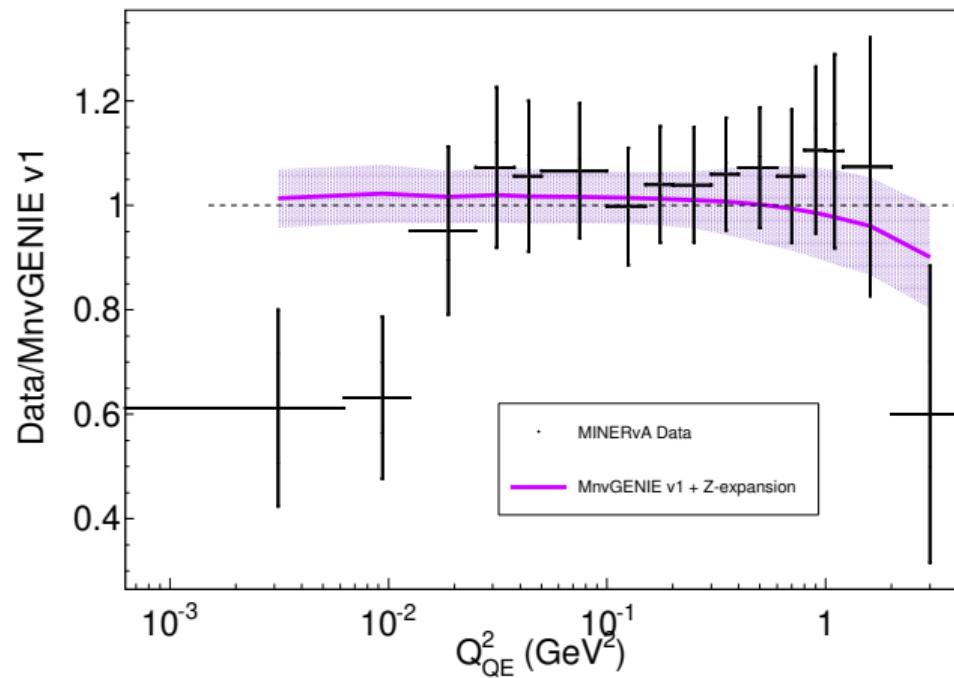
- Discrepancies in the higher vertex energy region—more protons?

- More vertex energy in the lowest p_T bins
- More cross section in the lowest Q_{QE}^2 bins
- Low Q^2 suppression, we think it's due to pions



ν double differential CCQE-Like measurements

- Discrepancies at the lowest Q_{QE}^2 bins



Highest Q^2_{QE} bins:
MnvGENIE-v1+ Z-expansion

ν double differential CCQE-Like measurements

- Discrepancies at the highest Q^2_{QE} bins suggesting non-dipole form factor

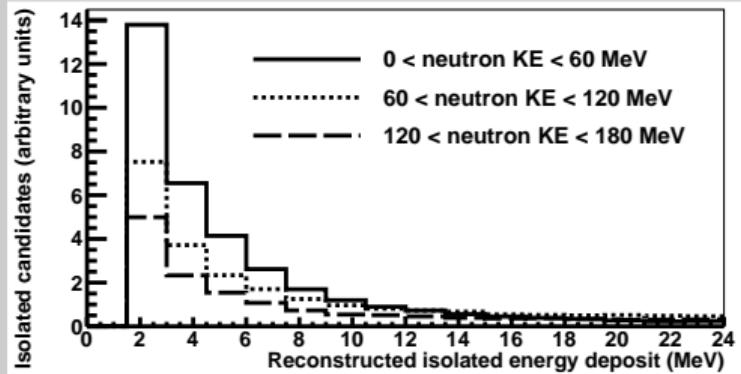
Going to higher dimensions dig up hidden discrepancies
Our ME results will feature much more statistics

Seeing neutrons

Bonus background from low recoil analysis: neutrons!

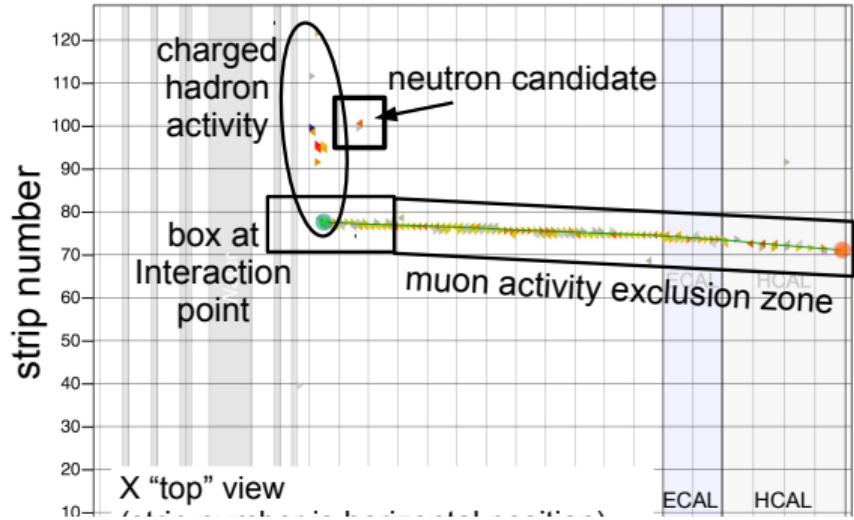
arXiv:1901.04892v1

Phys. Rev. Lett. 120, 221805 (2018)



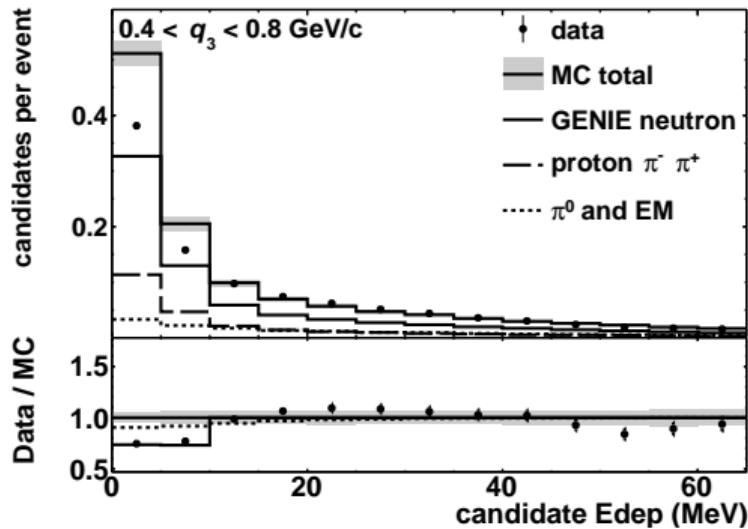
A lot of hadronic energy in anti-neutrino events come from neutron. E_{avail} treat neutron energies as background.

But we can also treat neutrons as the signal!



Neutron candidate selection

Neutron candidates energy deposits



Large discrepancies in the fraction of the lowest energy candidates, otherwise our simulation reproduces data well.

Neutron candidates multiplicity

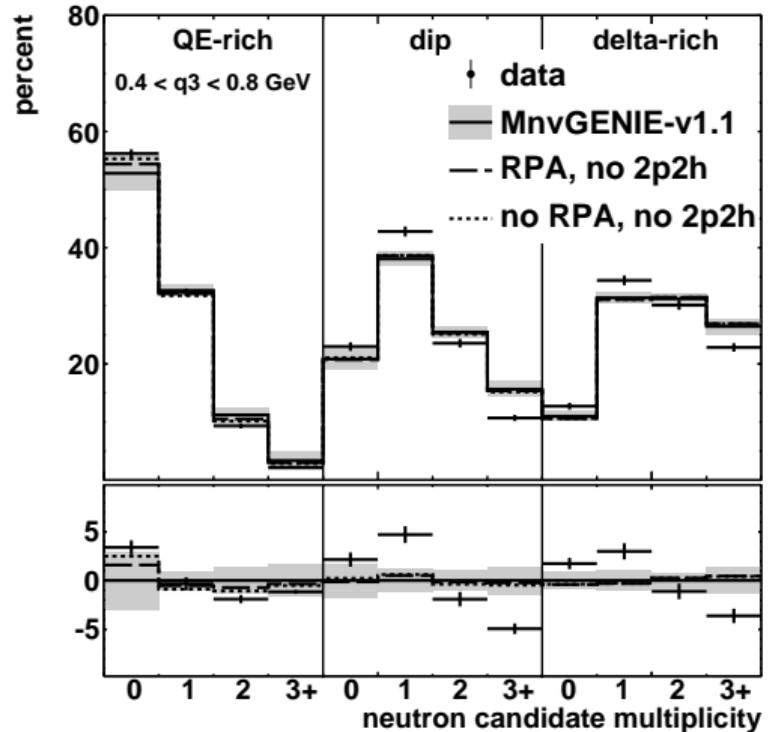
Regions are divided according to E_{avail} and the predicted dominant processes differ:

QE-rich: QE and 2p2h

dip: 2p2h

Δ -rich: Δ and some 2p2h

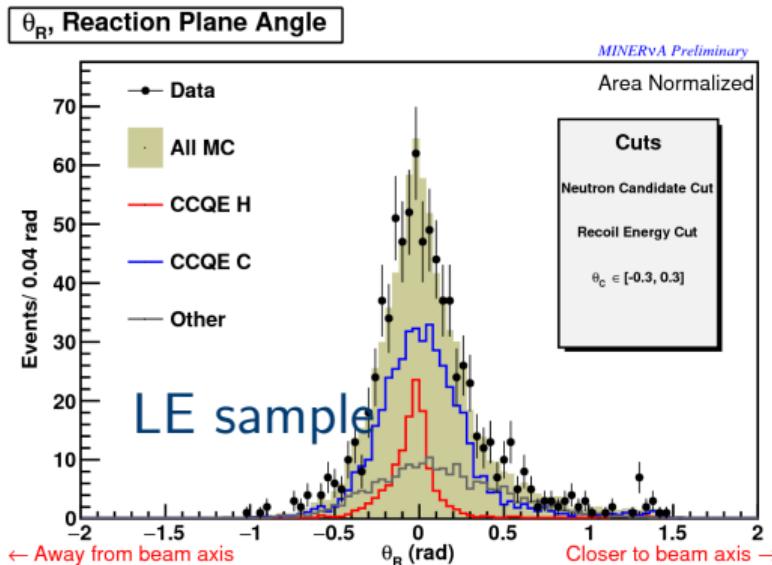
Neutron candidate multiplicities have larger discrepancies in the dip and Δ -rich region, mainly due to the lowest energy candidates.



MnVGENIE-v1.1 includes additional coherent pion production tuning based on Phys. Rev. Lett. 113, 261802 (2014) and Phys. Rev. D 97, 032014 (2018)

Some open questions on neutron detections being explored at MINER ν A

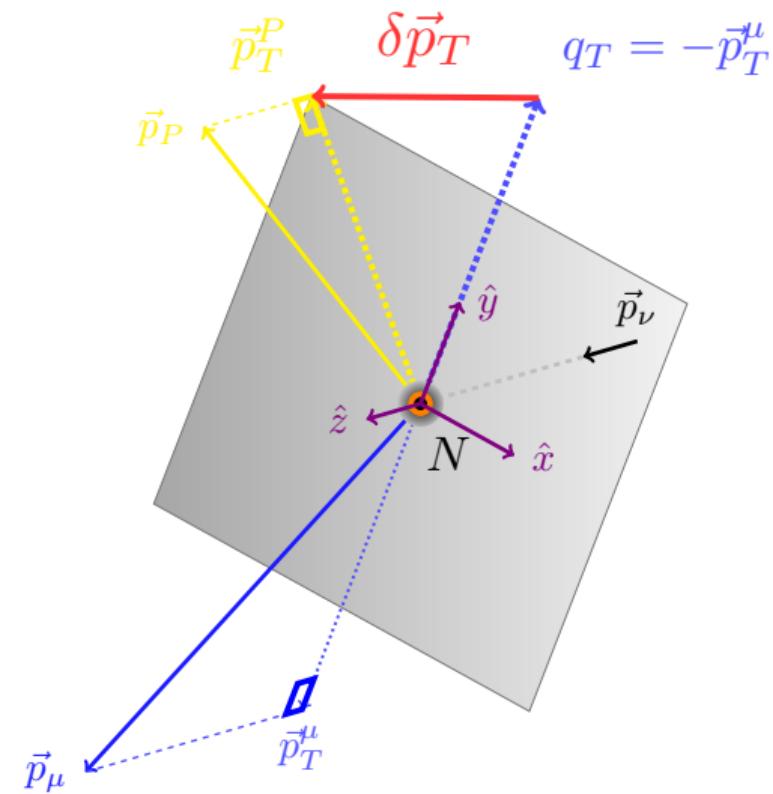
- Apply the same analysis to the nuclear targets?
- Turn candidate multiplicity to neutron multiplicity?
- Estimate the energy carried away by neutrons with direction information?
- Measure proton form factor from $\bar{\nu}H \rightarrow \mu^+ n$?

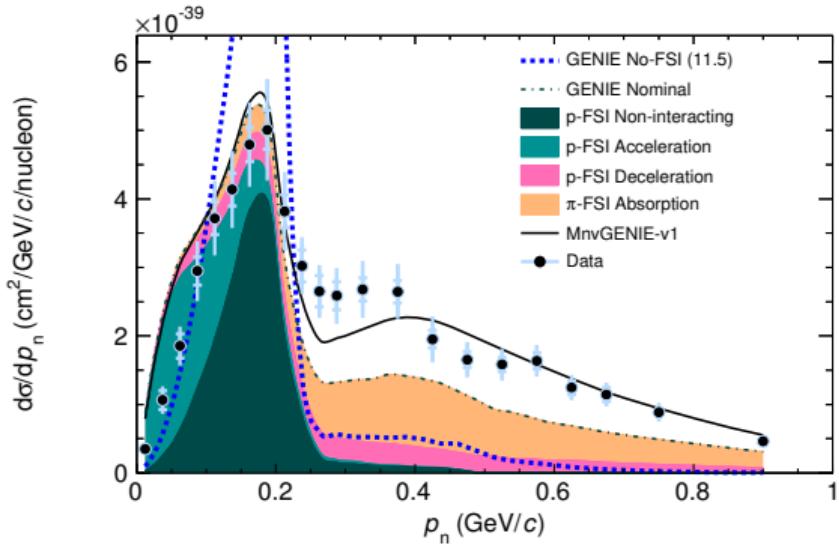
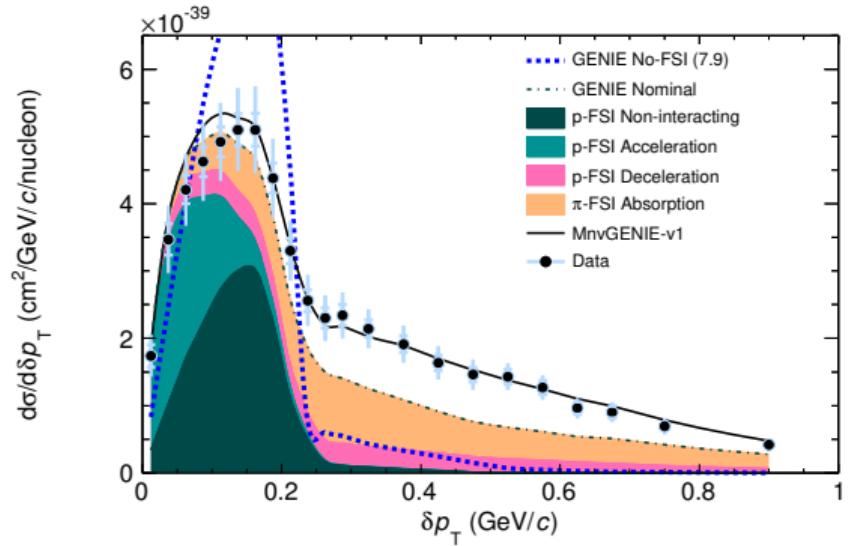


An angle with respect to free proton scattering

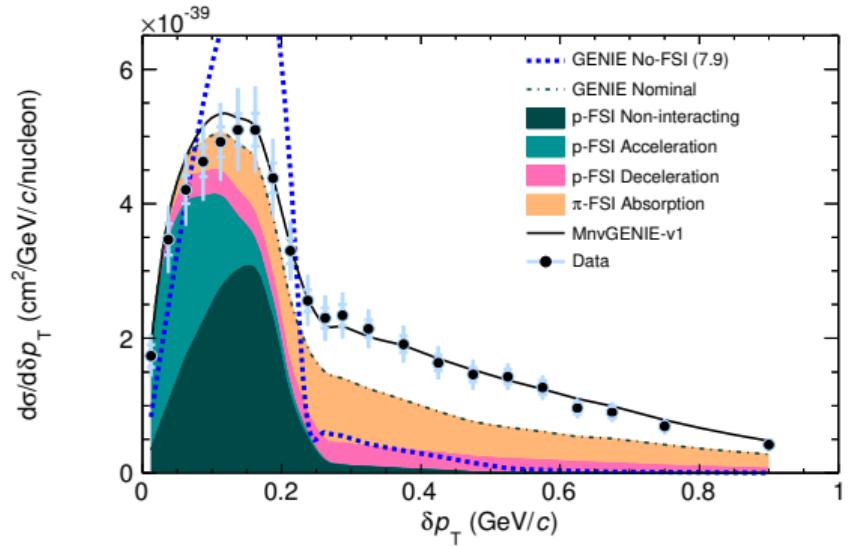
Disentangling the nuclear mess

Comparing the transverse components between the leptonic and hadronic final states offer new insights into nuclear effects.



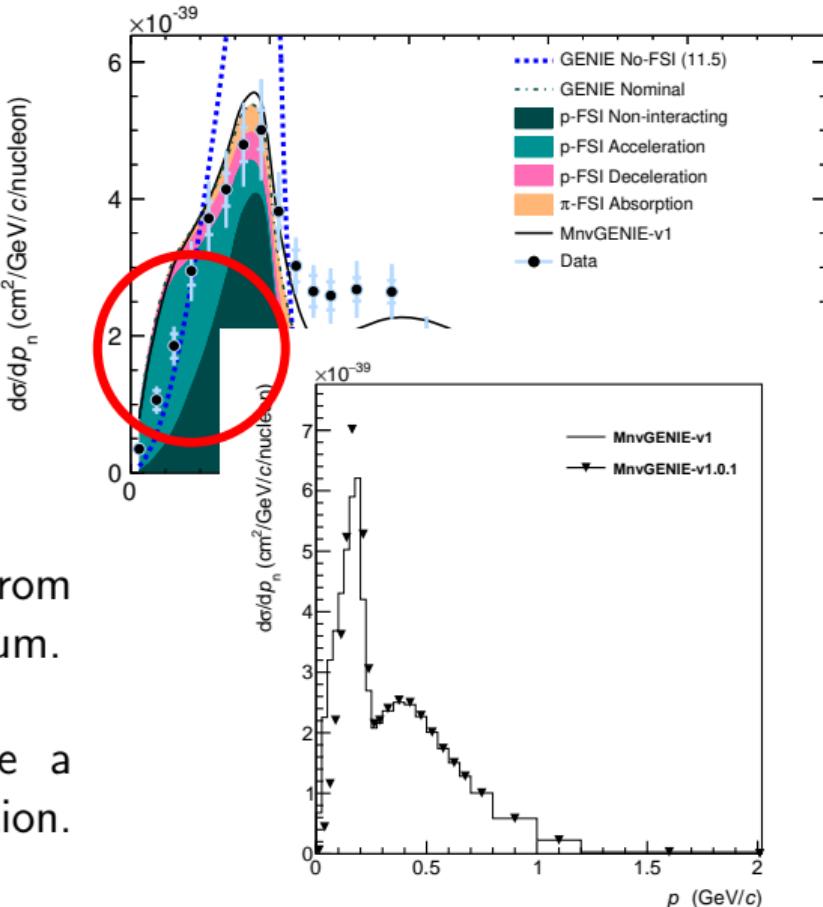


We can infer the initial neutron momentum from δp_T and shift in longitudinal proton momentum.

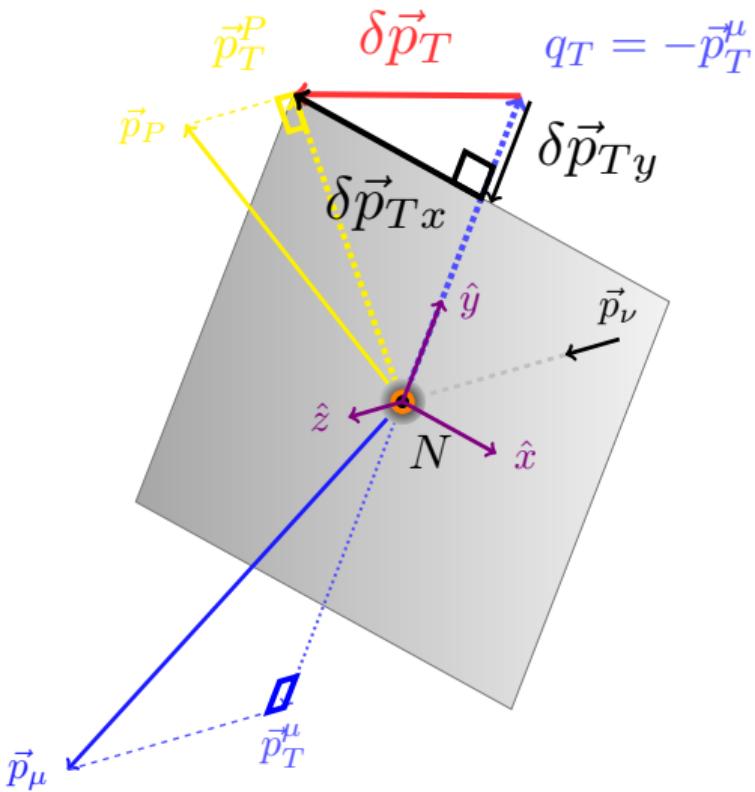


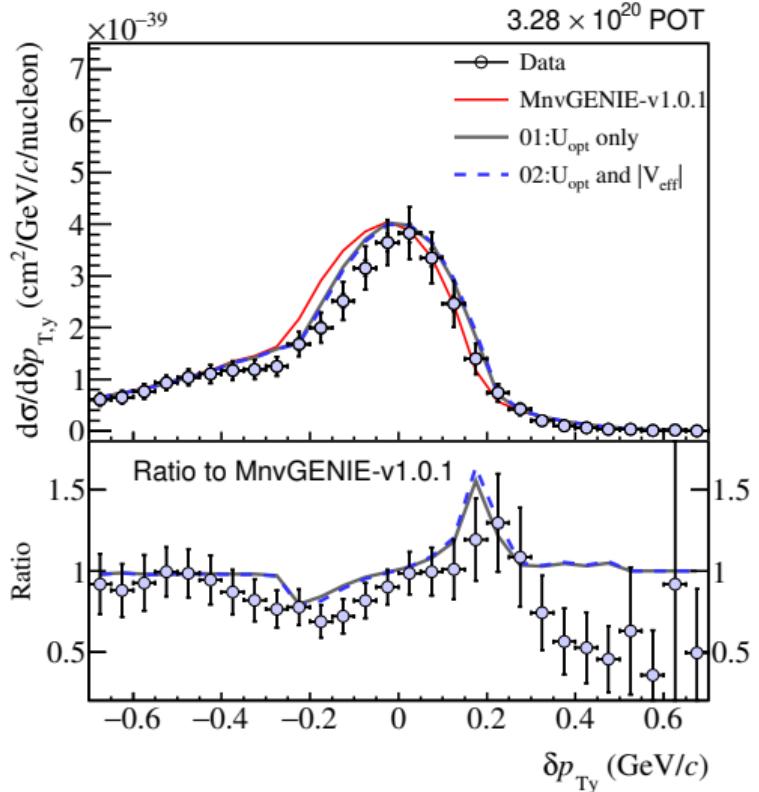
We can infer the initial neutron momentum from δp_T and shift in longitudinal proton momentum.

Weird “accelerating” FSI turns out to be a bug in GENIE, and we’ve found a solution.
arXiv:1906.10576



Turns out the projections of δp_T w.r.t. a muon-centric coordinate system are sensitive to different nuclear effects.

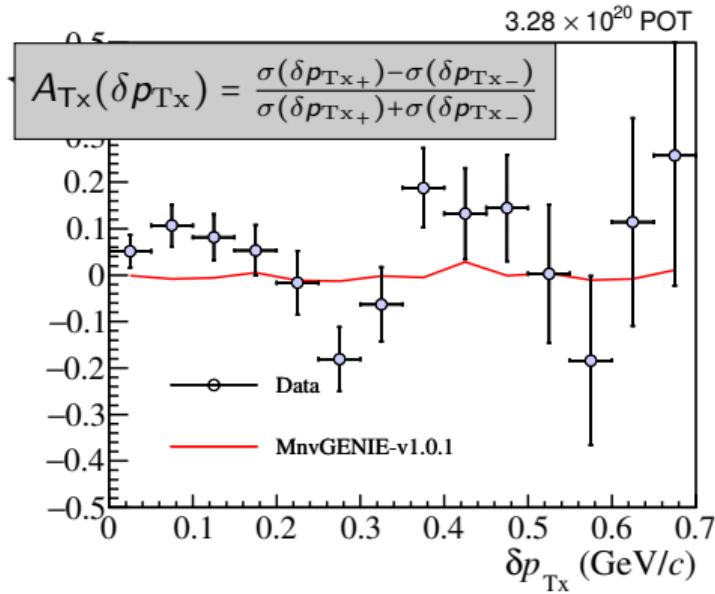
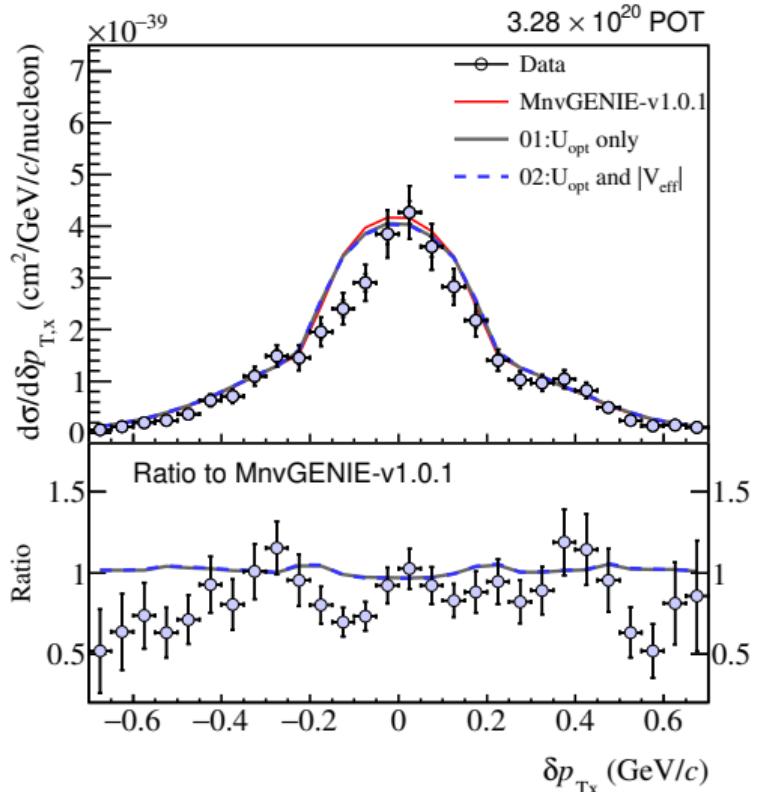




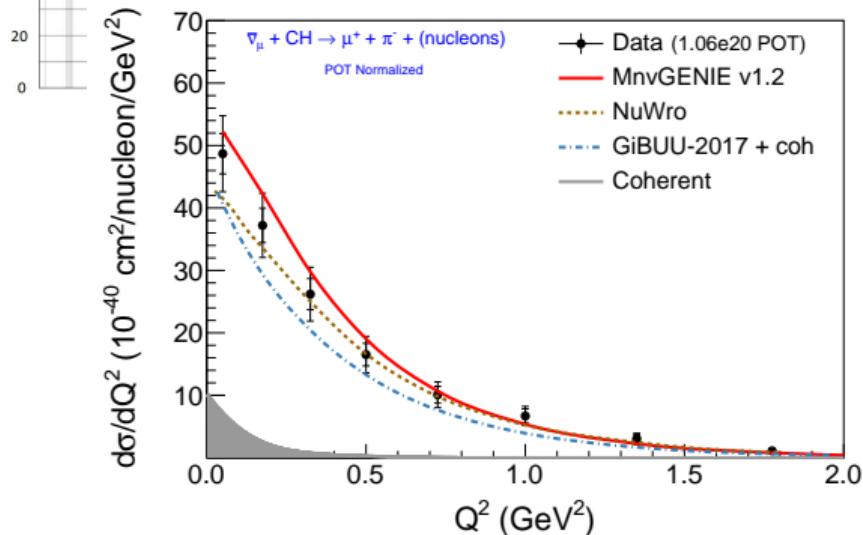
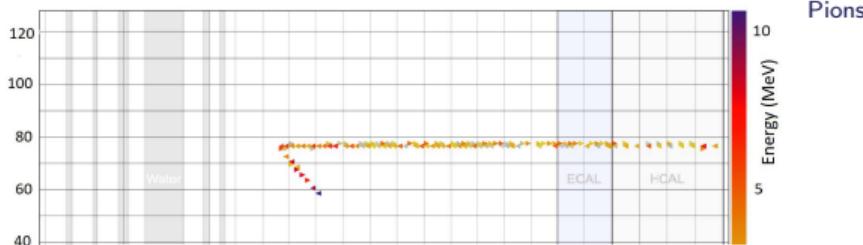
δp_{T_y} is sensitive to the binding energy implementation in GENIE

Default GENIE implements Relativistic Fermi Gas (RFG) model with the Moniz interaction energy (Nucl. Phys. B43, 605 (1972)), which are incompatible.

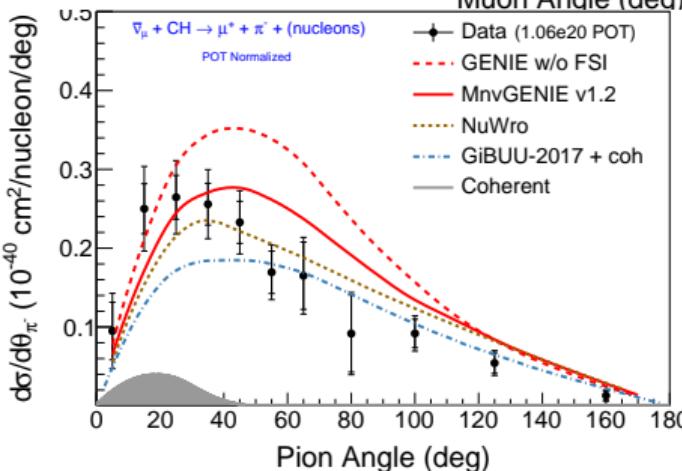
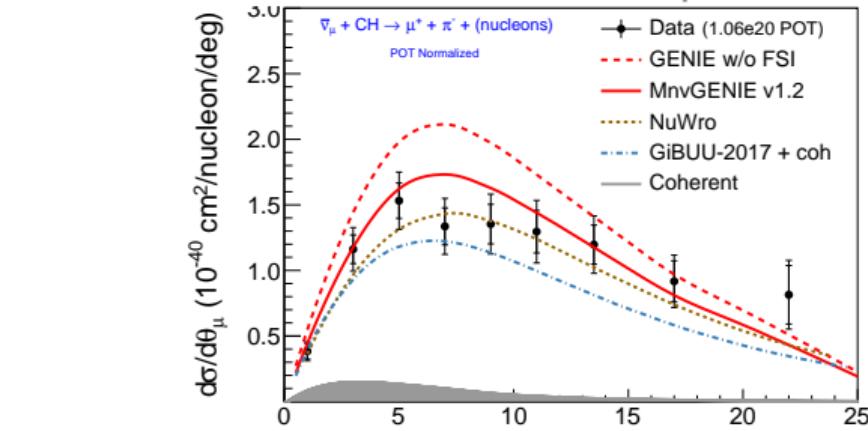
Modifying GENIE final state particles' energies according to theory motivated correction (Eur. Phys. J. C. (2019) 79: 293) improve agreements between data and MC.



Non-zero δp_{Tx} should be due to Fermi motion
 hints of unmodelled asymmetry that we think are pion absorption events
 (arXiv:1907.11212)



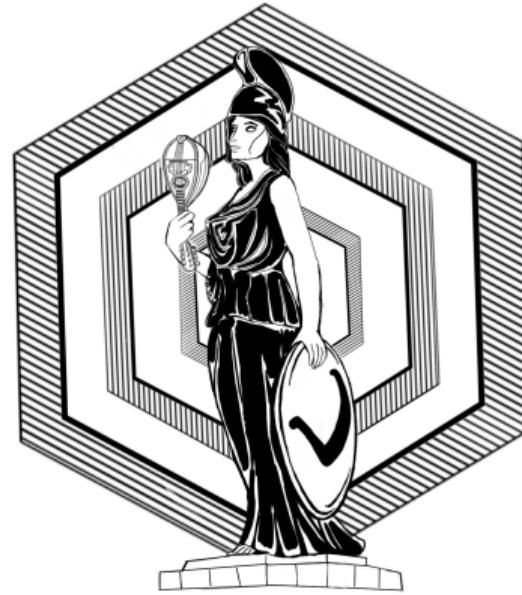
$\bar{\nu}$ CC π^- production, statistically limited disagreements in μ and π^- angles



Summary

MINER ν A has demonstrated:

- in-situ flux constrain
 - ▶ $\nu - e$ scattering
 - ▶ low- ν
- tune or identify model deficiencies
 - ▶ low recoil fits to 2p2h
 - ▶ transverse kinematic imbalances
- see the elusive neutrons
- measure cross sections to higher dimensions



Outlook

Low energy side:

- 33 published results
- 2 were submitted for publication
- 3 more Low Energy results almost ready

Medium energy side:

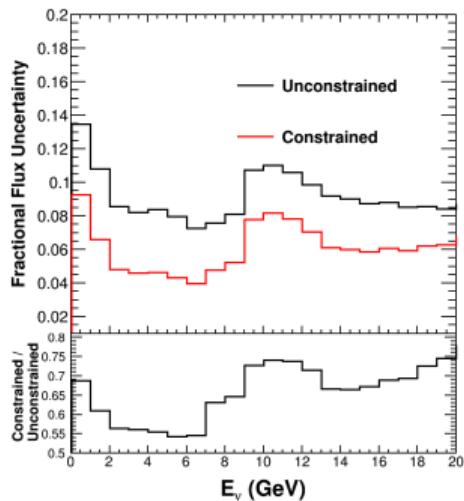
- $\nu - e$ cross section submitted for publication
- CCQE ν and $\bar{\nu}$ in the tracker
- CCQE analysis in the targets
- Pion productions in the tracker and nuclear targets
- DIS/SIS analysis



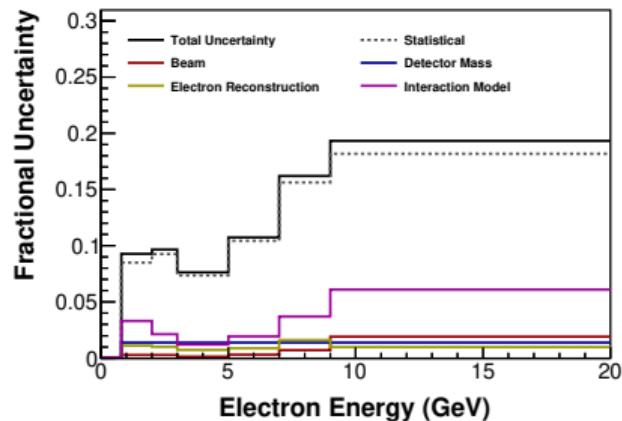
Thank You!

Backup

$\nu - e$ Resolution and Uncertainties



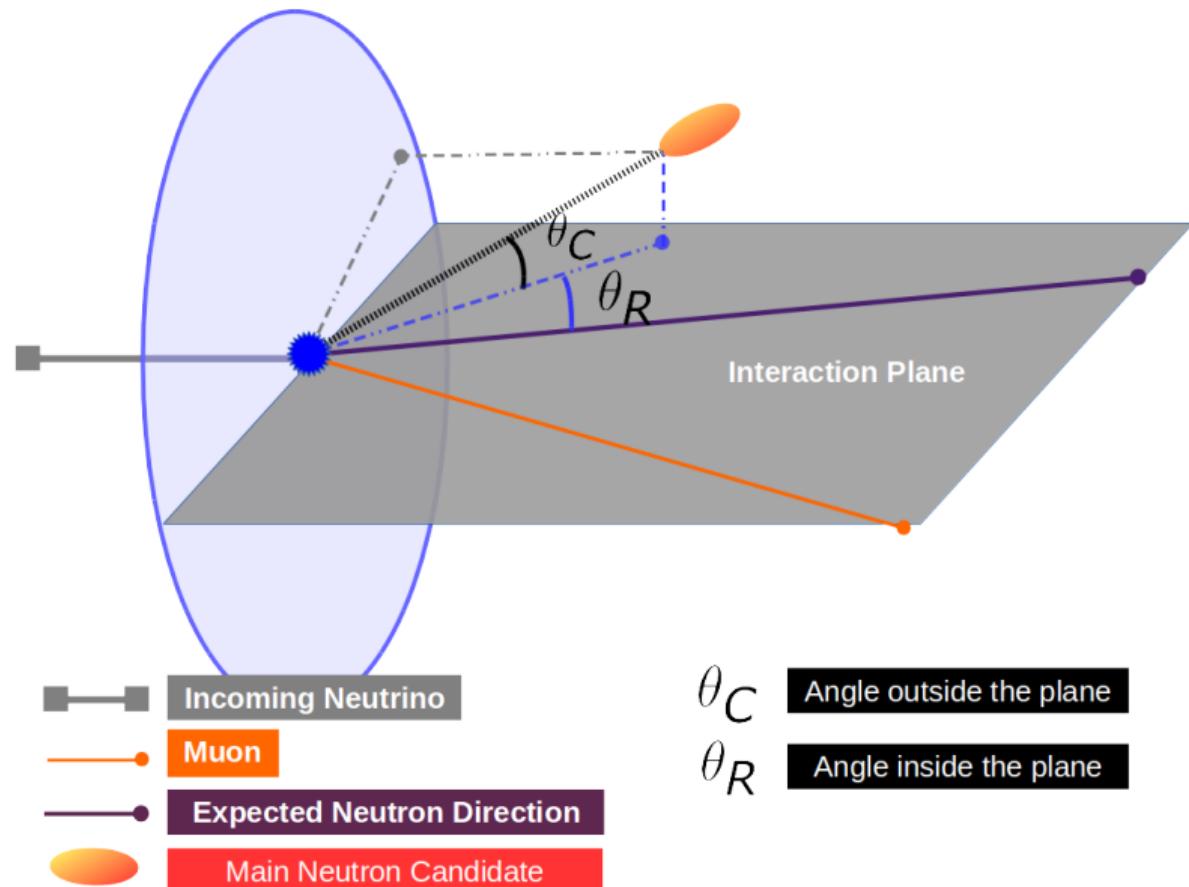
Source	Uncertainty (%)
Beam	0.21
Electron Reconstruction	0.57
Interaction Model	1.68
Detector Mass	1.40
Total Systematic	2.27
Statistical	4.17
Total	4.75

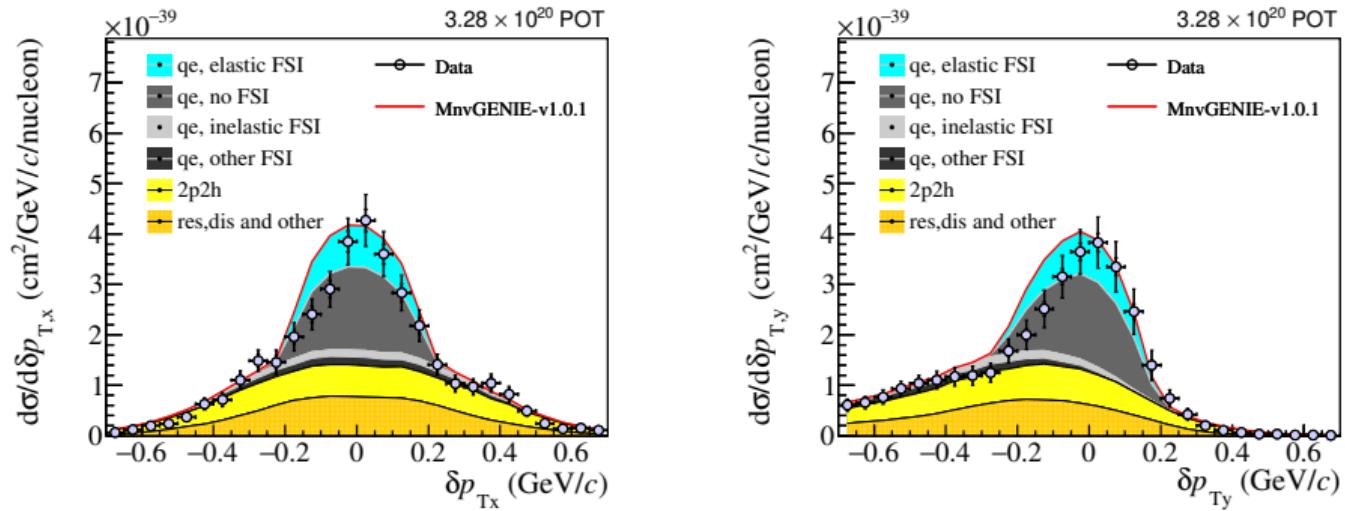


Resolutions (lowest energy to highest energy bin)

Energy resolution: 40 MeV ~ 60 MeV

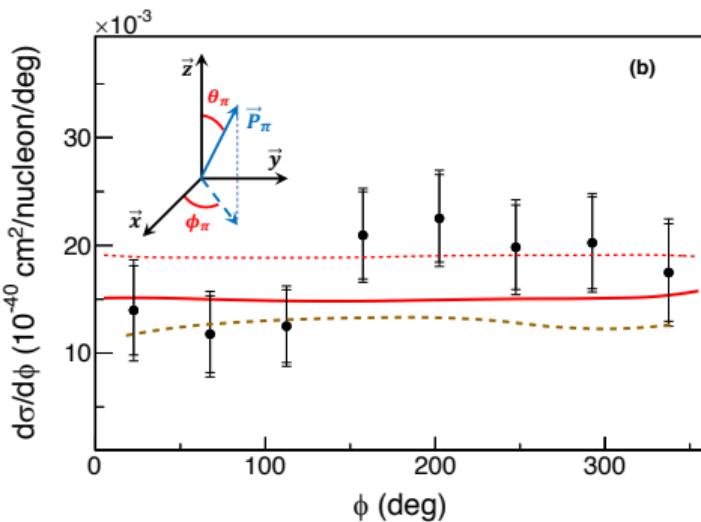
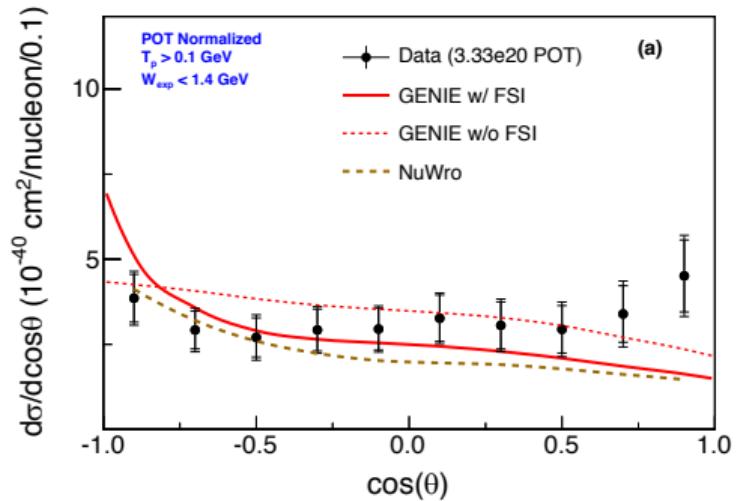
Angular resolution: $0.7^\circ \sim 0.3^\circ$





δp_{T_x} and δp_{T_y} compared to GENIE and it's event type and QE FSI components

Asymmetry in π^0 measurements



The asymmetry in the Adler's ϕ angle has been observed in the π^0 result. Stuck pions could in principle exhibit the same asymmetry and affect the observed final state proton through momentum conservation.