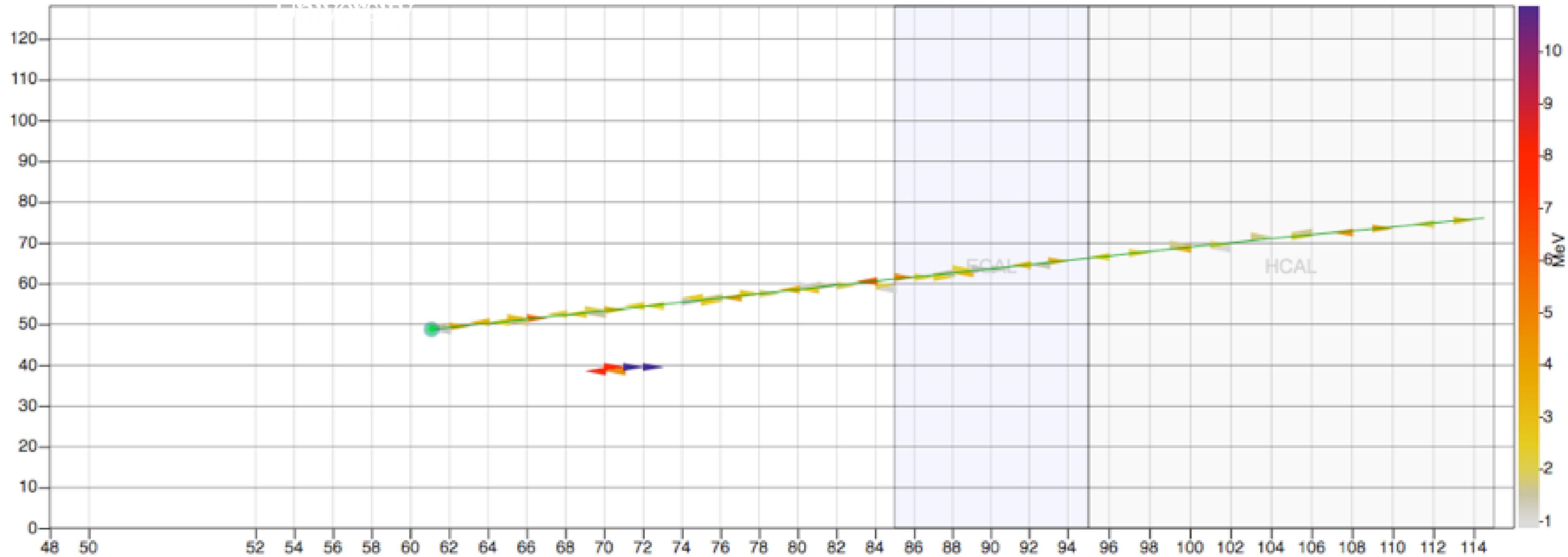


New high statistics results from the MINERvA experiment Medium Energy run

Heidi Schellman for the MINERvA Collaboration

Big question

Why is almost everything matter instead of anti-matter?

Answer may be CP-violating processes
Make particle/anti-particle and compare behavior

Quarks → B, K decays
Neutrinos → oscillations

Neutrino CP violation

Neutrinos oscillate between flavors!
Do neutrinos and anti-neutrinos behave the same?

Not necessarily!
Study the rates for

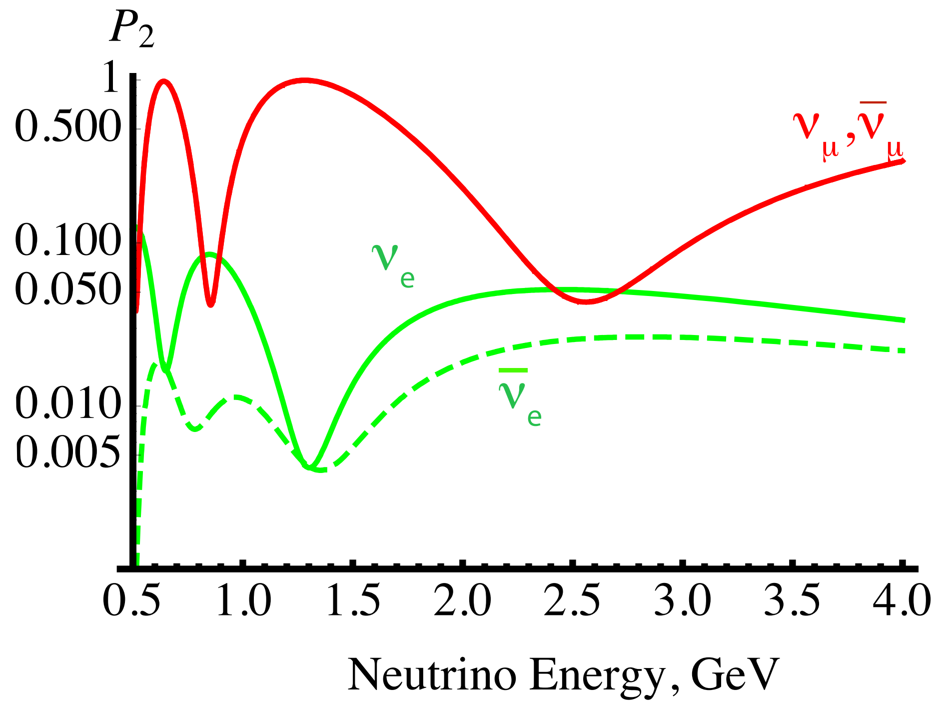
$$\nu_\mu \rightarrow \nu_e$$

$$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$$

as a function of E_ν

Start with a muon neutrino beam,
Look for electron neutrinos 1300 km away

probability of finding
each type of neutrino



Need to understand both neutrino and anti-neutrino interactions!

Oregon State

- What are the interaction rates for each type?
- What is the neutrino energy for each event?
- Two ways to estimate the energy:
    1. Sum up all of the final state energy
    2. Use quasi-elastic scattering kinematics for a subset of events.
- Method 2 is especially important for anti-neutrinos as even simple processes like

$$\overline{\nu} + p \to \ell^+ + n$$

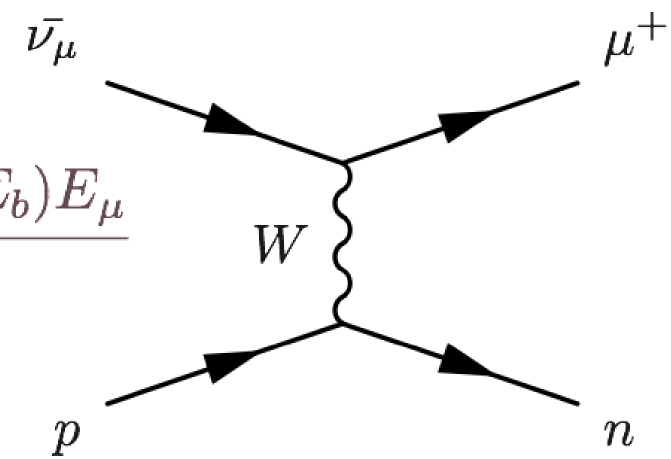
have hard-to-reconstruct final states that don't work with method 1.

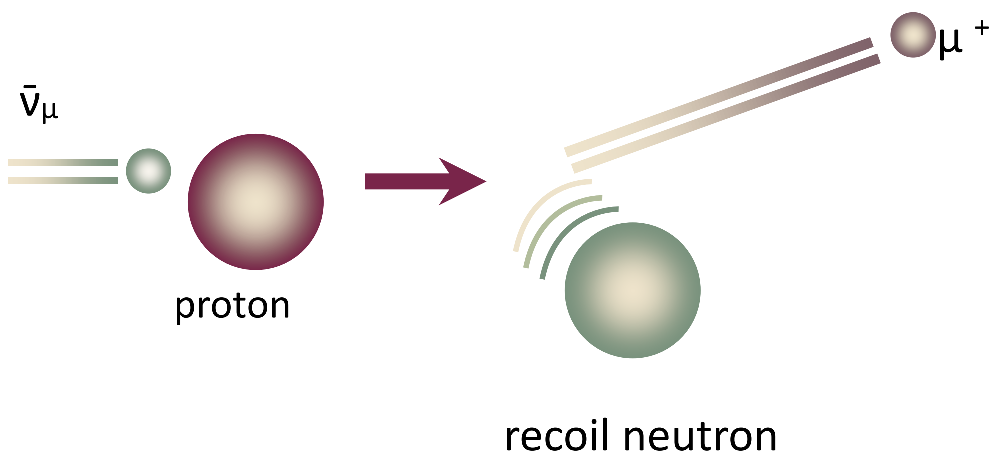
Quasi-elastic scattering on nucleons (CCQE)

Oregon State

$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

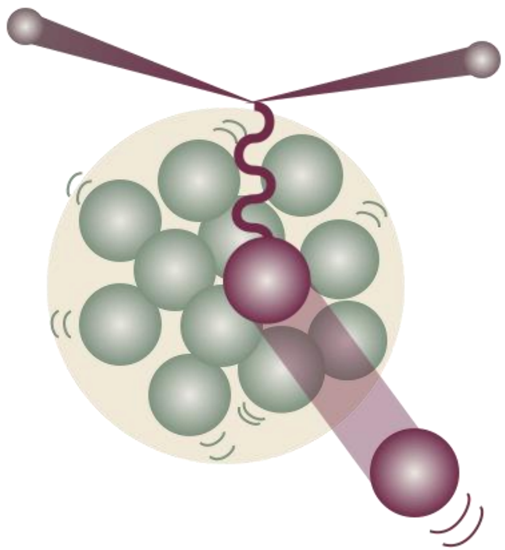
$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$





In principle 2-body scatter from a nucleon at rest allows full reconstruction of the kinematics from the muon alone.

Complications

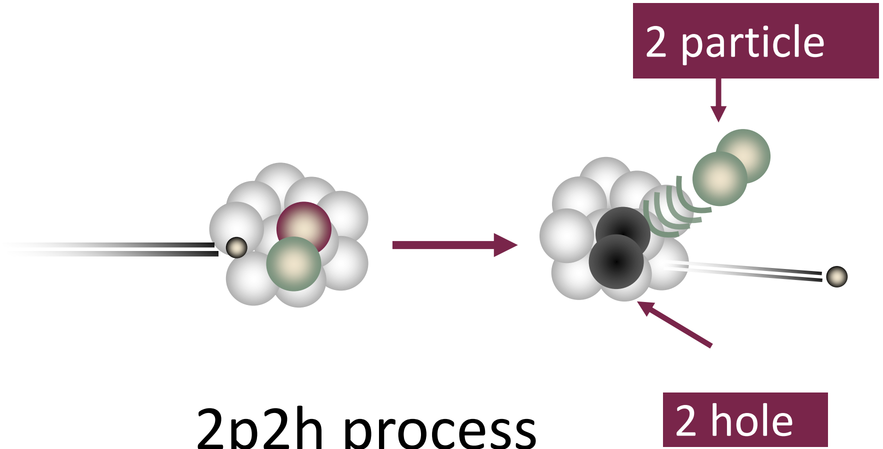


Nuclei are complex
Fermi motion ..
Screening …
No longer a scatter at rest!

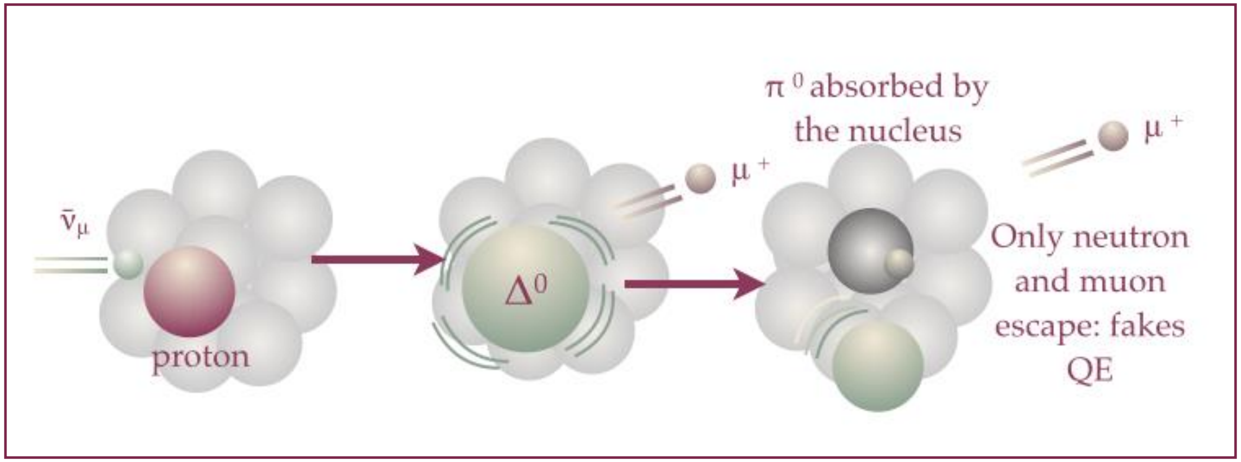
Electron-scattering experiments have found that, approximately 20% of the time, electrons scattered from **correlated pairs** of nucleons instead of single nucleons.

R. Subedi et al. Science, 320(5882):1476–1478, 2008

~90% of these pairs consist of a proton and a neutron.

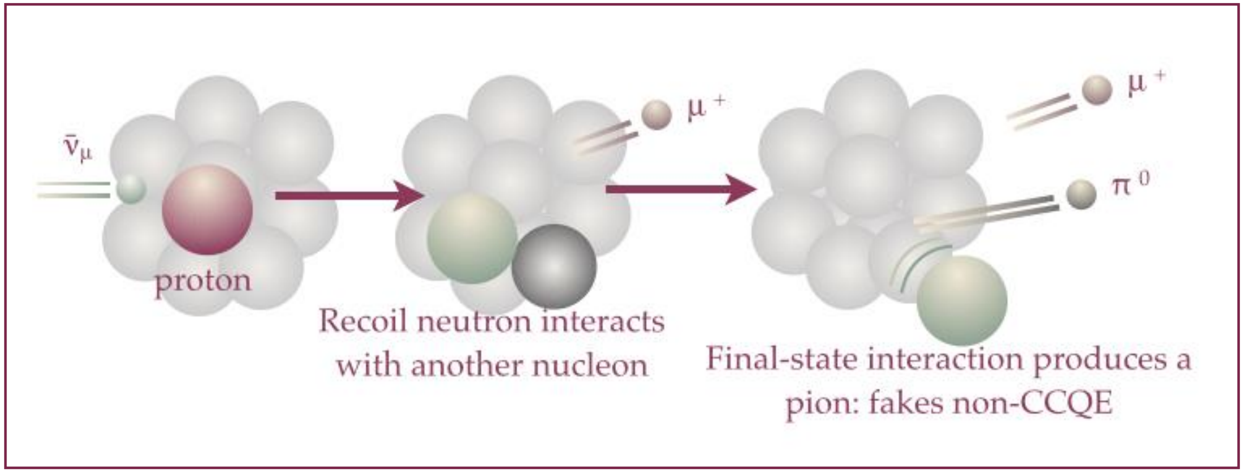


2p2h process

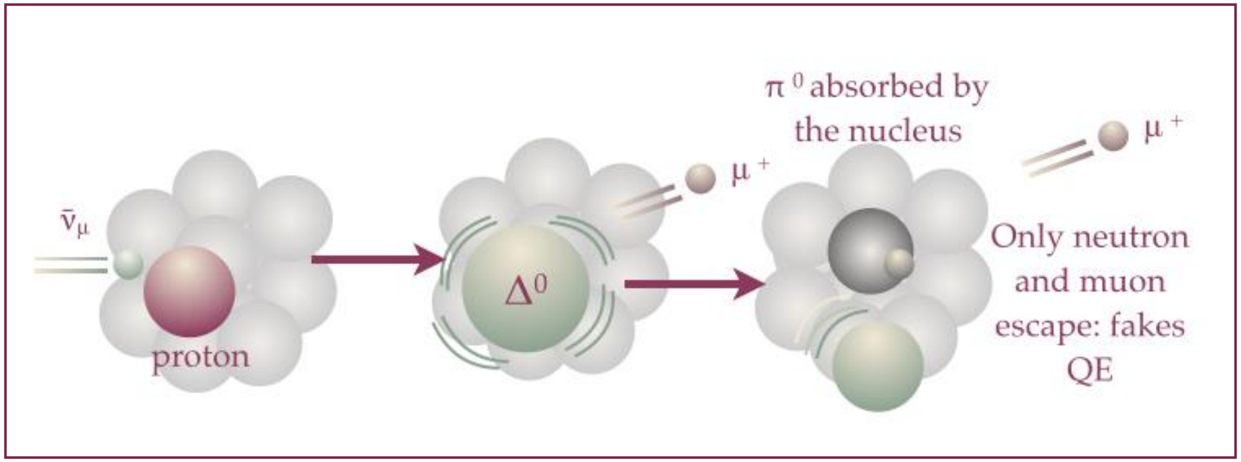


Initial interaction is not CCQE
But the observed event looks like it

Misidentification



Initial interaction is CCQE but the observed event is not!



QE-like: define a signal that is corresponds to to final state outside the nucleus.

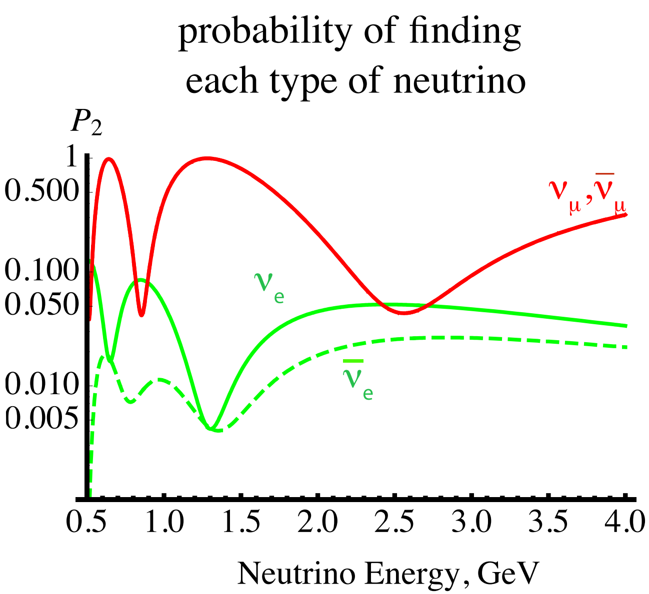
CCQE-LIKE NEUTRINO

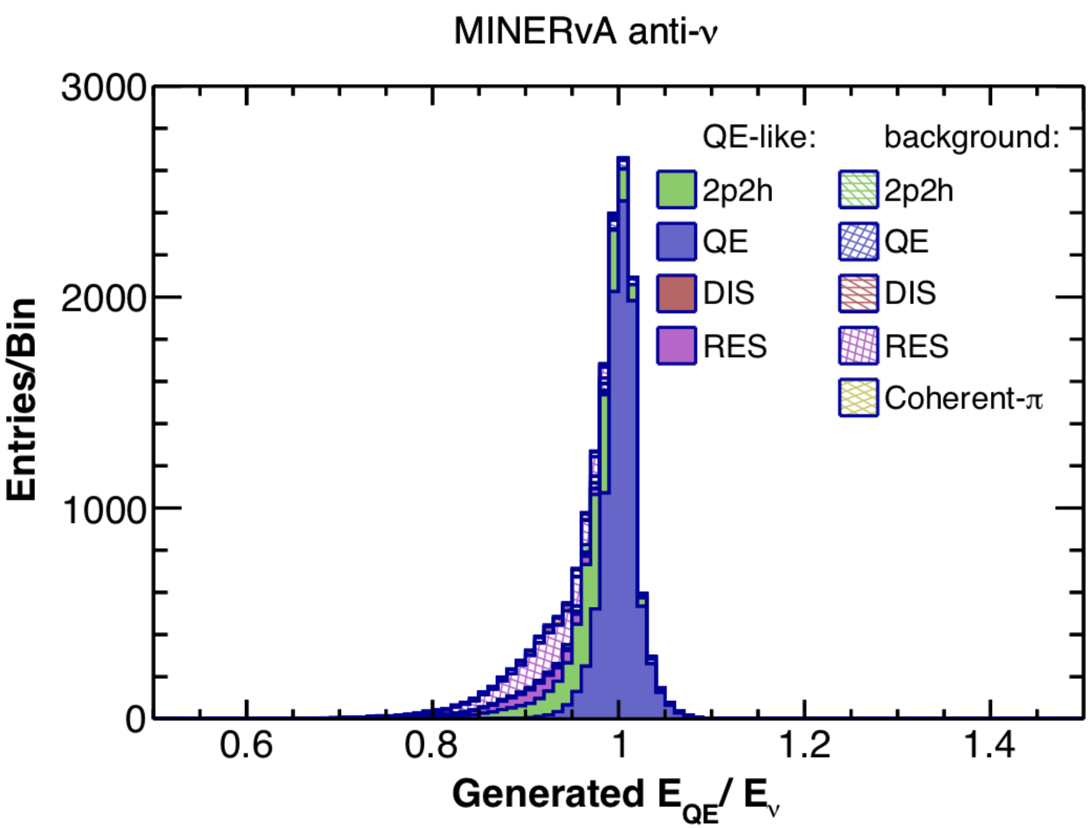
- One charged muon
- Any number of protons
- No pions
- Low additional recoil activity
- We allow any number of protons to include 2p2h contributions

Energy estimation

$$E_{\nu}^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

Works for both ν and anti-ν and is pretty good at estimating E_ν for pure QE scatters but nuclear effects bias it low.

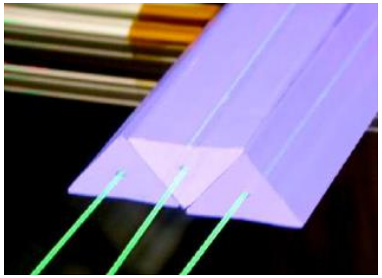


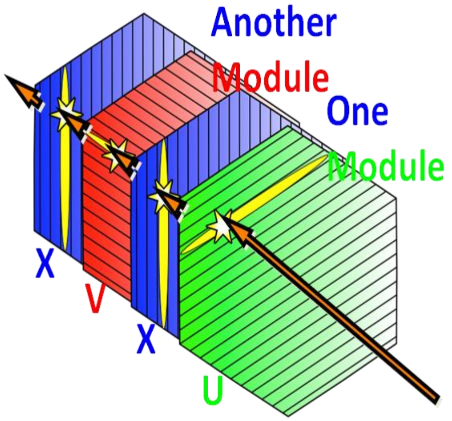


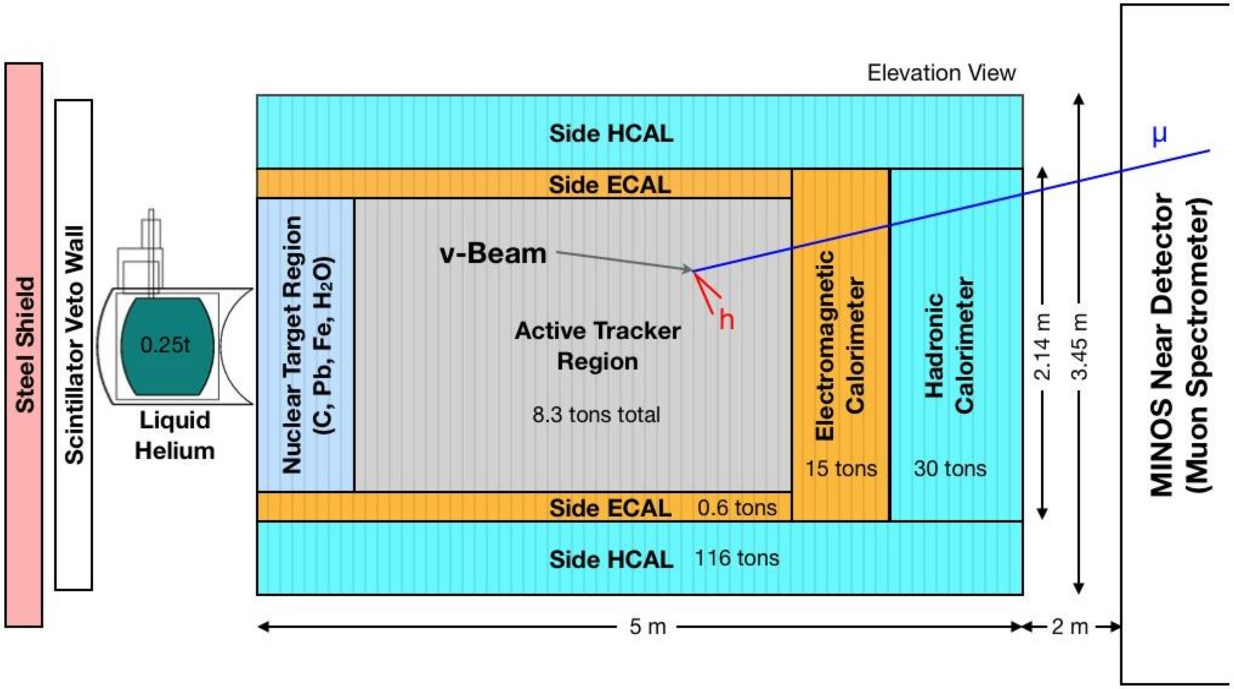
MINERvA Experiment @Fermilab

5.4 Ton Active Scintillator Fiducial Volume

Ran from 2010 to 2019



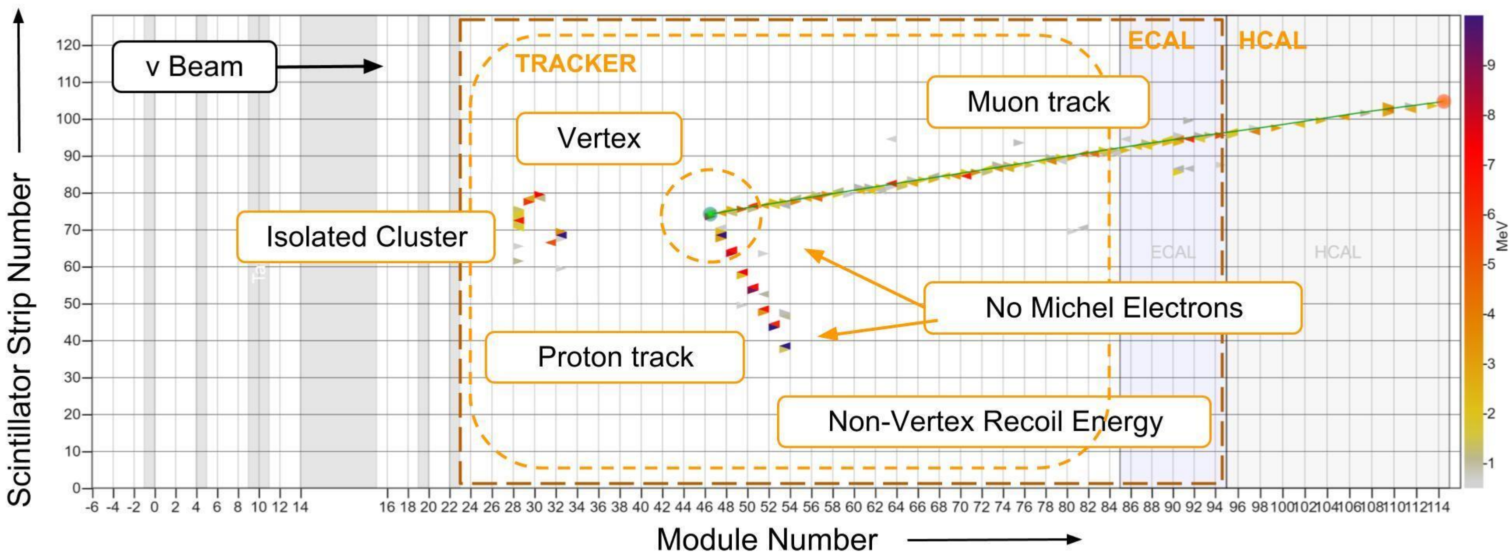




MINERvA

Quasi-elastic neutrino scattering on CH (scintillator)
Muons tracked and momentum analyzed
Protons > 100 MeV KE can be tracked
Neutrons only ~50% of the time

$$\nu_\mu + n \rightarrow \mu^- + p$$

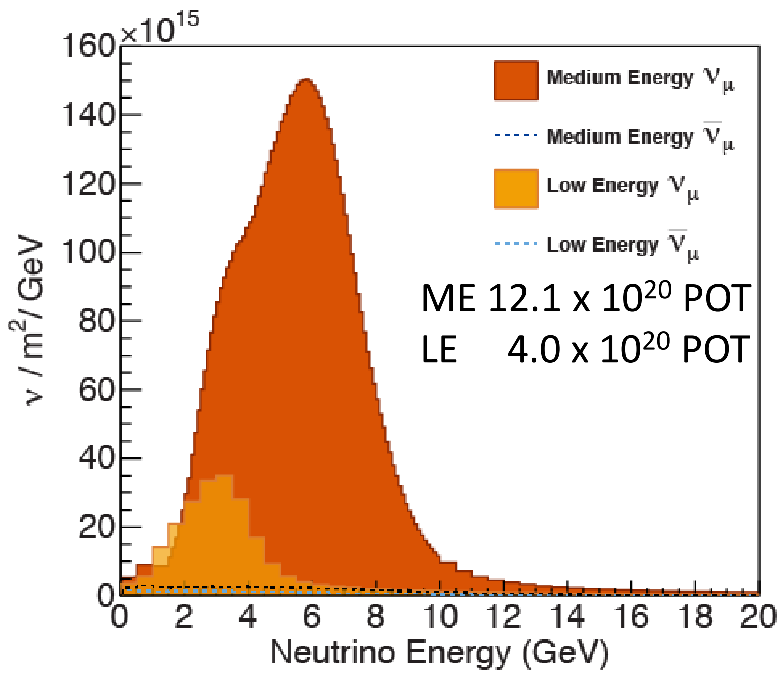


The main background is π from resonances and FSI faking protons

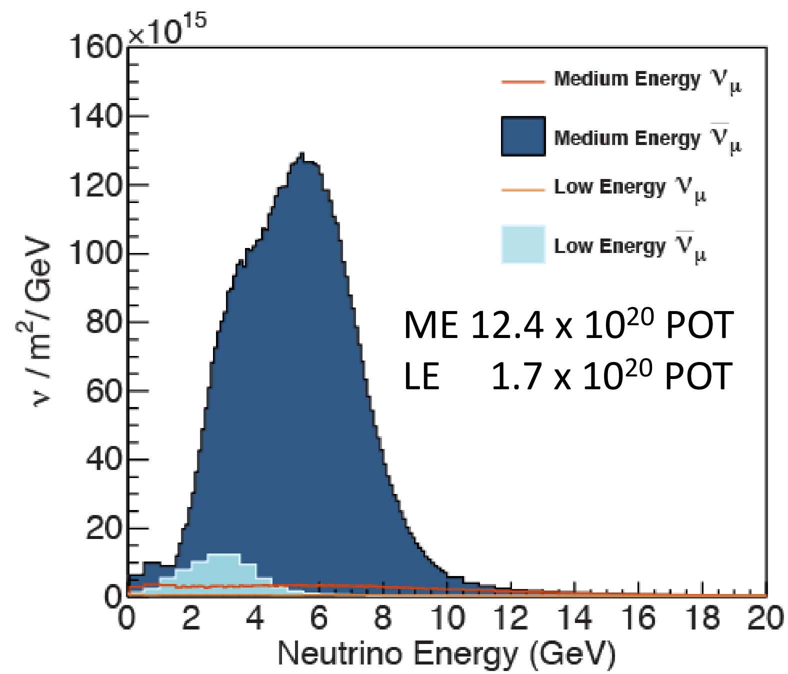
- Identify π^+ by Michel electron
- π^0 decay showers
- Multiple charged tracks

New data taken in Medium Energy NuMI beam

Neutrino flux



Anti-neutrino flux

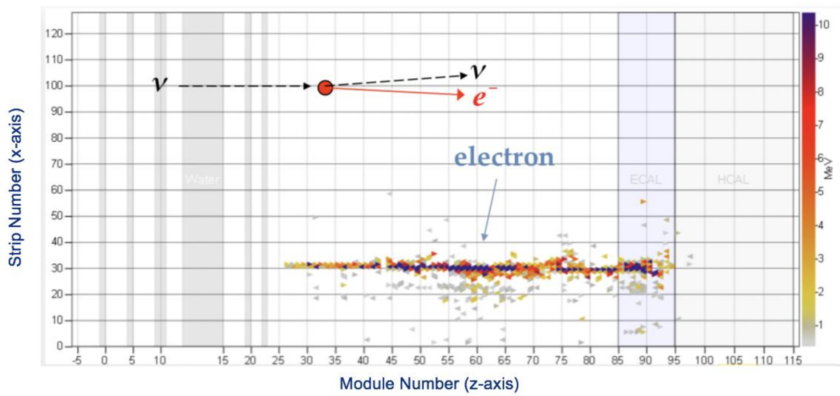


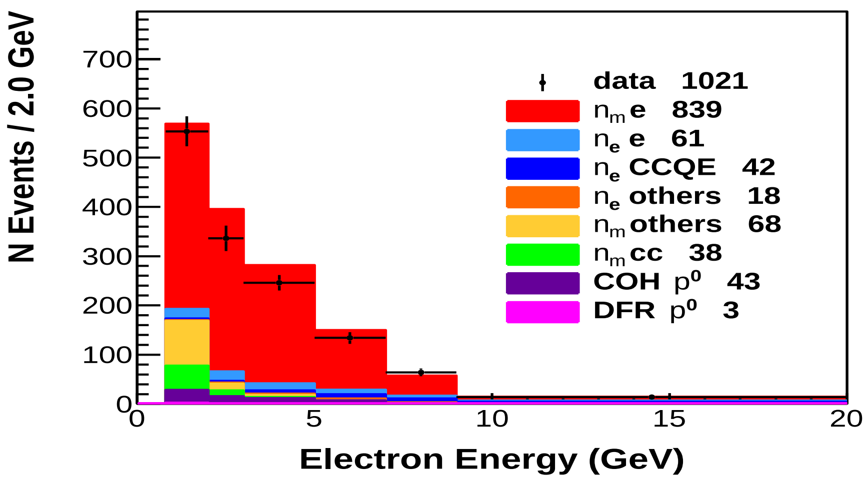
Absolute flux normalization via $\nu - e$ Scattering

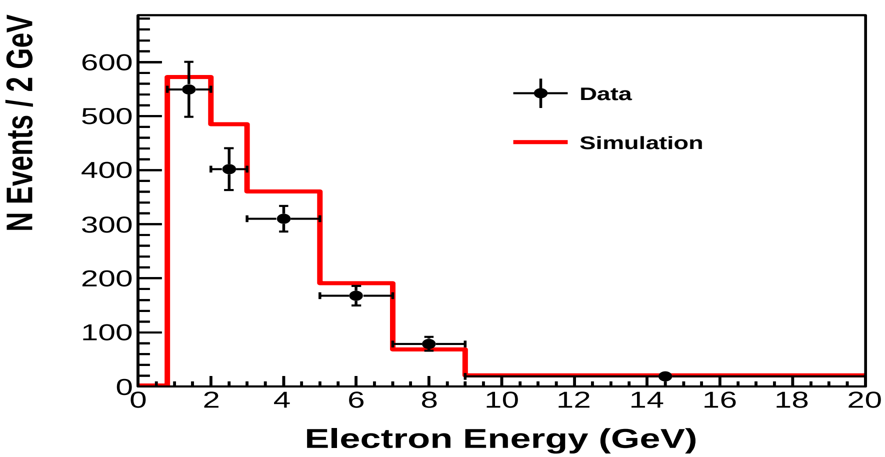
Oregon State

Experimental signature is a very forward single electron state.

Statistics are 1021 events → uncertainty ~ 3%



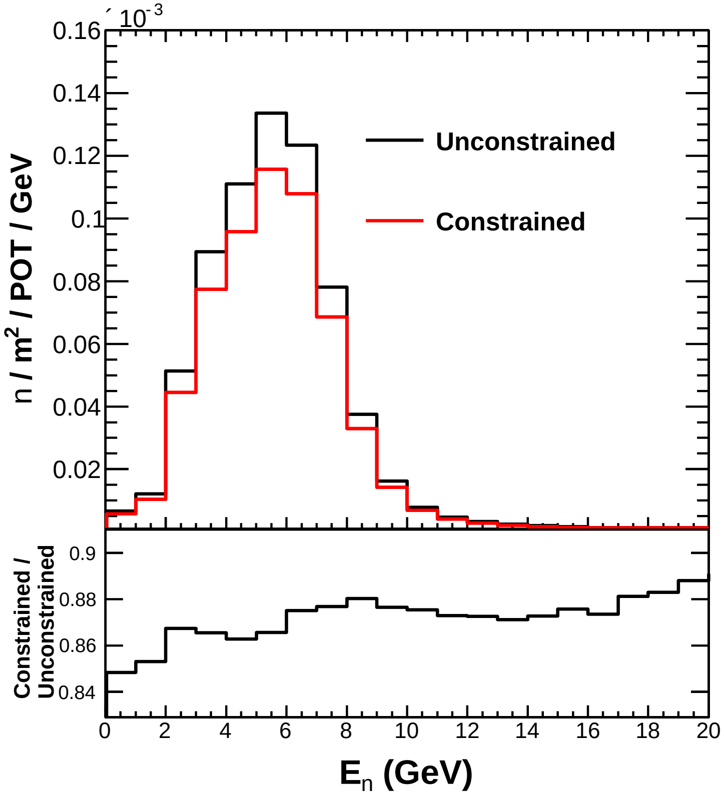


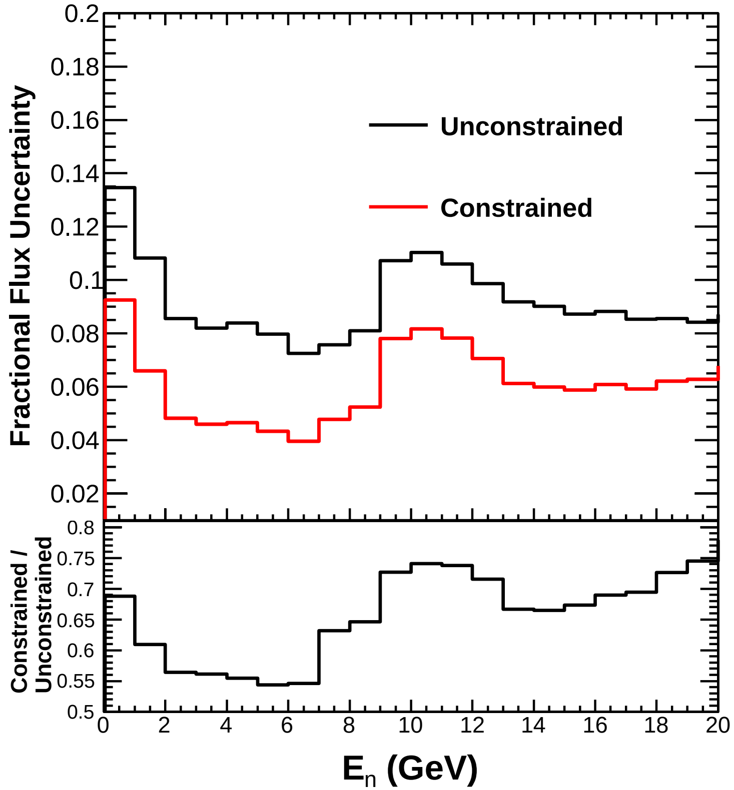


Use ν-e scattering to constrain the absolute ν flux

Phys. Rev. D 100, 092001 (2019)

Flux and Fractional Uncertainty



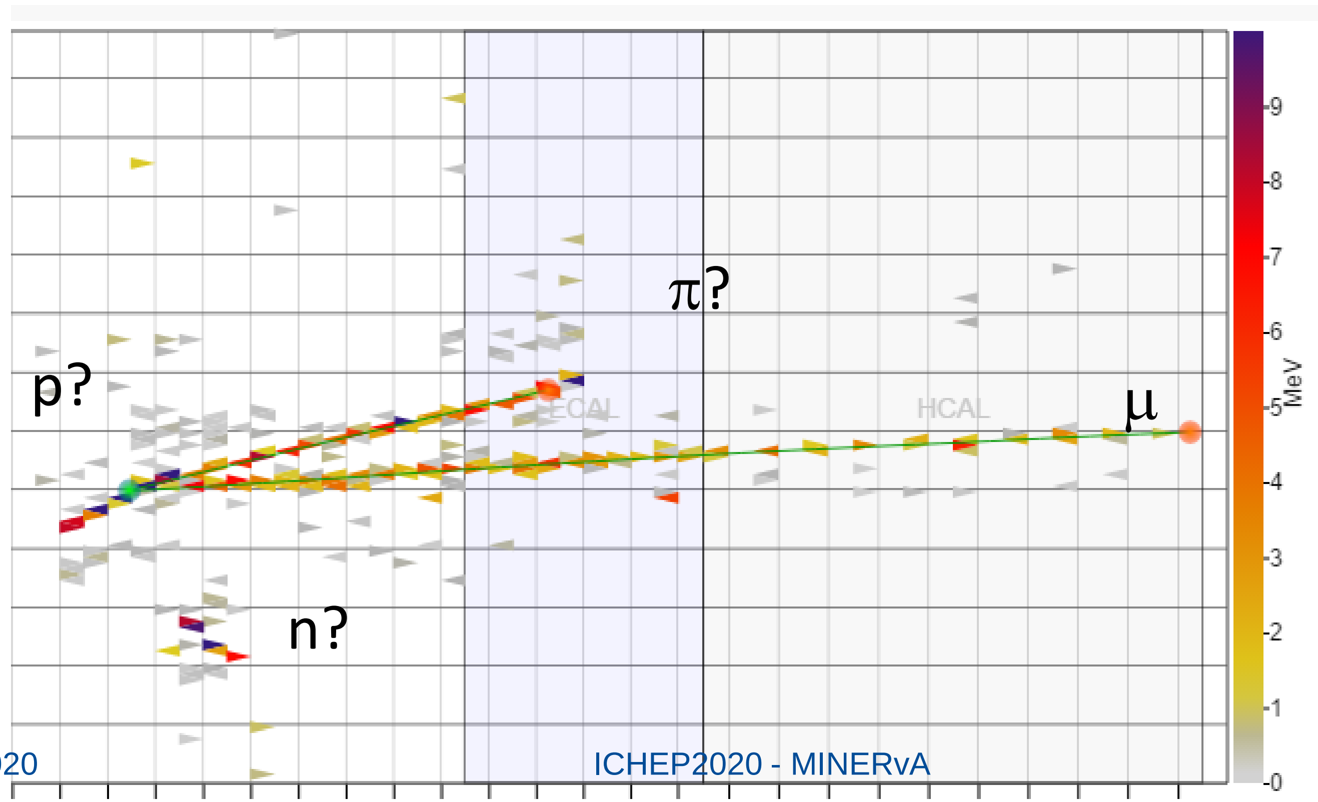


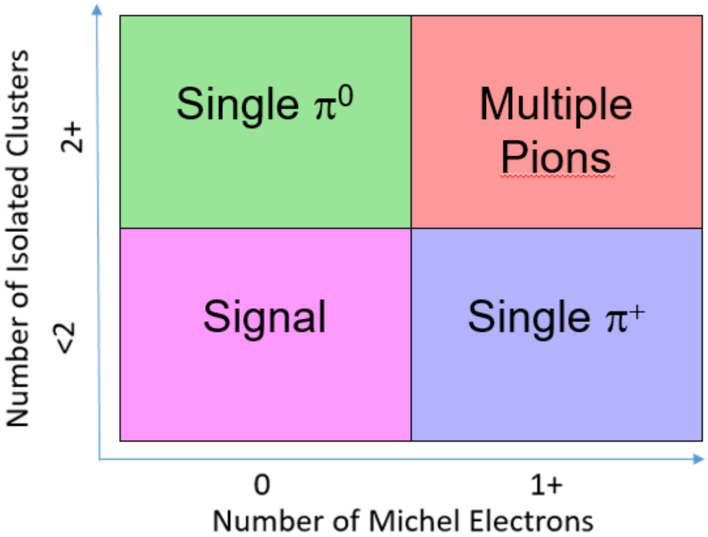
ν_μ flux in bins of neutrino energy before(black) and after(red) constraint is reduced by ~ 10 %

The flux uncertainty near the peak is reduced from 7.6 % to 3.9 % .

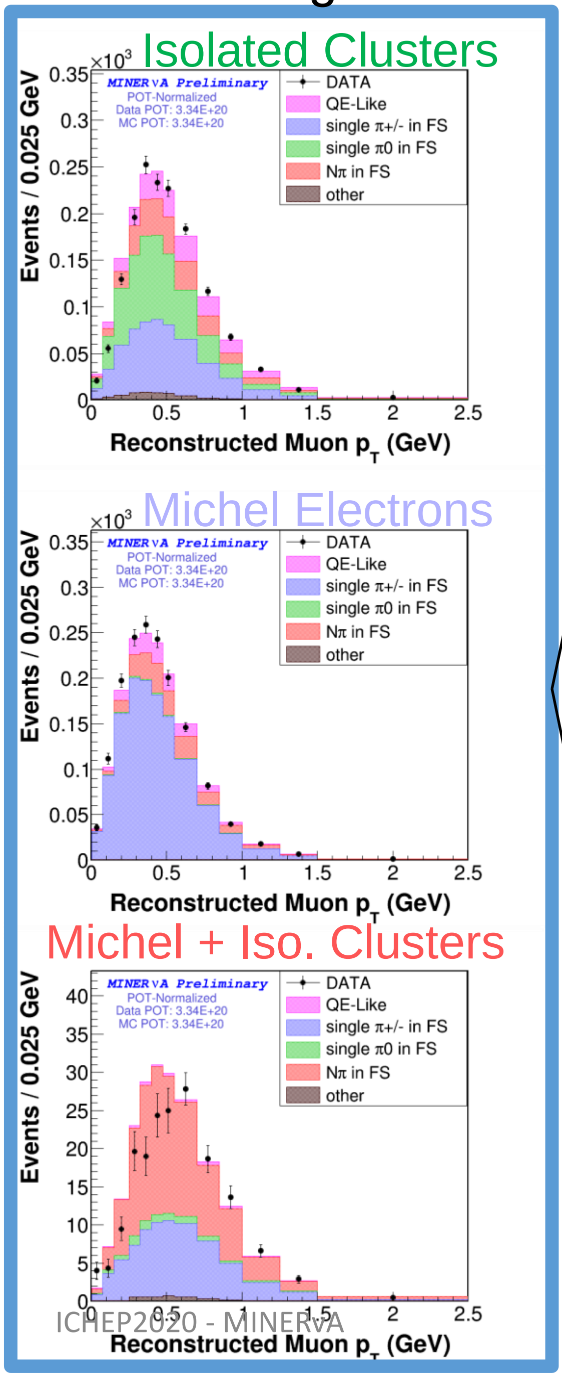
Now we can measure quasi-elastic $\nu + n \rightarrow \mu + p$

- Looking for $\nu + n \rightarrow \mu + p$ + possibly more nucleons
- Backgrounds would be π^{+-} and π^{0} faking nucleons
- Select events based on dE/dx and Michel decay particle identification
- Constrain pion background using side band fits

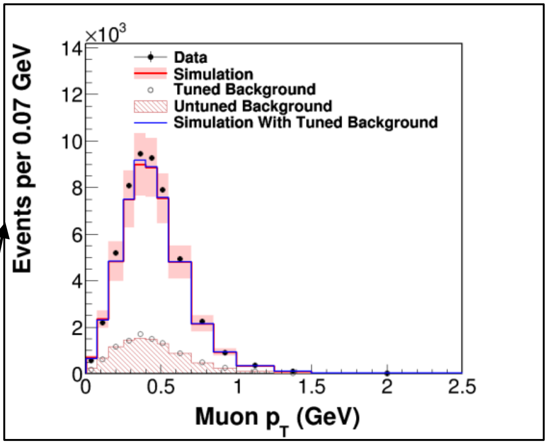


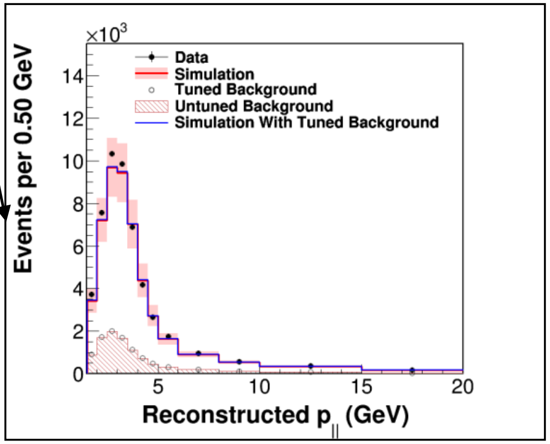


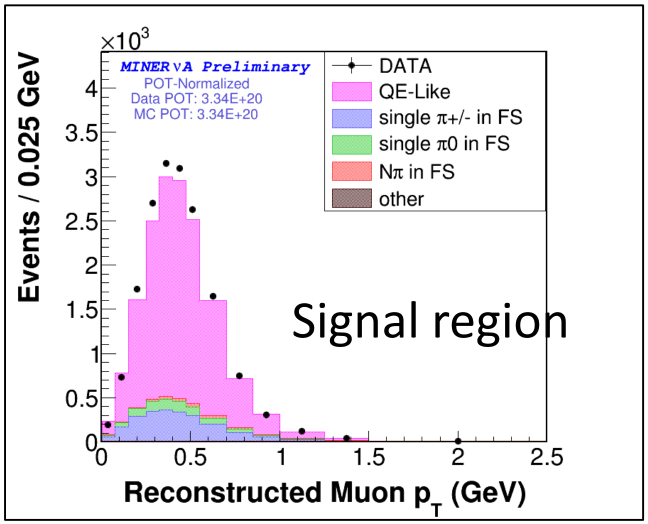
Fit 3 scaling factors



Estimate background







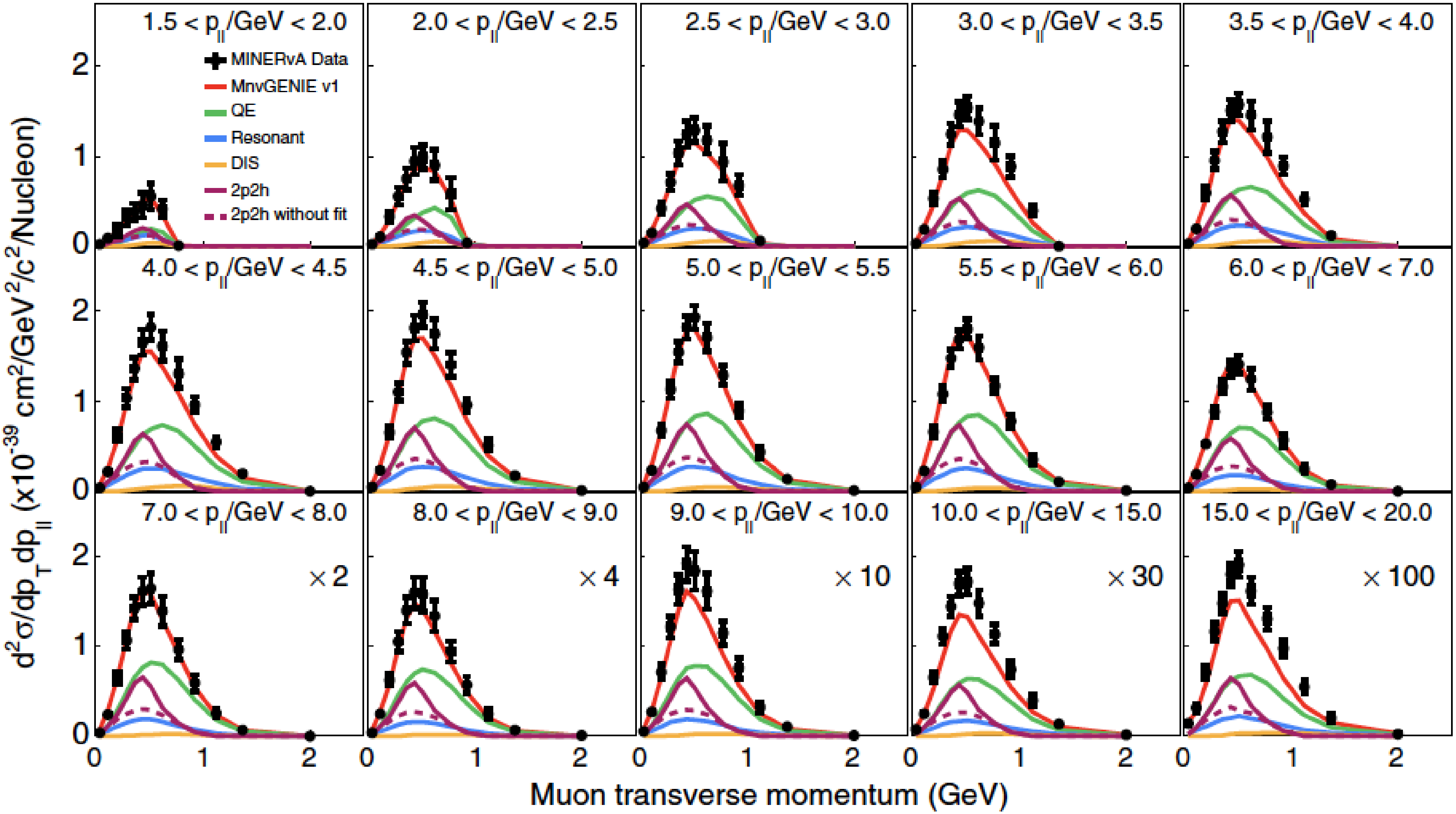
Scaling Factors as Function of p_T:

π^0,

$\pi^{+/-}$,

$N\pi$

Result: 2D neutrino cross-section measurement

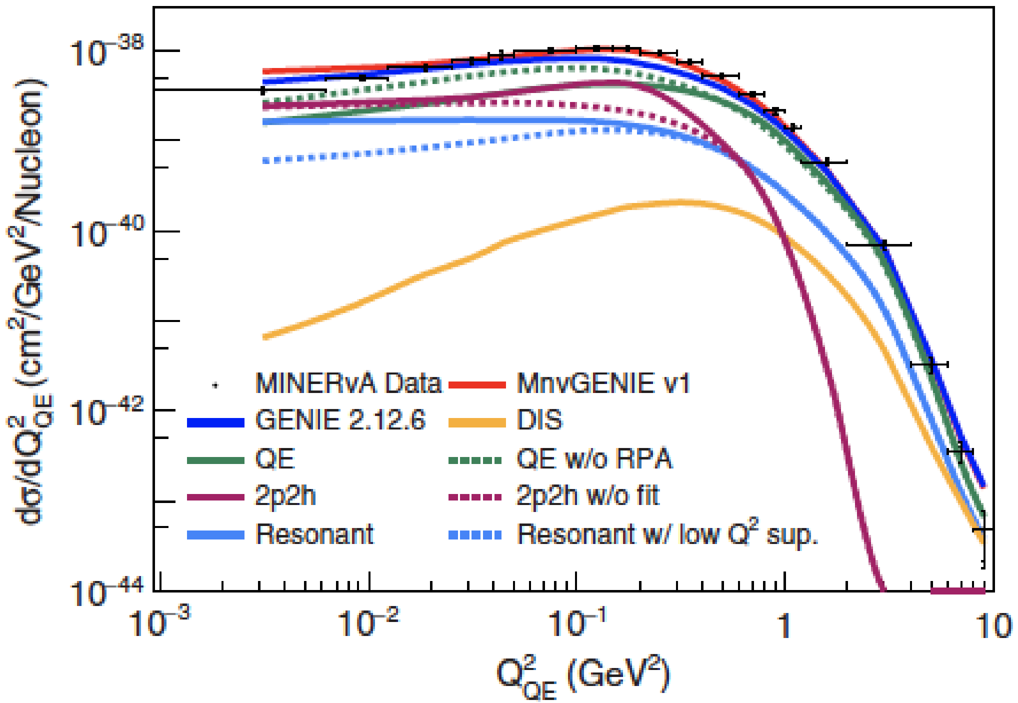


825,258 events
After background subtraction

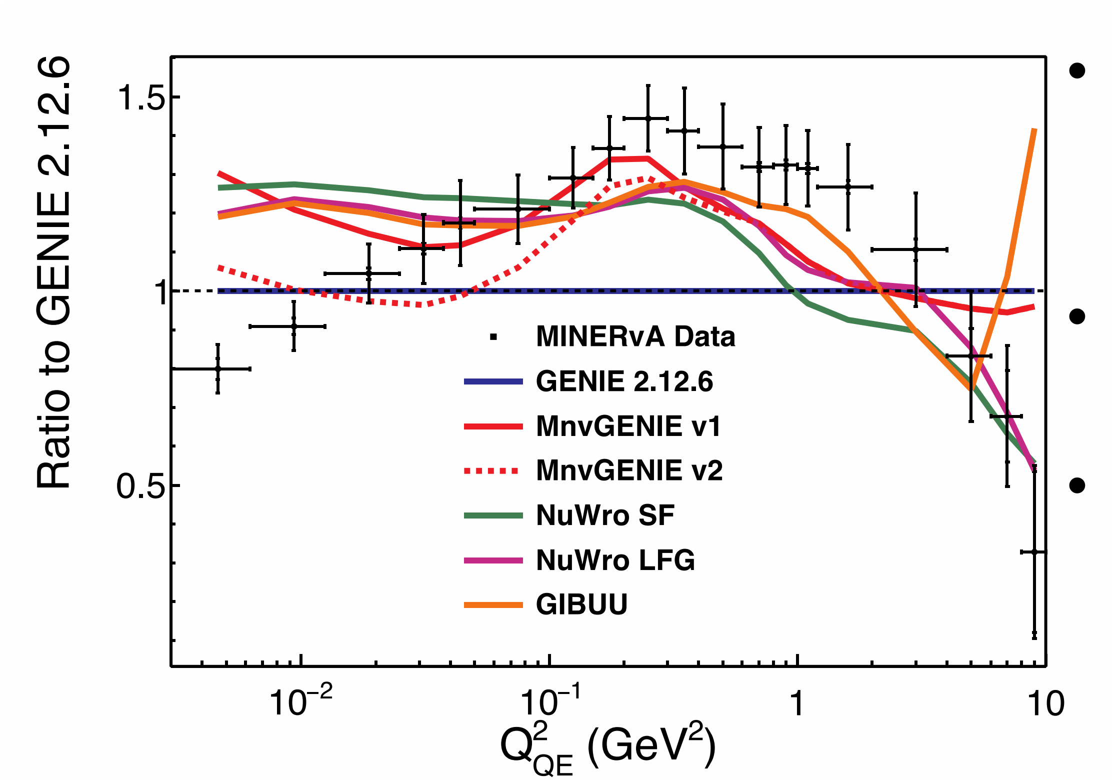
Carneiro *et al.*, PhysRevLett.124.121801

Can we model this?

- Default GENIE 2.12.6
  - (Relativistic Fermi Gas)
- Add in Random Phase Approximation (RPA) to account for screening at low Q^2
- Add ~20% 2p2h effects guided by Jlab results w/o RPA
- Add RPA and tune 2p2h to our neutrino data to get MnvGENIE v1



Compare to GENIE 2.12.6



- Tuned models can reproduce the high Q^2 behavior
- But significant discrepancies at low Q^2 for all models.
- More work is needed, let's look at other observables

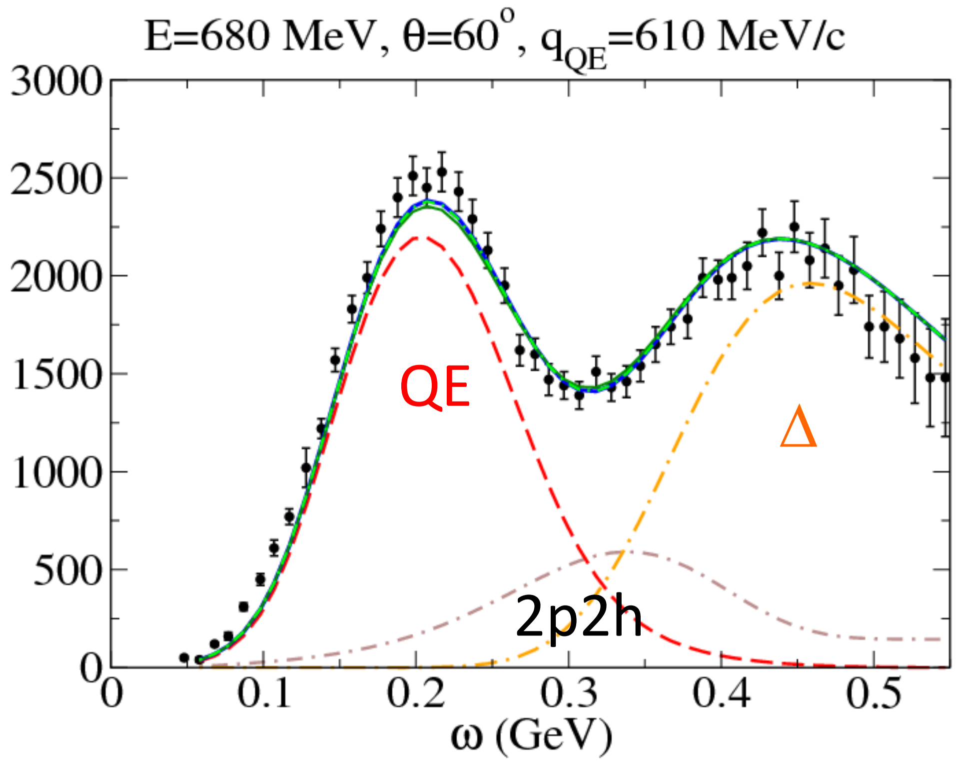
Same data as previous page

Multinucleon Effects and the hadronic energy

- Look at CC triple differential cross section in pt, pz and available hadronic energy
  - $\Sigma T_p \sim$ hadronic energy $\sim \omega$

Motivated by electron scattering data on C.

Megias et al., Phys.Rev. D94 (2016) 013012



Preview: Visible (recoil) Energy for CCQE-Like for neutrinos

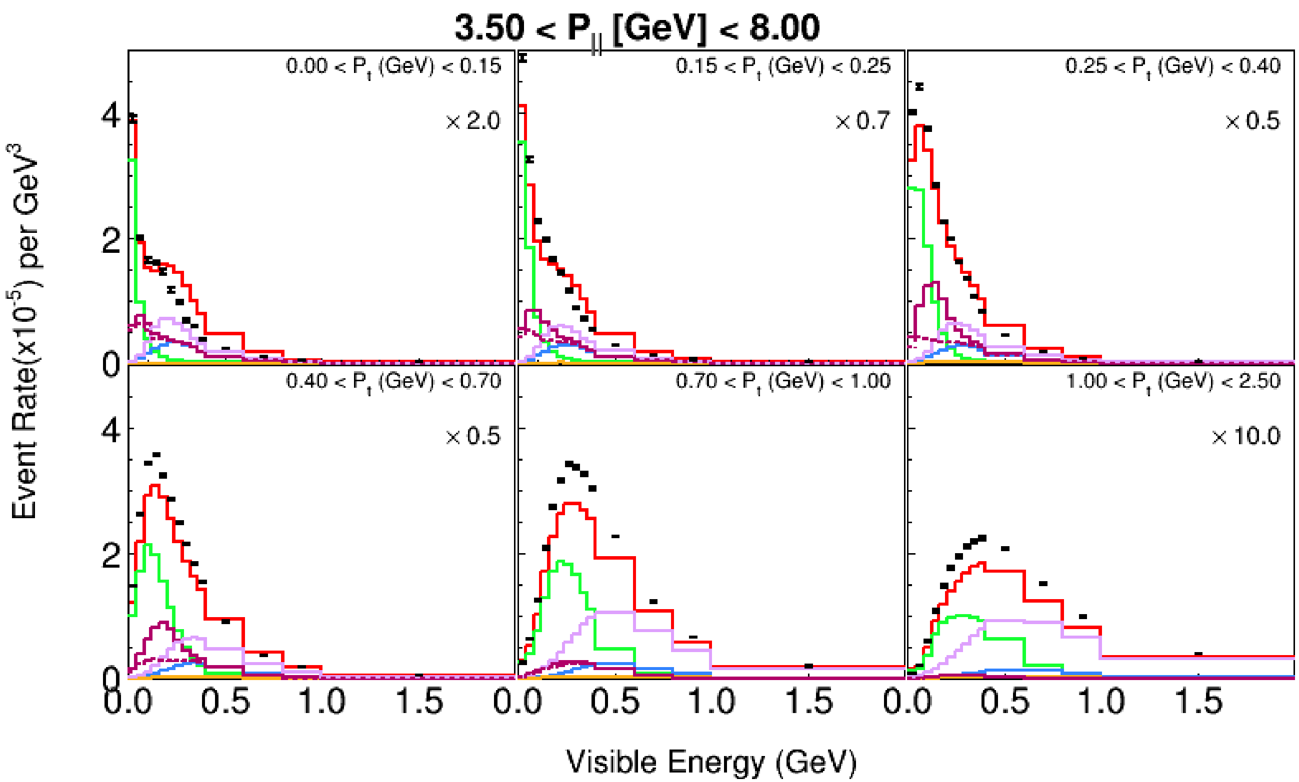
Medium energy : Improved sensitivity at high Q^2
Explore regions at low Q^2.

Different way of looking at the leptonic–hadronic 4–momentum sharing.

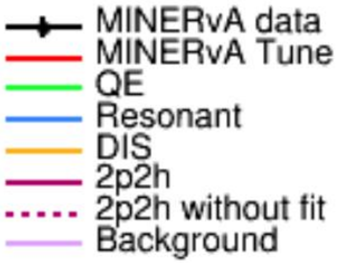
JETP Seminar by Dan Ruterbories (Oct 25 2019)

look at the visible energy in bins of p_T and $p_{||}$

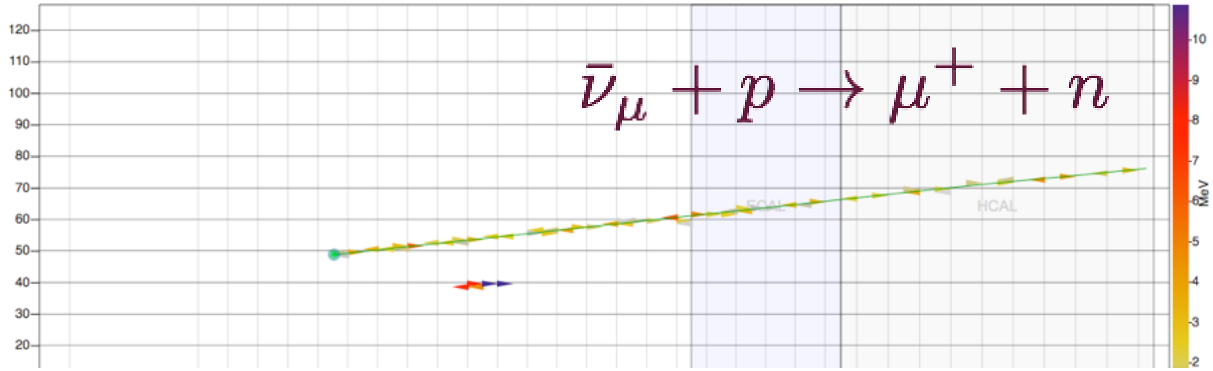
$$E_{available} = \Sigma T_{proton}$$



Panel = Bin of $P_{||,\mu}$
Cell = Bin of $P_{t,\mu}$
Bins = Bins of Recoil

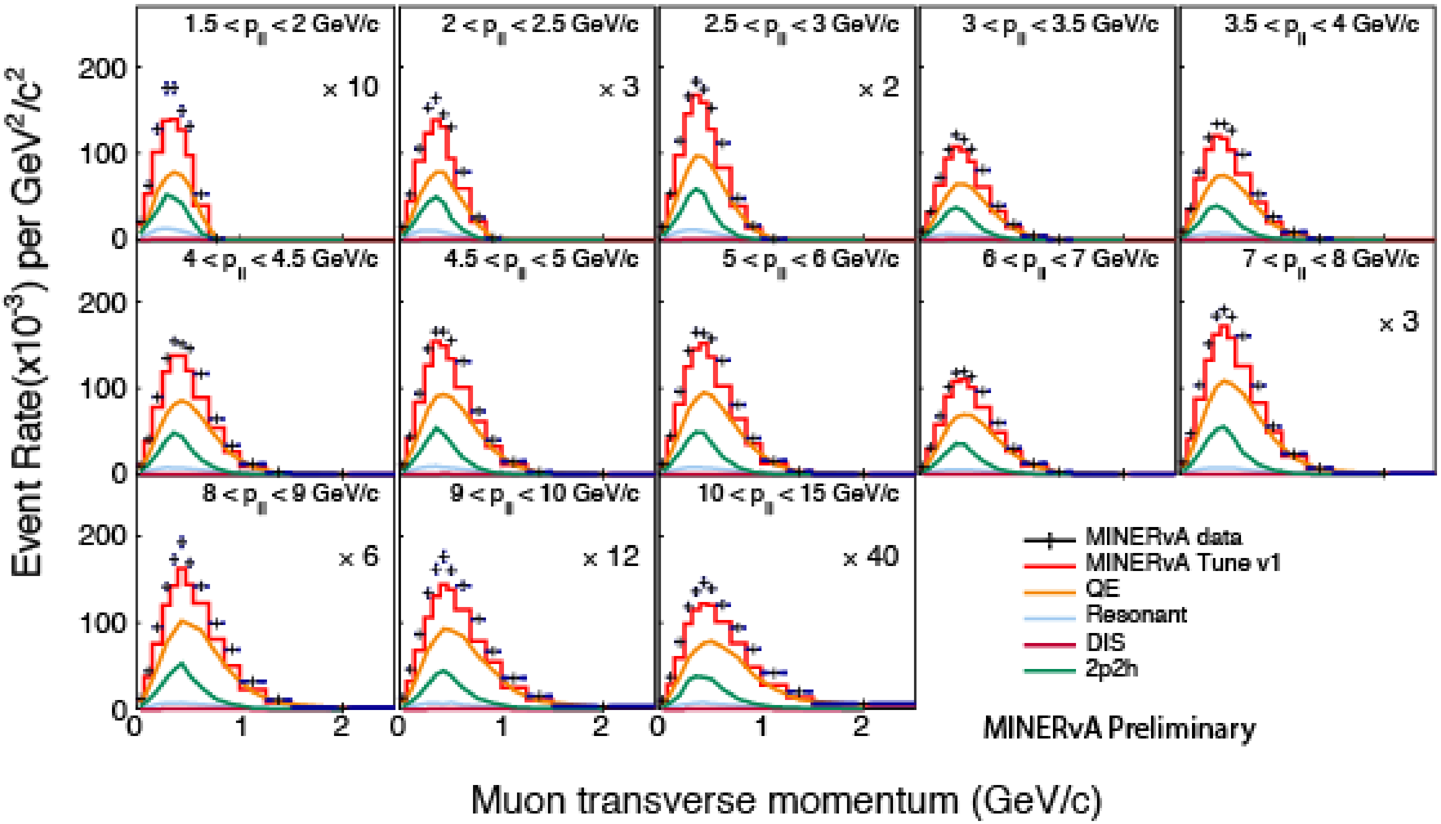


Preview: Anti-neutrino CCQE-like



8.47 x10^{20} POT
477,168 events after background subtraction

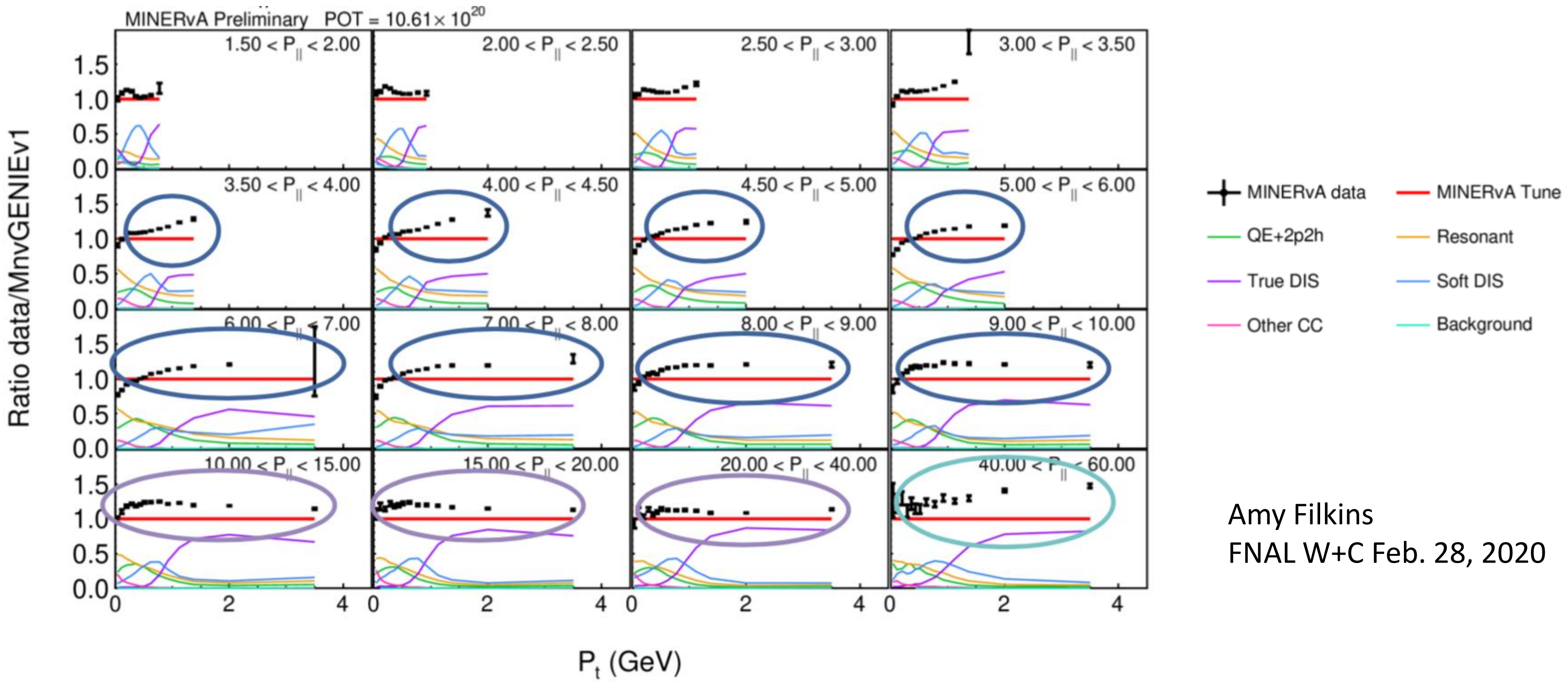
LE result with ~13K events:
Phys. Rev. D **97**, no.5, 052002 (2018)



Preview: Medium Energy Inclusive ν Analysis

Oregon State

Will have smaller uncertainties – Flux ~4-5% .
Better kinematic coverage – 4 new $p_{||}$ bins, 1 new p_T bin



Amy Filkins
FNAL W+C Feb. 28, 2020

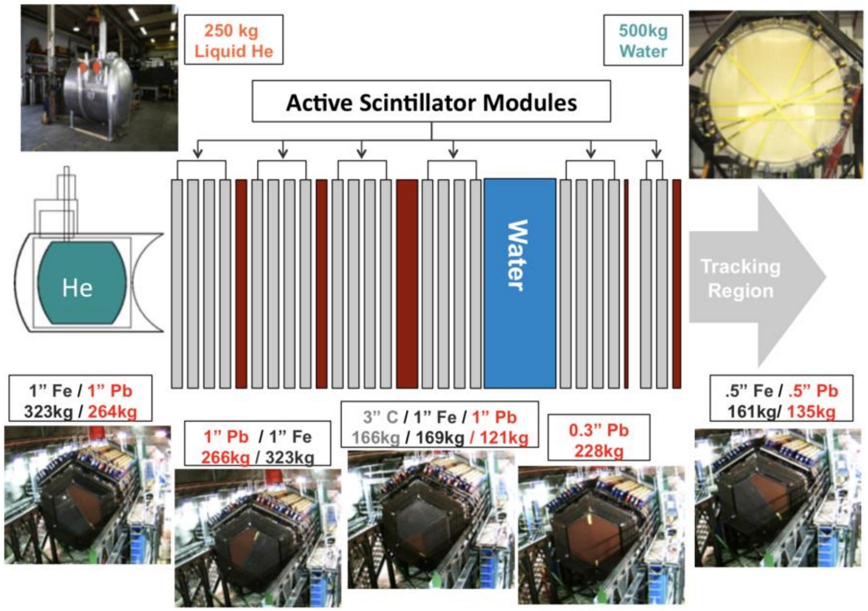
The event rates have consistent underprediction of data at high p_T and high $p_{||}$

LE result: Phys. Rev. D **97**, no.5, 052002 (2018)

Conclusion and Future Plans

New cross section measurements with lower flux uncertainties and high statistics:

- 3D measurements and Transverse kinematic imbalance variables
- Nuclear dependence using nuclear targets (Pb, Fe, H_2O, He)
- Detect neutrons
- High W events for shallow and deep inelastic scattering



Long term:

- MINERVA has an active data preservation project to make these data valuable for the long term.

Recent MINERvA Papers

Oregon State

A. Filkins *et al.* , “Double-differential inclusive charged-current ν_μ cross sections on hydrocarbon in MINERvA at E_ν ~ 3.5 GeV,” Phys. Rev. D **101**, no.11, 112007(2020)

M. F. Carneiro *et al.* , “High-Statistics Measurement of Neutrino Quasielasticlike Scattering at 6 GeV on a Hydrocarbon Target,” Phys. Rev. Lett. **124**, no.12, 121801 (2020)

T. Cai *et al.* , “Nucleon binding energy and transverse momentum imbalance in neutrino-nucleus reactions,” Phys. Rev. D **101**, no.9, 092001 (2020)

T. Le *et al.* , “Measurement of $\bar{\nu}_\mu$ Charged-Current Single π^- Production on Hydrocarbon in the Few-GeV Region using MINERvA,” Phys. Rev. D **100**, no.5, 052008 (2019)

E. Valencia *et al.* , “Constraint of the MINERνA medium energy neutrino flux using neutrino-electron elastic scattering,” Phys. Rev. D **100**, no.9, 092001 (2019)

P. Stowell *et al.* , “Tuning the GENIE Pion Production Model with MINERνA Data,” Phys. Rev. D **100**, no.7, 072005 (2019)

M. Elkins *et al.* , “Neutron measurements from antineutrino hydrocarbon reactions,” Phys. Rev. D **100**, no.5, 052002 (2019)

D. Ruterbories *et al.* , “Measurement of Quasielastic-Like Neutrino Scattering at $< E_\nu >$ 3.5 GeV on a Hydrocarbon Target,” Phys. Rev. D **99**, no.1, 012004 (2019)

G. N. Perdue *et al.* , “Reducing model bias in a deep learning classifier using domain adversarial neural networks in the MINERvA experiment,” JINST **13**, no.11, P11020 (2018)

X. G. Lu *et al.* , “Measurement of final-state correlations in neutrino muon-proton mesonless production on hydrocarbon at $\langle E_\nu \rangle$ = 3 GeV,” Phys. Rev. Lett. **121**, no.2, 022504 (2018)

R. Gran *et al.* , “Antineutrino Charged-Current Reactions on Hydro- carbon with Low Momentum Transfer,” Phys. Rev. Lett. **120**, no.22, 221805 (2018)

C. E. Patrick *et al.* , “Measurement of the Muon Antineutrino Double- Differential Cross Section for Quasielastic-like Scattering on Hydrocar- bon at $E_\nu \sim$ 3.5GeV,” Phys. Rev. D **97**, no.5, 052002 (2018)