The Next Decade of ν-nucleus Scattering Issues

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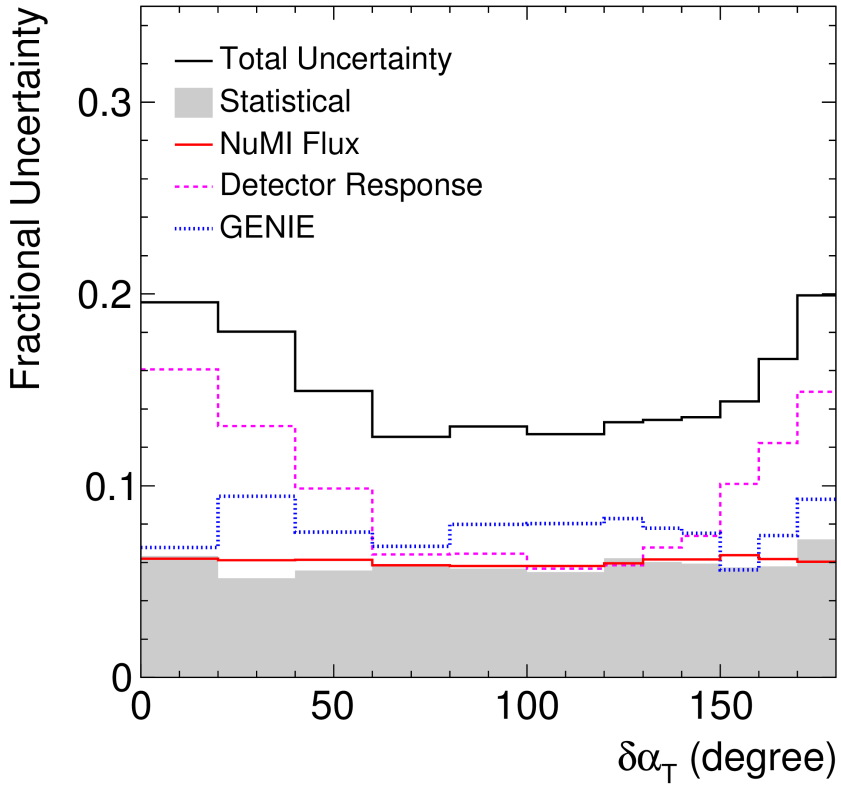
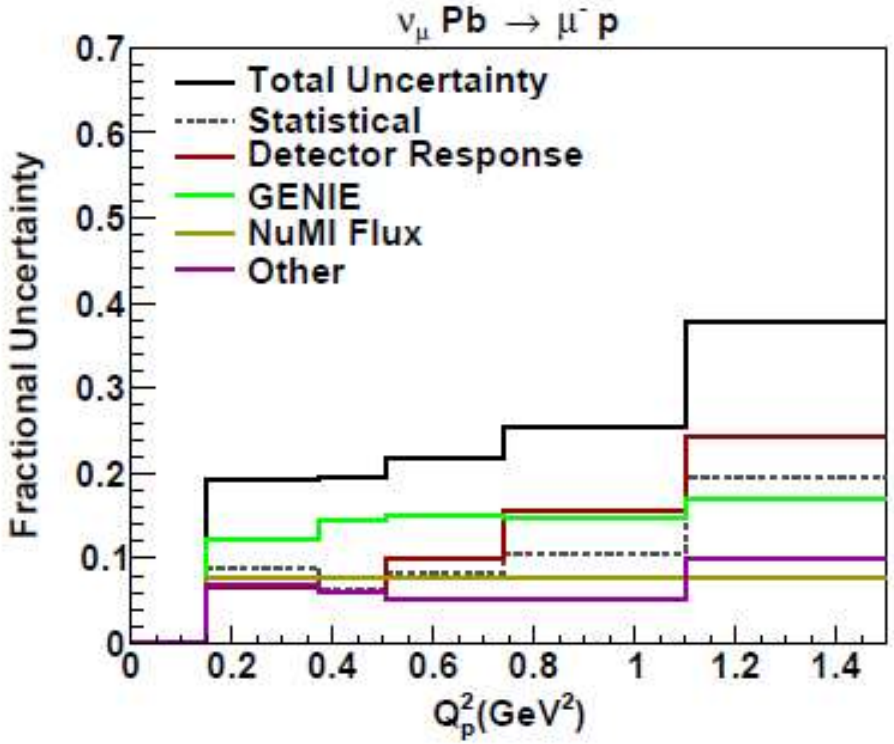
12 August 2018

Need to consider the NuSTORM **FACILITY**

- NuSTORM beam is wonderful but it is certainly not the whole story when measuring cross sections:
- Example of (lower statistics) MINERvA studies.





Where are we now!

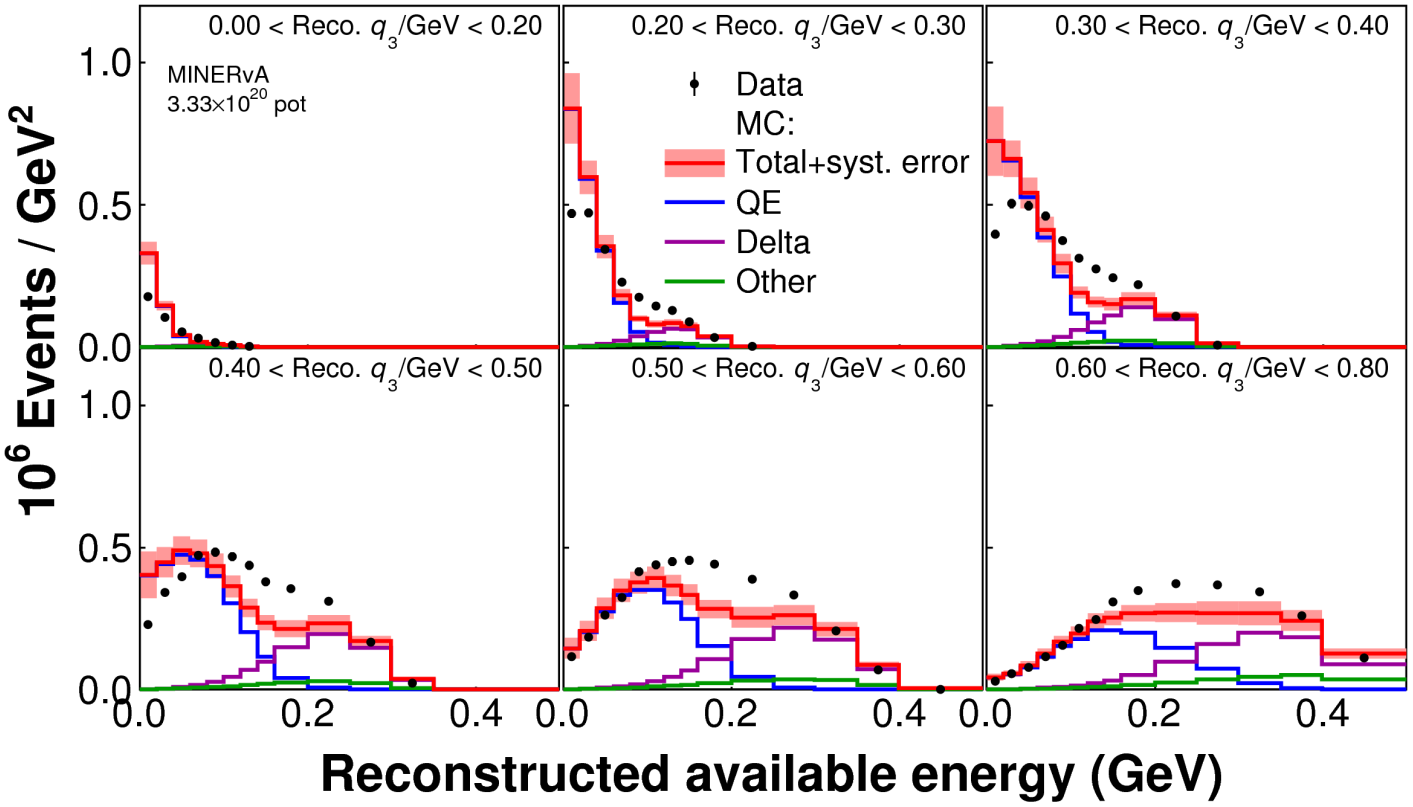
- Quasi-elastic: Major focus of study of MINERvA, T2K and NOvA. Essentially all on C, all with relatively minimal statistical errors and flux errors of (6-10)% with similar contributions from GENIE and from detector uncertainties.

- Delta Production: Major focus of MINERvA and more minimal contributions from NOvA and T2K due to neutrino energy range. Statistical errors larger than QE, larger GENIE uncertainties and roughly similar detector uncertainties except for π^0 studies that have larger systematics.

- Above the Delta an increasingly dark and dangerous place full of unknowns. Perhaps the thing we know best there is the flux!

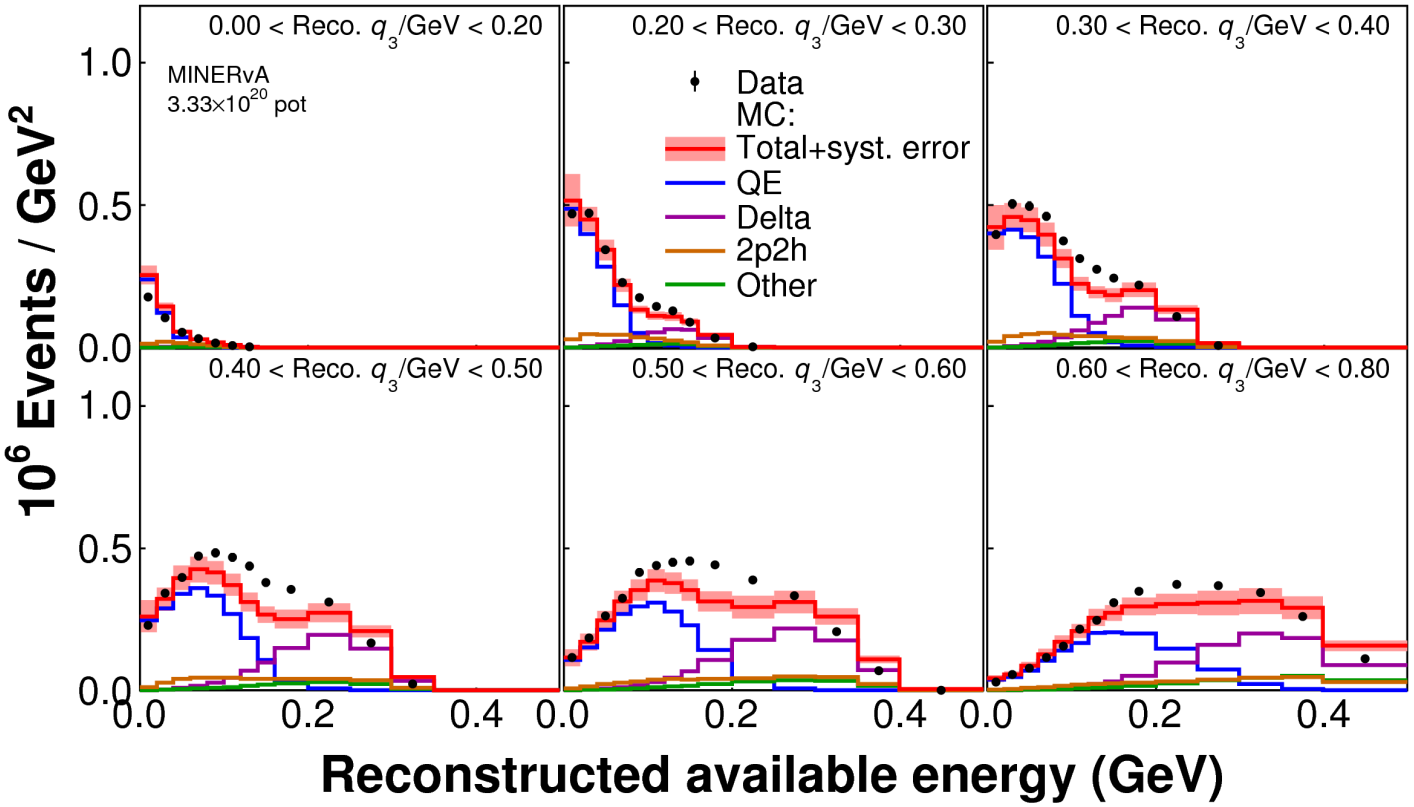
Where are we now?
Use recent MINERvA Study

- Use current GENIE models for QE and Delta production:
- Observed events versus GENIE prediction as a function of energy in q_3 bins (momentum of q vector):



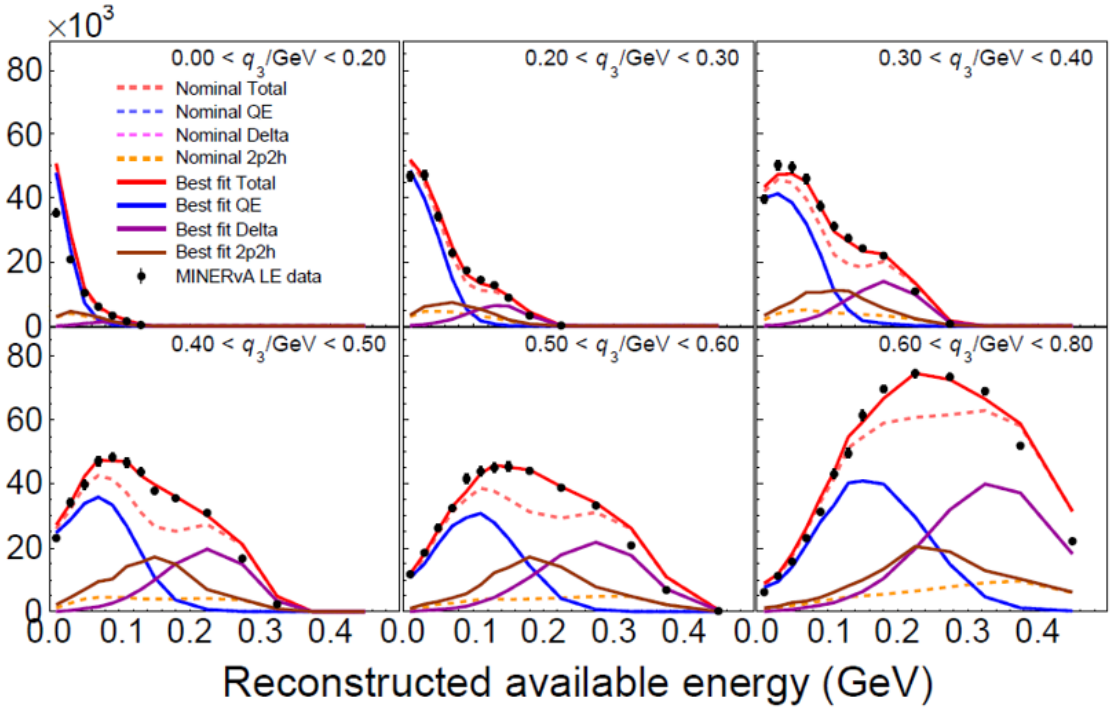
Introduce Valencia Model RPA and 2p2h

- Let's now add RPA and correlated nucleon pair corrections (2p2h)
- It shrinks the difference but is not enough….



Call this the "Minerva tune (MnvGENIE)" composed of RPA+2p2h+Low recoil fit+(non-resonant pion reduction)

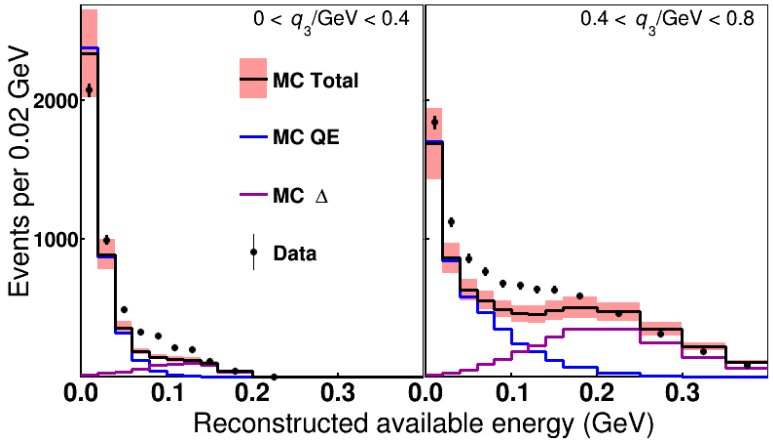
- Fit a 2D Gaussian in true (q_0,q_3) as a reweighting function to the 2p2h contributions to get the best agreement
- Only reweight 2p2h although the missing strength could be coming from QE and/or Delta and/or 2p2h!!
- No assurance that this fit works for other nuclei. Possible fit with other neutrino energy spectra on C in the works….



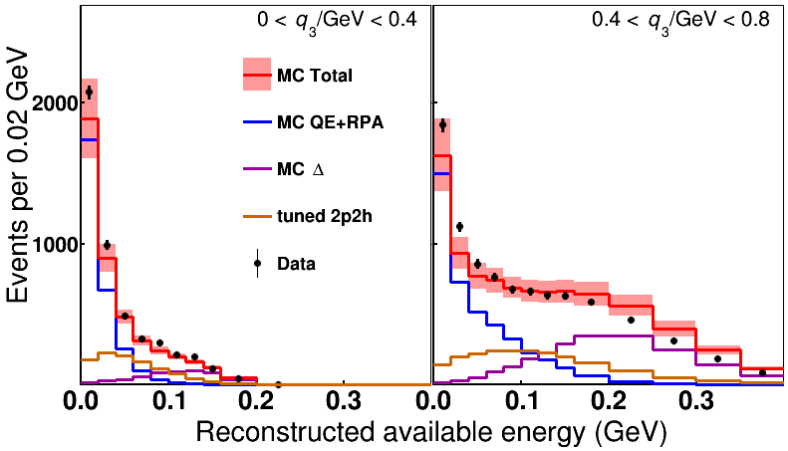
Does it work for other samples? Yes, major accomplishment

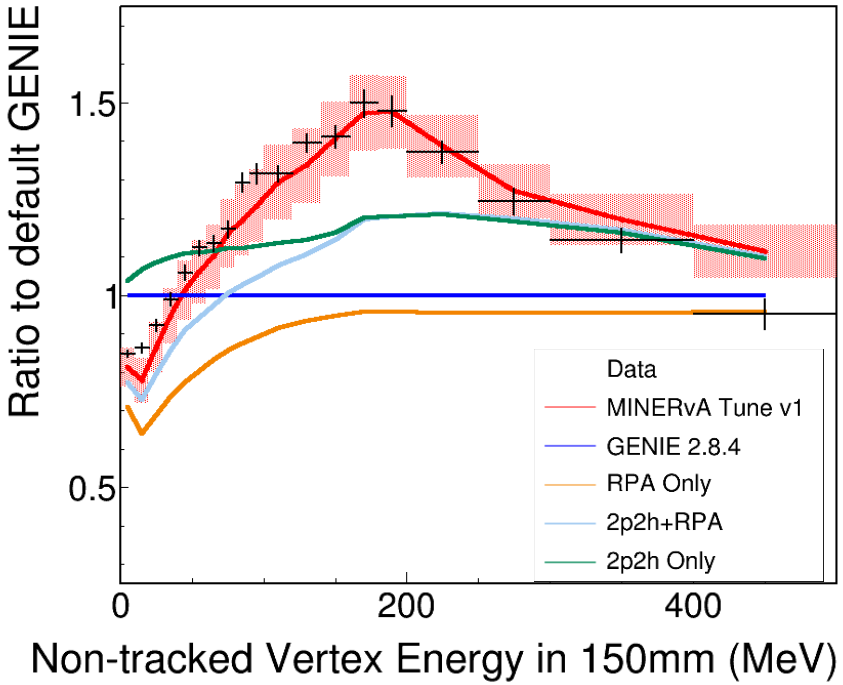
- This reweight works, surprisingly, for antineutrino and vertex energy as well

Nubar **before** enhancement with MINERvA tune

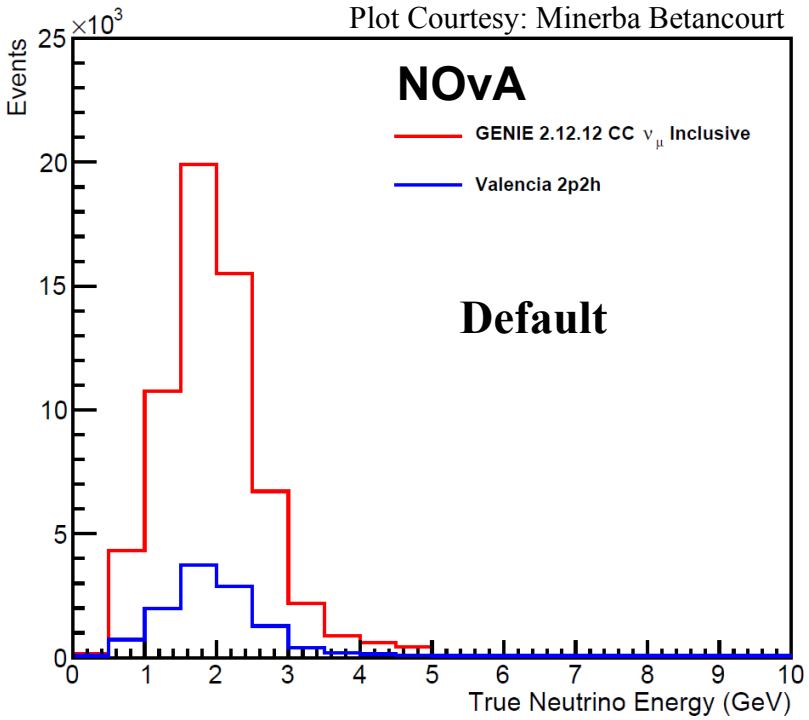


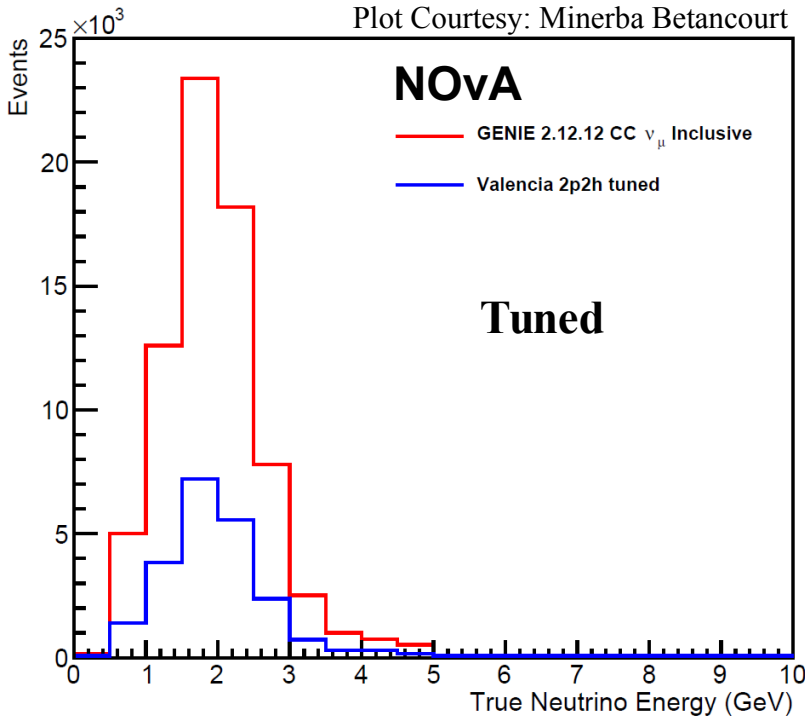
Nubar **after** enhancement with MINERvA tune





Implications when applied to other experiments

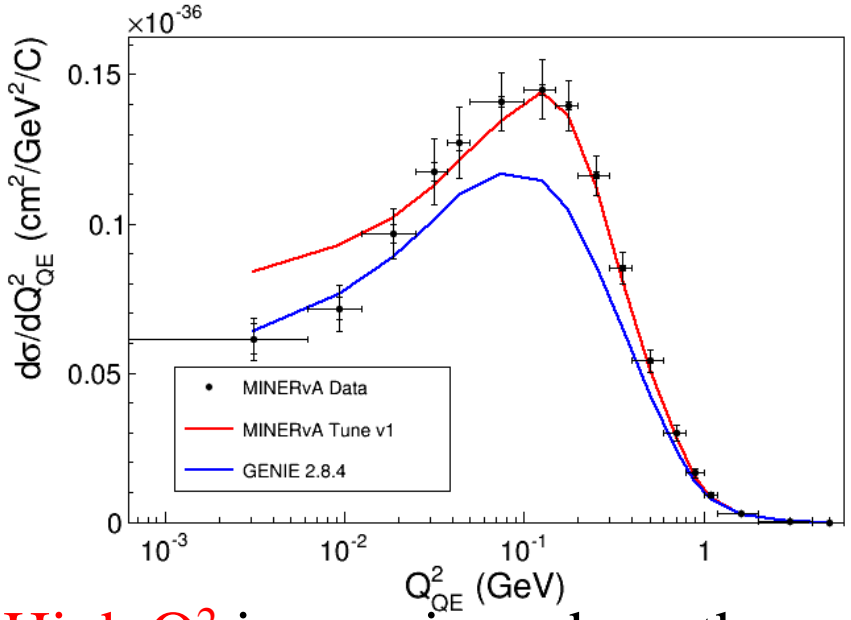


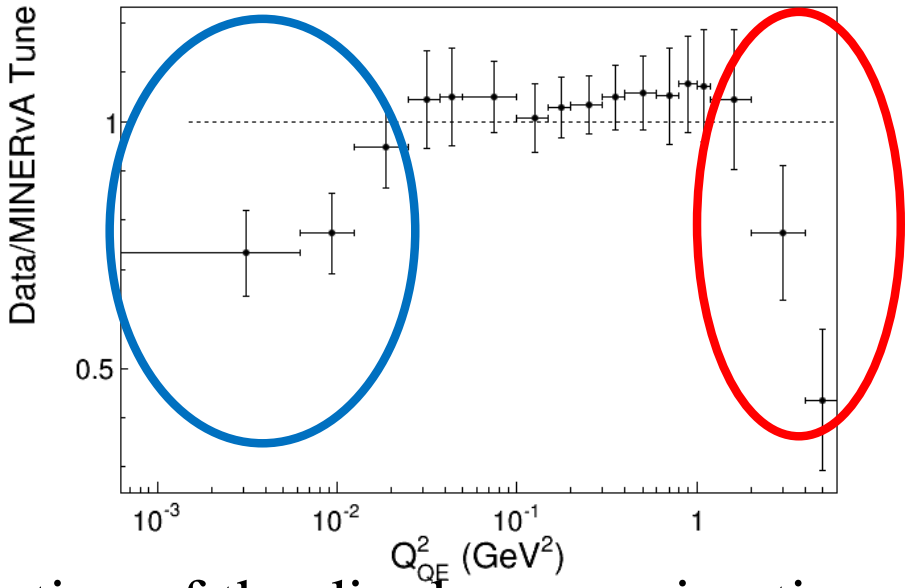


- GENIE 2.12.12 w/ Valencia 2p2h
  - Tuned w/ 2p2h-like enhancement vs. default
- Non-negligible change in **inclusive** energy spectrum at **NOvA** energy

Where does it **not** work?

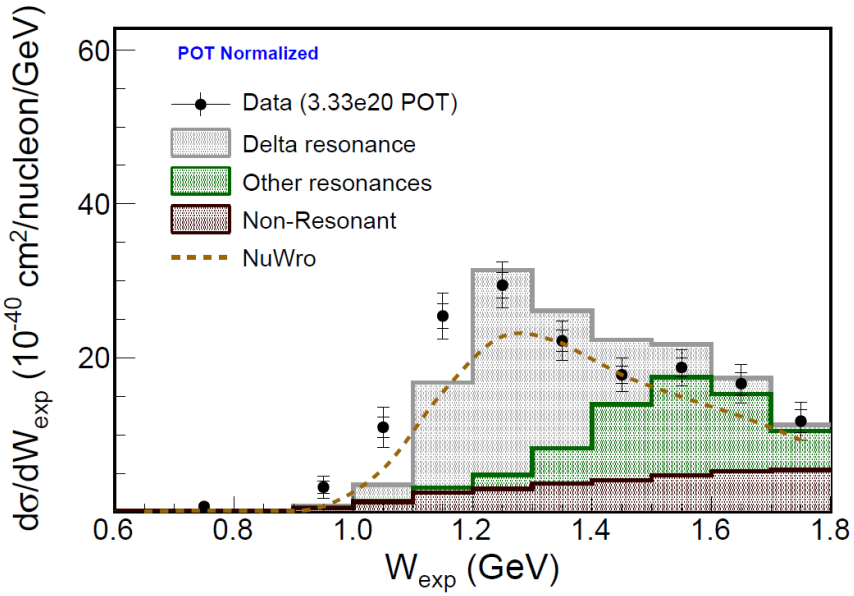
- Neutrino CCQE-like Sample



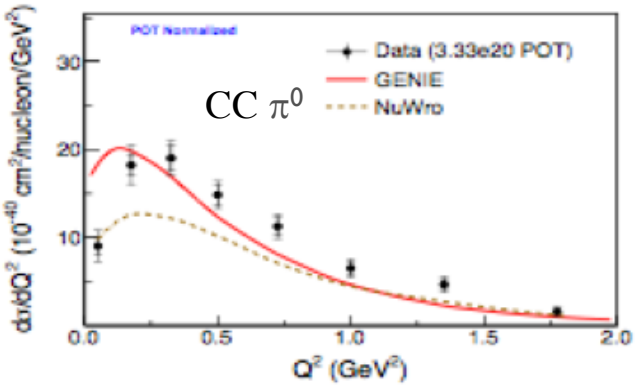


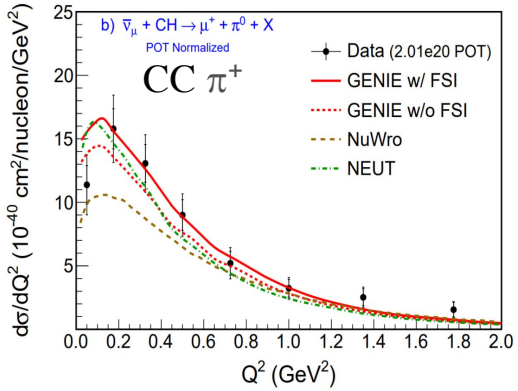
- High Q^2 is a region where the assumption of the dipole approximation starts to break down.
- Low Q^2 is a region of phase space where the fraction of events has an increased population of resonant pion qe-like events.
- Need low Q^2 reduction in resonant event production – RPA for resonances

Problems persist with resonance production.



- W_{exp} is derived assuming kinematics of a struck nucleon at rest
  - Neither generator takes into account interference between resonant and non-resonant processes
  - Fermi-motion simulation
  - In medium modification of Δ(1232)



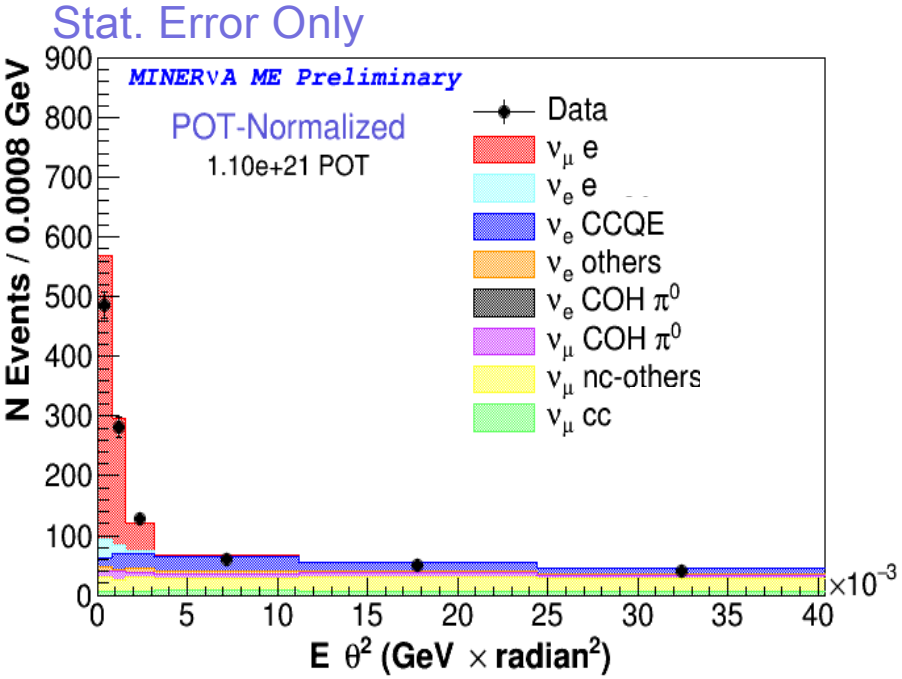


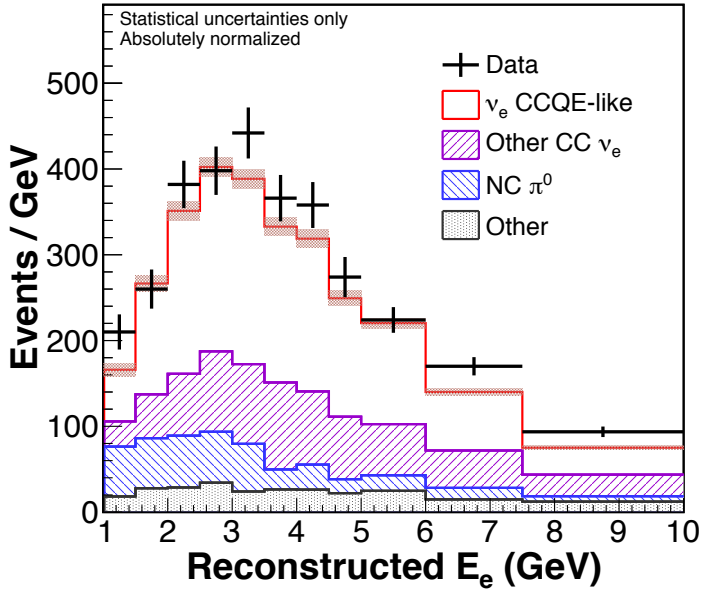
- π^0 production by neutrinos provides insight on π^0 –NC background to ν_e appearance
- π^0 production wants low Q2 reduction – RPA effect for resonance production
- Not as strong for π^+ production

Final State Electrons

ν_μ + e – scattering

ν_e + n scattering





- ME sample has about **800 ν+e events**
- Flux constraint ongoing
  - changes flux uncertainty from about 8% to 6% or better in the focusing peak

- Above from LE publication: ≈ 3200 events
- **Expect over twice as many in ME exposure**
- **Note this is only CCQE-like events!**

From the Δ up through DIS

- Essentially an unknown region.
  - Duality works differently for neutrinos compared to electron scattering
  - What about the interaction of duality with non-perturbative QCD effects (target mass and higher twist…)
- There is considerable discussion even about νDIS results
  - different nPDFs for ν-A compared to e/μ – A
- We are investigating this with MINERvA
- Need a higher energy beam to thoroughly investigate these regions.

What do we need and how could NuSTORM help!?!

- **More rapid response from Generators to improvements in theory models and experimental fits with new data.**
- NuSTORM characteristics (<1% flux precision)

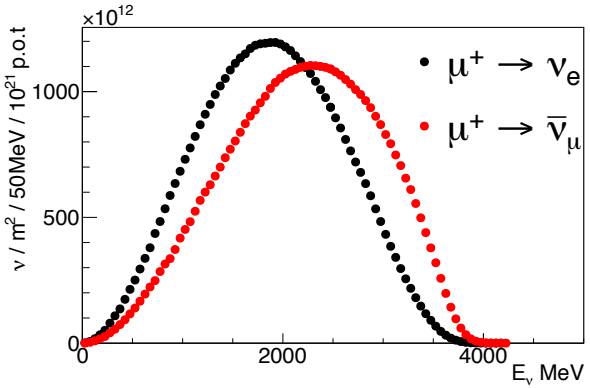


Table 2. Event sample at 50 m from the end of the decay straight per 100T for 10^{21} POT.

μ^+ Stored Channel	**k**Events	μ^- Stored Channel	**k**Events
ν_eCC	5,188	$\bar{\nu}_e$CC	2,519
$\bar{\nu}_\mu$CC	3,030	ν_μCC	6,060
ν_eNC	1,817	$\bar{\nu}_e$NC	1,002
$\bar{\nu}_\mu$NC	1,174	ν_μNC	2,074
π^+ Injected Channel	**k**Events	π^- Injected Channel	**k**Events
ν_μCC	41,053	$\bar{\nu}_\mu$CC	19,939
ν_μNC	14,384	$\bar{\nu}_\mu$CC	6,986

- Energy spectra good for QE and Delta production.
- Still reasonable for somewhat higher W resonances.
- Not as good for the SIS and DIS regions.
- Given a detector with a suite of targets that include Ar and well controlled detector systematics, a NuSTORM facility could provide the statistics and reduction in flux error that could confront the open questions we now have for QE and Delta production for both ν_μ and ν_e scattering.

How about nucleon targets

- Yes, we definitely could use much increased statistics off H and D targets. Summary below from Luis Alvarez Ruso.
- Possibility of using HP Gas TPC's filled with H or D but need to reduce quoted statistics by around a factor of 100 or so.
  - Do we want new more precise ν-nucleon cross section measuremens?
    - Relevant input for ν MC and theoretical models in general
    - New info about the axial structure of nucleons and other baryons
    - Radiative corrections
    - ChPT LECs, non-pole corrections to Goldberger-Treiman relations
    - New physics (perhaps combining c.s. & lepton/baryon polarization)
    - …
  - Do we NEED new more precise ν-nucleon cross section measuremens?
    - Our letter to Santa should be compelling:
    - ν-nucleon cross section should be crucial for future oscillation measurements
    - Experimental projections: c.s. uncertainties $\Rightarrow$ oscillation errors
  - Possible alternatives:
    - LQCD
    - (Polarized) electron scattering
    - H_2 enriched targets
    - …

Summary

- With NuSTORM beam we can:
  - Reduce the current best flux uncertainty from ≈ (5-6)% (with ν + e constraint) to ≈1%.
    - » Improve flux uncertainty of QE and lower W resonance studies.
  - Have a reliable and well-known flux of ν_e . Current best is order 8k events from MINERvA. New high-statistics study of ν_e events.
- To consider - what can DUNE beam and near detector suite accomplish.
  - Have heard they will have many thousand ν + e and can constrain flux to ”a couple” %?
  - Will have many 10^4 of ν_e events with smaller detector systematic uncertainties coming from LAr TPC and other near detectors in the suite?
- Ideal NuSTORM cross section experiment would be:
  - higher energy (shift peak to 4 GeV?) beam.
  - on a detector with multiple nuclear targets (including Ar for sure and H/D would be nice) with couple % detector systematics.
  - yielding statistics with negligible statistical error.
  - paired with a generator team giving rapid inclusion to new theoretical models that incorporate improved experimental results as soon as available.