MINERvA

Illuminating the Interaction of Neutrinos with Bound Nucleons in the Nuclear Environment

Daniel Ruterbories

on behalf of the MINERvA Collaboration

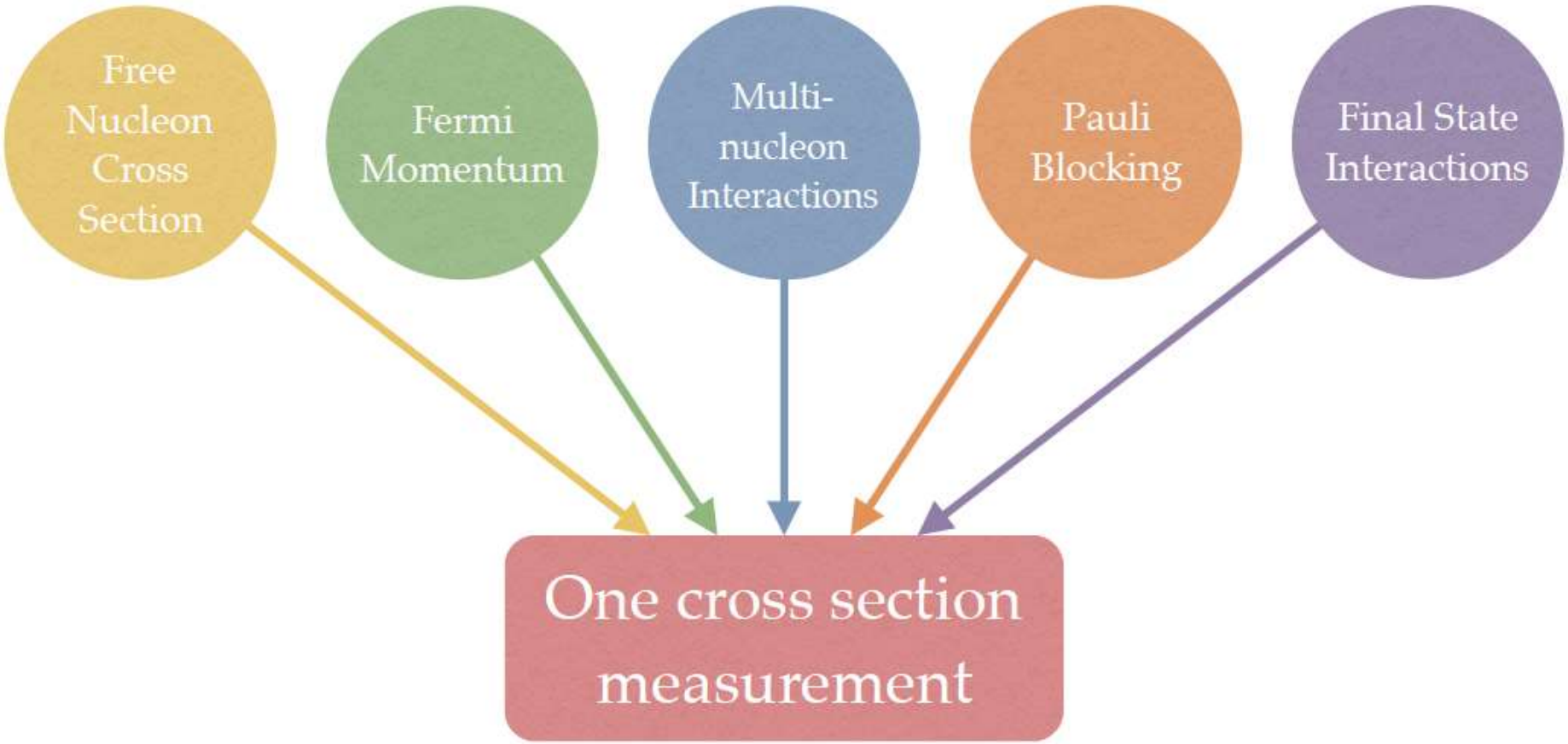
June 4th, 2018

Previously MINERvA@NEUTRINO

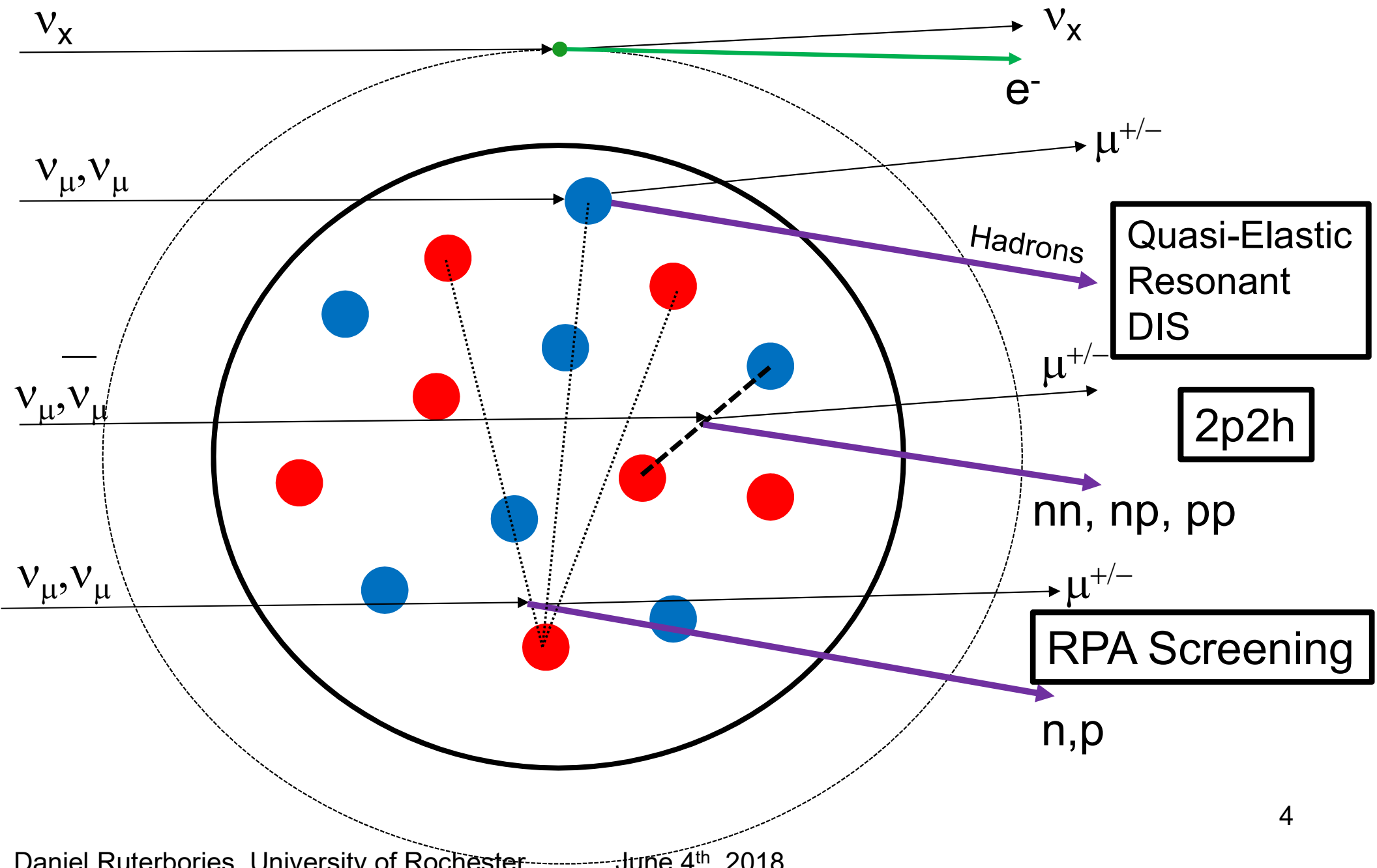
Approach

- Developing models of neutrino interactions is difficult — there are many, many unknown parameters, and we generally have to measure a bunch of them at once:

L.Fields NEUTRINO 2016



Big Picture-Initial State



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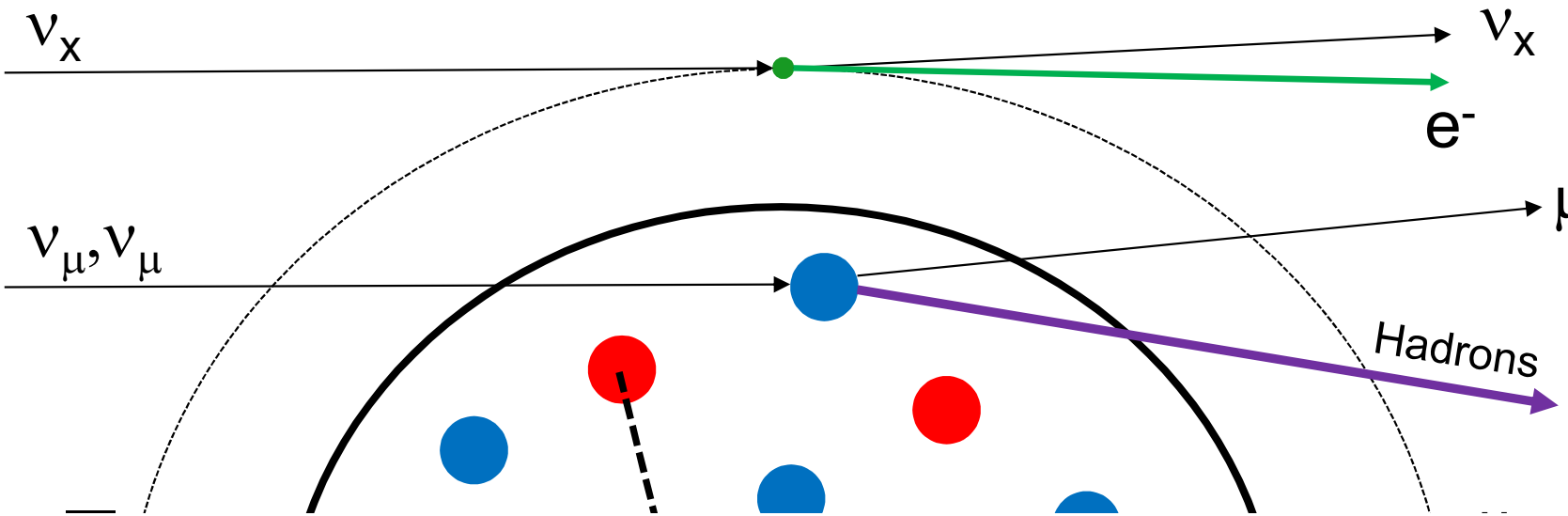
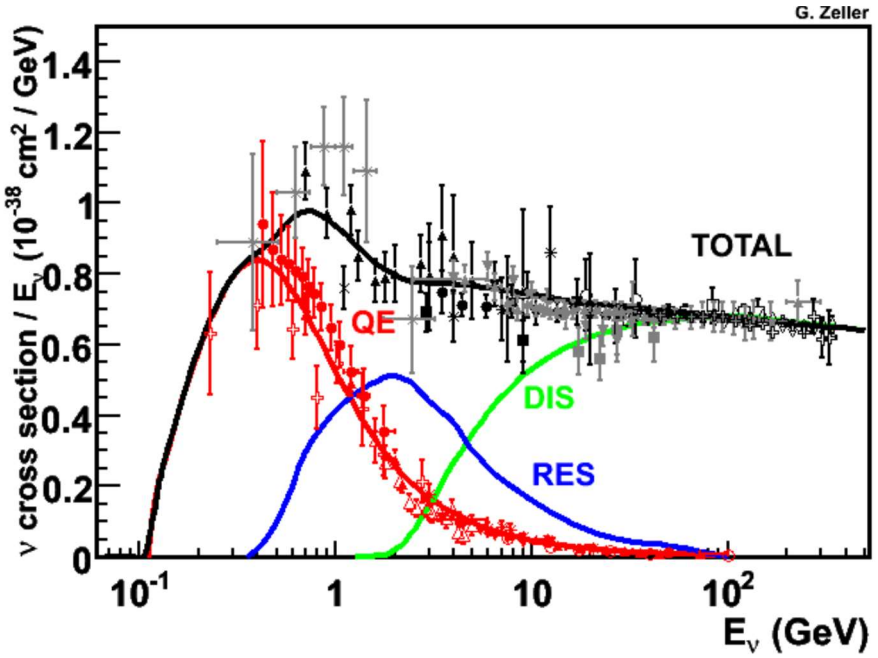
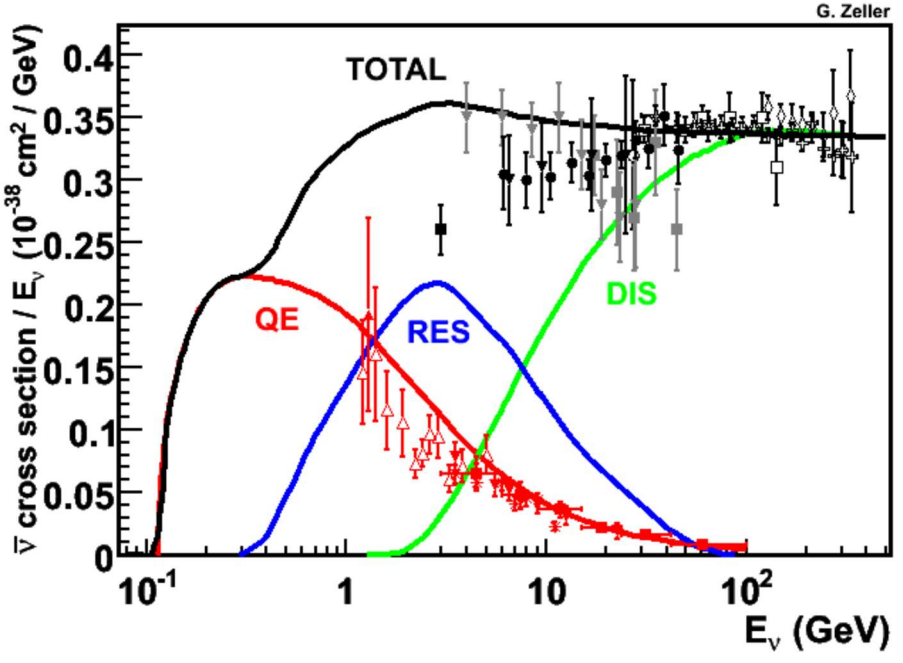


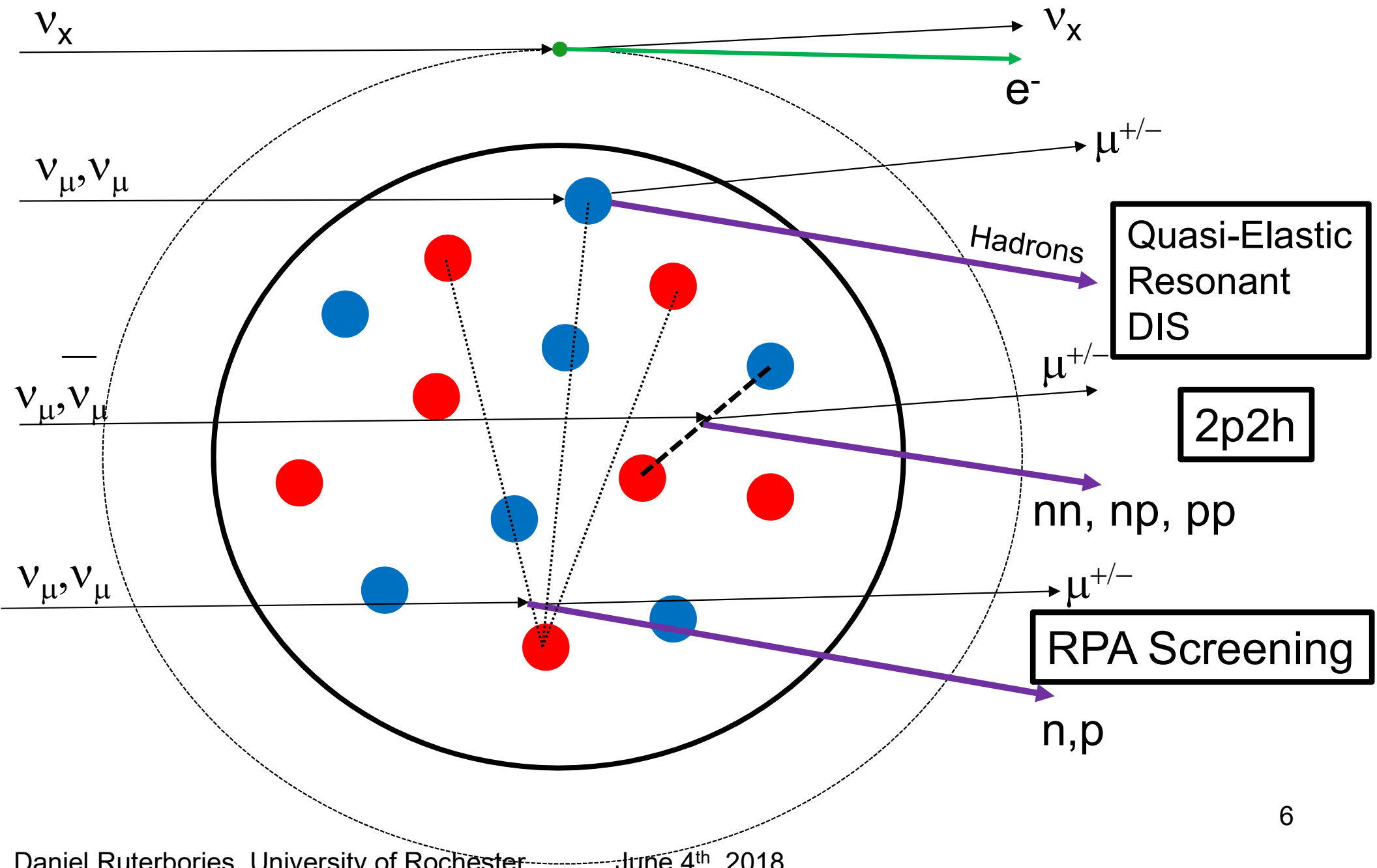
Quasi-Elastic
Resonant
DIS

Rev. Mod. Phys. 84, 1307–1341 (2012)



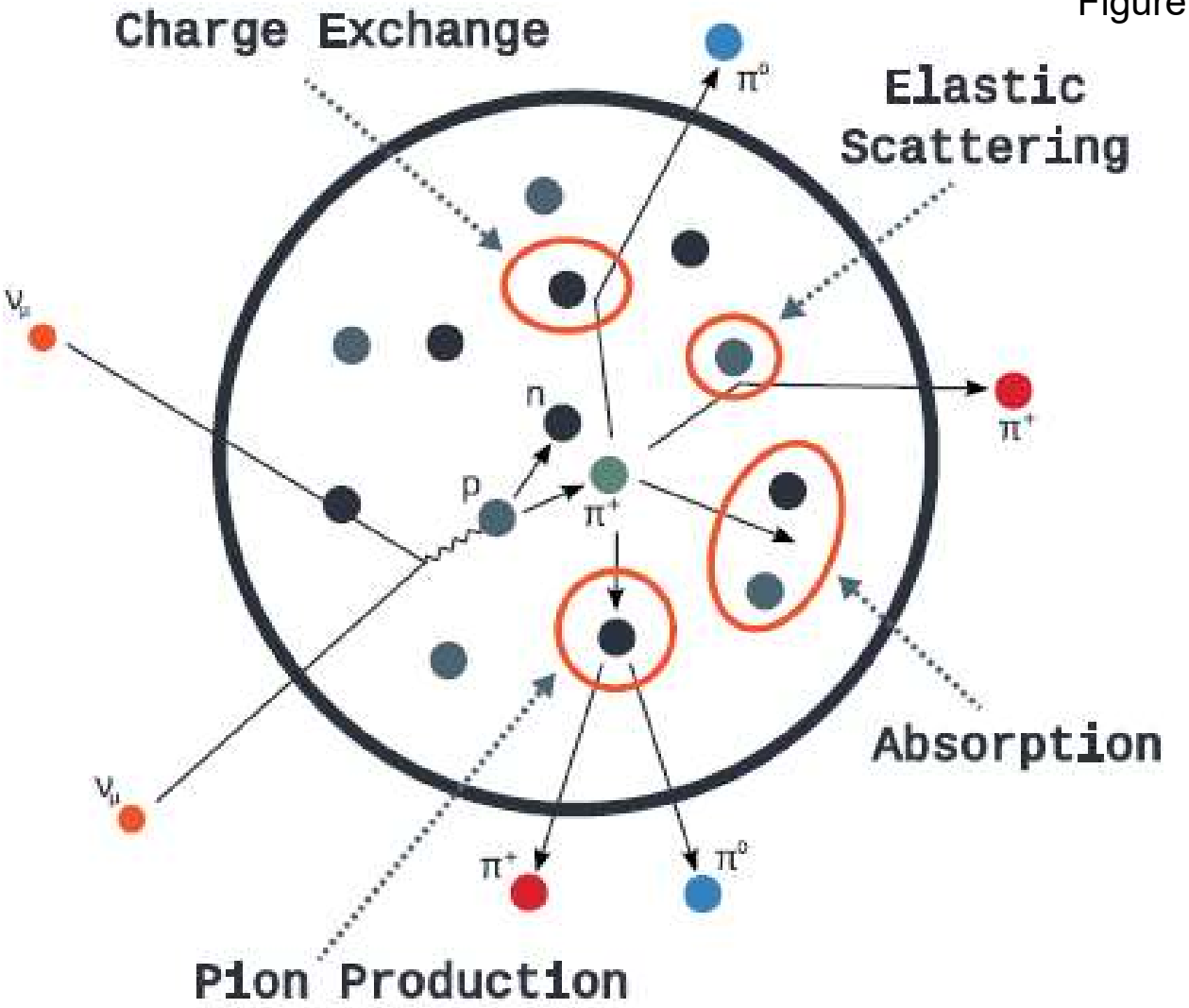


Big Picture-Initial State



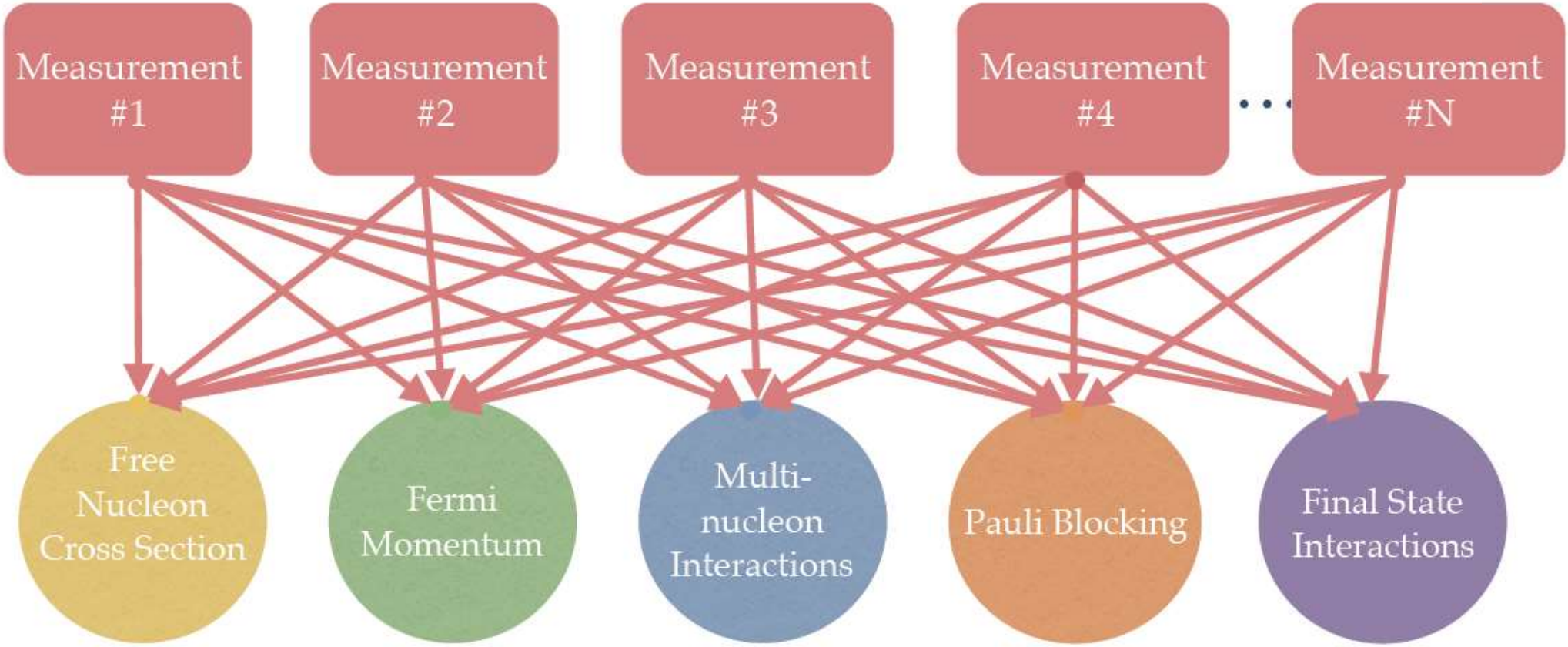
Big Picture
Final State Interactions (FSI)

Figure by Tomasz Golan



Approach

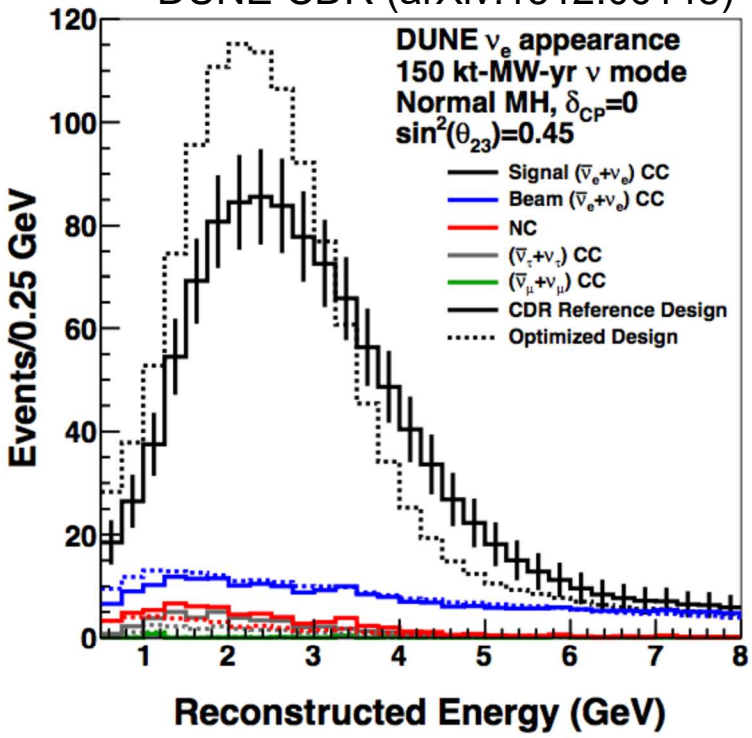
L.Fields NEUTRINO 2016



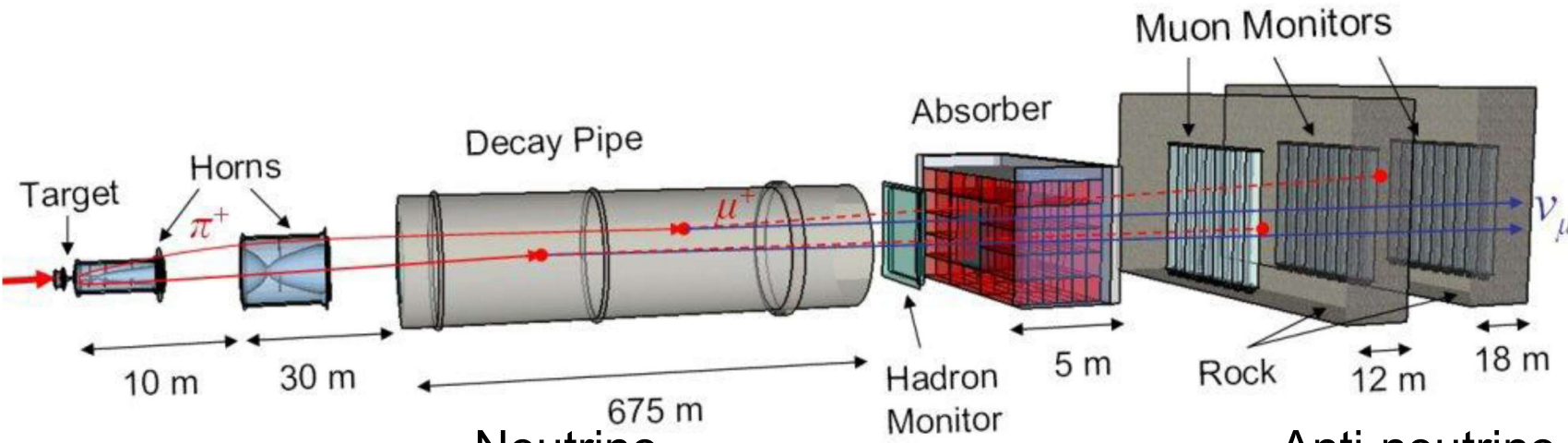
Constrained Cross Section Modeling
A Critical Input To Oscillation Experiments

- Oscillation results need
  - Event rates
  - Event spectra - E_ν
- Energy reconstruction biases
  - Particle kinematics
  - Calorimetry
  - **How well are the biases simulated**

DUNE CDR (arXiv:1512.06148)

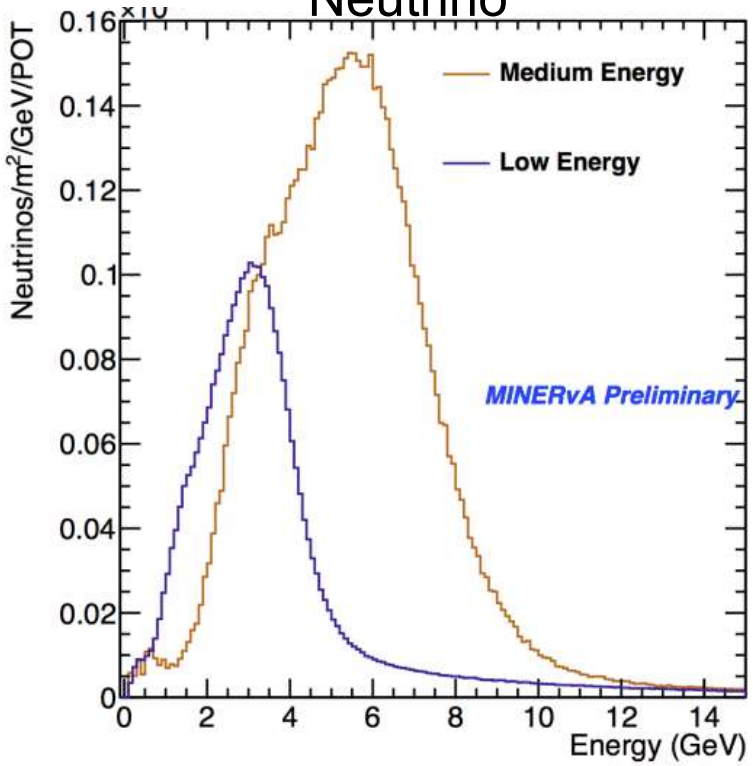


The NUMI beam

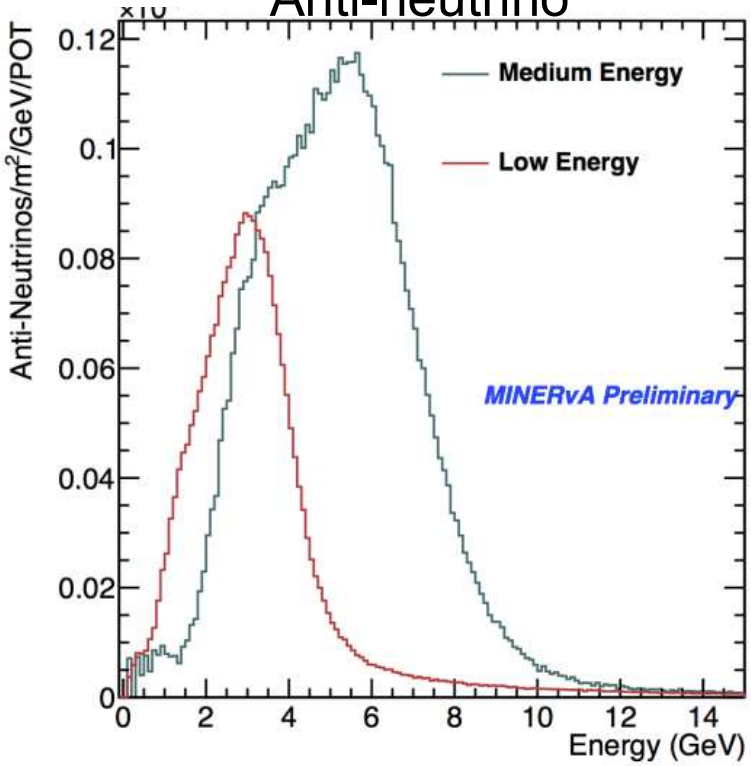


Towards MINERvA/MINOS

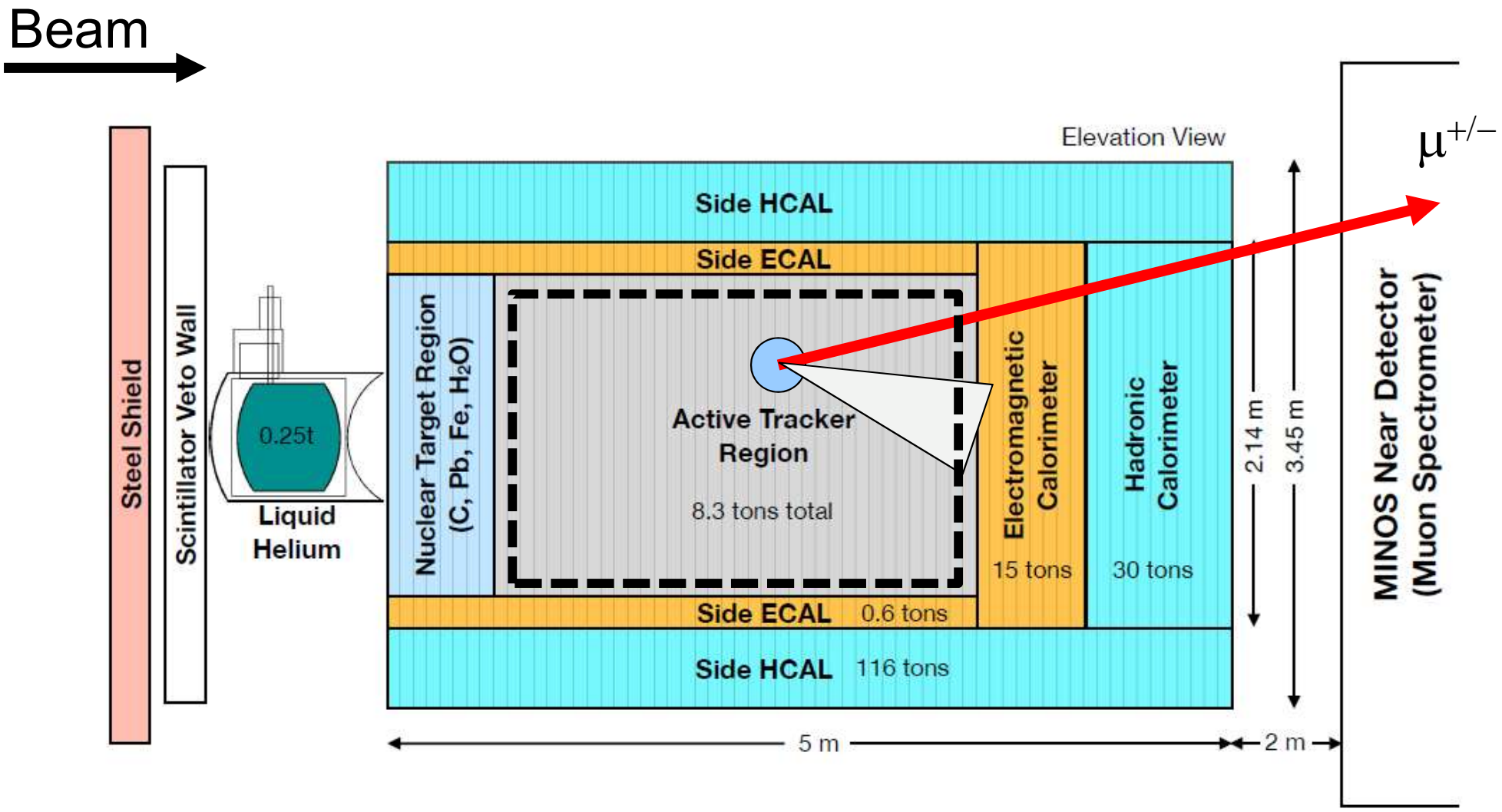
Neutrino



Anti-neutrino



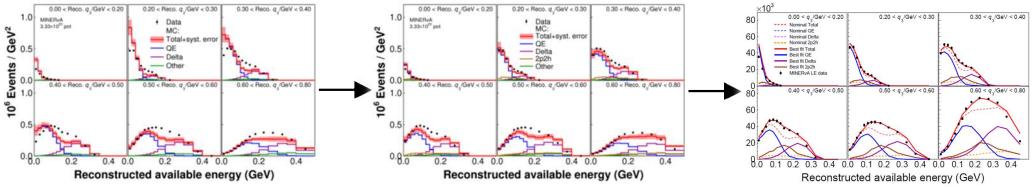
The MINERvA Detector

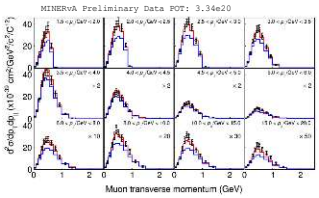


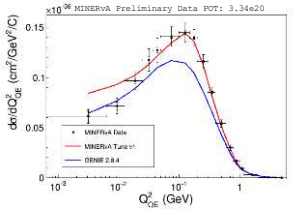
The MINERvA Picture

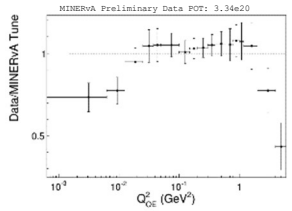
with a some of our results since Neutrino 2016

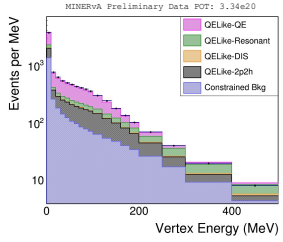
Initial and Final State

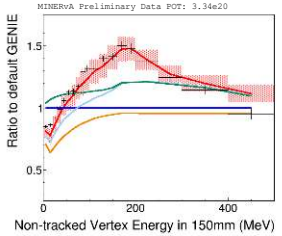


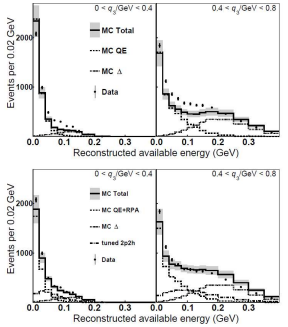


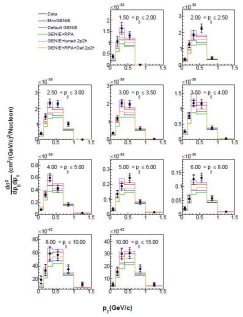


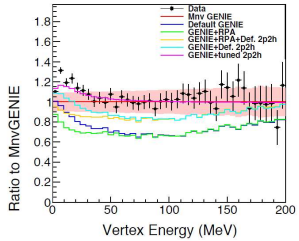


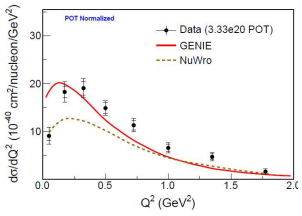


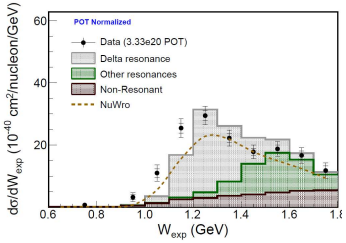


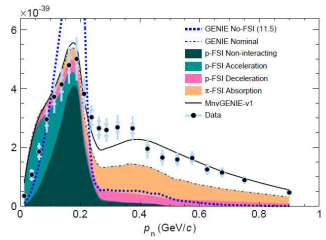


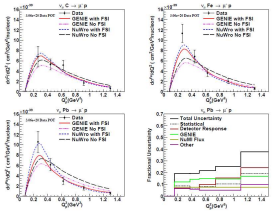




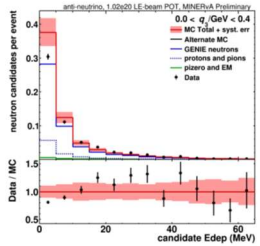








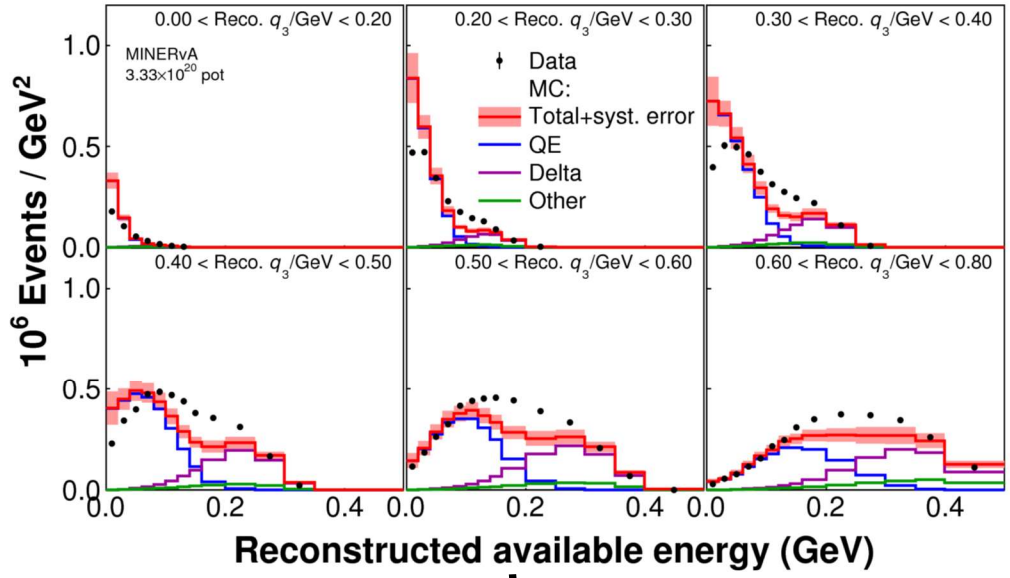
Neutrons

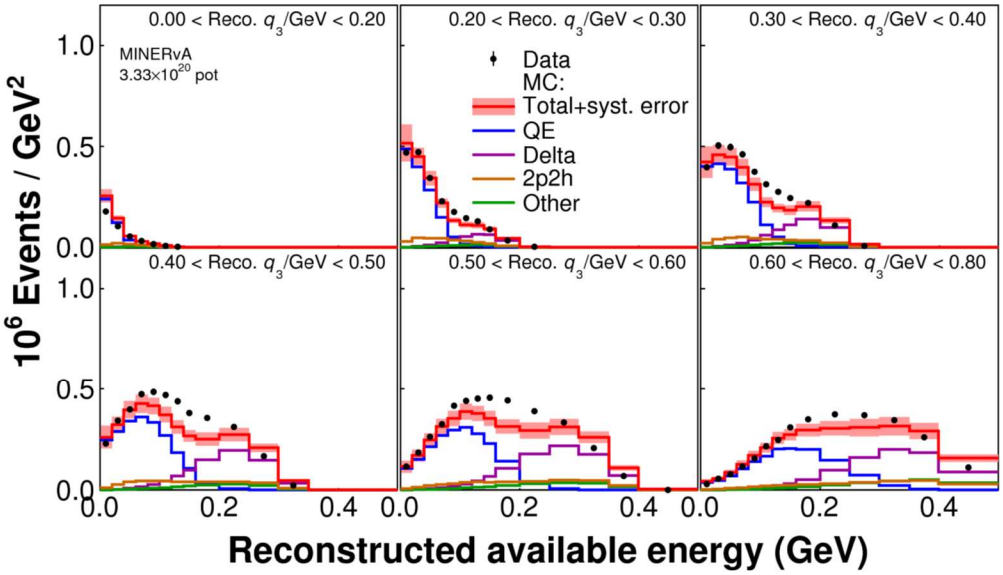


Surprise Guest!

Return of inclusive low recoil

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





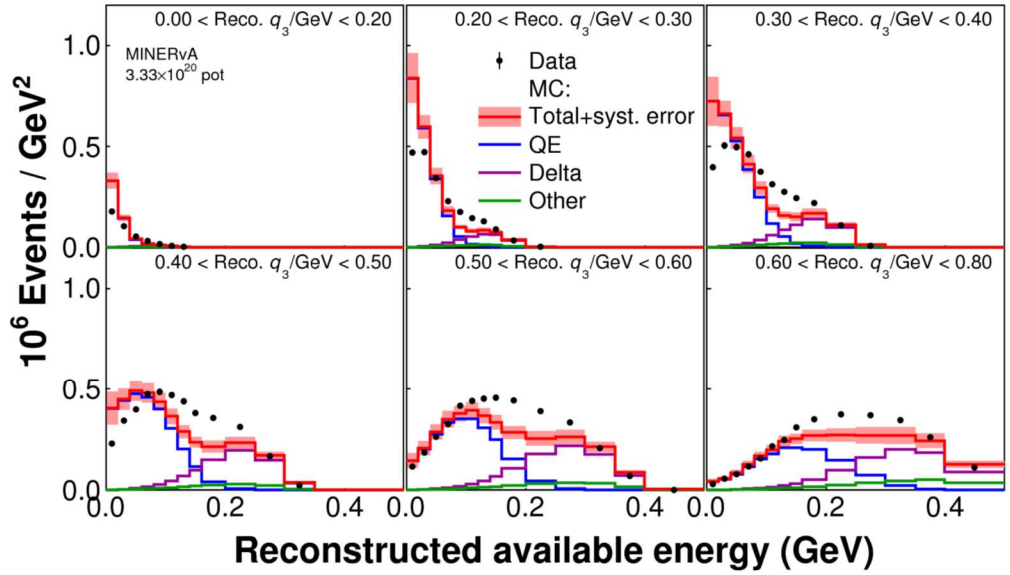
Add 2p2h and RPA

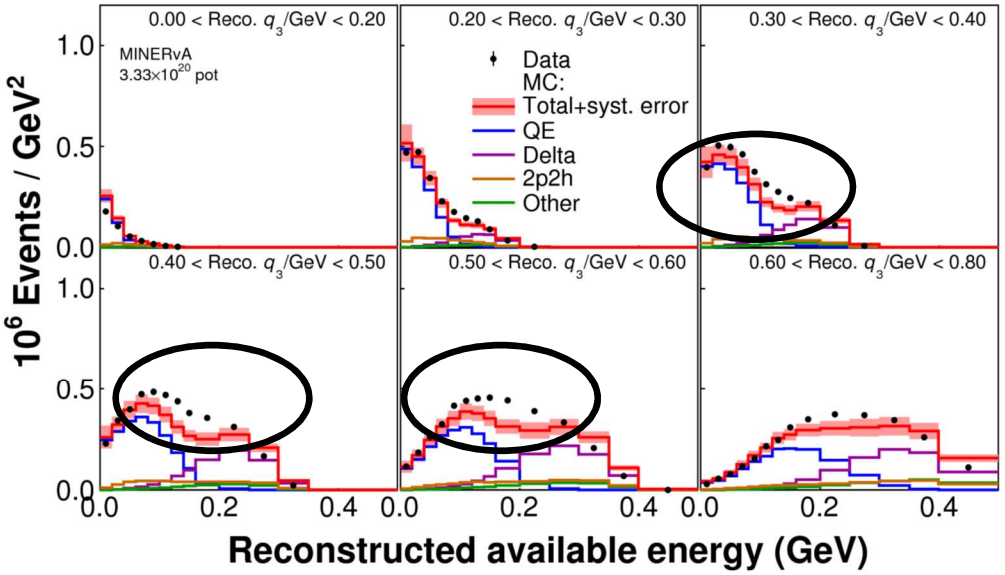
Shown at NEUTRINO 2016

Clearly shows marked improvement when adding 2p2h and RPA

Return of inclusive low recoil

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

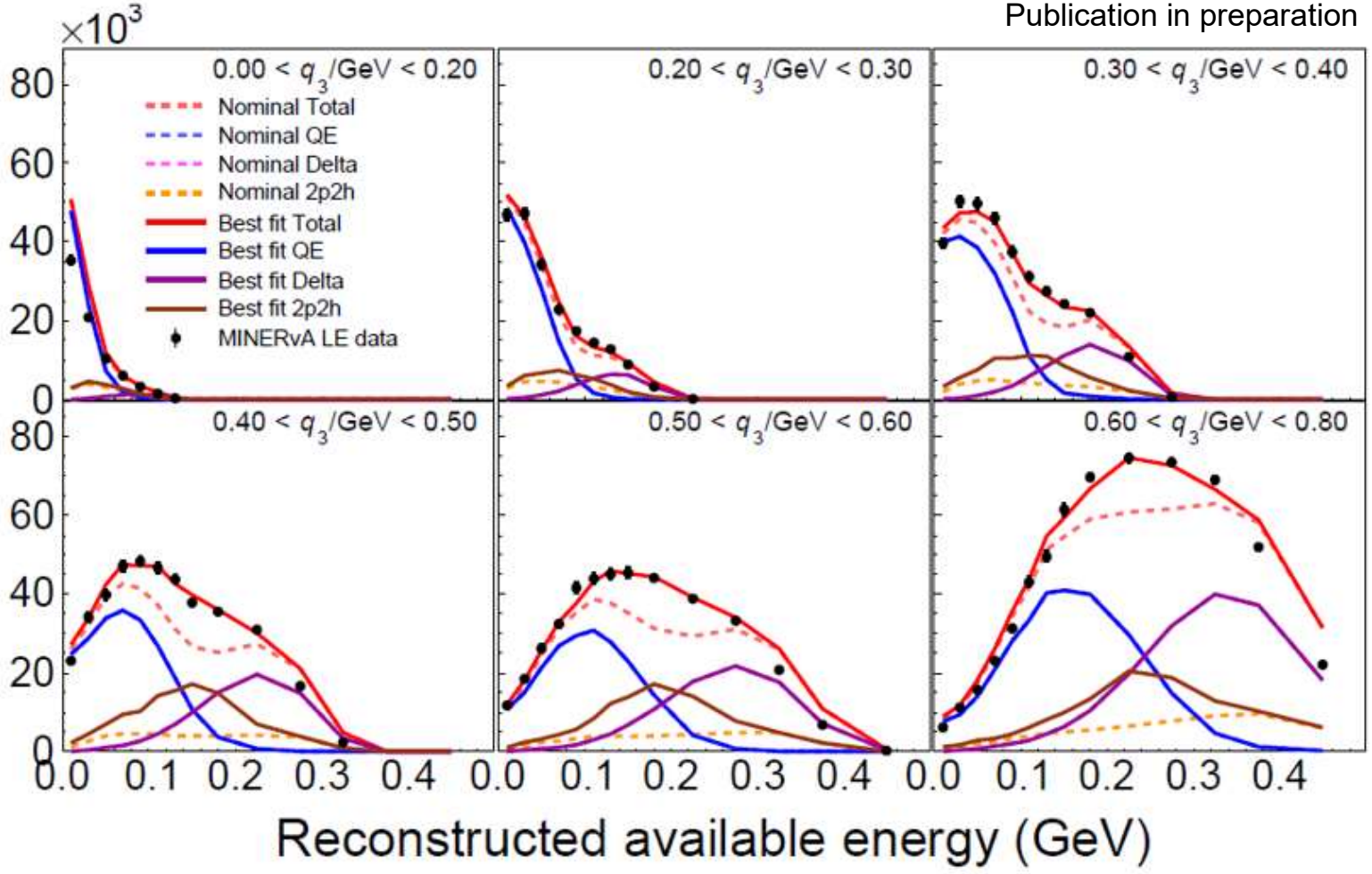




- Latest models available in simulation, but see a data excess at moderate $E_{available}$
- (*new*) Fit a 2D Gaussian in true (q_0,q_3) as a reweighting function to the 2p2h contributions to get the best agreement
  - Does not scale true QE or resonant production.

Return of inclusive low recoil

Publication in preparation



Will refer to this as the low recoil fit.

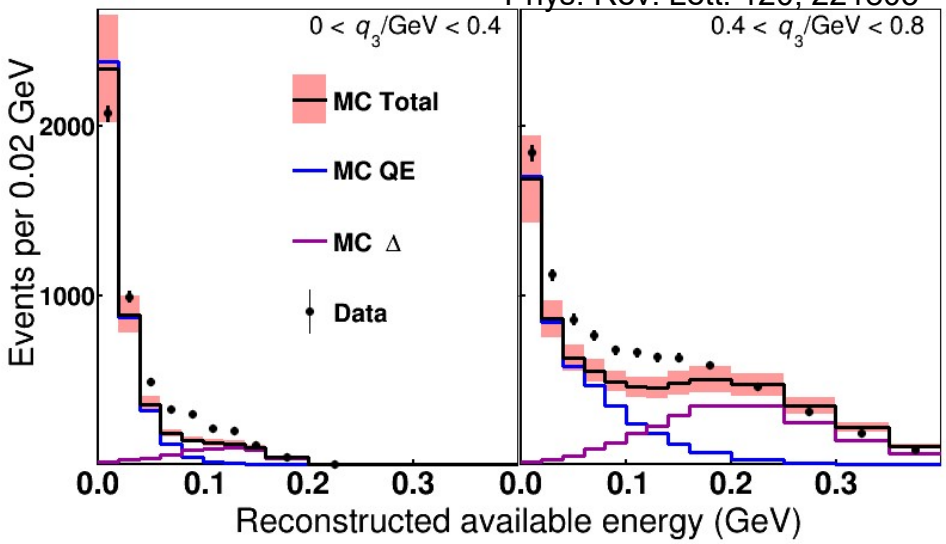
Minerva Tune (MnvGENIE) is composed of

RPA+2p2h+Low recoil fit+(non-resonant pion reduction)

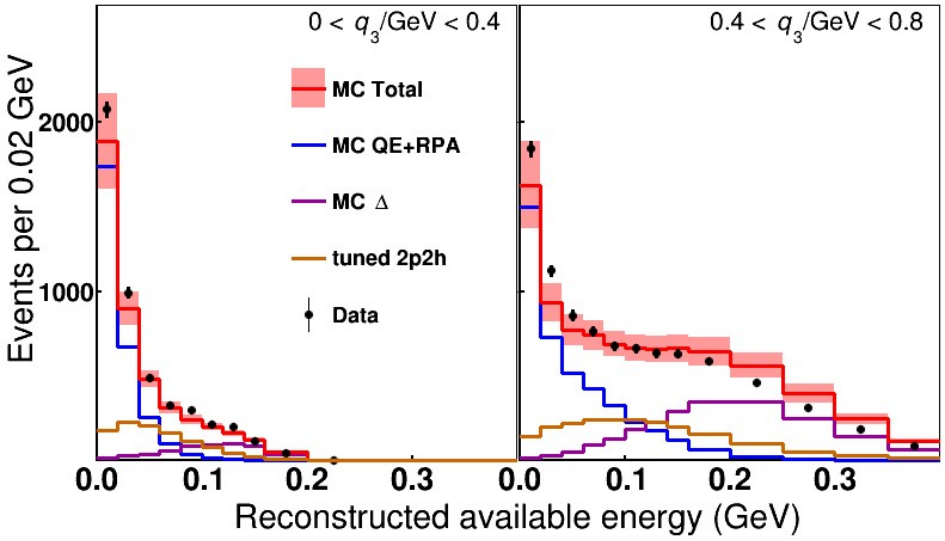
→ Application of arXiv 1601.01888

Introducing anti-neutrino inclusive low recoil

Phys. Rev. Lett. 120, 221805



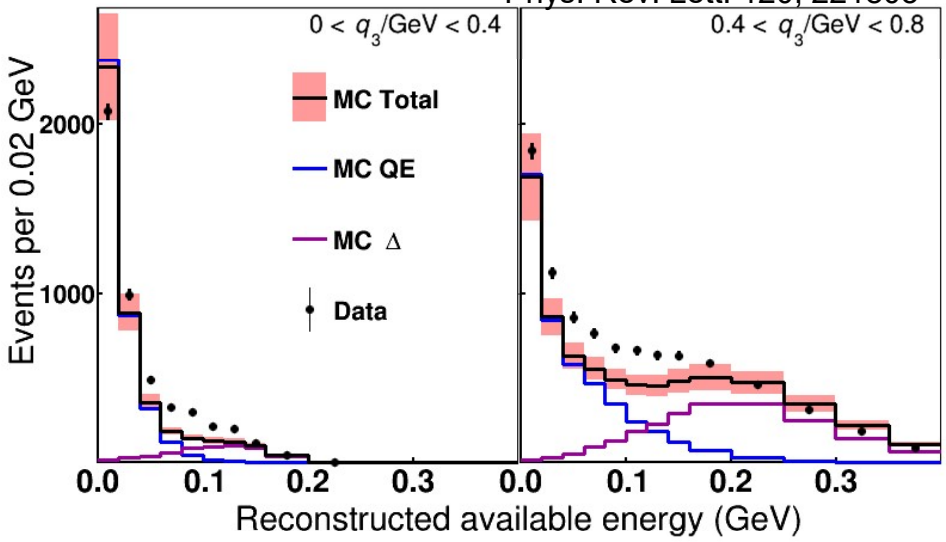
Before application of the low recoil fit

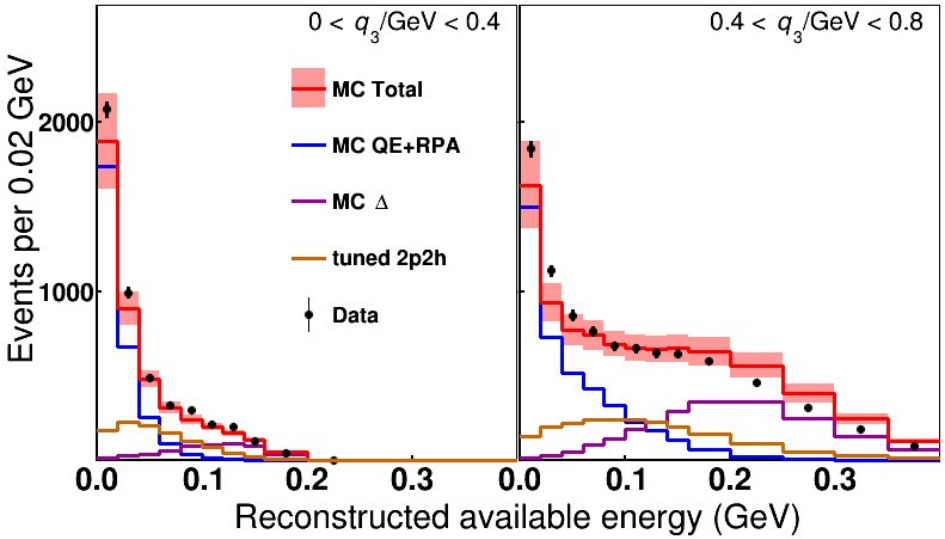


After application of the low recoil fit

Introducing anti-neutrino inclusive low recoil

Phys. Rev. Lett. 120, 221805



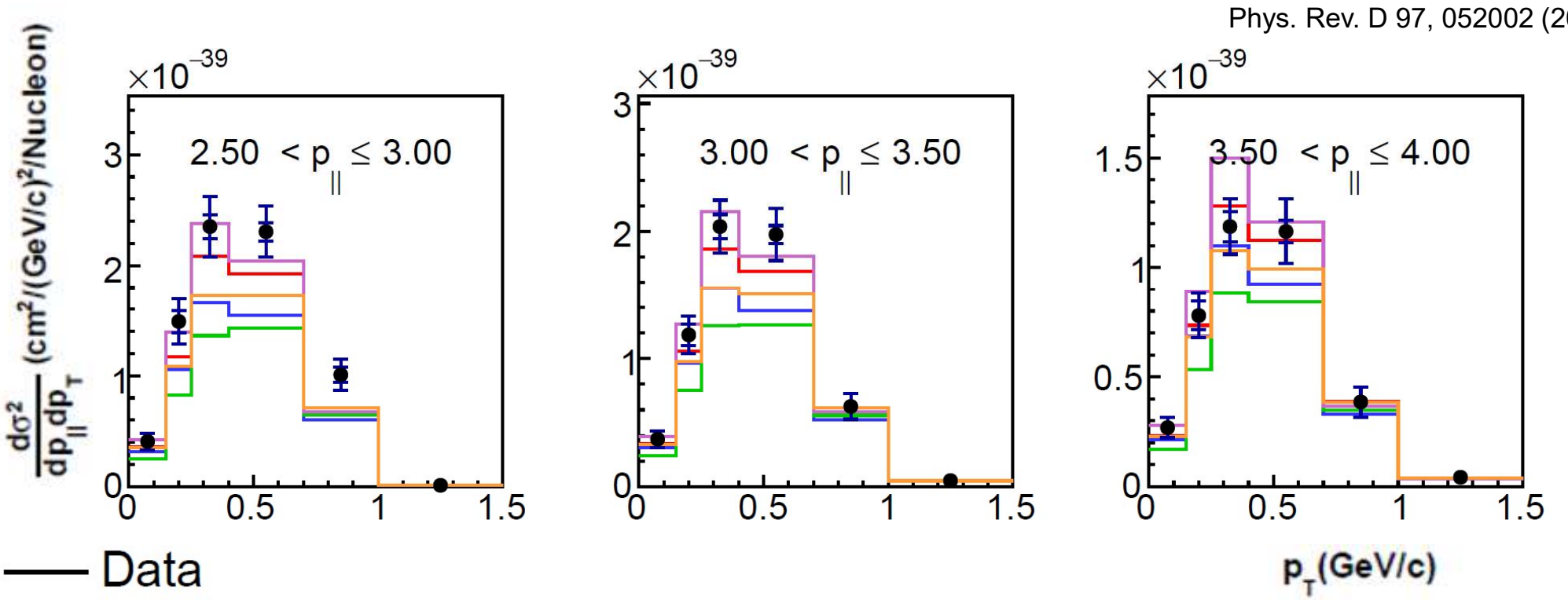


It is quite remarkable. An empirical neutrino sample based fit works well on the anti-neutrino sample!

Does this work on exclusive states??

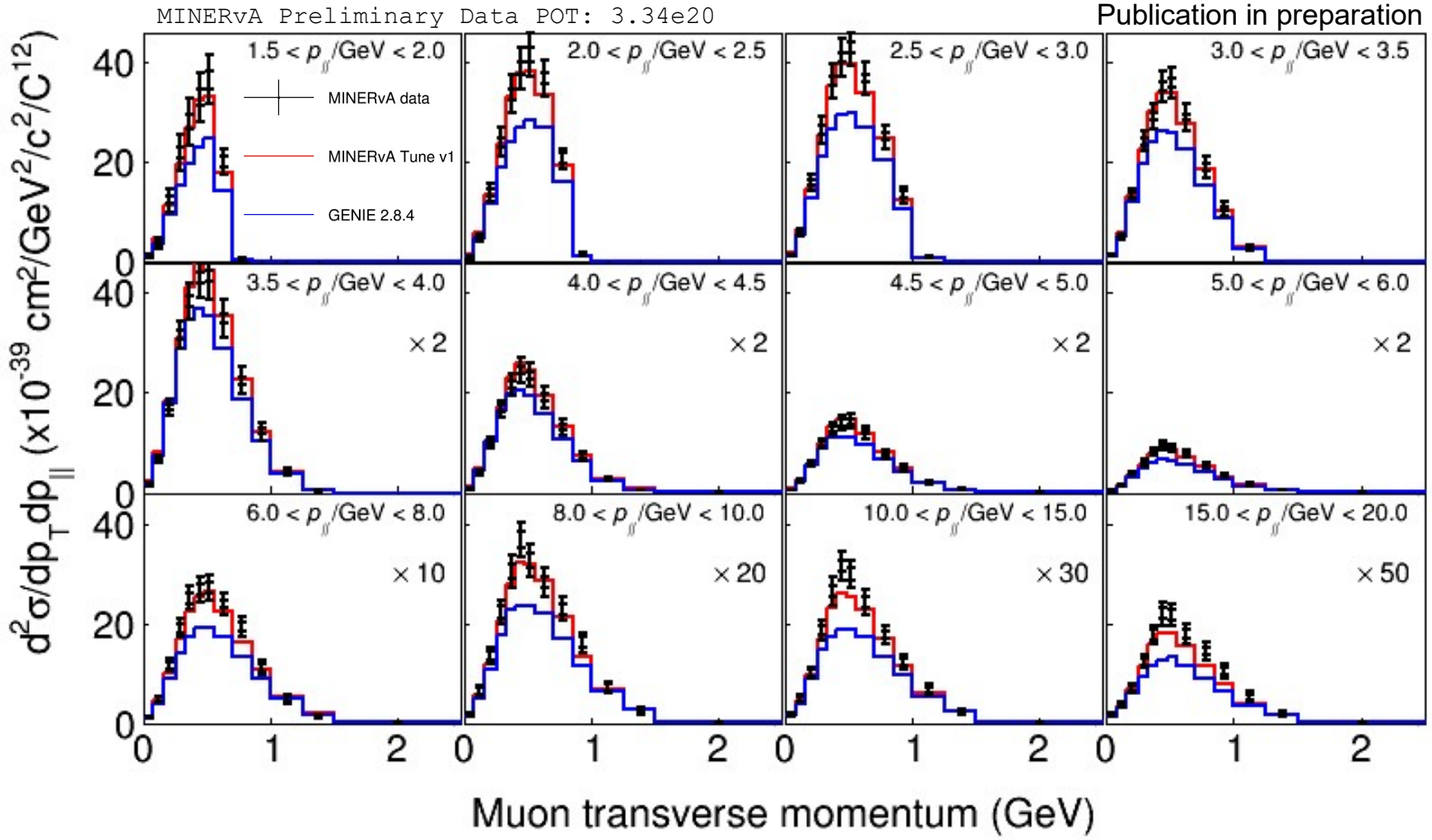
Return of anti-neutrino CCQE-like

Phys. Rev. D 97, 052002 (2018)



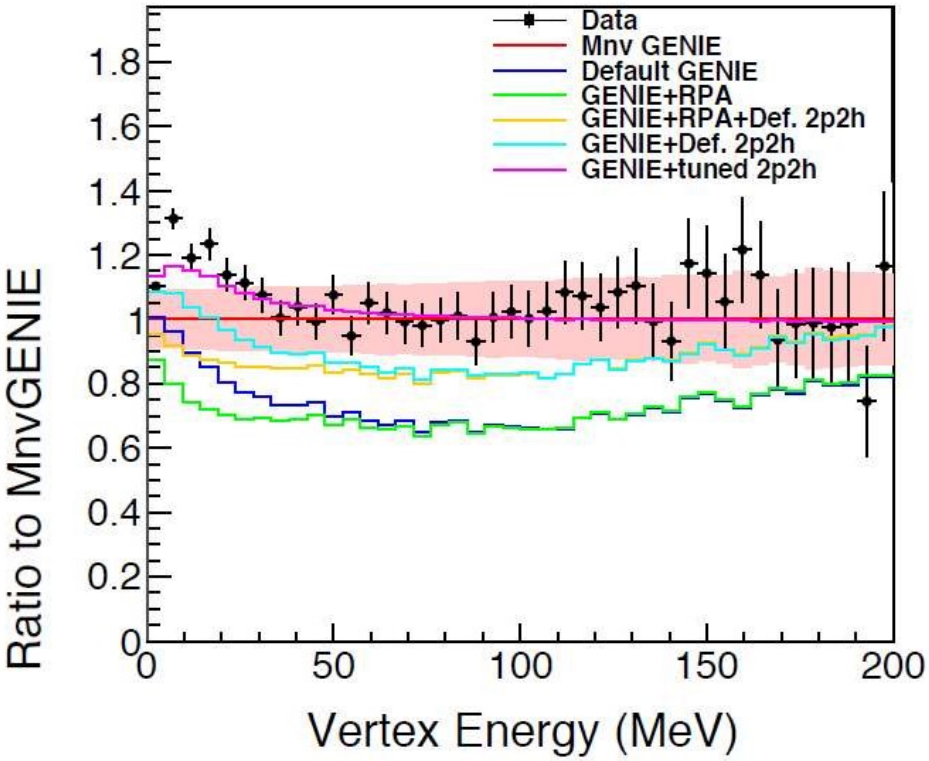
- Visually appears to agree better with enhancement
- Full χ^2 indicates a preference for models with RPA and 2p2h.

Neutrino CCQE-like

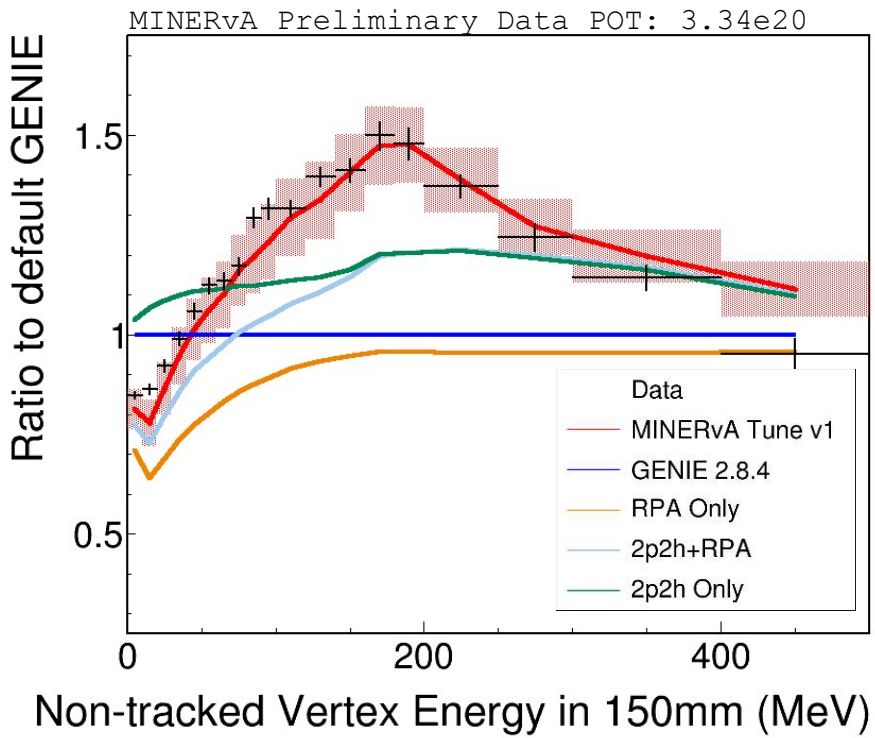


Vertex energy in QE-Like results

Phys. Rev. D 97, 052002 (2018)



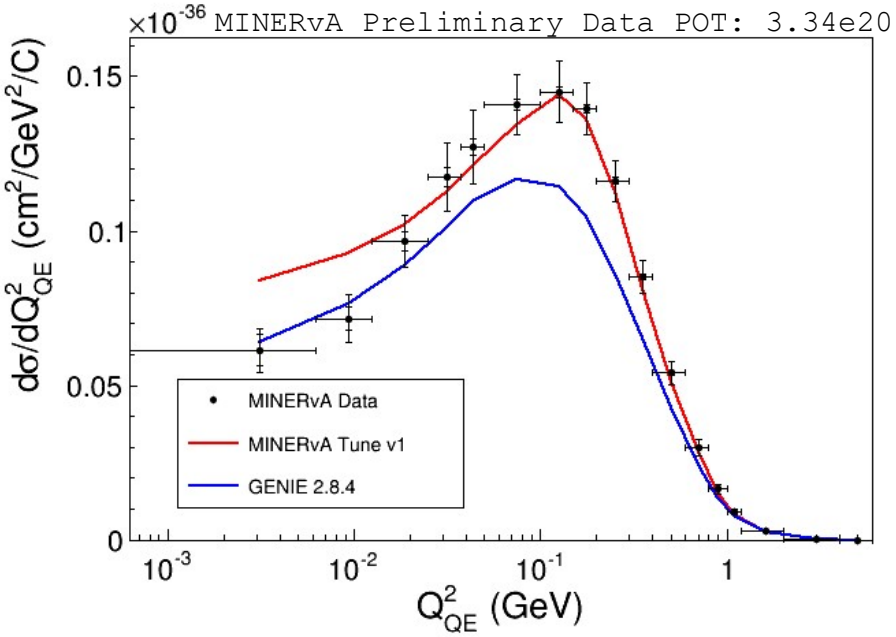
Publication in preparation



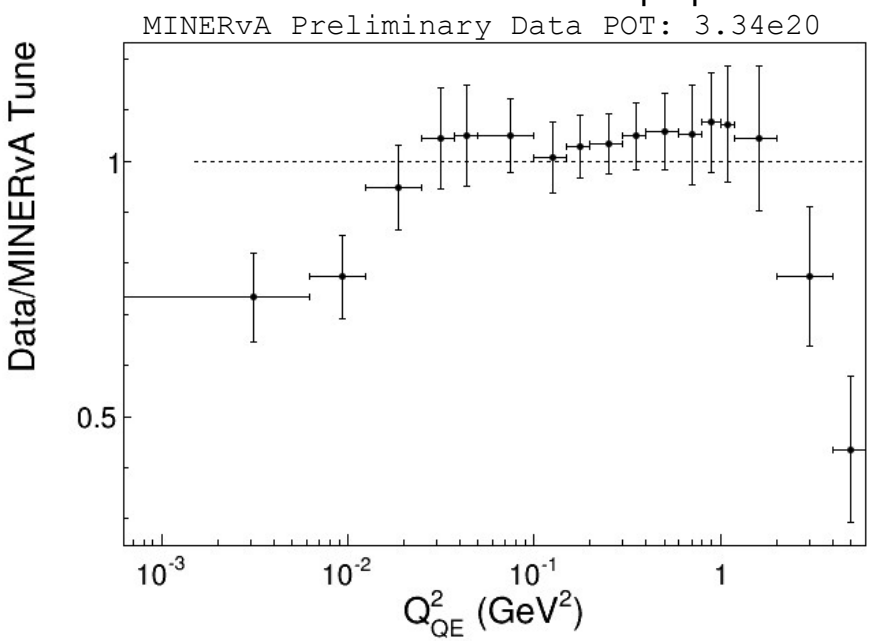
- The tune seems to enhance the events in the regions of vertex energy the data prefer!

Close, but not quite!

Neutrino CCQE-like Sample

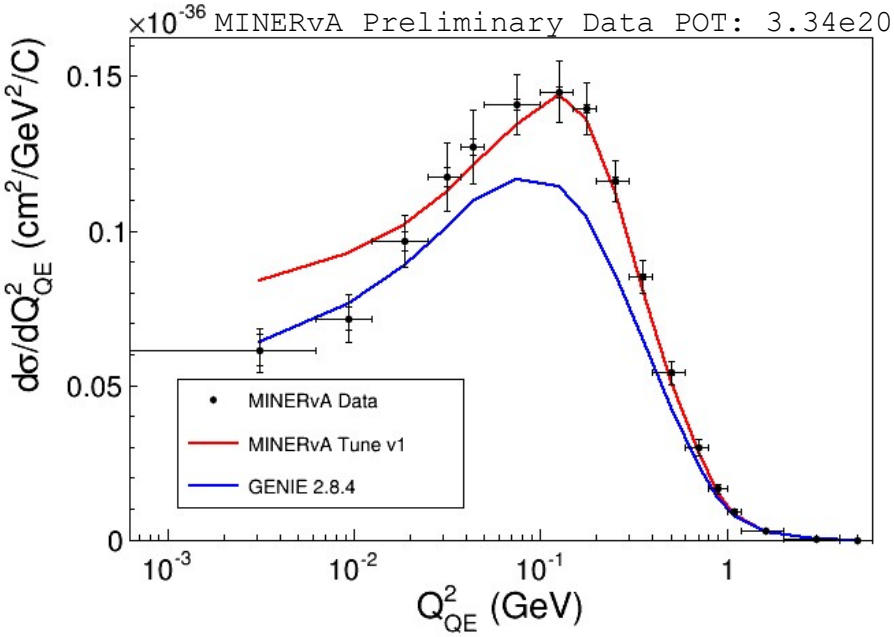


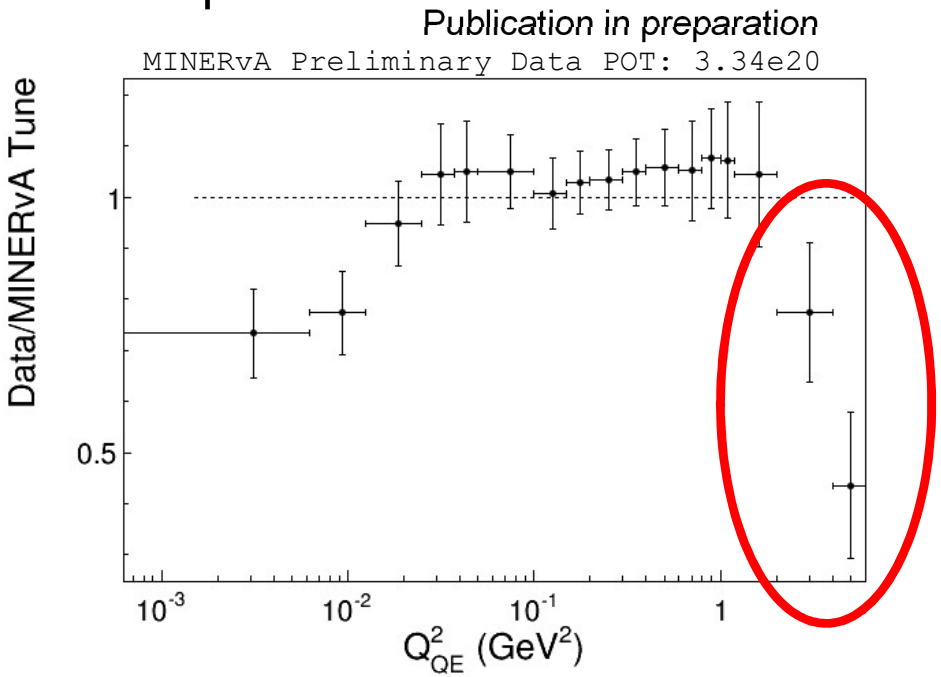
Publication in preparation



Close, but not quite!

Neutrino CCQE-like Sample

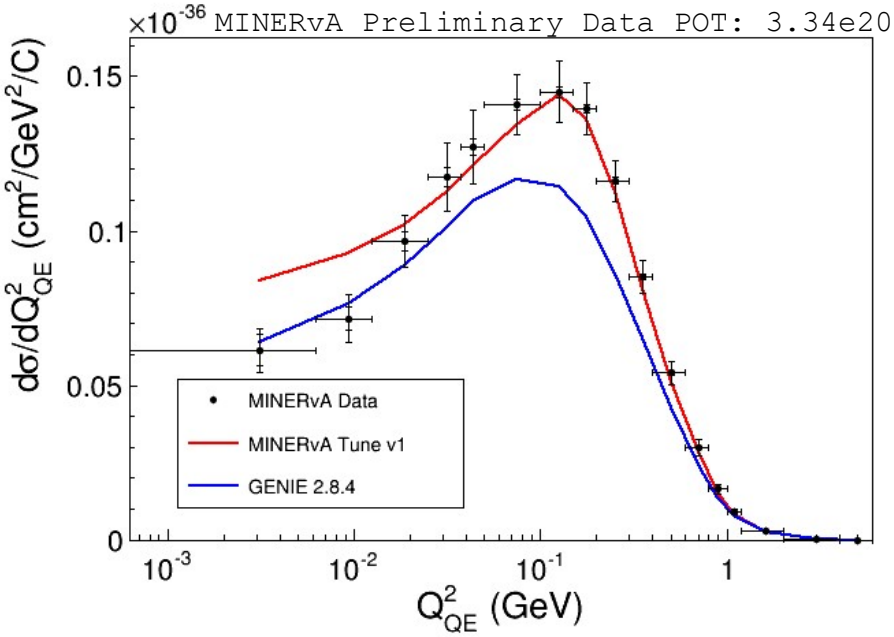




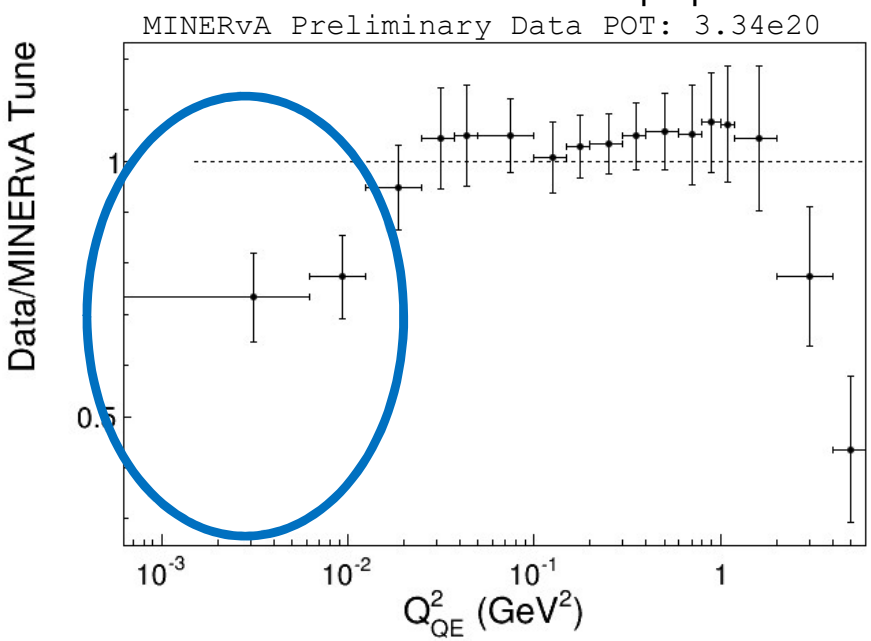
- High Q^2 is a region where the assumption of the dipole approximation starts to break down

Close, but not quite!

Neutrino CCQE-like Sample



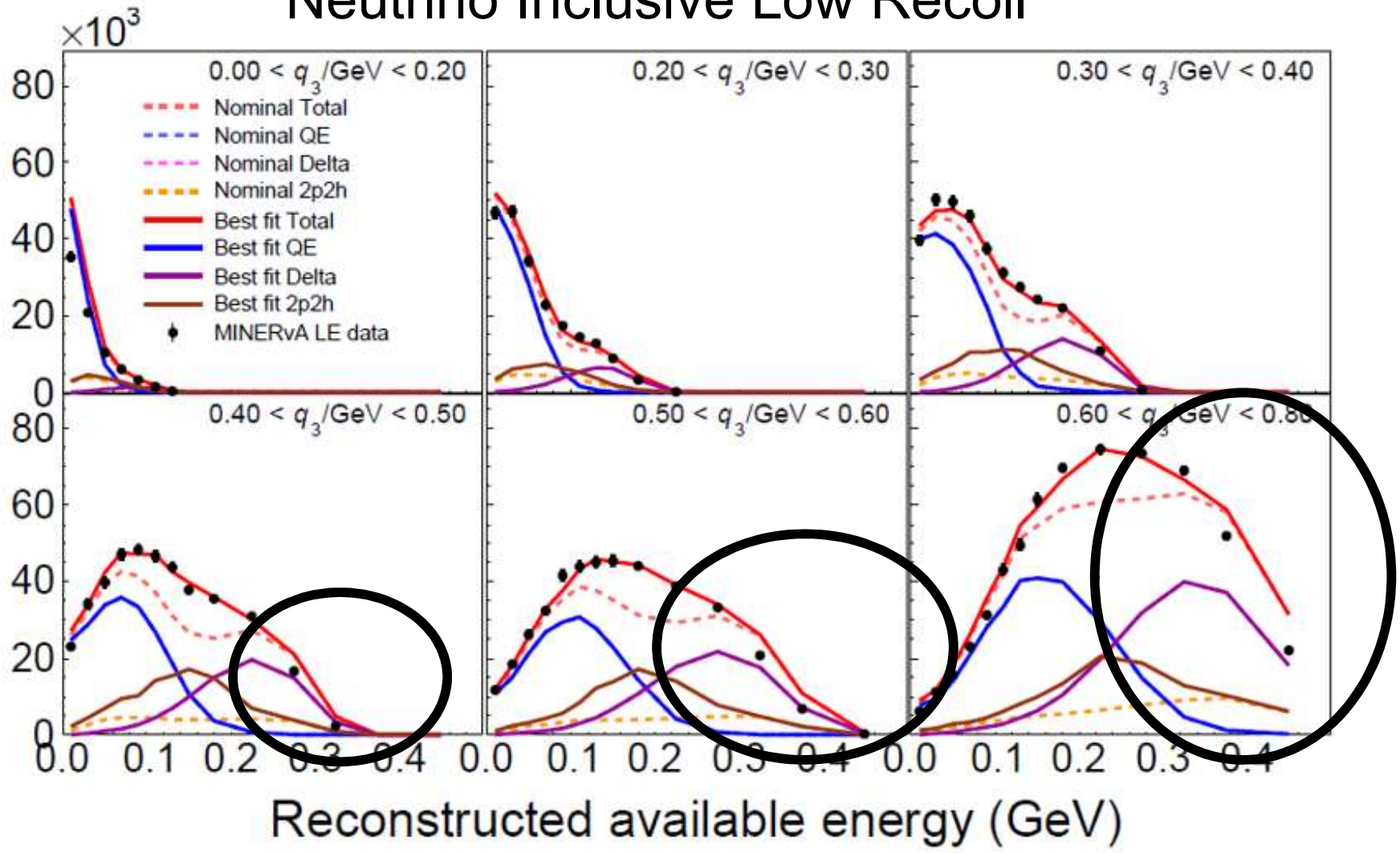
Publication in preparation



- 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.

Low Q^2 reduction effect needed

Neutrino Inclusive Low Recoil



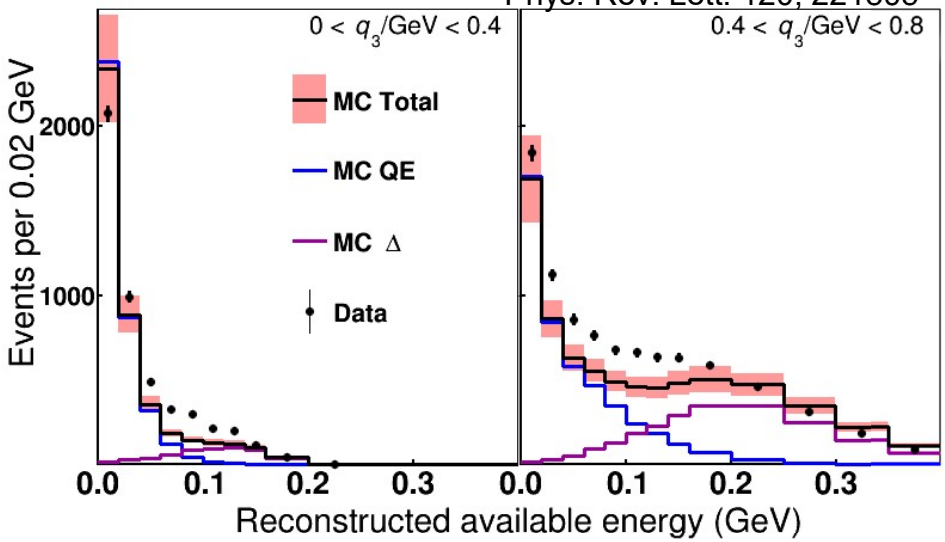
Regions of small Q^2 for resonant events

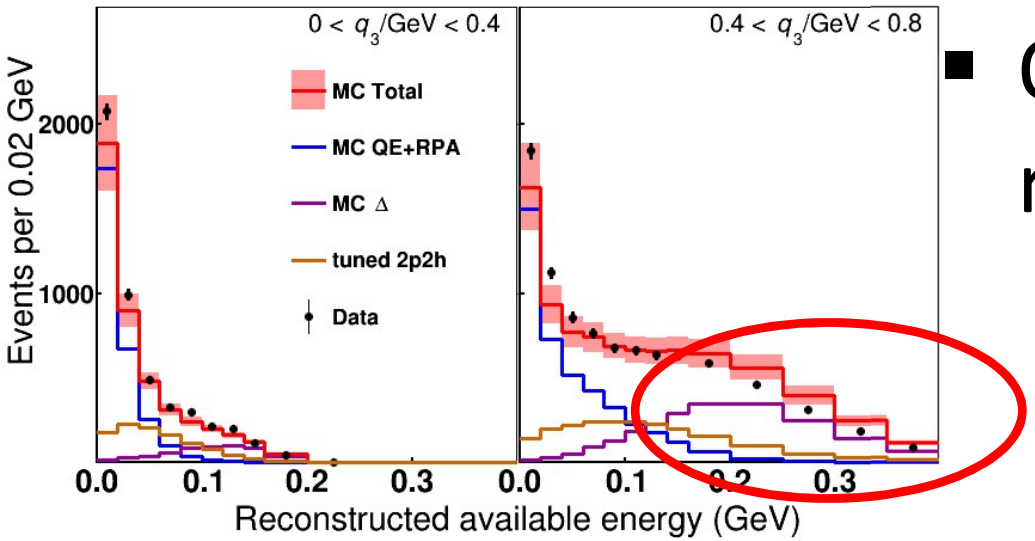
$\bar{\nu}$

Low Q^2 reduction effect needed

Anti-neutrino Inclusive Low Recoil

Phys. Rev. Lett. 120, 221805





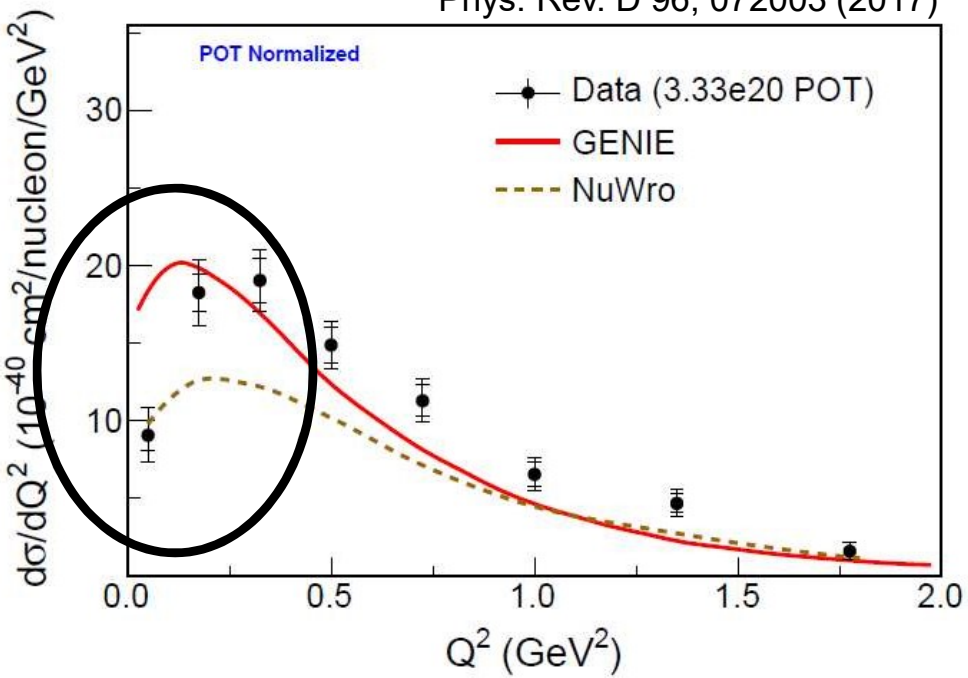
- Both inclusive analyses and neutrino CCQE-like see suppression at regions with low Q^2 for resonant events
- Onward to the pion results!

Regions of small Q^2 for resonant events

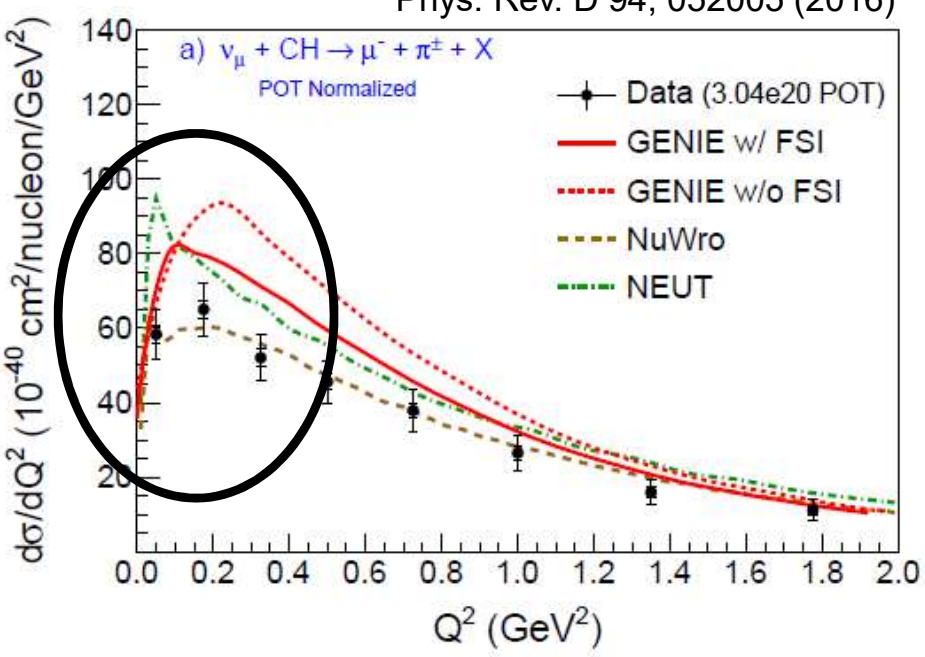
Low Q^2 reduction effect needed

- Recent $CC\pi^0$ result wants a low Q^2 reduction
- So does the anti-neutrino result $CC\pi^0$ result
- Not as strongly in the $CC\pi^+$ result

Phys. Rev. D 96, 072003 (2017)

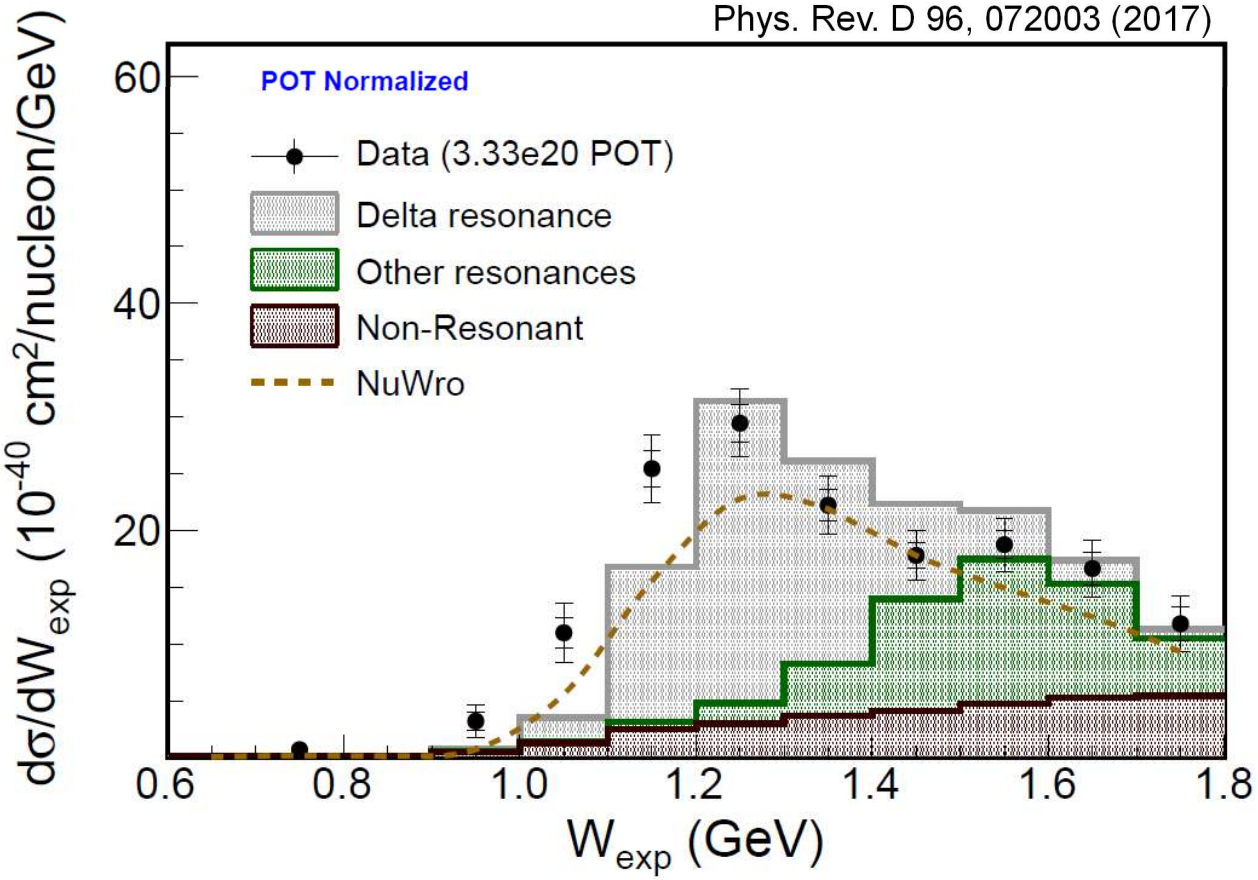


Phys. Rev. D 94, 052005 (2016)



What's going on?

Phys. Rev. D 96, 072003 (2017)

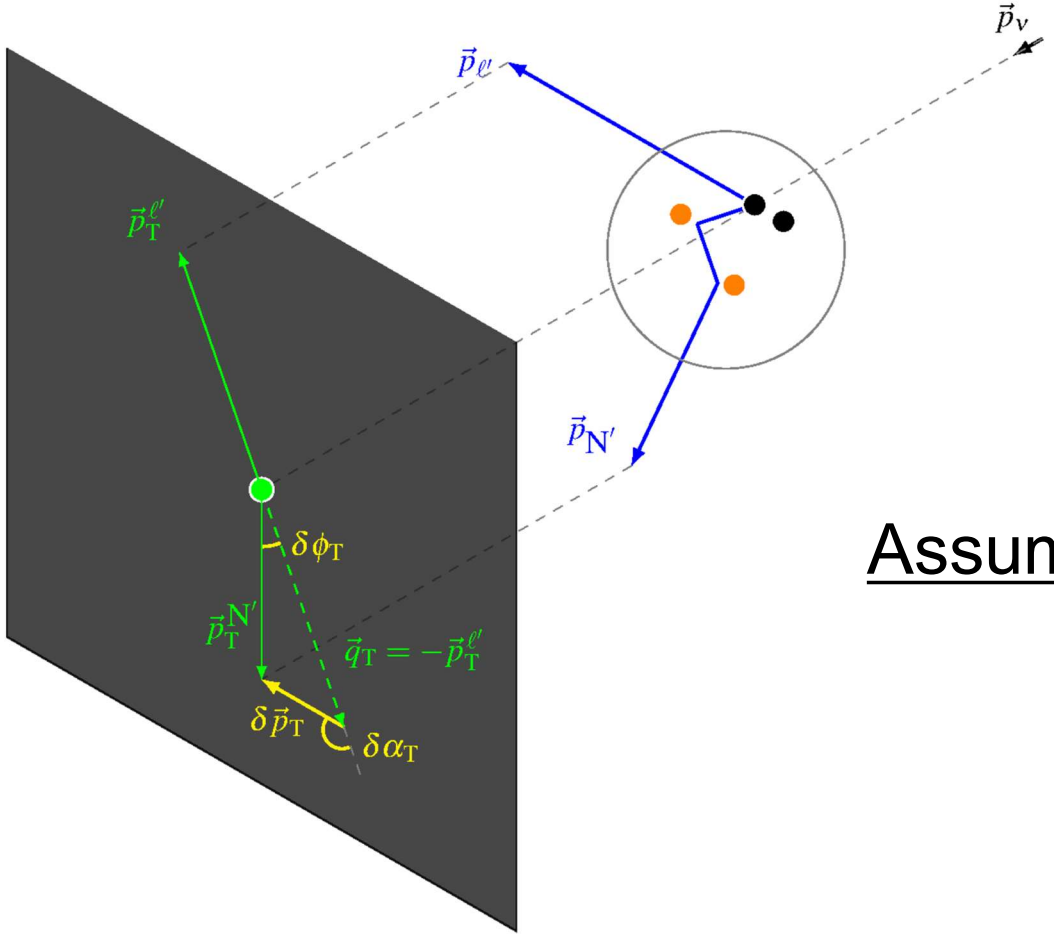


- W_{exp} is derived assuming kinematics of a struck nucleon at rest
  - Neither generator takes into account interference between resonant and non-resonant processes
  - Fermi-motion simulation
  - In medium modification of $\Delta(1232)$

A. Furmanski, J. Sobczyk, Phys.Rev.C95 (2017) no.6, 065501
X.-G. Lu *et al.* Phys. Rev. C 94, 015503 (2016)

New measurement variables

Transverse kinematic imbalance



p_n
Initial-state neutron momentum

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

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

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

Assume exclusive μ-p-A` final states

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

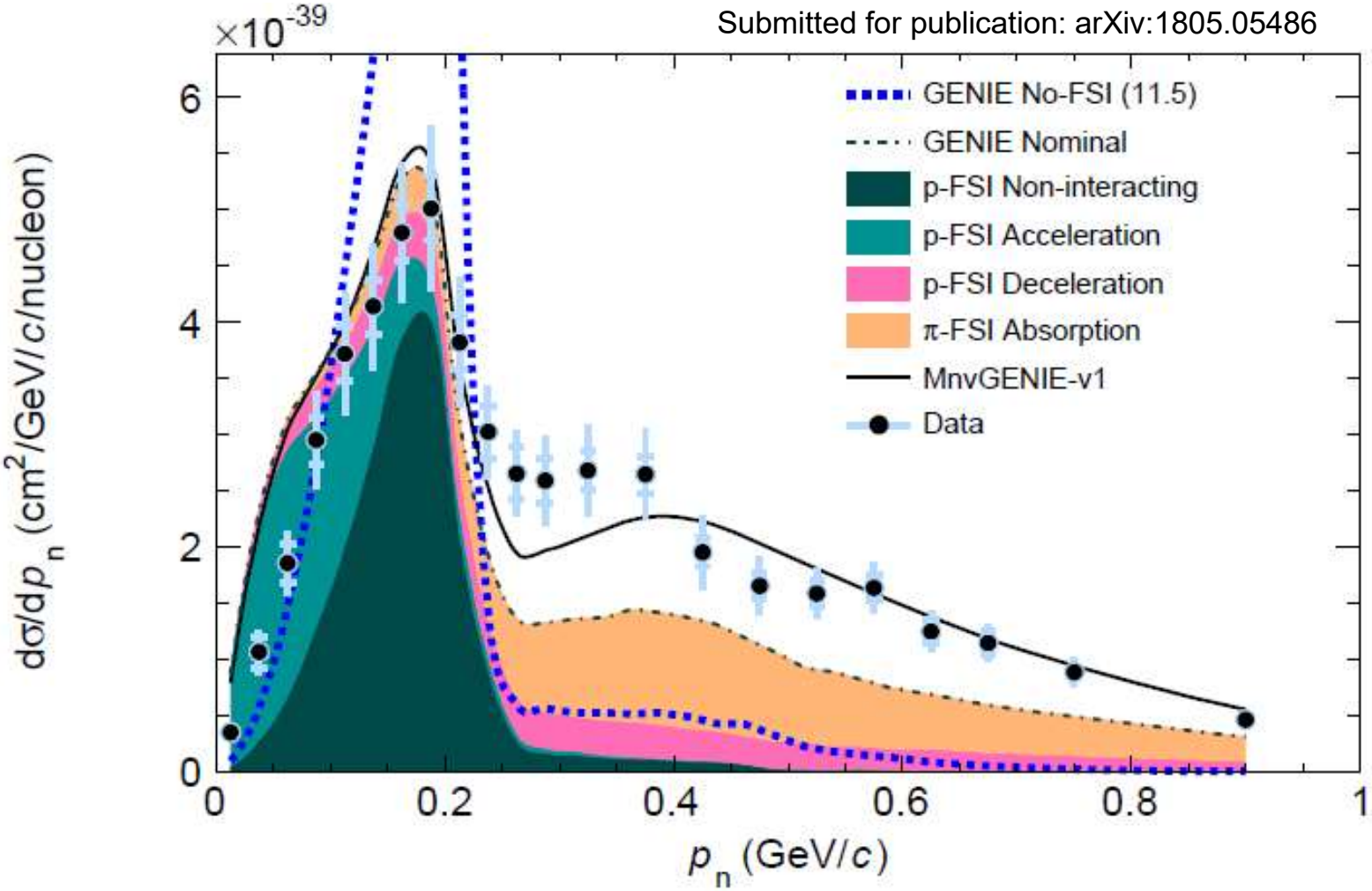
$$E_{\mathrm{A}'} = \sqrt{m_{\mathrm{A}'}^2 + p_{\mathrm{n}}^2}$$

see posters for details

Minerba Betancourt: ***"Measurement of nuclear effects via final-state correlations in quasi elastic-like events on hydrocarbon at MINERνA"*** (#119 Wednesday)

David Coplowe: ***"Measuring nuclear effects of semi-exclusive CCNpMπ^0 final states using the MINERνA Detector"*** (#112 Wednesday)

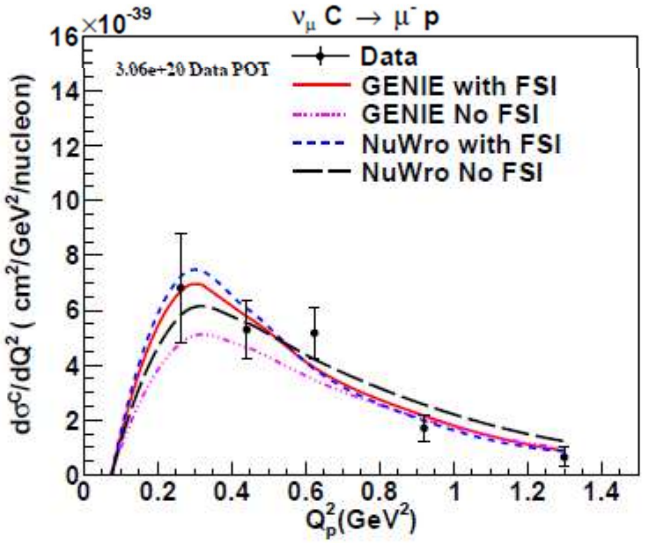
Focus on Fermi motion

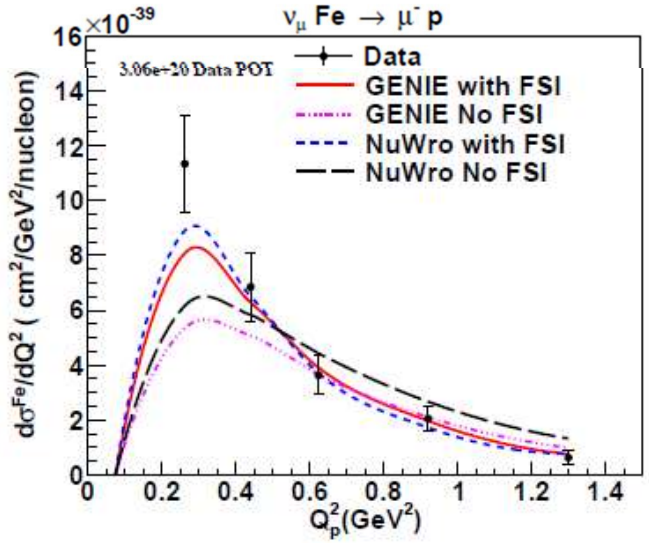


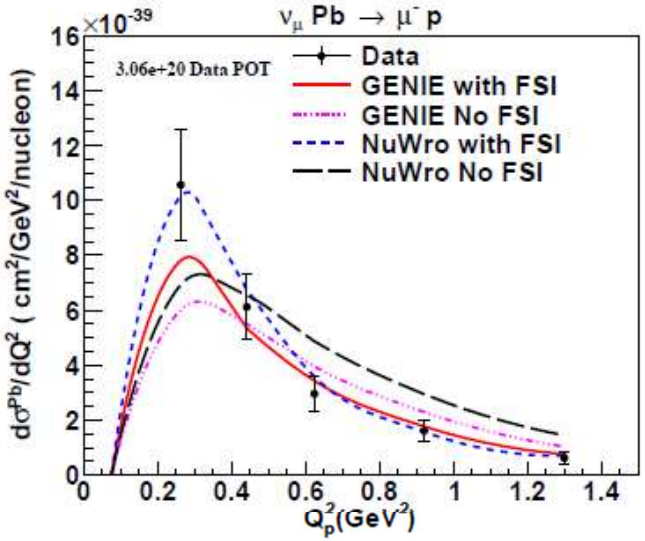
- Strong constraint on Fermi motion and transition between QE and QE-like processes

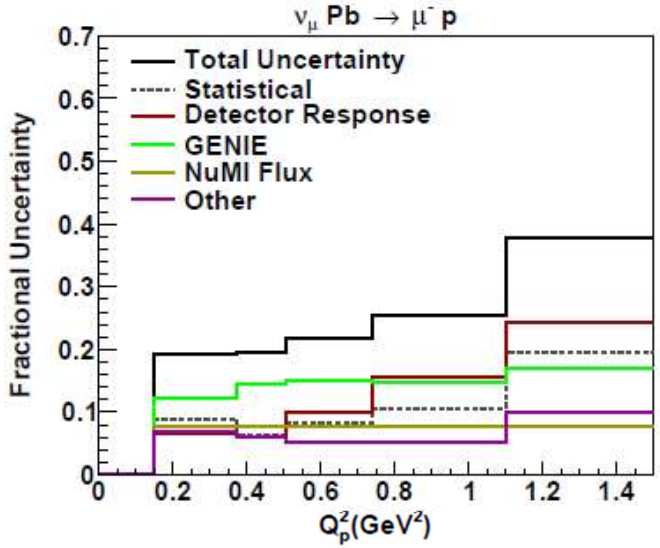
Final State Effects for non-carbon targets

Phys. Rev. Lett. 119, 082001 (2017)



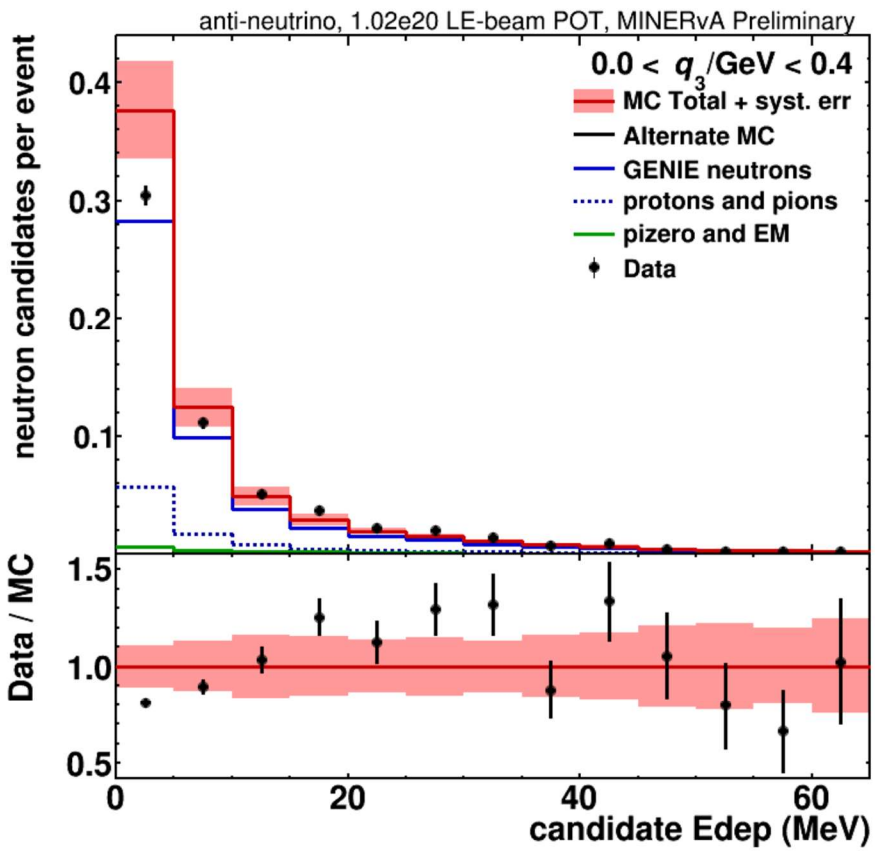




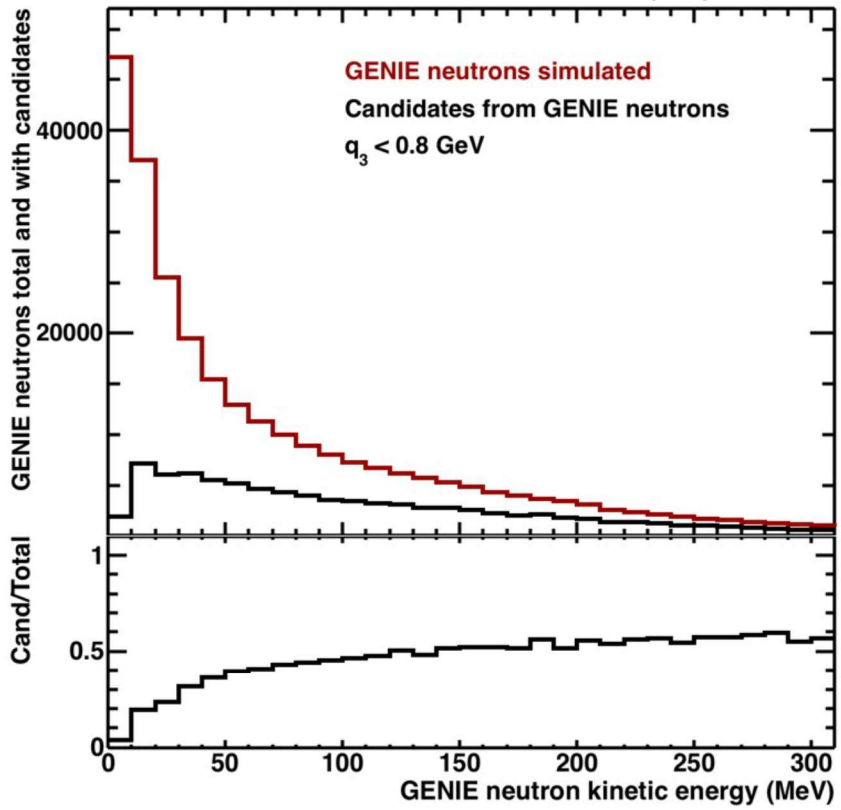


- A-dependence of FSI appears to not be correctly modeled

Don’t forget the neutrons

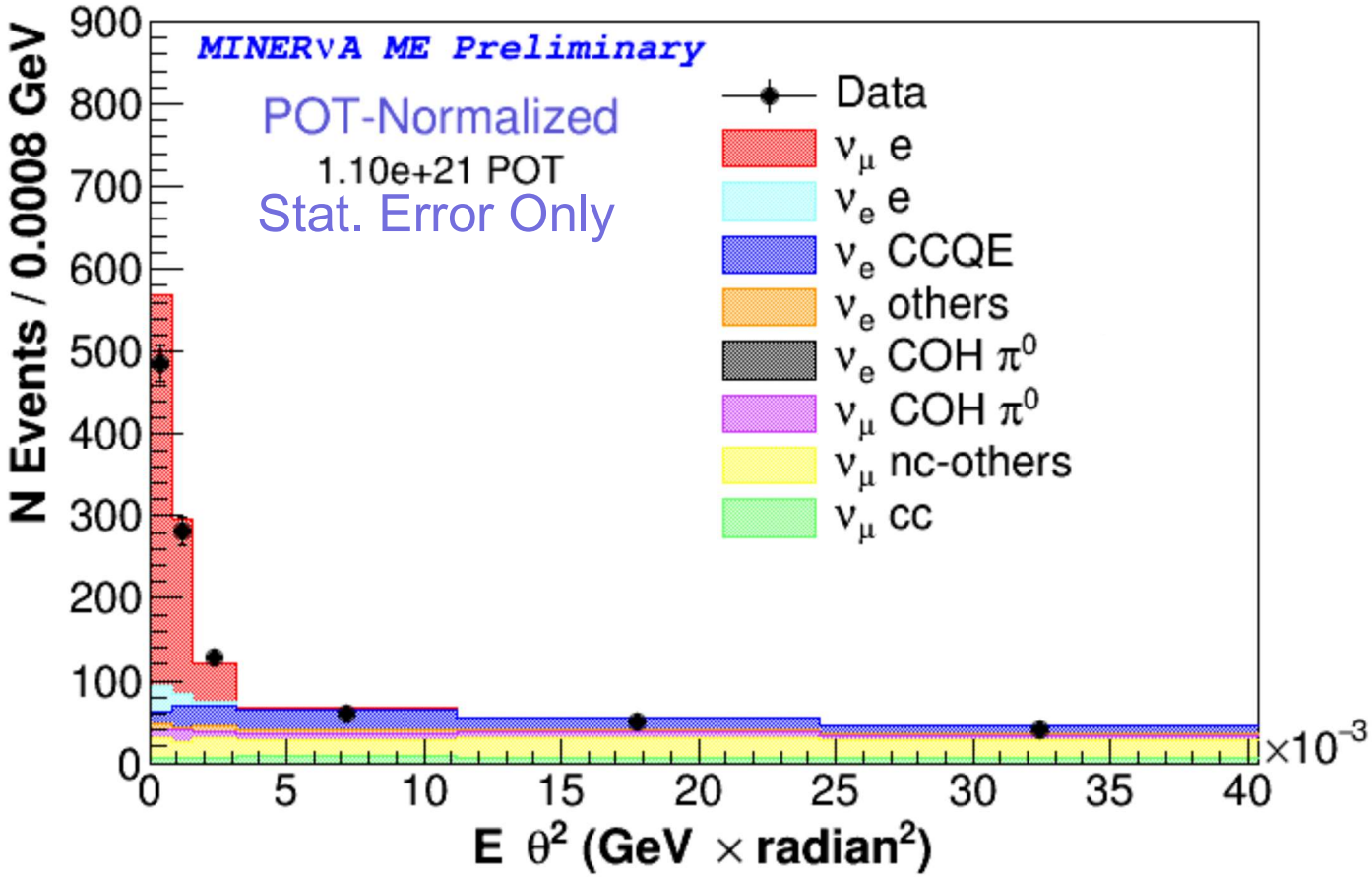


Publication in preparation



- 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.

First Medium Energy Result



- Selected sample has about 800 ν+e events
- In the process of finalizing systematics
- Flux constraint ongoing
  - changes flux uncertainty from about 8% to 6% in the focusing peak
- Proof of principle for future experiments

Conclusions

- By combining many analyses with different focuses MINERvA is creating a vision of what neutrino interactions in nuclei look like at a few GeV
  - RPA, 2p2h are necessary in a Fermi Gas model
  - Need more! Works for anti-nu pretty well
  - Pion model needs updating
  - FSI is needed and has issues with A-dependence
  - Nuclear model has issues we should focus on
  - Neutrons interact in hydrocarbons
- Will continue to develop new analysis variables and tunes
- The next dataset of MINERvA is starting to produce results. Stay tuned!

Thank You!