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Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Recent Measurements at MINERvA

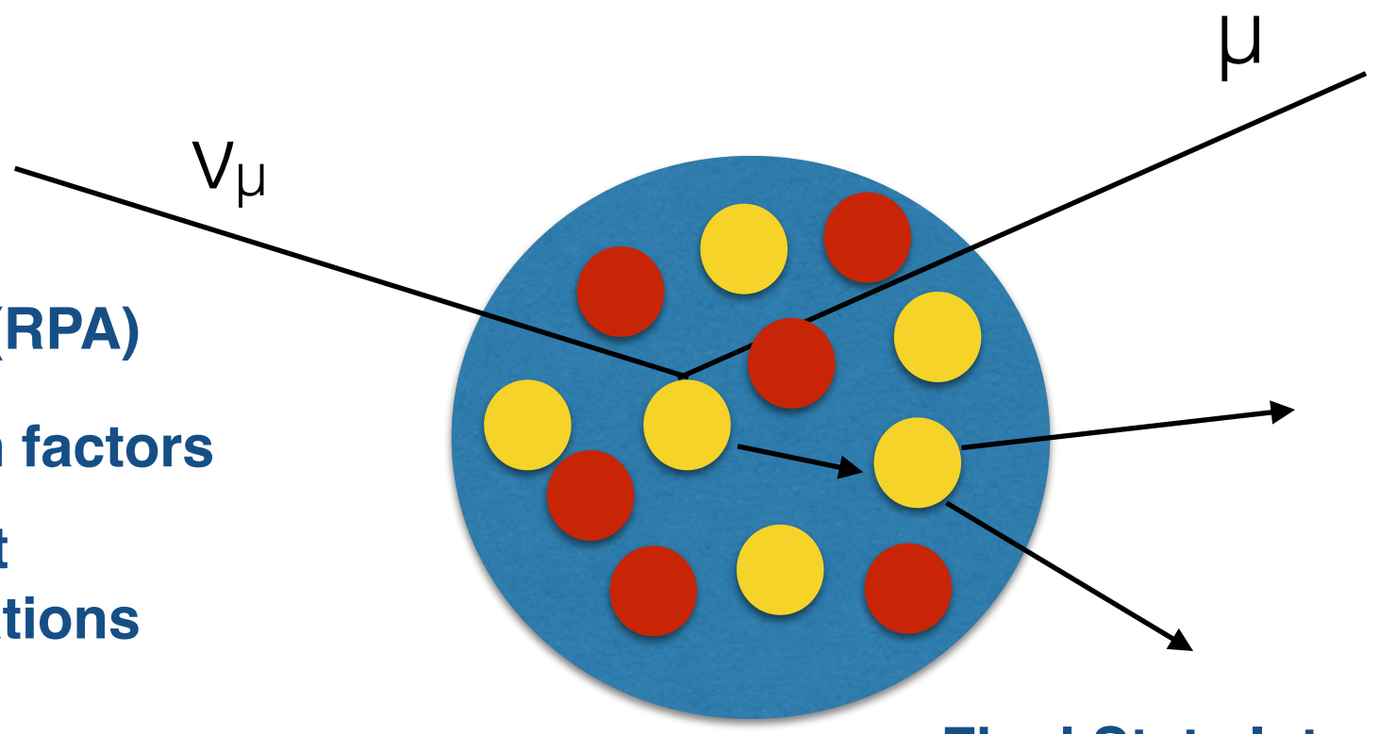
Minerba Betancourt, Fermilab

June 21, 2018

Users Meeting 2018

Introduction

- Understanding neutrino interactions is challenging
- Modeling the interactions and measuring them present different types of challenges



Nuclear long range correlations (RPA)

Nucleon form factors

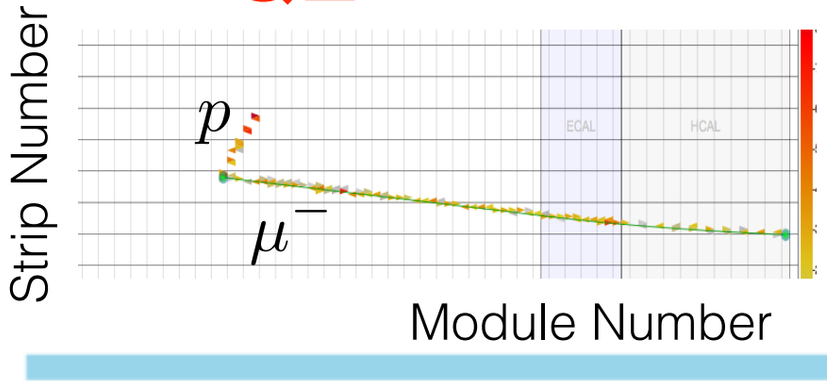
Nuclear short range correlations

Fermi motion
Pauli blocking
Removal Energy

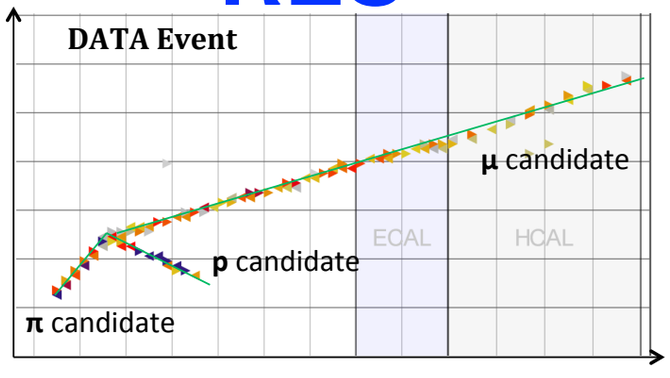
Final State Interactions

Meson Exchange Currents (MEC=2p2h)

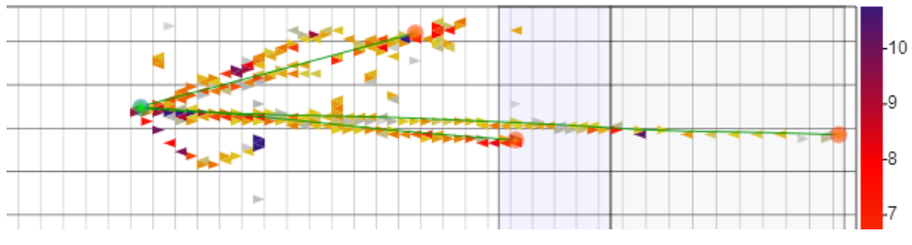
QE



RES



DIS



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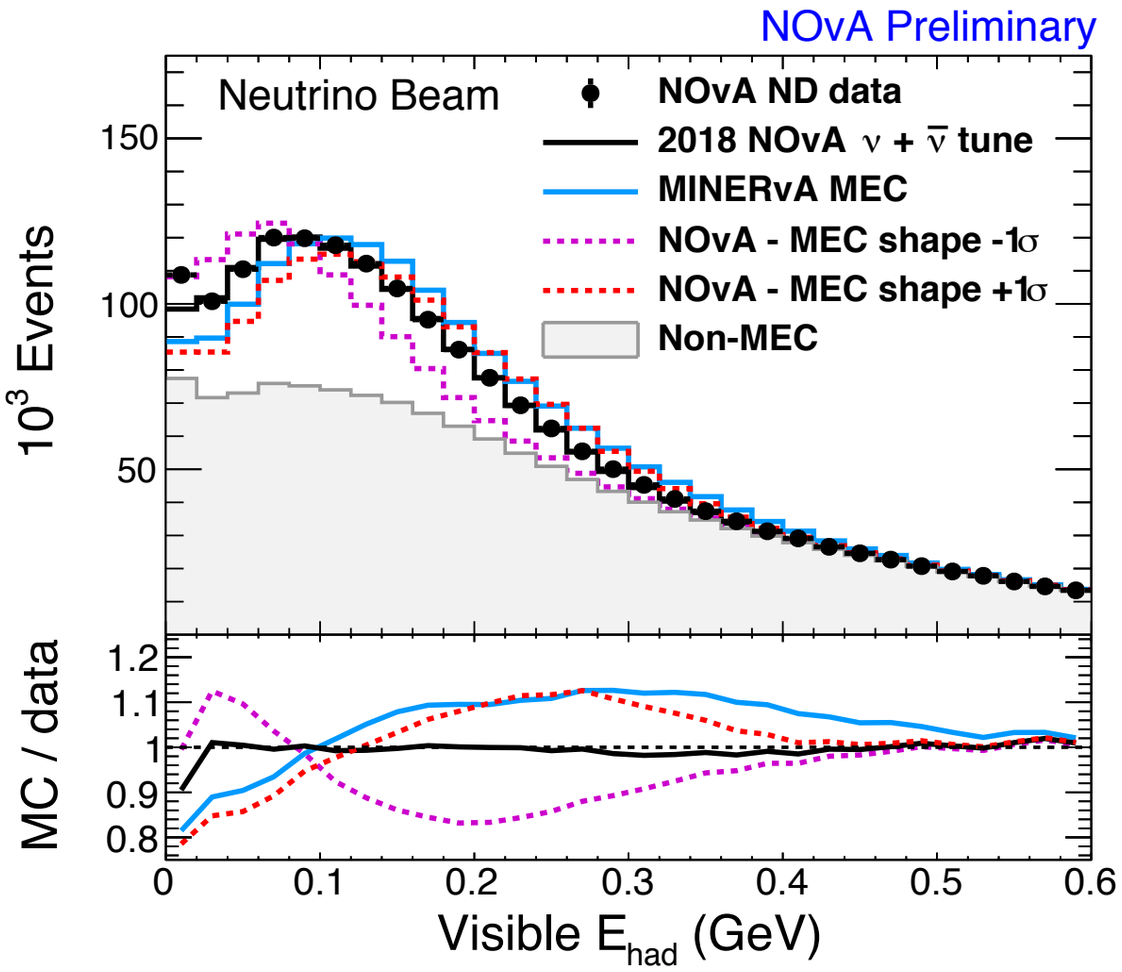
Detailed understanding of neutrino interactions is critical for Oscillation experiments

- We need to reconstruct the neutrino energy precisely
- Nuclear effects modify the kinematics of the particles, the reconstruction of the neutrino energy and contribute to the systematics
- Example of different models for multi-nucleon effects compared to NOvA Near Detector data



Fermilab Wine and Cheese Seminar, June 15 2018, Alex Himmel

MINERvA MEC: Theoretical prediction from Valencia Model PRC 70, 055503 (2004) tuned with MINERvA data

NOvA MEC: GENIE Empirical MEC tuned with NOvA ND data

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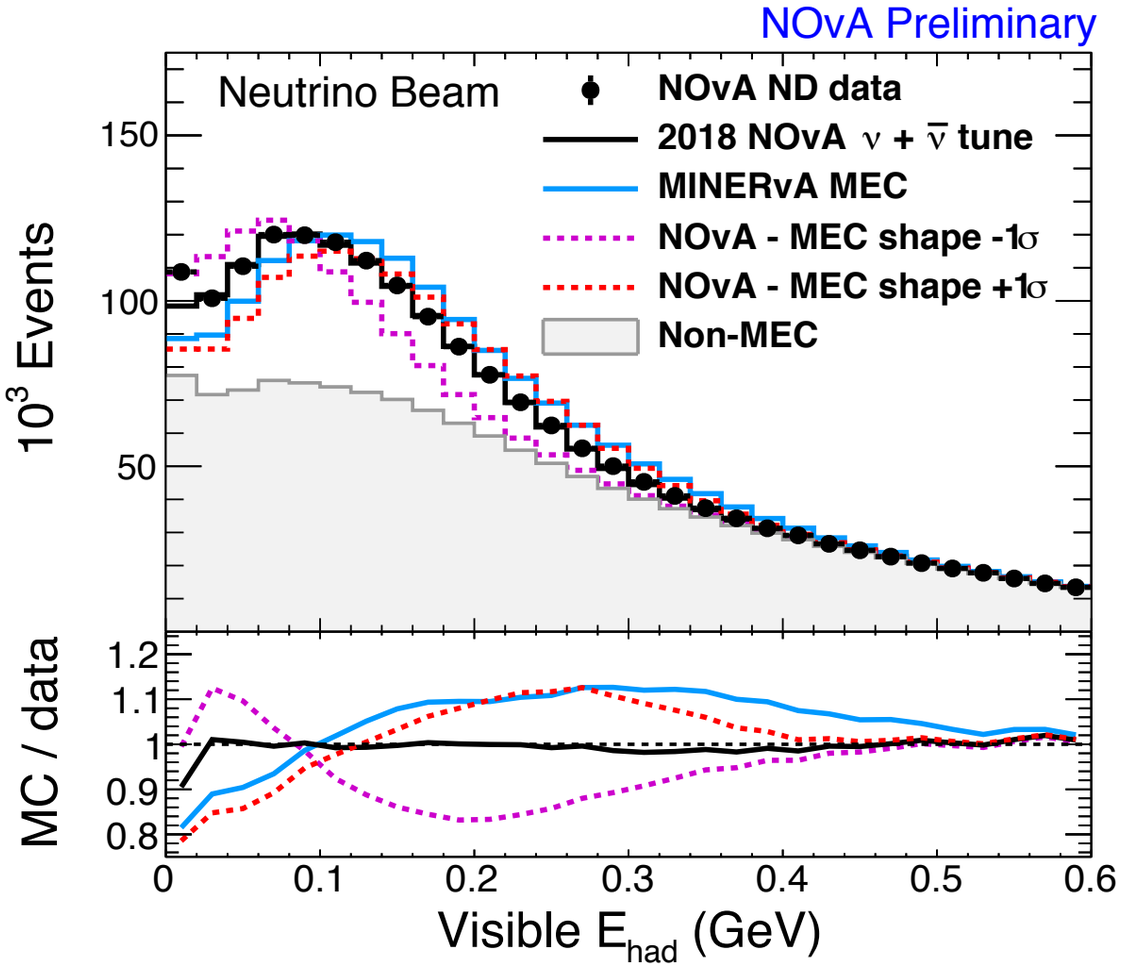

The most important systematics

- **Neutrino cross sections**
  - **Particularly nuclear effects (RPA and MEC)**
- **Neutron uncertainty**

Fermilab Wine and Cheese Seminar, June 15 2018, Alex Himmel

MINERvA MEC: Theoretical prediction from Valencia Model PRC 70, 055503 (2004) tuned with MINERvA data

NOvA MEC: GENIE Empirical MEC tuned with NOvA ND data

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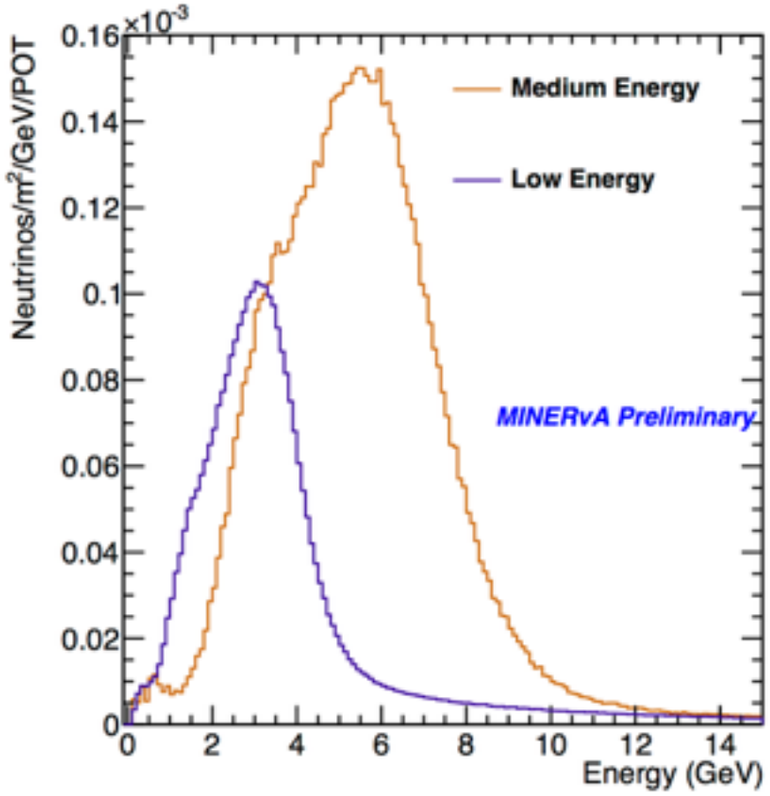
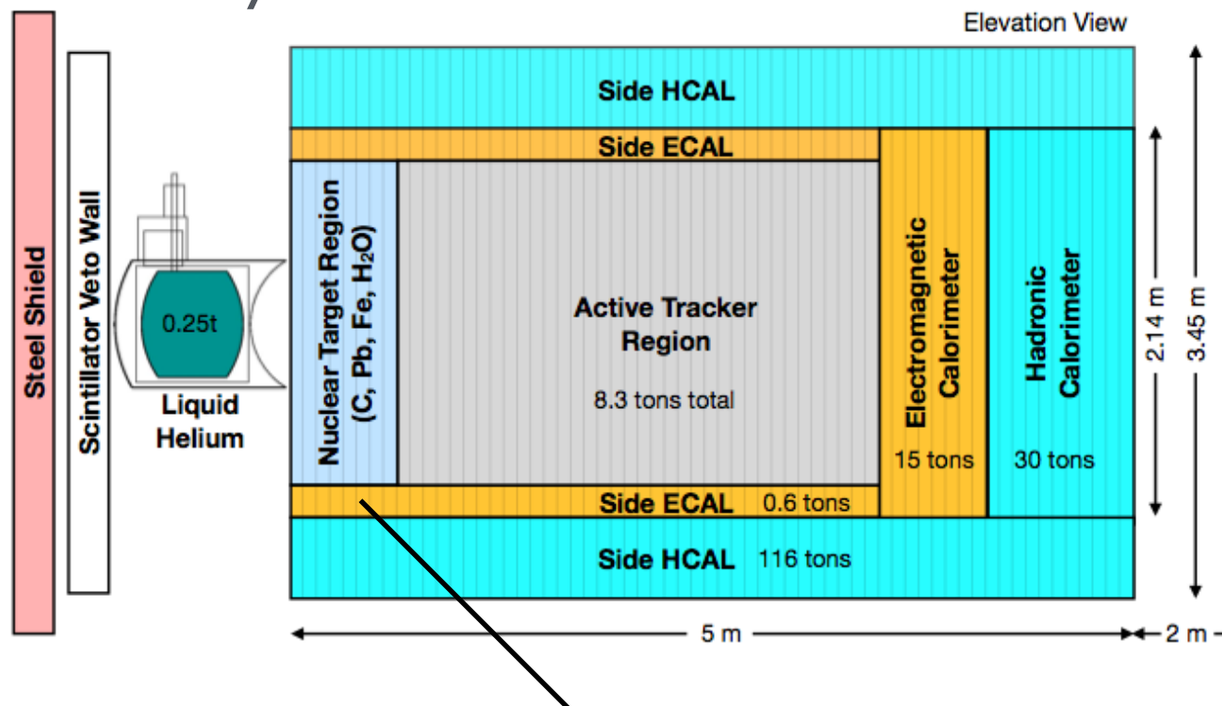
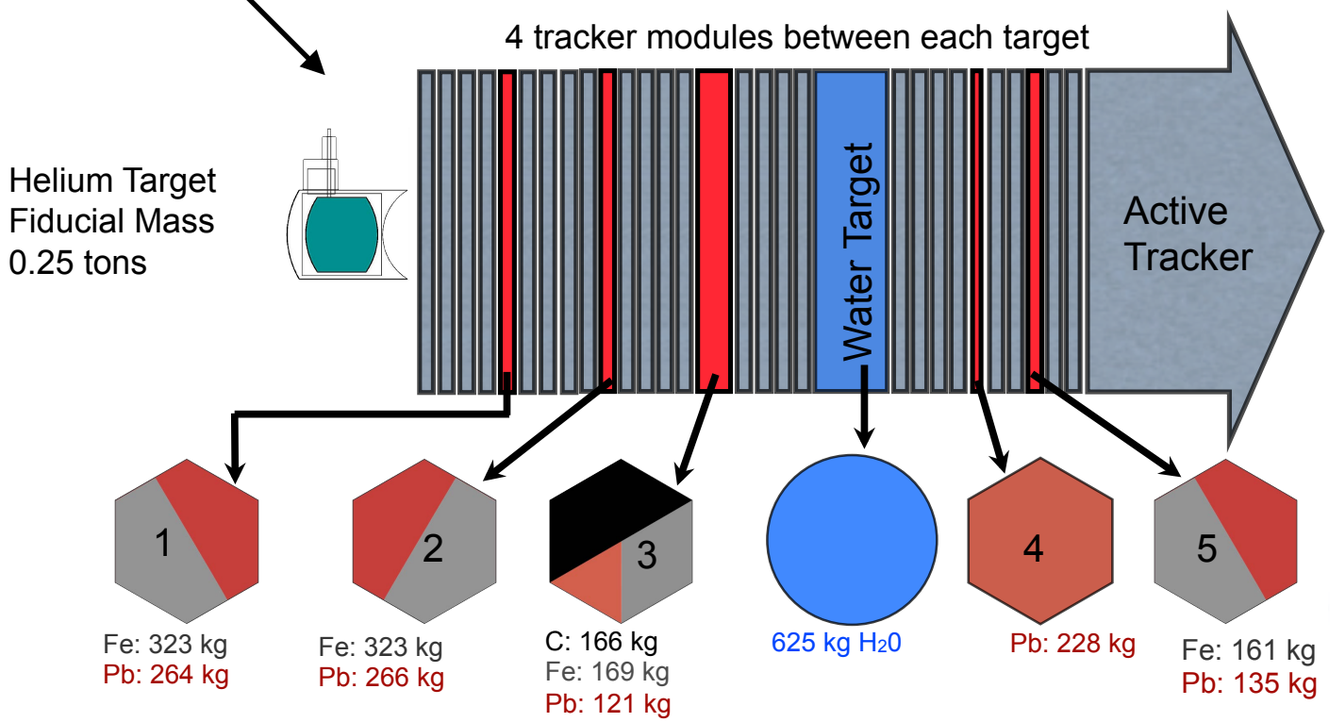
MINERvA Experiment

- Fine-grained scintillator tracker surrounded by calorimeters
- We have different nuclear targets which allows us to study nuclear effects and see how the different processes are affected by the nucleus





Thanks to MINOS



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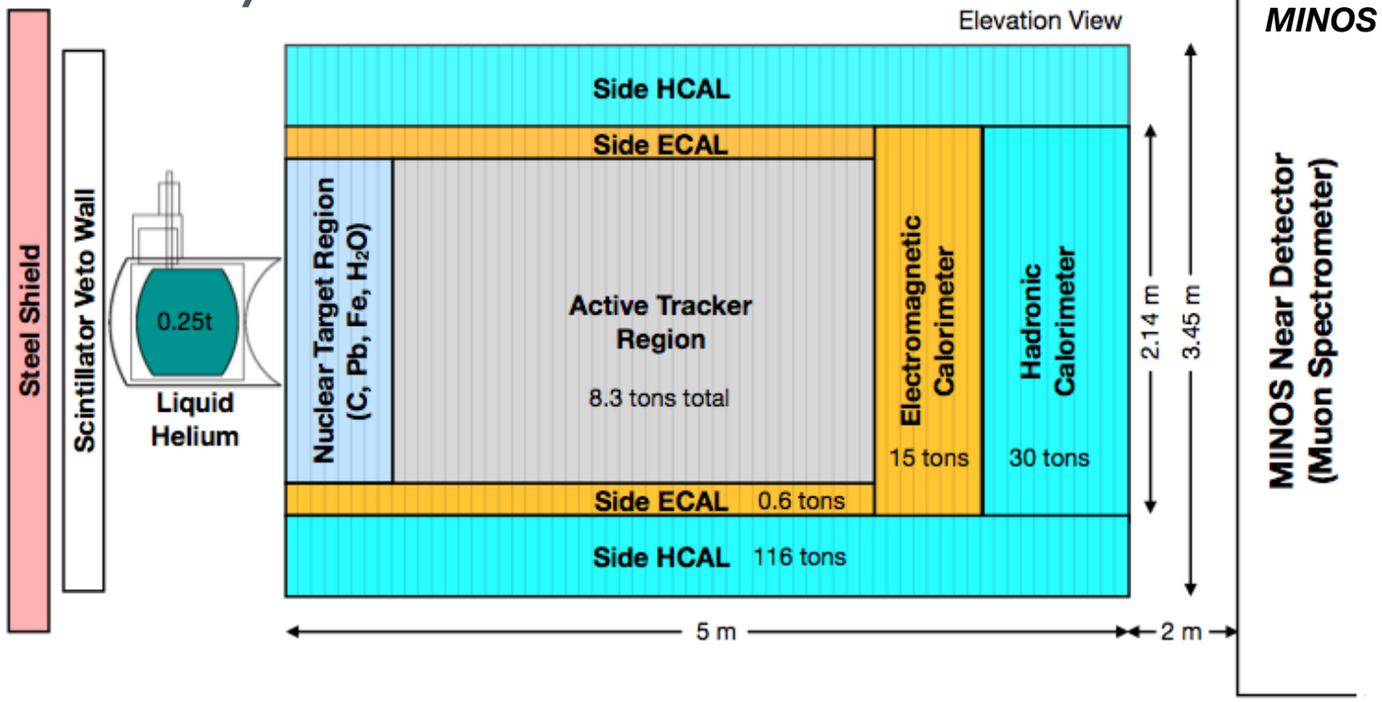

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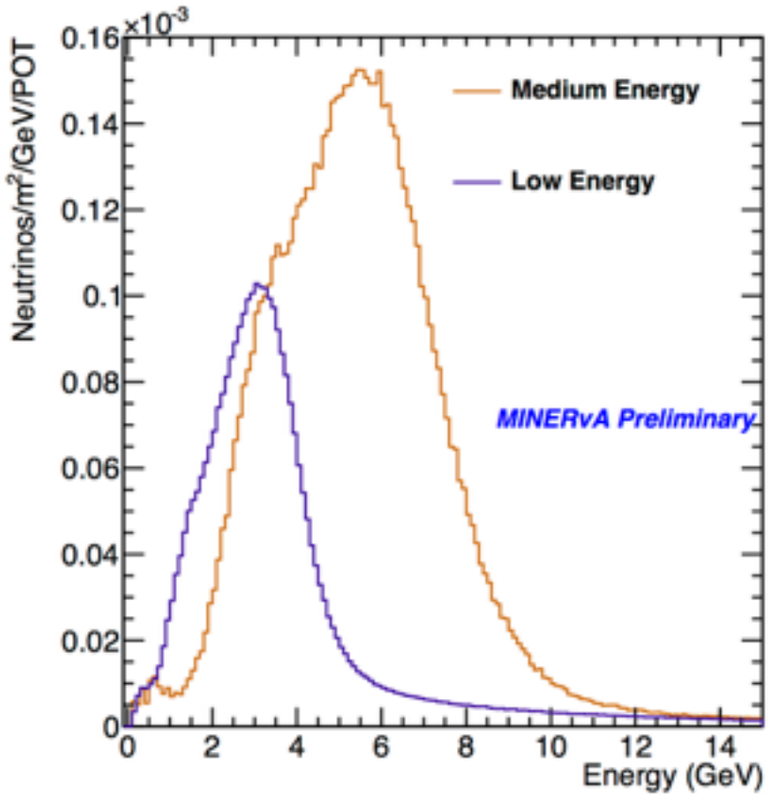
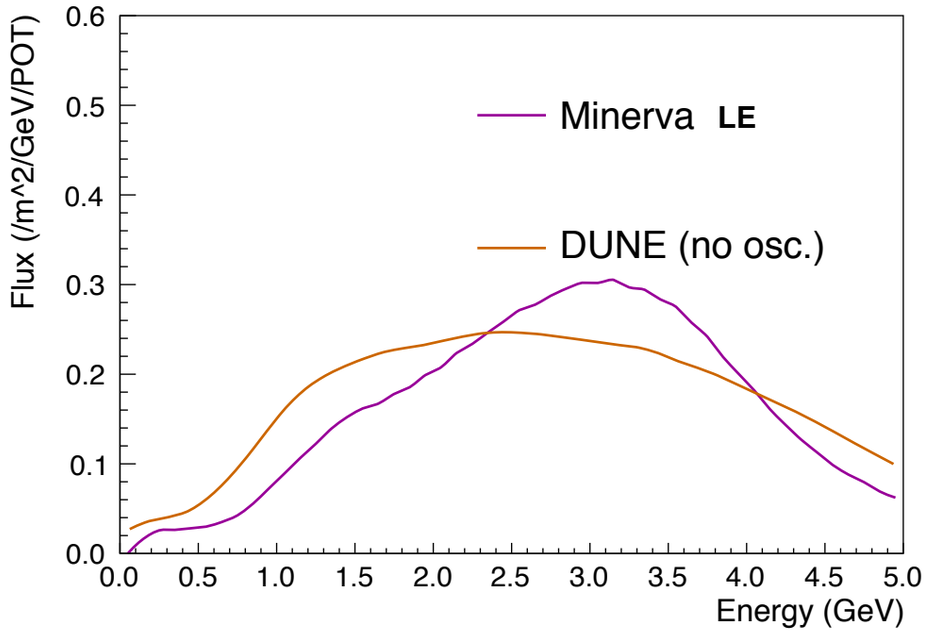


- MINERvA flux covers most of the DUNE flux



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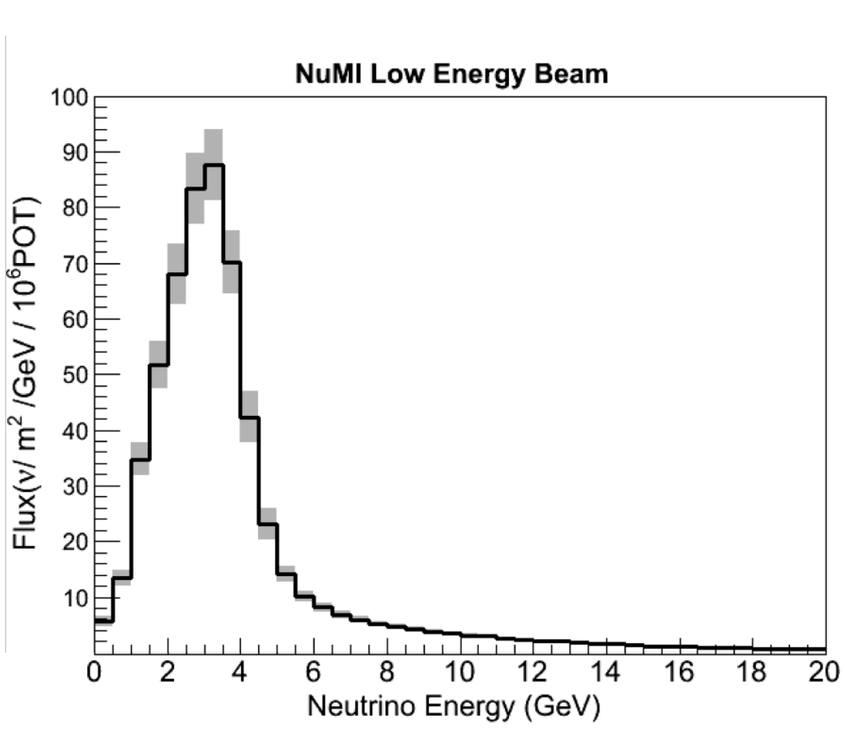
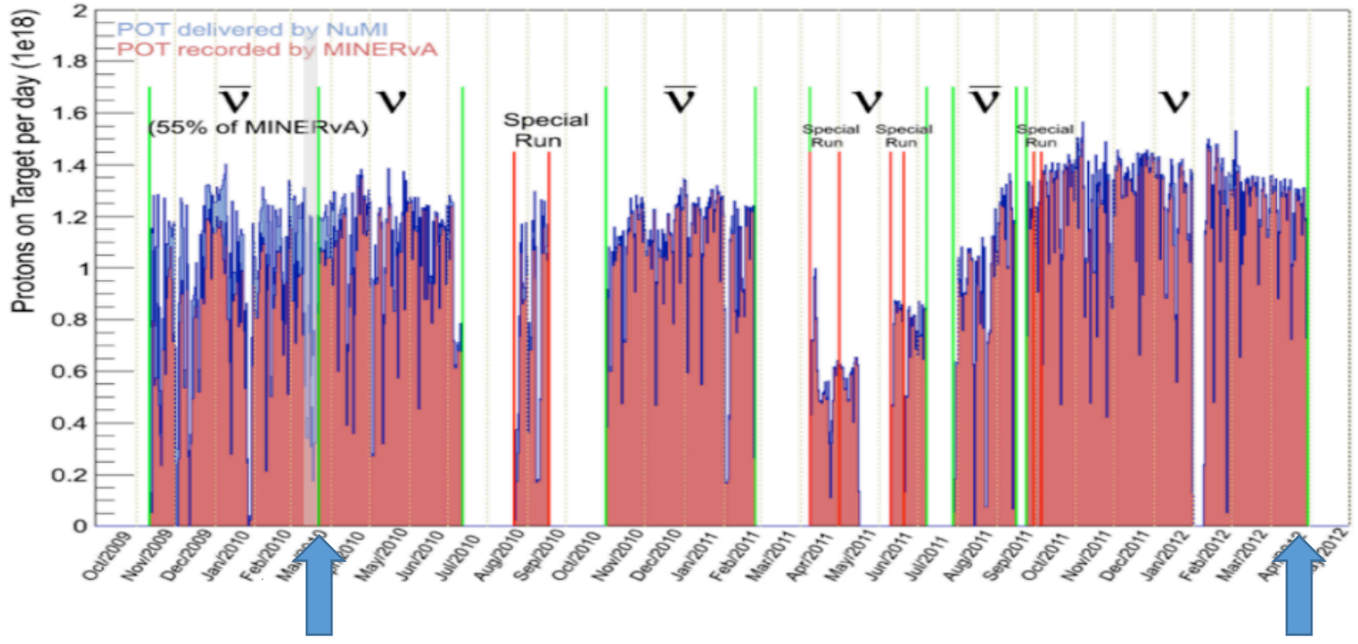
Low Energy Neutrino Beam

- 24 papers using the neutrino energy <Eν>=3.5 GeV, highlights:
  - Charged current π^0
  - Antineutrino low recoil analysis double differential cross section
  - Neutrino and antineutrino CCQE double differential cross sections
  - Measurements of nuclear effects with CCQE



Phys. Rev. D 94, 092005 (2016)



- **Data Collection:** March 2010 - April 2012
- **Protons on Target (P.O.T) Used:** 3.33e20

Thanks to the acceleration division

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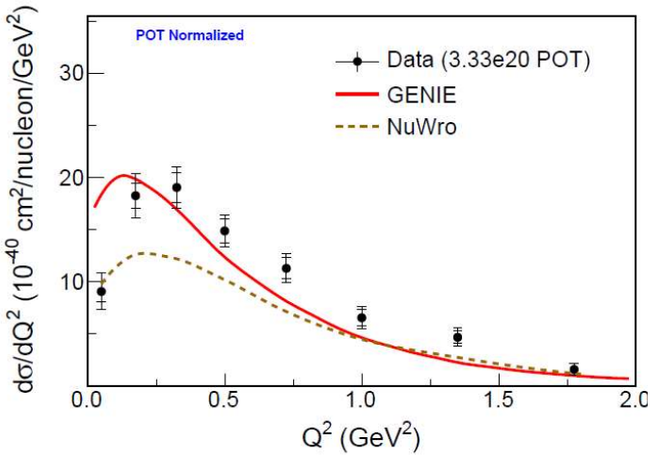
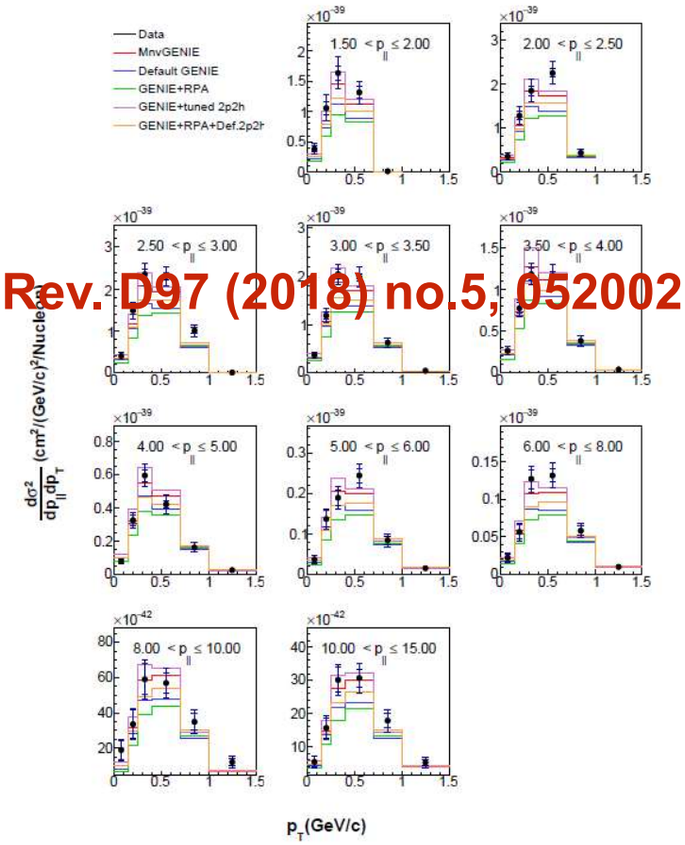
Several Publications (2017-2018)

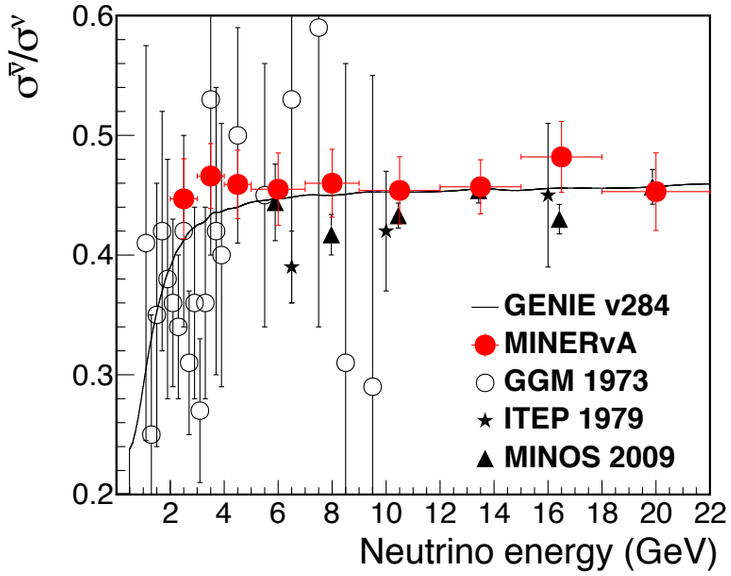
Phys.Rev. D96 (2017) no.7, 072003



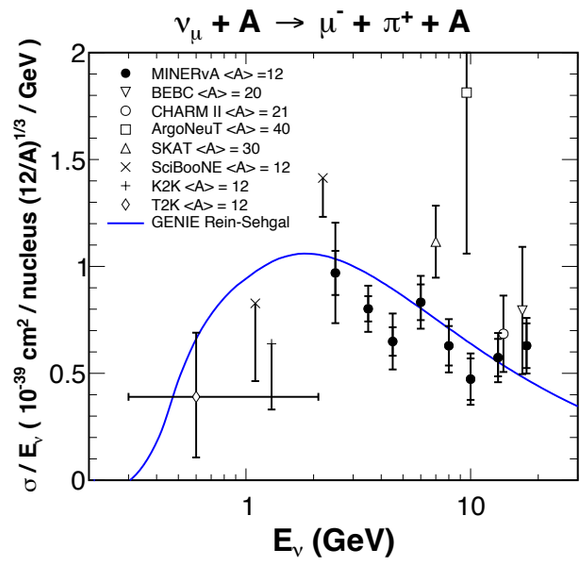
Phys.Rev. D97 (2018) no.5, 052002

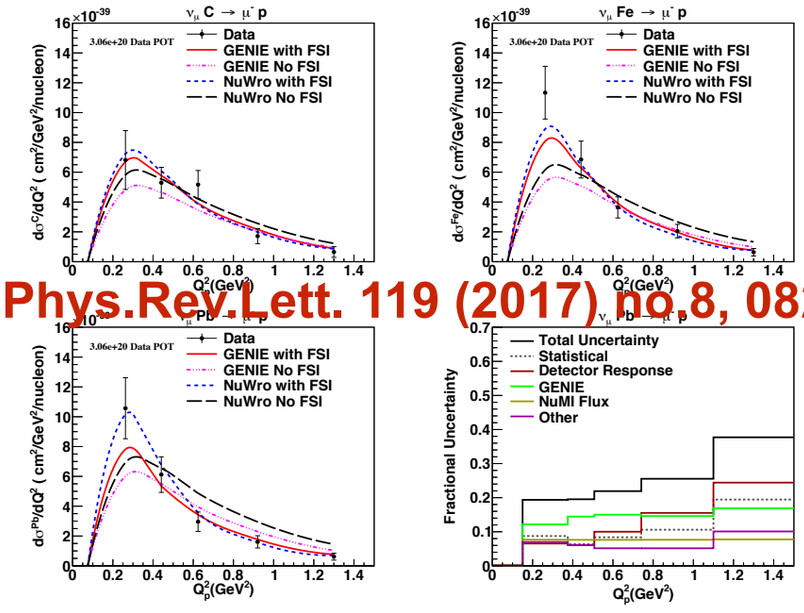


Phys.Rev. D95 (2017) no.7, 072009



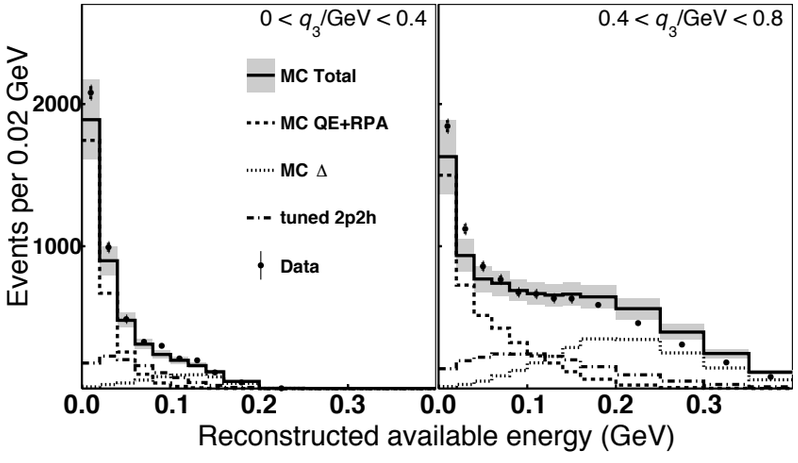
Phys.Rev. D97 (2018) no.3, 032014



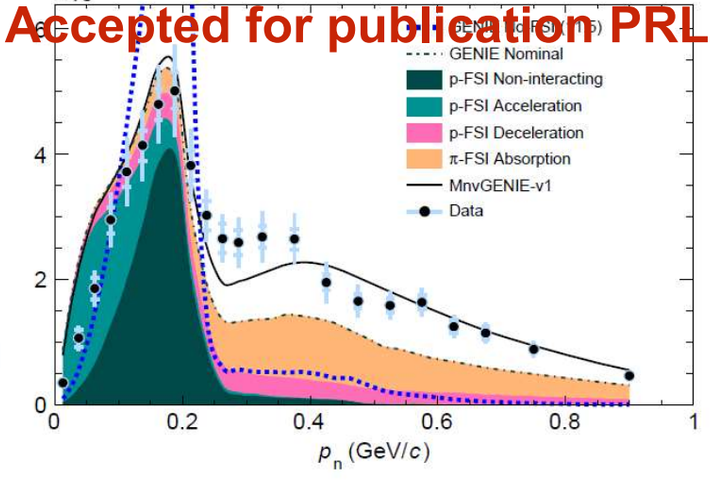


Phys.Rev.Lett. 119 (2017) no.8, 082001

Phys.Rev.Lett. 120 (2018) no.22, 221805



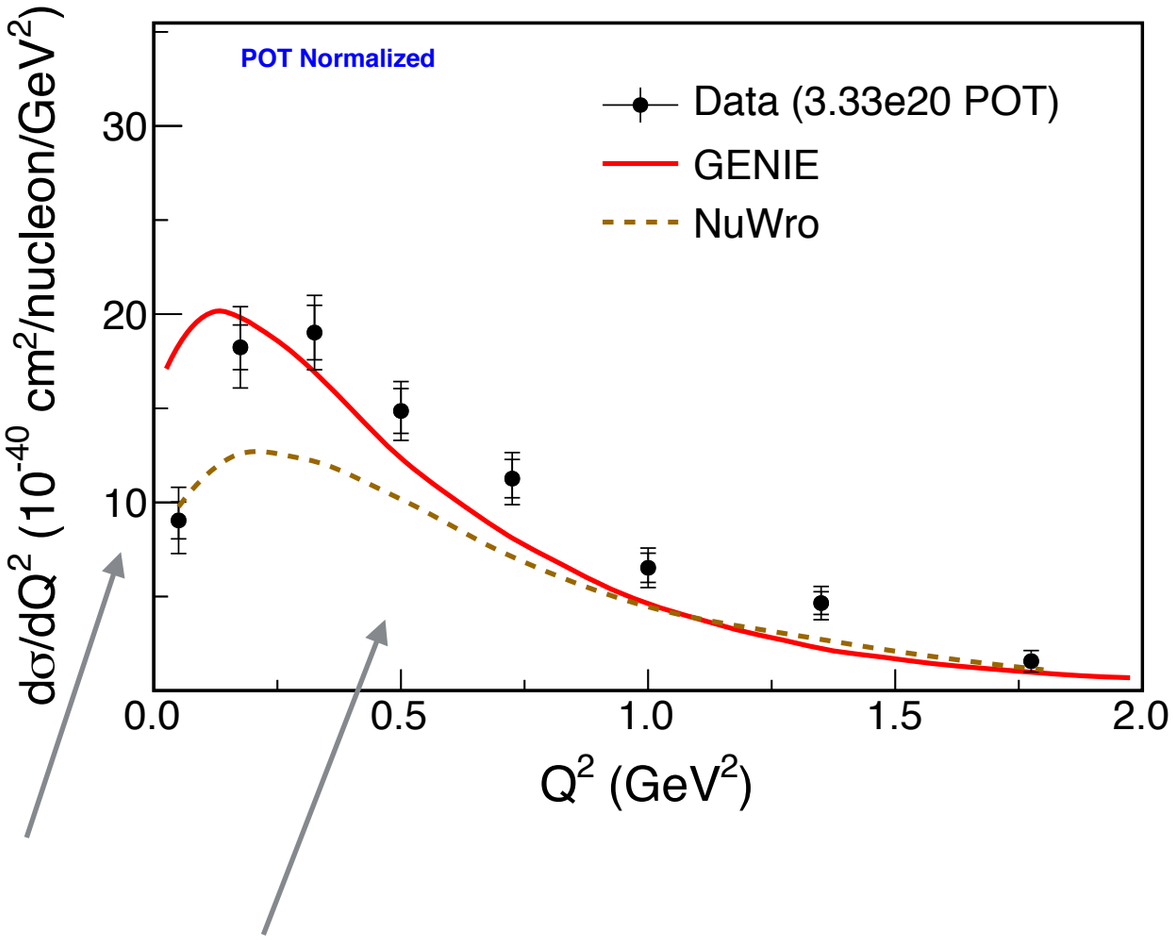
arXiv:1805.05486
Accepted for publication PRL



Measurement of νμ-CC(π^0)

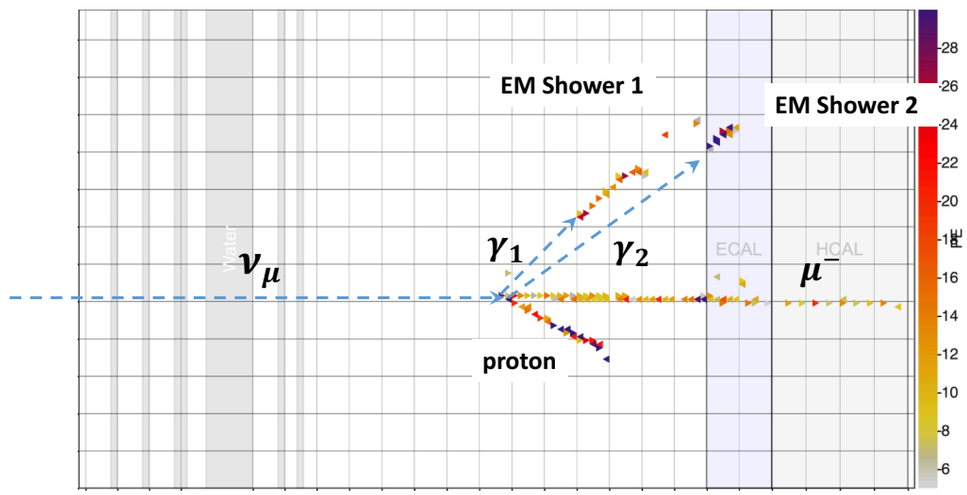
- π^0 production by neutrinos provides insight on ν_μ-NC(π^0) background to ν_e appearance
- Knowledge of cc(pi) production constrains systematics for resonance and non resonance models

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



$$\nu_\mu + \{n\}_C \rightarrow \mu^- + \pi^0 + p$$

$$\pi^0 \rightarrow 2\gamma$$



Phys.Rev. D96 (2017) no.7, 072003

- These disagreements identify areas that need of improvement
- Measurement of pπ^0 invariant mass and decay angular distributions …

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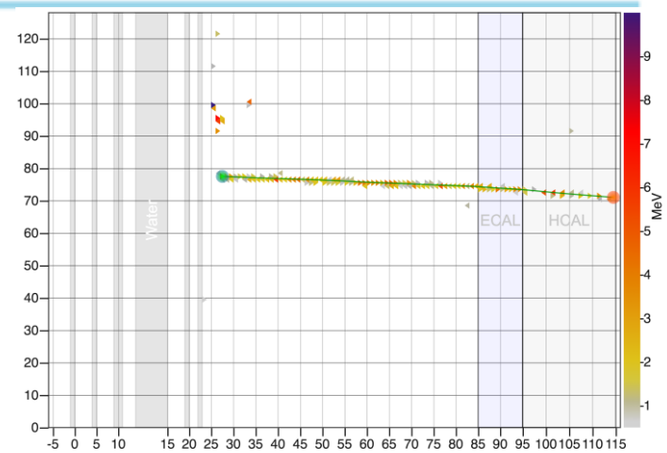
Identification of Multinucleon Effects In Antineutrinos

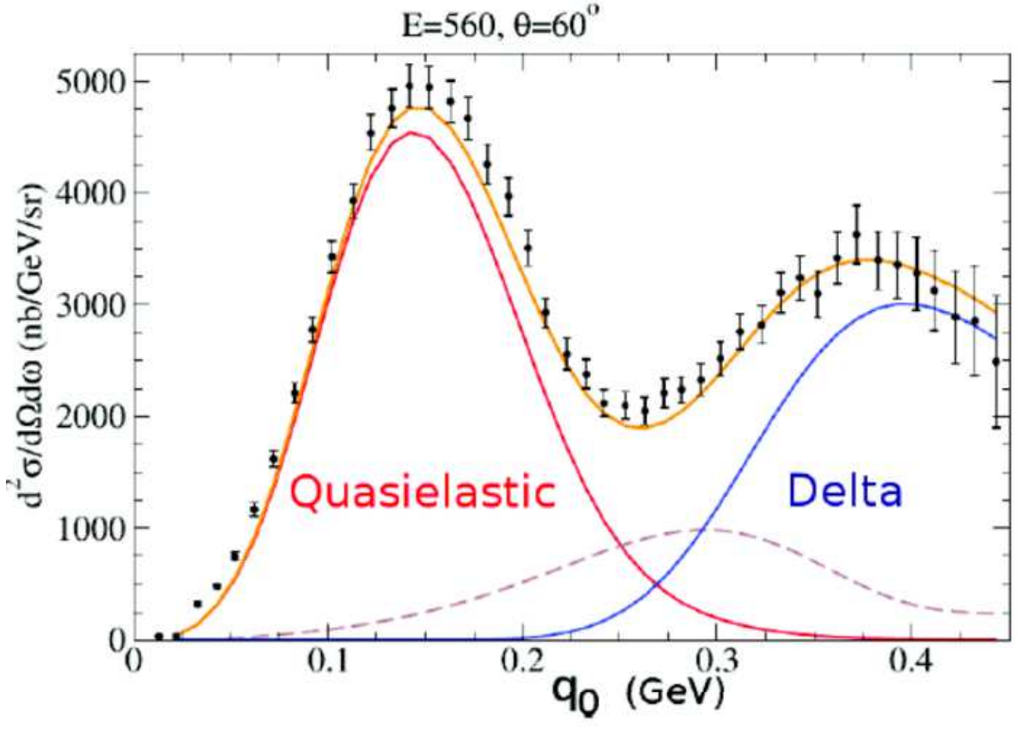
- Inclusive CC double differential cross section in q_0 and q_3
  - q_0: calorimetric hadronic energy
  - q_3: is the three momentum transfer $q_3 \equiv |\mathbf{q}| = \sqrt{Q^2 + q_0^2}$



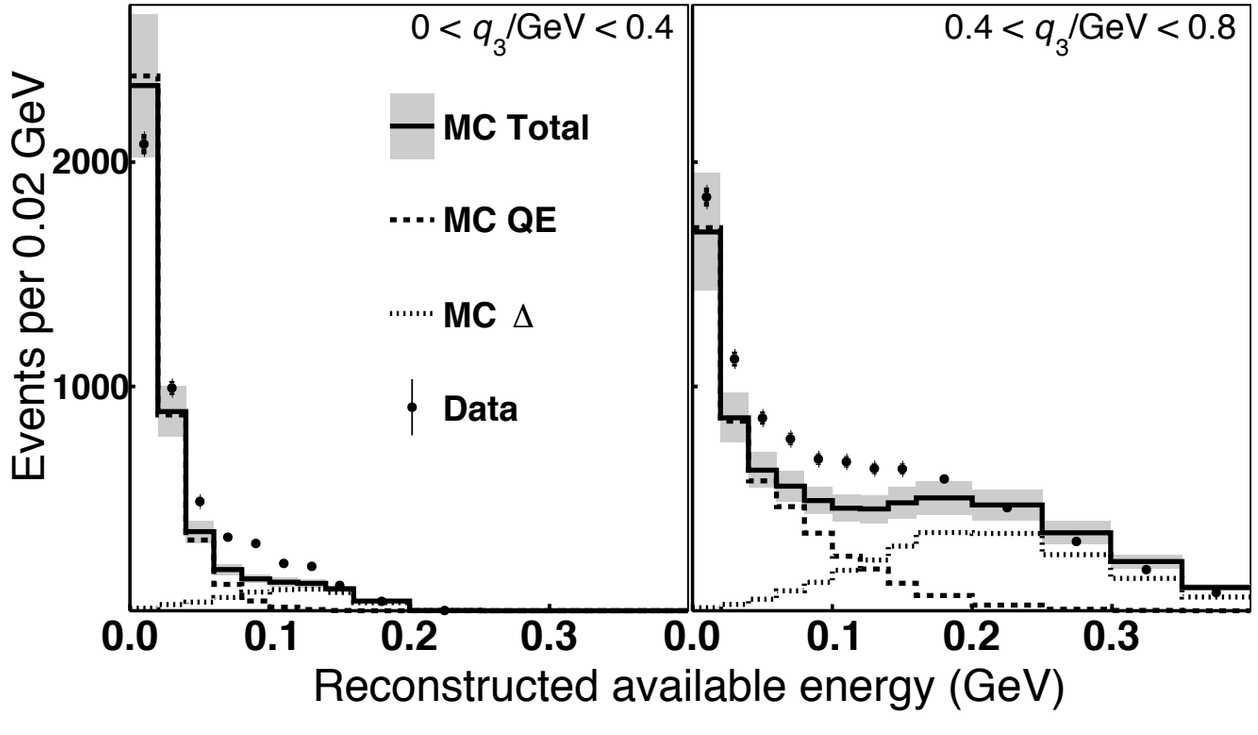
From electron scattering

Similar measurement for antineutrinos using the hadronic system and the lepton

Adapted from G. D. Megias, NuFact 2015



$q_0 = E_e - E_{e'}$



Phys.Rev.Lett. 120 (2018) no.22, 221805

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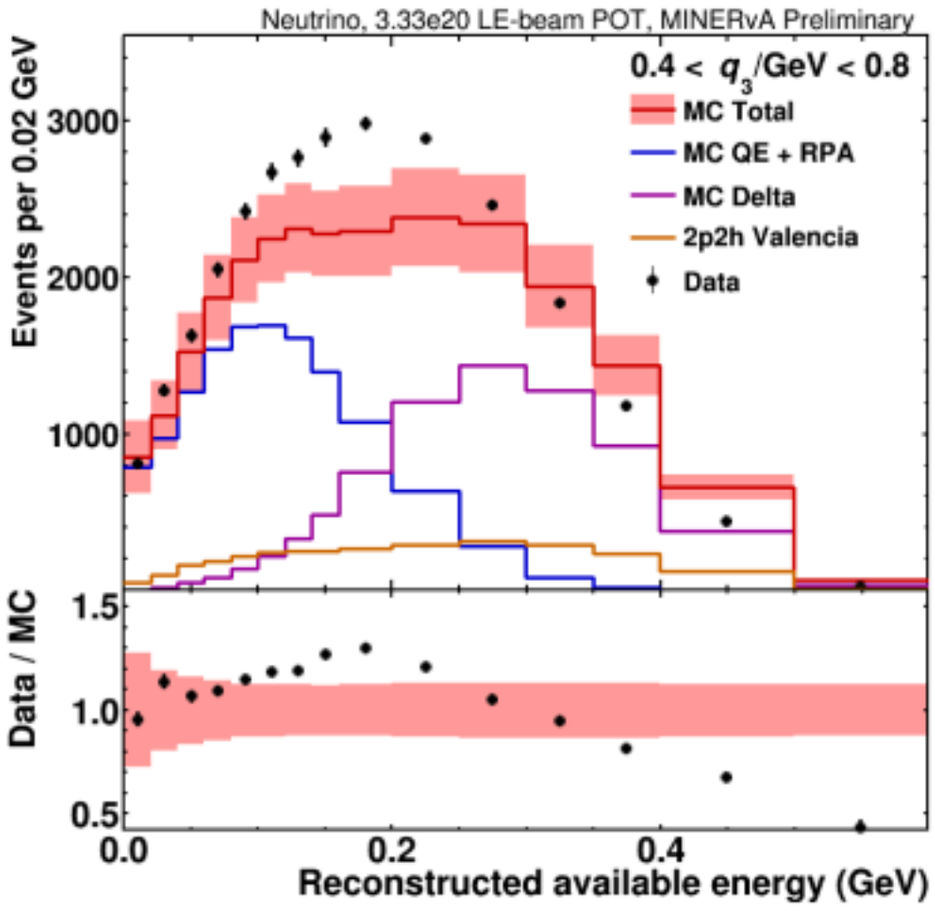
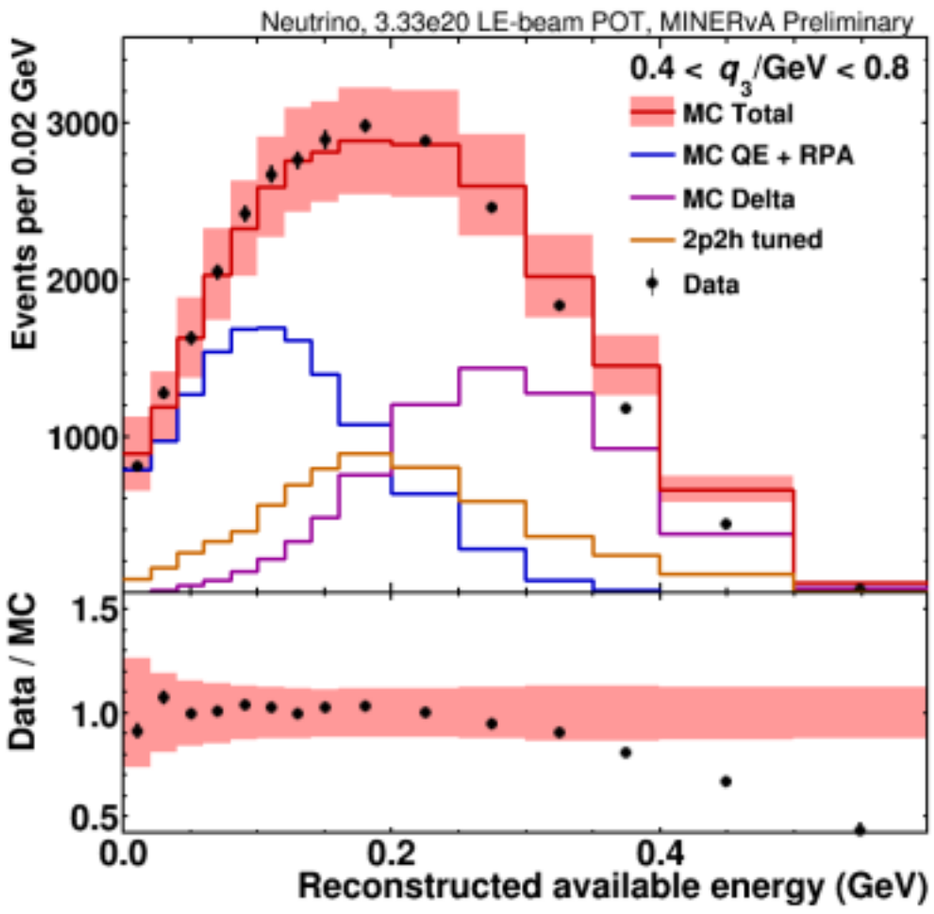
From the Inclusive Neutrino Low Recoil Measurements

- Adding in models of RPA (a charge screening effect) and multi nucleon (2p2h) improves agreement in some regions, but not in others

Phys.Rev.Lett. 116 (2016) 071802



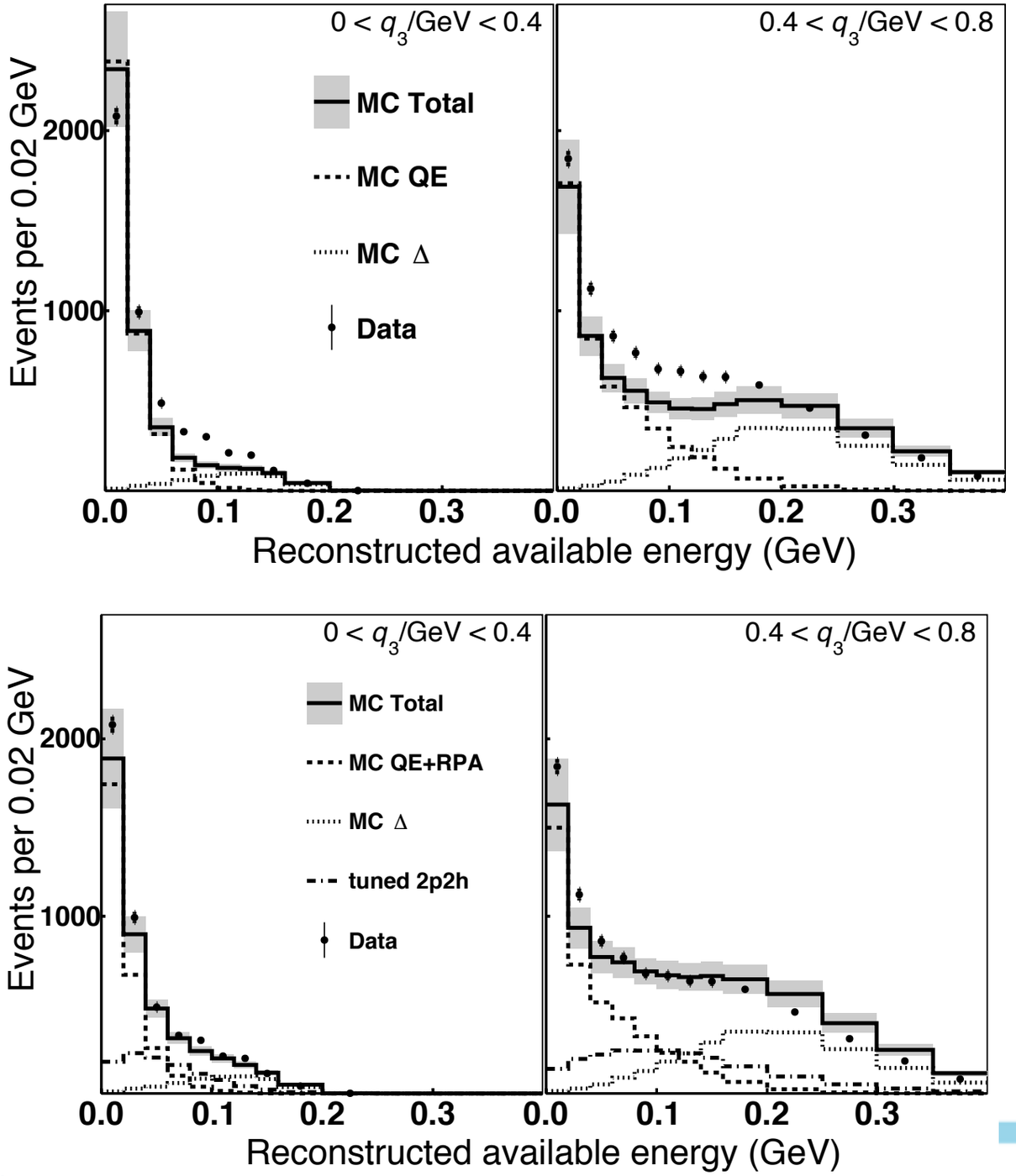
Tuning the 2p2h



- Fitting a 2D Gaussian in true (q0, q3) as a reweighting function to the 2p2h contribution to get the best agreement between data and MC
- The QE and RES interactions are unchanged

Nuclear Effects at low Three Momentum Transfer (Antineutrino)

- Applying the extracted 2p2h weights from the neutrino sample to antineutrino



Phys.Rev.Lett. 120 (2018) no.22, 221805

Before

After

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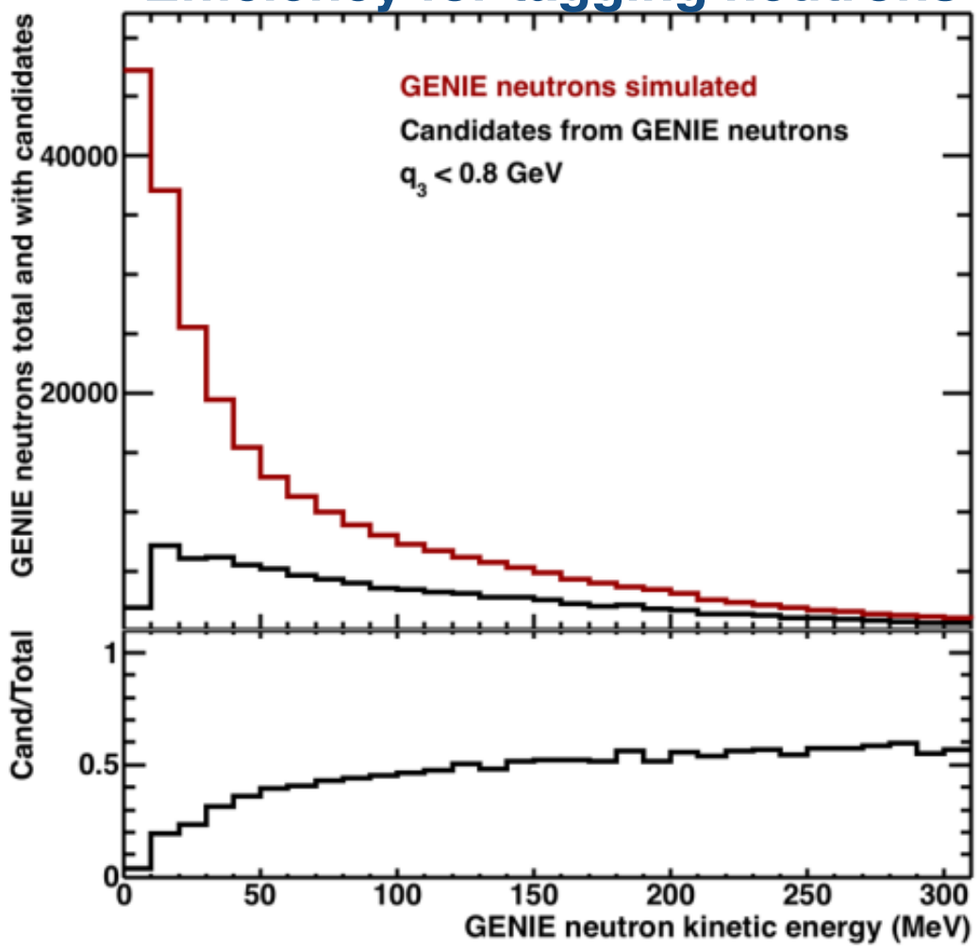
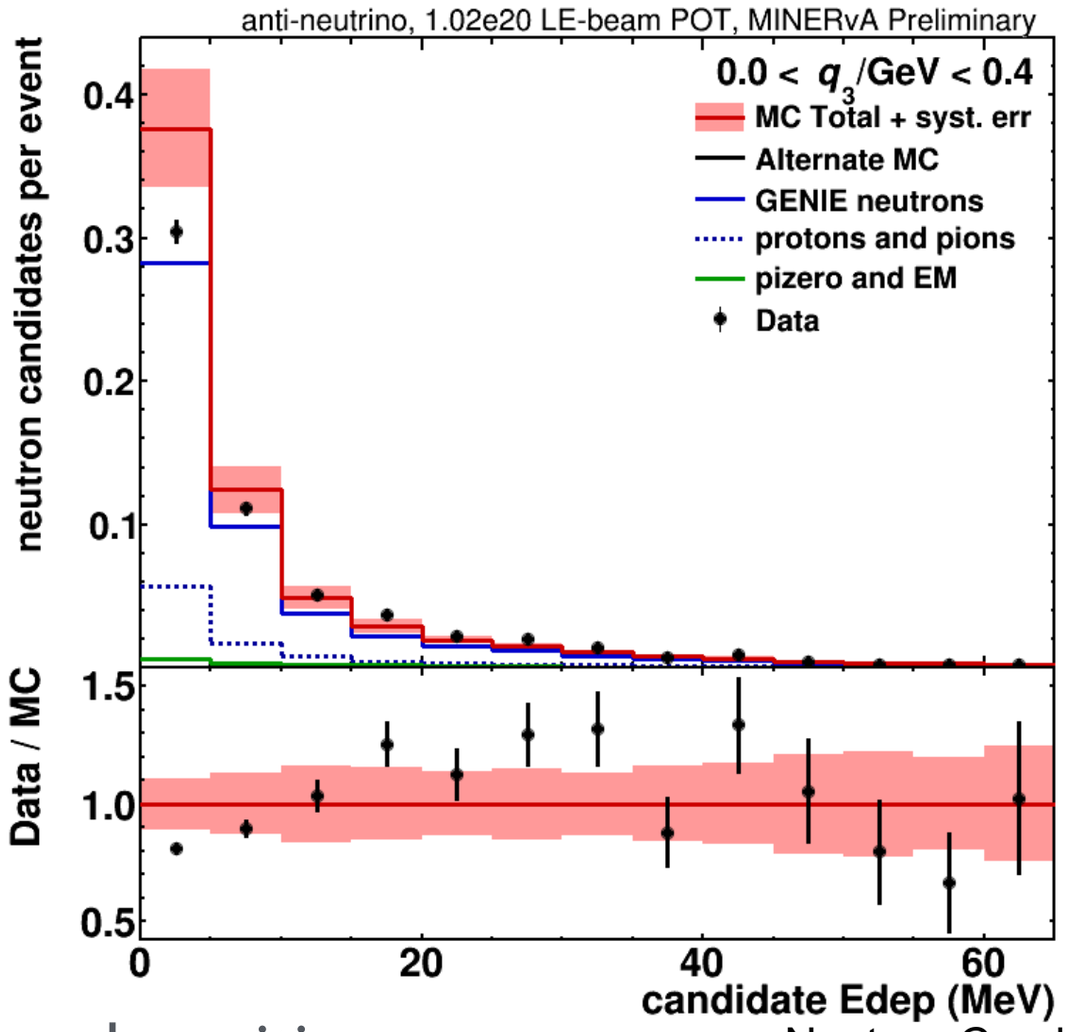
Neutron Candidate Energy Deposition

- Neutrons are important for the accurate reconstruction of neutrino energy and systematics
- MINERvA has a new neutron detection algorithm in scintillator

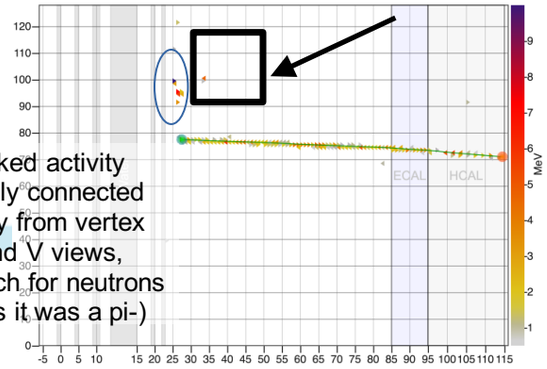
Efficiency for tagging neutrons





- Excess in the MC in the first bin small energy deposition

Neutron Candidate



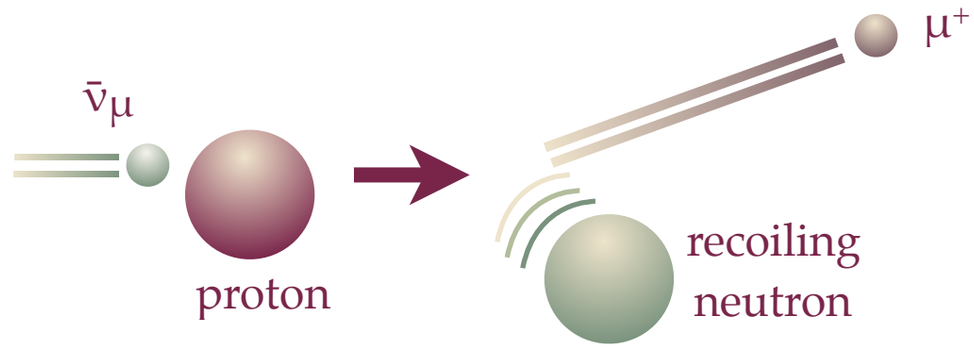
Rik Gran
Fermilab Wine&Cheese, Nov 03-2017

Paper in preparation

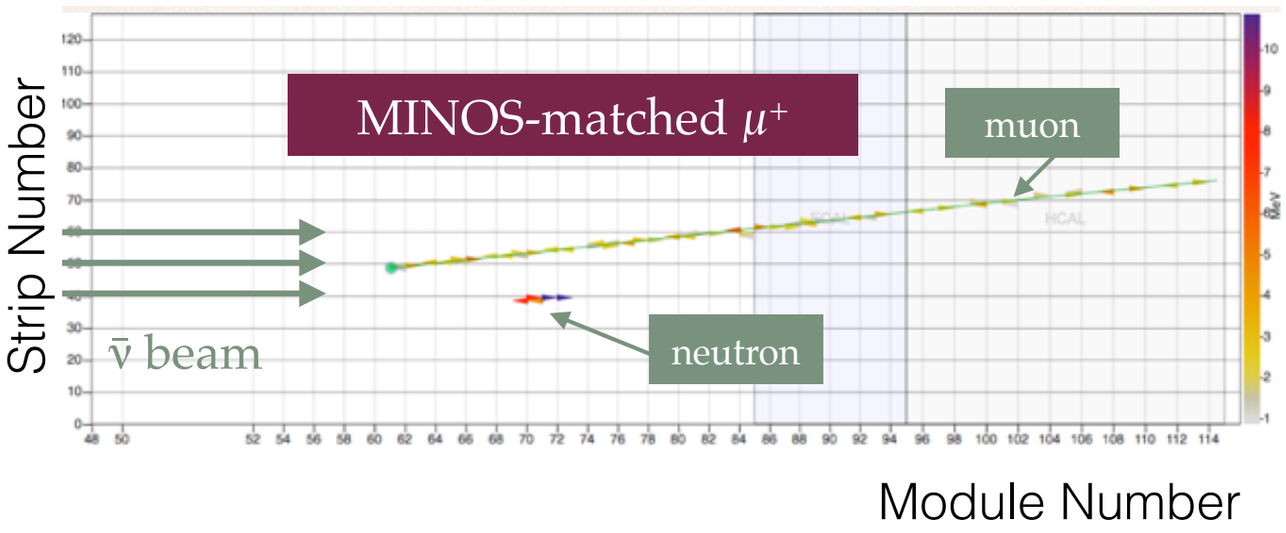
Double Differential Cross Sections (Antineutrinos and Neutrinos)

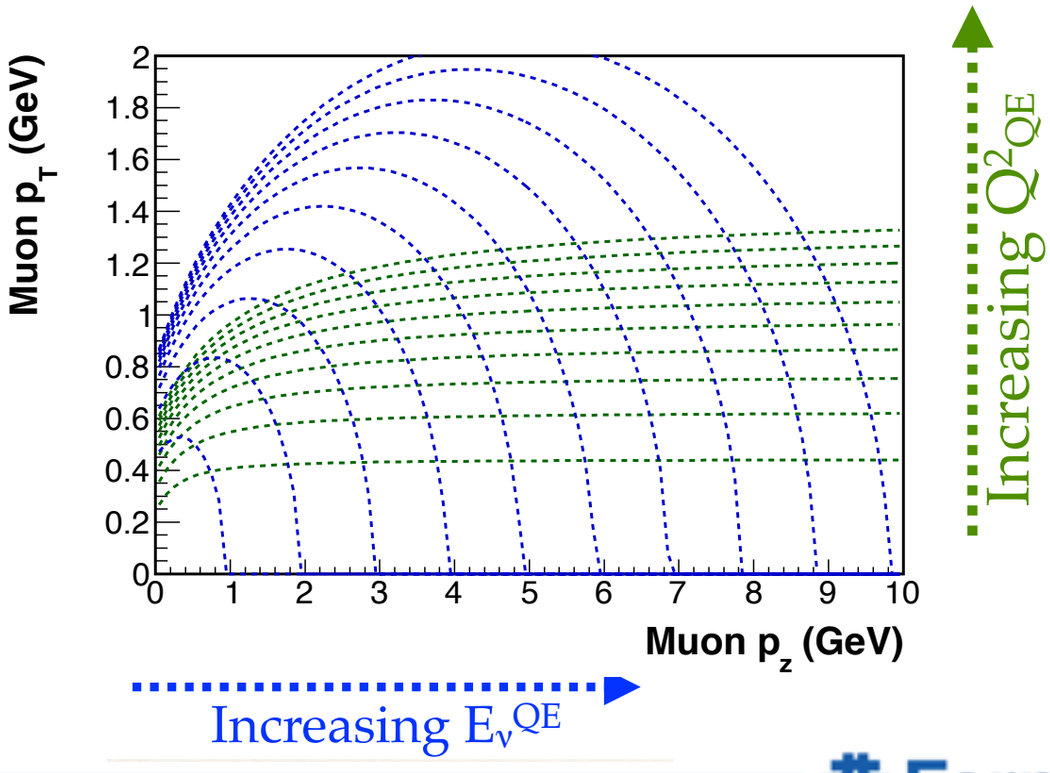
- Using the kinematics of the muon
- Double differential cross sections for antineutrinos

$$\frac{d^2\sigma}{dP_T dP_{||}}$$



- Muon longitudinal $P_{||}$ and transverse momentum P_T are measurable quantities
- P_T and $P_{||}$ are less model dependent than Q^2 and neutrino energy





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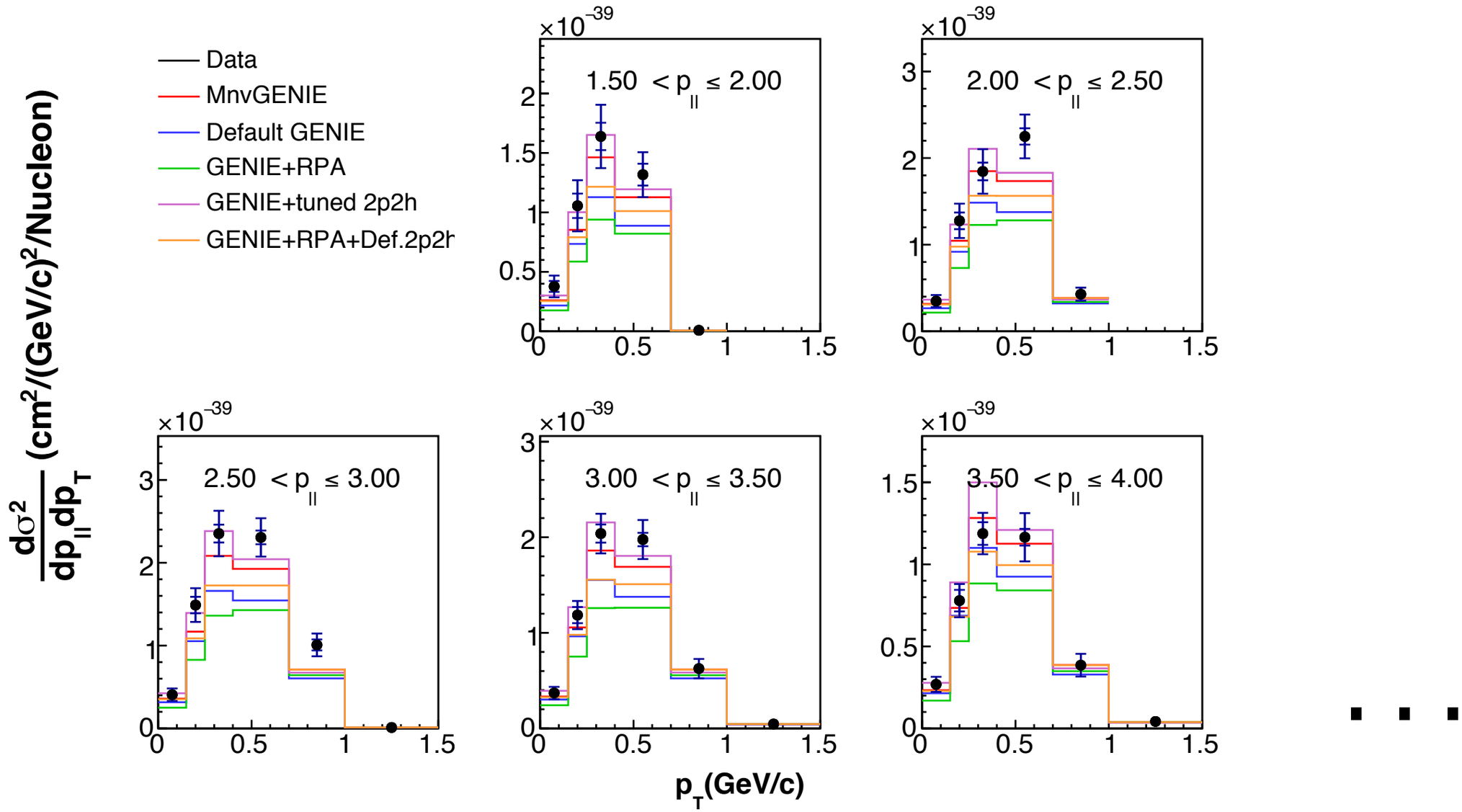
Double Differential Cross Sections for Antineutrinos

Quasi-Elastic scattering using the muon kinematics (P_T and $P_{||}$)



Phys.Rev. D 97 116 (2018) no. 5, 052002

- We see agreement between data and a simulation that includes nuclear effects
- Best chi2 indicates a preference for models with RPA and 2p2h

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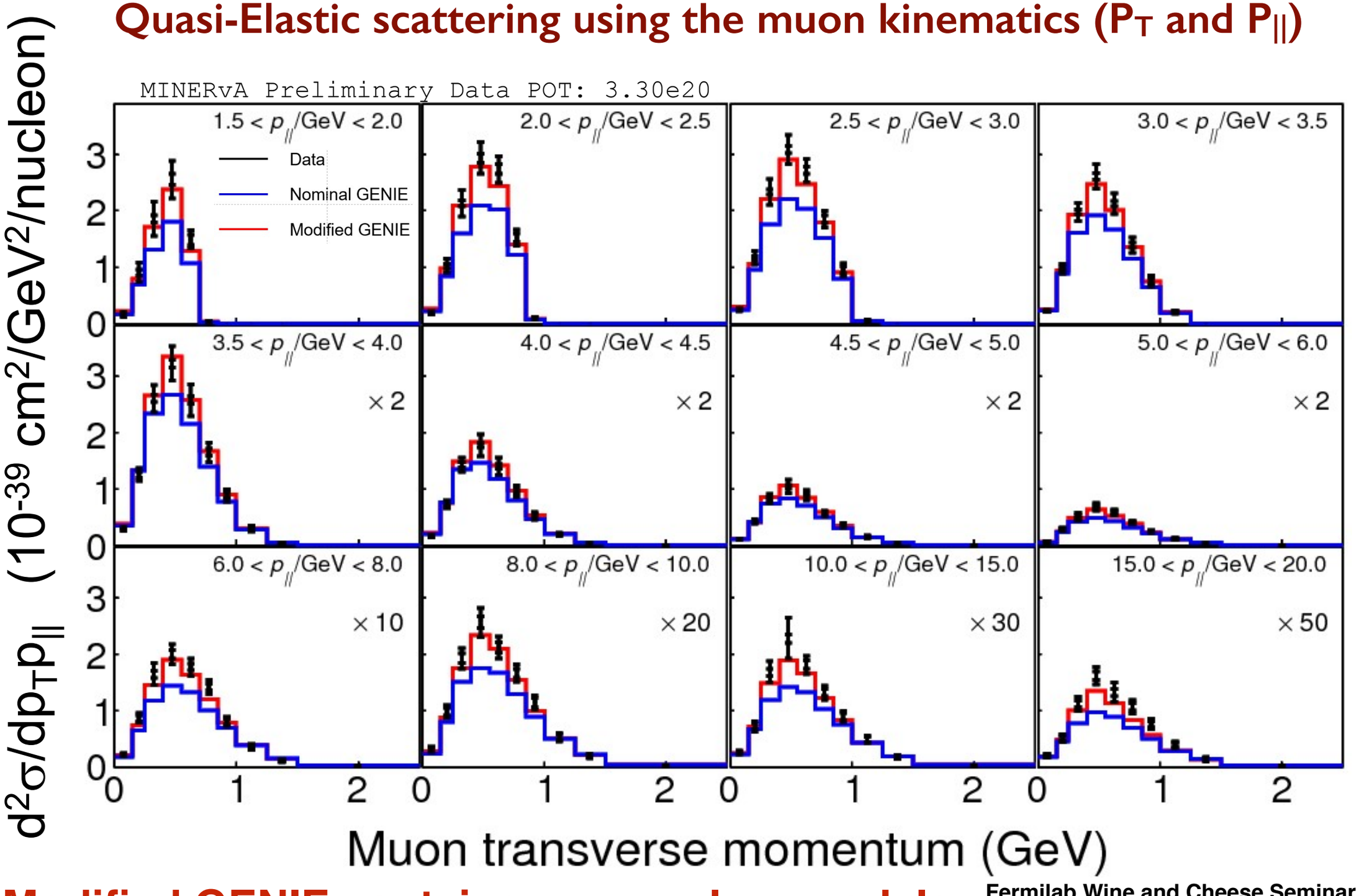
Double Differential Cross Section (Neutrinos)

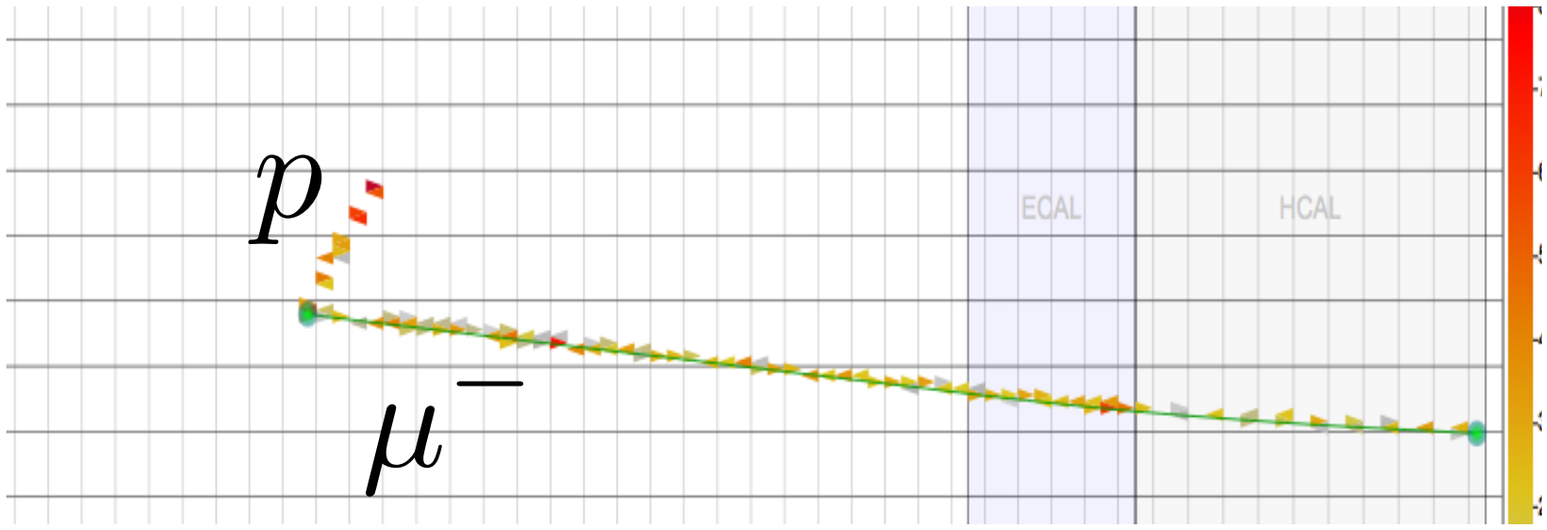
Quasi-Elastic scattering using the muon kinematics (P_T and $P_{||}$)



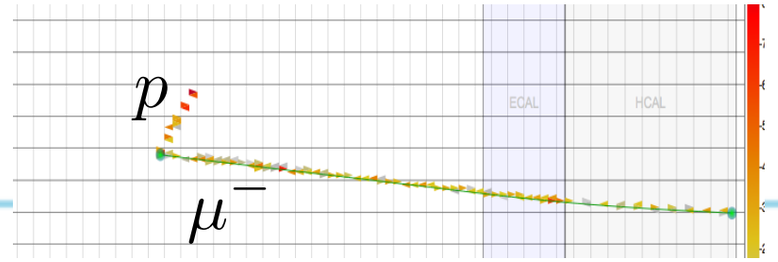
Modified GENIE contains new nuclear models

Paper in preparation

Quasi-Elastic Scattering using the Muon and Proton Kinematics



Initial Neutron Momentum

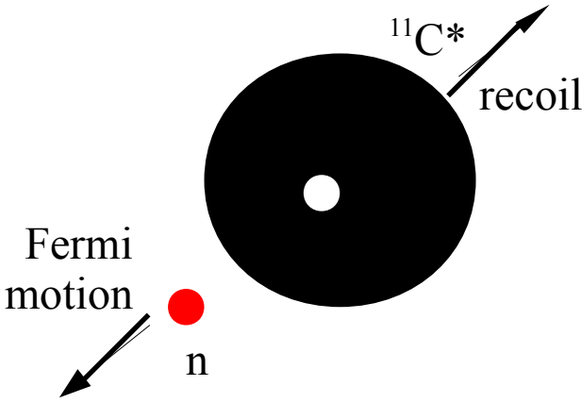


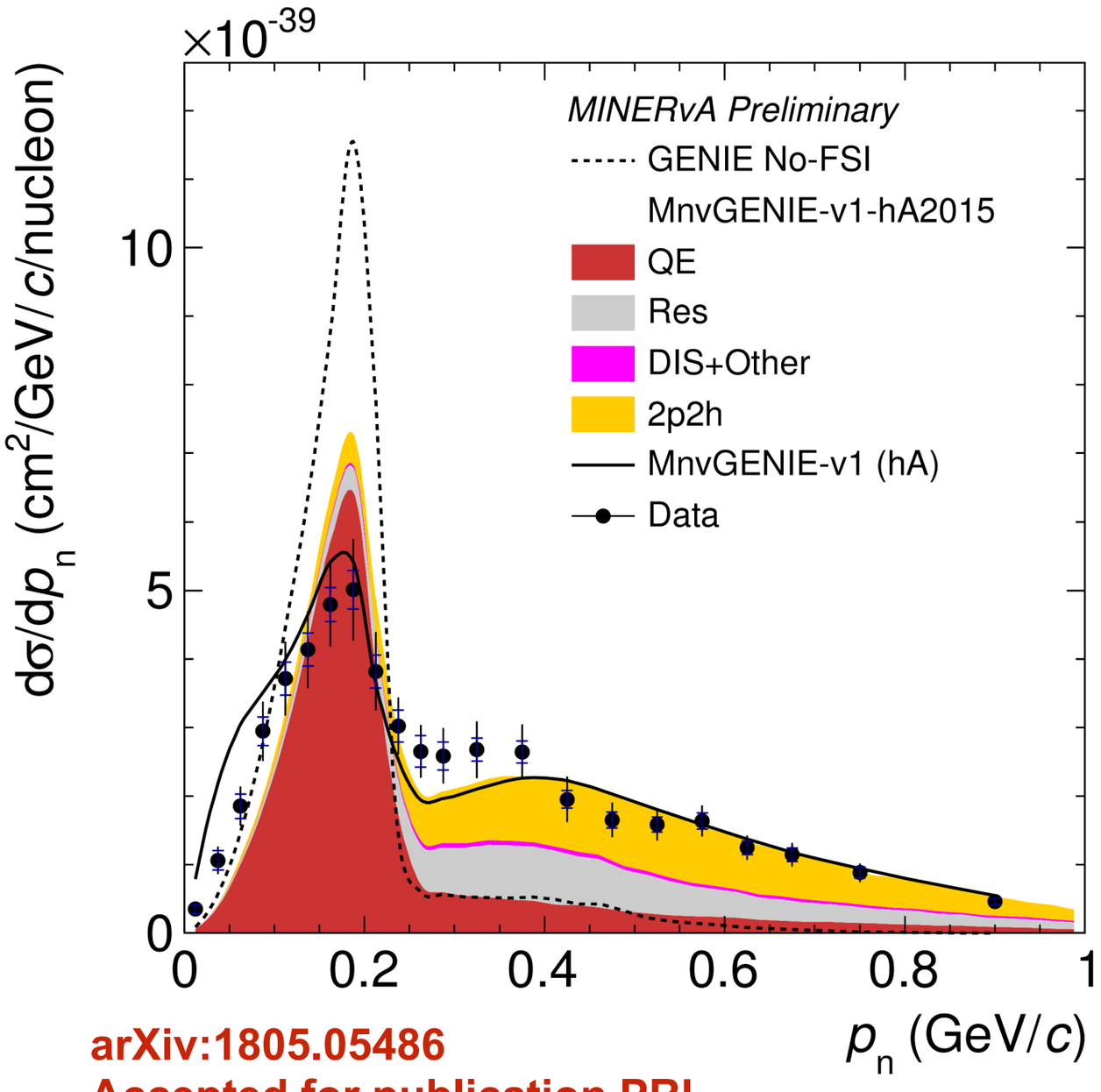
- Differential cross section in initial struck neutron momentum p_n

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

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

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





arXiv:1805.05486
Accepted for publication PRL

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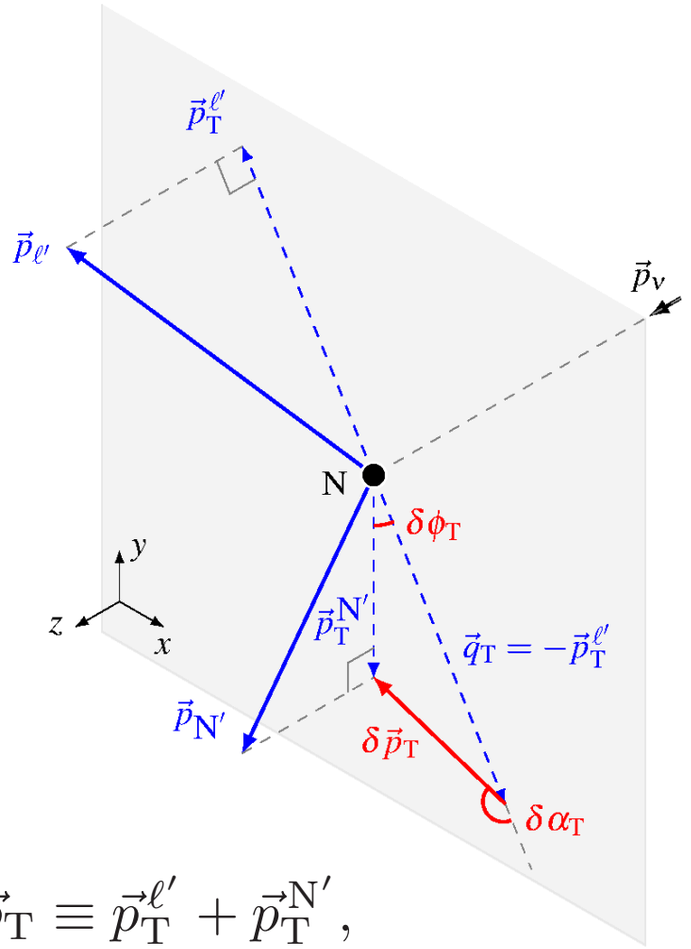
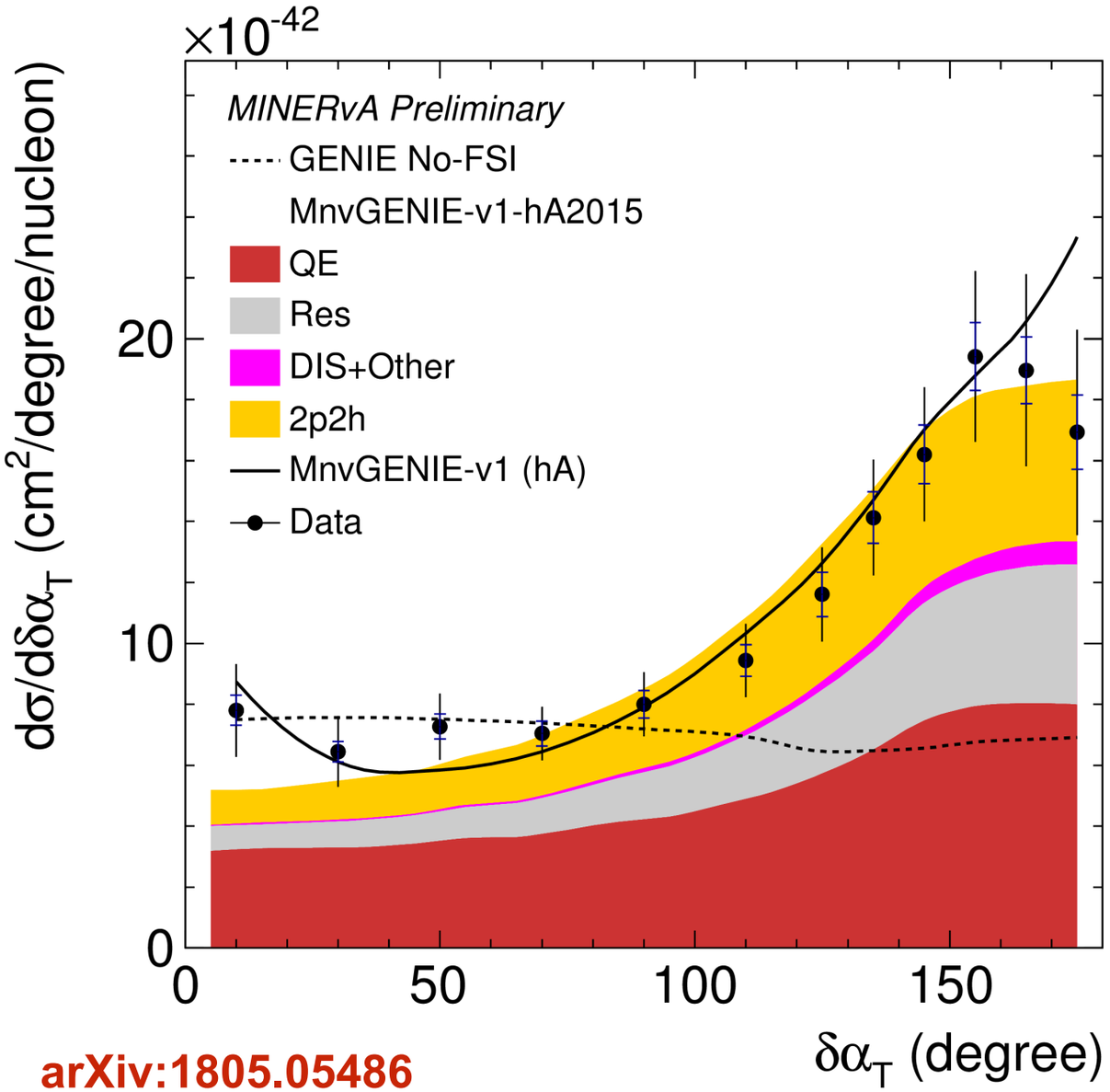
Transverse Kinematic Imbalances

- Differential cross section in transverse boosting angle $\delta\alpha_T$
  - The transverse boosting angle $\delta\alpha_T$ represents the direction of the transverse momentum imbalance



$$\delta\vec{p}_{\mathrm{T}} \equiv \vec{p}_{\mathrm{T}}^{\,\ell'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'},$$

$$\delta\alpha_{\mathrm{T}} \equiv \arccos\frac{-\vec{p}_{\mathrm{T}}^{\,\ell'} \cdot \delta\vec{p}_{\mathrm{T}}}{p_{\mathrm{T}}^{\ell'}\delta p_{\mathrm{T}}},$$



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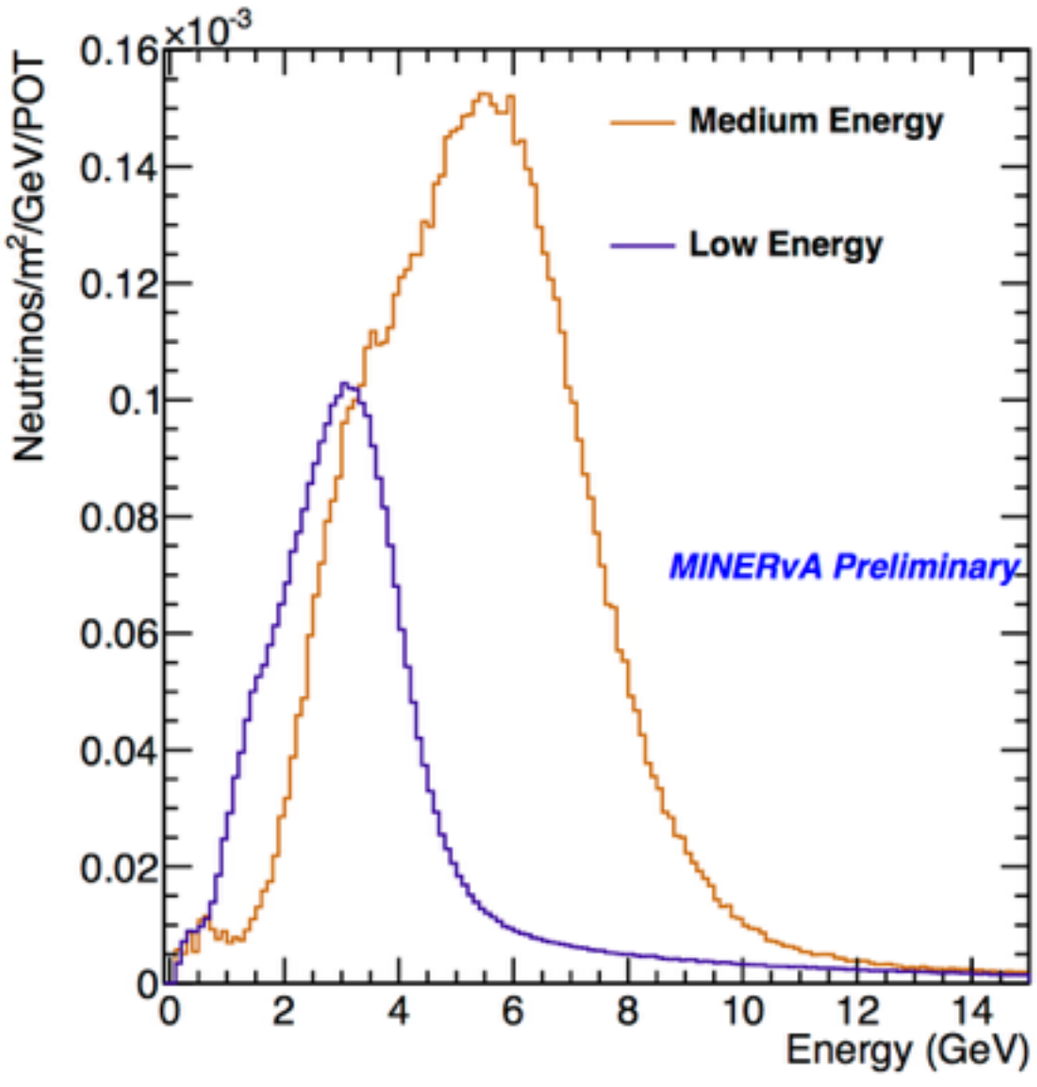
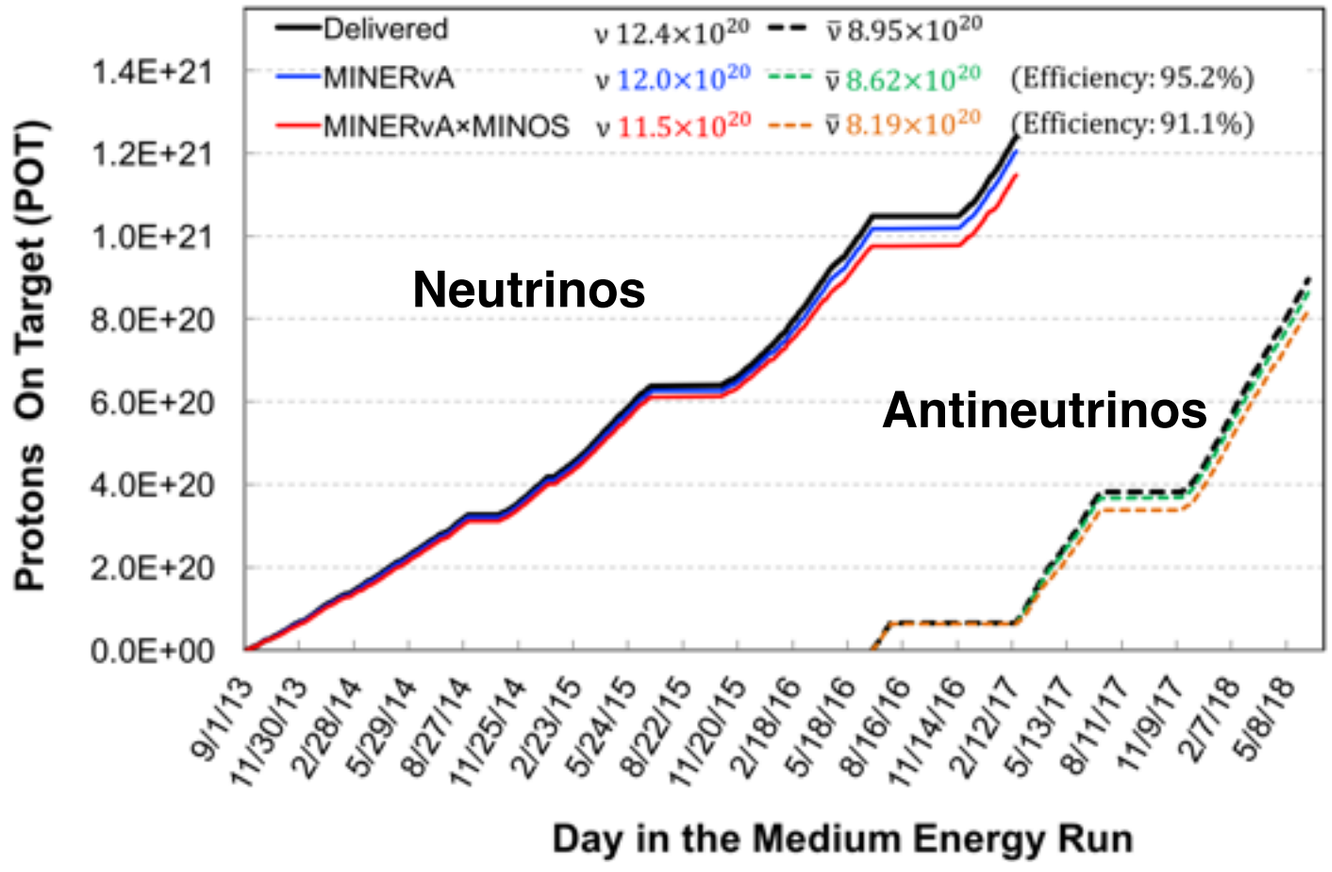
Medium Energy Data set

- NuMI medium energy beam yielding high statistics
- Ongoing analyses of quasi-elastic, pion production, DIS and inclusive off nuclear targets
  - New measurements with high statistics

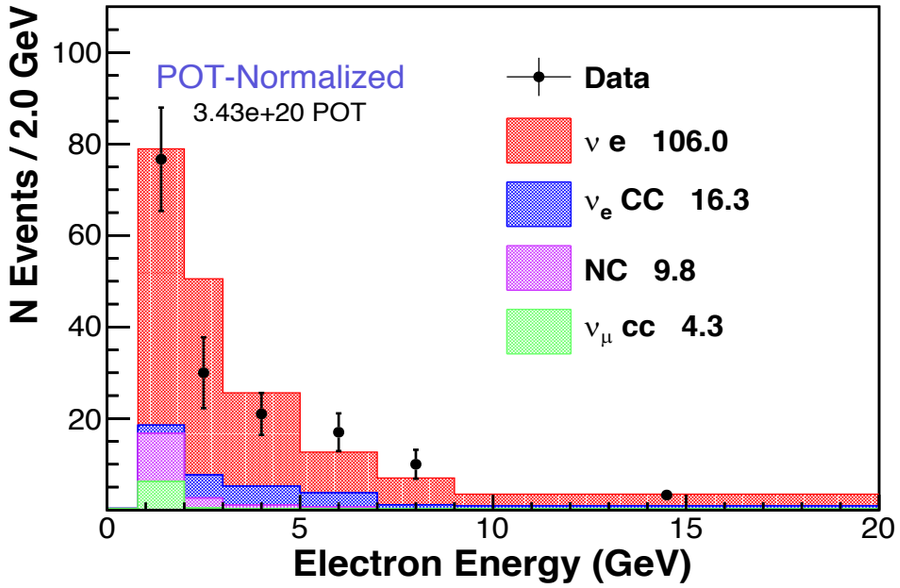




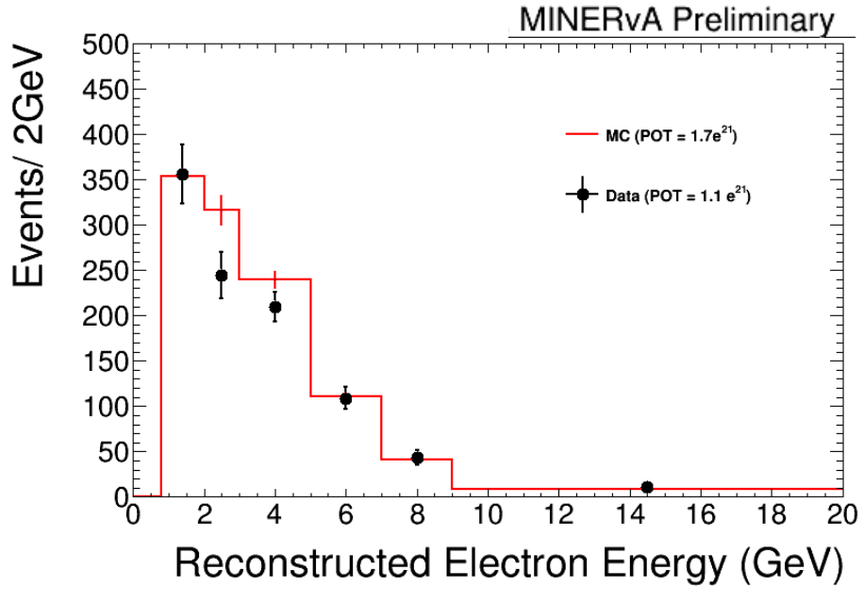
Thanks to the acceleration division

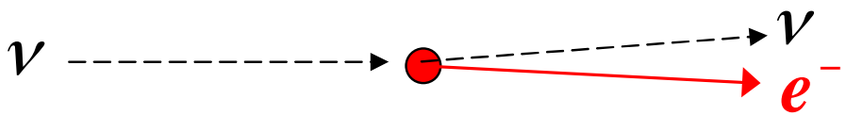
Neutrino Electron Scattering

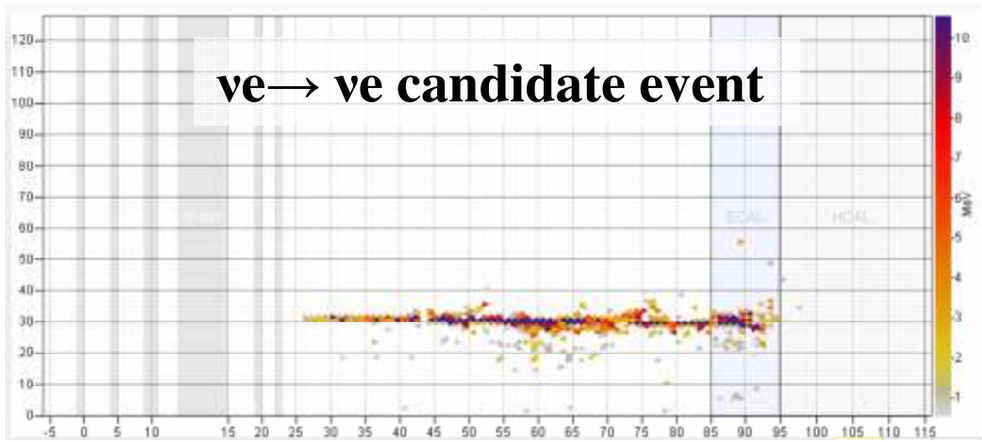
- Constrain flux with in-situ measurement: ν+e scattering
- Low energy results (121 ν+e events)



- Preliminary medium energy results







- Selected sample in medium energy 800 ν+e events
- In the process of finalizing systematics
- Flux constraint on going: changes flux uncertainty from 8% to 6% in the focusing peak
- Proof of principle for DUNE

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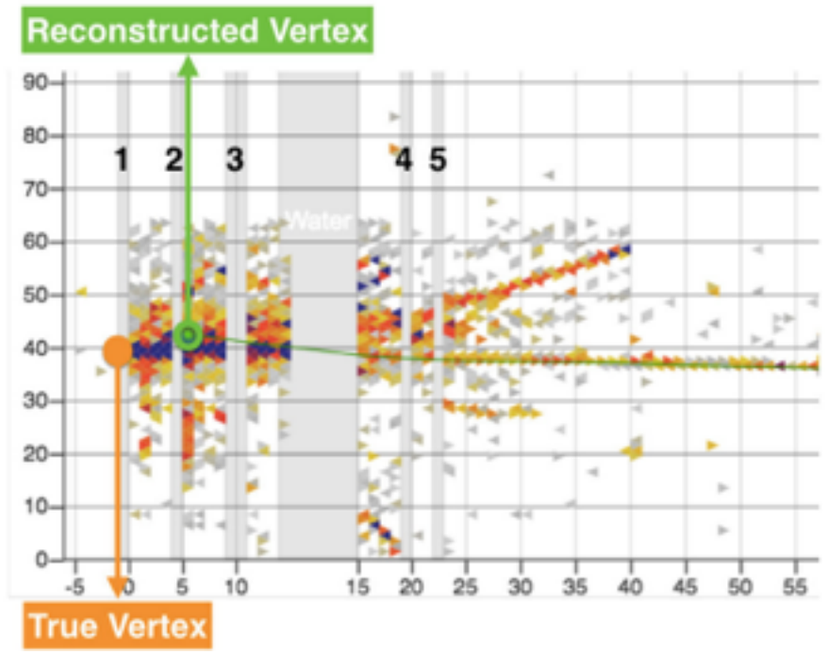
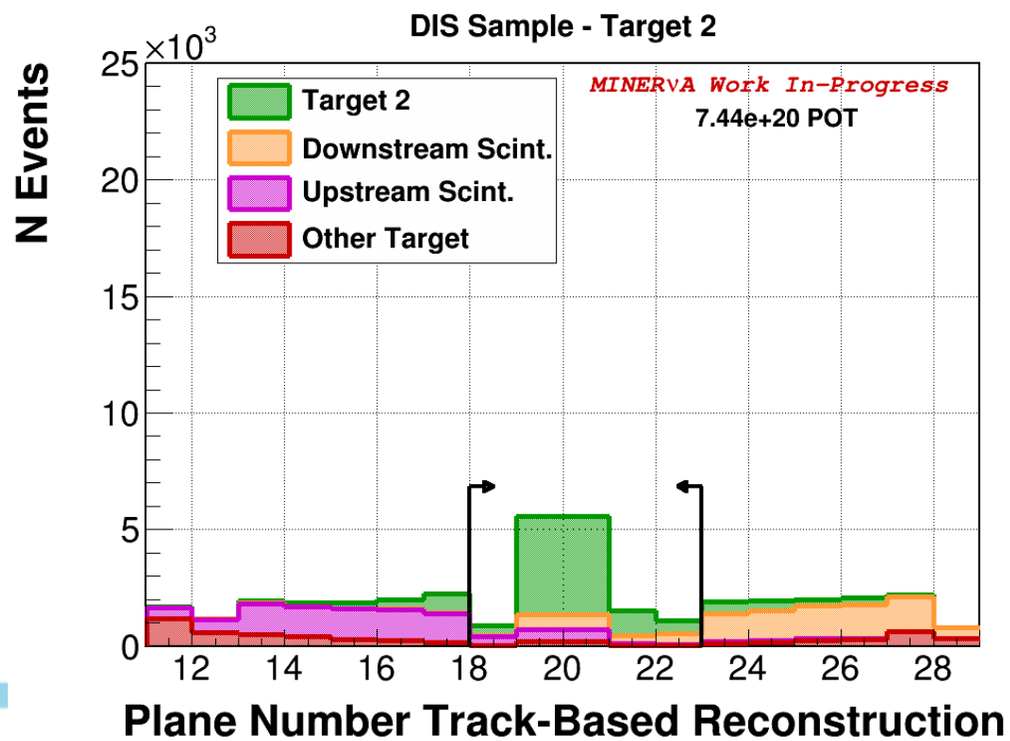
See Deepika Jena's Poster

Charged Current Deep Inelastic Scattering off Nuclear Targets

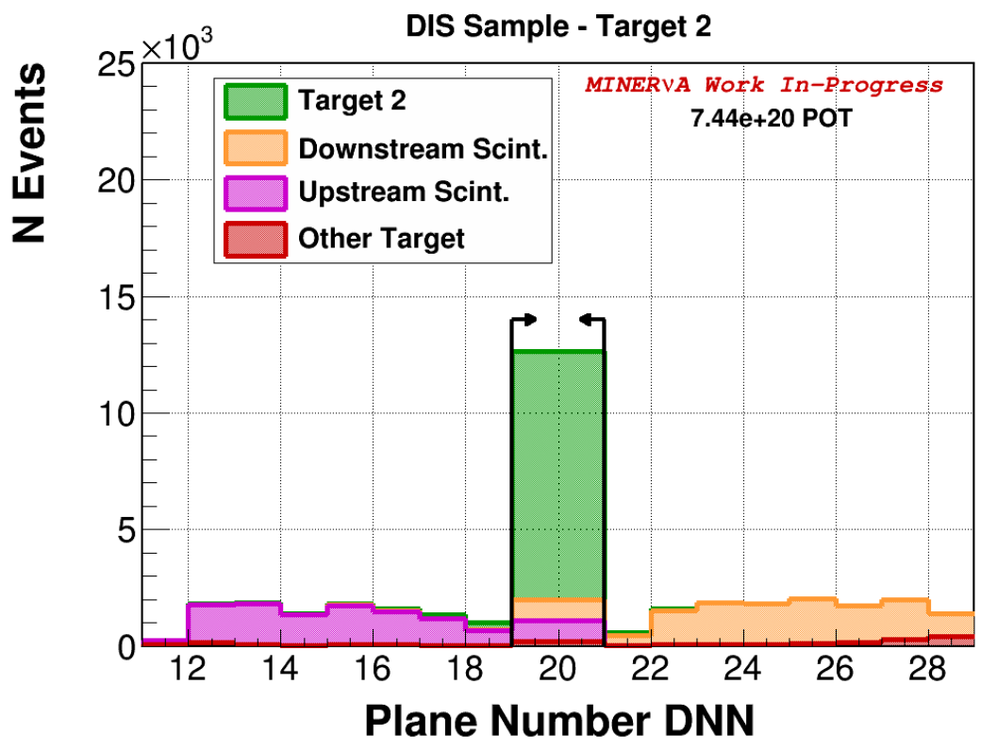
- New improvements to the reconstruction
  - Using a Deep Neural Network Machine Learning algorithm to identify the event vertex in the nuclear target, the efficiency was significantly improved, paper in preparation
- Stay tune for Deep Inelastic results!



Plane number for the Default Reconstruction



Plane number for the Deep Neural Network



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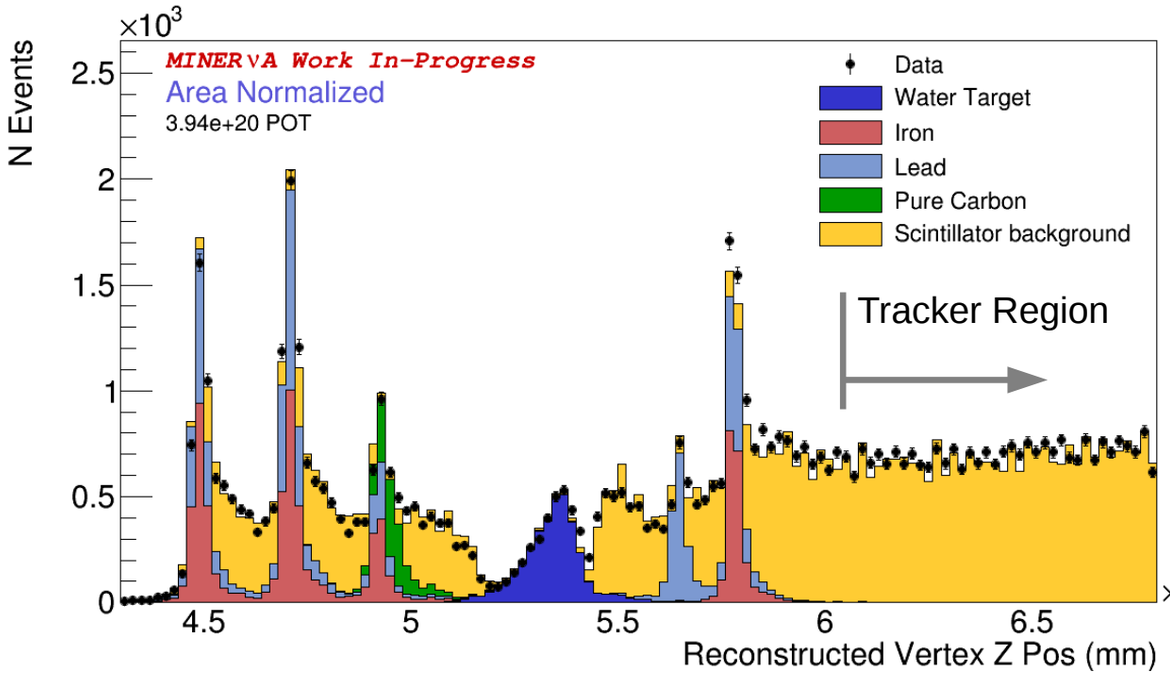
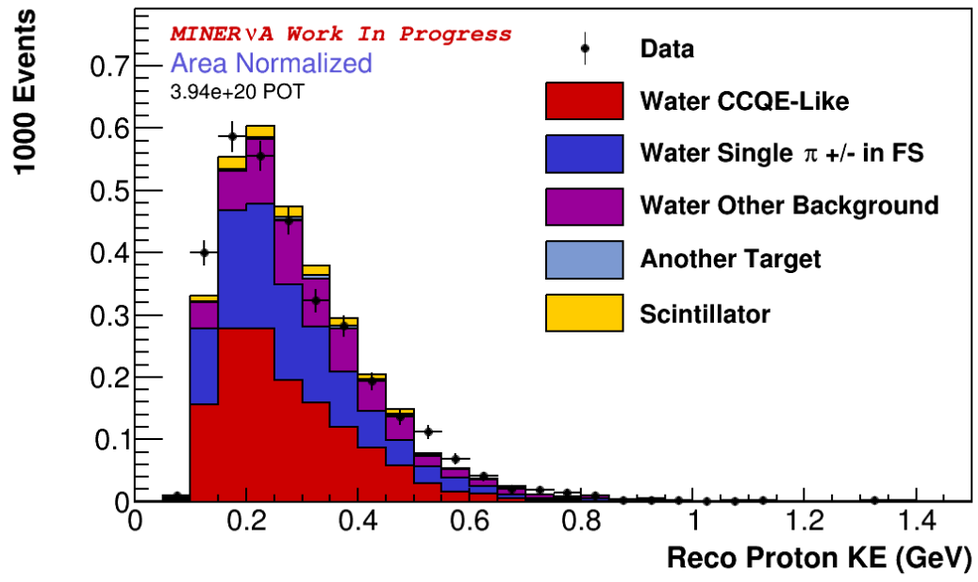
Charged Current Quasi Elastic Scattering off Nuclear Targets

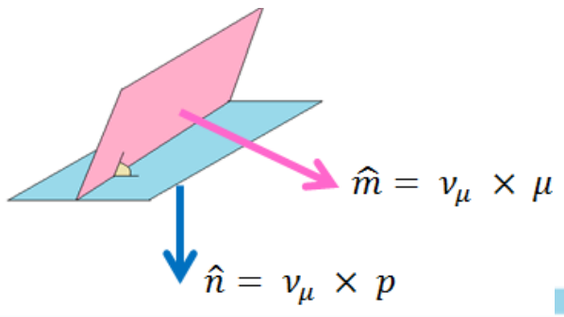
- Ongoing analysis of quasi-elastic like interactions, events with both 1 and 2 track are measured
- High statistics sample to study QE on carbon, iron, lead and water



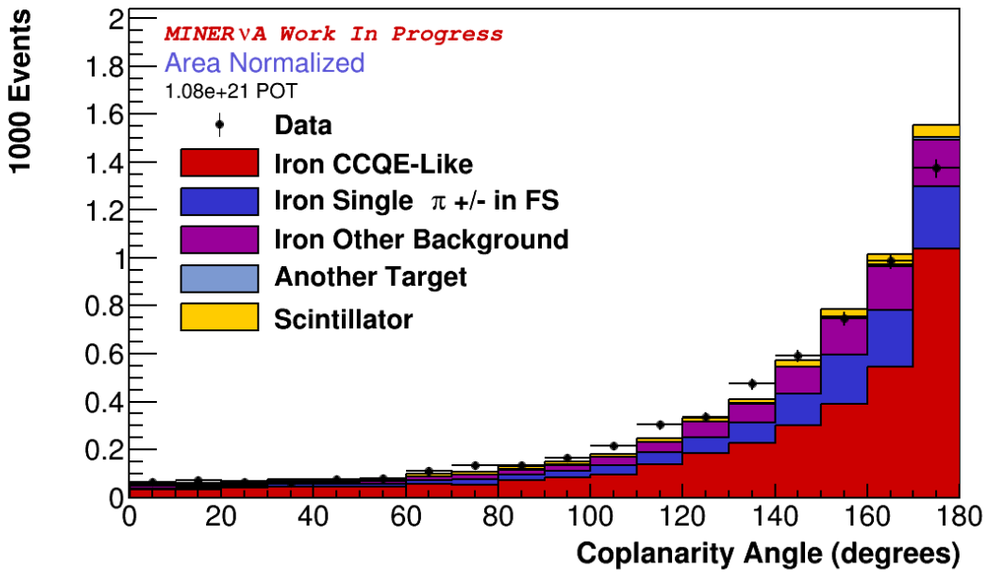
Proton kinetic energy in the water target



- Rich sample to study nuclear effects
  - Example: final state interactions



Coplanarity angle in the Iron target



See Jeffrey Kleykamp's Poster

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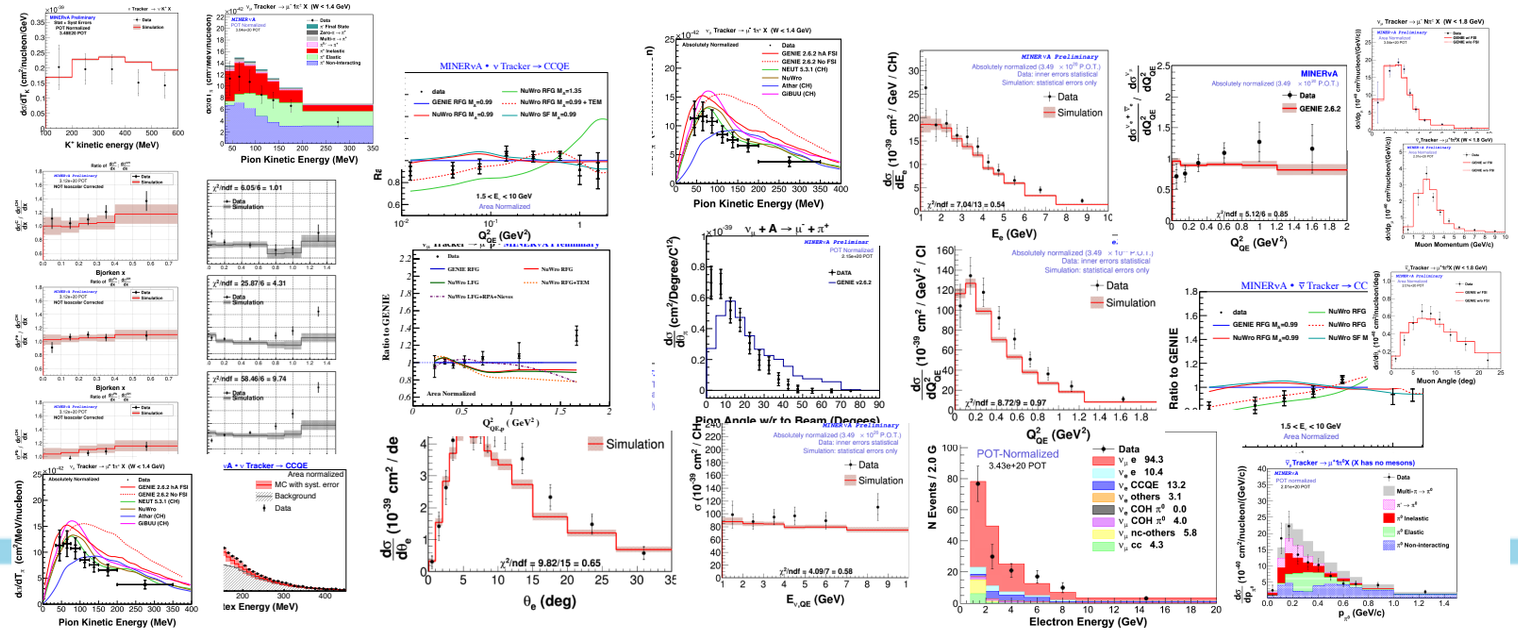
Summary

- MINERvA has made excellent progress this past year, reported new measurements
  - Charged current pion production
  - Double differential cross section for Quasi-elastic interactions for neutrinos and antineutrino
  - Double differential cross section for charged current antineutrinos
  - New CCQE measurements to probe initial and final state nuclear effects
- MINERvA is preparing many new analyses with the medium energy data set
  - We are grateful to Fermilab's Accelerator Division for getting us 3/4 of the way done with Antineutrino Run!
- Oscillation experiments depend on modeling nuclear effects correctly for precision oscillation measurements!



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Thank you

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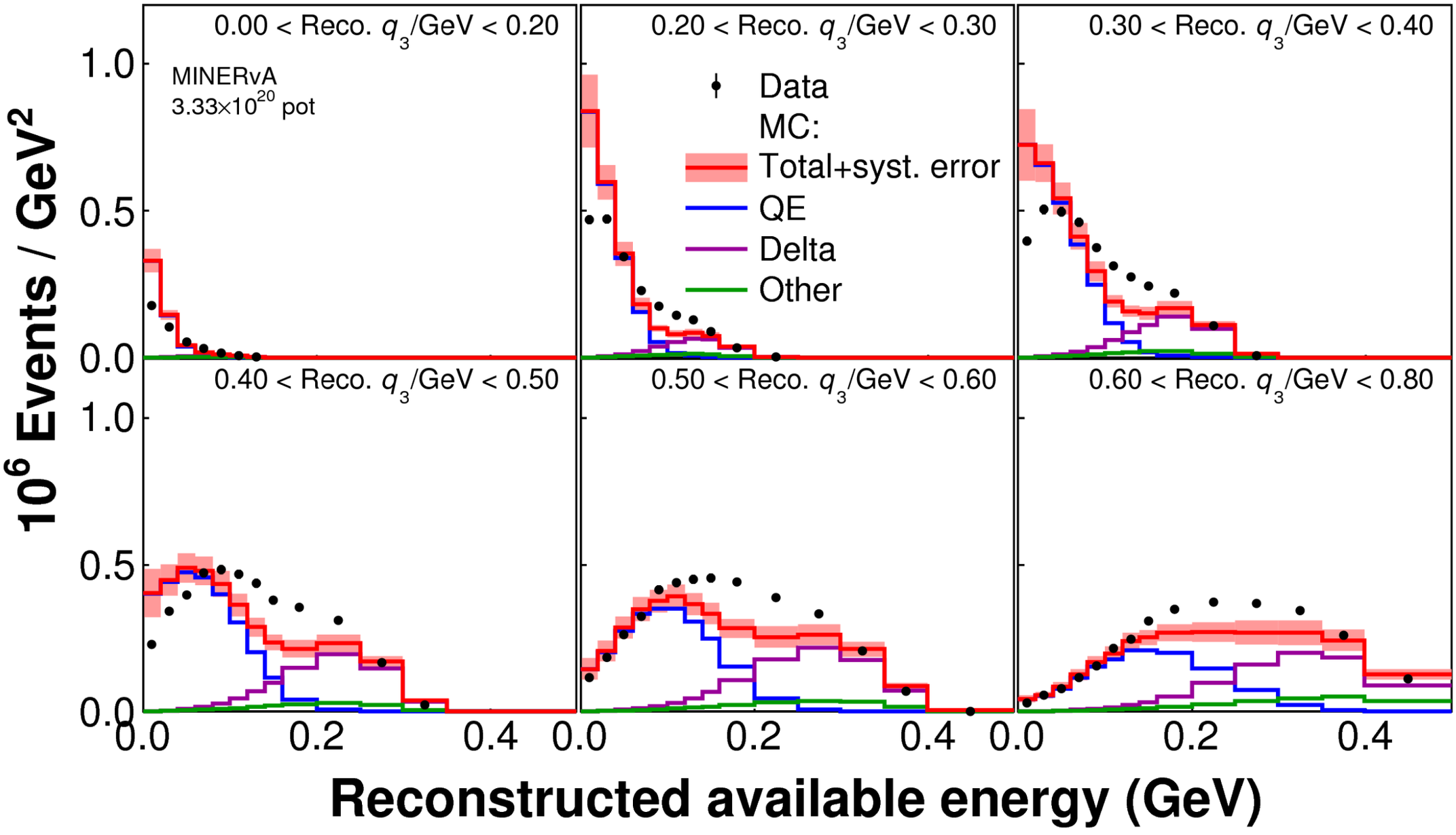
Backup Slides

Selected Events

- Inclusive charged current selected events



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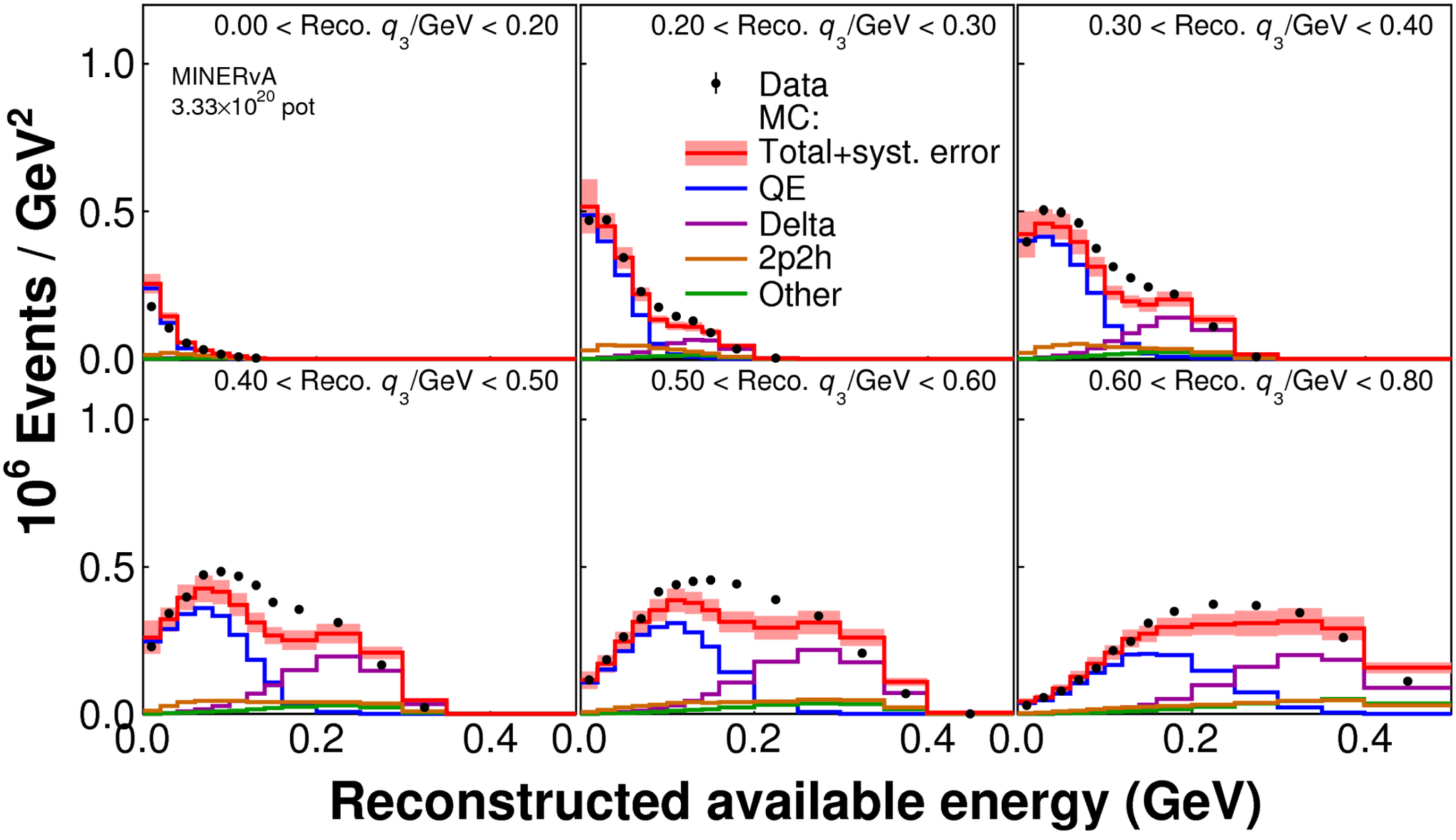
Selected Events

- Inclusive charged current selected events
- Includes pion weights, RPA and MEC



- Adding in models of RPA (a charge screening effect) and multi nucleon (2p2h) improves agreement in some regions, but not in others

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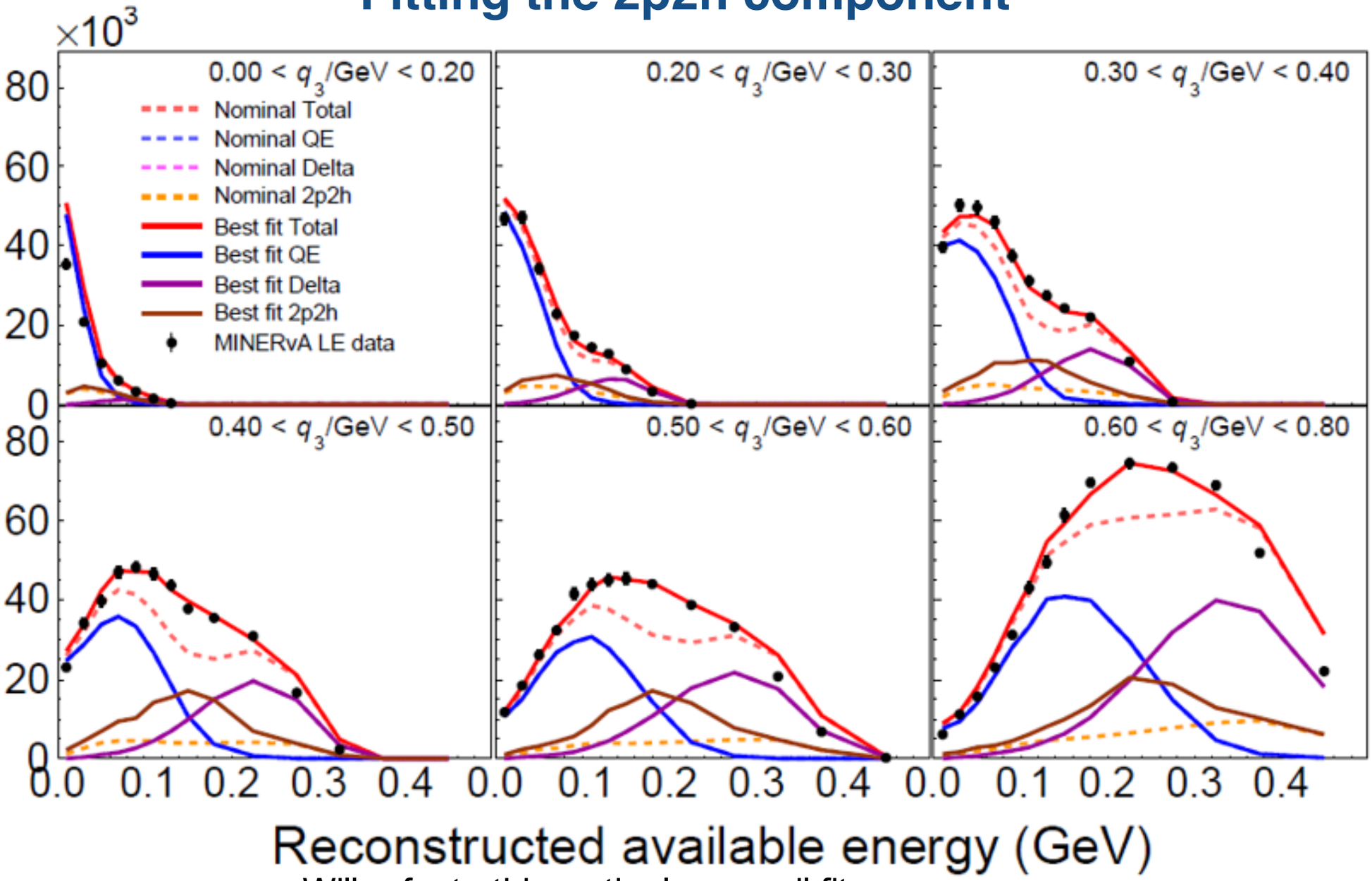
Selected Events

- Inclusive charged current selected events

Fitting the 2p2h component



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

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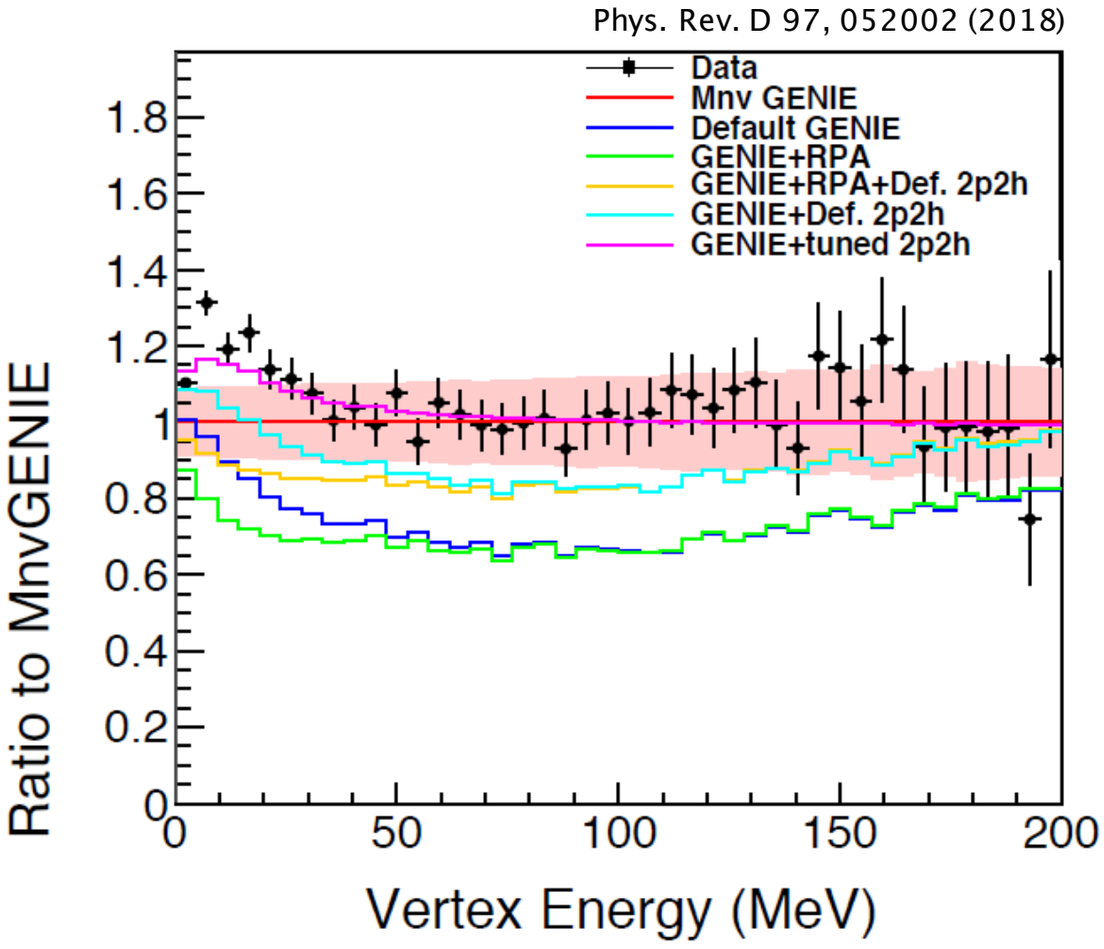
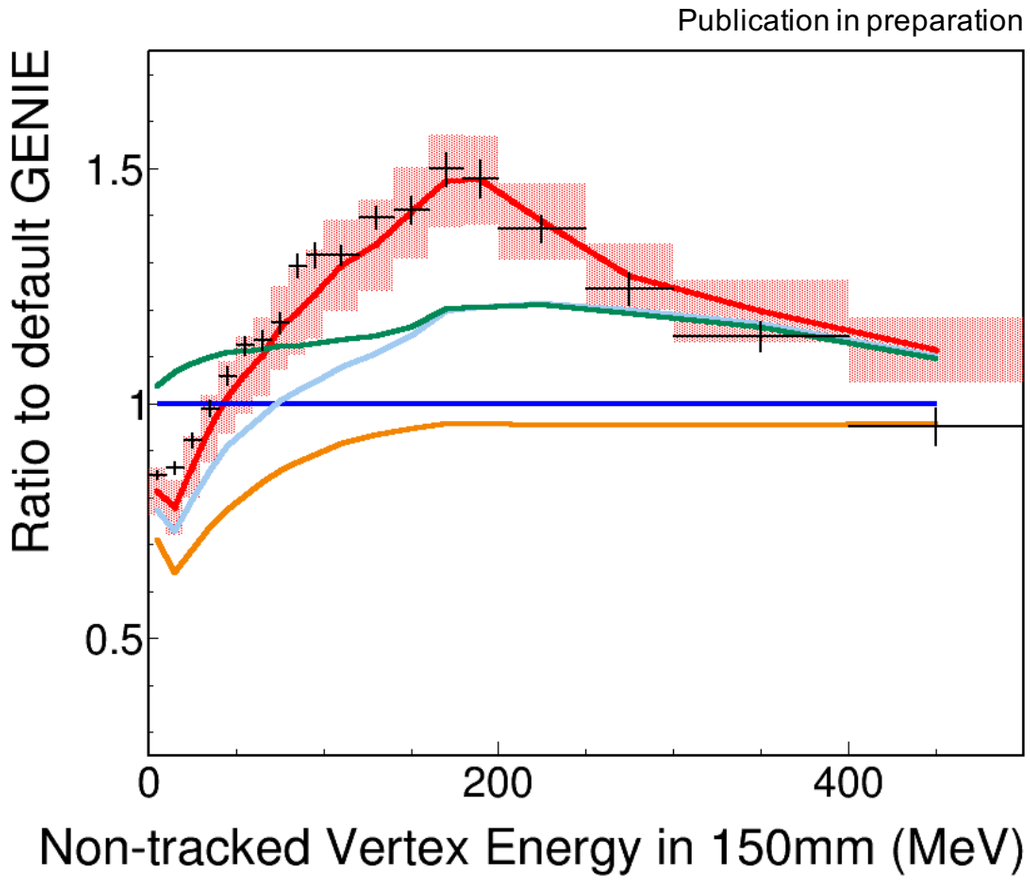
Vertex Energy in QE-Like results



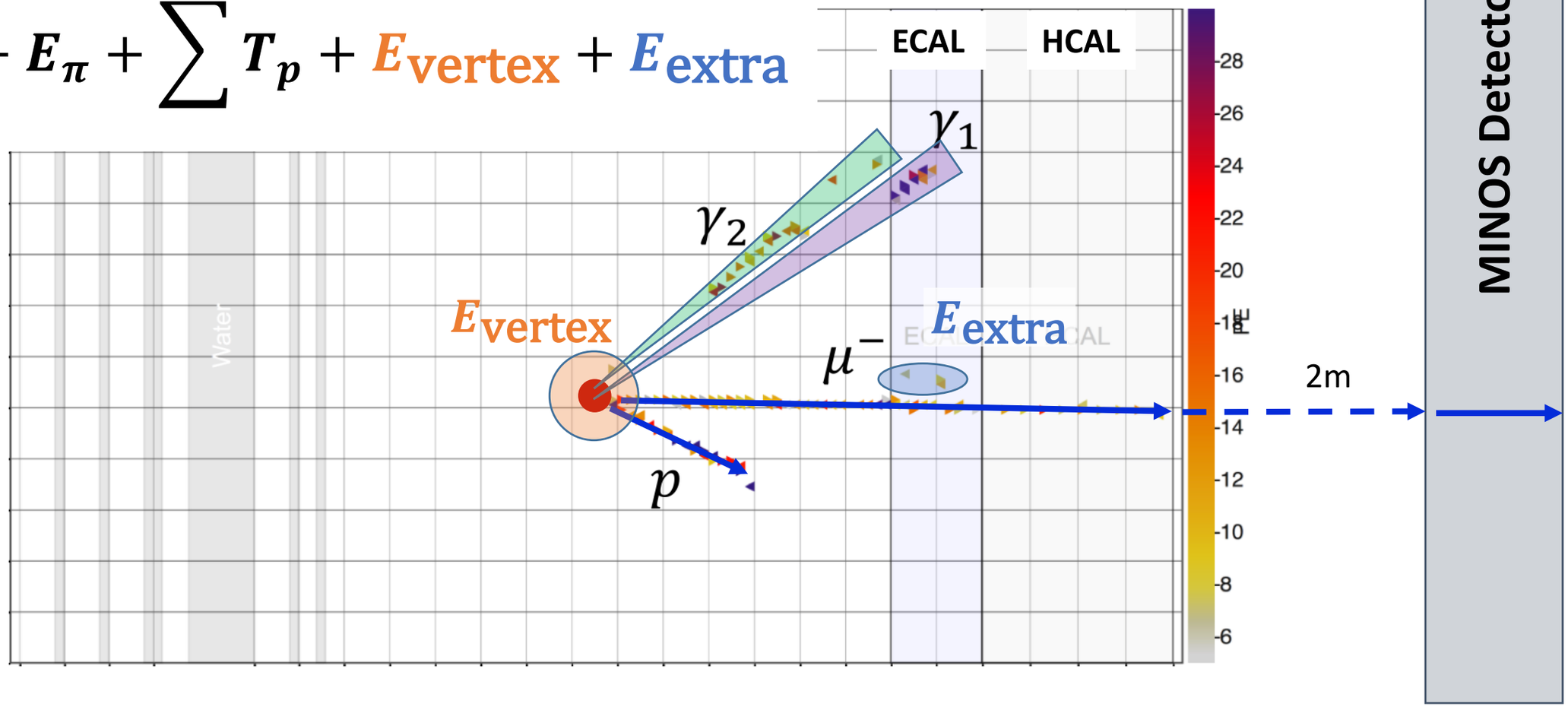


- The tune seems to enhance the events in the regions of vertex energy the data prefer!

Measurement of νμ-CC(π^0)

5. **Estimate Neutrino Energy using all final state particles + vertex & extra energy**

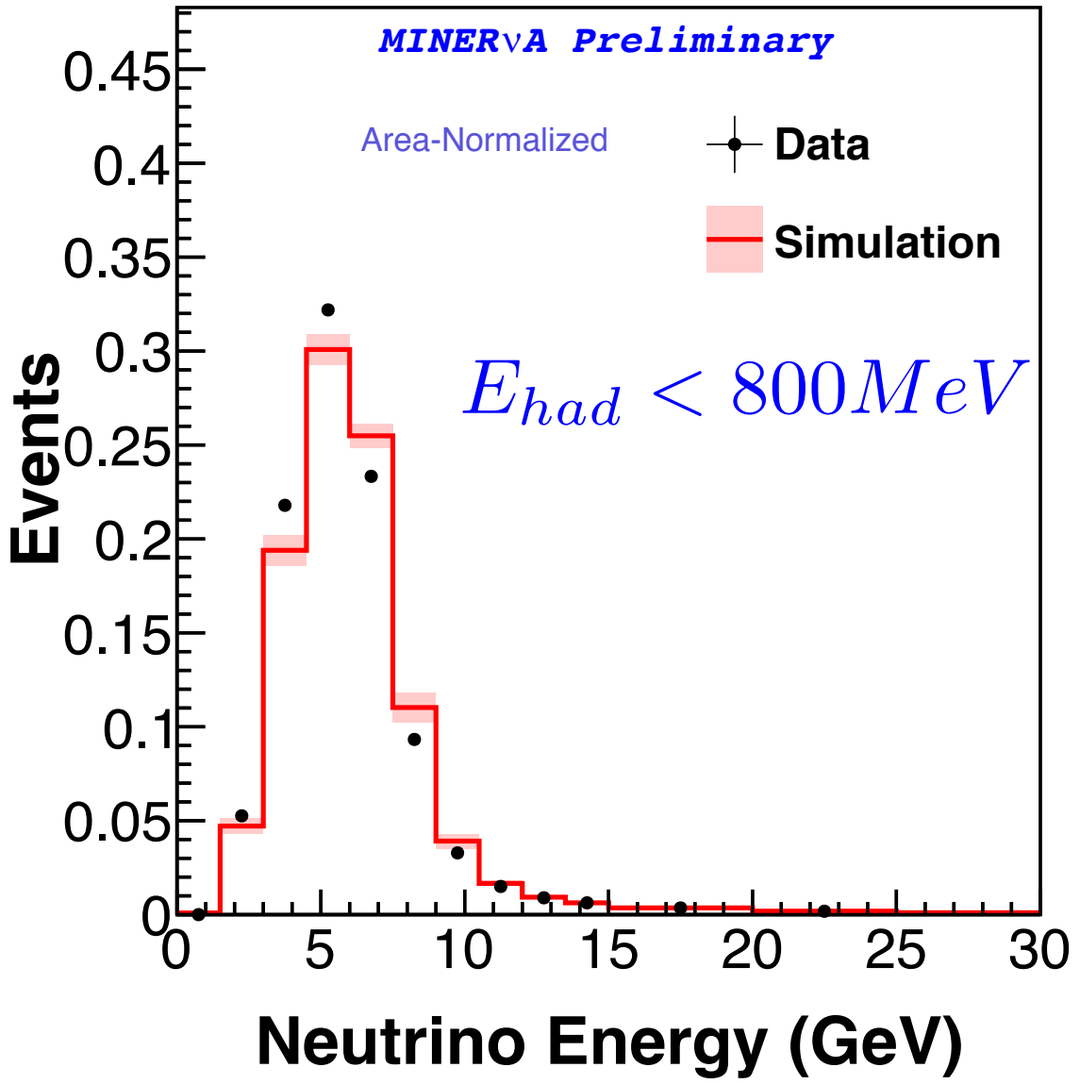
$$E_\nu = E_\mu + E_\pi + \sum T_p + E_{\text{vertex}} + E_{\text{extra}}$$



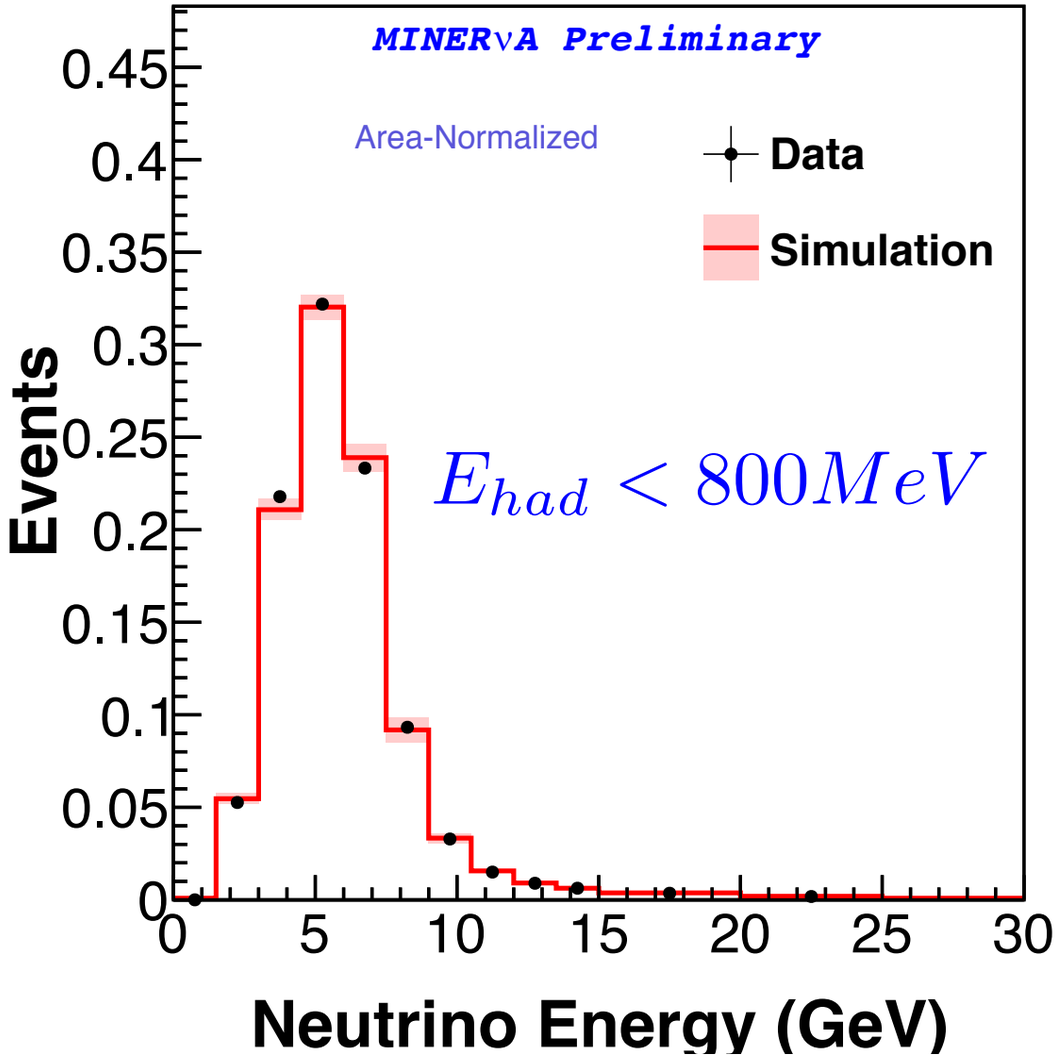
Flux in the Medium Energy

- Some disagreements between the data and MC

Nominal



After the fits



- Fitting the low ν MC against the data with focusing parameters as fit parameters. The weight function produced by the fit is used to solve the data/mc discrepancy