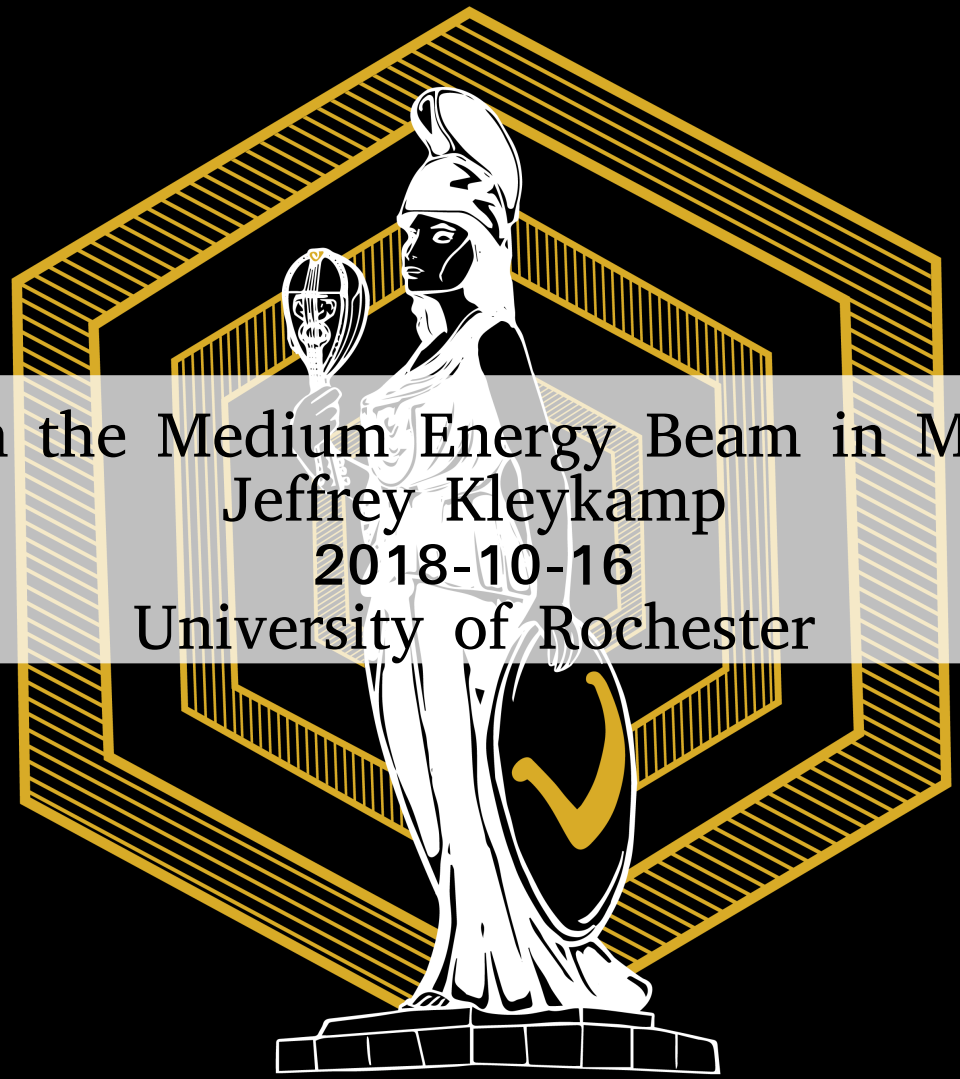


CC0Pi in the Medium Energy Beam in MINERvA

Jeffrey Kleykamp

2018-10-16

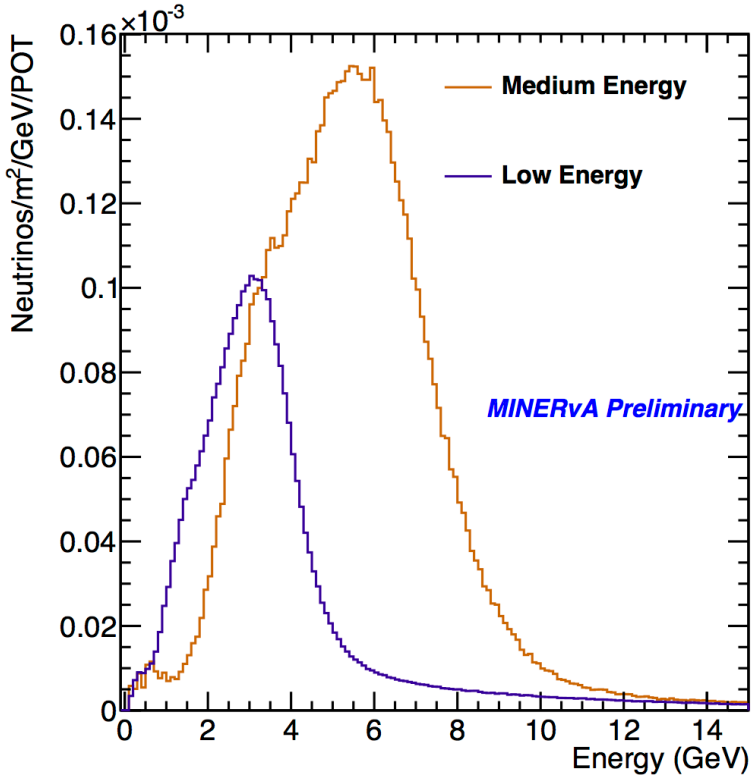
University of Rochester

What is CCQE-like (CC0Pi)

- CCQE events are some of the most basic neutrino-nucleus interactions
  - Billiard ball physics
- Simulates CCQE events but based only on final state particles
  - Reduces model dependence
- 1 muon, zero pions, and any number of nucleons
- Includes events where the pion is absorbed in the nucleus

CCQE-like in Medium Energy?

- Already released low energy beam results
- Medium Energy beam results
- Larger kinematic range than our low energy beam
  - More resonant events with pion absorption
- More statistics in regions already explored



Explanation of Signal Definition

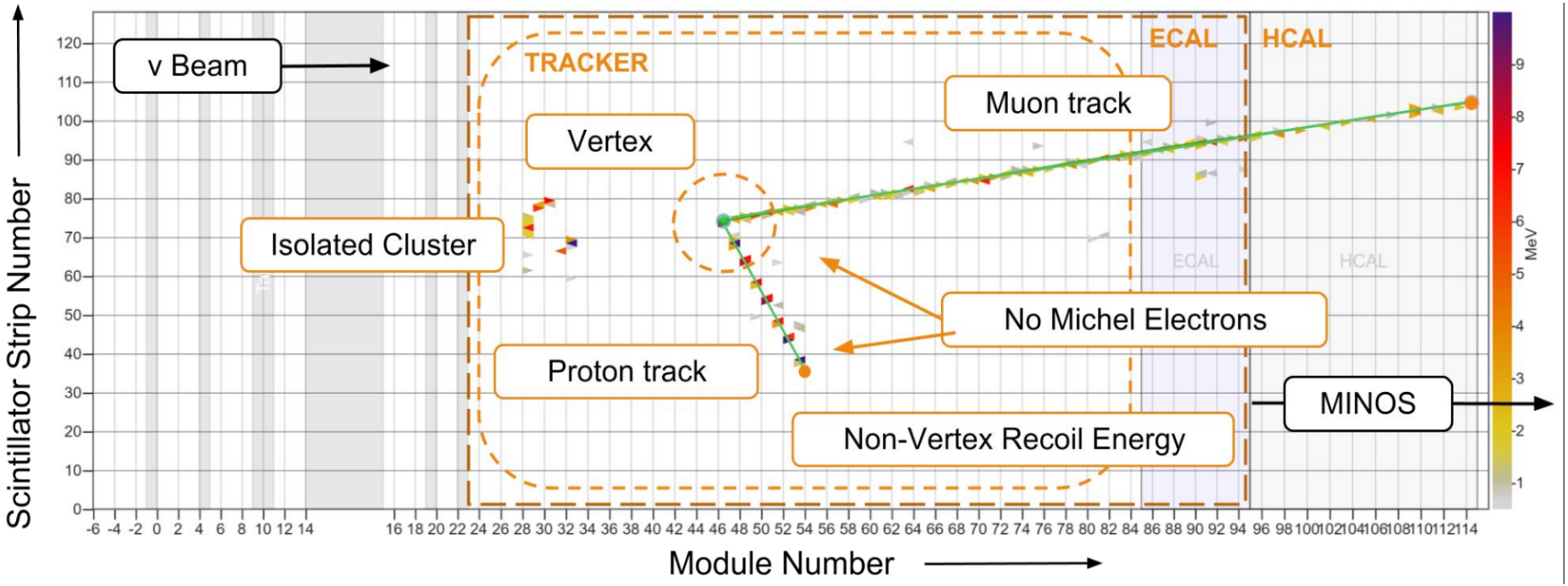
- CCQE-like signal is defined by
  - Final state particles
  - Kinematics of the final state particles
  - Everything else is background
- We use a sideband tuned version of the background to subtract from the selected events
- Use signal events in our unfolding and efficiency correction
- Careful definition of signal makes model comparisons easier

Signal Definition

- CCQE-like (CC0Pi)
- Defined based on outgoing particles only

- Final state:
  Muon + any number of nucleons.
  No mesons (pions)
  No heavy baryons, or photons > 10 MeV

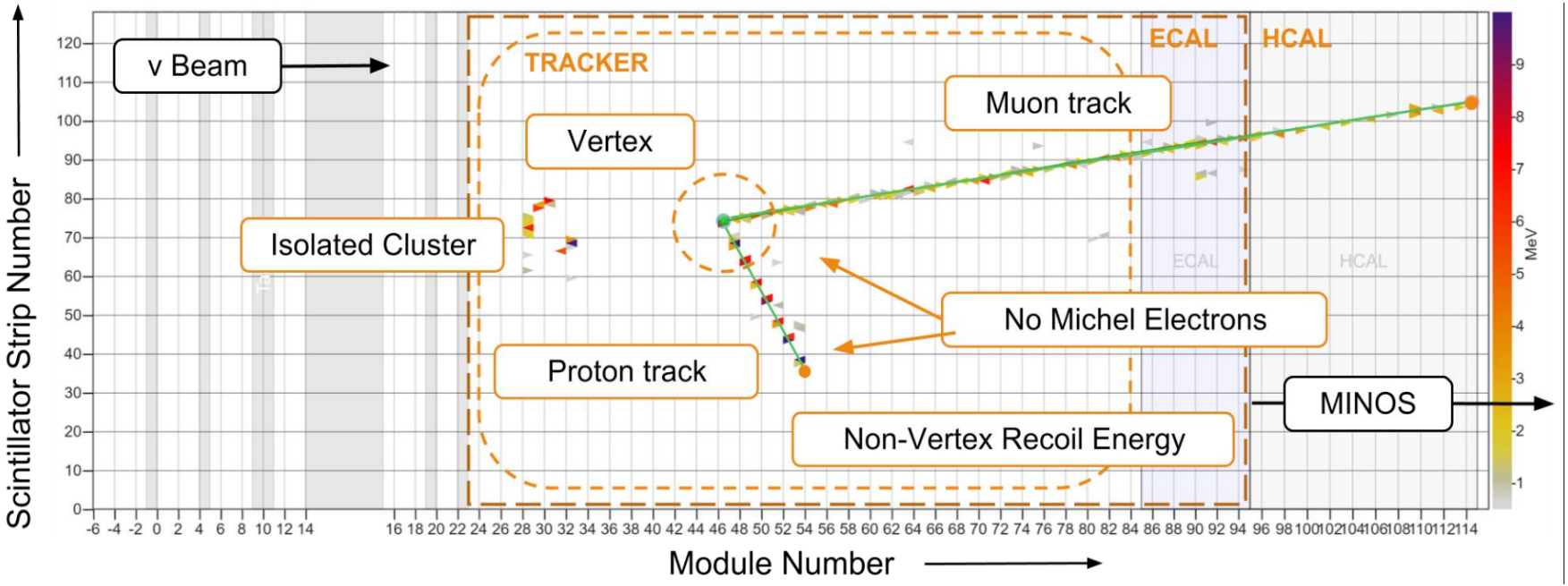
Reconstructed Sample Selection



- Muon Reconstructed in Minos
  - For energy reconstruction
- Reconstructed Muon Angle < 20 Degrees

- Proton dE/dX PID
- No Michel Electrons
- N Isolated Energy Clusters < 2
- Non-Vertex Recoil Energy < 500 MeV

Reconstructed Sample Selection



- Muon Reconstructed in Minos
  - For energy reconstruction
- **Reconstructed Muon Angle < 20 Degrees**

- Proton dE/dX PID
- No Michel Electrons
- N Isolated Energy Clusters < 2
- Non-Vertex Recoil Energy < 500 MeV

Signal Definition

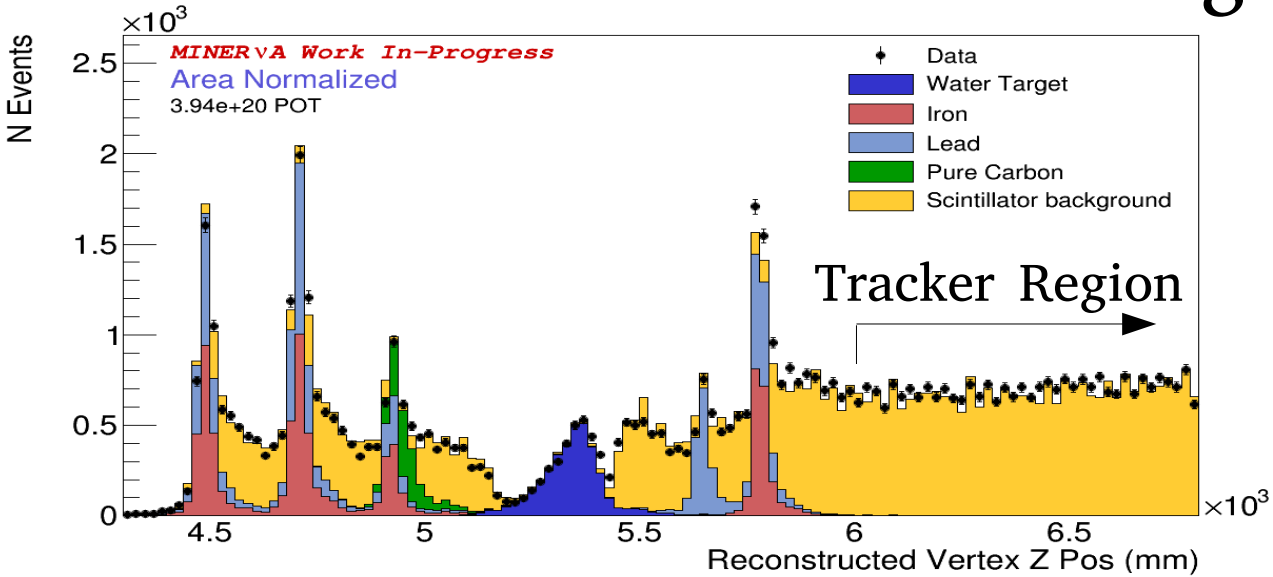
- CCQE-like (CC0Pi)
- Defined based on outgoing particles only

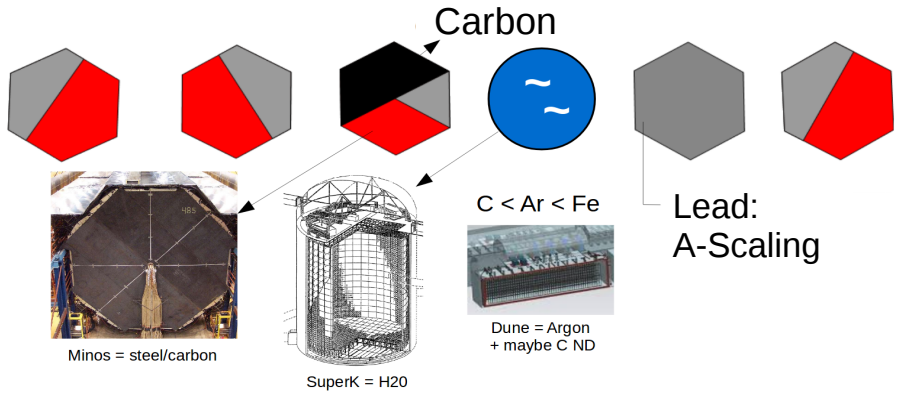
- Final state:
  Muon + any number of nucleons.
  No mesons (pions)
  No heavy baryons, or photons > 10 MeV

  Muon Angle < 20 Degrees

What about Minerva's Nuclear Targets?

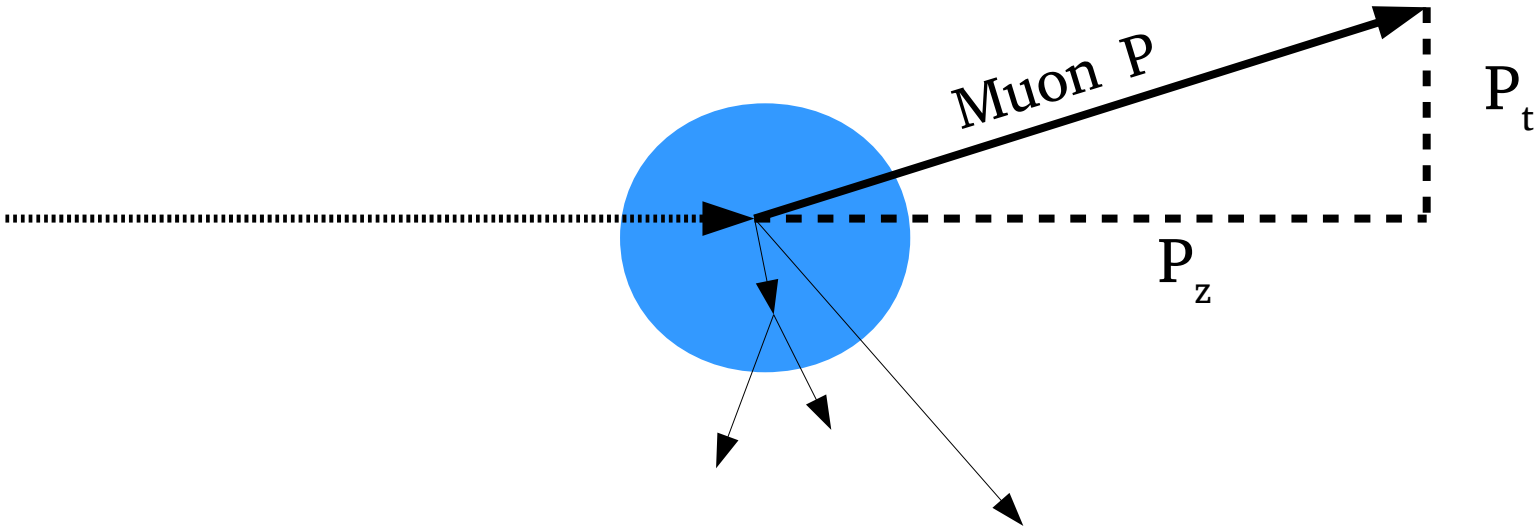
Neutrino Beam





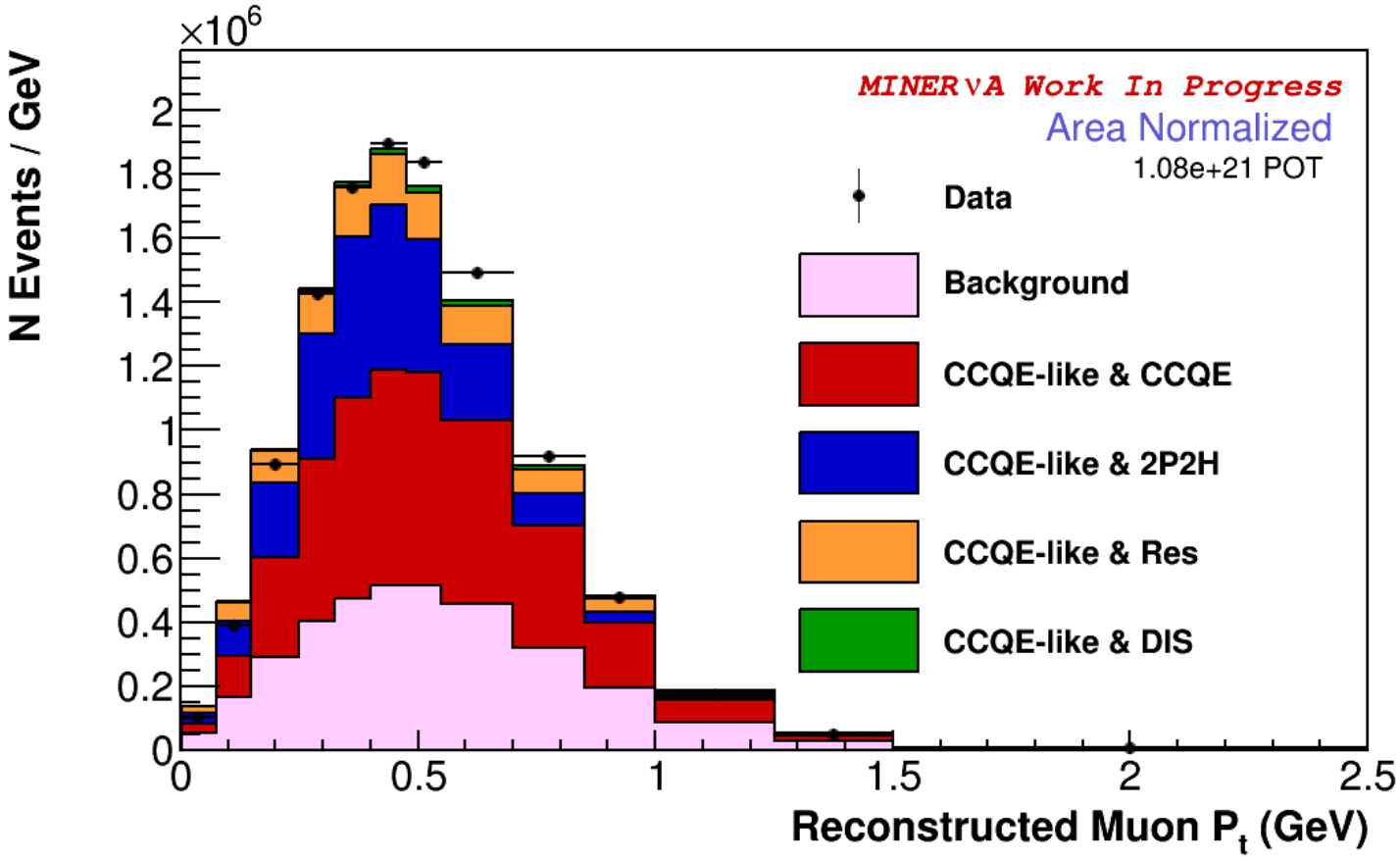
What are we measuring

- Working on a number of medium energy CCQE-like results
- Today: Muon Pt in the nuclear targets



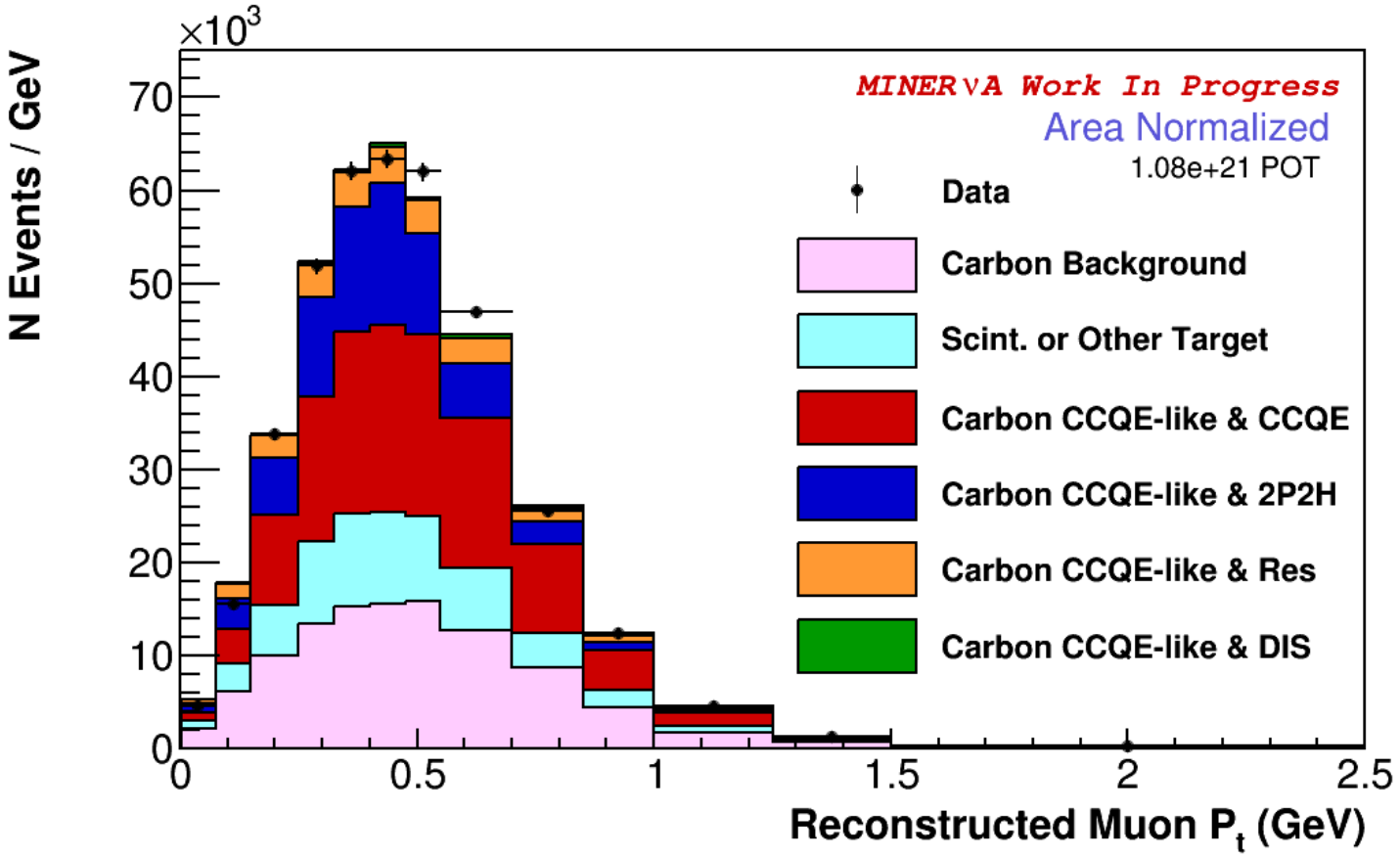
Tracker

1.1 million events



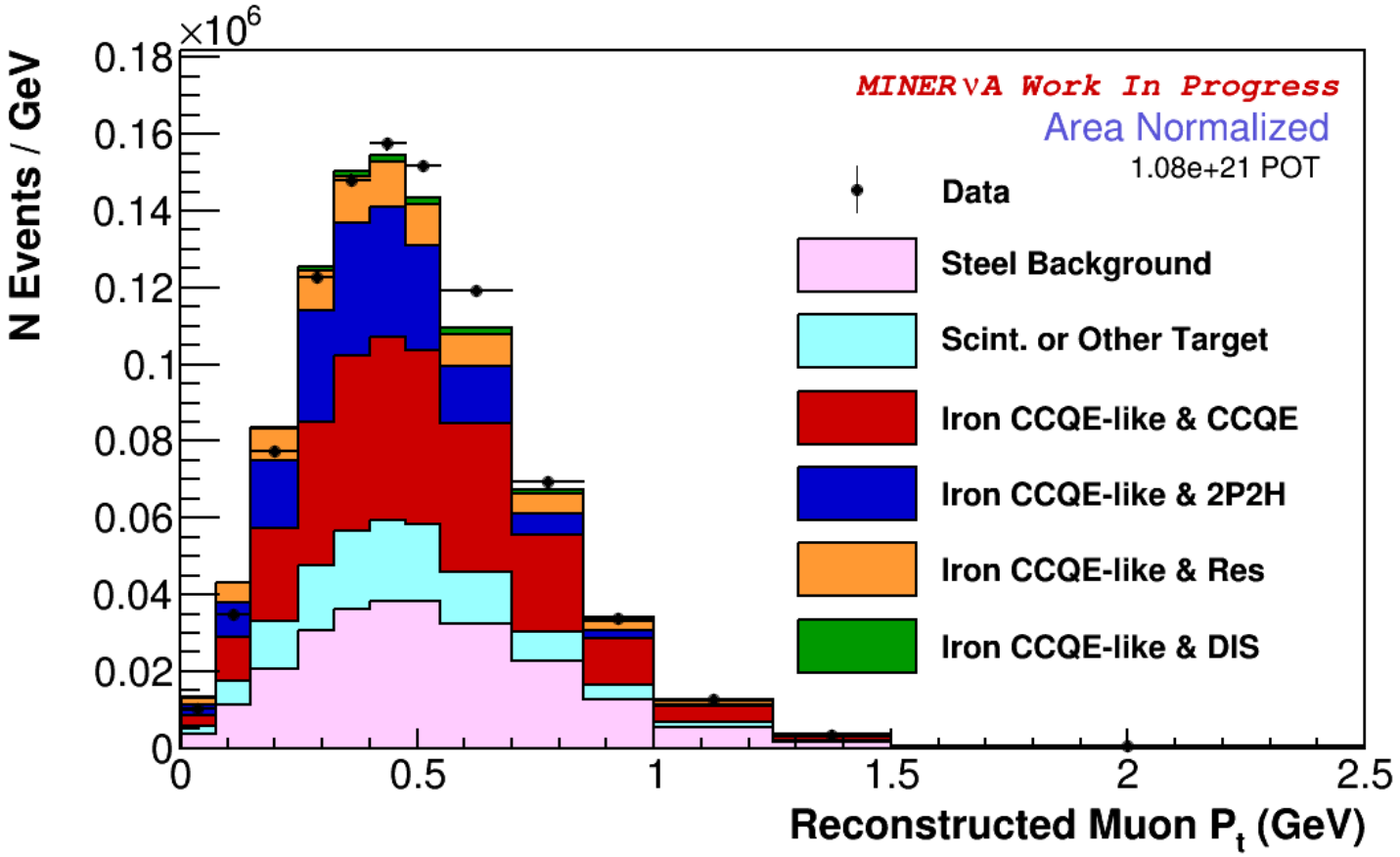
Carbon

37k events



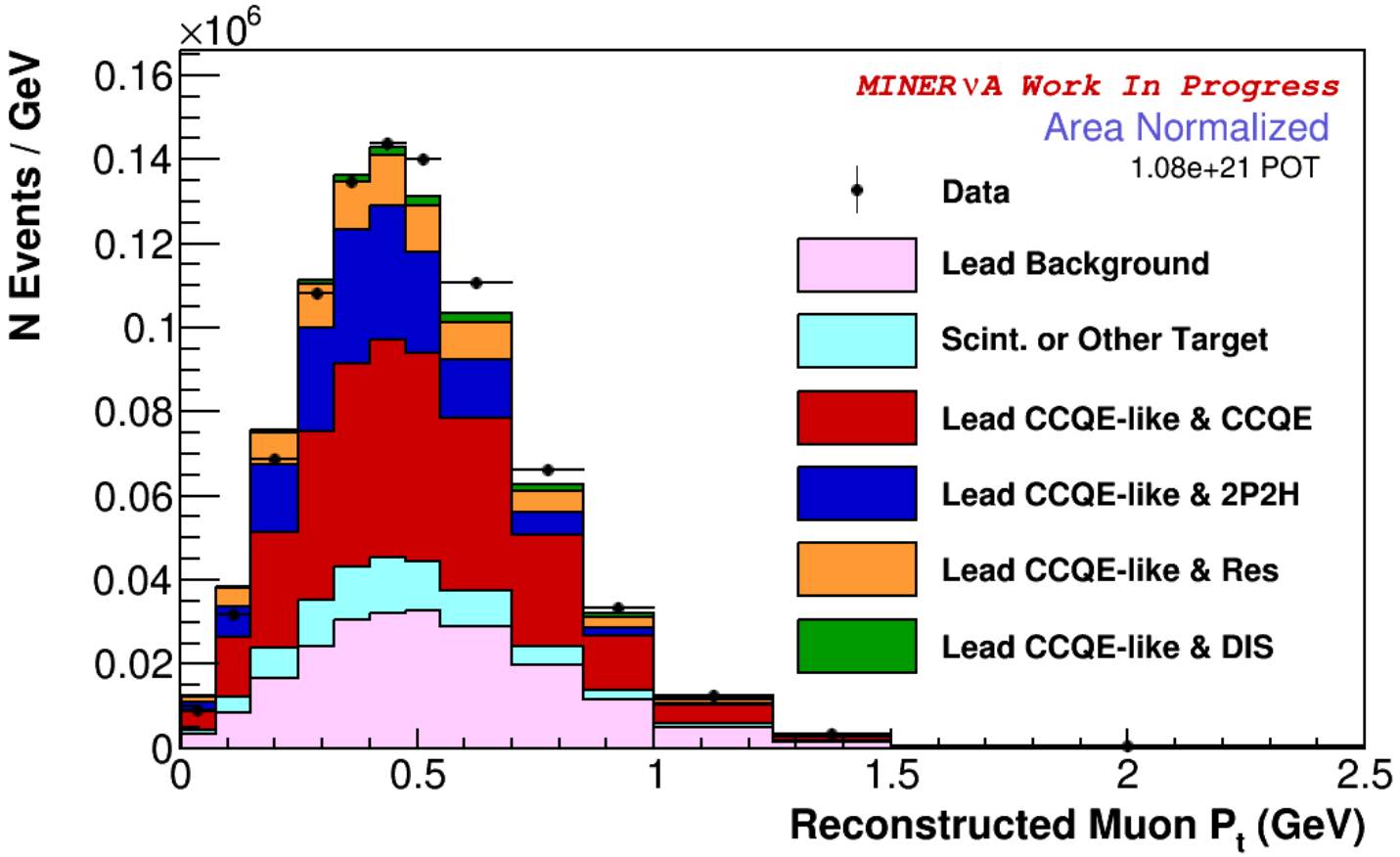
Iron

210k events

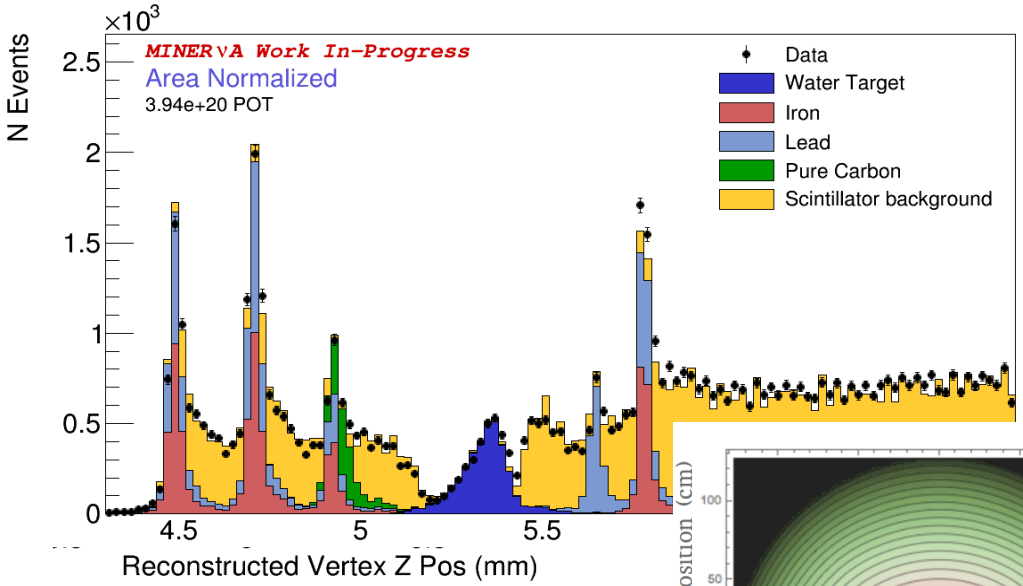


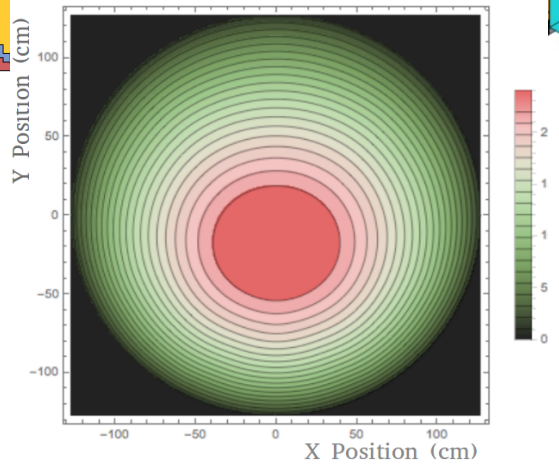
Lead

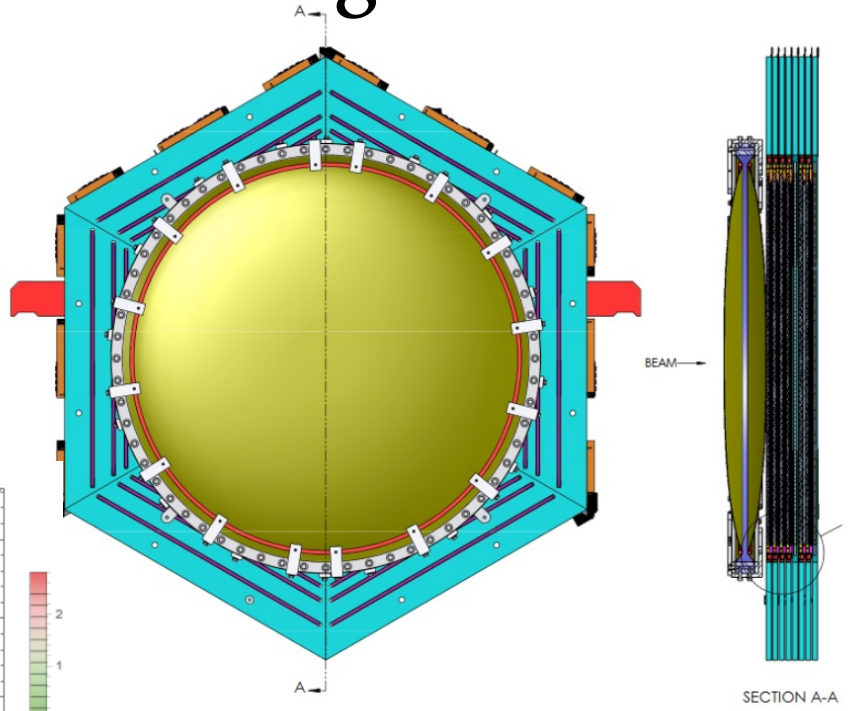
180k events



What about the Water Target?



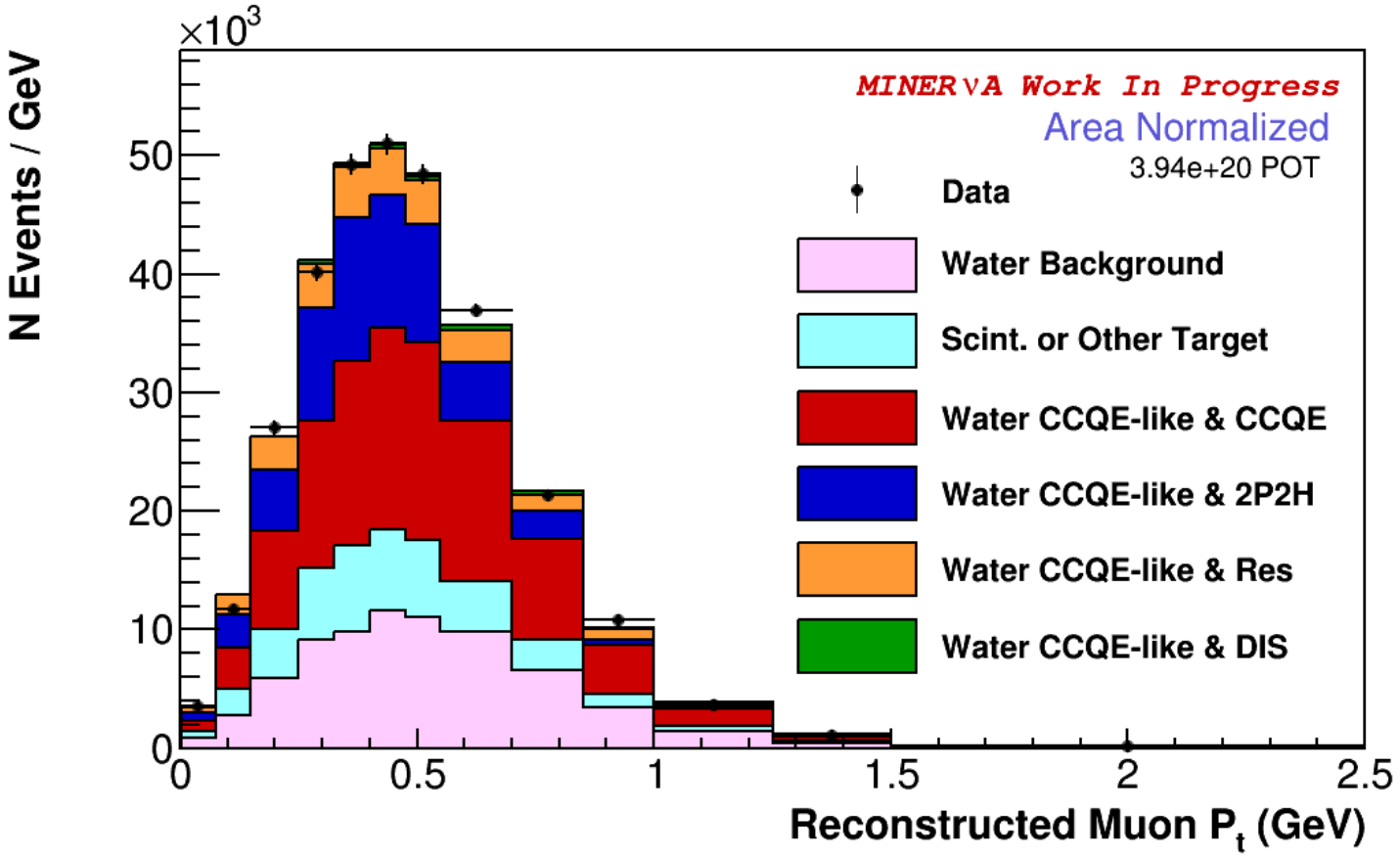




Simulation of water target

Water

29k events



Ingredients to Cross Section

- Event Rate

$$(\frac{d\sigma}{dX})_i = \frac{1}{T_n \Phi} \frac{1}{\Delta X_i} \frac{\sum_j U_{ij}(N_j^{data} - N_j^{bkg})}{\epsilon_i}$$

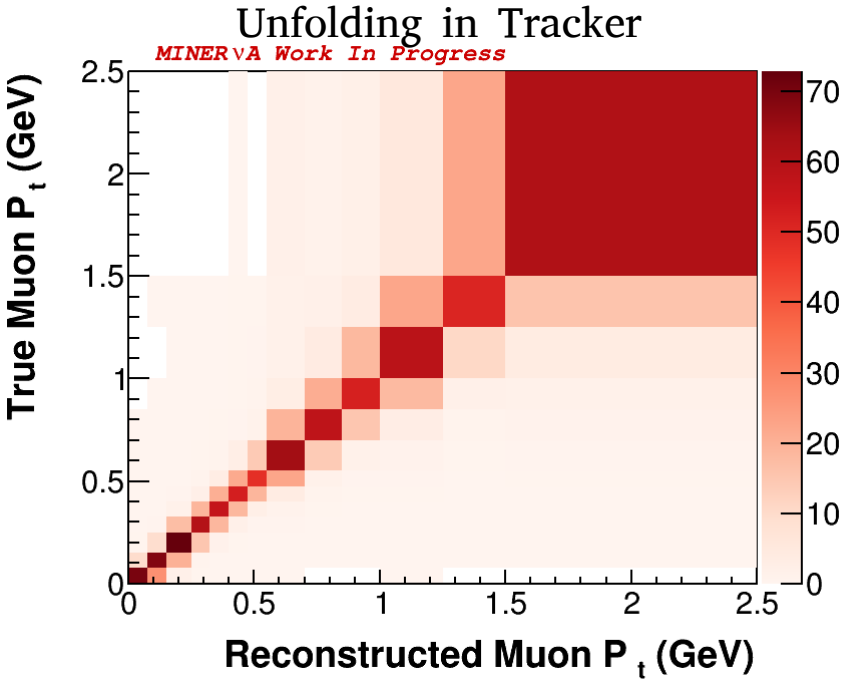
Ingredients to Cross Section

- Event Rate
- Sideband-Constrained Background

$$(\frac{d\sigma}{dX})_i = \frac{1}{T_n \Phi} \frac{1}{\Delta X_i} \frac{\sum_j U_{ij}(N_j^{data} - N_j^{bkg})}{\epsilon_i}$$

Ingredients to Cross Section

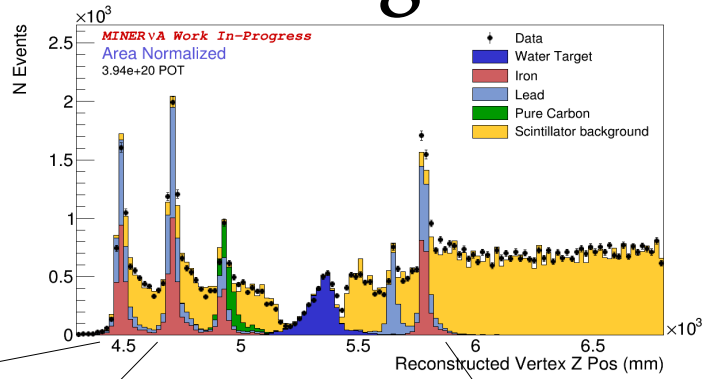
- Event Rate
- Sideband-Constrained Background
- Unfolding Matrix

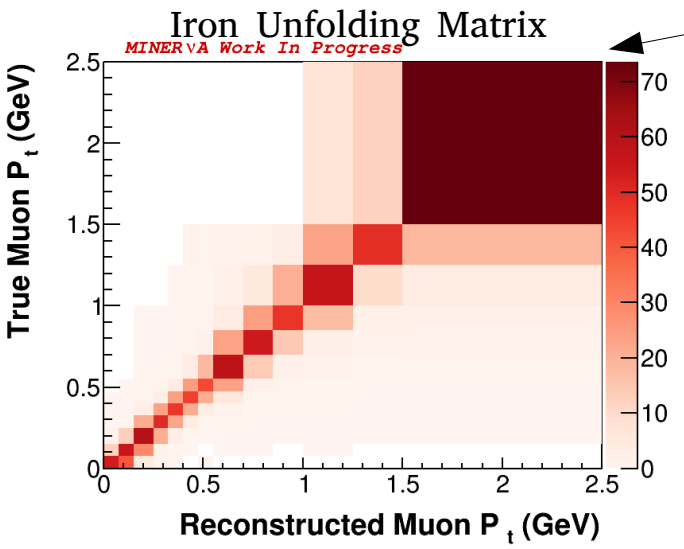


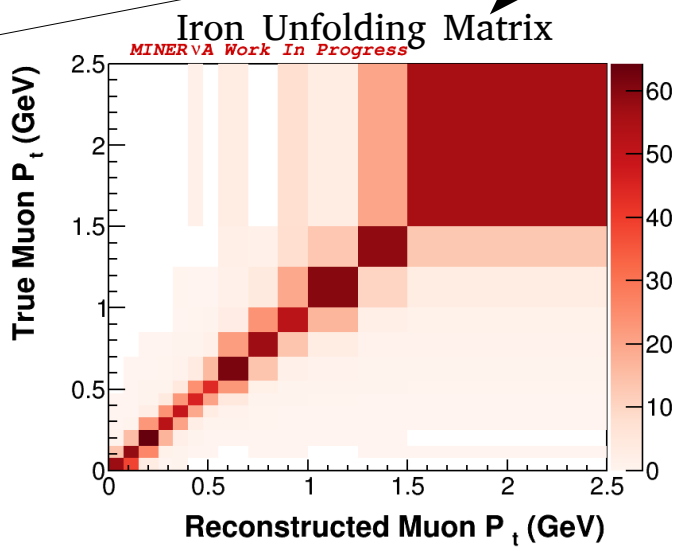
$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi}\frac{1}{\Delta X_i}\frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

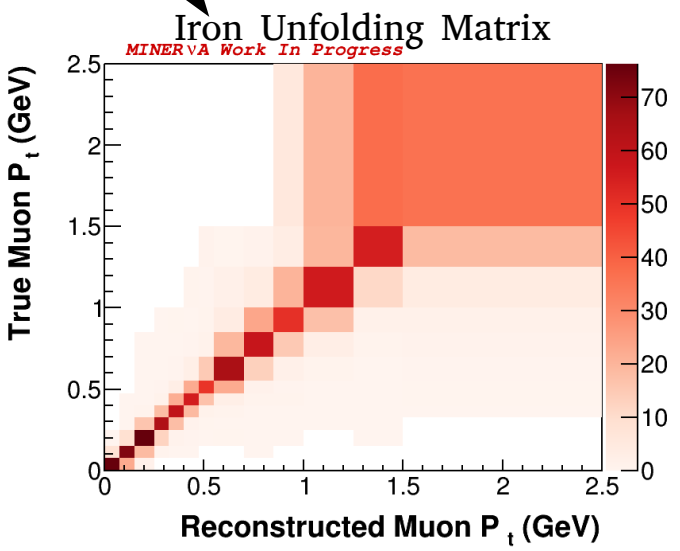
Unfolding in Nuclear Targets

- Unfolding is done per-target



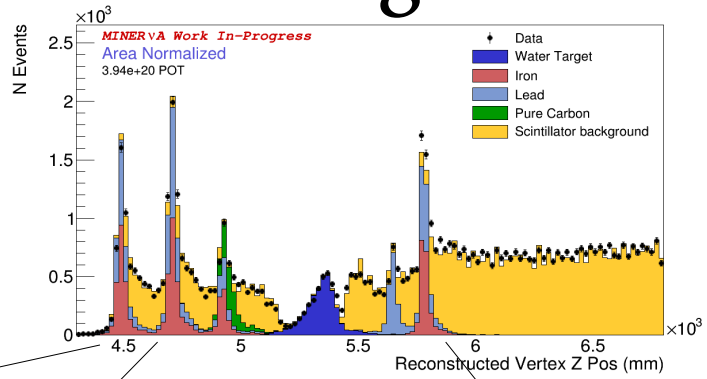


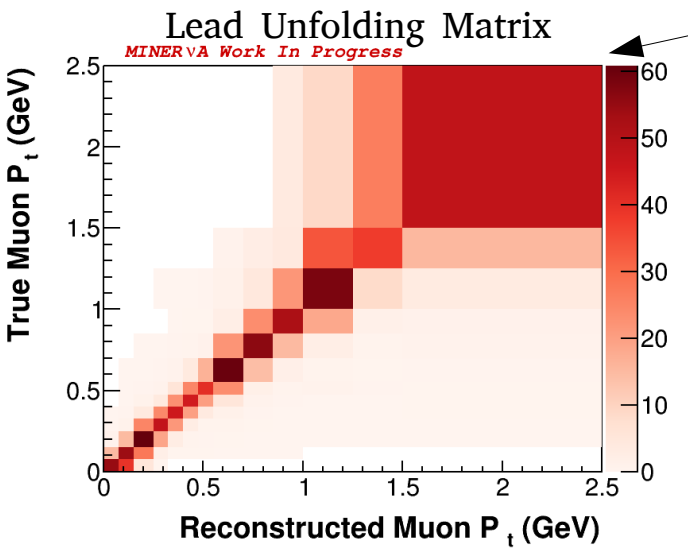


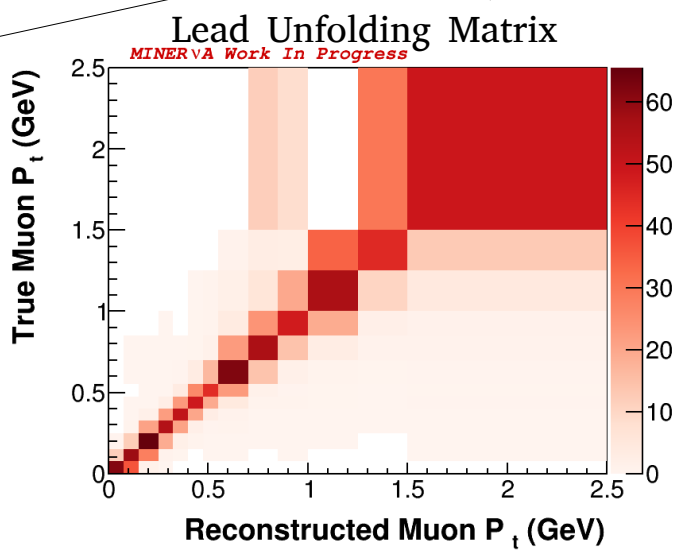


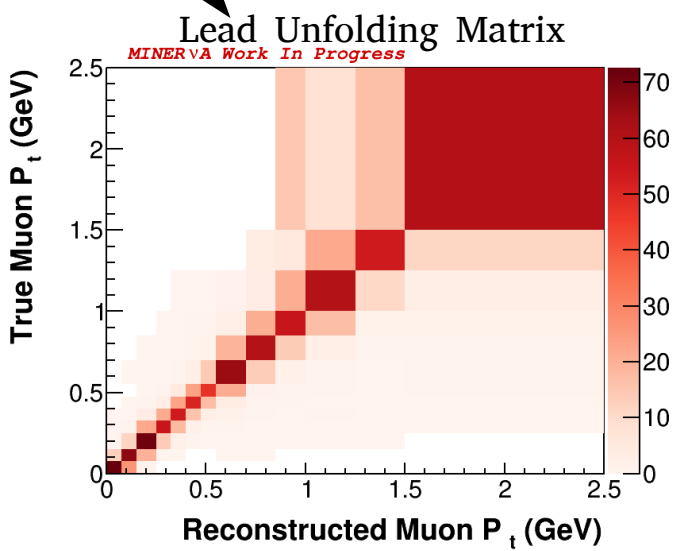
Unfolding in Nuclear Targets

- Unfolding is done per-target



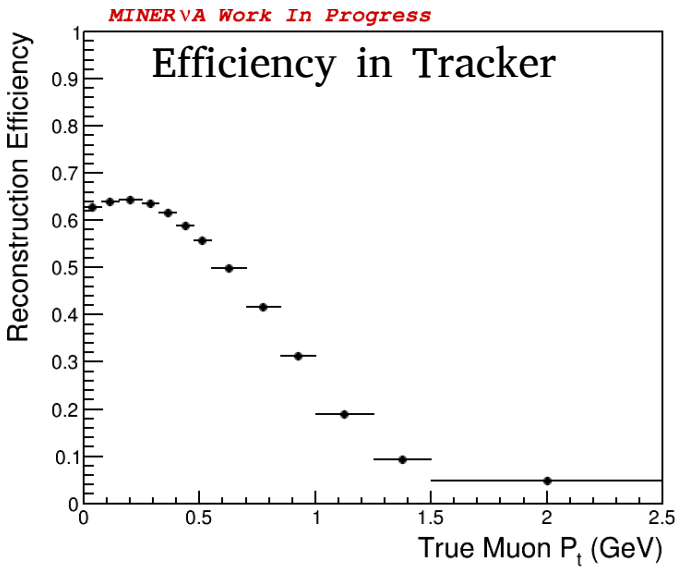






Ingredients to Cross Section

- Event Rate
- Sideband-Constrained Background
- Unfolding Matrix
- Efficiency Correction

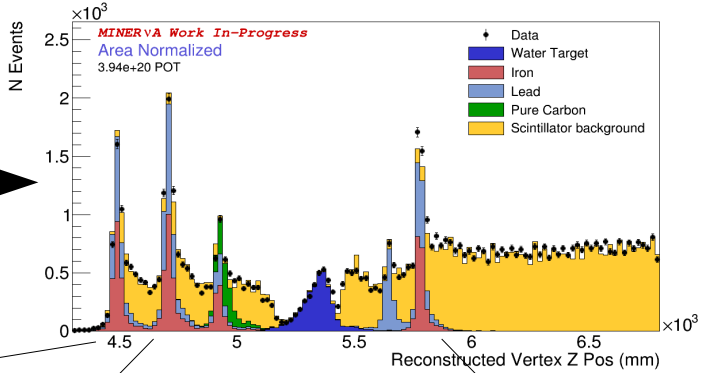


$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi} \frac{1}{\Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

Efficiency Correction

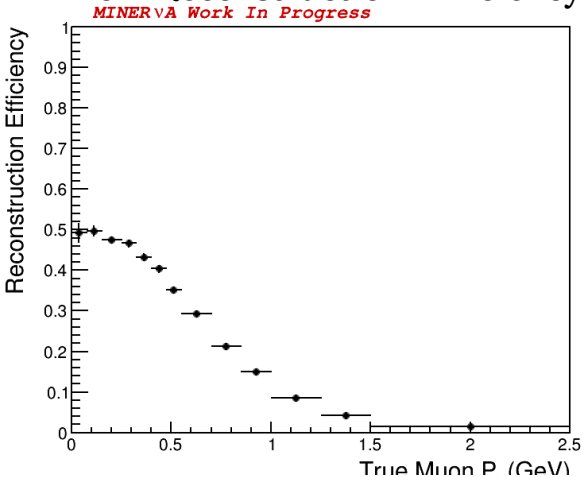
- Efficiency is corrected per-target

Neutrino Beam Direction

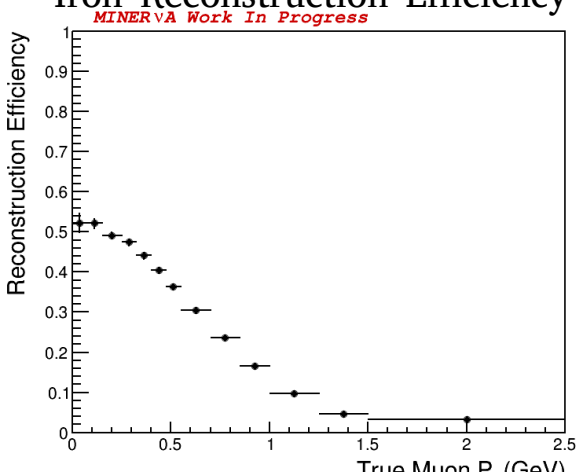


MINOS

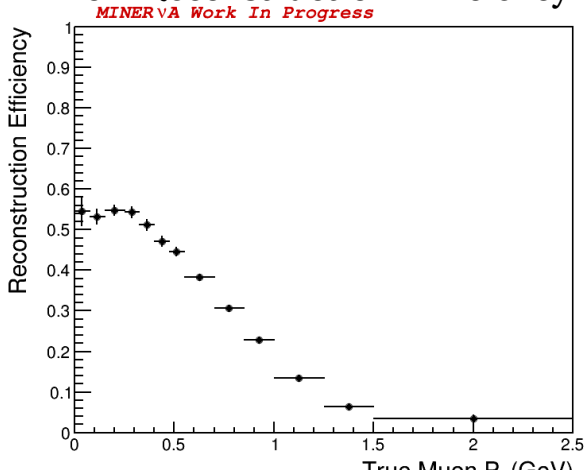
Iron Reconstruction Efficiency



Iron Reconstruction Efficiency



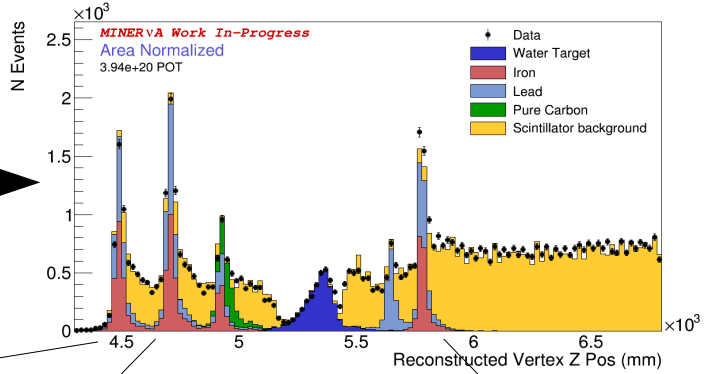
Iron Reconstruction Efficiency



Efficiency Correction

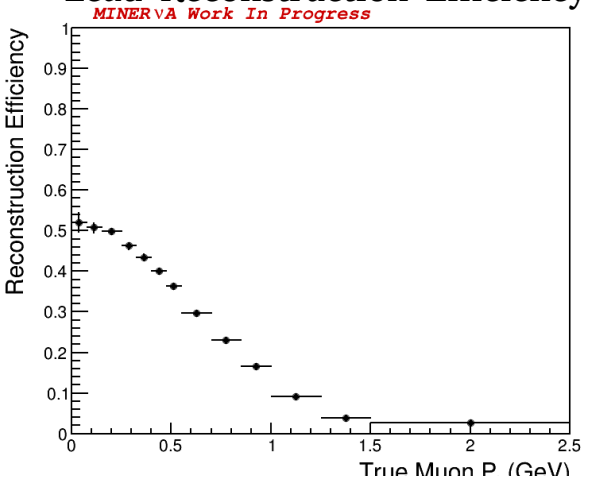
- Efficiency is corrected per-target

Neutrino Beam Direction

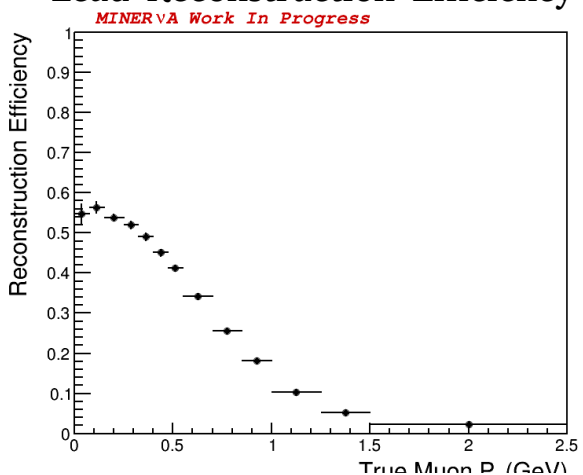


MINOS

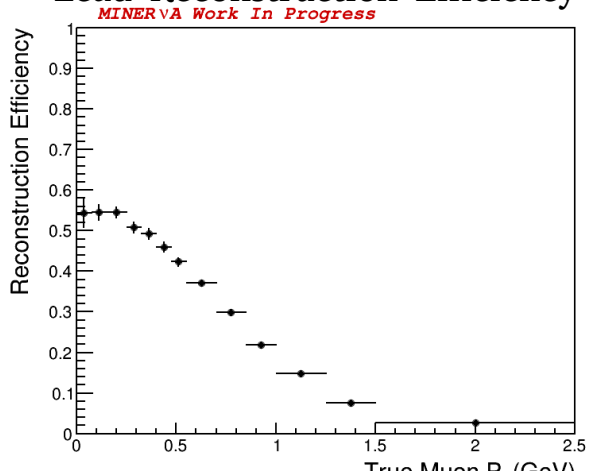
Lead Reconstruction Efficiency



Lead Reconstruction Efficiency



Lead Reconstruction Efficiency



Ingredients to Cross Section

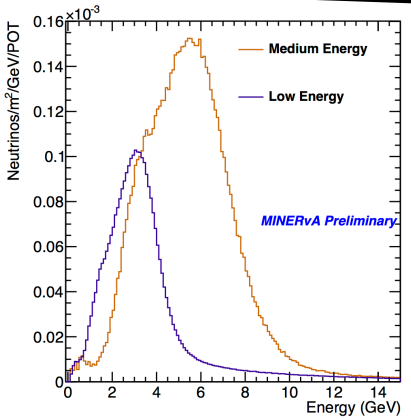
- Event Rate
- Sideband-Constrained Background
- Unfolding Matrix
- Efficiency Correction
- Number of Targets
  - Based on a careful measurement of target dimensions and density

$$(\frac{d\sigma}{dX})_i = \frac{1}{T_n \Phi} \frac{1}{\Delta X_i} \frac{\sum_j U_{ij}(N_j^{data} - N_j^{bkg})}{\epsilon_i}$$

Ingredients to Cross Section

- Event Rate
- Sideband-Constrained Background
- Unfolding Matrix
- Efficiency Correction
- Number of Targets
- Flux

$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi} \frac{1}{\Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$



“You’ve shown all the components, so you’re going to show us the cross section?”

Medium Energy Nuclear Target Muon Pt XSec?

- Would've loved to show nuclear target cross sections
- Still trying to understand our systematics
- Expect CCQE-like results in nuclear targets soon
  - 2d Muon P_t vs P_z
  - Transverse Kinematic Imbalance
    - See Rob Fine's talk next

In the meantime…

Presenting Minerva's First Public Medium Energy XSection Result

Muon Q^2 in CH

How is Muon Q^2 XSec Extracted?

- Uses very similar procedure to extract cross section
  - 8.25e20 PoT, ~1.1 million reconstructed events
- Background is tuned in muon pt
  - Tuned by looking at sidebands where we reconstructed:
    - a michel (isolates single charged pion events)
    - more than 2 isolated energy clusters (isolates single neutral pion events)
    - or both (isolates multi pion events)
- Showing Q^2 because it's not as affected by flux
  - See Deepika Jena's flux talk tomorrow

How is Muon Q^2 XSec Extracted?

- Defined by

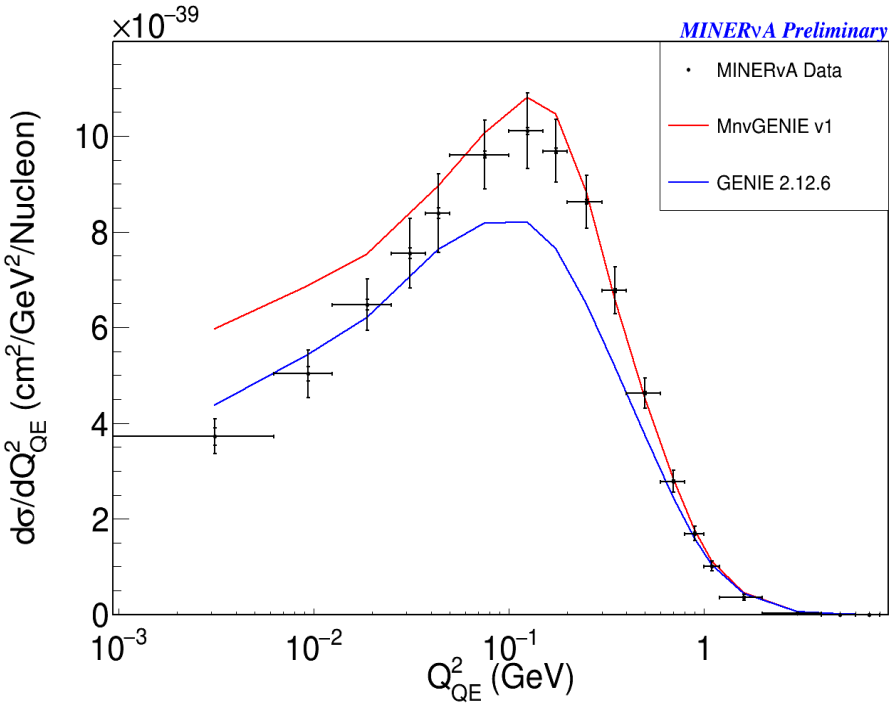
$$Q^2_{QE} = 2E^{QE}_{\nu}(E_{\mu} - p_{\mu}\cos\theta_{\mu}) - m^2_{\mu}$$

$$E^{QE}_{\nu} = \frac{m^2_p - (m_n - E_b)^2 - m^2_{\mu} + 2(m_n - E_b)E_{\mu}}{2(m_n - E_b - E_{\mu} + p_{\mu}\cos\theta_{\mu})}$$

- Unfolding/efficiency is done in Q^2 vs Muon P_t and then projected onto Q^2
  - For a future of several 2d xsec
  - Eg. Muon P_t vs P_z

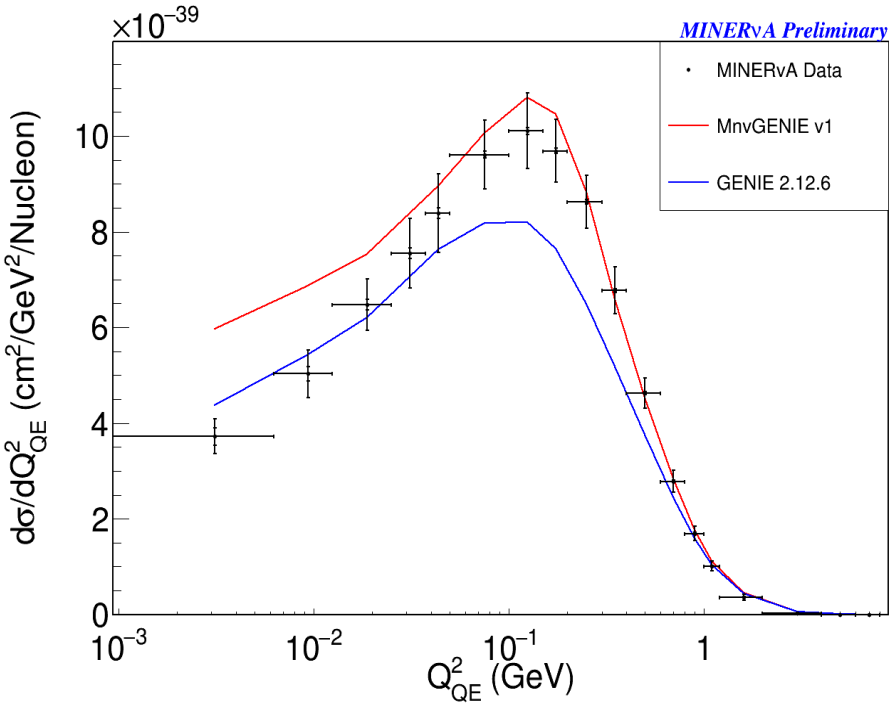
$$(\frac{d\sigma}{dX})_i = \frac{1}{T_n \Phi}\frac{1}{\Delta X_i}\frac{\sum_j U_{ij}(N^{data}_j - N^{bkg}_j)}{\epsilon_i}$$

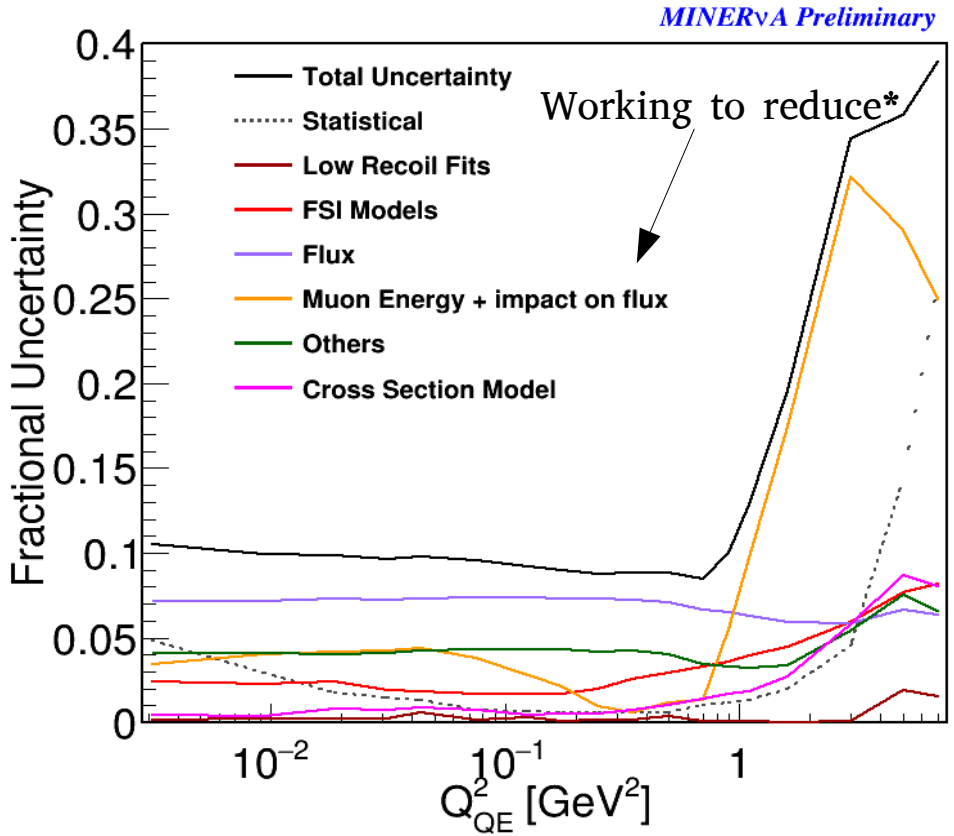
Muon Q^2 XSec



- MnvGENIE v1 based on GENIE 2.12.6 with Nieves 2p2h
- 2p2h tuned up based on low recoil analysis in low energy beam
  - Phys.Rev.Lett.116 (2016) 071802
  - arXiv:1705.02932
- Quasielastic events tuned down at low Q^2 with a Valencia RPA correction
  - RPA PRC 70, 055503, and PLB 638, 325, PRD 88, 113007
- See Xianguo Lu's upcoming talk for more details

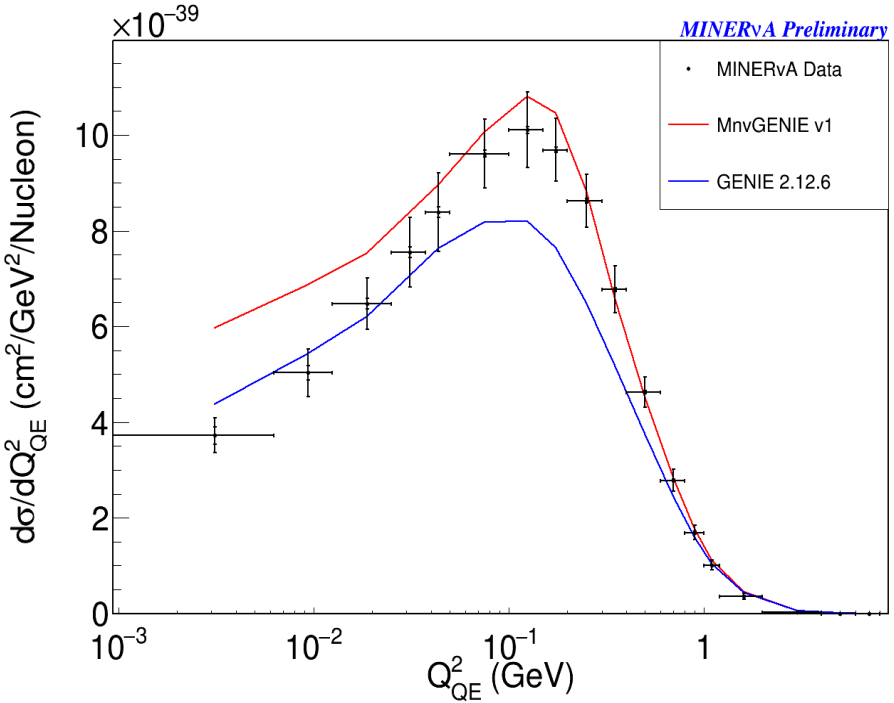
Muon Q^2 XSec w/ Fractional Uncertainty

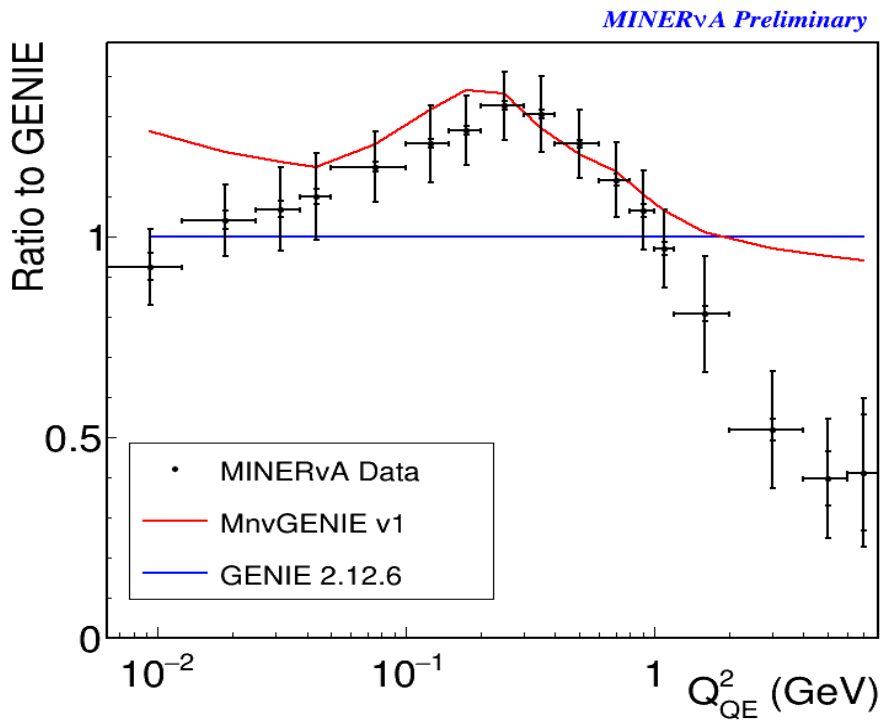




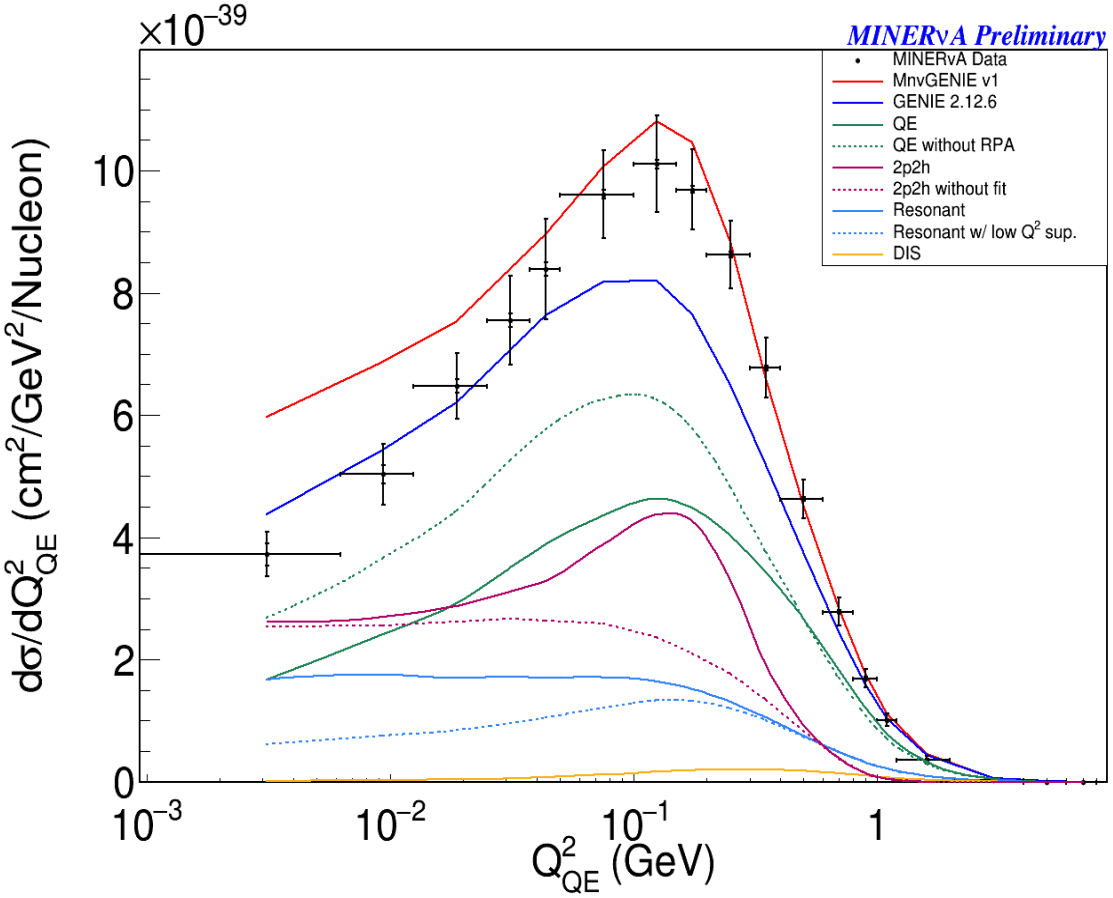
*See Deepika Jena's flux talk tomorrow

Muon Q^2 in CH

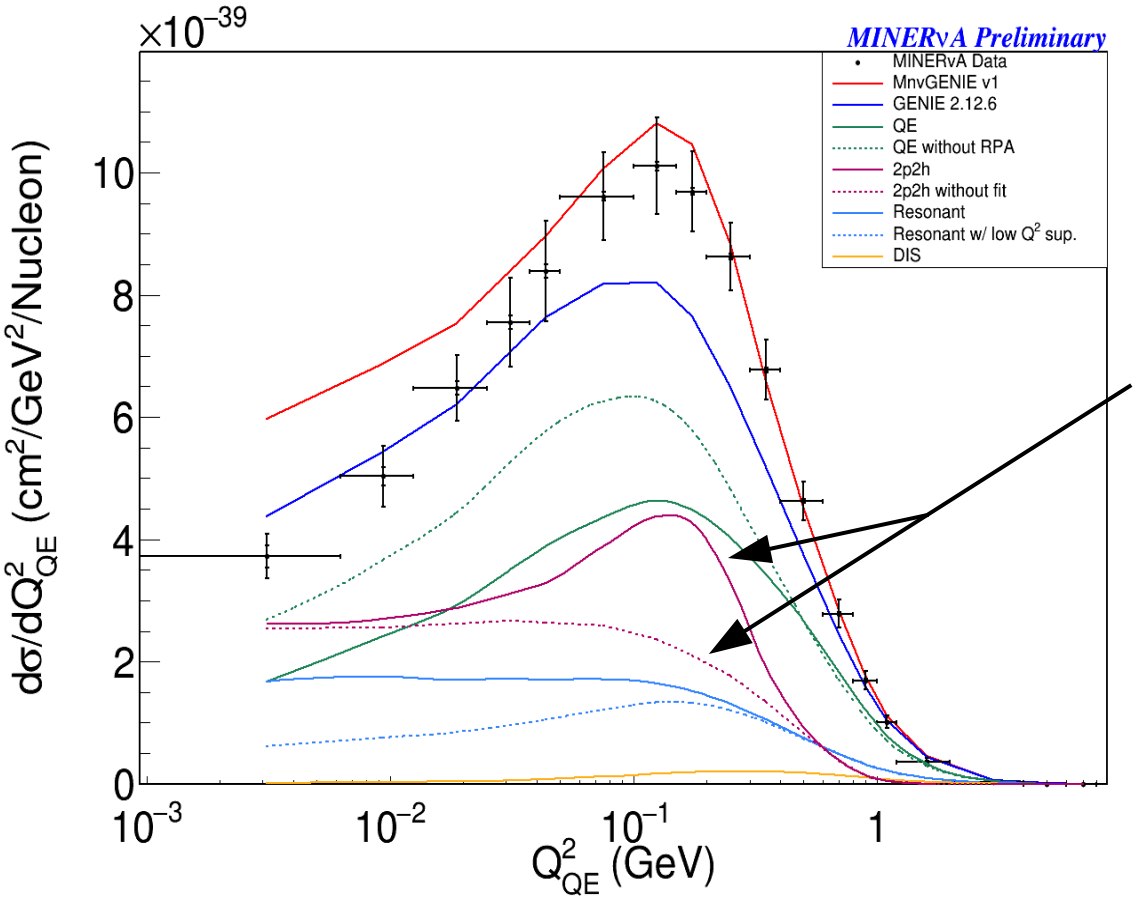

MINERvA Preliminary
×10⁻³⁹
dσ/dQ²QE (cm²/GeV²/Nucleon)
Q²QE (GeV)
MINERvA Data
MnvGENIE v1
GENIE 2.12.6


MINERvA Preliminary
Ratio to GENIE
Q²QE (GeV)
MINERvA Data
MnvGENIE v1
GENIE 2.12.6

XSec With Models



XSec With Models

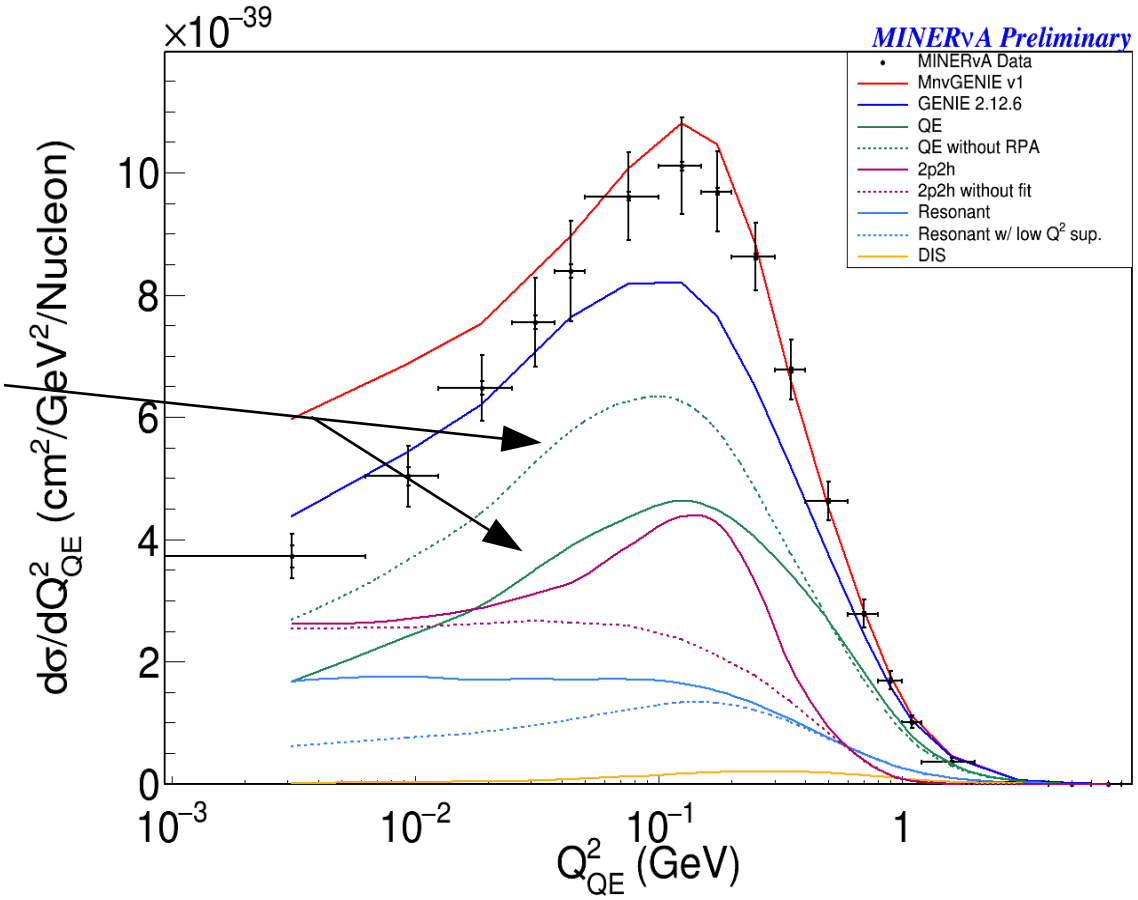


Effect of 2p2h Fit to Low Recoil Sample

Phys.Rev.Lett.116 (2016) 071802

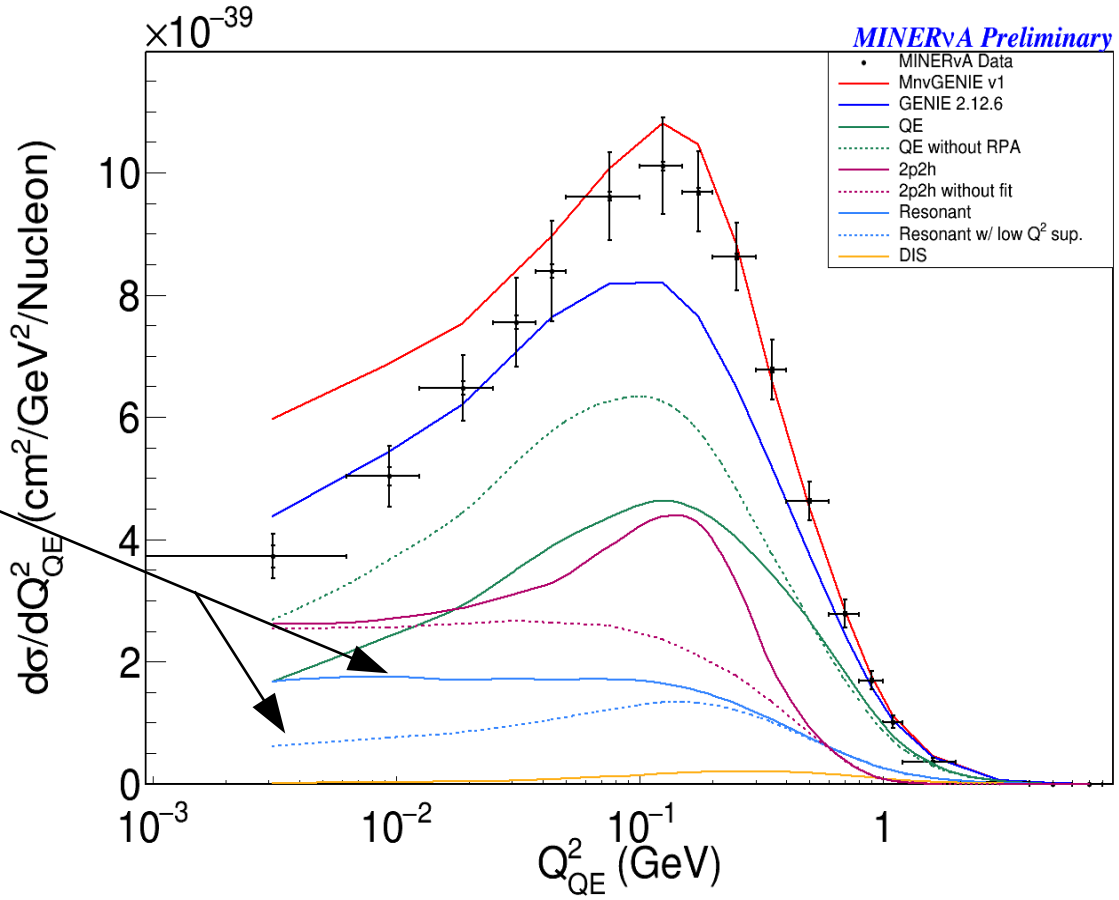
XSec With Models

Effect of the RPA correction in QE events



XSec With Models

Effect of a low Q^2 suppression in Resonant Events
(Using empirical model used by Minos.
Phys. Rev. D 91, 012005 (2015)
Not applied to MnvGENIE v1)



Summary

- Hopefully we've whet your appetite for MINERvA's Medium Energy Nuclear Target results
  - 2D muon P_t vs P_z and Transverse Kinematic Imbalance
- CCQE-like Muon Q^2 is one of many upcoming Medium Energy Era cross sections
  - Pion variables in nuclear targets
  - DIS
  - Neutrons!
  - And much more!

Thank you

Acknowledgements

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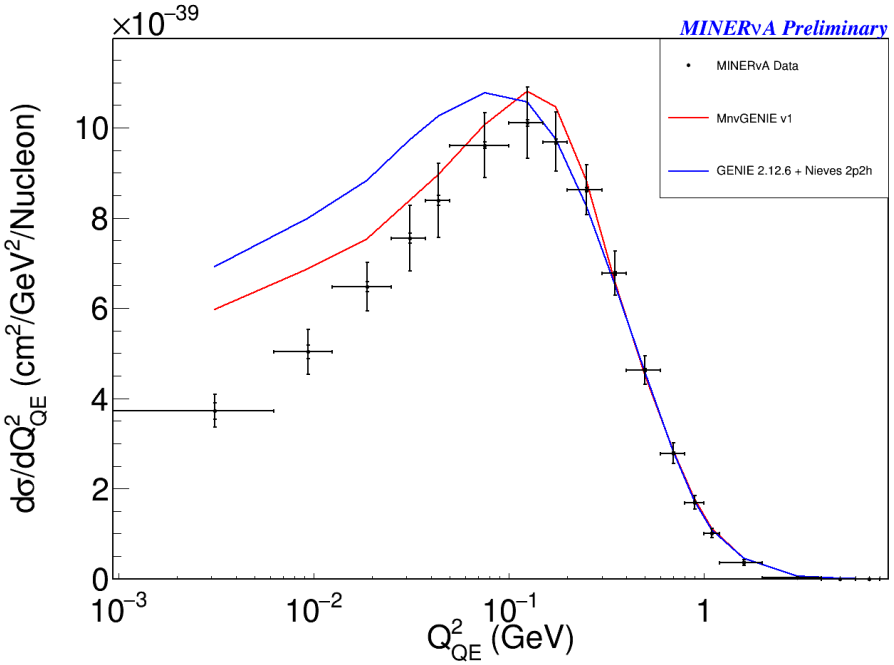
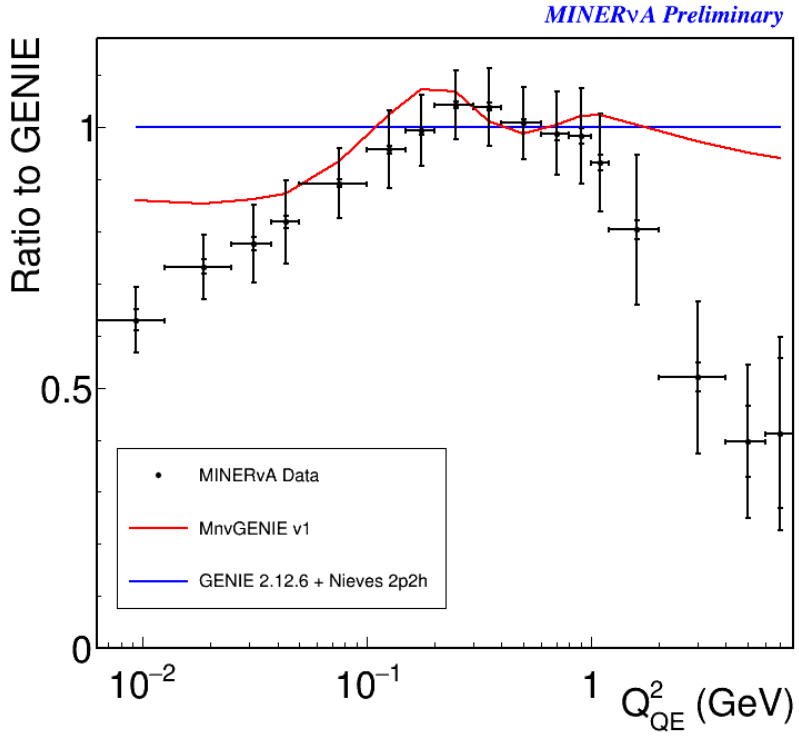
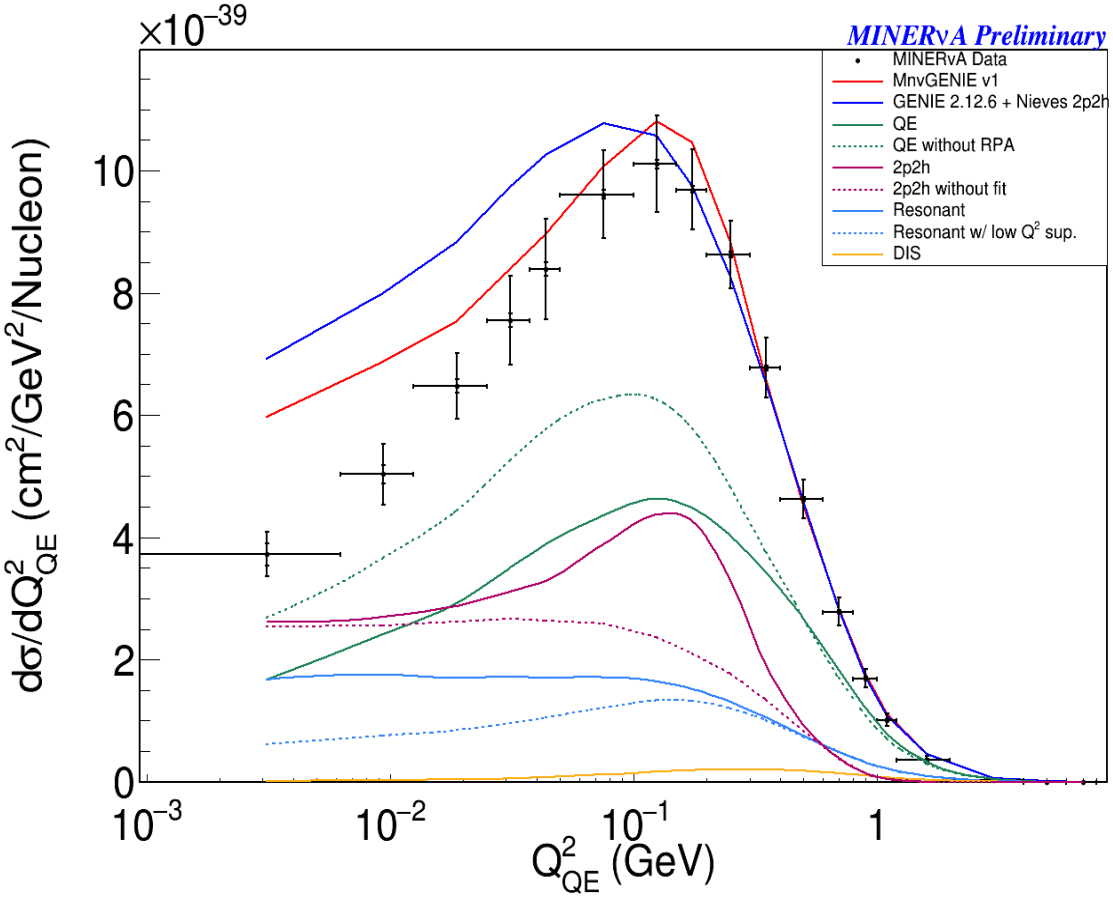
Backup

Genie 2.12.6 With Nieves 2p2h





Genie 2.12.6 With Nieves 2p2h



XSec With Models, Log Log Scale