Recent results from MINERvA

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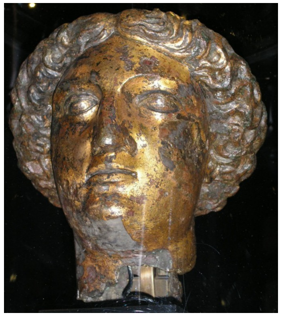
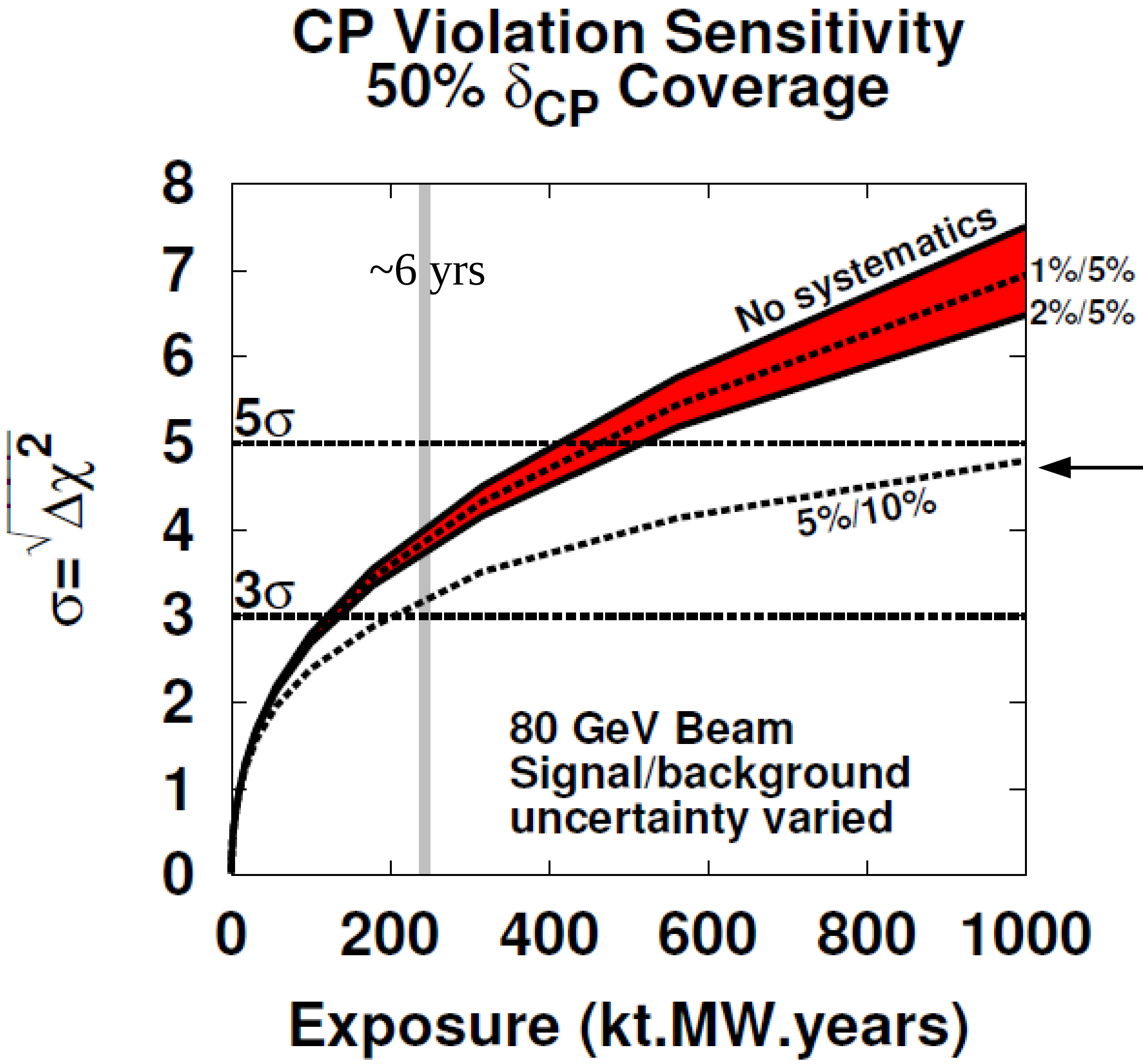
HEP2016 – Valparaiso, Chile
7 January, 2016



Neutrino interactions and oscillation experiments

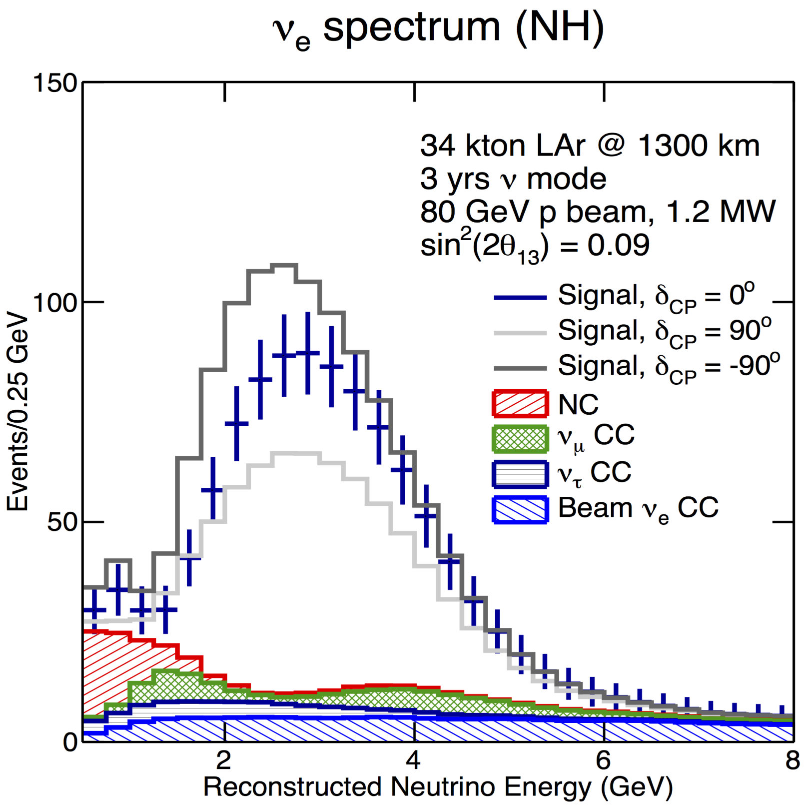


where we want to be:
1% signal / 5% background

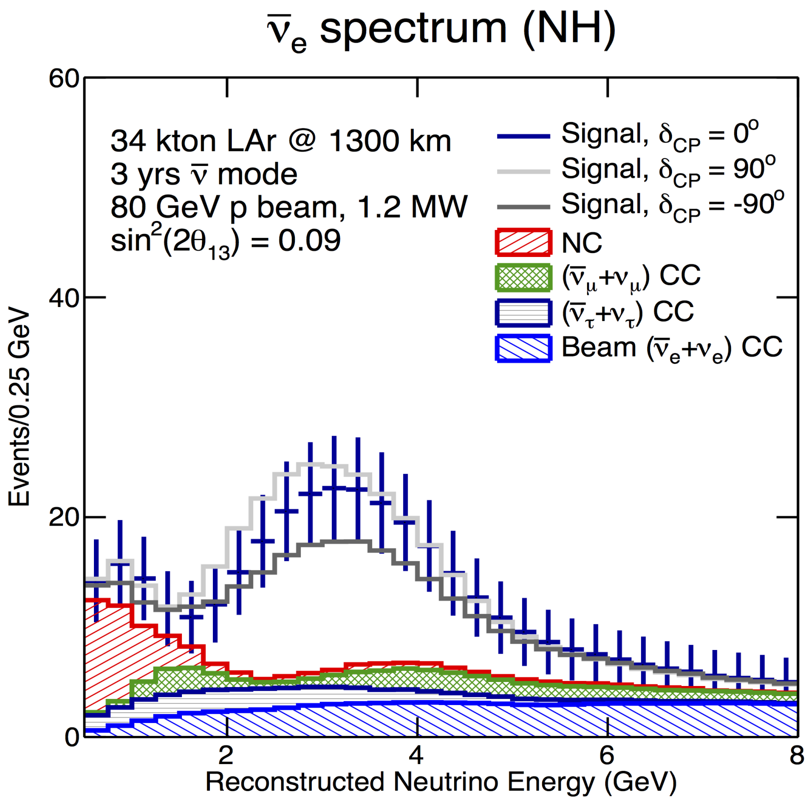
where we are now:
~5-10%

Neutrino interaction uncertainties are really important for DUNE!

Neutrino energy reconstruction is important



ν_e spectrum (NH)



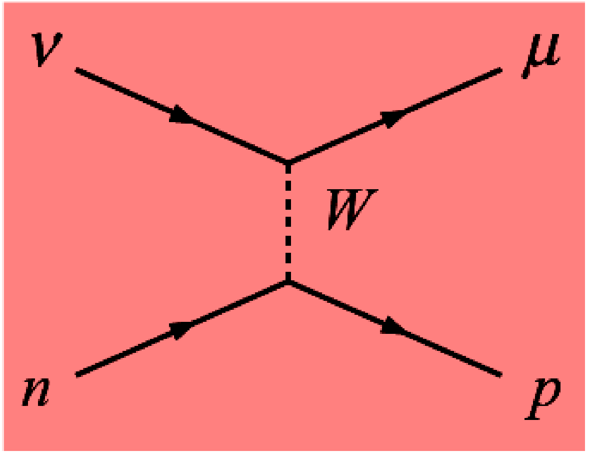
$\bar{\nu}_e$ spectrum (NH)

True neutrino energy ↔ reconstructed neutrino energy

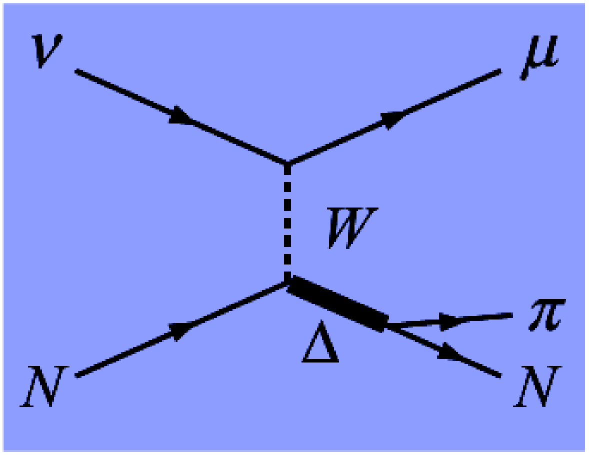
Energy response is different for different particles, and different for neutrinos and antineutrinos

Neutrino cross sections

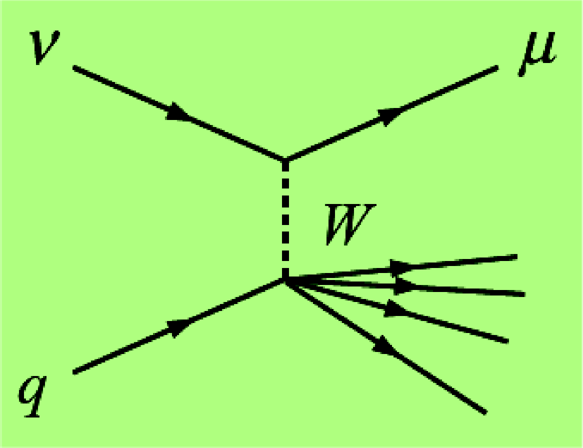
Quasielastic (QE)

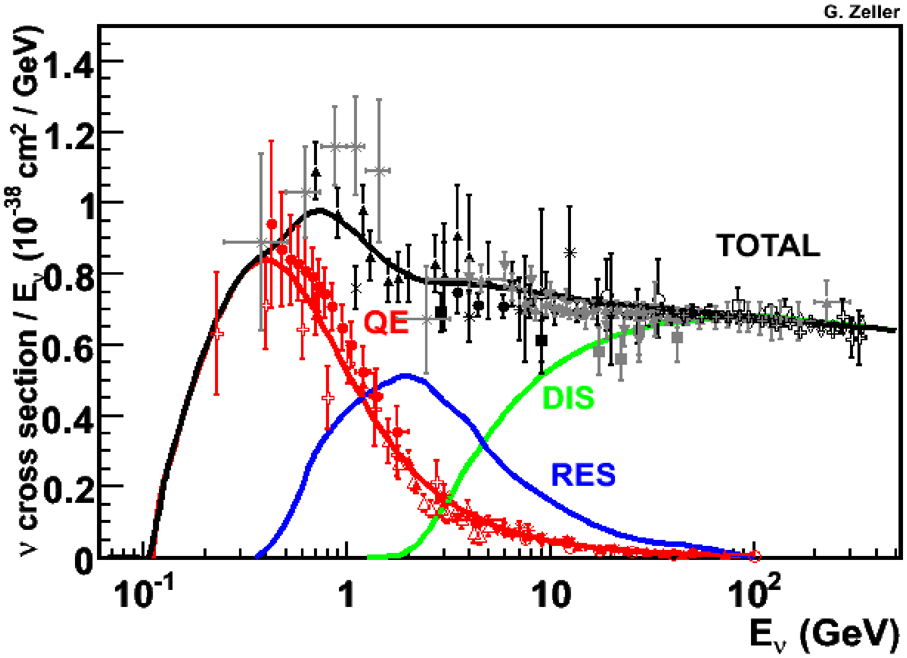


Resonance



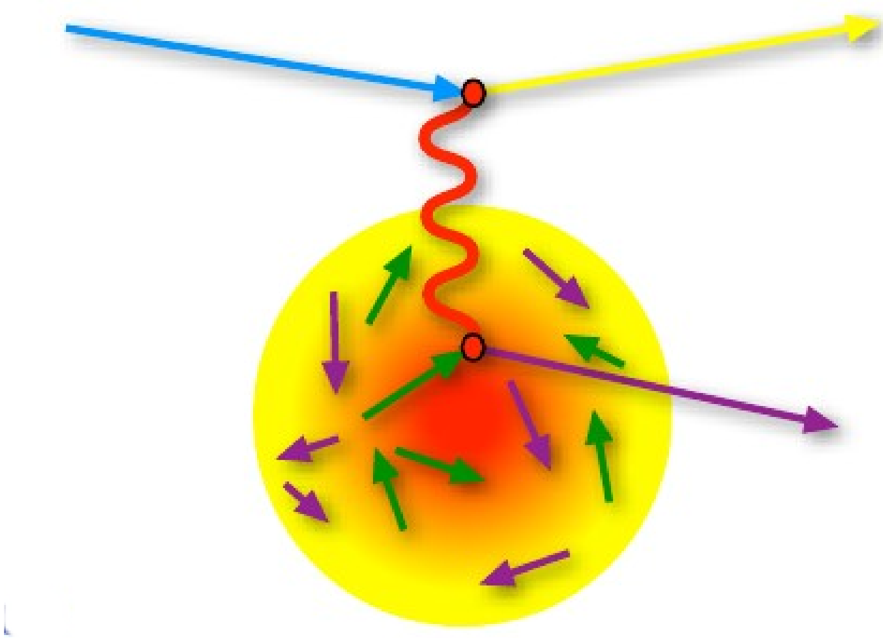
DIS





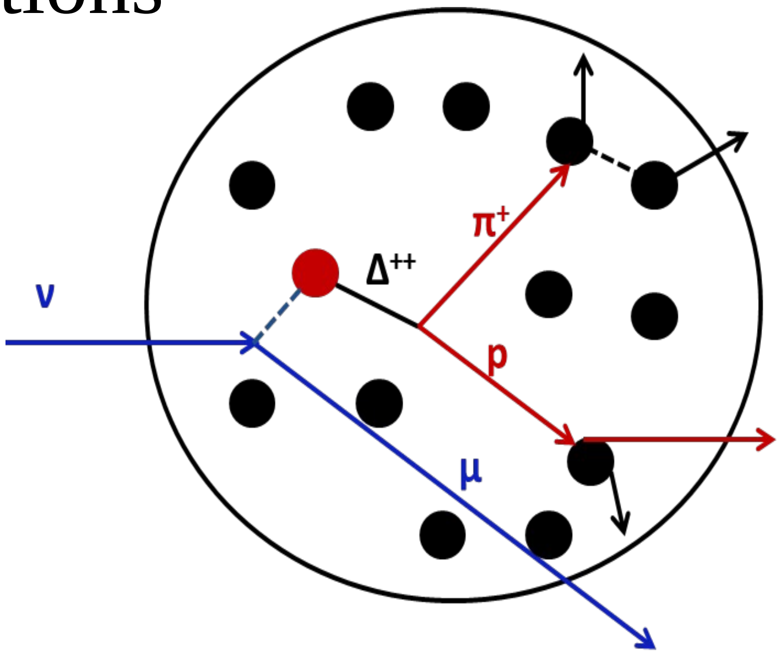
Accelerator-based neutrino oscillation experiments need good models for all three of these processes!

The effect of the nucleus



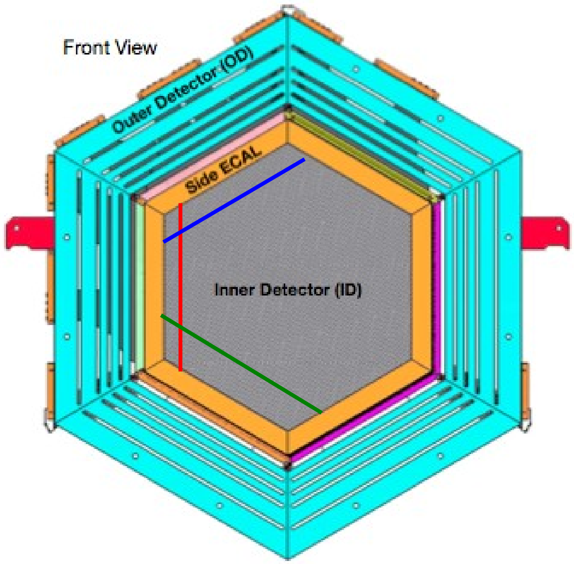
Experiments use heavy targets (C, O, Ar, Fe etc.) to increase interaction rate

Nuclear effects modify interactions

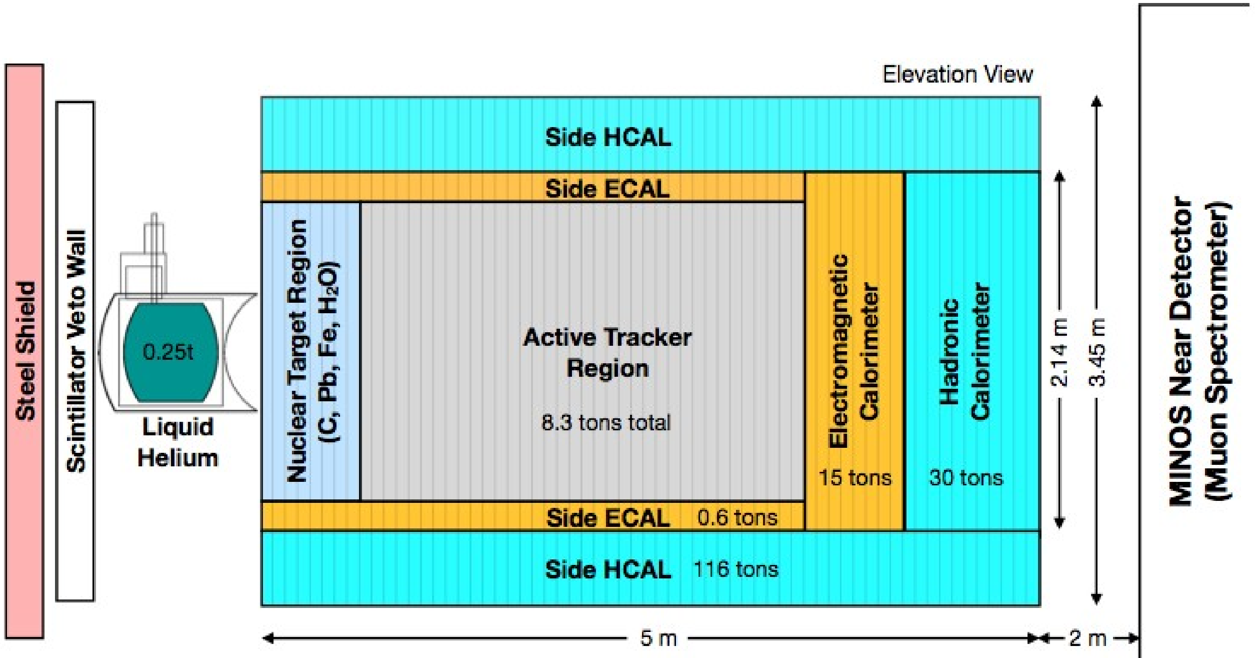


Final state interactions (FSI) between outgoing hadrons and residual nucleus change the particle content in your detector

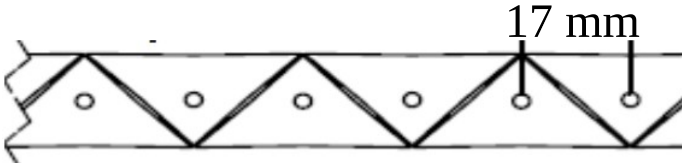
The MINERvA experiment



Plane views:
1. Vertical bars
2. +60°
3. –60°



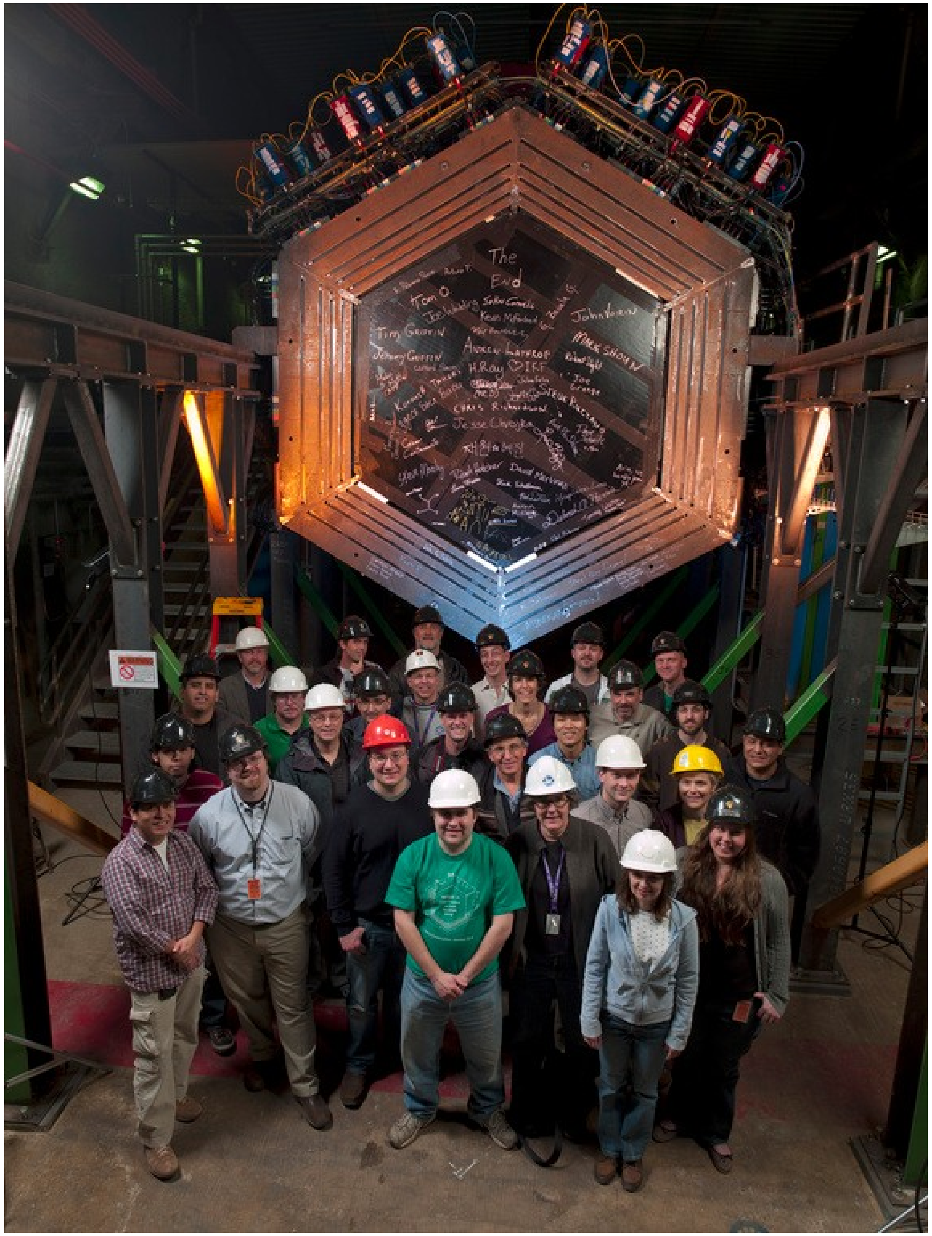
208 active planes × 127 scintillator bars



Charge-sharing triangular strips for ~3mm position resolution

Nucl. Inst. and Meth. A743 (2014) 130
arXiv:1305.5199

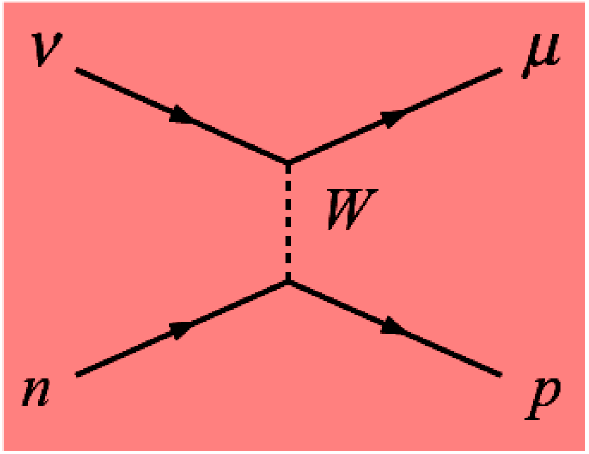
The MINERvA experiment



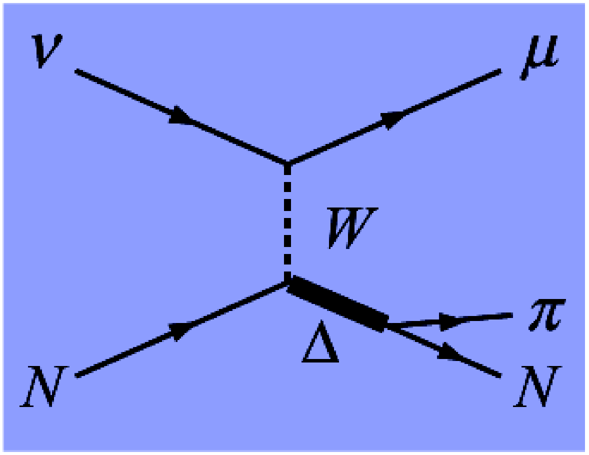
Outline of recent results

- Charged-current quasi-elastic scattering of muon and electron neutrinos
- Charged and neutral pion production
- Nuclear effects at low momentum transfer
- Deep inelastic scattering on different nuclei – Jorge Morfín's talk yesterday

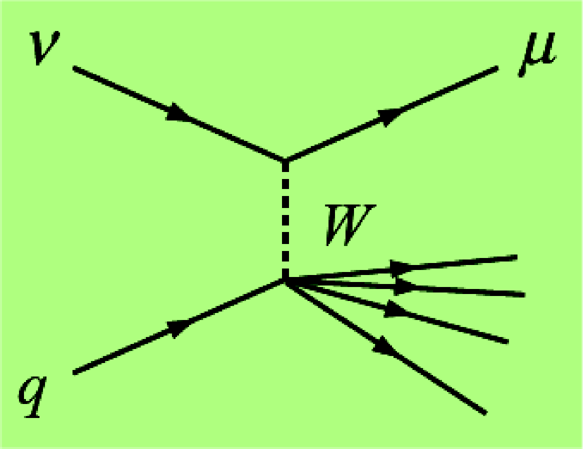
Quasielastic (QE)



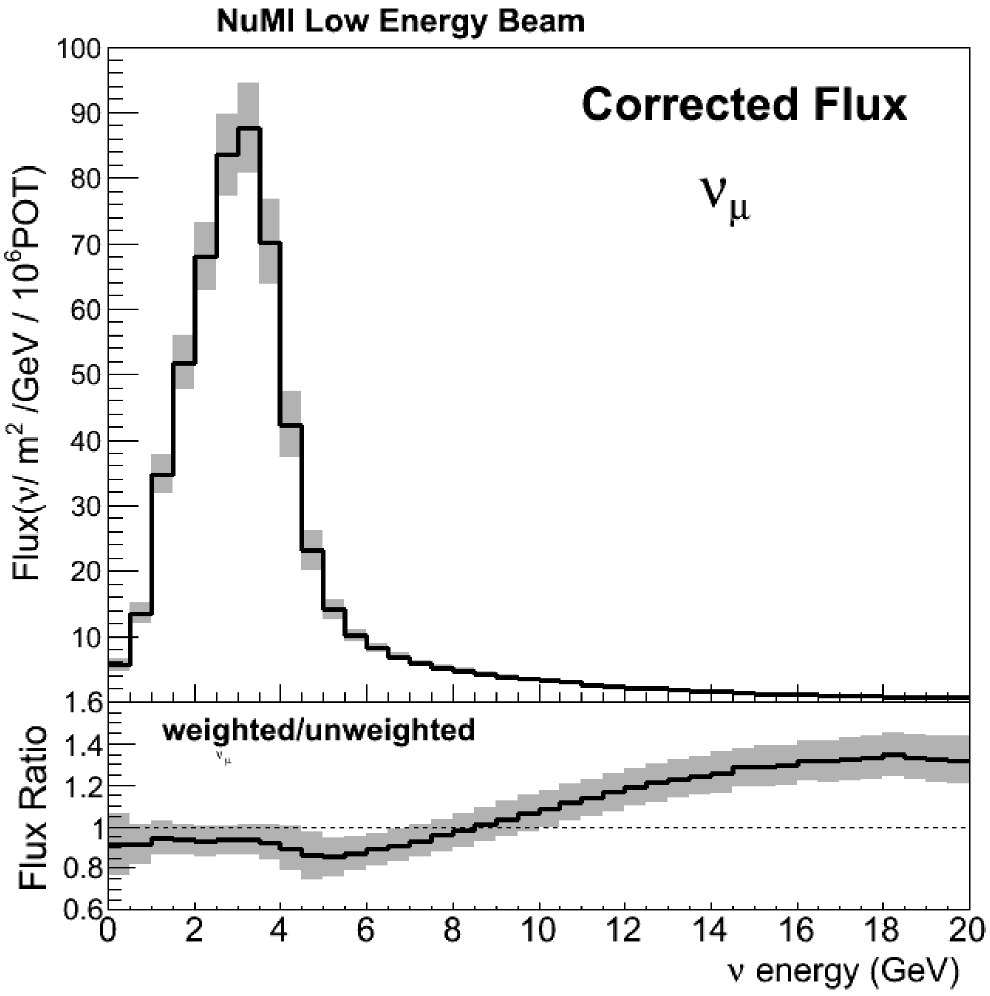
Resonance

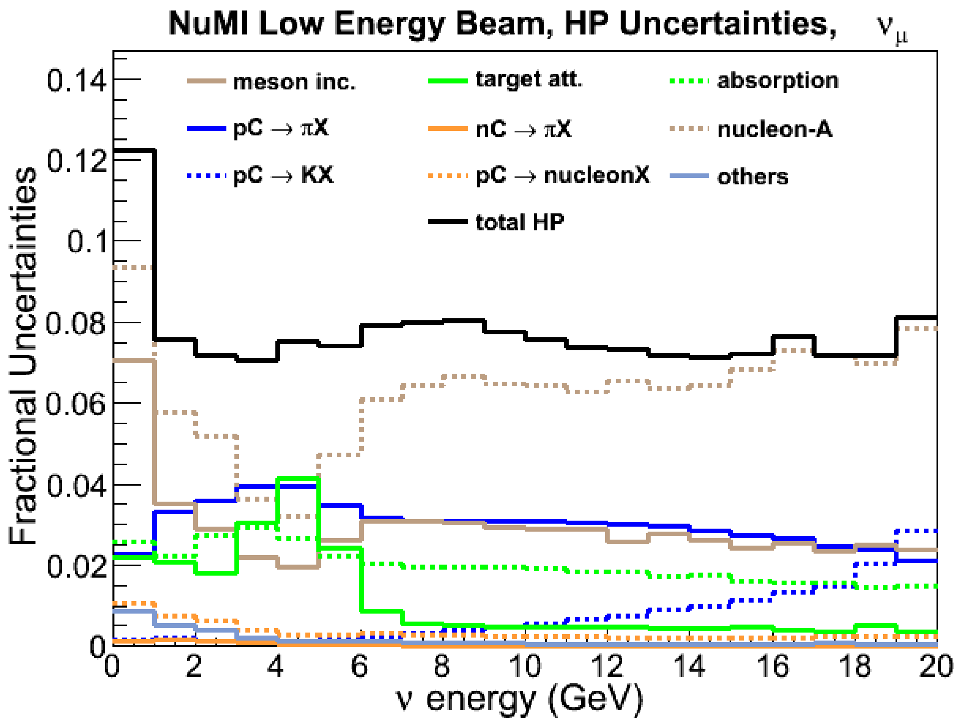


DIS

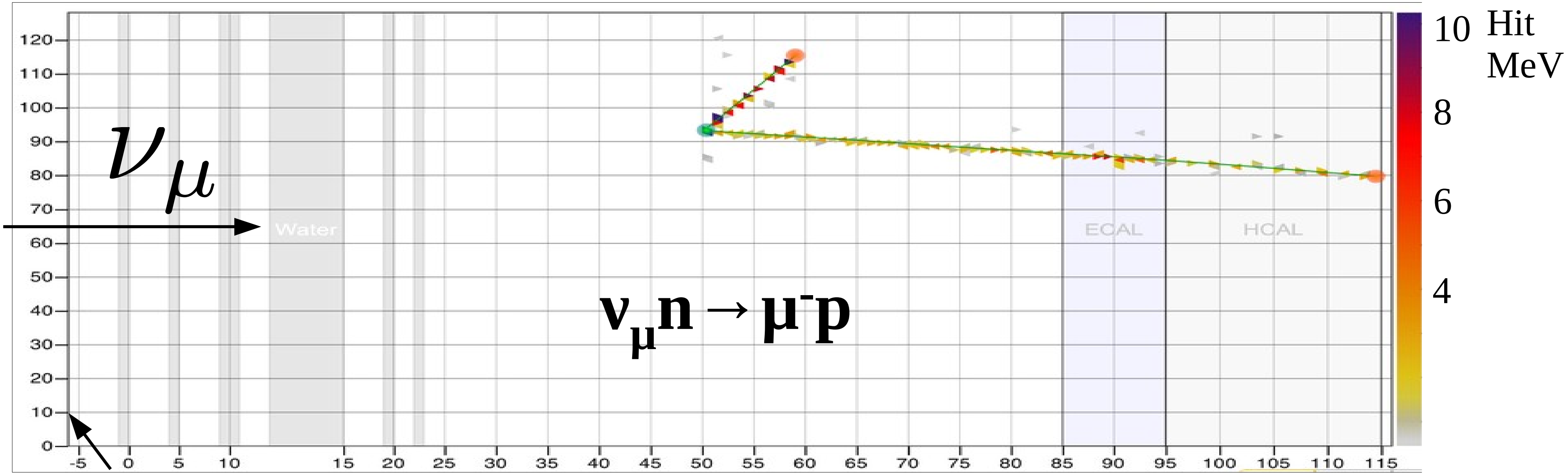


Updated flux prediction based on hadron production data





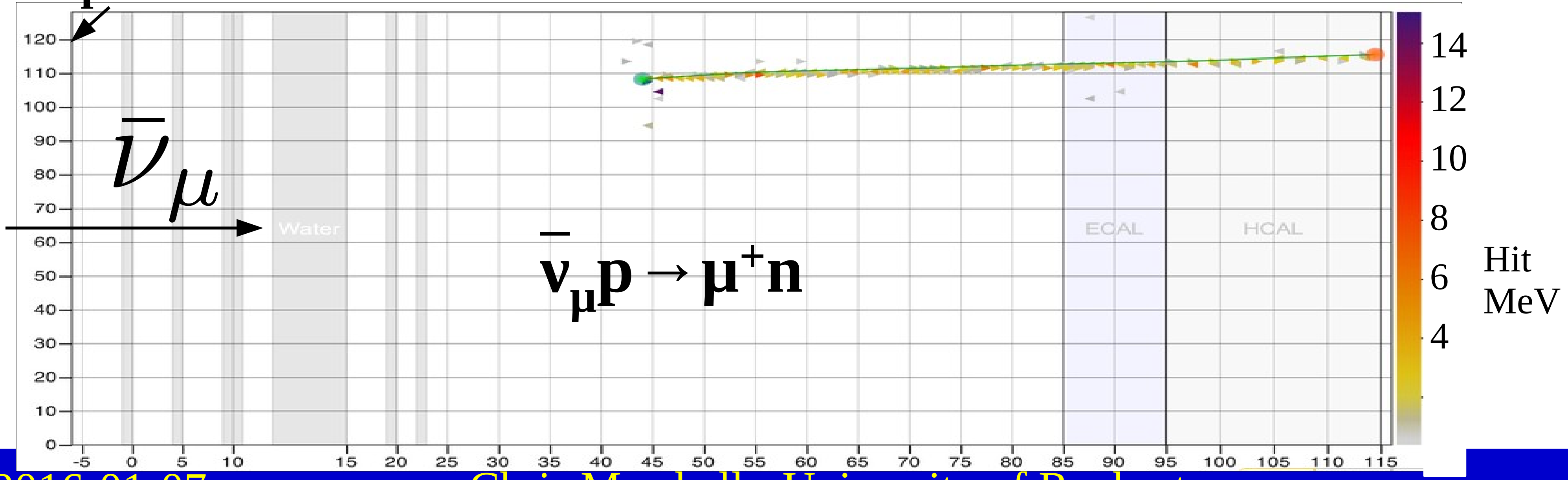
Muon (anti)neutrino CCQE



ν_μ

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

Strip number **Module number** ⟶

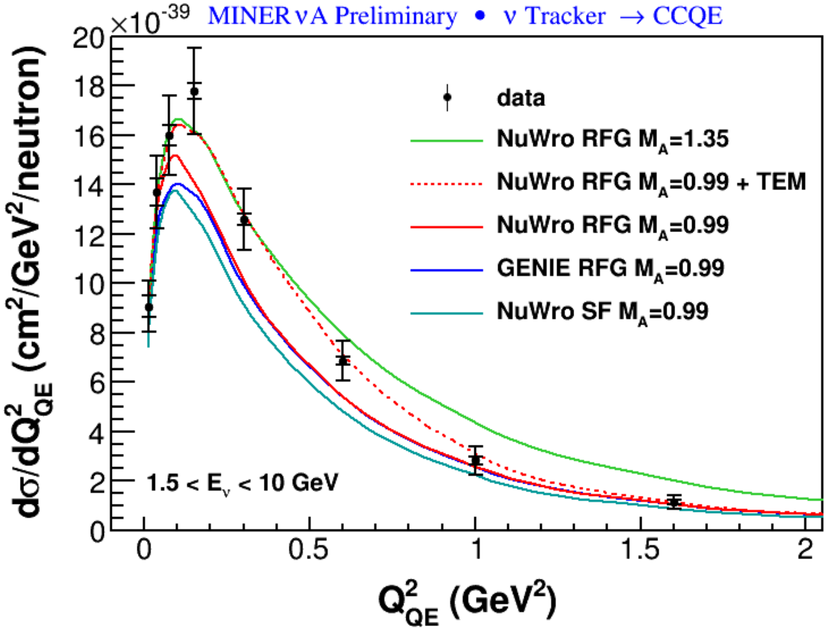


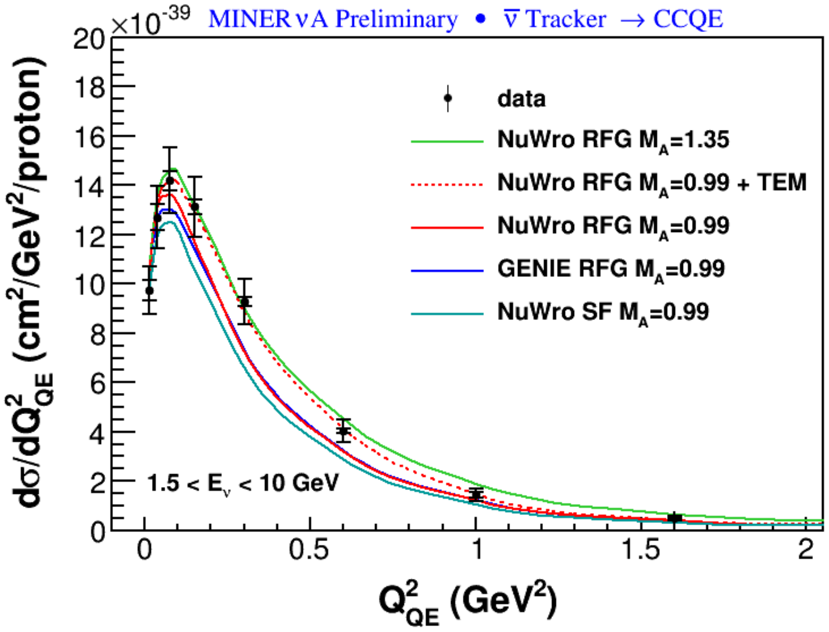
$\bar{\nu}_\mu$

$\bar{\nu}_\mu p \rightarrow \mu^+ n$

Updated cross sections

$$Q^2_{QE} = -m_l^2 + 2E_\nu^{QE}(E_l - \sqrt{E_l^2 - m_l^2}cos\theta_l)$$

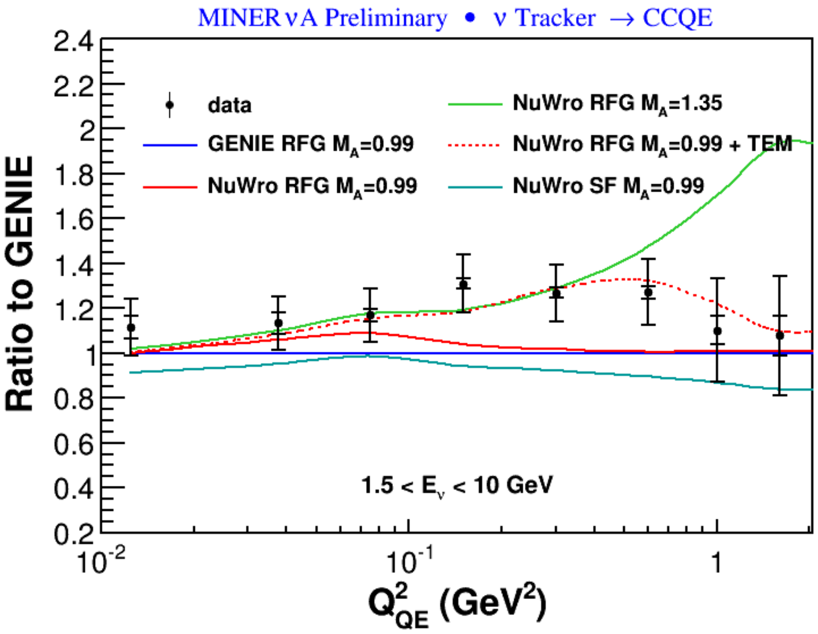


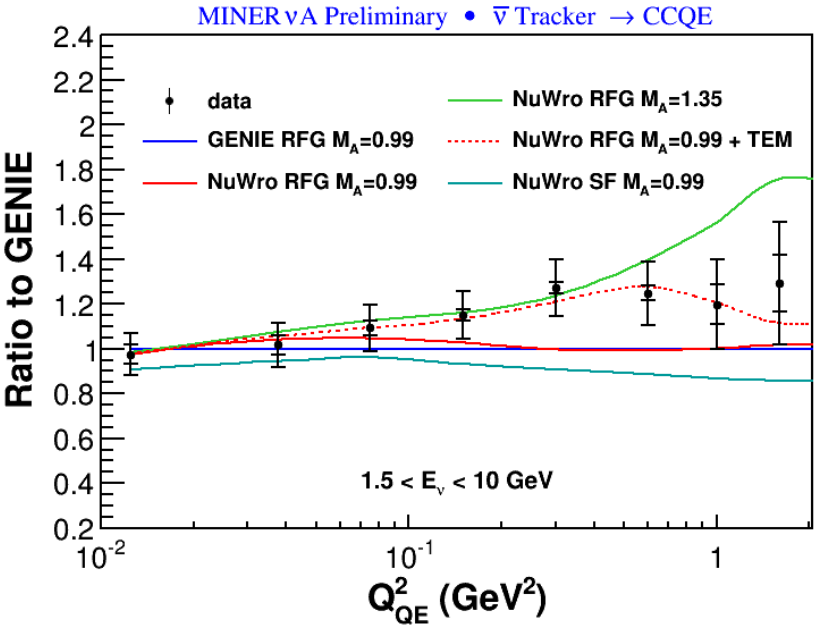


- Result has been updated with new flux prediction

Phys. Rev. Lett. 111, 022501 (2013)
Phys. Rev. Lett. 111, 022502 (2013)

Ratio to nominal model





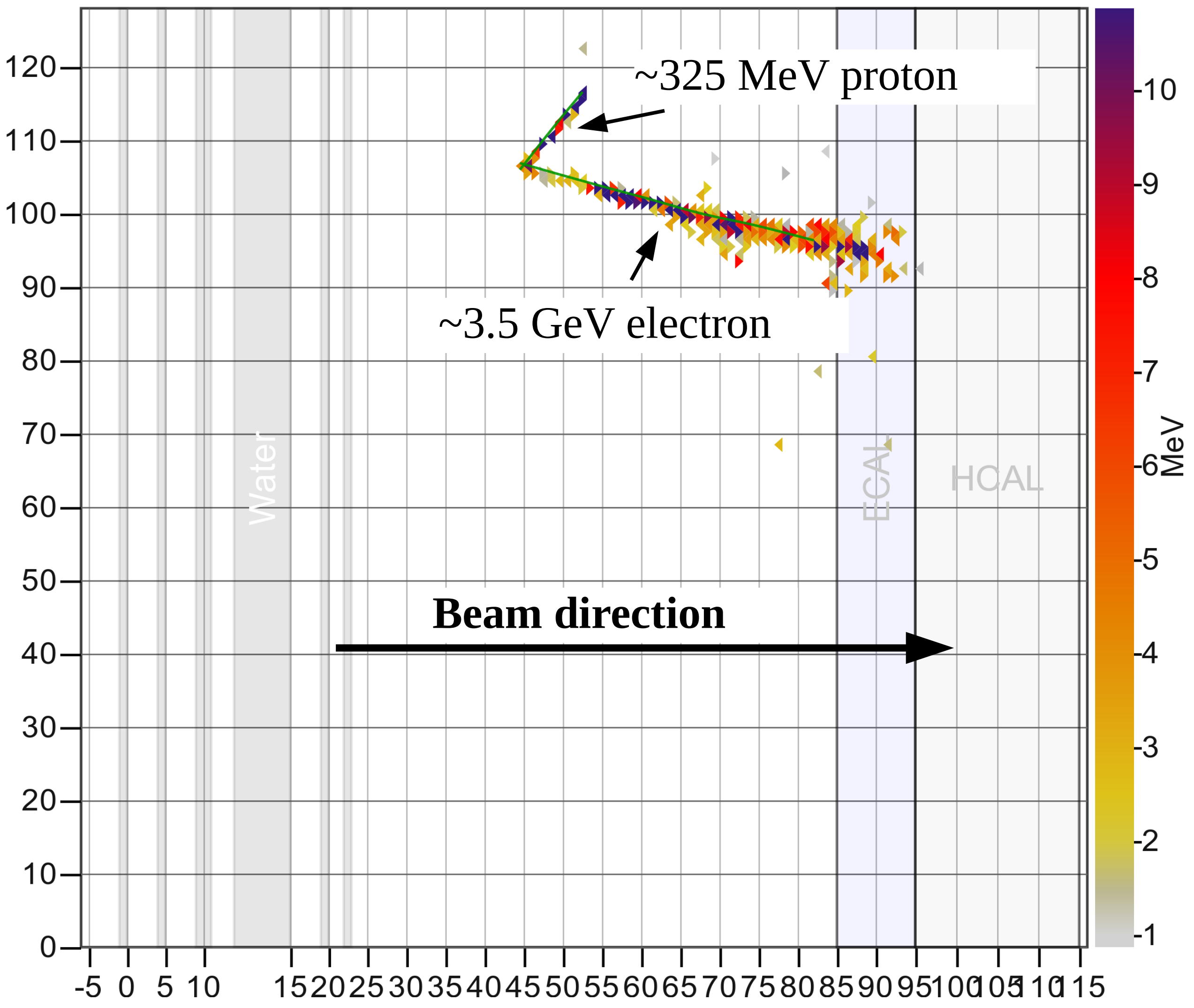
$M_A = 1.35$ ———— best fit to MiniBooNE data

TEM - - - - - - - - empirical model based on electron scattering data

GENIE ———— independent nucleons in mean field

SF ———— more realistic nucleon momentum-energy relation

Electron neutrino CCQE



~325 MeV proton

~3.5 GeV electron

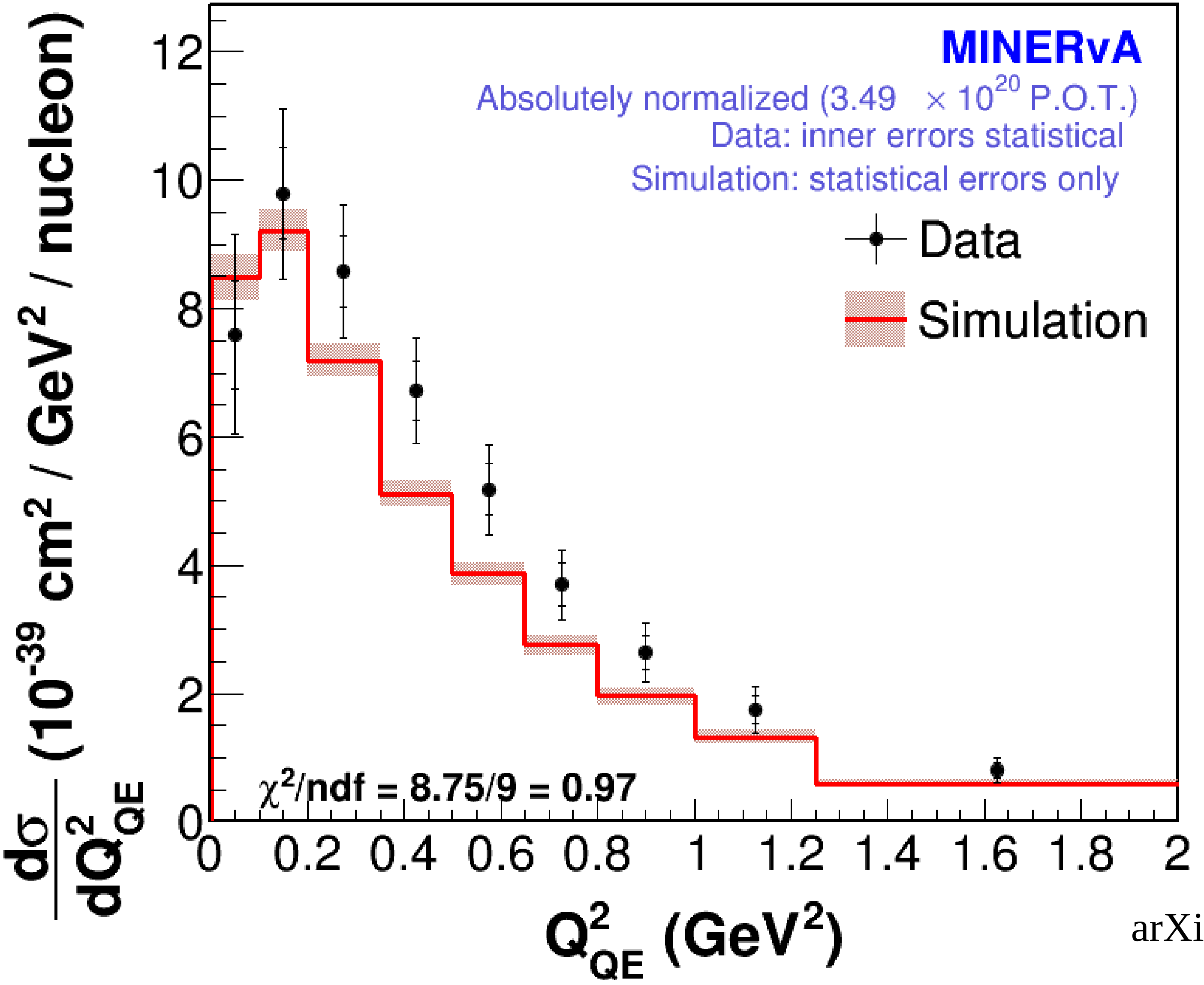
Beam direction

Signal process in ν_e appearance experiments (T2K, NOvA, DUNE)

~1% of NuMI beam is electron neutrinos

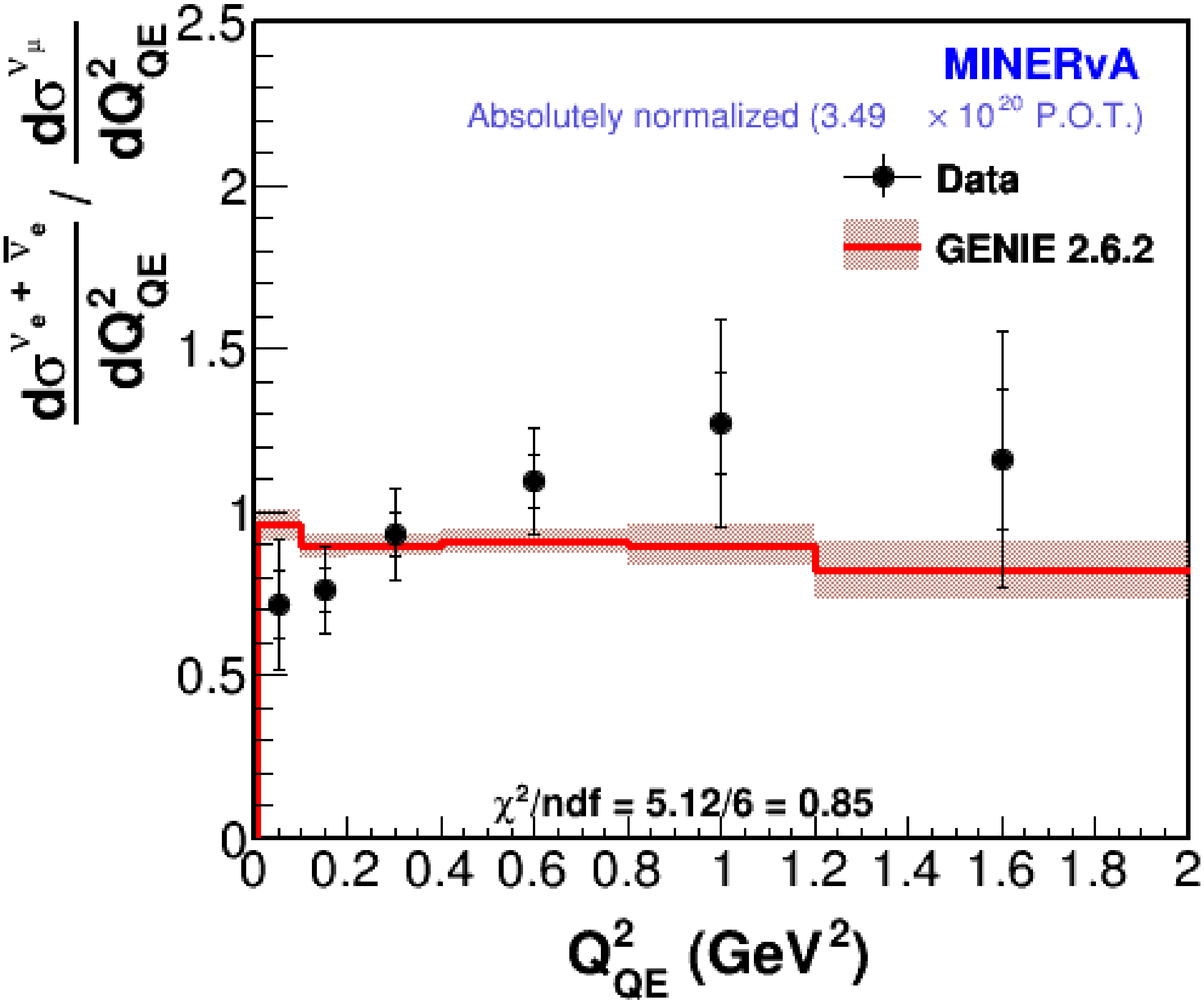
ν_e CCQE cross section

$$Q^2_{QE} = -m_l^2 + 2E_\nu^{QE}(E_l - \sqrt{E_l^2 - m_l^2}cos\theta_l)$$



arXiv:1509.05729

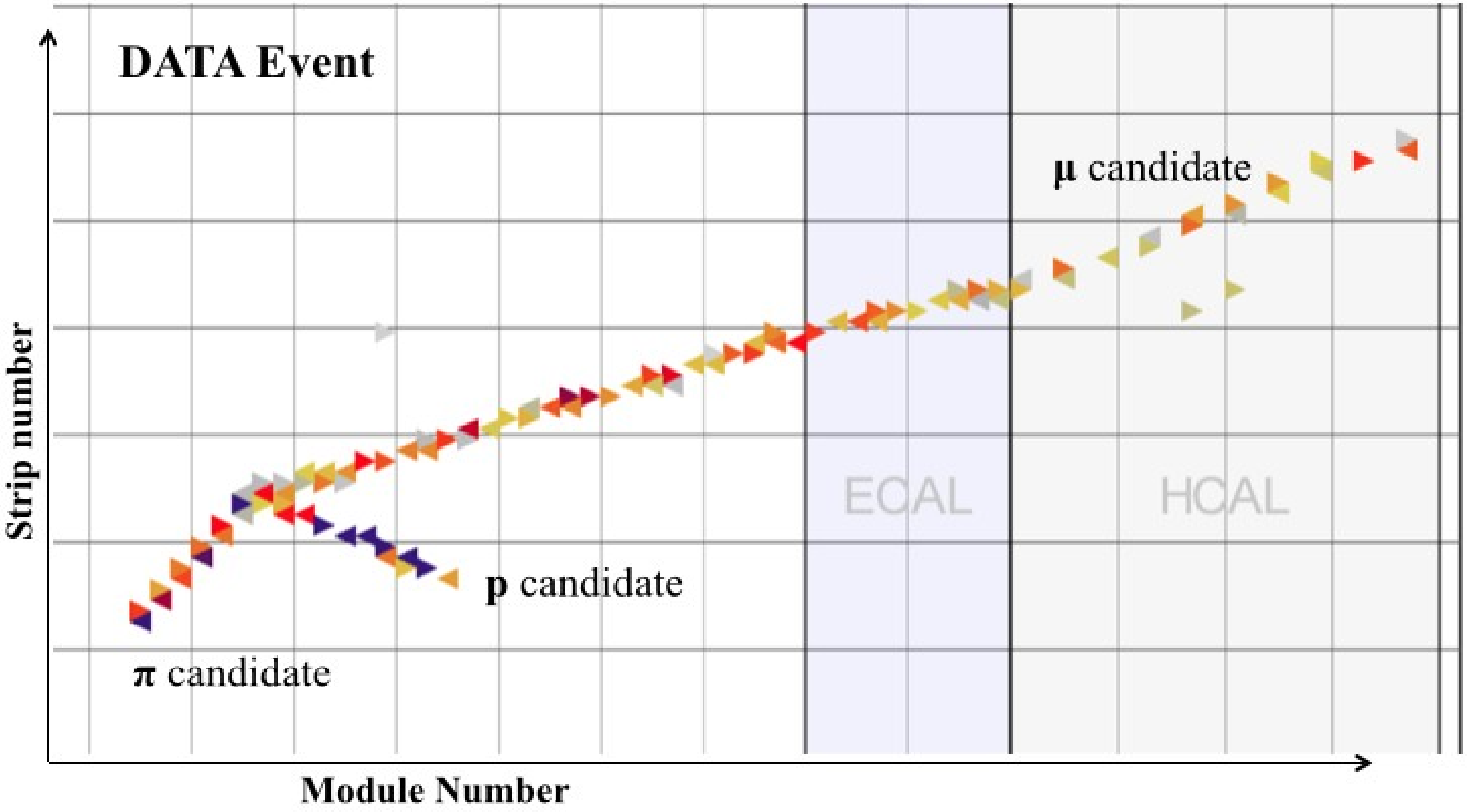
Electron / Muon ratio



Ratio is consistent with 1.0

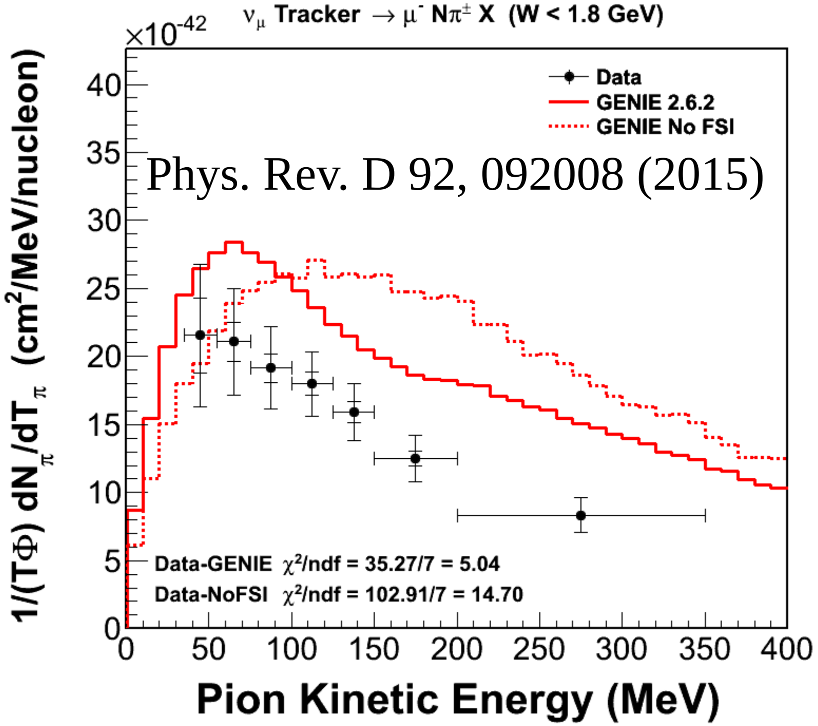
Shape is not significant due to correlated uncertainties

ν_μ $\pi^\pm$ production

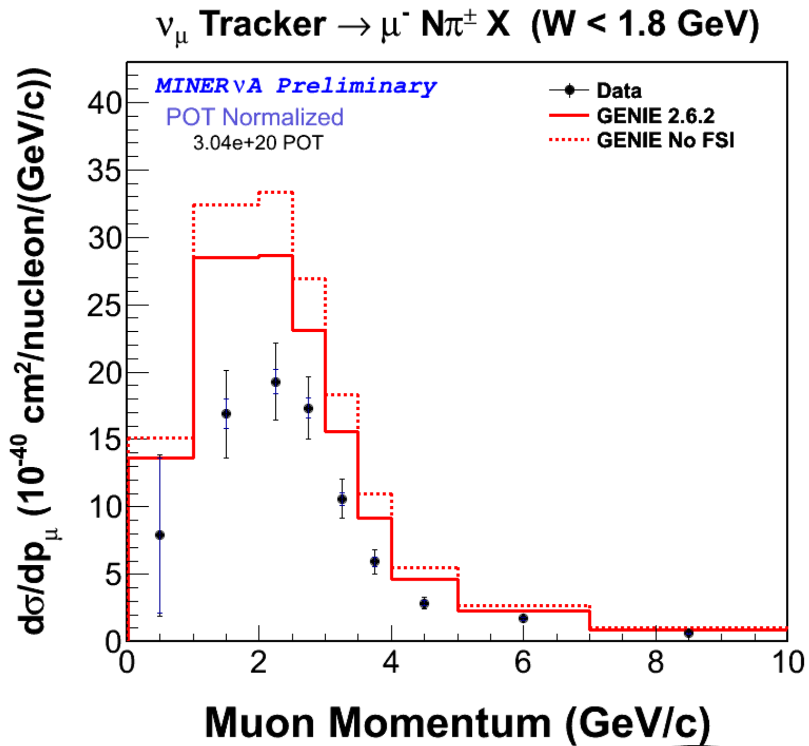


Pion and muon spectra

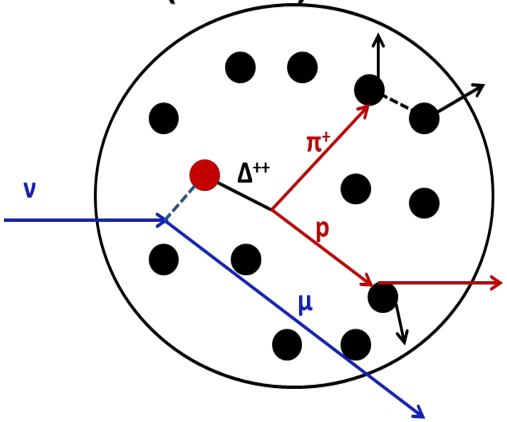
ν_μ CC $\pi^\pm$



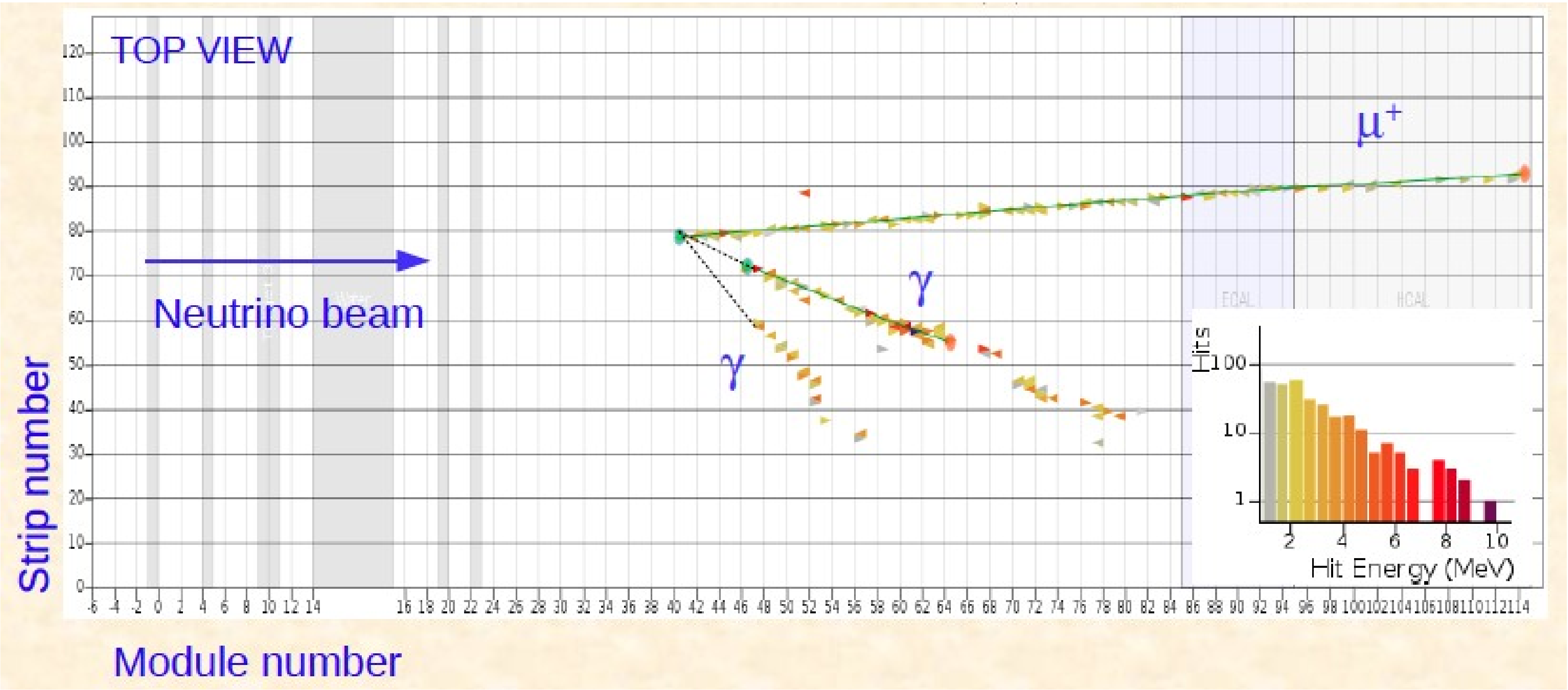
Phys. Rev. D 92, 092008 (2015)



- π^+ spectrum is affected by FSI, μ^- spectrum is not
  - FSI reduces the cross section due to pion absorption
- Cross section is overpredicted by GENIE
- Shapes agree with GENIE

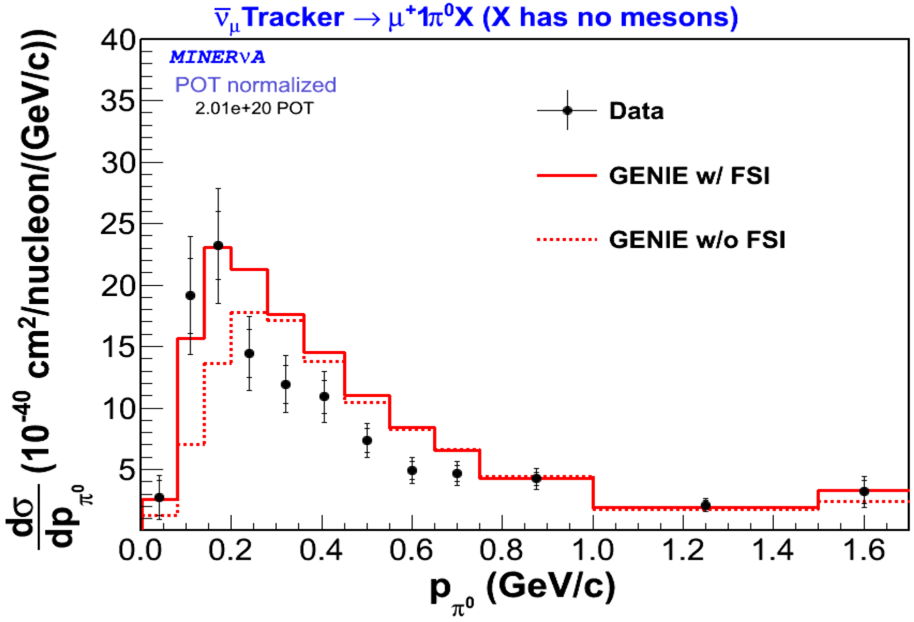


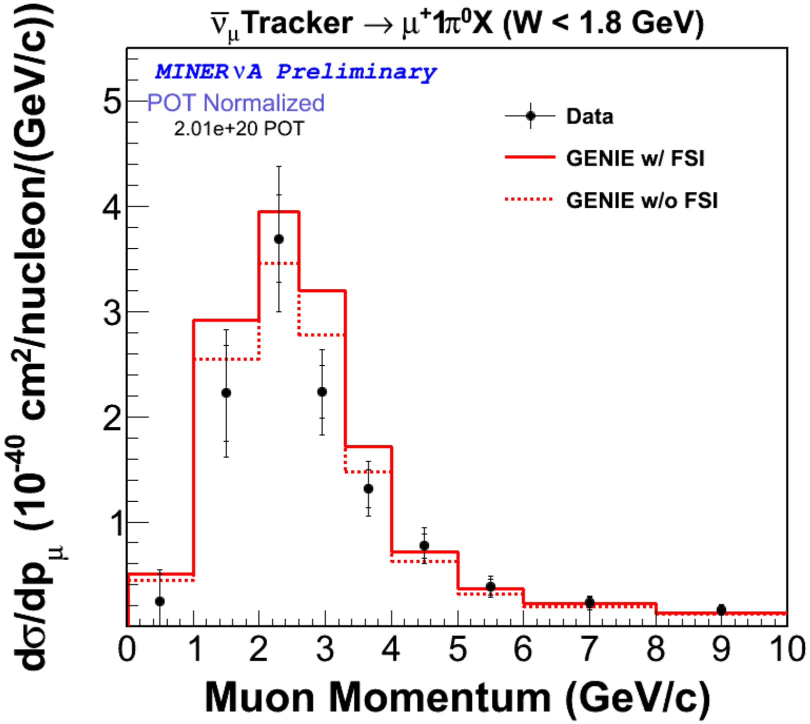
$\bar{\nu}_\mu$ π^0 production



Pion and muon spectra

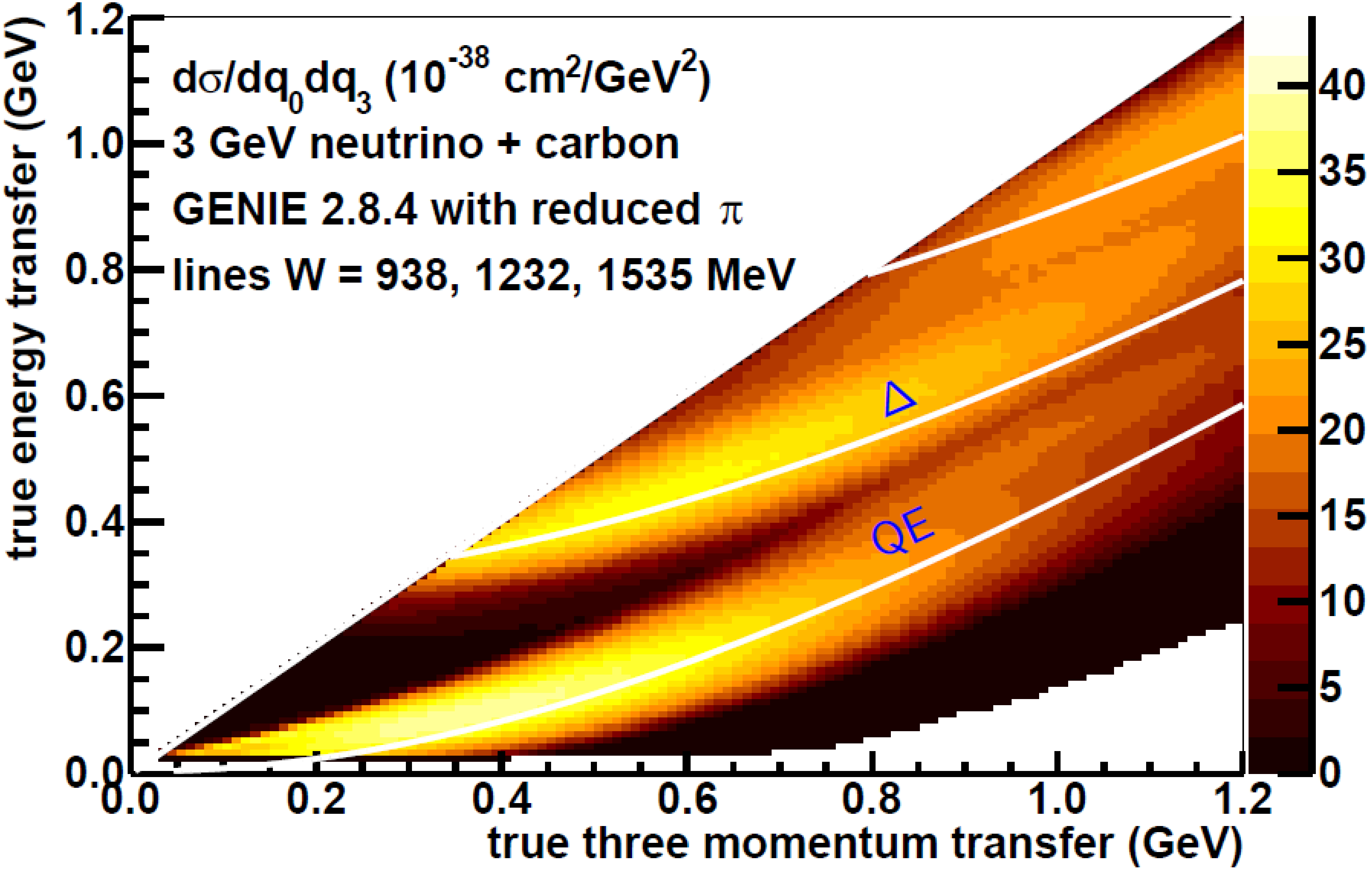
$\bar{\nu}_\mu$ CC π^0


Phys.Lett. B749 (2015) 130-136

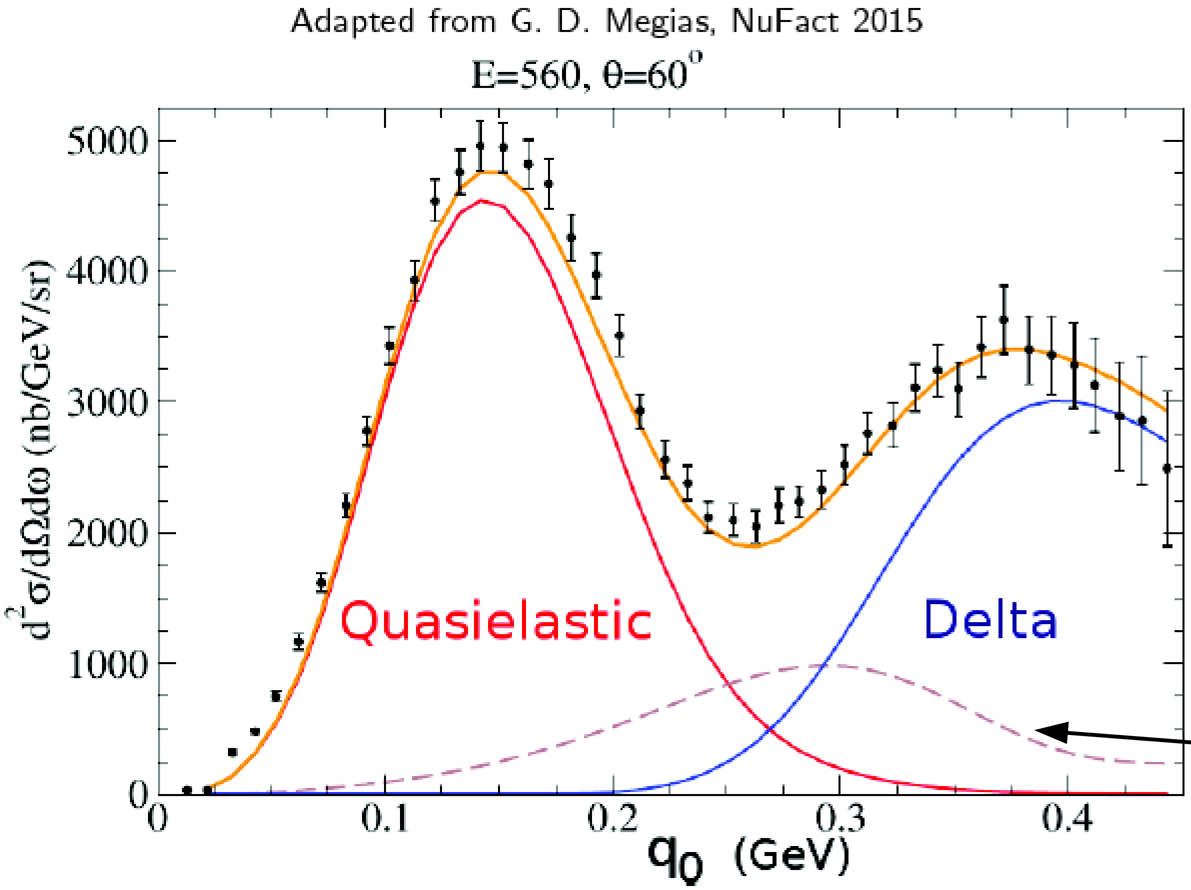


- π^0 spectrum is affected by FSI, μ^+ spectrum is not
  - FSI enhances the cross section due to $\pi^\pm$ charge exchange
- Shapes agree with GENIE

Nuclear effects at low momentum transfer



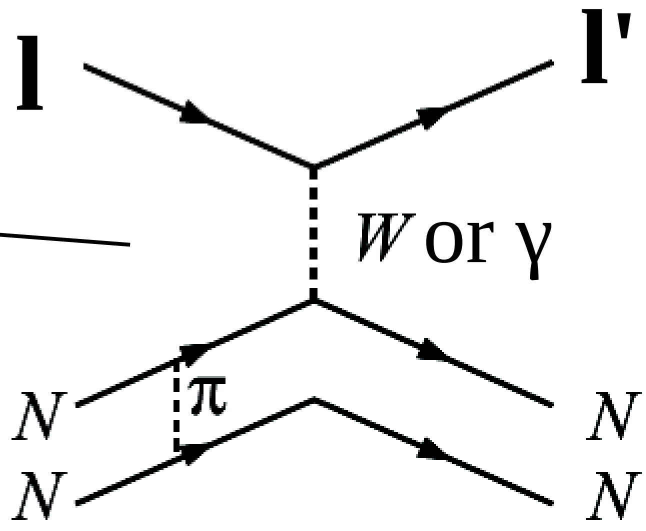
Old news in electron scattering



Adapted from G. D. Megias, NuFact 2015

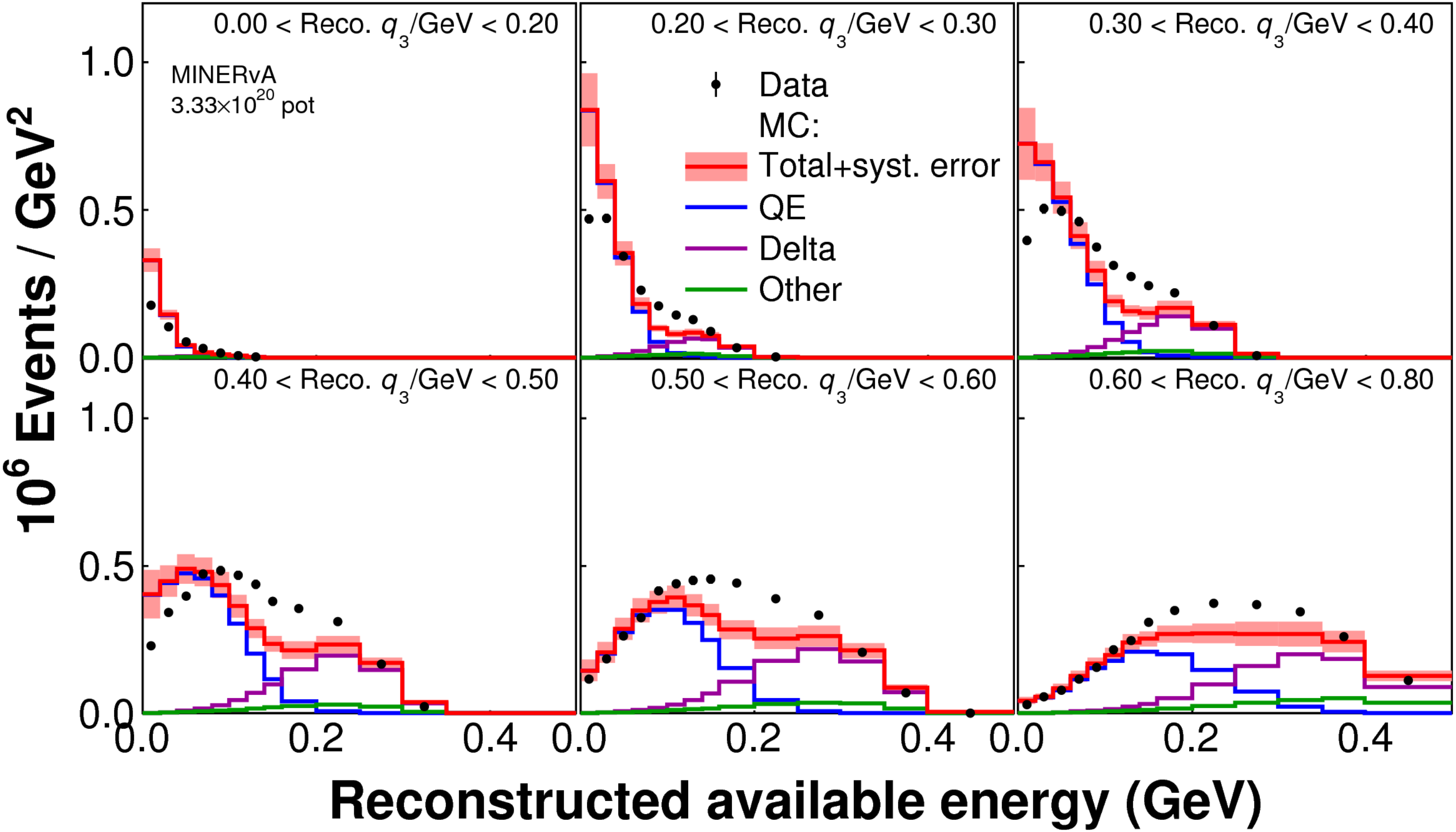
$$q_0 = E_e - E_{e'}$$

MINERvA can measure q_0 and q_3 by looking at the hadronic side of the interaction



Comparison with GENIE

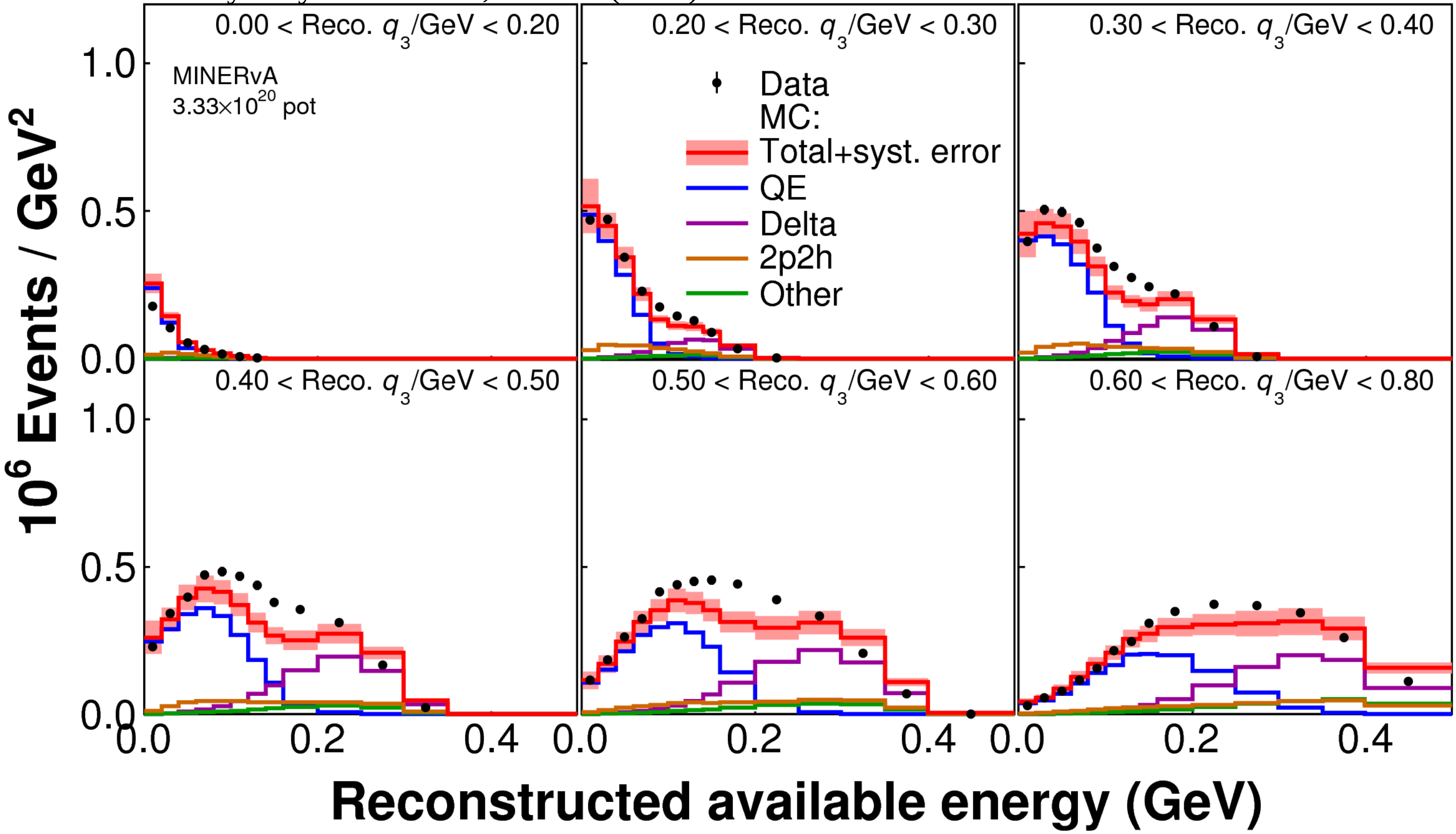
π production reduced to agree with MINERvA data



add 2p2h, RPA effects

theory: Phys. Rev. D 88, 113007 (2013)

Our paper: arXiv:1511.05944 (PRL)



Summary

- MINERvA is measuring neutrino-nucleus cross sections with unprecedented precision

  → better models for neutrino oscillation experiments

- Taking data now in higher-energy beam configuration
- Much more to come – stay tuned!

Thank you

The MINERvA collaboration

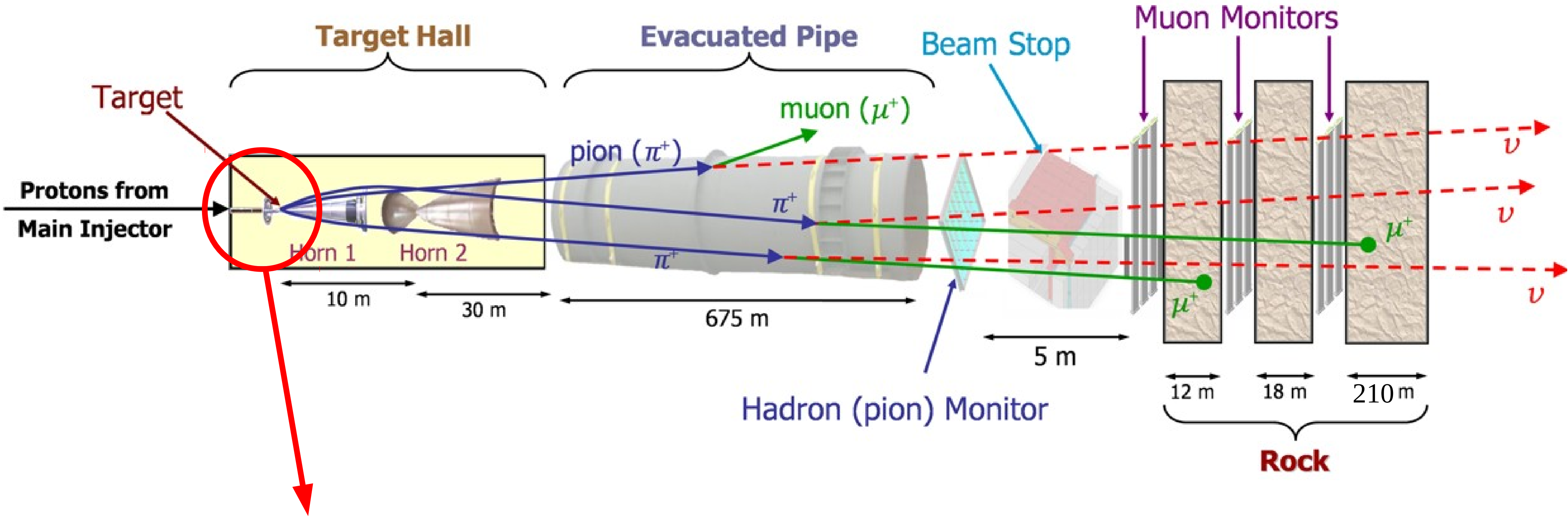
Backup slides

Flux backups

1 NuMI beam
2 electron neutrino flux
3-4 neutrino-electron scattering constraint

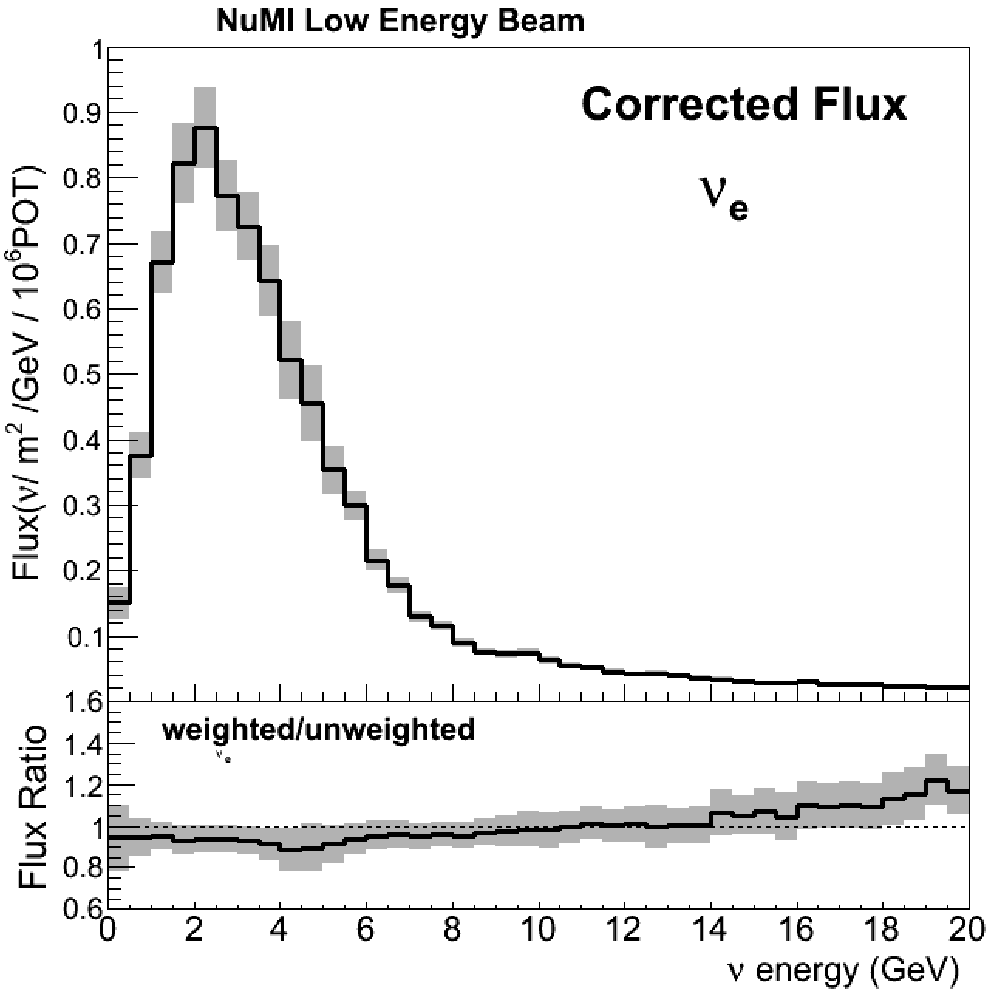
The NuMI neutrino beam

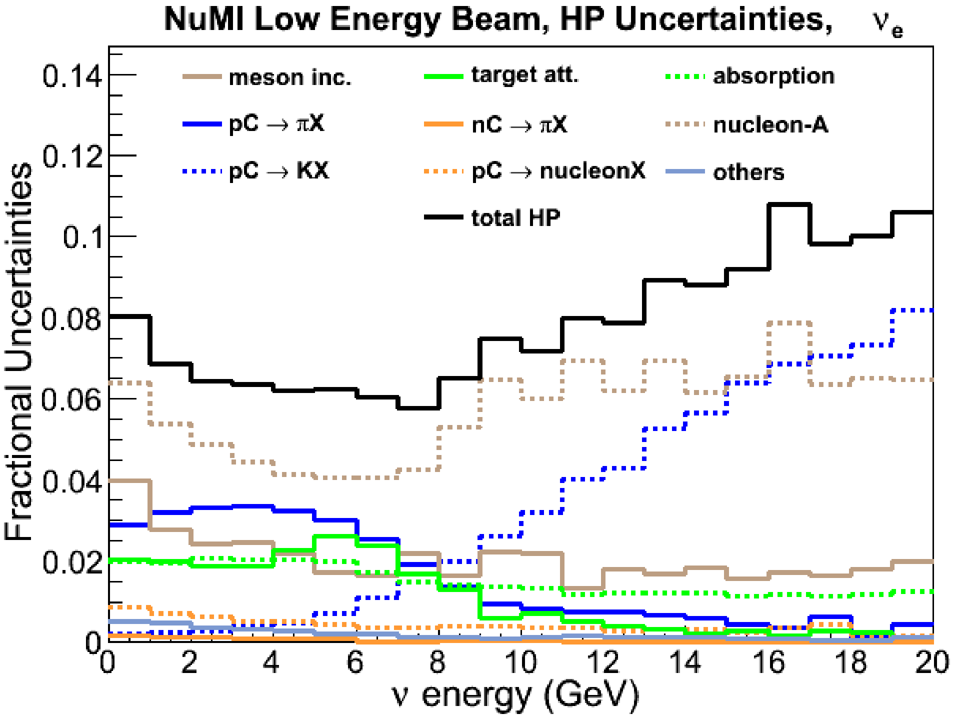
Z. Pavlovic



Must predict proton + carbon → pions interactions in order to know the neutrino flux

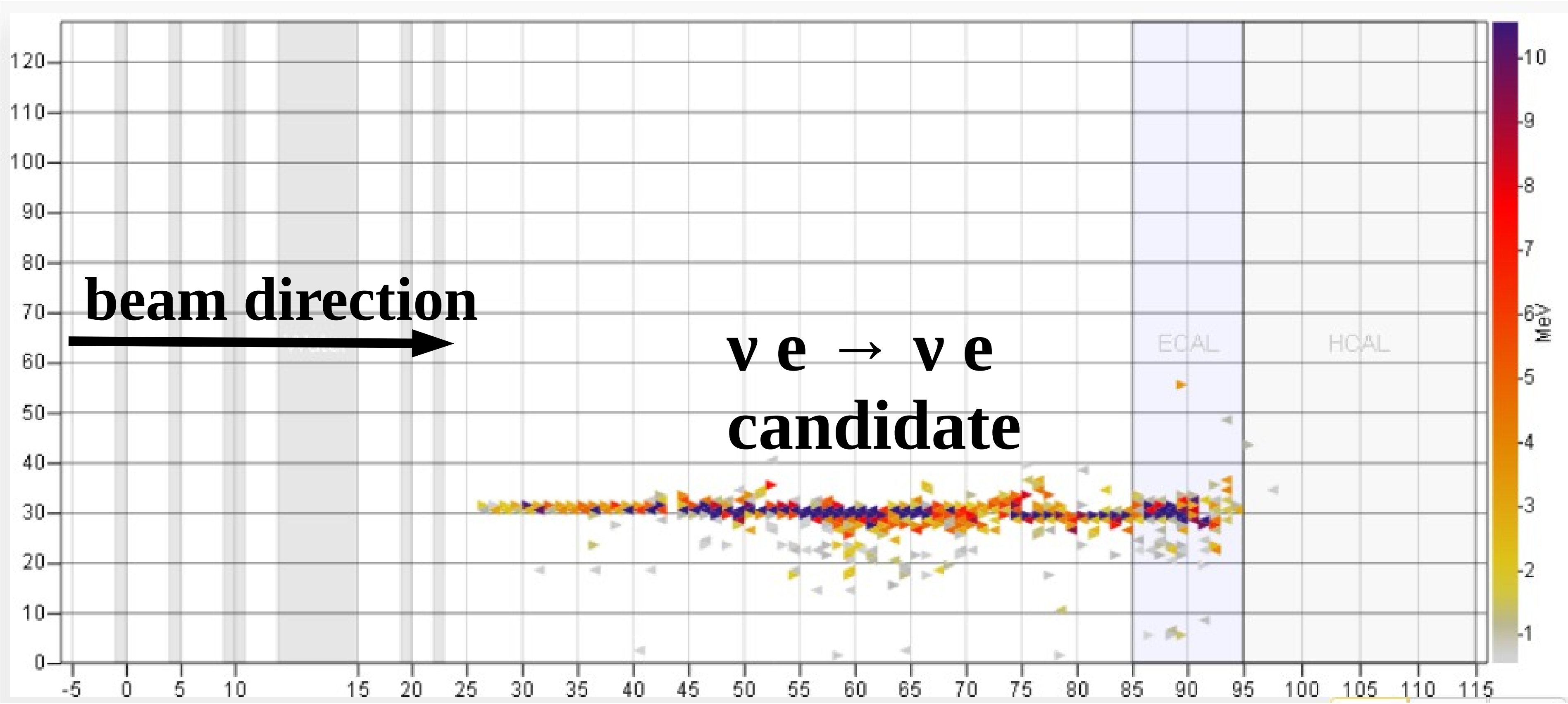
Updated flux prediction based on hadron production data





Neutrino-electron scattering constrains the flux

top view



strip number

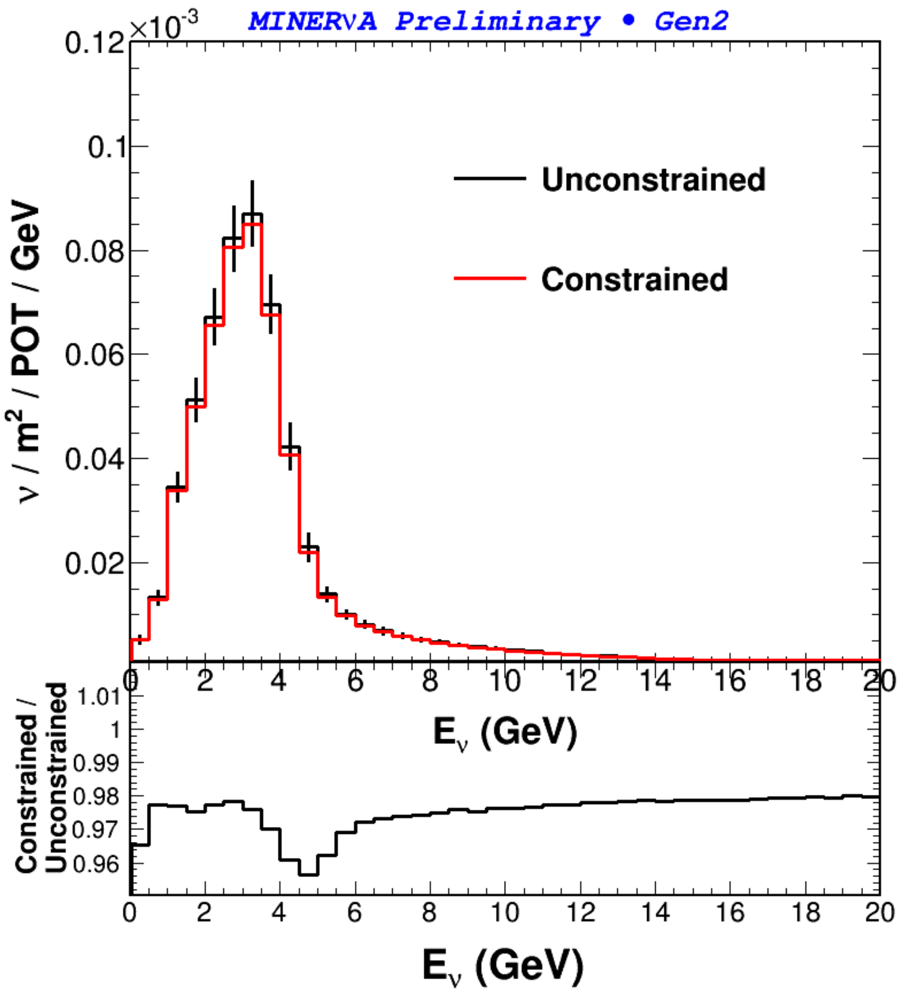
beam direction

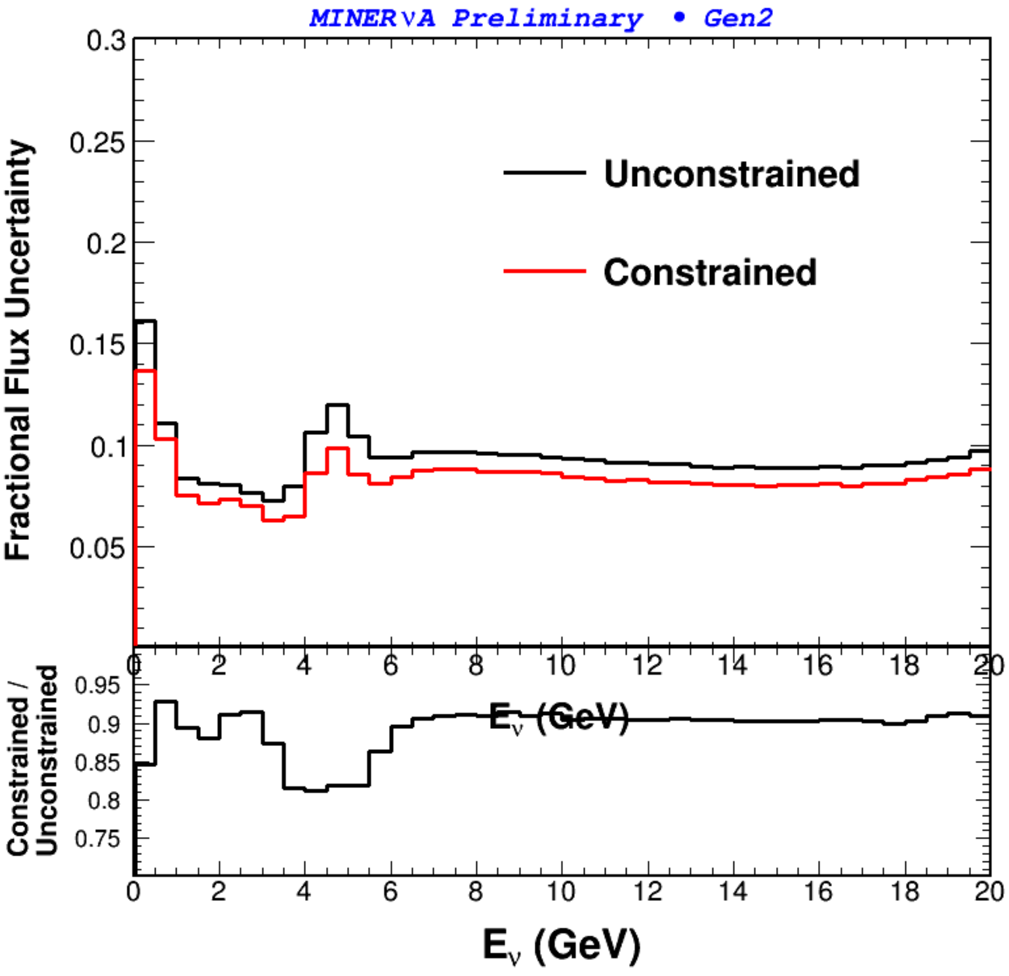
ν e → ν e candidate

hit energy

module number

Neutrino-electron scattering constrains the flux





ν_μ CCQE backups

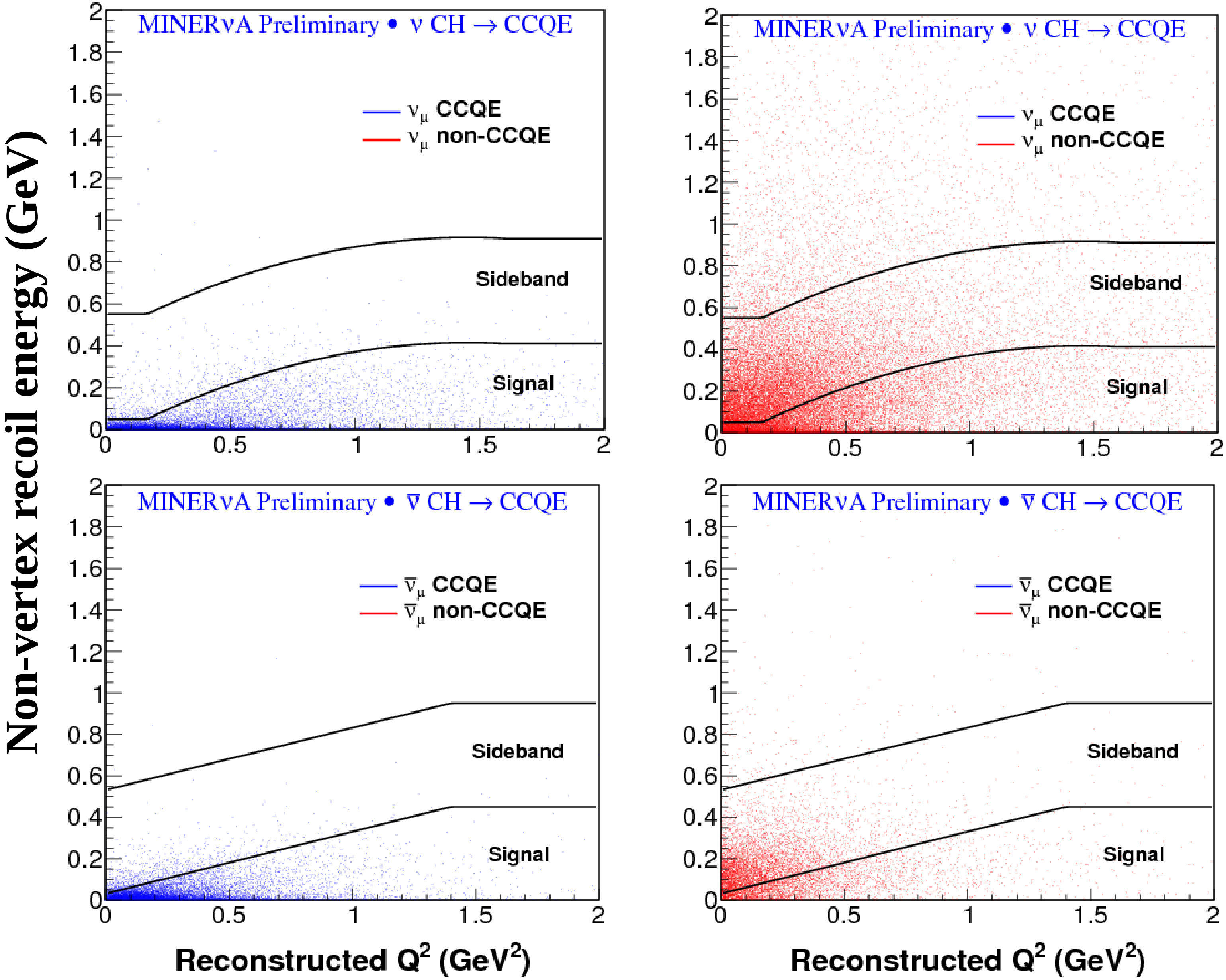
1 event selection
2 vertex energy
3-4 vertex energy fits

CCQE event selection

ν_μ

QE

$\bar{\nu}_\mu$

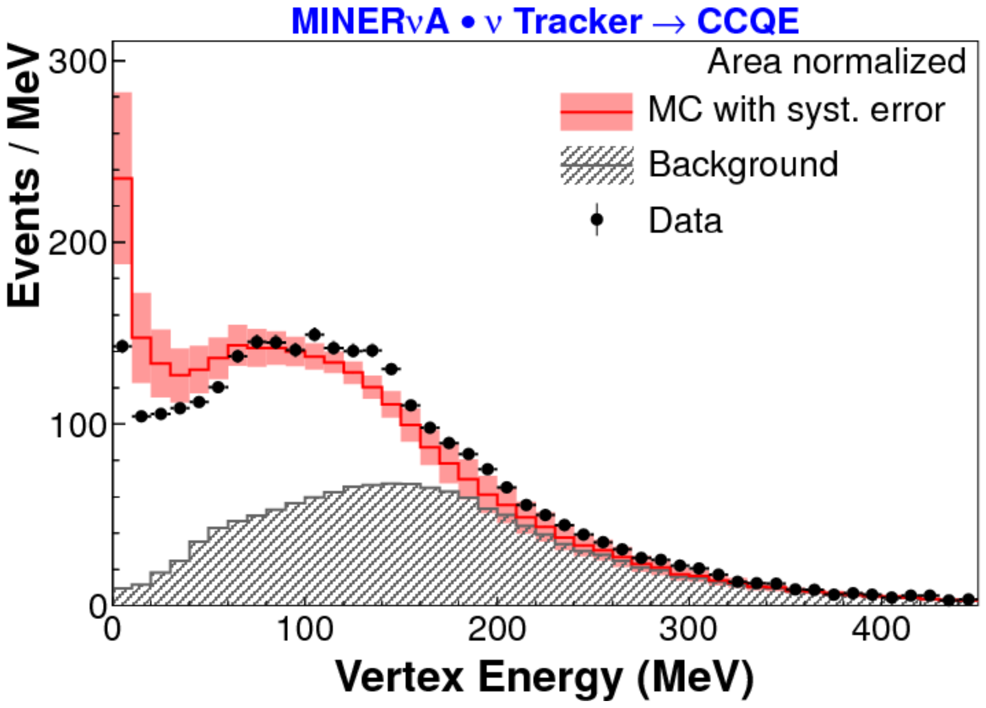


ν_μ

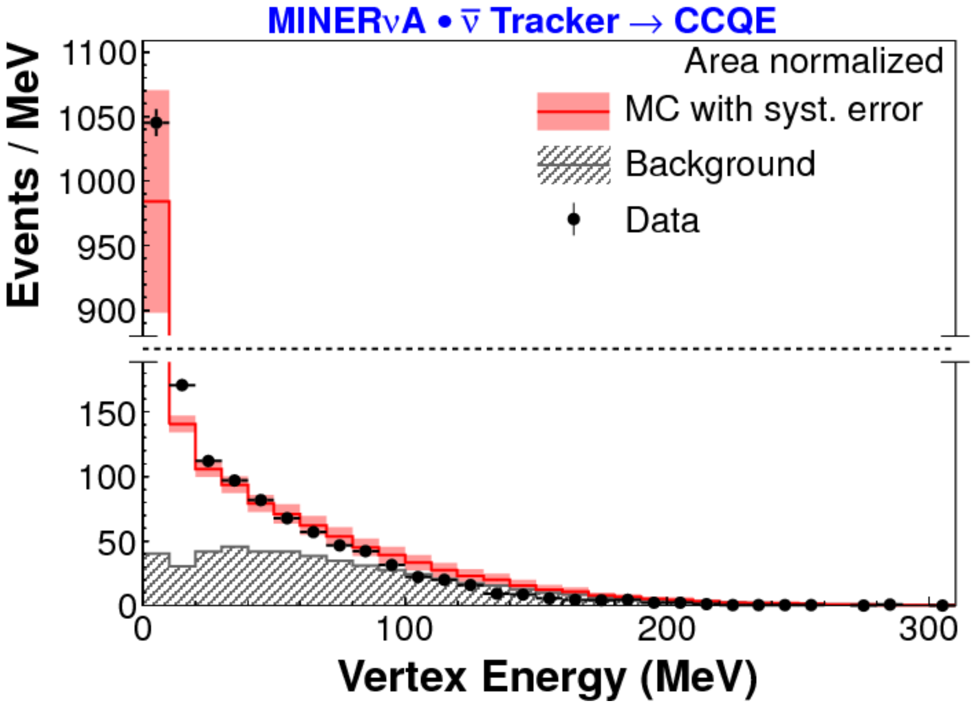
$\cancel{\text{QE}}$

$\bar{\nu}_\mu$

Vertex energy

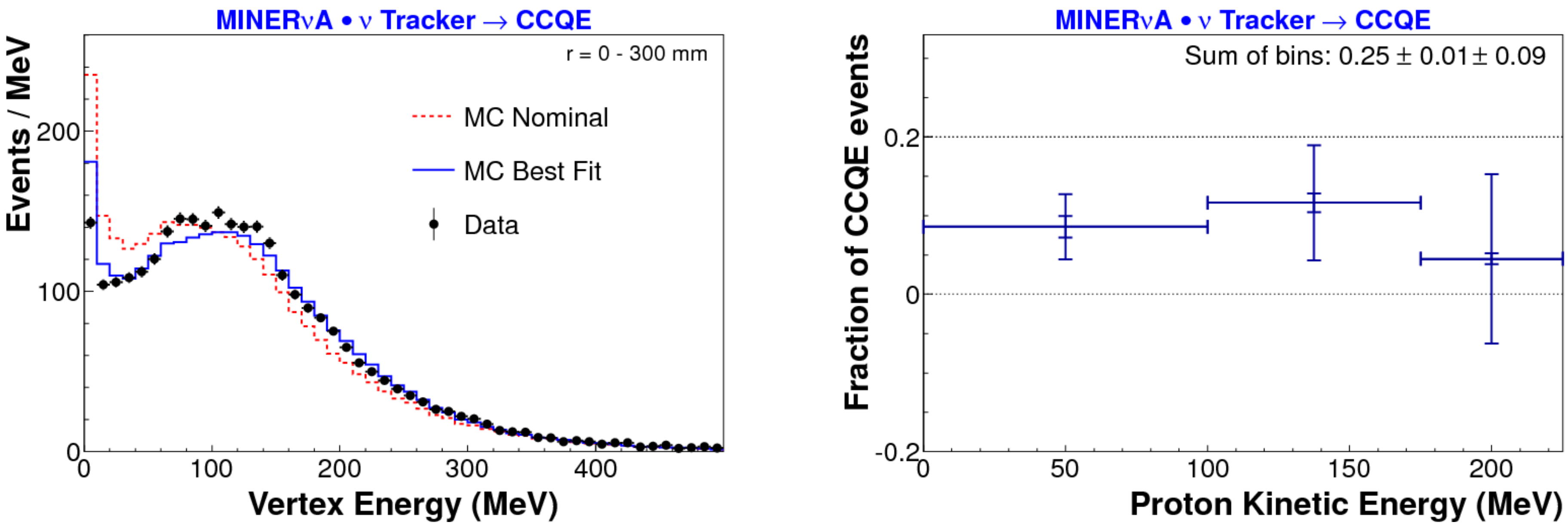


Neutrino mode - 30cm



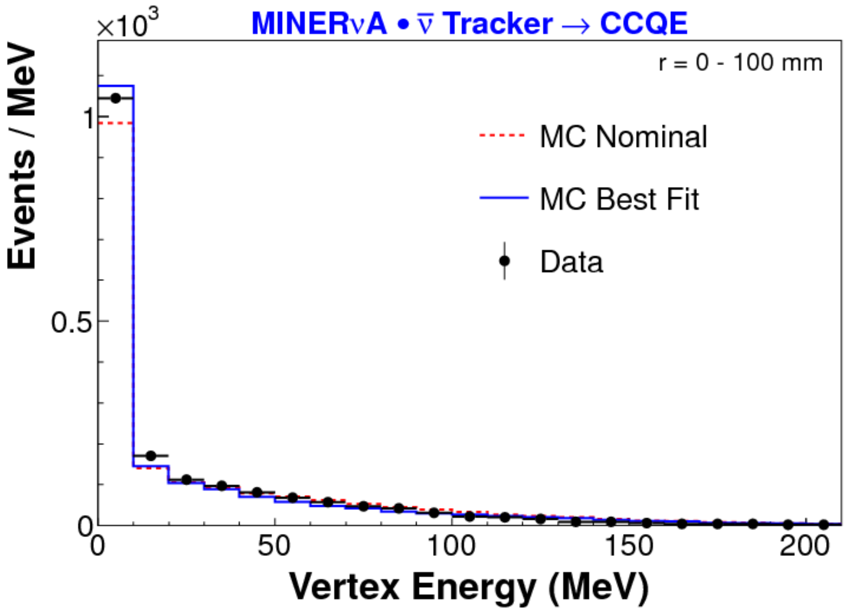
Antineutrino mode - 10cm

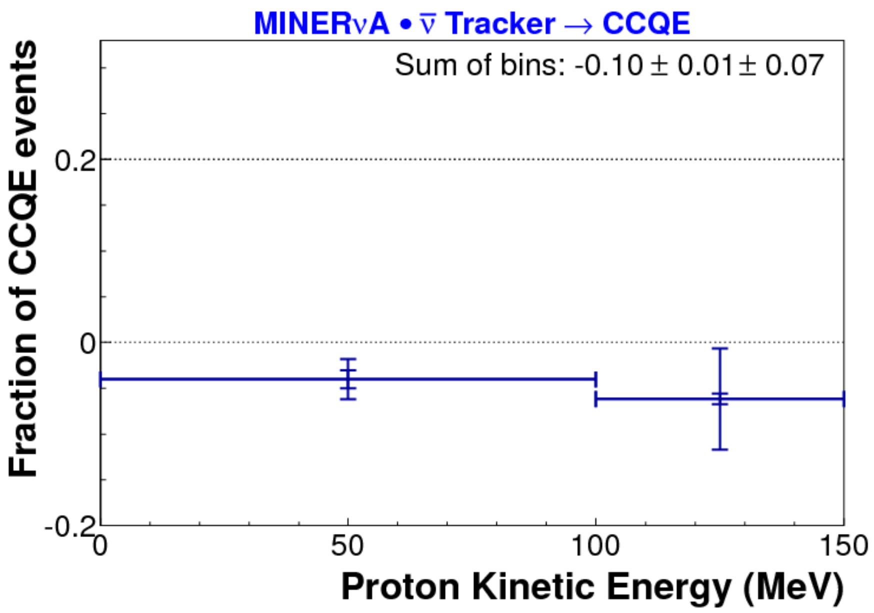
Vertex energy fit – neutrino



- Fit wants to add low-energy protons to (25 ± 10)% of CCQE events

Vertex energy fit – antineutrino



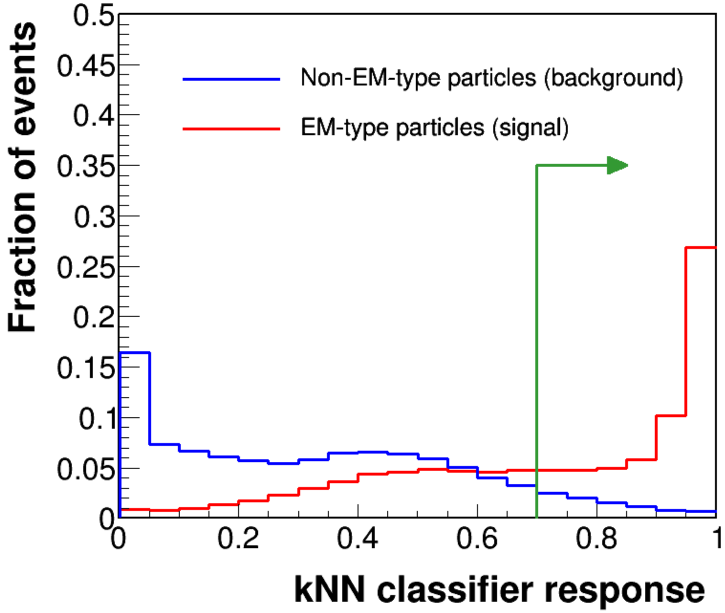


- Consistent with no additional protons
- Fit wants to “add” proton to (-10 ± 8)% of CCQE events

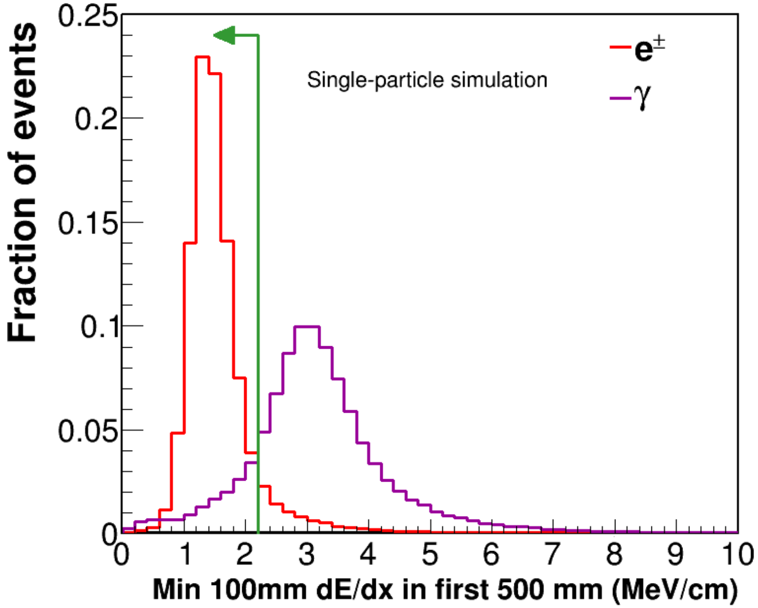
ν_e CCQE backups

1 event selection
2 electron energy and angle distributions
3 summary of systematic uncertainties
4 correlated uncertainties

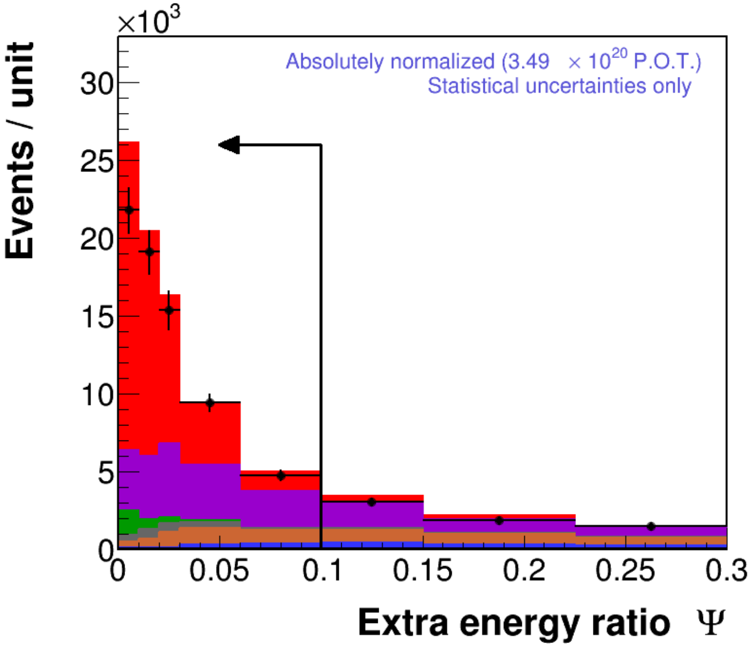
ν_e CCQE selection



1. Select EM-like showers with kNN classifier

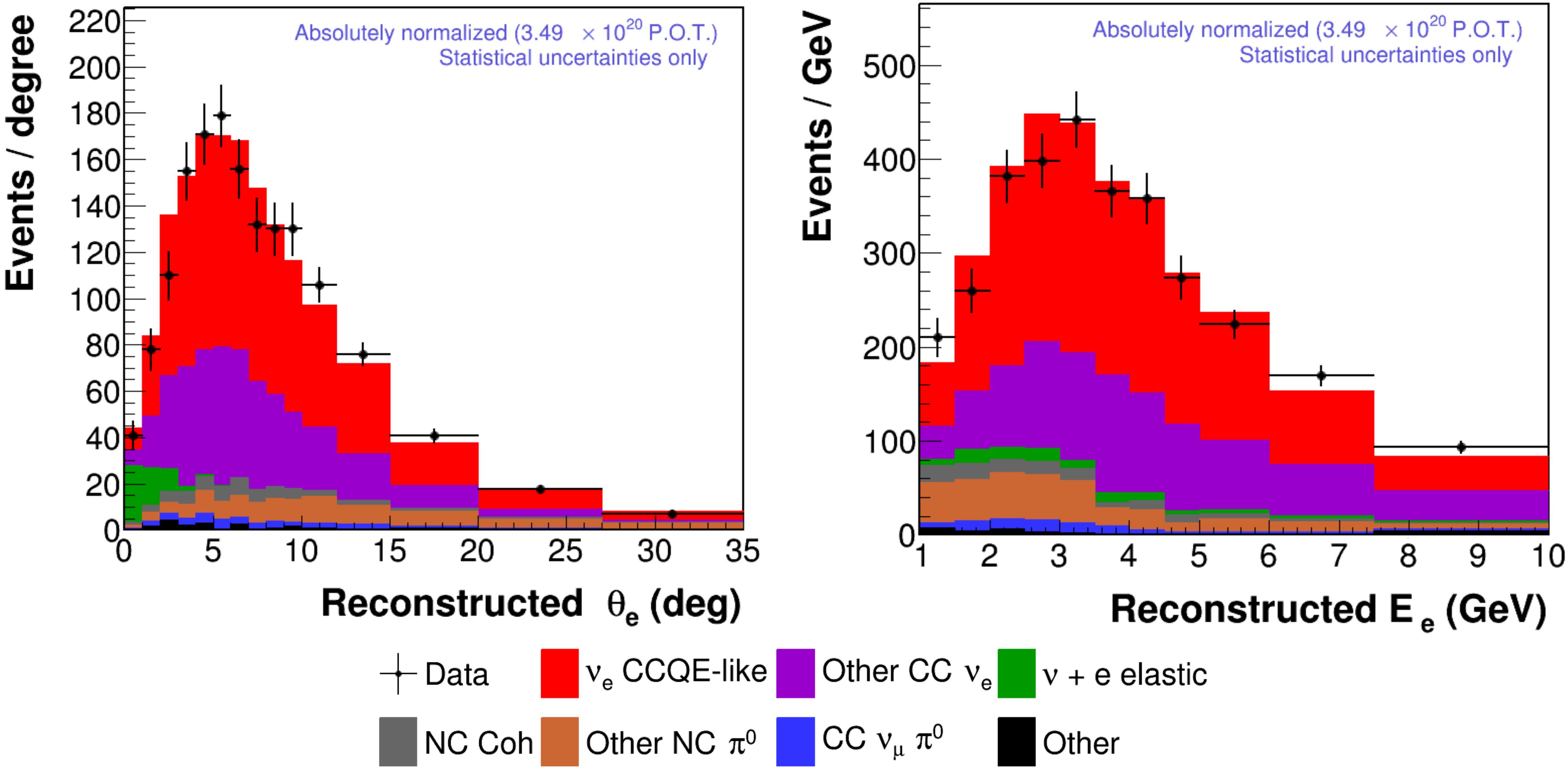


2. Select electron-like showers by requiring small energy at front of track



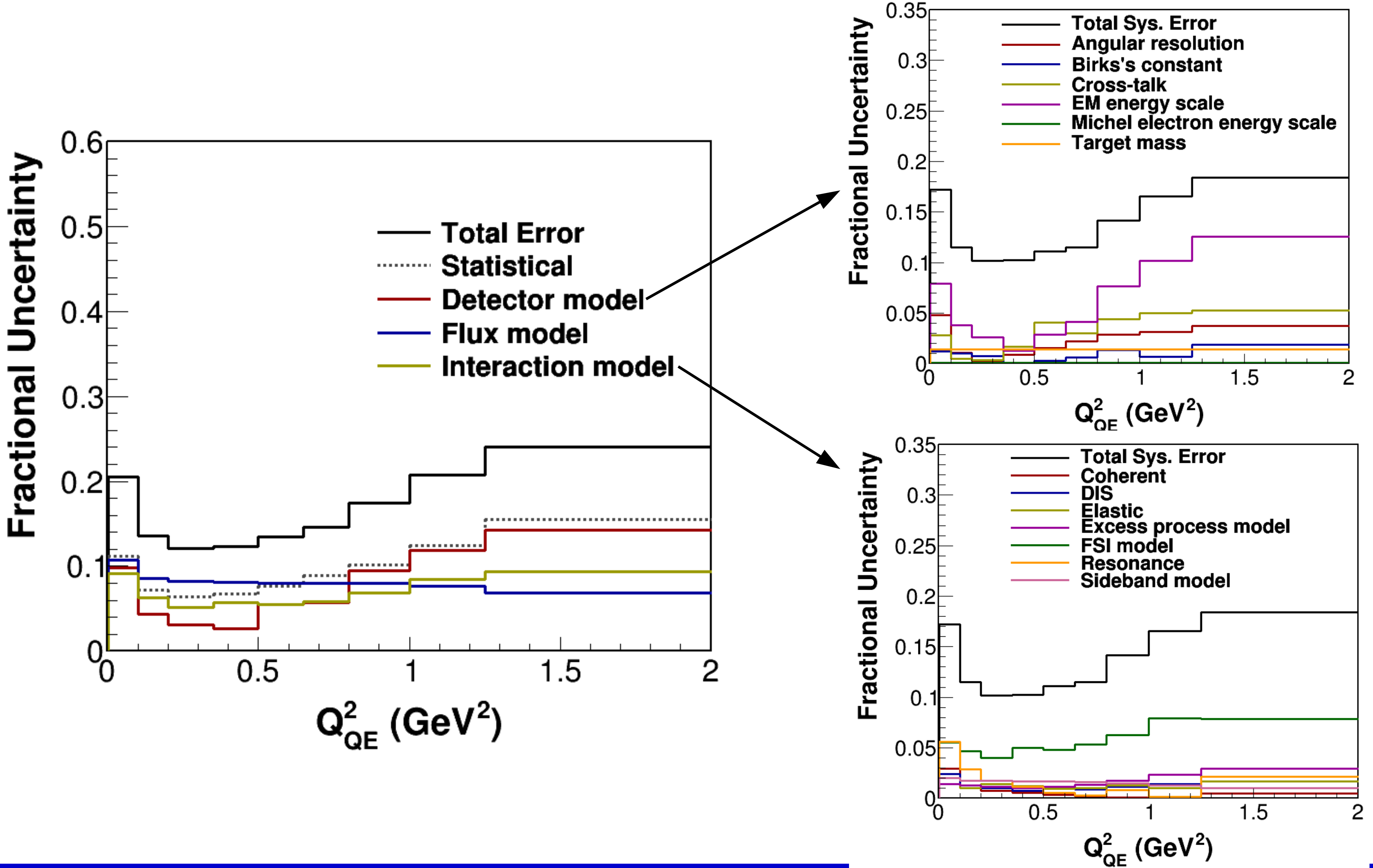
3. Select QE-like events be requiring small extra energy in detector

ν_e CCQE selected events

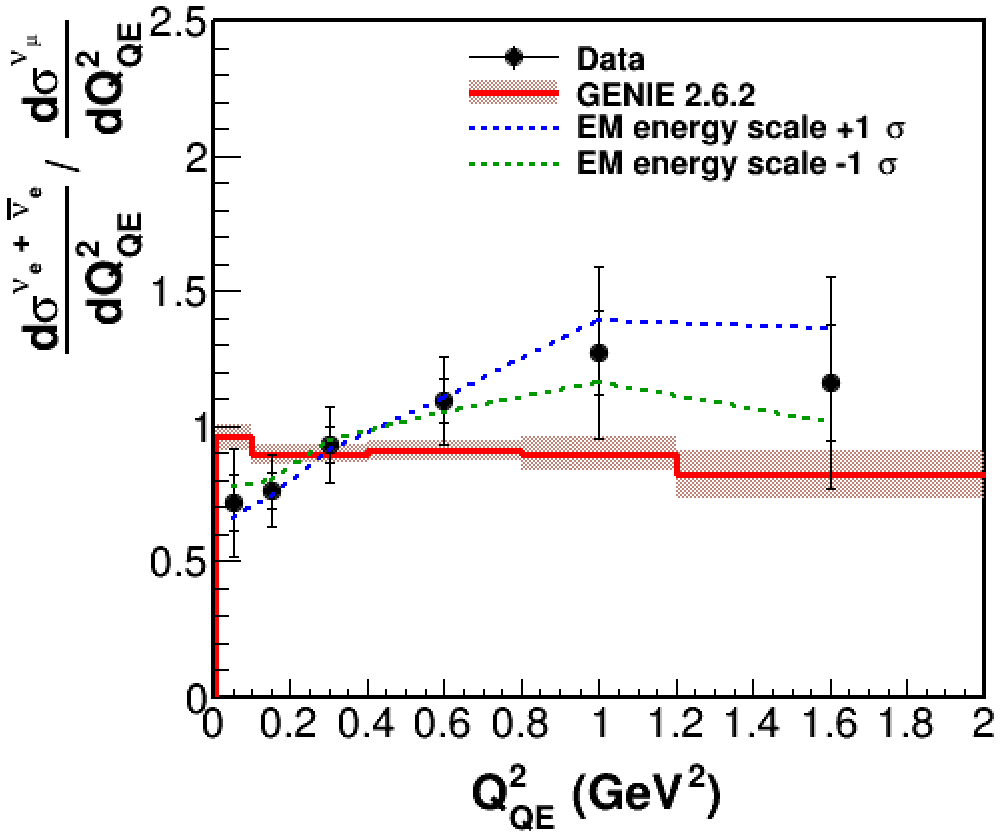


$$Q^2_{QE} = -m_l^2 + 2E_\nu^{QE}(E_l - \sqrt{E_l^2 - m_l^2}cos\theta_l)$$

ν_e CCQE uncertainties



ν_e CCQE correlated errors



Ratio is not exactly 1.0 in simulation because:

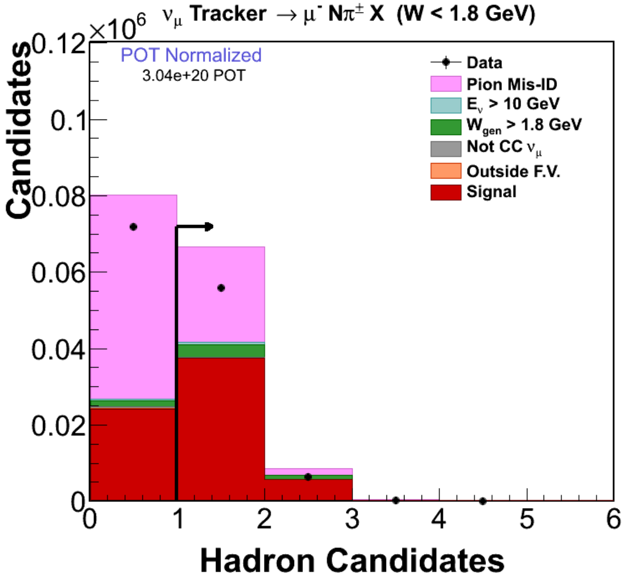
1. Electron XS contains antineutrinos
2. Lepton mass effects

Even though it looks like there is shape, it is consistent with flat due to bin-to-bin correlations

Pion production backups

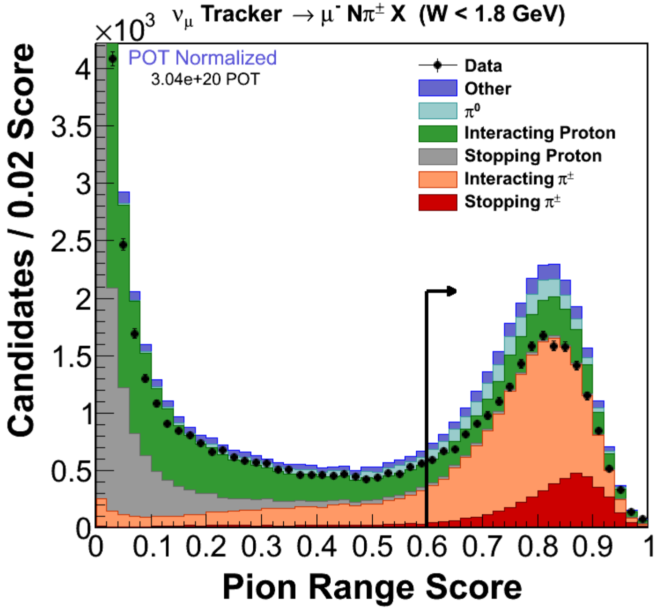
1 $\pi^{\pm}$ event selection
2 π^0 invariant mass distribution
3 FSI summary

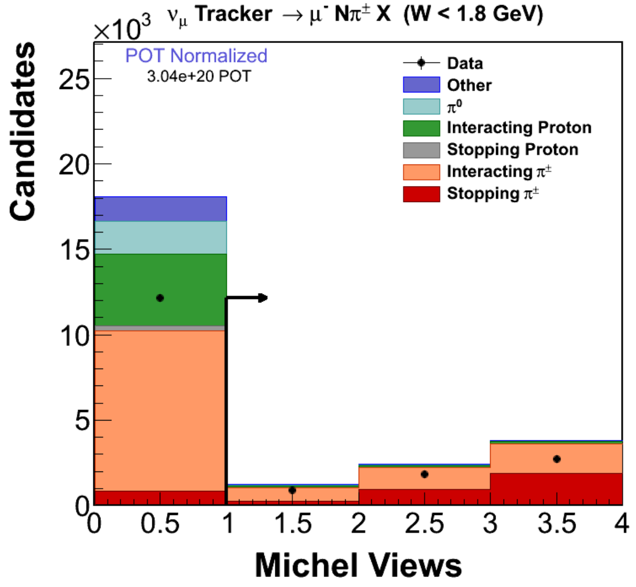
$\pi^{\pm}$ event selection



1. Require at least one hadron track candidate

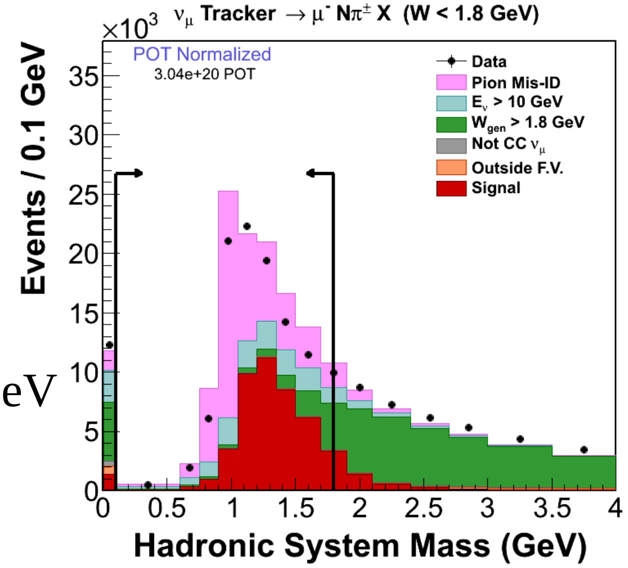
2. Require pion-like track dE/dX



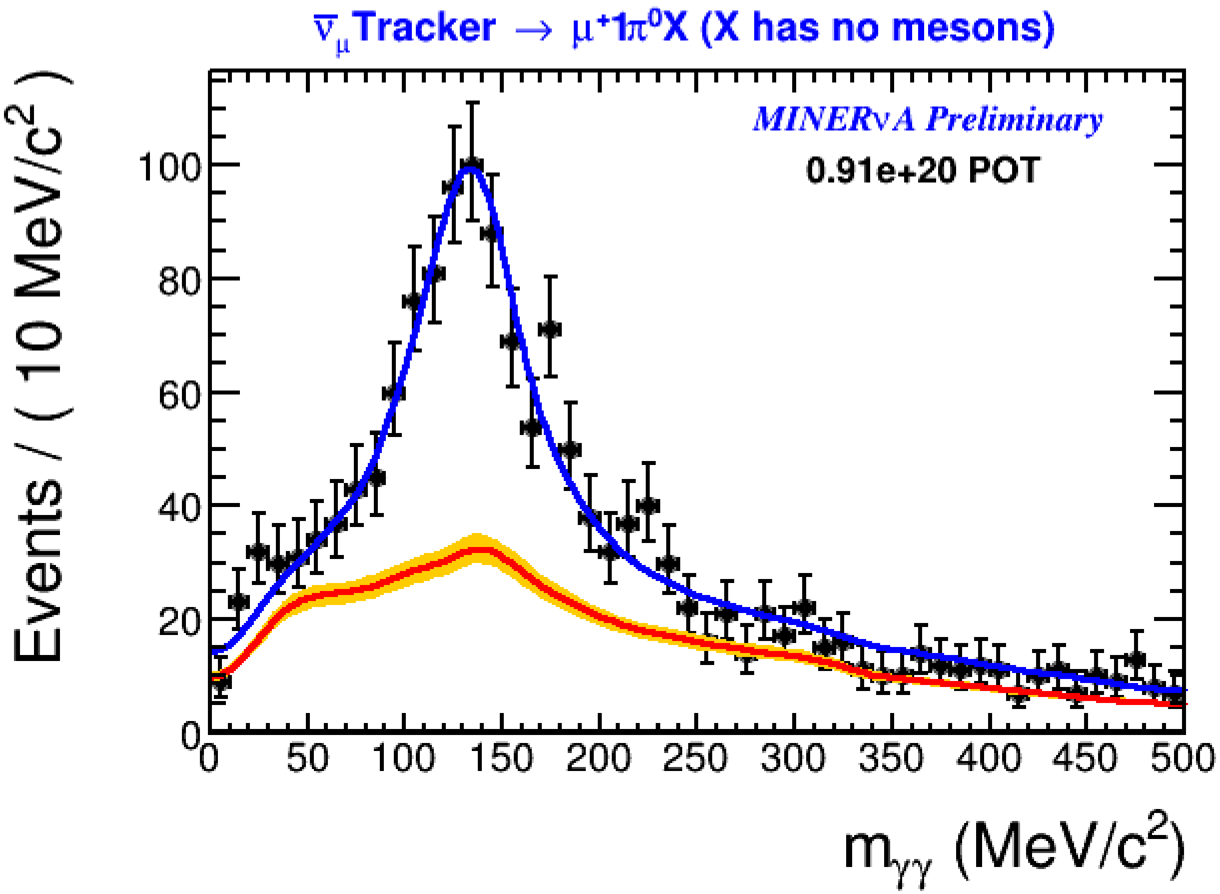


3. Require endpoint decay electron from π → μ → e

4. Require W < 1.8 GeV

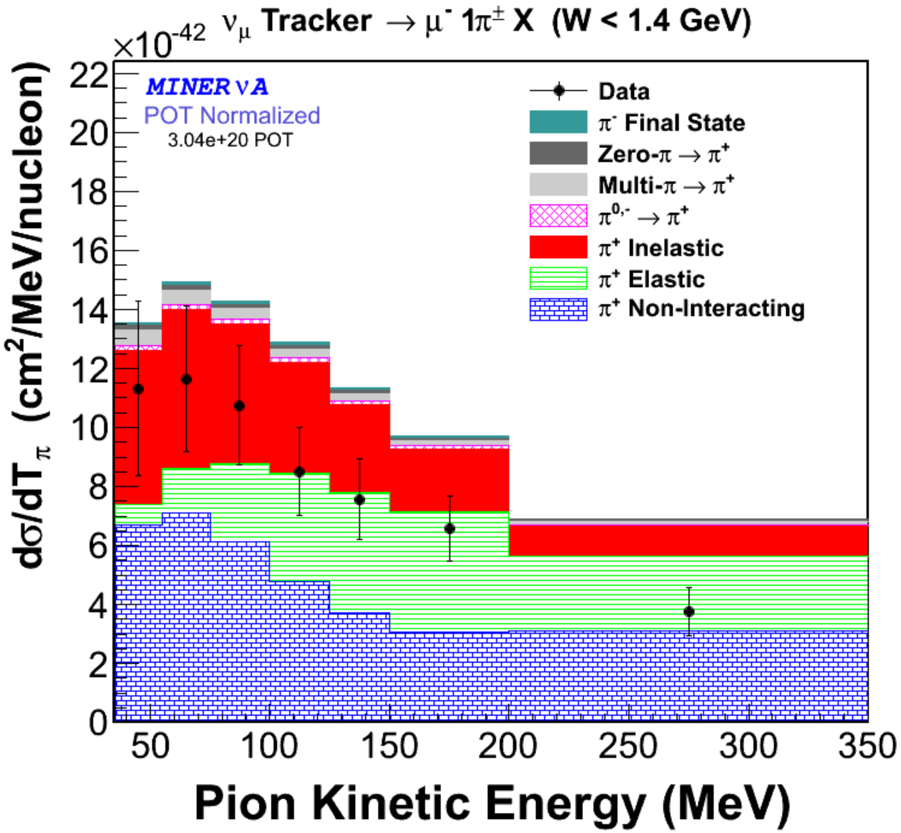


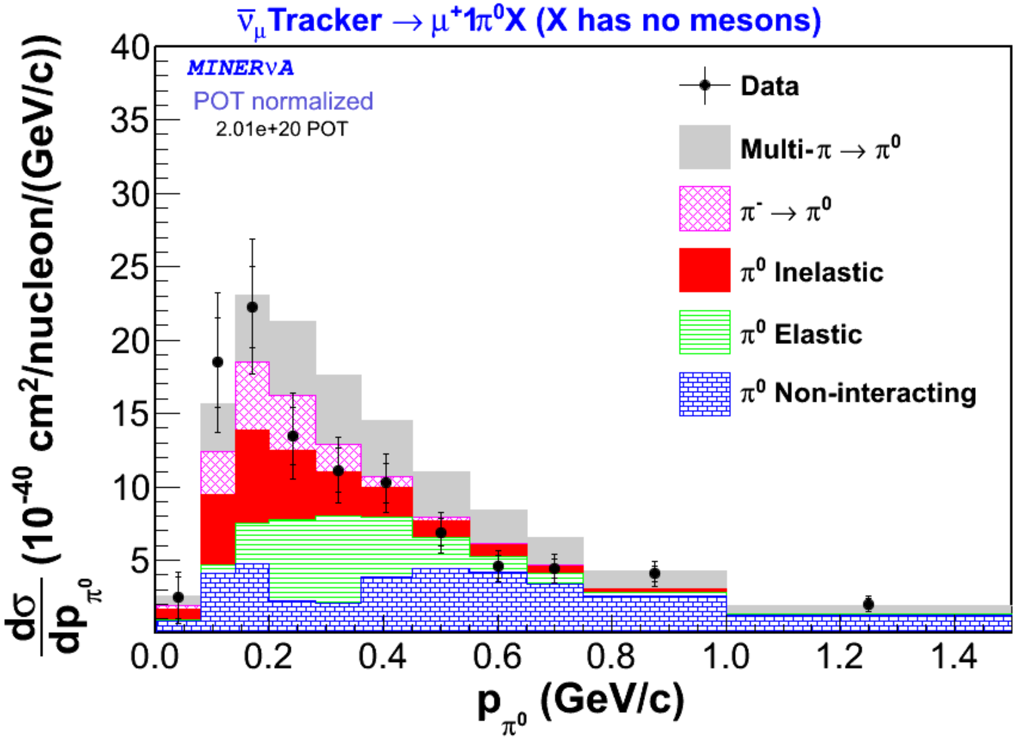
π^0 event selection



Require two photon showers, with invariant mass consistent with π^0

FSI summary

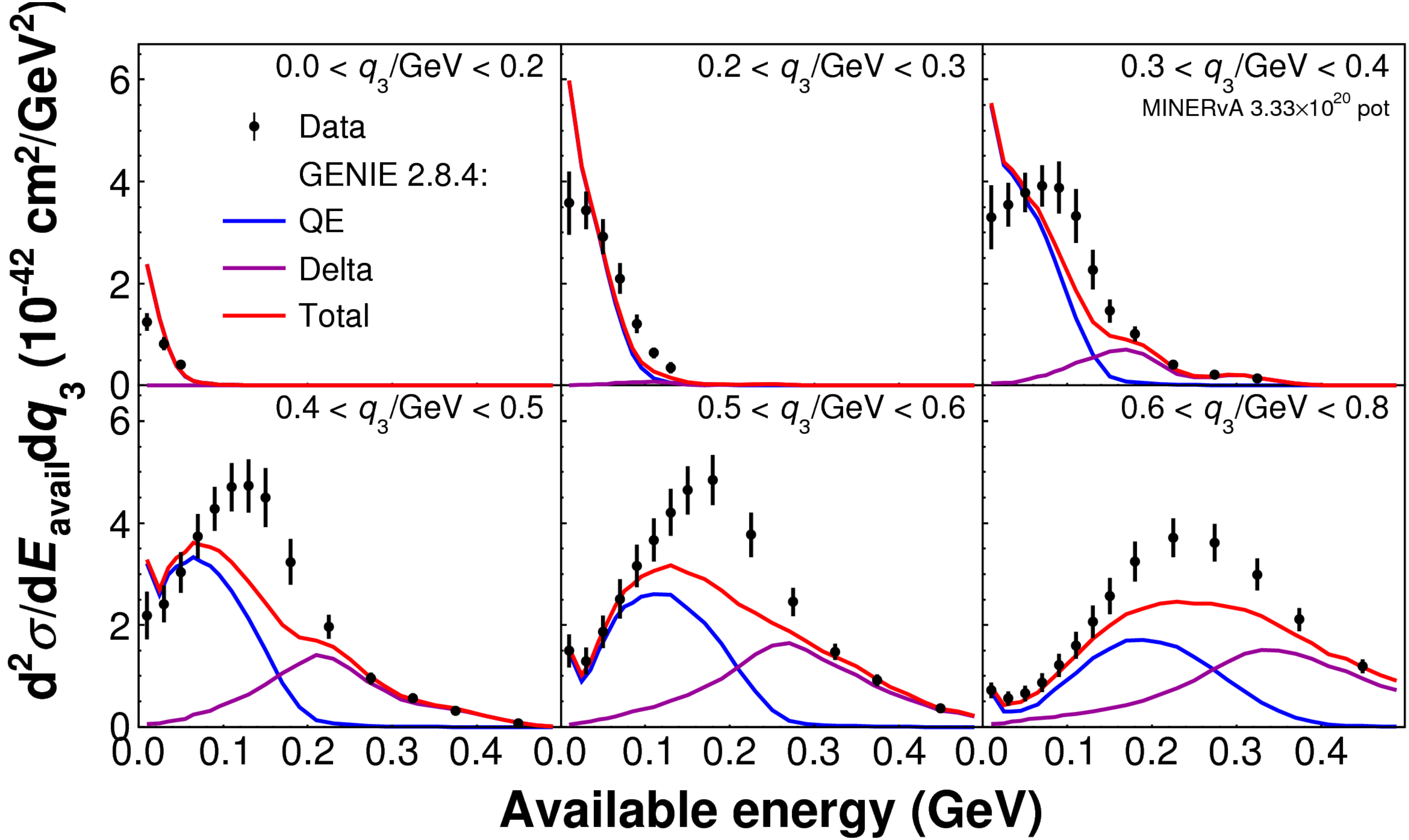

×10^-42 ν_μ Tracker → μ^- 1π^± X (W < 1.4 GeV)
MINERνA
POT Normalized
3.04e+20 POT
Data
π^- Final State
Zero-π → π^+
Multi-π → π^+
π^0,- → π^+
π^+ Inelastic
π^+ Elastic
π^+ Non-Interacting
dσ/dT_π (cm²/MeV/nucleon)
0
2
4
6
8
10
12
14
16
18
20
22
50
100
150
200
250
300
350
Pion Kinetic Energy (MeV)


ν̄_μ Tracker → μ^+1π^0X (X has no mesons)
MINERνA
POT normalized
2.01e+20 POT
Data
Multi-π → π^0
π^- → π^0
π^0 Inelastic
π^0 Elastic
π^0 Non-interacting
dσ/dp_π0 (10^-40 cm²/nucleon/(GeV/c))
5
10
15
20
25
30
35
40
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
p_π0 (GeV/c)

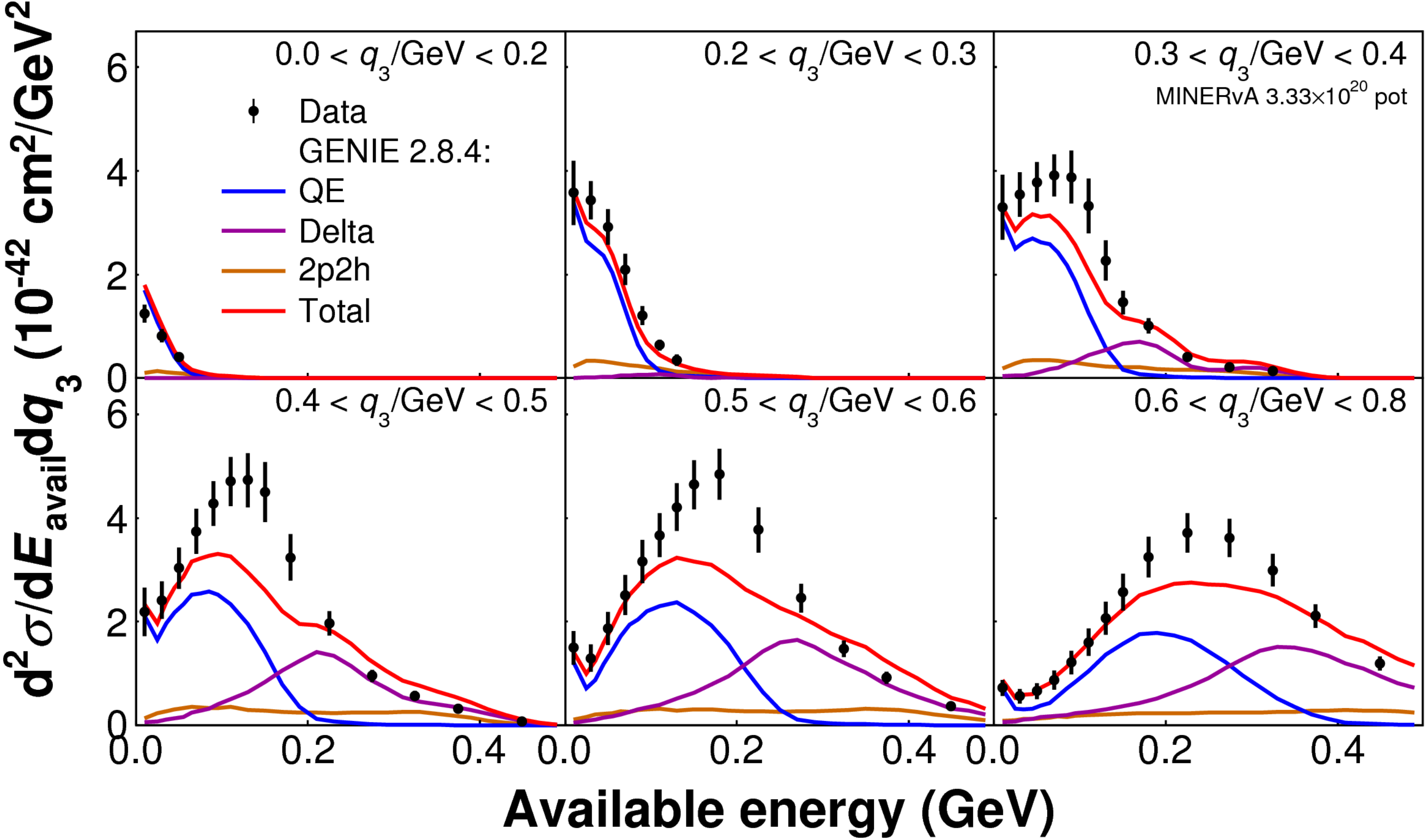
RPA/2p2h backups

1-2 cross sections
3 Model dependence
4 selection efficiency
5-6 2D ratios

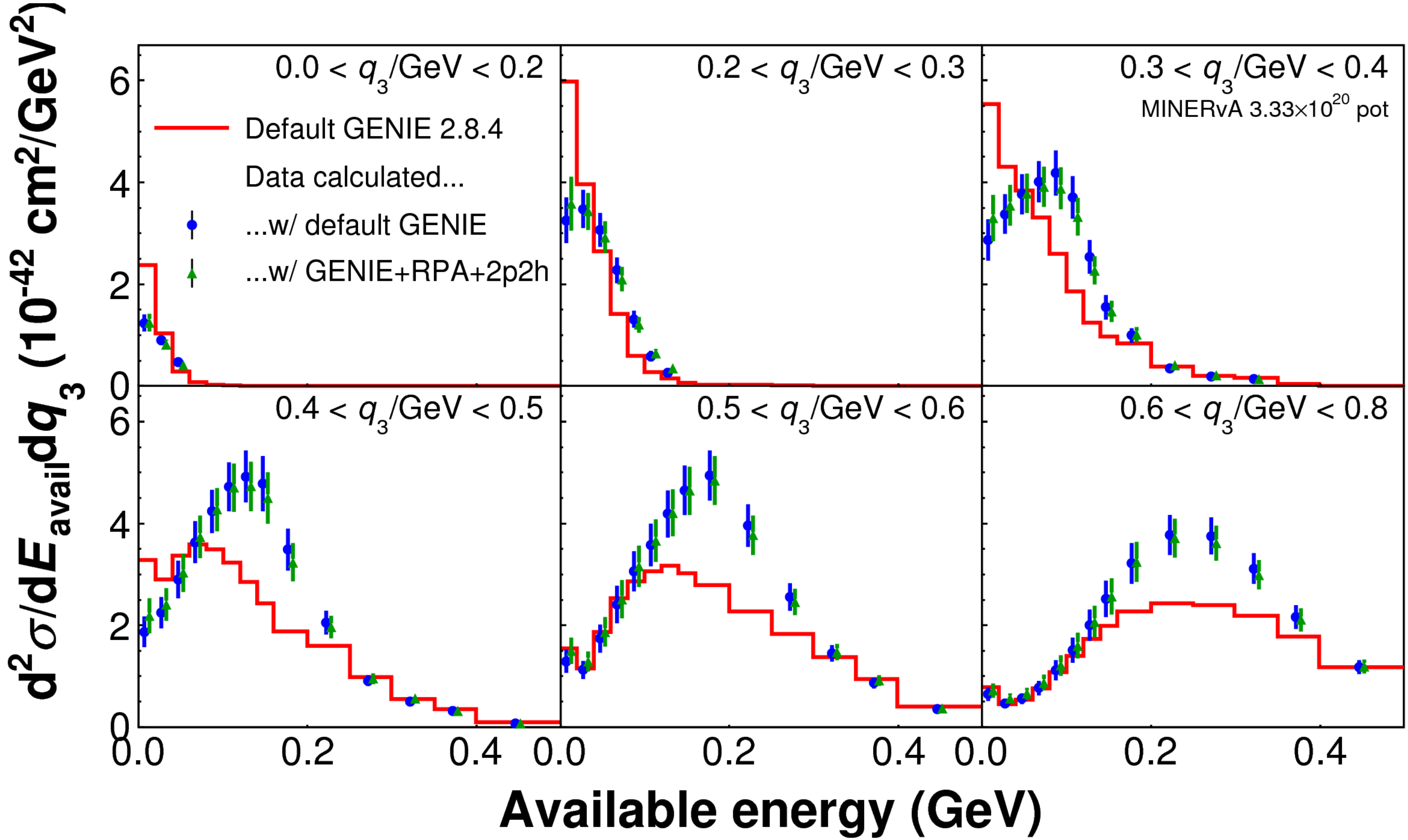
Cross sections vs. GENIE



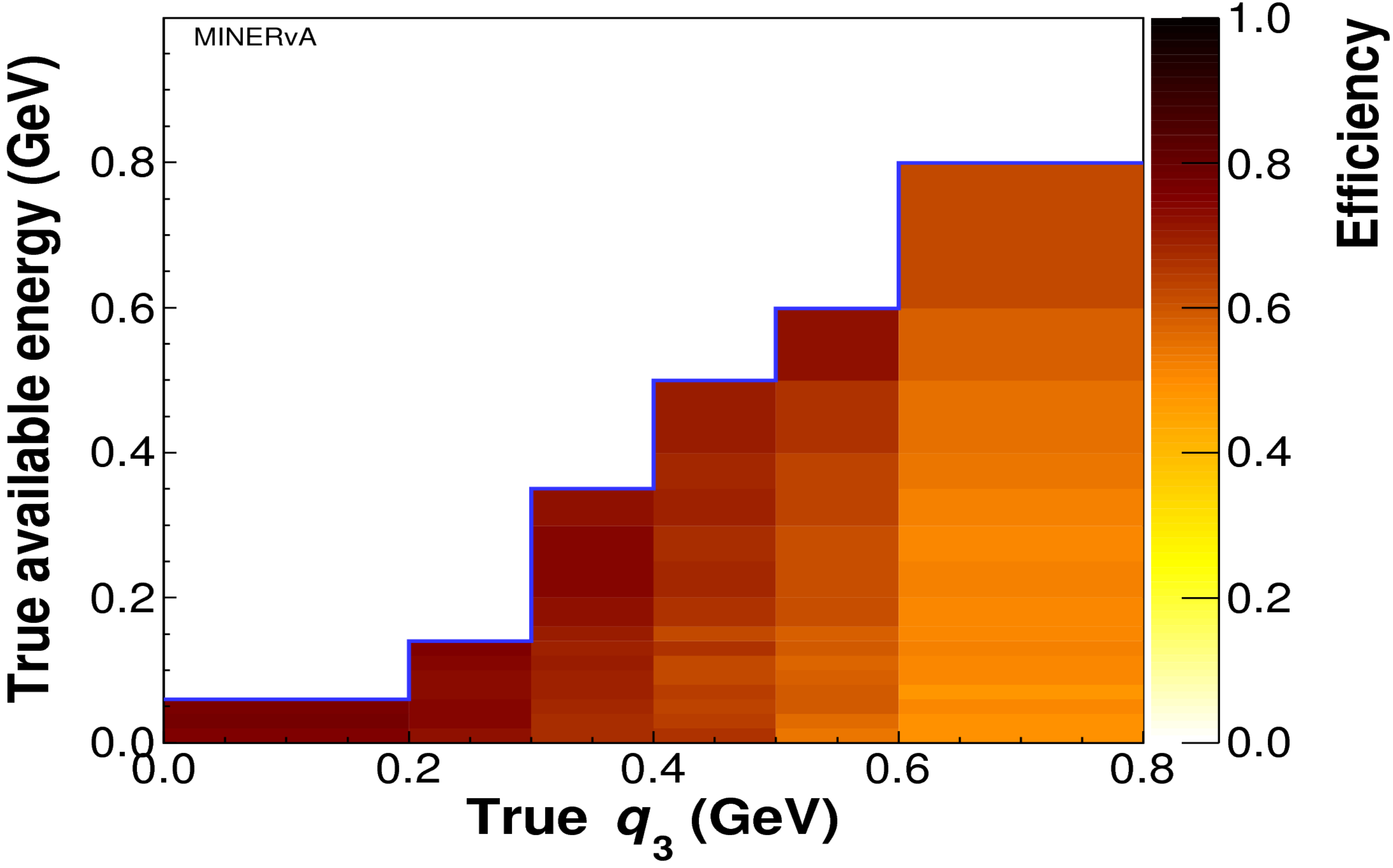
Cross sections vs. GENIE with RPA, 2p2h added



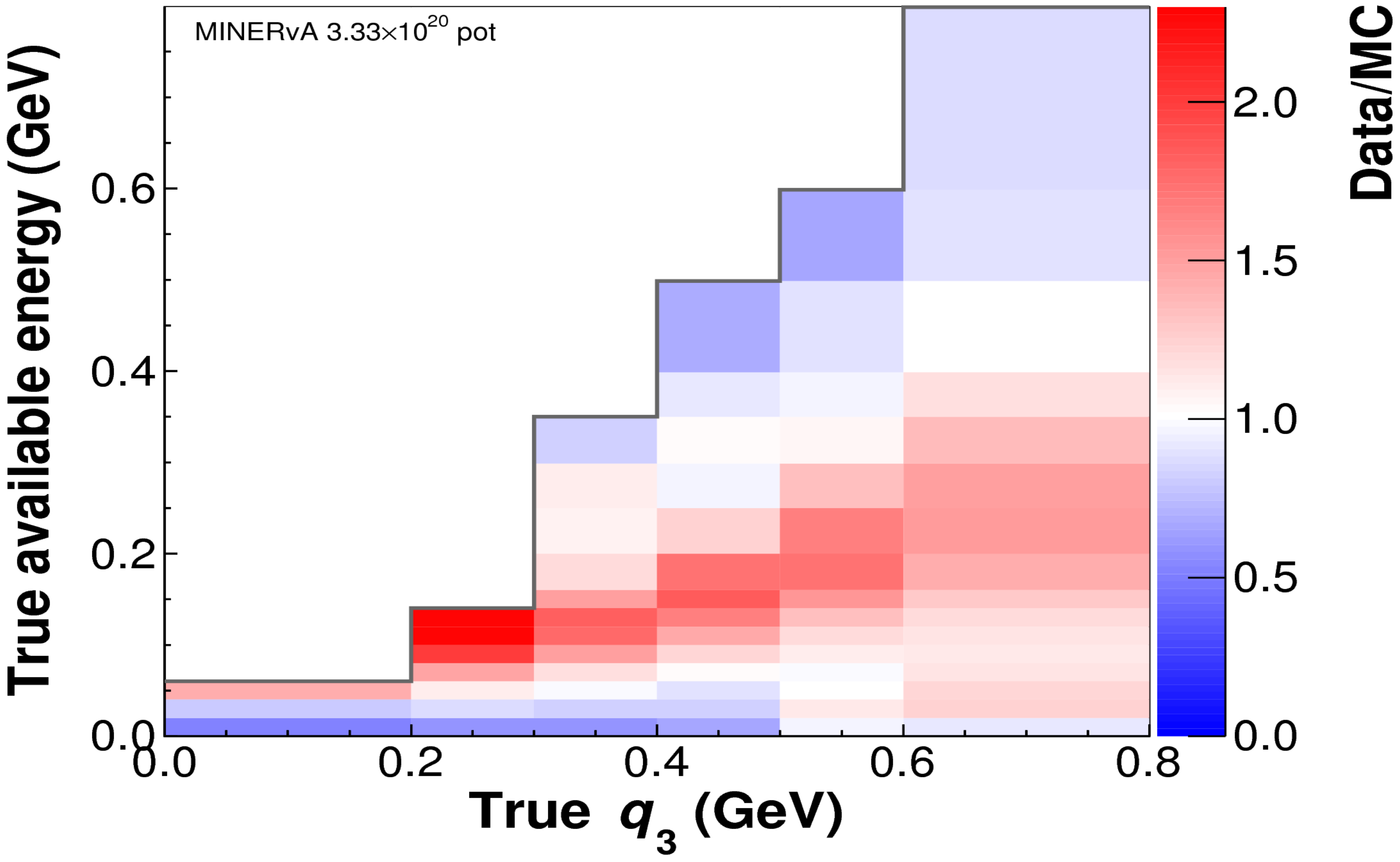
Model dependence



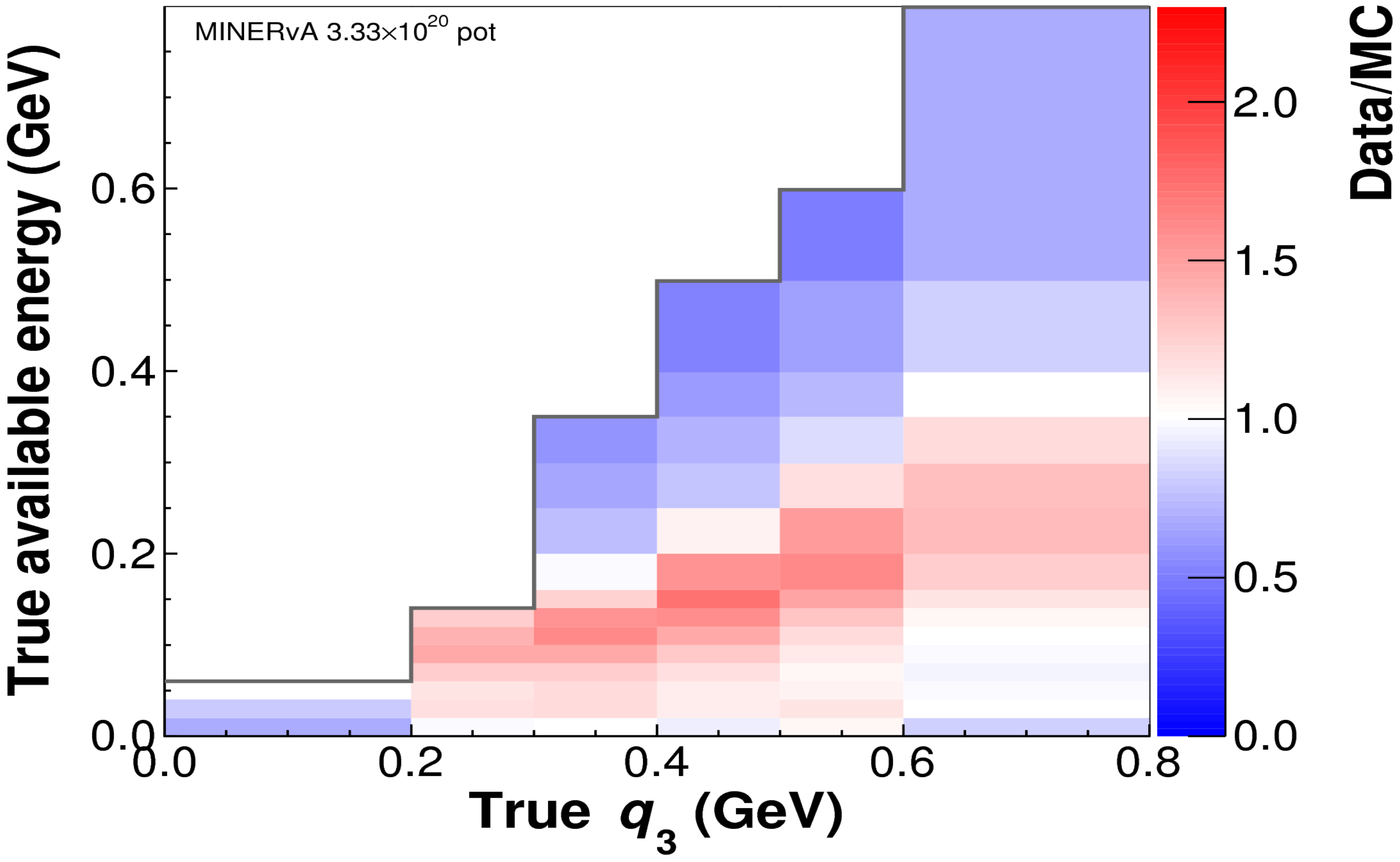
Selection efficiency



Ratio to GENIE



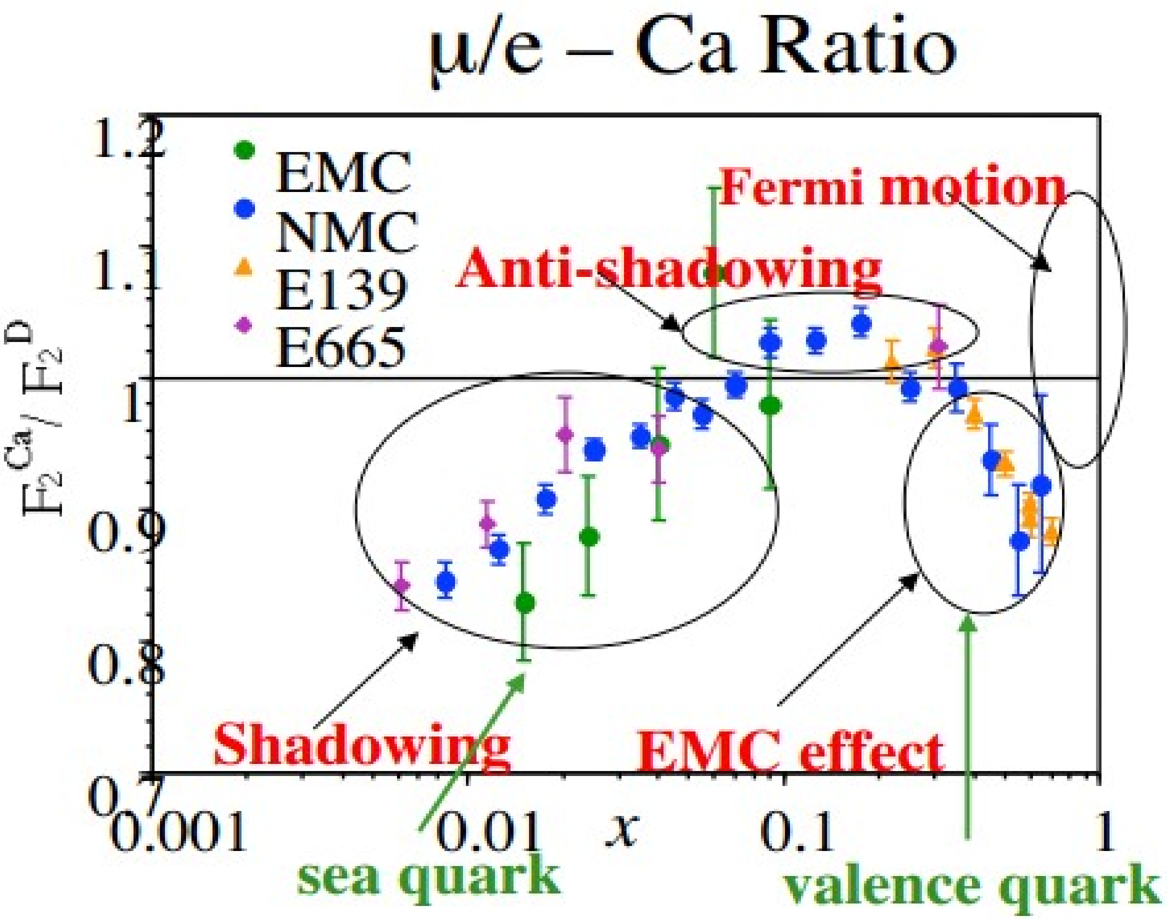
Ratio to GENIE
with RPA, 2p2h added



Nuclear target DIS backups

1 Non-DIS backgrounds
2 Wrong nucleus backgrounds
3 Ratios vs. neutrino energy
4 x ratio uncertainties

Charged lepton deep inelastic scattering

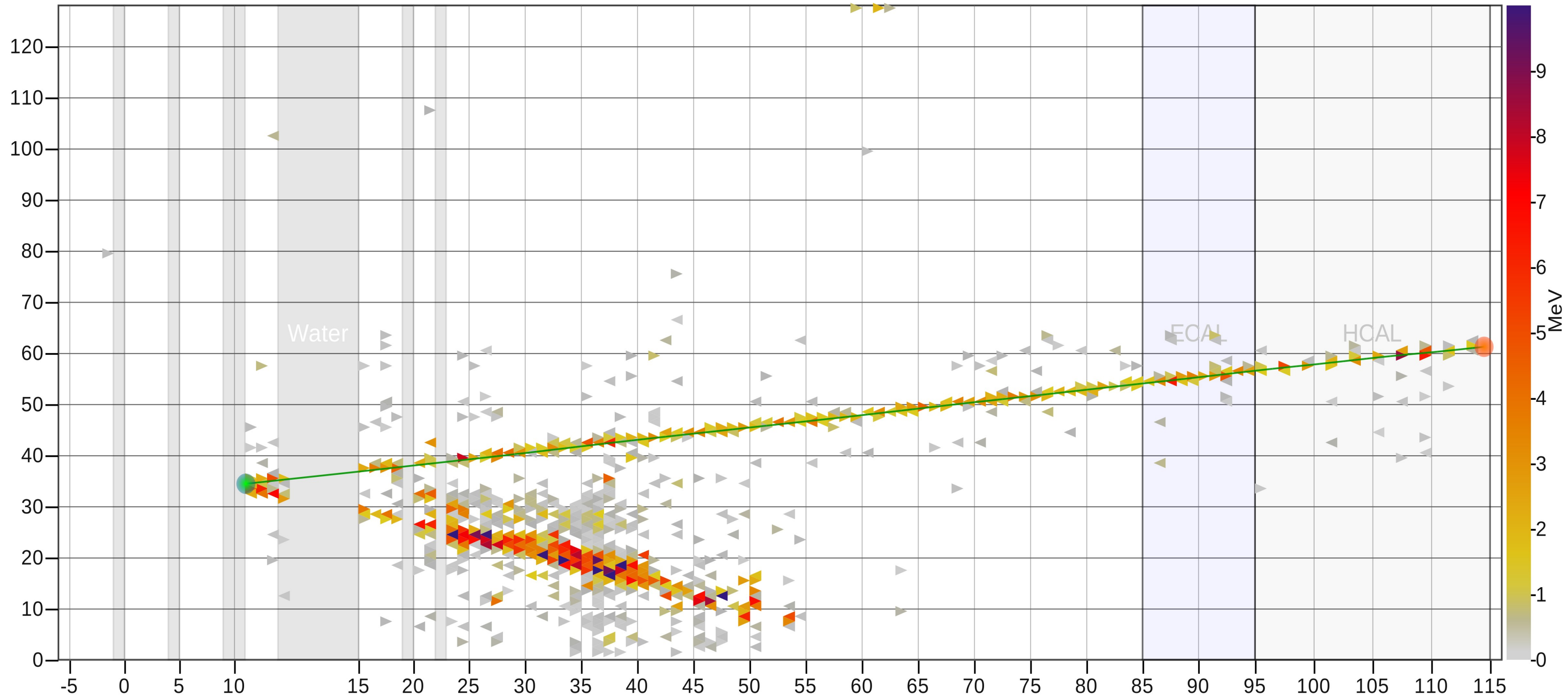


Ratios of heavy nuclei to deuterium show effects that depend on Bjorken-x

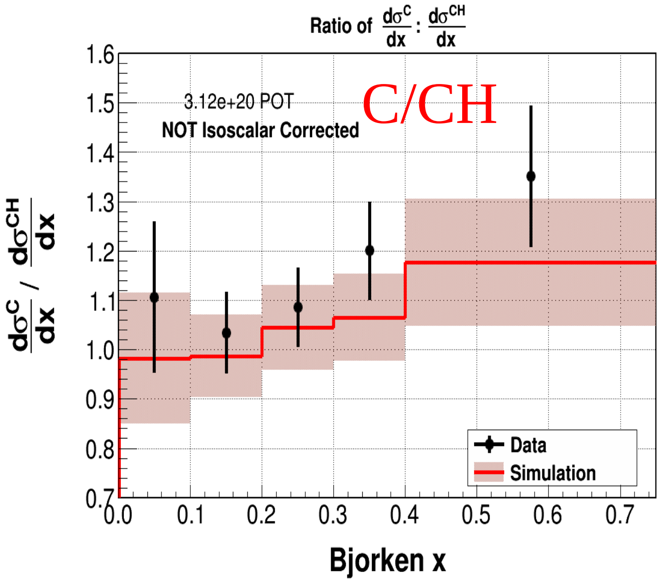
What do we see for neutrino scattering?

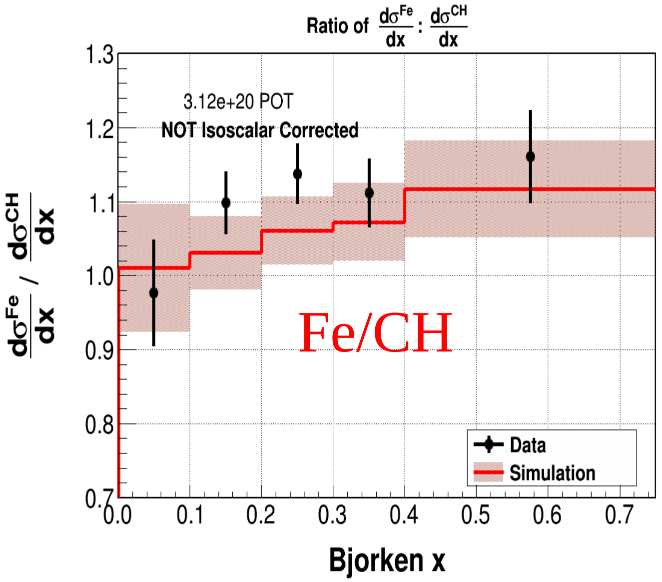
We are taking ratios to CH, not D

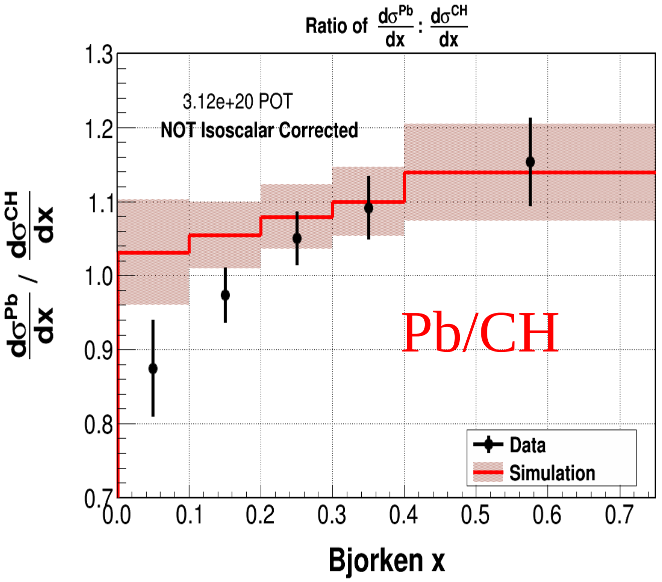
DIS in nuclear targets



Ratios of dσ/dx

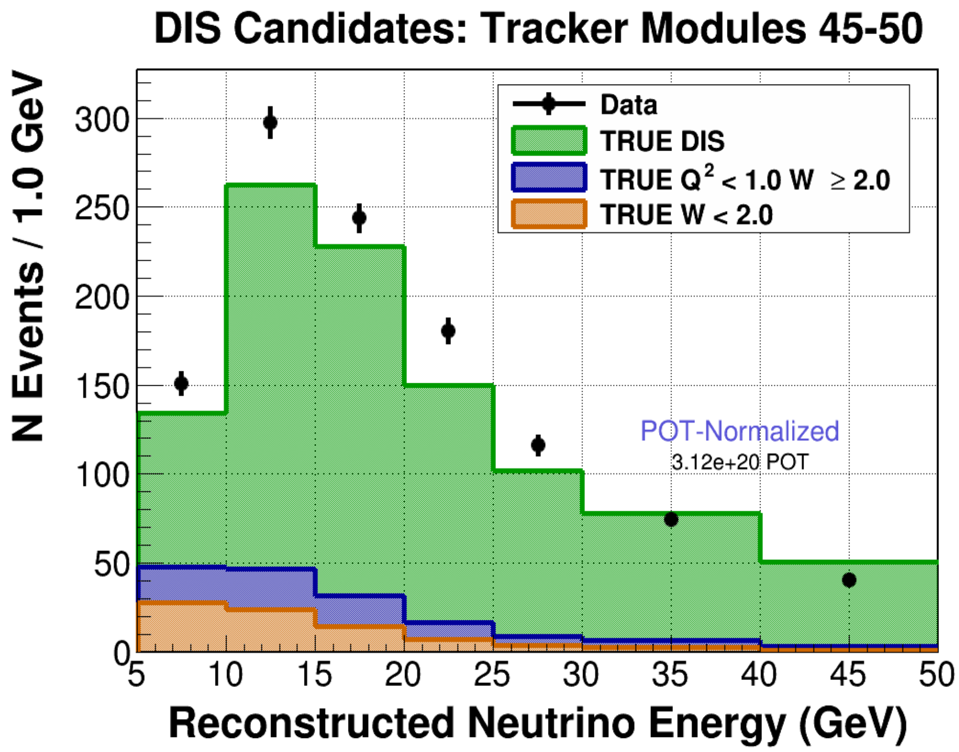


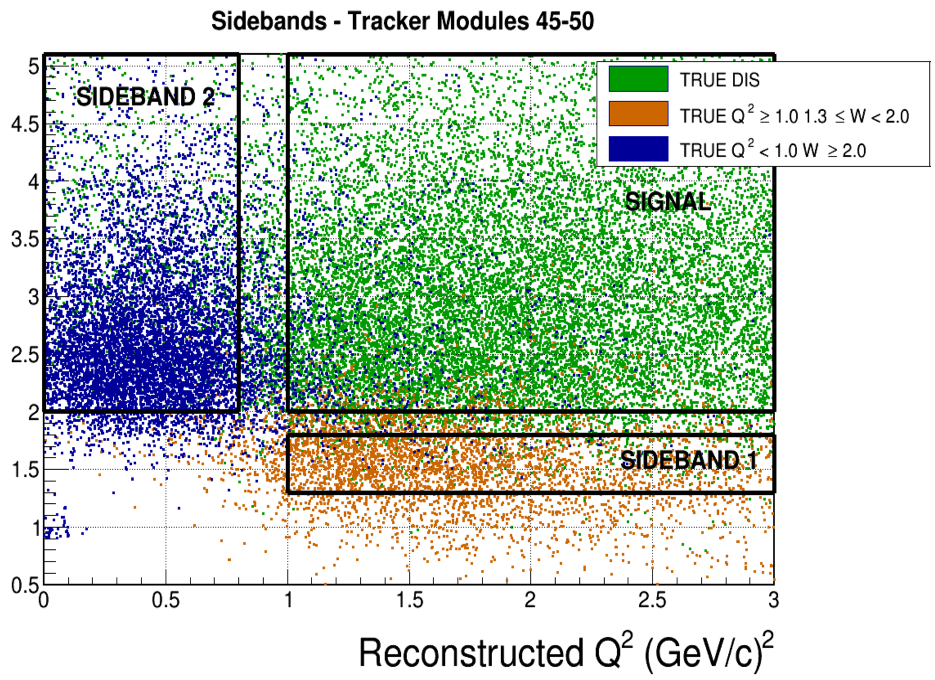




- Simulation assumes x-dependent nuclear effects are the same for every nucleus
- Data deficit at low x in lead is consistent with additional nuclear shadowing

Non-DIS Backgrounds



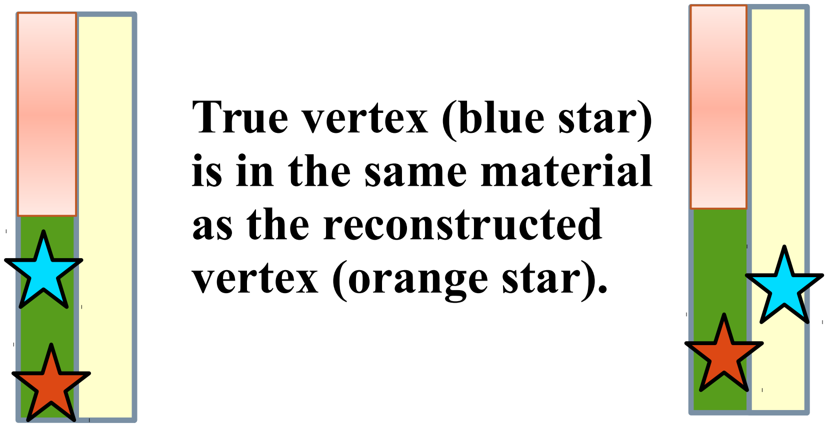


Select sample with reco $Q^2 > 1$ GeV^2, reco $W > 2$ GeV

Backgrounds are events with true $Q^2 < 1$ GeV^2 or true $W < 2$ GeV

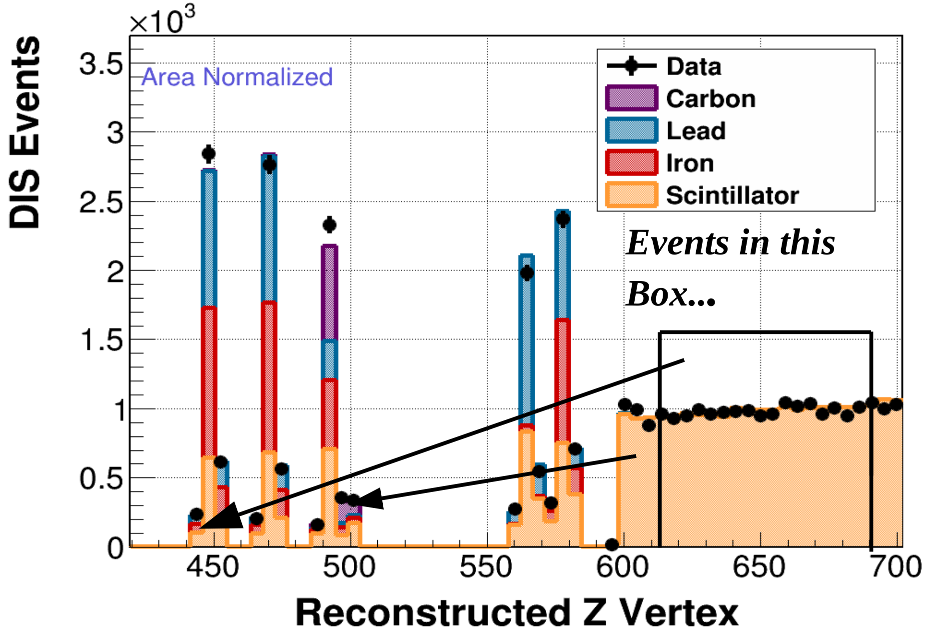
Tune backgrounds using sidebands adjacent to signal region

Wrong nucleus backgrounds



True vertex (blue star) is in the same material as the reconstructed vertex (orange star).

Accept events with reconstructed vertex inside a passive nuclear target

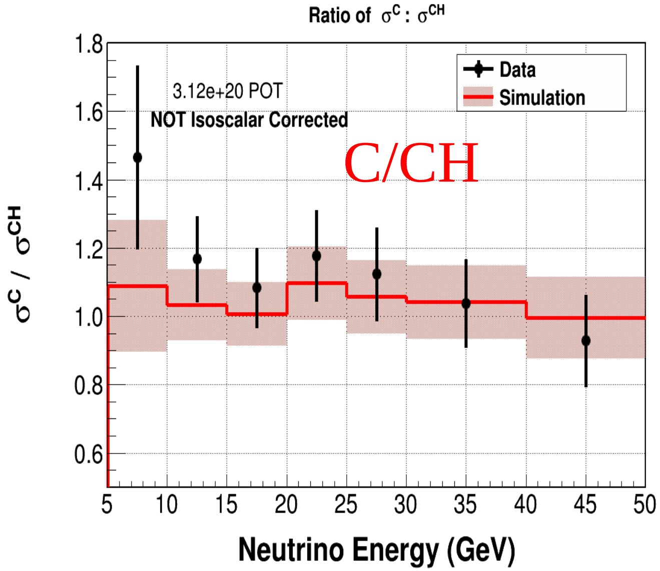


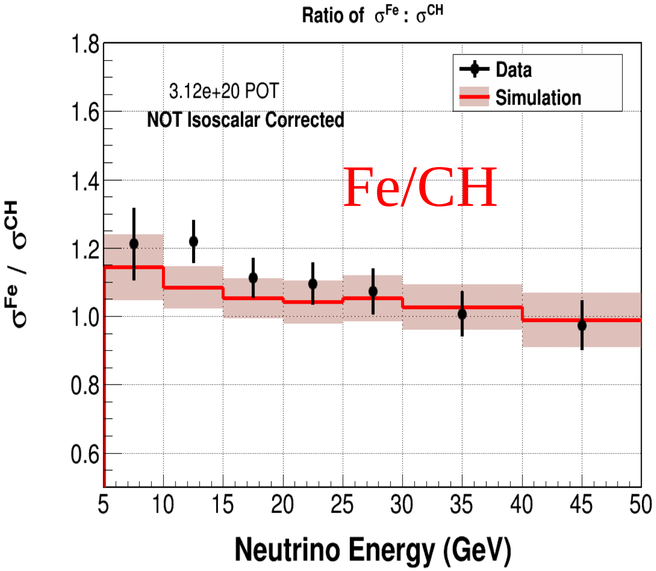
Events in this Box...

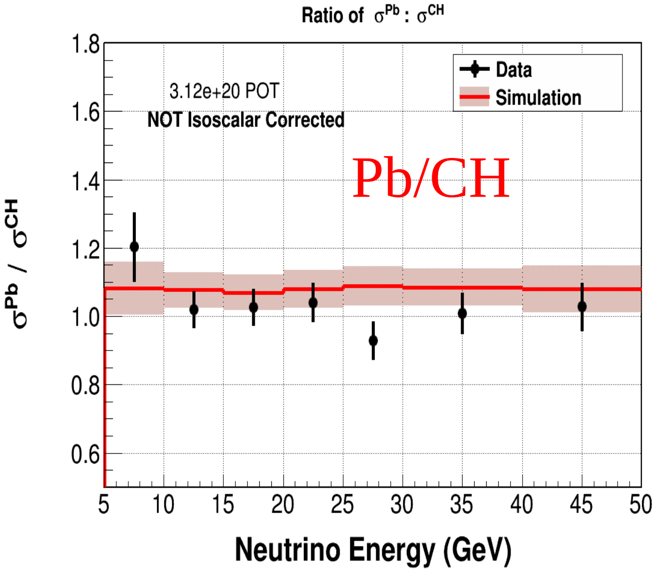
...Used to predict BG events here

Subtract events with true vertex in plastic scintillator using extrapolation from tracker region

Ratios vs. neutrino energy

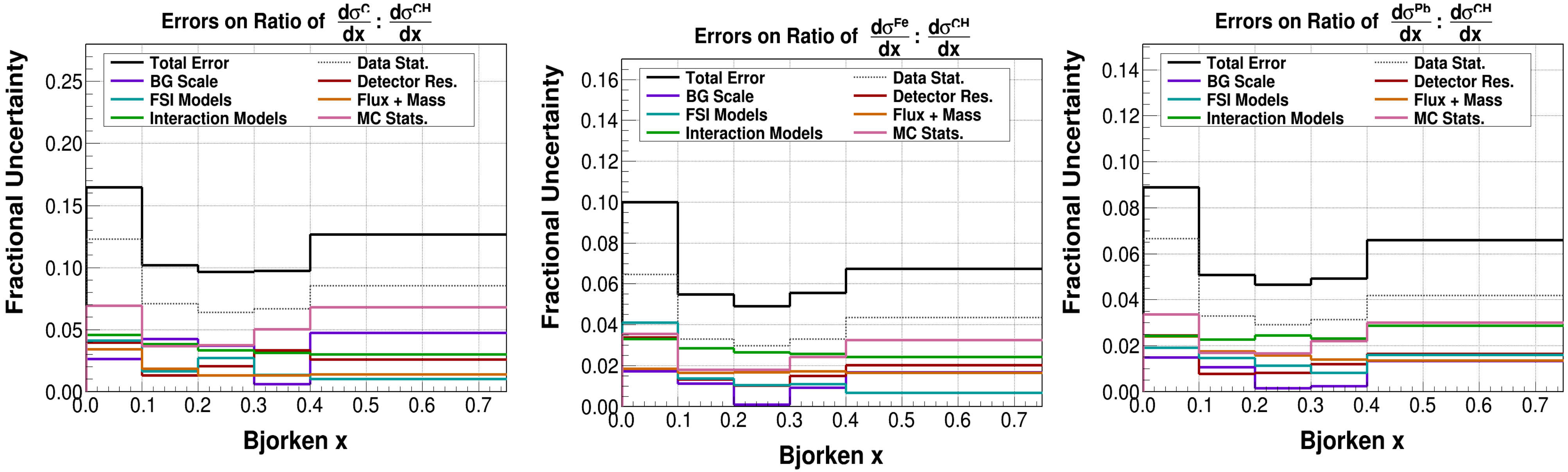






Slight trend of data deficit at high neutrino energy for heavier nucleus, which is related to the data deficit at low x

x ratio uncertainties



Flux + mass uncertainty largely cancels in the ratios

Systematics all at ~5% level or lower, stat errors are <5% for all but lowest x bin

Will have great low-x stats in medium energy data!