Fermilab

NORTHWESTERN UNIVERSITY

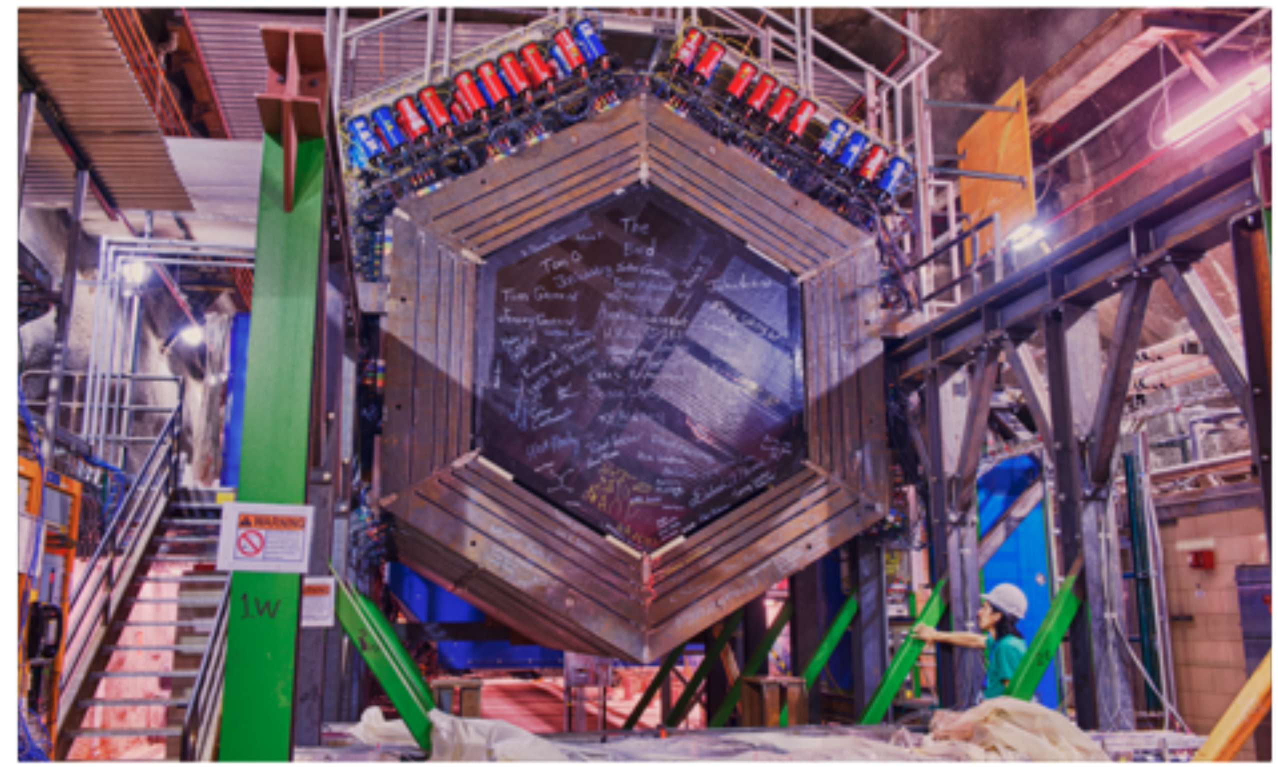
Charged Current Quasi-Elastic Scattering at MINERvA

Cheryl Patrick, Northwestern University, USA, for the MINERvA collaboration

Nu Int 14, May 19-24 2014, U.K.

CCQE at MINERνA

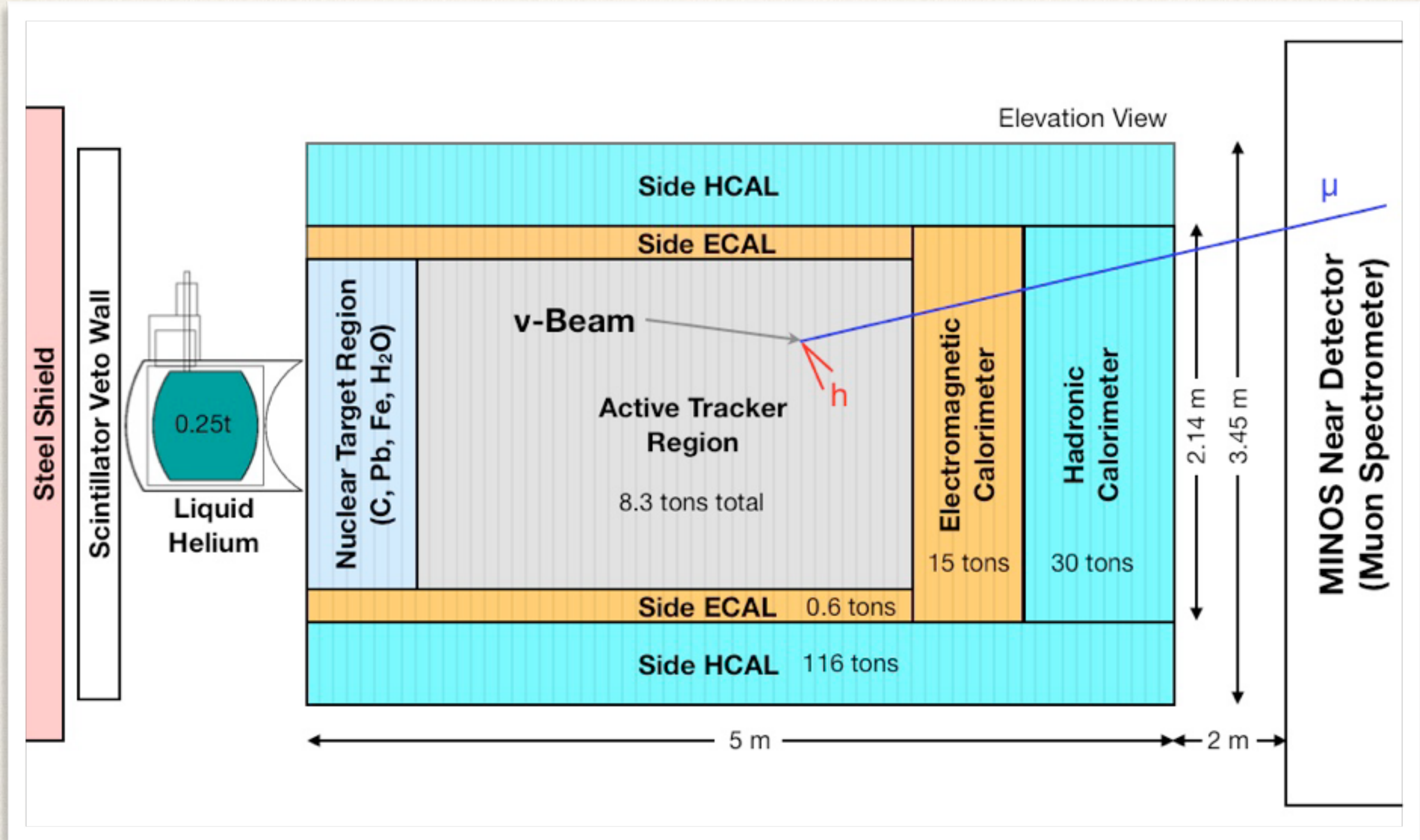
- Two papers with quasi-elastic results published since the last NuInt:
  - L. Fields, J. Chvojka et al. (MINERvA Collaboration), Measurement of Muon Antineutrino Quasielastic Scattering on a Hydrocarbon Target at Eν~3.5 GeV, Phys. Rev. Lett. 111, 022501 (2013)
  - G. A. Fiorentini, D. W. Schmitz, P. A. Rodrigues et al. (MINERvA Collaboration), Measurement of Muon Neutrino Quasielastic Scattering on a Hydrocarbon Target at Eν~3.5 GeV, Phys. Rev. Lett. 111, 022502 (2013)



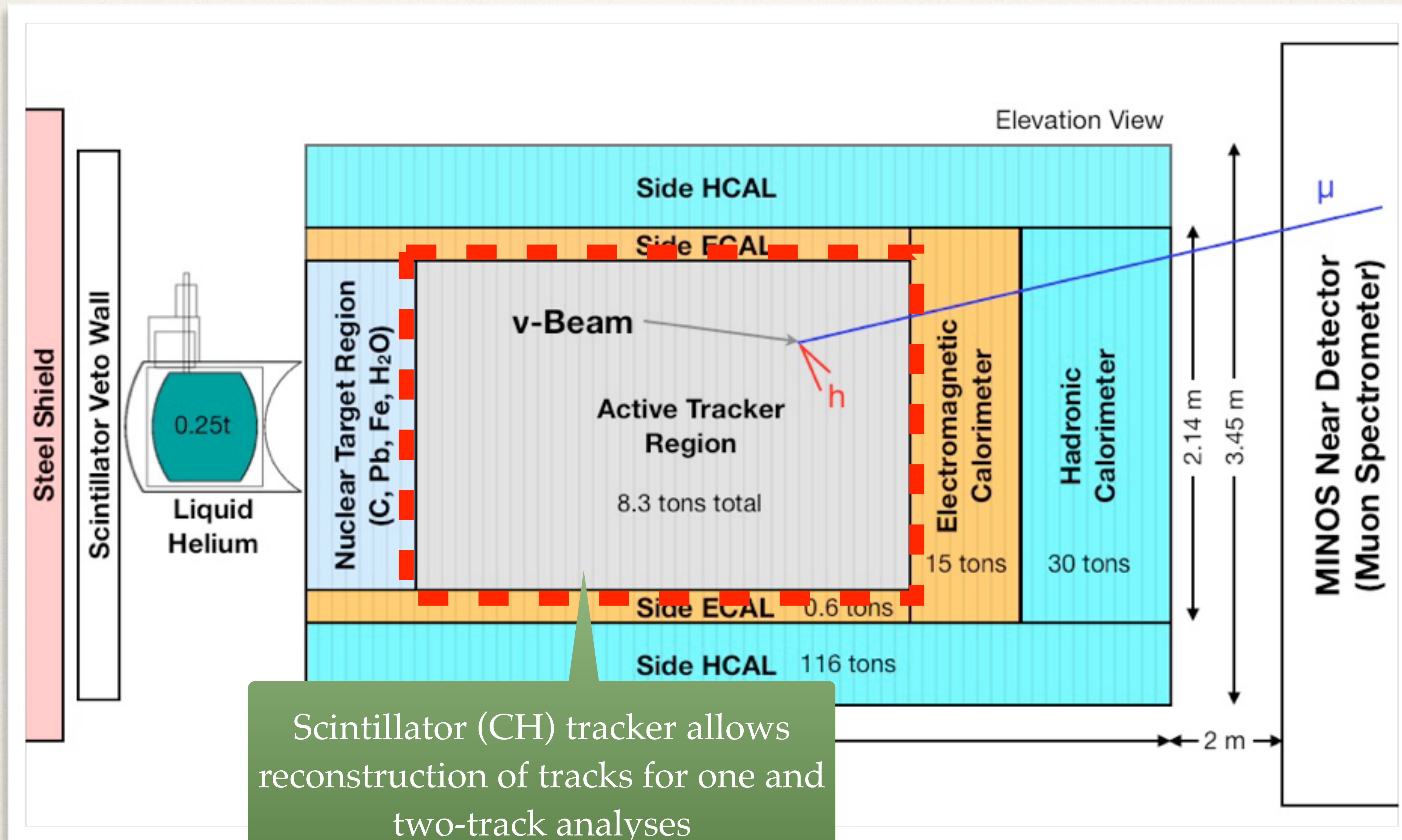
- We report **neutrino and antineutrino charged-current quasi-elastic cross-sections dσ/dQ²** on CH scintillator and comparisons to **theoretical models**
- Additional model comparisons are being shown here for the **first time**
- **Carrie McGivern's talk** will explain about further quasi-elastic analyses we're working on **right now**
- And please come and see the **poster** describing all of our quasi-elastic studies

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

MINERνA detector

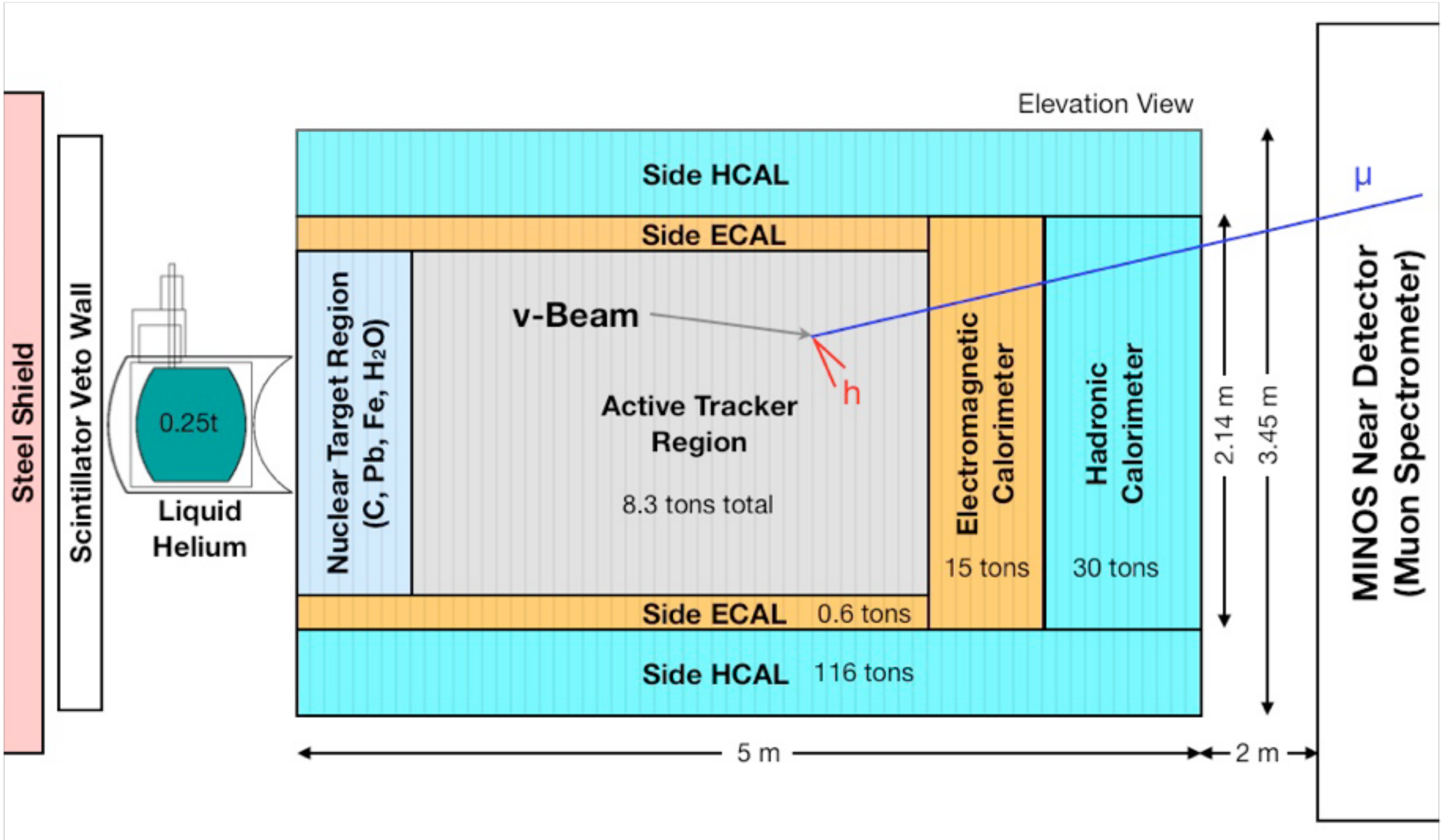


MINERvA detector

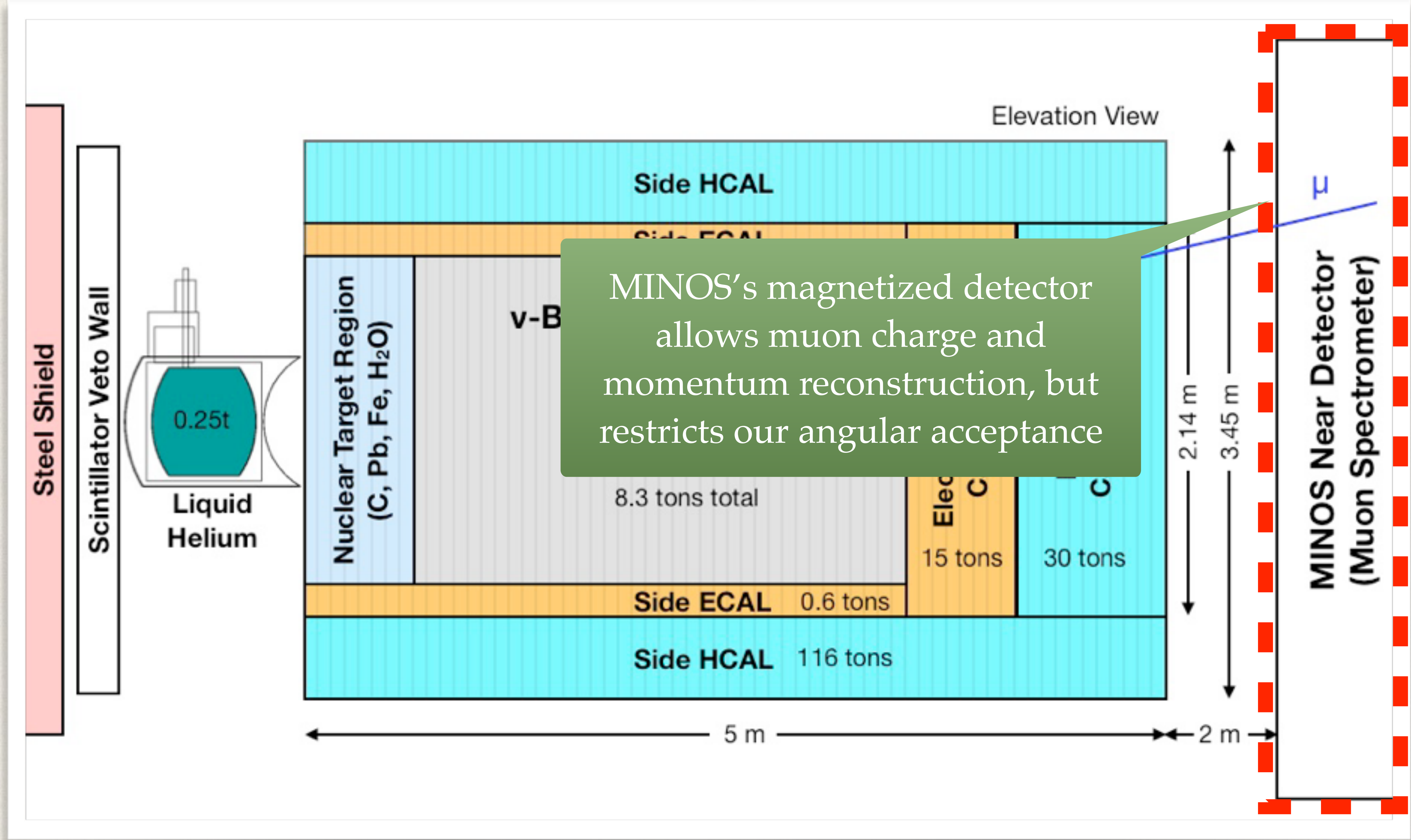


Scintillator (CH) tracker allows reconstruction of tracks for one and two-track analyses

MINERνA detector

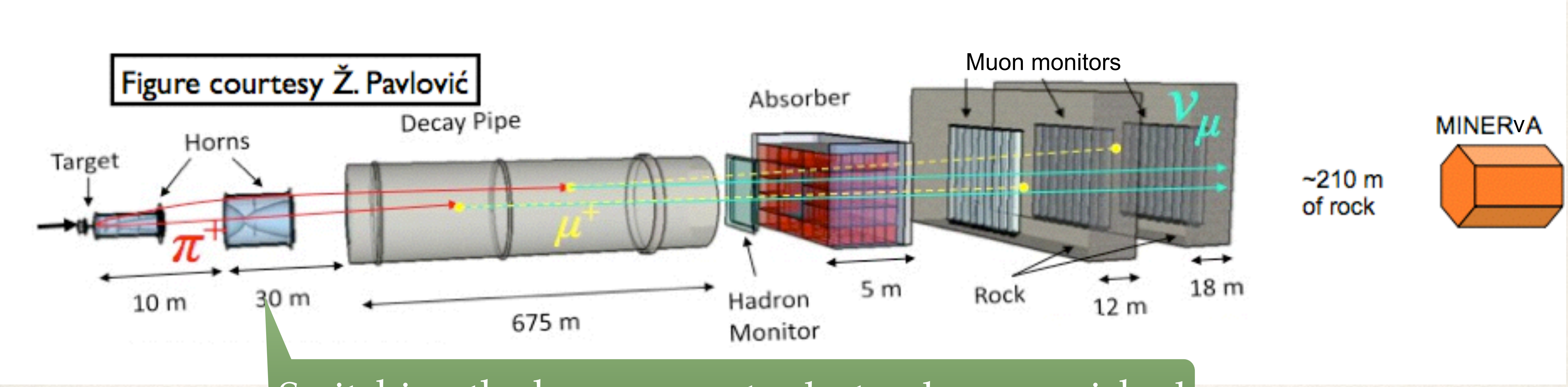


MINERvA detector



MINOS's magnetized detector allows muon charge and momentum reconstruction, but restricts our angular acceptance

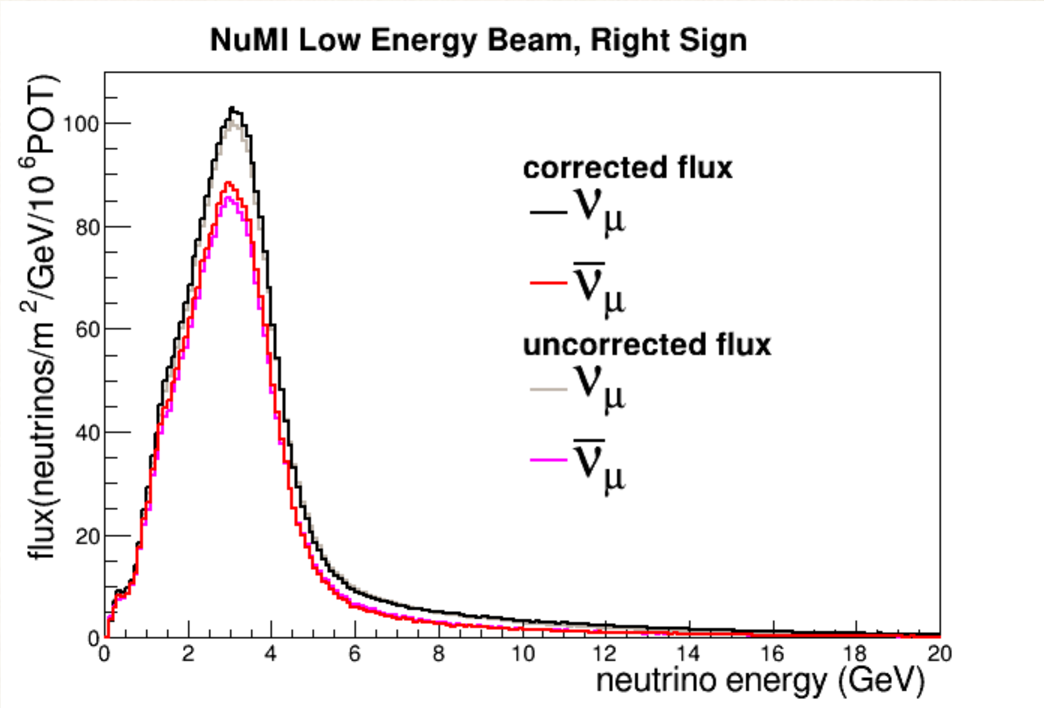
The NuMI beam



Switching the horn current selects a beam enriched in neutrinos or antineutrinos

- These studies use data from the low energy run with E_ν ~3.5 GeV
- Our sample studies E_ν from 1.5 to 10 GeV, spanning MiniBooNE's and NOMAD's ranges
- See Debbie Harris's talk for more beam details

For the published analyses:
Antineutrino: 1.01 x 10^{20} POT
Neutrino: 9.42x 10^{19} POT



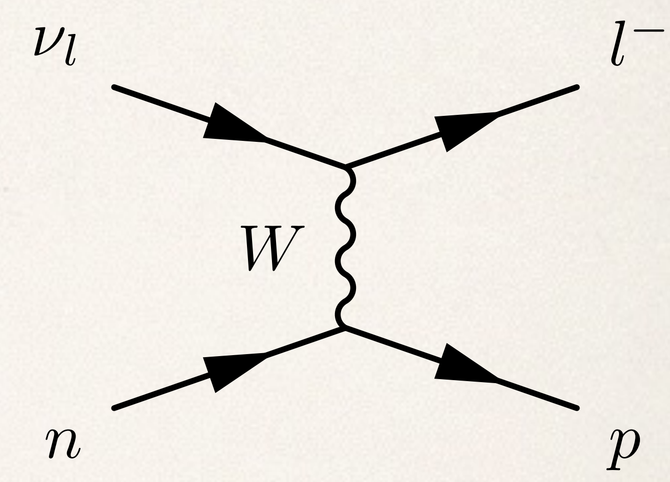
Our Monte Carlo: GENIE 2.6.2

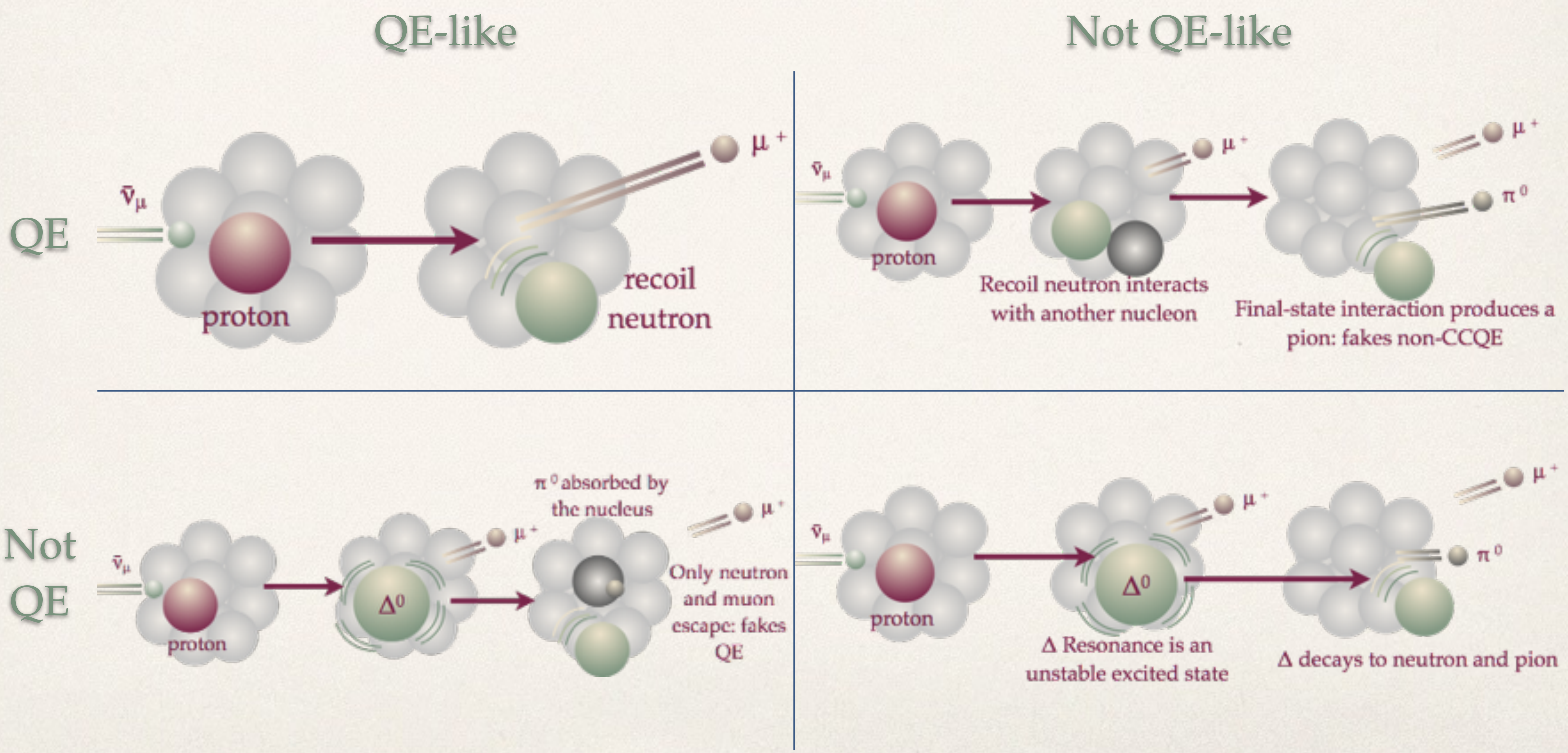
Interaction models	**CCQE: axial form-factor**	Dipole with axial mass 0.99 GeV
	CCQE:Vector form-factors	BBBA05
	CCQE: Pseudoscalar form-factors	PCAC/Goldberger-Treiman
	Resonance and coherent	Rein-Seghal
	DIS	GRV94/GRV98 with Bodek-Yang
	DIS and QEL charm	*Kovalenko, Sov.J.Nucl.Phys.52:934 (1990)*
Nuclear effects	**Nuclear model**	RFG, Fermi momentum=225MeV, Pauli blocking, Bodek-Ritchie tail
	FSI modeling	INTRANUKE-hA *(S. Dytman, AIP Conf Proc, 896, pp. 178-184 (2007))*
	Hadronization model	AGKY – transitions between KNO-based and JETSET *T. Yang, AIP Conf. Proc.967:269-275 (2007)*
	Formation zone	SKAT

C. Andreopoulos, et al., NIM 288A, 614, 87 (2010)

CCQE signal definition

- Our signal is defined as an event in which the **primary interaction is quasi-elastic** (regardless of final-state particles)
- Incoming (anti)neutrino energy between 1.5 and 10 GeV
- Interaction within our scintillator tracker fiducial region





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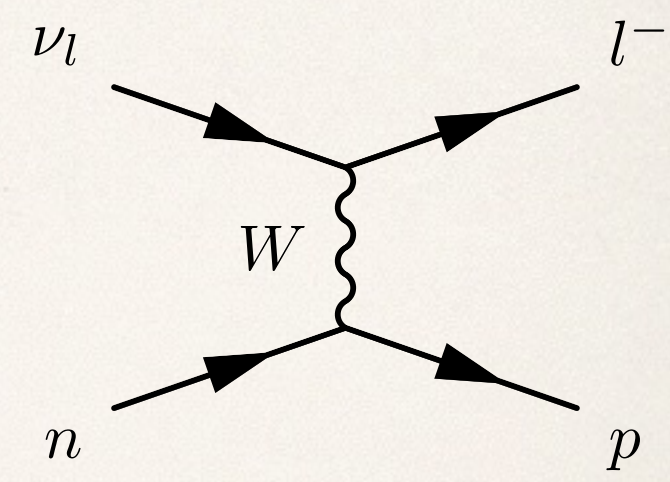

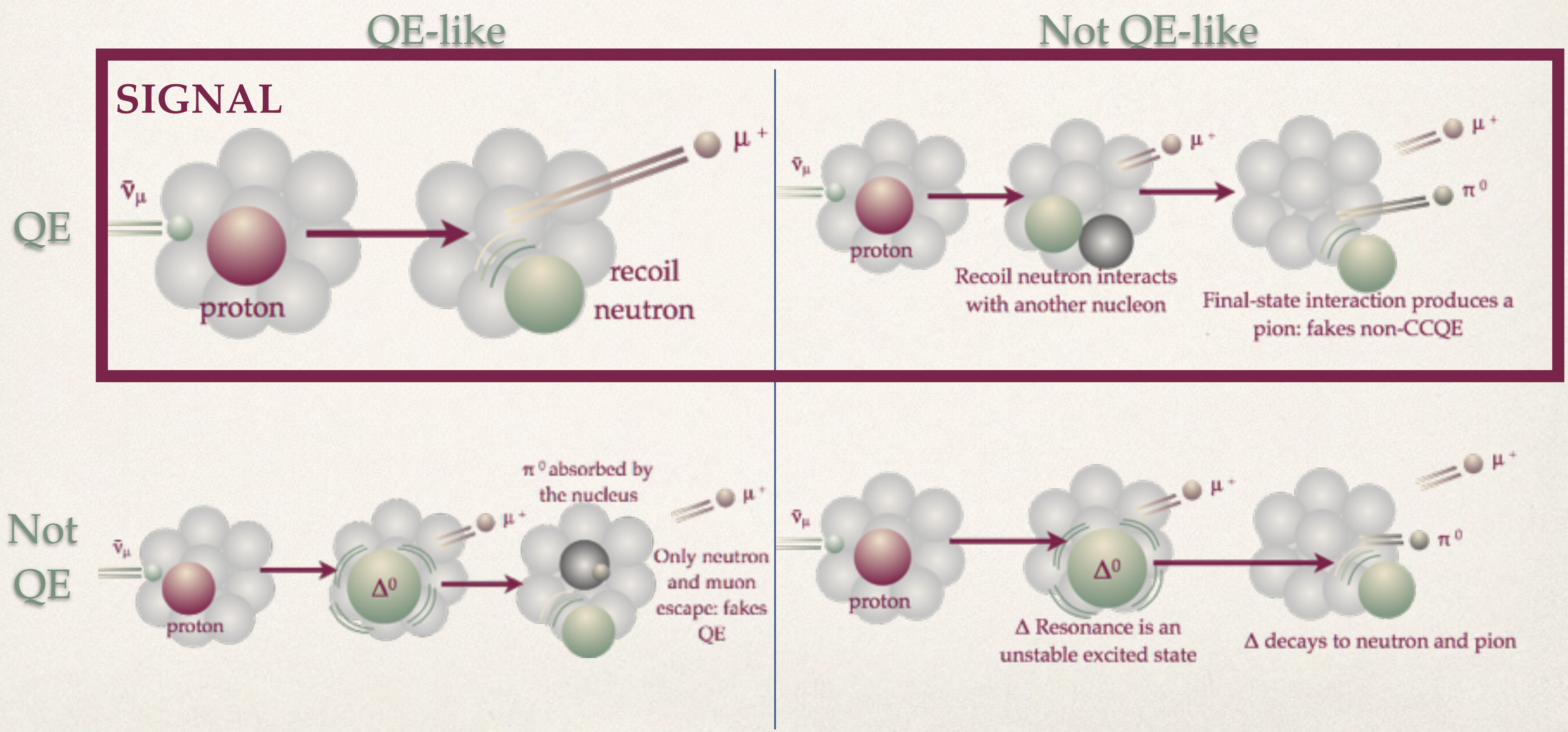

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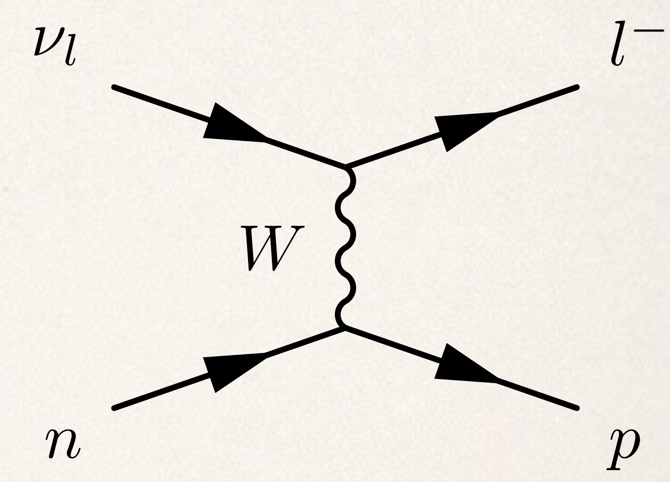
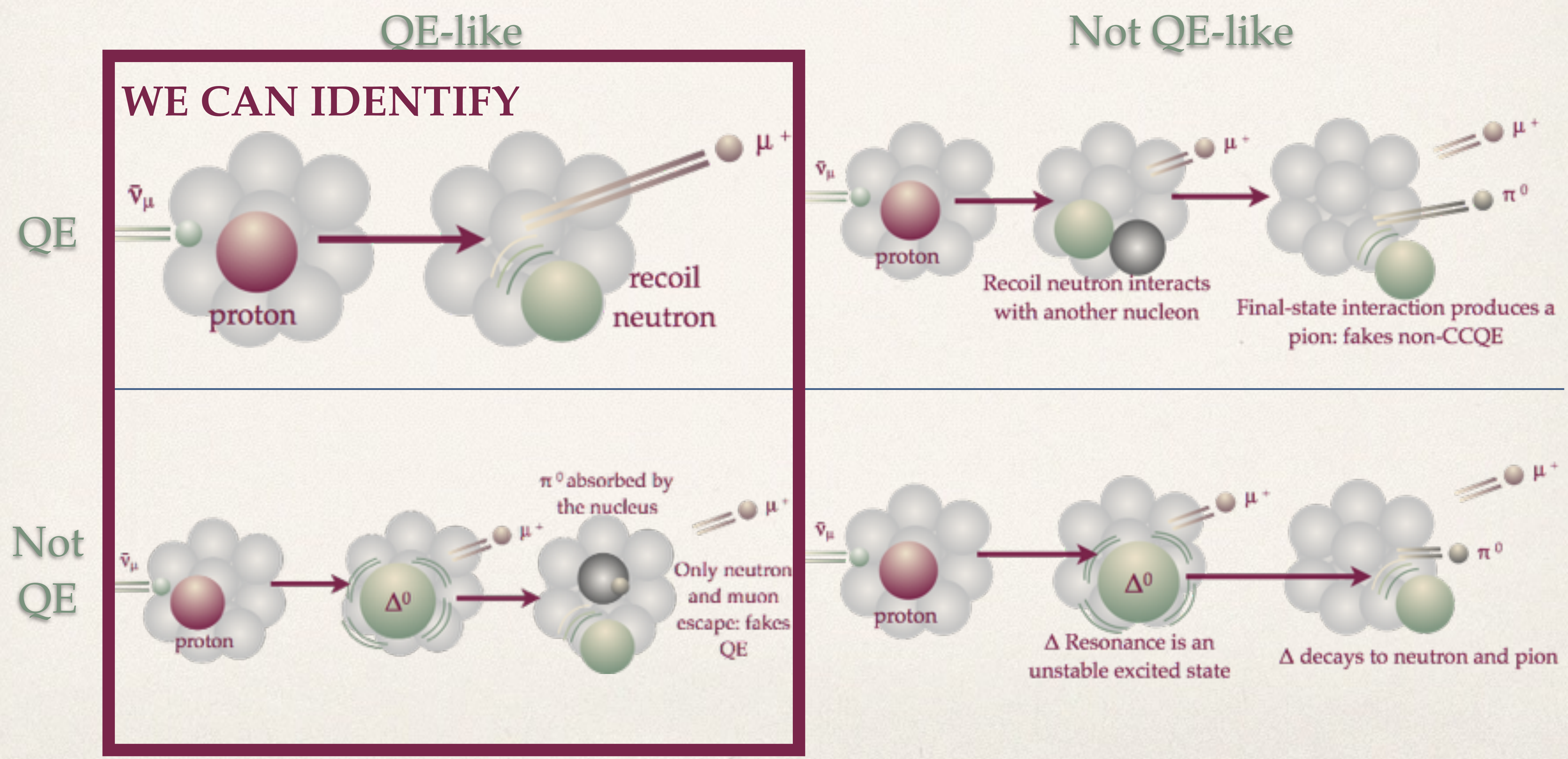
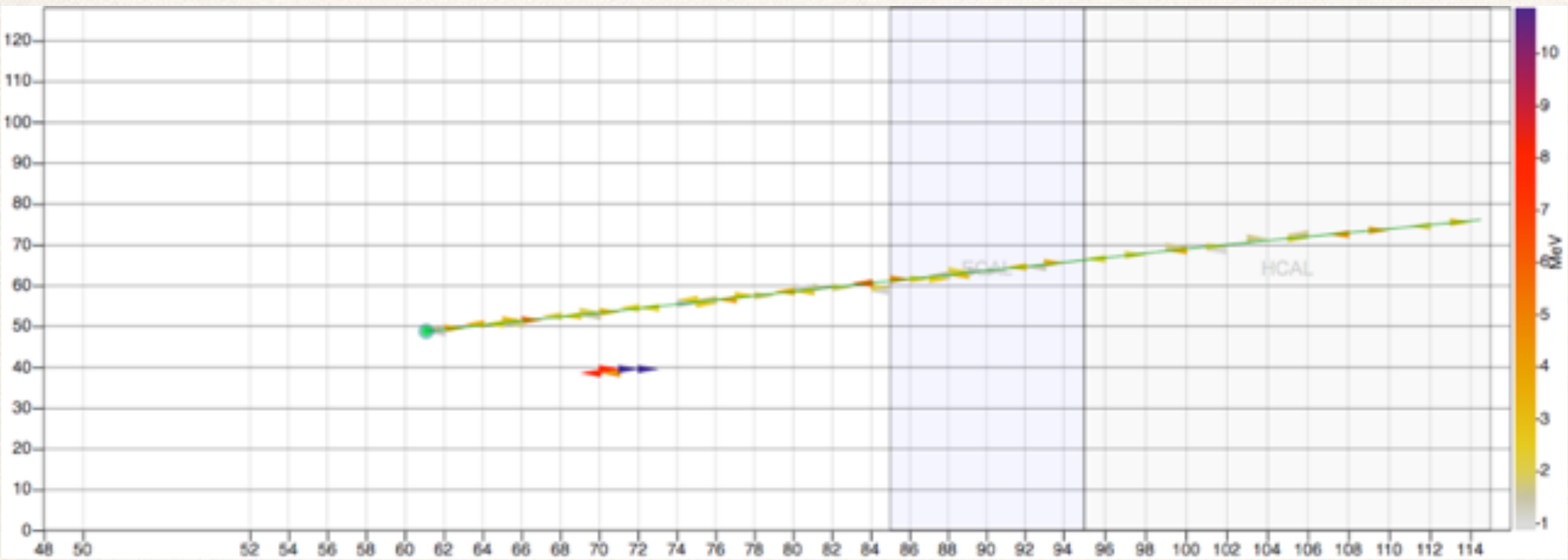


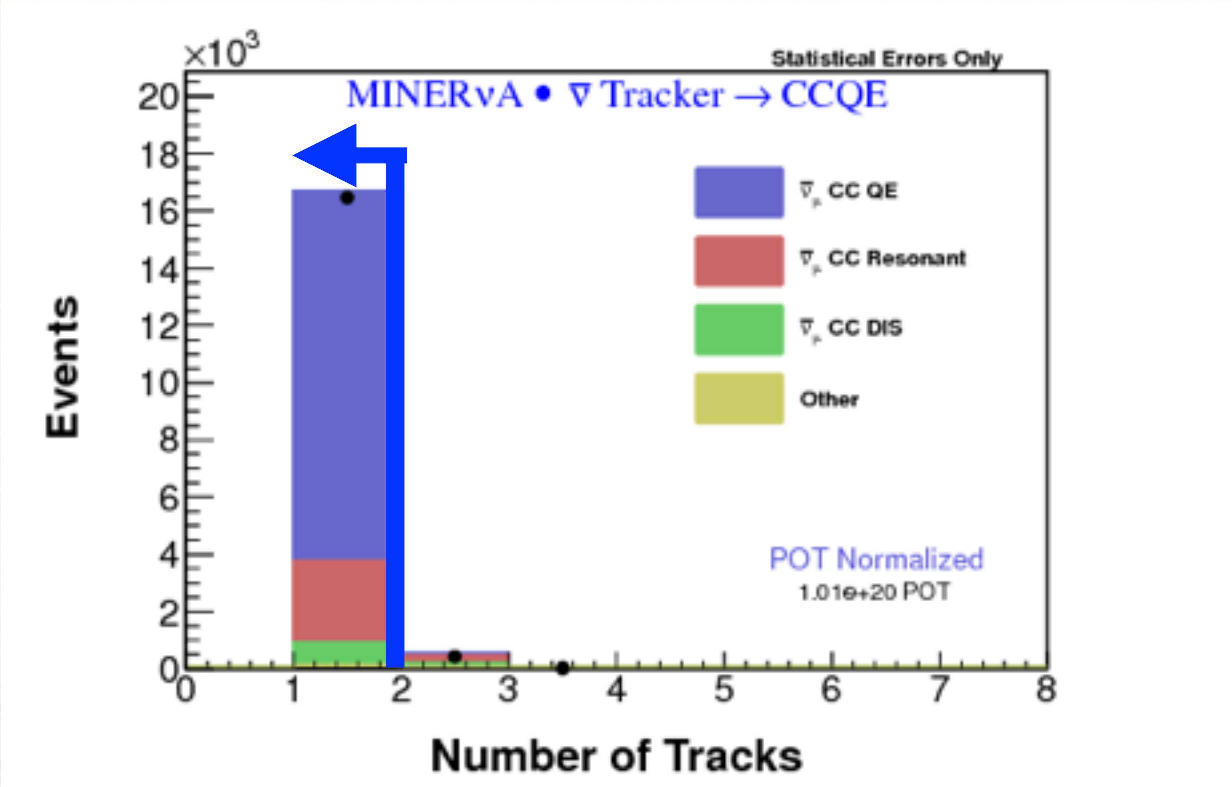


Event selection: tracks: $\bar{\nu}$

Antineutrino mode $\bar{\nu}_\mu + p \to \mu^+ + n$



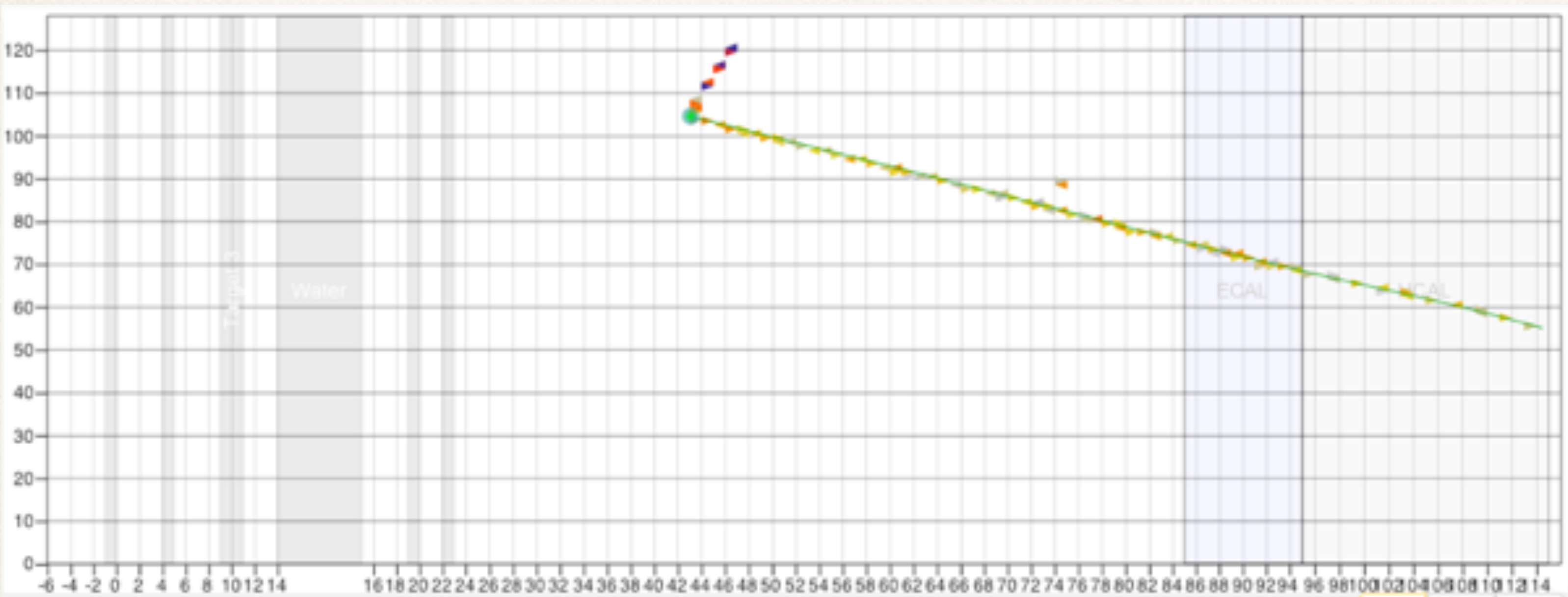
- Muon track charge matched in MINOS as a $\boldsymbol{\mu}^+$
- **No additional tracks from the vertex**
- The ejected neutron may scatter, leaving an energy deposit, but it does not make a track from the vertex



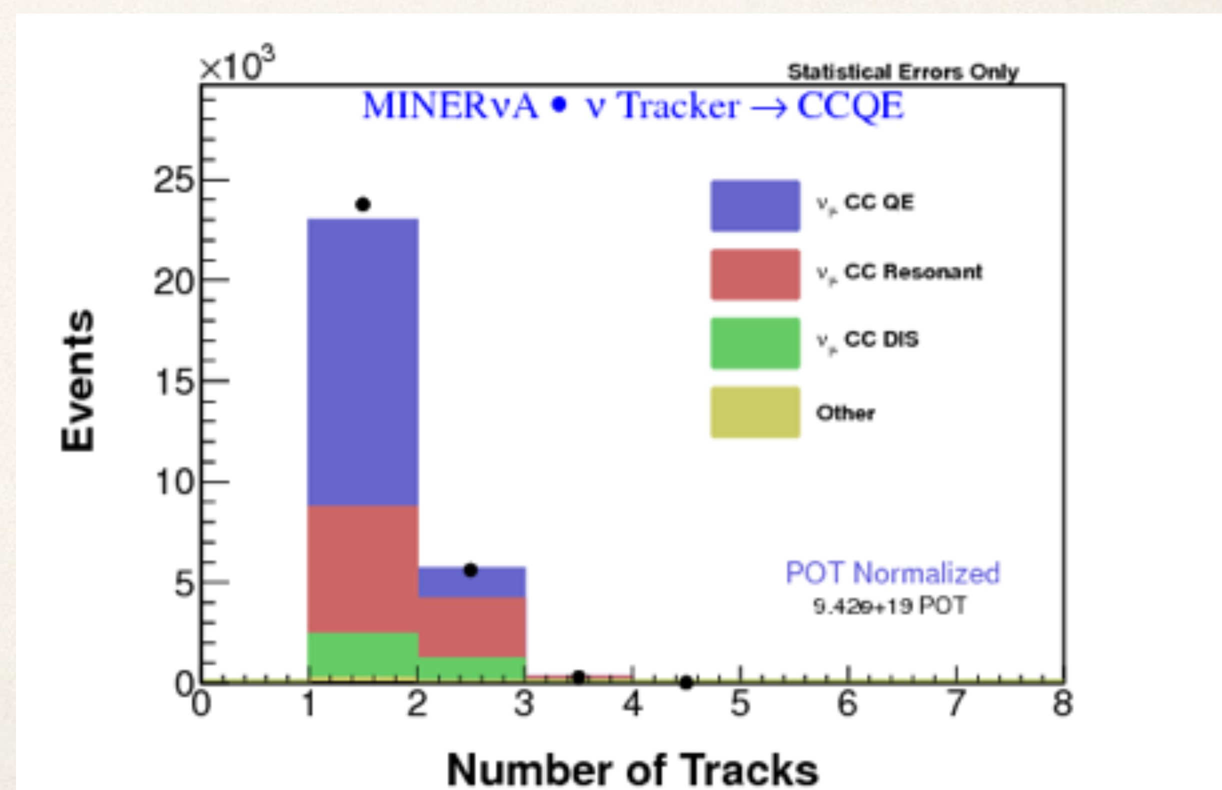
Event selection: tracks: ν

Neutrino mode

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

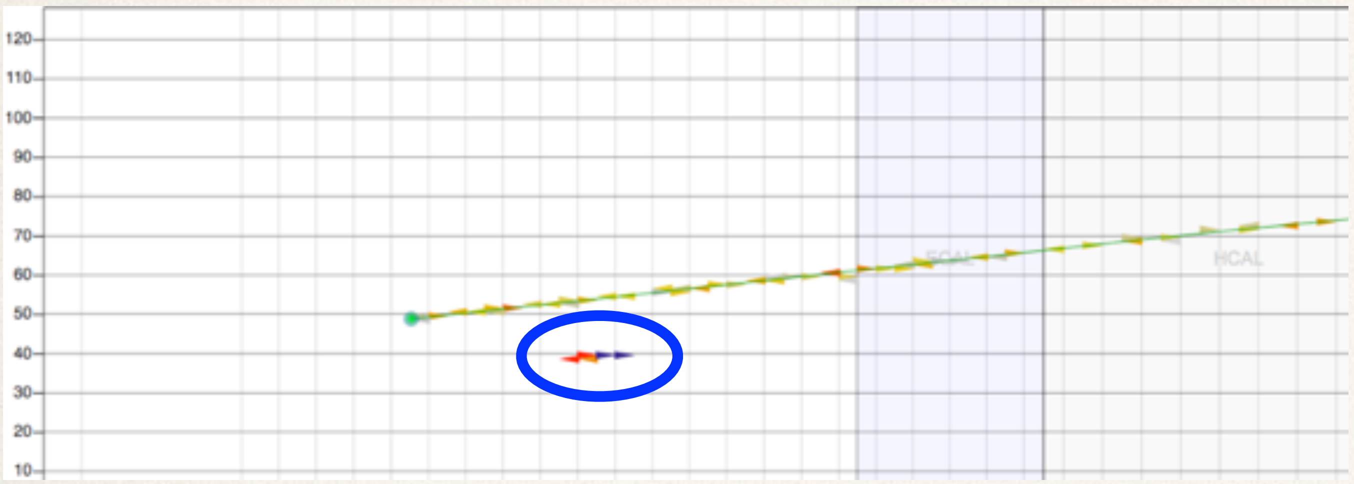


- Muon track charge matched in MINOS as a μ^-
- **No requirement** on the number of additional **tracks from the vertex**
- The ejected proton may make a track, as in the example
- An alternate study requires this proton track - see Carrie McGivern's talk

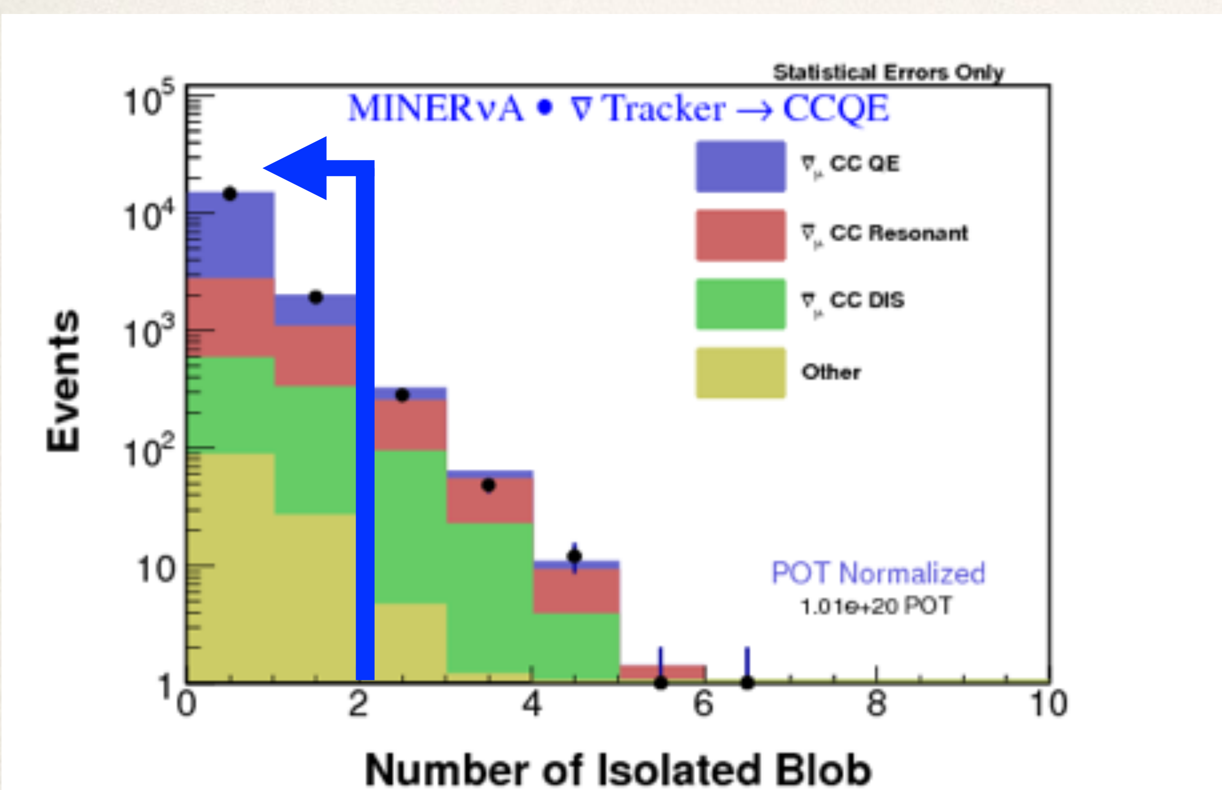


Event selection: isolated energy

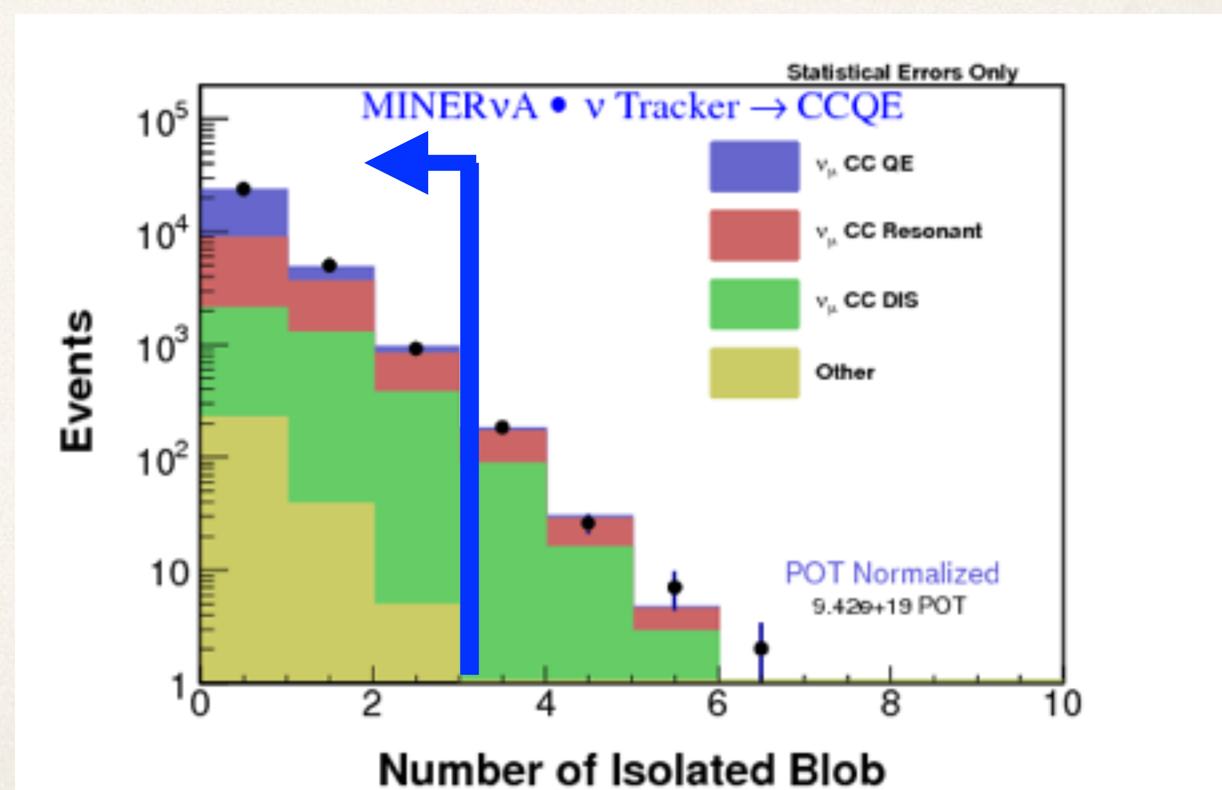
Antineutrino mode $\bar{\nu}_\mu + p \to \mu^+ + n$



- Energy deposits outside of the muon track, excluding cross-talk
- Neutron scattering may deposit energy
- Frequently, only the muon track is visible; no isolated deposits
- This cut makes little difference at low Q^2, but greatly improves purity at high Q^2

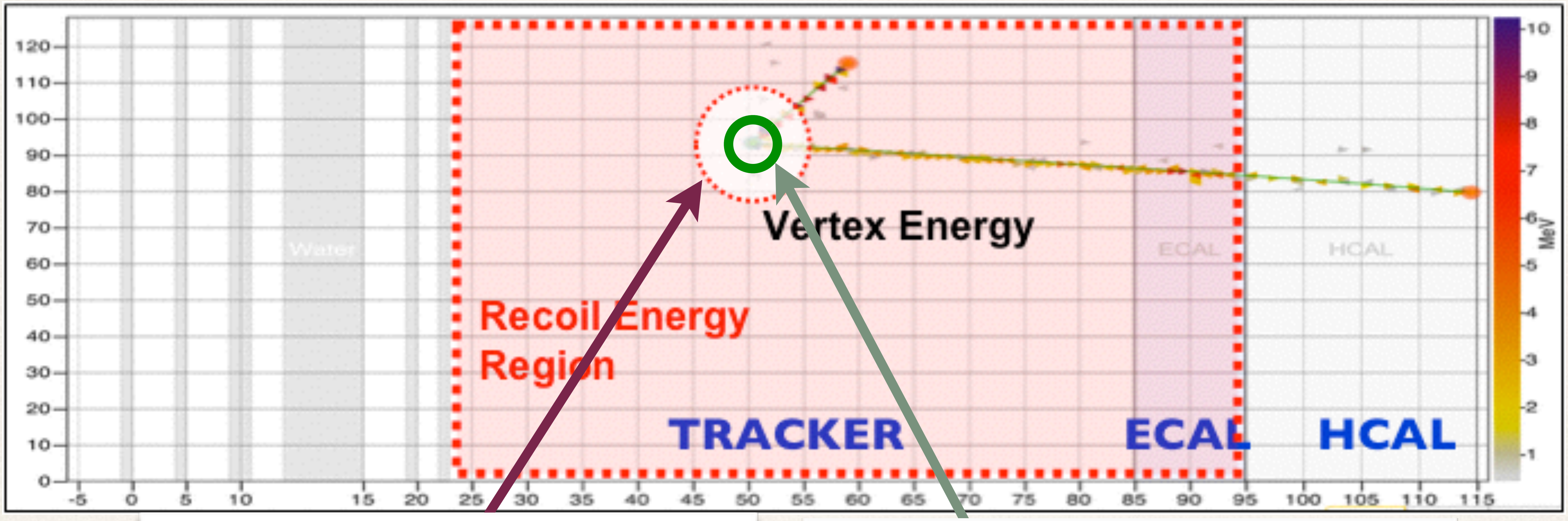


✤ Antineutrino - maximum **1** isolated



✤ Neutrino - maximum **2** isolated deposits

Event selection: recoil energy

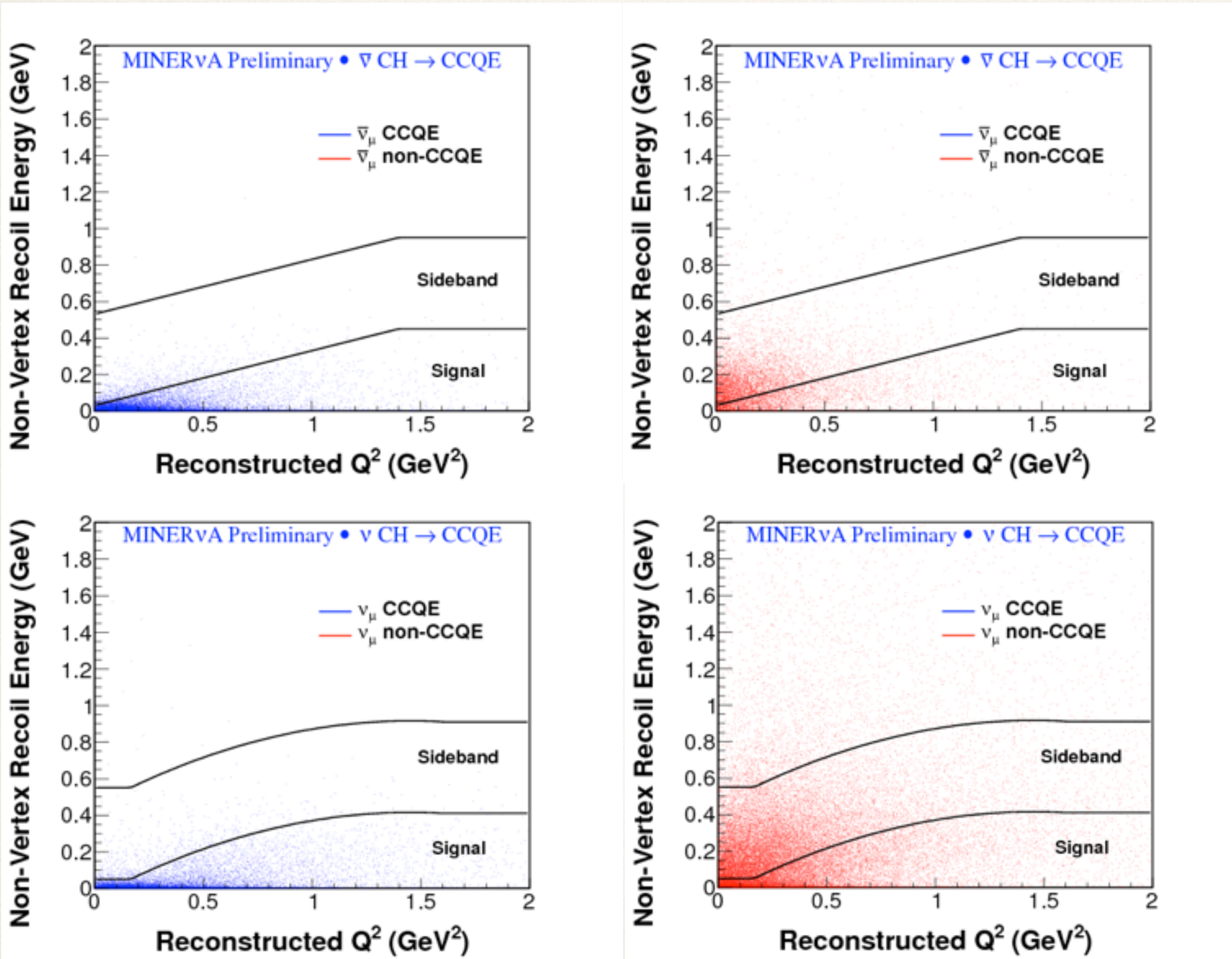


Exclude vertex region:
30 g/cm² for neutrino mode
Contains < 225 MeV protons

Antineutrino mode
exclude 10 g/cm²
Contains < 120 MeV protons

- Backgrounds typically contain pions, which will deposit energy in the detector
- A cut is therefore made on the total calorimetrically-corrected recoil energy
- The energy is summed over the region shown
- The area around the vertex is excluded, as it is suspected that nuclear effects could lead to additional low-energy nucleons in this area, even in CCQE events

Event selection: recoil



$\bar{\nu}$

ν

QE

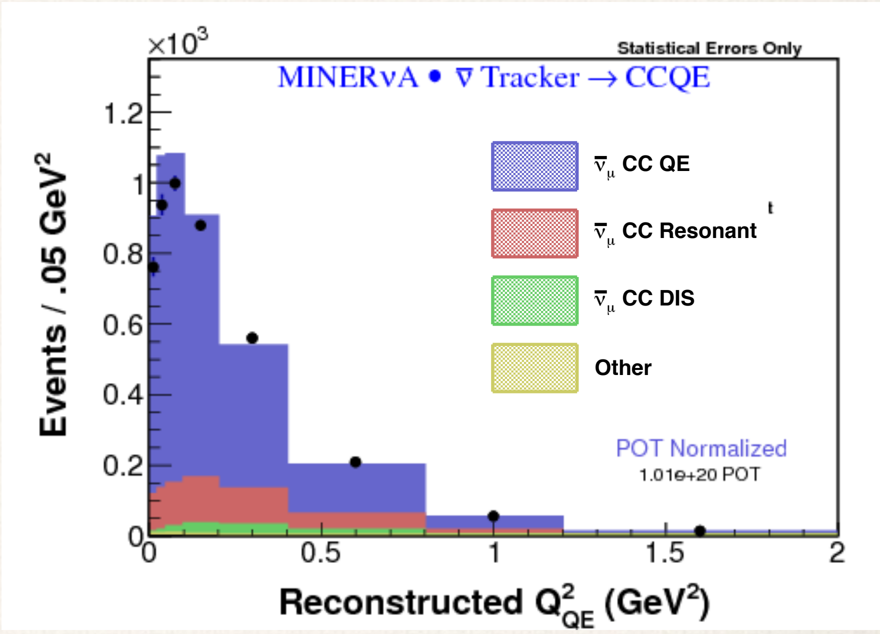
Not QE

Summary of cuts

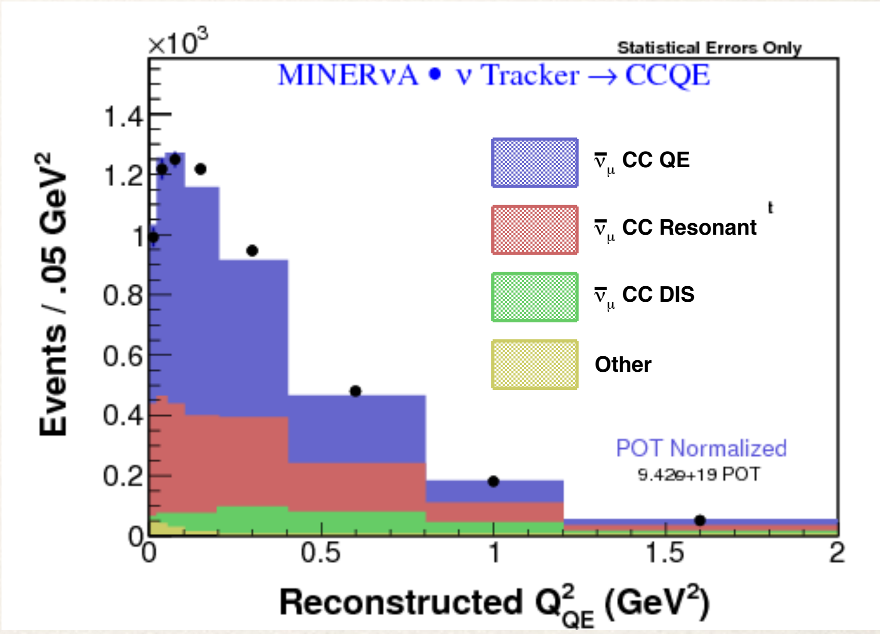
- The muon must be matched to a MINOS track
  - μ^- for neutrino mode; μ^+ for antineutrino mode
- The event vertex must be within the fiducial volume
  - within the central 110 planes of the scintillator tracking region
  - no closer than 22cm to any edge of the planes
- There must be no tracks apart from the muon (antineutrino mode)
- We limit the number of isolated energy showers
  - maximum 2 (neutrino) or 1 (antineutrino)
- We make the Q^2-dependent recoil energy cut
- We cut on reconstructed neutrino energy: $1.5 < E_\nu^{QE} < 10$GeV

$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

(Formula for antineutrino mode; for neutrino mode switch m_p and m_n. E_b is binding energy; this is 30 MeV for antineutrino mode, and 34 MeV for neutrino.)

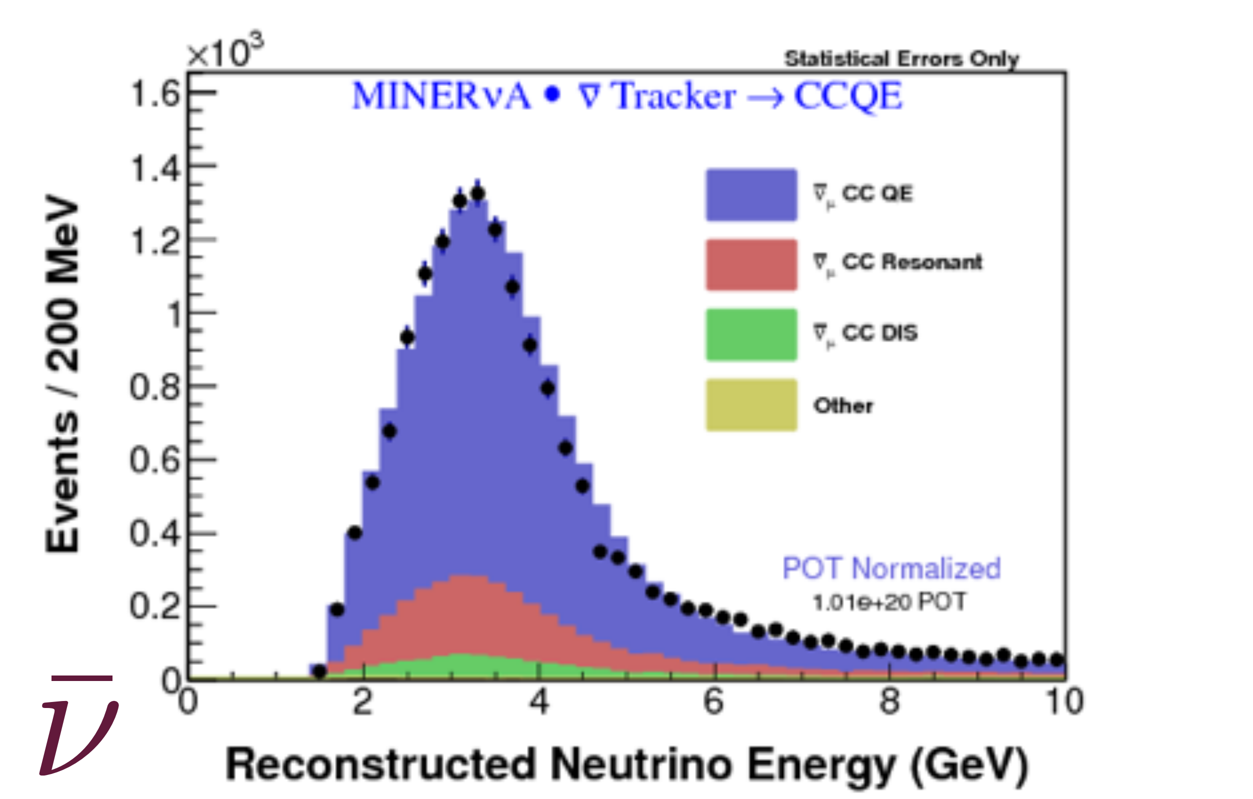


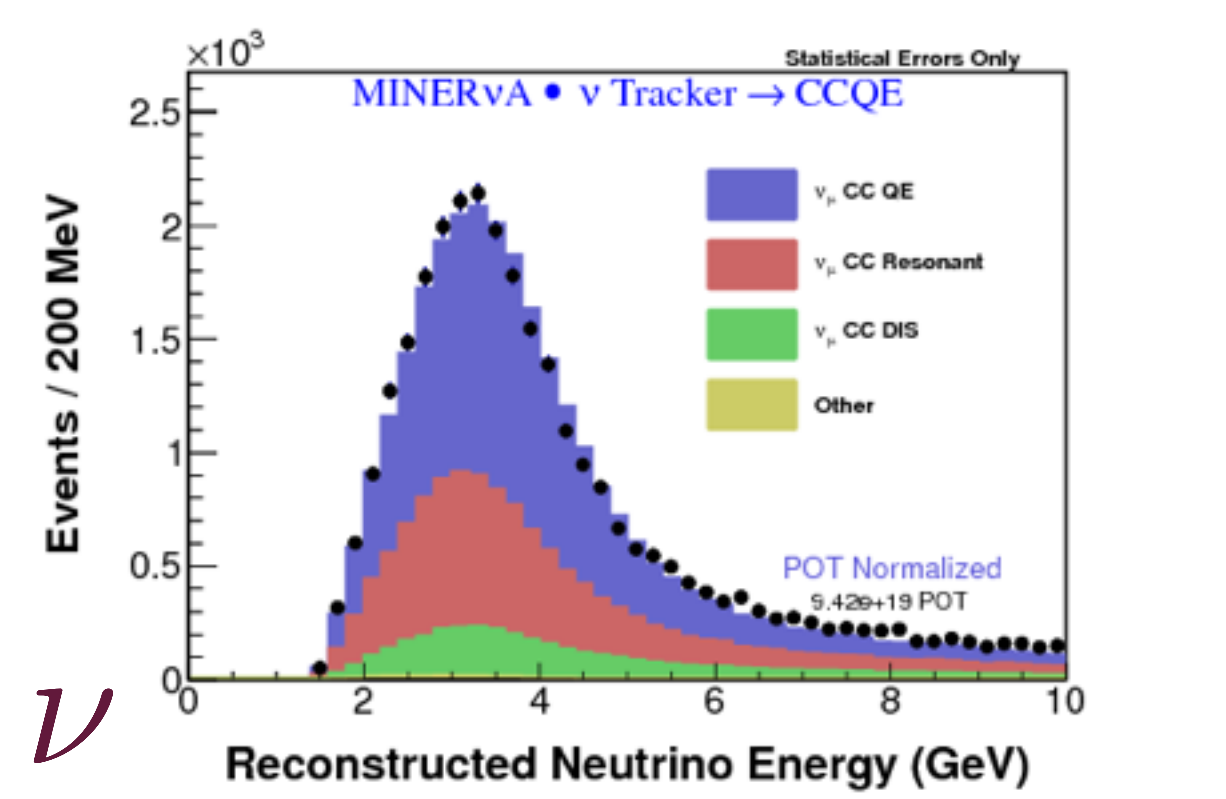
ν̄: 54% efficiency, 77% purity



ν: 47% efficiency, 49% purity

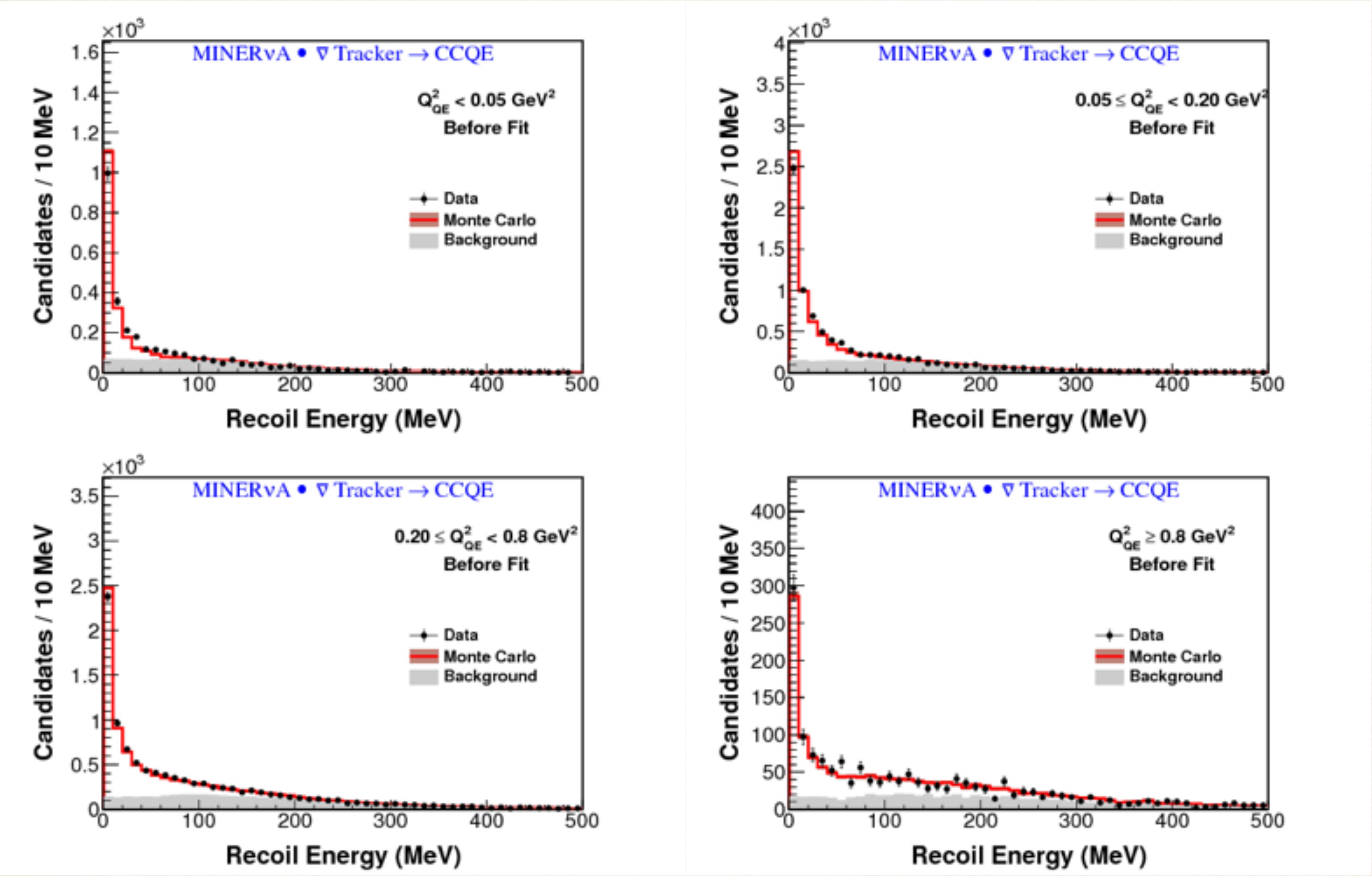
Background subtraction





- Backgrounds include events such as
  - Quasi-elastic-like resonant events, where the pion is absorbed
  - QE-like deep-inelastic scattering events
  - Other DIS or resonant events which are not removed by our cuts

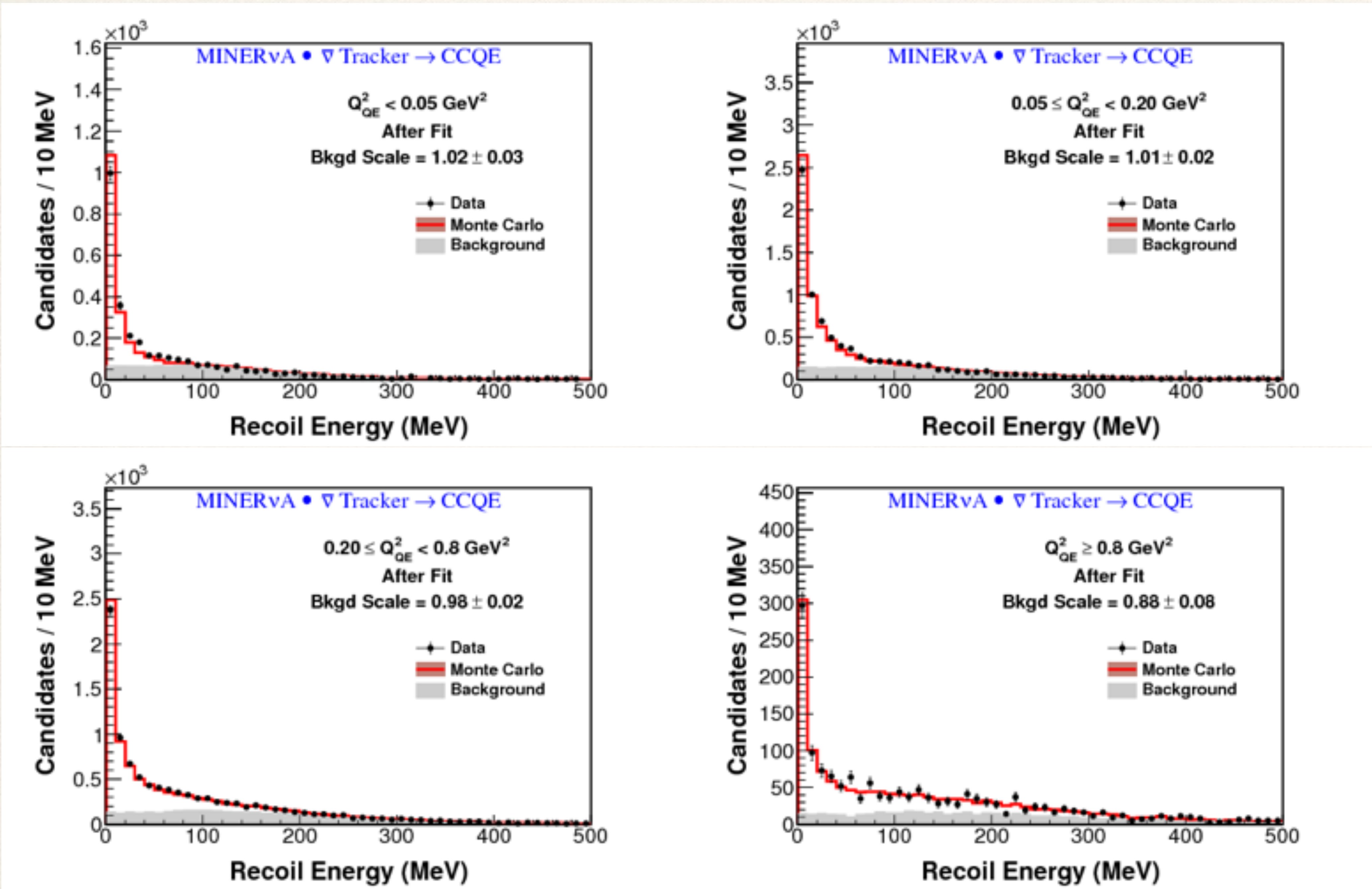
Background subtraction: before



These plots show data for **antineutrinos, before** the background fit

We use data to estimate our backgrounds by performing a fraction fit of simulated signal and background recoil energy distributions from our Monte Carlo, in each of 4 Q^2 bins

Background subtraction: after



These plots show data for **antineutrinos, after** the background fit

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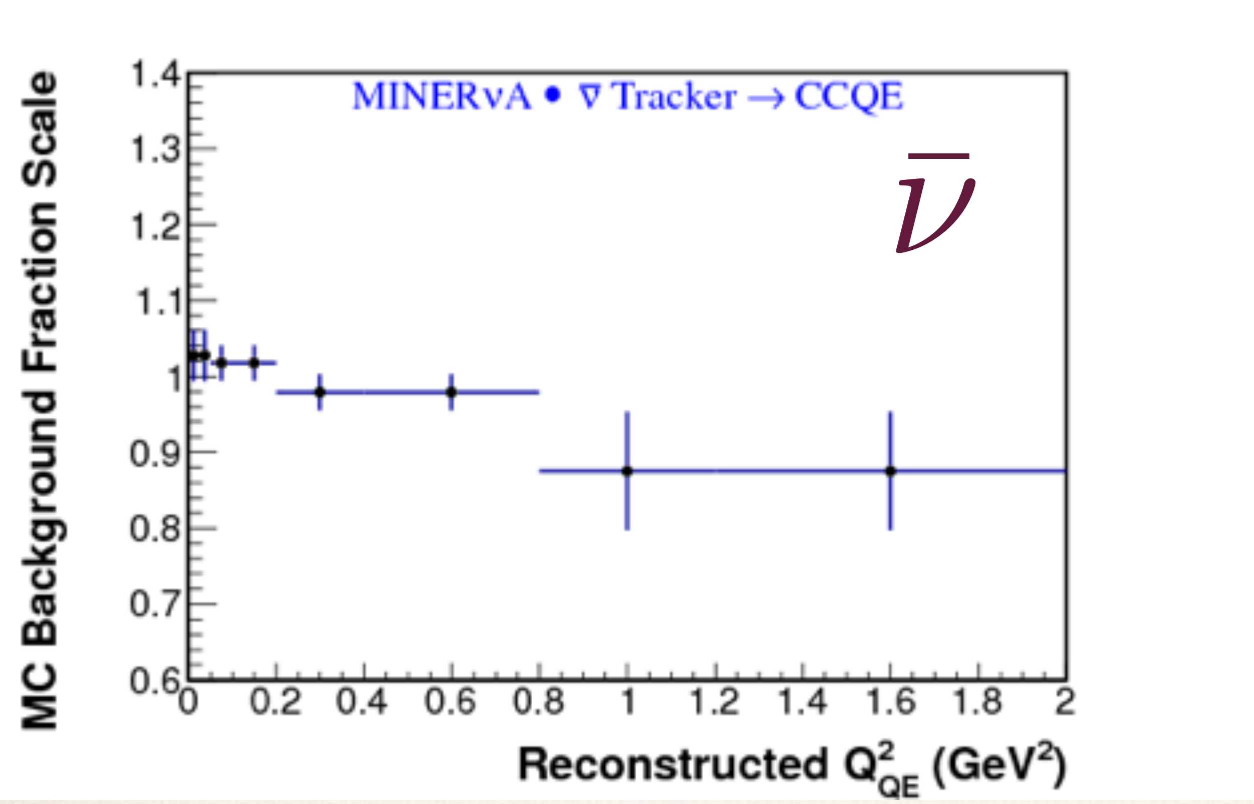
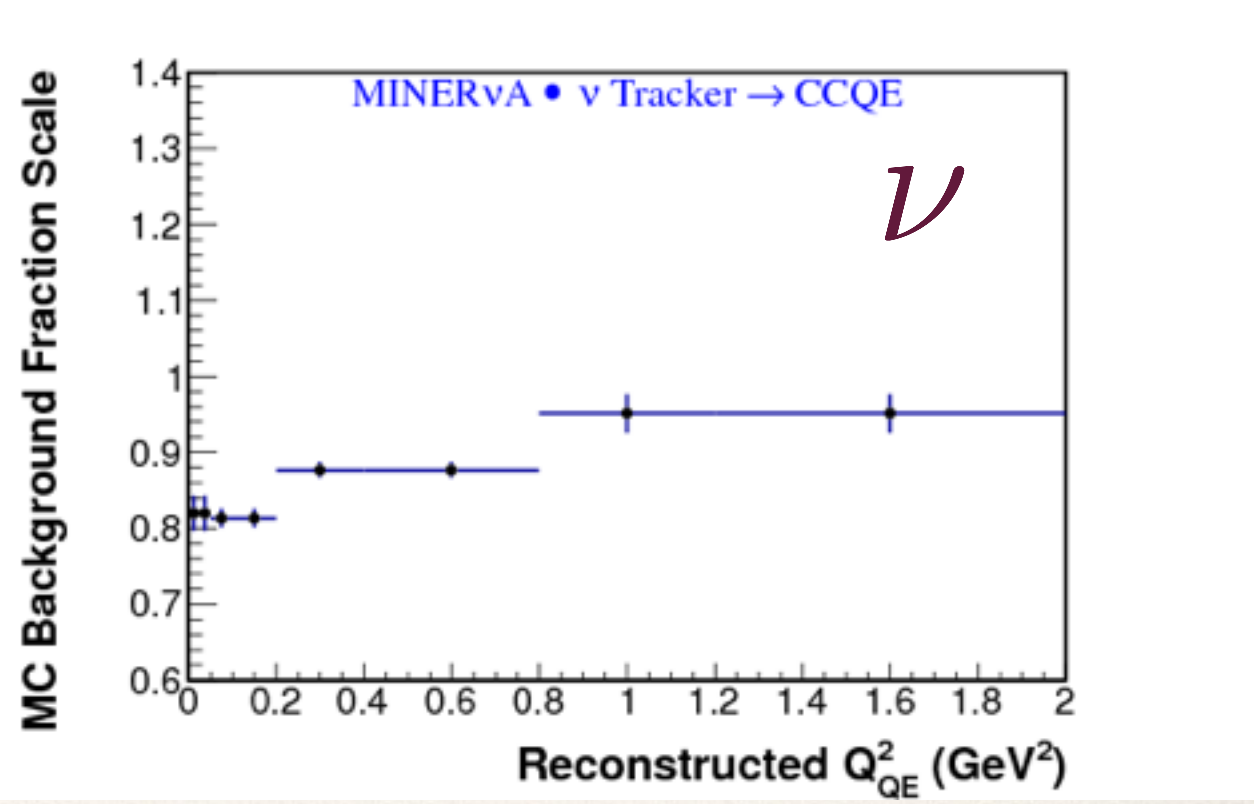
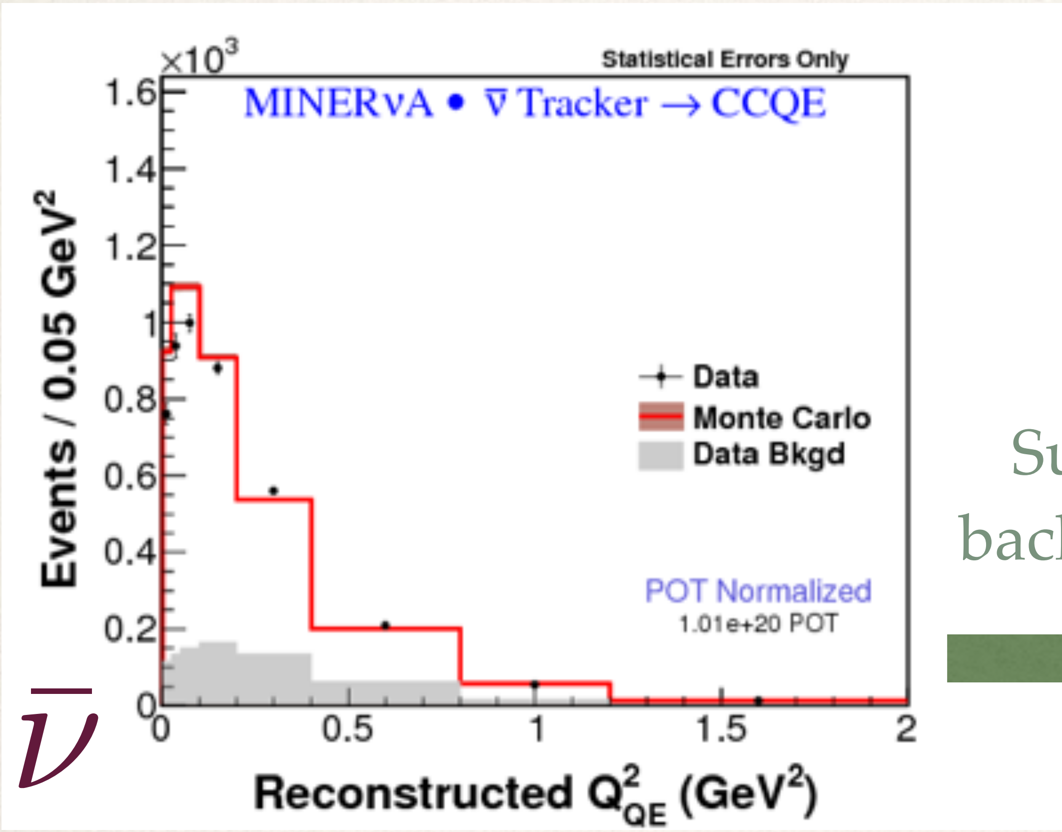
Background scales



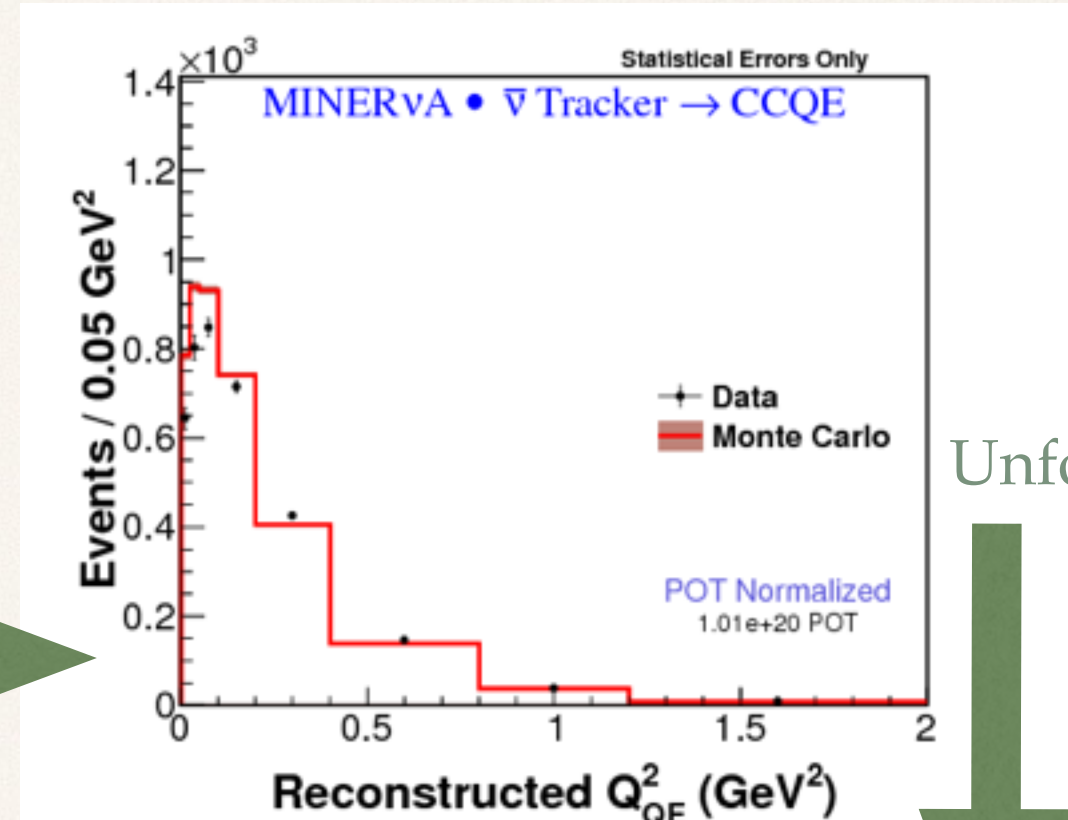


The background scales are shown for both antineutrinos and neutrinos

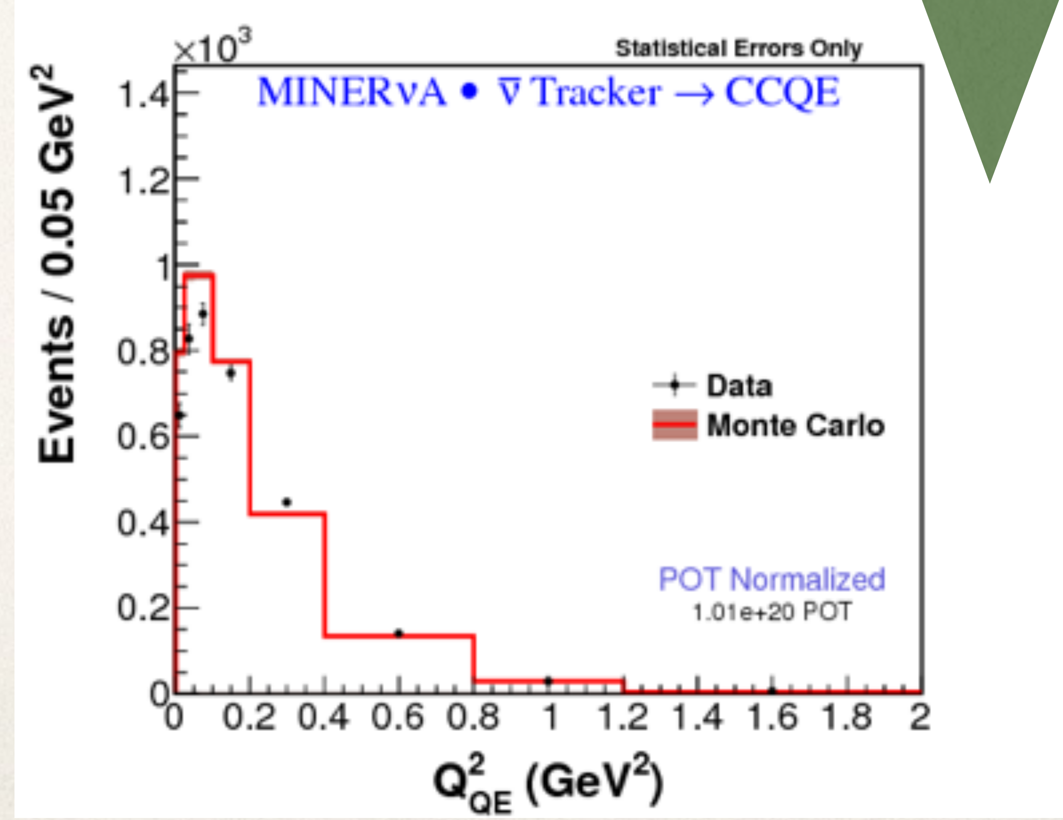
Unfolding



Subtract background

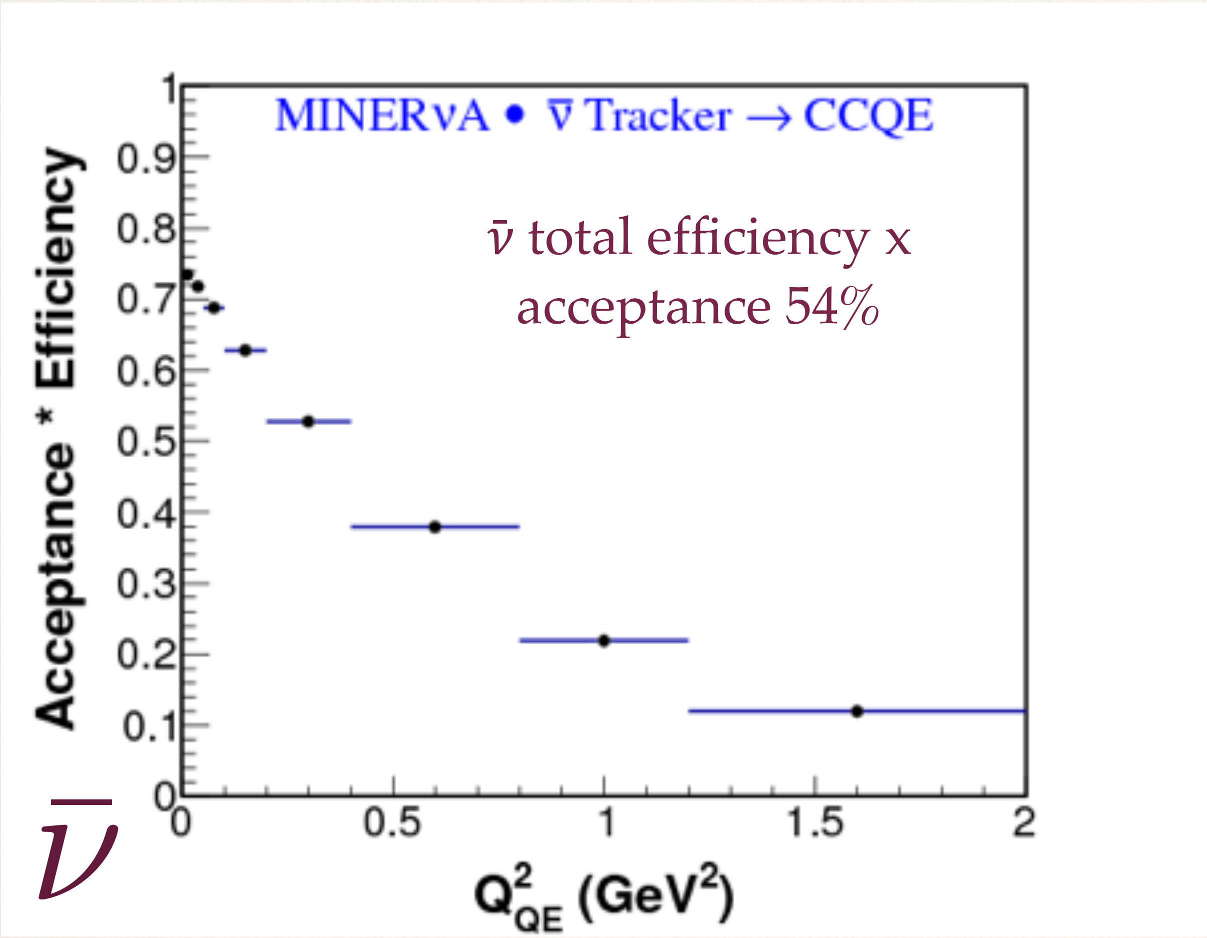


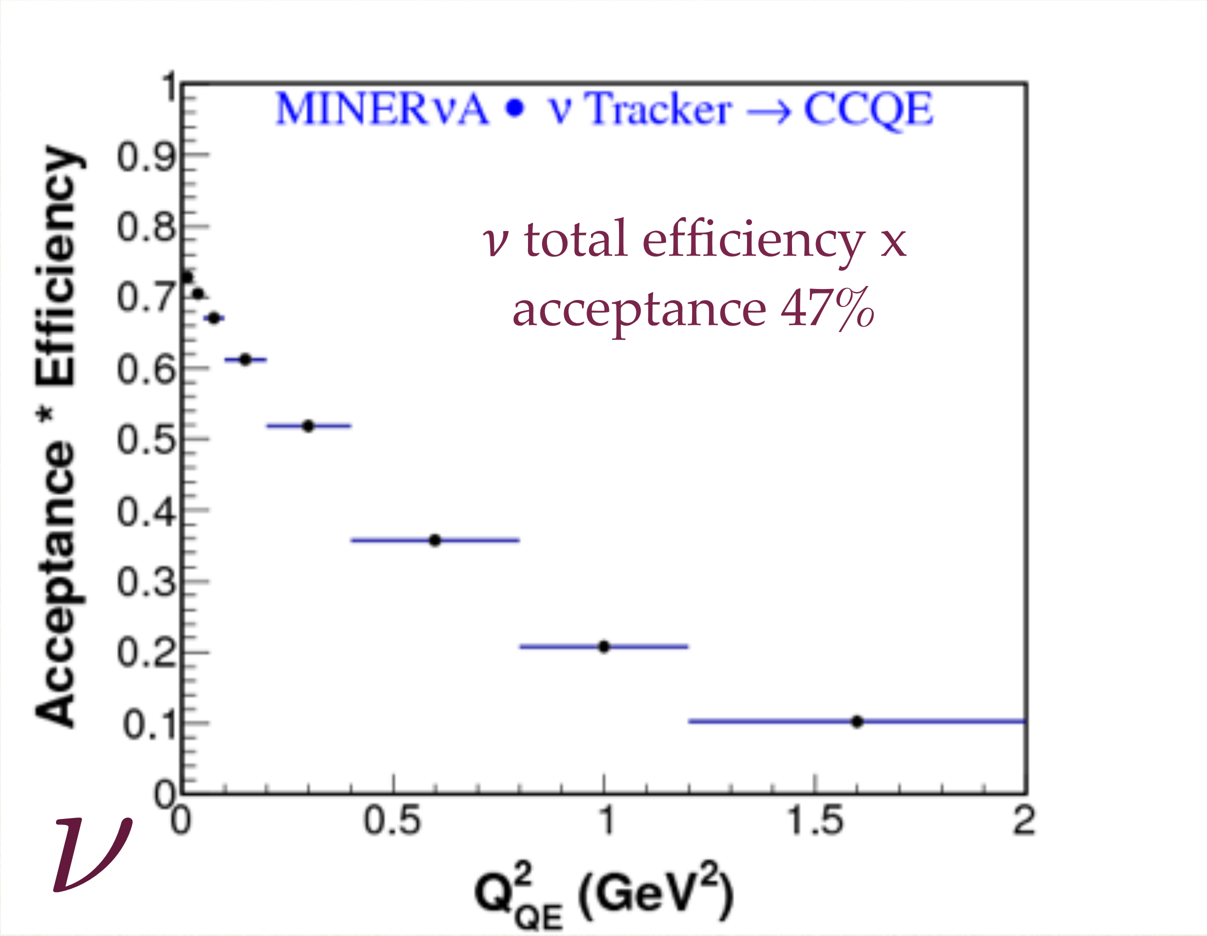
Unfold



- We use four iterations of a Bayesian unfolding method
- The unfolding maps reconstructed Q^2_{QE} to generated Q^2_{QE}
- Note: True Q^2_{QE} refers to Q^2 as constructed from true muon kinematics in the CCQE hypothesis, NOT to the actual 4-momentum transfer squared

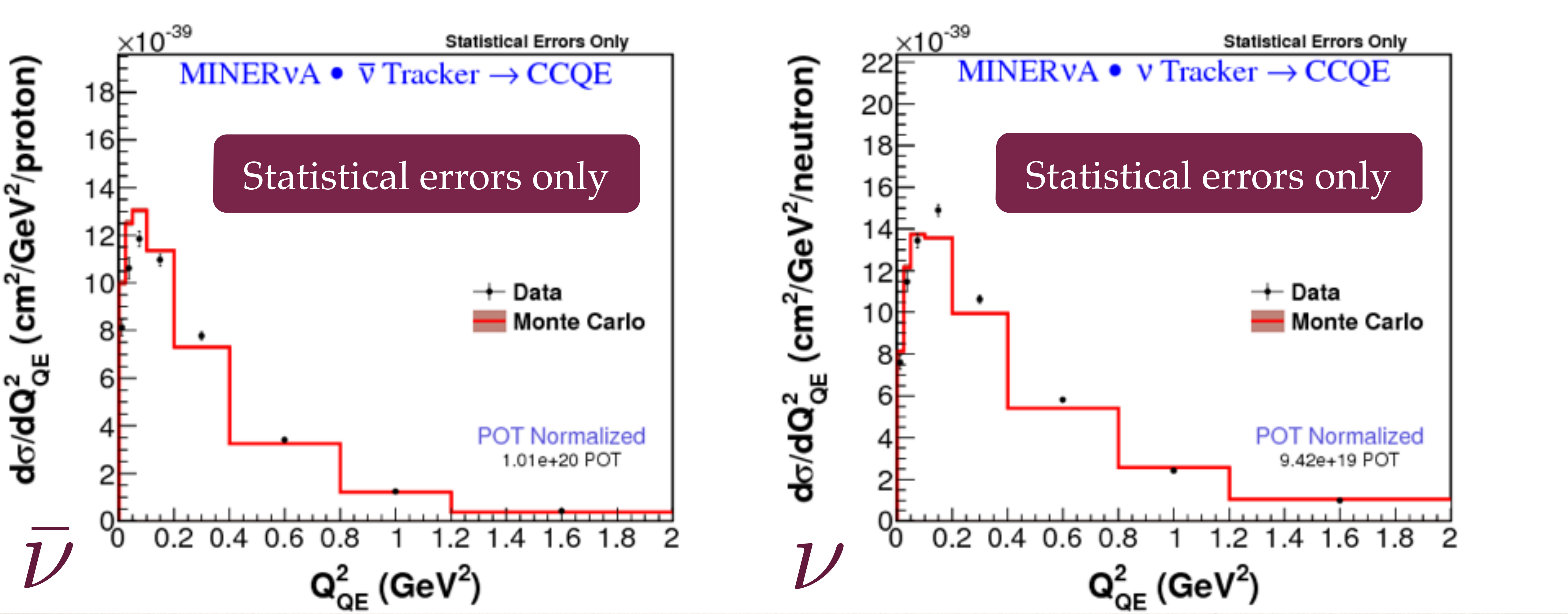
Efficiency and acceptance





- The MINOS-match requirement limits acceptance at high muon angle
- See Carrie McGivern's talk for ways to address this

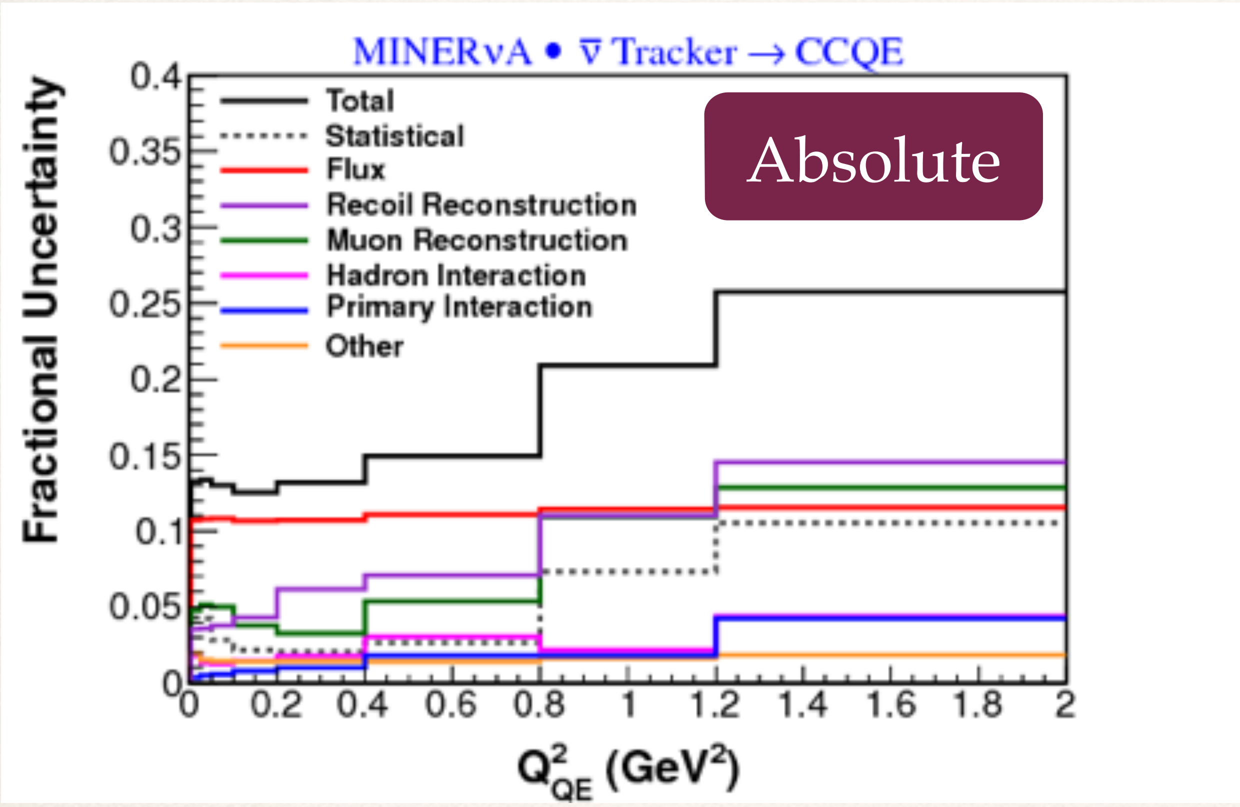
Cross-sections



- To get a final cross-section, we normalize by number of **target nucleons**, number of **protons on target** and integrated (anti)neutrino **1.5-10 GeV flux** per proton on target

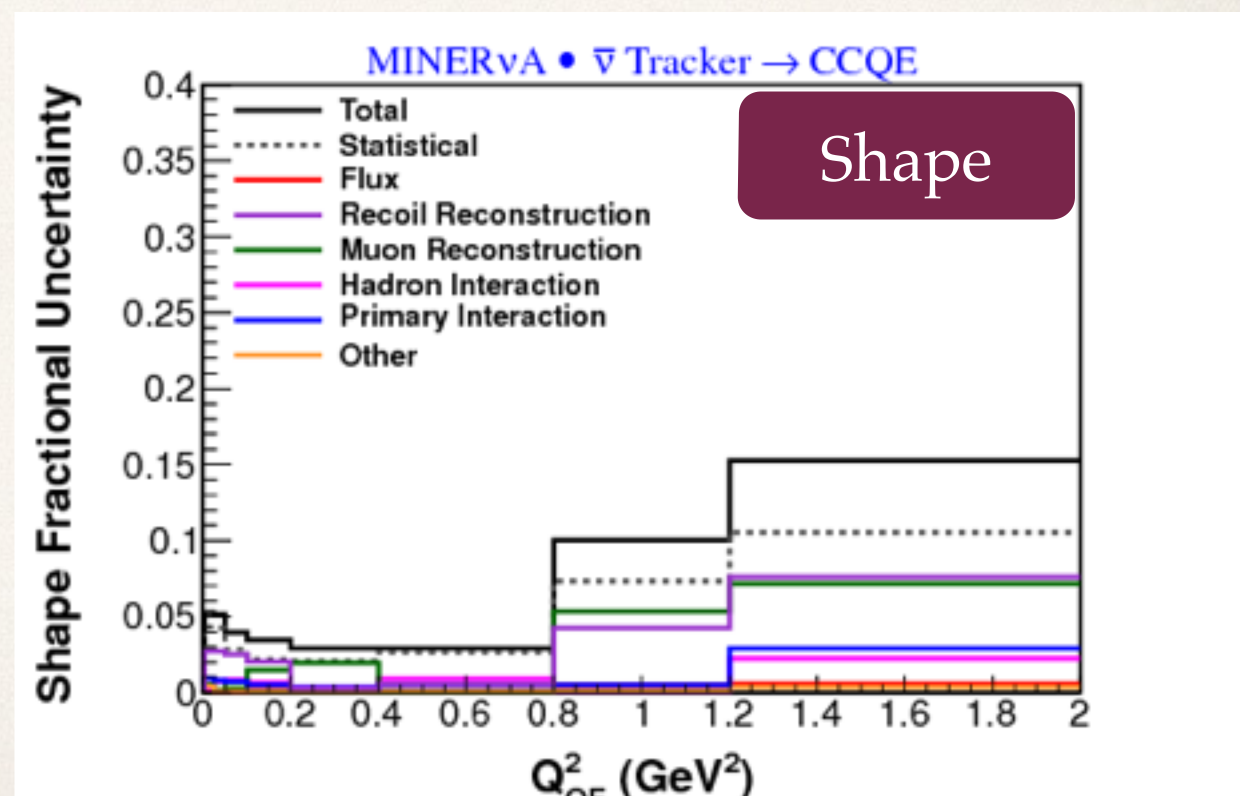
	Antineutrino	**Neutrino**
Protons on target	1.01 e20	9.42 e19
Integrated flux (1.5-10 GeV)	2.43 e-8 /cm^2/POT	2.91 e-8 /cm^2/POT
Target nucleons	1.91 e30 protons	1.65 e30 neutrons

Systematic uncertainties ($\bar{\nu}$)



- Flux uncertainty
- Statistical uncertainty
- Hadron interaction model uncertainty
- Total uncertainty

- Plot above shows absolute uncertainties
- Plot to right shows shape-only uncertainties
- **Flux** dominates the **absolute** uncertainty
- **Uncertainty in flux mostly affects normalization**, not shape
- Statistical uncertainties dominate the shape distribution, and total uncertainty is reduced



Comparing cross-sections to models

We use two frameworks for modeling cross-sections:

GENIE, the Monte Carlo we use to estimate our acceptance *C. Andreopoulos, et al., NIM 288A, 614, 87 (2010)*

NuWro (see T. Golan's talk at NuInt14) *K. M. Graczyk and J. T. Sobczyk, Eur.Phys.J. C31, 177 (2003)*

And the following nuclear models:

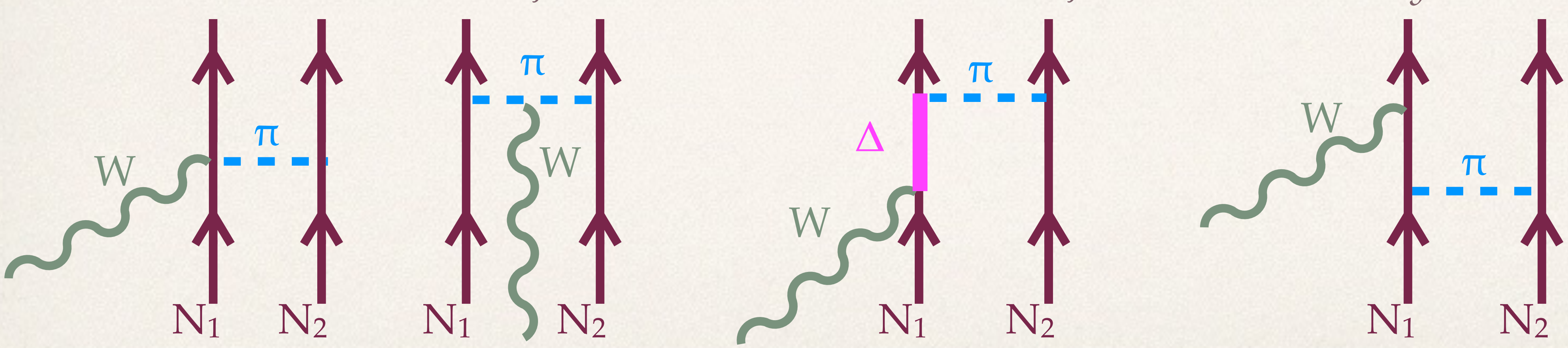
- Relativistic Fermi Gas (RFG) (GENIE and NuWro) *R. Smith and E. Moniz, Nucl.Phys. B43, 605 (1972); A. Bodek, S. Avvakumov, R. Bradford, and H. S. Budd, J.Phys.Conf.Ser. 110, 082004 (2008) ; K. S. Kuzmin, V. V. Lyubushkin, and V. A. Naumov, Eur.Phys.J. C54, 517 (2008)*
  - Constant binding energy; Fermi-distributed momenta. p_F=225 MeV (GENIE), 221 MeV (NuWro)
- Spectral functions (SF) (NuWro only) *O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Nucl.Phys. A579, 493 (1994)*
  - takes correlations into account when calculating initial-state momenta and removal energies

- Local Fermi Gas (LFG) (NuWro only)
  - Fermi momentum and binding energy are a function of position in the nucleus
  - Pauli blocking is less restrictive than for RFG
- Random Phase Approximation (RPA) (NuWro only)
  - Models long-range correlations due to particle-hole excitations
  - RPA suppresses the cross-section at low Q^2

New models

Corrections for nuclear effects

- We can simulate interactions between initial-state nucleons by adding a correction term to our nuclear models
- On our plots, we indicate a cross-section modified in this way by using a dotted line in the same color as the initial nuclear model that was modified
- We currently have two different simulations for these effects:
  - The **transverse enhancement model (TEM)** parameterizes an enhancement seen in electron-nucleus scattering data, by modifying the magnetic form-factor. This is believed to be caused by nucleon-nucleon correlations. It is a correction to nuclear models **without RPA**. *A. Bodek, H. Budd, and M. Christy, Eur.Phys.J. C71, 1726 (2011)*
  - The **Nieves** model includes **meson-exchange current** diagrams. Some of these diagrams correspond to nucleon-nucleon correlations. It is a correction to nuclear models **with RPA.** *J. Nieves, I. Ruiz Simo and M. J. Vicente Vacas, Phys. Rev. C 83 (2011) 045501*



Contact/pion-in-flight *Δ-meson exchange current* *Correlation*

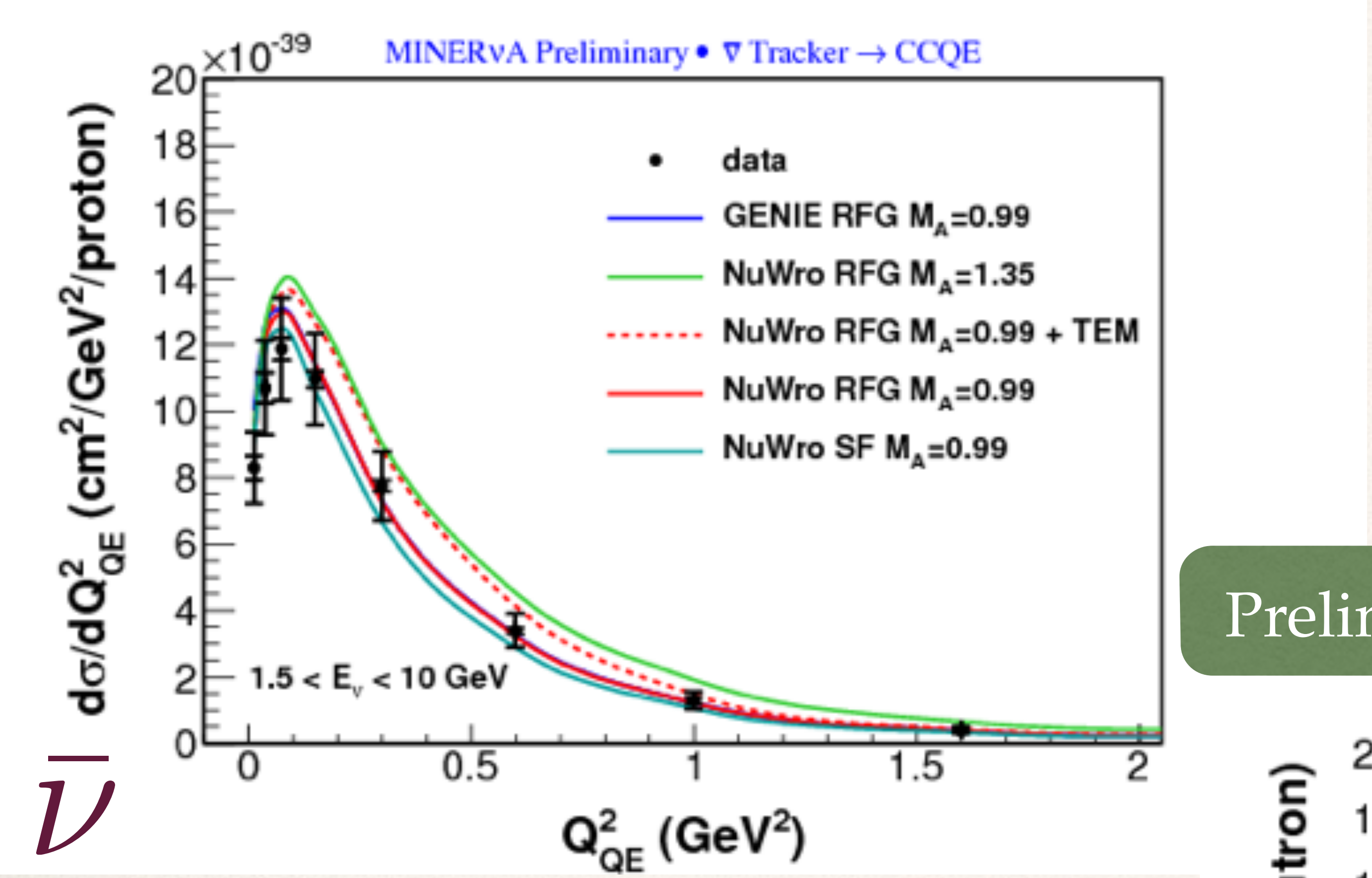
New model

Examples of some MEC interactions, based on a more detailed list from J Morfín

Today's distributions

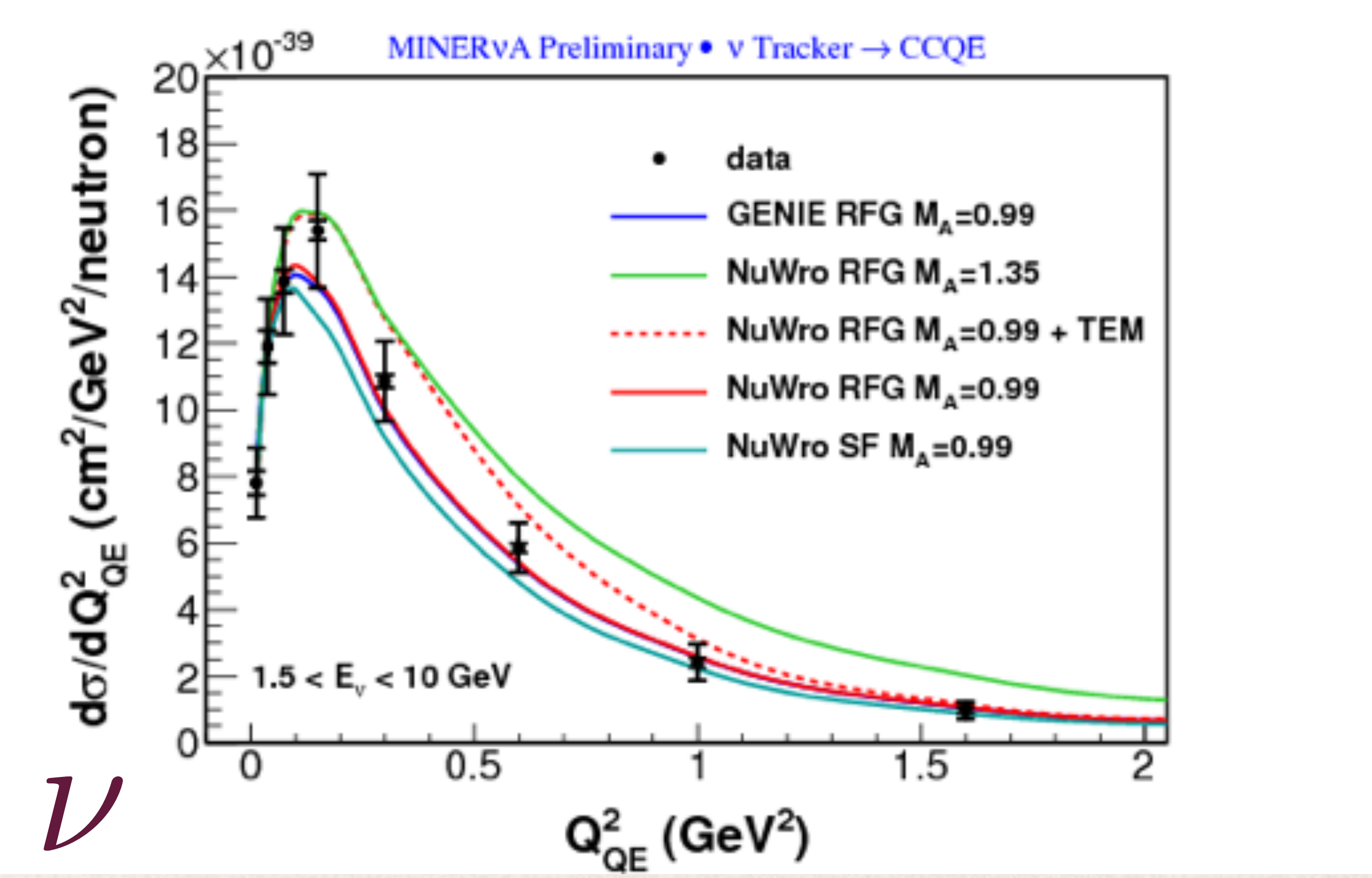
- The plots I show today use NuWro version nuwro11p, a newer version that was used in our 2013 papers
- We also use our latest MINERvA reconstruction code, including an improved flux measurement
  - However, systematics have not been recalculated
  - Instead , for these preliminary plots, we use the new central values, with the total uncertainty values as used in our 2013 papers
- In all plots, the inner marker on the error bars represents statistical uncertainty, while the outer marker represents total uncertainty

Cross-section model comparisons



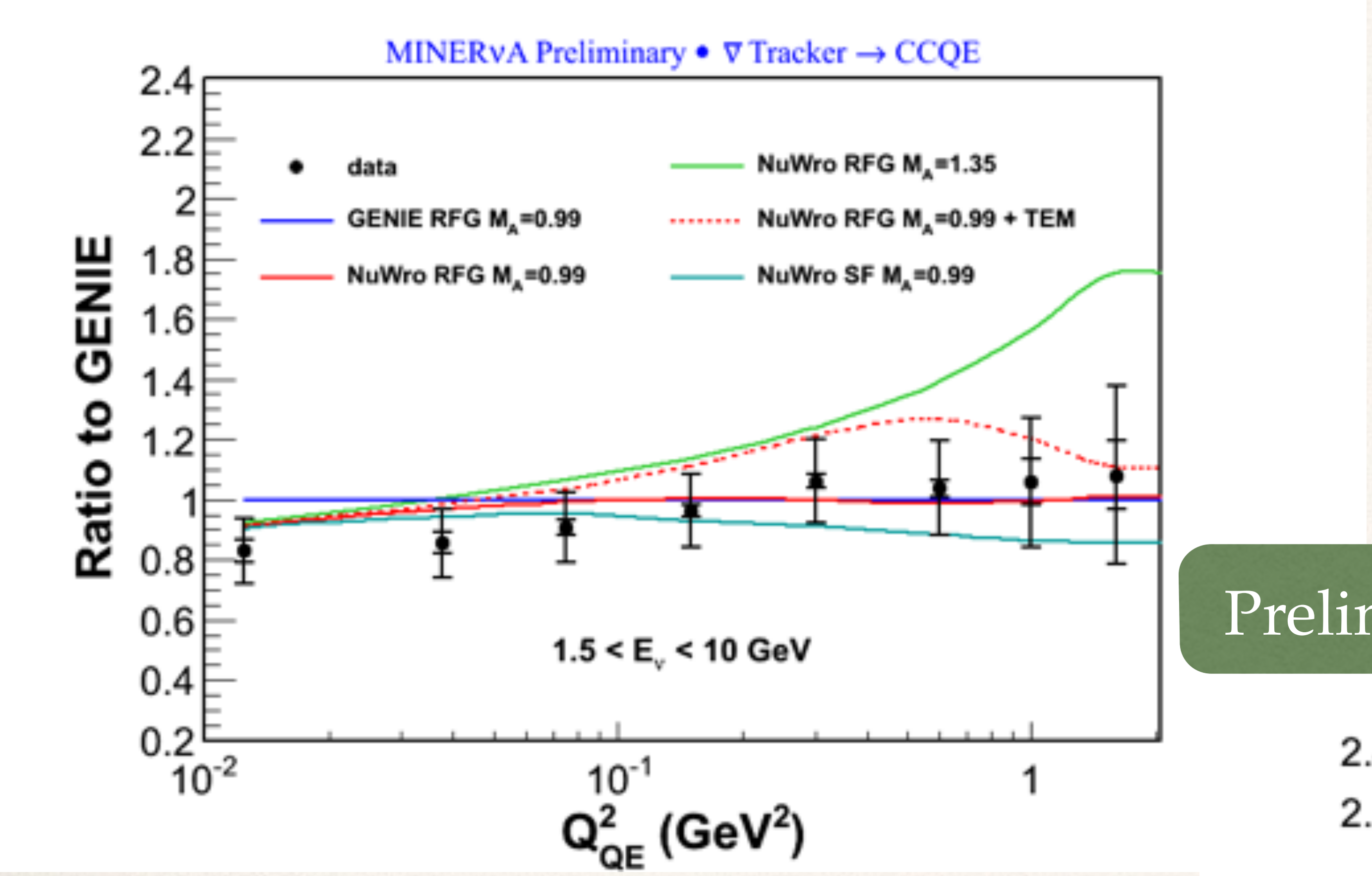
- It's hard to distinguish between the different curves, especially at high Q^2 where the cross-section is small
- A **ratio plot** will make it easier to see the differences

Preliminary



GENIE RFG M_A=0.99
NuWro RFG M_A=0.99
NuWro RFG M_A=1.35
NuWro RFG M_A=0.99+TEM
NuWro SF M_A=0.99

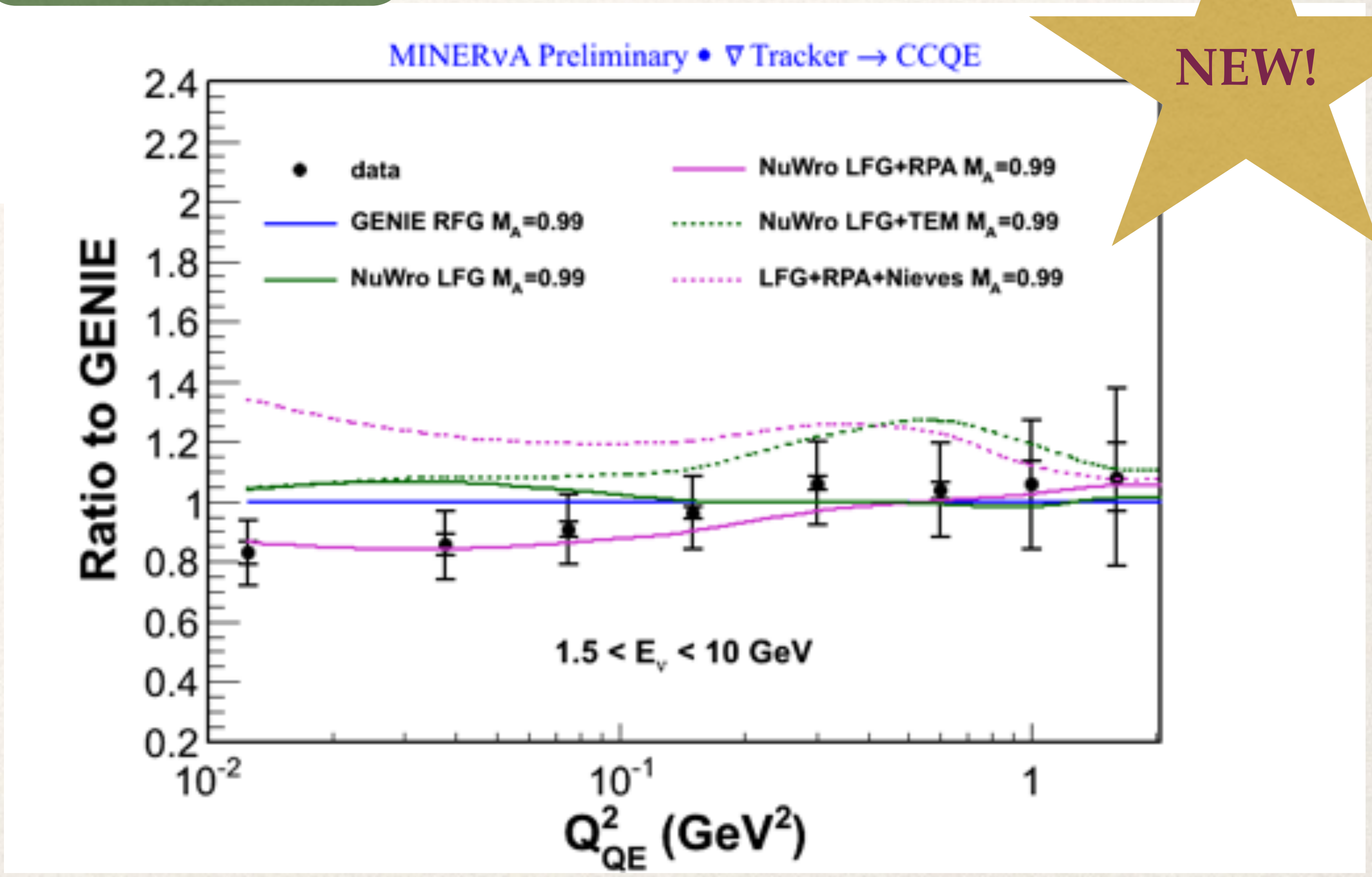
Rate model comparisons ($\bar{\nu}$)



- Here, we have taken a **ratio** to our GENIE Monte Carlo distribution, to make it easier to differentiate between models
- Due to flux uncertainty, a **shape-only** fit may be still more valuable

Preliminary

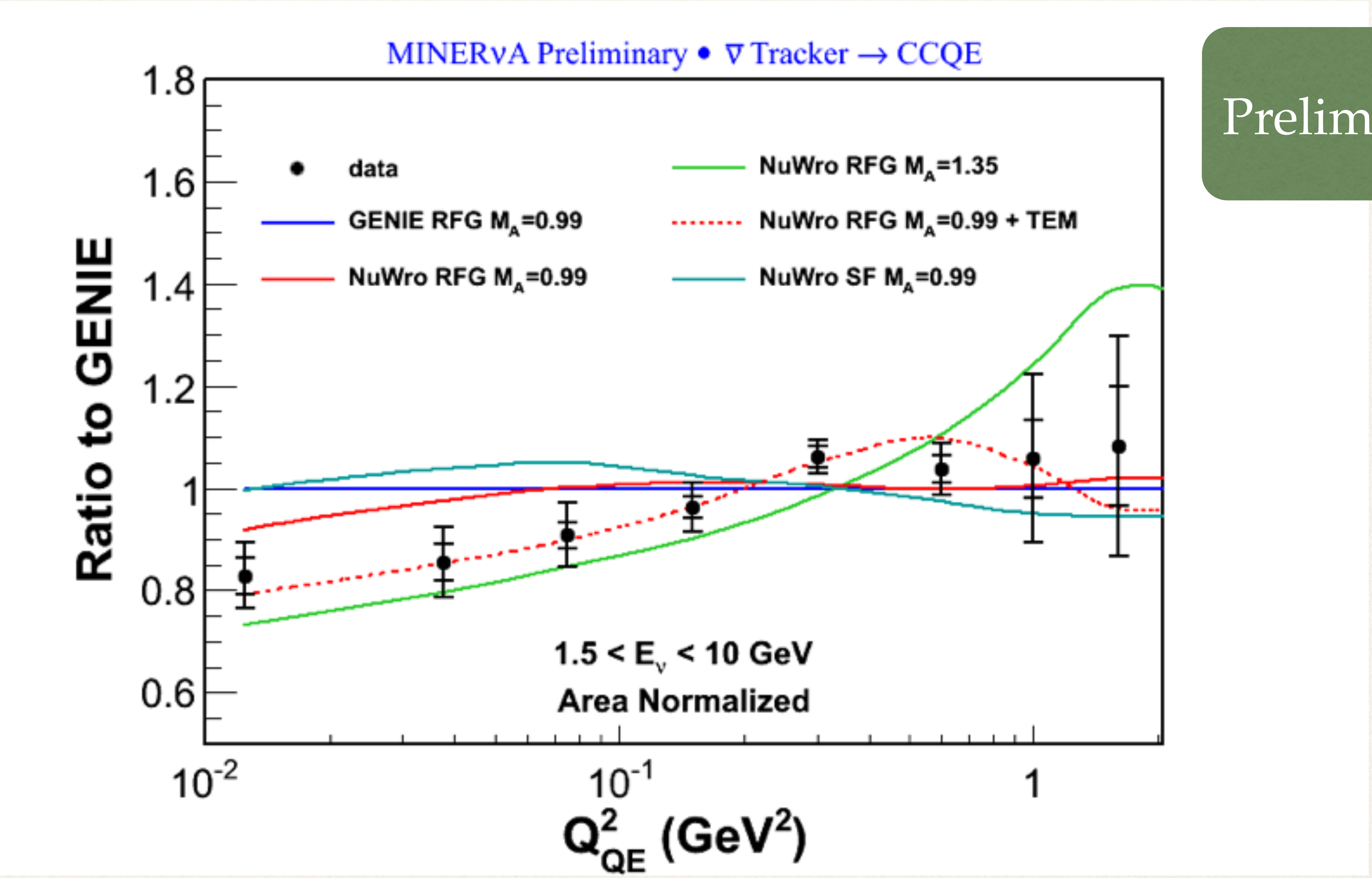
NEW!



- GENIE RFG M_A=0.99
- NuWro RFG M_A=0.99
- NuWro RFG M_A=1.35
- NuWro RFG M_A=0.99+TEM
- NuWro SF M_A=0.99

- NuWro LFG M_A=0.99
- NuWro LFG+RPA M_A=0.99
- NuWro LFG+TEM M_A=0.99
- NuWro LFG+RPA+Nieves M_A=0.99

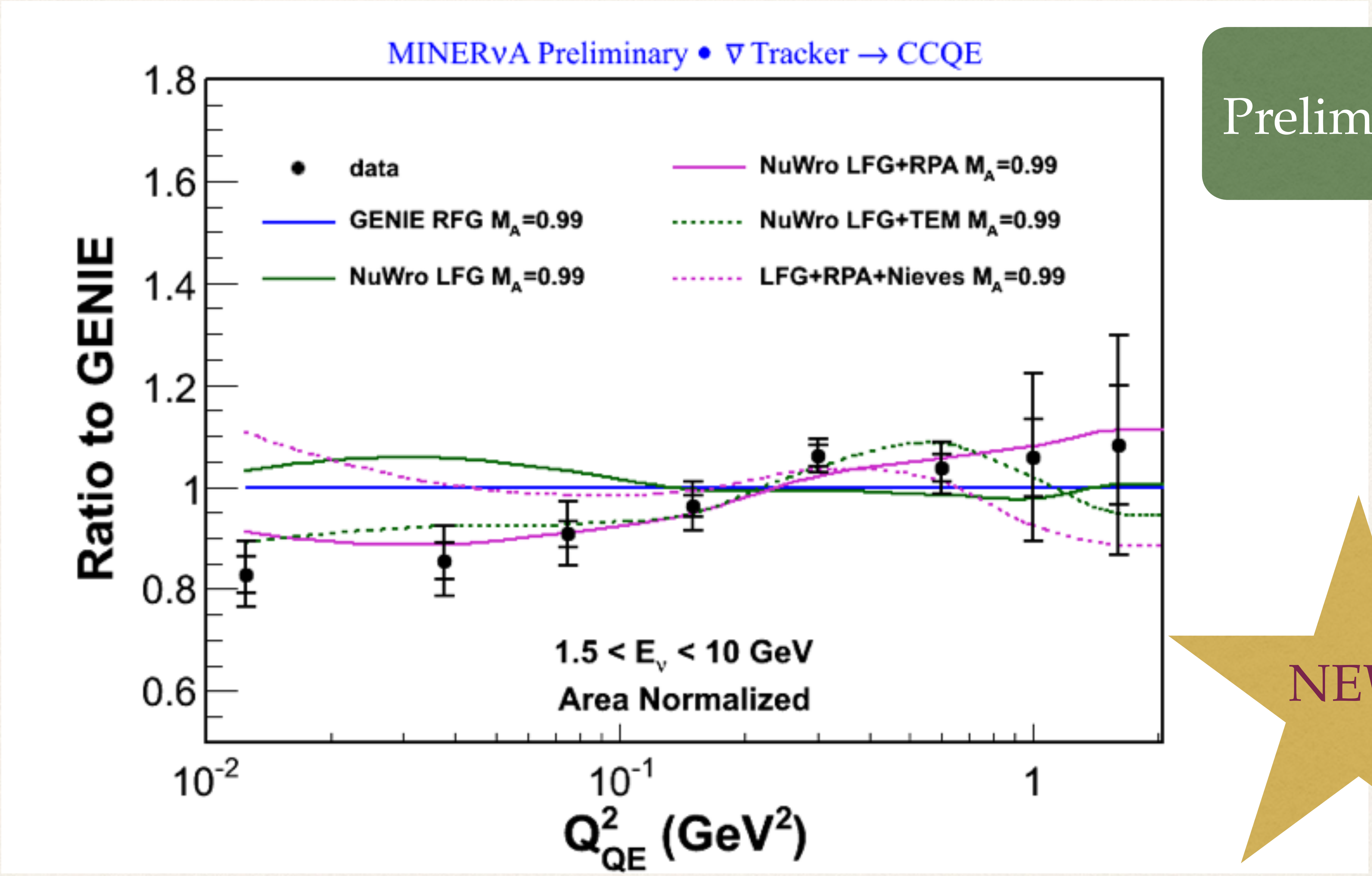
Antineutrino: shape-only ratio (RFG)



Preliminary

Data appears to favor TEM, suggesting initial-state nucleon-nucleon correlations

Antineutrino: shape-only ratio (LFG)



Preliminary

NEW!

Again, the TEM model appears promising, as does RPA. However, we must also consider **correlations between bins** when evaluating the models

χ^2 for fits to antineutrino data

Preliminary

Model	Rate χ^2/d.o.f (8 degrees of freedom)	Shape χ^2/d.o.f (7 degrees of freedom)
GENIE RFG M_A=0.99	2.2	2.44
NuWro RFG M_A=0.99	1.19	1.37
NuWro RFG M_A=1.35	1.98	1.27
NuWro RFG M_A=0.99 + TEM	**0.667**	**0.447**
NuWro SF M_A=0.99	1.89	2.61
NuWro LFG M_A=0.99	3.61	3.97
NuWro LFG + RPA M_A=0.99	**0.771**	**0.953**
NuWro LFG + TEM M_A=0.99	**1.54**	**1.09**
NuWro LFG + RPA + Nieves M_A=0.99	7.06	4.63

χ^2 for fits to antineutrino data

Preliminary

Model	Rate χ^2/d.o.f (8 degrees of freedom)	Shape χ^2/d.o.f (7 degrees of freedom)
GENIE RFG M_A=0.99	2.2	2.44
NuWro RFG M_A=0.99	1.19	1.37
NuWro RFG M_A=1.35	**1.98**	**1.27**
NuWro RFG M_A=0.99 + TEM	0.667	0.447
NuWr		2.61
NuWr		3.97
NuWr		0.953
NuWr		1.09
NuWro LFG + RPA + Nieves M_A=0.99	7.06	4.63

While this line does not appear to be a good match to data, negative correlations between bins mean its χ^2 is much lower than it would appear. This is to do with the shape of the line relative to the data, rather than its absolute value.

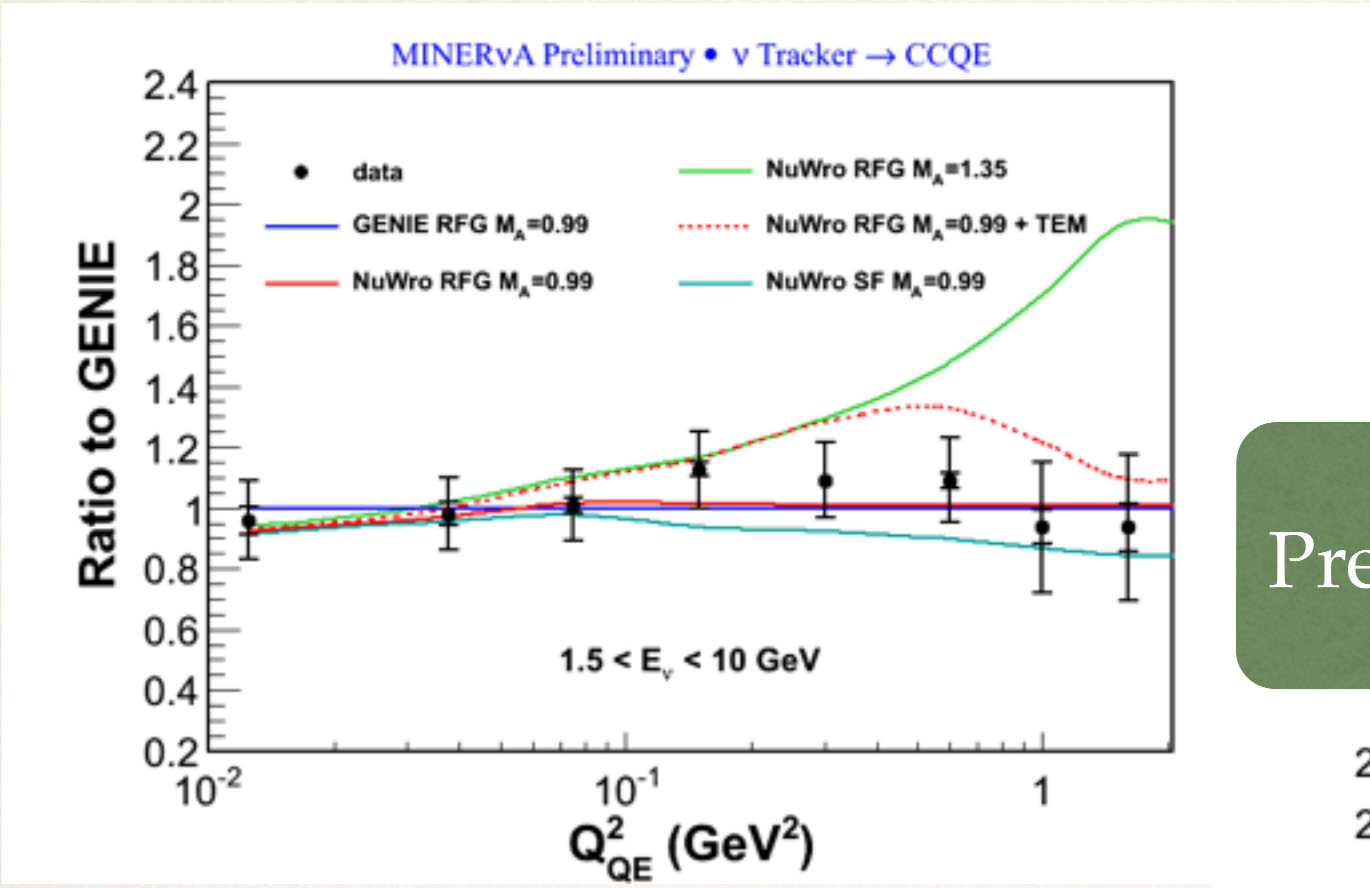
χ^2 for fits to antineutrino data

Preliminary

Model	Rate χ^2/d.o.f (8 degrees of freedom)	Shape χ^2/d.o.f (7 degrees of freedom)
GENIE RFG M_A=0.99	2.2	2.44
Nu[illegible]	[illegible]	1.37
Nu[illegible]	[illegible]	1.27
Nu[illegible]	[illegible]	0.447
Nu[illegible]	[illegible]	2.61
NuWro LFG M_A=0.99	[illegible]	3.97
NuWro LFG + RPA M_A=0.99	0.771	0.953
NuWro LFG + TEM M_A=0.99	1.54	1.09
NuWro LFG + RPA + Nieves M_A=0.99	**7.06**	**4.63**

This higher χ^2 does not tell us about either the LFG, RPA or Nieves models individually, but rather that the convolution of the three of them does not appear to be a close match to our data.

Rate model comparisons (ν)



GENIE RFG M_A=0.99

NuWro RFG M_A=0.99

NuWro RFG M_A=1.35

NuWro RFG M_A=0.99+TEM

NuWro SF M_A=0.99

NuWro LFG M_A=0.99

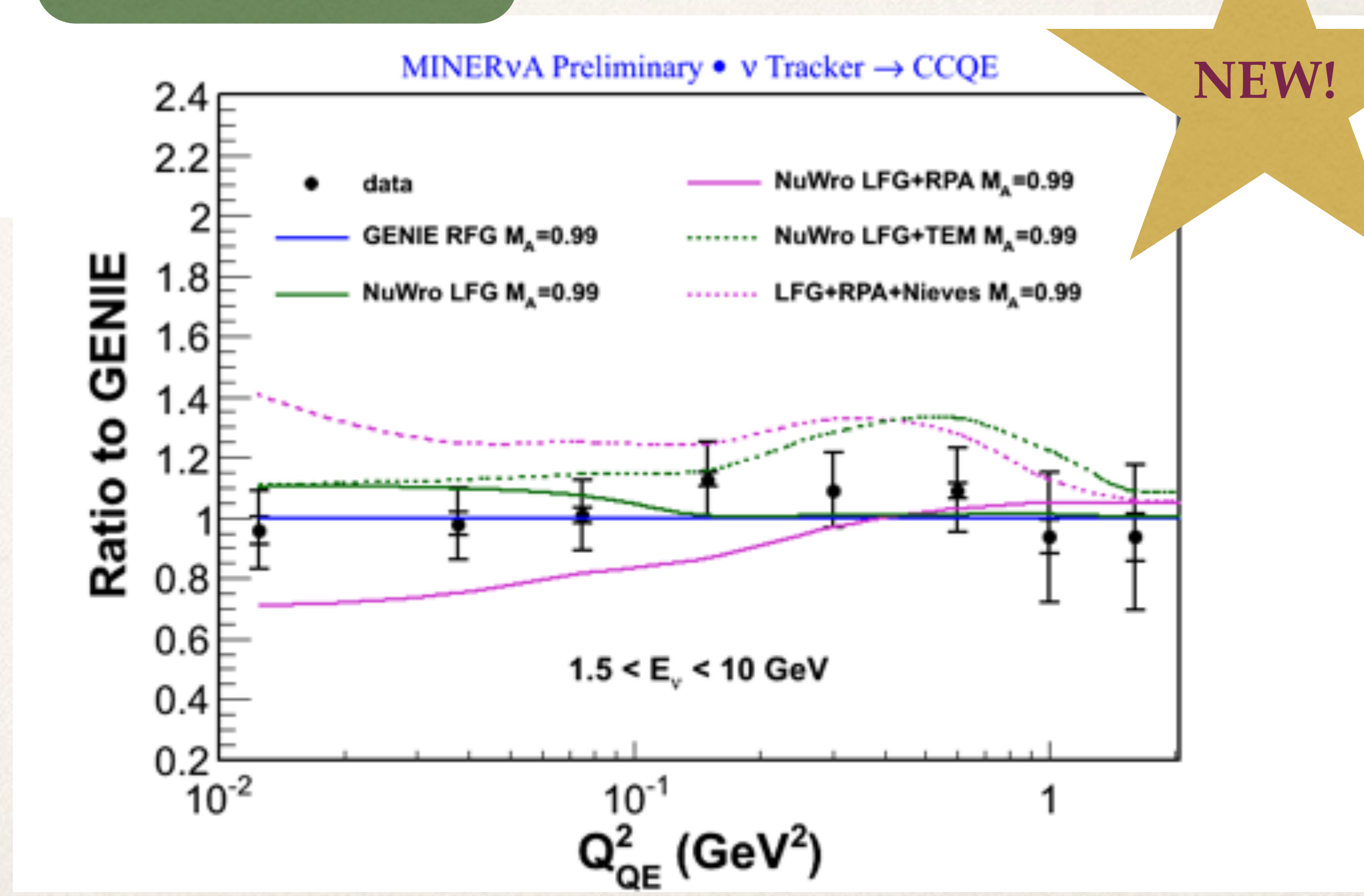
NuWro LFG+RPA M_A=0.99

NuWro LFG+TEM M_A=0.99

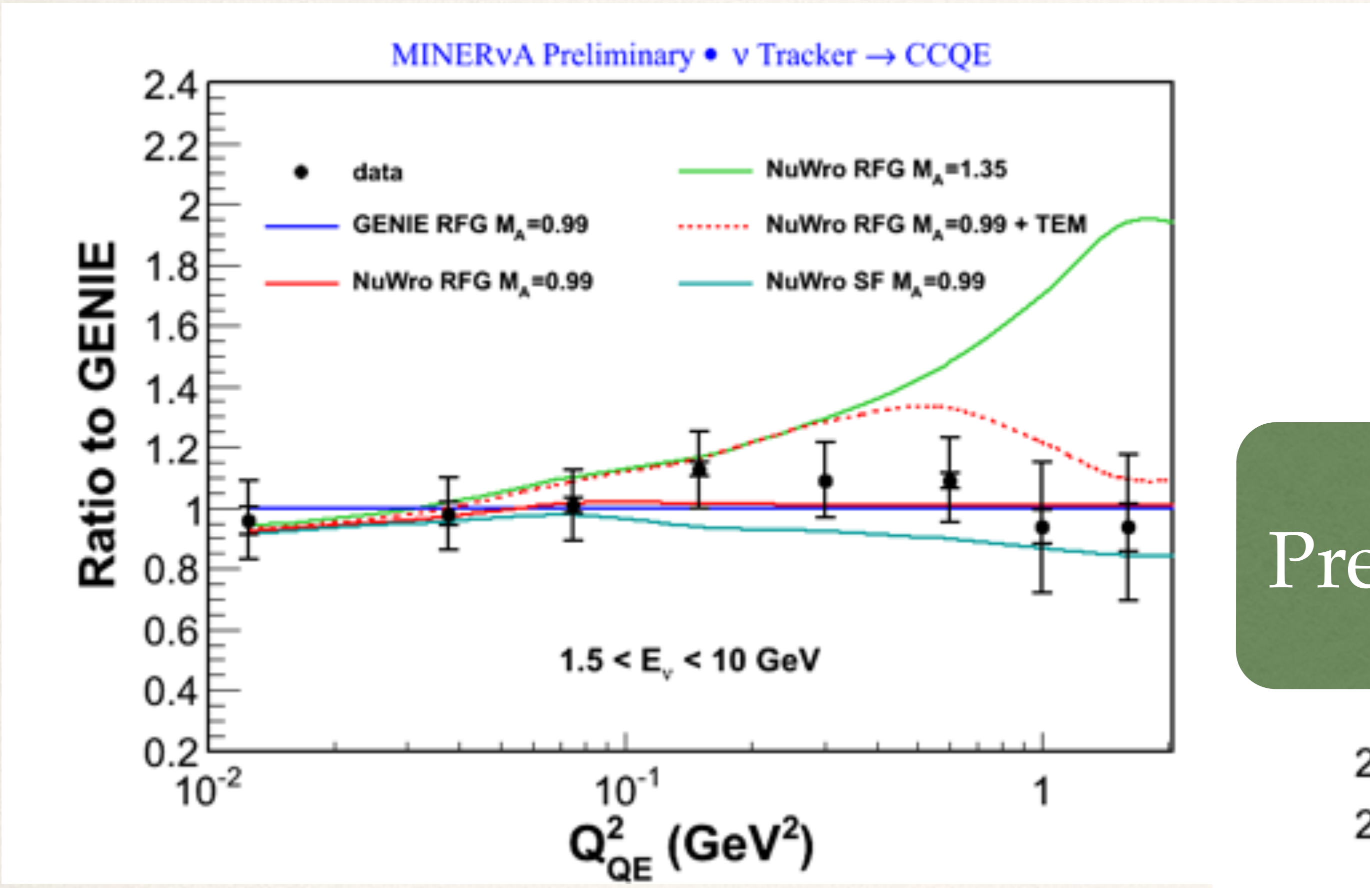
NuWro LFG+RPA+Nieves M_A=0.99

Preliminary

NEW!



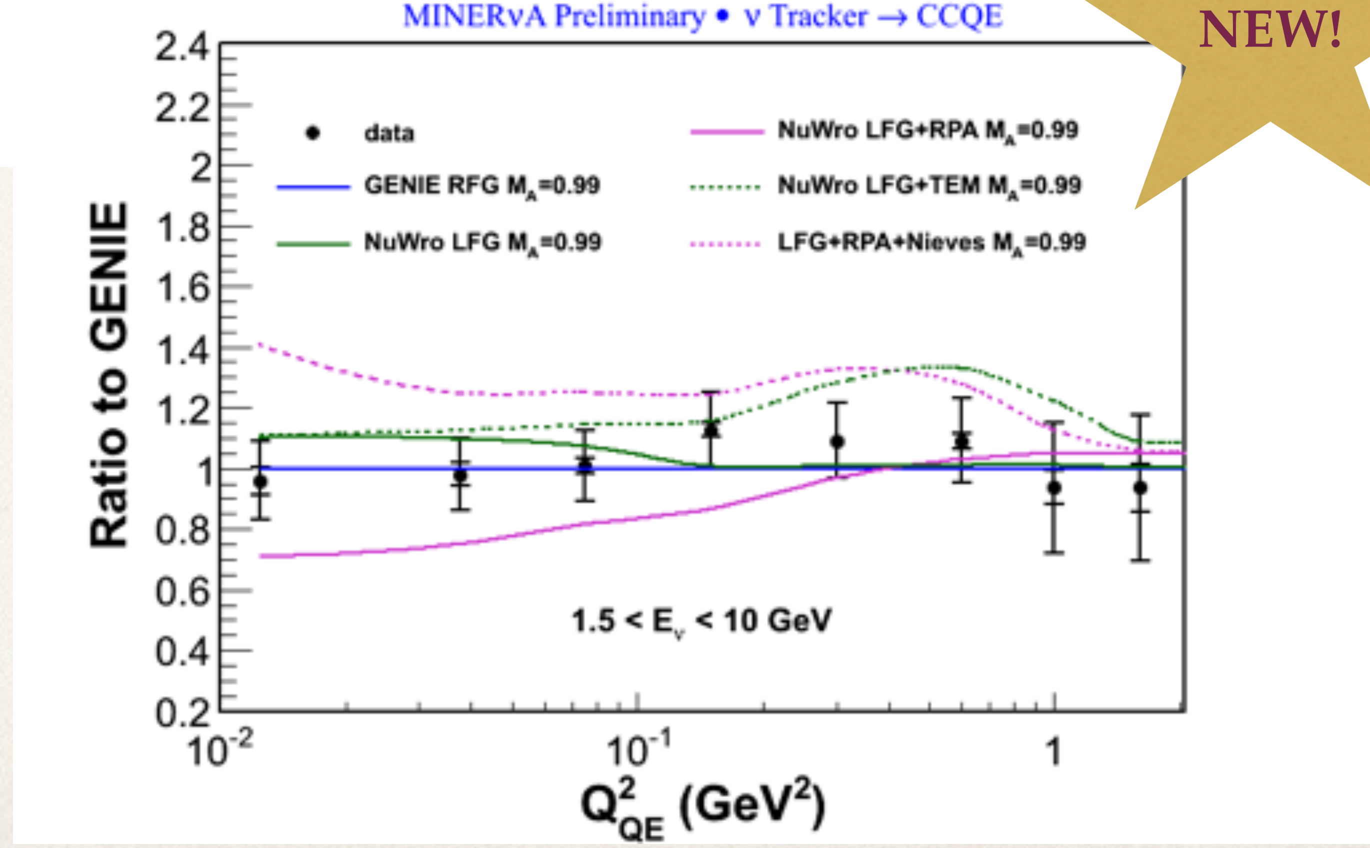
Rate model comparisons (ν)



- Again, a **shape-only** comparison with models would avoid misleading results due to flux uncertainty

Preliminary

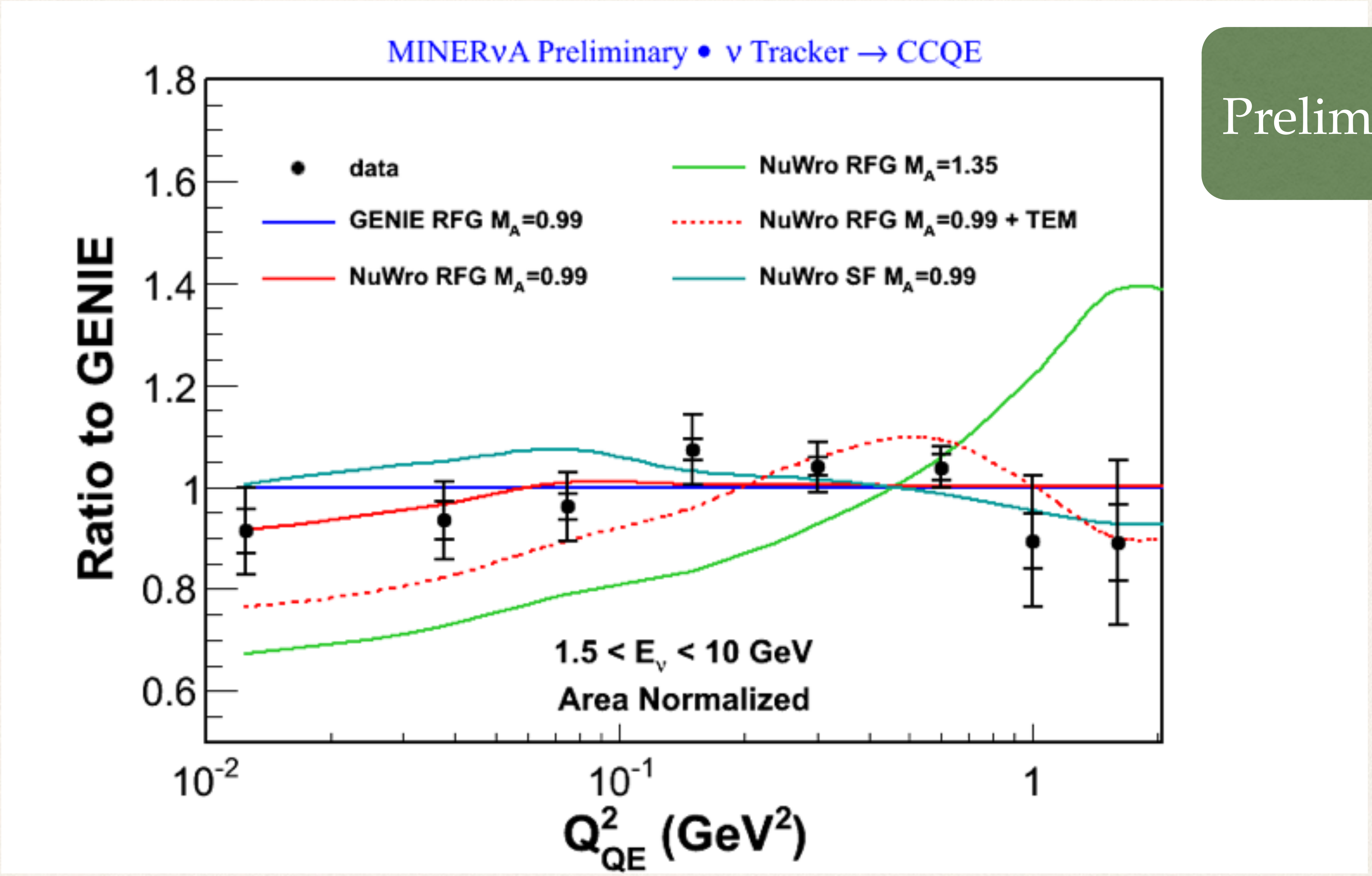
NEW!



GENIE RFG M_A=0.99
NuWro RFG M_A=0.99
NuWro RFG M_A=1.35
NuWro RFG M_A=0.99+TEM
NuWro SF M_A=0.99

NuWro LFG M_A=0.99
NuWro LFG+RPA M_A=0.99
NuWro LFG+TEM M_A=0.99
NuWro LFG+RPA+Nieves M_A=0.99

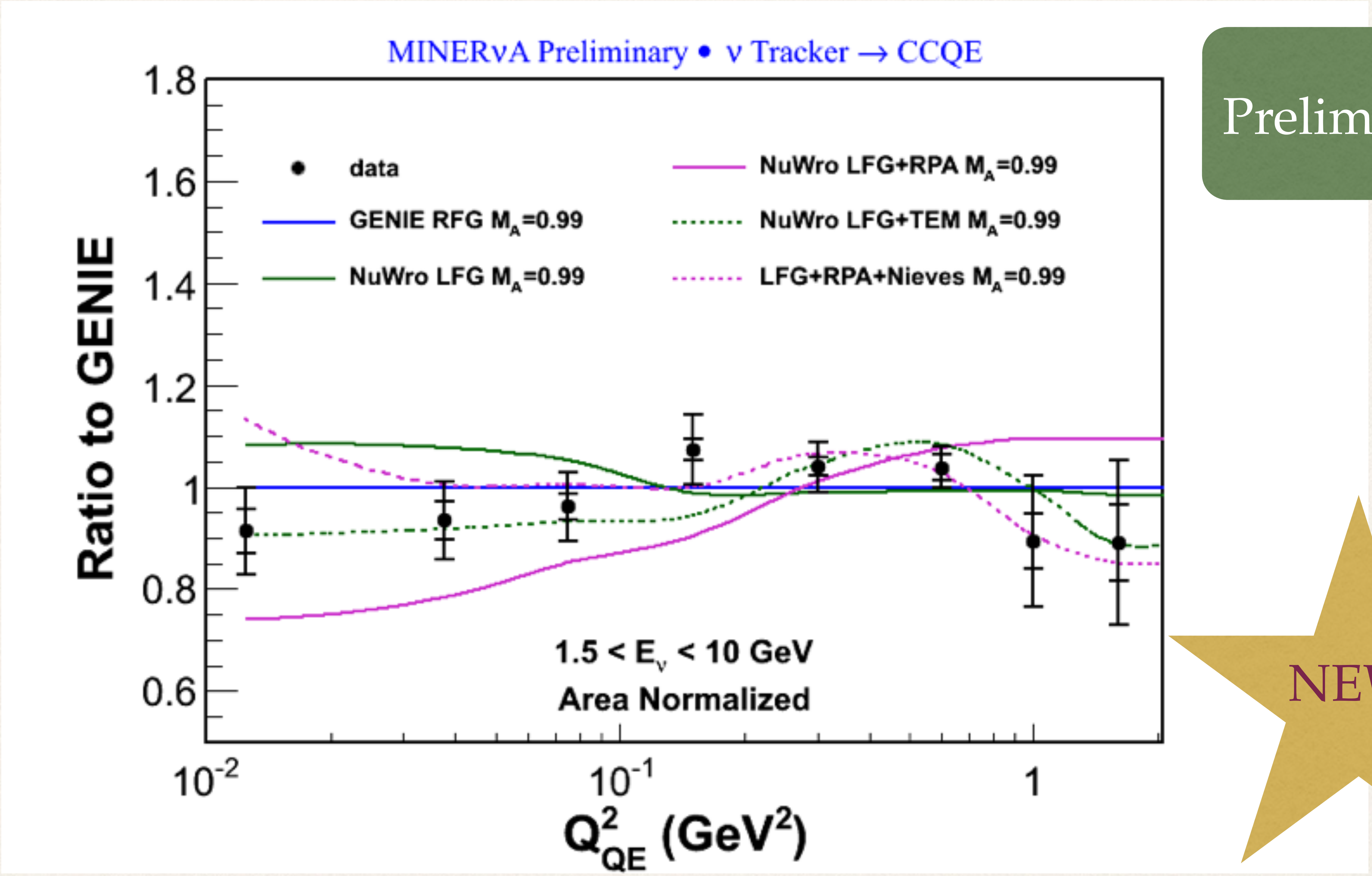
Neutrino: shape-only ratio (RFG)



Preliminary

1

Neutrino: shape-only ratio (LFG)



Preliminary

NEW!

Again, the TEM model appears promising, but the χ^2 will be able to tell us about how the models compare when we take correlations into account

χ^2 for fits to neutrino data

Preliminary

Model	Rate χ^2/d.o.f (8 degrees of freedom)	Shape χ^2/d.o.f (7 degrees of freedom)
GENIE RFG M_A=0.99	1.86	2.06
NuWro RFG M_A=0.99	**1.47**	**1.66**
NuWro RFG M_A=1.35	3.38	1.99
NuWro RFG M_A=0.99 + TEM	2.92	2.26
NuWro SF M_A=0.99	2.64	3.43
NuWro LFG M_A=0.99	4.77	5.3
NuWro LFG + RPA M_A=0.99	**1.73**	**1.83**
NuWro LFG + TEM M_A=0.99	3.53	2.75
NuWro LFG + RPA + Nieves M_A=0.99	5.49	4.1

χ^2 for $\bar{\nu}$ and ν rates, combined

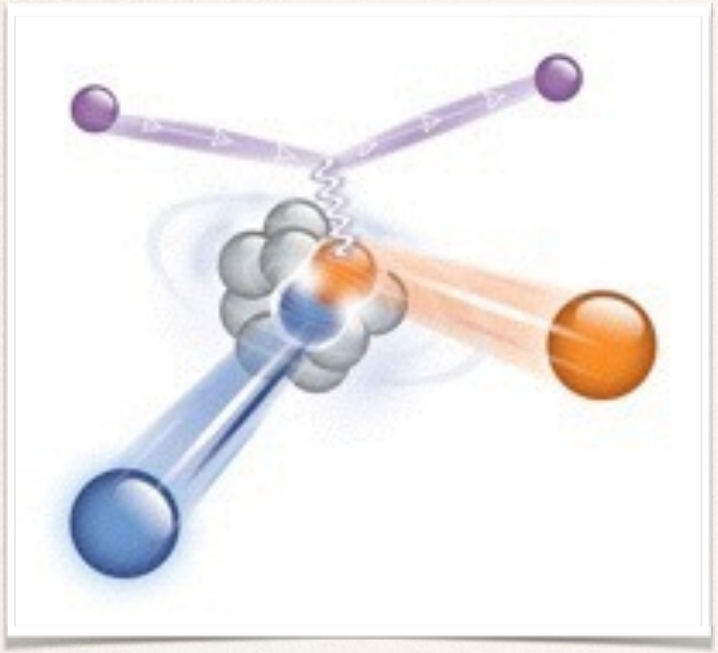
Preliminary

Model	Combined rate χ^2/d.o.f (16 degrees of freedom)
GENIE RFG M_A=0.99	2.04
NuWro RFG M_A=0.99	**1.53**
NuWro RFG M_A=1.35	3.14
NuWro RFG M_A=0.99 + TEM	**1.92**
NuWro SF M_A=0.99	2.22
NuWro LFG M_A=0.99	3.88
NuWro LFG + RPA M_A=0.99	**1.93**
NuWro LFG + TEM M_A=0.99	2.59
NuWro LFG + RPA + Nieves M_A=0.99	5.79

Comments on model fits

- **Correlations** between bins can have a dramatic effect on χ^2 values, and cannot be ignored when determining goodness of fit
- **Shape-only** comparisons help reduce flux uncertainty, but have much more significant bin-bin correlations
- Antineutrino mode, in particular, hints at possible nuclear effects including **nucleon-nucleon correlations**
- Our nuclear models are complex and involve the convolution of several elements (initial state momentum distributions, correlation models etc).
  - Our results are due to the combined effect of the elements used in each model
  - We do not yet have enough information to draw a conclusion about whether the specific models can reproduce our data

Energy around the vertex



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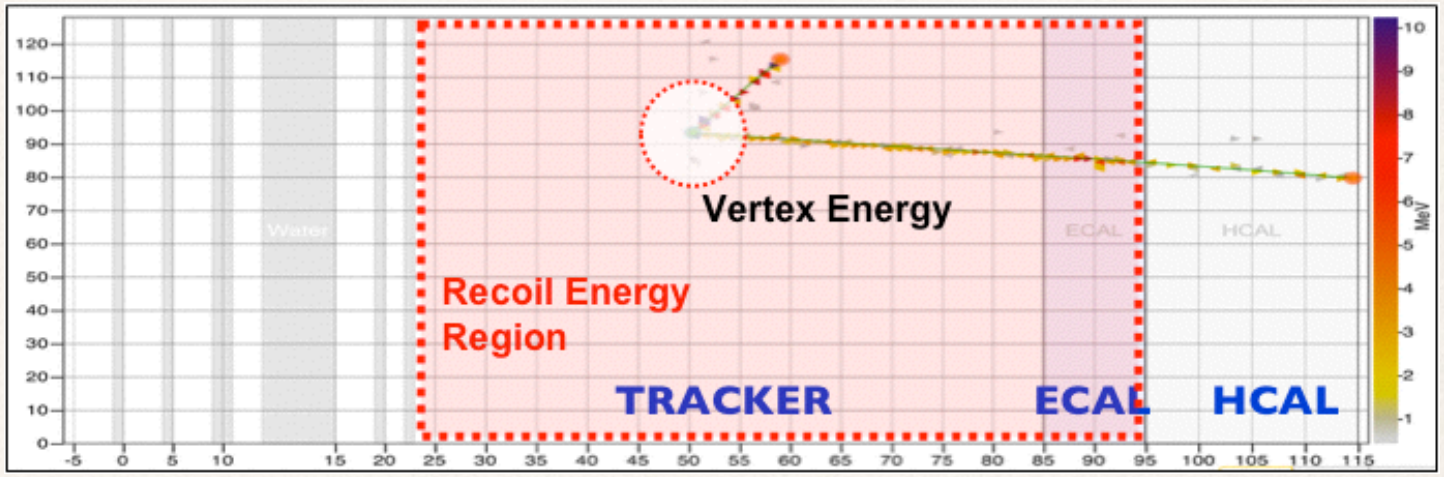
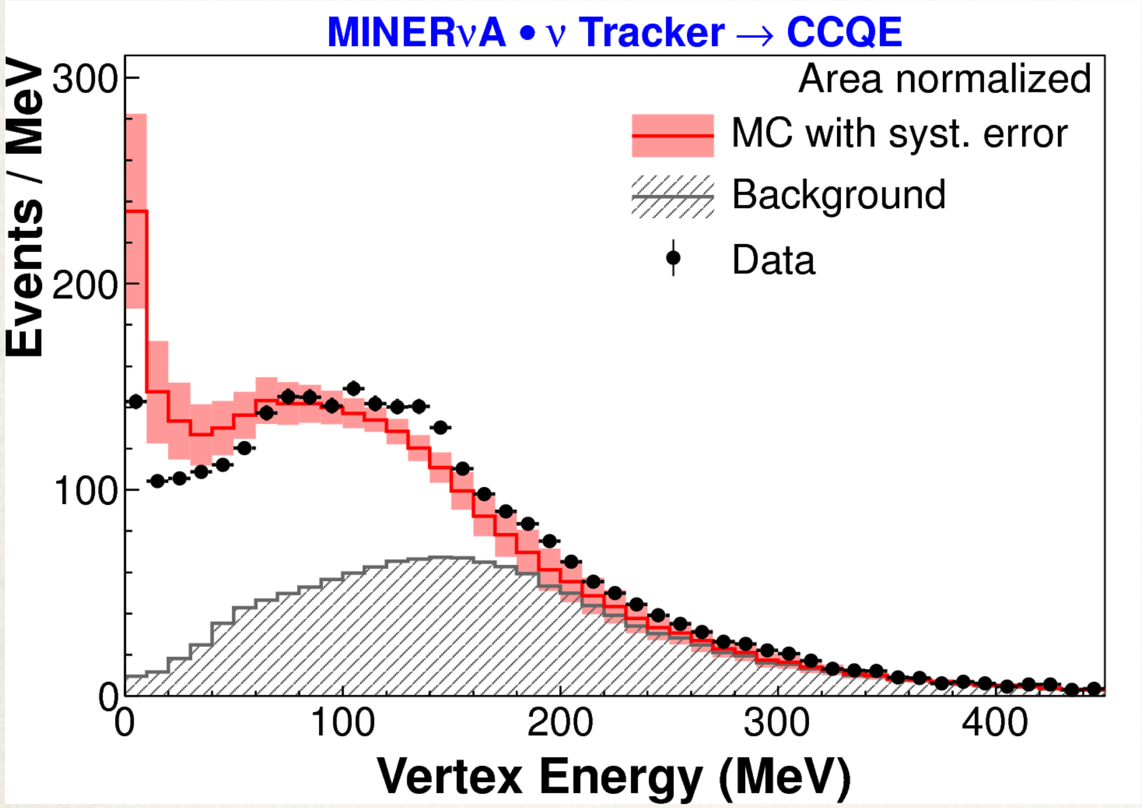
- Transverse enhancement parameterizes a model with **correlated pairs** of nucleons
- If a neutrino interacts with a paired nucleon, its partner may also be ejected



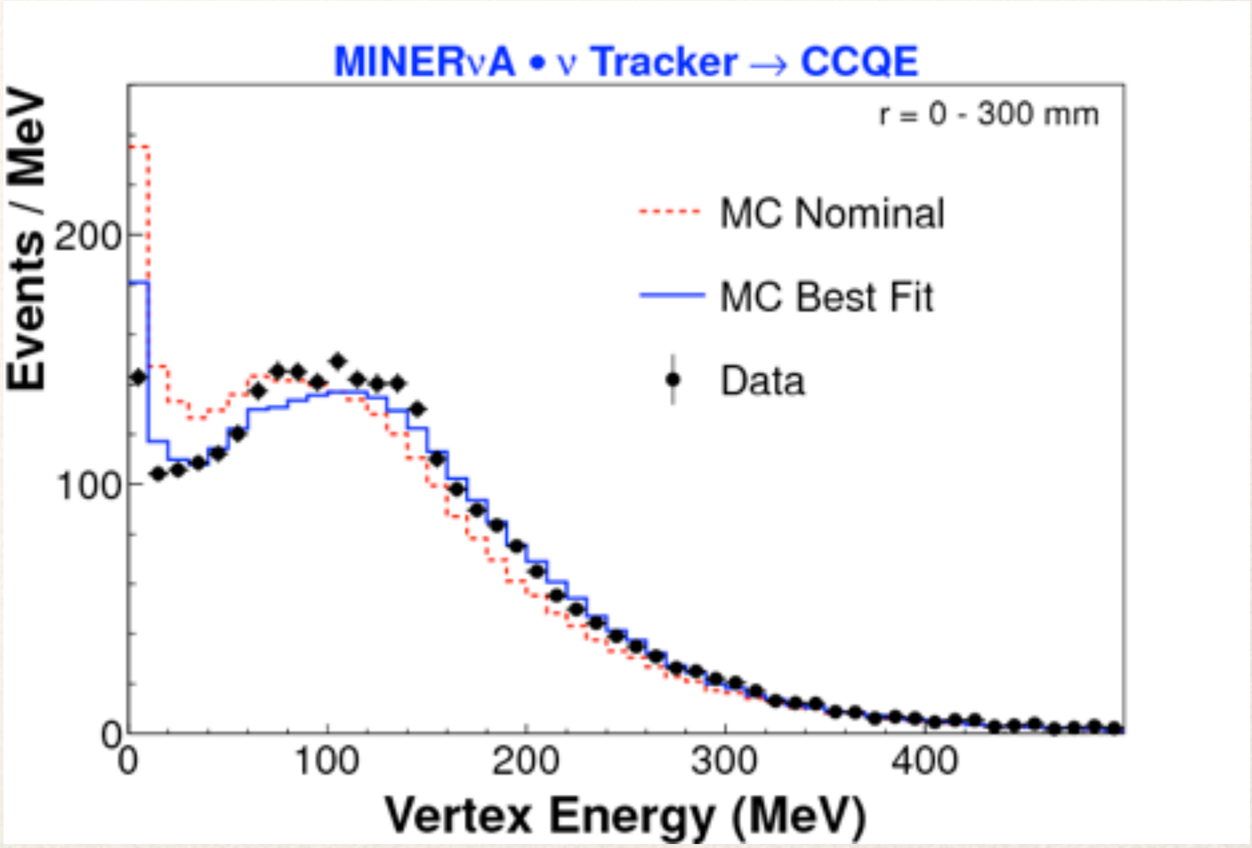
- Recall that we neglected an **area around the vertex** when we counted the total recoil energy
- We now compare the non-track energy deposited within that region to our Monte Carlo, to look for evidence of **additional nucleons**
- Our "vertex region" would contain nucleons with an energy up to 225 MeV (neutrino mode) or 120 MeV (antineutrino mode)

Vertex energy - extra protons



- A **harder neutrino-mode energy spectrum** is seen in data than Monte Carlo
- It is not seen in antineutrino mode
- We simulated extra protons with kinetic energies up to 225 MeV to see how this would change the Monte Carlo distribution

- Modeling an **additional proton 25±9%** of the time gave the best fit to the data
- Final state protons suggests initial state **proton-neutron correlations**
- This would explain why no such effect was seen for **antineutrino mode**; we would expect **low-energy neutrons**, to which we have low sensitivity



Summary

- MINERνA has measured **differential cross-sections** $d\sigma/dQ^2$ for both neutrino and antineutrino quasi-elastic scattering from scintillator
- The data suggest a **transverse enhancement model**, which parameterizes nucleon-nucleon correlations, may be a good fit
- We saw evidence of additional **low-energy protons** around the vertex in neutrino-mode interactions, around 25% of the time.
- This suggests **proton-neutron correlations.**
- We are keen to work with theorists to compare our data with models as they are developed
- Several further studies are underway: see Carrie McGivern's talk

Thank you!

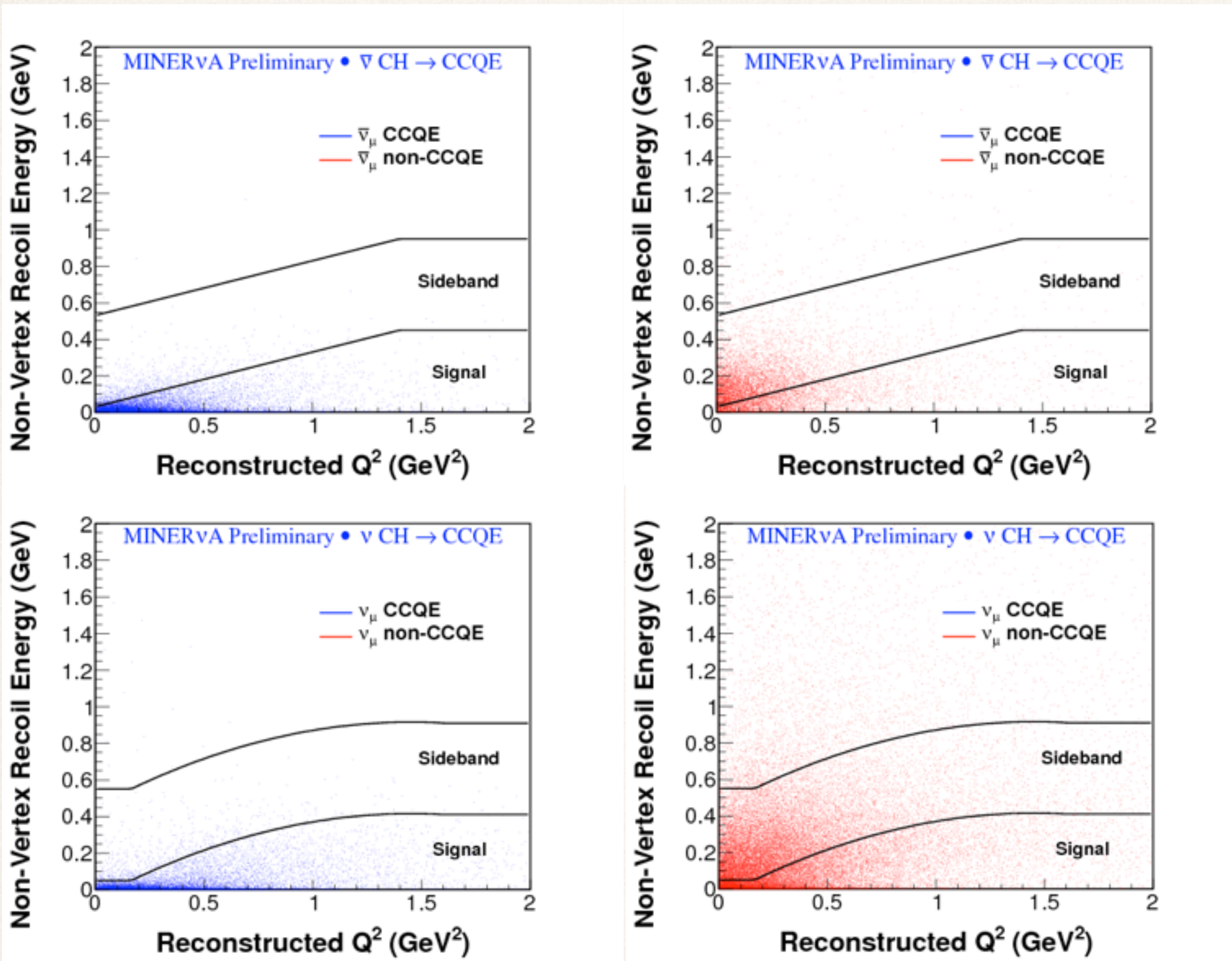
Backup slides

Event selection: recoil

QE Not QE

$\bar{\nu}$

ν



$\text{Recoil} < 0.03 + 0.3Q^2_{QE}(Q^2 < 1.4)$

$\text{Recoil} < 0.45(Q^2 >= 1.4)$

$\text{Recoil} < 0.05(Q^2 < 0.166)$

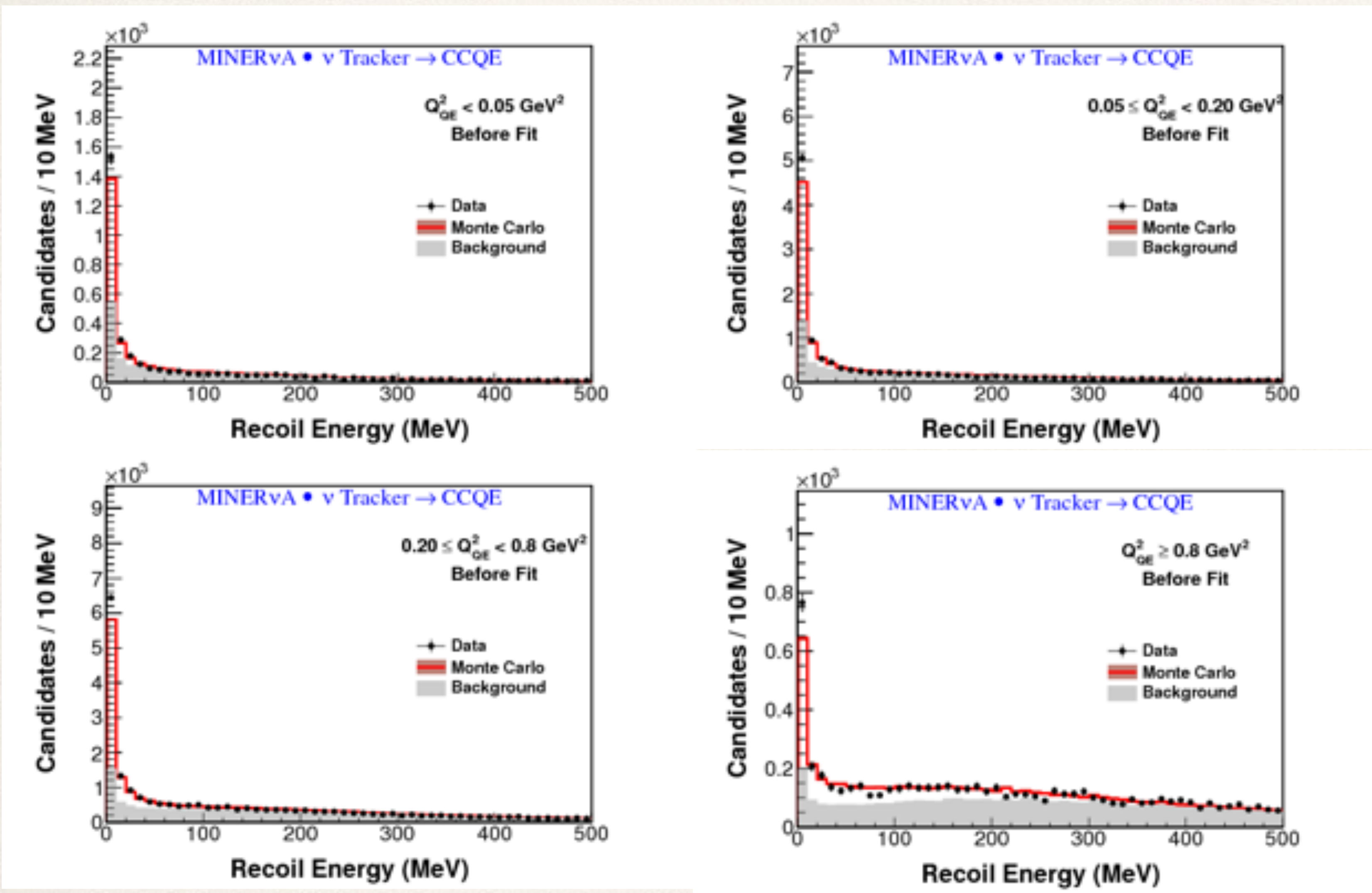
$\text{Recoil} < -0.05 + 0.64Q^2 - 0.22Q^4$
$(0.166 <= Q^2 < 1.61)$

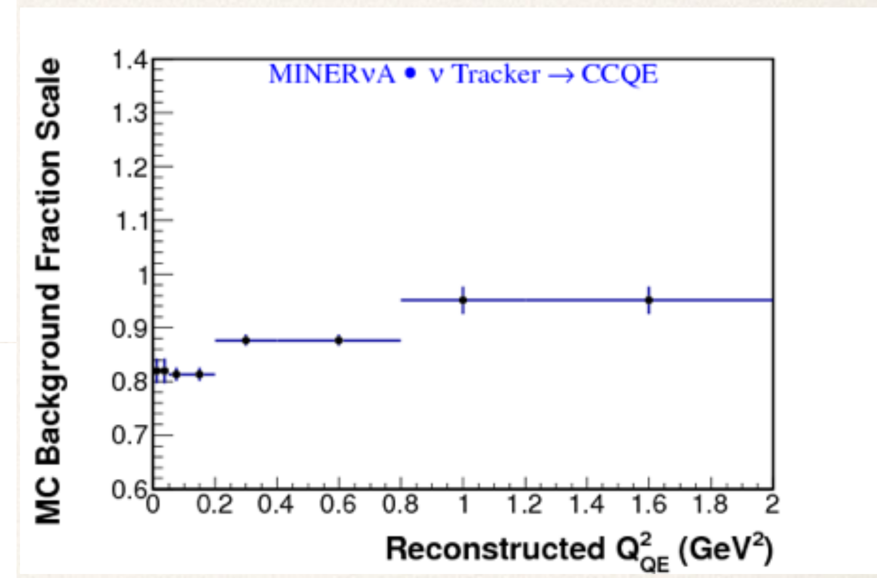
$\text{Recoil} < 0.41(Q^2 >= 1.61)$

Energies in GeV; Q^2 in GeV^2

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

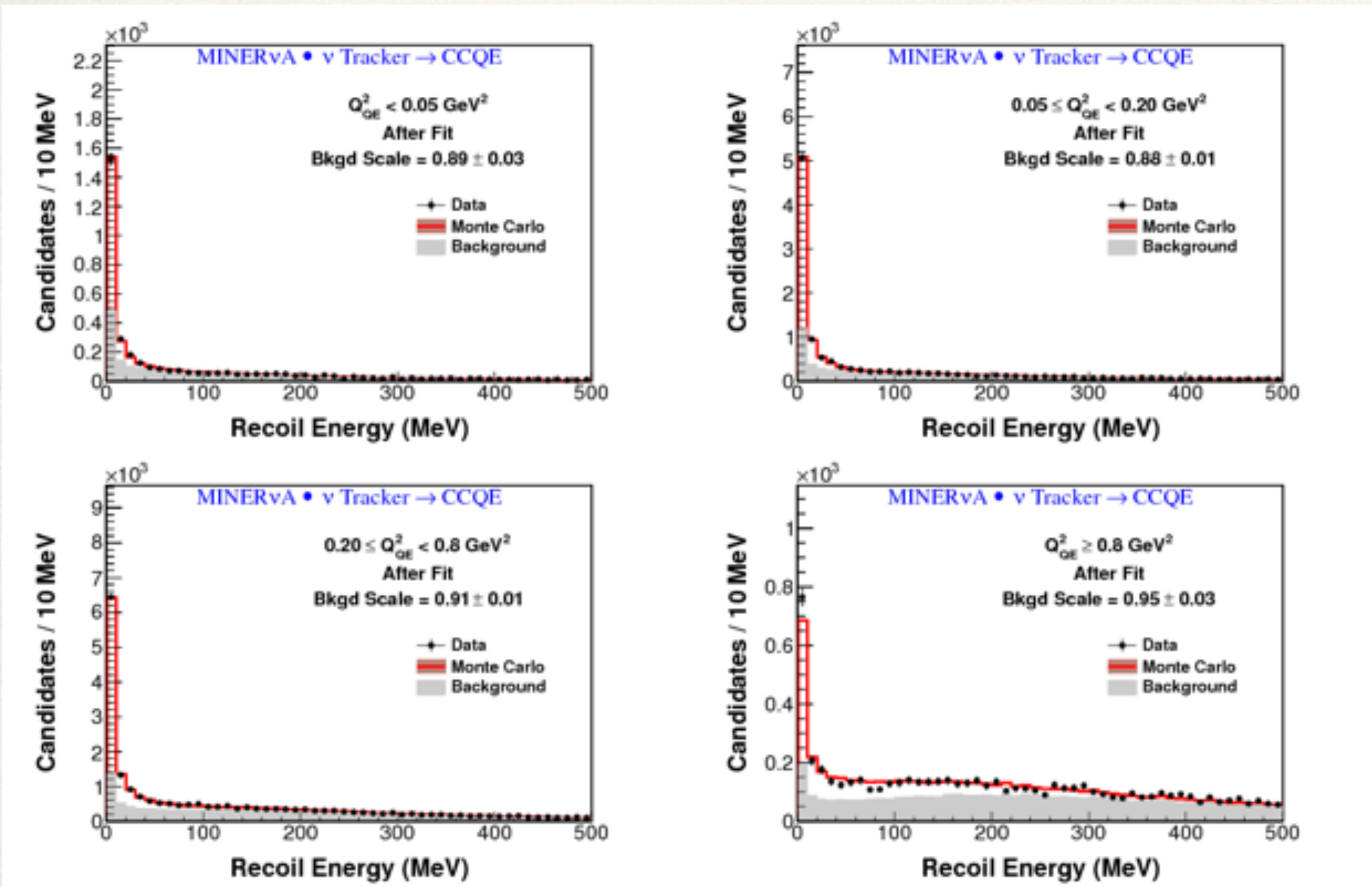
Background subtraction: before

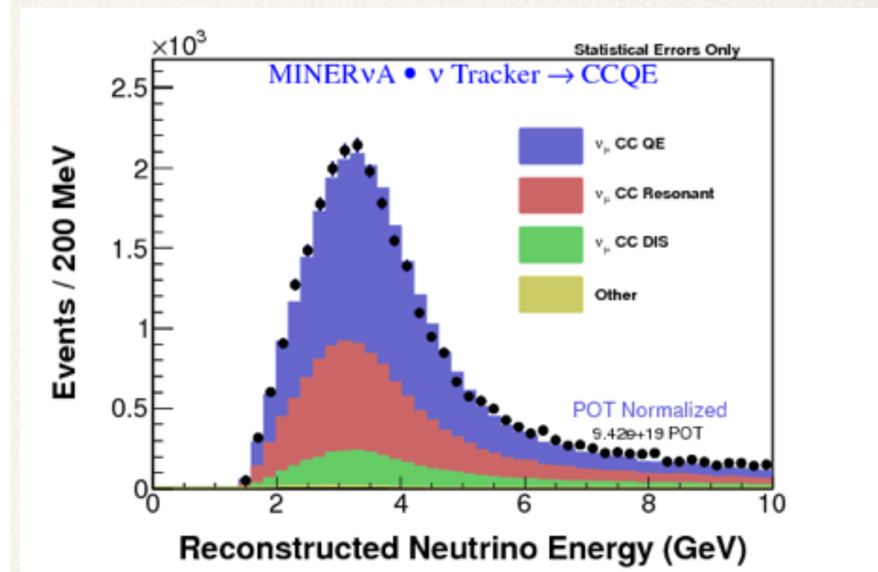




- We use data to estimate our backgrounds by performing a fraction fit of signal and background recoil energy distributions from our Monte Carlo, in each of 4 Q^2 bins
- Plots show fits for **neutrinos**

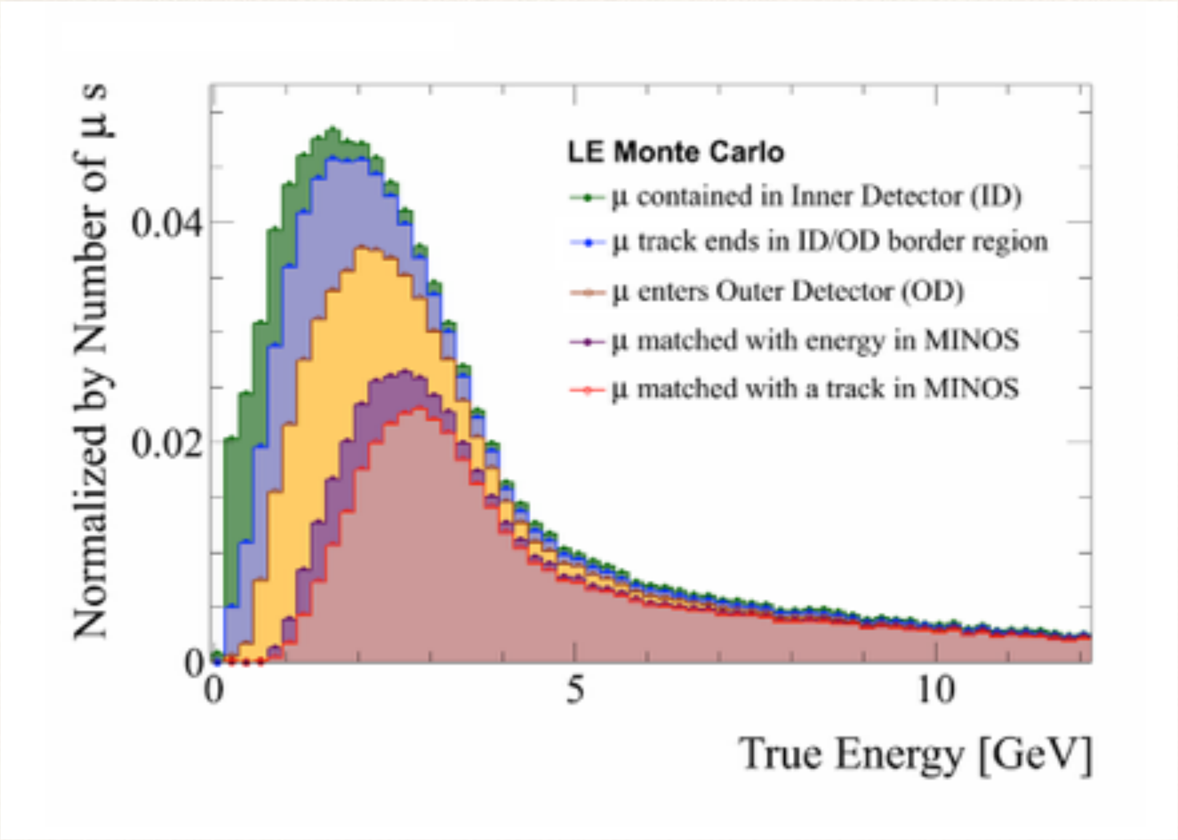
Background subtraction: after

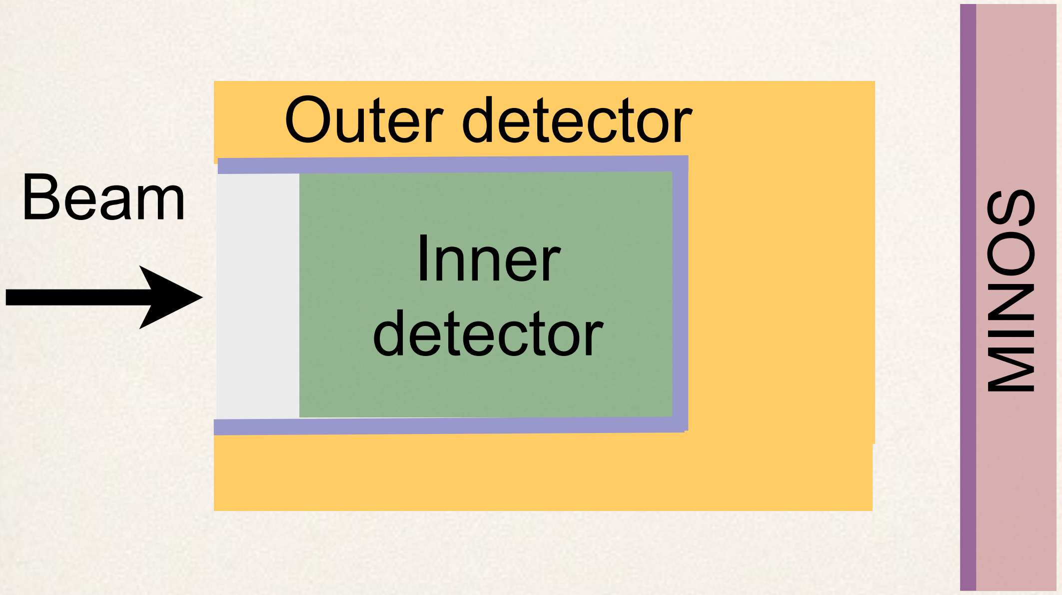


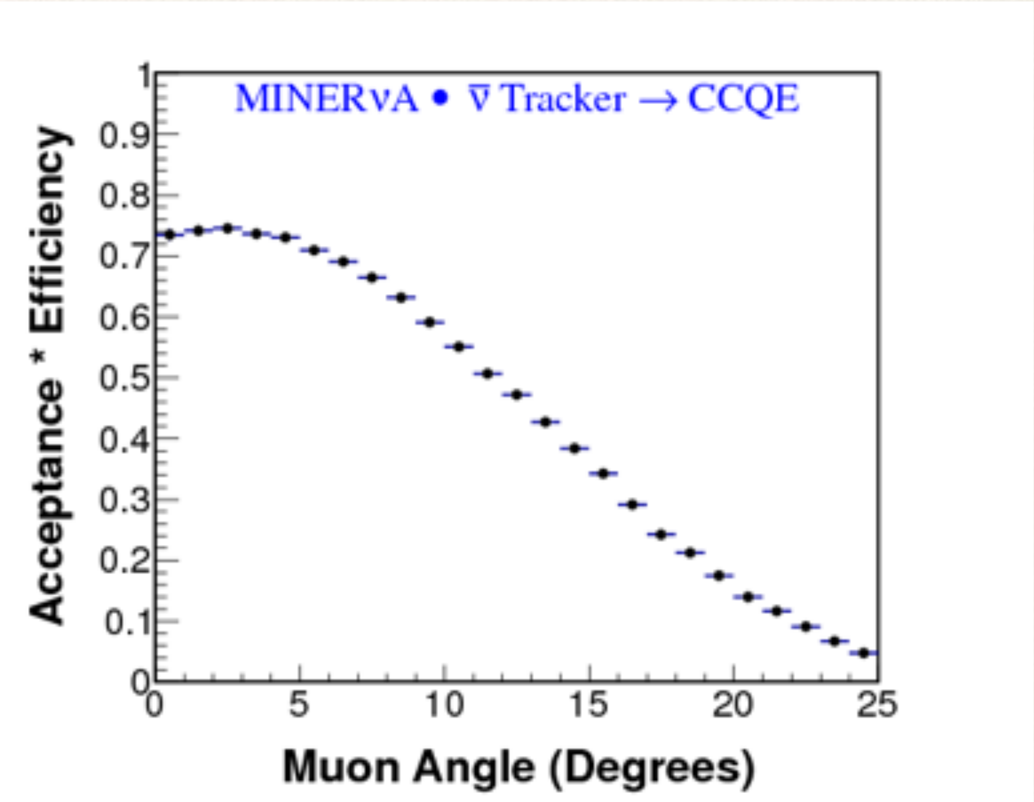


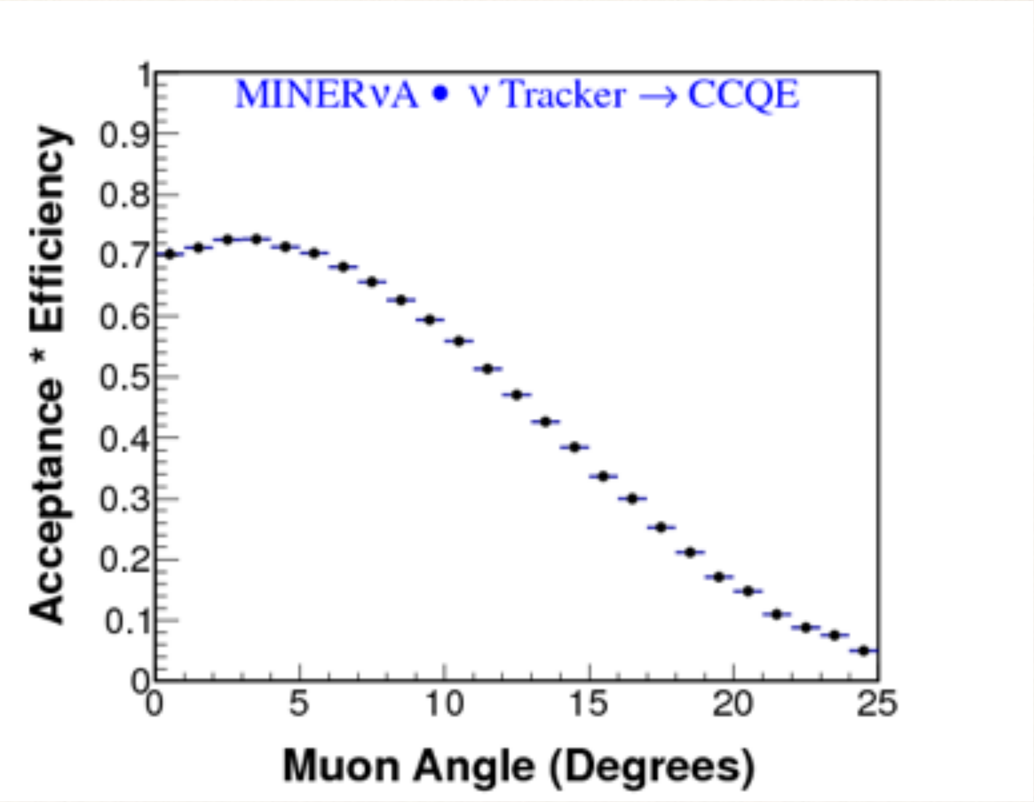
- We use data to estimate our backgrounds by performing a fraction fit of signal and background recoil energy distributions from our Monte Carlo, in each of 4 Q^2 bins
- Plots show fits for **neutrinos**

MINOS-match requirement



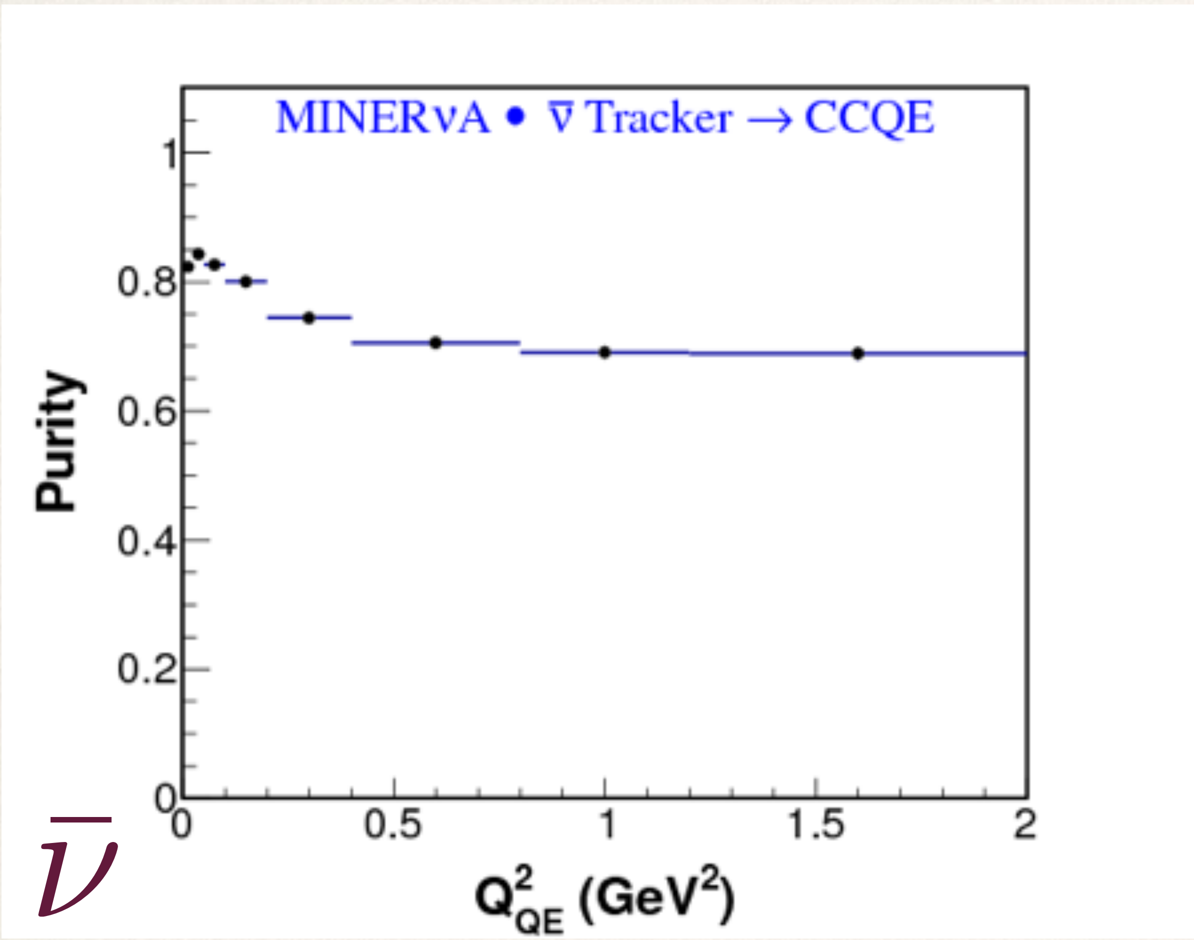






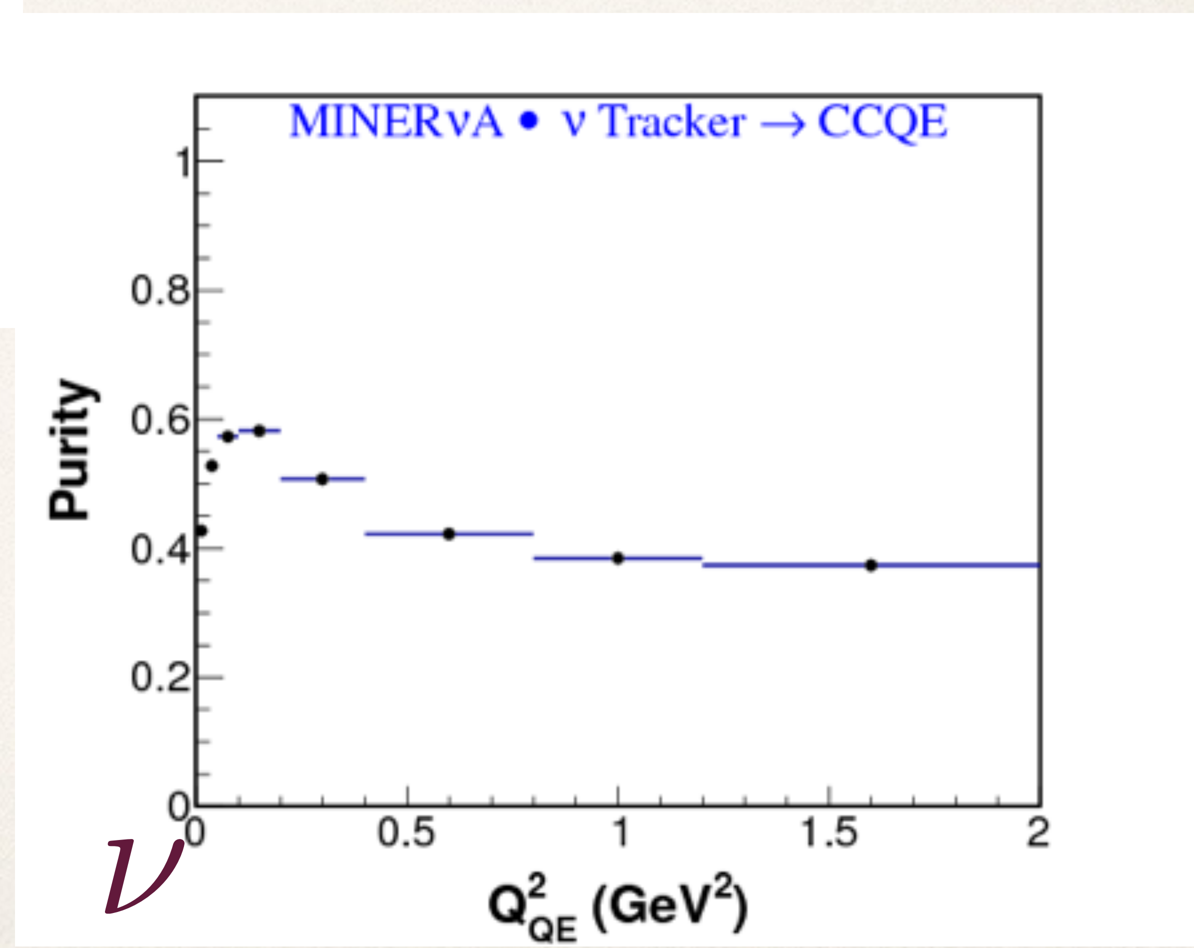
- MINOS-match requirement limits angular acceptance

Purity

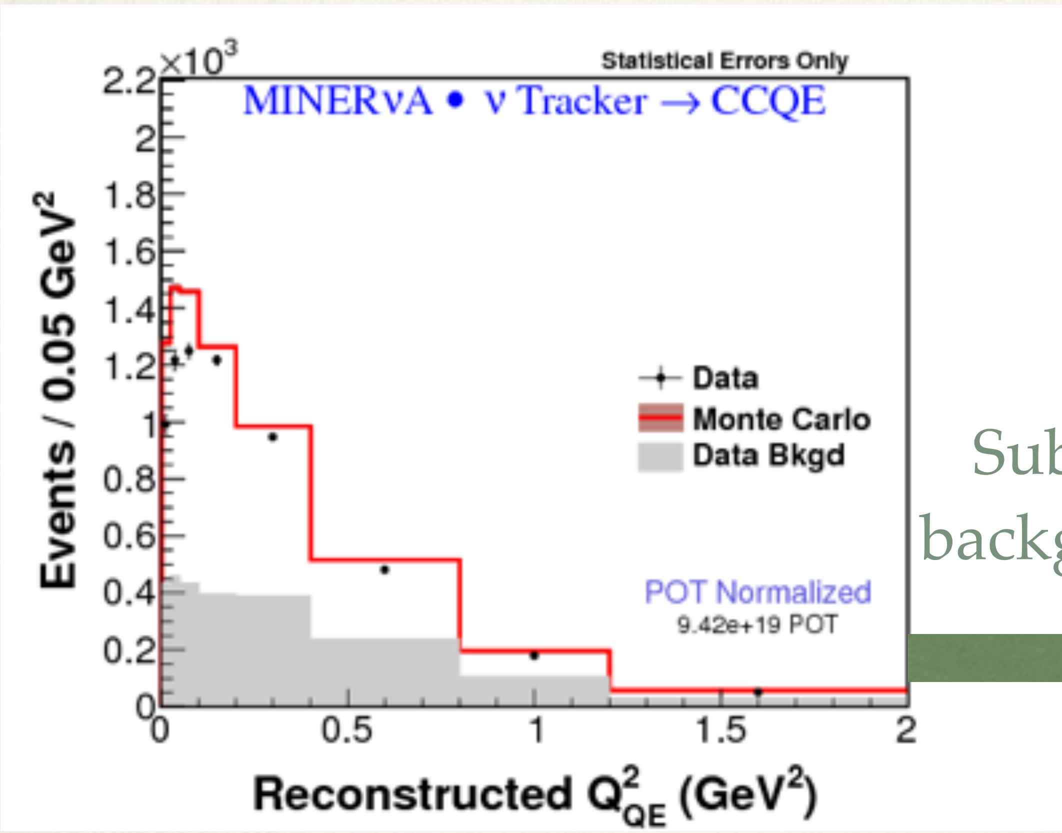


ν̄: 77% purity

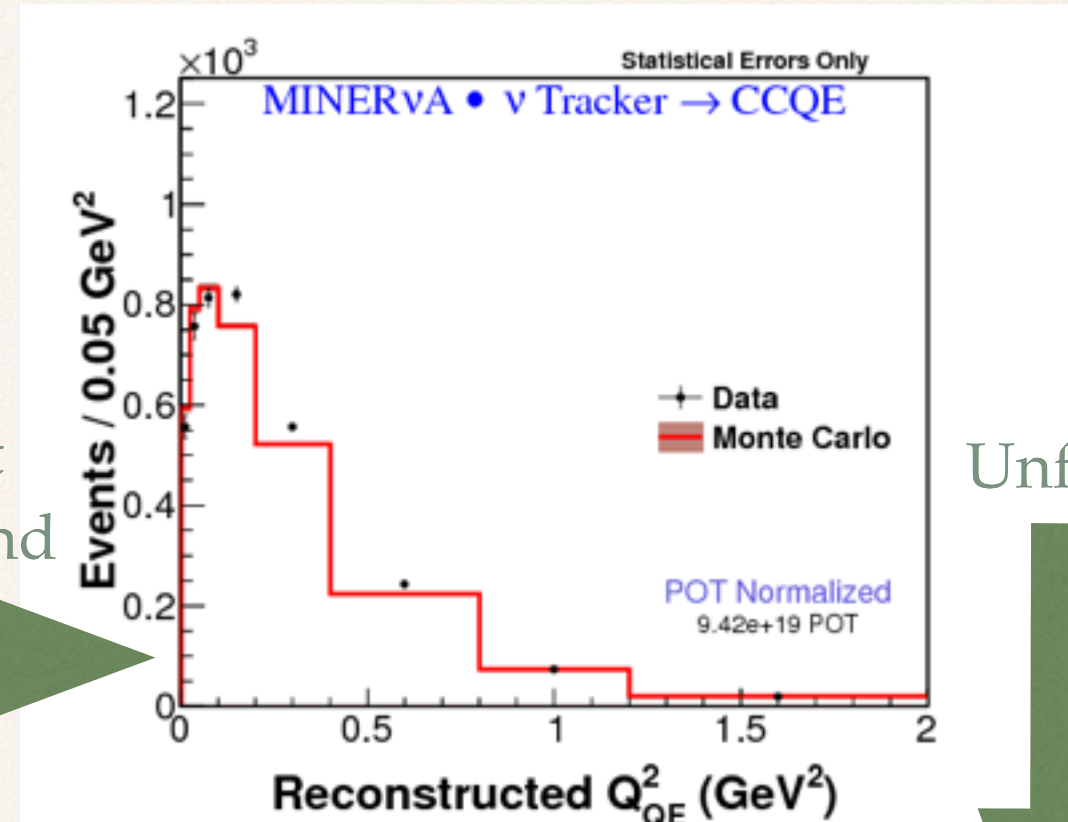
ν: 49% purity



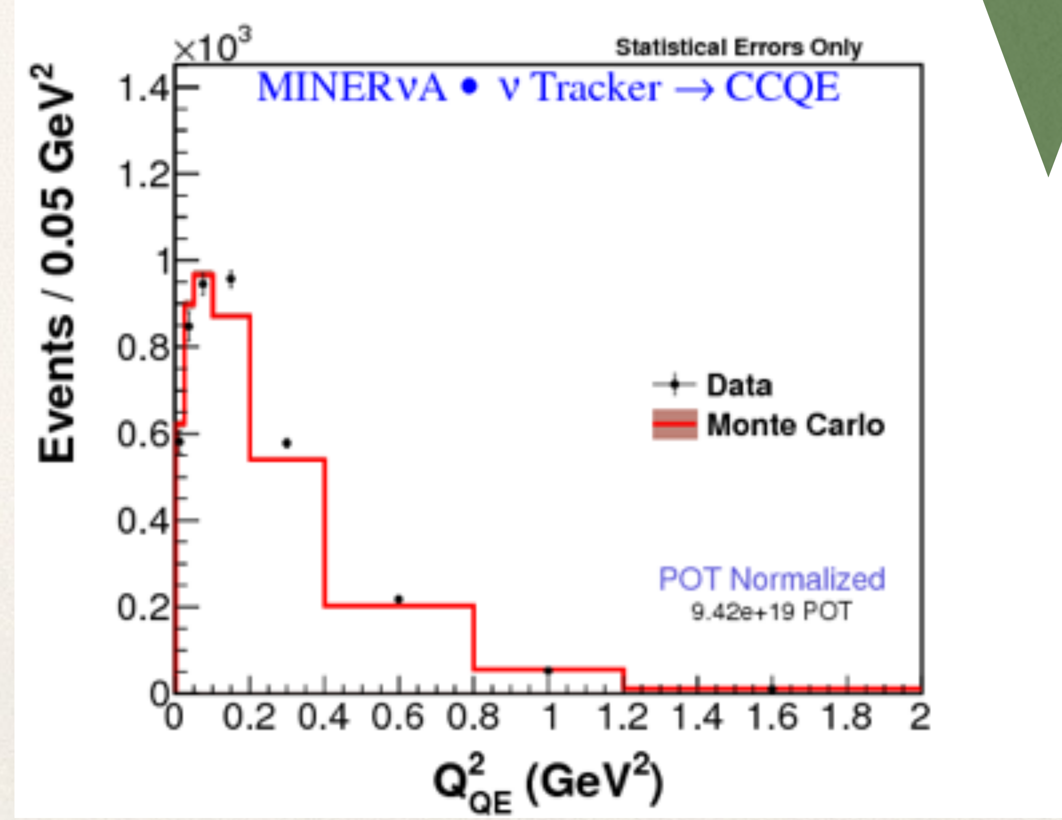
Unfolding - neutrino mode



Subtract background

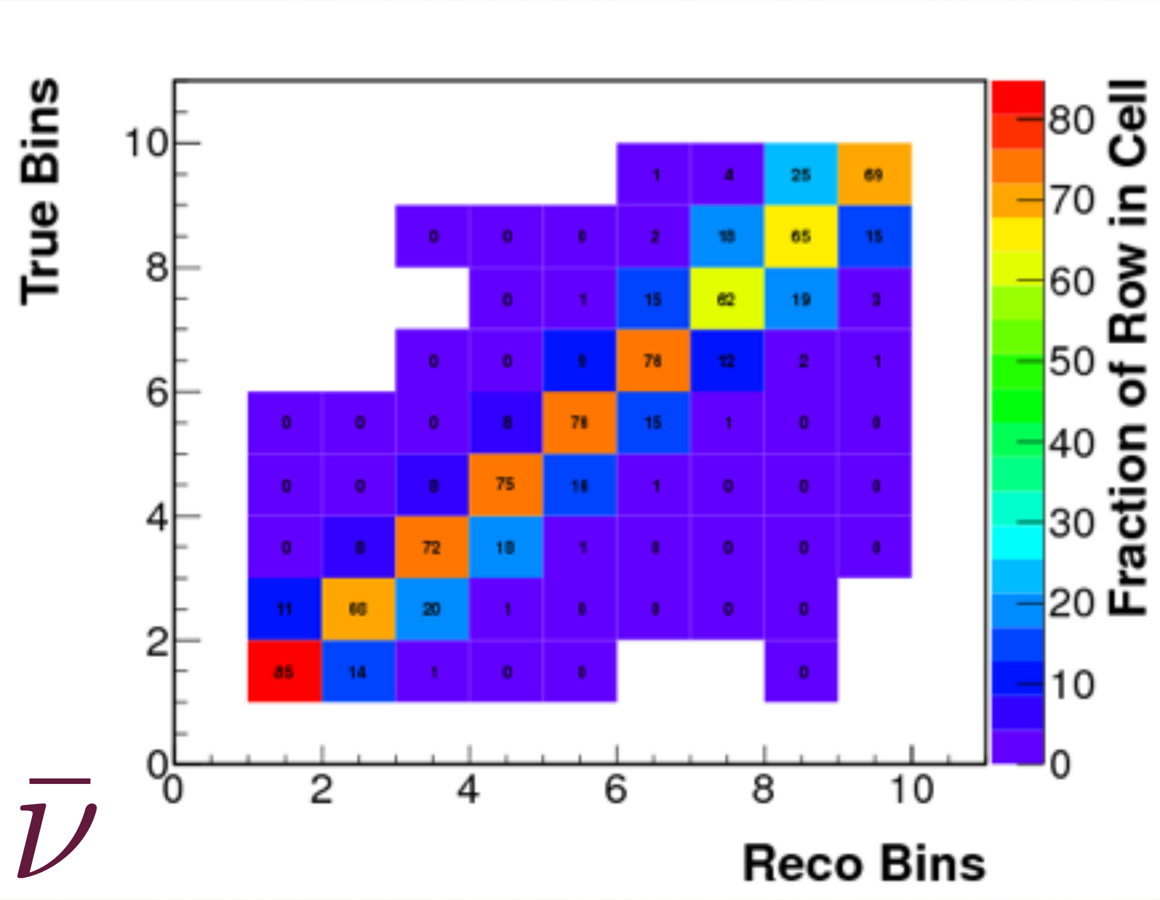


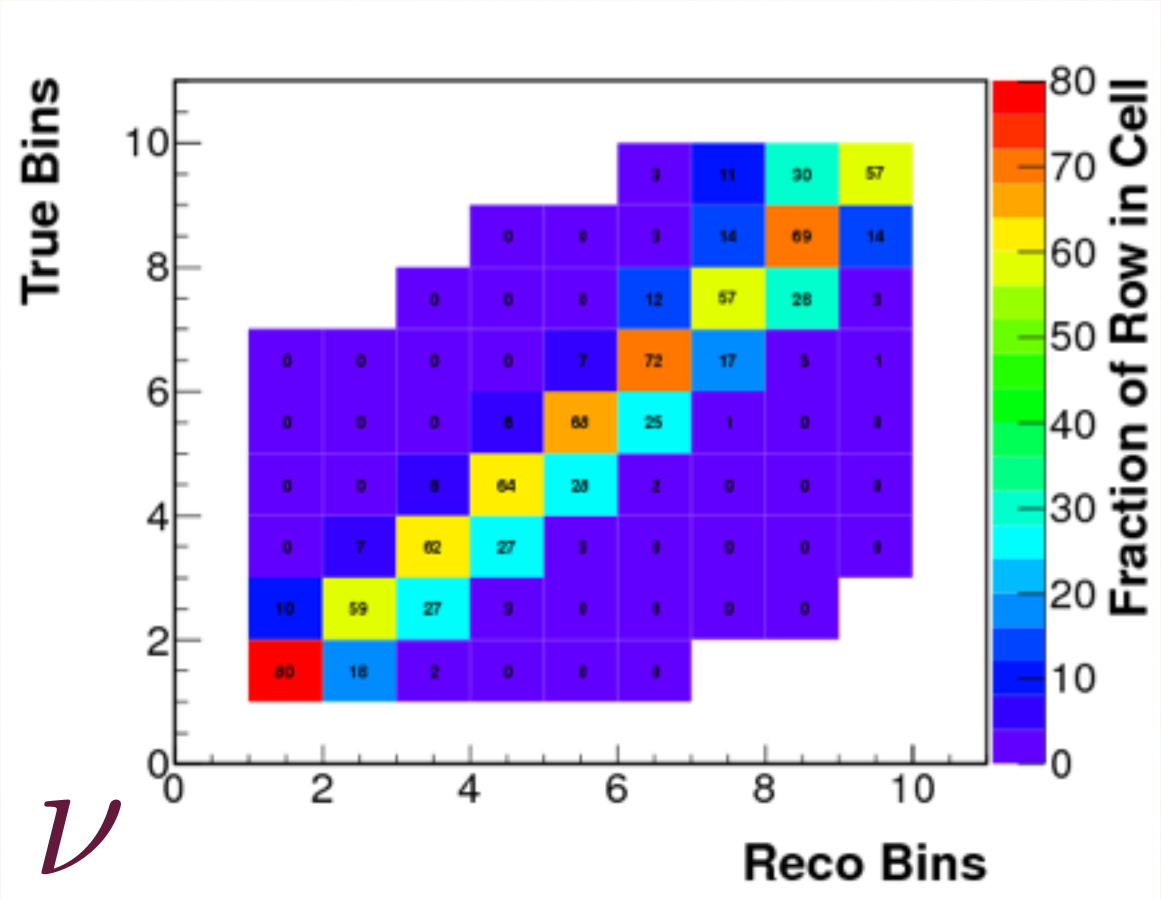
Unfold



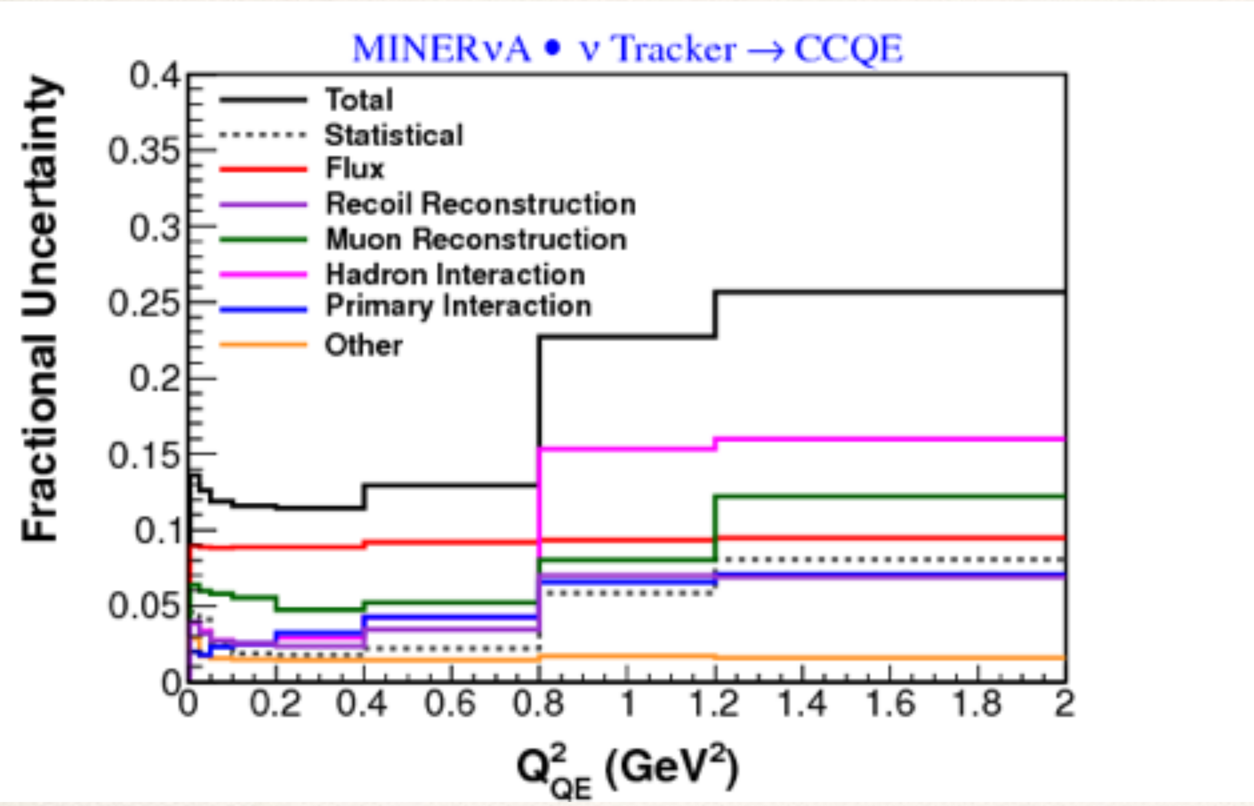
- We use four iterations of a Bayesian unfolding method

Migration matrices for unfolding



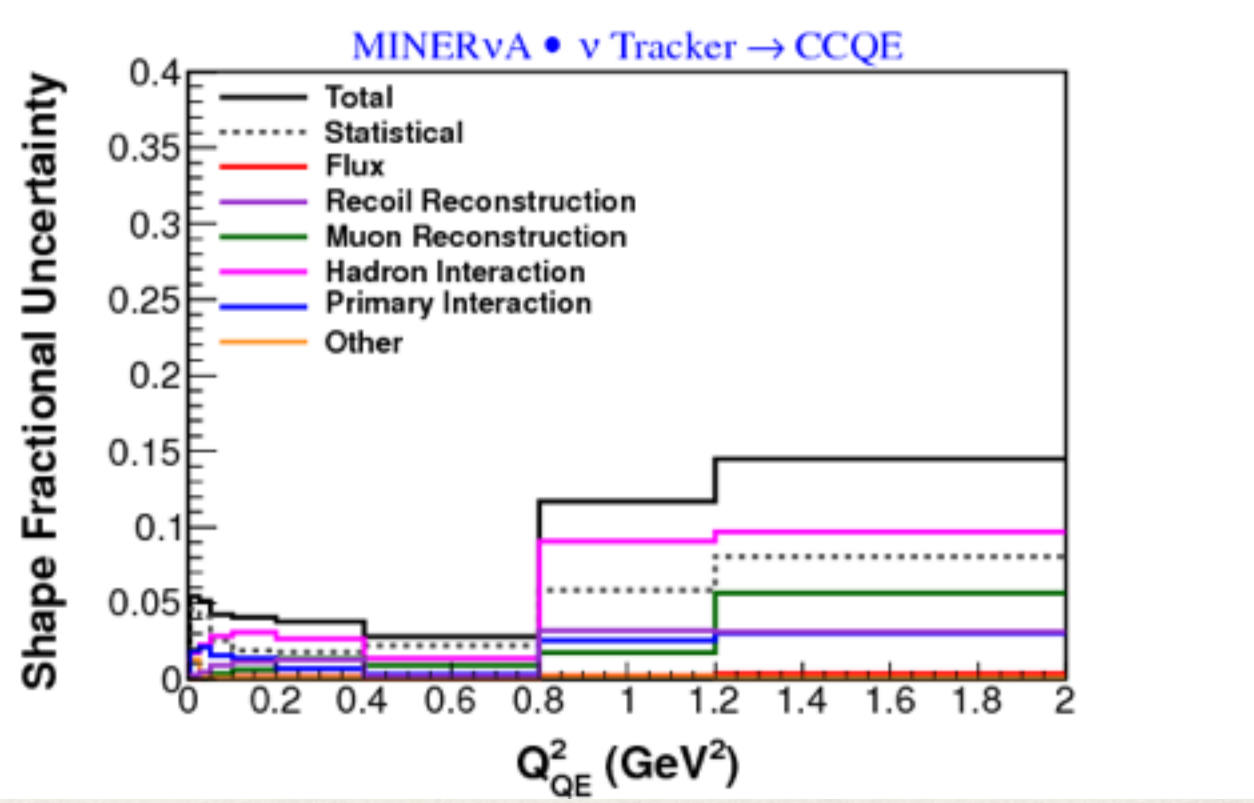


Systematics (neutrino)

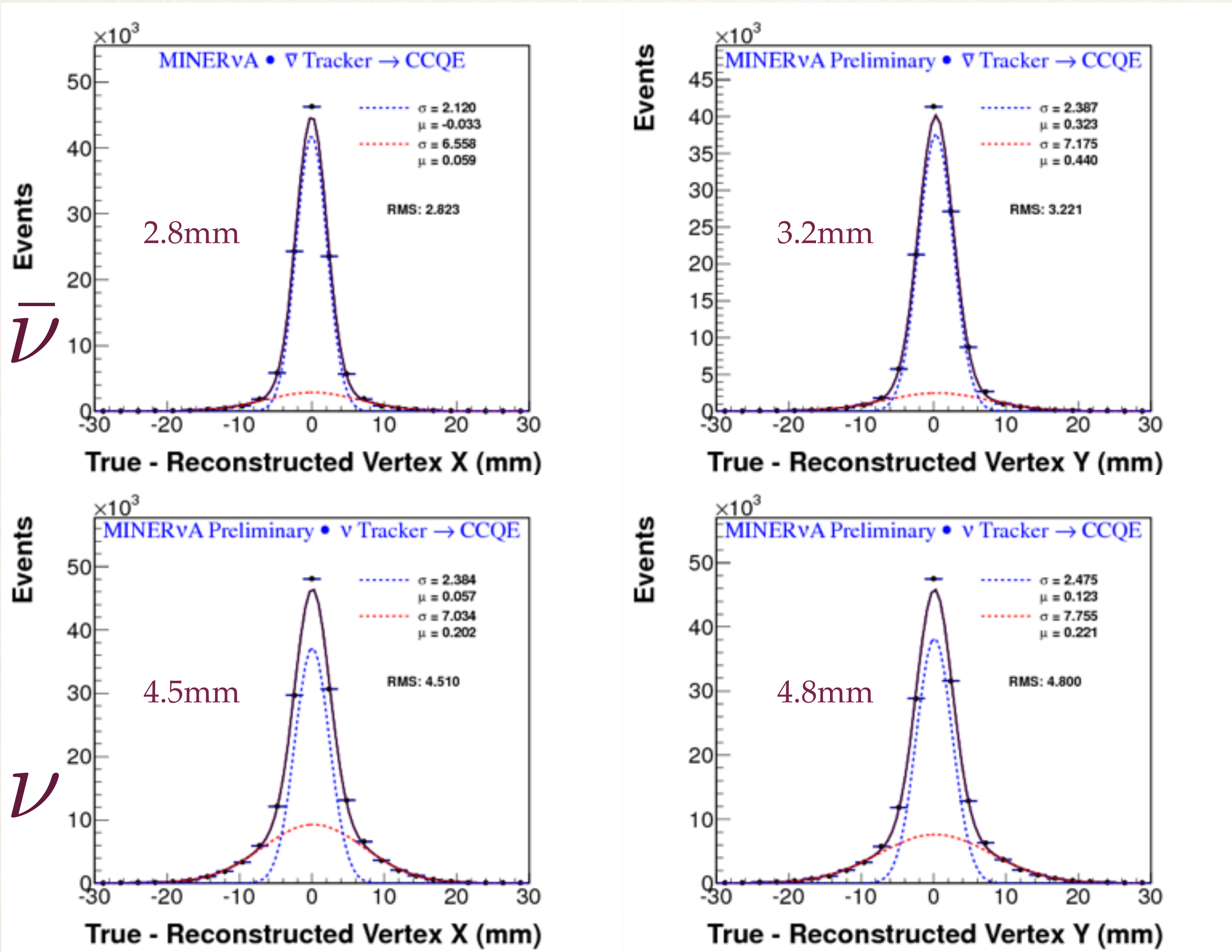


- Flux uncertainty
- Statistical uncertainty
- Hadron interaction model uncertainty
- Total uncertainty

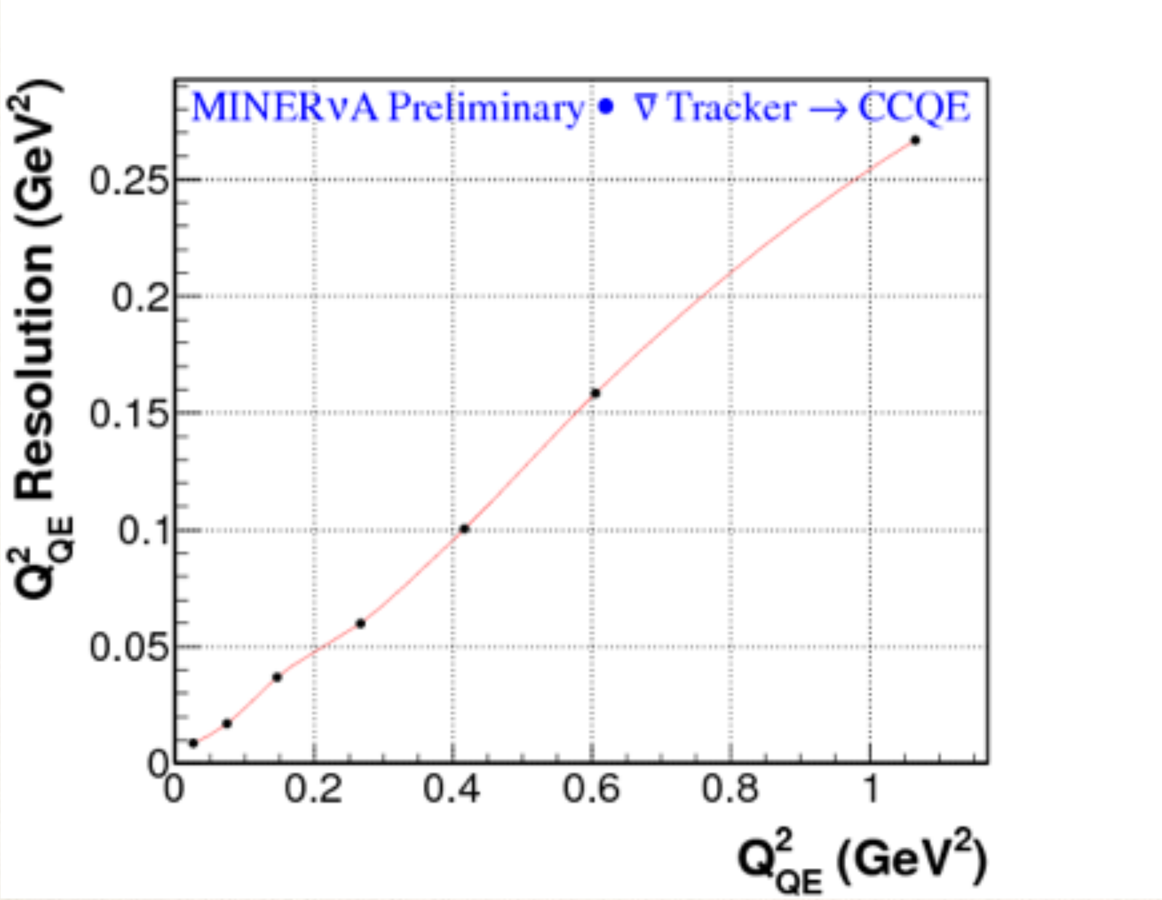
- Hadron interaction model uncertainty is greater in neutrino mode
- This refers to GENIE's modeling of final-state interactions
- Remember our signal is true CCQE as defined by primary interaction, but all we can identify in our data is QE-like

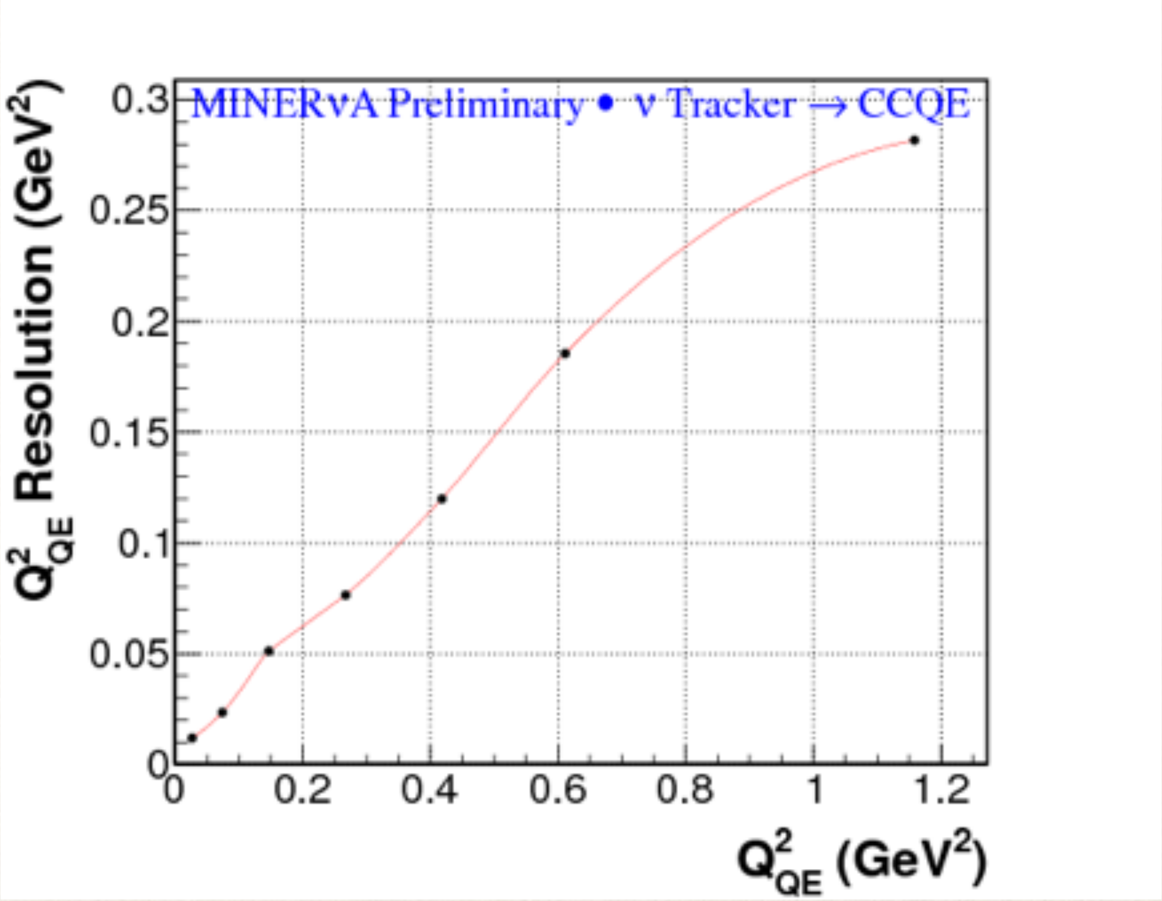


Vertex resolution < 5mm

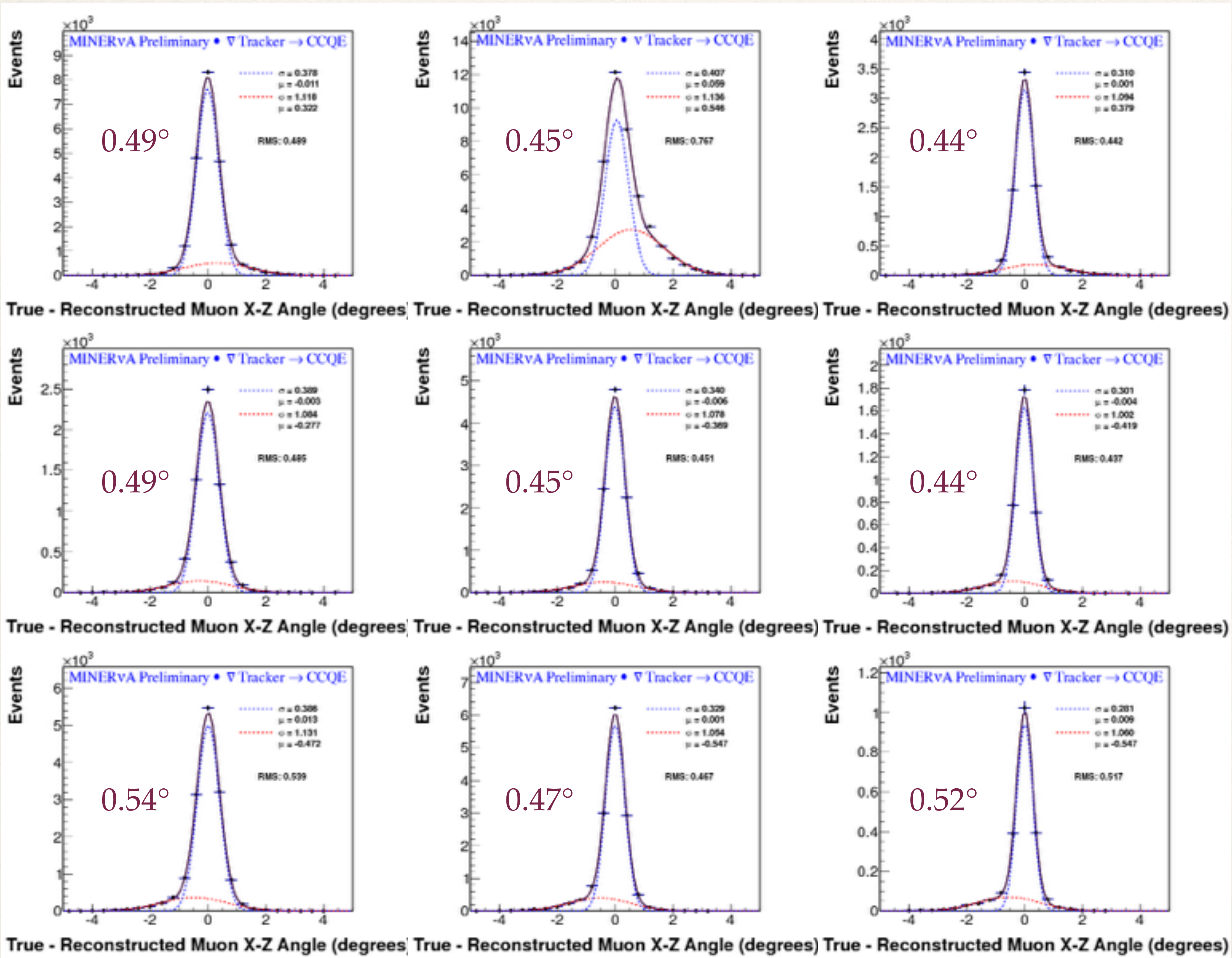


Q^2_{QE} resolution ~ $Q^2_{QE}/4$





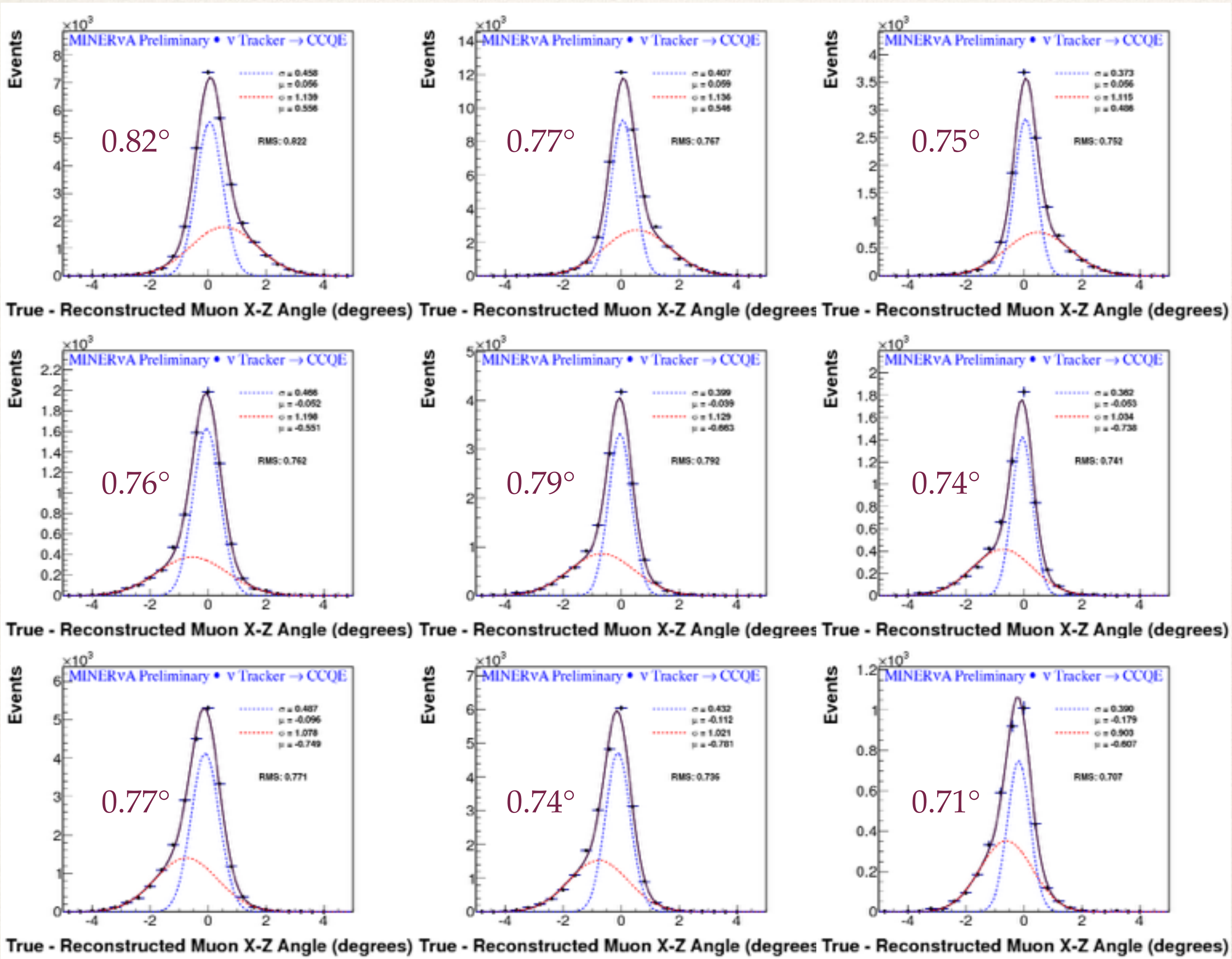
Angular resolution: x-z plane, $\bar{\nu}$



$E_\mu < 3$GeV,
3 - 5 GeV,
> 5GeV

$\theta_{\mu,x} < 1°$,
1 - 4°,
> 4°

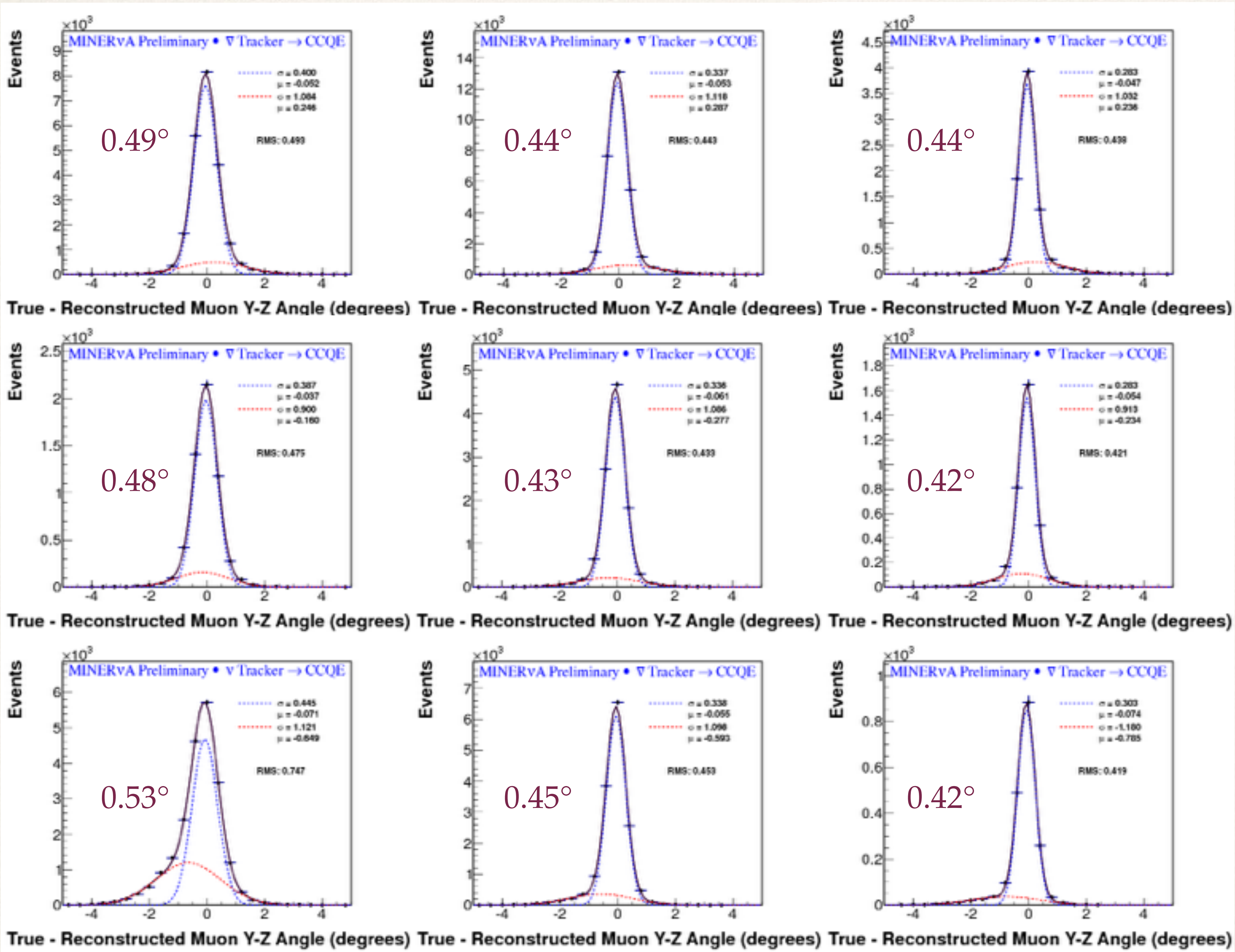
Angular resolution: x-z plane, ν



$E_{\mu} < 3\text{GeV}$,
3 - 5 GeV,
> 5GeV

$\theta_{\mu,x} < 1°$,
1 - 4°,
> 4°

Angular resolution: y-z plane, $\bar{\nu}$

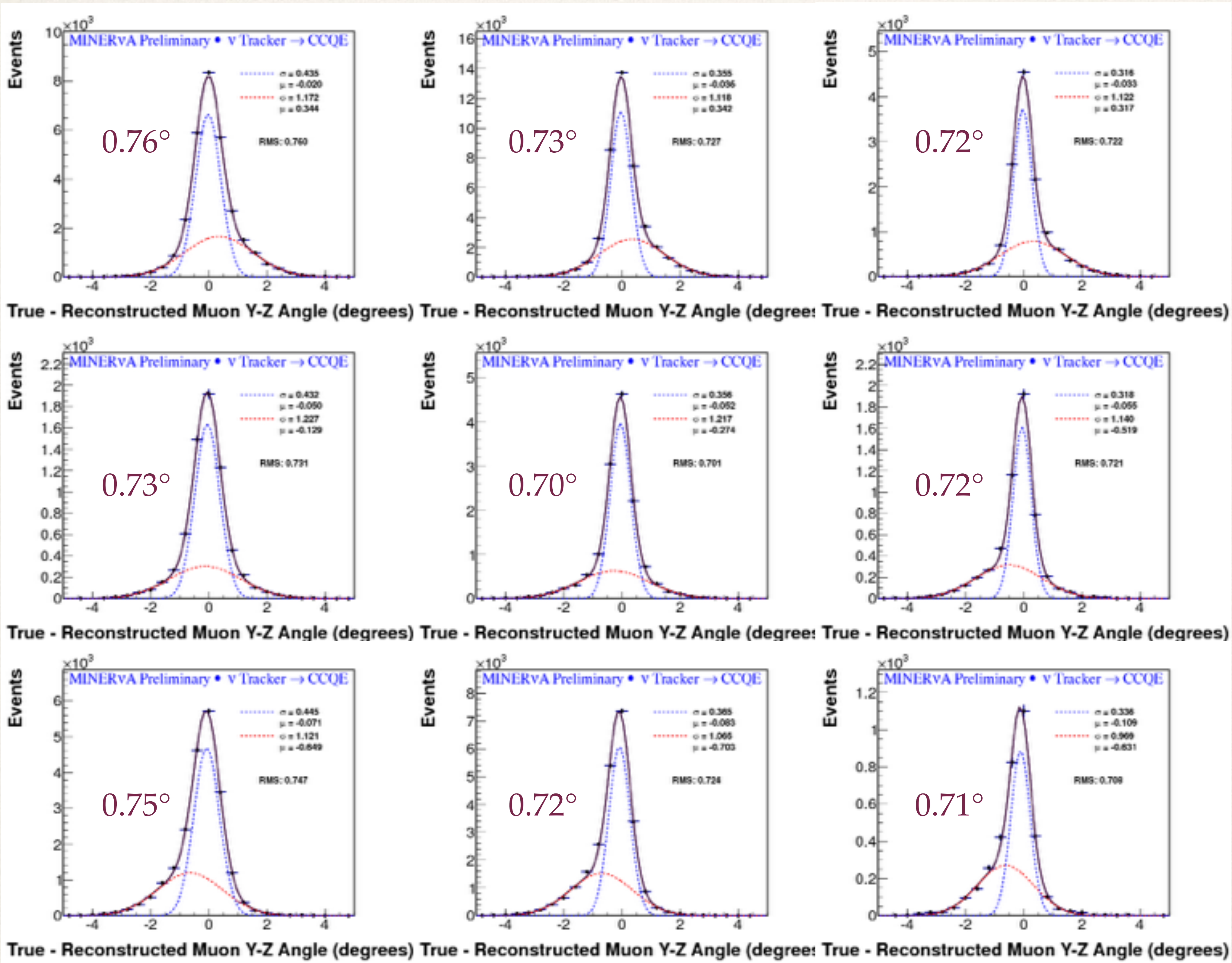


$E_\mu < 3$GeV,
3 - 5 GeV,
> 5GeV

$\theta_{\mu,y} < 1°$,
1 - 4°,
> 4°

Note: the beam is in the y-z plane, slightly misaligned from the z axis

Angular resolution: y-z plane, ν

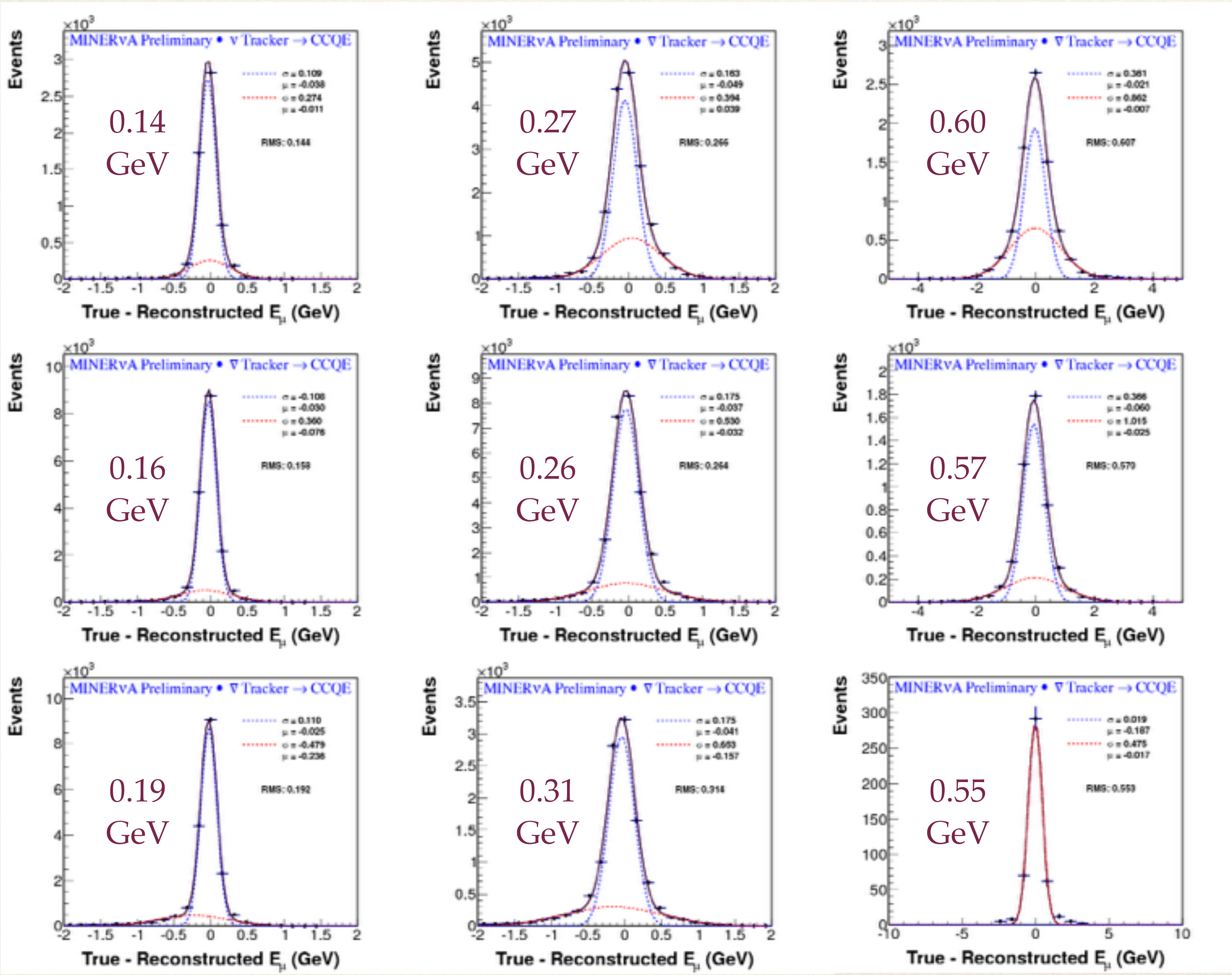


$E_{\mu} < 3$GeV,
3 - 5 GeV,
> 5GeV

$\theta_{\mu,y} < 1°$,
1 - 4°,
> 4°

Note: the beam is in the y-z plane, slightly misaligned from the z axis

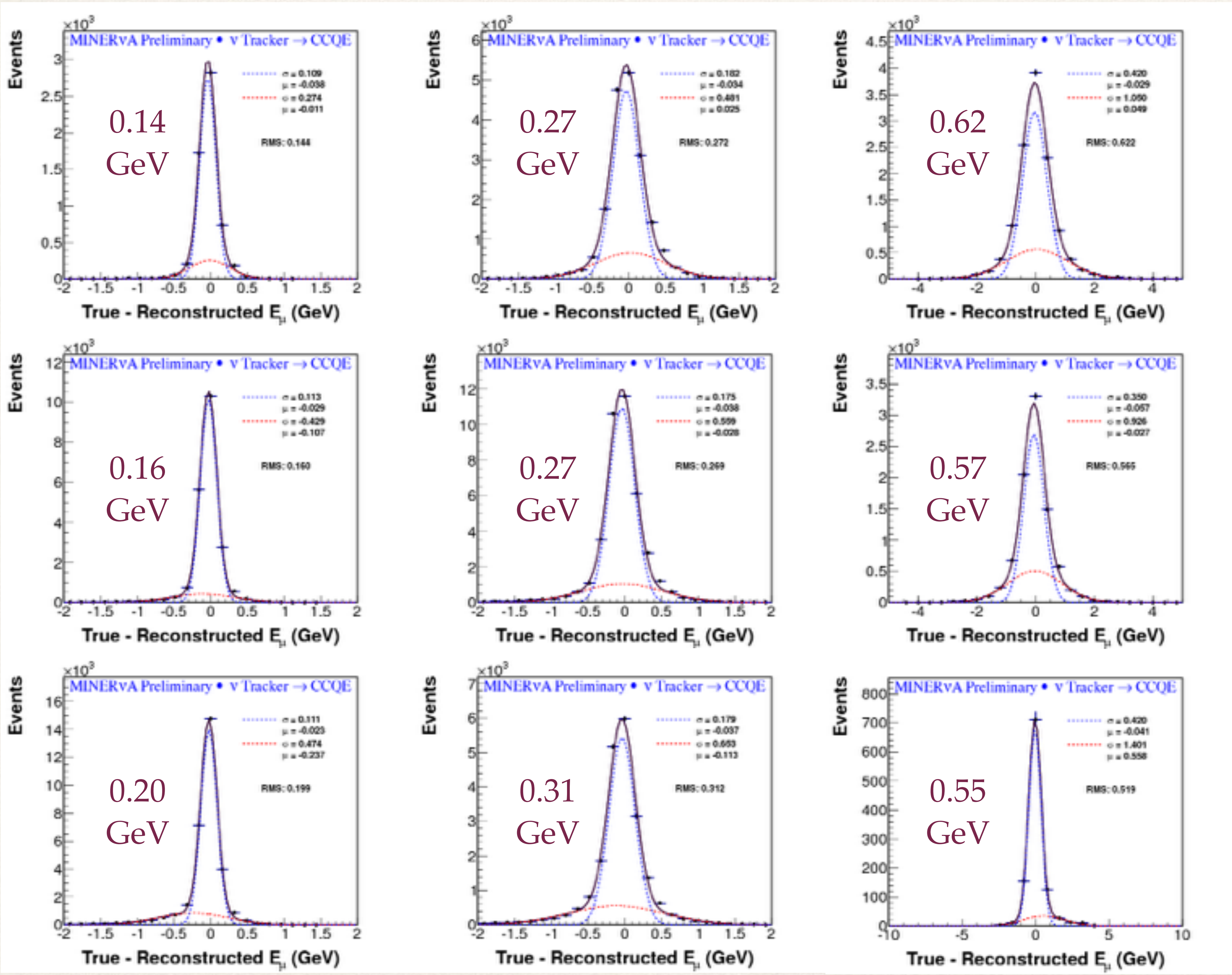
Muon energy resolution, $\bar{\nu}$



$E_\mu < 3$GeV,
3 - 5 GeV,
> 5GeV

$\theta_\mu < 5°$,
5-10°,
$> 10°$

Muon energy resolution, ν



$E_\mu < 3\text{GeV}$,
3 - 5 GeV,
$> 5\text{GeV}$

$\theta_\mu < 5°$,
5-10°,
$> 10°$

χ^2 for fits to published $\bar{\nu}$ data

NuWro model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/ d.o.f	2.64	1.06	2.9	2.14
Shape χ^2/ d.o.f	2.9	**0.66**	1.73	2.99

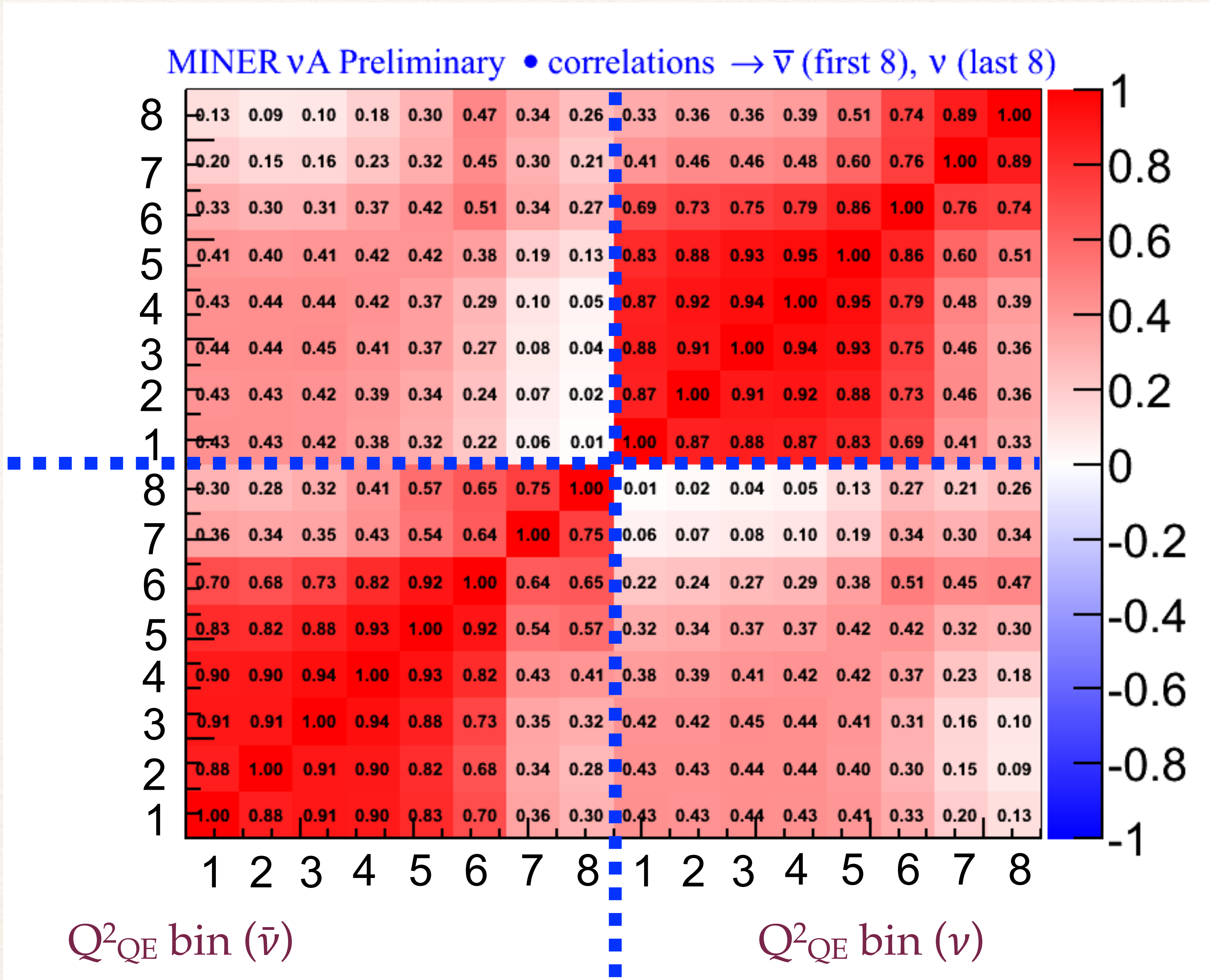
χ^2 for fits to published ν data

NuWro model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f	4.1	**1.7**	2.1	3.8

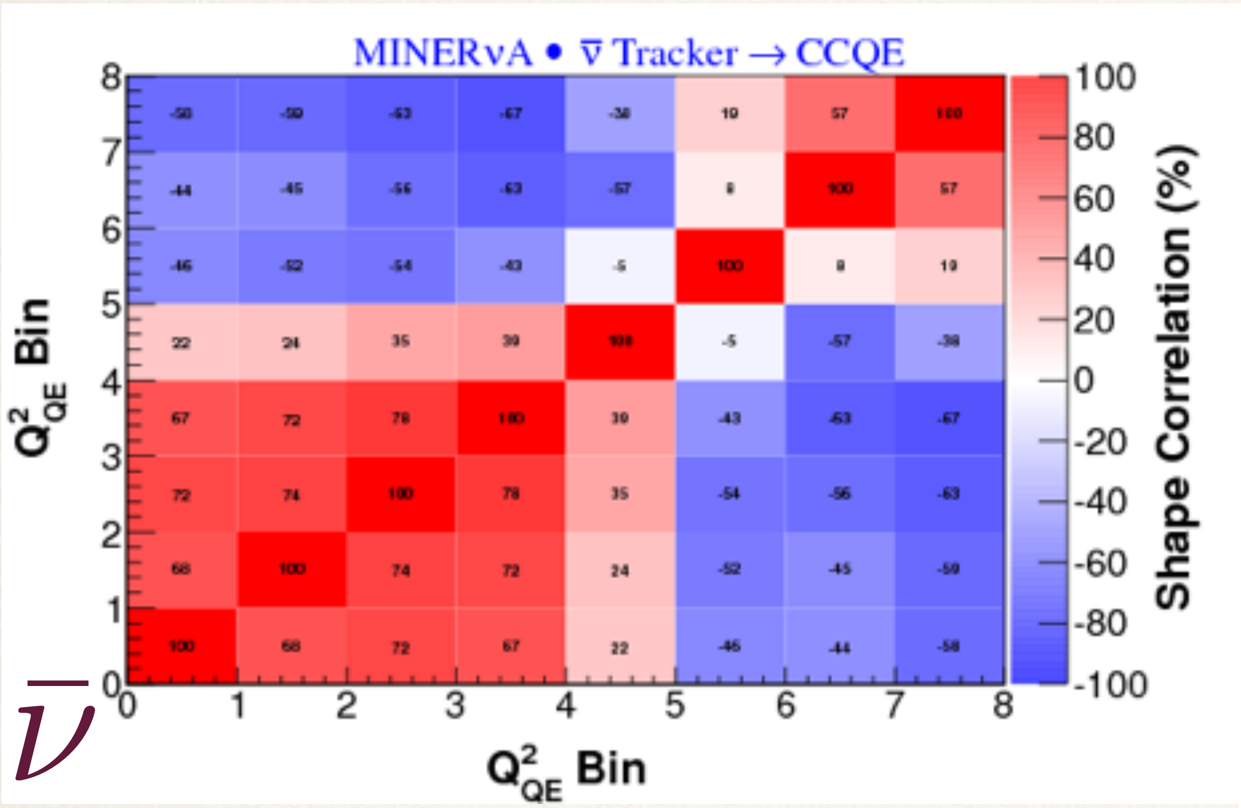
Correlation matrix - absolute

Q^2_{QE} bin (ν)

Q^2_{QE} bin ($\bar{\nu}$)



Correlation matrices: shape-only



- Red indicates positive correlation
- Blue indicates negative correlation

- The strong positive and negative correlations between bins can lead to surprisingly low χ^2/NDF when data is compared to models that at first glance seem poor fits
- Conversely, a model that appears to be a good fit can have a poor χ^2/NDF