ν_e charged-current quasi-elastic (CCQE) scattering in the MINERvA experiment

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U. of Rochester

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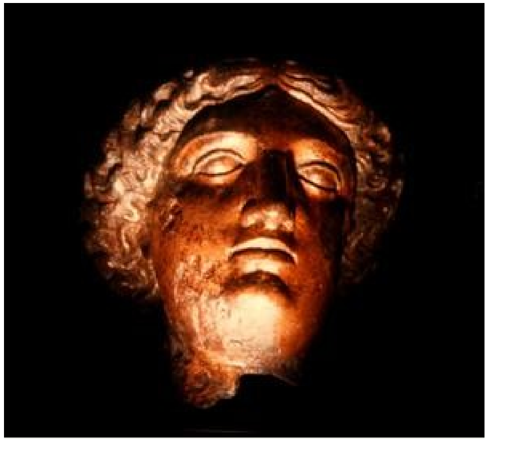


Inputs to $\nu_\mu \rightarrow \nu_e$ oscillation measurements

Observation fitted to prediction templates to extract parameters (Δm^2, θ, δ)

$$N_{FD}(E_\nu) = \Phi_{\nu_\mu} \times P_{\nu_\mu \rightarrow \nu_e}(E_\nu) \times \sigma_{\nu_e}(E_\nu) \times \boldsymbol{R}(E_\nu, E_{visible}) + N_{bg}$$

flux prediction

oscillation probability

ν_e cross-section

detector effects smearing matrix

accelerator ν_μ beams typically have an intrinsic ~1% ν_e component

The ν_e cross-section enters *twice* in the prediction: so a precision result necessitates a precision input.

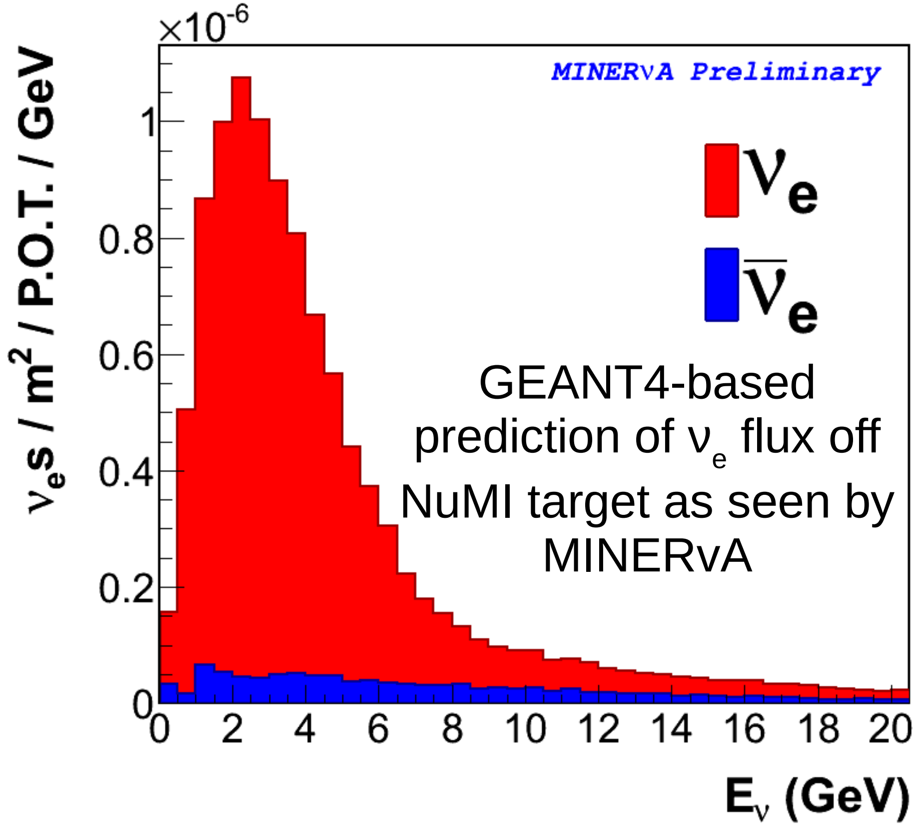
Signal definition

$$\pi^+ \rightarrow \nu_\mu \mu^+$$

$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$$

Electron neutrinos from beam muon decay.
About 10% $\overline{\nu}_e$. MINERvA is not magnetized...
so e^+ looks like e^-.

⇒ **Choose signal to include antineutrinos: one electron or positron in final state**



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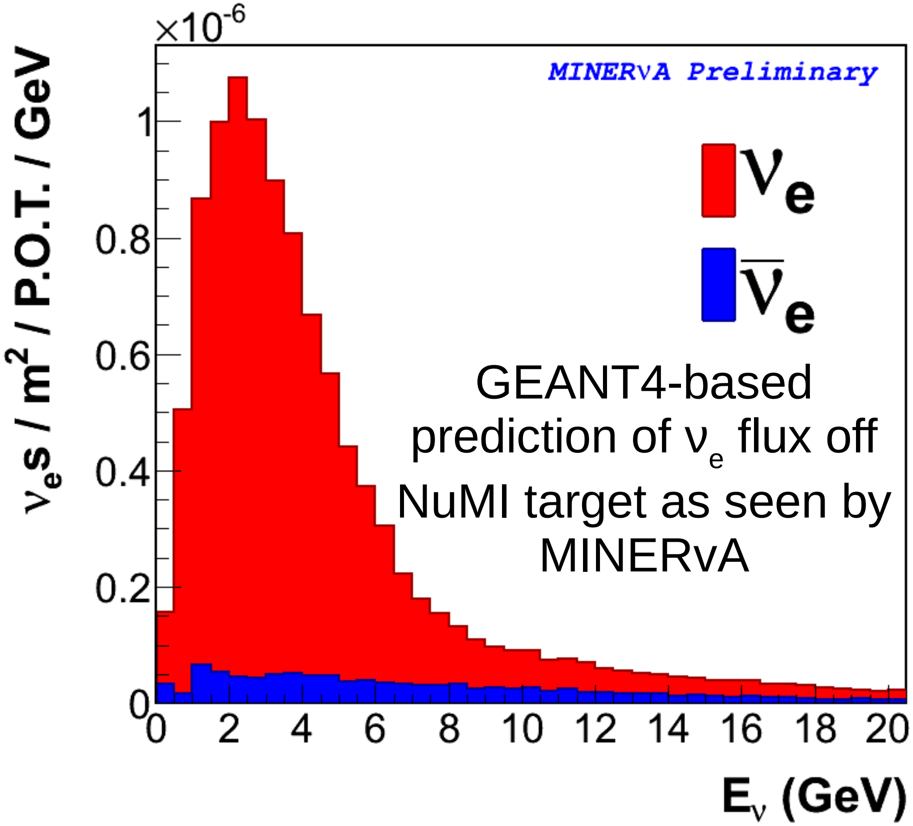
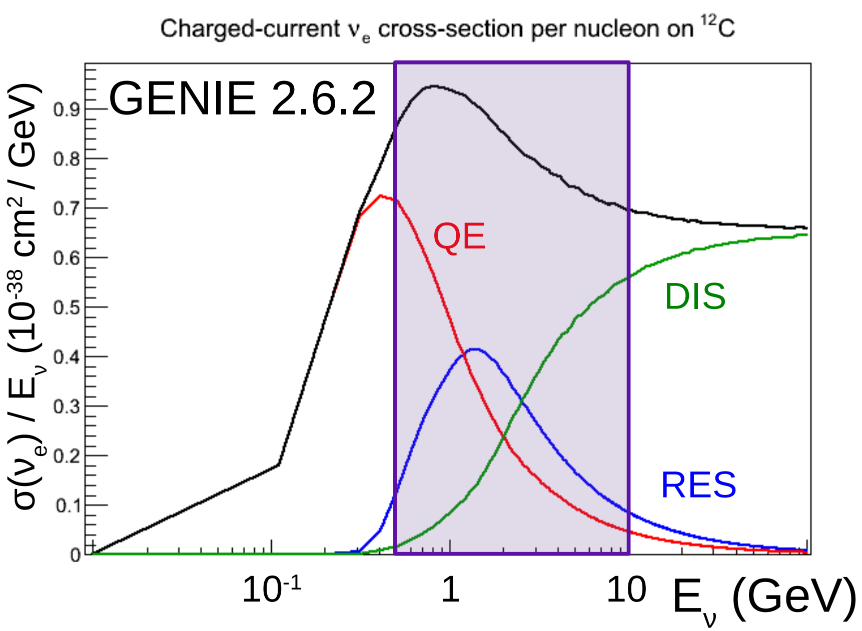
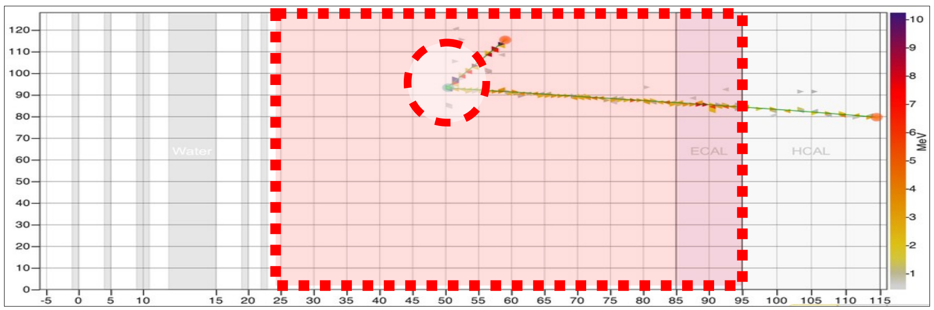




Initial- and final-state effects can cause absorption or creation of hadrons; confusion from DIS (incl. from ν_μ DIS) makes electron ID efficiency lower at moderate energies.

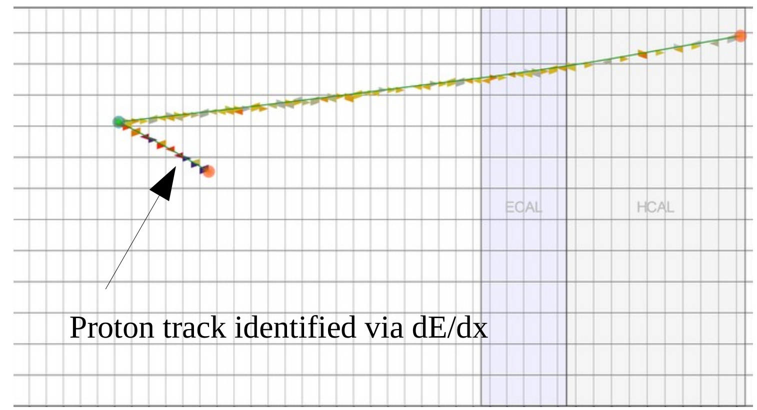
⇒ Choose signal to be *quasielastic-like*: any number of nucleons, but no other hadrons allowed in final state

Constellation of MINERvA CCQE



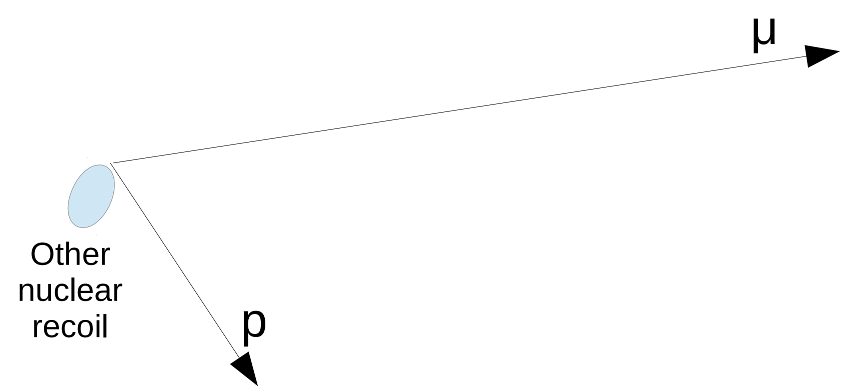
ν_μ “muon + low recoil”: $d\sigma/dQ^2_\mu$

(see Thursday's talk)



ν_μ “muon + proton”: $d\sigma/dQ^2_p$

(see Thursday's talk)

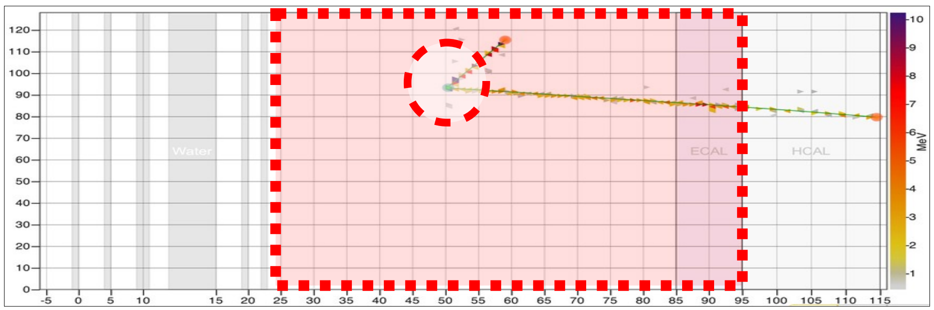


ν_μ “muon + N proton(s)”:

$d^2\sigma/dp_{T\mu}dpz_\mu$

(forthcoming)

Constellation of MINERvA CCQE



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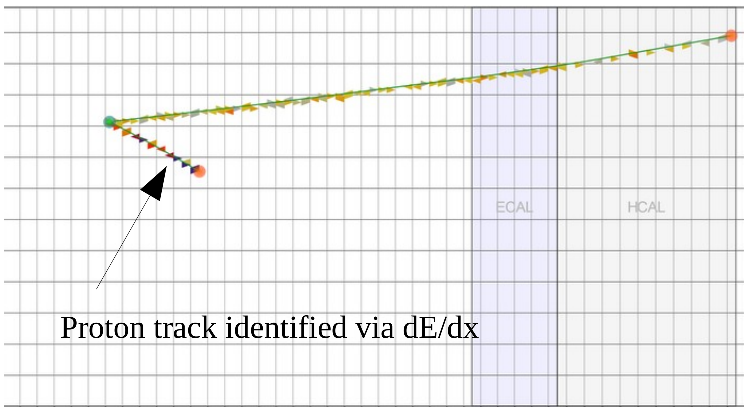
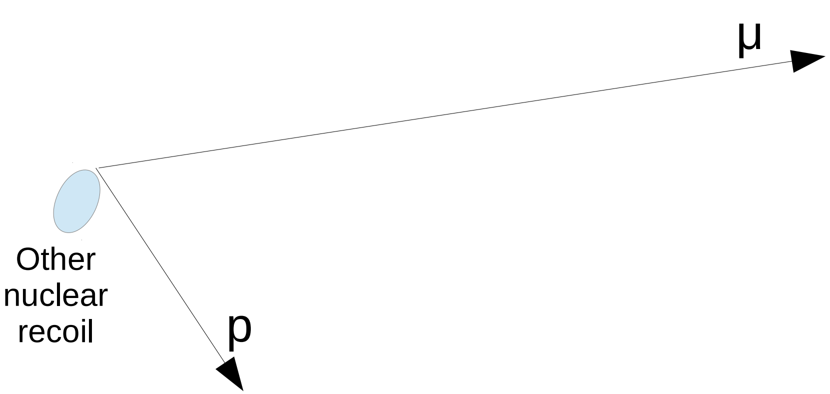


ν_μ "muon + proton": $d\sigma/dQ^2_p$
(see Thursday's talk)

Today's result
(ν_e CCQE)
is most similar
to this one

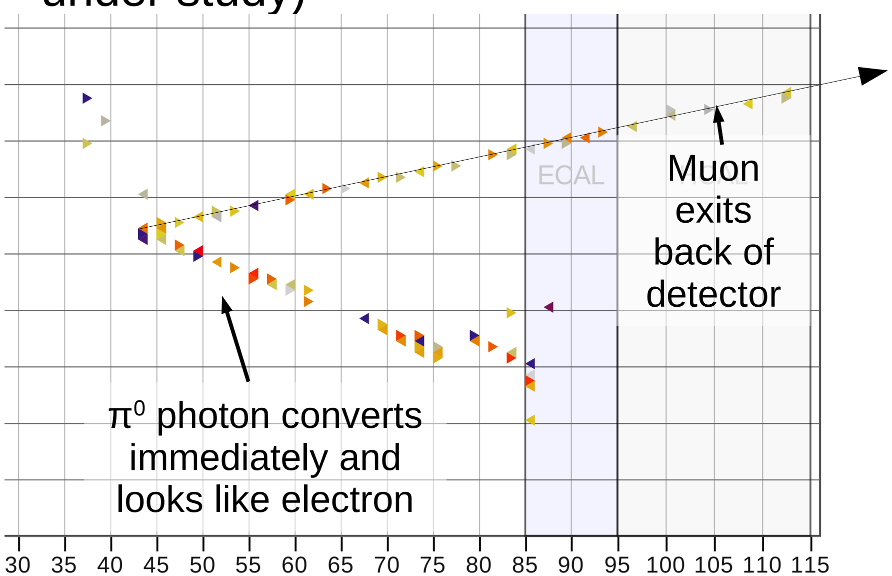


ν_μ "muon + N proton(s)":
$d^2\sigma/dp_{T\mu}dp_{z\mu}$
(forthcoming)

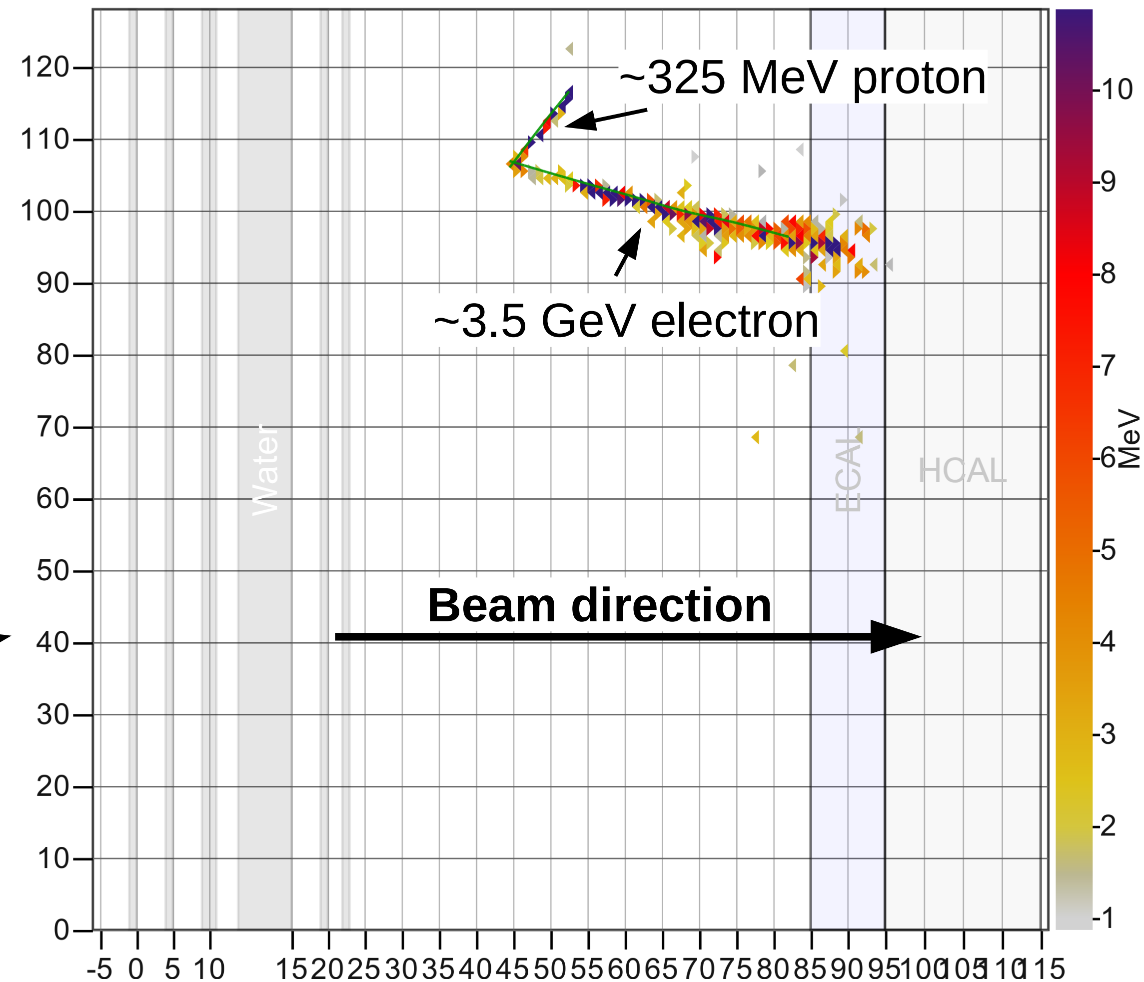
Isolating ν_e-like events

Event "pre-selection" (EM-enriched):

- One (or more) reconstructed track(s) (>85% of $e^{\pm}$ in inner detector region begin with track due to low-Z material)
- No obvious muons (never ν_e):
  - No tracks exiting back of detector
  - No Michel electron candidates
- Cut on multivariate PID classifier combining details of energy profile
- Cut at $E_e > 1$ GeV for this talk (backgrounds for $E_e < 1$ GeV stilll under study)

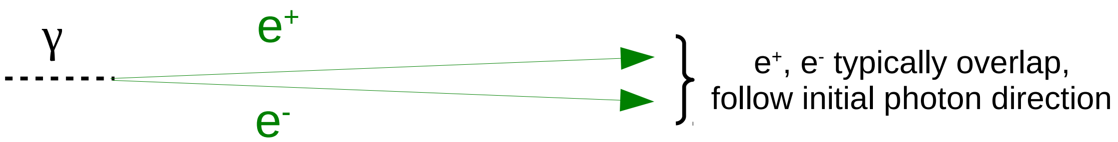


Simulated background rejected by muon cuts



Event display of simulated ~4 GeV ν_e interaction in MINERvA

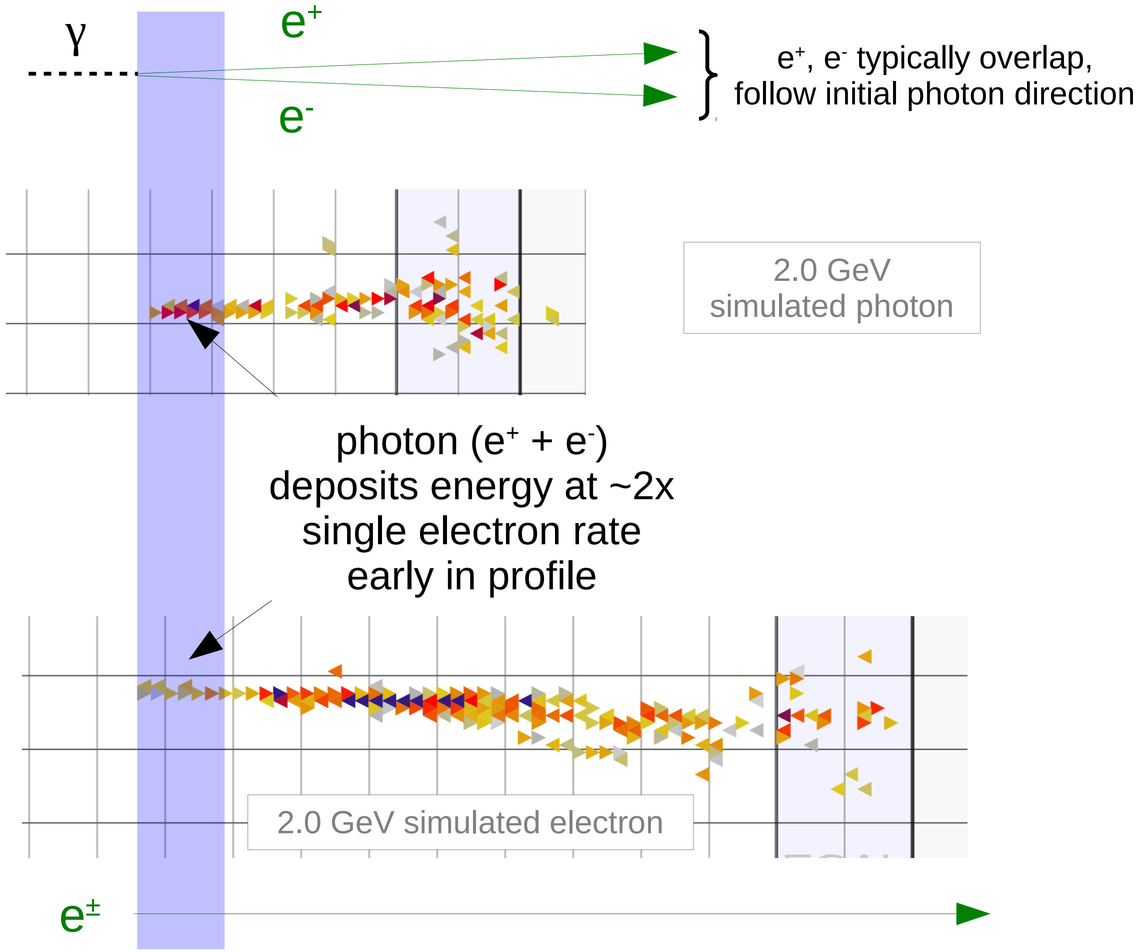
Isolating ν_e events:
Photon rejection



The energy deposition pattern early in the track helps discriminate between photons (background) and electrons

Isolating ν_e-like events:

Photon rejection



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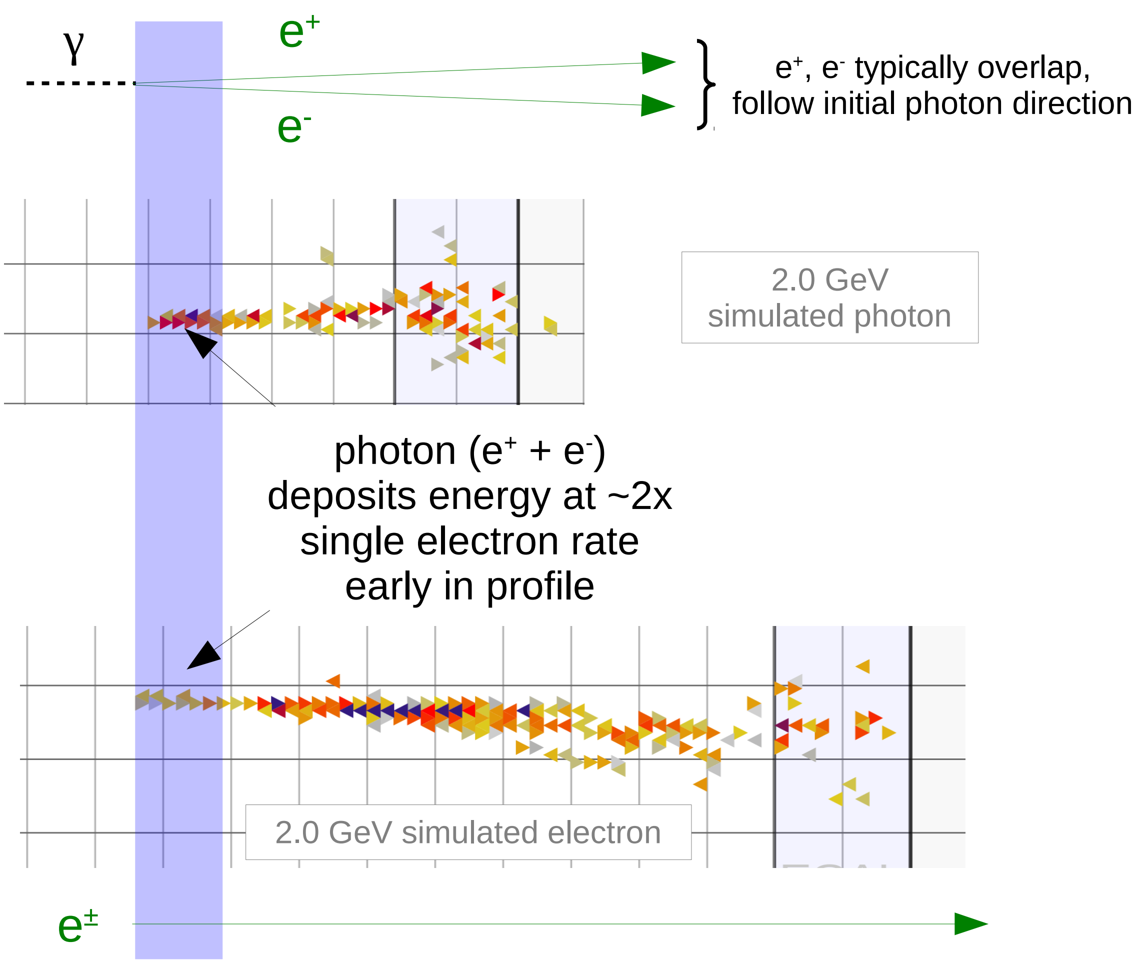
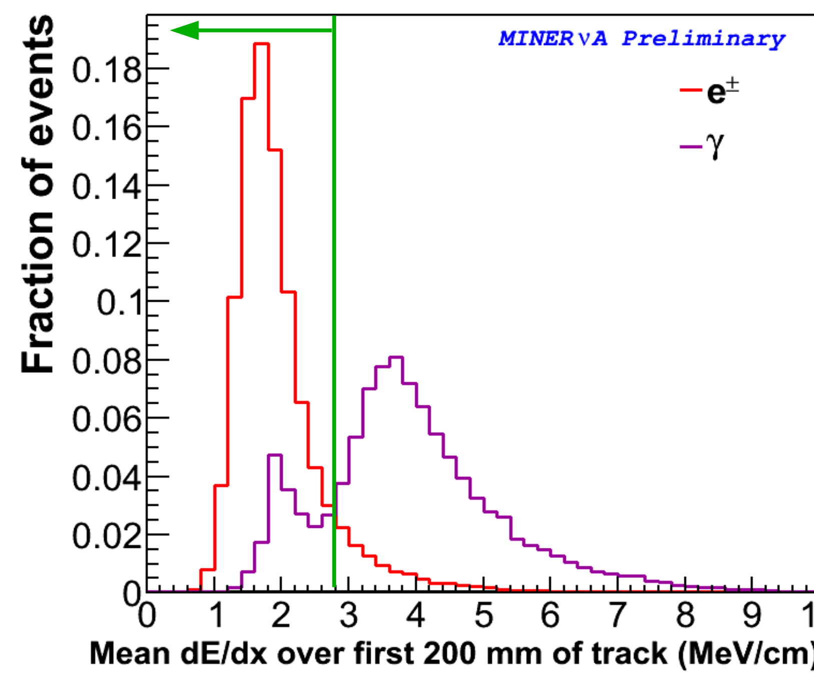


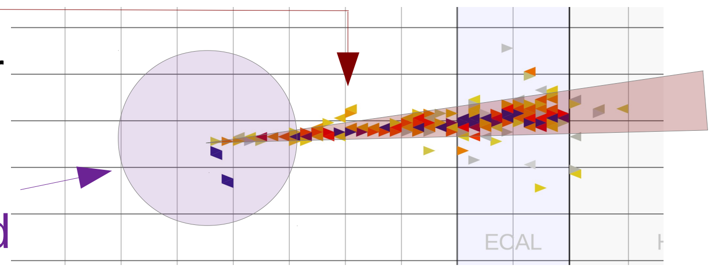


The energy deposition pattern early in the track helps discriminate between photons (background) and electrons

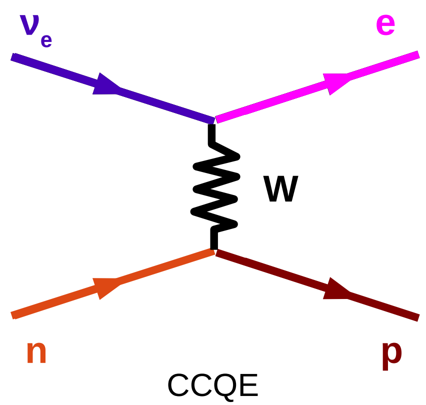
Isolating ν_e-like events:

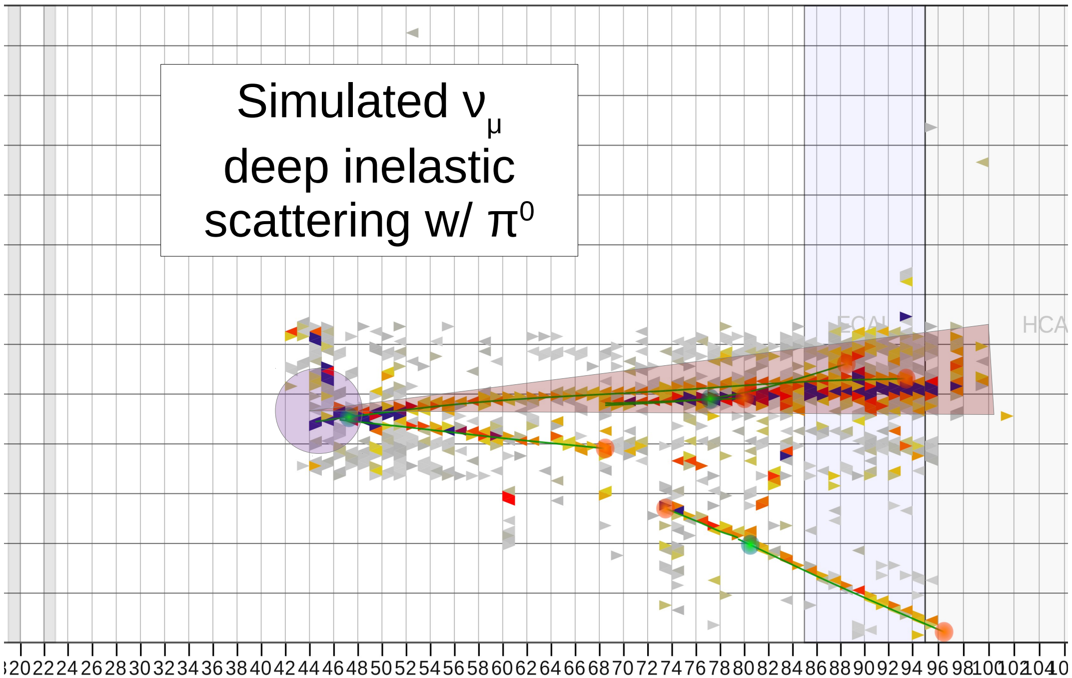
Quasi-elastic-like topology selection

Anything not within a 7.5° electron cone or a vertex activity region of 30 cm radius or tracked as a proton is “extra energy.”



Simulated ν_e CCQE



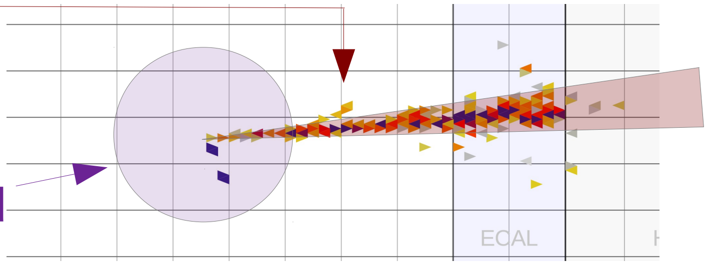


Simulated ν_μ deep inelastic scattering w/ π^0

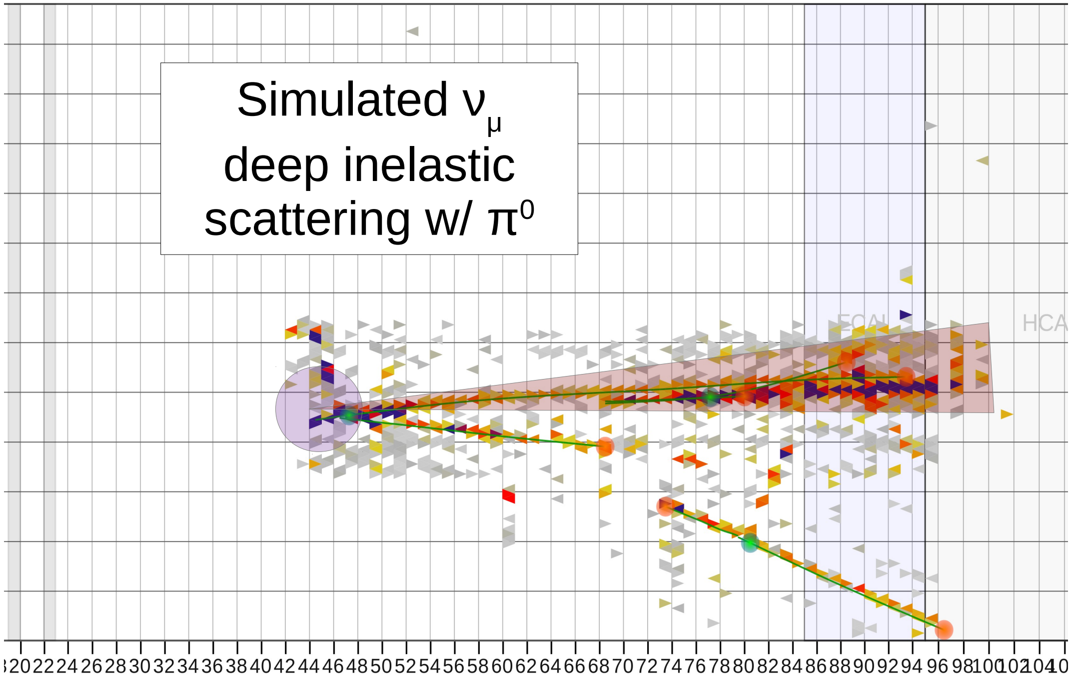
Isolating ν_e-like events:
Quasi-elastic-like topology selection

Anything not within a 7.5° electron cone or a vertex activity region of 30 cm radius or tracked as a proton is "extra energy."

Cut on $\Psi = \frac{E_{extra}}{E_{cone}}$



Simulated ν_e CCQE



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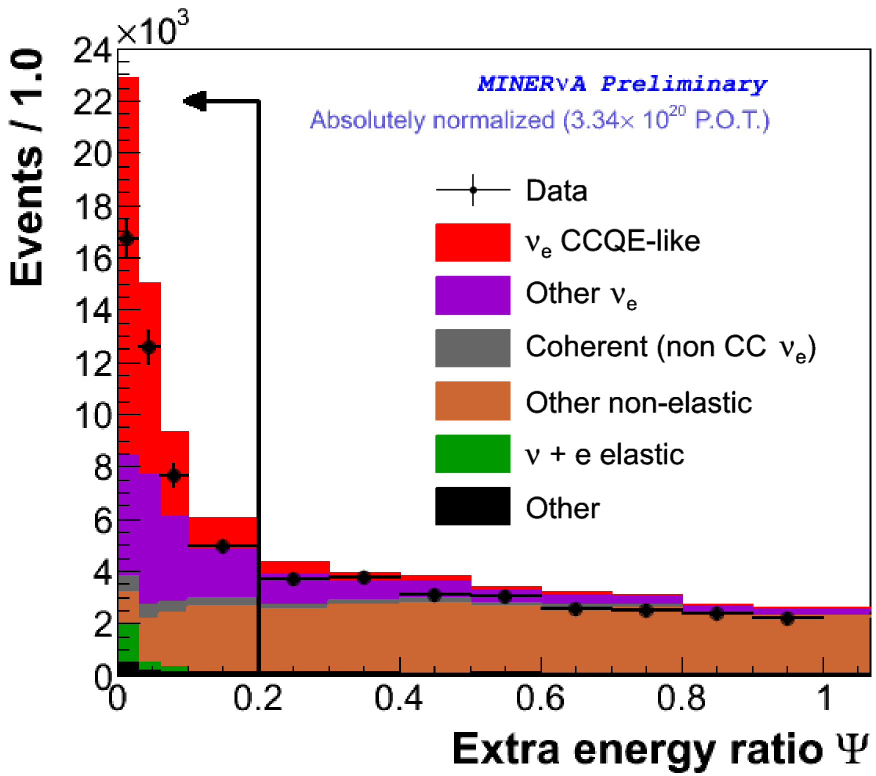
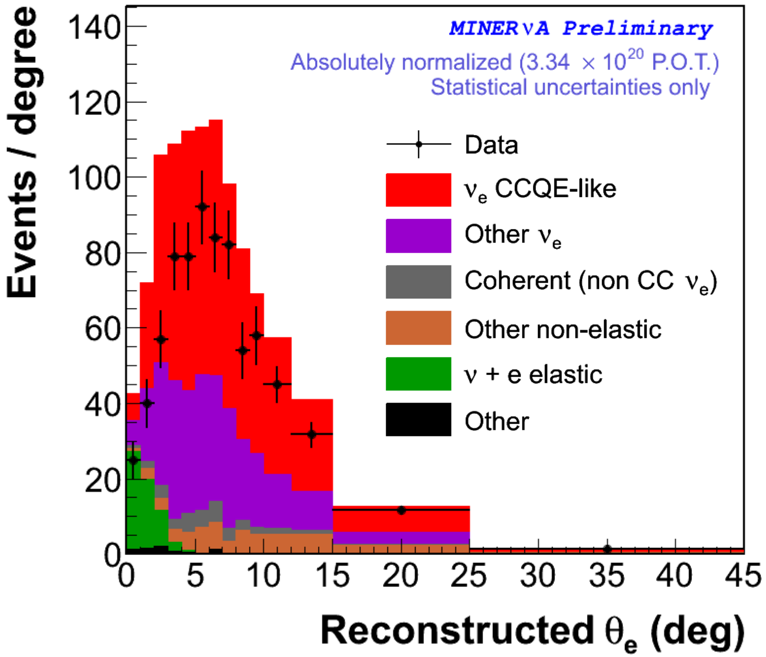
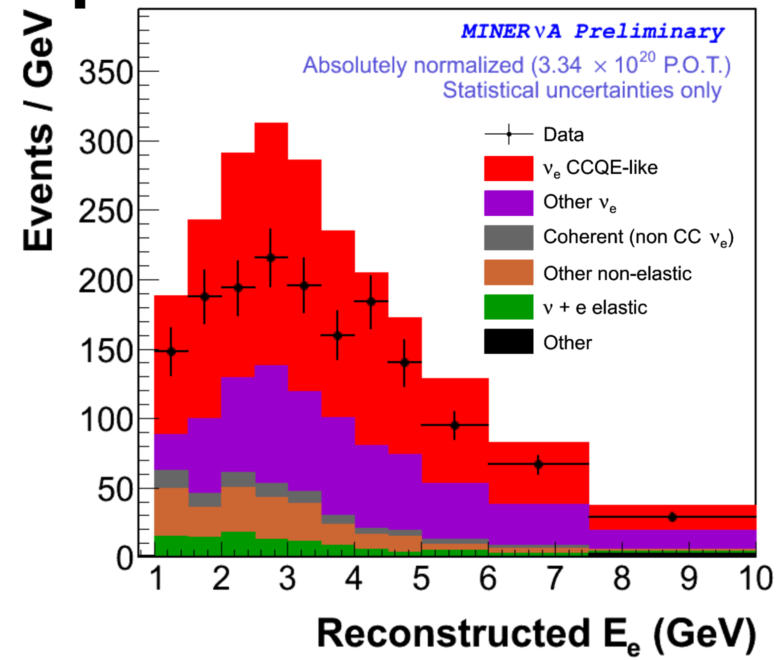


(Actual cut is a function of E_{vis}. Cut illustrated is at most probable value of E_{vis} = 0.4 GeV.)

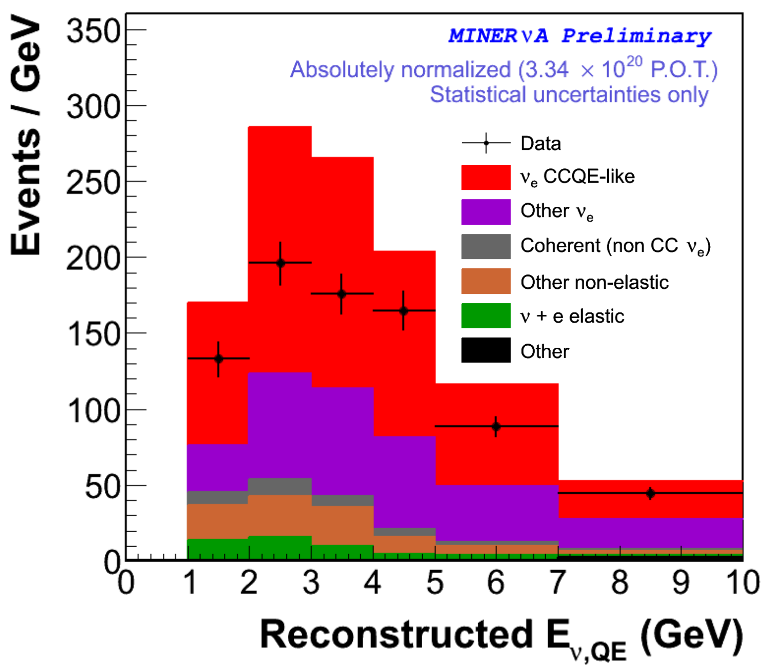
Selected sample

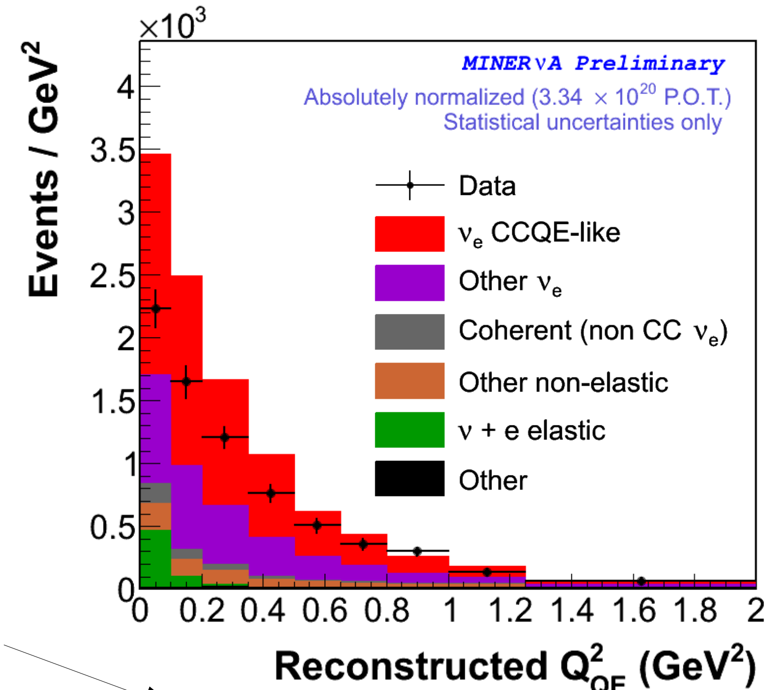




Sample is 52.1% ν_e CCQE

(83.9% ν_e from any channel)





Infer ν kinematics from lepton's

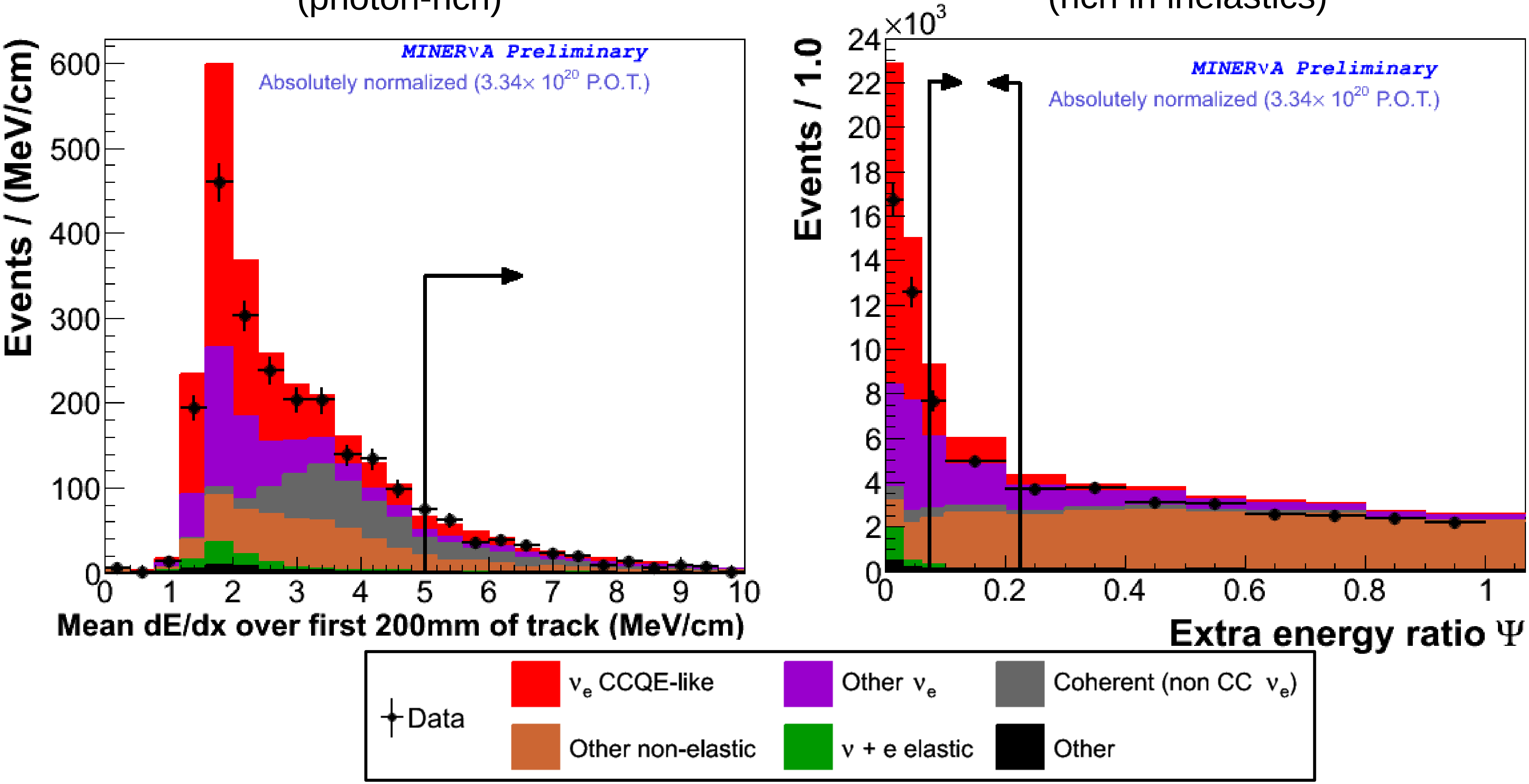
$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

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

Constraining backgrounds

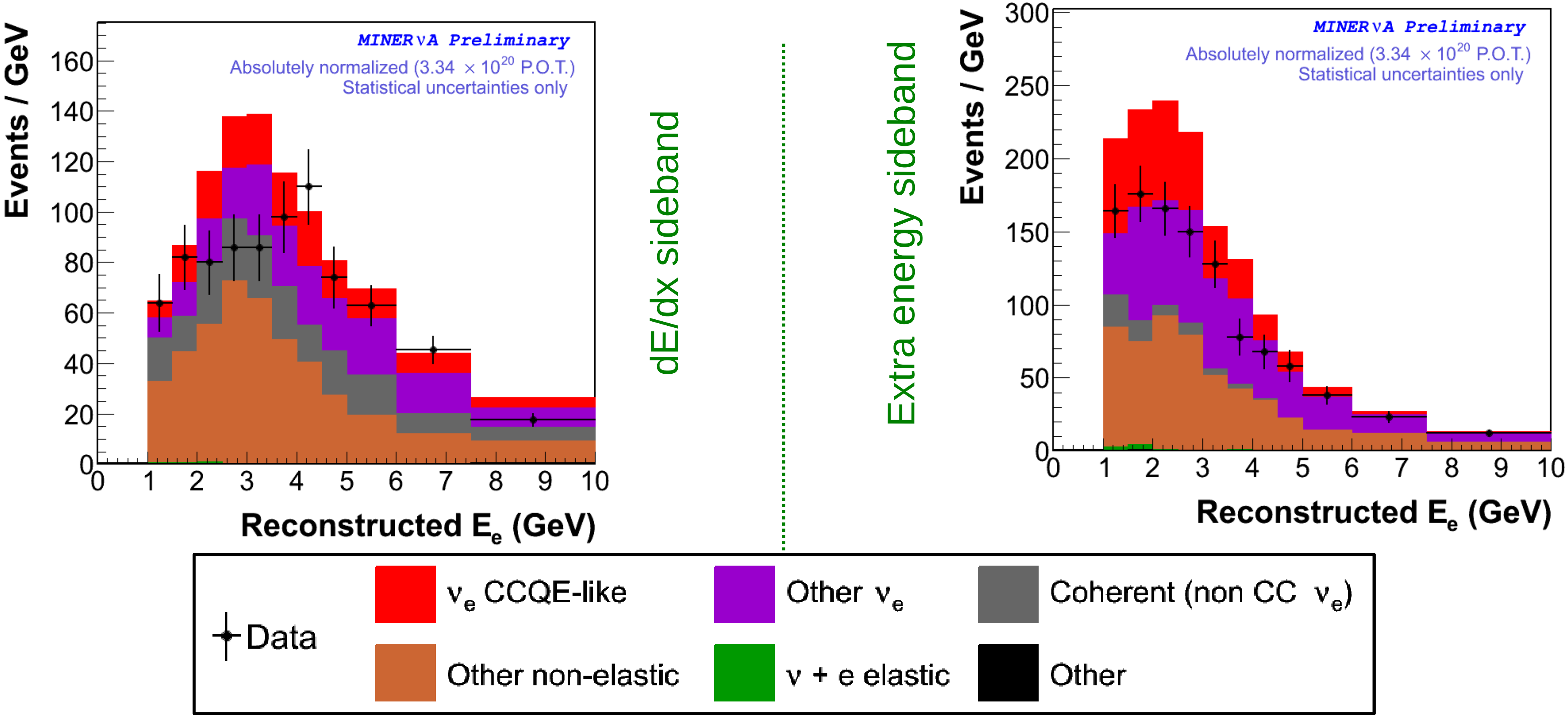
Sideband 1: larger dE/dx
(photon-rich)

Sideband 2: larger "extra energy"
(rich in inelastics)



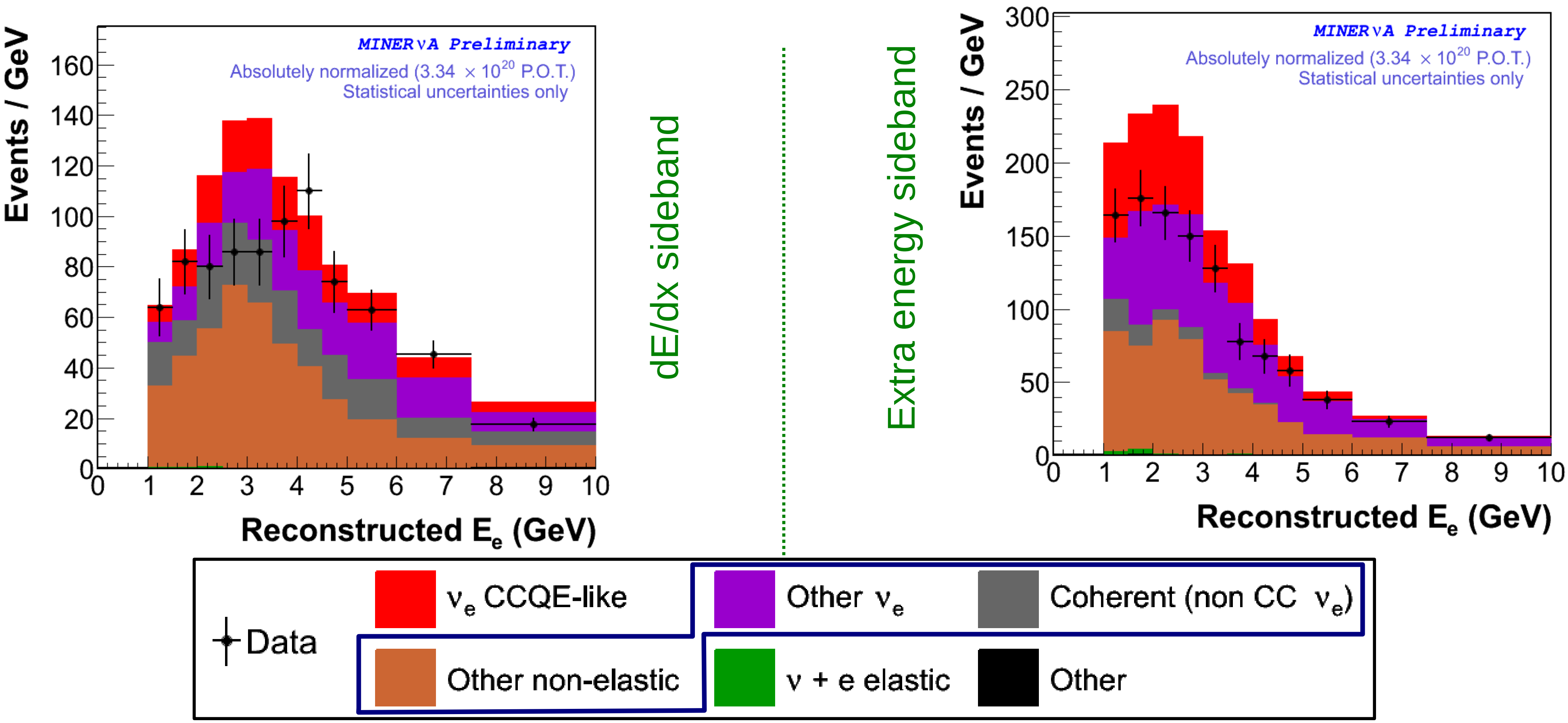
We select two sidebands rich in the major backgrounds...

Constraining backgrounds



… and examine the normalizations of two distributions in each sideband
(one of them, candidate electron energy, shown here;
we also use candidate electron angle).

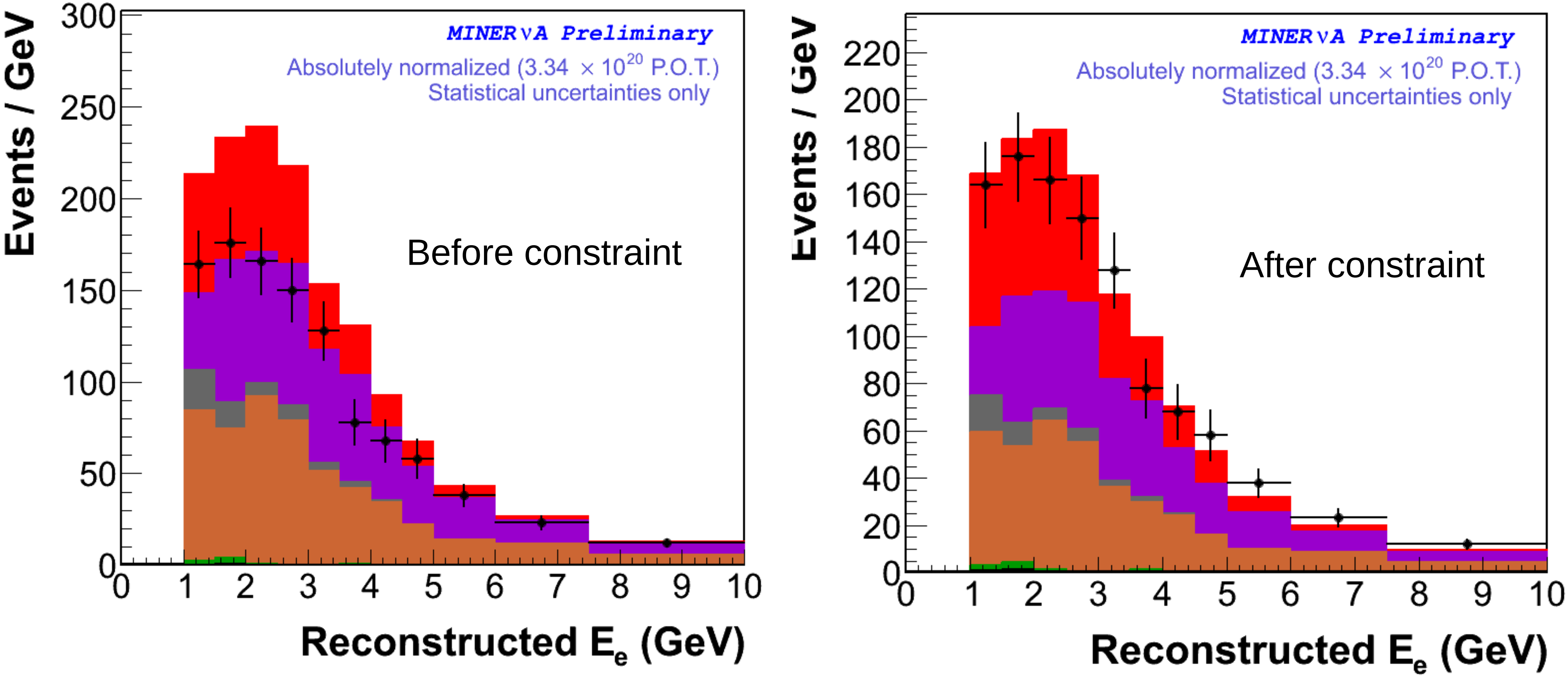
Constraining backgrounds



… and examine the normalizations of two distributions in each sideband (one of them, candidate electron energy, shown here; we also use candidate electron angle).

We fit the normalizations of the "other ν_e," "coherent," and "other non-elastic categories" together, using the four distributions simultaneously.

Constraining backgrounds



This is one of four (sideband, variable) combinations that are fitted simultaneously.

The fitted scale factor is 0.69 (same trend as inelastics in other MINERvA analyses)

Steps to a cross-section

(unsmearing matrix)

$$\left(\frac{d\sigma}{dE_e}\right)_i = \frac{1}{\Phi} \times \frac{1}{T_n} \times \frac{1}{\left(\Delta E_e\right)_i} \times \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bknd}\right)}{\epsilon_i}$$

(efficiency)

(number of targets)

(bin width)

Steps to a cross-section

(unsmearing matrix)

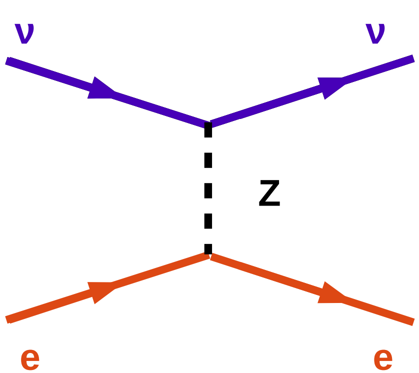
$$\left(\frac{d\sigma}{dE_e}\right)_i = \frac{1}{\Phi} \times \frac{1}{T_n} \times \frac{1}{(\Delta E_e)_i} \times \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bknd}\right)}{\epsilon_i}$$

Flux

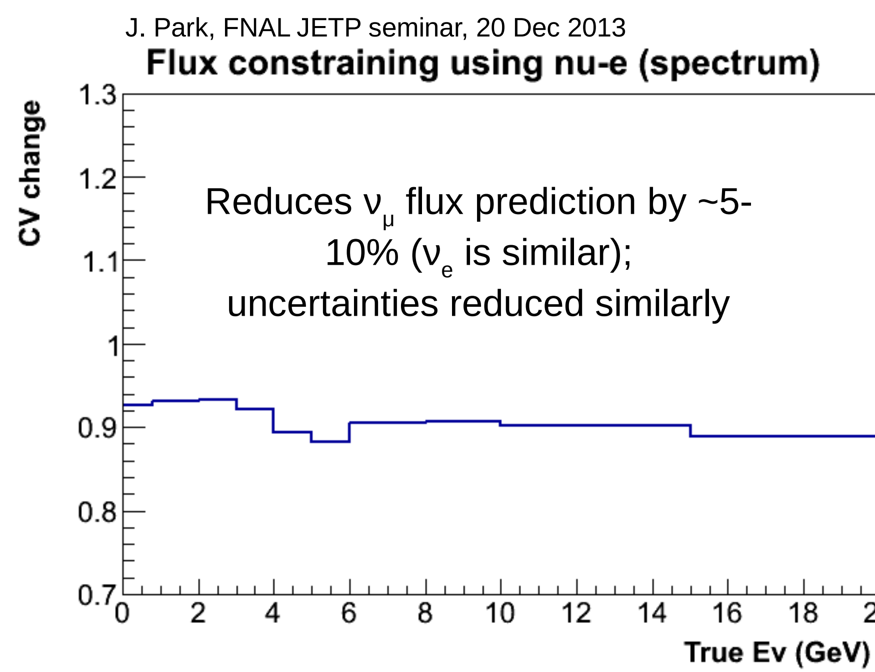
(number of targets)

(bin width)

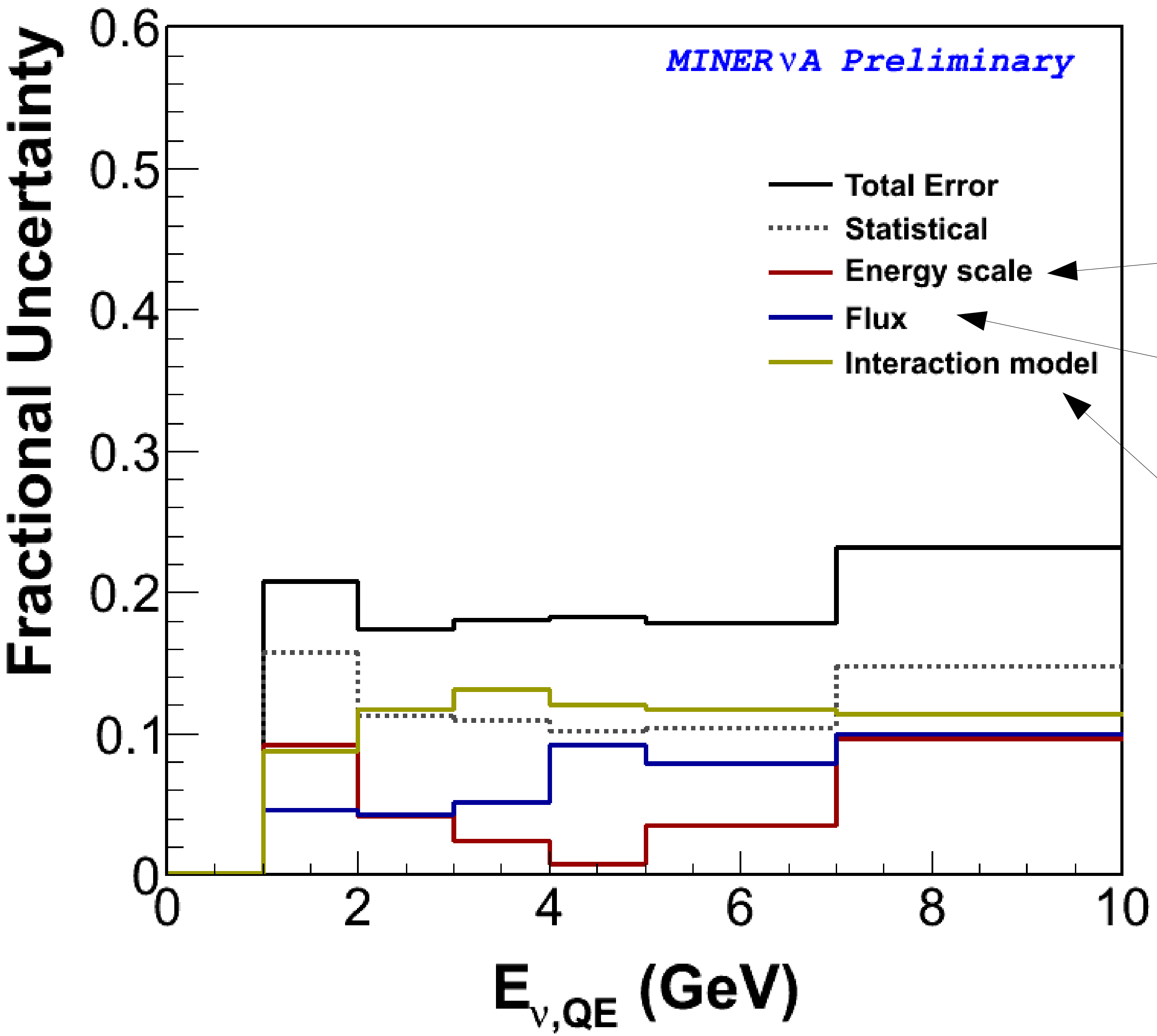
(efficiency)



We constrain the flux using a separate *in situ* measurement of the neutrino-electron elastic scattering rate (also constrains this background)



Uncertainty summary



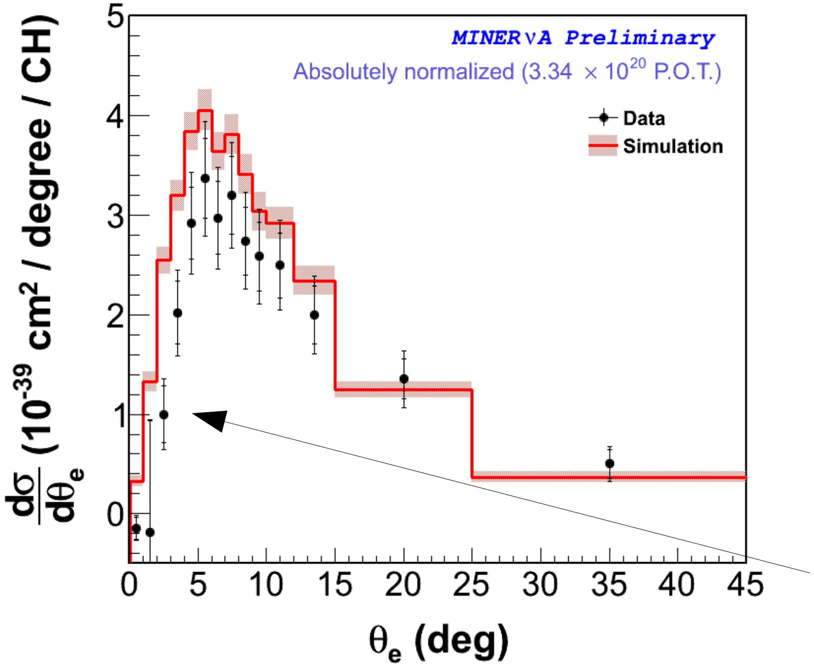
Estimated using the π^0 mass peak in a separate measurement

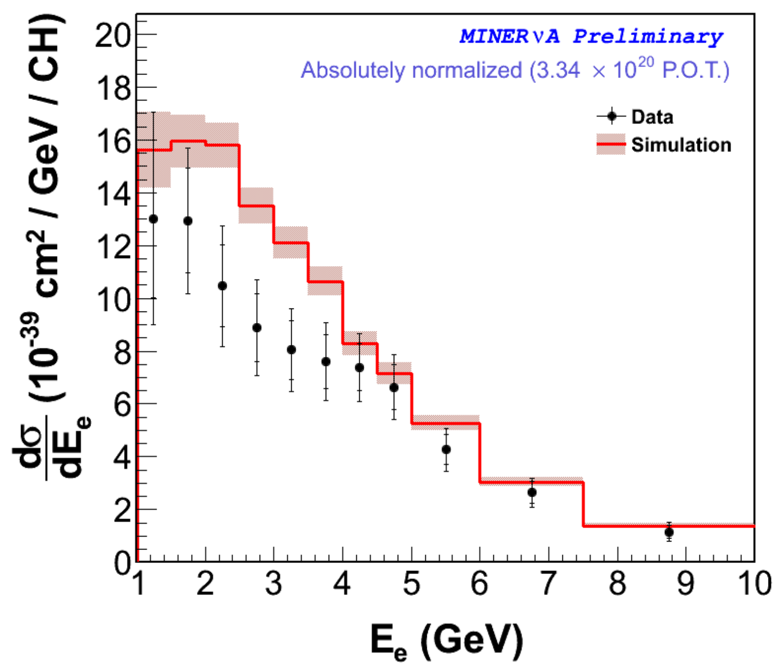
Constrained as noted previously

Mostly enters in background subtraction

Uncertainties due to the GENIE interaction model and the statistics are roughly comparable

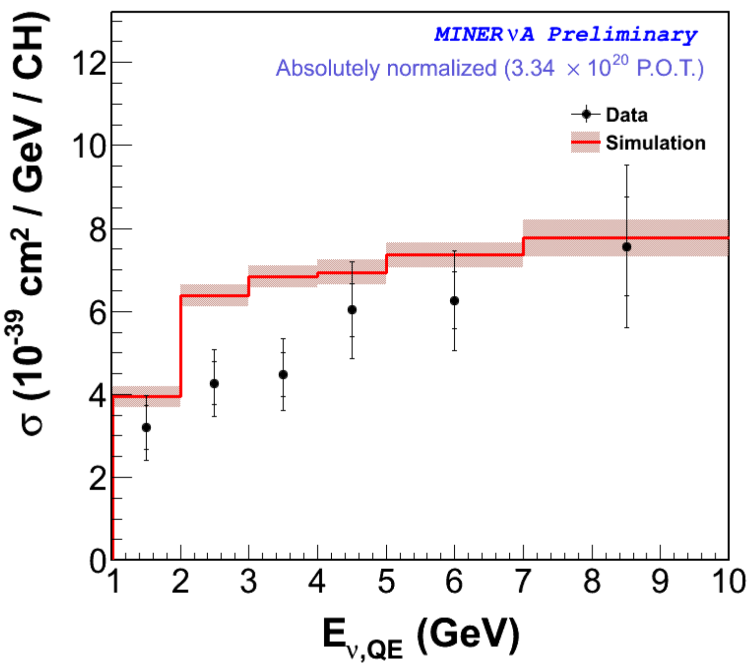
Cross-sections

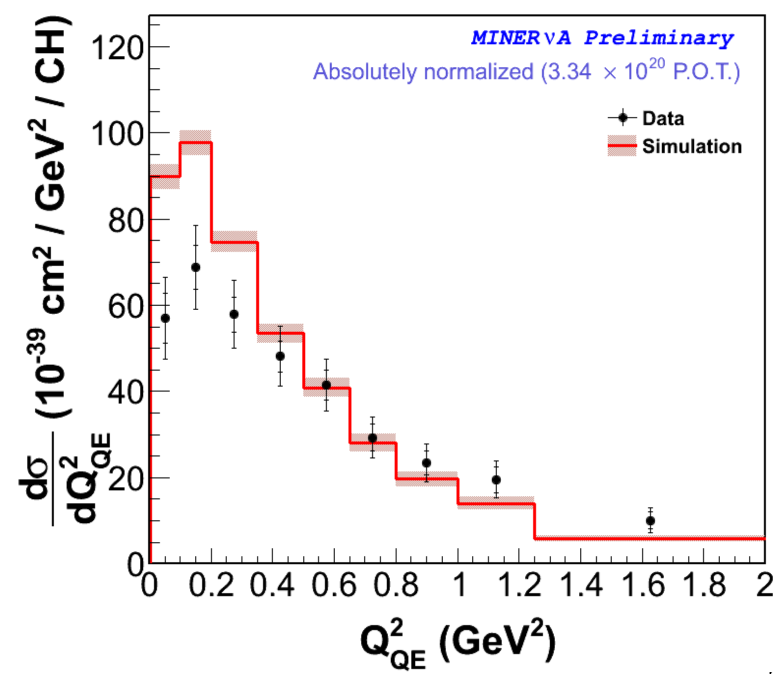




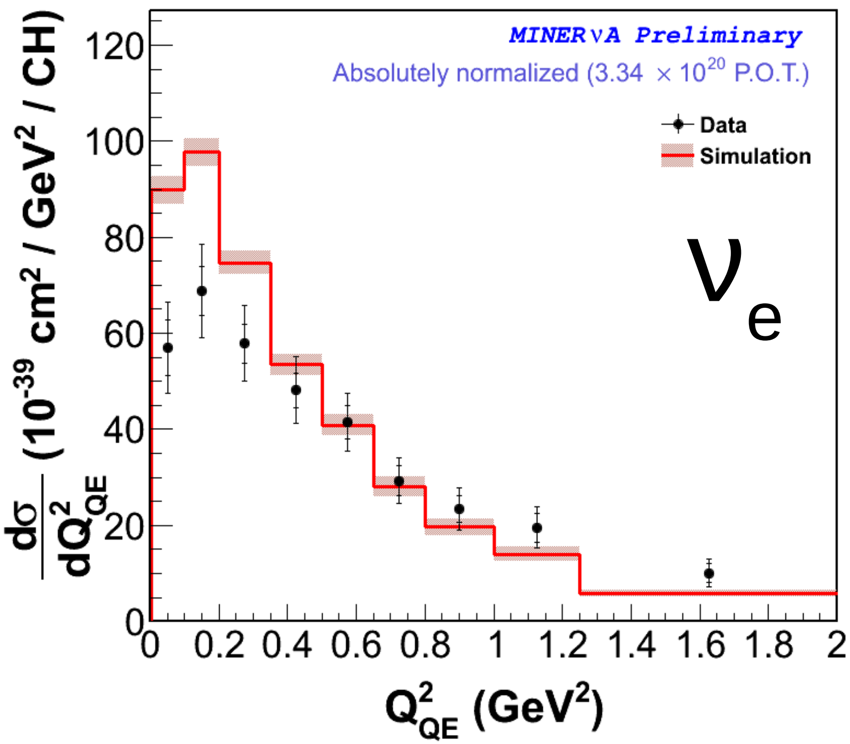
Observation

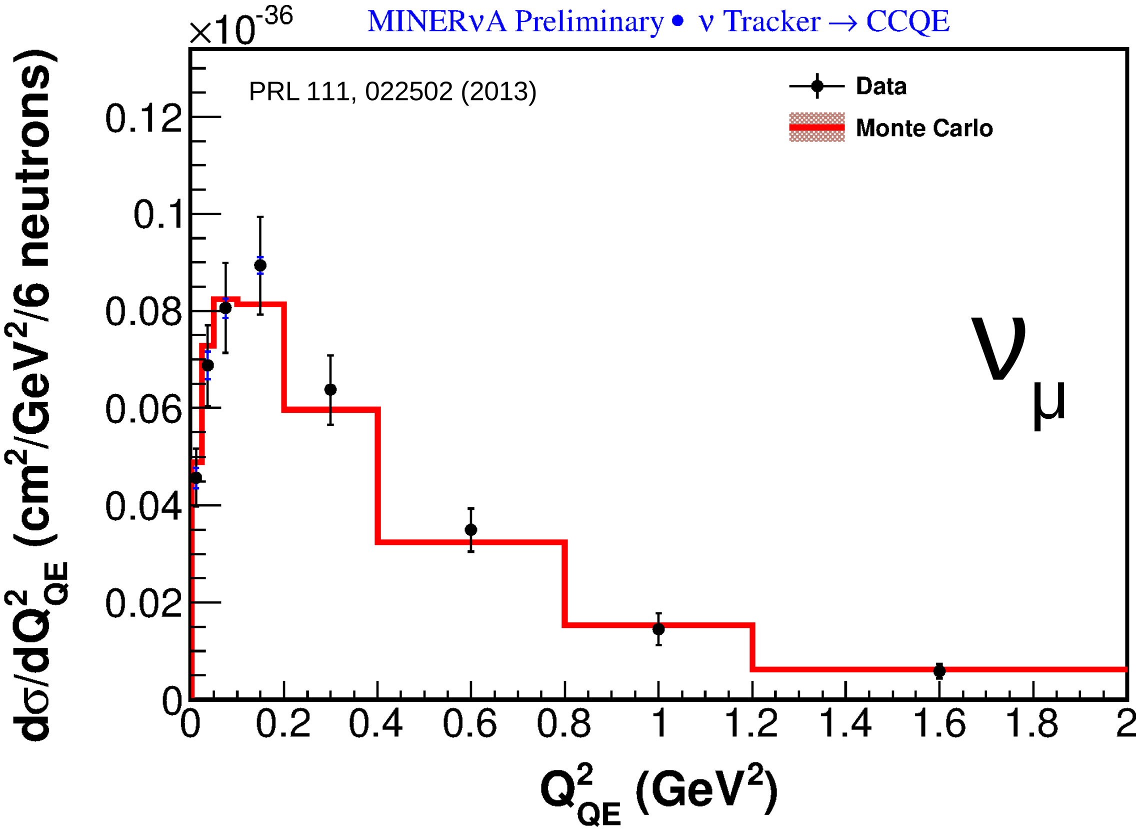
The simulation (GENIE 2.6.2) overpredicts the rate at low angles!





Comparison to ν_μ





Observations

- GENIE ν_e prediction is larger in normalization than ν_μ, while data trend is opposite
- Data ν_e spectrum is harder than ν_μ in Q^2

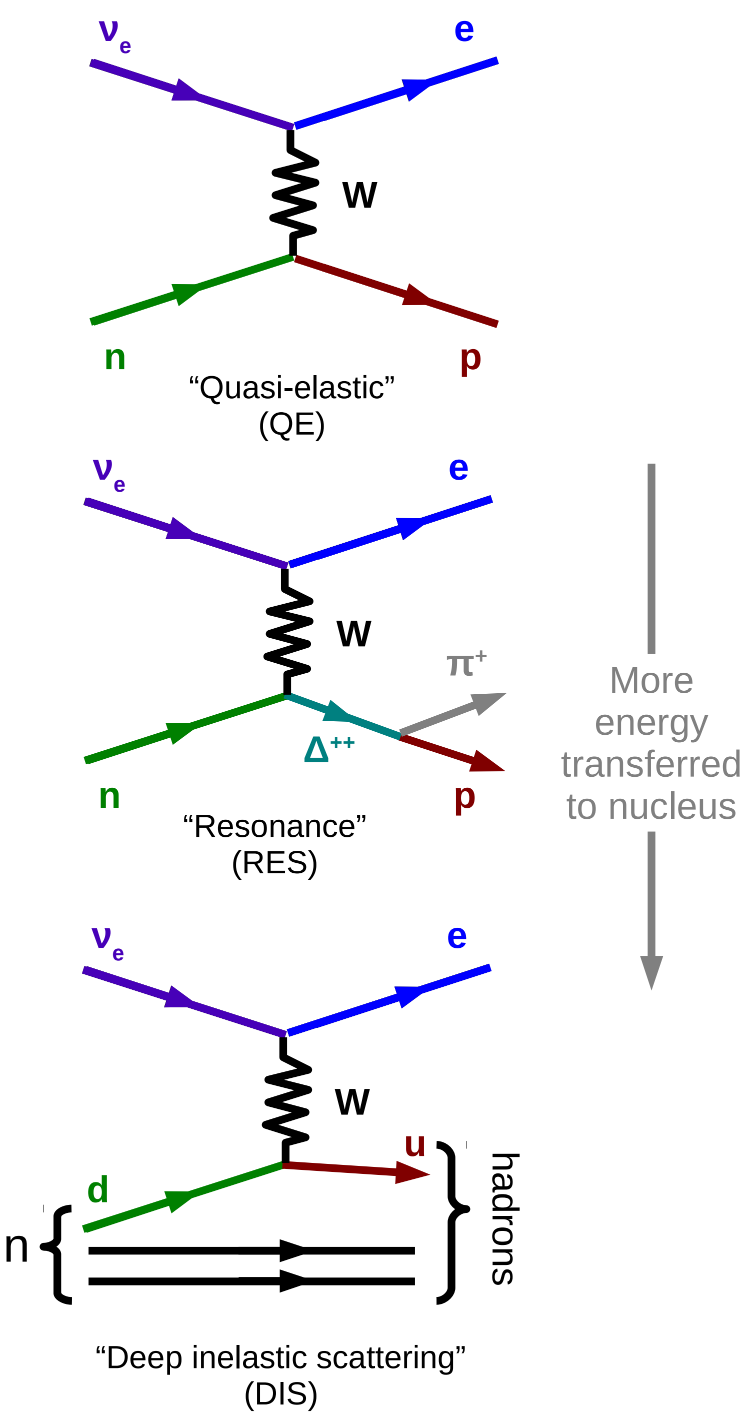
Summary and outlook

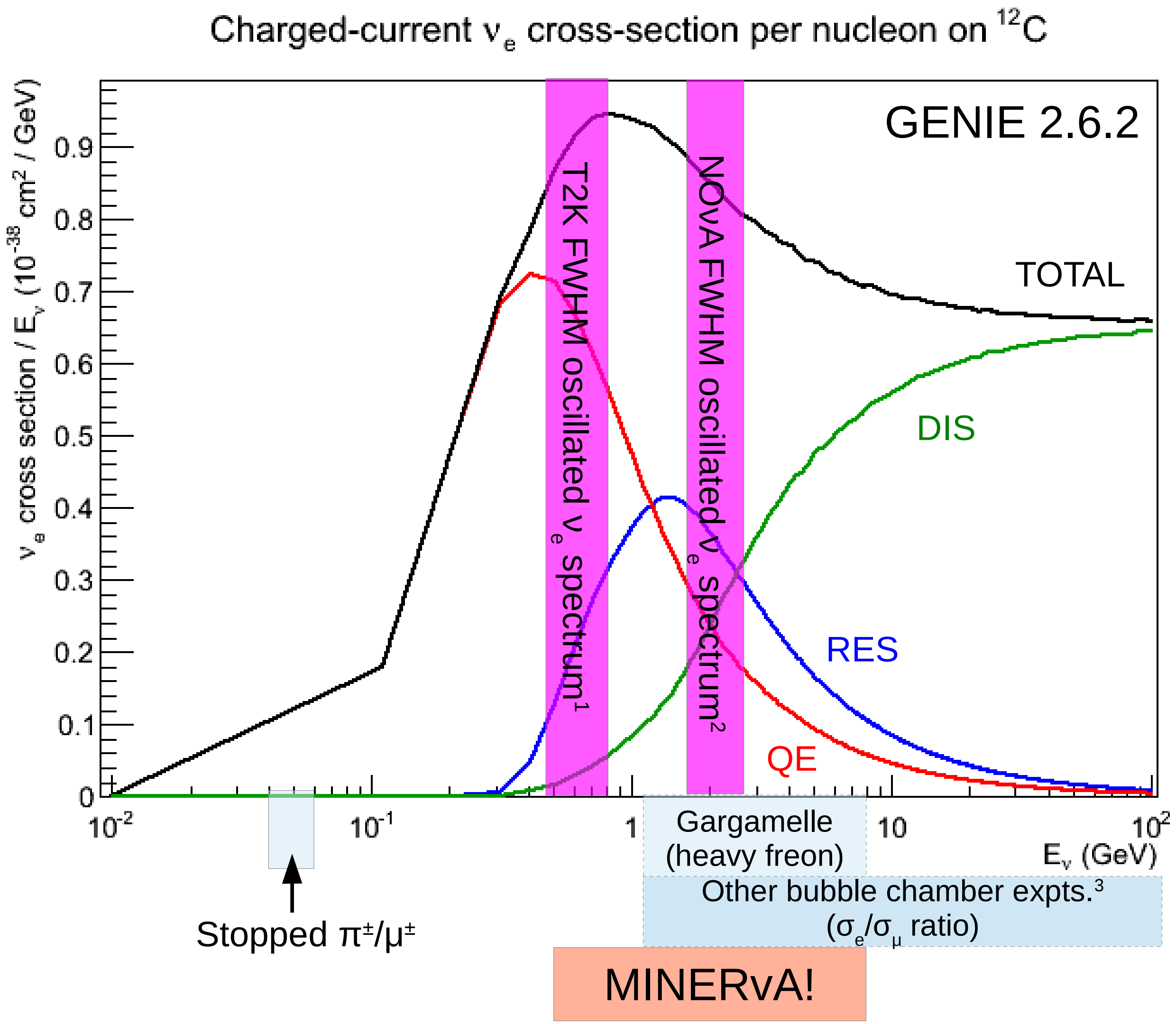
- ν_e cross-sections are important for oscillation expts.
- We observe a discrepancy at low angles between GENIE 2.6.2 and our data in $d\sigma/d\theta_e$
- The Q^2 spectrum appears to be harder for ν_e CCQE than for ν_μ CCQE
- Work is ongoing to characterize the backgrounds in the $E_e < 1$ GeV region
- Further study of systematics is ongoing

Thanks for your attention!

Backup slides follow

Existing measurements and needs





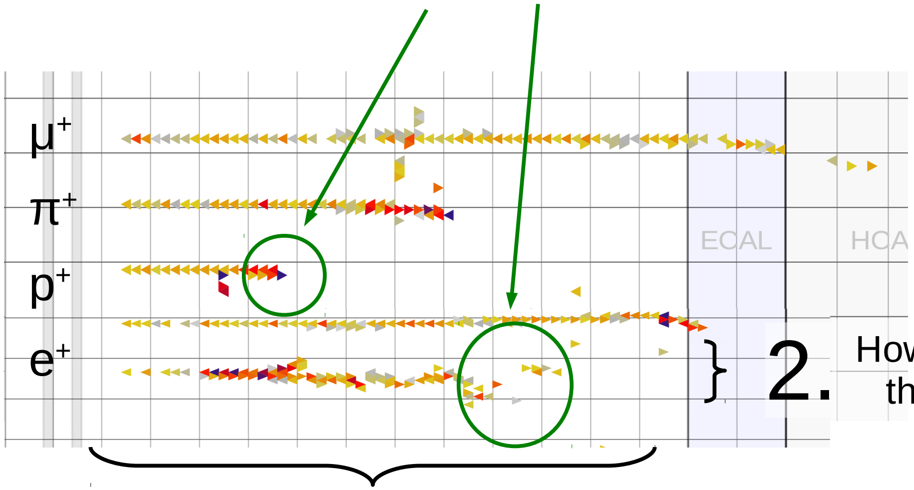
But few measurements!
Thus, present oscillation exp'ts rely on lepton universality and $\sigma(\nu_\mu)$...

[1] B. Kirby, Ph. D. thesis, T2K-THESIS-020
[2] R. Patterson, Neutrino 2012
[3] FNAL E53, SKAT, BEBC, CHARM

Isolating ν_e-like events:

EM-like final state selection

1. What fraction of energy is deposited at the track end?



2. How “wide” is the track?

3. What is the track's mean dE/dx?

We train a multivariate classifier using these three characteristics of the energy deposition profile of the shower-like object

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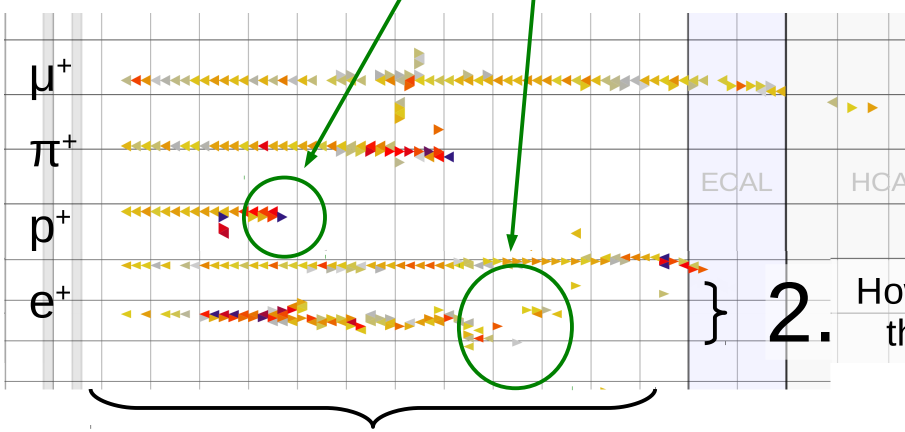

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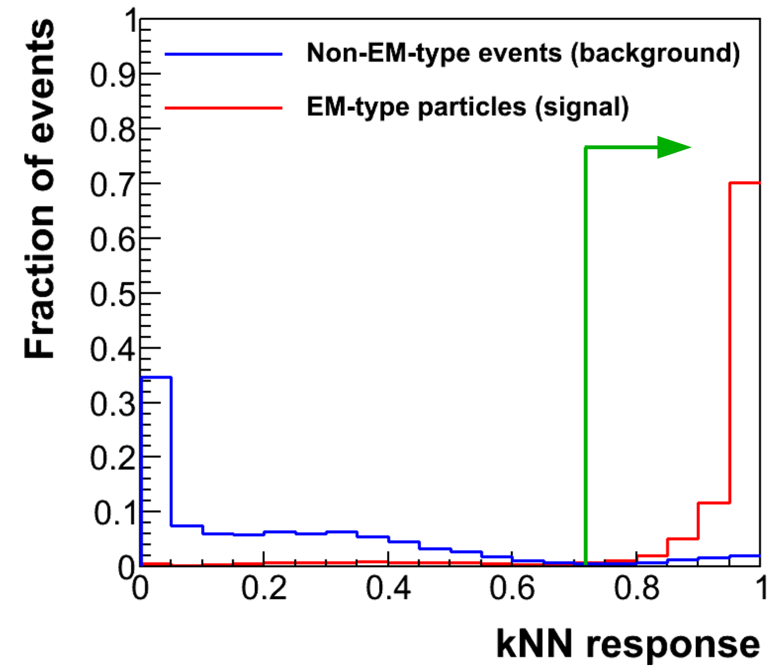
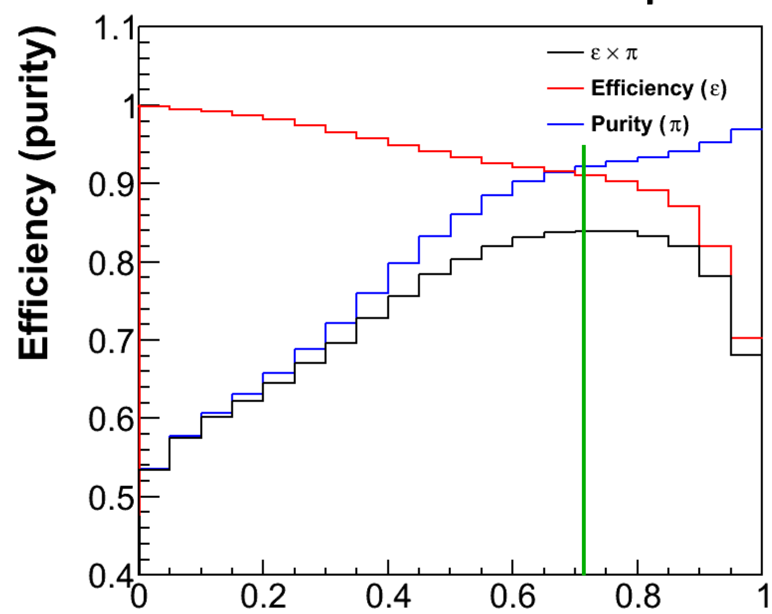
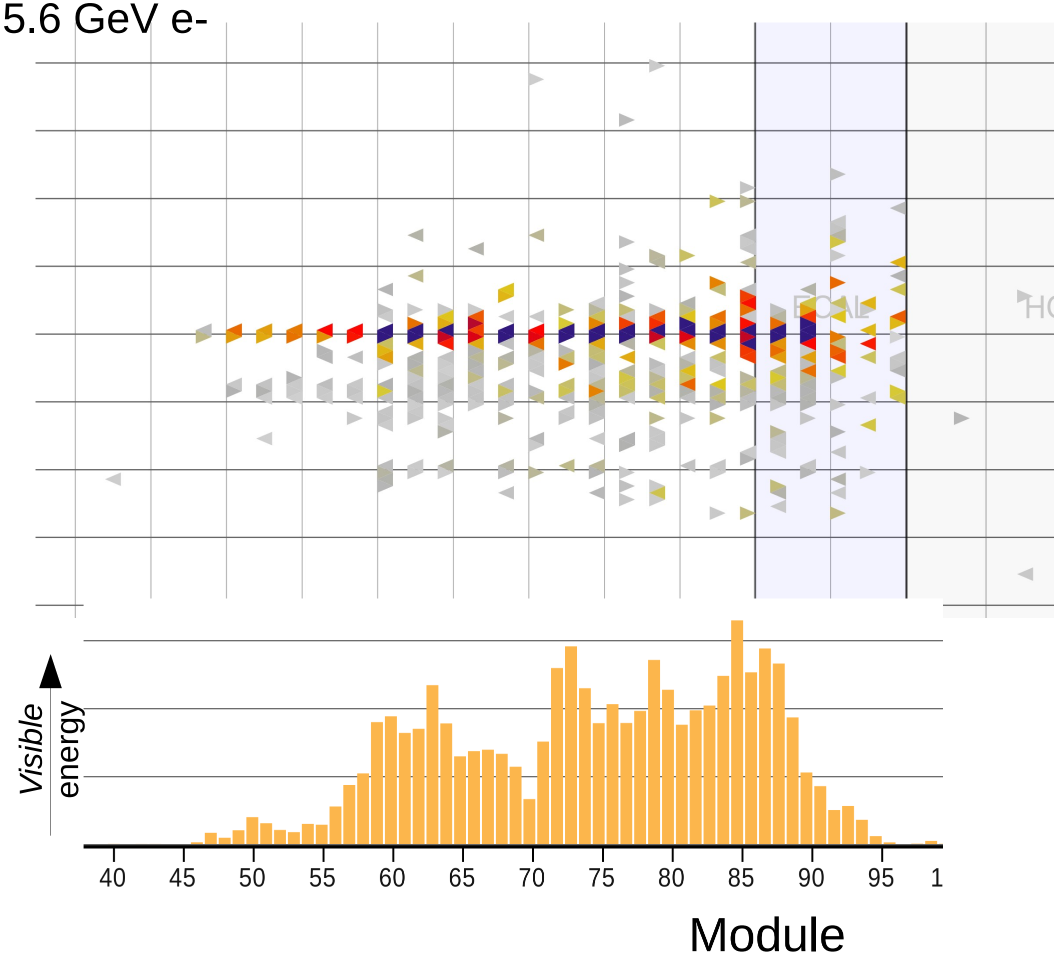


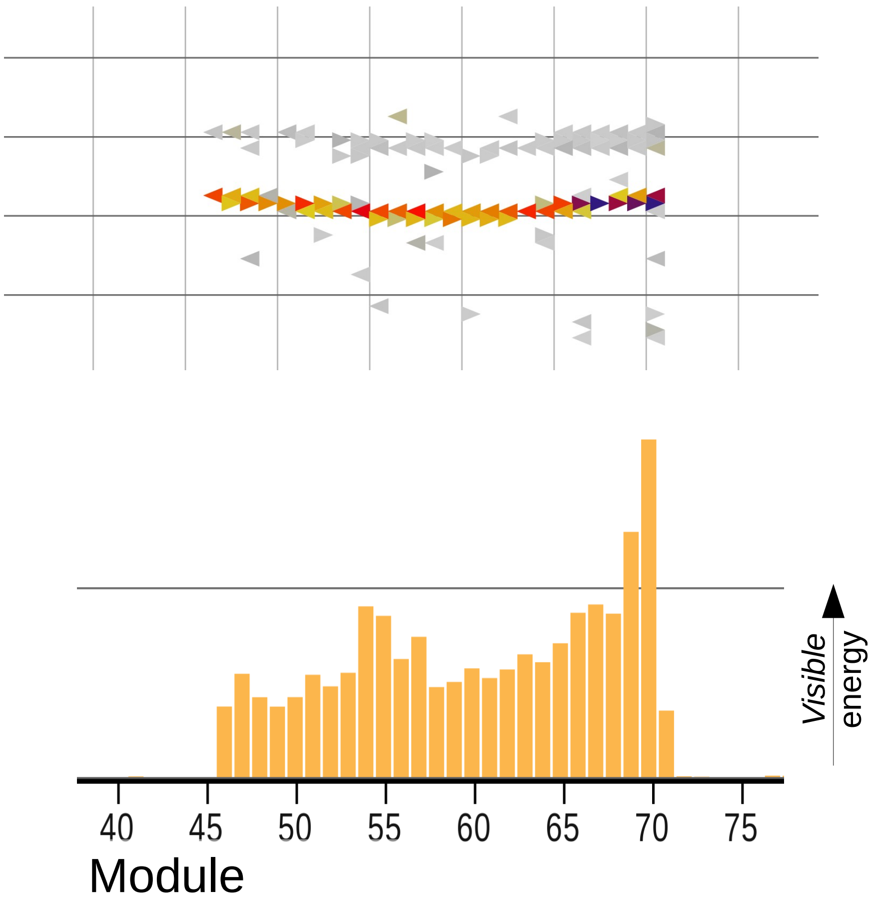


PID variable: endpoint energy fraction

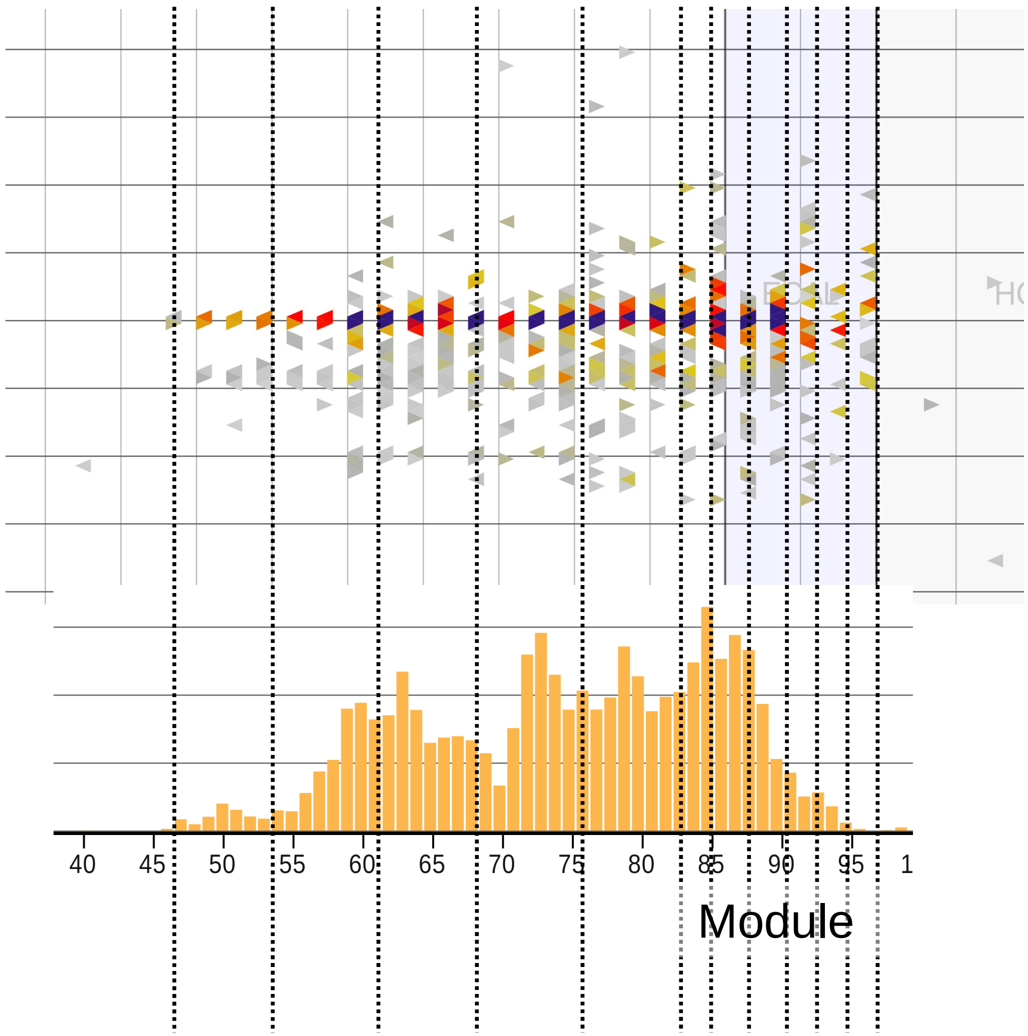
5.6 GeV e-

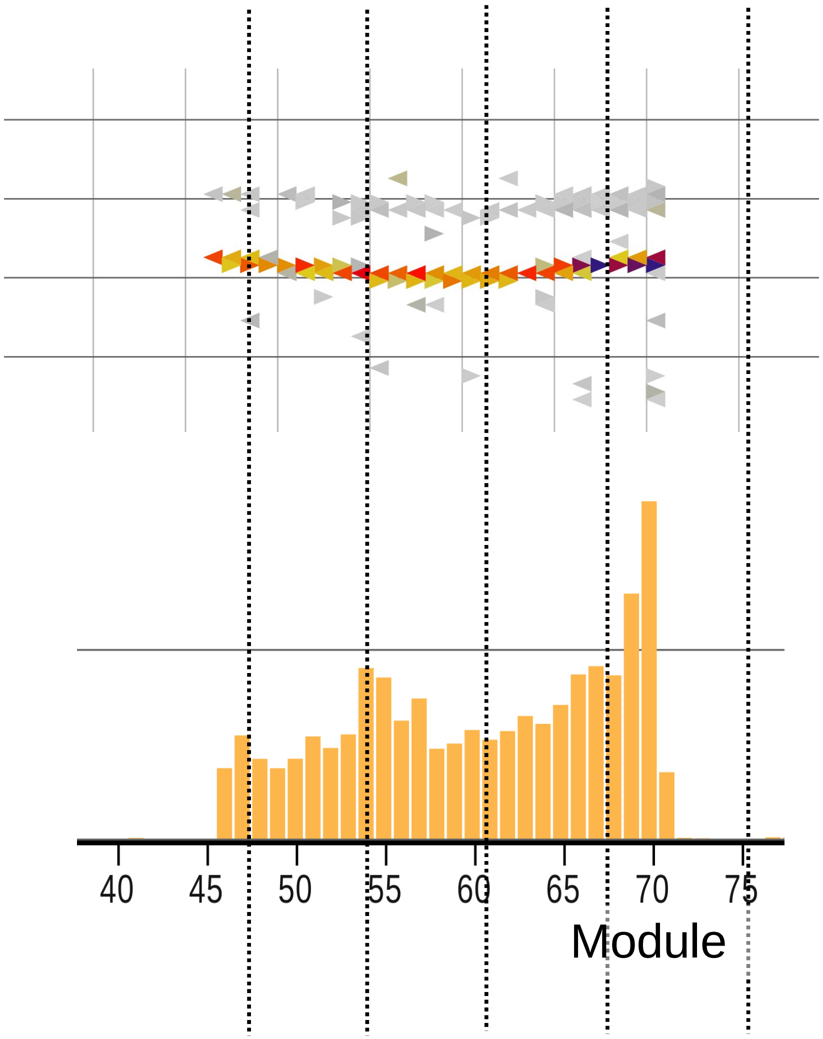


470 MeV p+



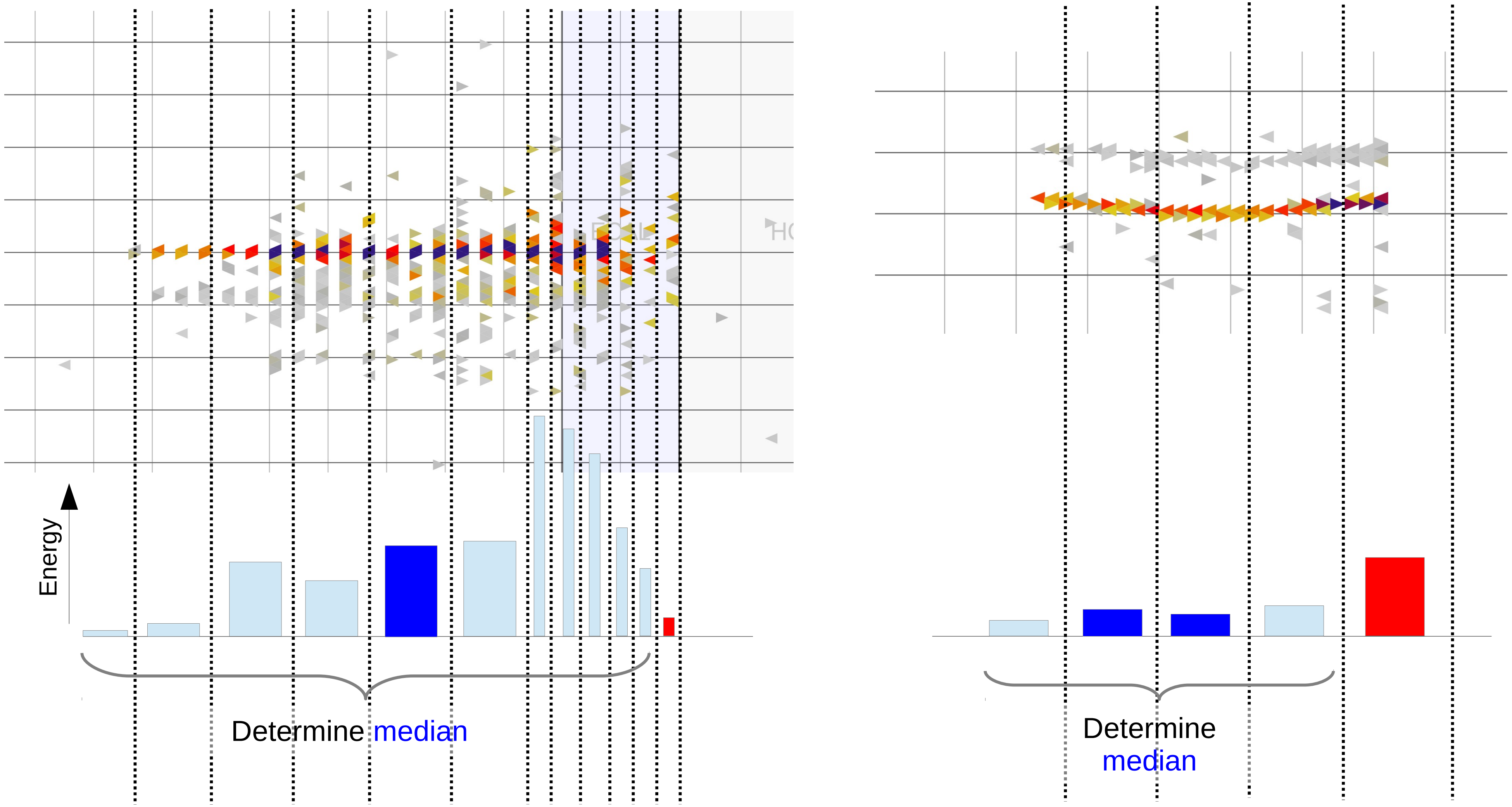
PID variable: endpoint energy fraction





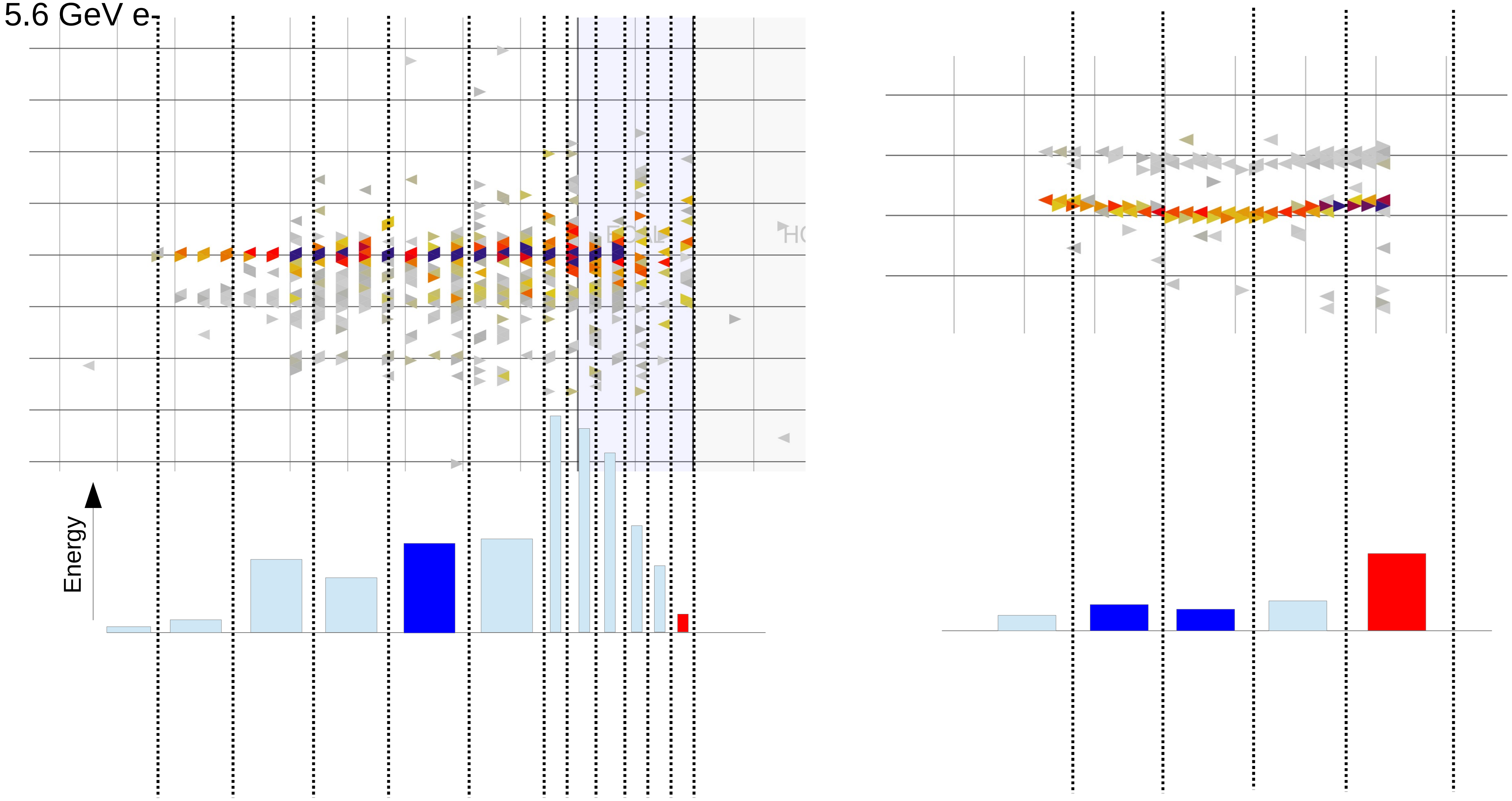
1. Divide the energy deposits into bins of 10 g/cm^2 of areal density.

PID variable: endpoint energy fraction



2. Correct the energy deposits for the calorimetry.
3. Determine the median of the energy deposits (excluding the last one).

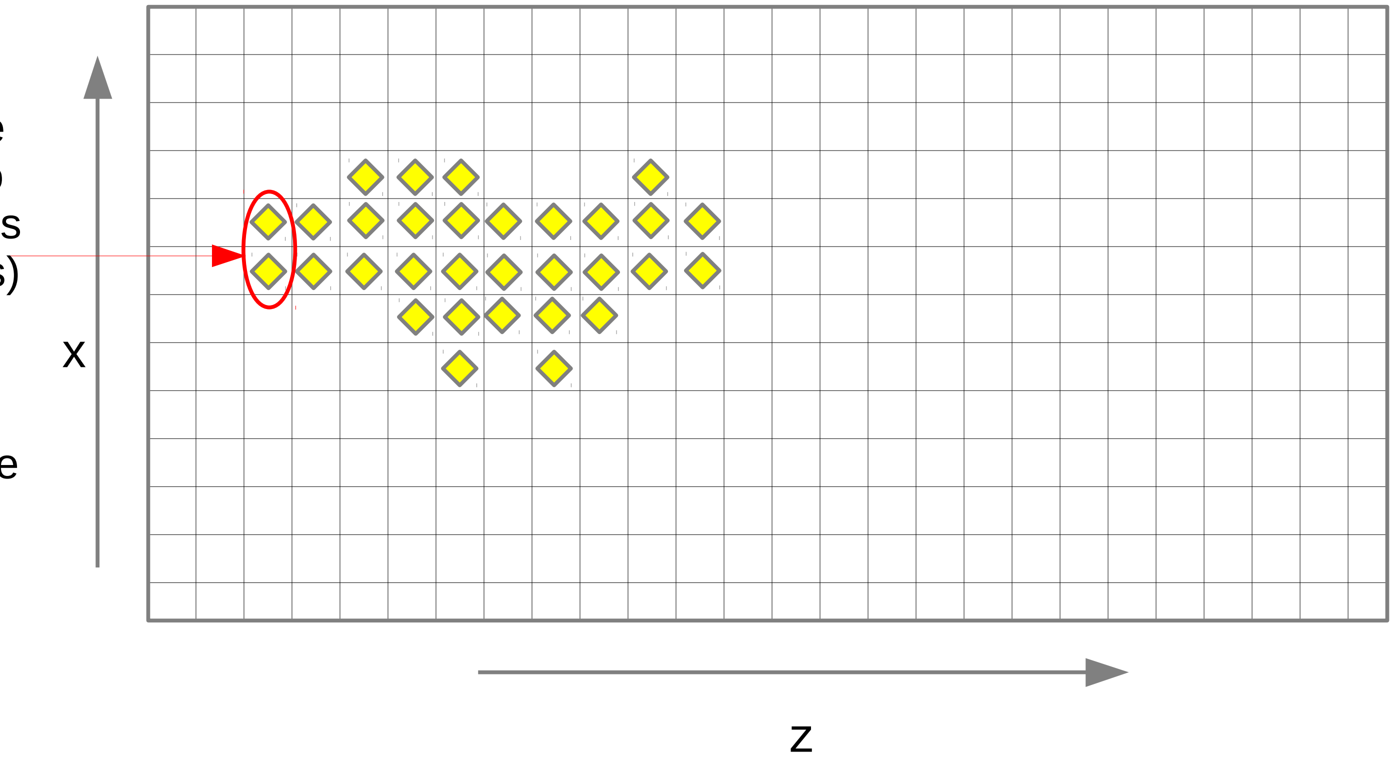
PID variable: endpoint energy fraction



4. Endpoint energy fraction = $\frac{E_{last}}{E_{median}}$

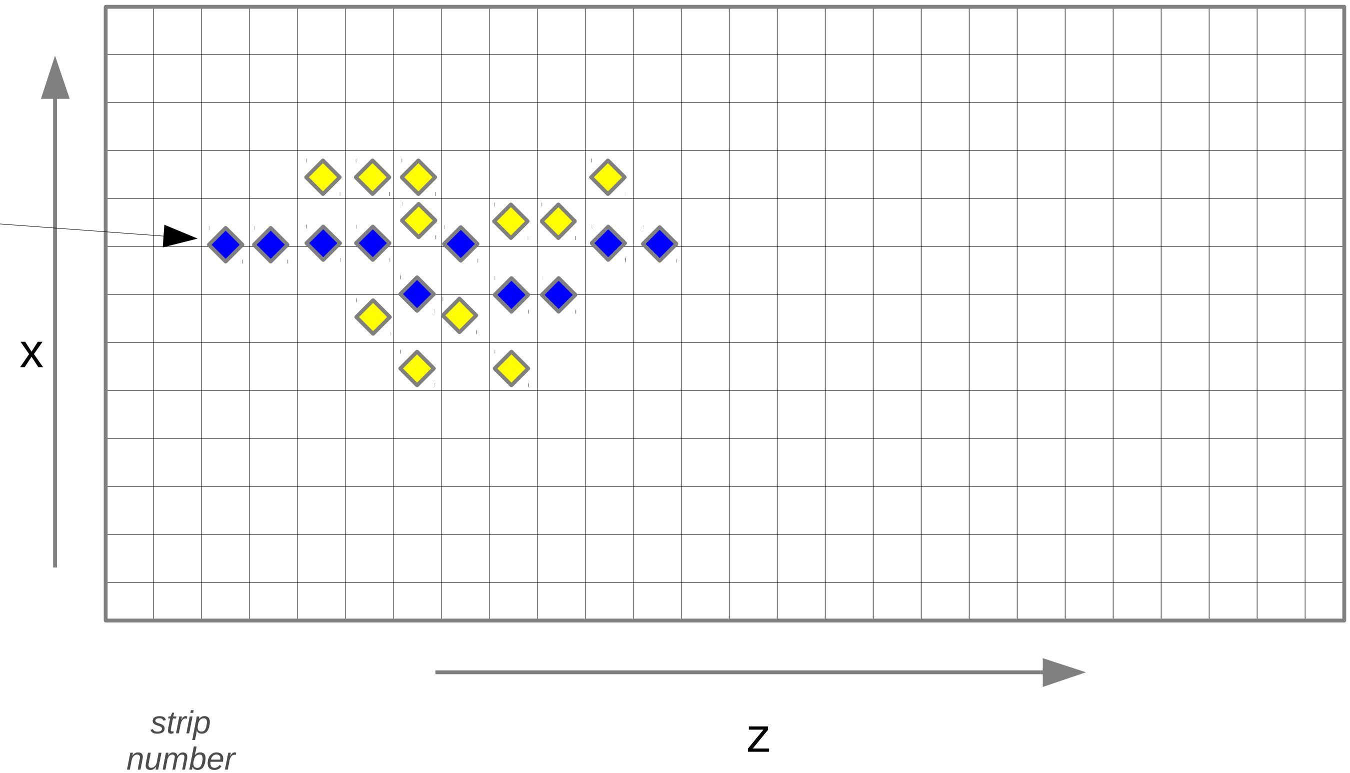
PID variable: shower “width”

Merge MIP-like pairs like this one (two brightest strips are neighbors) into one pseudo-strip with the sum of their charge

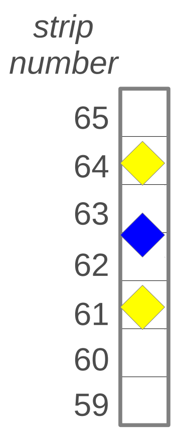


PID variable: shower "width"

(the blue ones were merged)



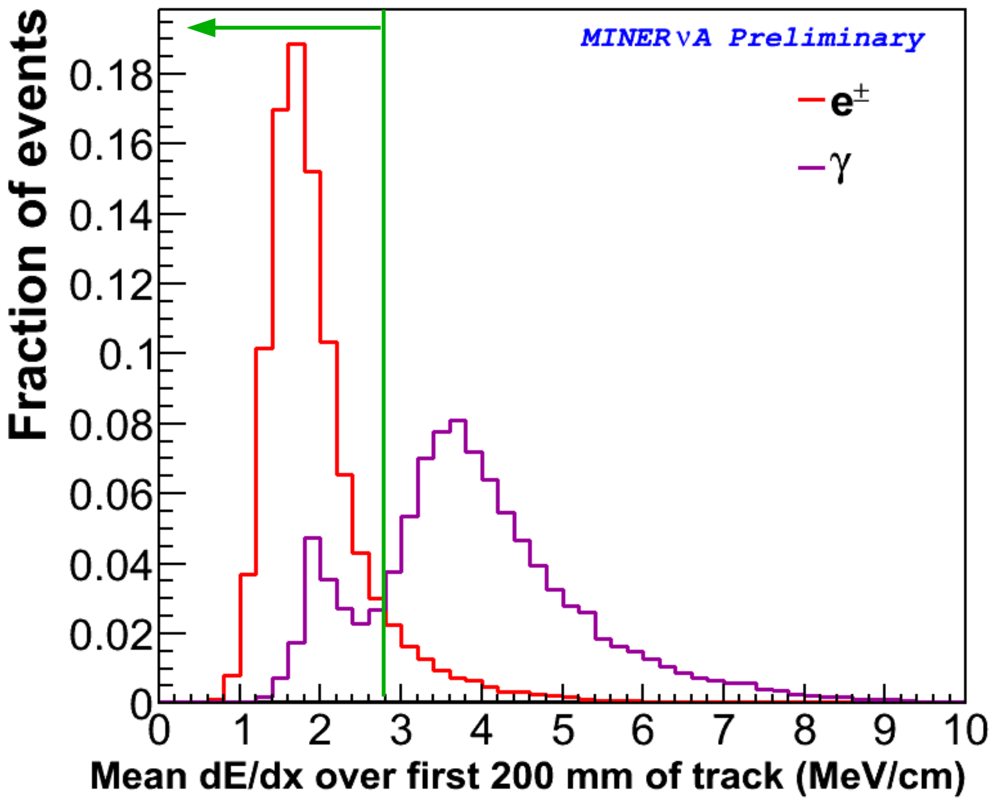
For each plane:

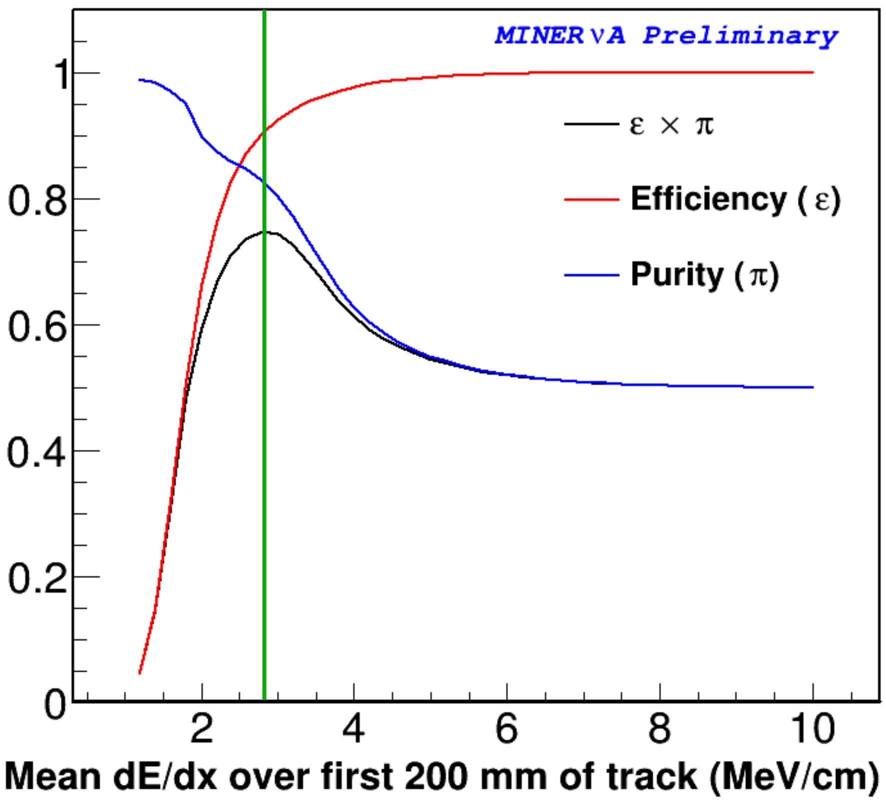


Take standard deviation of illuminated strip numbers (after merging), weighted by charge, in this plane

Then use the median of those standard deviations to characterize the event's "width"

Photon rejection cut

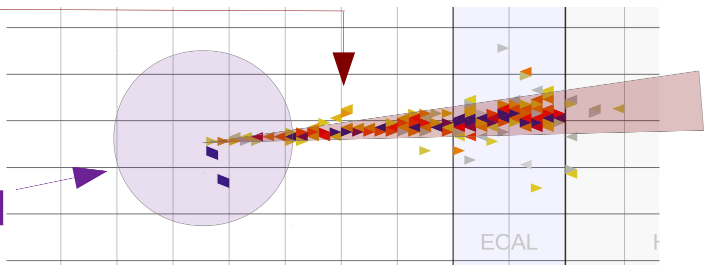




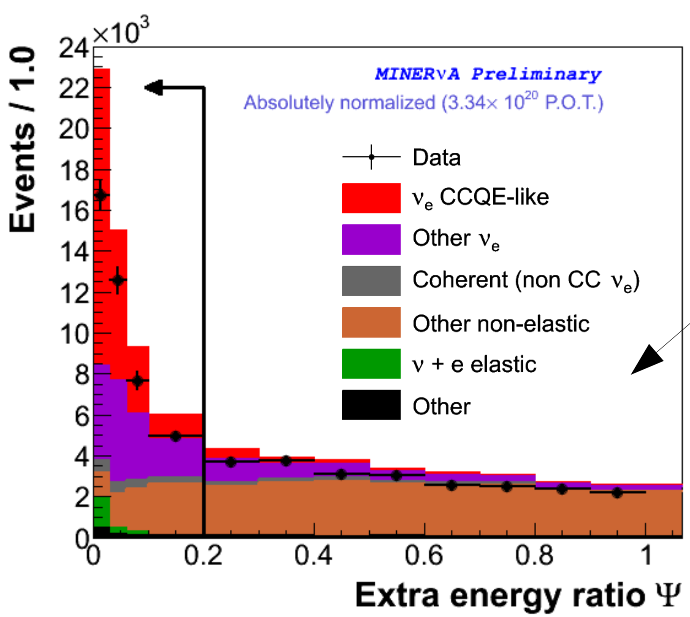
“Extra energy” cut

Anything not within a 7.5º electron cone or a vertex activity region of 30 cm radius or tracked as a proton is “extra energy.”

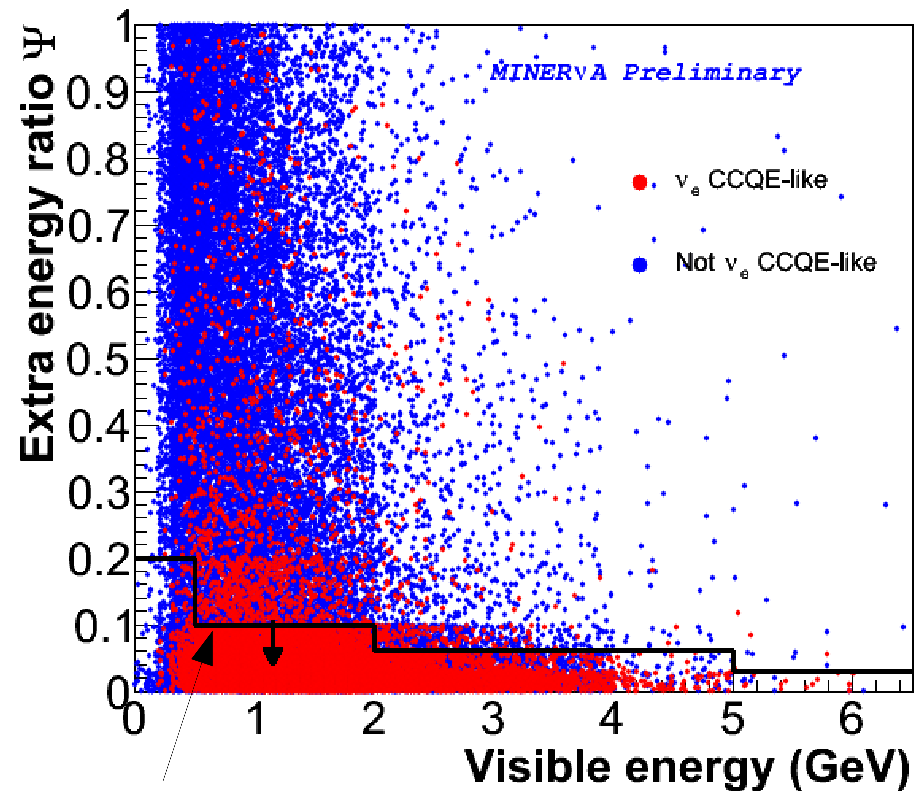
Cut on $\Psi = \frac{E_{extra}}{E_{cone}}$



Simulated ν_e CCQE

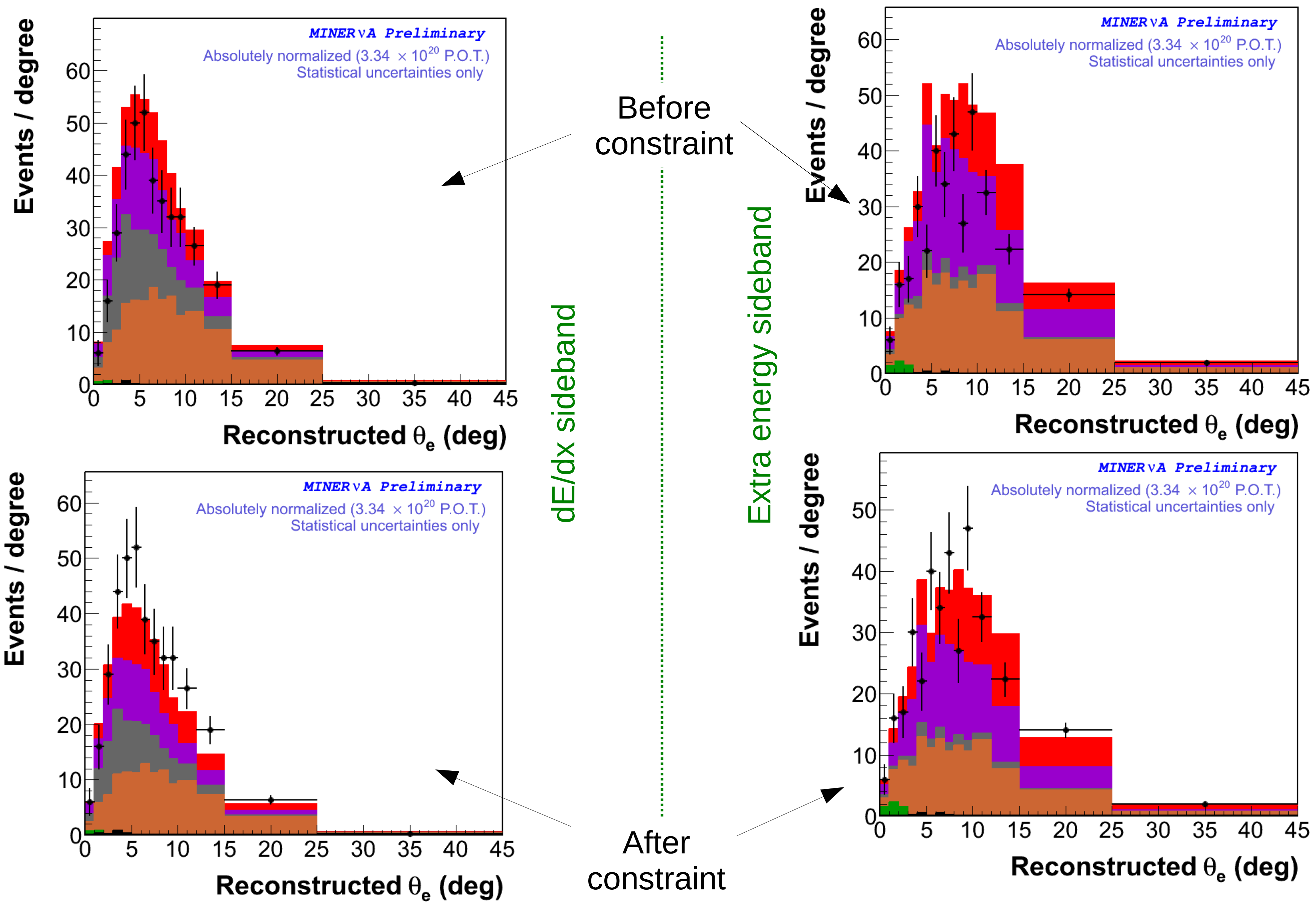


After marginalizing over all E_{vis}. Cut illustrated is at most probable value of E_{vis}= 0.4 GeV.



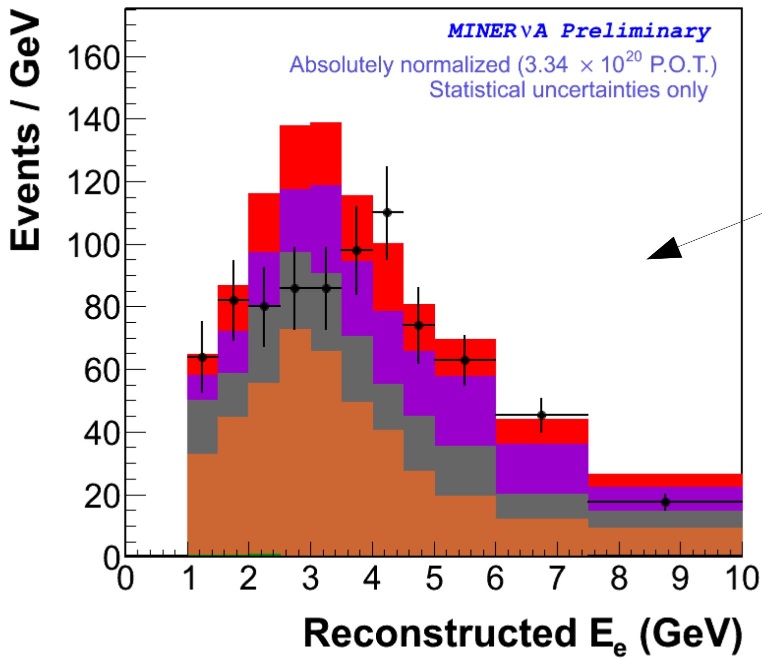
Actual cut

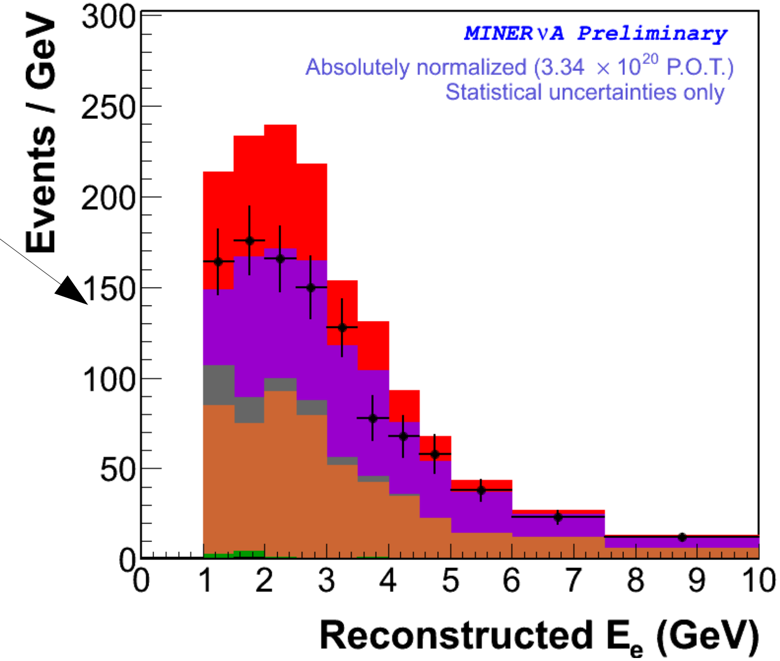
Background constraint: θ_e



Background constraint: E_e

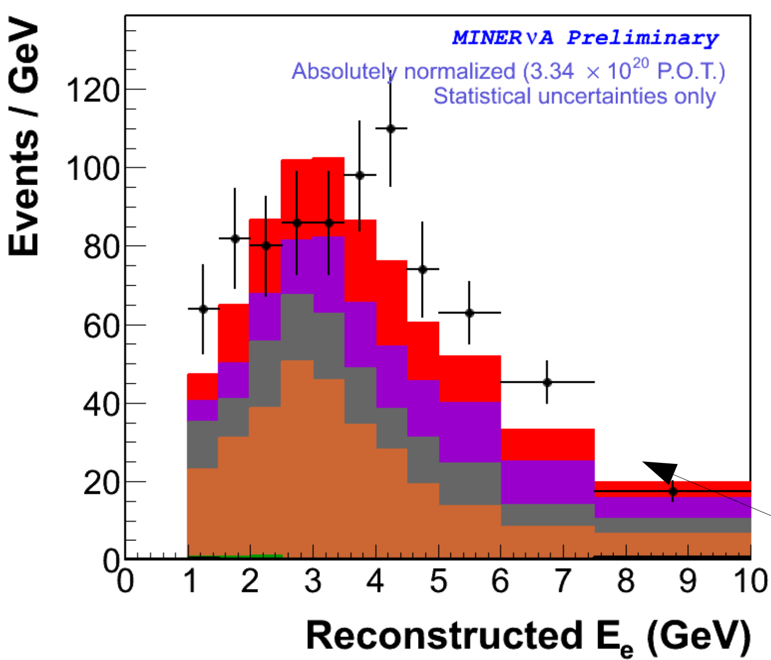
Before constraint

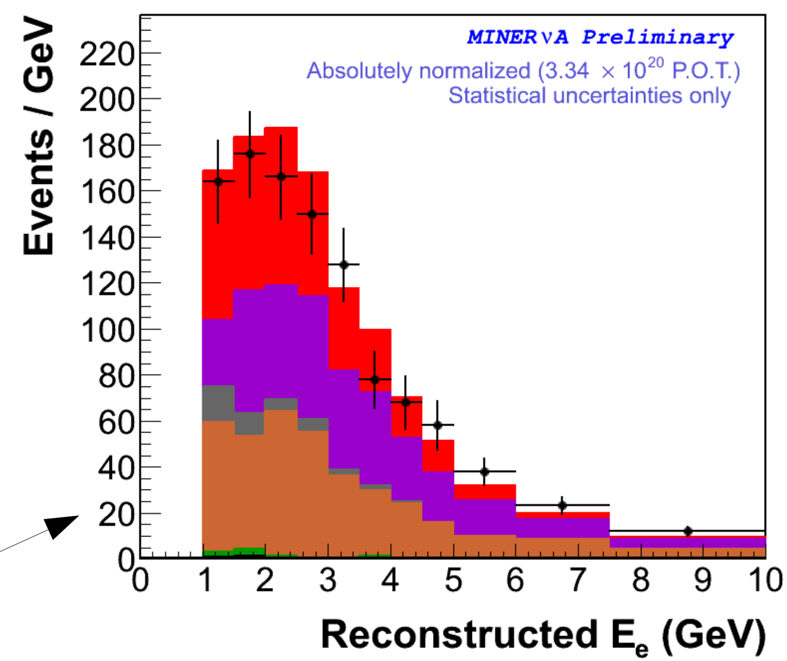




dE/dx sideband

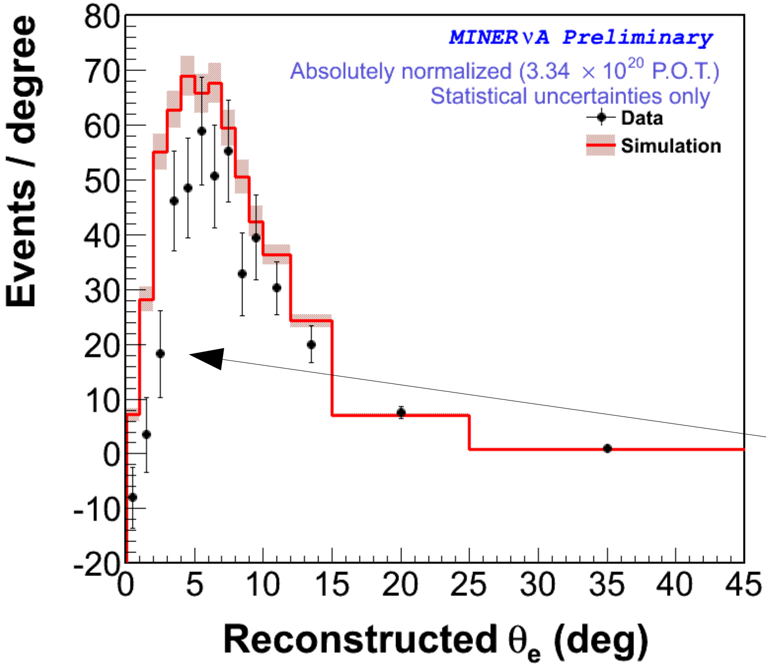
Extra energy sideband

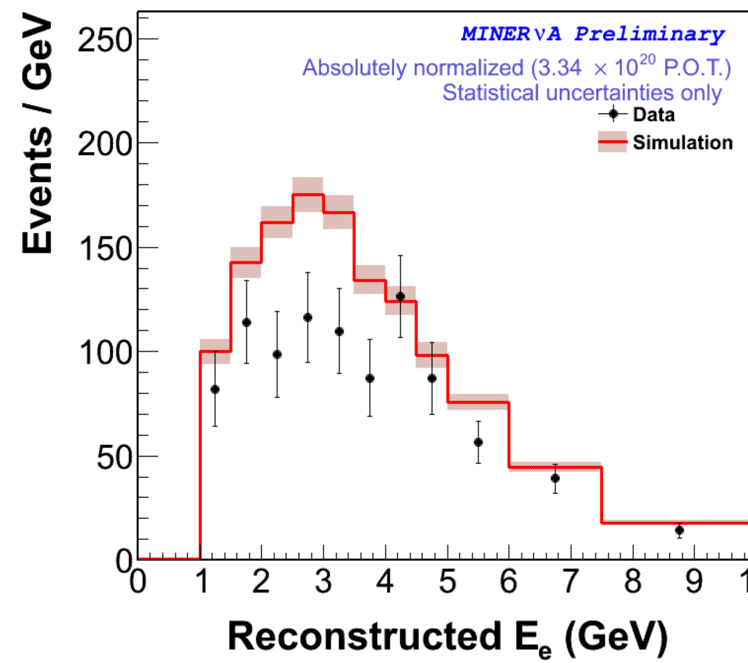




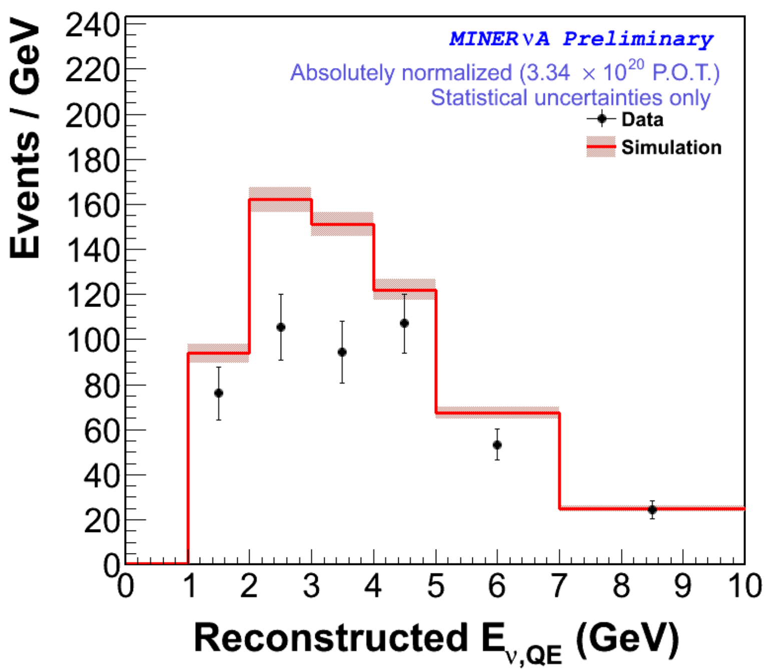
After constraint

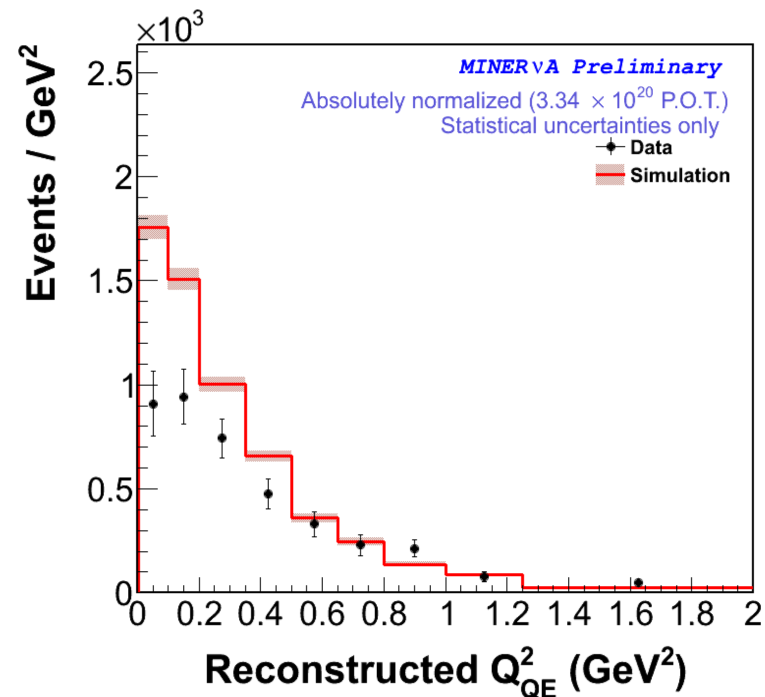
Background-subtracted distributions



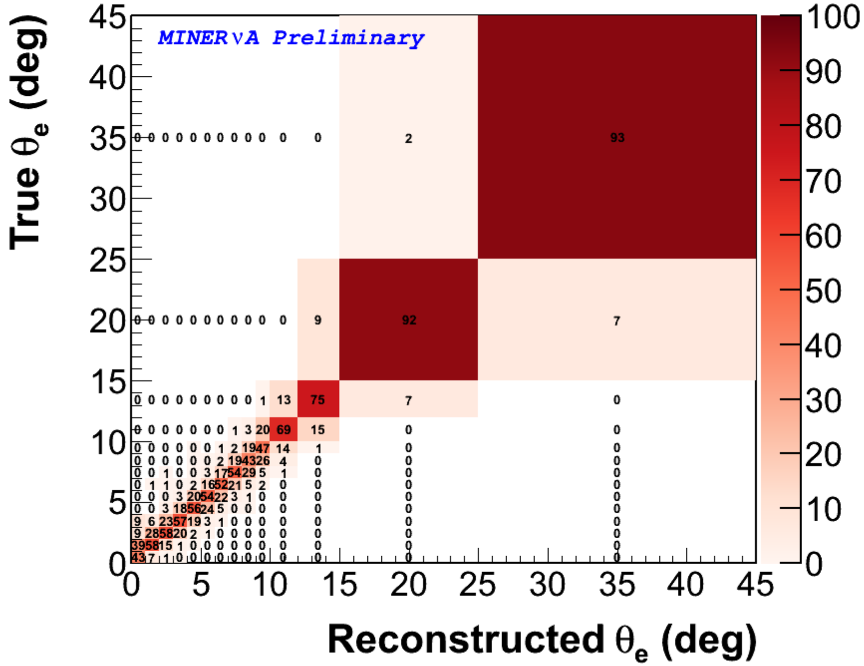


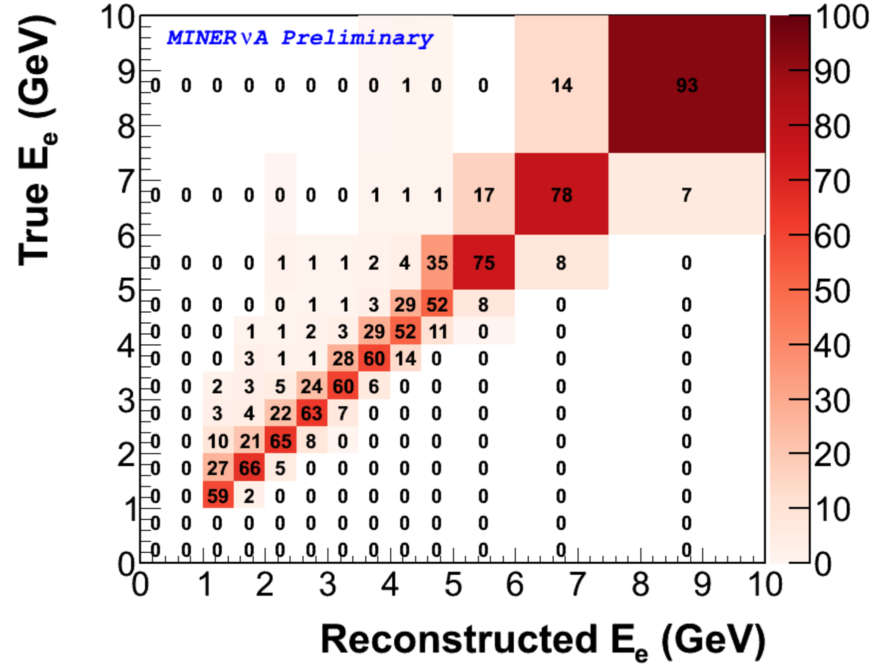
Notice the model's excess in the forward region...

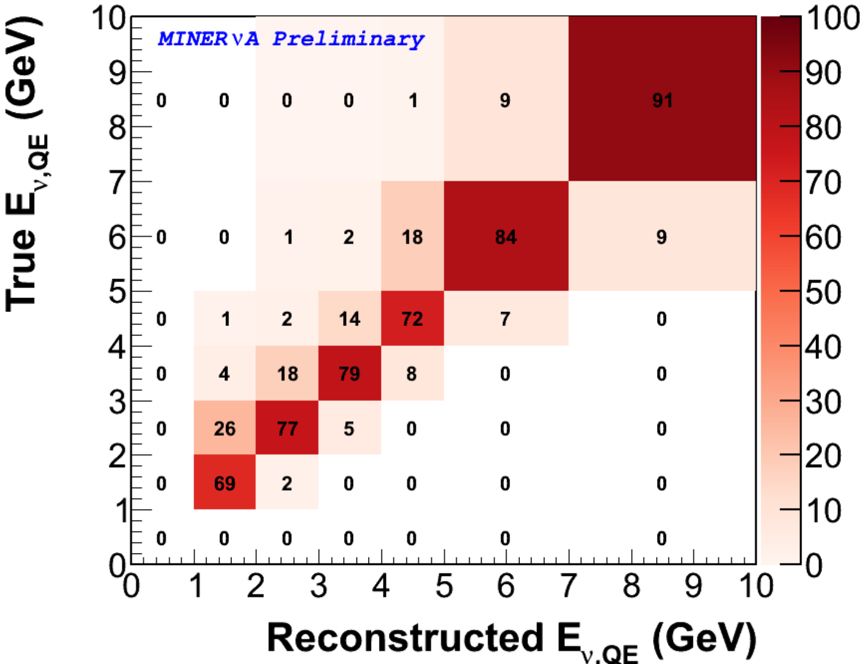


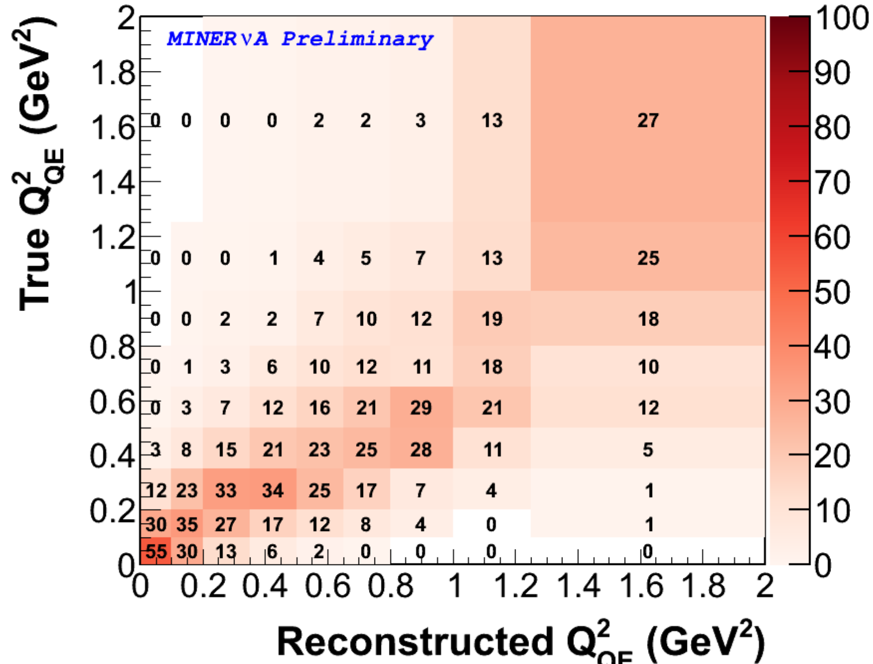


Migration matrices

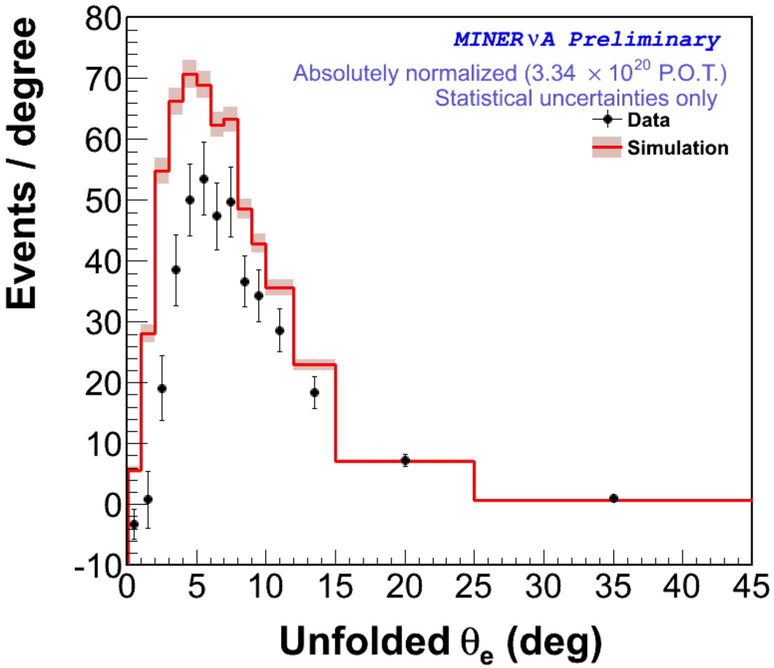


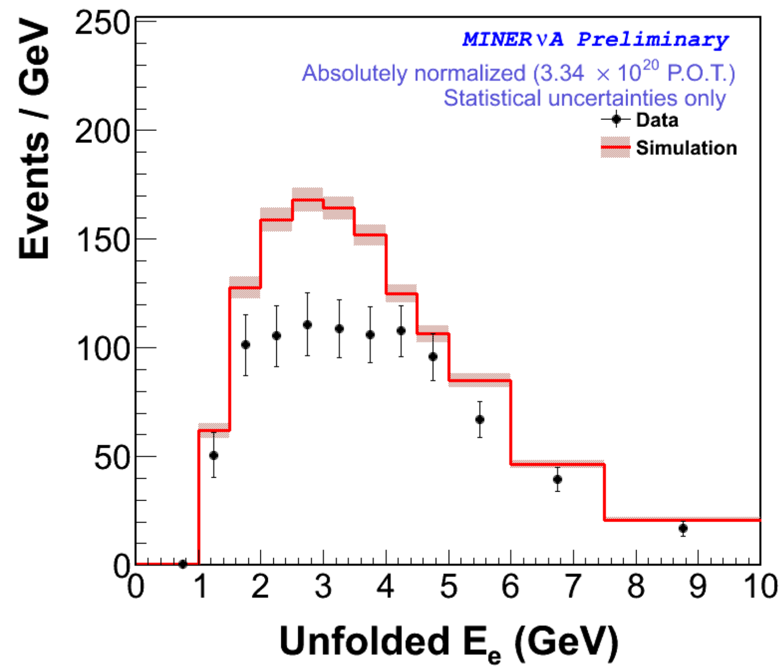




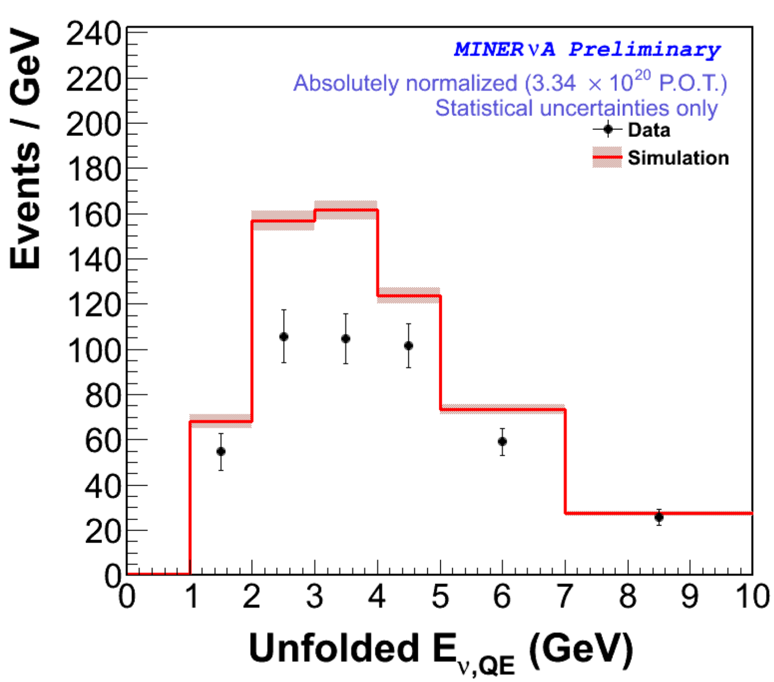


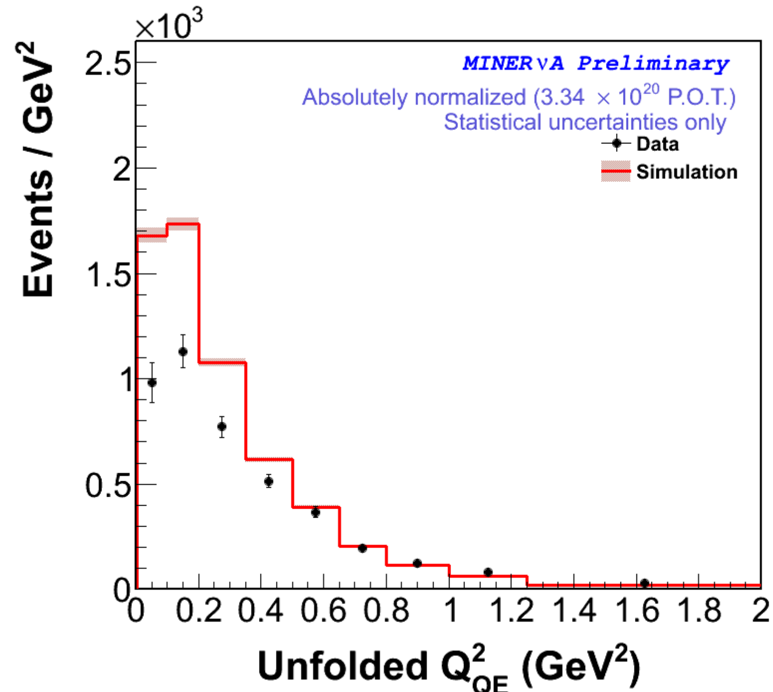
Unfolded distributions



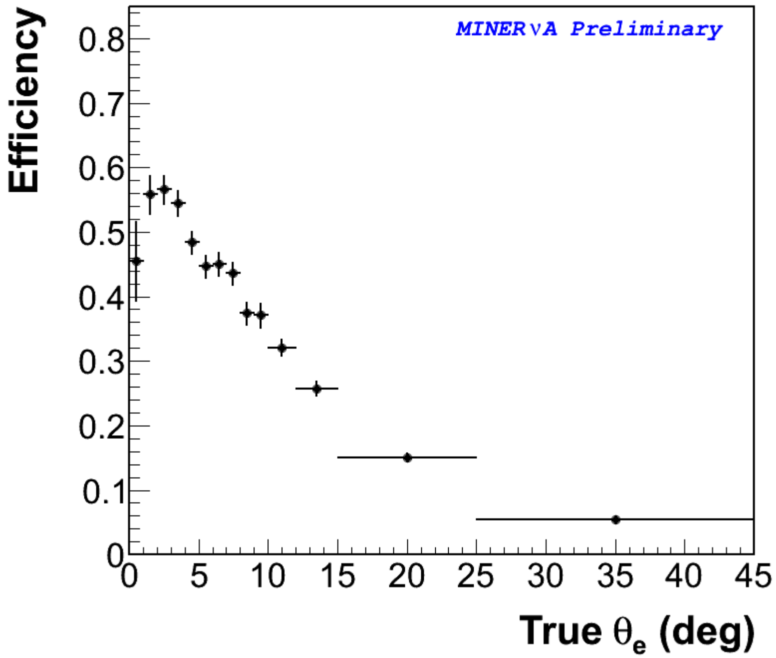


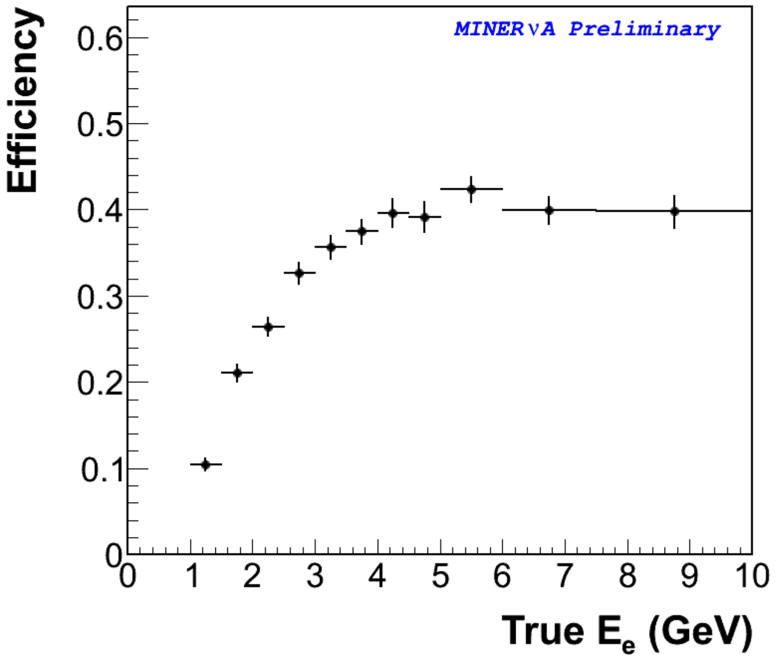
We use *one* iteration of a Bayesian unfolding technique.



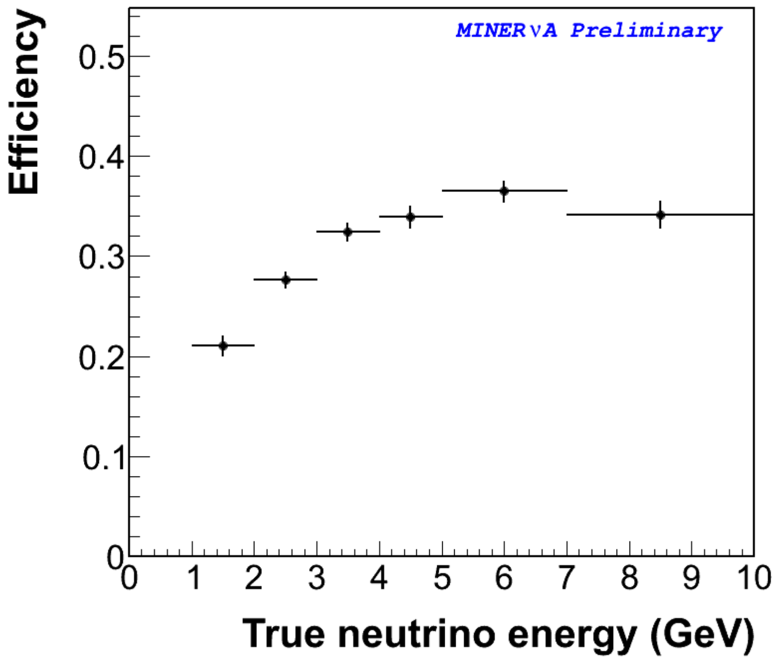


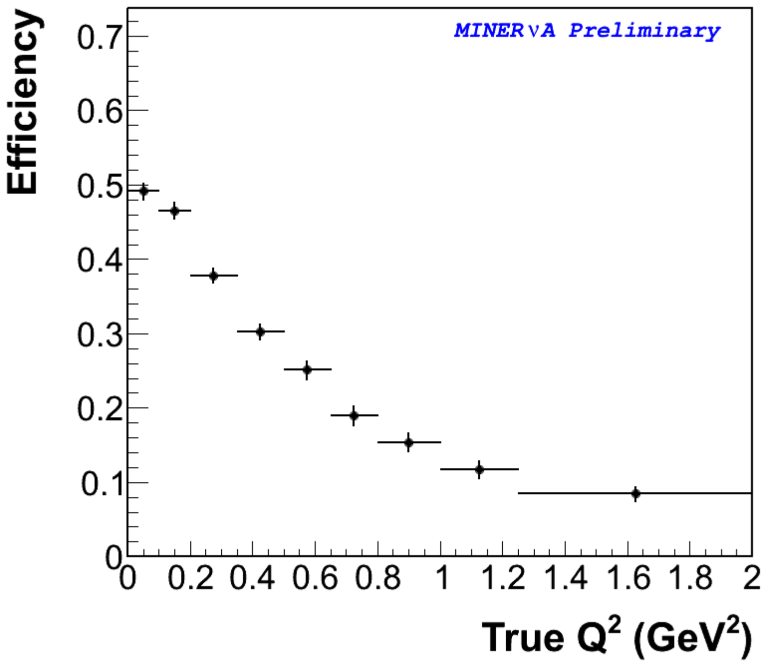
Efficiency



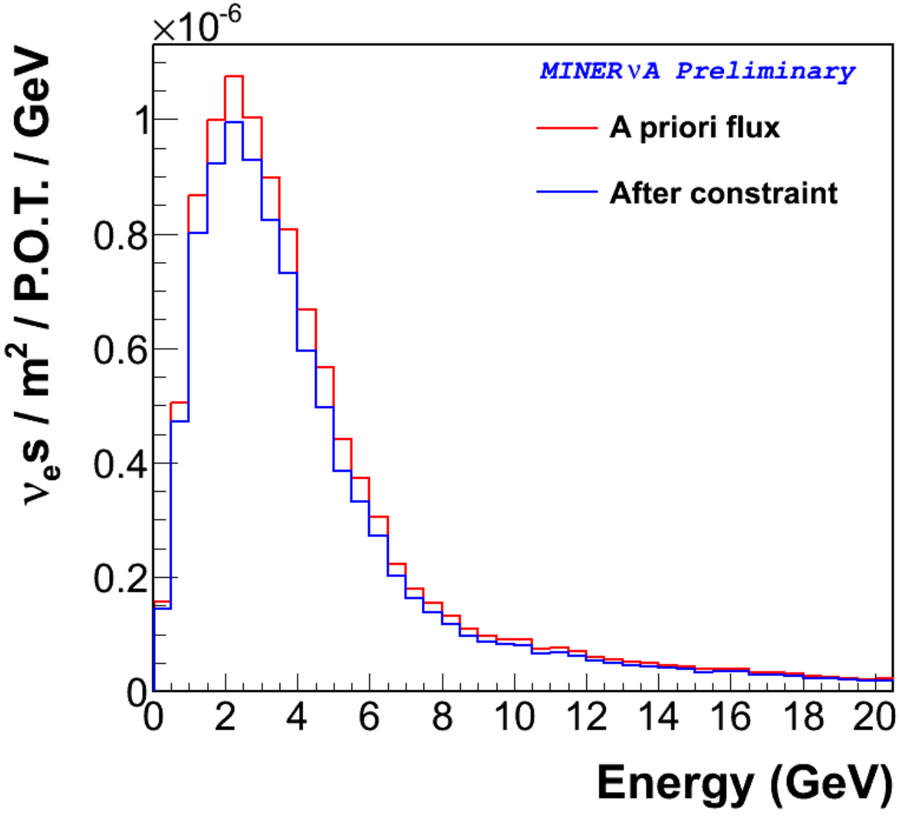


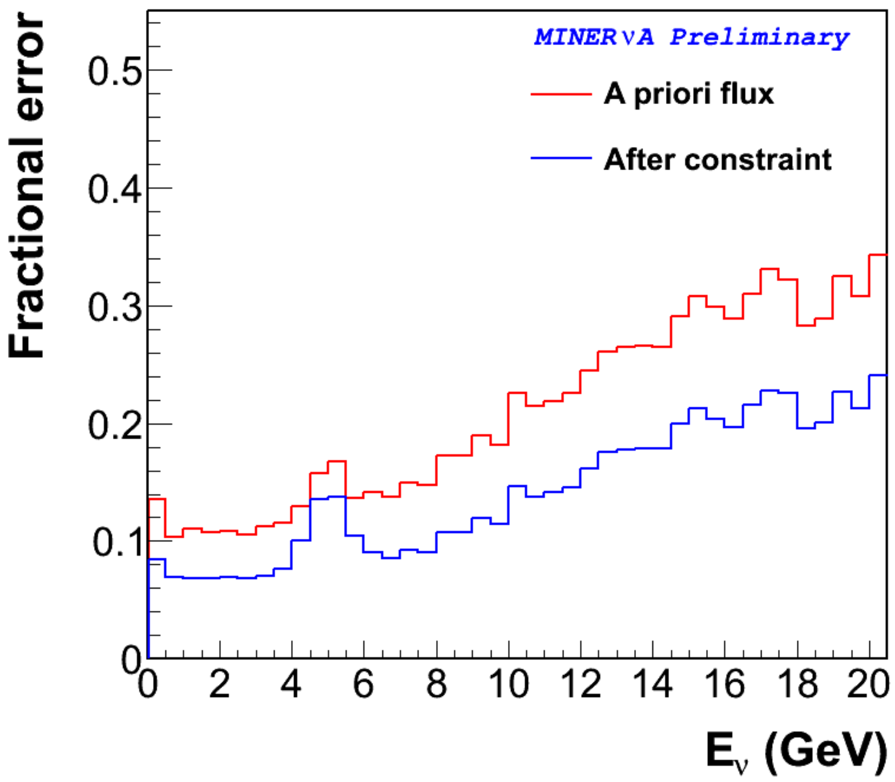
Mean selection efficiency is 30.9%.





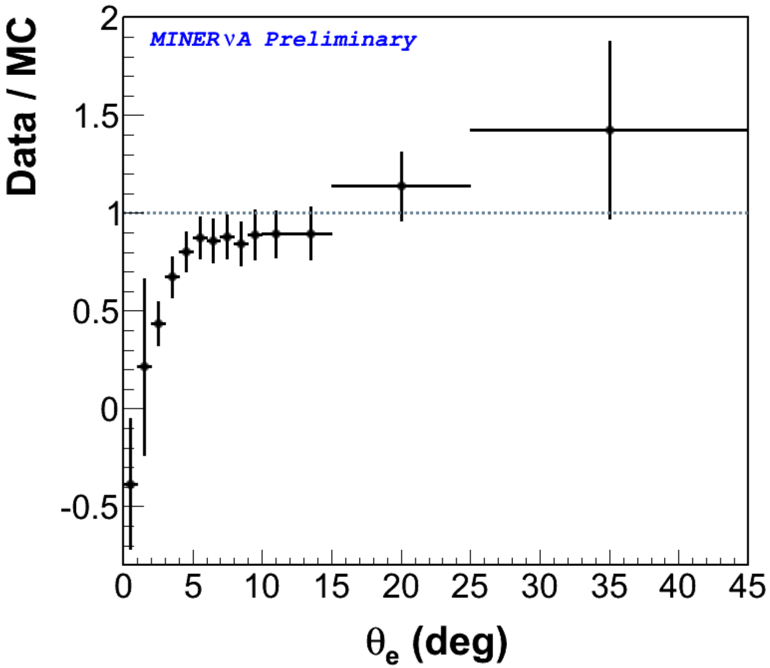
Constrained flux prediction

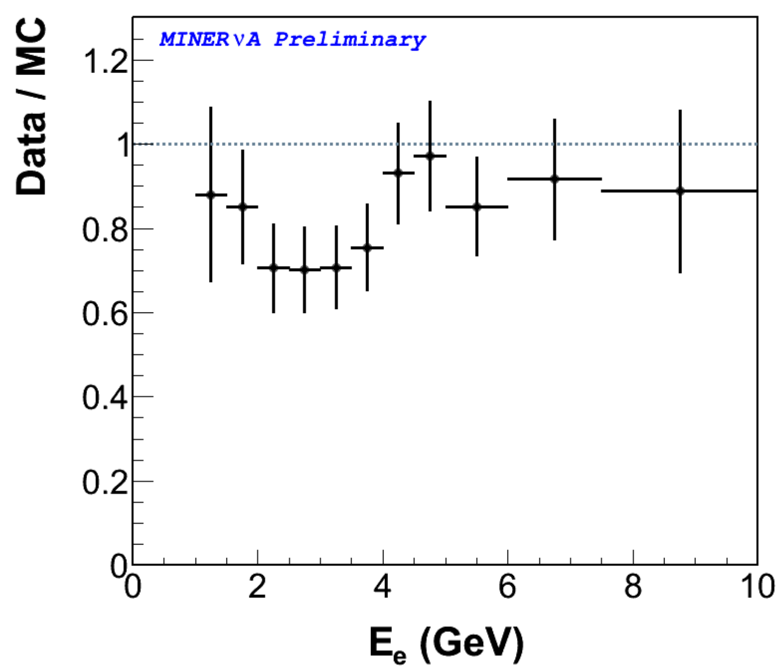


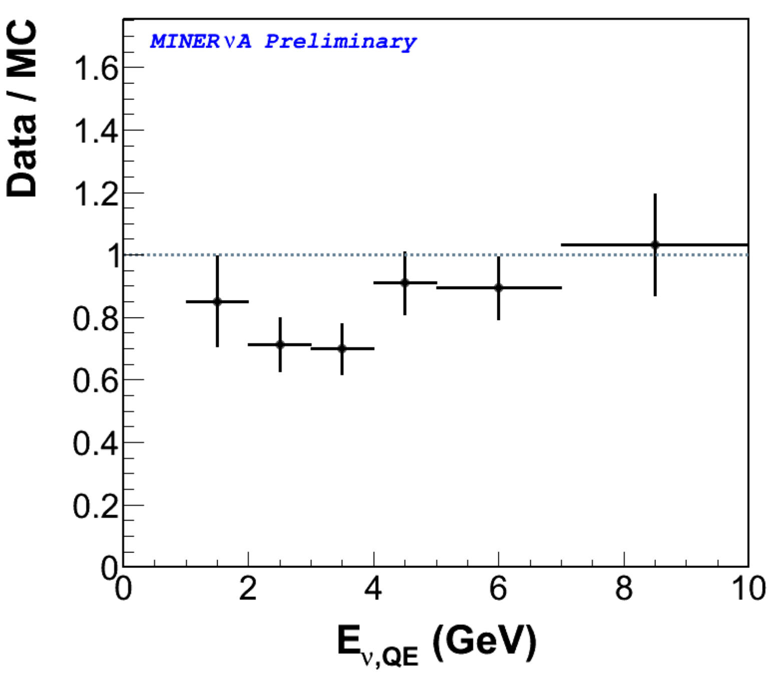


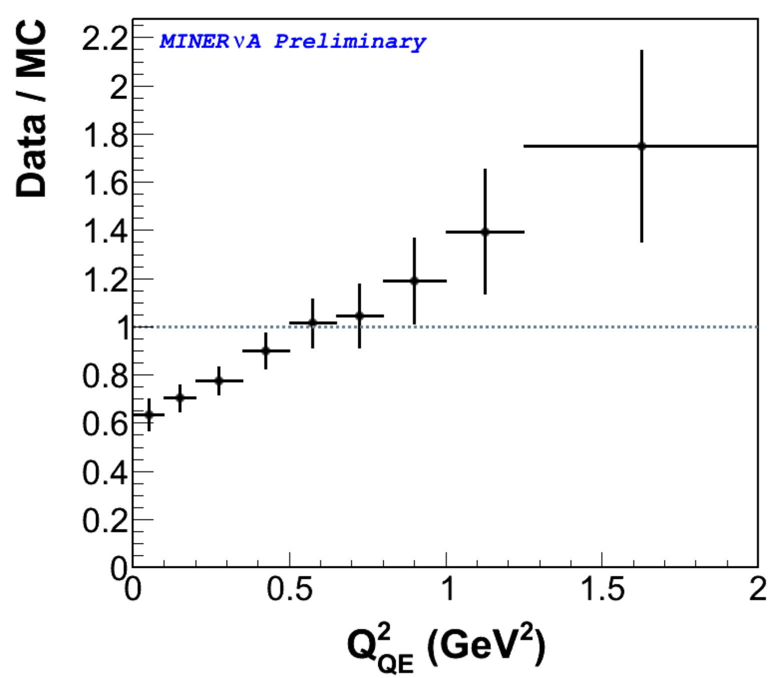
Reduction of 5-10% in prediction,
and 5-10 percentage points in predicted uncertainty as well

Data/MC ratios

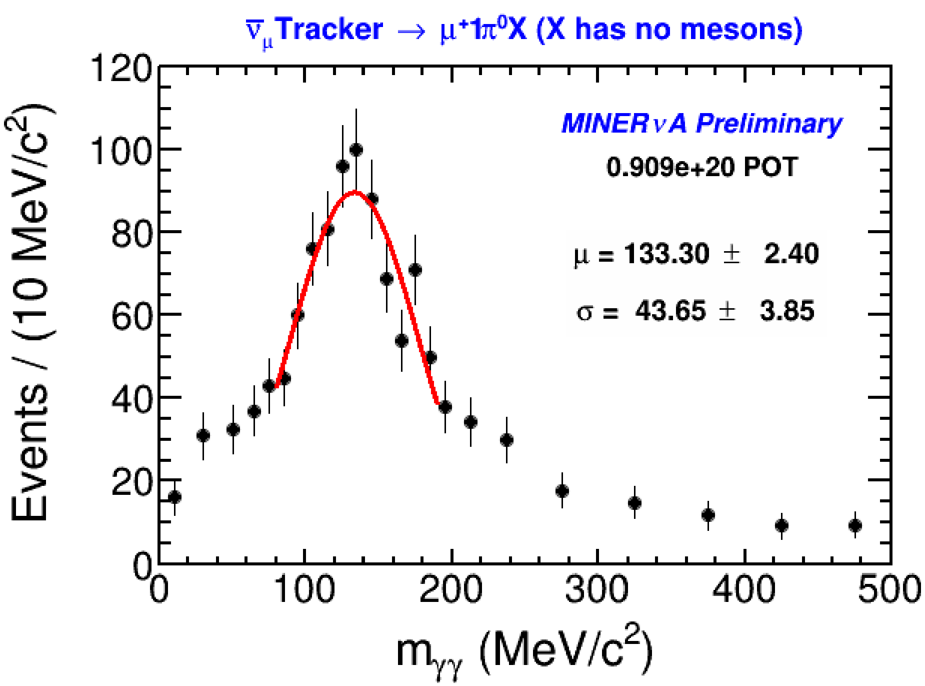






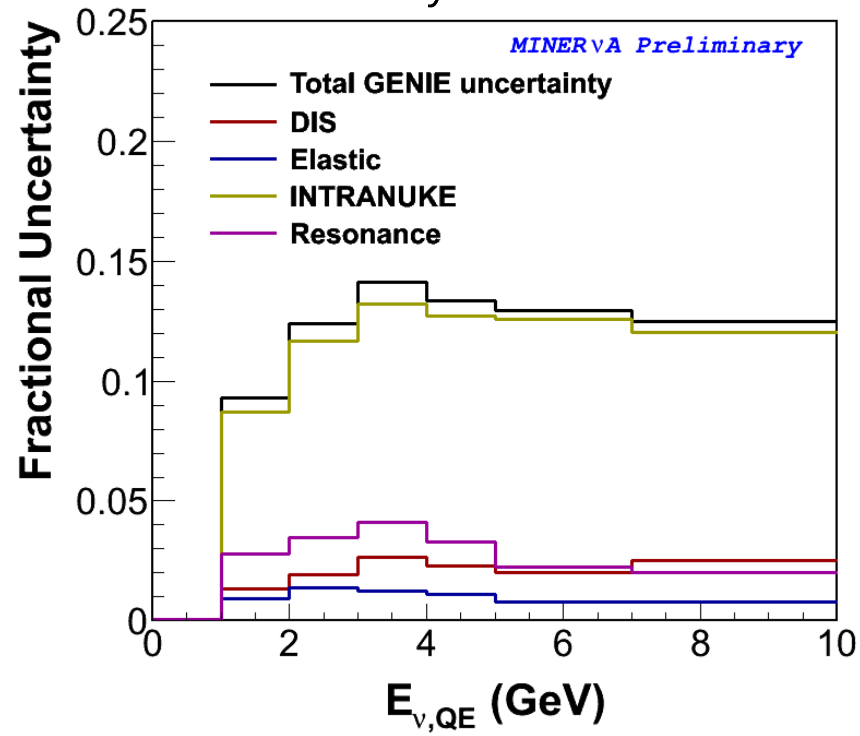


Non-flux uncertainties



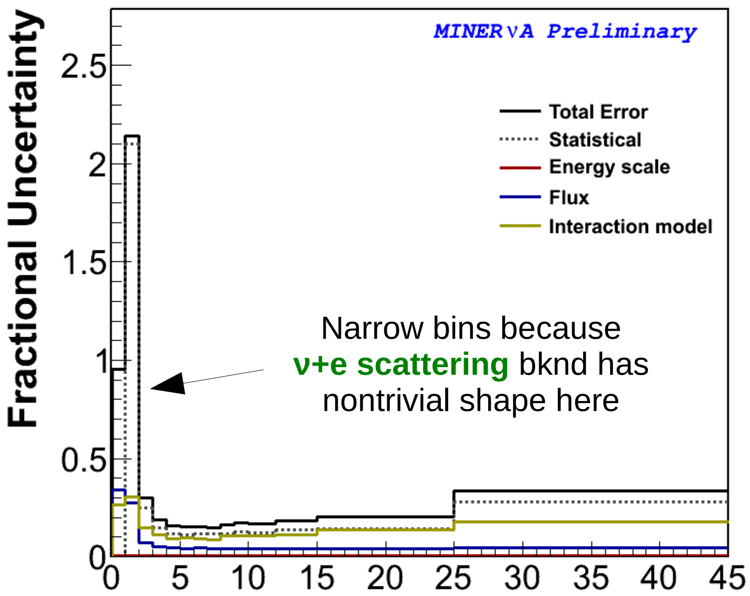
1.8% EM <u>energy scale uncertainty</u> from fitting π^0 mass peak

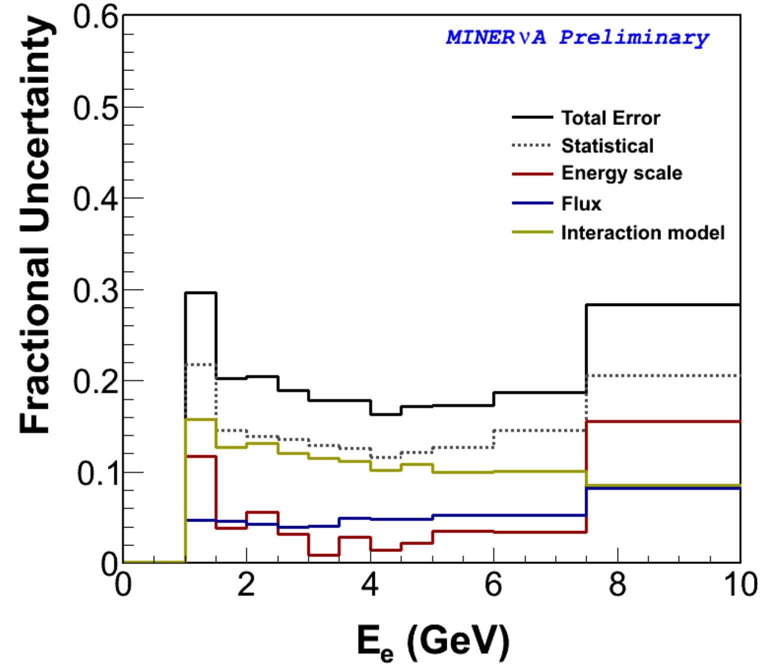
Uncertainty on measured σ^{CCQE}



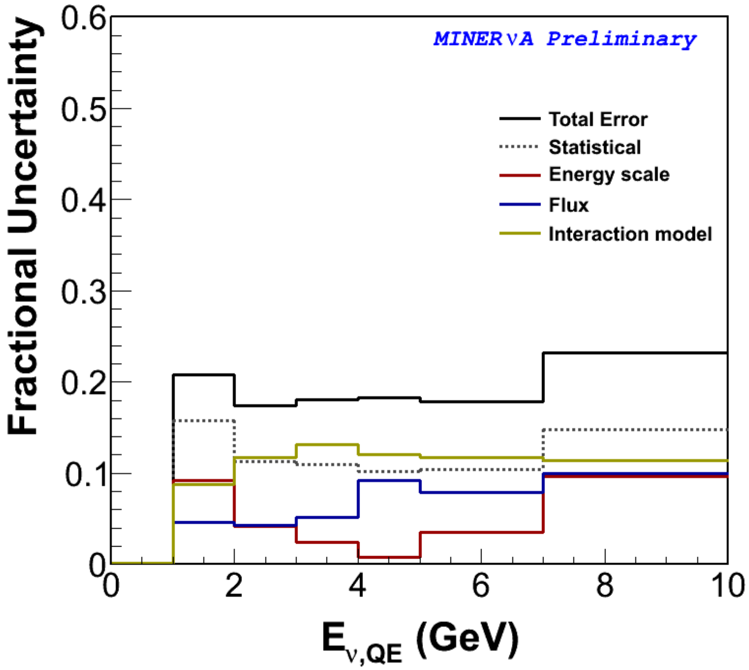
GENIE generator uncertainties are dominated by uncertainties on <u>inelastic pion interactions</u> and <u>pion absorption</u> in final-state interaction model (both of which affect the π^0 content of the background prediction and the prediction of the signal within the sidebands)

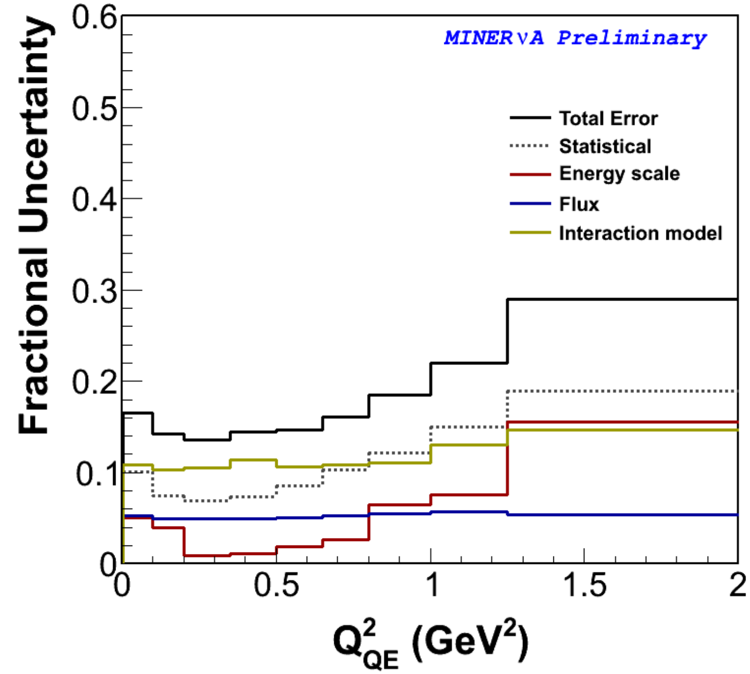
Cross-section uncertainties





The GENIE interaction model and statistics are comparable in most cases (depending on binning)





Cross-section uncertainties