ν_e CCQE scattering in the MINERvA experiment

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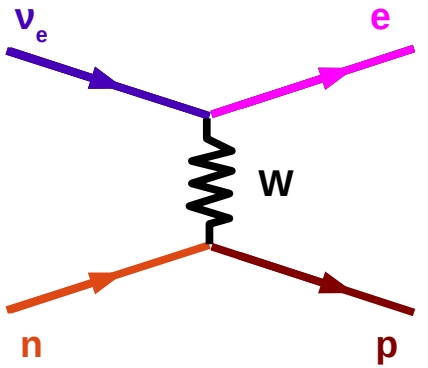
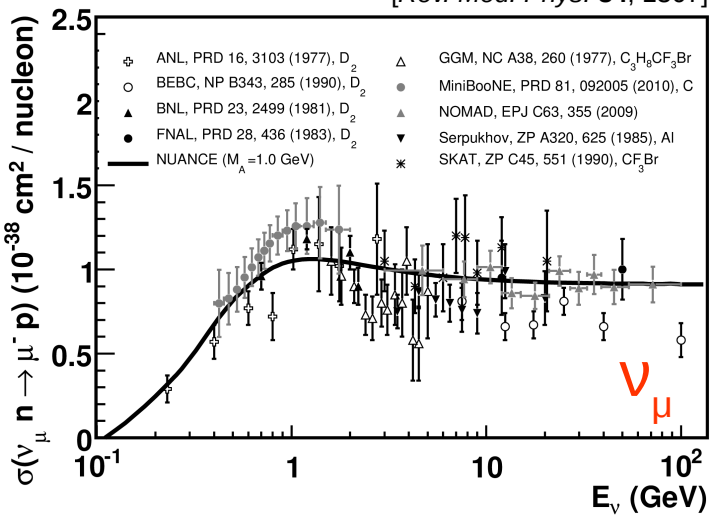
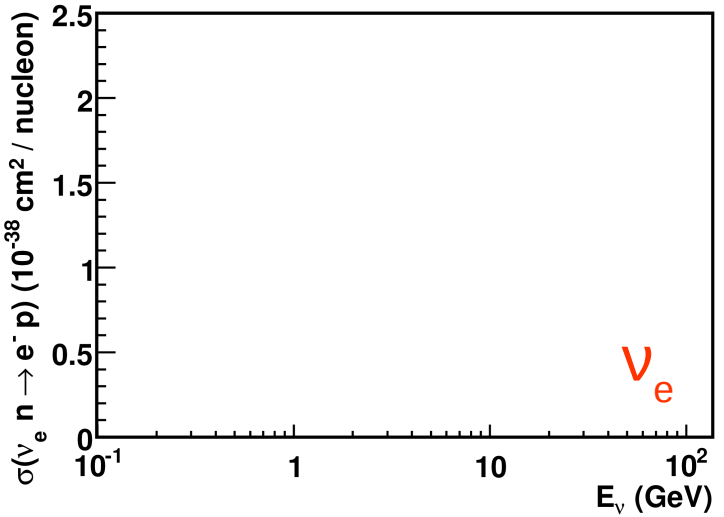
ν_e CCQE



- Signal reaction for ν_e appearance experiments, but no direct measurements
  - T2K: 80% of signal
  - NOvA: 50% of signal
- Comparison to ν_μ CCQE scattering probes nuclear physics
  - Different thresholds in Q^2 ($m_\mu/m_e \sim 200$) expose different kinematic regimes

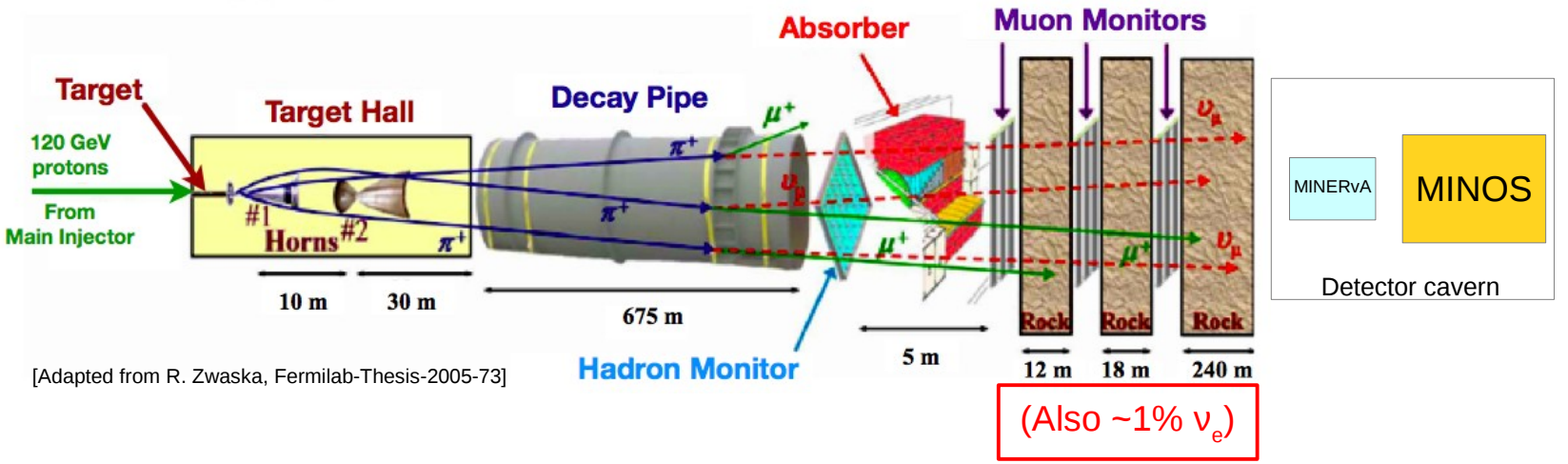
[*Rev. Mod. Phys.* **84**, 1307]



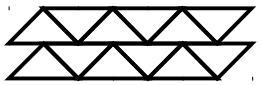


The MINERvA experiment

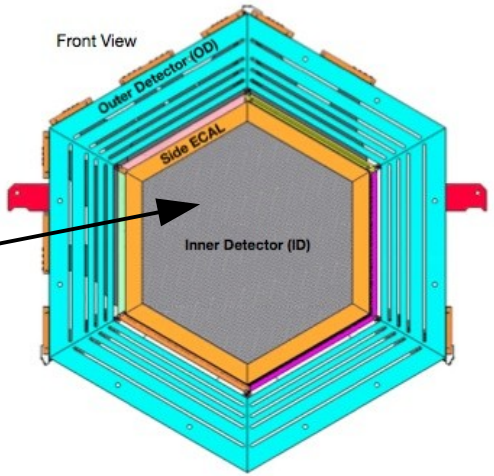
Neutrinos from NuMI neutrino beam at Fermilab

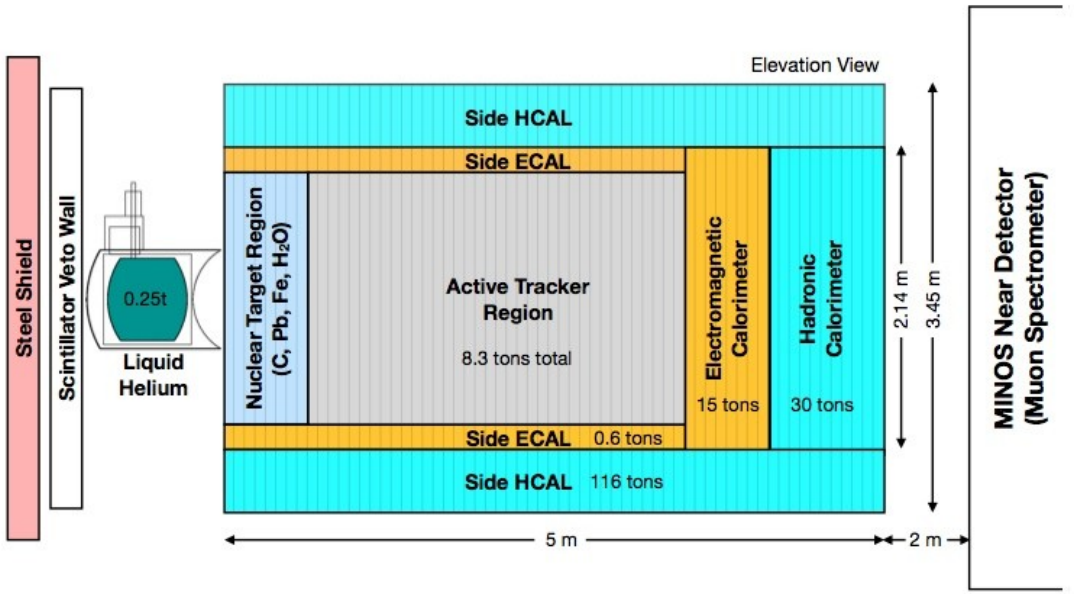


[Adapted from R. Zwaska, Fermilab-Thesis-2005-73]



Triangular inner detector scintillator strips



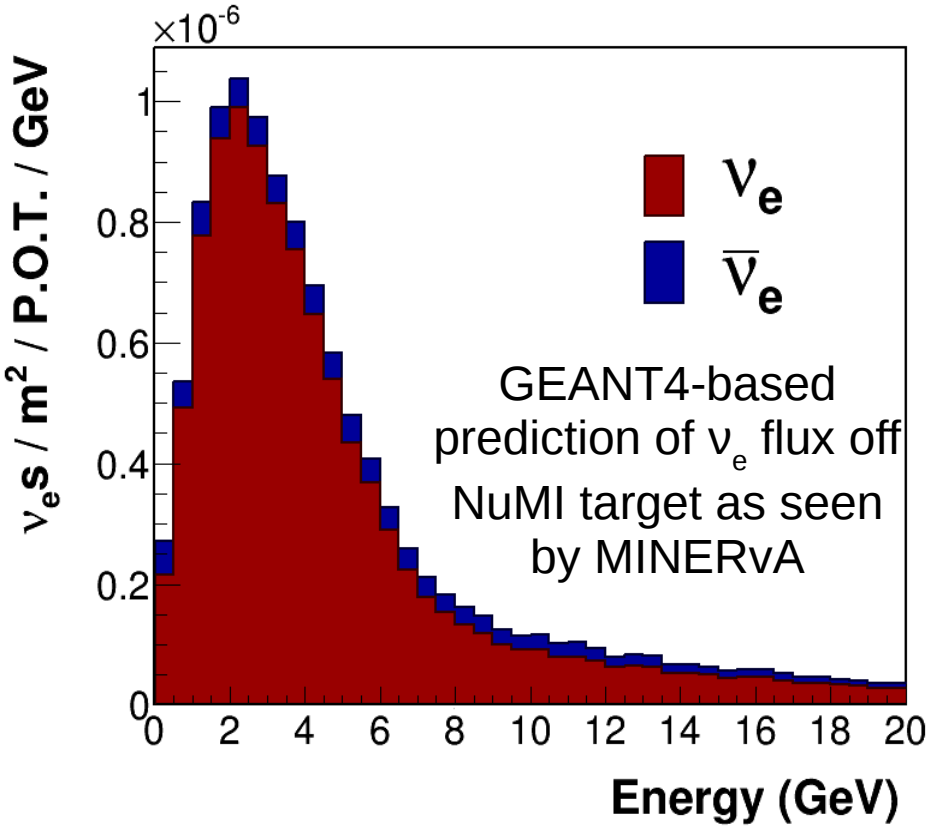


Signal definition

$$\pi^+ \rightarrow \nu_\mu \mu^+$$
$$\hookrightarrow e^+ \nu_e \overline{\nu_\mu}$$

Electron neutrinos from beam muon decay. About 10% $\bar{\nu}_e$. 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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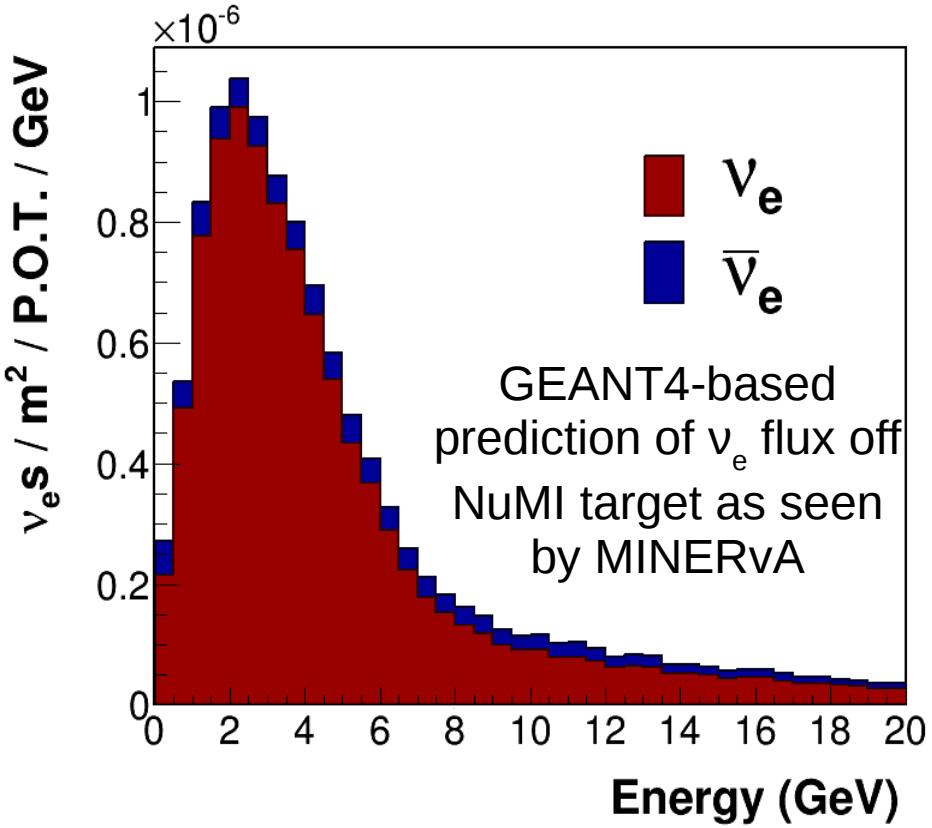
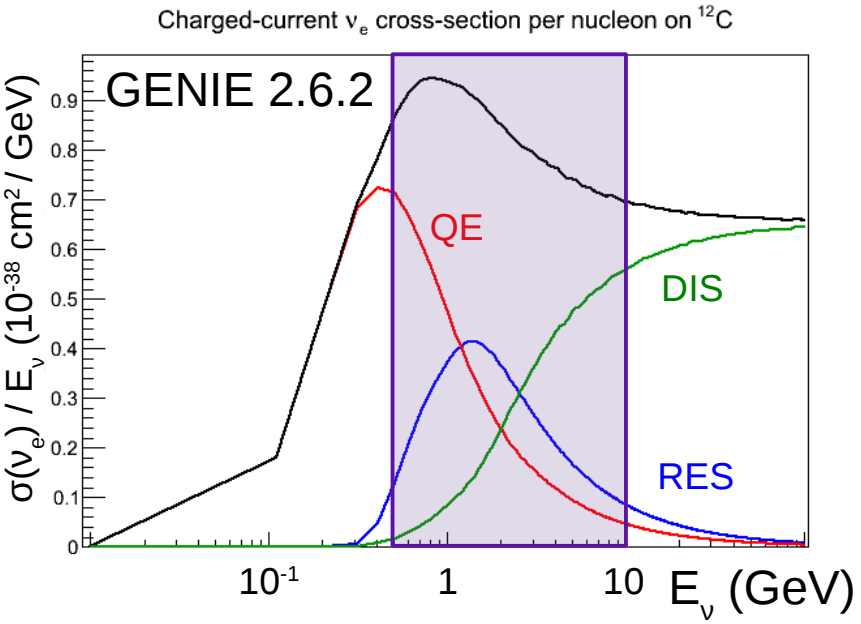




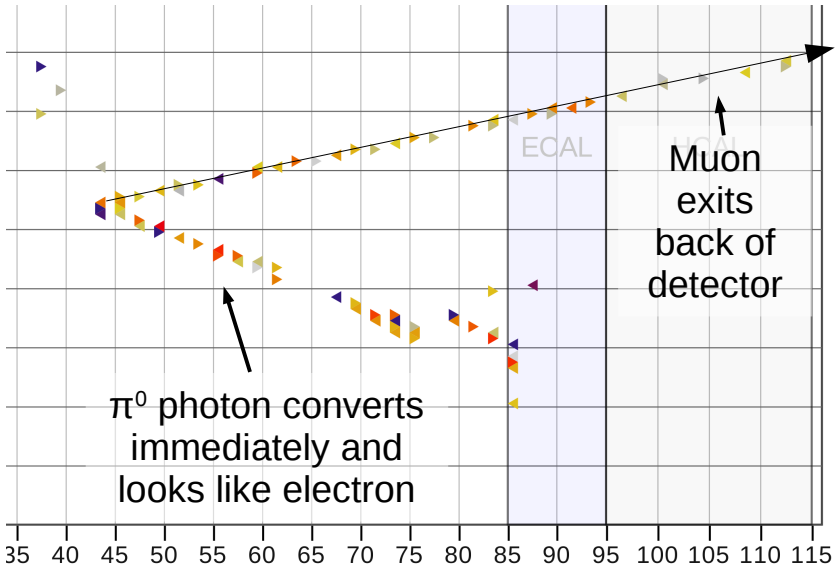
Choose exclusive-channel signal: CCQE
But initial- and final-state effects can cause absorption or creation of hadrons.

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

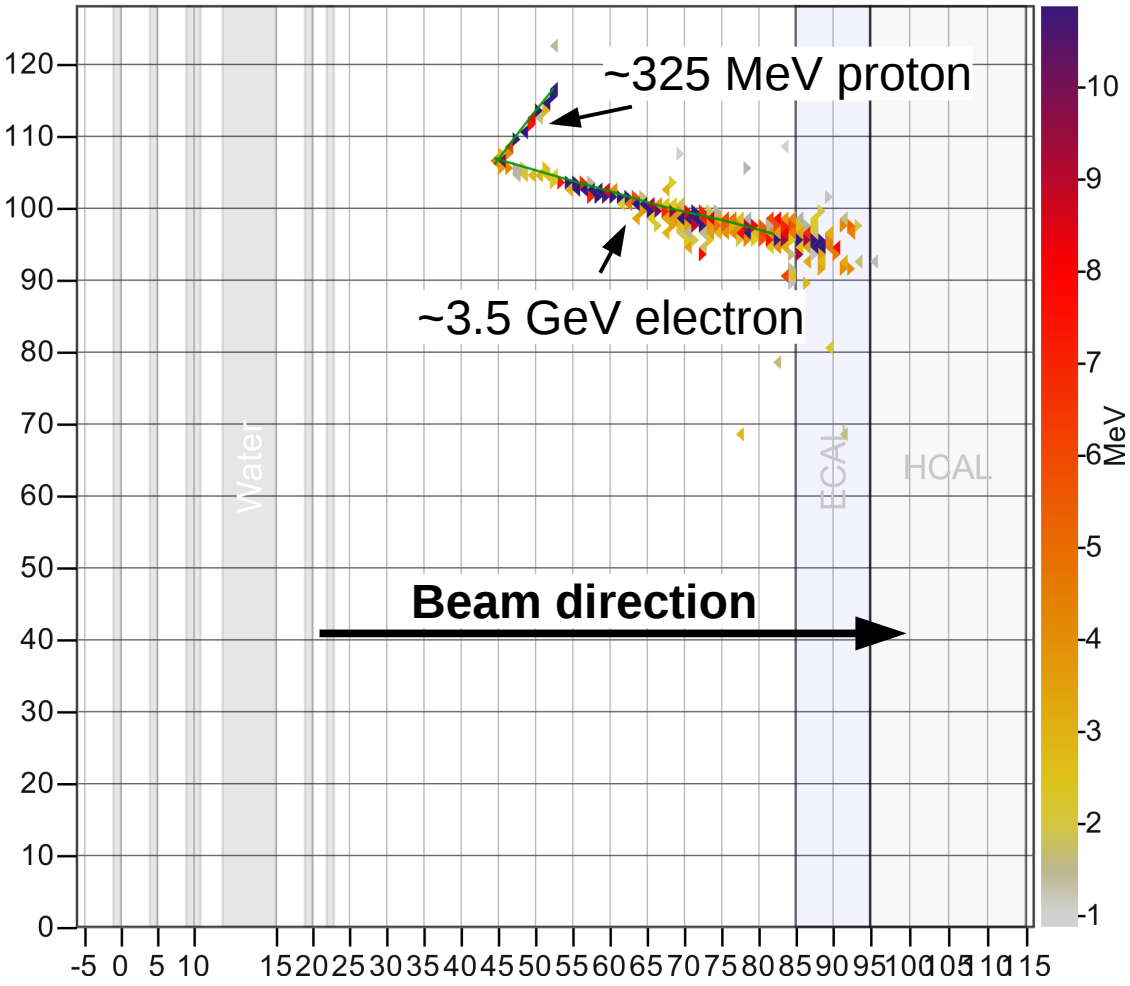
Isolating ν_e-like events

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 $\mu \rightarrow e$ decay candidates ("Michel electrons")
- Cut on multivariate PID classifier combining details of energy profile



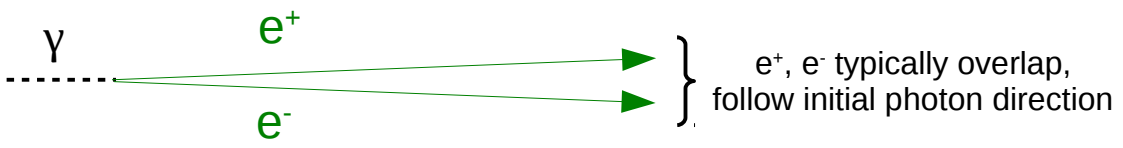
Simulated background rejected by muon cuts



Event display of simulated ~4 GeV ν_e interaction in MINERvA

Isolating ν_e events:

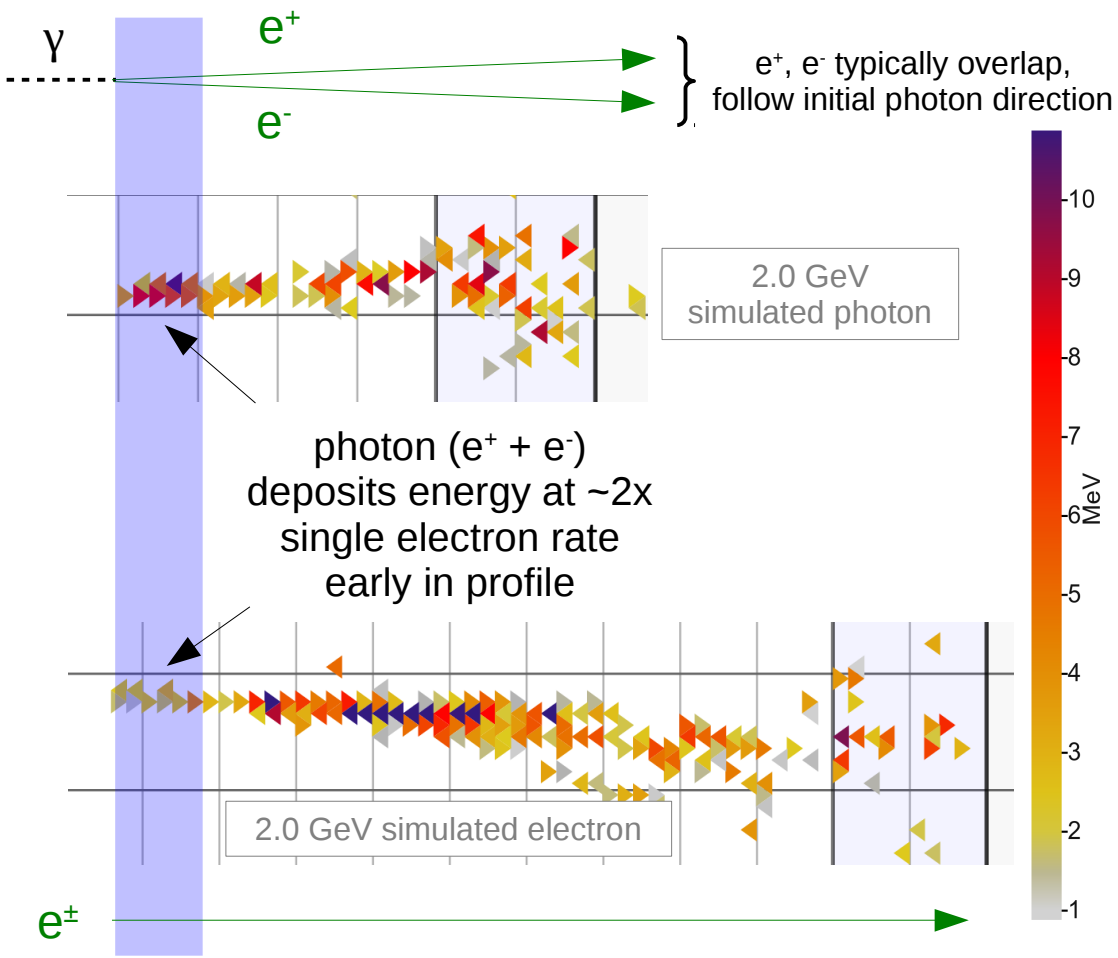
Photon rejection



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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Isolating ν_e-like events:

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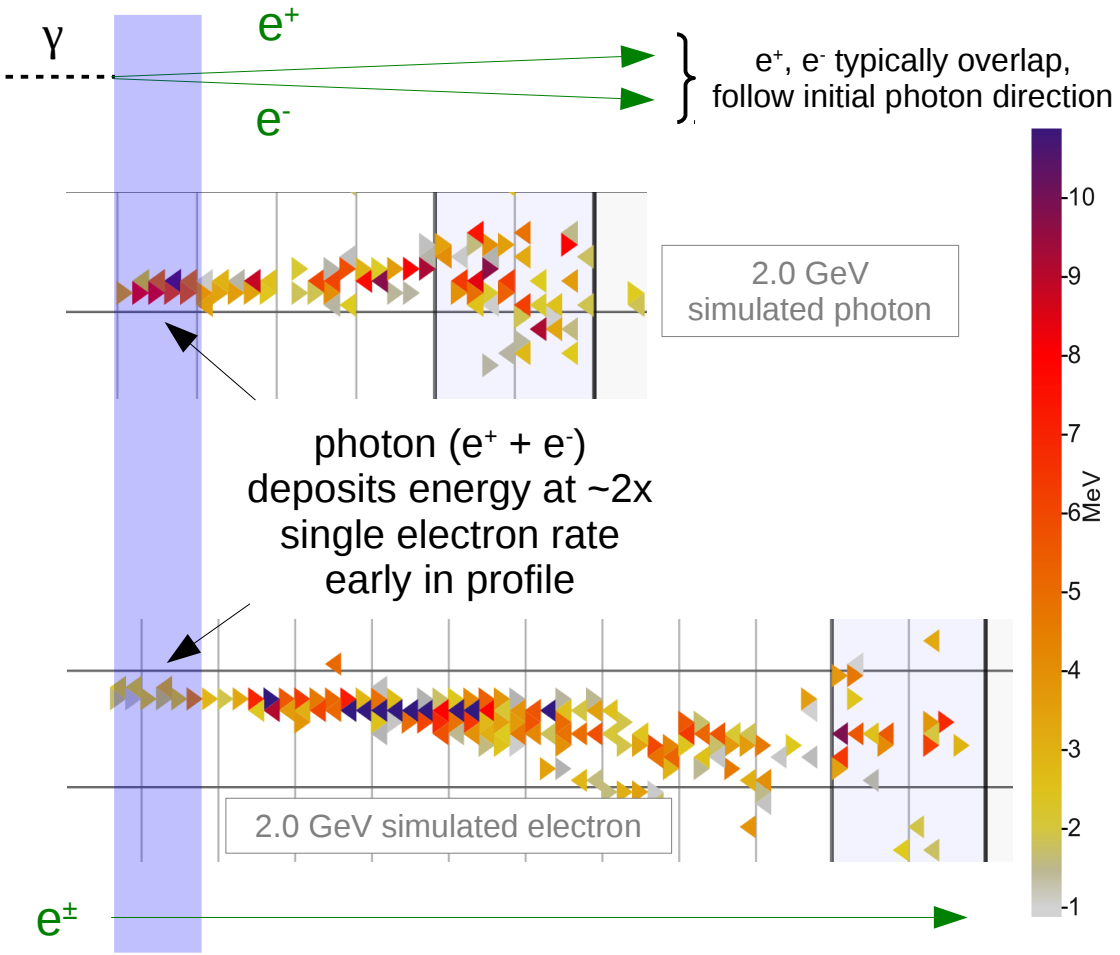
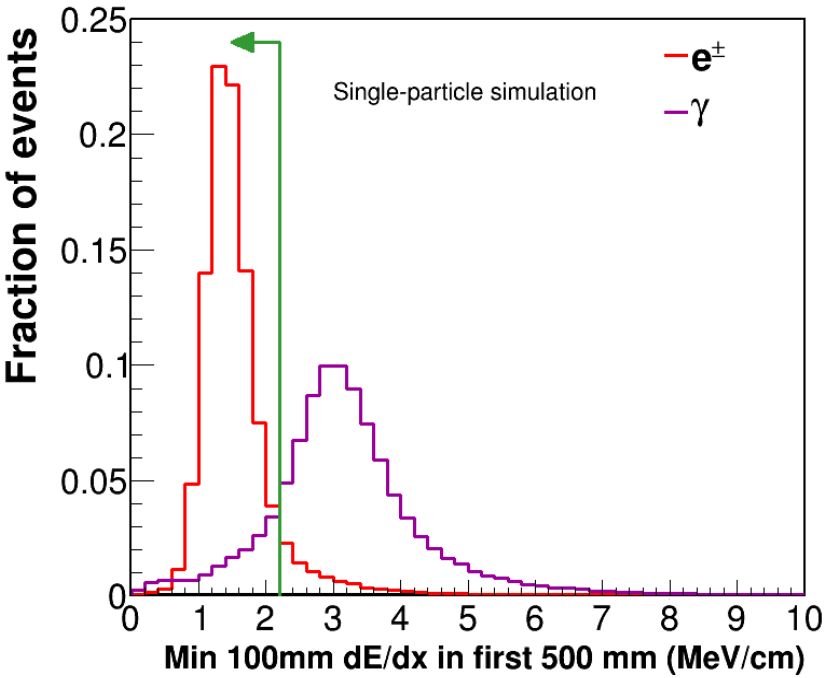




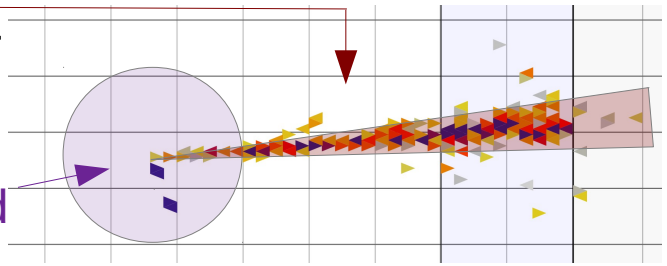
The energy deposition pattern early in the track helps discriminate between photons (background) and electrons

Isolating ν_e-like events:

Quasi-elastic-like topology selection

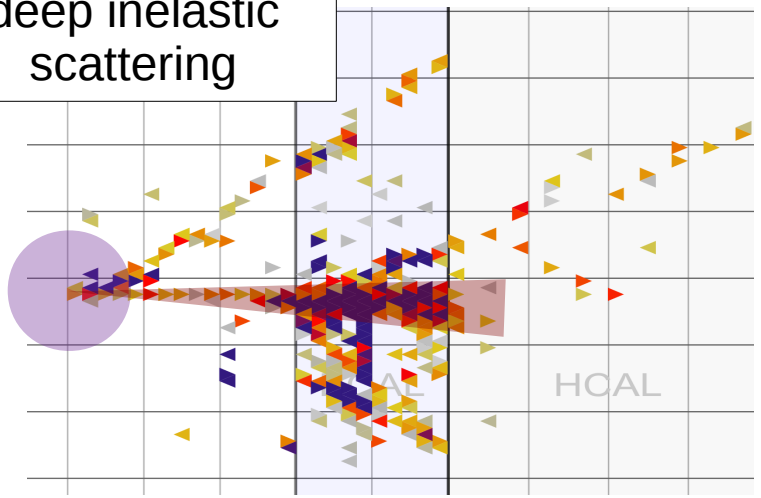
Anything not within a 7.5º electron cone or a vertex activity region of 30 cm radius or tracked as a proton is "extra energy."

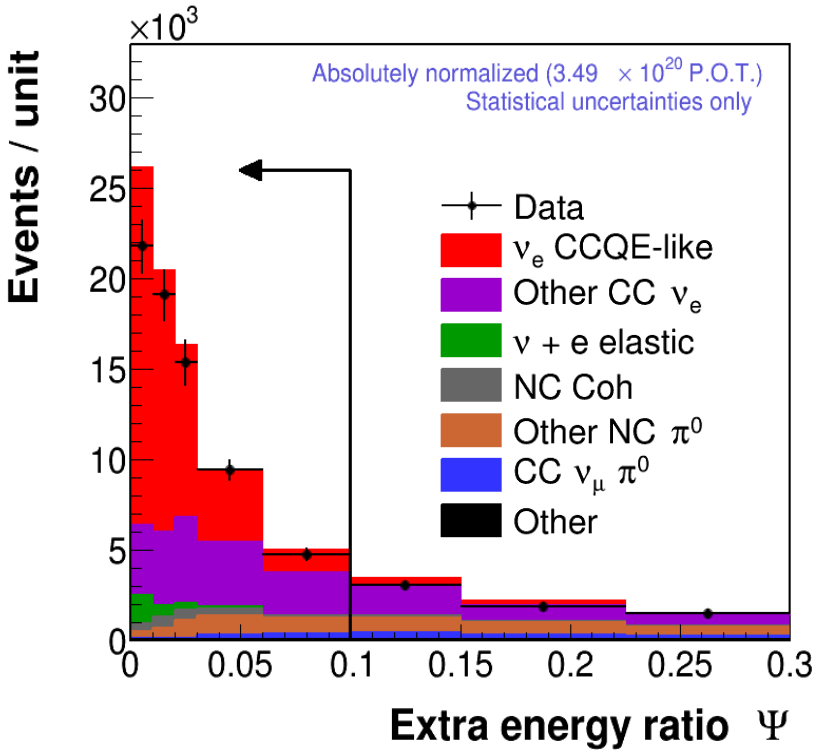
Cut on $\Psi = \frac{E_{extra}}{E_{cone}}$



Simulated ν_e CCQE

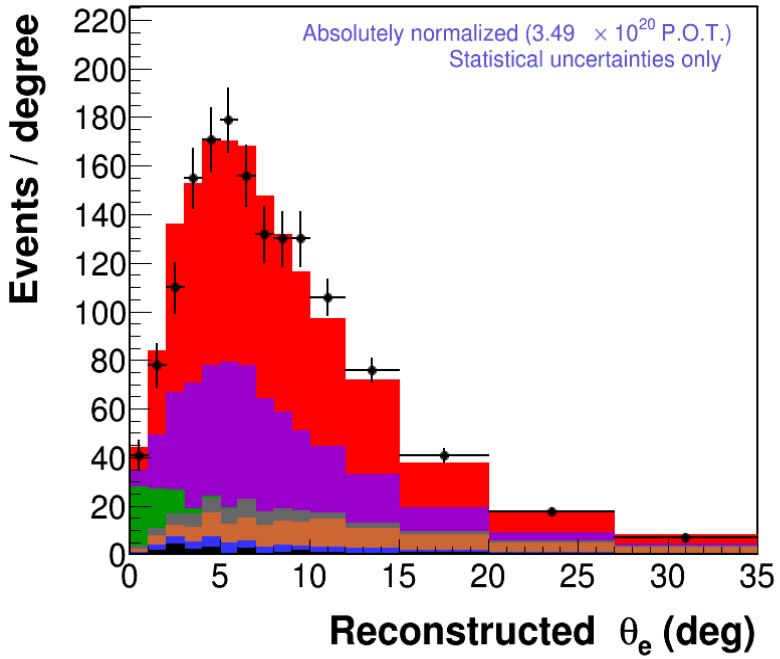
Simulated ν_e deep inelastic scattering





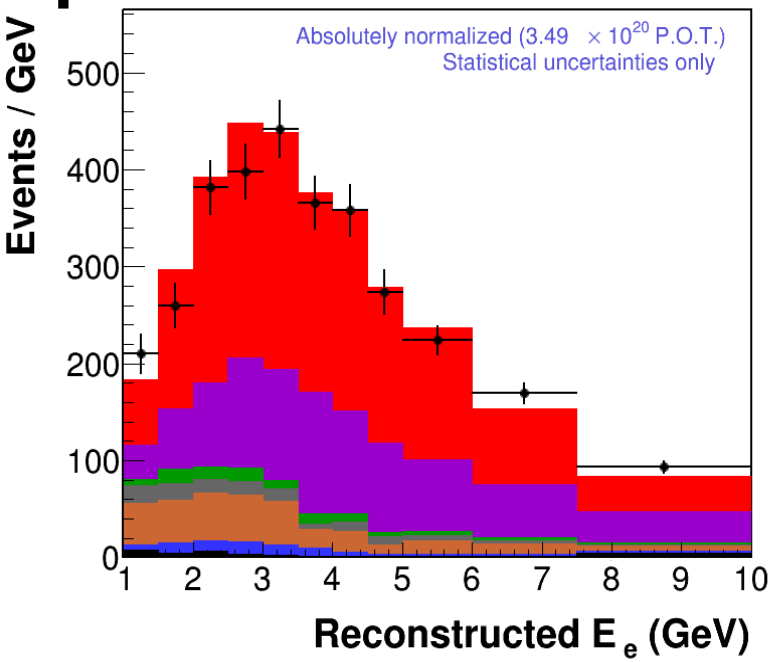
(Actual cut is a function of E_{vis}. This plot illustrates cut near most probable value of E_{vis} = 1.25 GeV.)

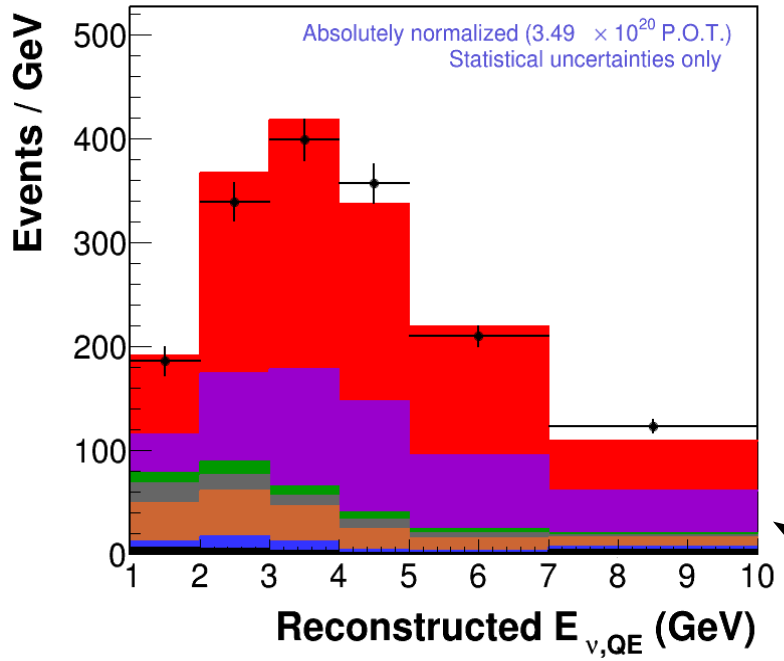
Selected sample

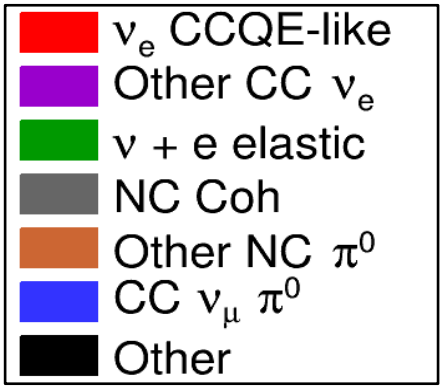


Sample is 52.1% ν_e CCQE

(83.9% ν_e from any channel)

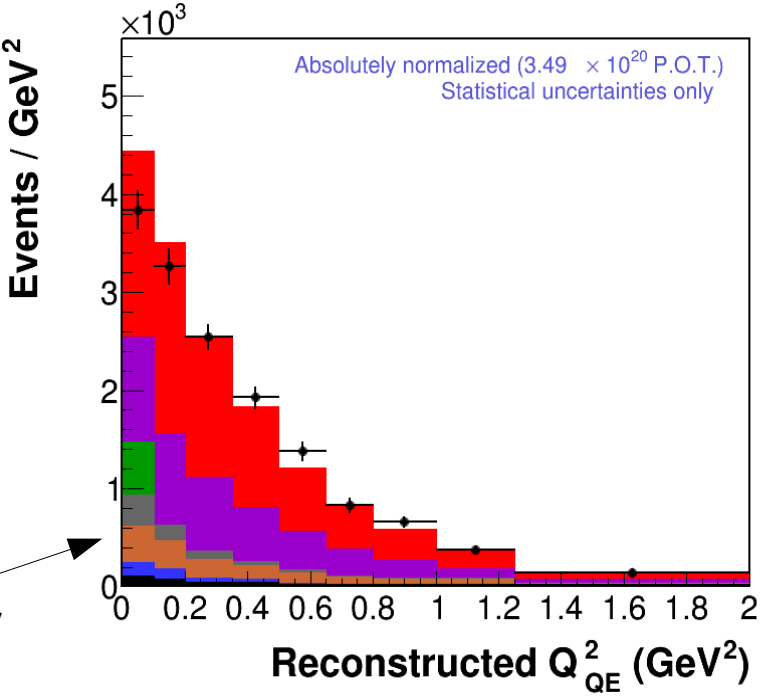






Infer ν kinematics from lepton's

(use QE hypothesis + stationary target assumptions)



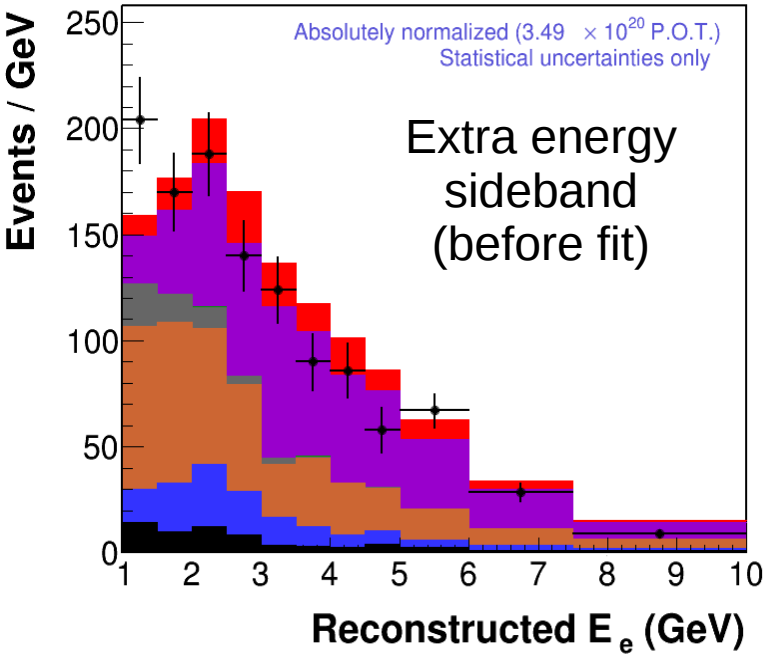
Constraining backgrounds

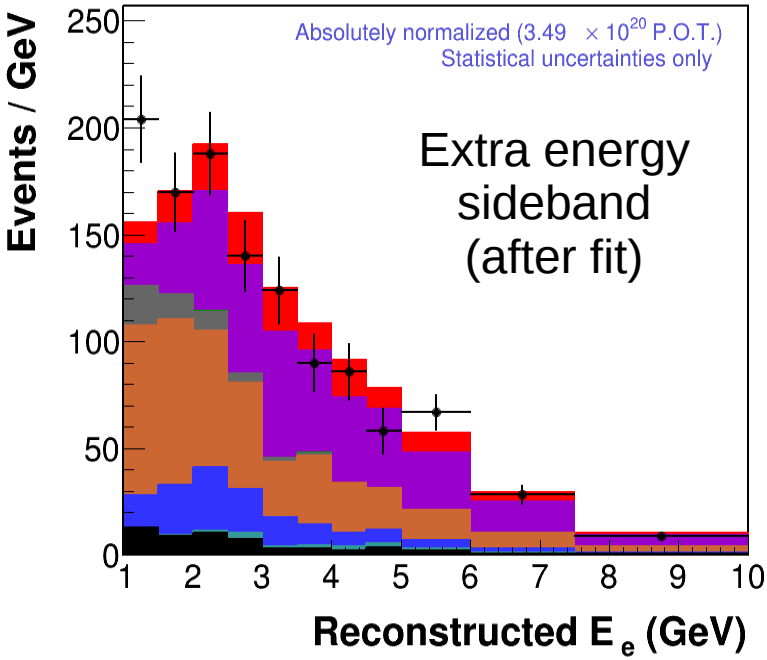
Normalizations of backgrounds are constrained using sidebands in Michel match, extra energy

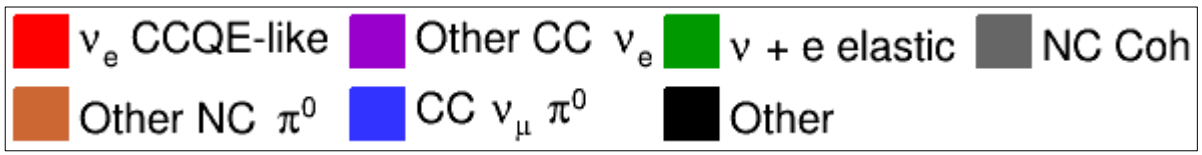
Fitted scale factors (relative to GENIE predicted normalization) are minor:

Inelastic ν_e: 0.89 ± 0.08

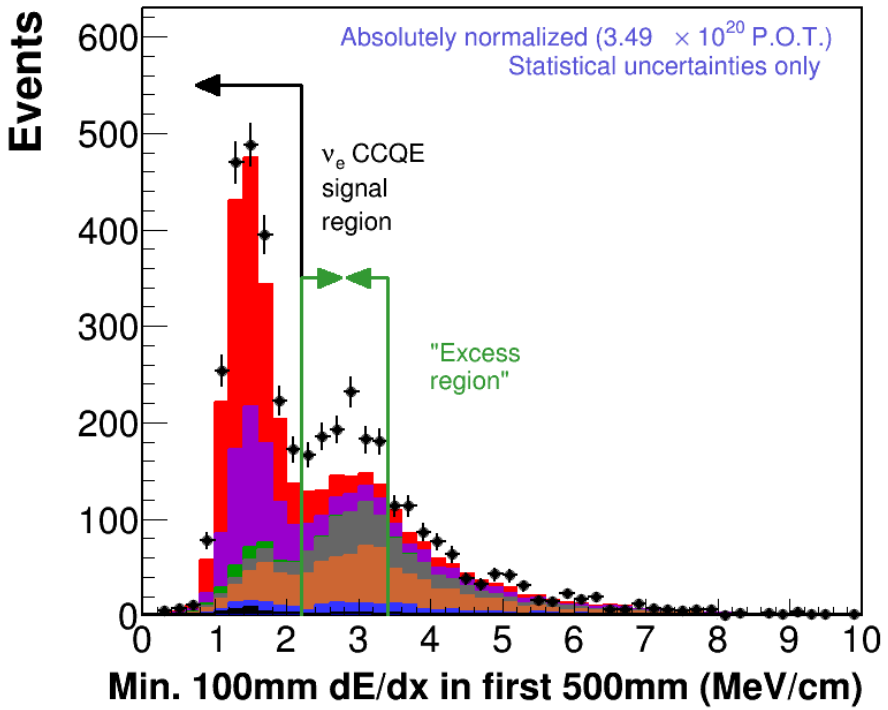
NC & CC incoherent π^0: 1.06 ± 0.12

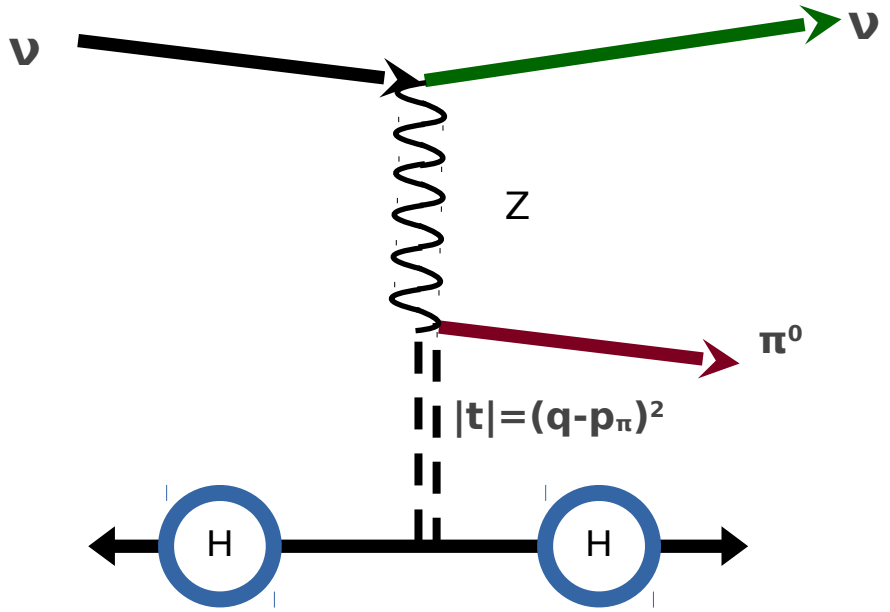






Unmodeled background:
NC diffractive scattering from H





Conceptually similar to NC coherent scattering:

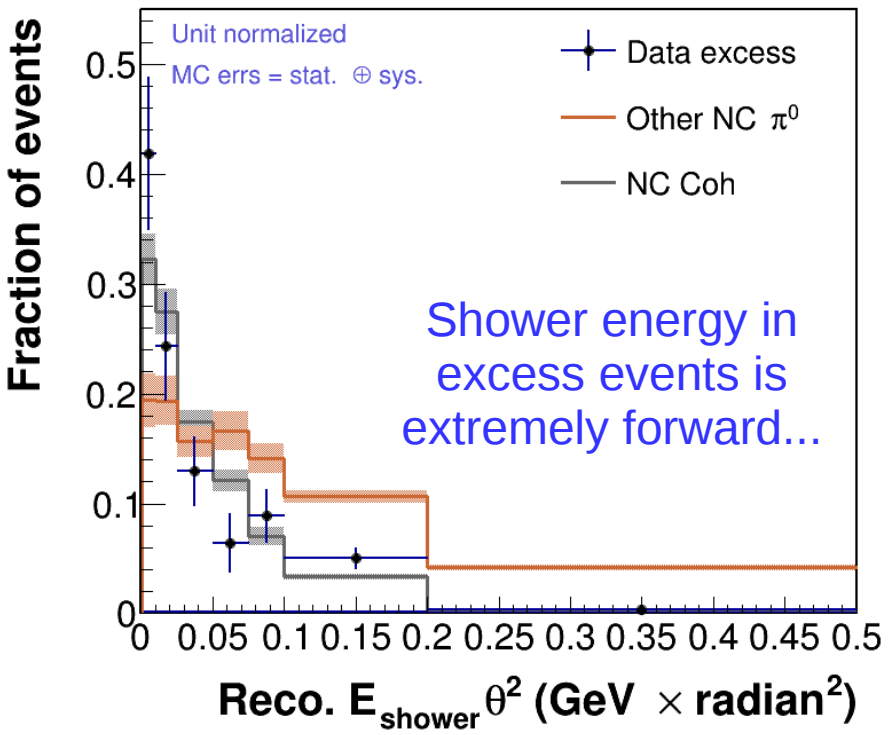
- Little momentum transfer to target
- Vector meson emitted in forward direction

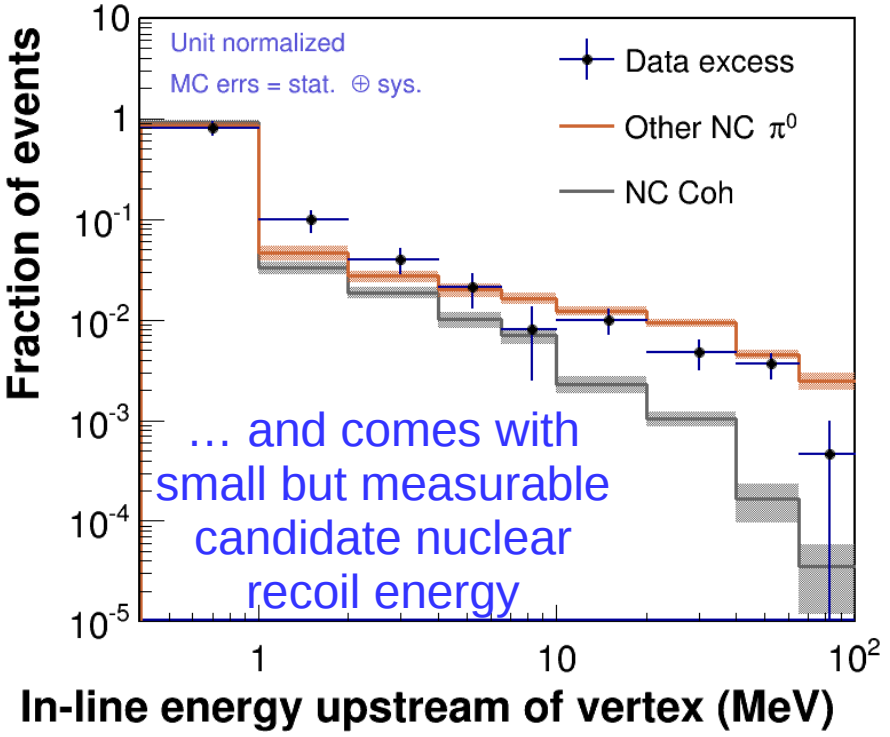
Unique to diffractive scattering from H:

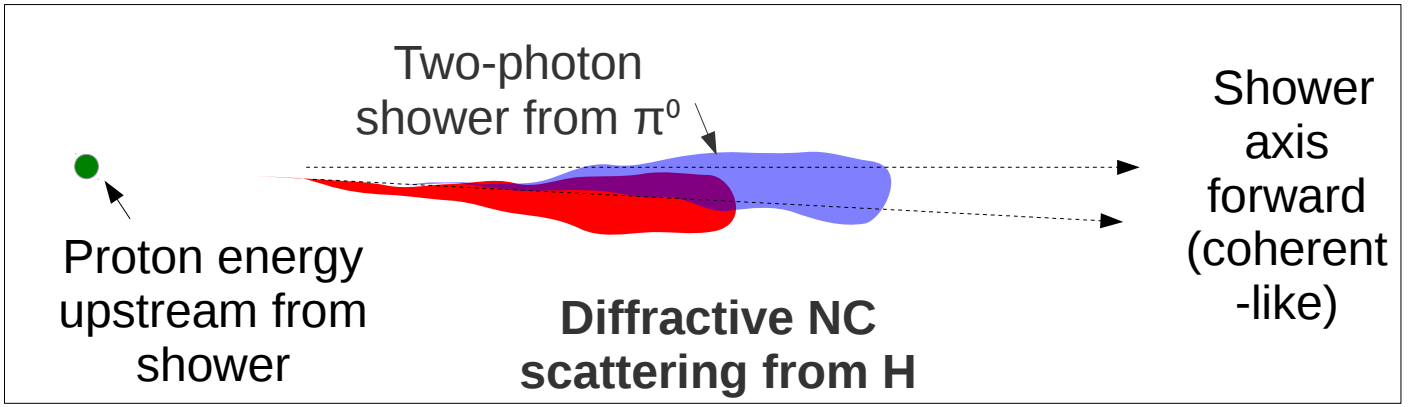
- Recoiling H nucleus (single proton) sometimes visible

<u>Not in (default) GENIE model</u>

Unmodeled background:
NC diffractive scattering from H

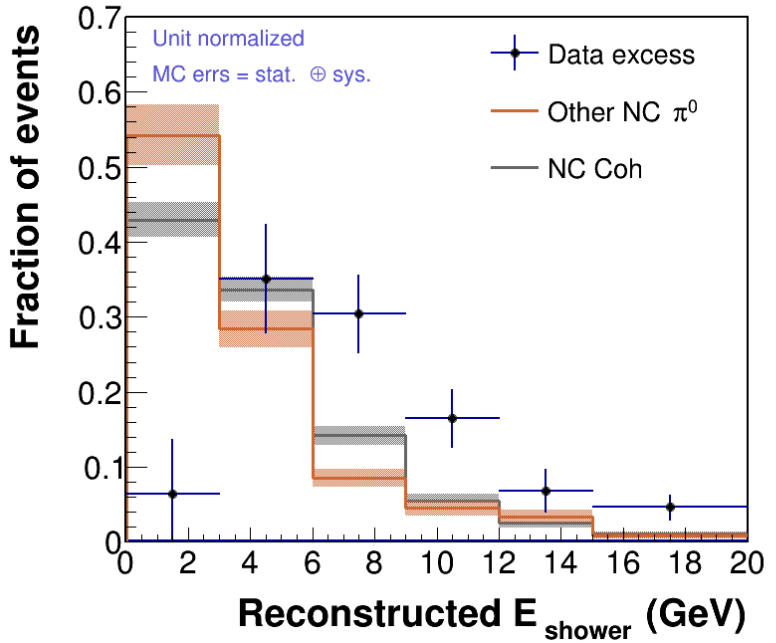




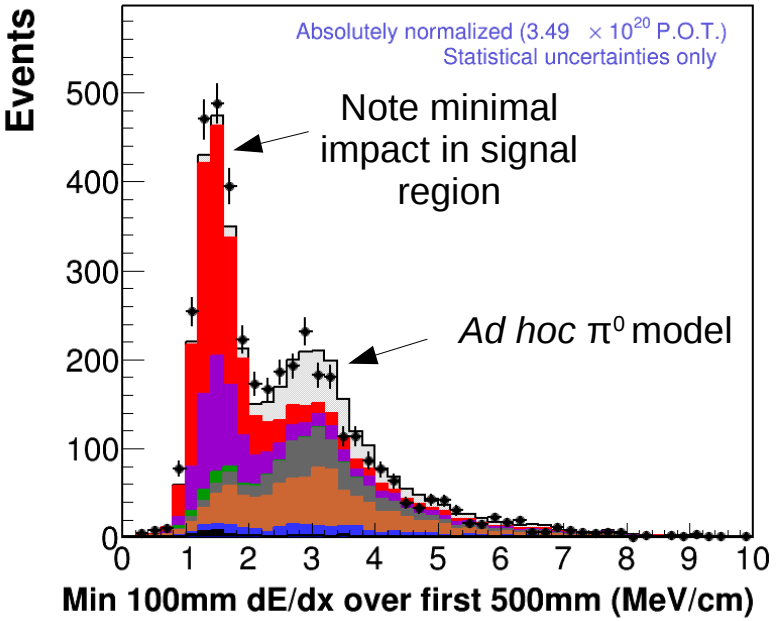


Unmodeled background:
NC diffractive scattering from H

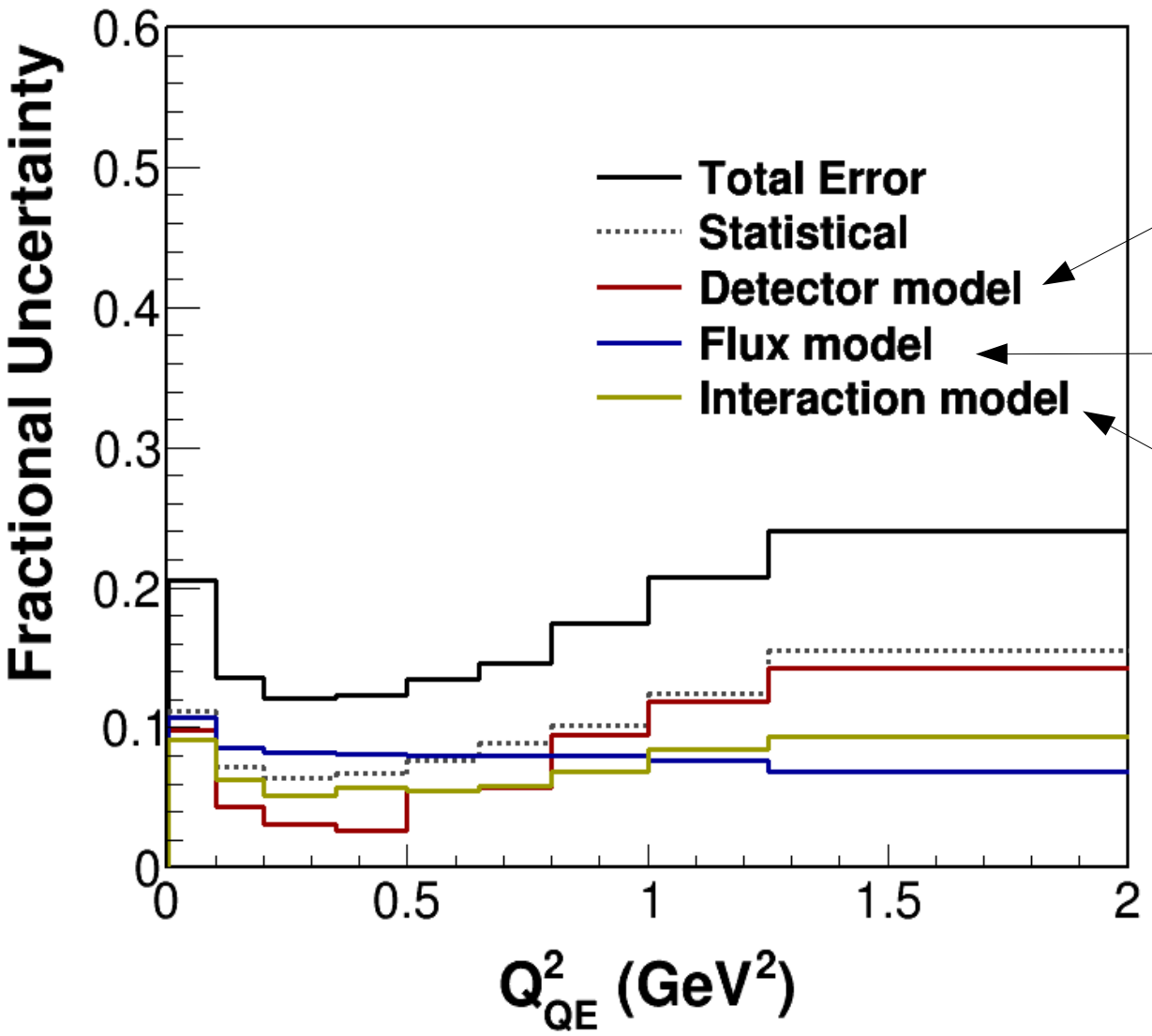
Observe unusually hard pion energy spectrum



Model excess using *ad hoc* single-particle π^0 sample tuned to fit kinematics



Uncertainty summary



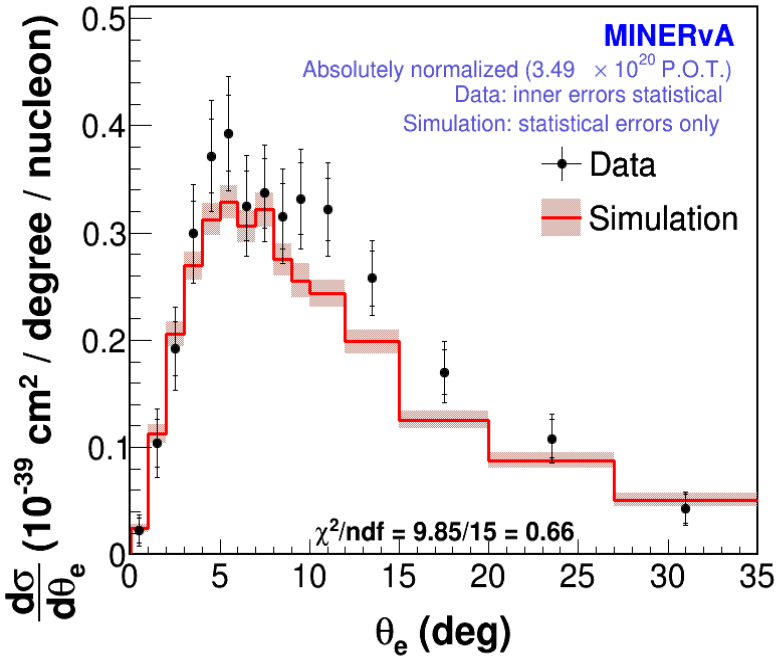
Includes energy scale estimated using the π^0 mass peak in a separate measurement; resolutions; other detector effects

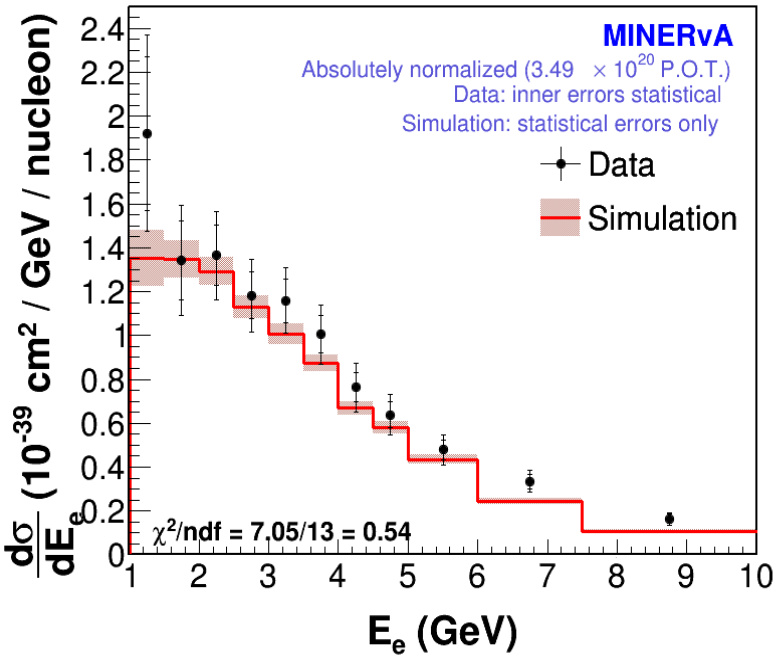
Constrained by *in situ* ν+e elastic scattering measurement

Mostly enters in background subtraction (from GENIE 2.6.2)

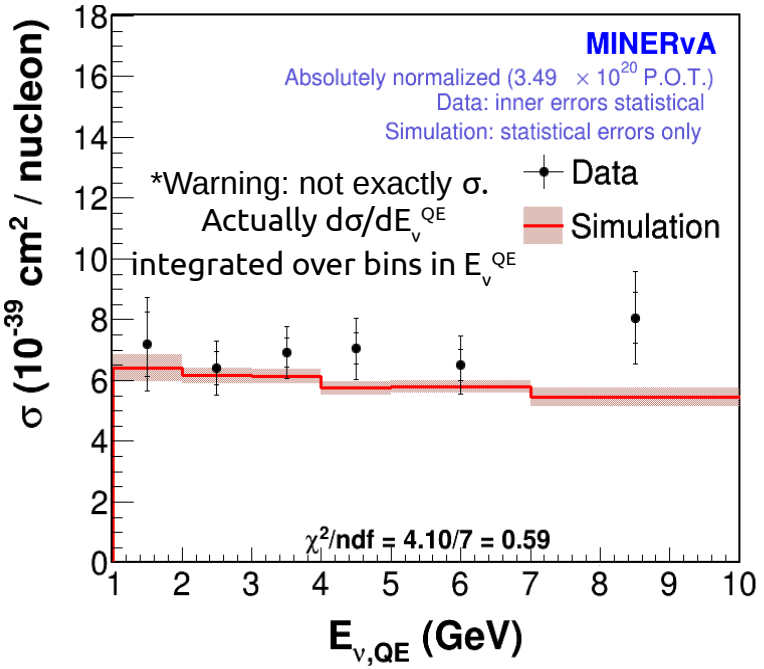
Systematic uncertainties and the statistics are roughly comparable

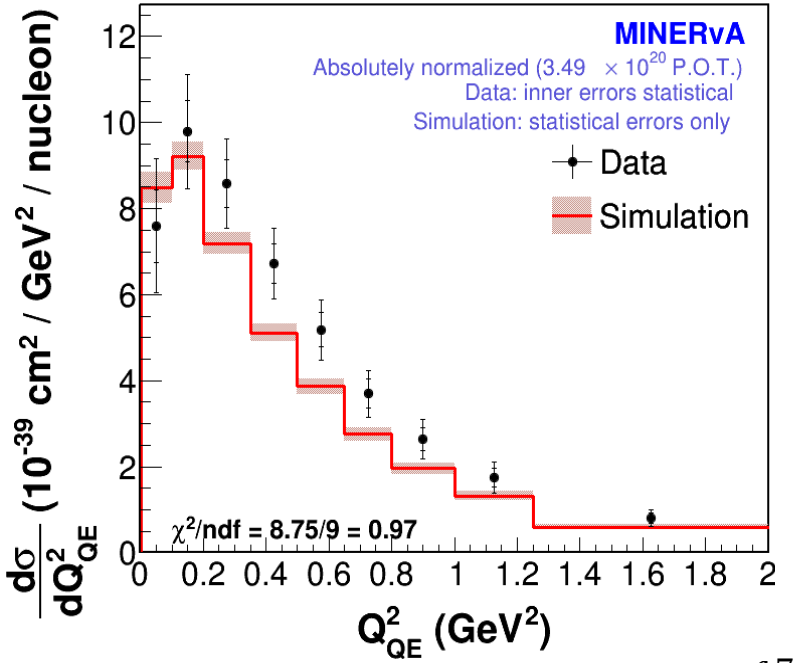
Cross-sections





Measured cross-sections are consistent with the prediction from GENIE 2.6.2

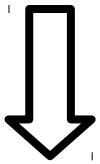




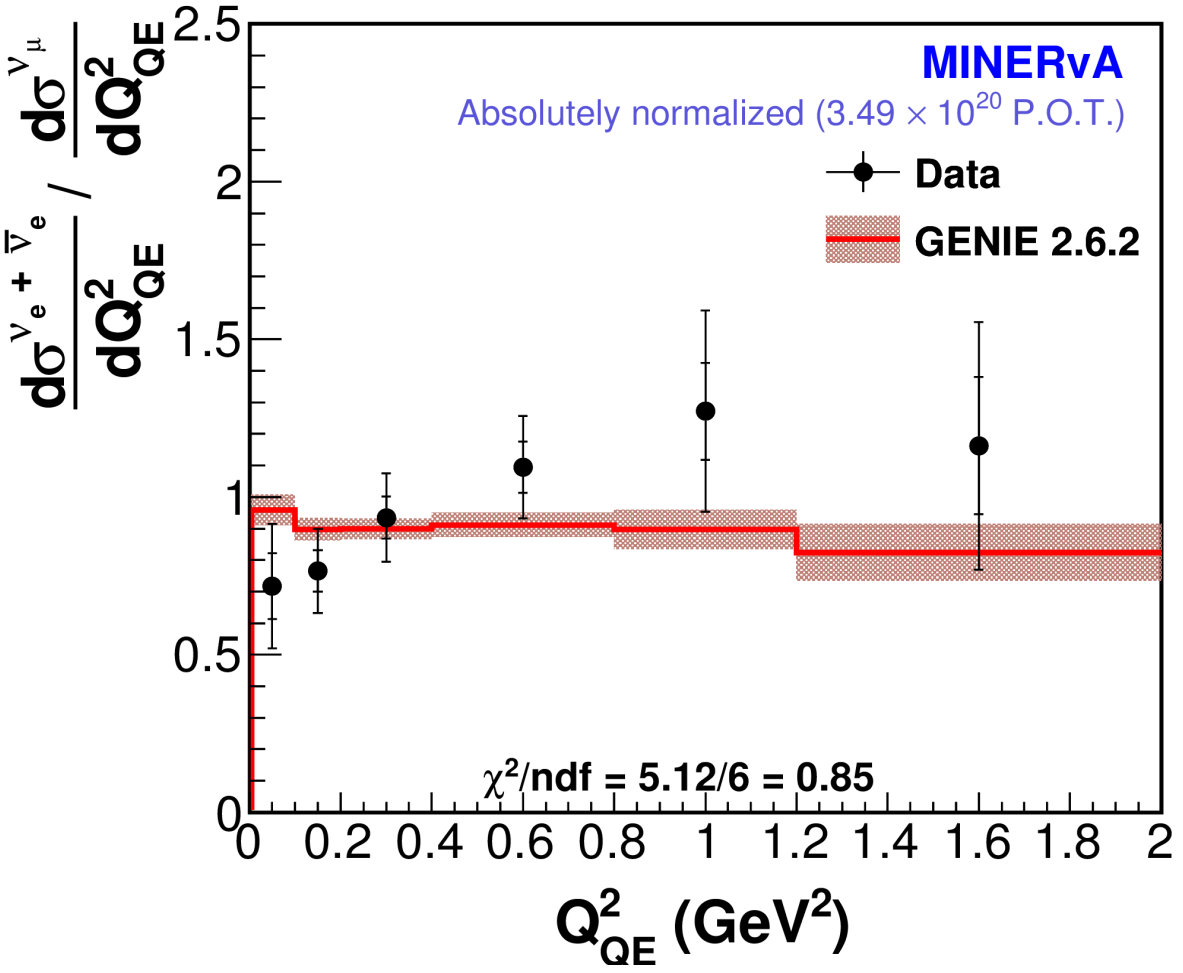
Comparison to ν_μ

When compared to prior MINERvA ν_μ CCQE measurement, **ratio is consistent with GENIE prediction.**

(Apparent shape is only significant at ~1σ level due to bin-to-bin correlated systematic errors with similar behavior.)



Upper bound on scale of nuclear effects when comparing ν_e and ν_μ CCQE scattering is 15-30%



Summary and outlook

- ν_e cross sections are important both for oscillation expts. and for better understanding nuclear medium
- First ν_e exclusive process measurement consistent with GENIE 2.6.2 at ~1σ
- ν_e/ν_μ ratio provides upper bound on impact of nuclear effects on $\nu_e \rightarrow \nu_\mu$ extrapolation
- Observation of unmodeled diffractive scattering process underscores need for continuing work on models for potential ν_e background reactions
- Publications forthcoming (CCQE submitted to PRL; diffractive scattering in preparation)

Thanks for your attention!

Backup slides follow

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

The ν_e cross-section prediction is a vital ingredient in these measurements...

Measured quantity, compared to data

$$N = \left(\Phi_{\nu_\mu} \times P_{\nu_\mu \rightarrow \nu_e} + \Phi_{\nu_e} \right) \times \sigma_{\nu_e}$$

Main beam flux prediction

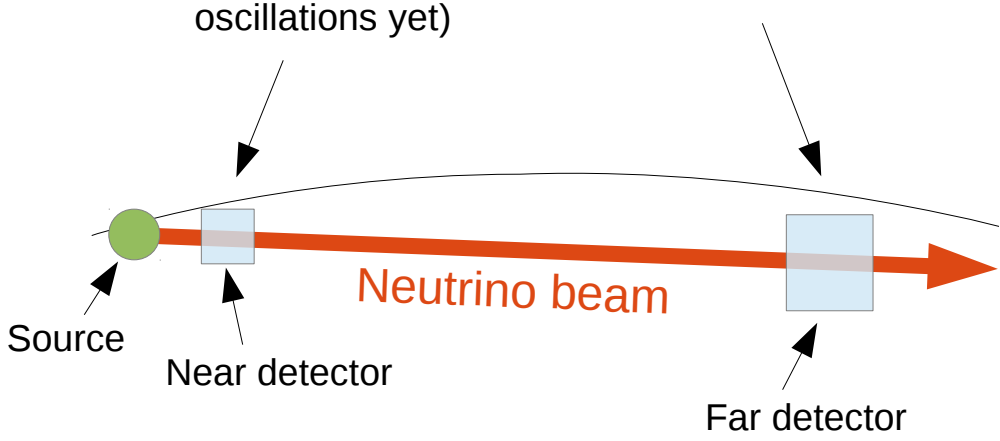
Oscillation probability (unknown parameters – Δm^2, θ, δ – here)

Accelerator ν_μ beams typically have an **intrinsic ~1% ν_e flux**

$$\Phi_{\nu_e} \sigma_{\nu_e} \neq \Phi_{\nu_\mu} \sigma_{\nu_e}$$

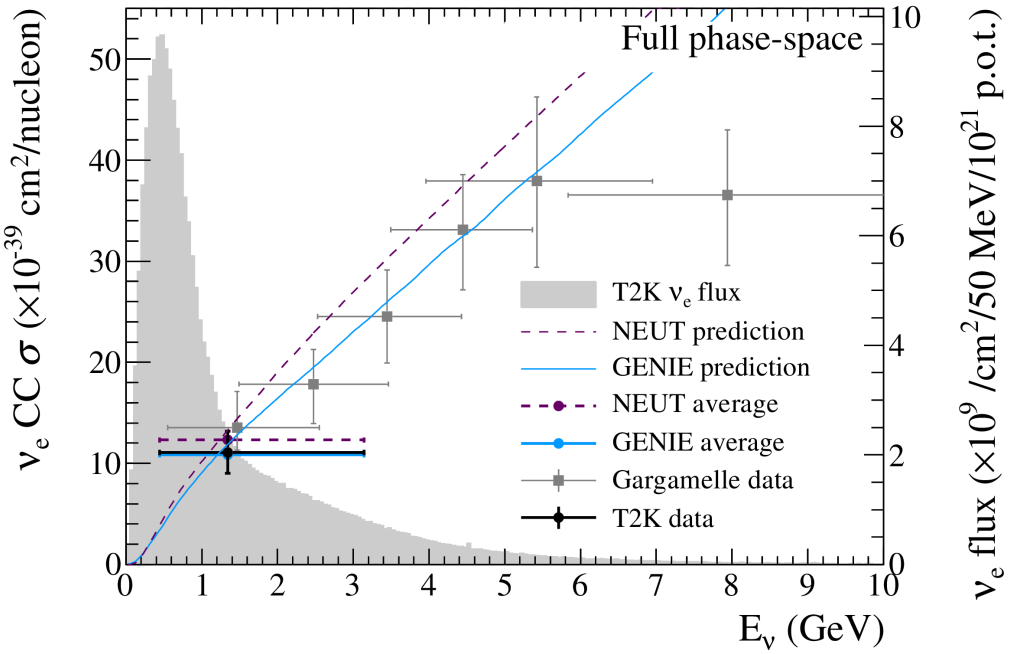
(only source of ν_es is intrinsic beam ν_e... no oscillations yet)

(oscillated ν_es have ν_μ spectrum)

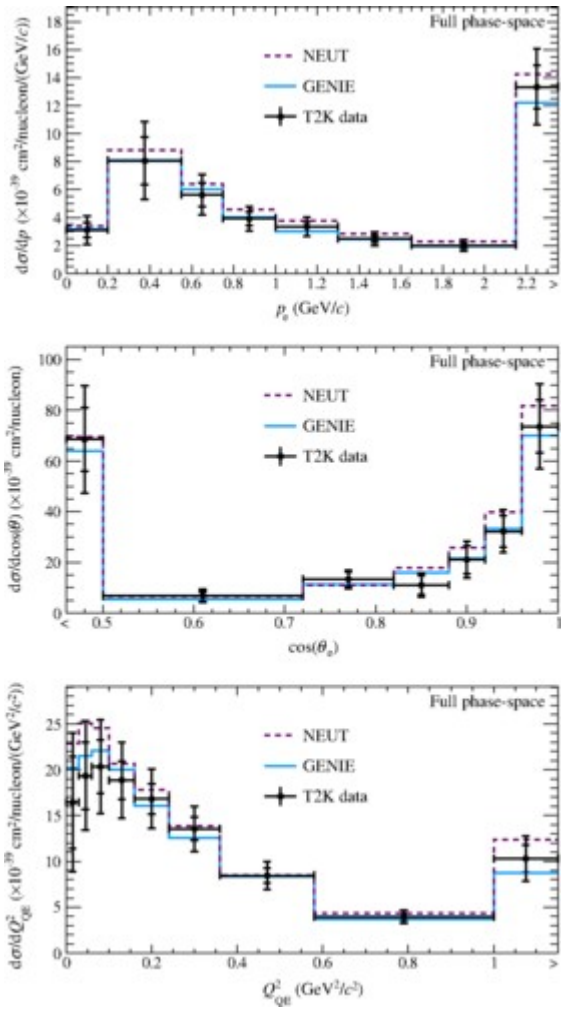


… and a near detector doesn't save you from having to measure it!

Existing ν_e cross-section measurements



$\sigma_e(E_\nu)$:
Gargamelle (1978) on CF_3Br;
T2K (2014) on CH
Nucl. Phys. B133, 2015
Phys. Rev. Lett. 113, 241803

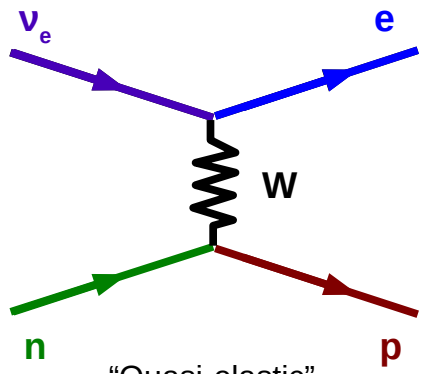


$d\sigma_e/dE_e$, $d\sigma_e/d\theta_e$, $d\sigma_e/dQ^2$:
T2K (2014) on CH
Phys. Rev. Lett. 113, 241803

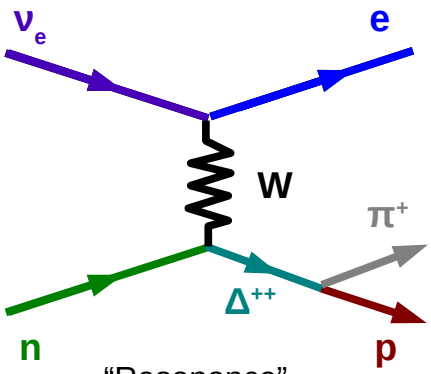
Difficult measurement...
Low stats ↔ large errors, no exclusive reactions.

Gargamelle: 244 events at ~90% purity
T2K: 315 events at ~65% purity

Existing measurements and needs

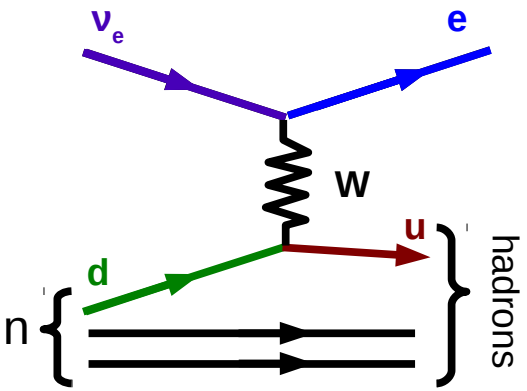


"Quasi-elastic"
(QE)

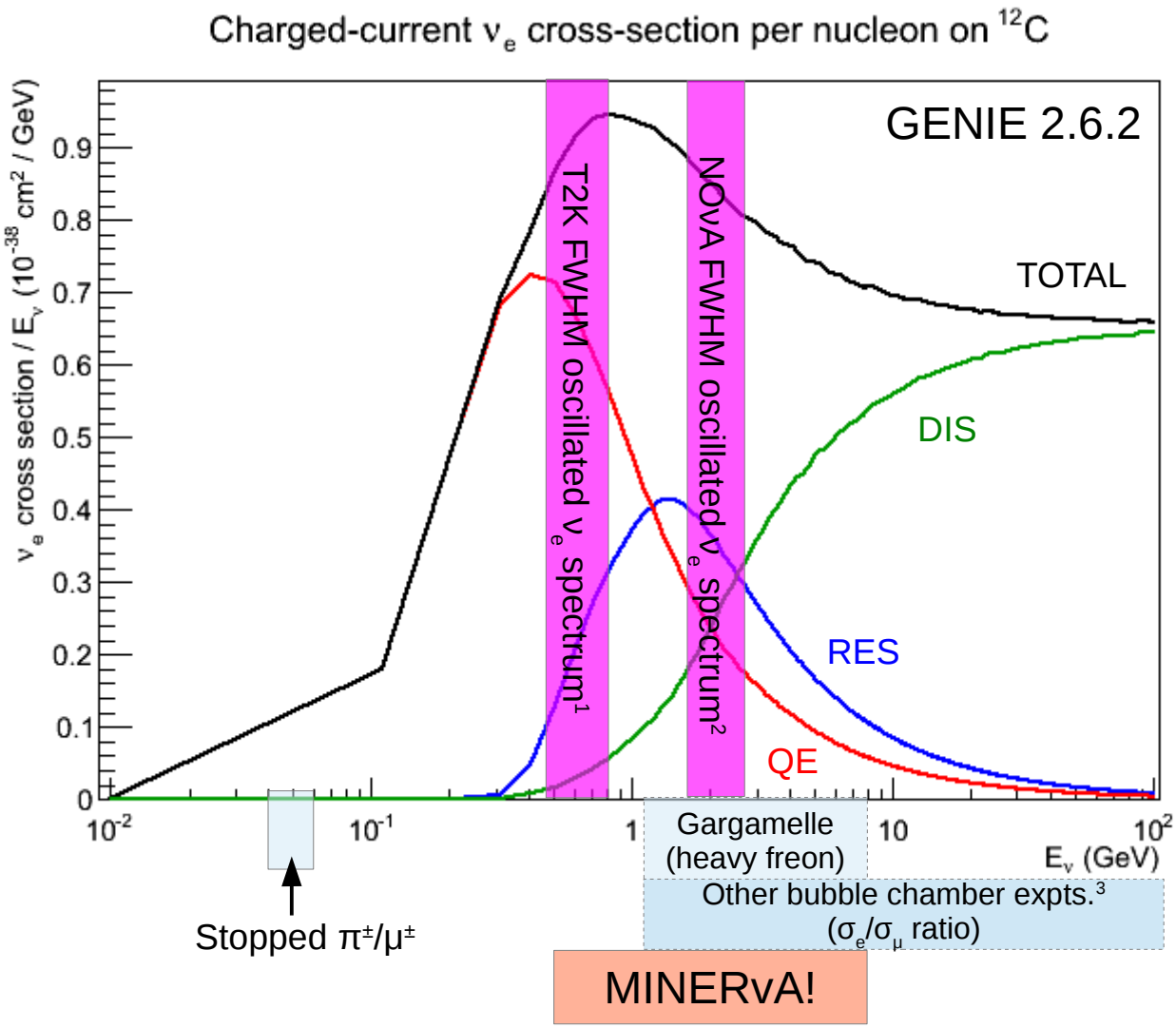


"Resonance"
(RES)

More energy transferred to nucleus



"Deep inelastic scattering"
(DIS)



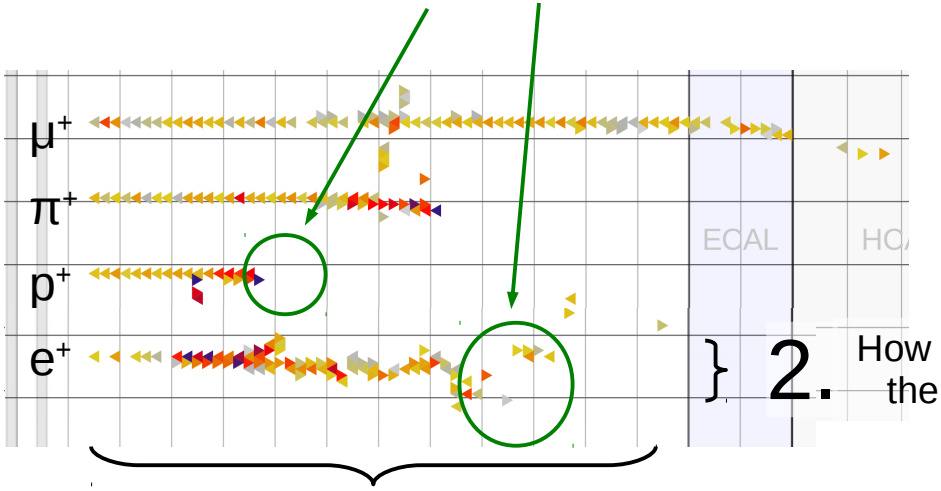
But few measurements!
Thus, present oscillation exp'ts rely on lepton universality and $\sigma(\nu_\mu)$...

[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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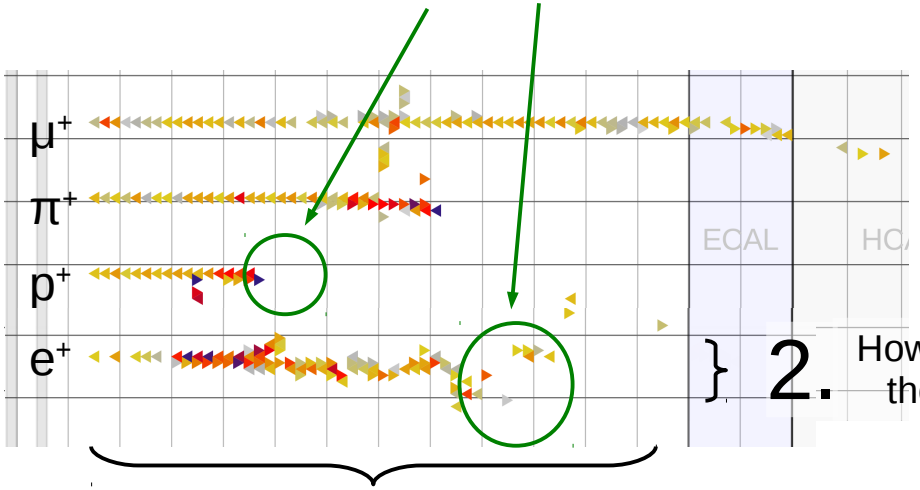

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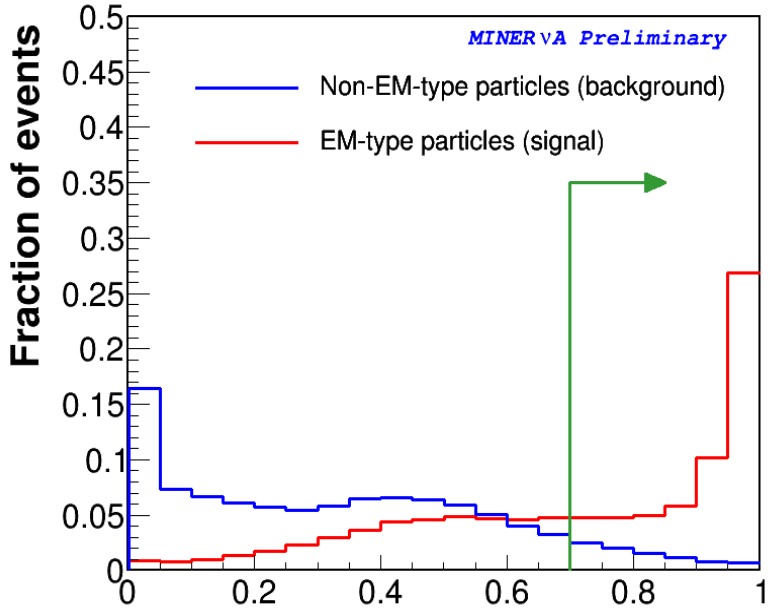
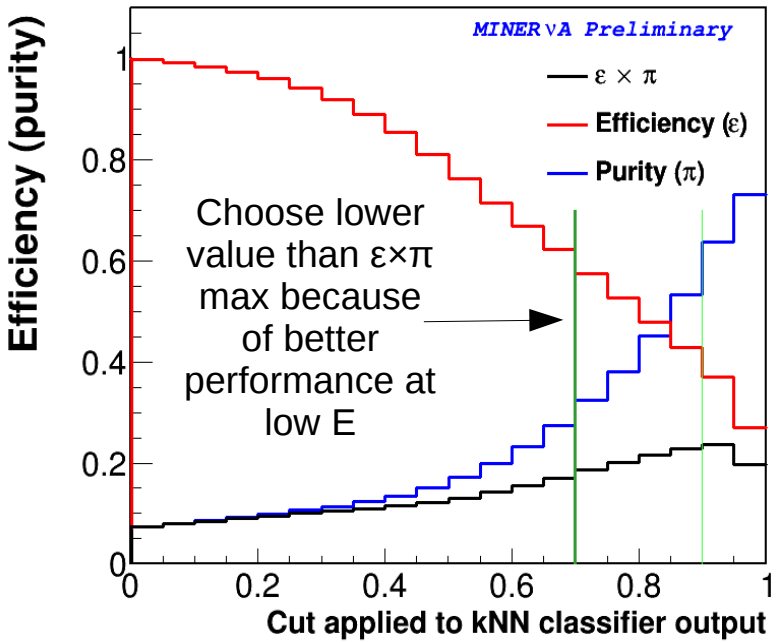
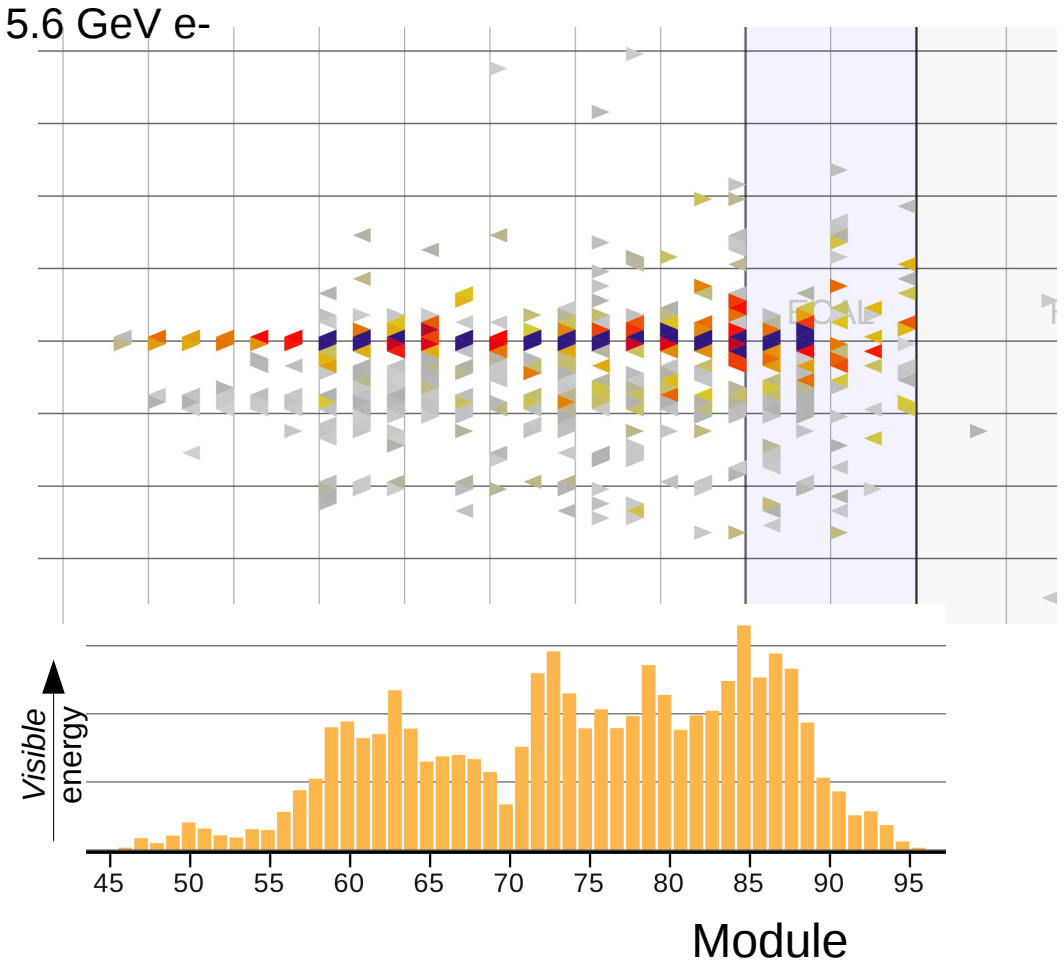
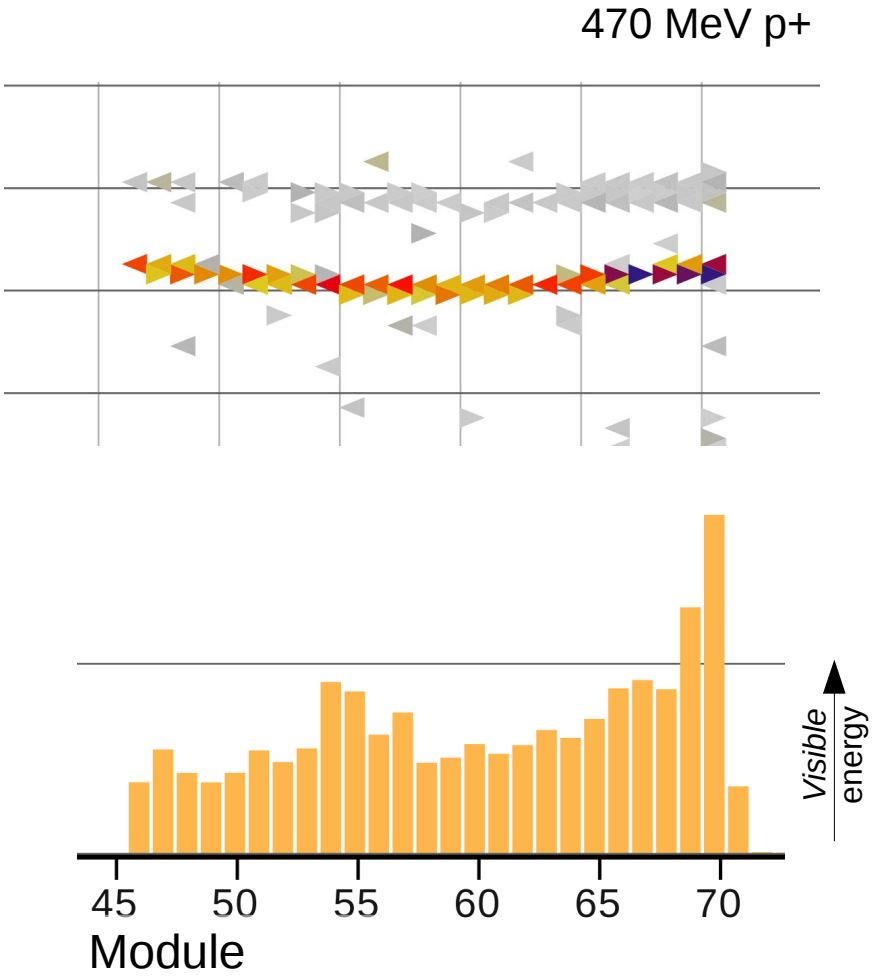




PID variable: endpoint energy fraction





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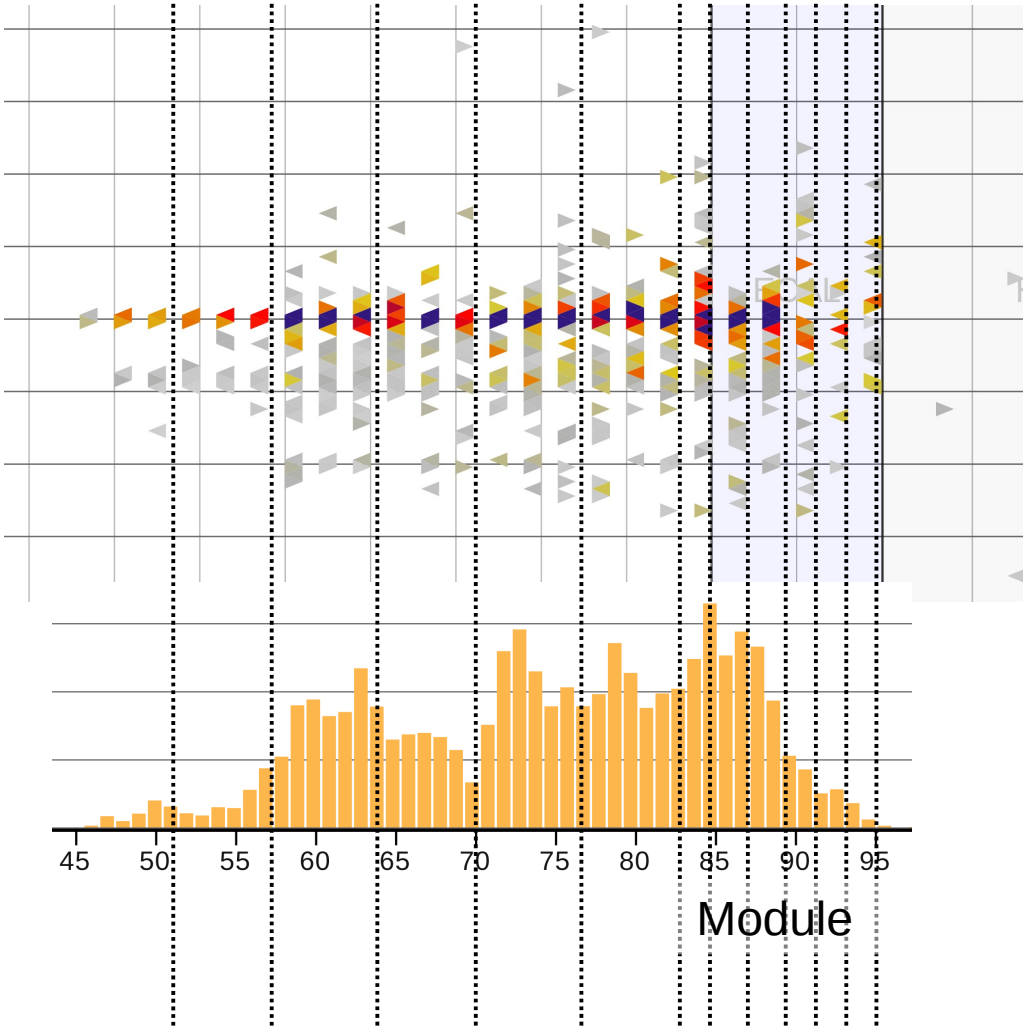
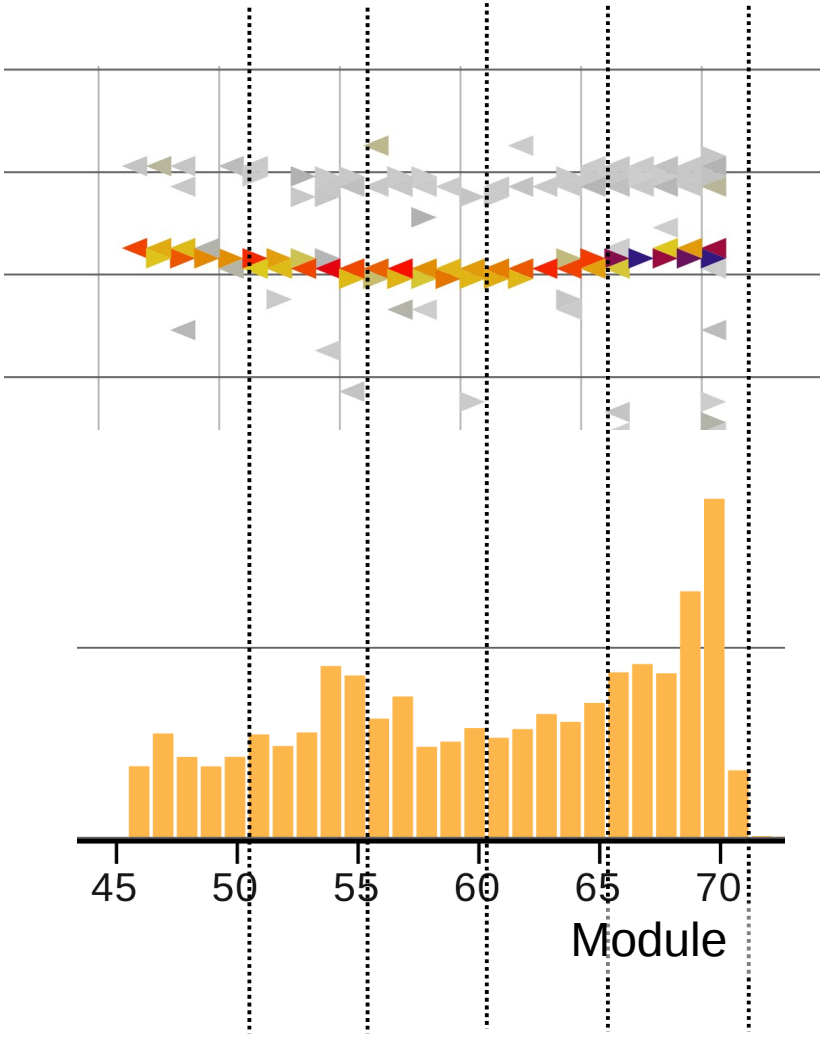
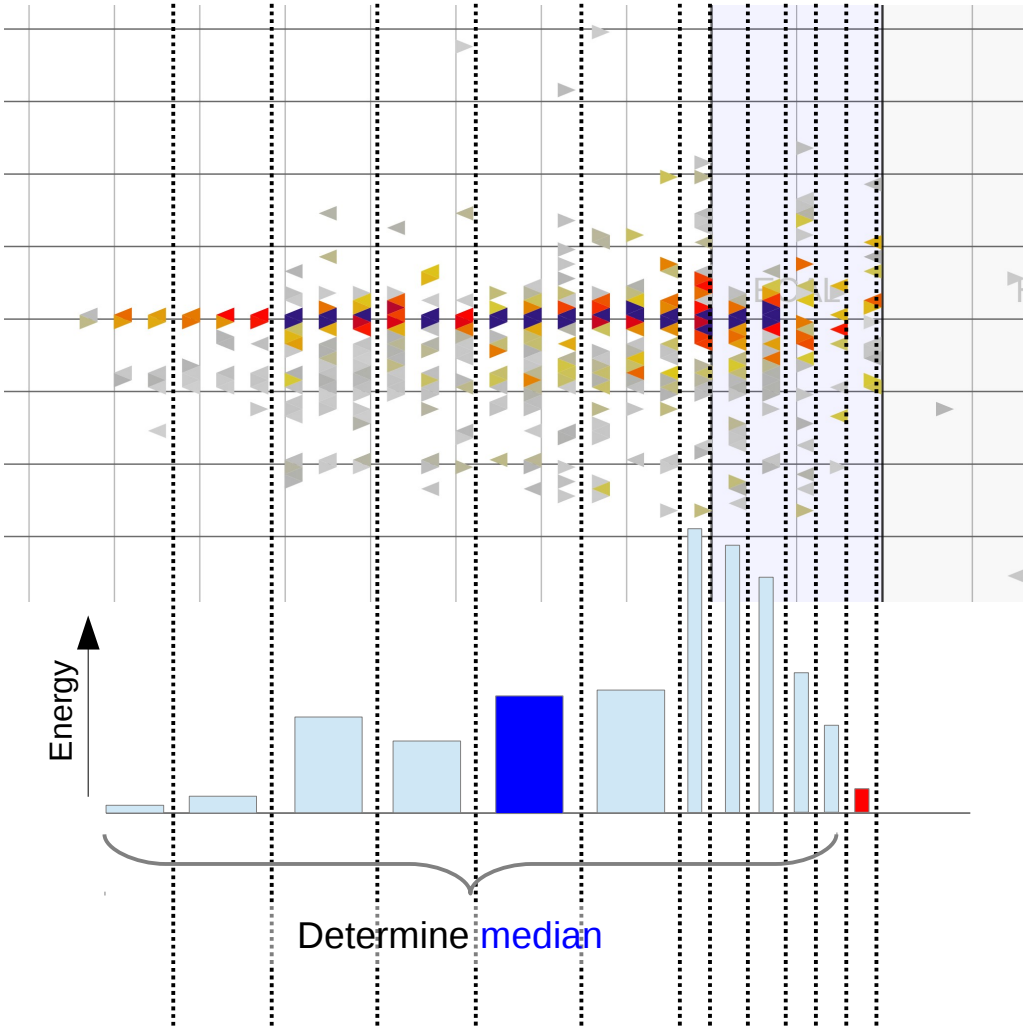
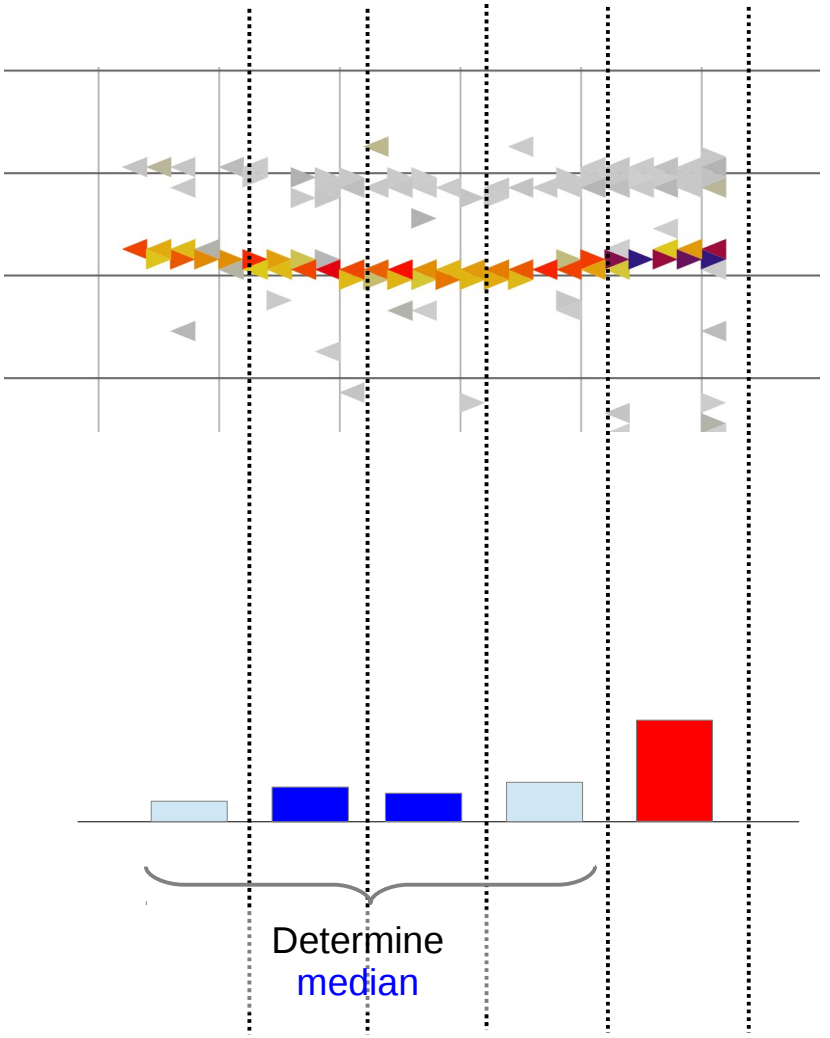




1. Divide the energy deposits into bins of 10 g/cm^2 of areal density.

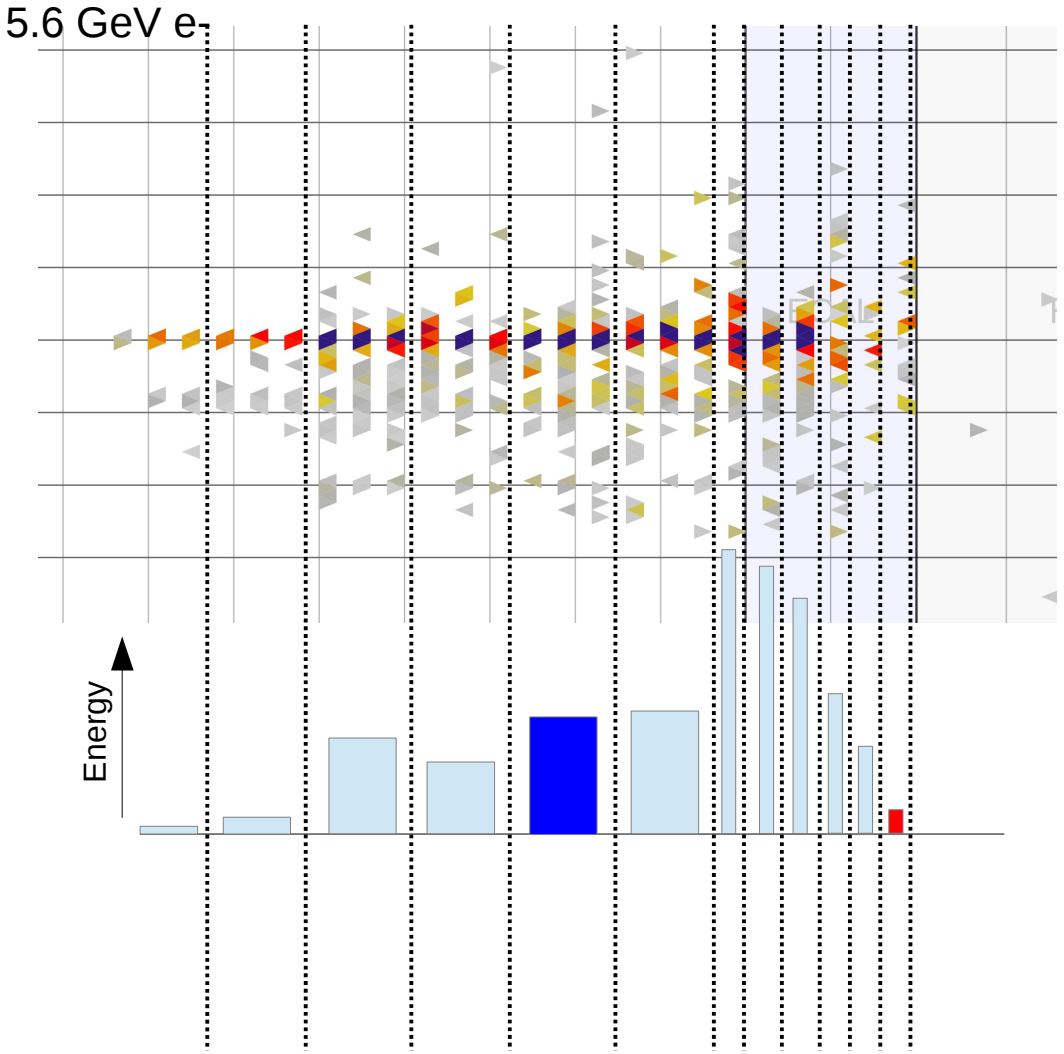
PID variable: endpoint energy fraction

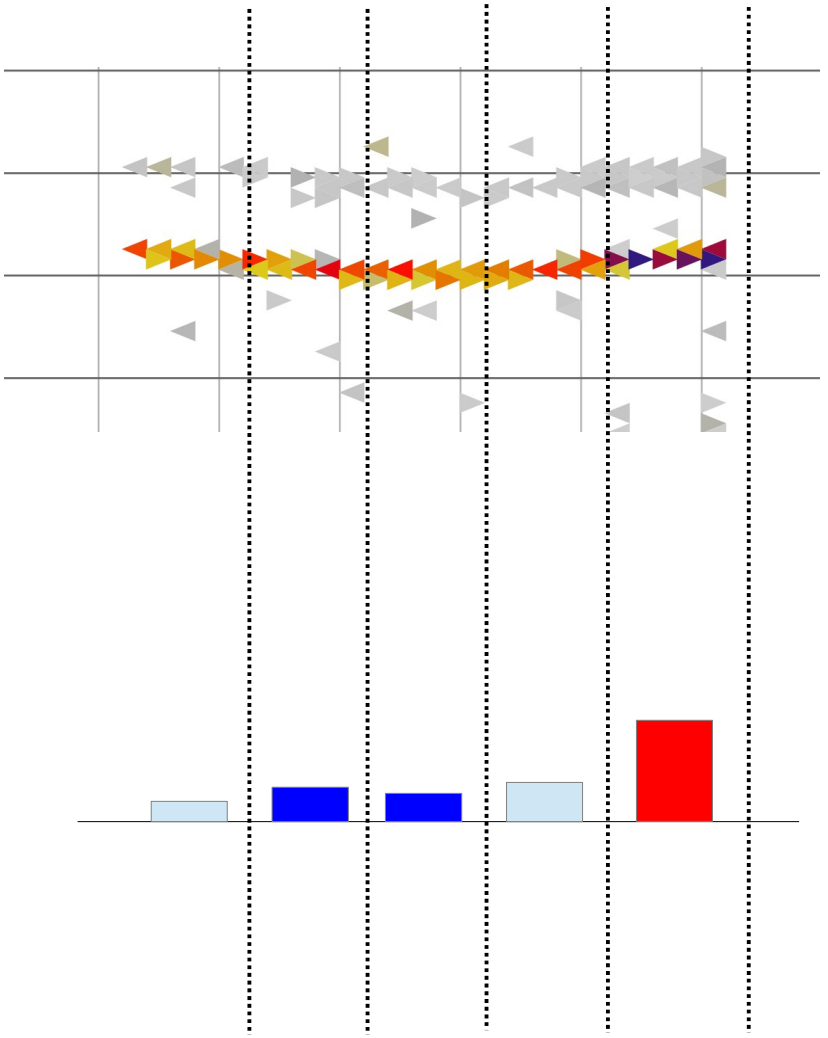




2. Correct the energy deposits for the calorimetry.
3. Determine the median of the energy deposits (excluding the last one).

PID variable: endpoint energy fraction

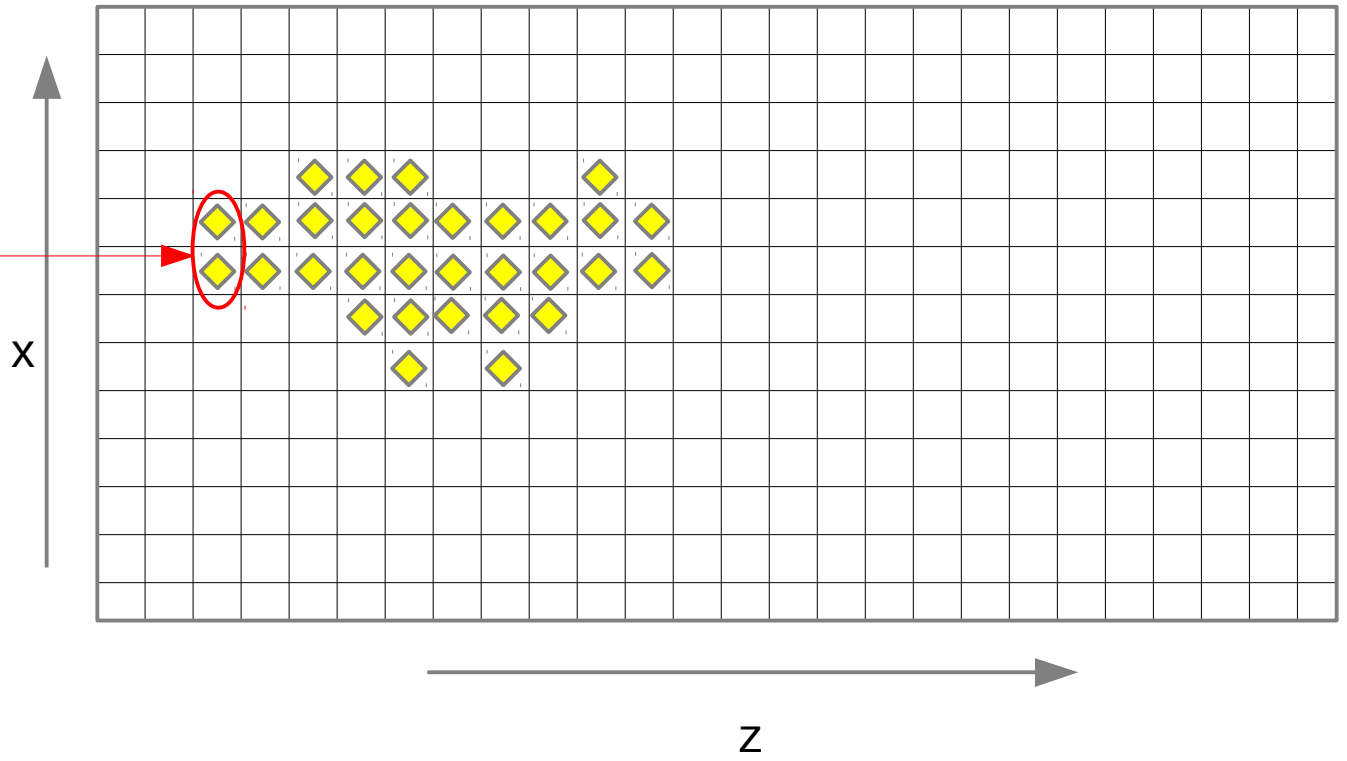




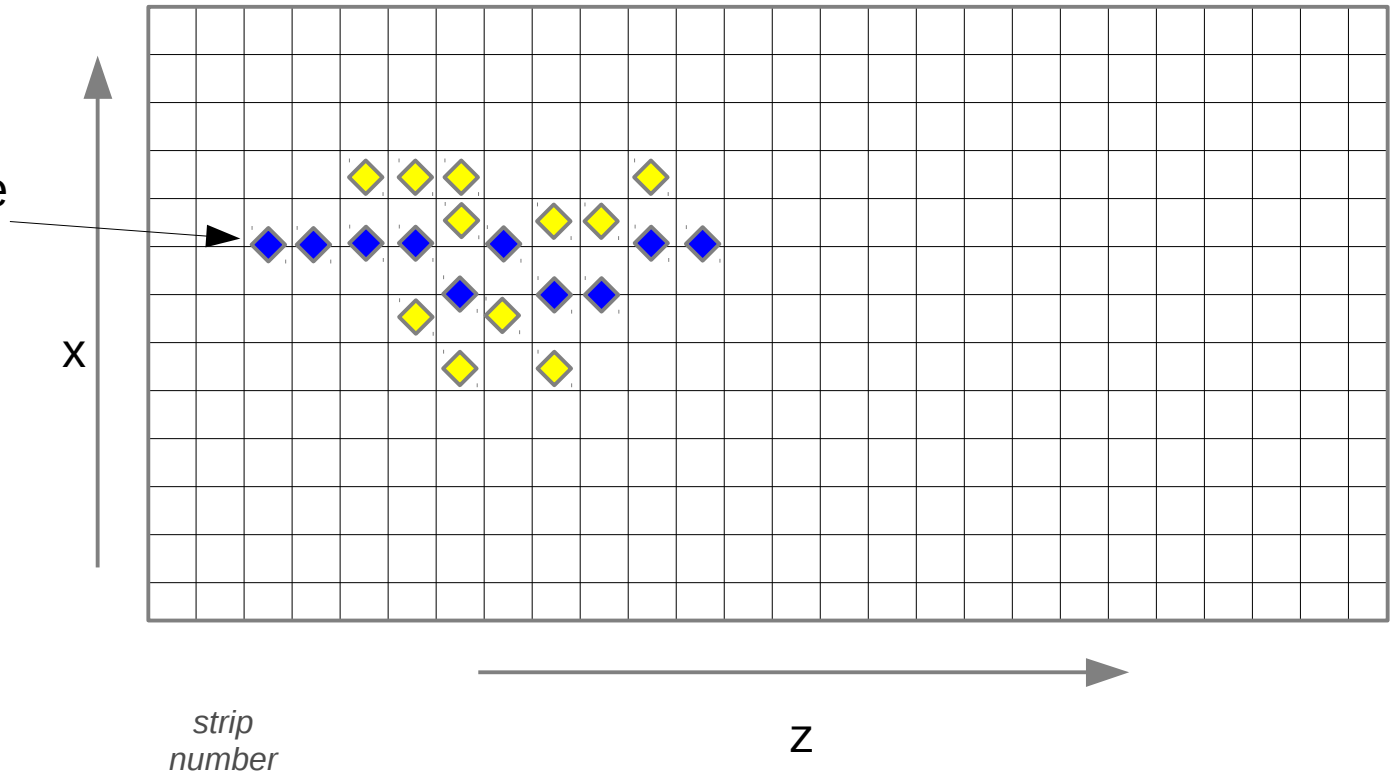
4. Endpoint energy fraction = $\frac{E_{last}}{E_{median}}$

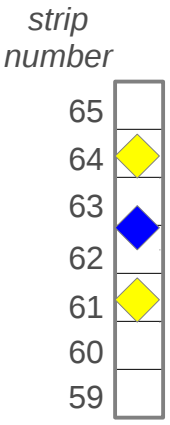
PID variable: shower “width”

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”



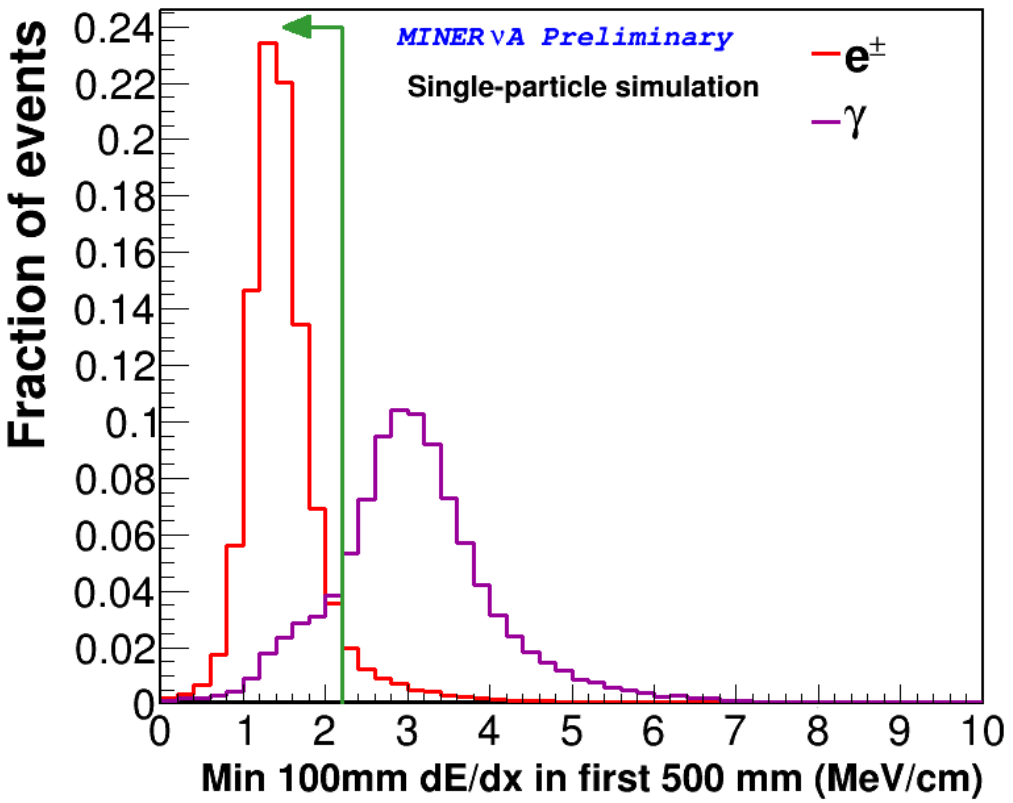


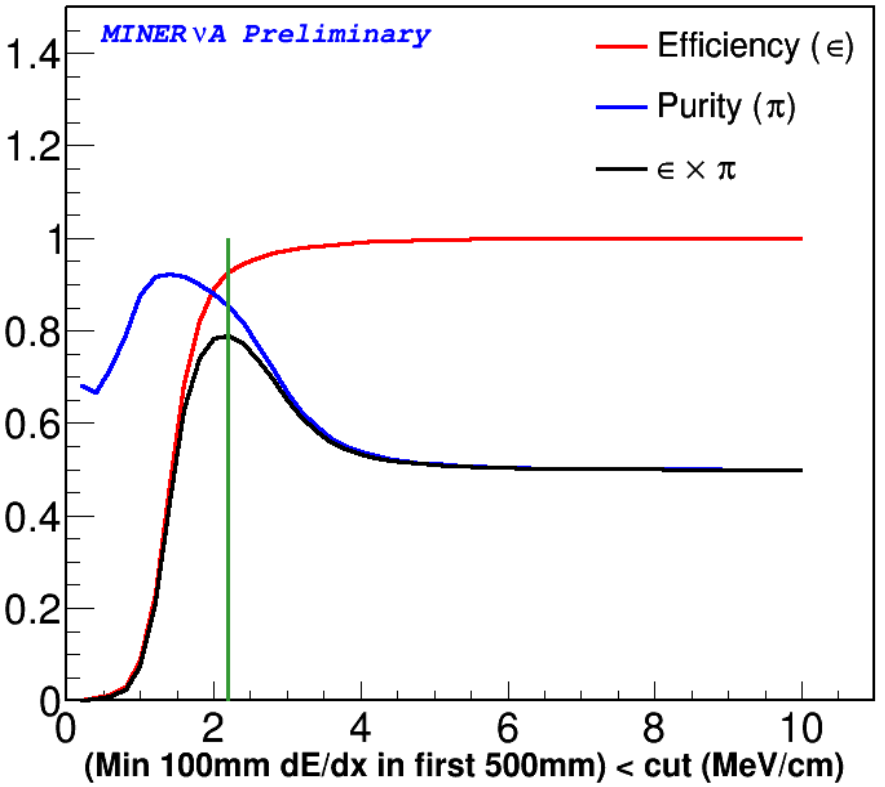
For each plane:

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

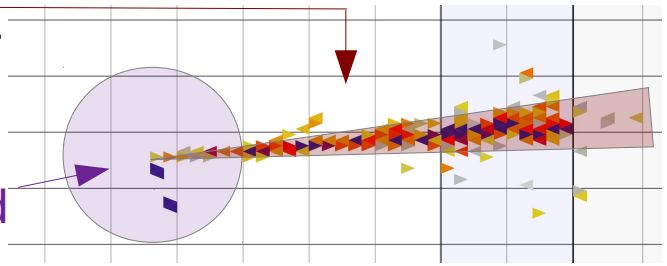




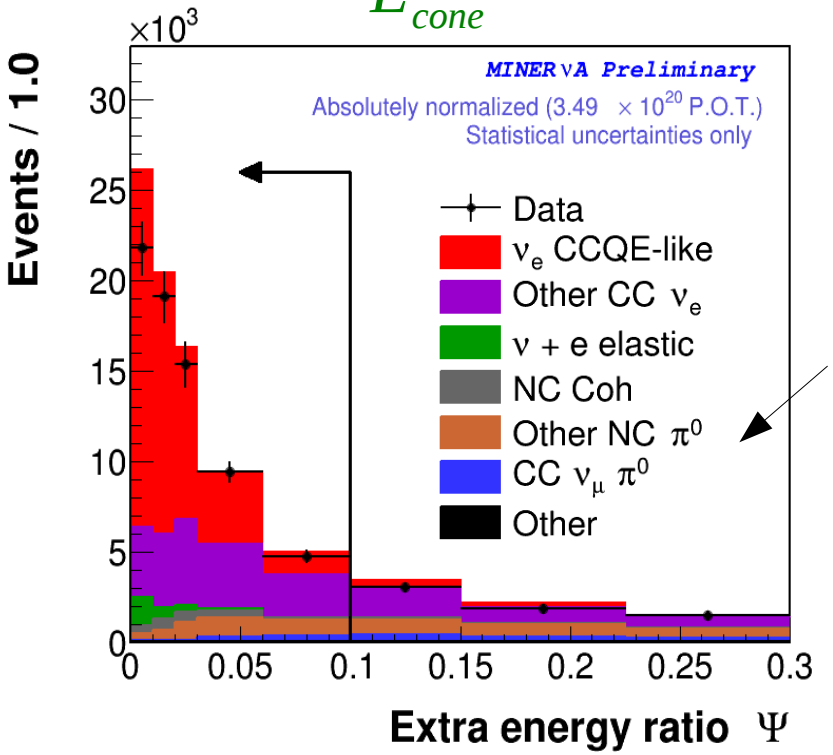
“Extra energy” cut

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.”

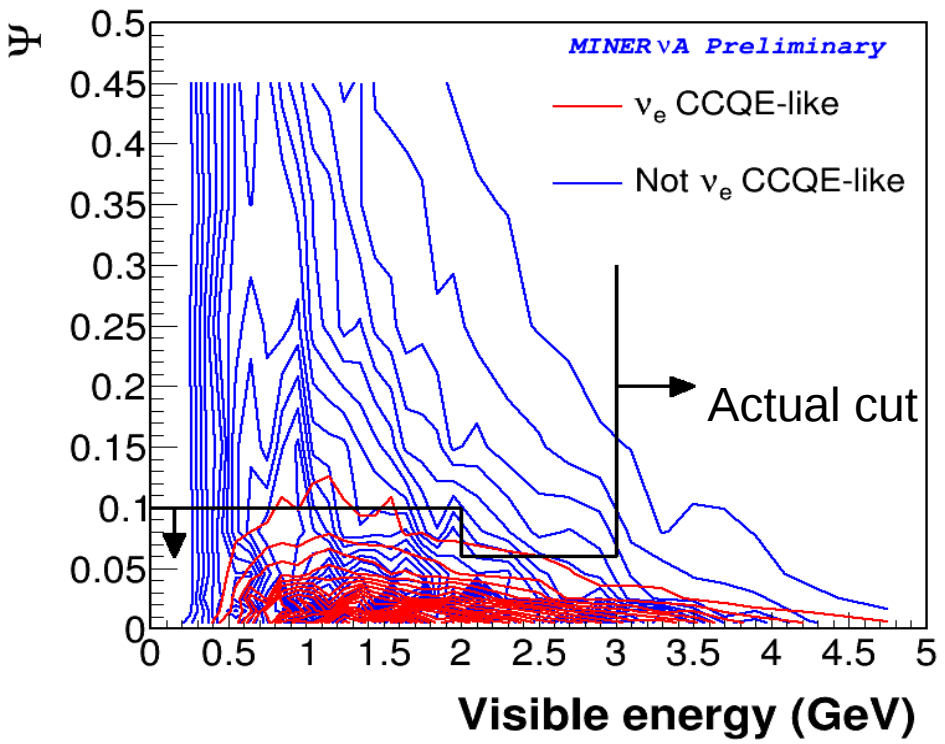
Cut on $\Psi = \frac{E_{extra}}{E_{cone}}$



Simulated ν_e CCQE

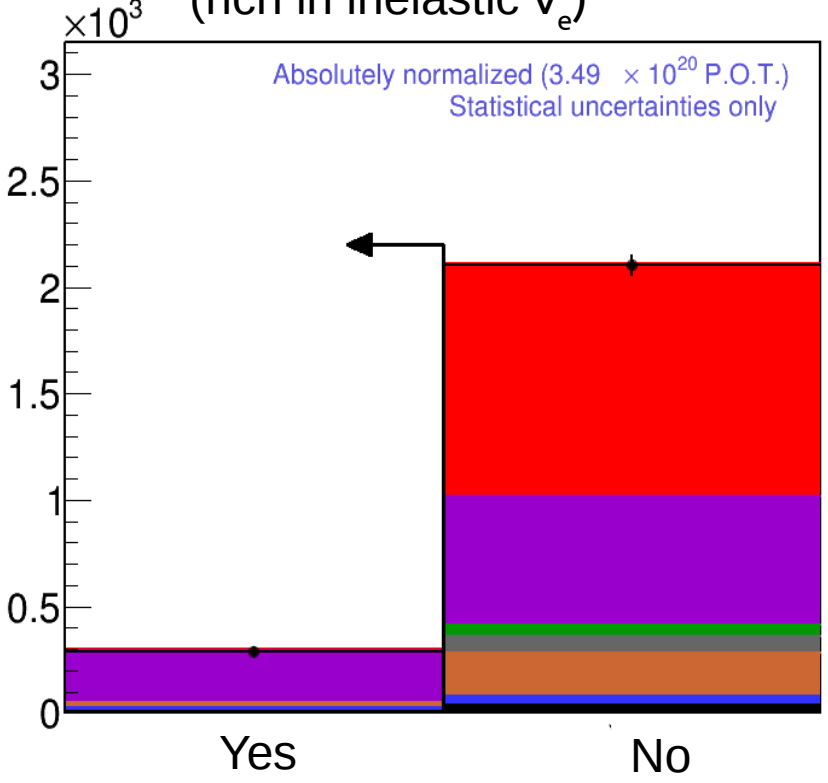


After marginalizing over all E_{vis}. Cut illustrated is around most probable value of E_{vis} = 1.25 GeV.



Constraining backgrounds

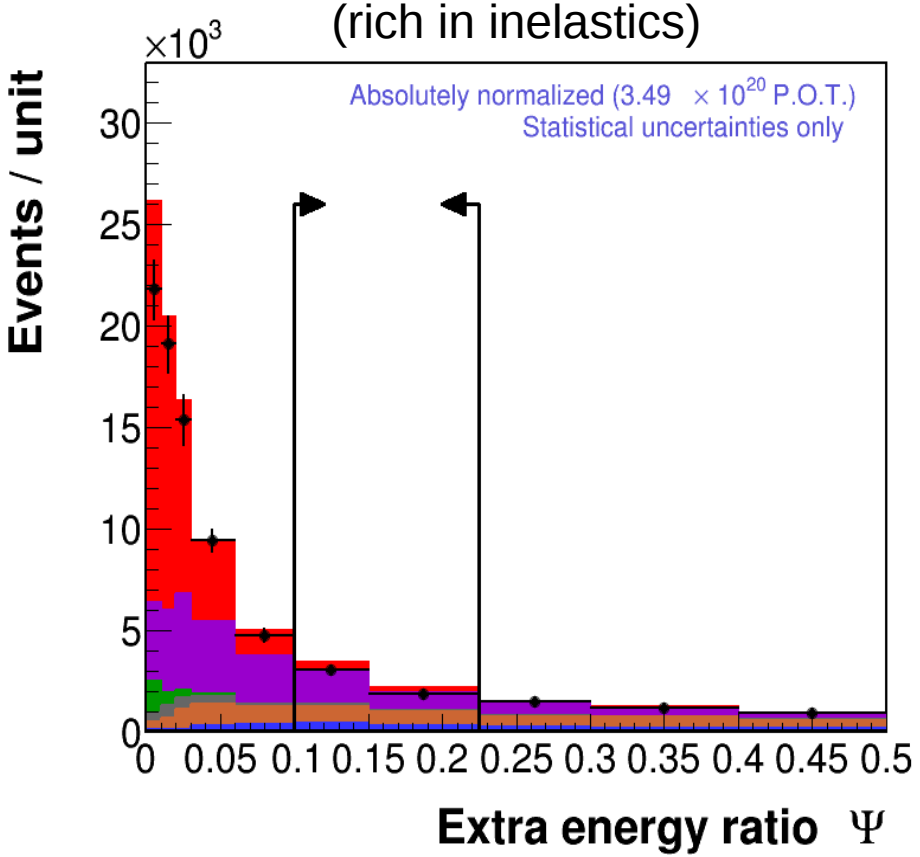
Sideband 1: contains Michel e±
(rich in inelastic ν_e)

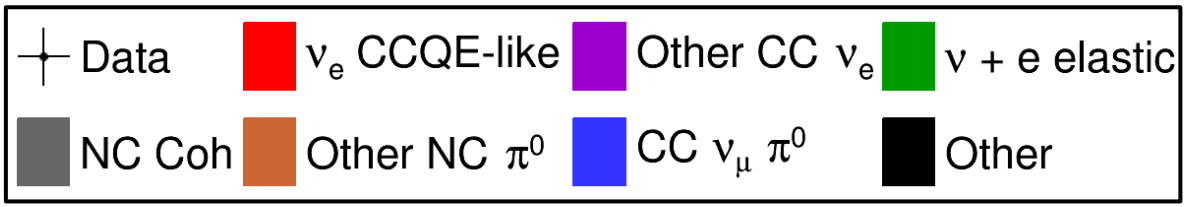


Does event have a Michel electron?

$(\pi \rightarrow \mu \rightarrow e)$

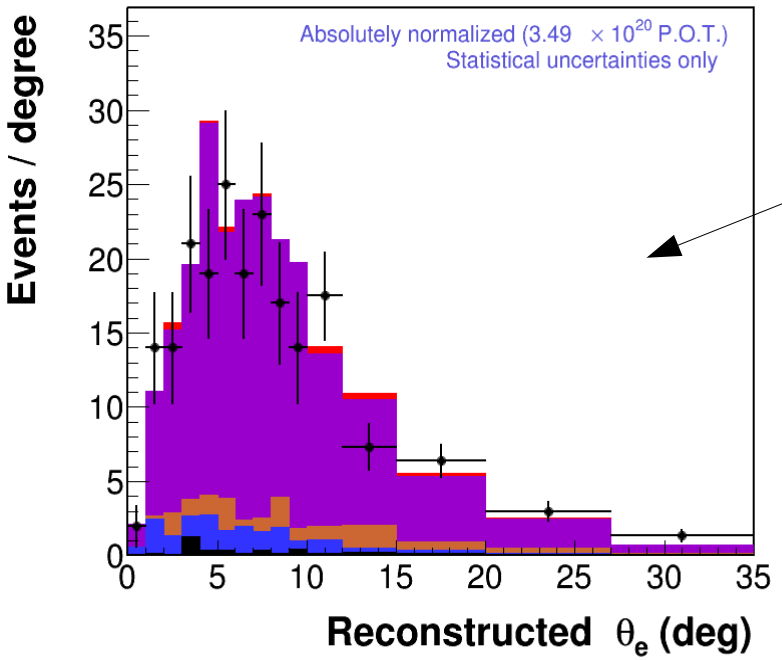
Sideband 2: larger "extra energy"
(rich in inelastics)

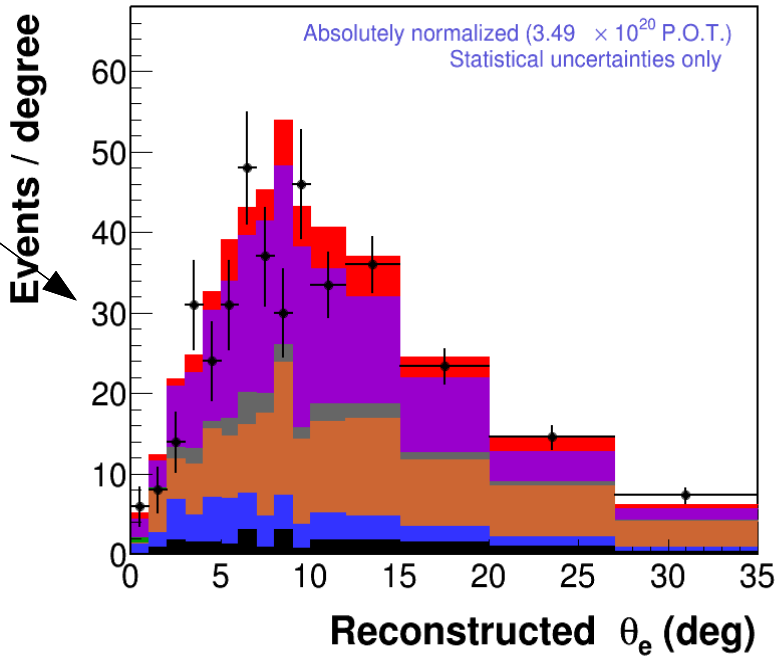




Select two sidebands rich in the major backgrounds...

Background constraint: θ_e

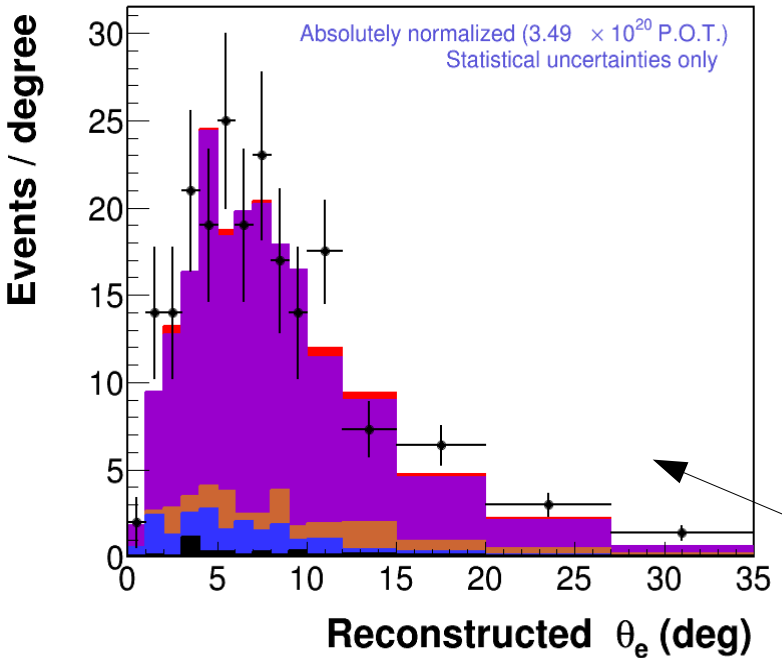


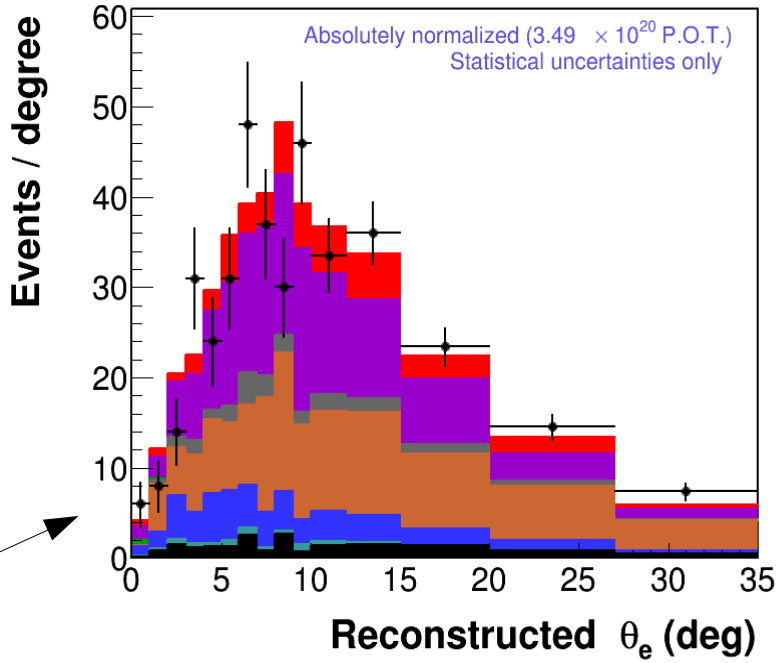


Before constraint

Michel electron sideband

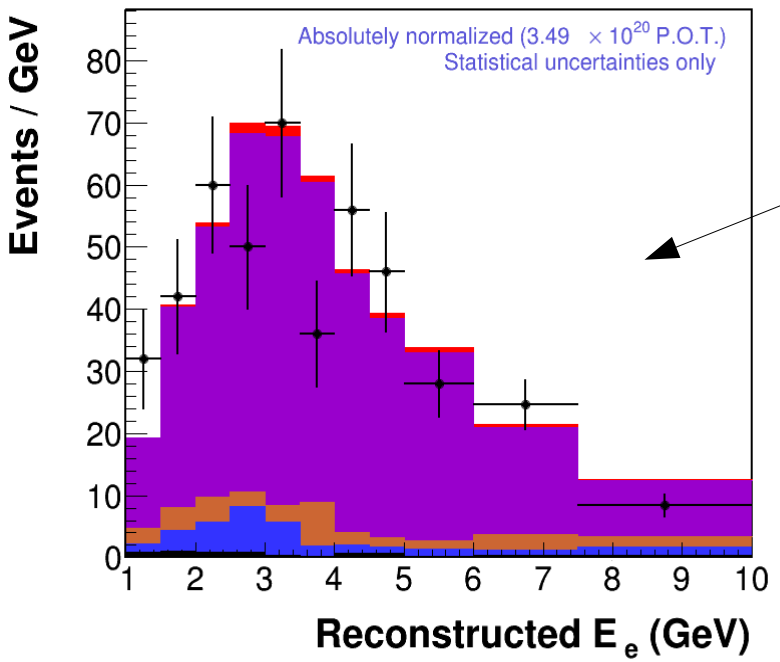
Extra energy sideband

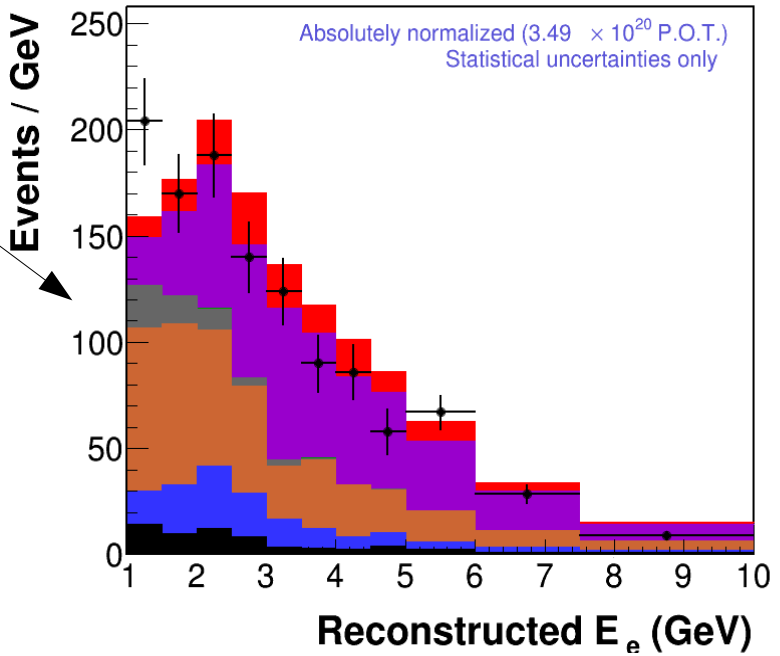




After constraint

Background constraint: E_e

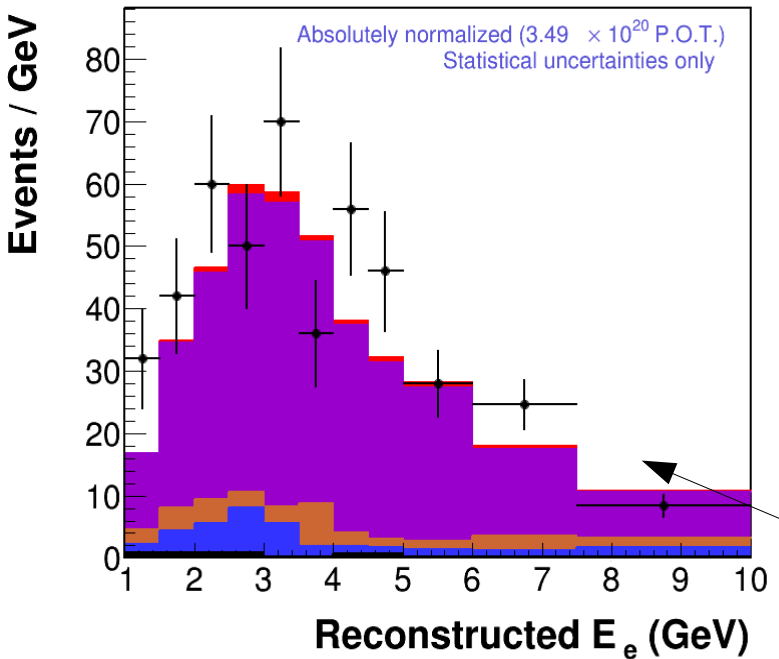


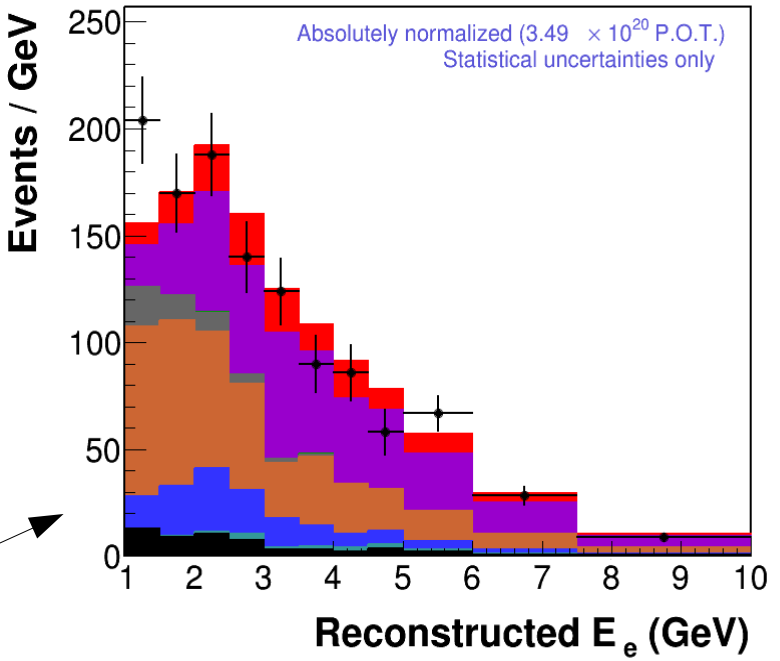


Before constraint

Michel electron sideband

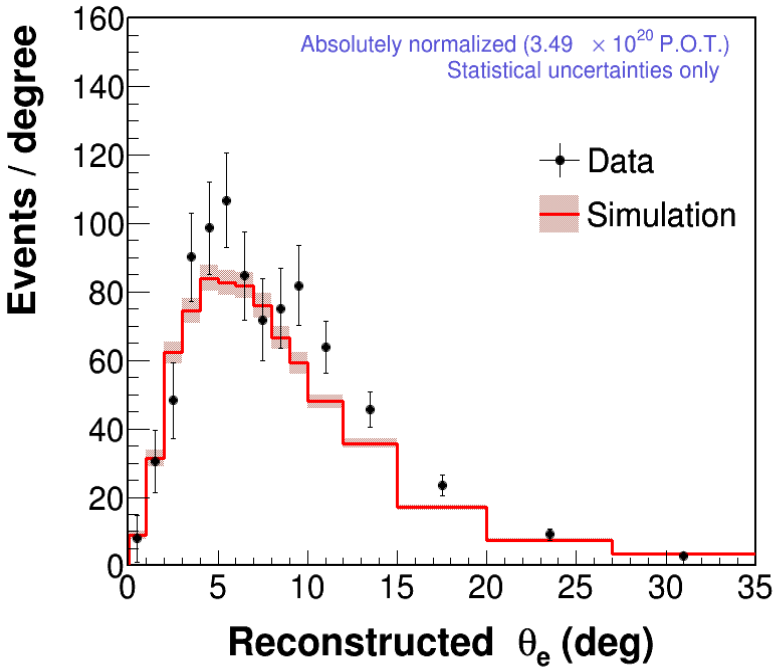
Extra energy sideband

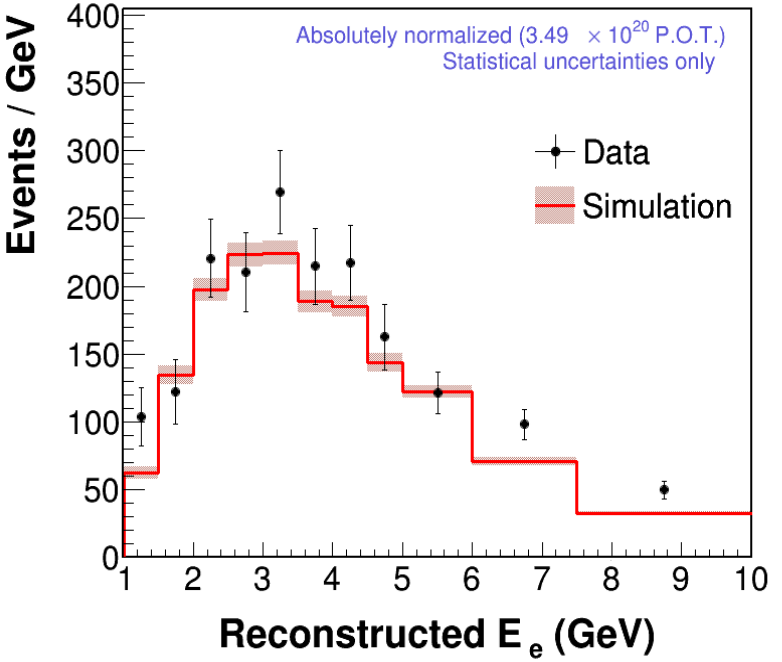


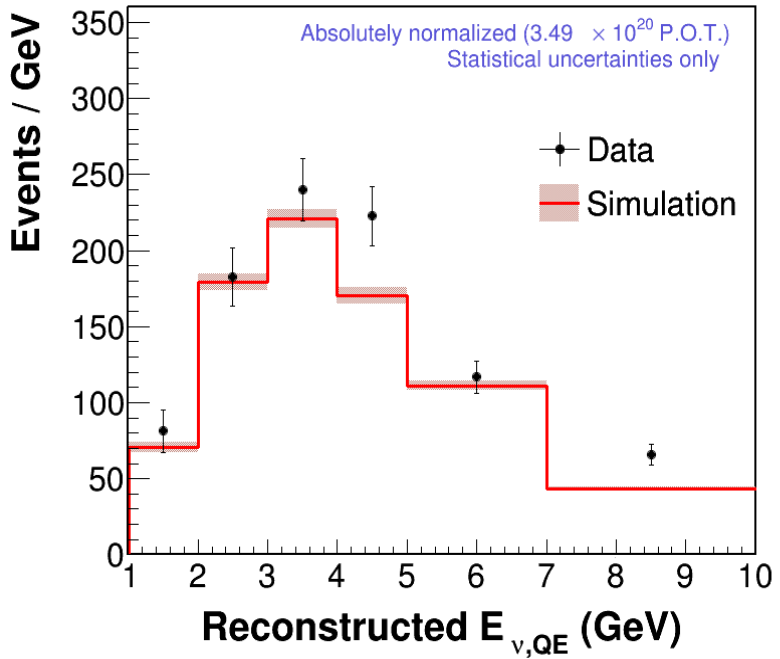


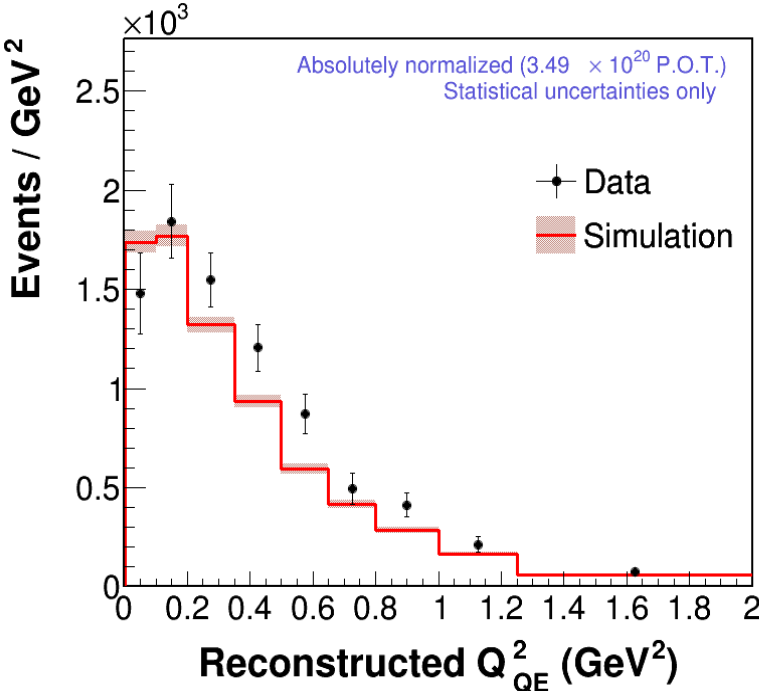
After constraint

Background-subtracted distributions

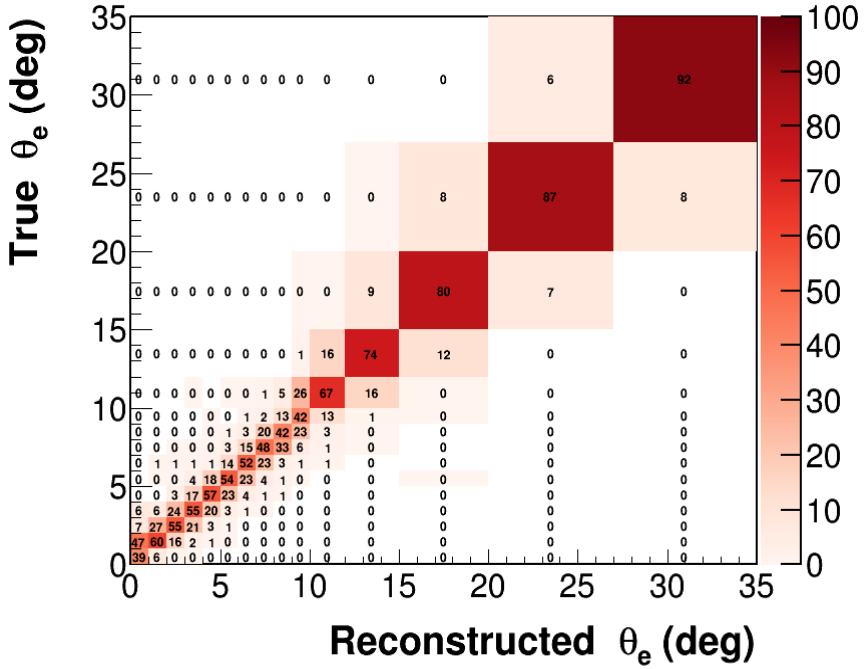


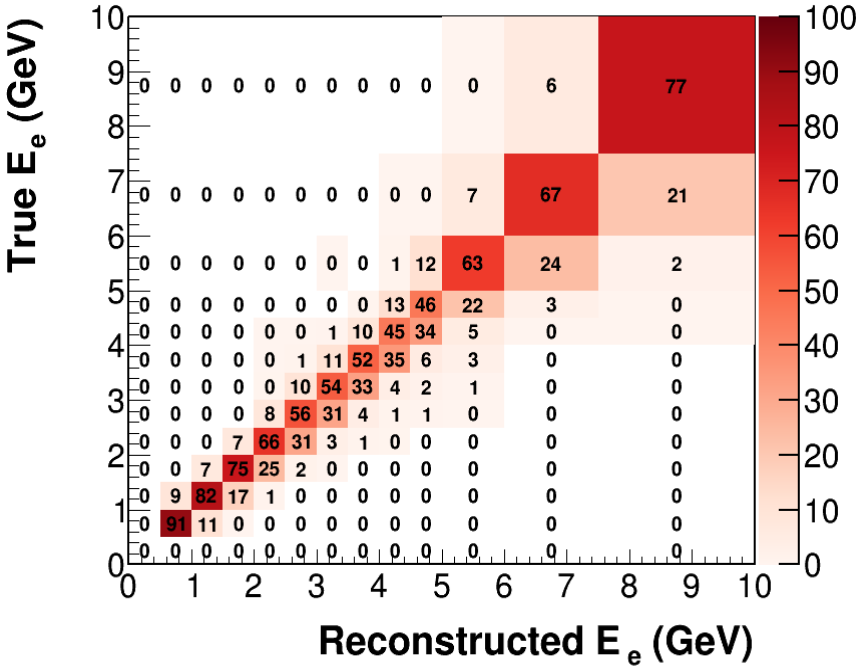


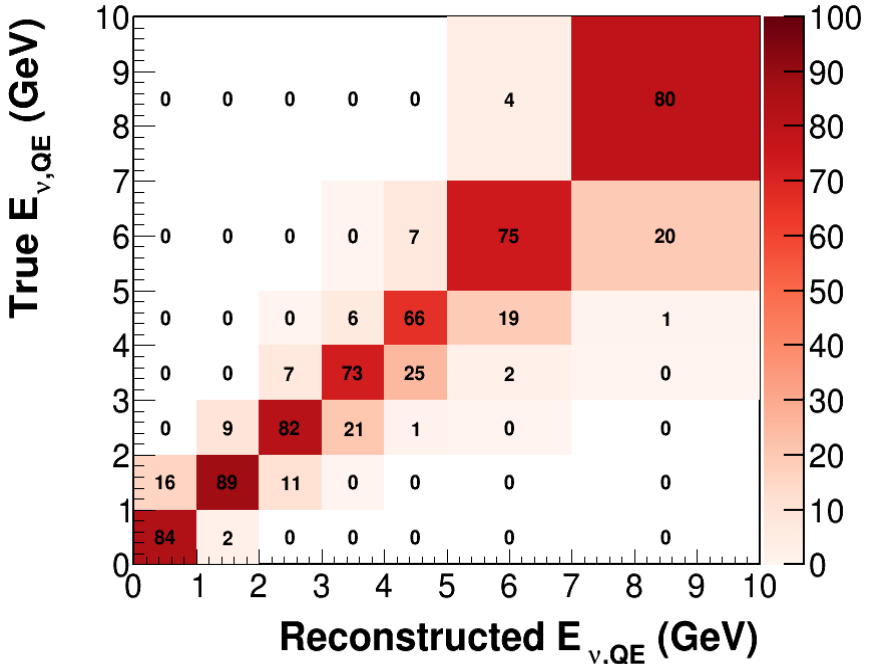


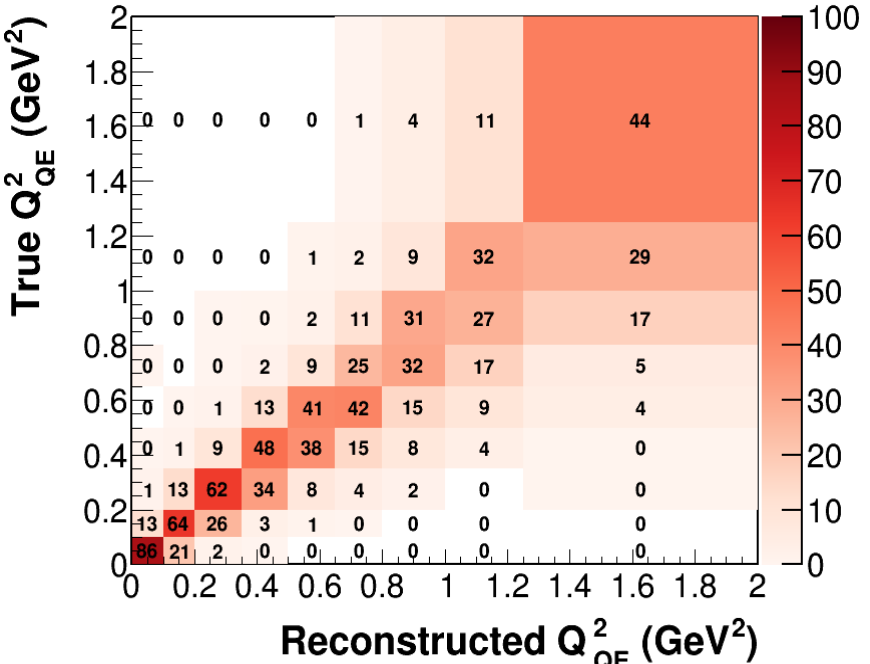


Migration matrices

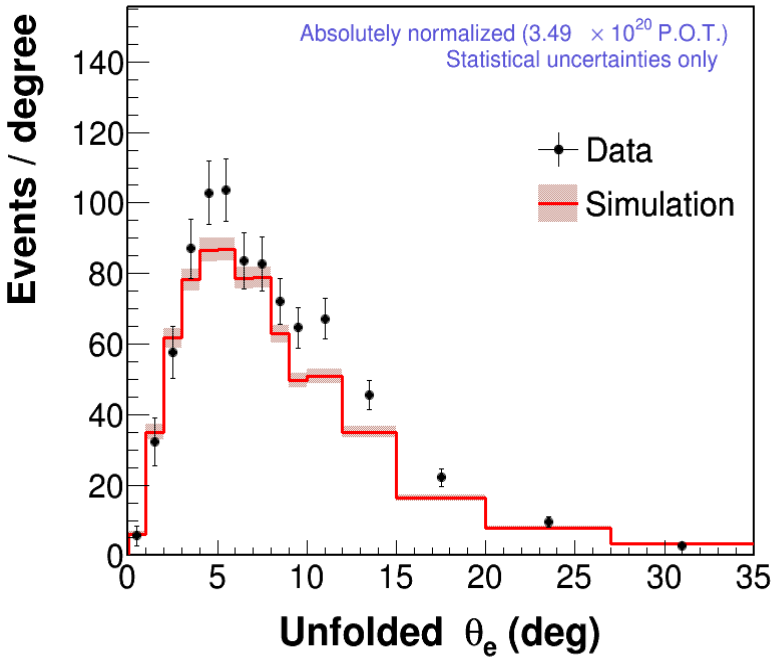


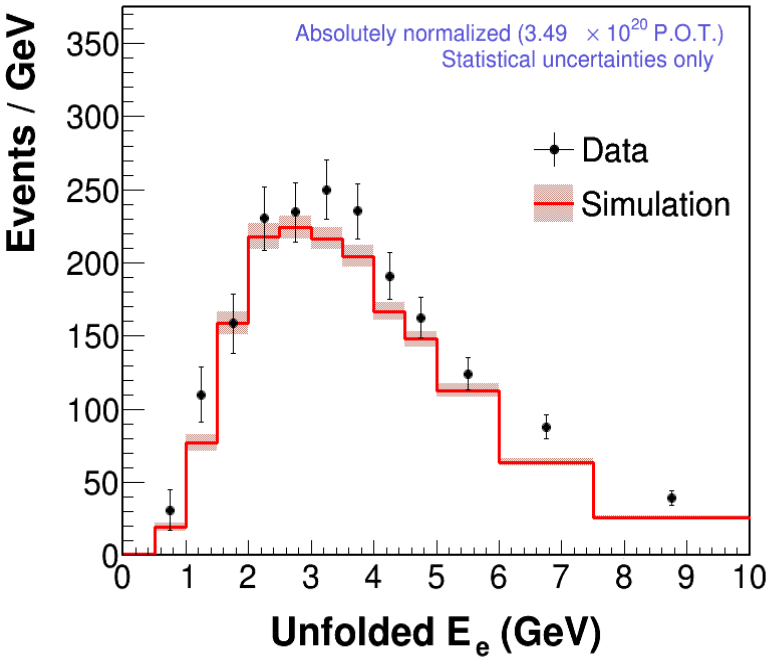




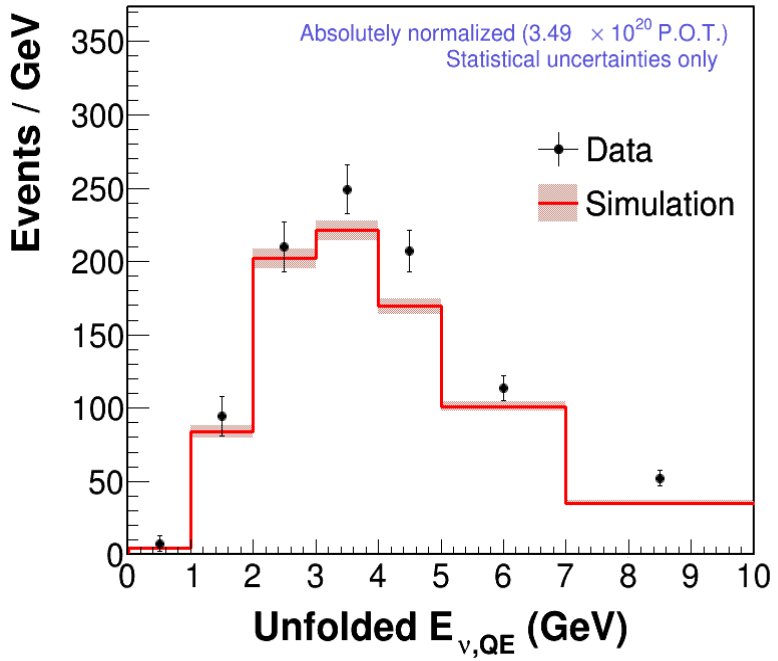


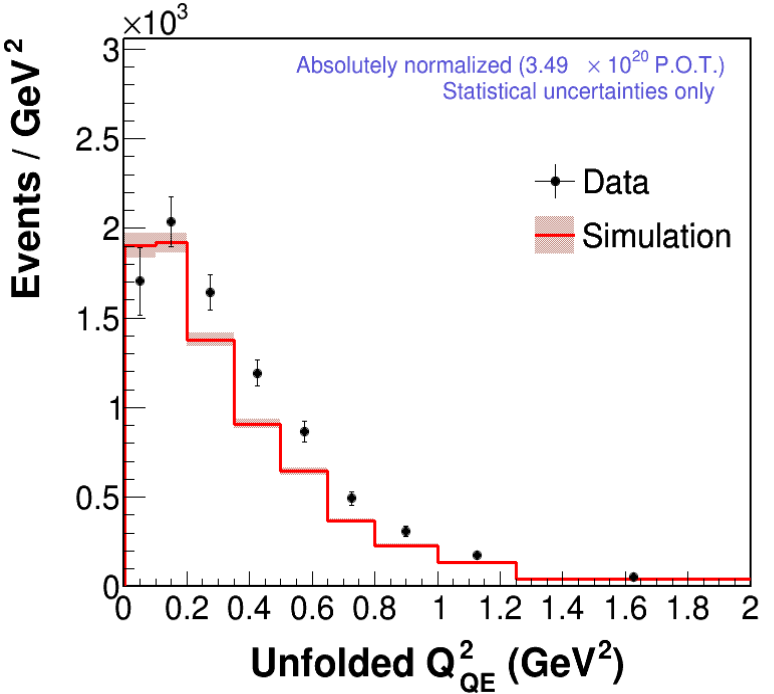
Unfolded distributions



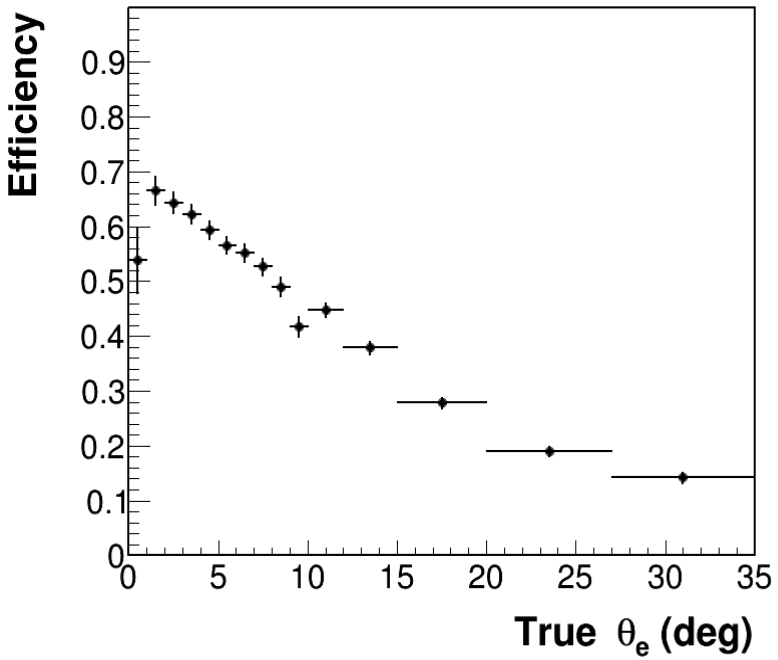


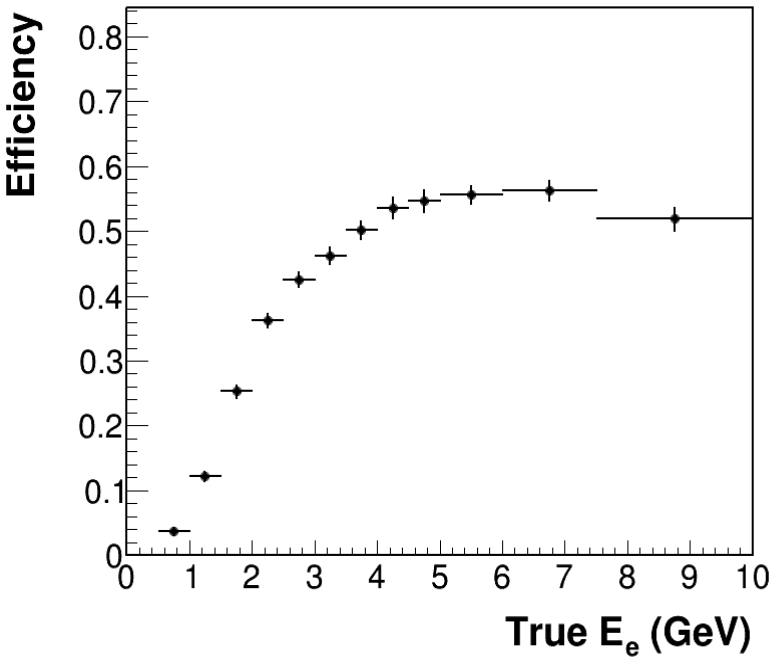
We use *one* iteration of a Bayesian unfolding technique.



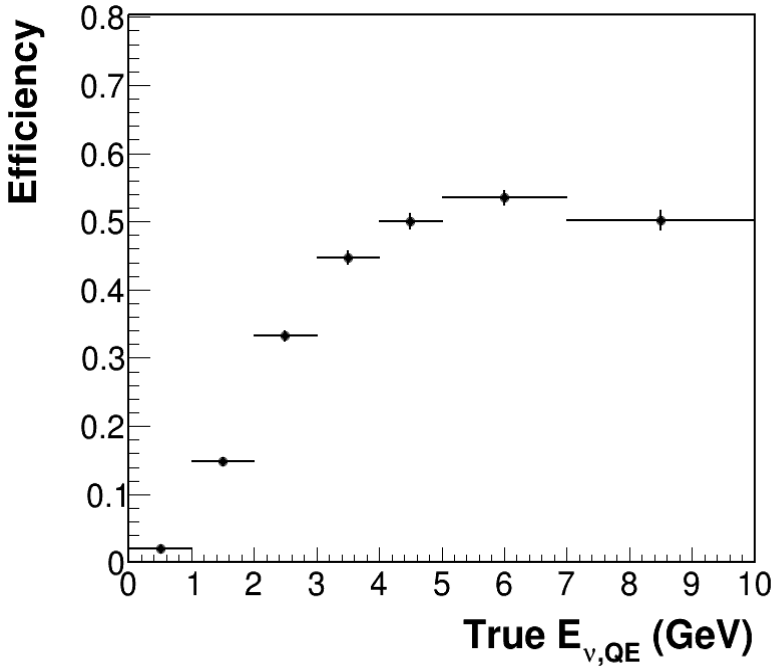


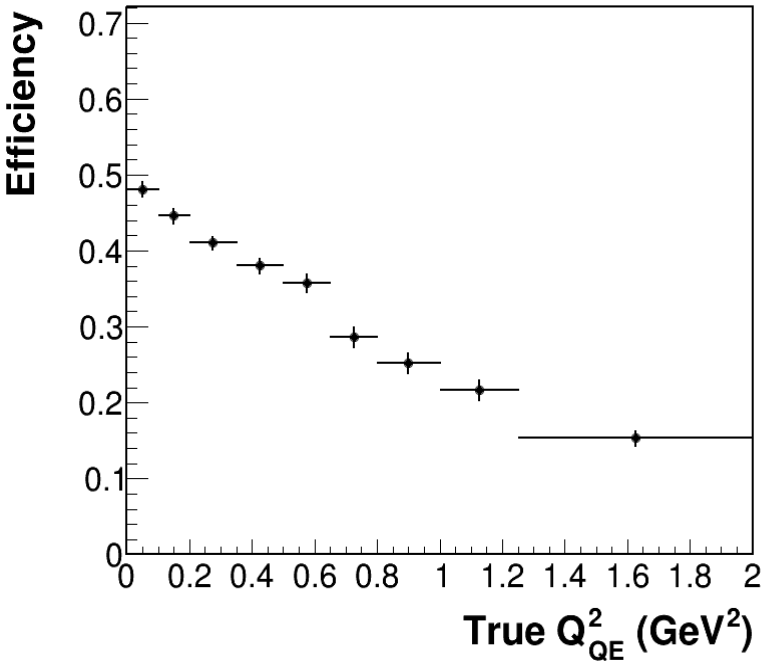
Efficiency



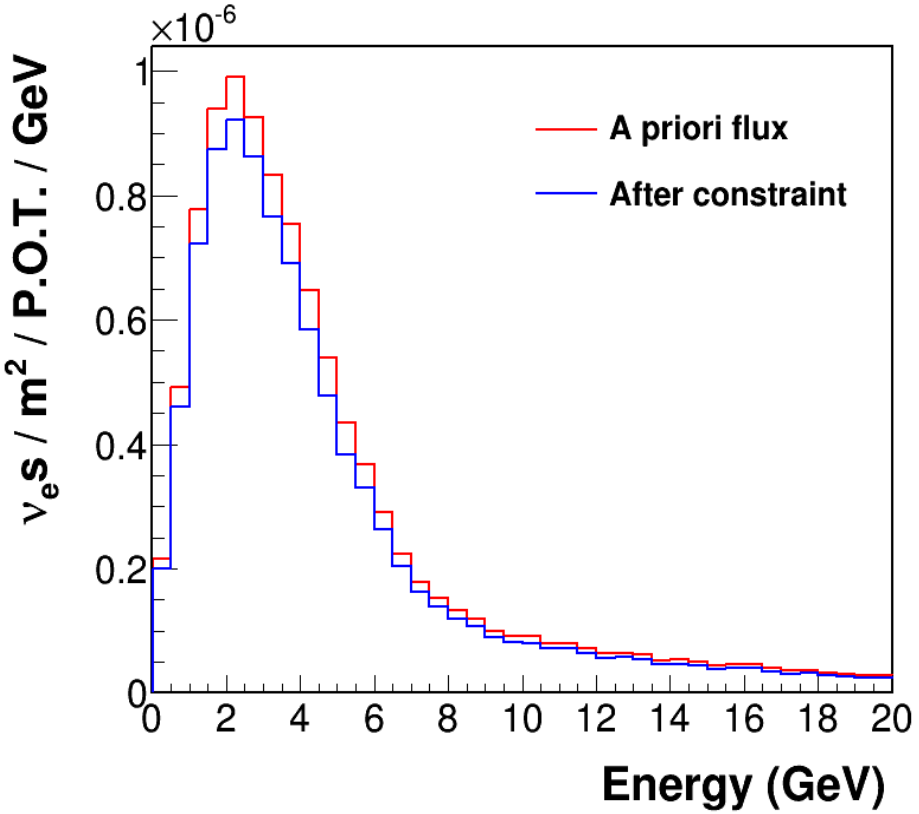


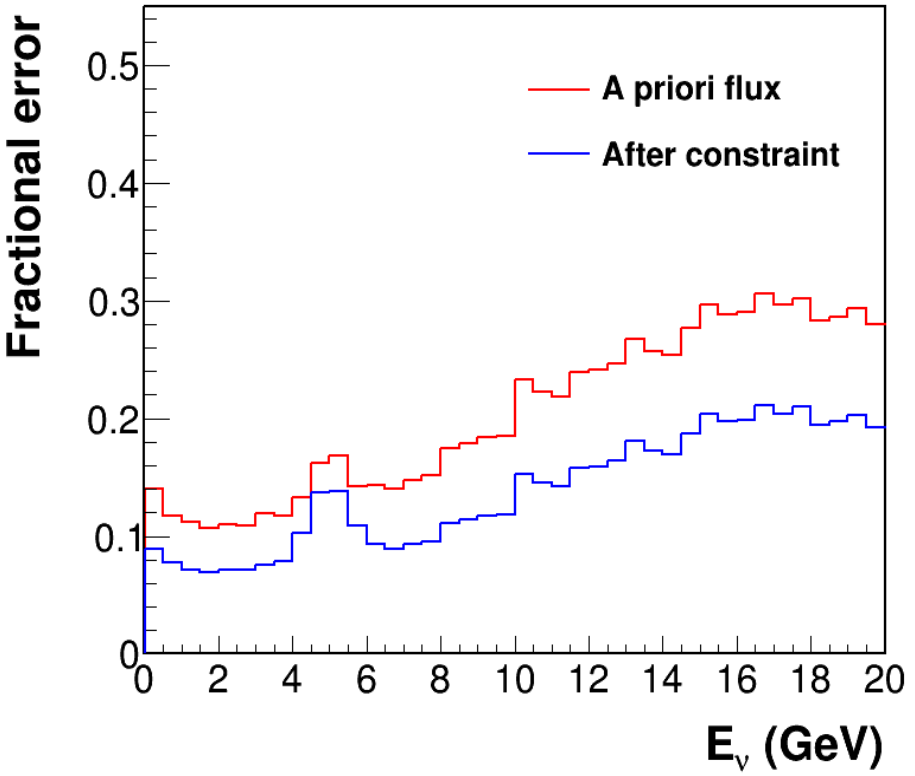
Mean selection efficiency is 35.3%.





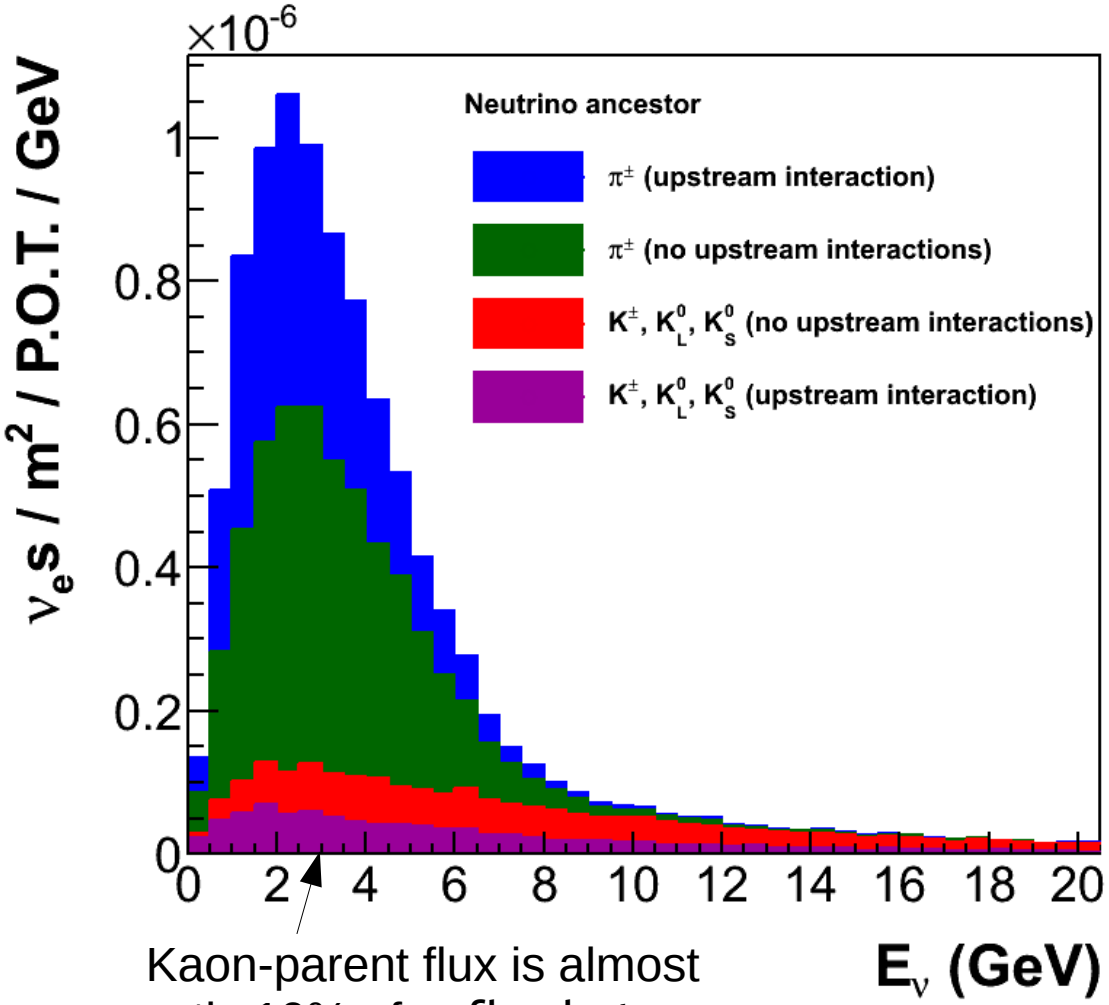
Constrained flux prediction



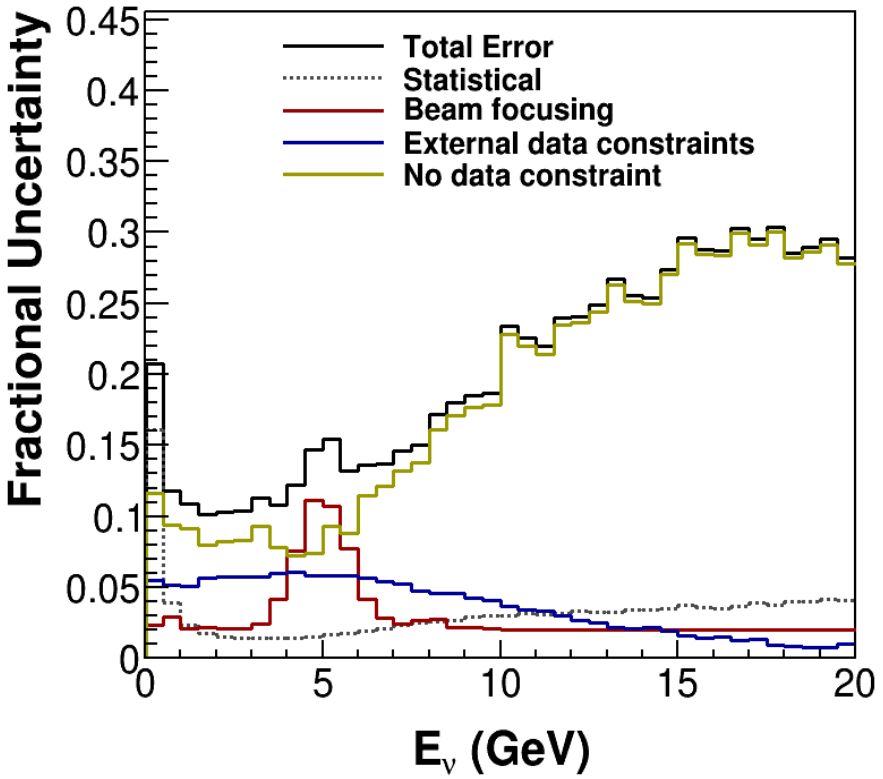


Reduction of 5-10% in prediction,
and 5-10 percentage points in predicted uncertainty as well

Flux prediction: ancestry

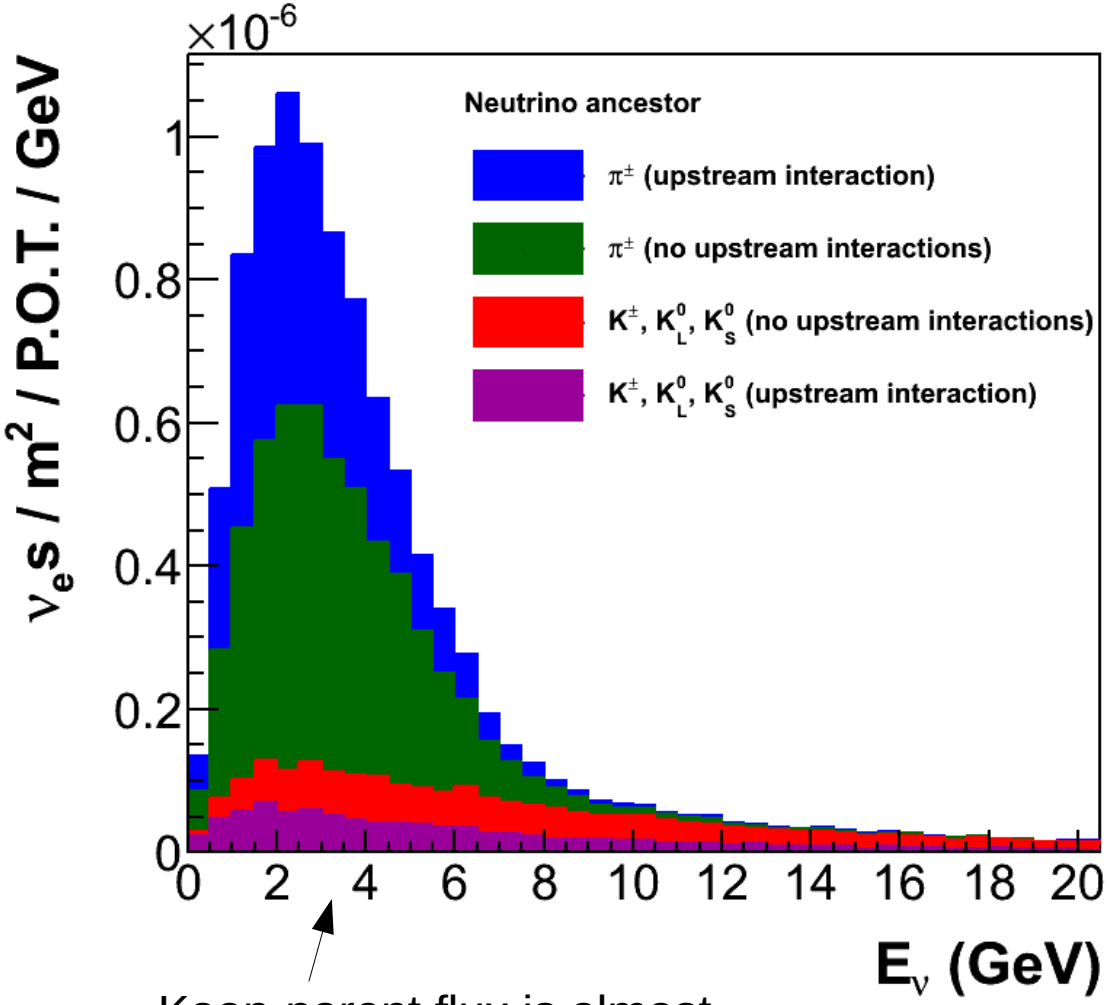


Kaon-parent flux is almost exactly 10% of ν_e flux between 0 and 10 GeV



A priori uncertainties

Flux prediction: ancestry



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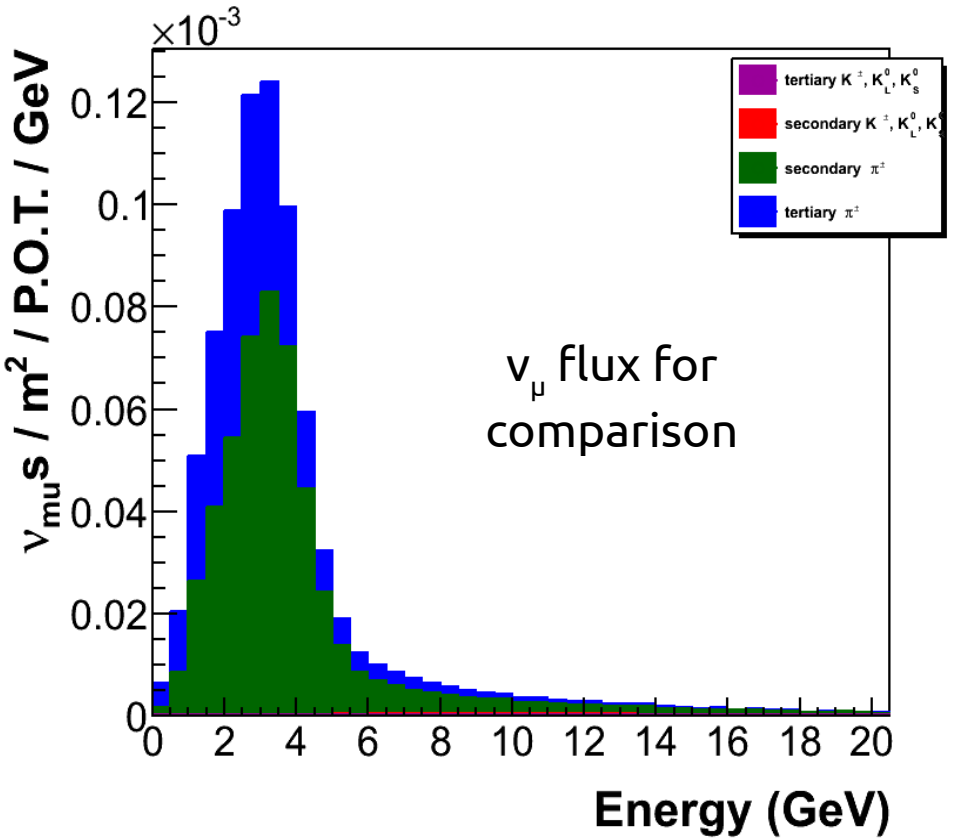
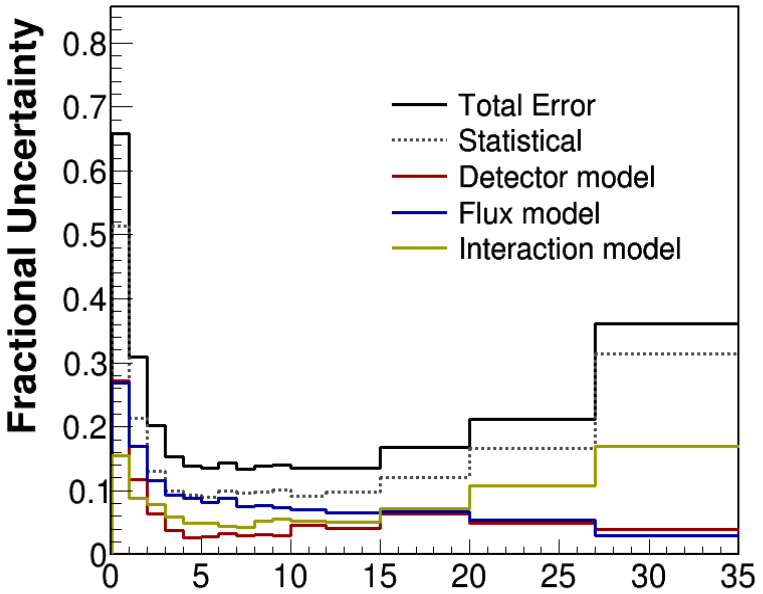
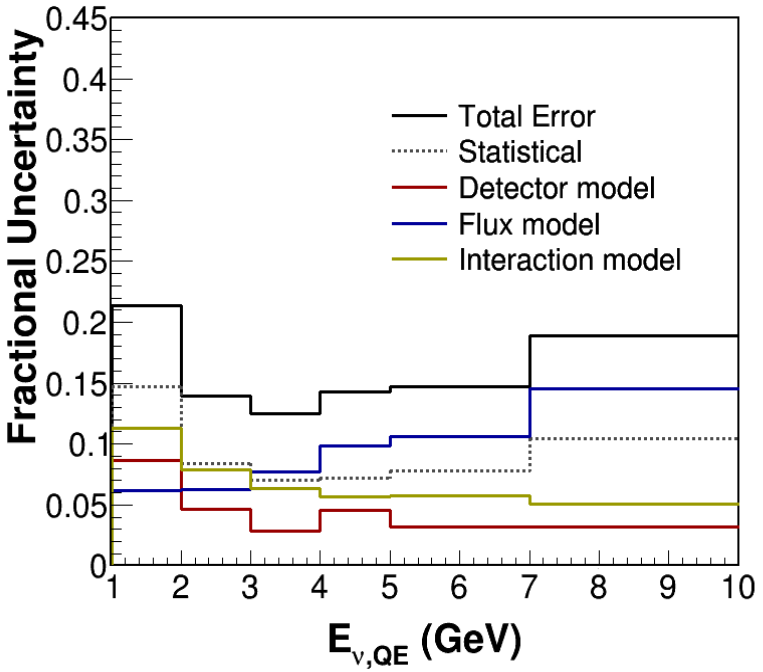


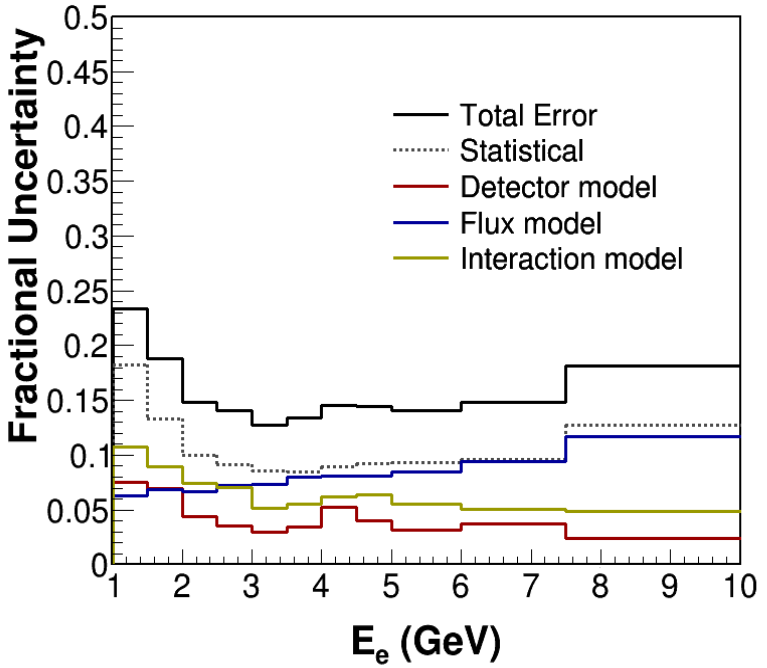
ν_μ flux for comparison

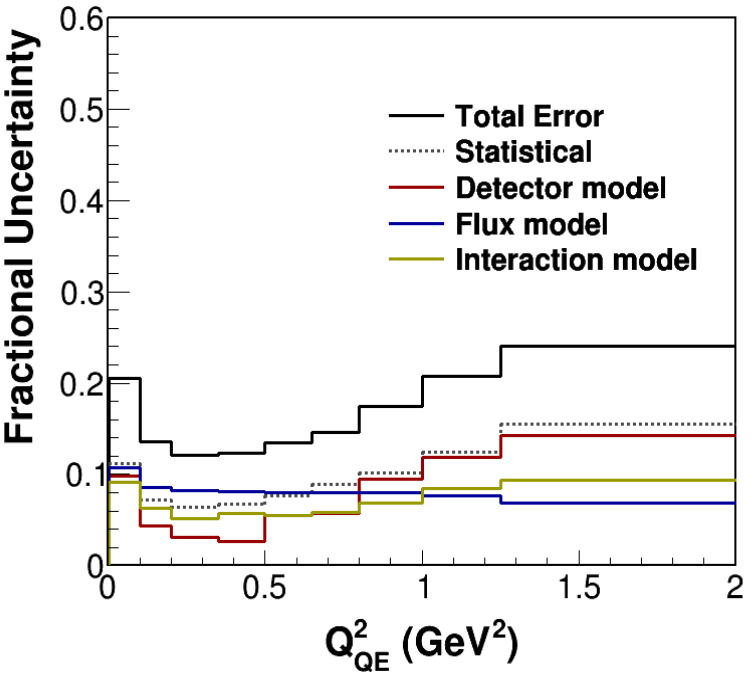
Cross-section uncertainties





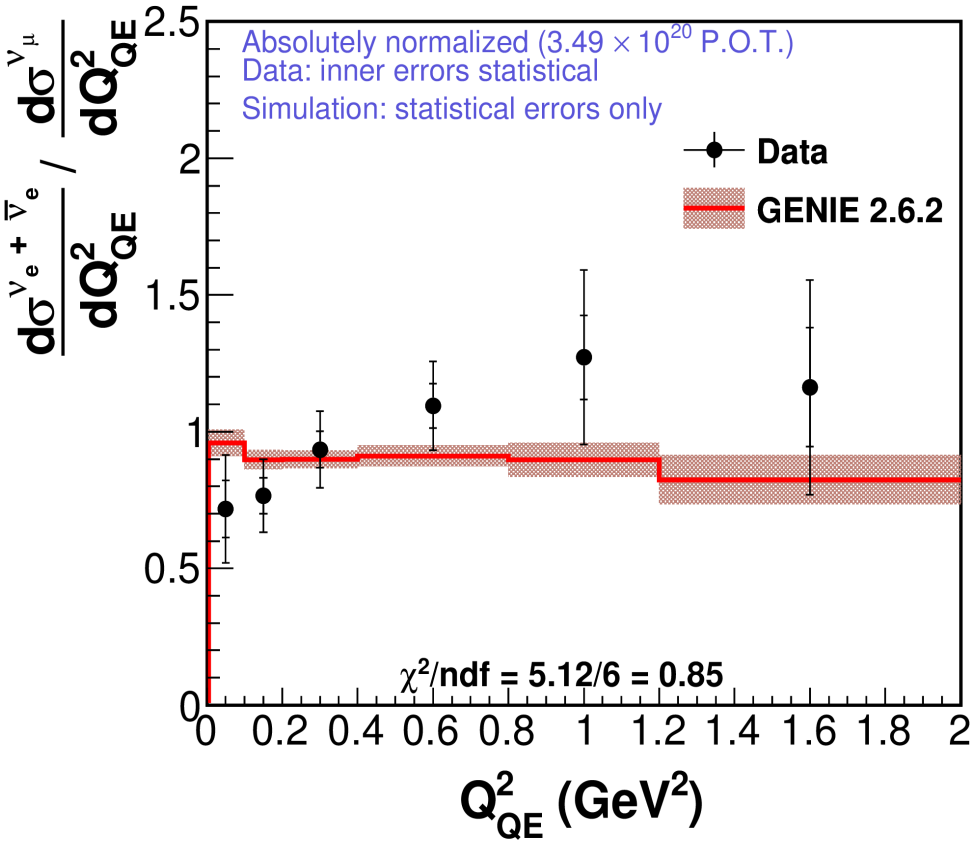
The GENIE interaction model and statistics are comparable in most cases (depending on binning)

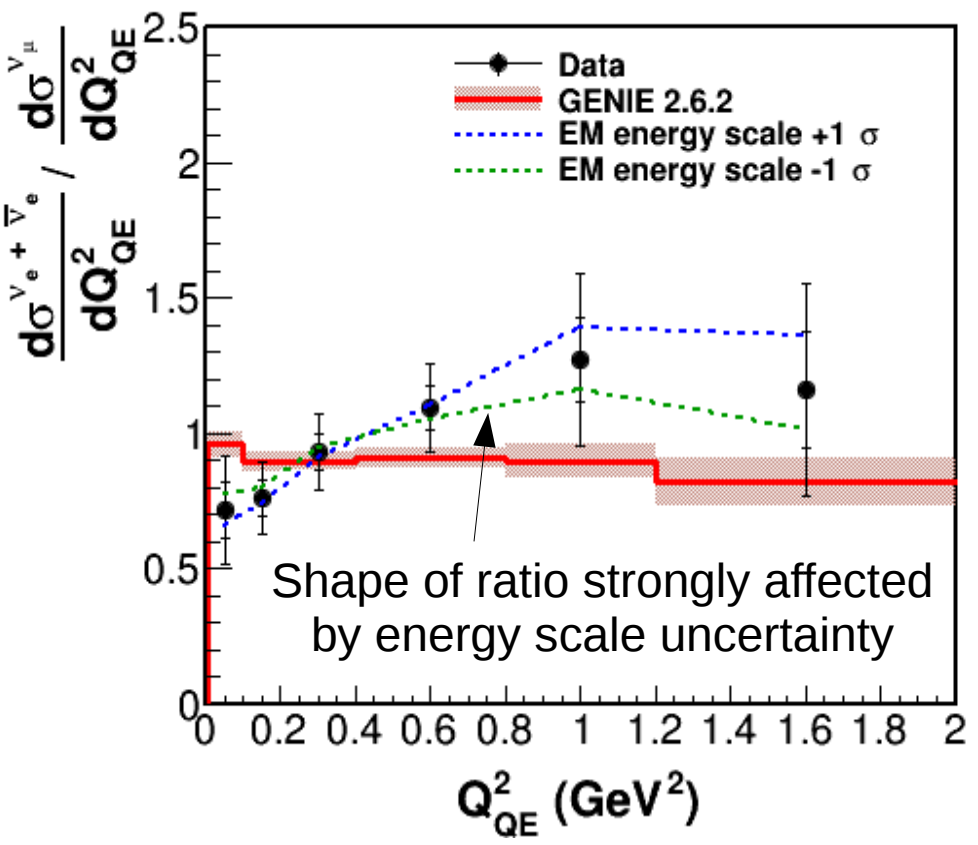




ν_e-ν_μ comparisons

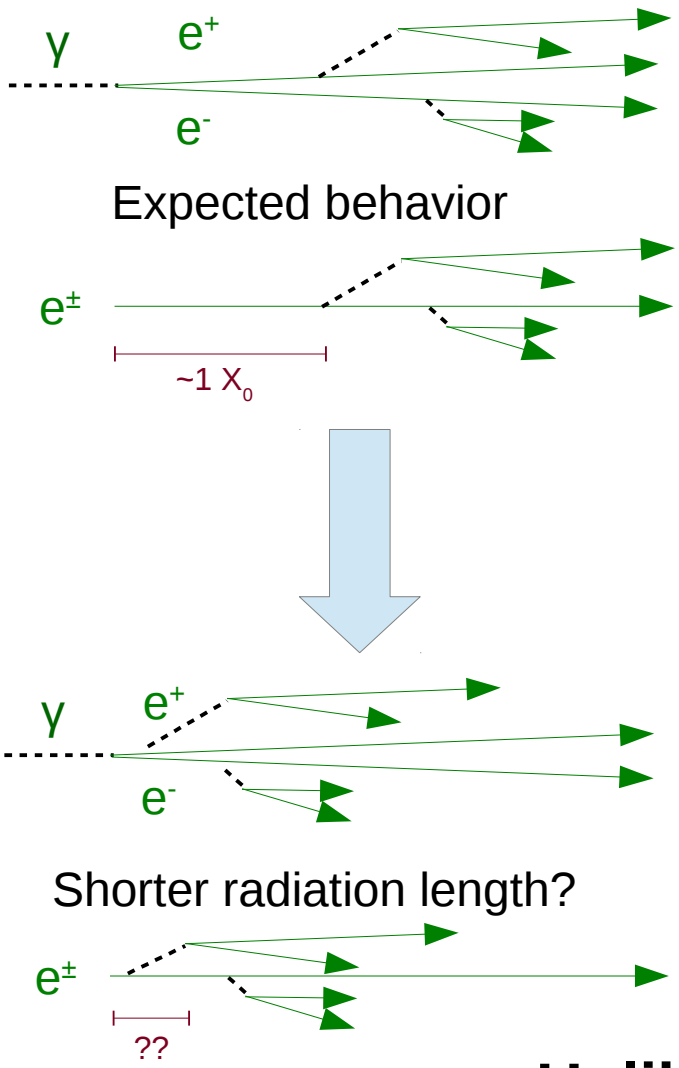
Q^2 is the fundamental independent variable in the CCQE models.
We can compare $d\sigma/dQ^2$ to a previous measurement from MINERvA on ν_μ to directly test the principle of lepton universality our models rely on.

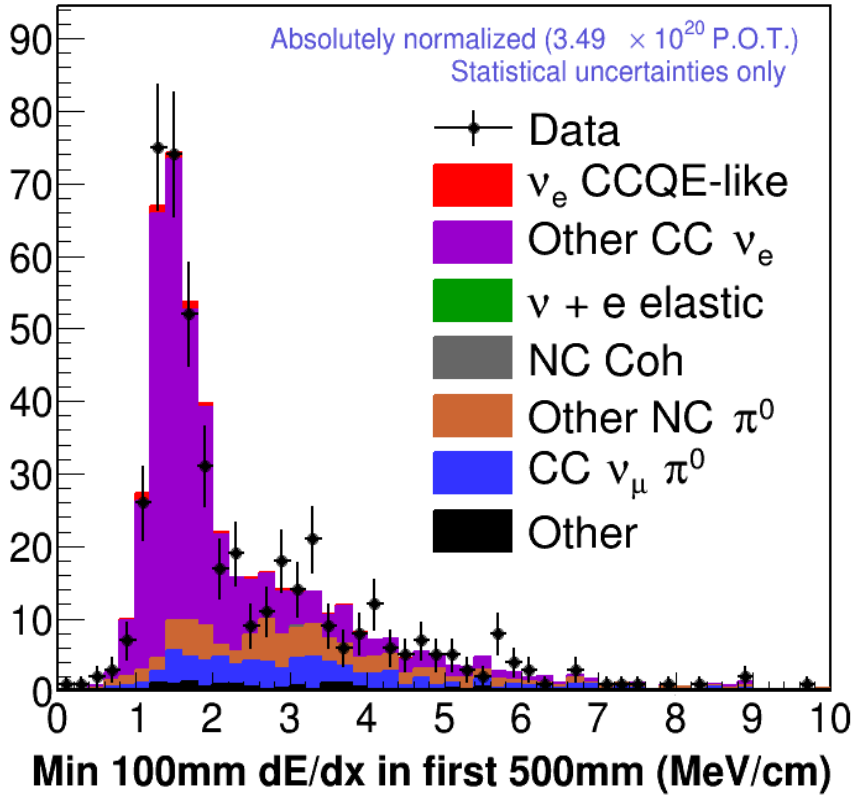




p.s.... beware: don't read too much into the shape.
The shape is not significant when the correlations in the uncertainties are taken into account.

Could it just be more electrons?



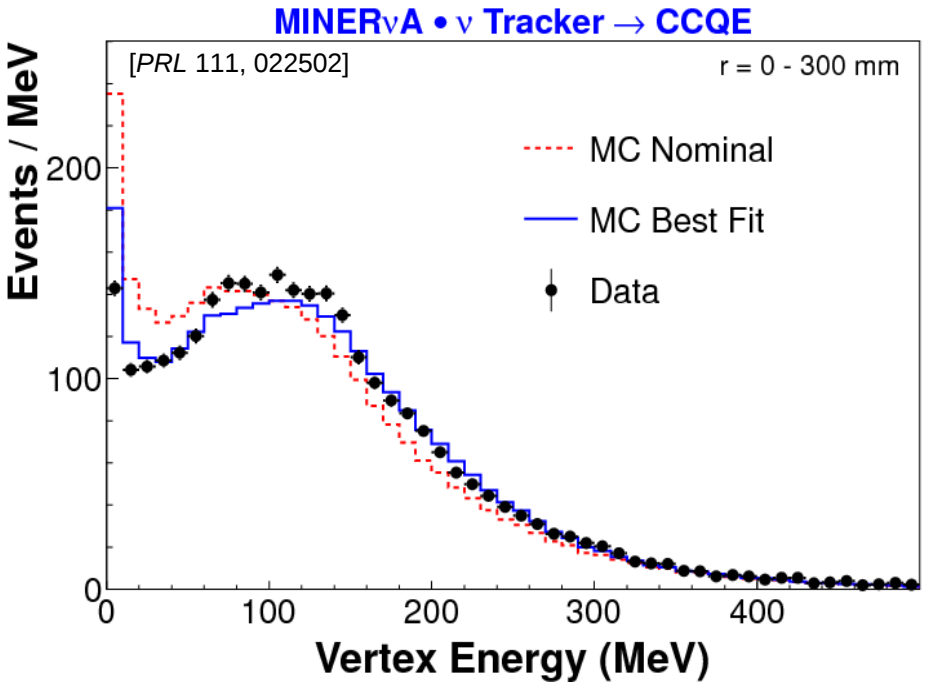


Michel electron sideband is heavily dominated by ν_e.

Very well modeled (χ^2/n.d.f. = 63.5/50).

Unlikely to be an electron shower modeling problem.

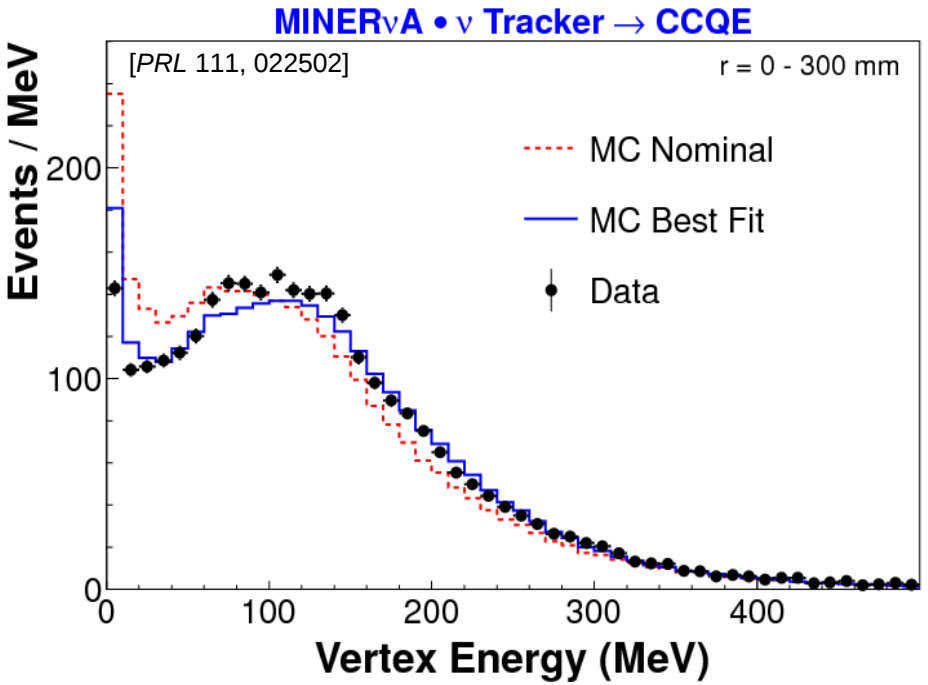
Could it be extra nuclear activity?



MINERvA muon neutrino CCQE found evidence that sometimes more particles are produced at the vertex than the simulation predicts.

Does the excess stem from overlap between extra particles and the electron shower?

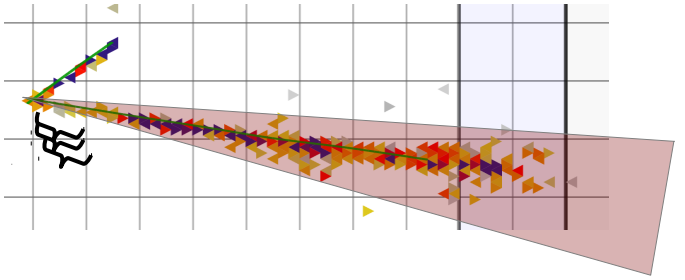
Could it be extra nuclear activity?



MINERvA muon neutrino CCQE found evidence that sometimes more particles are produced at the vertex than the simulation predicts.

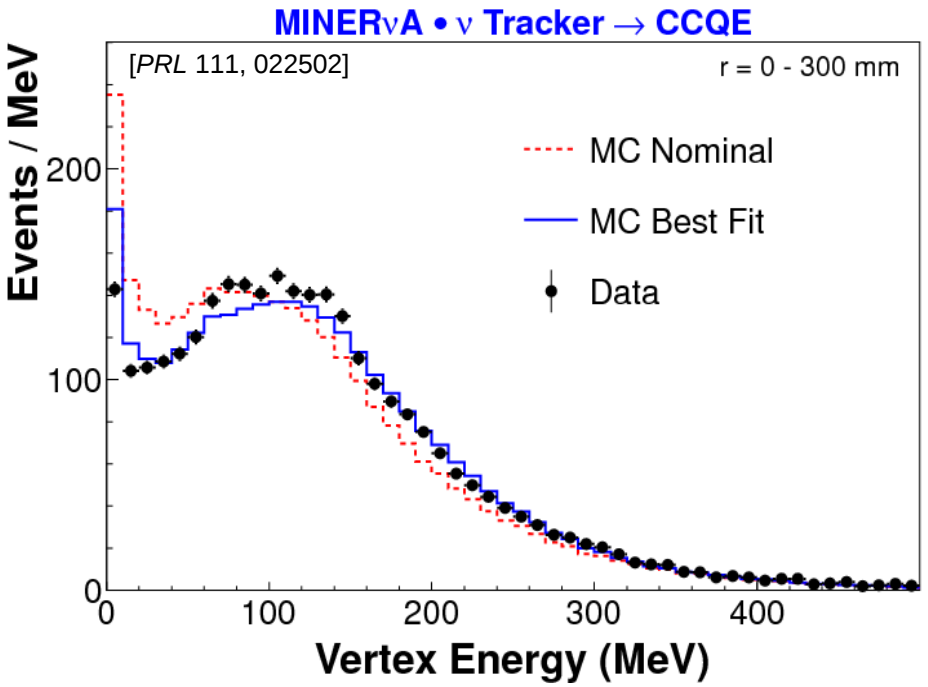
Does the excess stem from overlap between extra particles and the electron shower?

(Simulated signal event)



Use a sliding techinque that looks for the *minimum* 100mm dE/dx in the first 500mm of cone. Designed to "step over" overlaps from nuclear activity

Could it be extra nuclear activity?



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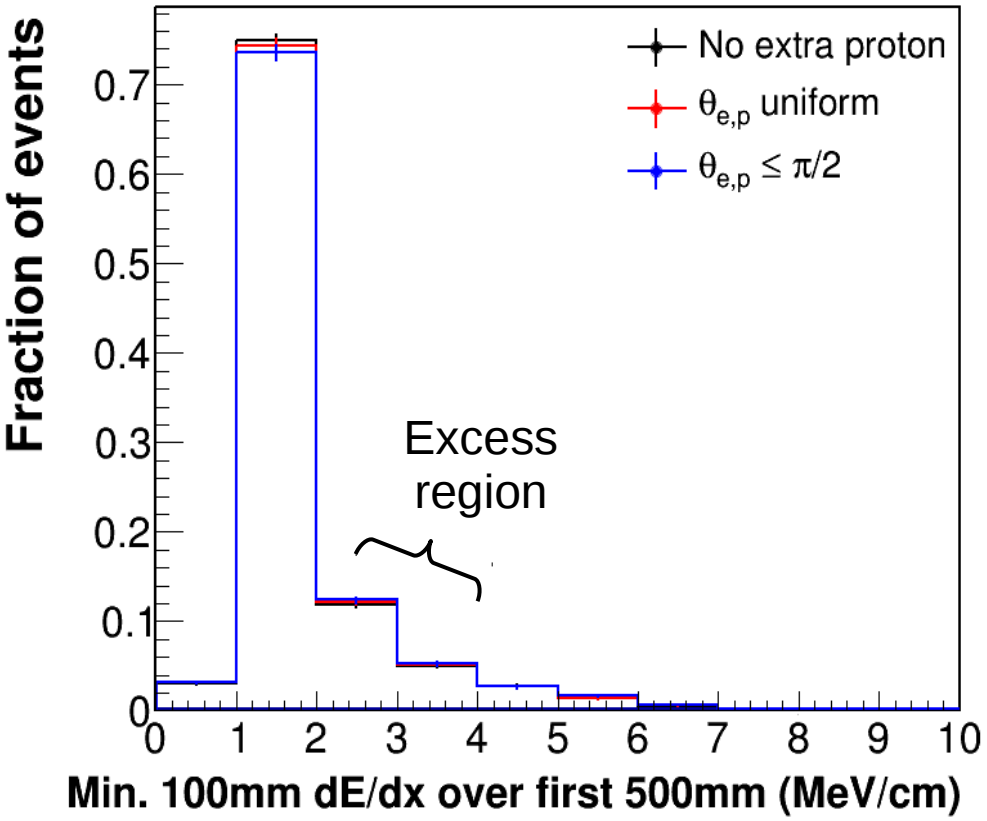

Toy studies with extra protons of 0-200 MeV added randomly to 25% of ν_e CCQE events do not create a measurable excess.

Not likely due to extra particles in ν_e CCQE events.