Electron neutrino quasielastic scattering

and

Observation of neutral-current diffractive-like process

at MINERvA

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Fermilab Joint Experimental-Theoretical Physics Seminar
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Overview

- Introduction and motivation
  - Significance of ν_e cross sections for ν oscillation
  - The MINERvA experiment
- ν_e CCQE (0π) in MINERvA
  - Selection and reconstruction of events
  - Cross section extraction
- NC diffractive-like background
  - Characterization of event sample
  - Discussion of significance
- Summary and conclusions

Introduction and motivation

The promise of ν_e appearance

ν_e appearance is a centerpiece in modern ν physics!

T2K

BooNE
BOOSTER NEUTRINO EXPERIMENT

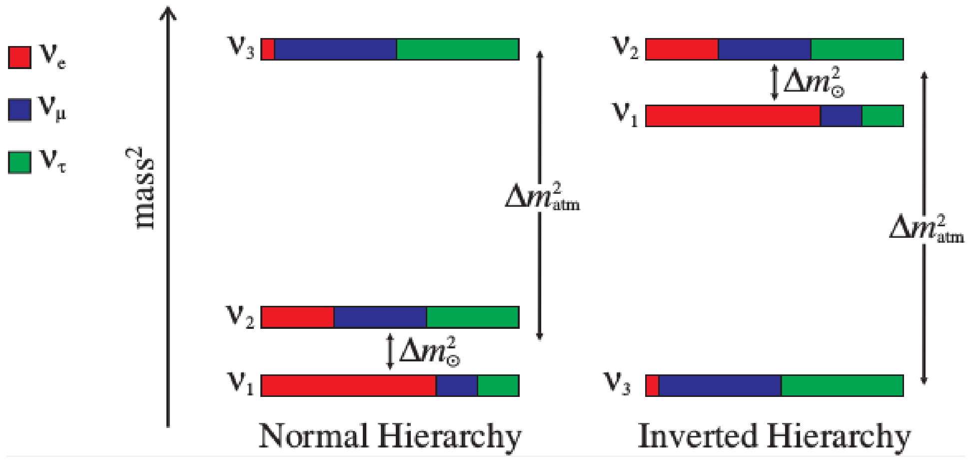
NOvA

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Hyper-Kamiokande

The promise of ν_e appearance

ν_e appearance oscillation experiments can help answer **fundamental questions** about leptons:



e.g.: How are the neutrino masses distributed?

⬇

(Are neutrinos their own antiparticles?)

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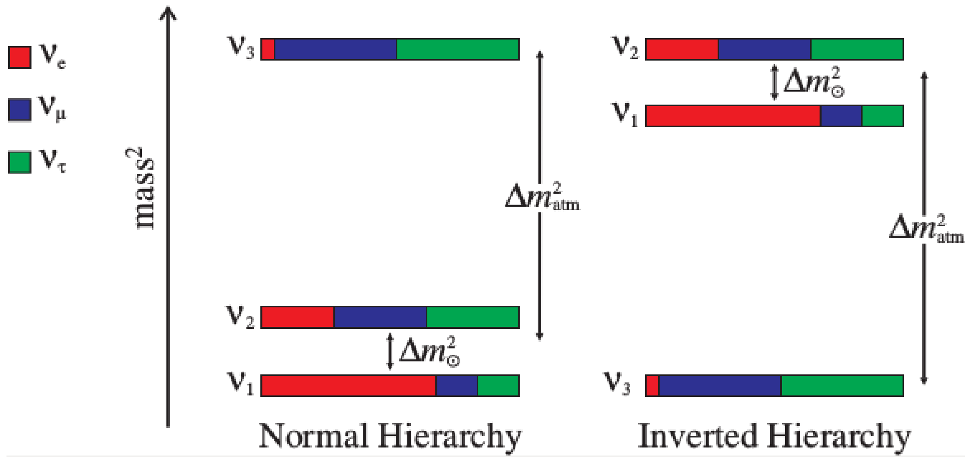

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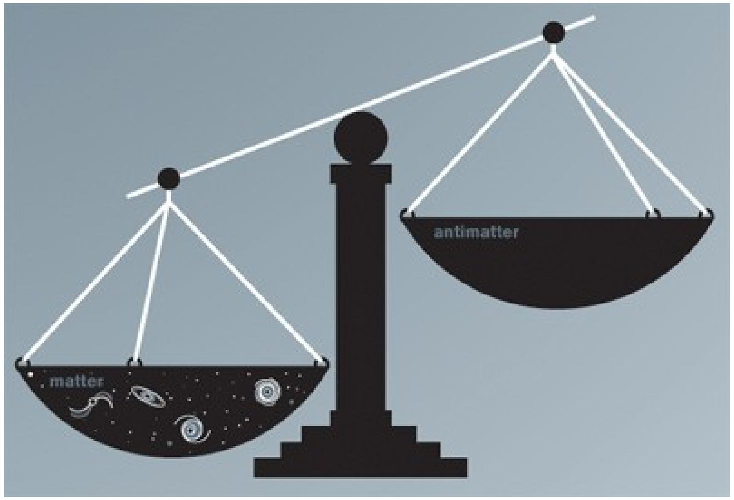


e.g.: Do leptons violate CP symmetry?

⬇

(Why is there more matter than antimatter in the universe?)

How cross sections figure into the story

Have:

(intrinsic ν_e contamination has separate spectrum)

$\Phi_{\nu_\mu} \; \sigma_{\nu_\mu}$

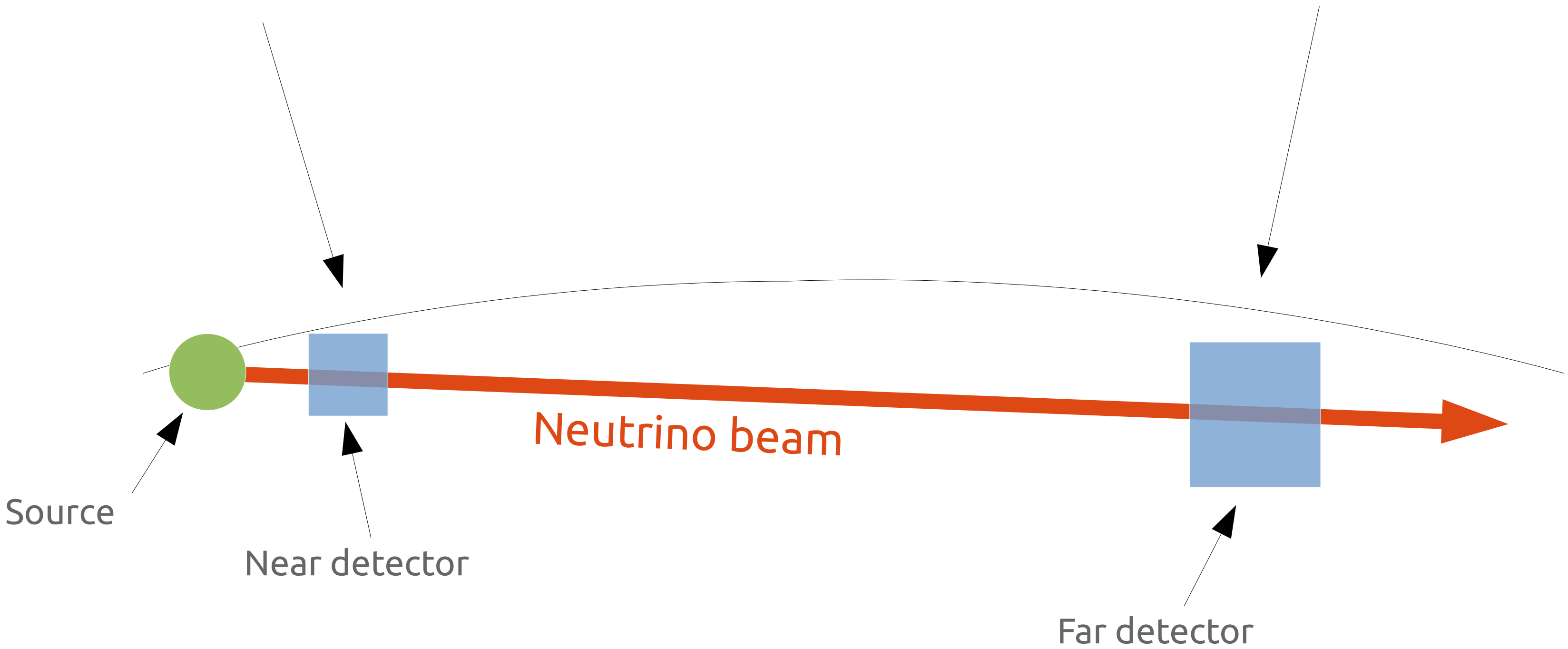
$\Phi_{\nu_e} \; \sigma_{\nu_e}$

Need model!

Need:

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

(oscillated ν_es have ν_μ spectrum)



How cross sections figure into the story

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

Need model!

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

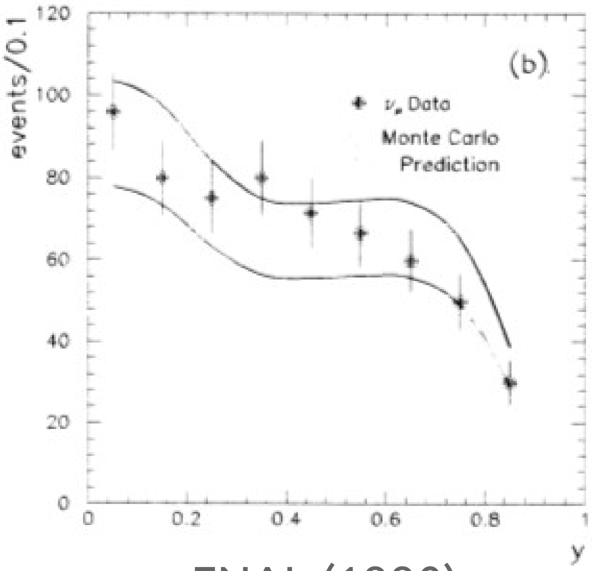
Traditionally:

- Get Φ_{ν_μ} from near detector constraint
- Lean on *lepton universality* to work out σ_{ν_e} from σ_{ν_μ}

Why worry?

Lepton universality has been extensively checked.

So what's the problem?



FNAL (1990)

Phys. Rev. D **41**: 2653

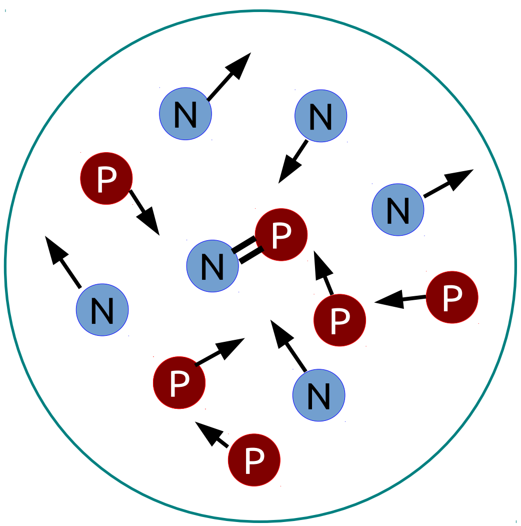
(and many others)

Why worry?

Lepton universality has been extensively checked.
So what's the problem?

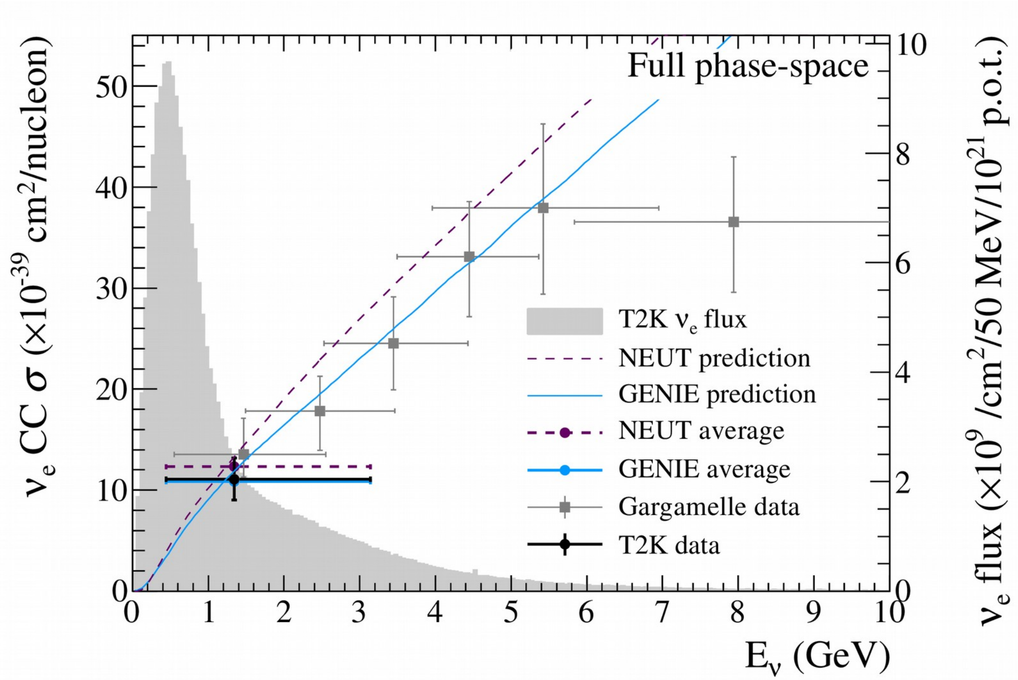
It's that #@%&! nucleus.

- Detectors built from complex materials
- Substituting m_e for m_μ exposes different range of available kinematics ($m_\mu/m_e \sim 200$)
  - Parameterizations used in ν-N cross sections have uncertainties – different amounts of uncertainty integrated for different kinematic space (Day and McFarland, *PRD* **86** 053003)
  - Nuclear effects (correlations between nucleons) different in different kinematic regimes (e.g., Pandey *et al.*, *PRC* **92** 024606; Nieves *et al.*, *PRC* **83** 045501)

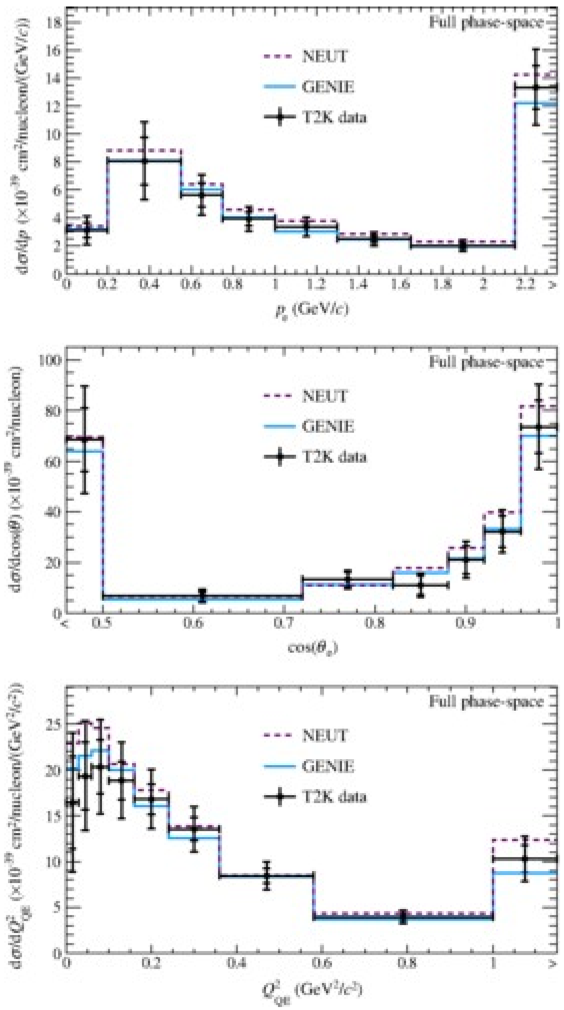


A direct measurement quantifies how safe $m_\mu \rightarrow m_e$ is.

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



$d\sigma_e/dE_e$, $d\sigma_e/d\theta_e$, $d\sigma_e/dQ^2$:
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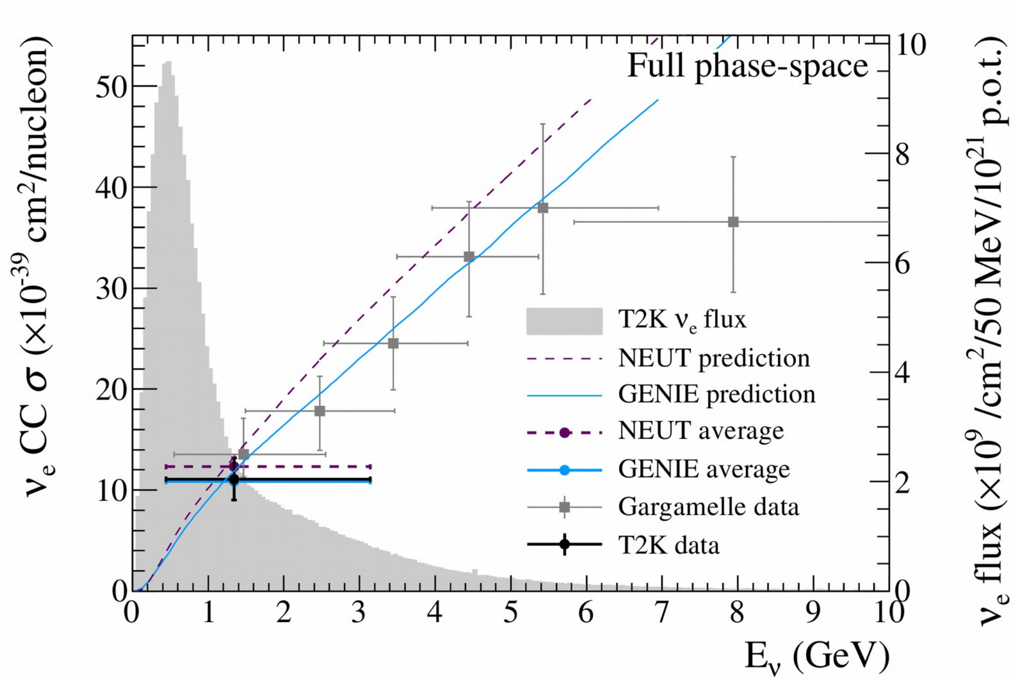

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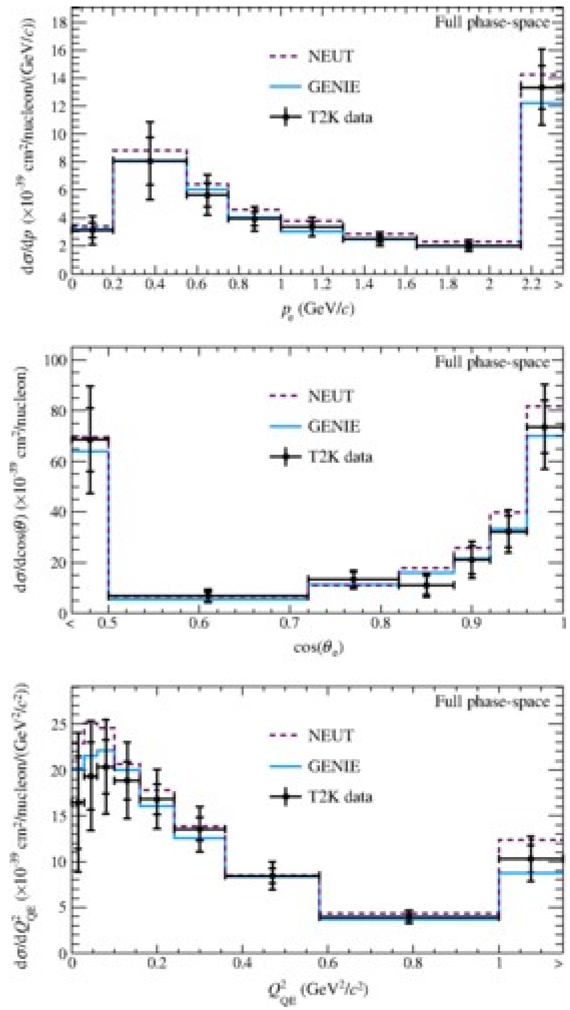

$d\sigma_e/dE_e$, $d\sigma_e/d\theta_e$, $d\sigma_e/dQ^2$:
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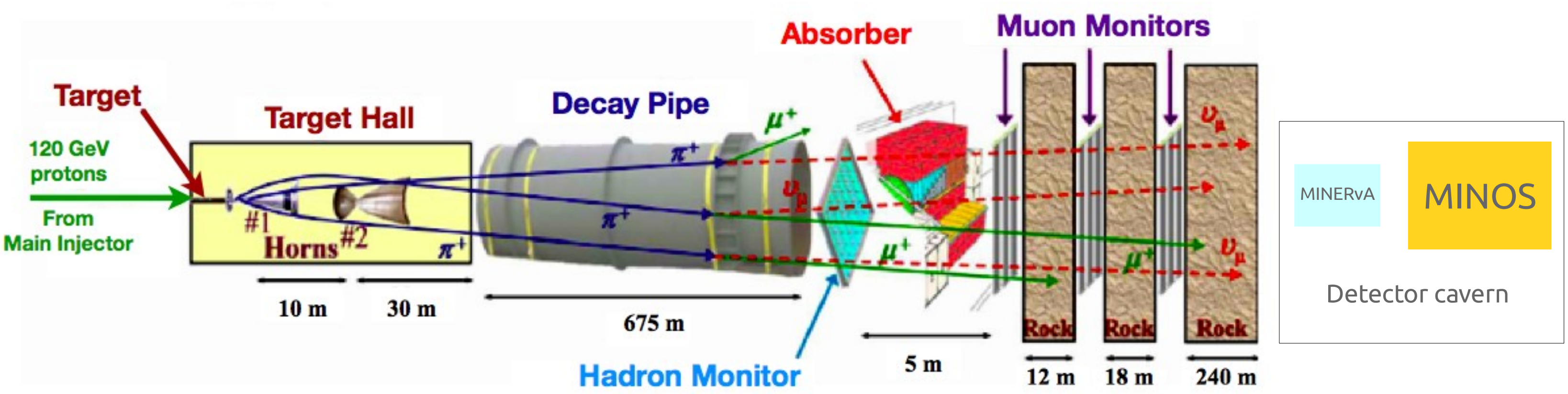
Difficult measurement...
Low stats ↔ large errors, no exclusive reactions.

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

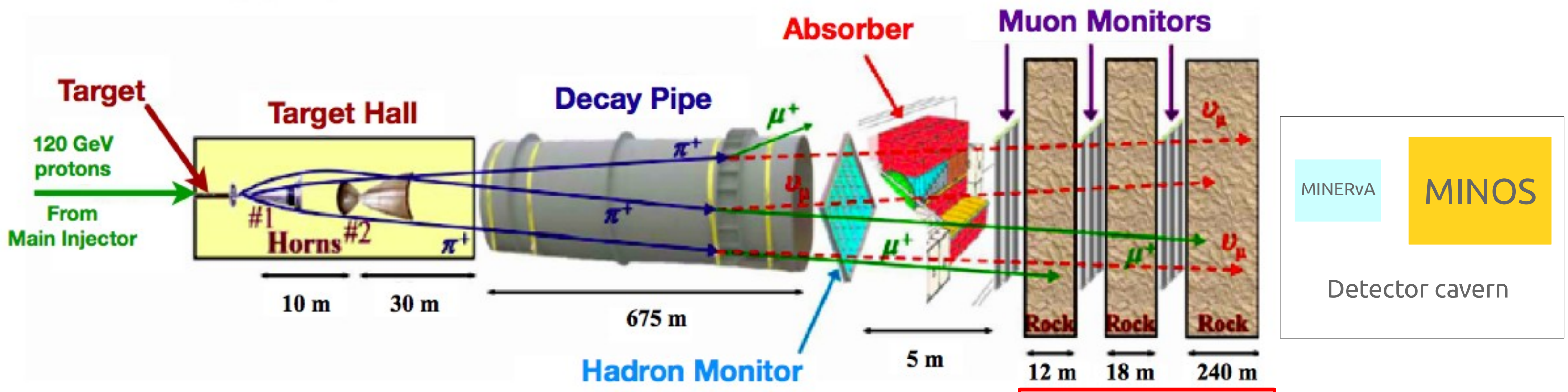
Experimental prospects



$$\pi^+ \to \nu_\mu \mu^+$$

NuMI is the highest-intensity (GeV-scale) ν_μ beam in the world...

Experimental prospects



(Also ~1% ν_e)

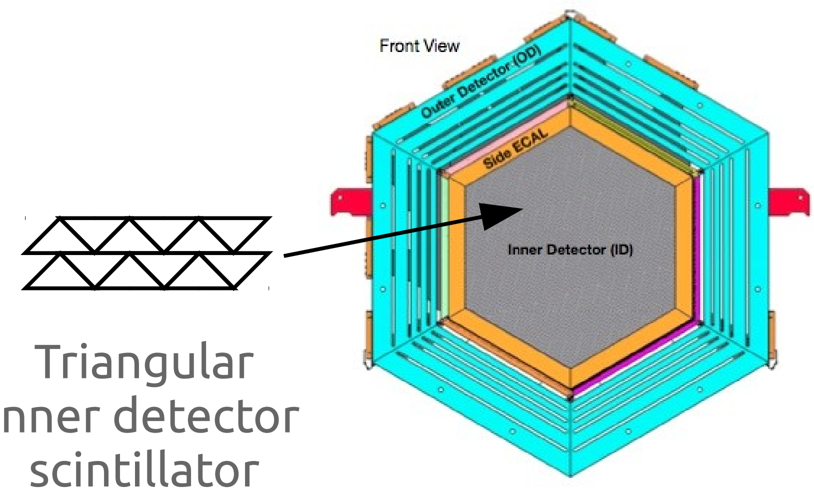
$$\pi^+ \rightarrow \nu_\mu \mu^+$$
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

NuMI is the highest-intensity (GeV-scale) ν_μ beam in the world…

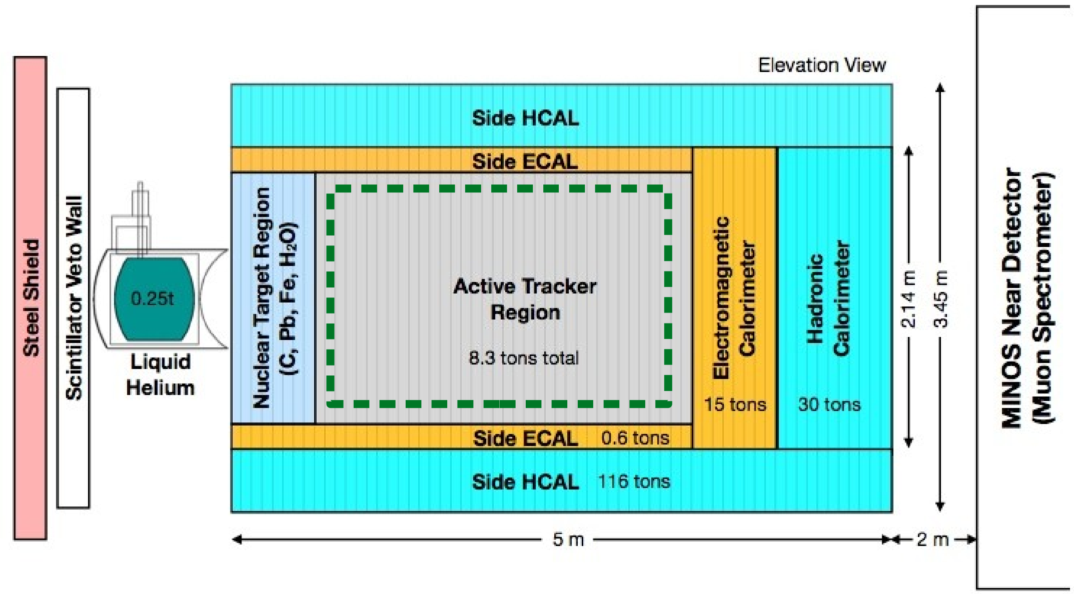
… and therefore the highest-intensity (accelerator energy) ν_e beam in the world too.

An on-axis cross section experiment could potentially have the statistics to perform the first exclusive cross section measurement!

Experimental prospects



Triangular inner detector scintillator strips

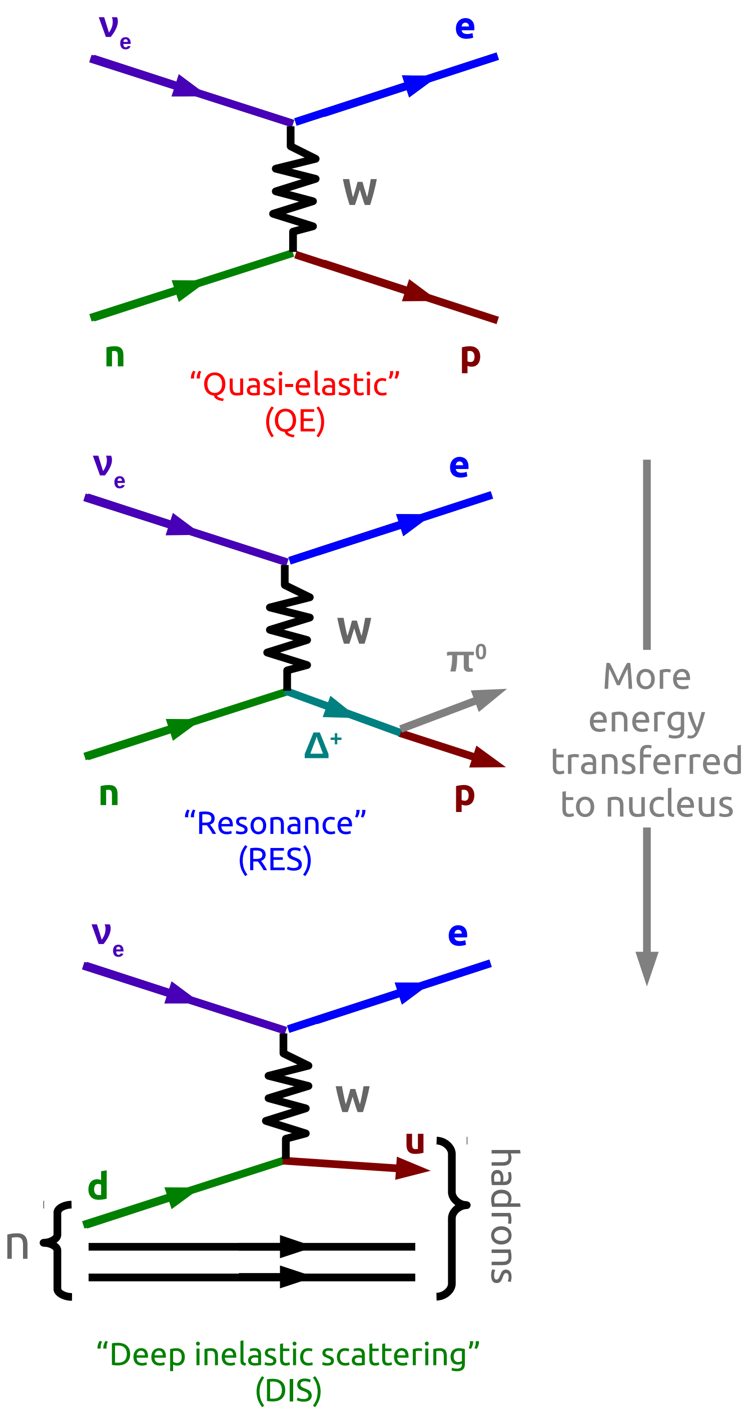


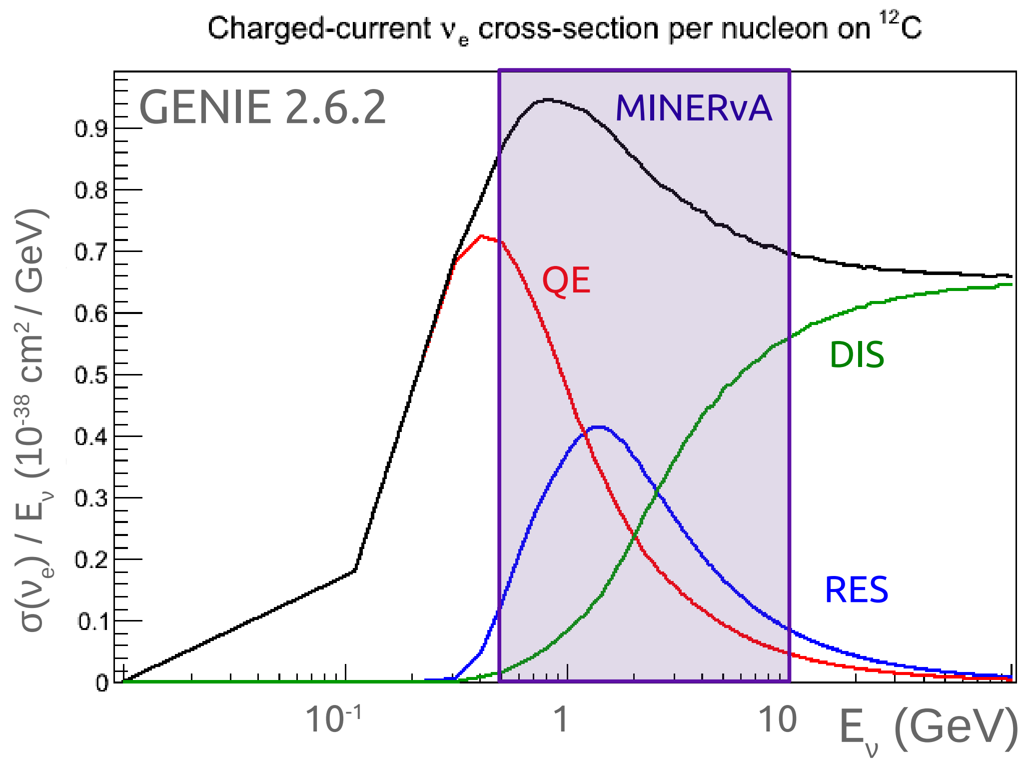
MINERvA is <u>designed</u> for cross sections (central fiducial region is a fine-grained scintillator tracker) and is on-axis in NuMI.

Perfect!

ν_e CCQE at MINERvA

Signal definition





Choose to pursue the quasi-elastic (CCQE) channel:

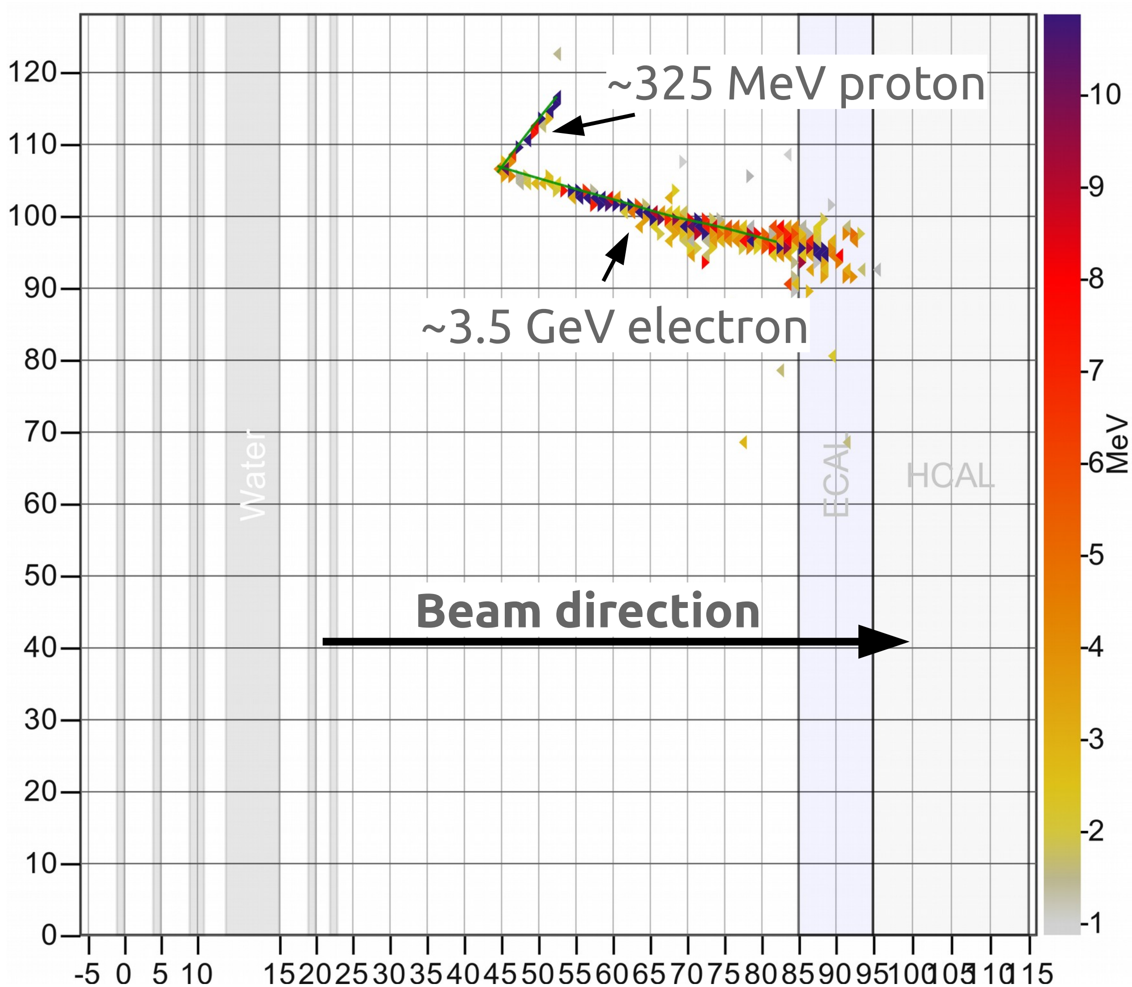
- Evaluation of exclusive-state model:
  - <u>Important signal reaction for off-axis ν oscillation</u> that is well-represented at MINERvA energies
  - Direct comparison to MINERvA ν_μ measurement
- Easier final-state electron identification (less other confusion in event)

Signal definition

Signal is really <u>quasielastic-like</u>:

- One electron or positron (MINERvA isn't magnetized)
- Any number of nucleons (nuclear effects; FSI tricky – reduce model dependence)
- No other hadrons

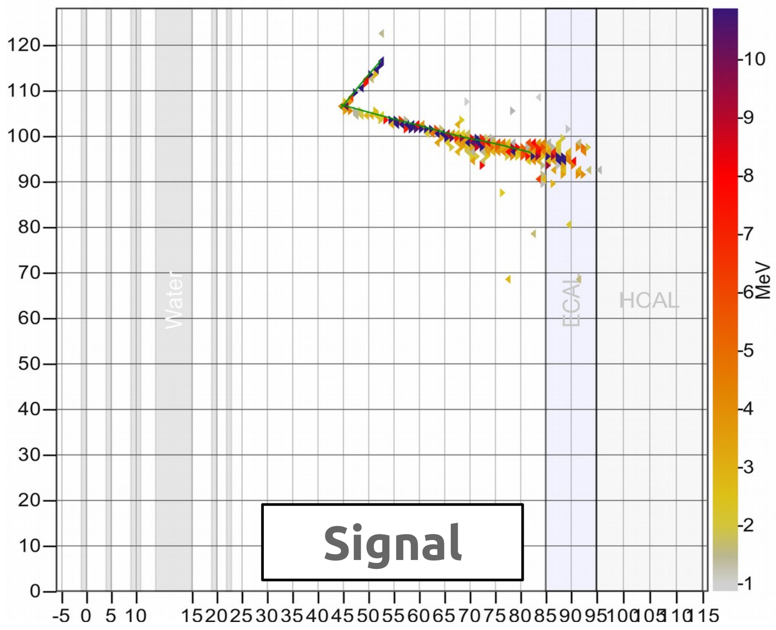
(This strategy should seem familiar from other data sets – e.g., MiniBooNE)

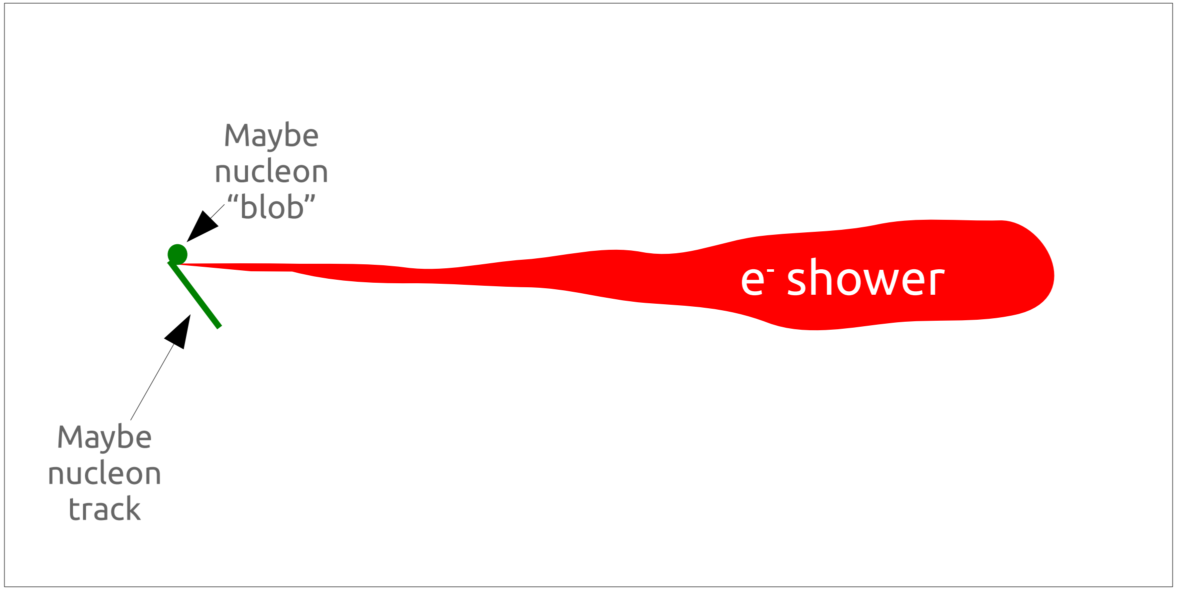


Event display of simulated ~4 GeV ν_e interaction in MINERvA

Event selection

- Stages of event selection:
    1) Muon elimination
    2) Selection of electromagnetic shower-like particles
    3) Rejection of photons
    4) CCQE-like event selection





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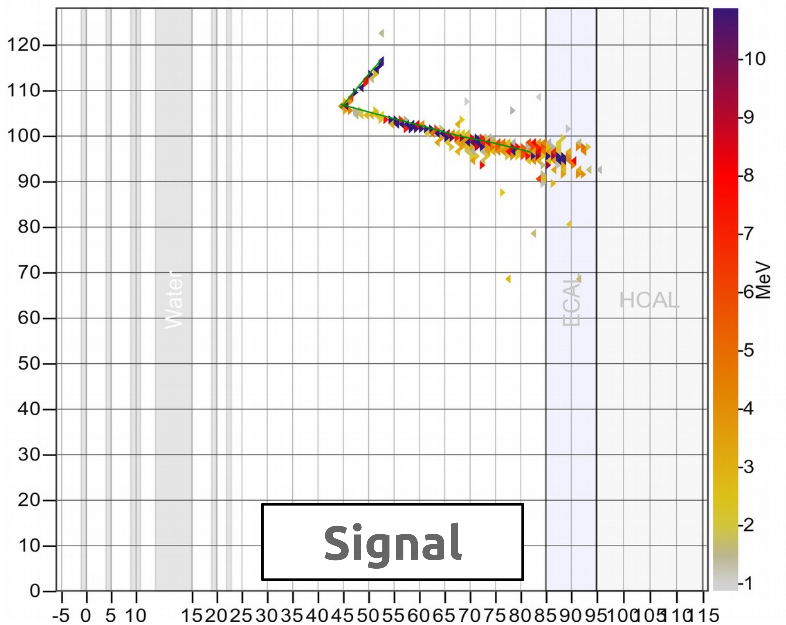
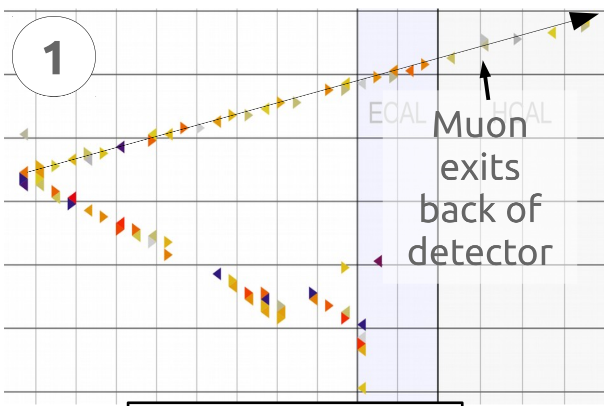
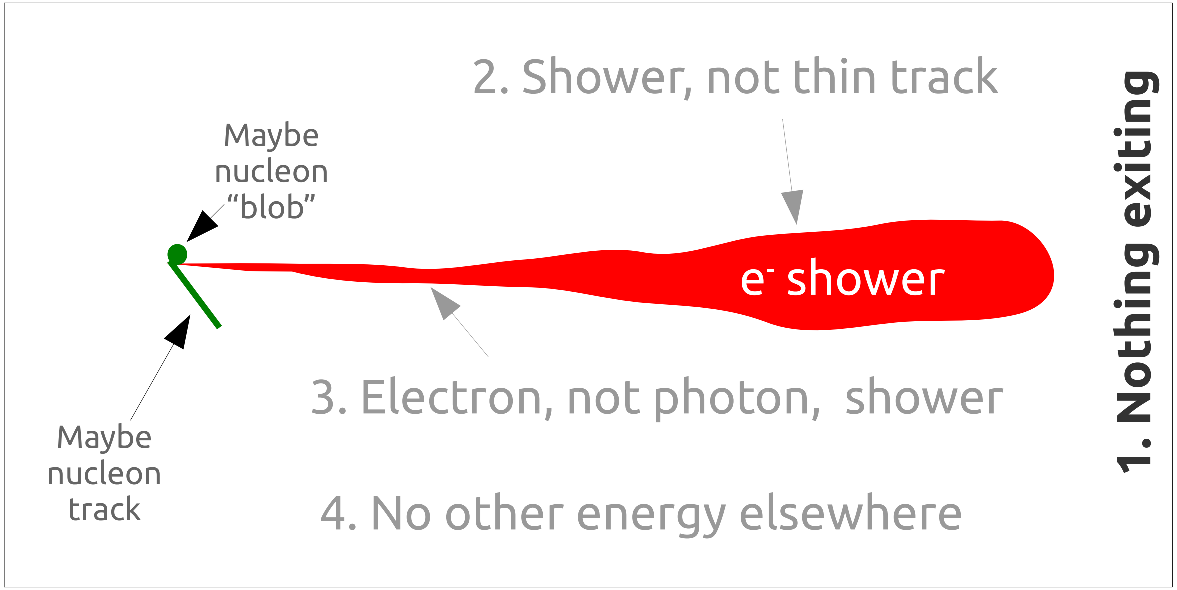




ν_μ CC background



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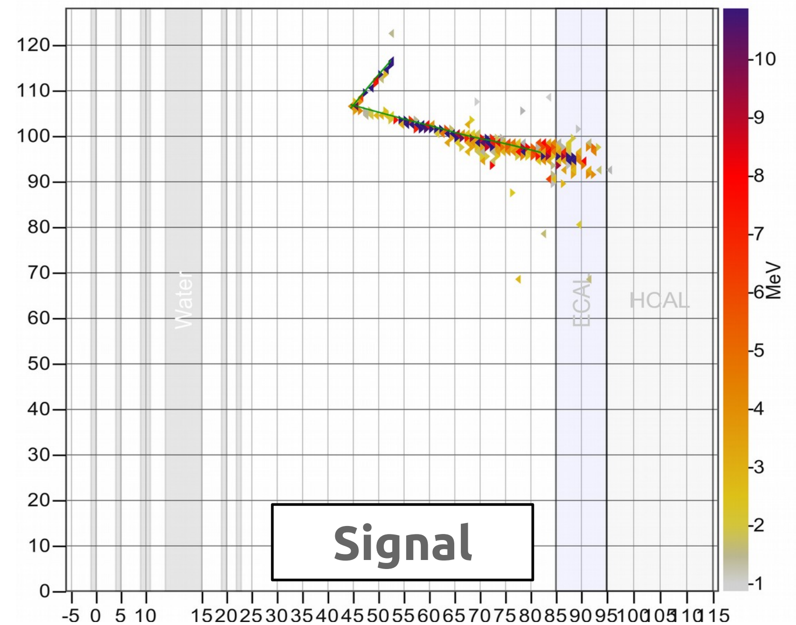
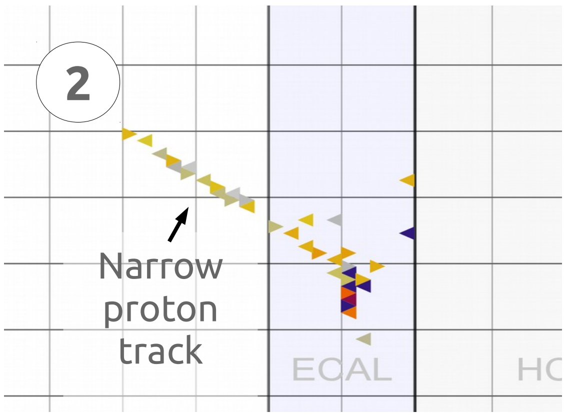
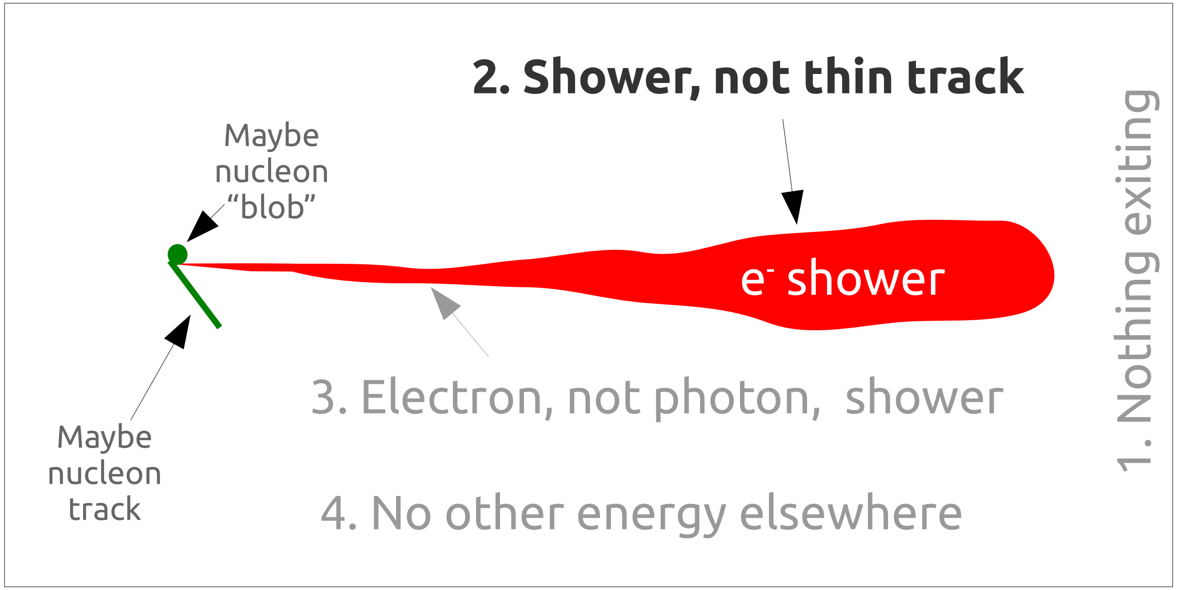


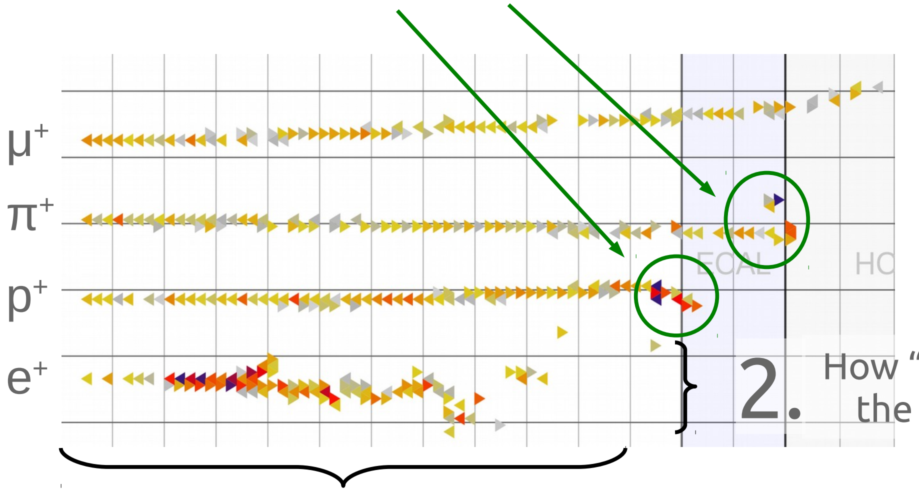


NC background



Isolating ν_e-like events: EM-like final state selection

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

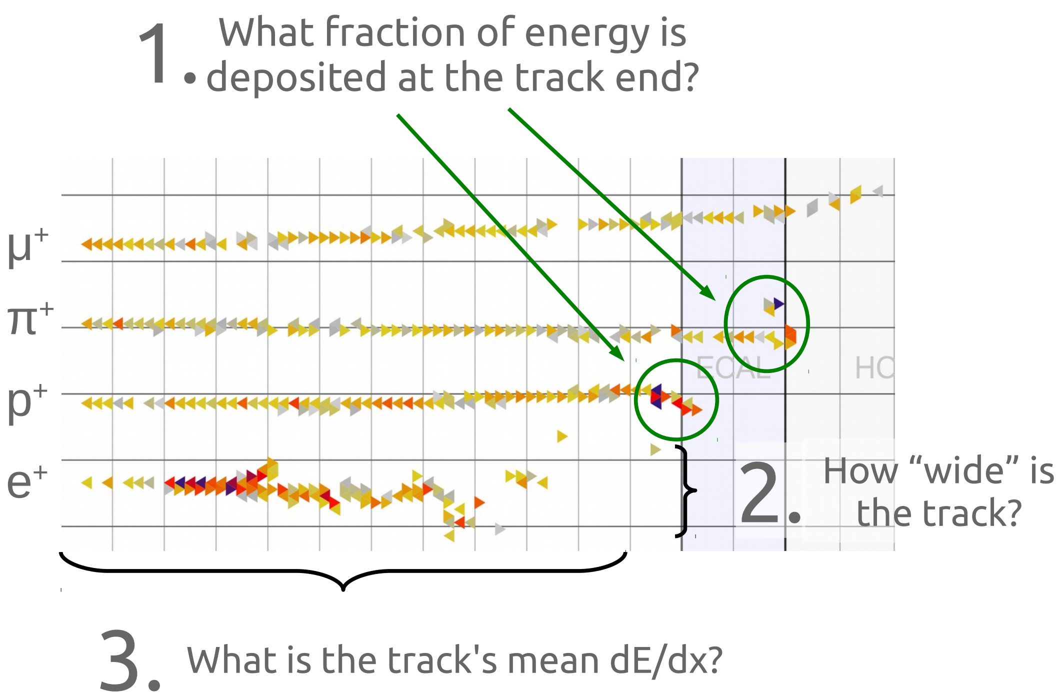


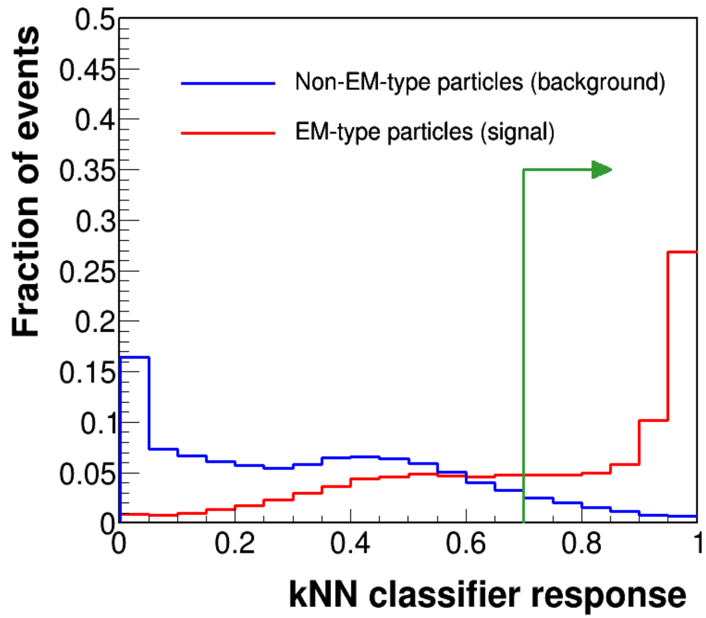
2. How "wide" is the track?

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

Train a multivariate classifier using these three characteristics of the energy deposition profile of the shower-like object (then reject MIP-like tracks that slip through)

Isolating ν_e-like events: EM-like final state selection





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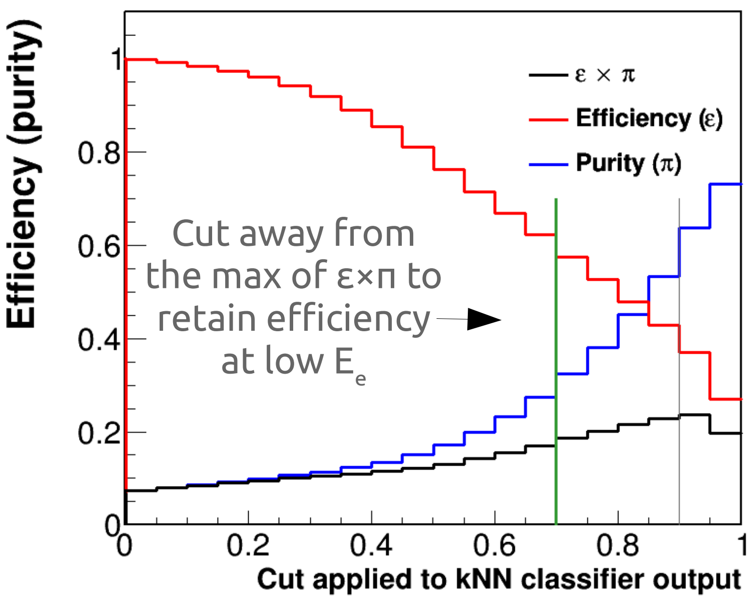

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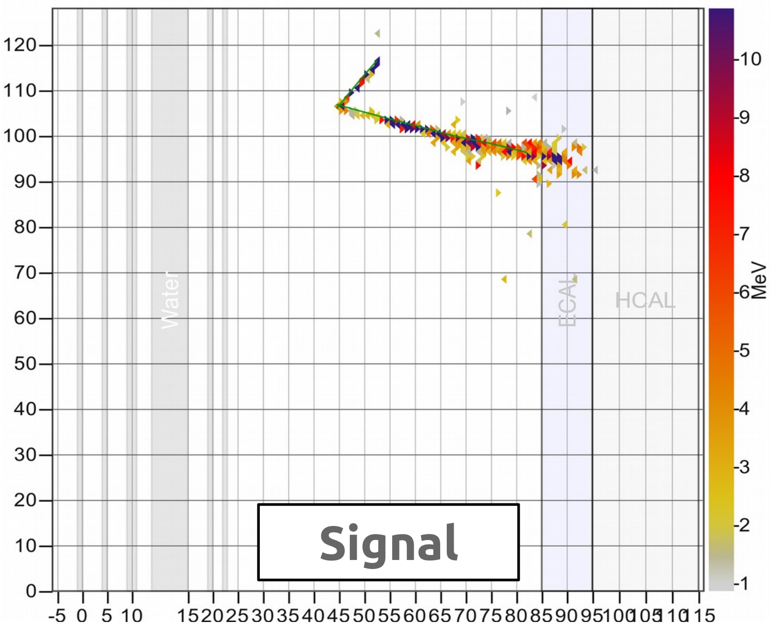
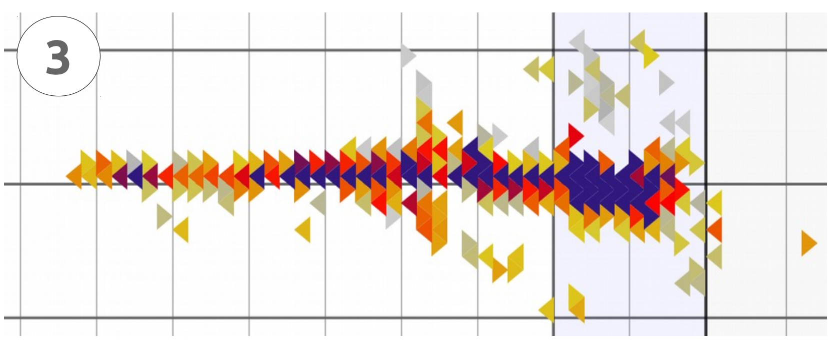
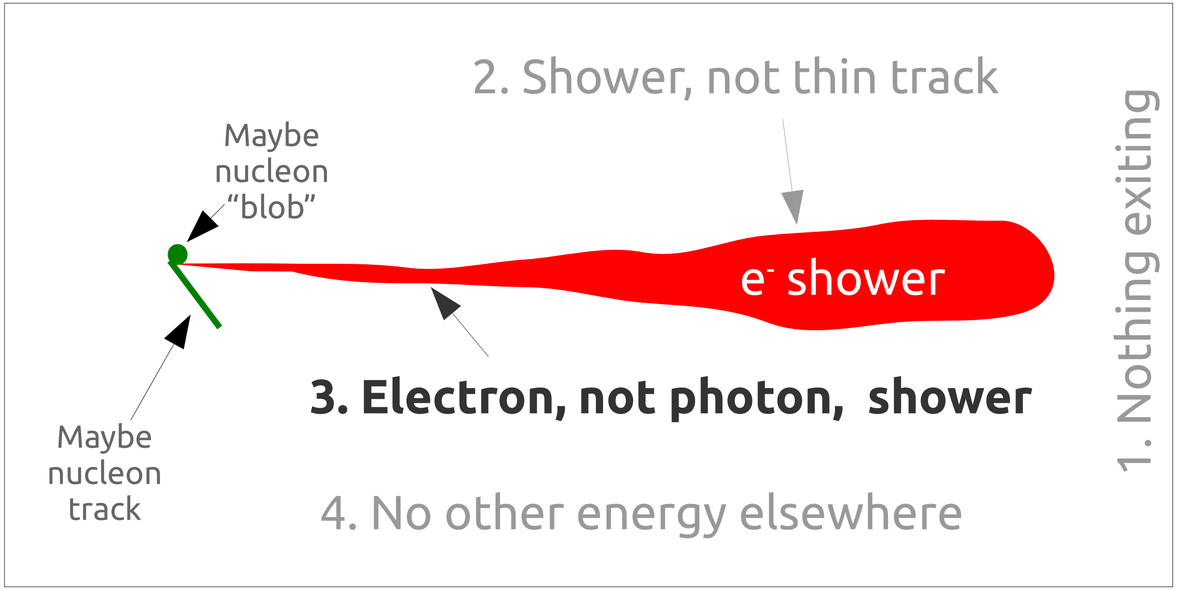
  4) CCQE-like event selection

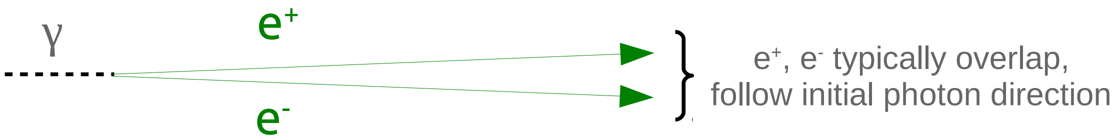




π^0 background

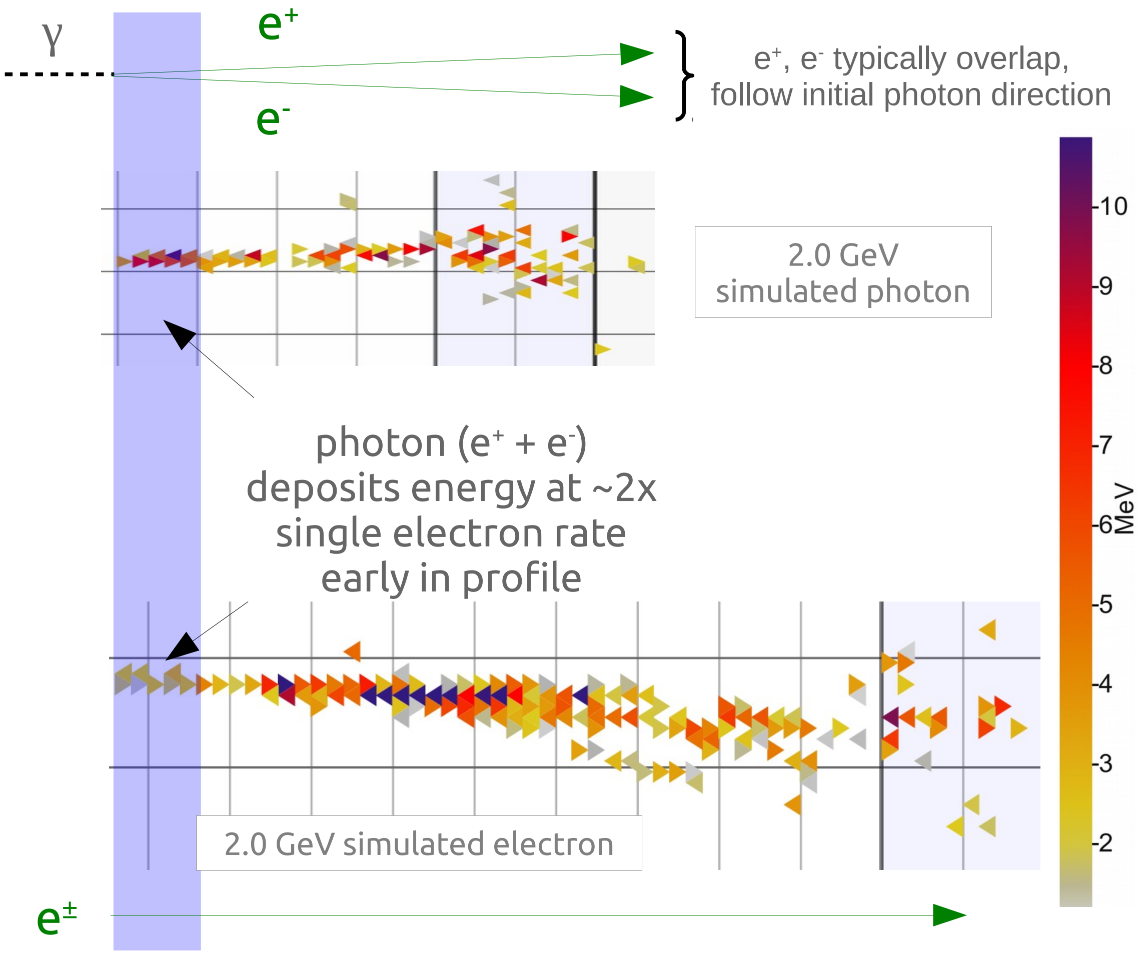


Isolating ν_e events: Photon rejection



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

Isolating ν_e events: Photon rejection



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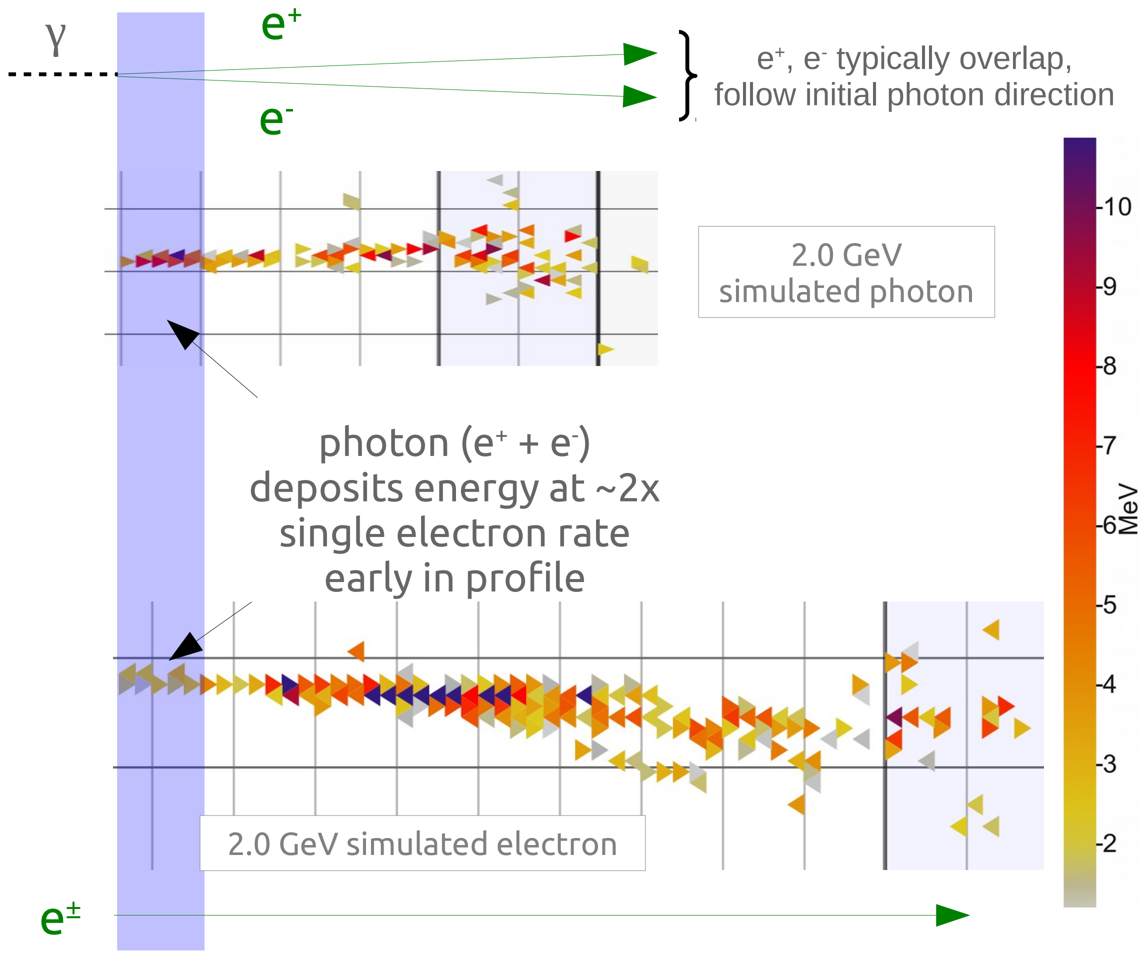

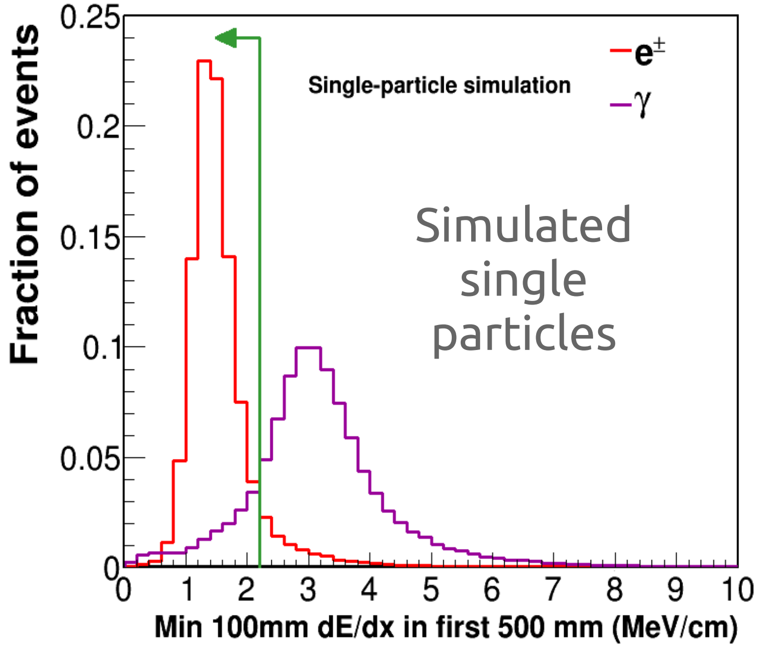

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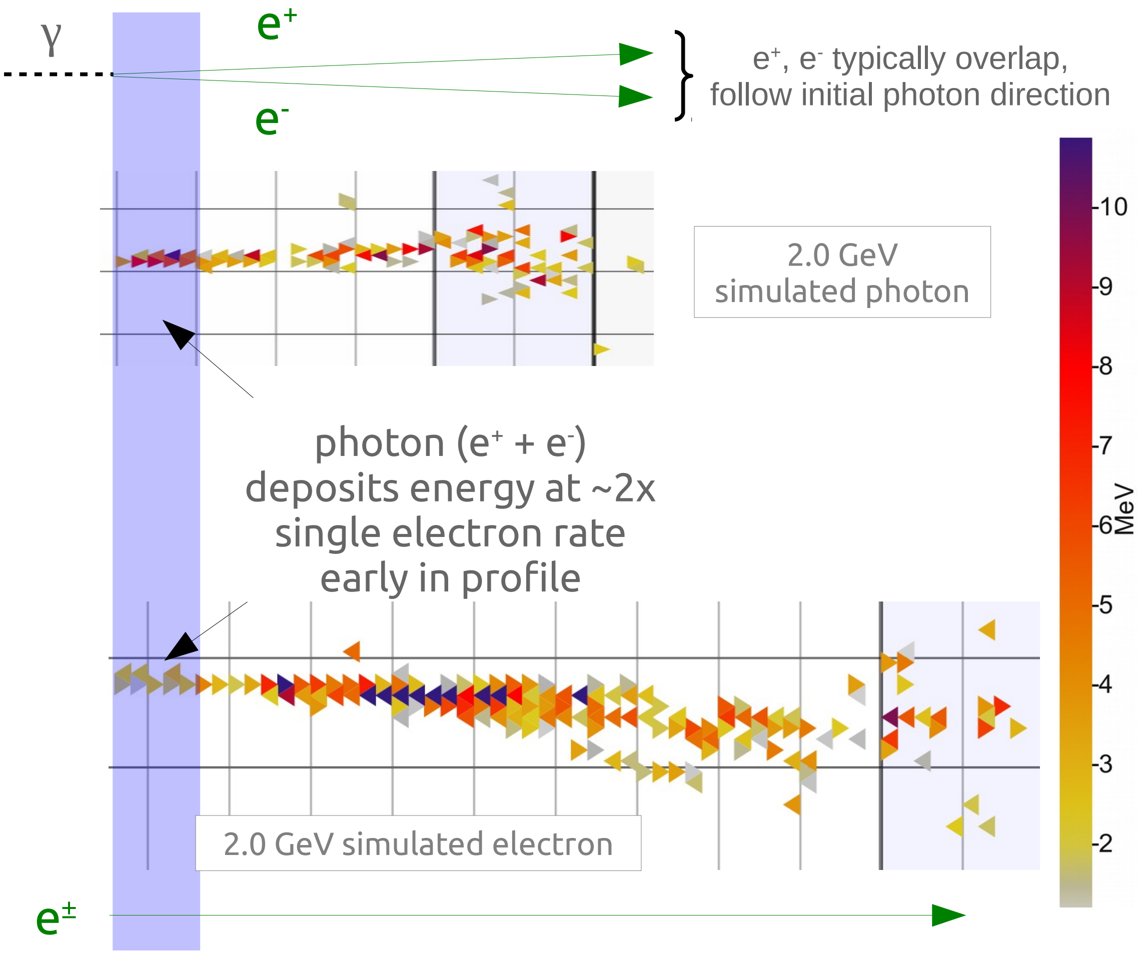

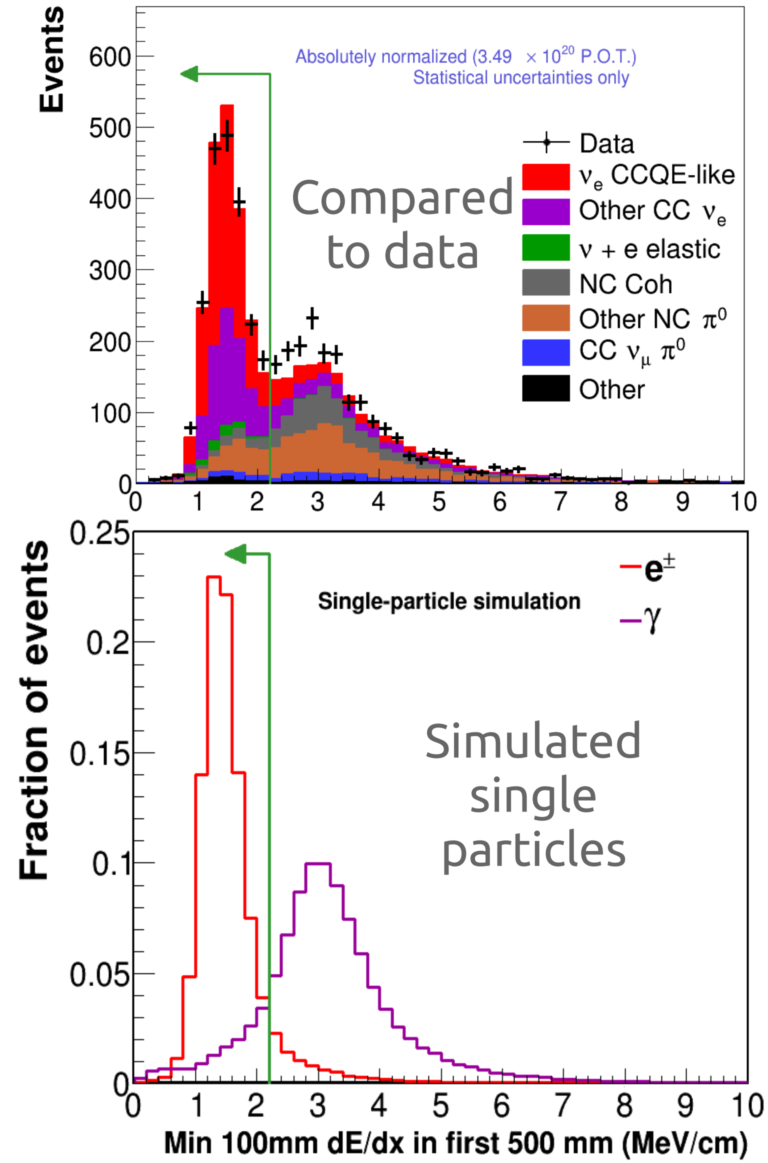

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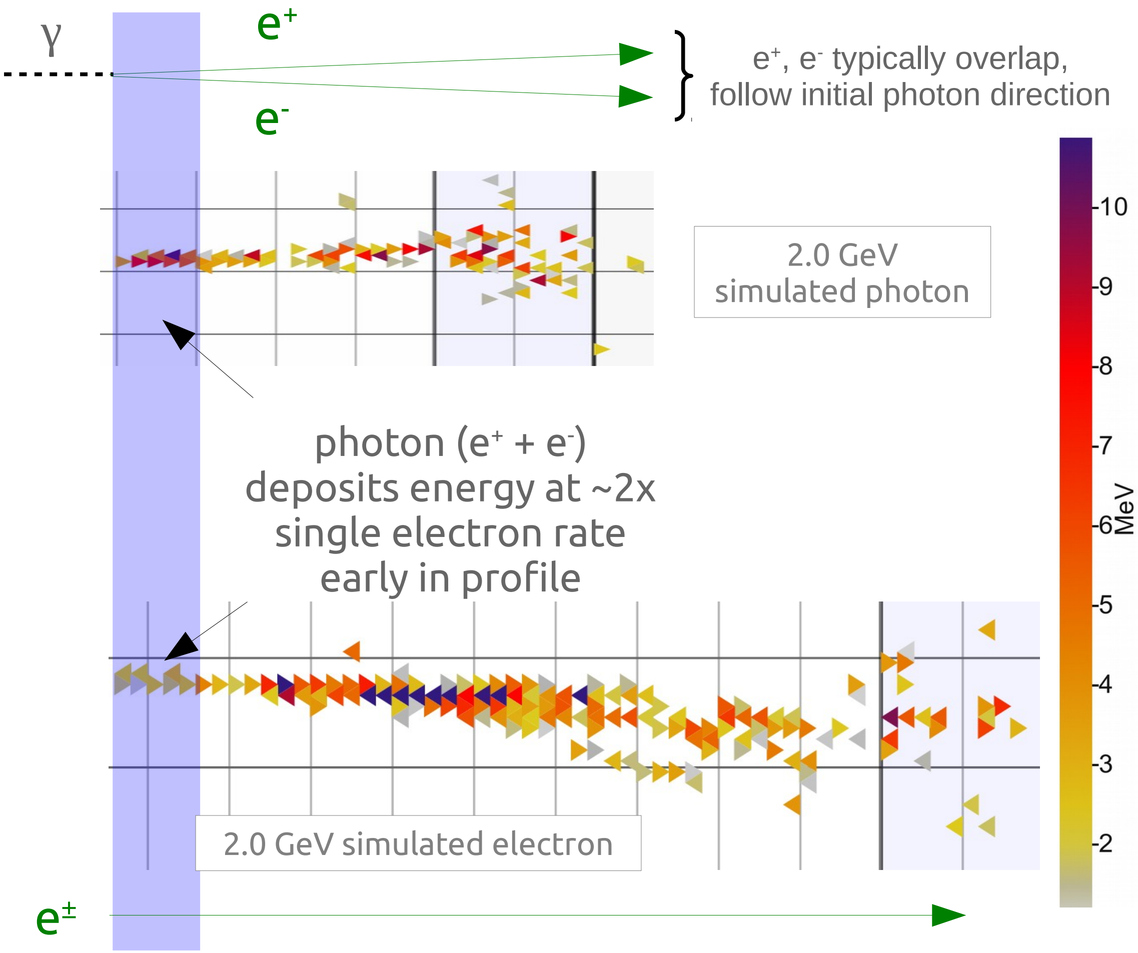

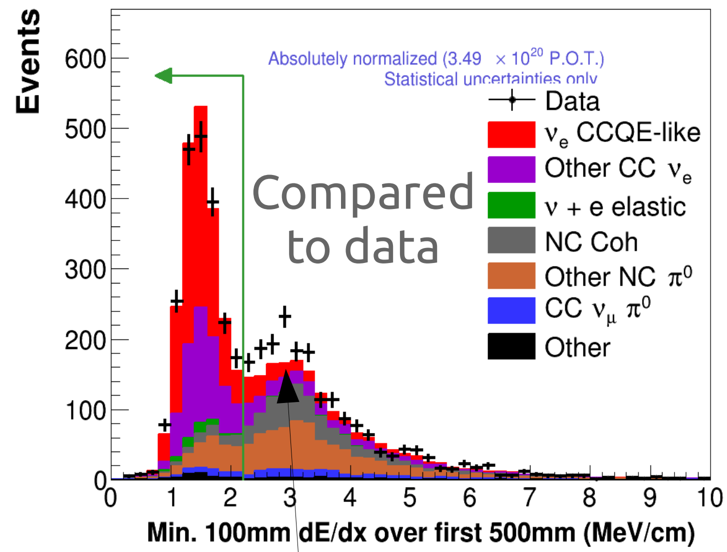

"Wait. That's a pretty serious disagreement!"

Yep, it is. (Now imagine if we used a detector incapable of fine-grained dE/dx, like a Cherenkov one...)

I'll return to this point shortly.

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

Event selection

- Stages of event selection:
  1) Muon elimination
  2) Selection of electromagnetic shower-like particles
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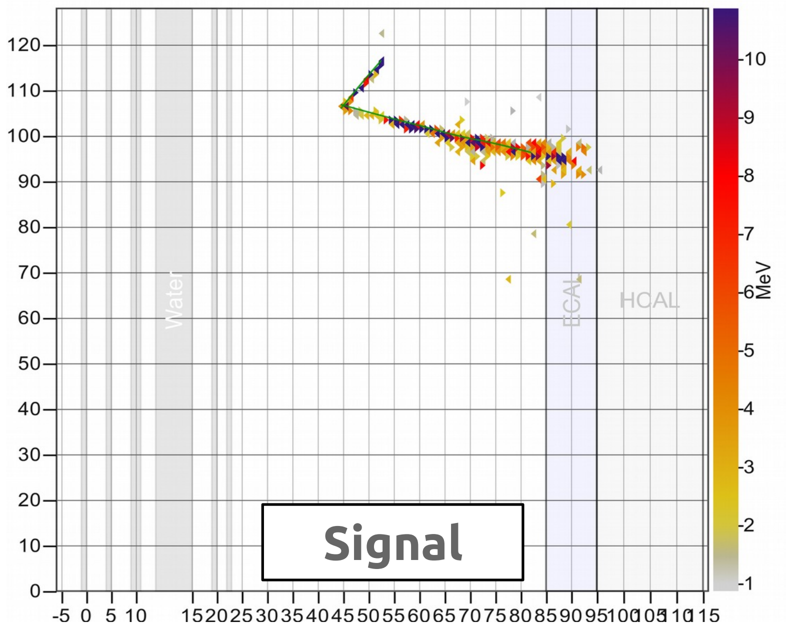
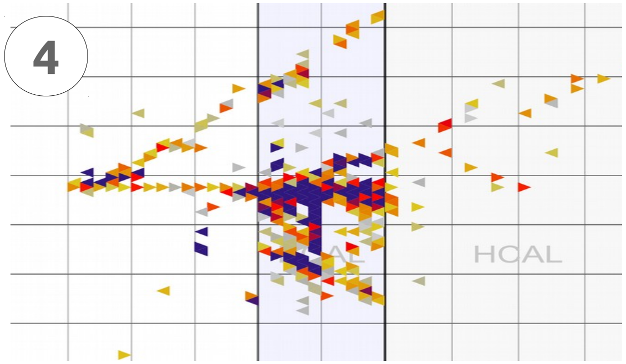
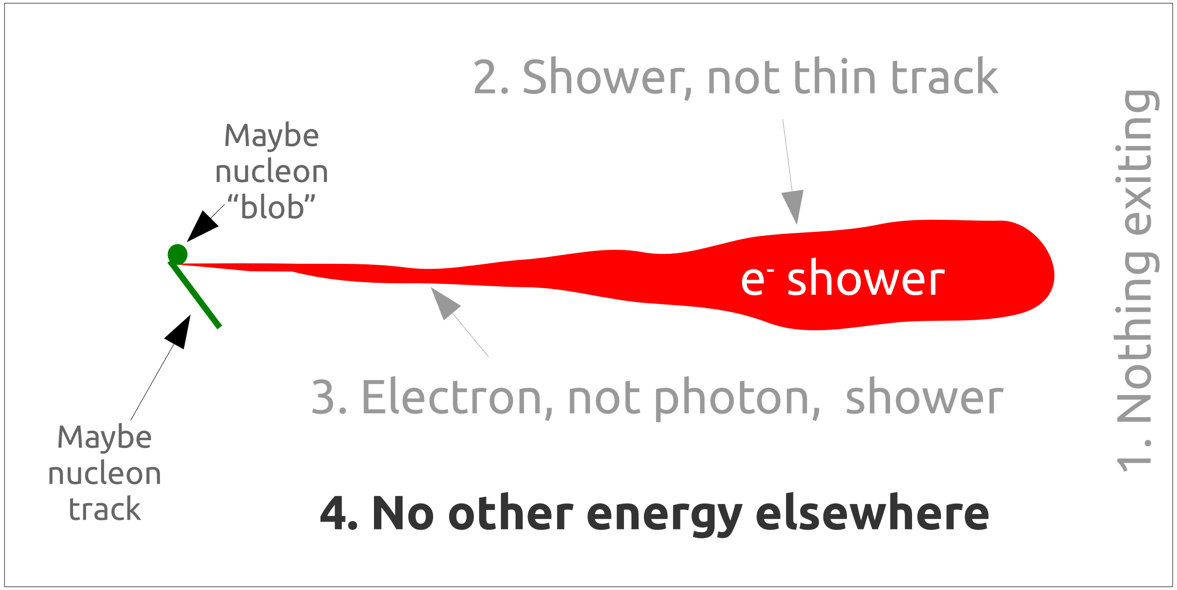
  4) CCQE-like event selection



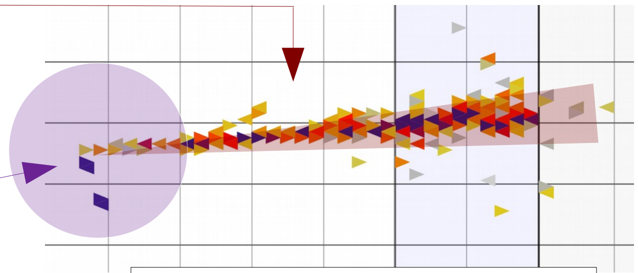


ν_e inelastic background

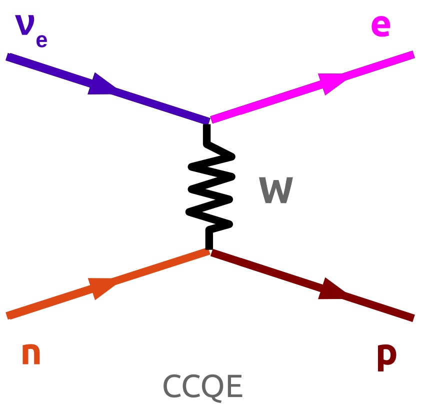


Isolating ν_e-like events: Quasielastic-like topology selection

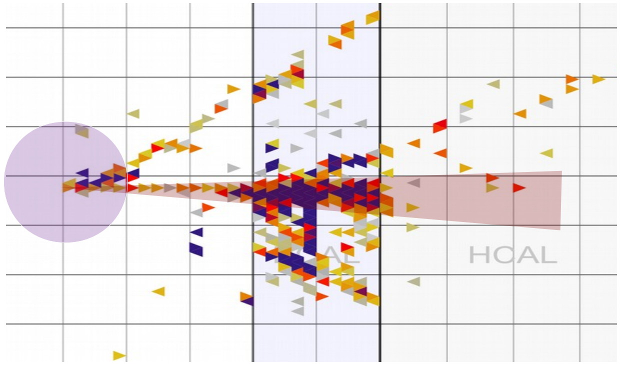
Anything not within a 7.5° electron cone or a vertex activity region of 30 cm radius or tracked as a proton is "extra energy."



Simulated ν_e CCQE



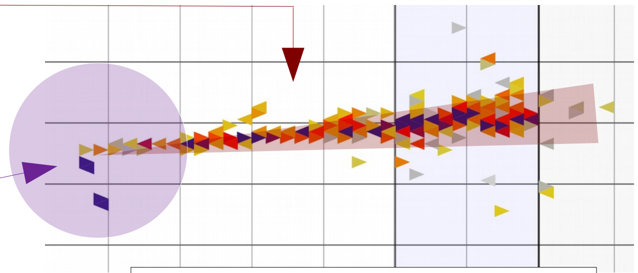
Simulated ν_e deep inelastic scattering



Isolating ν_e-like events: Quasielastic-like topology selection

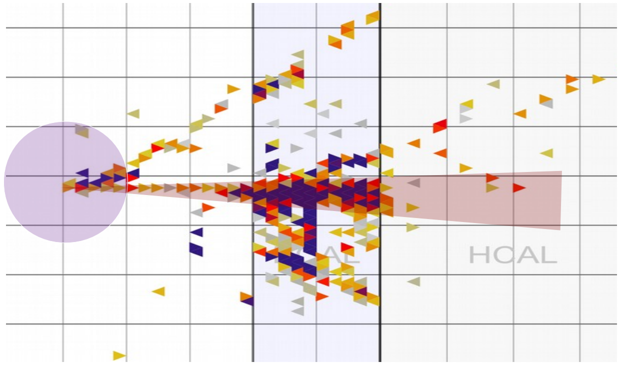
Anything not within a 7.5° electron cone or a vertex activity region of 30 cm radius or tracked as a proton is "extra energy."

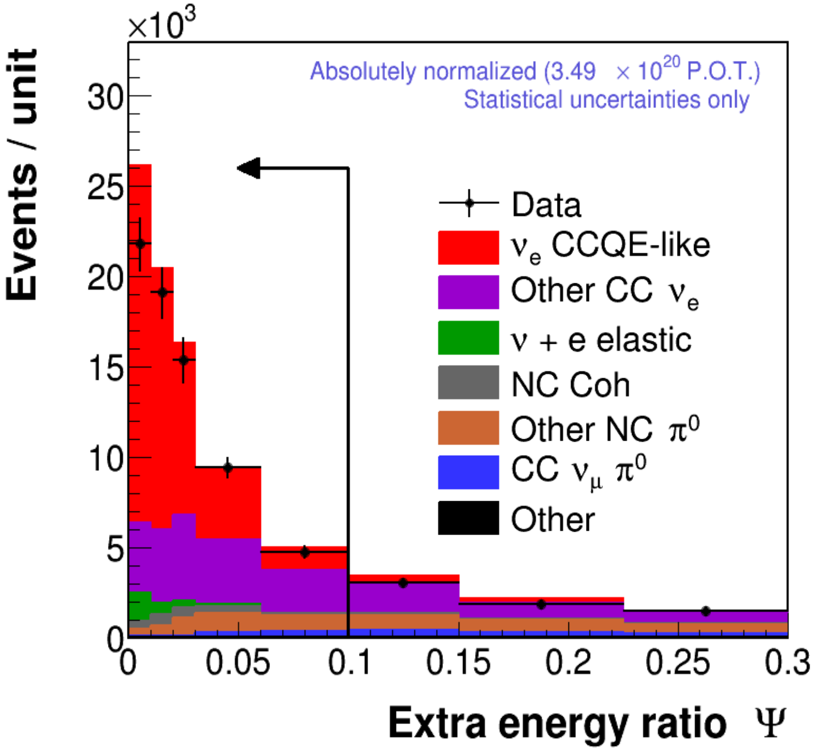
Cut on $\Psi = \frac{E_{extra}}{E_{cone}}$



Simulated ν_e CCQE

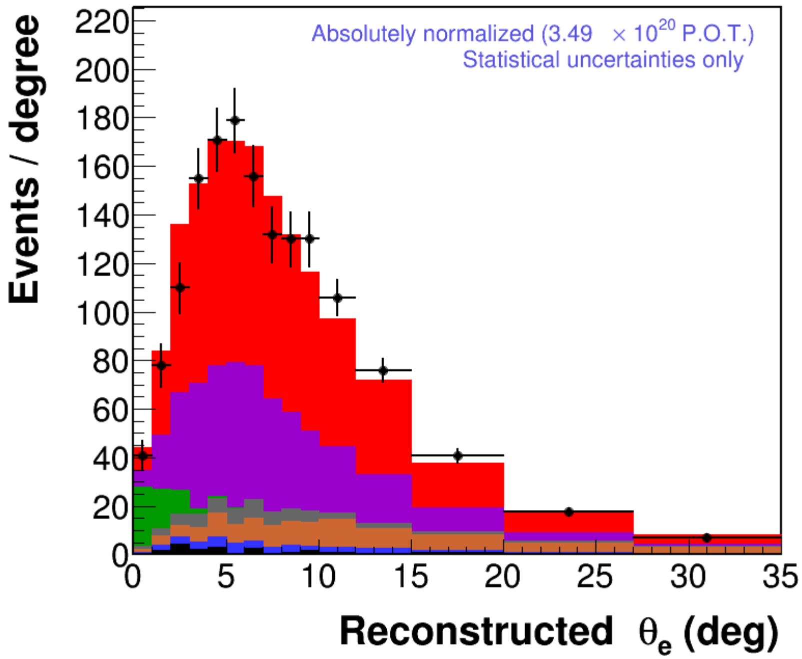
Simulated ν_e deep inelastic scattering





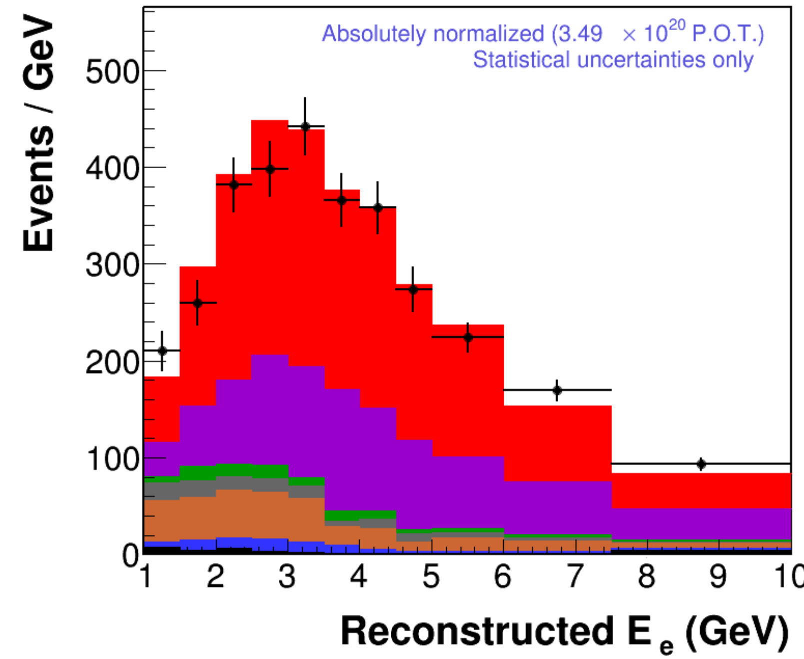
(Actual cut is a function of E_{vis}. This plot illustrates cut near most probable value of E_{vis} = 1.25 GeV.)

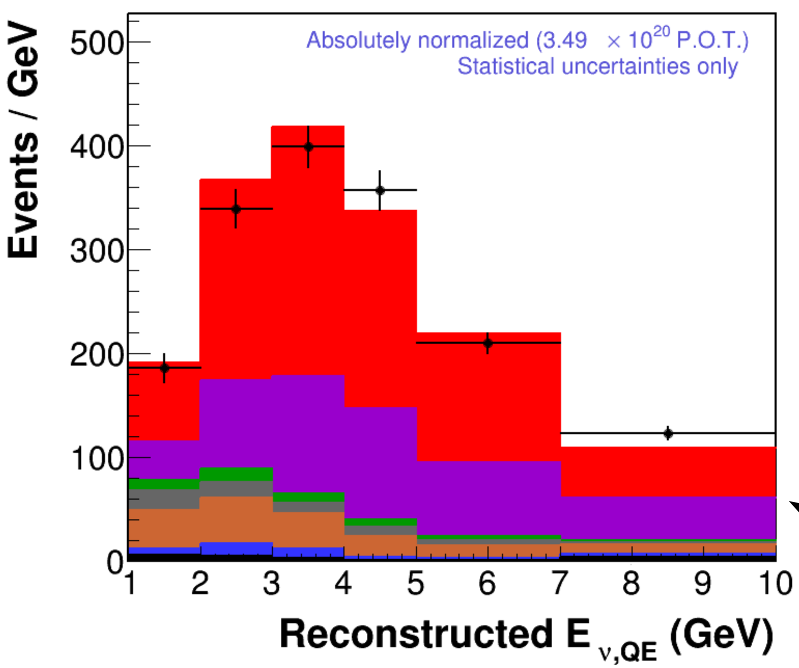
Selected sample

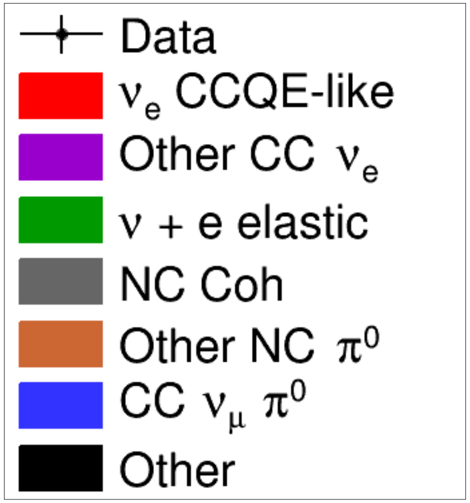


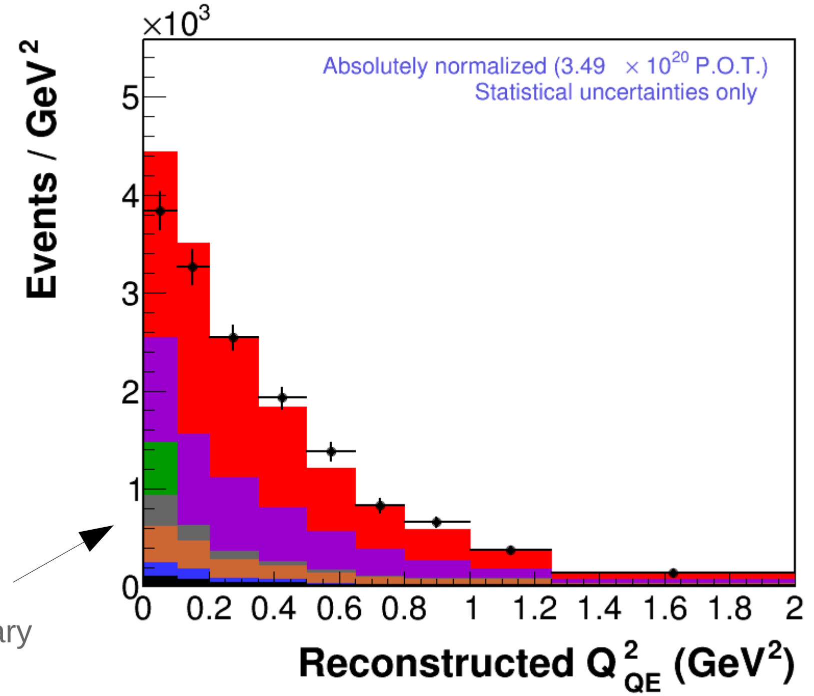
MC sample is 52.2% ν_e CCQE

(80.1% ν_e from any channel)









Infer ν kinematics from lepton's

(use QE hypothesis + stationary target assumption)

Steps to a cross section

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

(unsmearing matrix) → U_{ij}

(selected sample) → N_j^{obs}

(predicted background) → N_j^{bknd}

(flux) → Φ

(number of targets) → T_n

(bin width) → $(\Delta\xi)_i$

(efficiency) → ϵ_i

Steps to a cross section

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(flux) — Φ

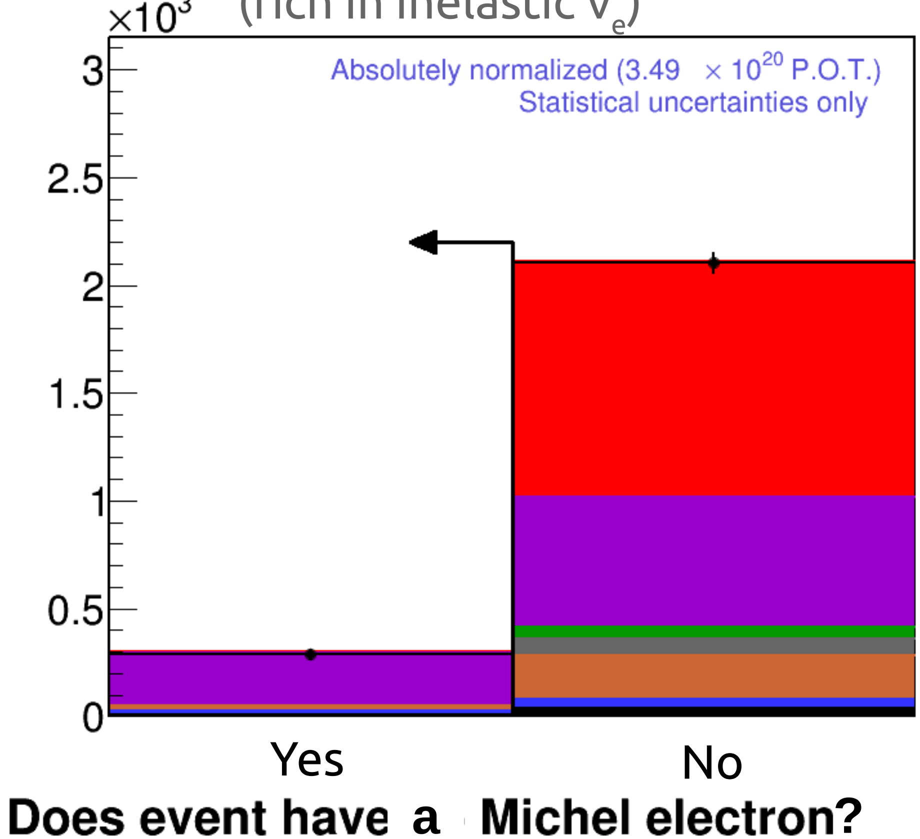
(number of targets) — T_n

(bin width) — $(\Delta\xi)_i$

(efficiency) — ϵ_i

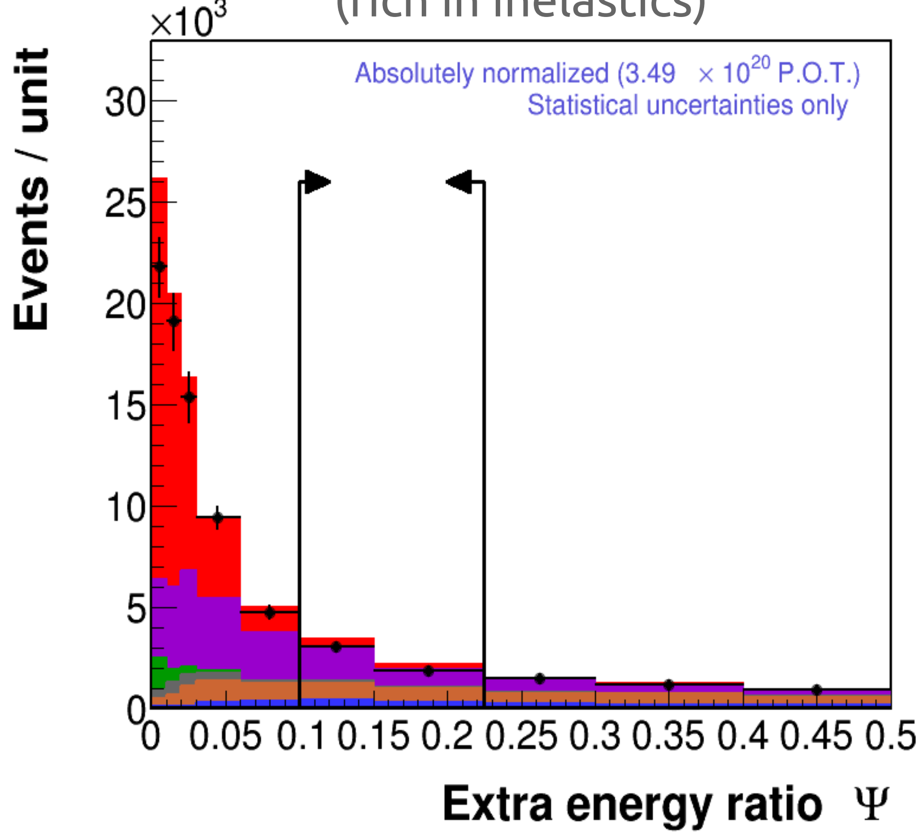
Constraining backgrounds

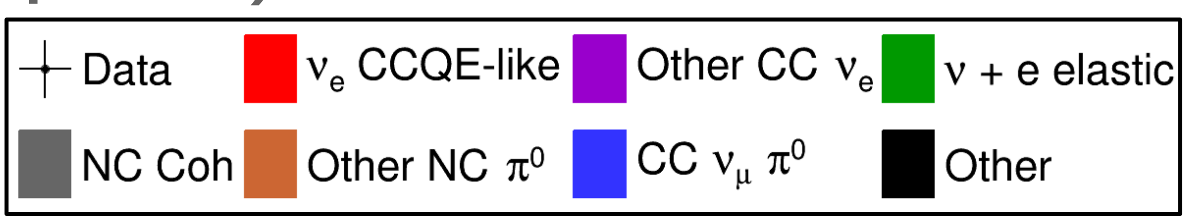
Sideband 1: contains Michel $e^{\pm}$
(rich in inelastic ν_e)



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

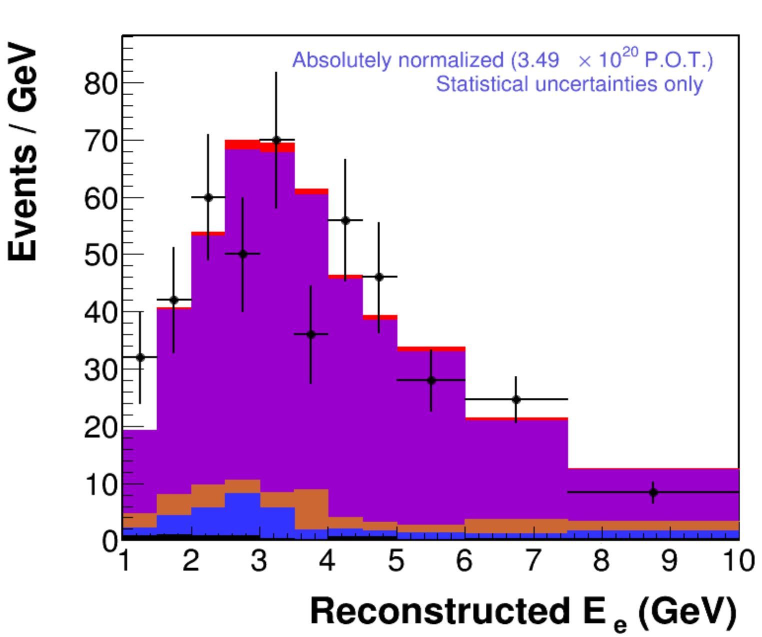
Sideband 2: larger "extra energy"
(rich in inelastics)



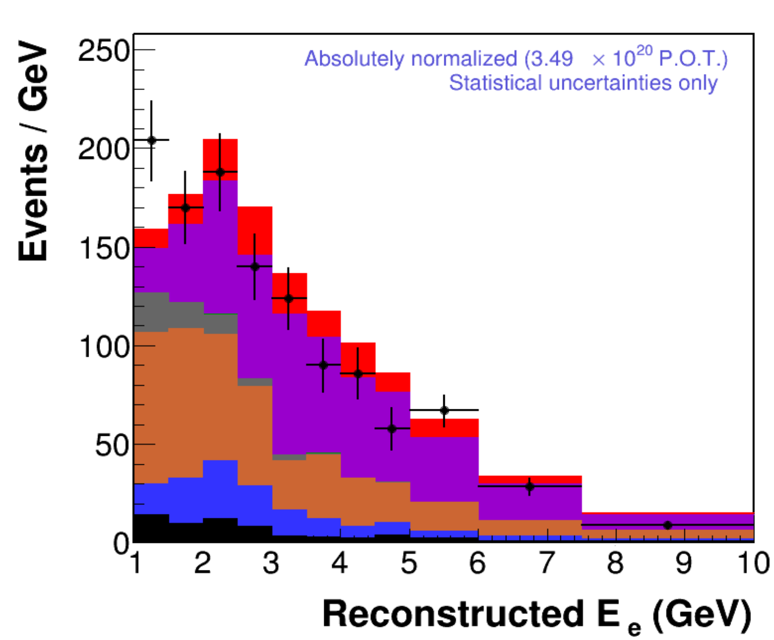


Select two sidebands rich in the major backgrounds...

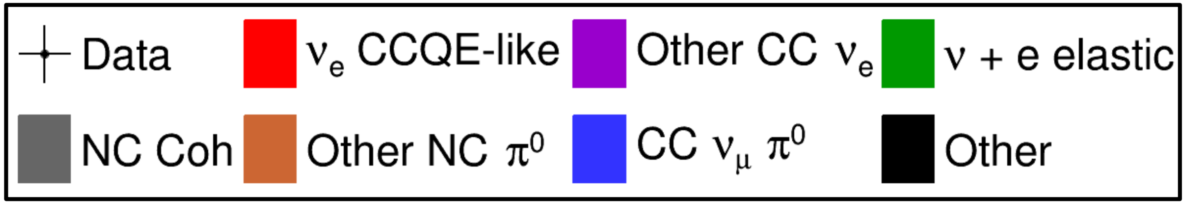
Constraining backgrounds



Michel-match sideband

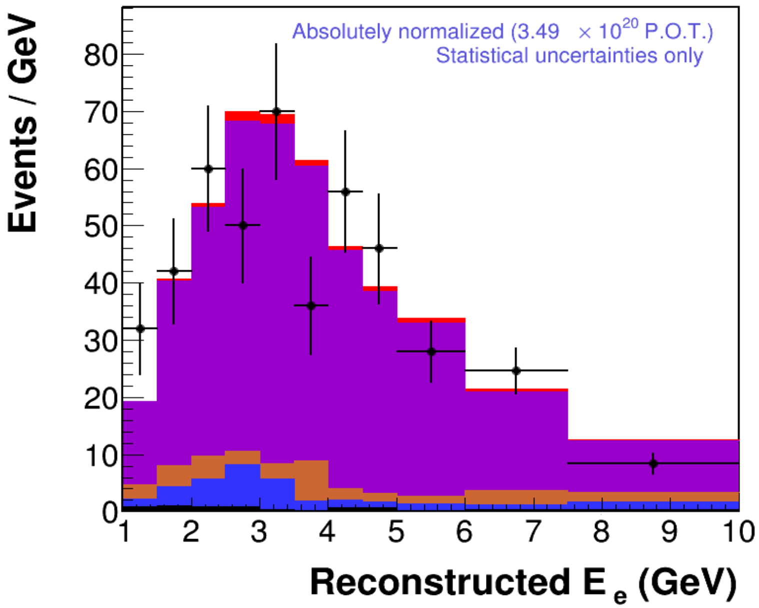


Extra energy sideband

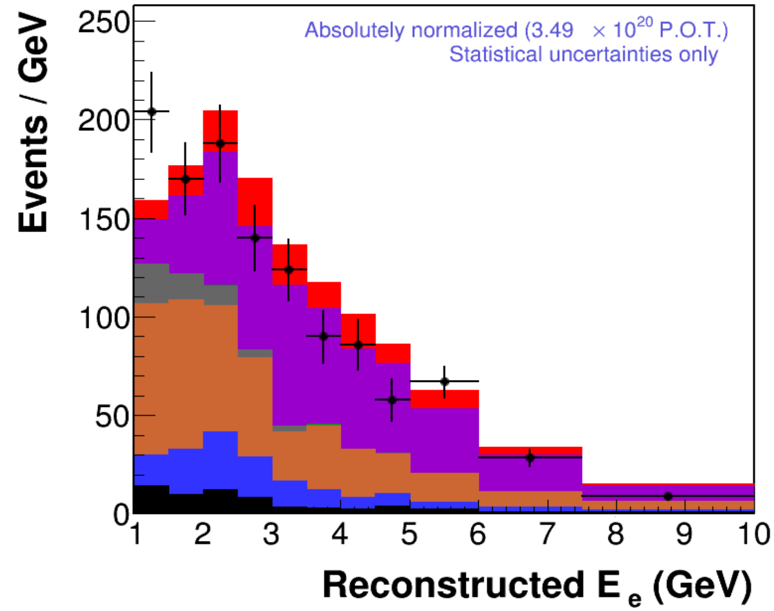


… and examine the normalizations of two distributions in each sideband (one of them, candidate electron energy, shown here; candidate electron angle is also used).

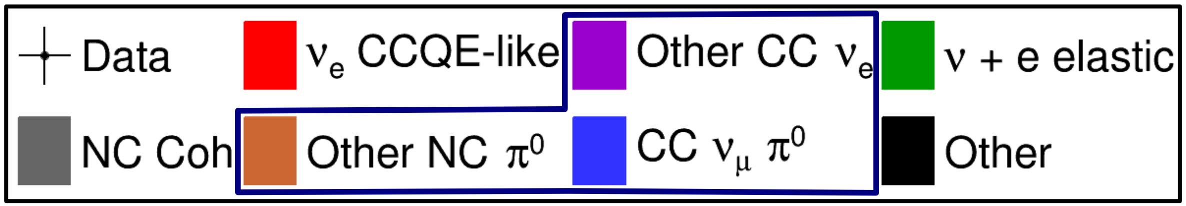
Constraining backgrounds



Michel-match sideband



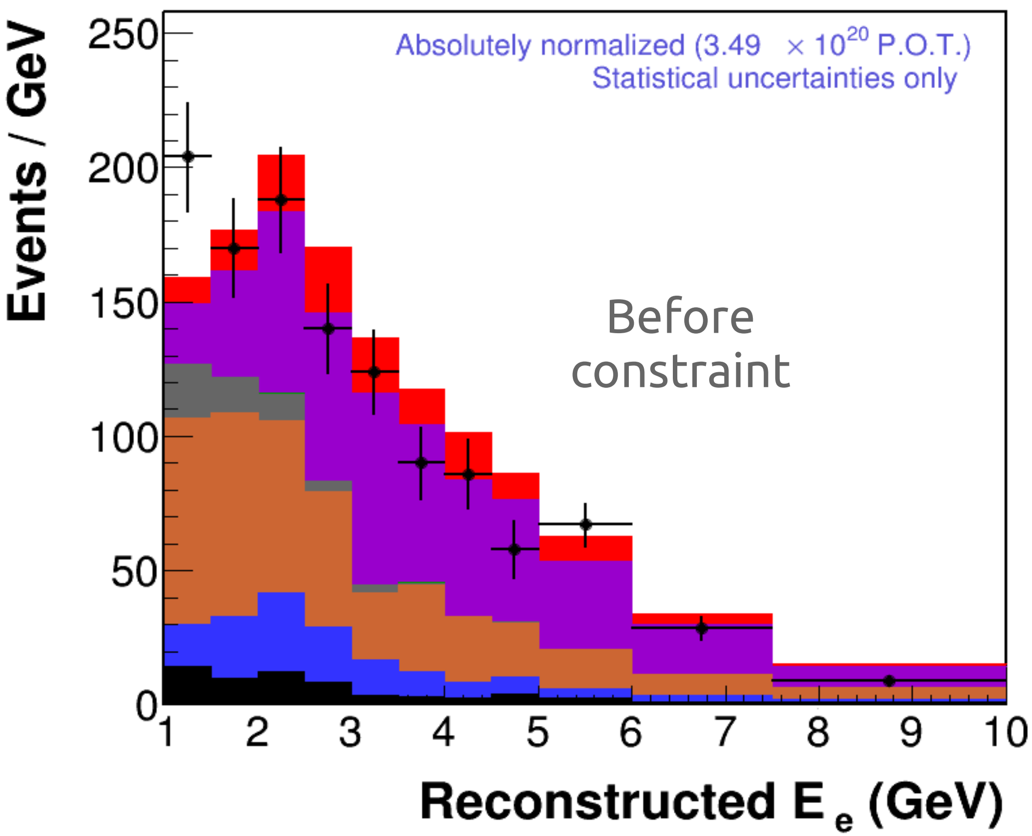
Extra energy sideband

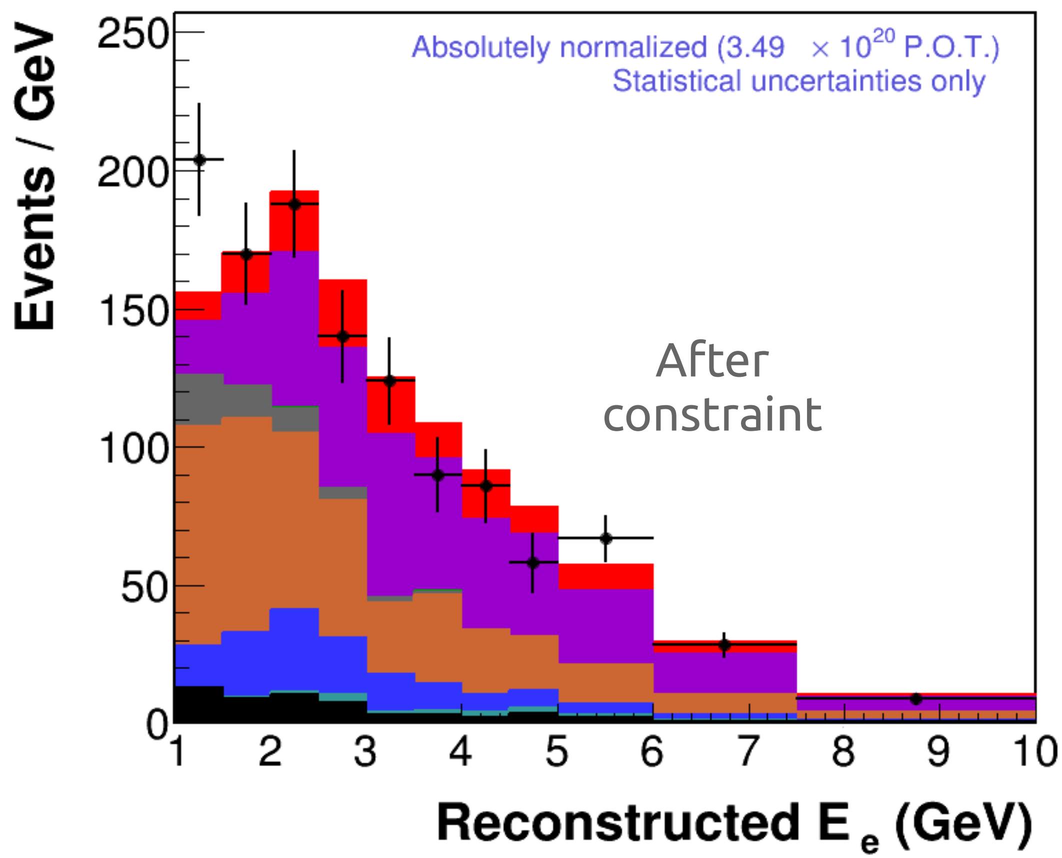


… and examine the normalizations of two distributions in each sideband (one of them, candidate electron energy, shown here; candidate electron angle is also used).

Then, fit the normalizations of the "other ν_e" and "other NC π^0"+"CC ν_μ π^0" categories, using the four distributions simultaneously.

Constraining backgrounds

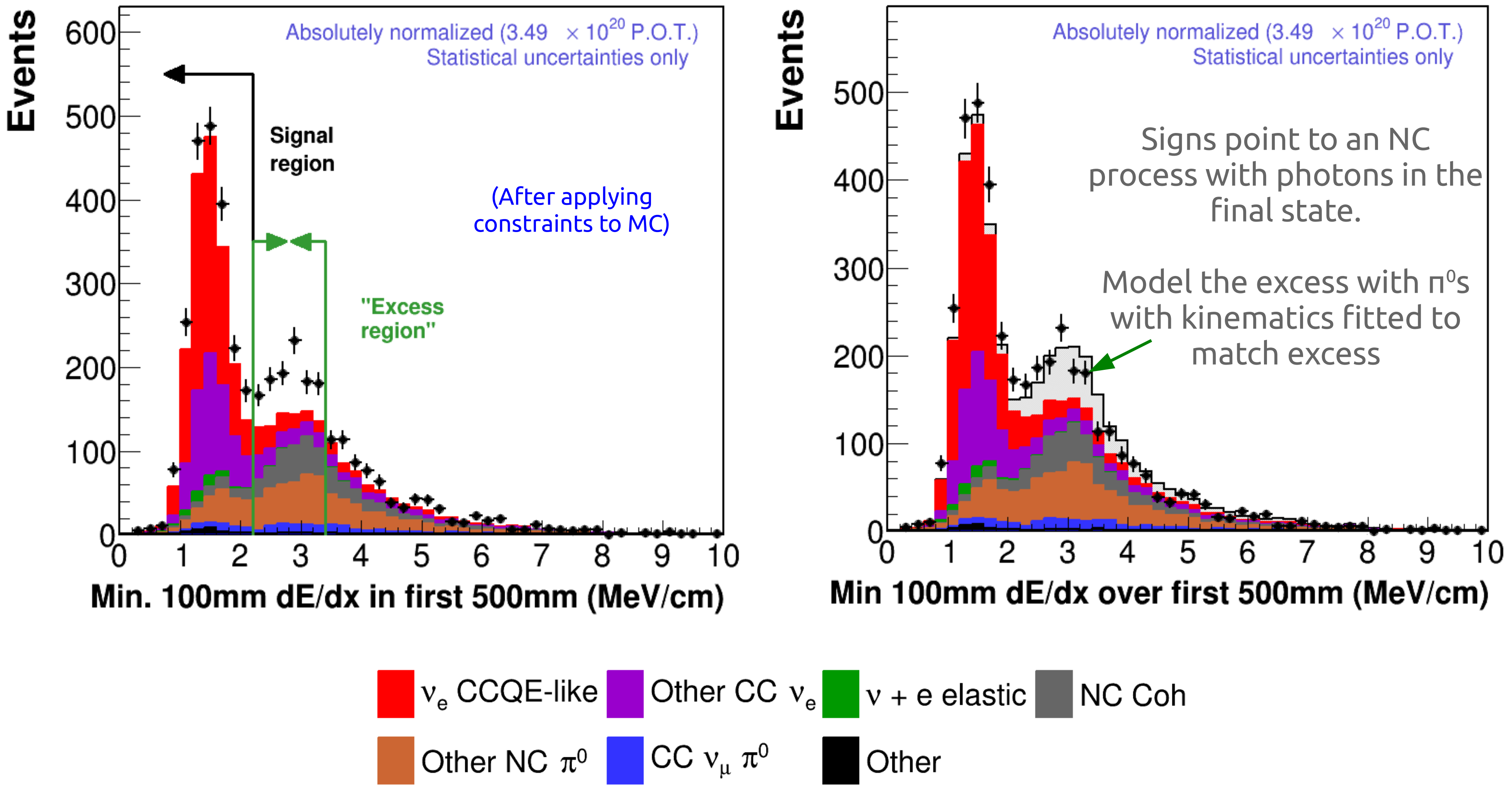




This is one of four (sideband, variable) combinations that are fitted simultaneously.
(Here: electron energy in "extra energy" sideband.)

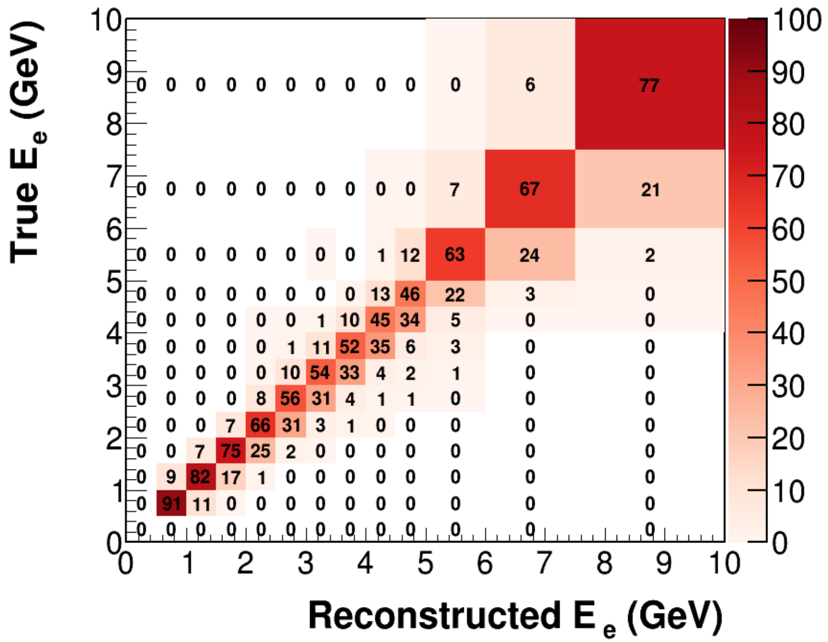
Scale factors:
0.90 for "other ν_e", 1.11 for "other NC π^0"+"CC ν_μ π^0"

Unmodeled data excess



The (minimal) contribution in the signal region from the "mystery" process is subtracted along with the other backgrounds.
Will return to the question of its identity shortly.

Steps to a cross section



Unfold the *observable* quantities, using a Bayesian technique, to correct for the simulated resolutions

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

(unsmearing matrix) → U_{ij}

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(bin width) → $(\Delta\xi)_i$

(efficiency) → ϵ_i

Steps to a cross section

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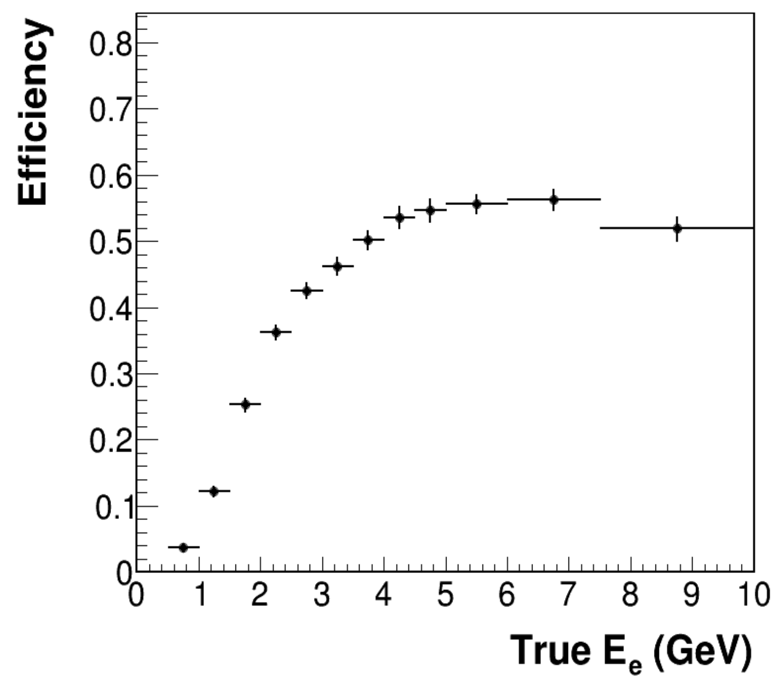
(unsmearing matrix) (selected sample) (predicted background)

(flux) (number of targets) (bin width) (efficiency)

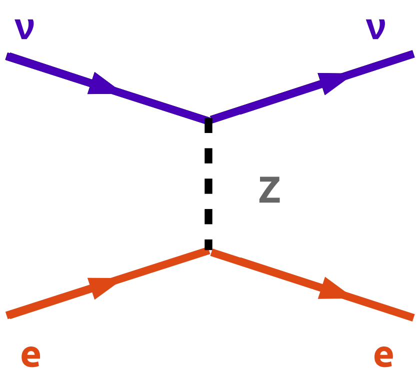
Corrections for the predicted efficiency applied in each variable separately



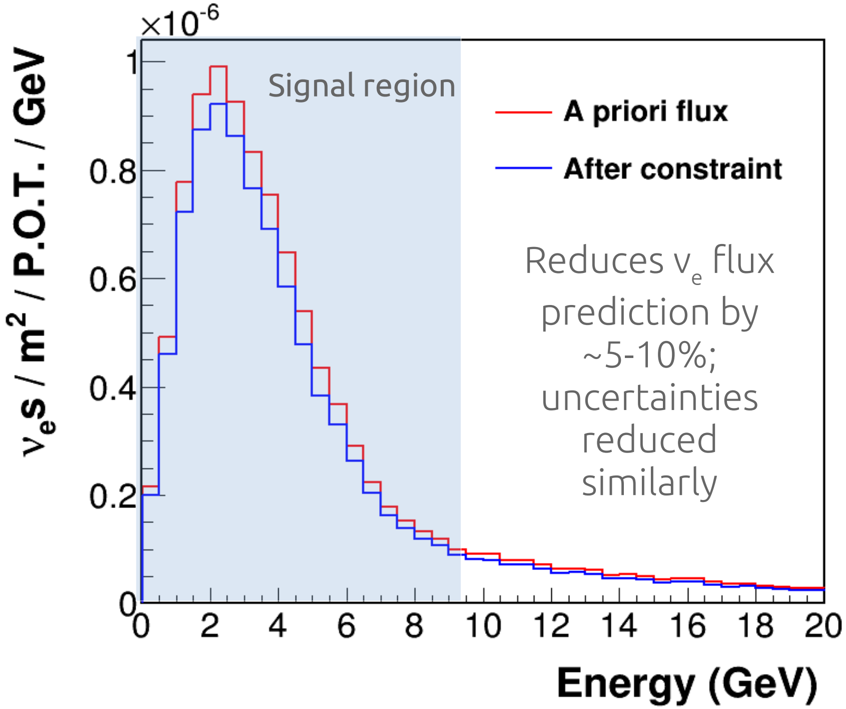
Steps to a cross section

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

(flux) — Φ; (number of targets) — T_n; (bin width) — $(\Delta\xi)_i$; (unsmearing matrix) — U_{ij}; (selected sample) — N_j^{obs}; (predicted background) — N_j^{bknd}; (efficiency) — ϵ_i

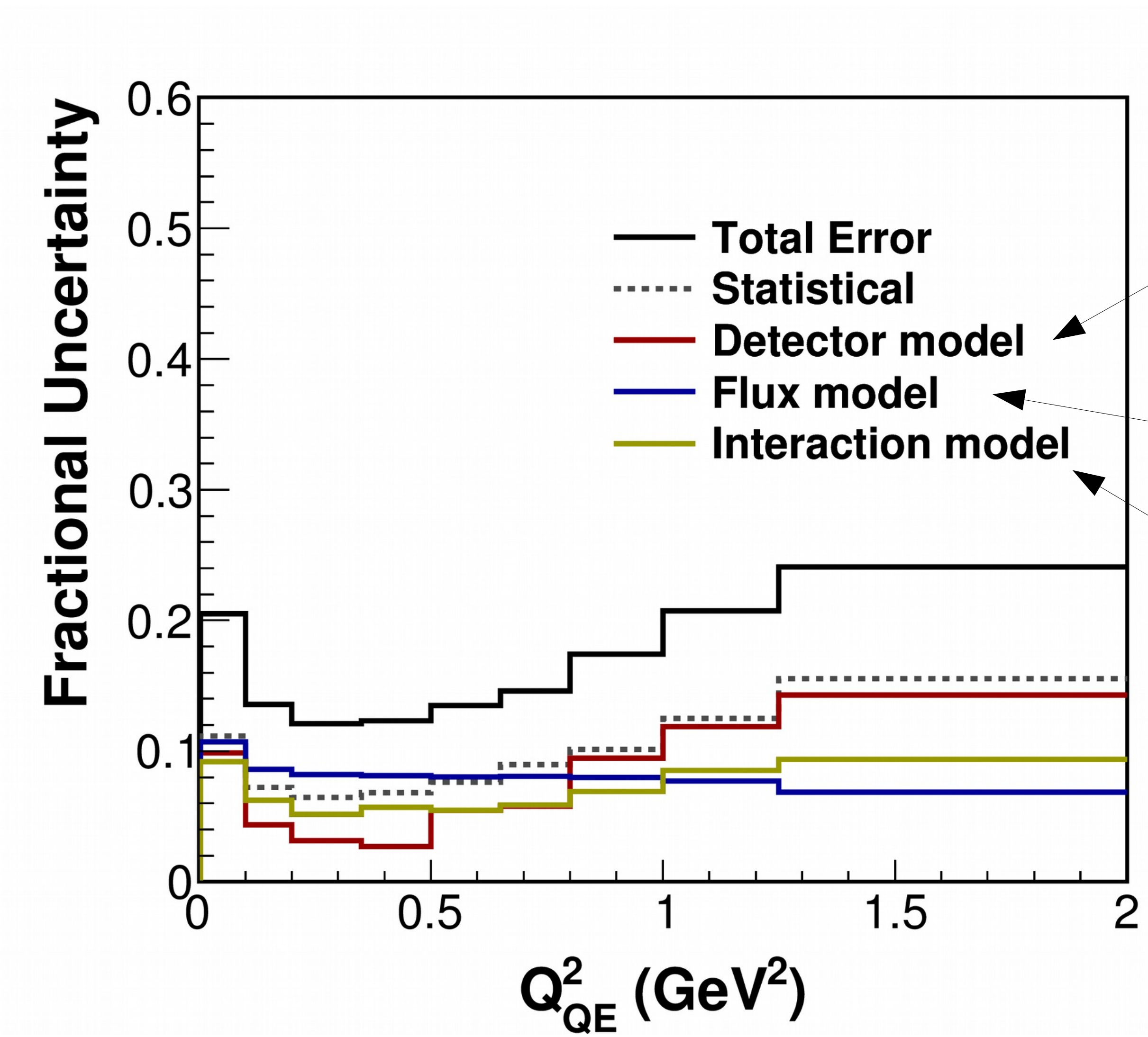


The *a priori* flux is constrained using a separate *in situ* measurement of the neutrino-electron elastic scattering rate (also constrains this background)



Reduces ν_e flux prediction by ~5-10%; uncertainties reduced similarly

Uncertainty summary

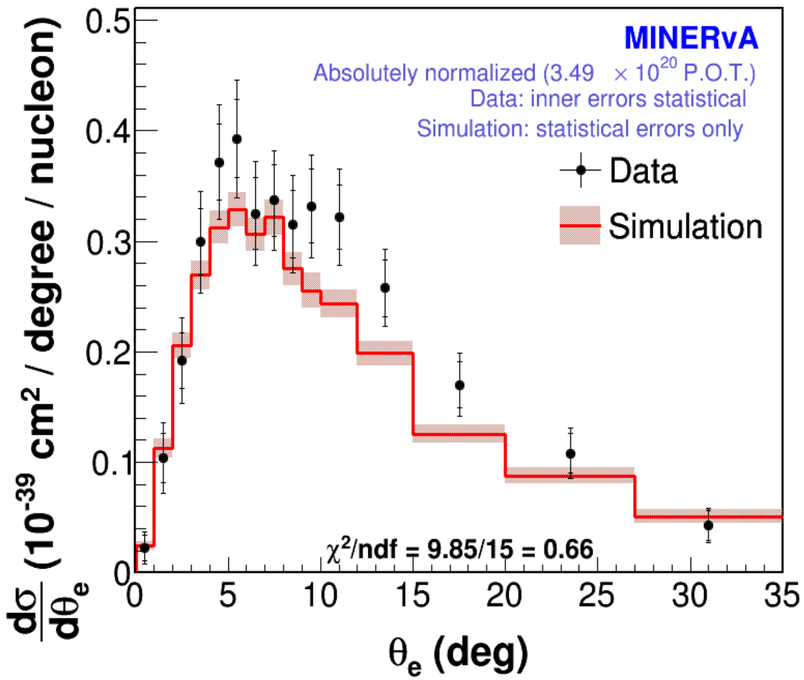


Includes energy scale estimated using the π^0 mass peak in a separate measurement; resolutions; other detector effects

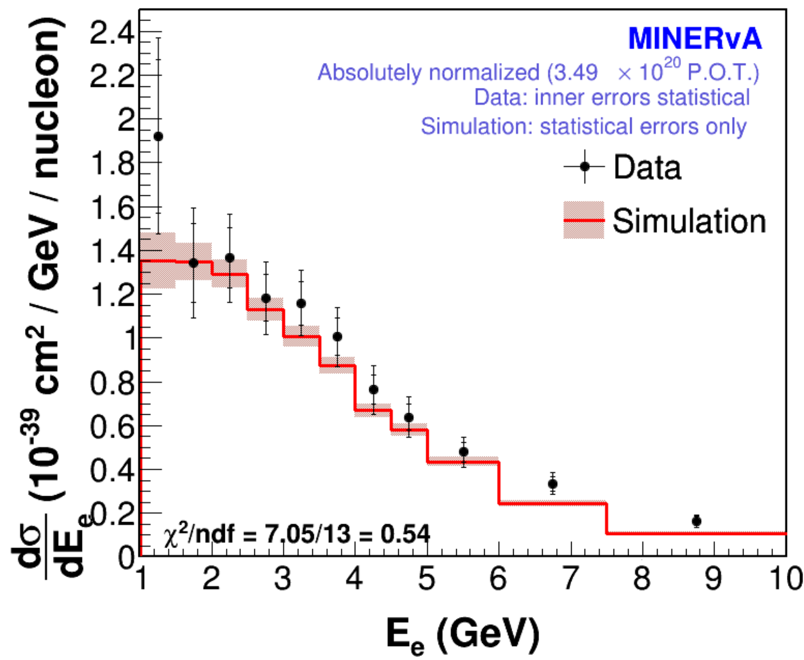
Constrained as noted previously

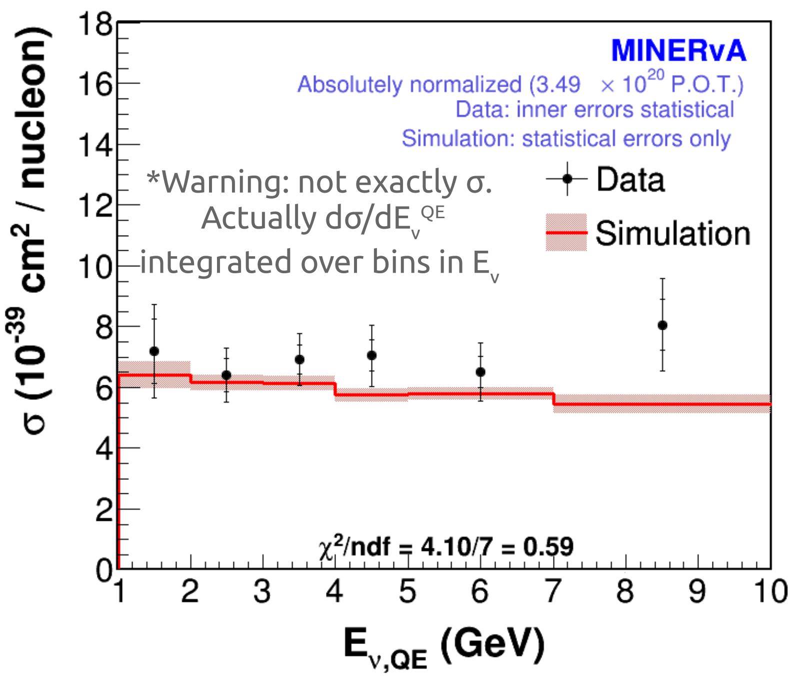
Mostly enters in background subtraction (from GENIE 2.6.2)

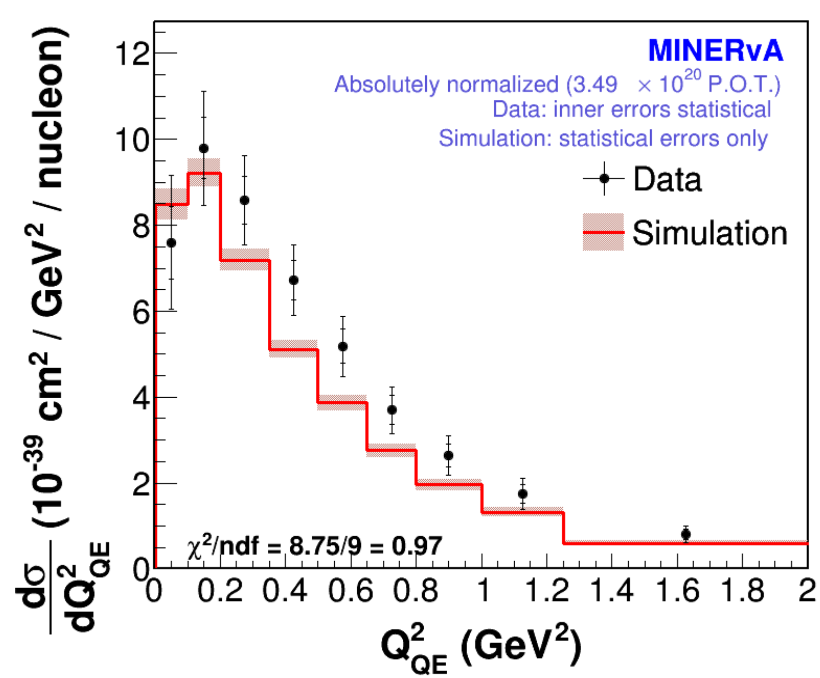
cross sections



The result and the prediction from GENIE 2.6.2 are statistically consistent.

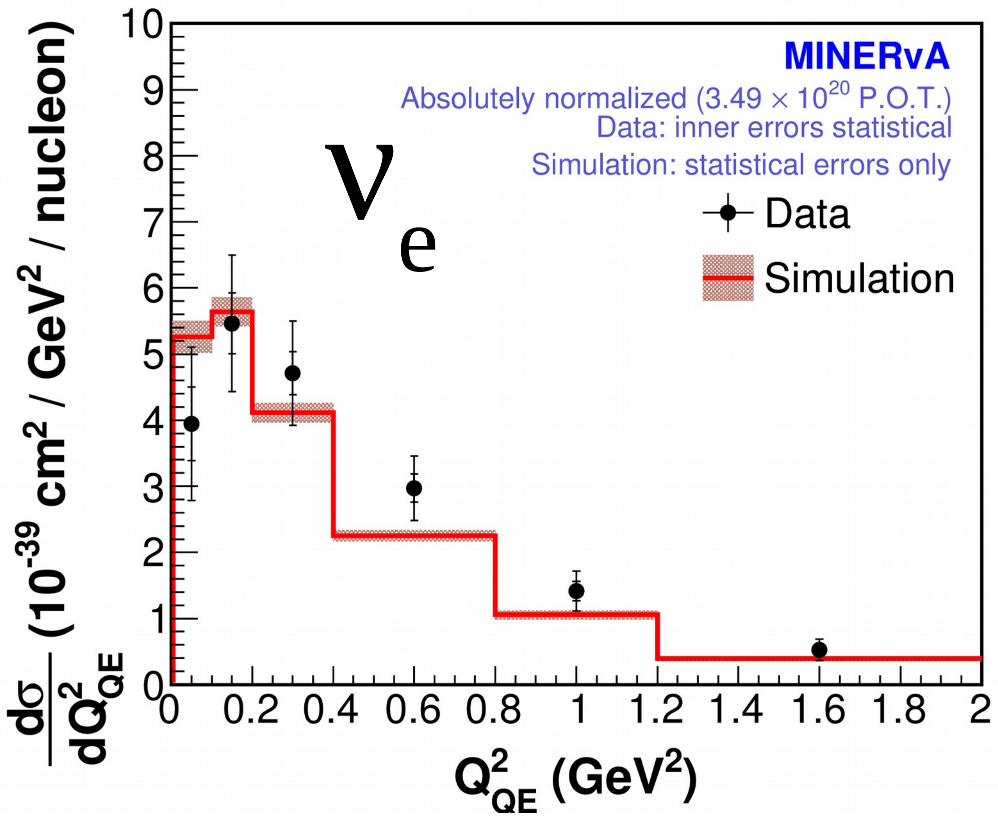


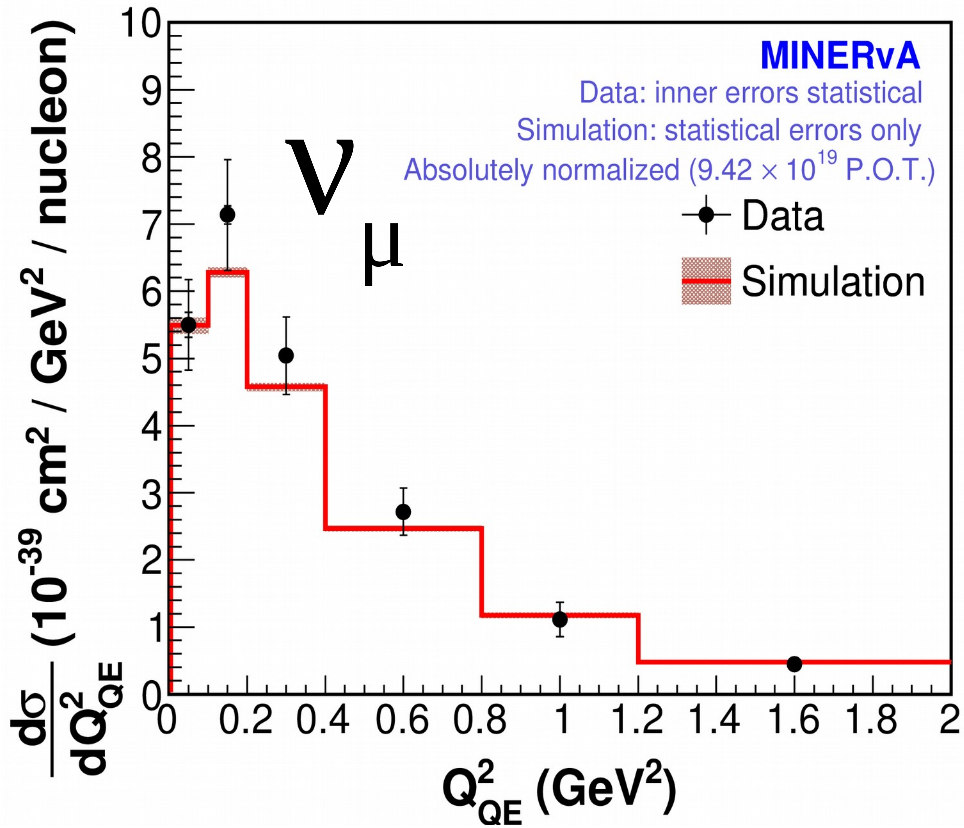




ν_e-ν_μ comparisons

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.





Both the ν_μ and the ν_e cross sections
more or less agree with the model.

ν_e-ν_μ comparisons

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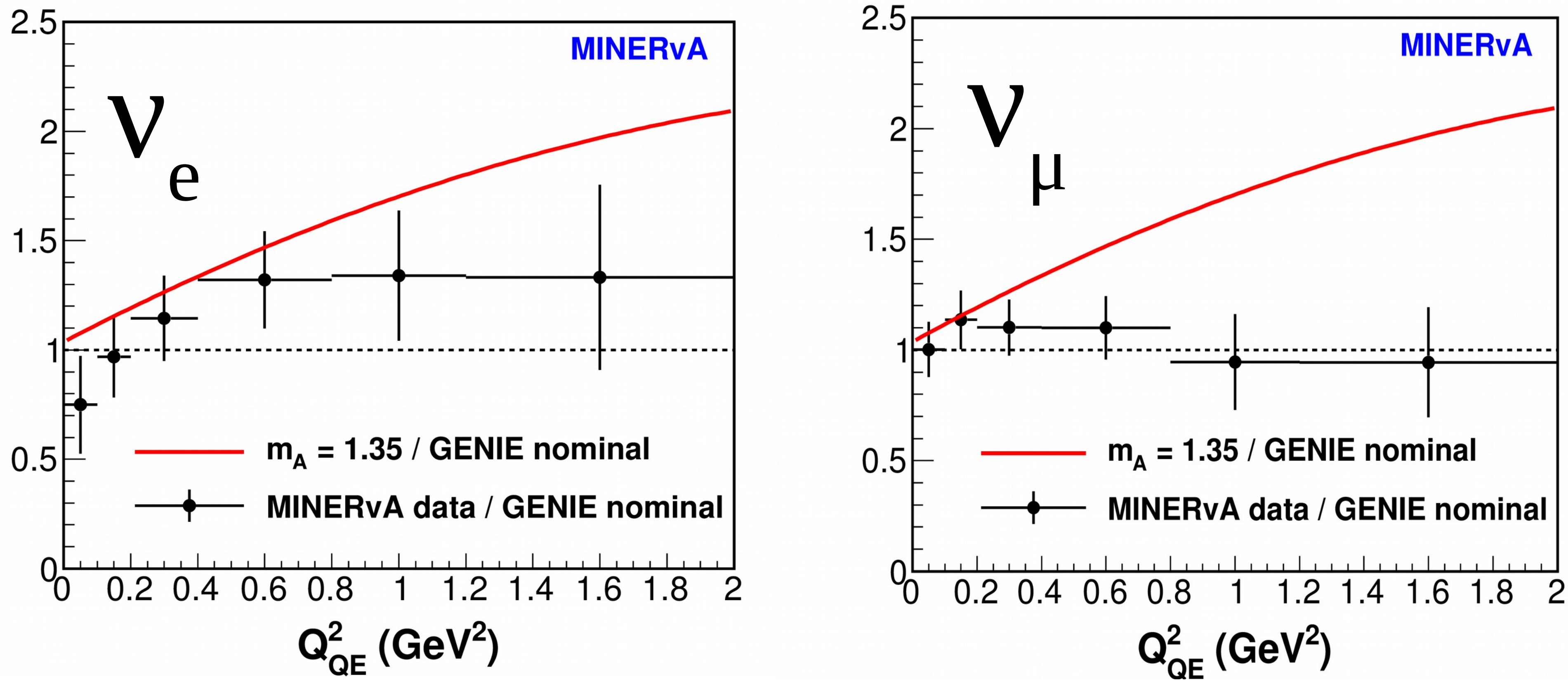

For scale, compare our "agreeing with the model" with a well-known puzzle in CCQE scattering

ν_e-ν_μ comparisons

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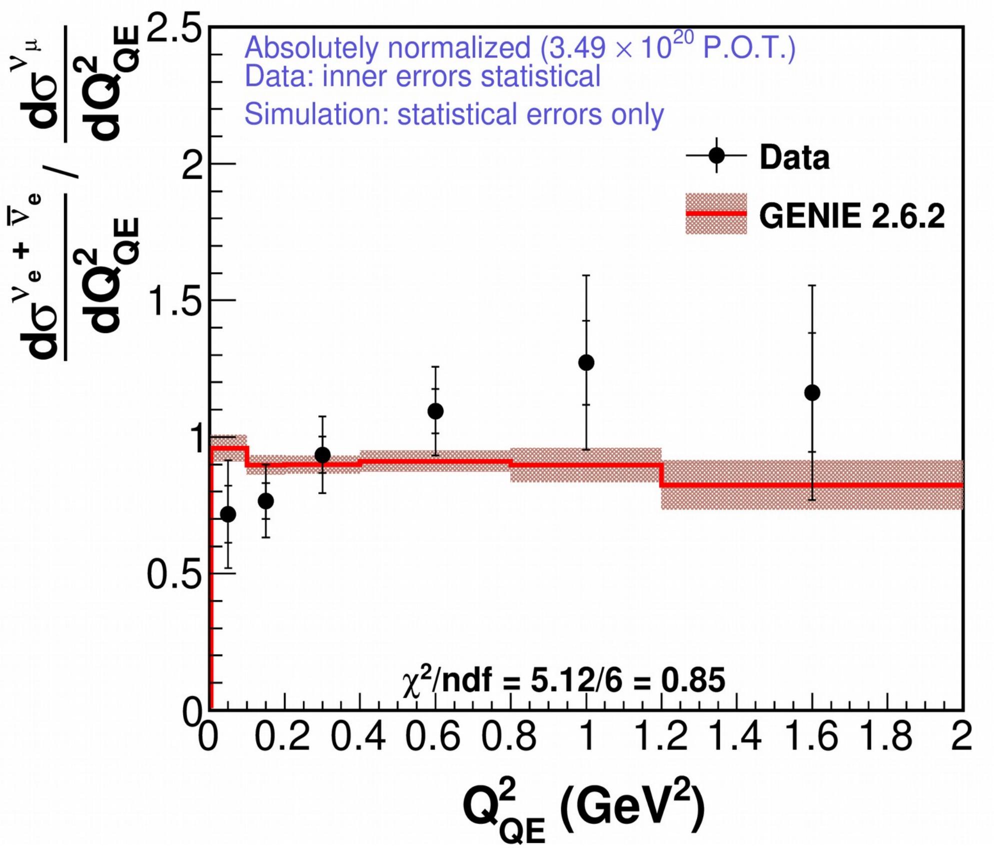

The ratio shows the same level of agreement as well.
Conclusion: <u>using $\sigma_{\nu\mu}$ for $\sigma_{\nu e}$ is justified.</u>

ν_e-ν_μ comparisons

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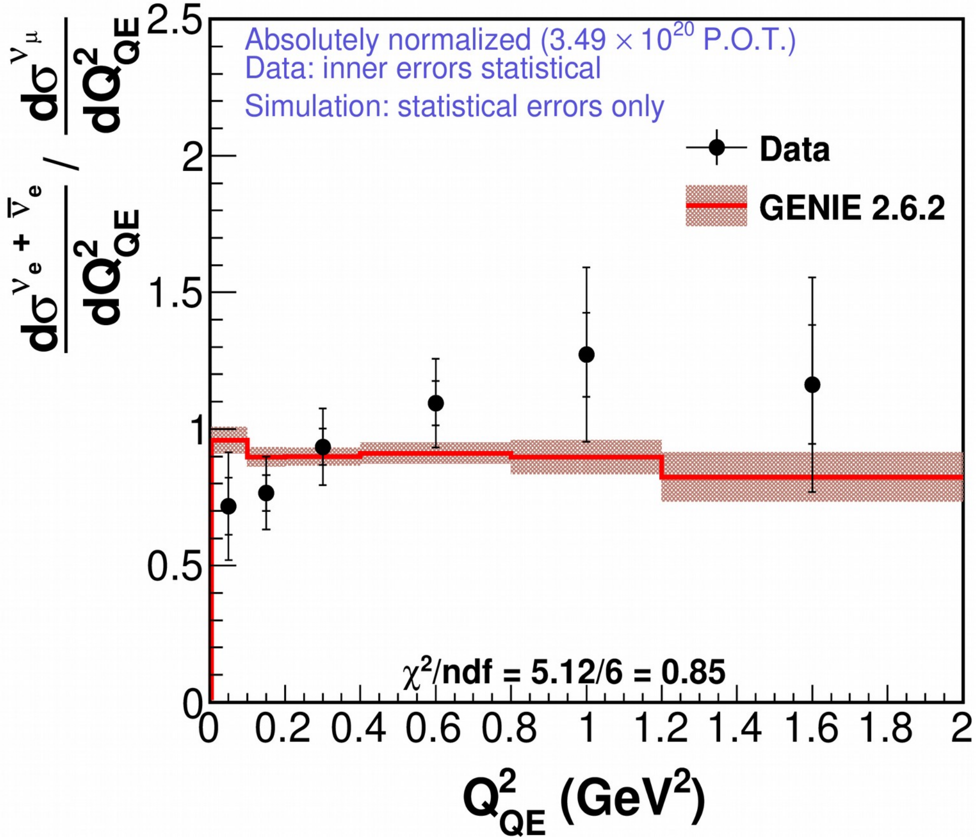
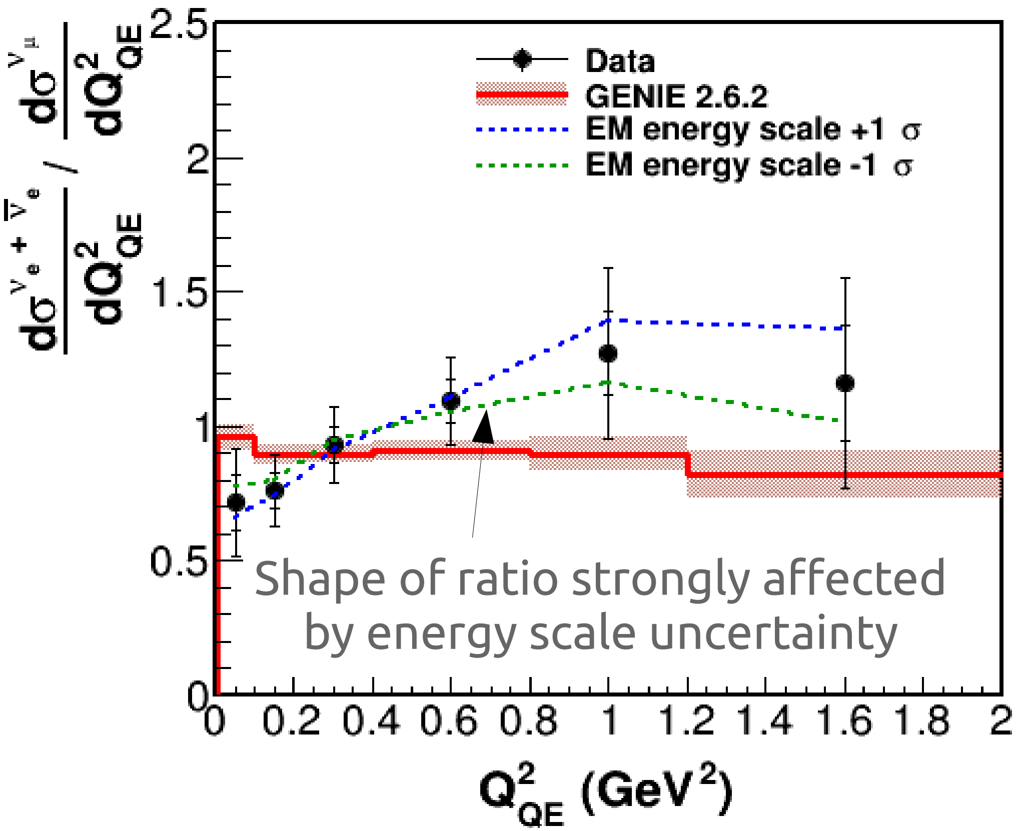
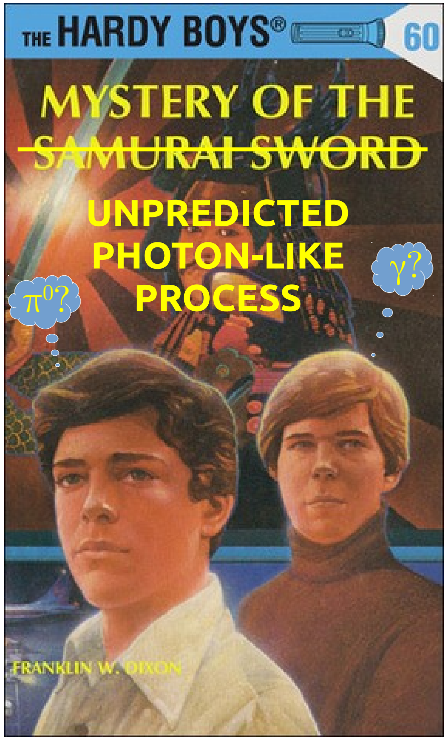


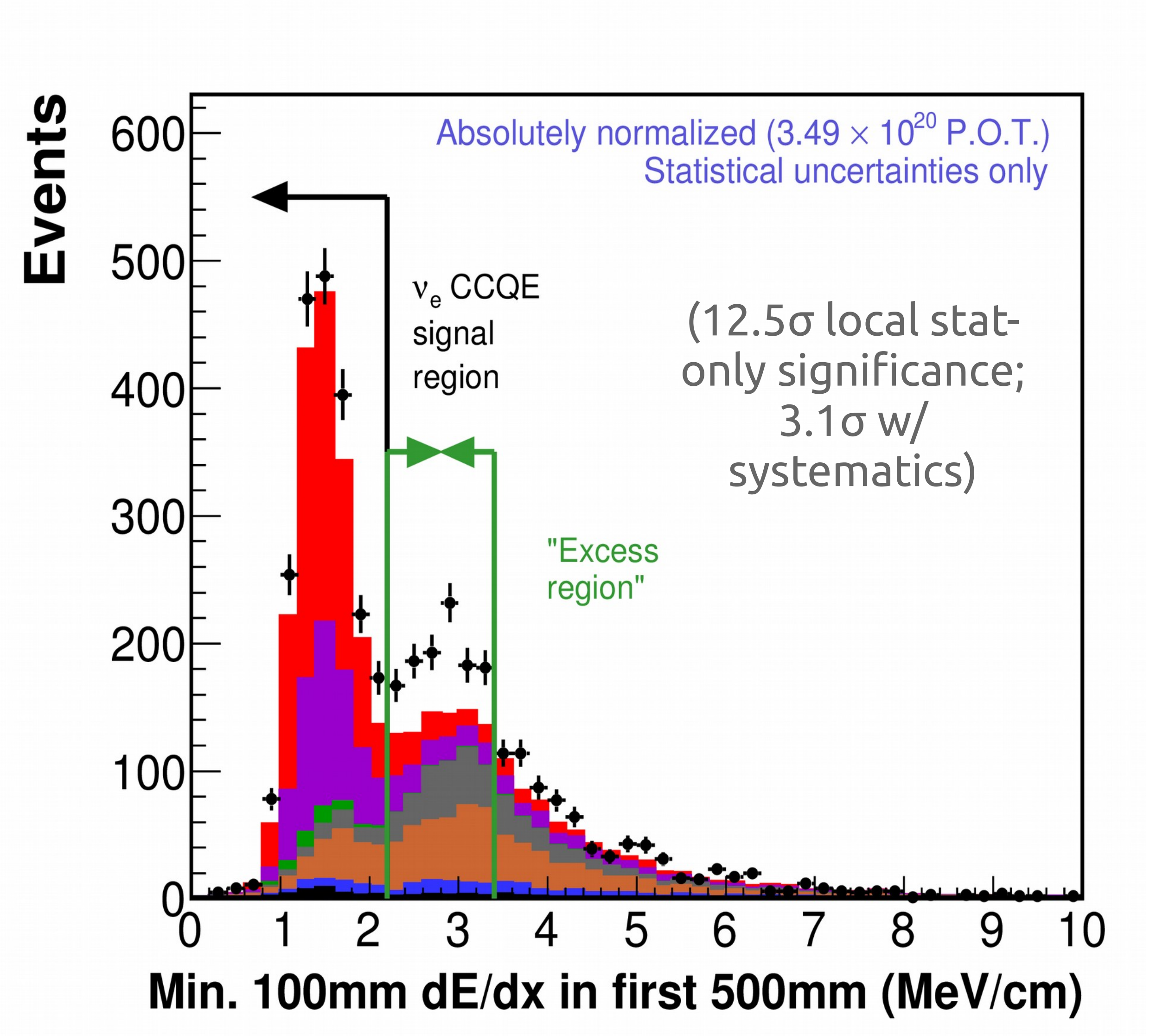


p.s.... beware: don't read too much into the shape.
The shape is not significant when the correlations in the uncertainties are taken into account.

Investigating
the mystery process



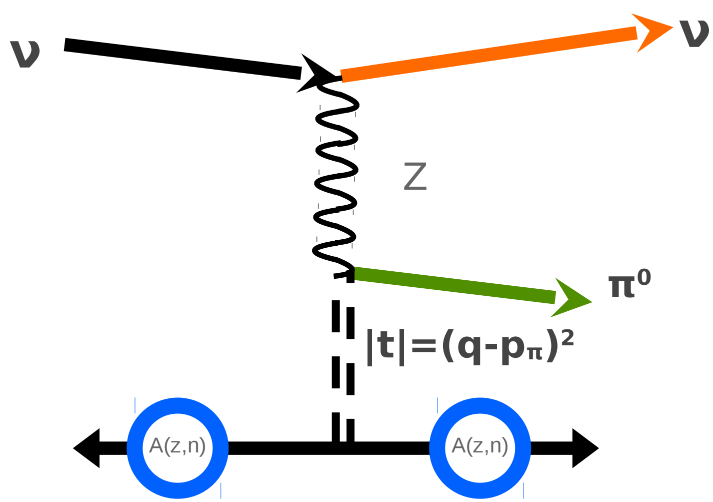
Excess



(12.5σ local stat-only significance; 3.1σ w/ systematics)

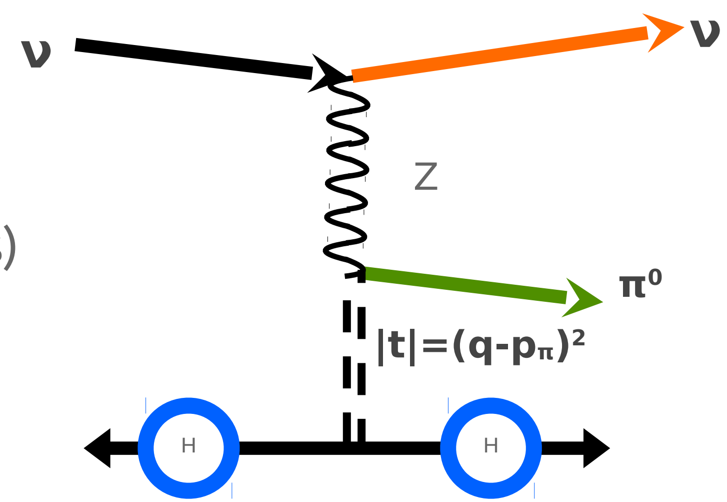
Excess

- We believe our excess is due to NC diffractive scattering from Hydrogen
  - MINERvA tracker is hydrocarbon (lots of H)
  - No default model in GENIE
  - Event characteristics very similar… (next slide)



PCAC-based NC coherent production from *nuclei*

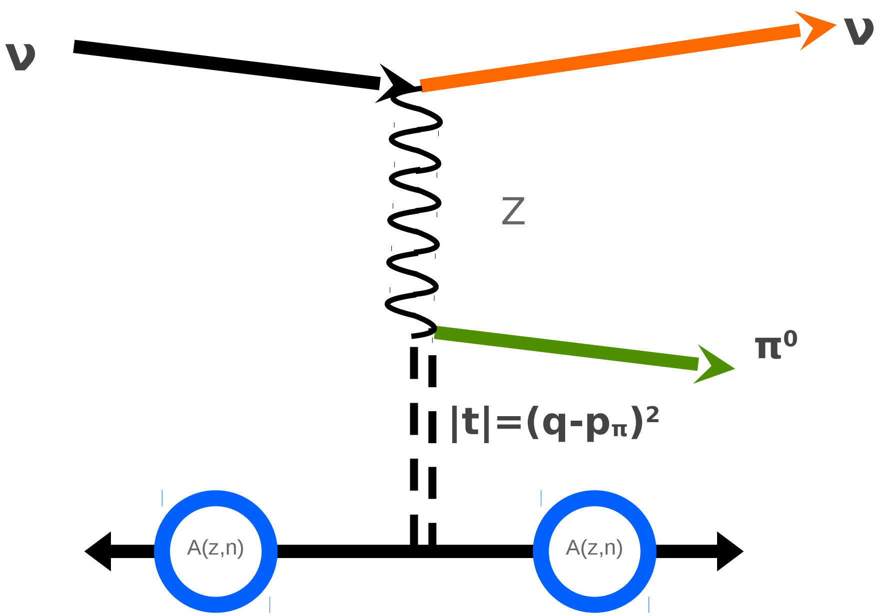
(analogous)



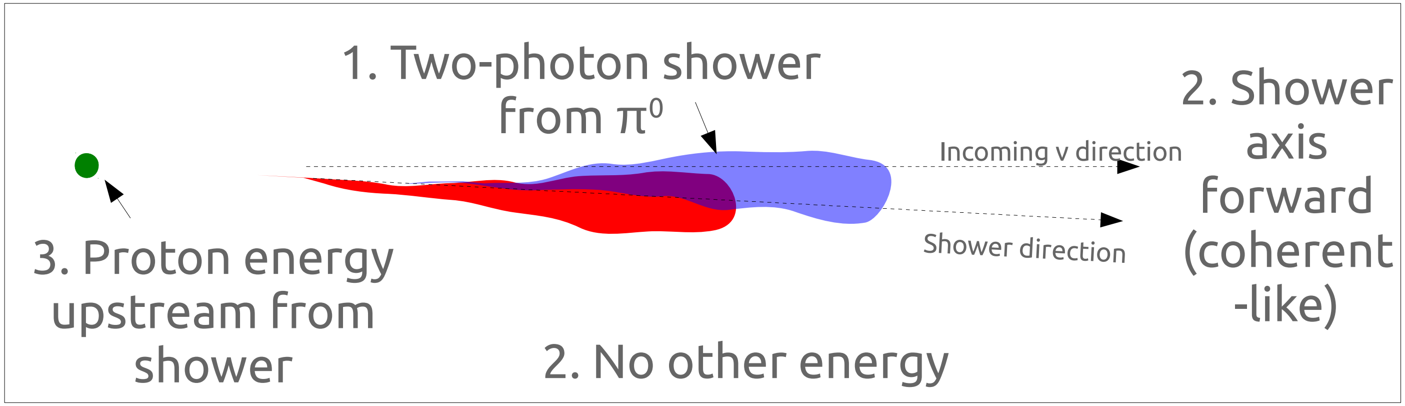
PCAC-based NC diffractive production from *H*

Excess

- Characteristics of excess match diffractive process very well:
  1) Two-photon π^0 shower
  2) Coherent-like scattering:
     - Forward kinematics
     - Very little other energy
  3) Visible proton energy
- Predominantly higher-energy showers



NC diffractive production from *H*



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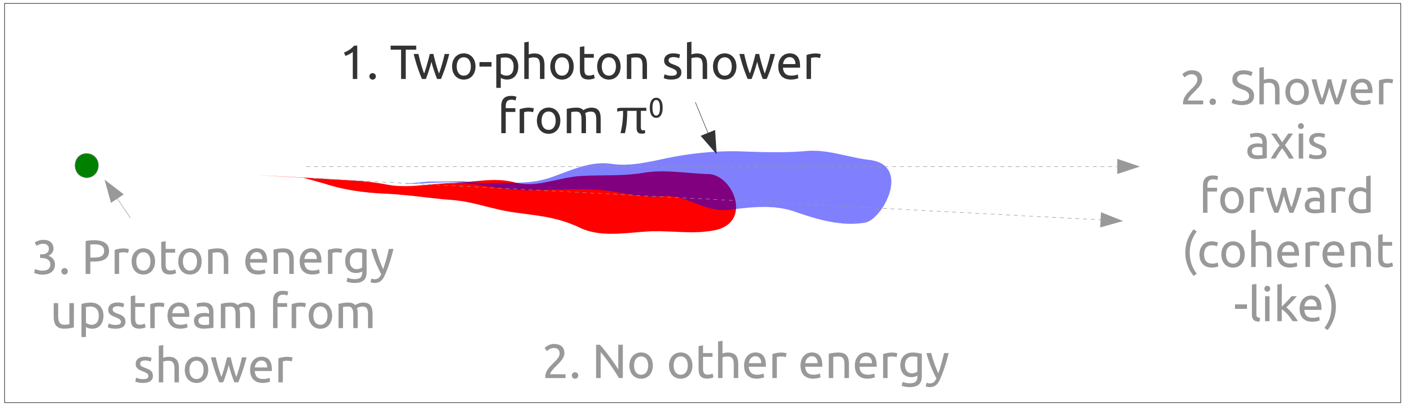
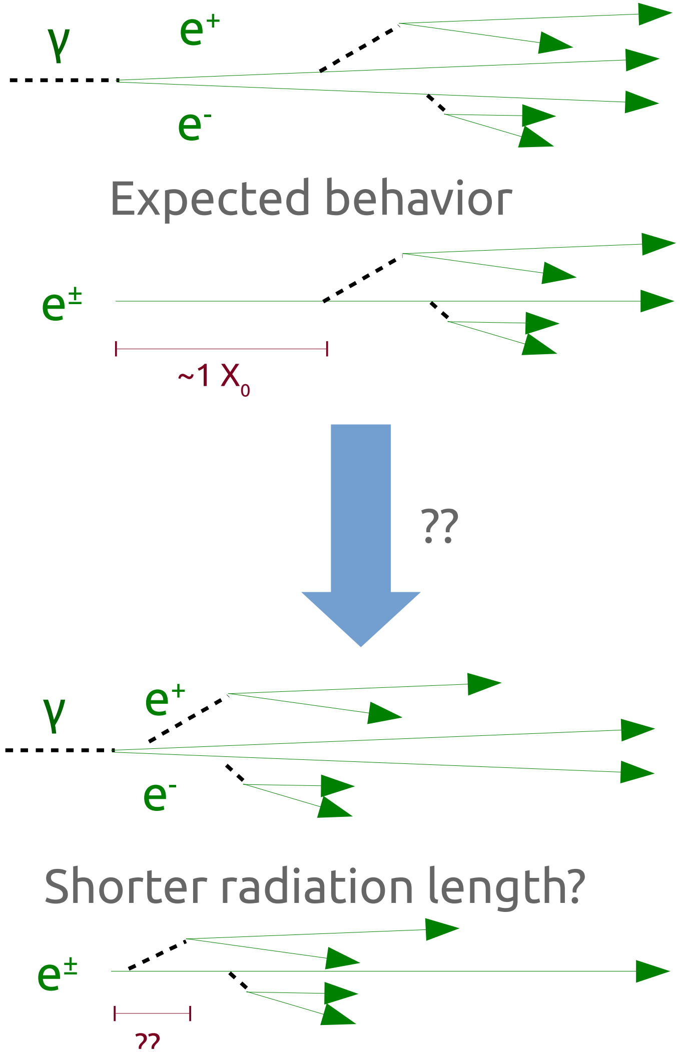
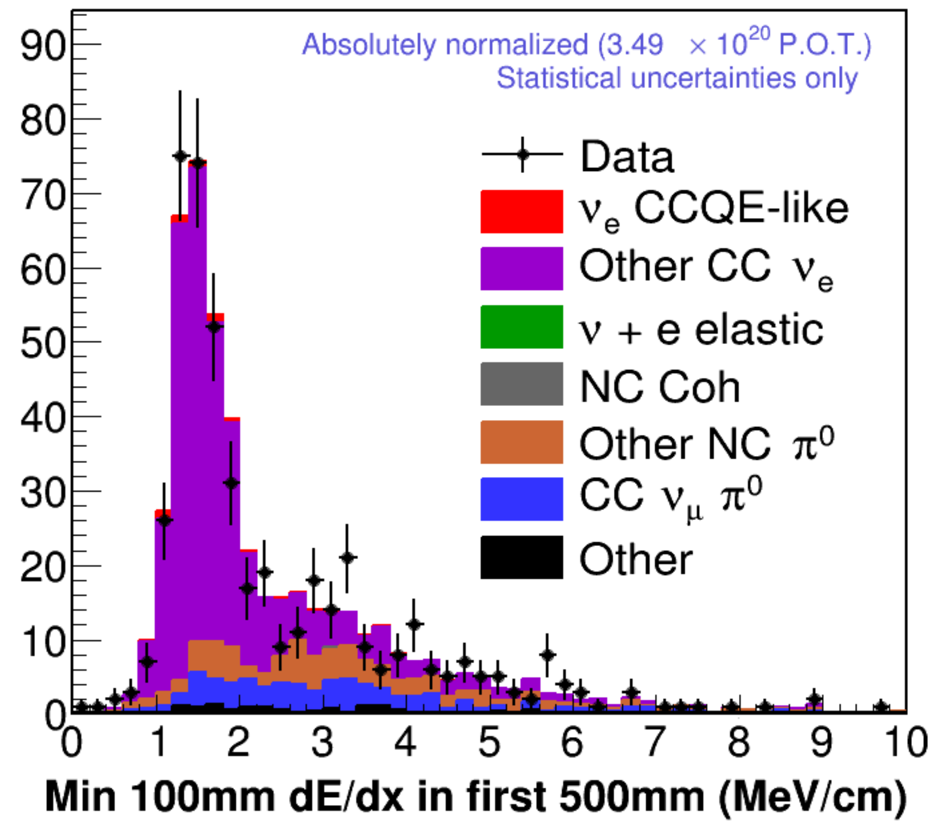


Could it just be more electrons?



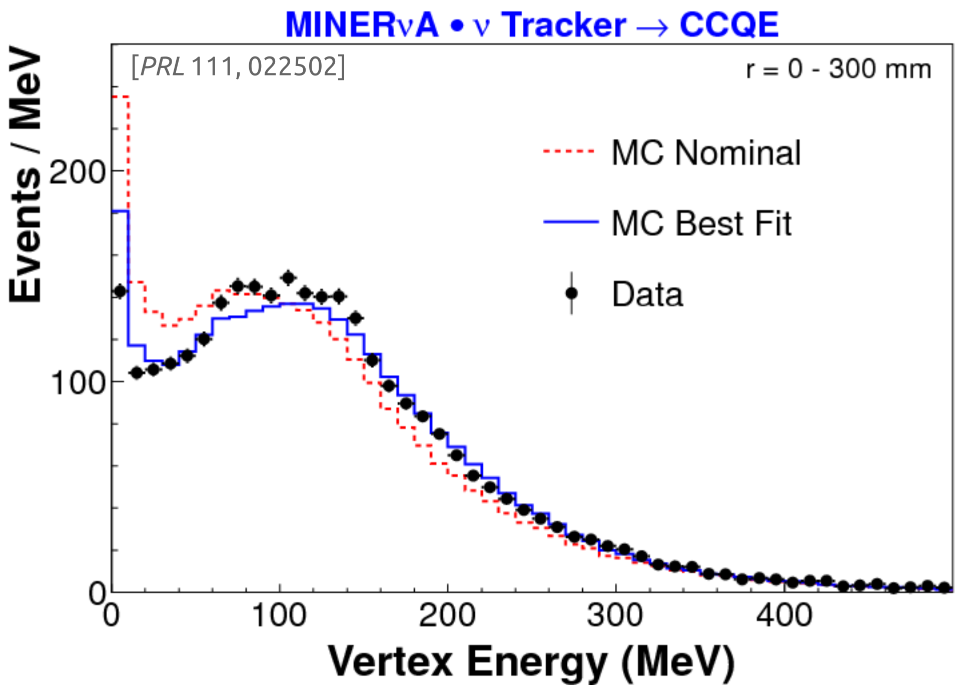


Michel electron sideband is heavily dominated by ν_e.

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

Unlikely to be an electron shower modeling problem.

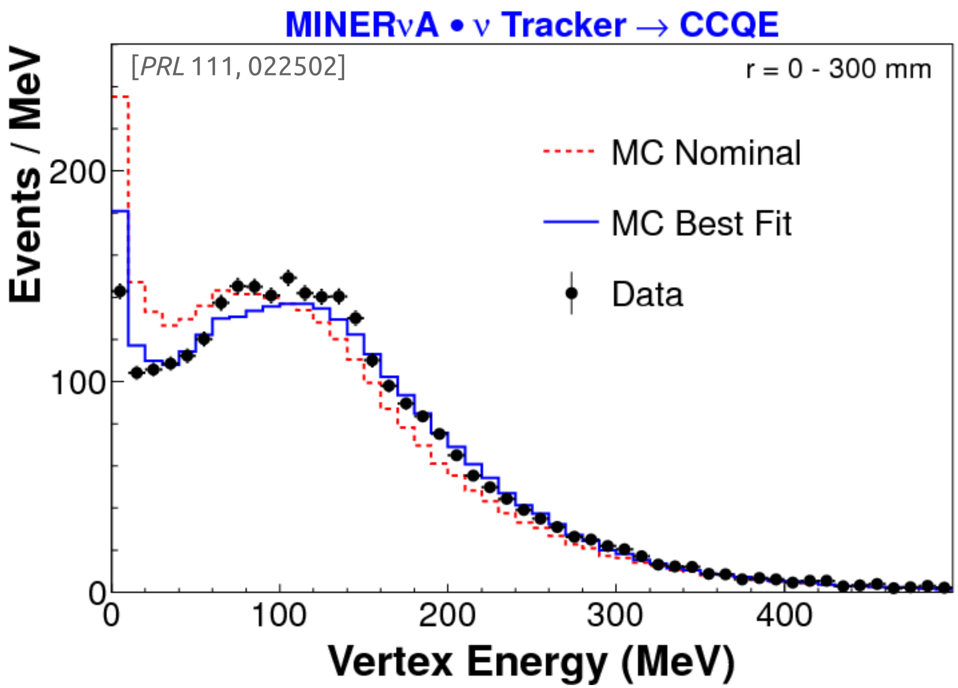
Could it be extra nuclear activity?



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.

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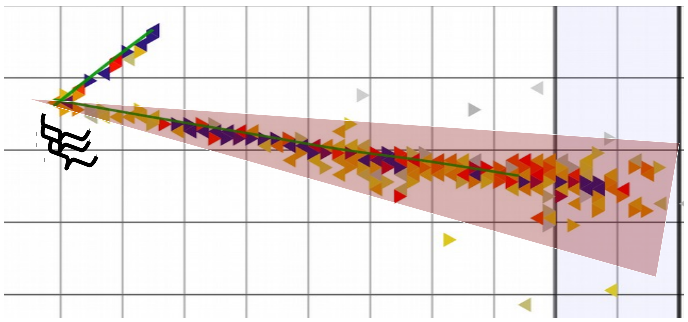
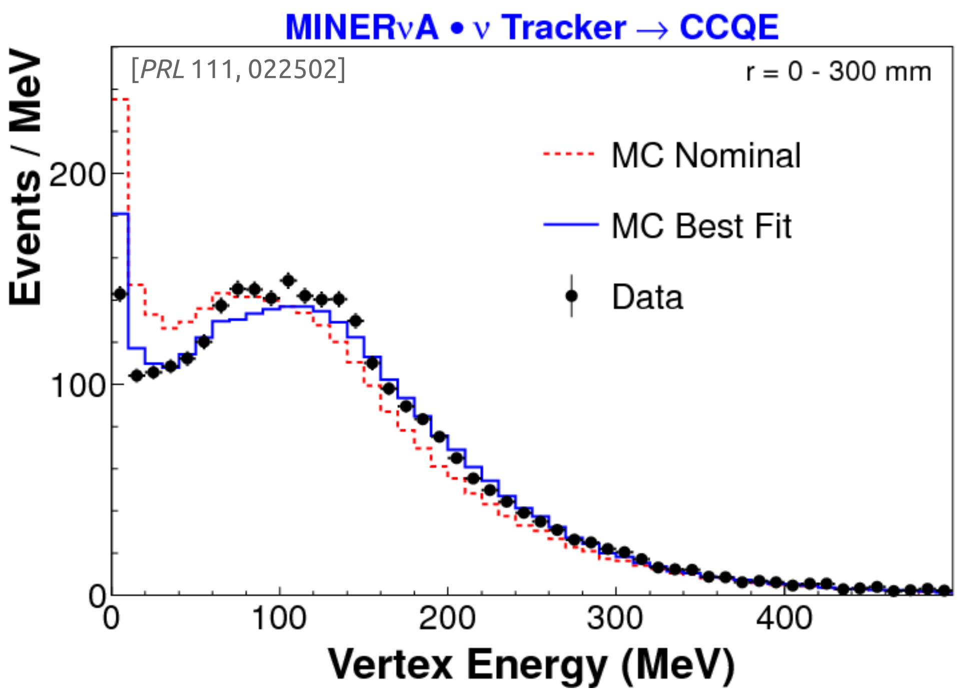
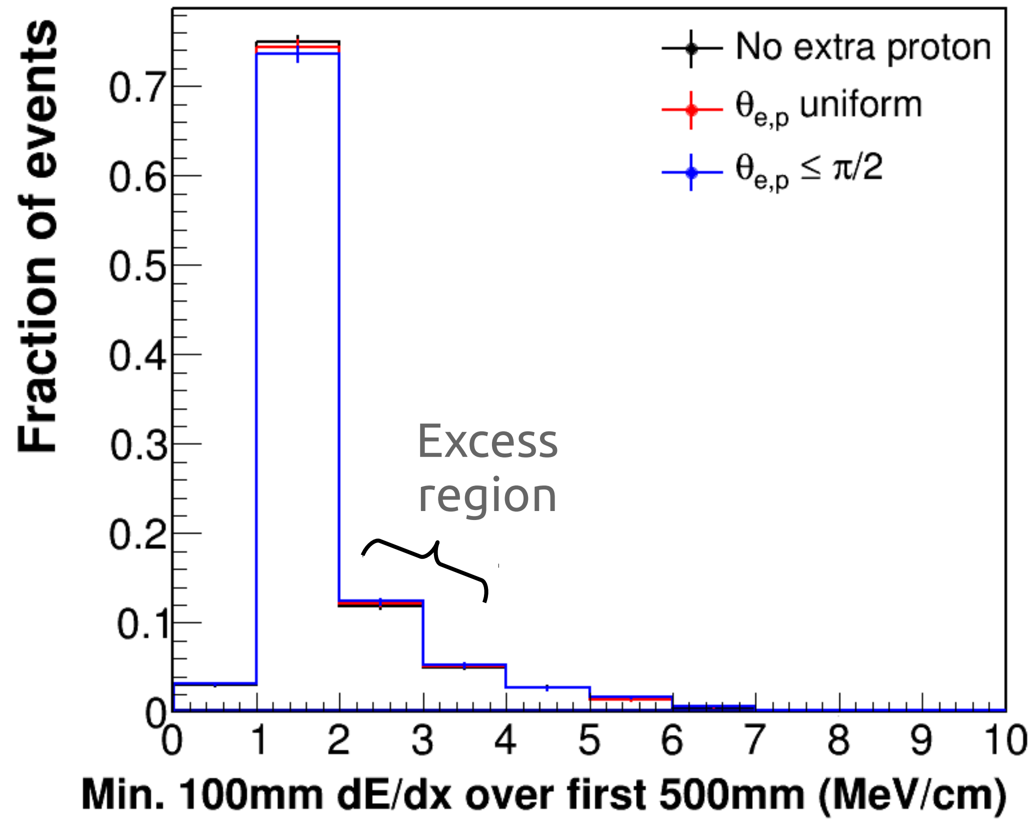
(Simulated signal event)



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?





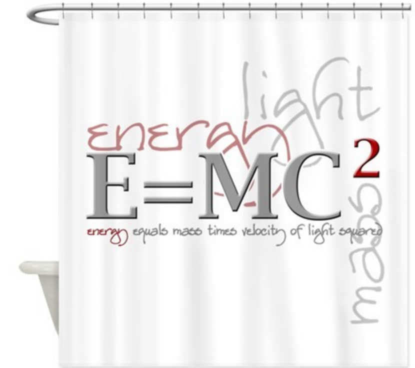
MINERvA muon neutrino CCQE found evidence that sometimes more particles are produced at the vertex than the simulation predicts.

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

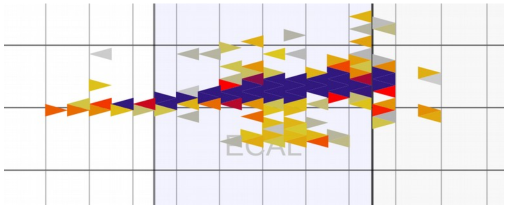
Toy studies with extra protons of 0-200 MeV added randomly to 25% of ν_e CCQE events do not create a measurable excess.

Not likely due to extra particles in ν_e CCQE events.

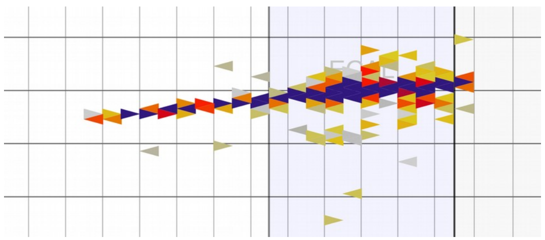
Identifying the shower energy



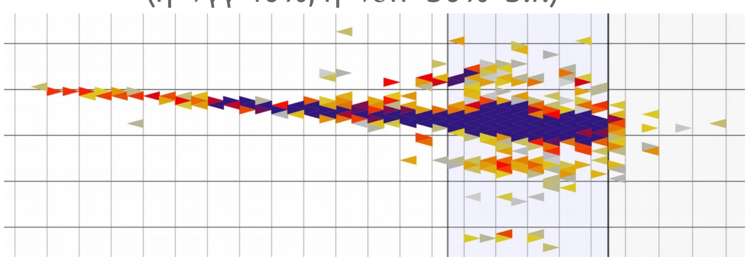
6.9 GeV simulated γ



4.8 GeV simulated π^0
($\pi^0 \rightarrow \gamma\gamma$ 99% b.f.)



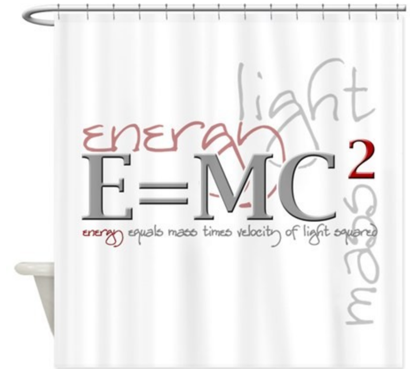
16 GeV simulated η
($\eta \rightarrow \gamma\gamma$ 40%, $\eta \rightarrow 3\pi^0$ 30% b.f.)



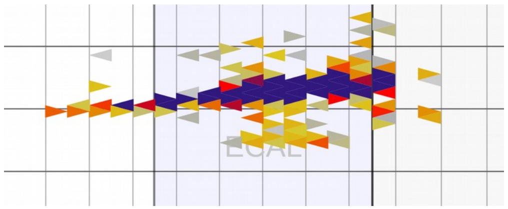
<u>Challenge</u>:

Can't reliably differentiate between single- and multi-photon showers on event-by-event basis

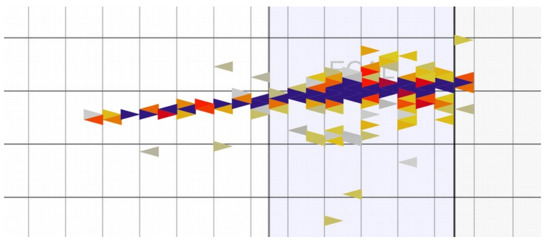
Identifying the shower energy



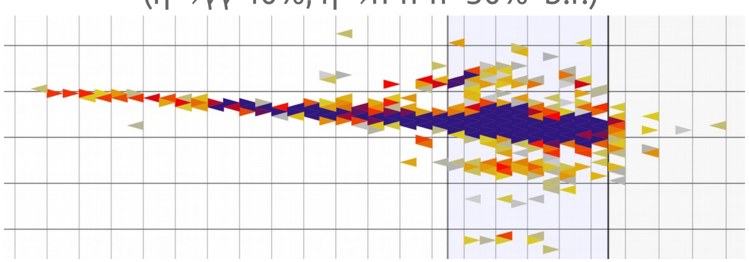
6.9 GeV simulated γ



4.8 GeV simulated π⁰
($\pi^0 \to \gamma\gamma$ 99% b.f.)



16 GeV simulated η
($\eta \to \gamma\gamma$ 40%, $\eta \to \pi^0\pi^0\pi^0$ 30% b.f.)

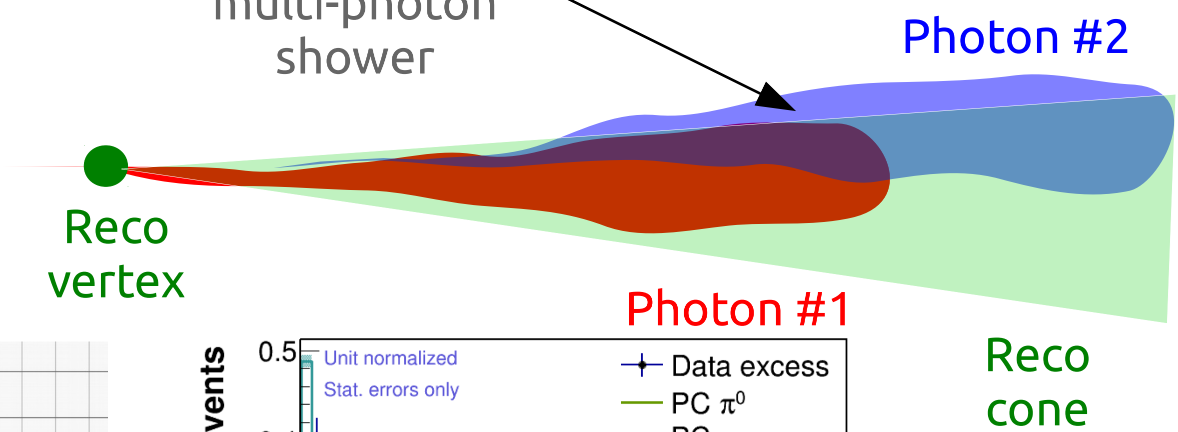


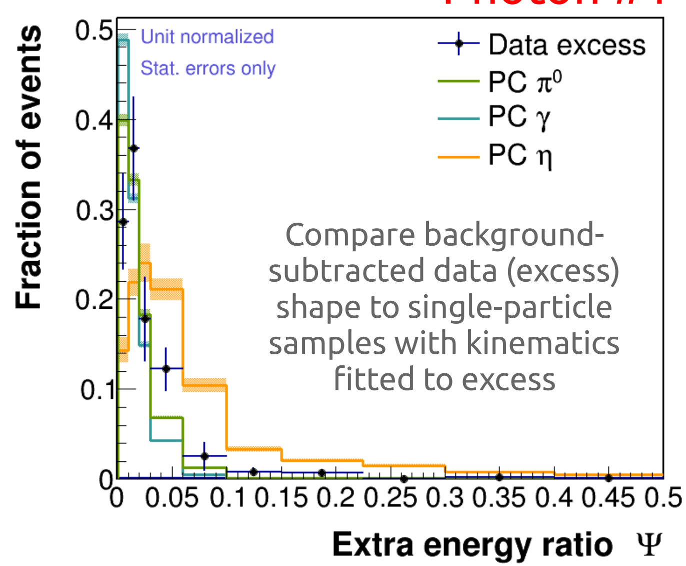
Challenge:

Can't reliably differentiate between single- and multi-photon showers on event-by-event basis

Attempt to separate *statistically*

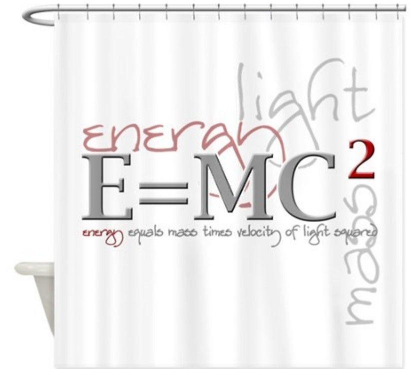
Expect more extra energy (larger Ψ) for multi-photon shower



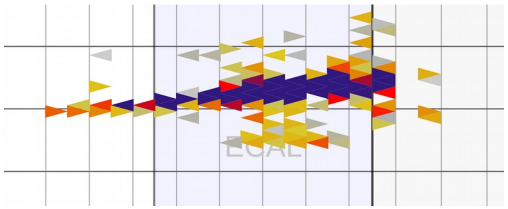


Disfavors η

Identifying the shower energy

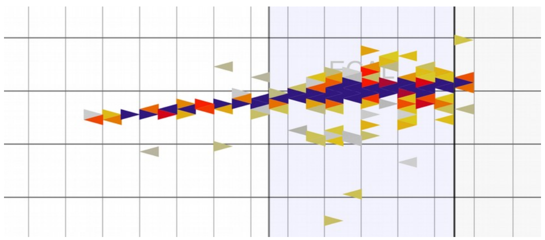


6.9 GeV simulated γ



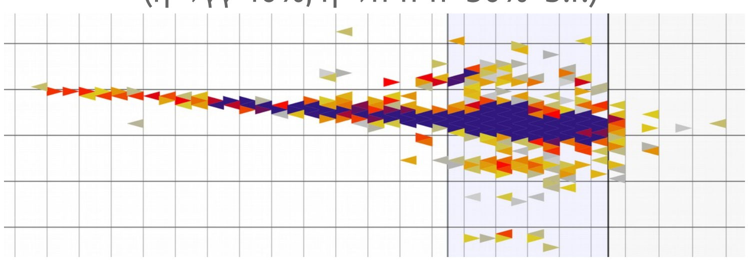
4.8 GeV simulated π⁰

(π⁰→γγ 99% b.f.)



16 GeV simulated η

(η→γγ 40%, η→π⁰π⁰π⁰ 30% b.f.)

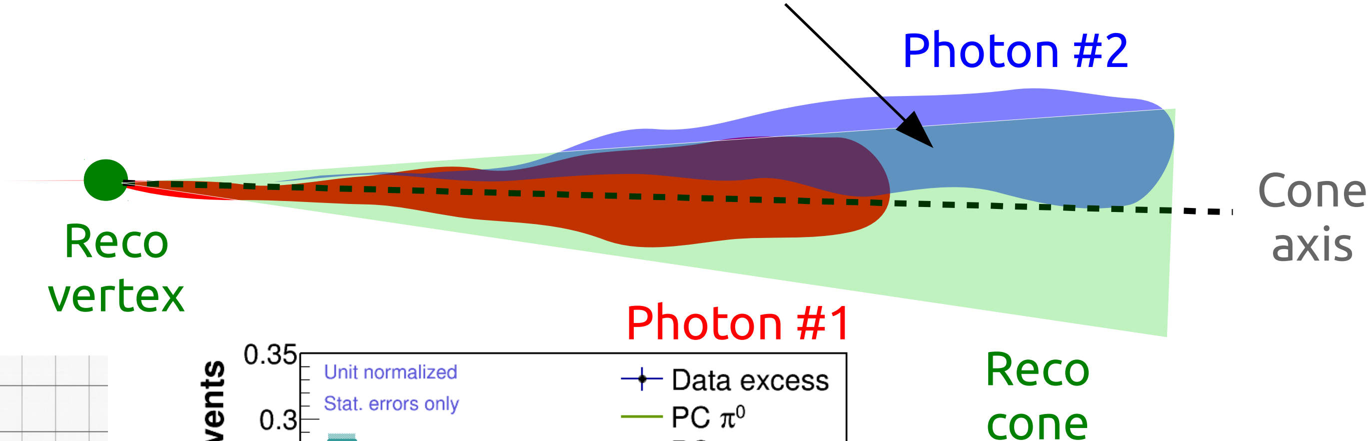


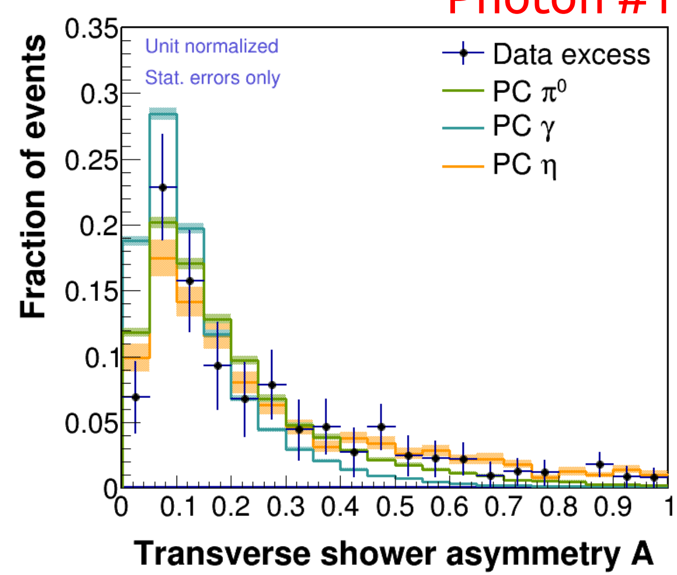
<u>Challenge</u>:

Can't reliably differentiate between single- and multi-photon showers on event-by-event basis

<u>Attempt to separate *statistically*</u>

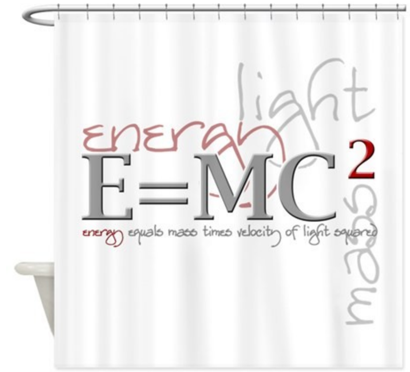
Expect energy to be distributed asymmetrically around cone axis for multi-photon shower



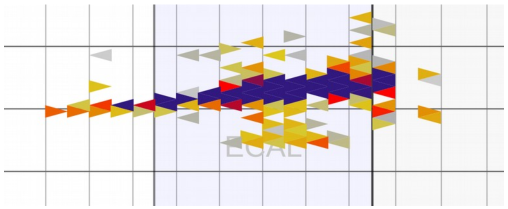


<u>Disfavors γ</u>

Identifying the shower energy

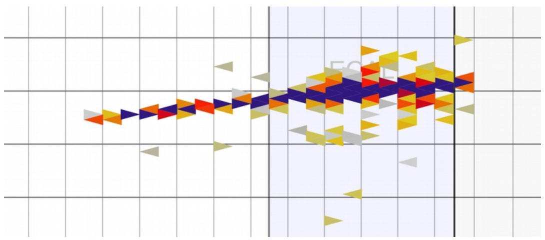


6.9 GeV simulated γ



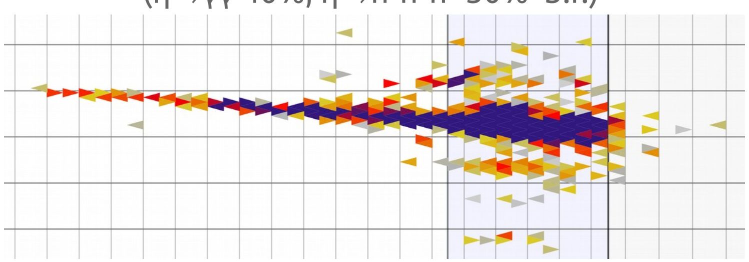
4.8 GeV simulated π⁰

(π⁰→γγ 99% b.f.)



16 GeV simulated η

(η→γγ 40%, η→π⁰π⁰π⁰ 30% b.f.)

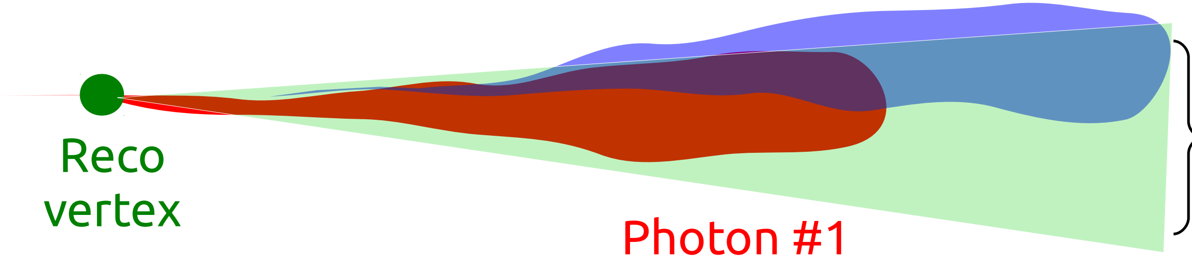


Challenge:

Can't reliably differentiate between single- and multi-photon showers on event-by-event basis

Attempt to separate *statistically*

Photon #2

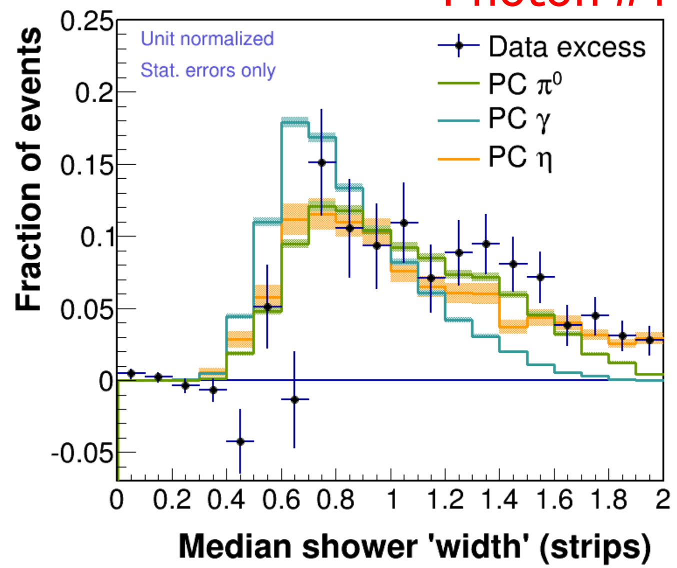


Reco vertex

Photon #1

Reco cone

Expect shower to be wider on average for multi-photon shower



Disfavors γ

Identifying the shower energy

So:

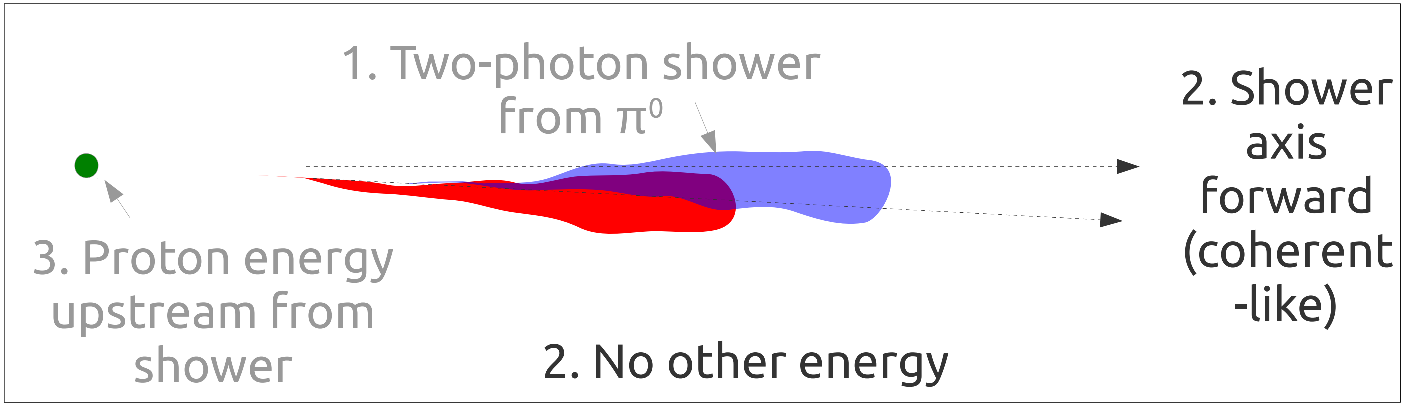
- Ruled out electrons
- Ruled out single photons
- Ruled out heavier mass state decaying to neutrals (η)

<u>Conclusion:</u>

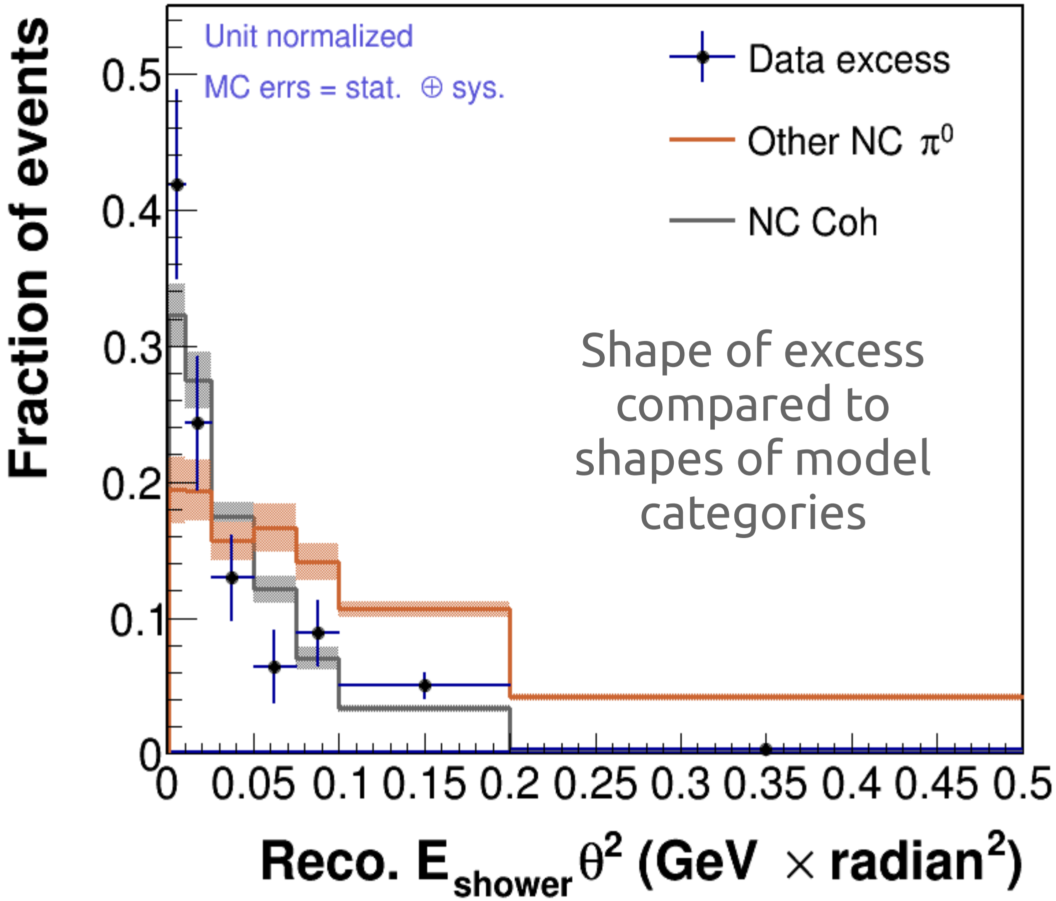
Excess most consistent with showers from π^0s

Excess

- Characteristics of excess:
  1) Two-photon π^0 shower
  2) Coherent-like scattering:
     - Forward kinematics
     - Very little other energy
  3) Visible proton energy
- Predominantly higher-energy showers



Kinematics



$E\theta^2$ approximately energy-independent measure of "forwardness"

↓

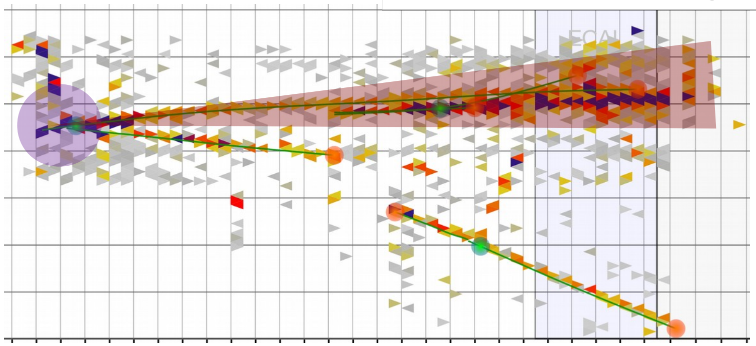
Small $E\theta^2 \Rightarrow$ more forward

<u>Conclusion:</u>

Excess coherent-like in kinematics

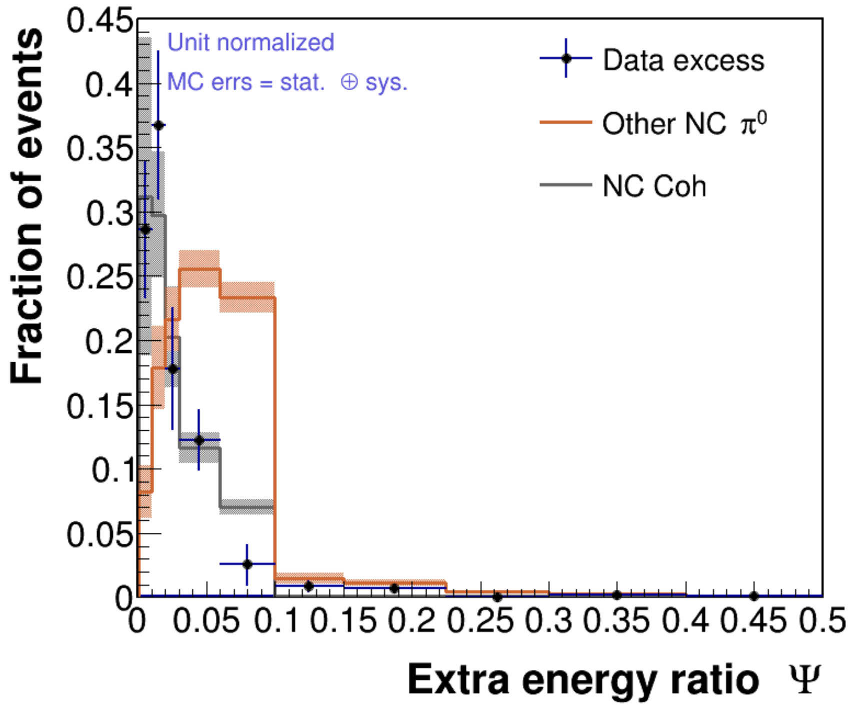
What else is in these events?

Simulated ν_μ deep inelastic scattering w/ π^0

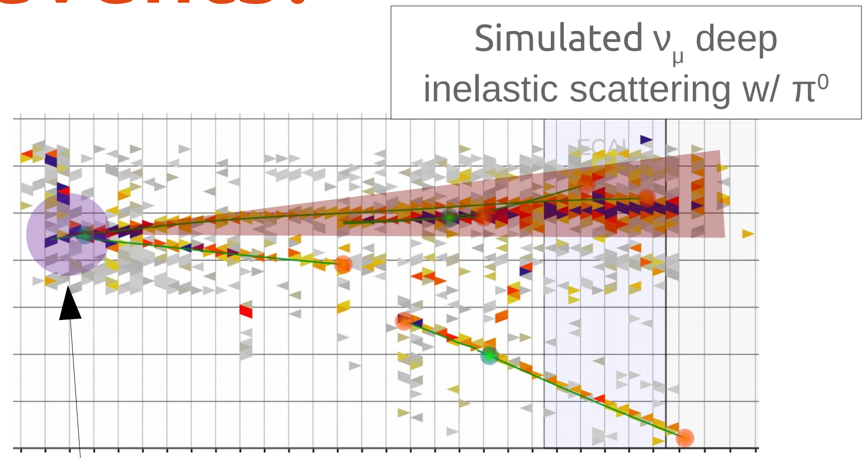


Extra energy ratio provides roughly shower-energy-indendent measure of other energy in event

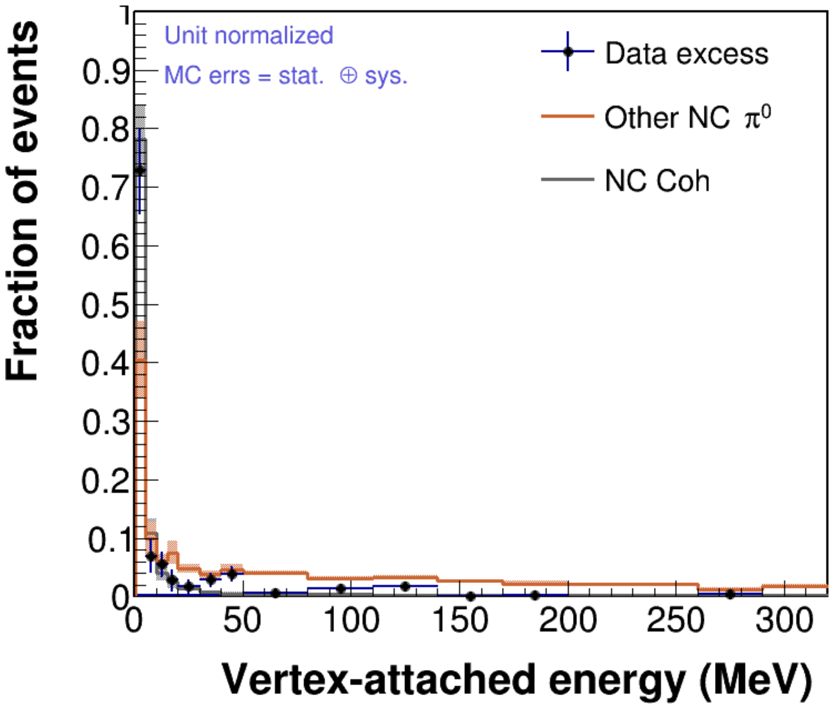
$$\Psi = \frac{E_{extra}}{E_{cone}}$$



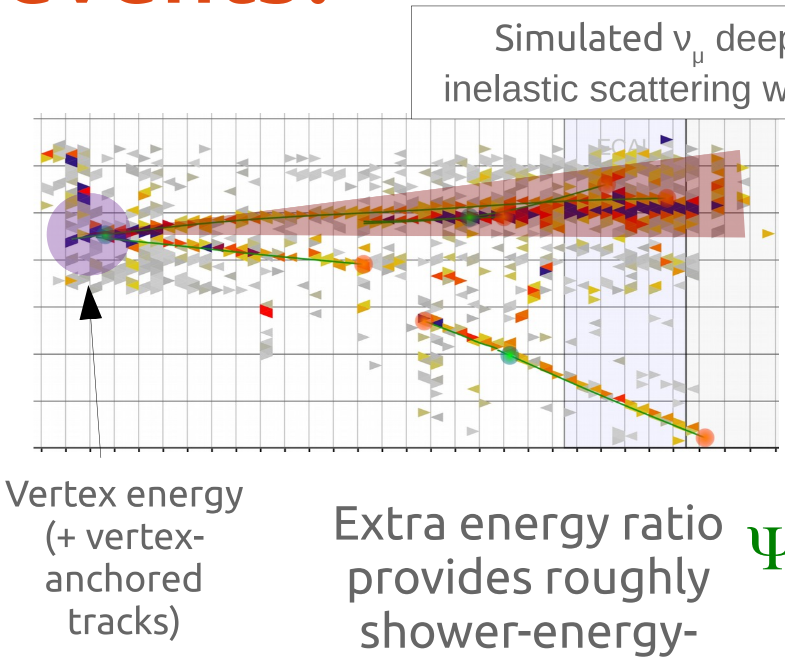
What else is in these events?



Vertex energy (+ vertex-anchored tracks)



What else is in these events?

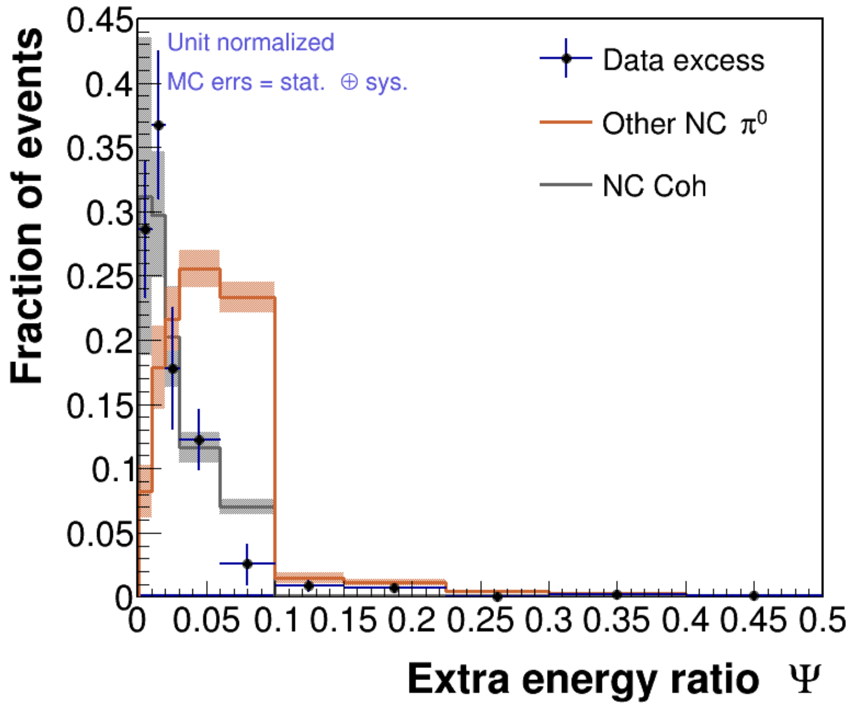


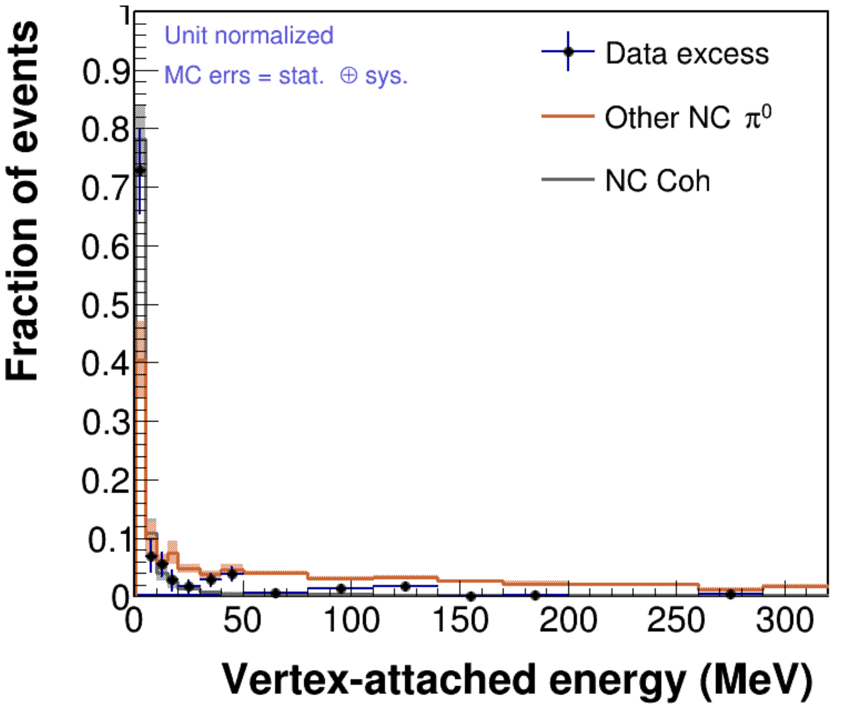
Extra energy ratio provides roughly shower-energy-indendent measure of other energy in event

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

Excess again consistent with NC coherent, in which a π^0 is the *only* final-state particle that interacts in the detector.

So: <u>very little non-shower energy.</u>





Excess

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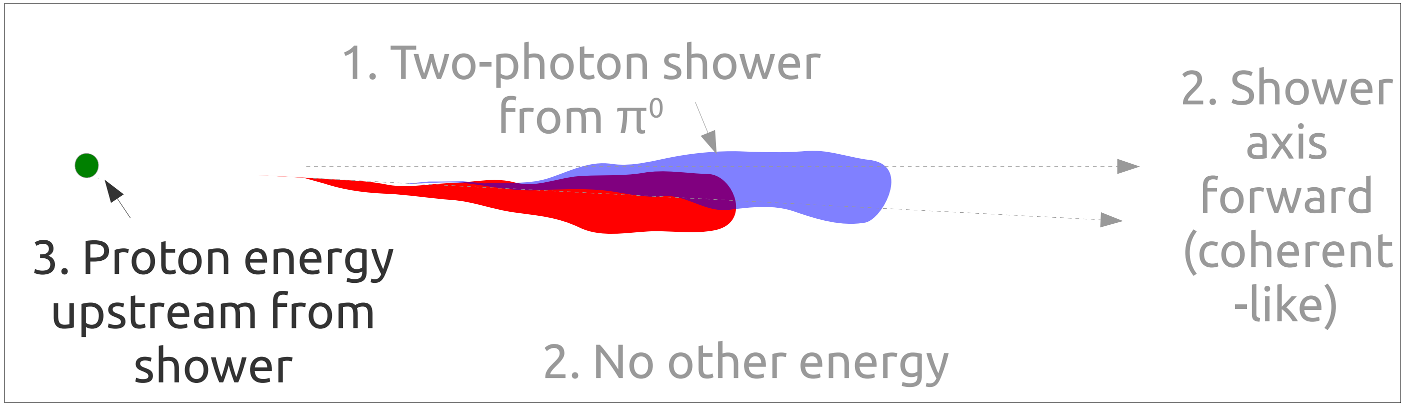
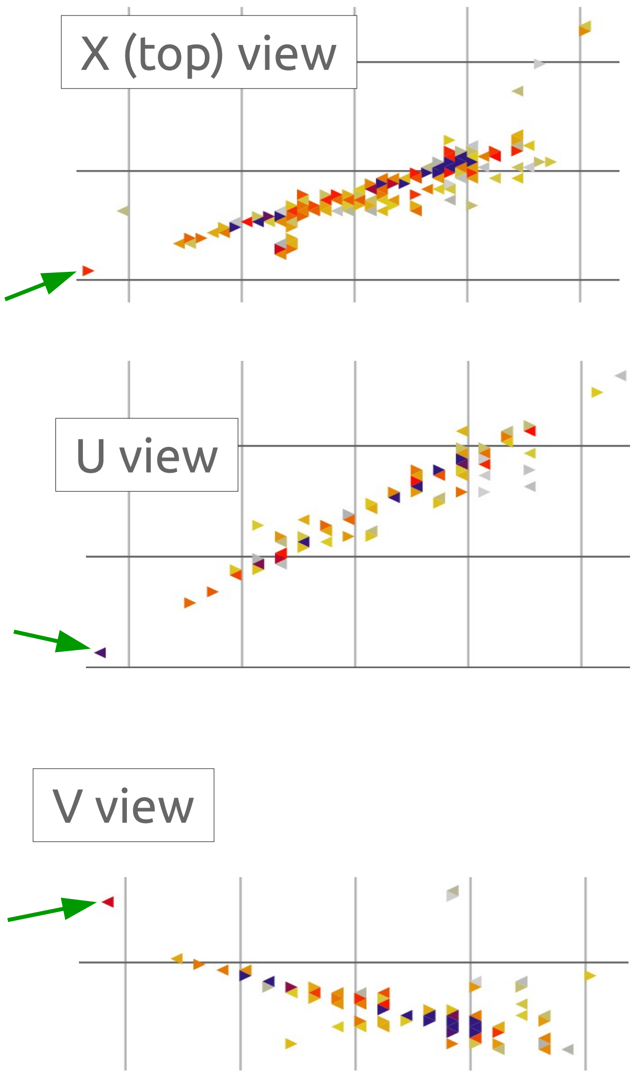
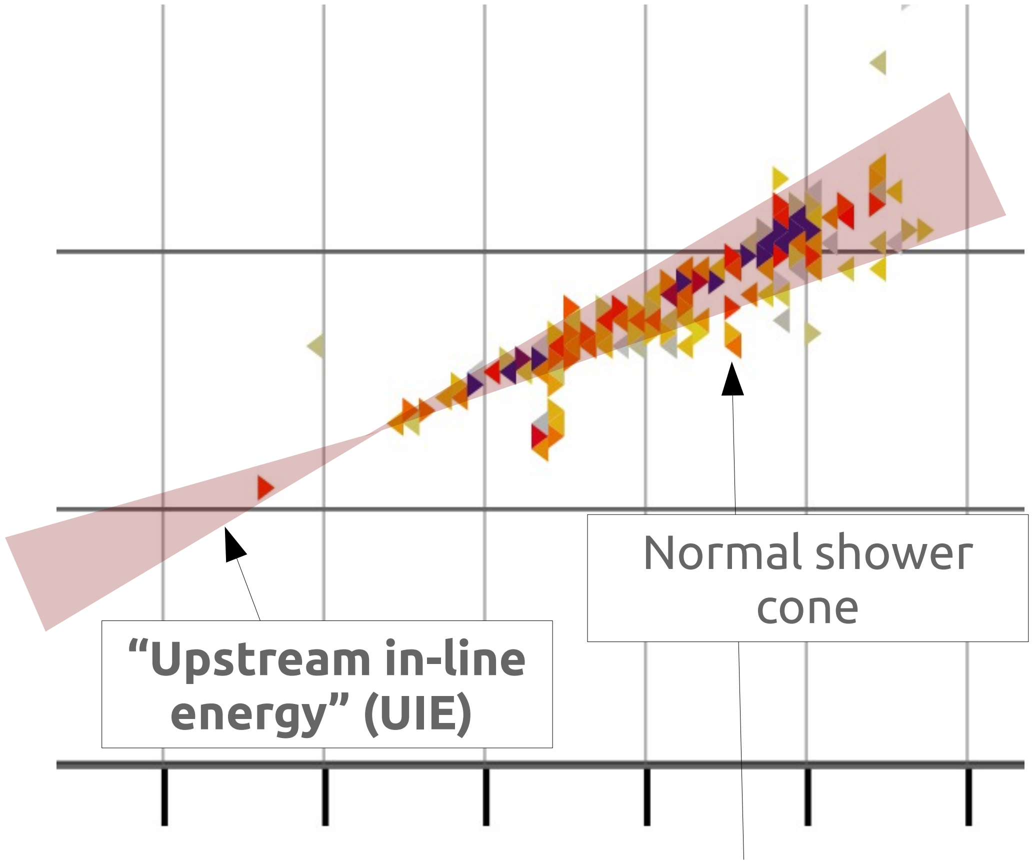


What else is in these events?

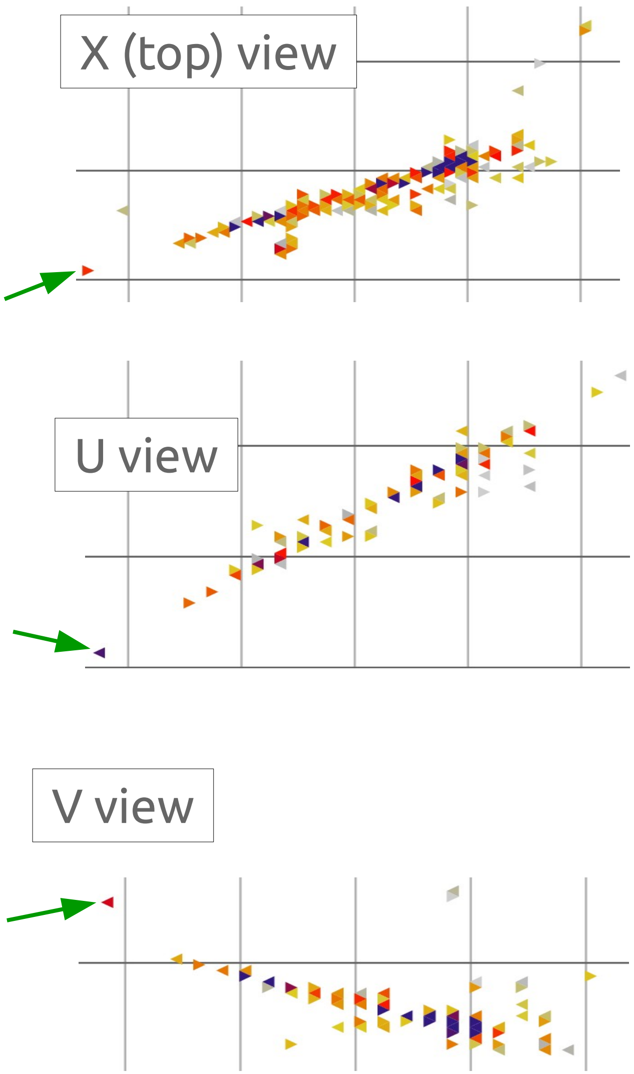


Data event in excess region



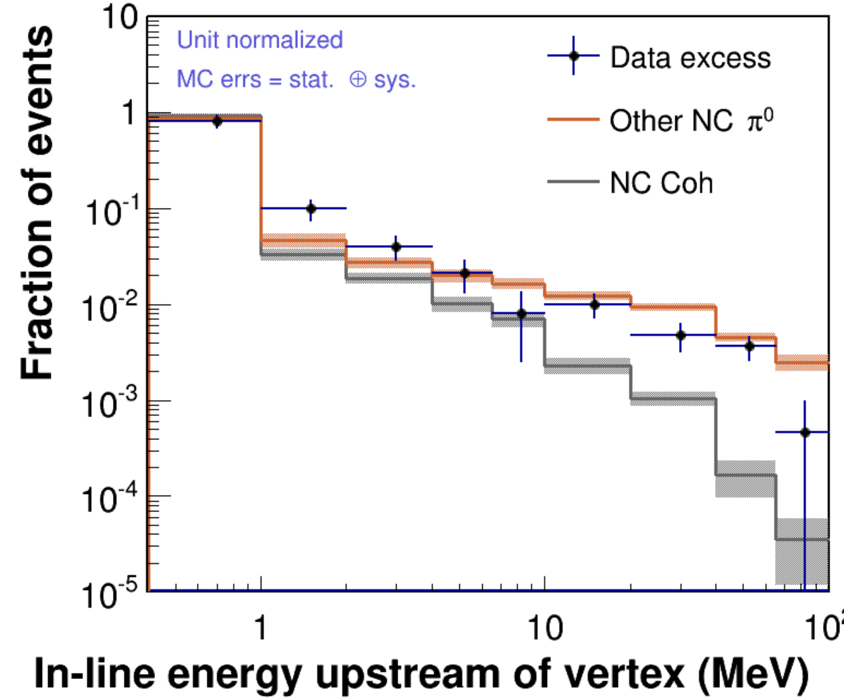
Measure **"upstream in-line" energy**: energy inside cone along same axis as shower cone but backwards.

What else is in these events?

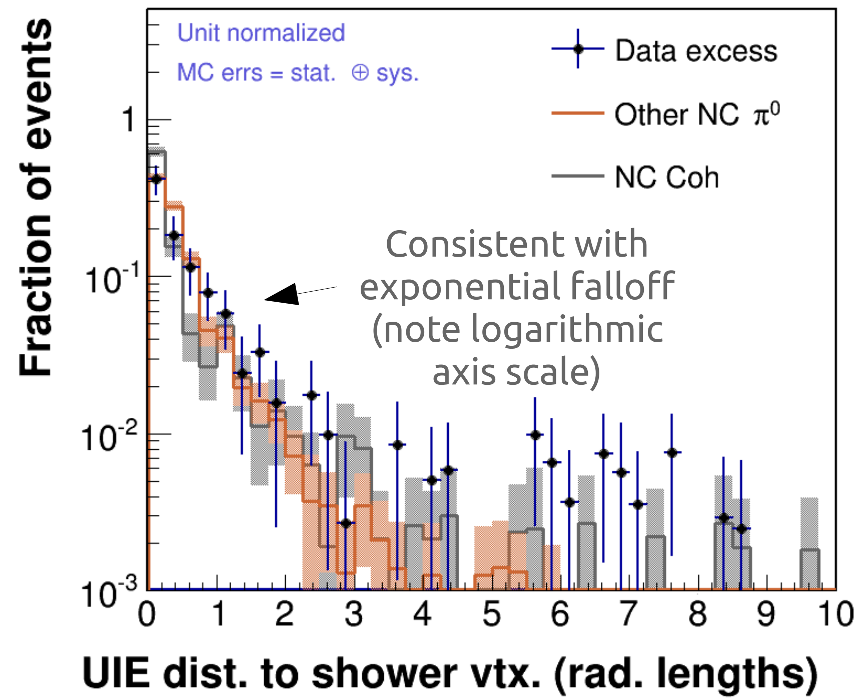


Data event in excess region

Excess prefers <u>more upstream inline energy than coherent</u> (but not *much* more)...



... and the distance to it is <u>consistent with an exponential falloff</u>, which is the pattern expected if photons traveling from UIE location and pair-producing stochastically



Excess

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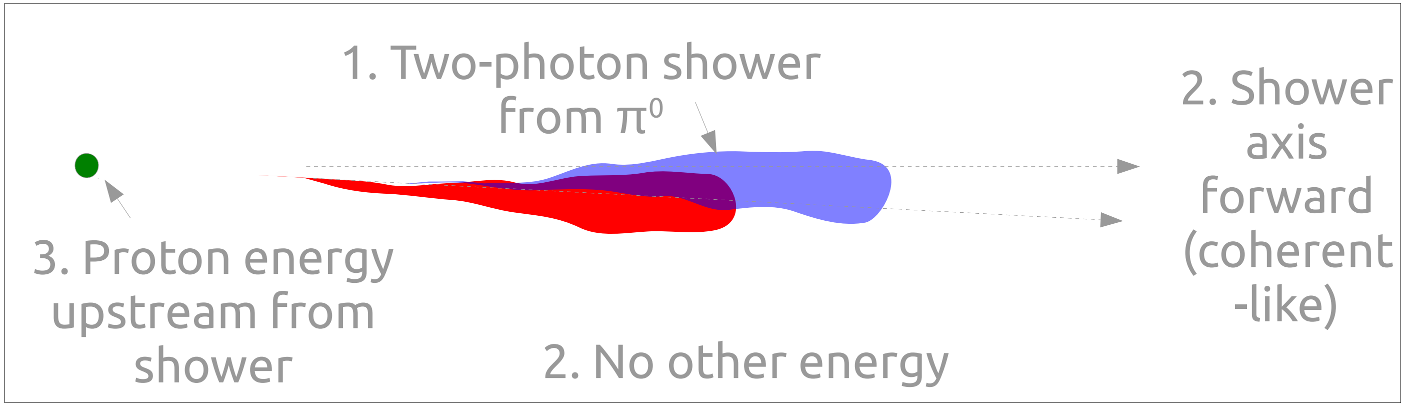
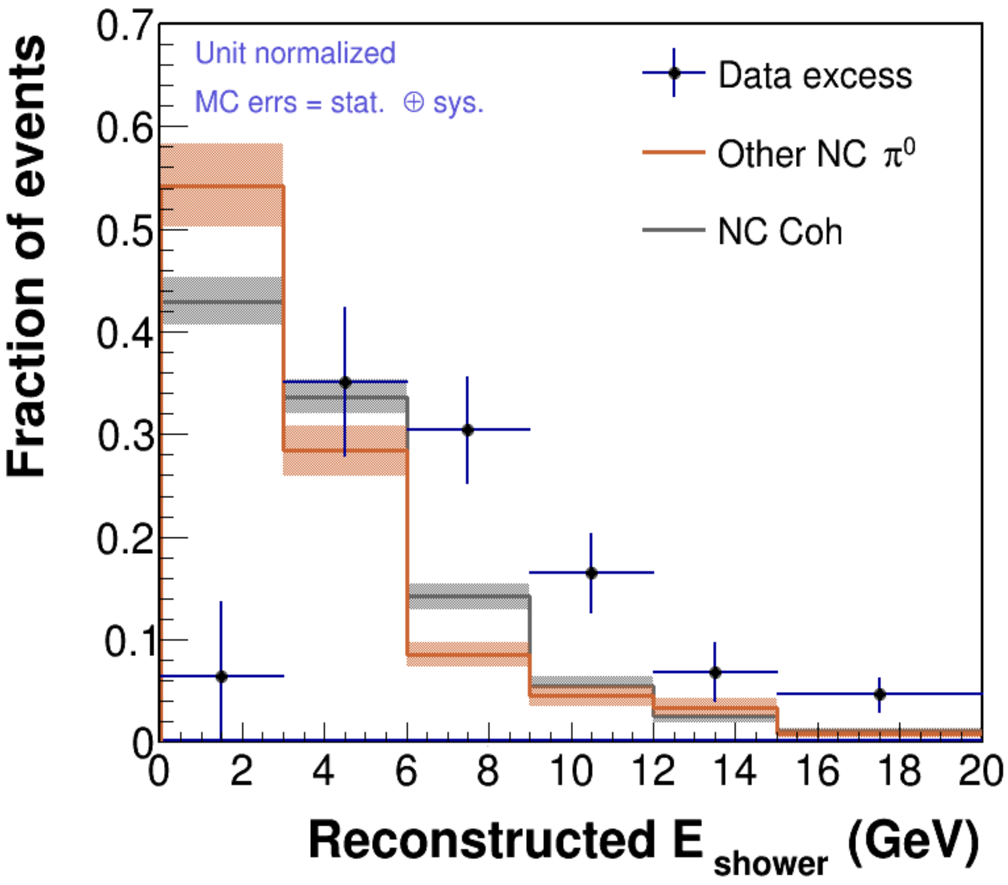
- **Predominantly higher-energy showers**



Kinematic range

<u>Observation:</u>

Excess shower energy spectrum significantly stronger than GENIE NC π^0 models



NC diffractive π^0 off H

- GENIE *does* have one (beta-quality) implementation:
  - Based on model from D. Rein (*NPB* **278**:61, 1986)
  - Not enabled by default
    - Not vetted like default models
    - Would double-count: global single-pi tune predates this model
  - Our testing seems to imply implementation may have some issues
- We tried it anyway to see how it compares

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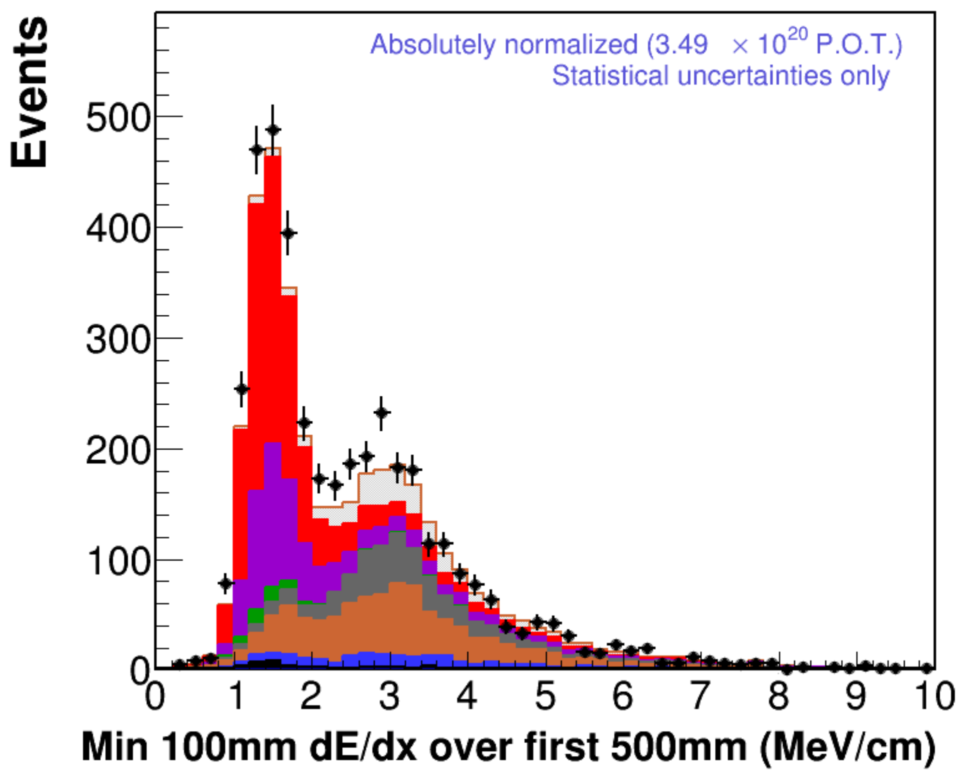

Behavior in *dE/dx* promising...

NC diffractive π^0 off H

- GENIE *does* have one (beta-quality) implementation:
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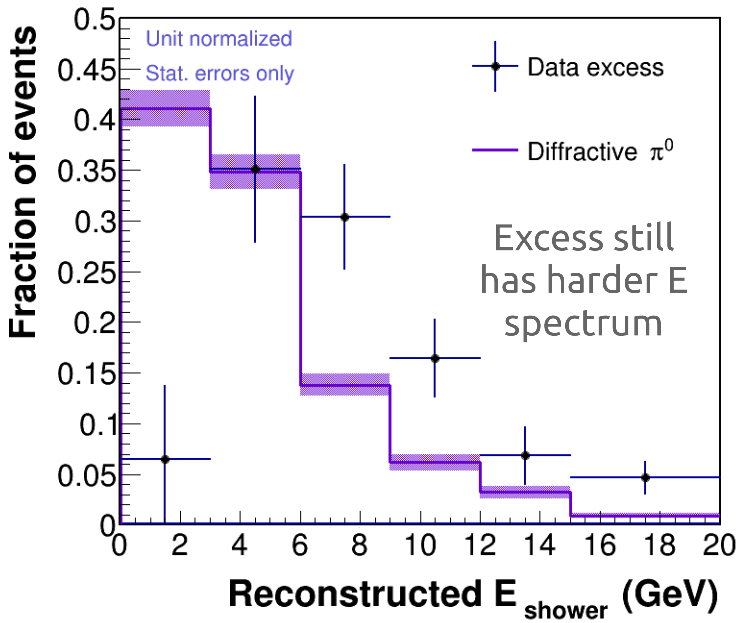
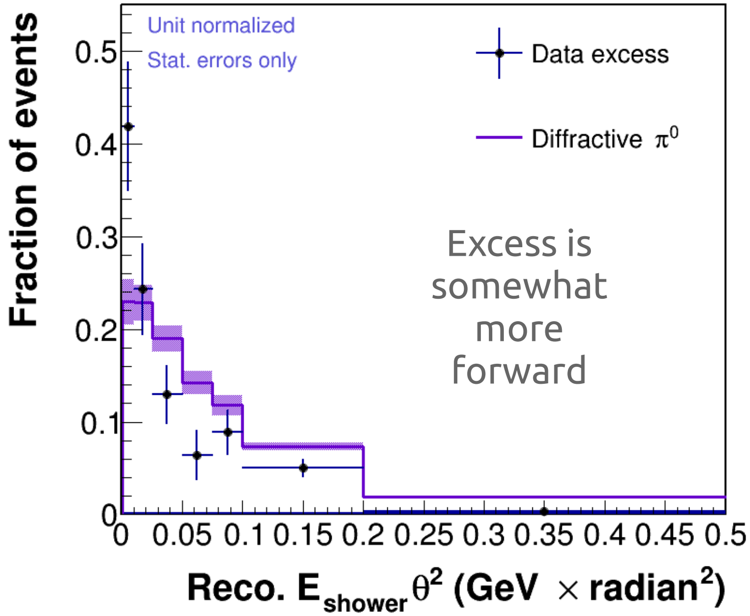
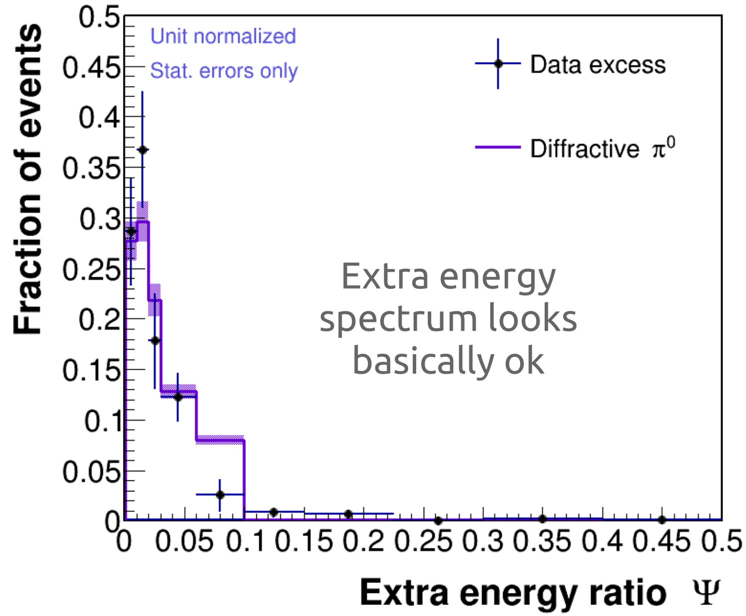


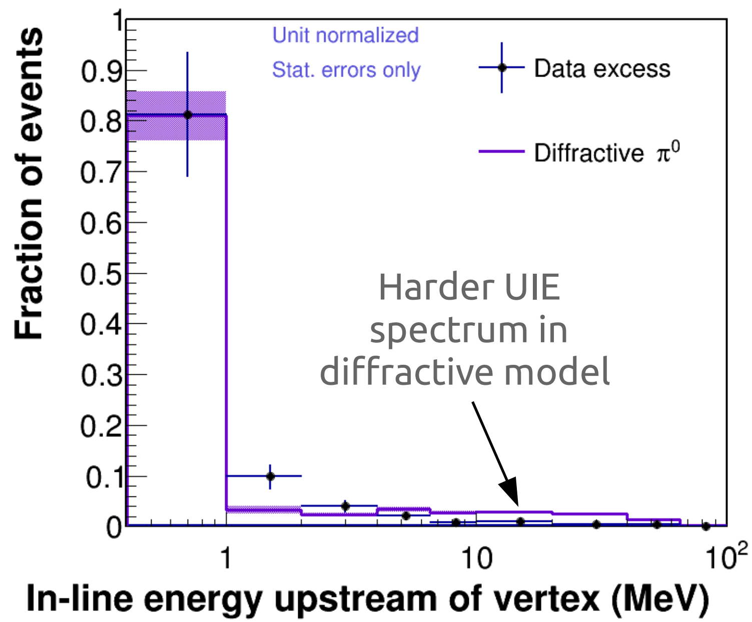


... but kinematics are rather different than those of the excess...

NC diffractive π⁰ off H

- GENIE *does* have one (beta-quality) implementation:
  - Based on model from D. Rein (*NPB* **278**:61, 1986)
  - Not enabled by default
    - Not vetted like default models
    - Would double-count: global single-pi tune predates this model
  - Our testing seems to imply implementation may have some issues
- We tried it anyway to see how it compares
- <u>Qualitative features are similar</u>
- We conclude that <u>the excess is likely due to NC diffractive production</u>, but <u>this model cannot quantitatively predict it</u>





... and its protons have too much KE for our UIE distribution

Cross section comparisons

Process	Total cross section integrated over MINERvA flux (×10^{-39} cm^2) / CH
MINERvA data excess	0.19 ± 0.02 (stat) ± 0.08 (sys)
GENIE NC diffractive (Rein)	1.6
GENIE NC diffractive, E_π > 3 GeV	0.10
GENIE NC coherent (Rein-Sehgal)	1.8
GENIE NC coherent, E_π > 3 GeV	0.16
GENIE NC inclusive	~120
GENIE CC inclusive	~400

Excess process roughly corresponds in size to channels that are ~1% of total cross section in MINERvA flux.

(But, then imagine you're looking for rare ν_e oscillation events and can't separate e from γ...)

(GENIE 2.6.2 used for model calculations)

Summary and conclusions

- ν_e appearance oscillation measurements may yield fundamental insights in the lepton family
- ν_e cross sections are a vital ingredient in oscillation results, but challenge means few direct measurements exist
- MINERvA measurement of ν_e CCQE-like cross section:
  - Is first-ever exclusive-process ν_e cross section
  - Agrees with ν_μ CCQE measurement from MINERvA, supporting lepton universality hypothesis
- Observation of unpredicted NC diffractive-like process underscores need for sustained investment in generators

Thank you on behalf of MINERvA!

2015 collaboration meeting

Overflow

Numbers

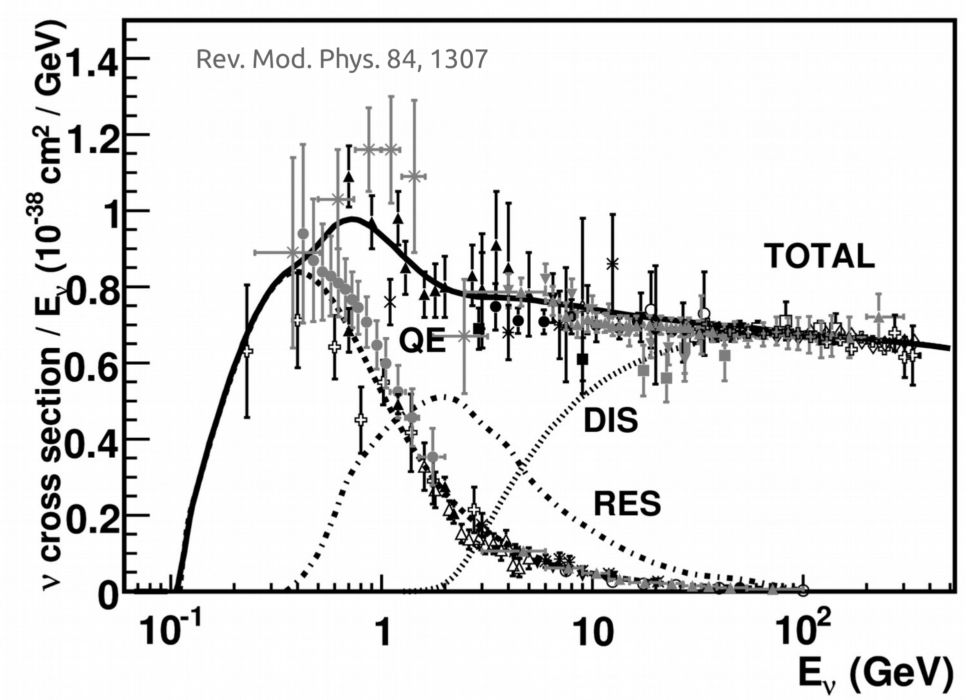
- 3.49×10^{20} POT of data
- 2105 selected events (CCQE-like):

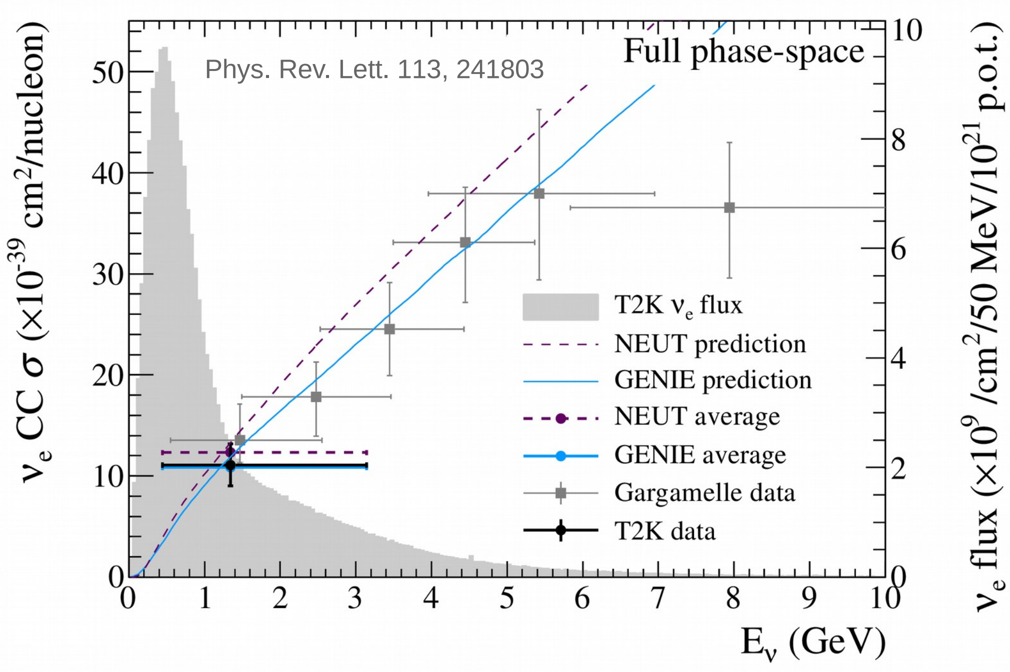
  estimated 1090 signal events (52% purity)

  + 604 other electron neutrino events (sample is 80% ν_e)

  + 54 other electron final state events (sample is 83% electron final state)
- Scale factors:
  - ν_e CC inelastic: 0.89 ± 0.08
  - NC & CC incoherent: 1.06 ± 0.12
- 371 selected events (excess)

The abundance of ν_μ cross sections





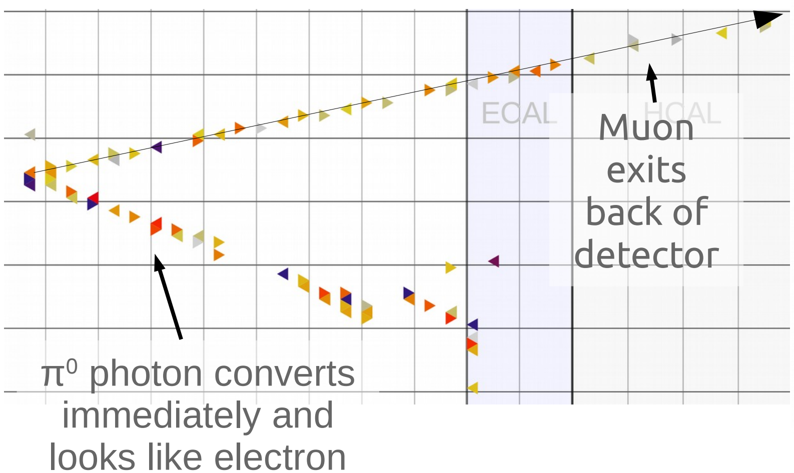
ν_μ ν_e

There is a wealth of ν_μ cross section data available, by comparison...

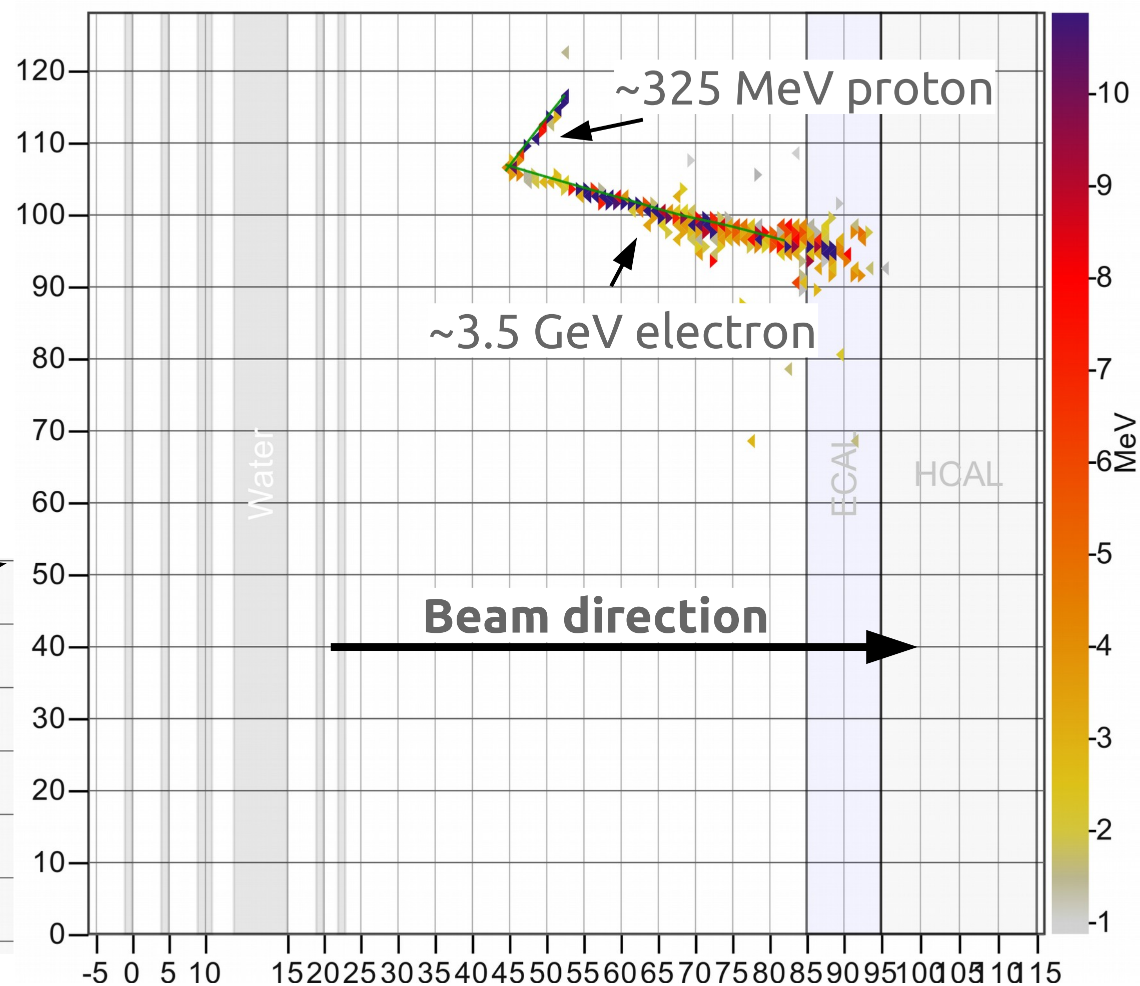
Isolating ν_e events: Data reduction

Event pre-selection:

- One (or more) **reconstructed track(s)** (>95% of $e^\pm$ in fiducial region begin with track)
- **No obvious muons** (never ν_e):
  - No tracks exiting back of detector
  - No Michel electron (e from μ decay) candidates (also rejects pions: $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$)



Simulated background rejected by muon cuts

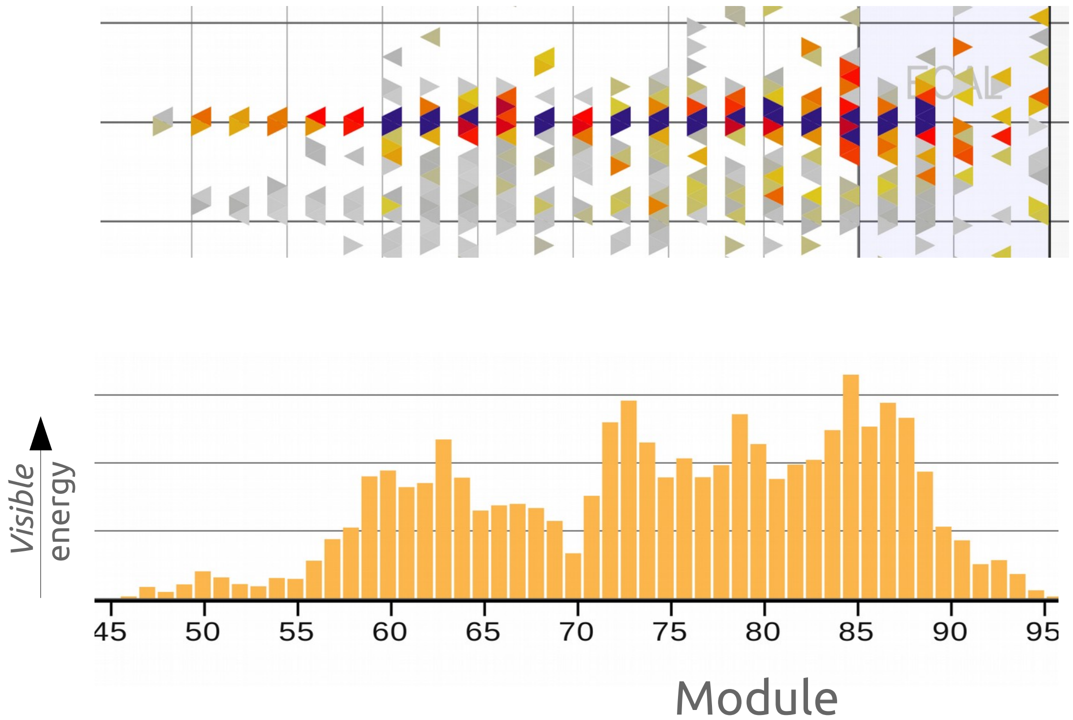


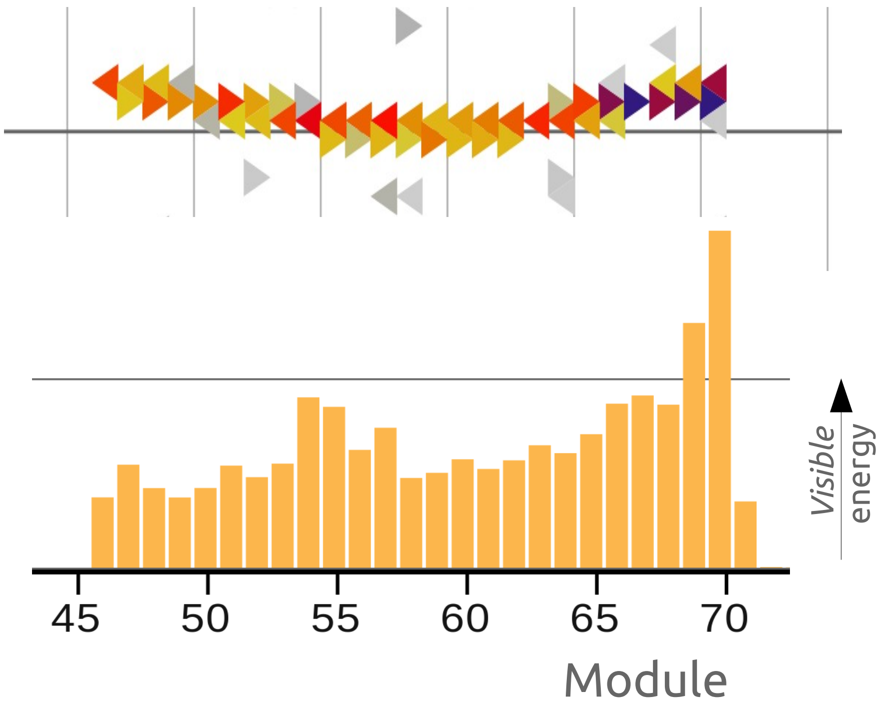
Event display of simulated ~4 GeV ν_e interaction in MINERvA

PID variable: endpoint energy fraction

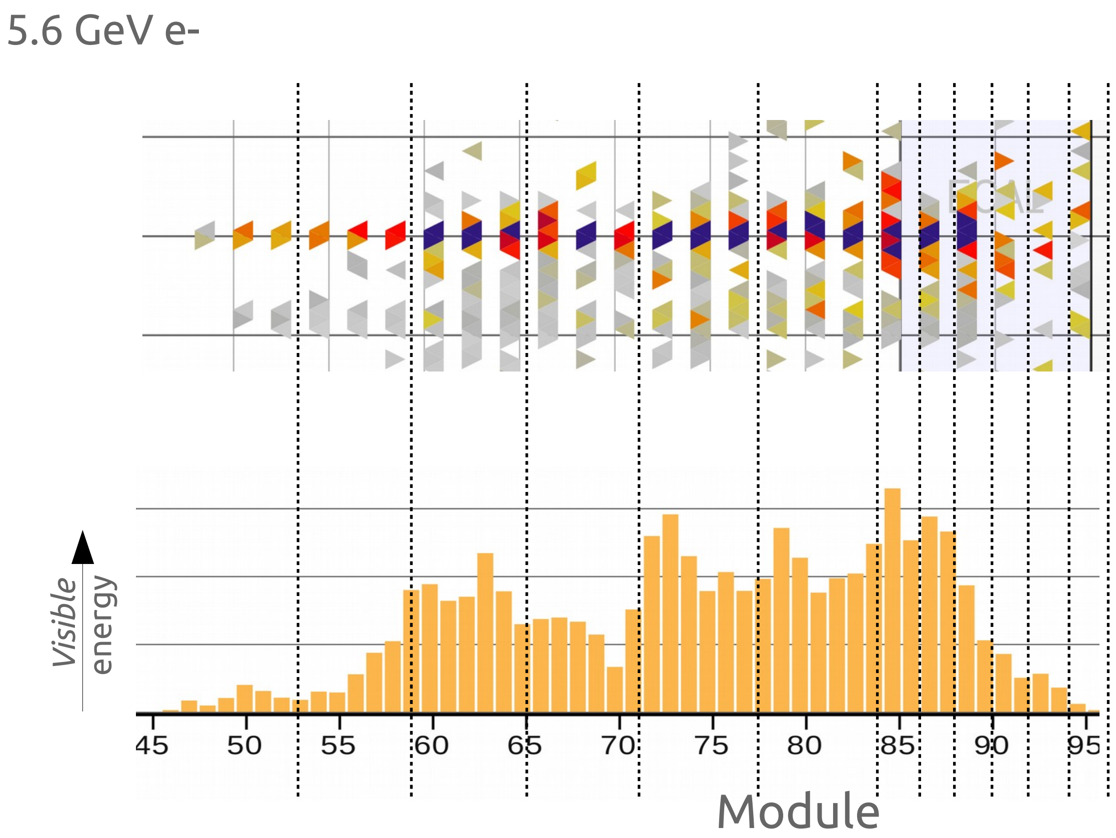
5.6 GeV e-

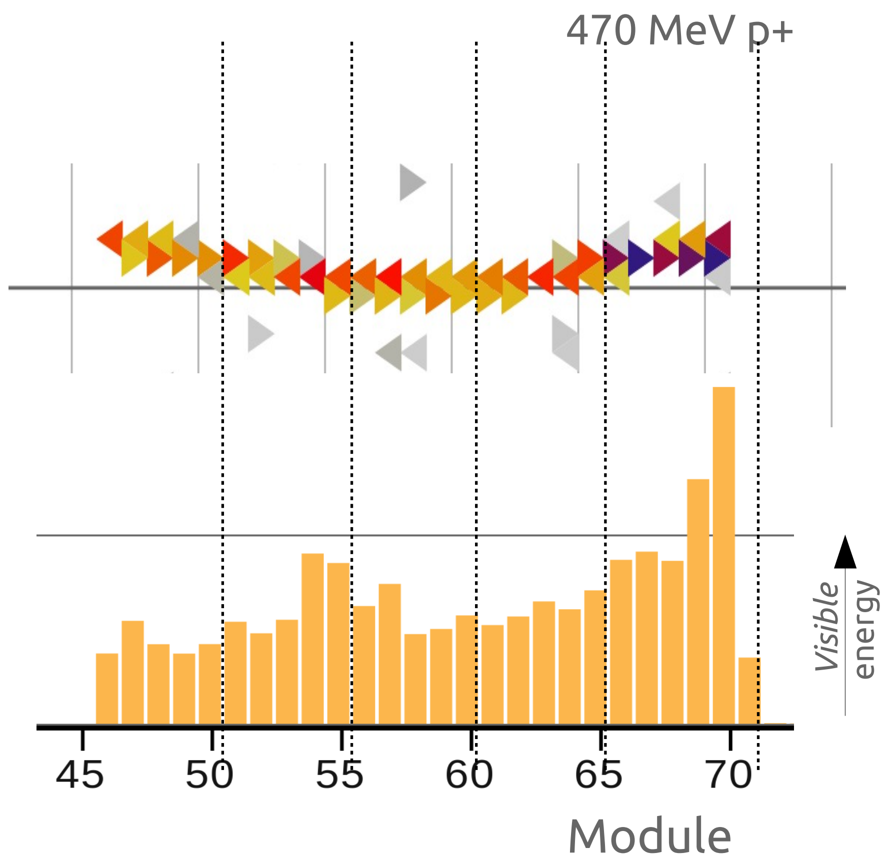
470 MeV p+





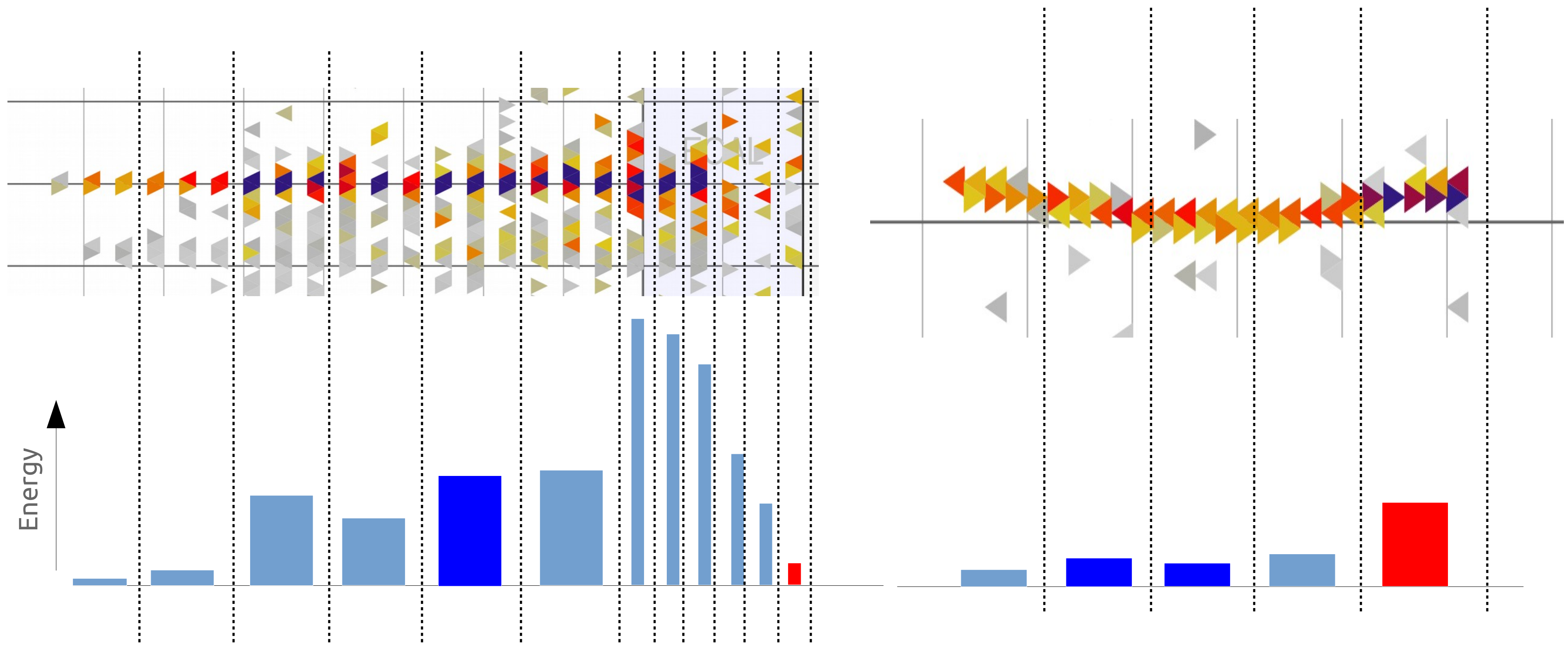
PID variable: endpoint energy fraction





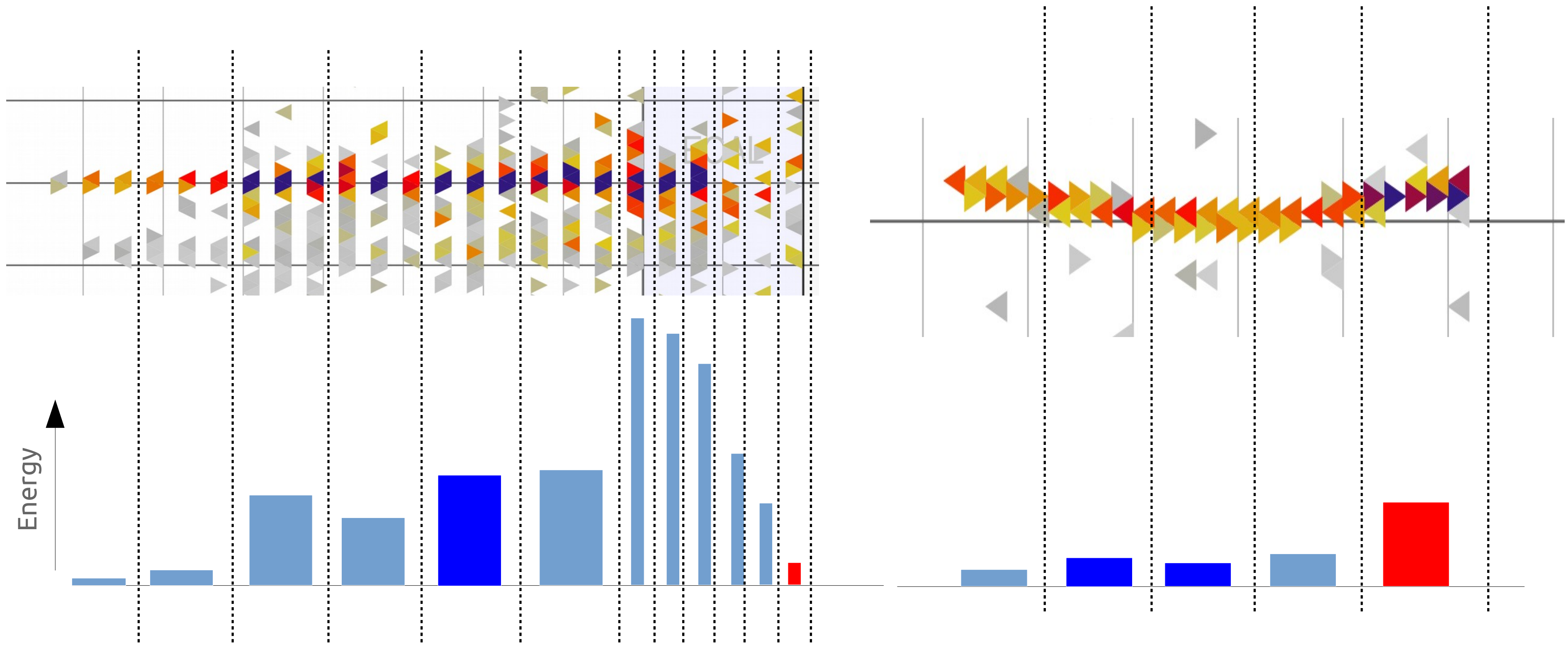
1. Divide the energy deposits into bins of 10 g/cm² of areal density.

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).

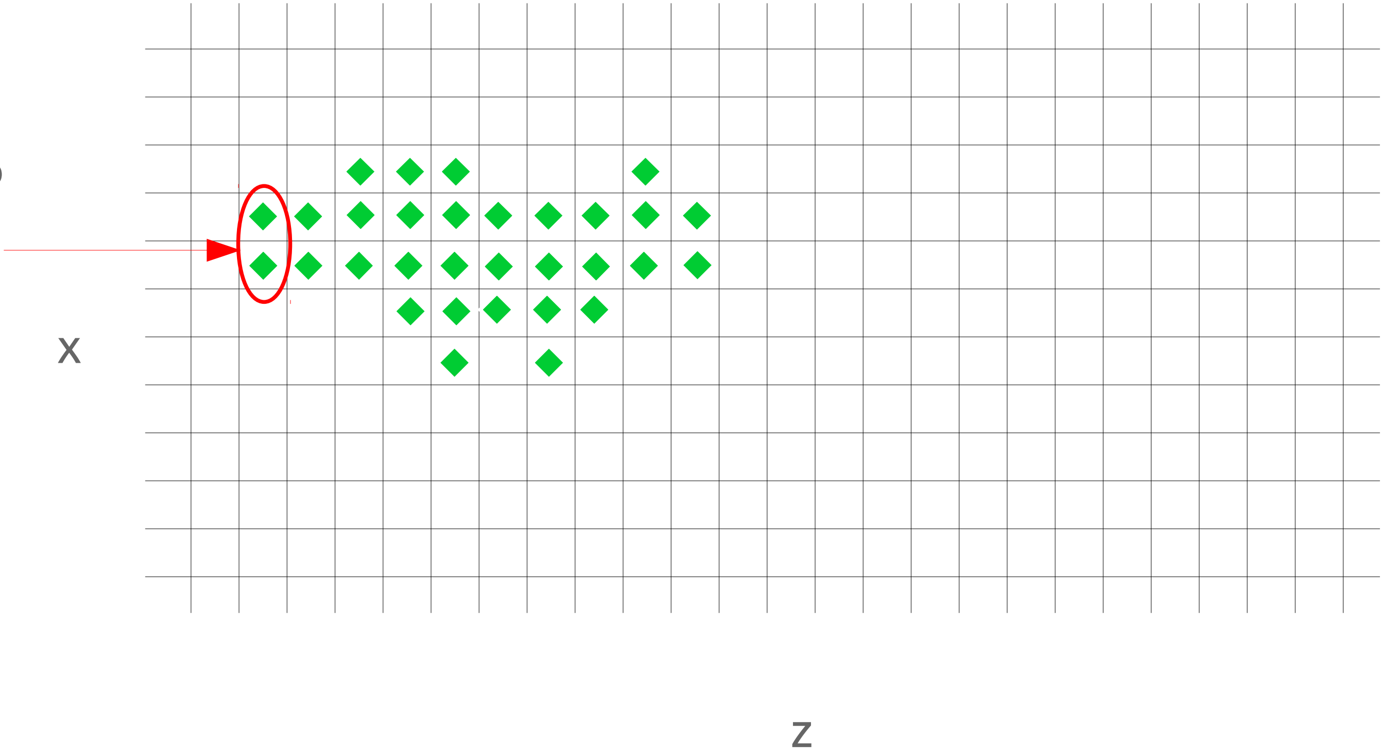
PID variable: endpoint energy fraction



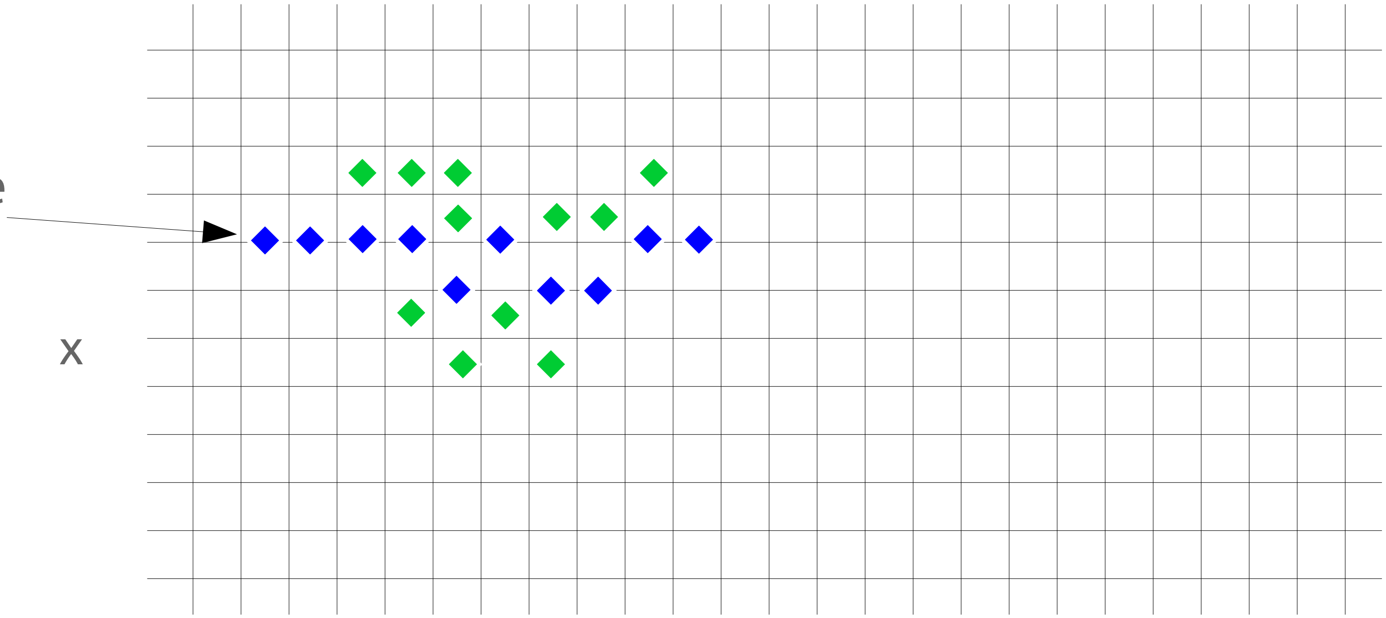
4. Endpoint energy fraction = $\dfrac{E_{last}}{E_{median}}$

PID variable: shower “width”

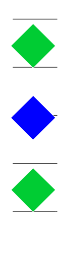
Merge MIP-like pairs like this one (two brightest strips are neighbors) into one pseudo-strip with the sum of their charge



PID variable: shower “width”



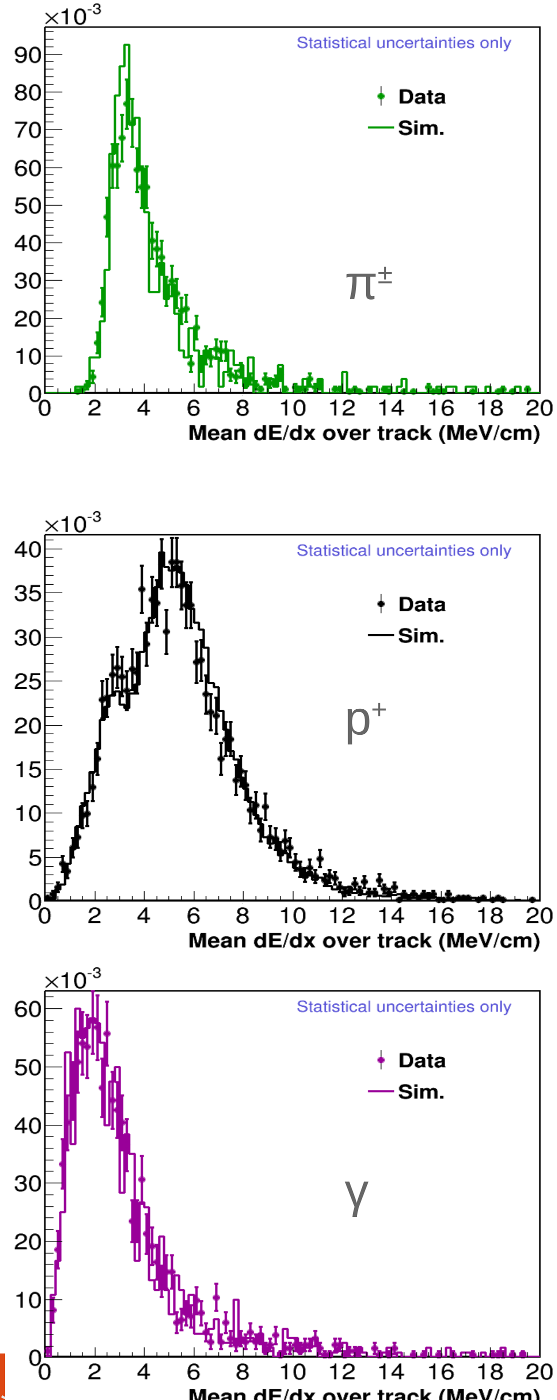
For each plane:



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

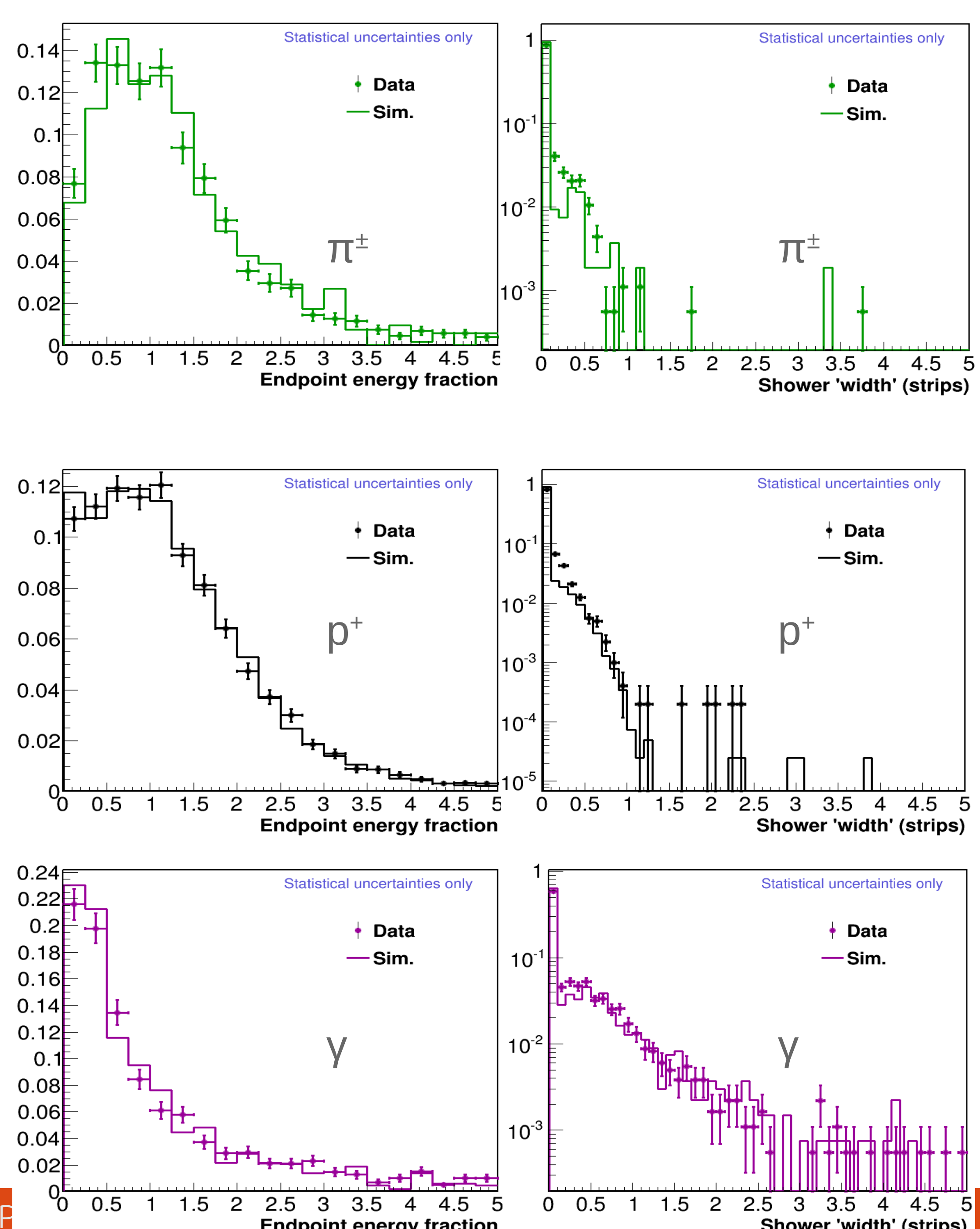
Then use the median of those standard deviations to characterize the event's “width”

Benchmarking the PID

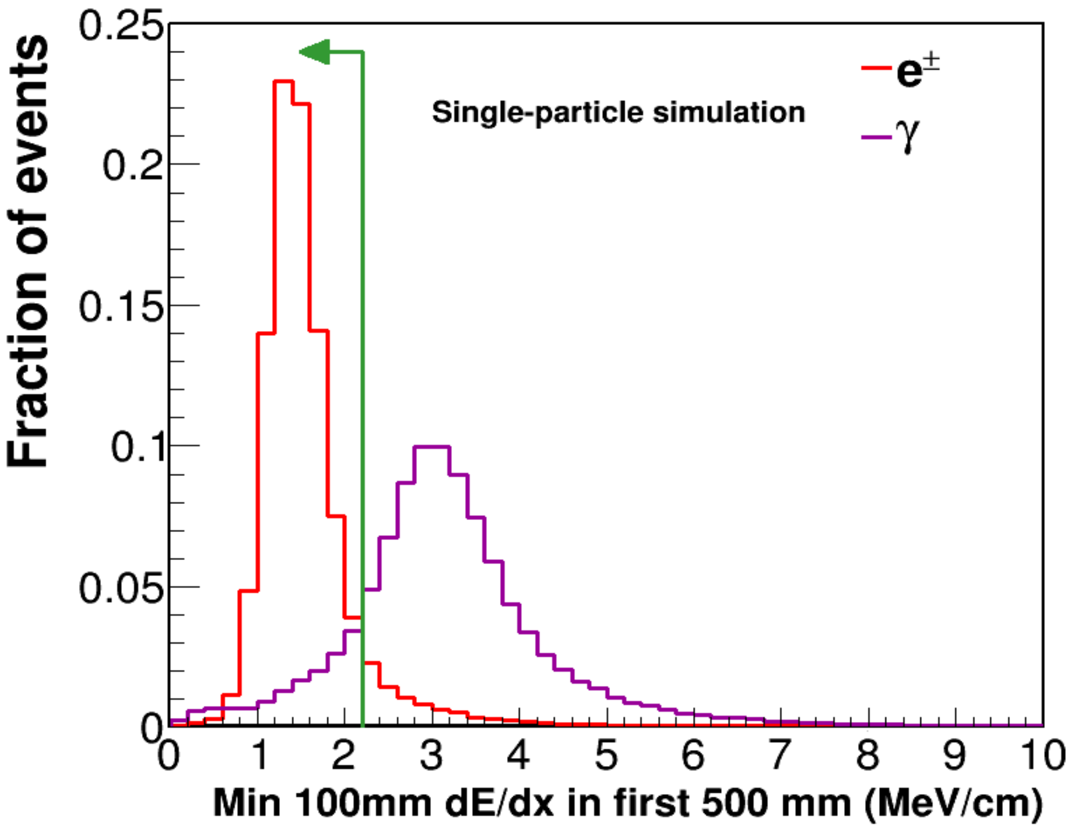


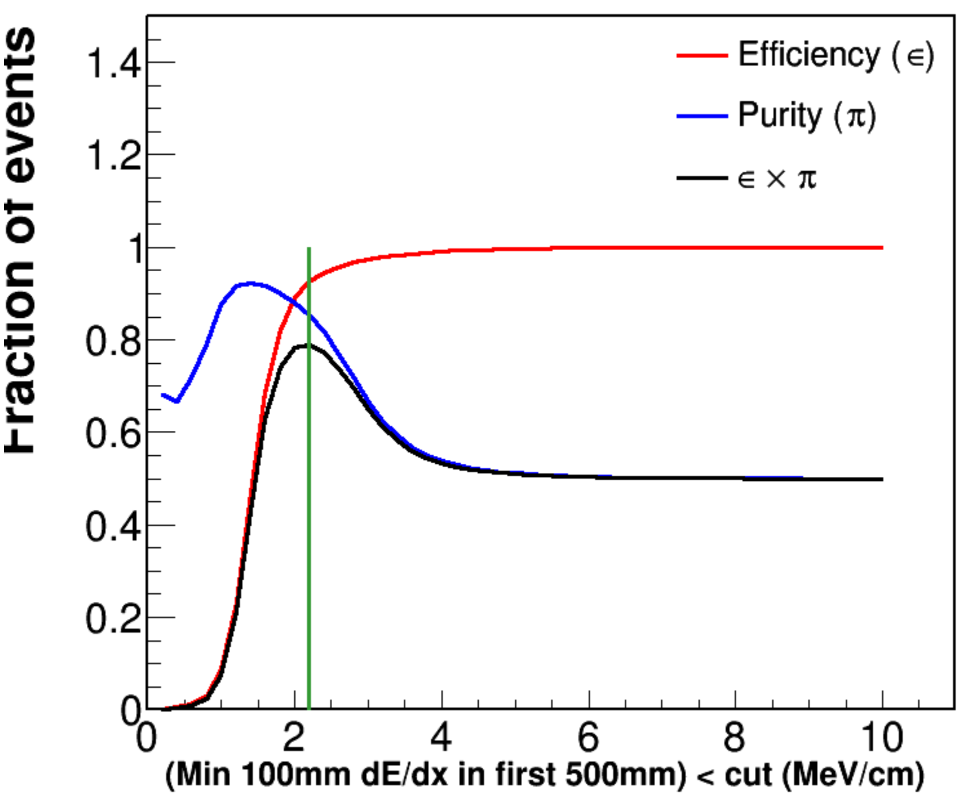
Samples were selected by other analyses in MINERvA:

- π± from Δ± arXiv:1406.6415
- p+ in CCQE in Phys.Rev. D91, 071301
- γ from π0 in Phys.Lett. B749, 130



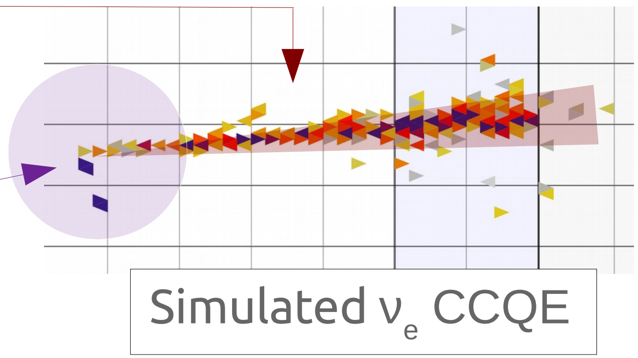
Photon rejection cut



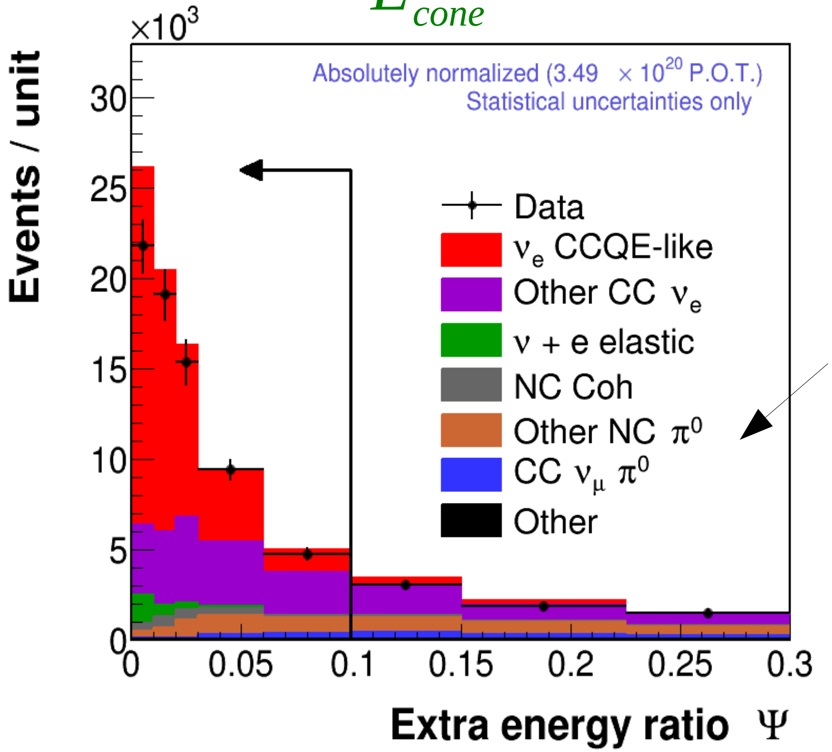


“Extra energy” cut

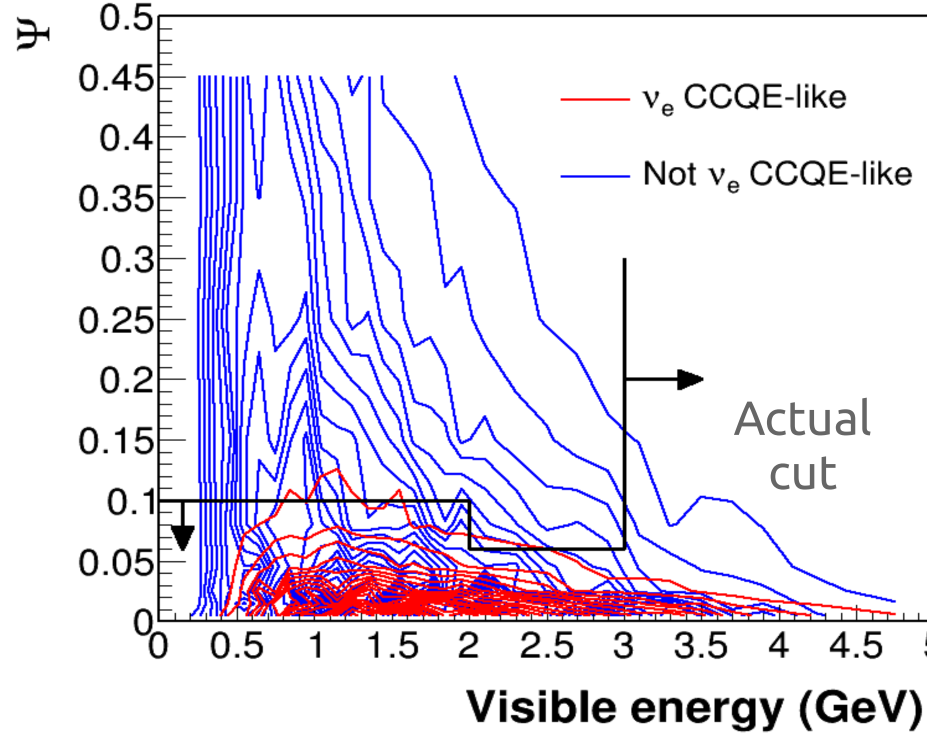
Anything not within a 7.5º electron cone or a vertex activity region of 30 cm radius or tracked as a proton is “extra energy.”



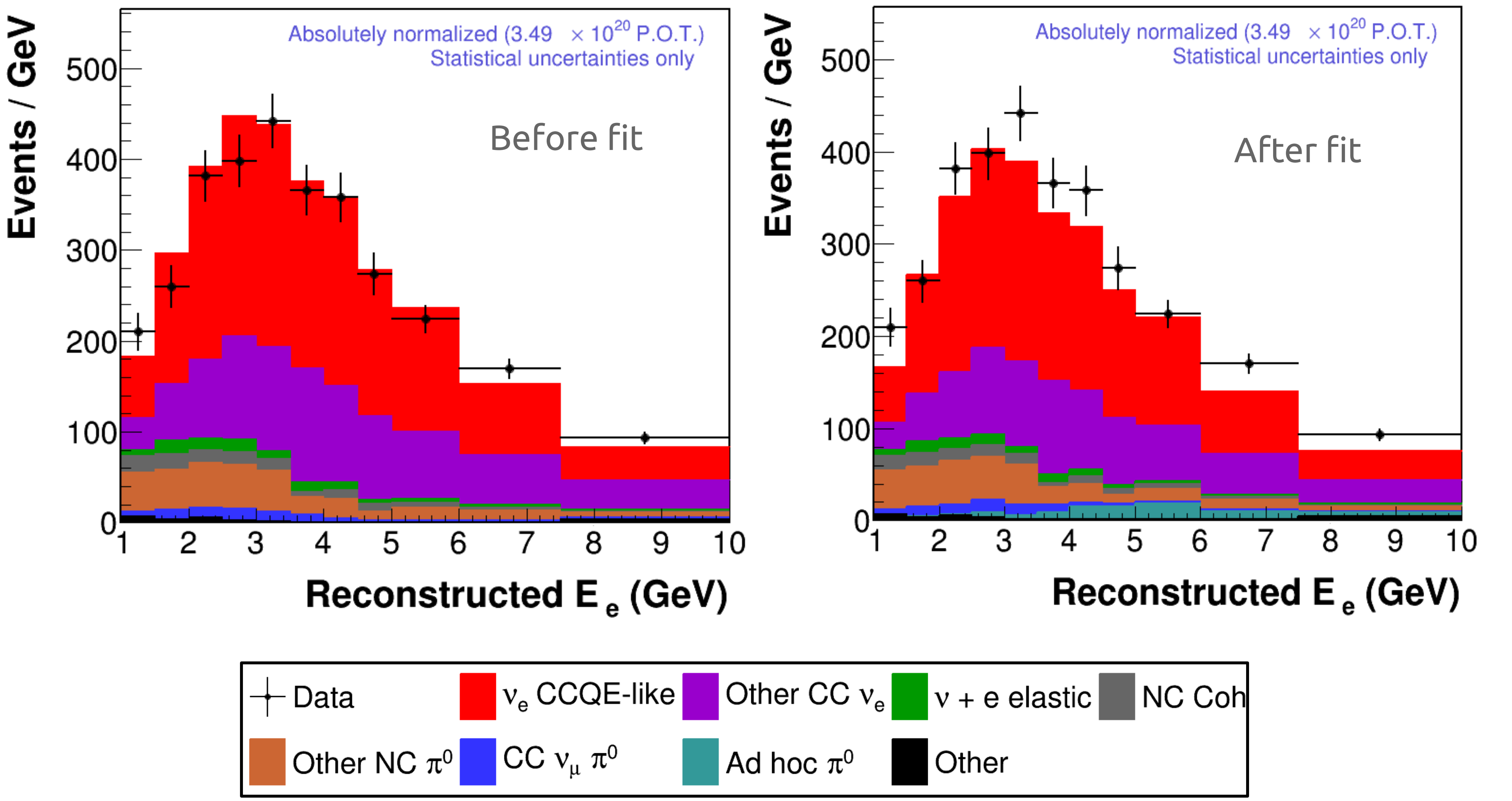
Cut on $\Psi = \frac{E_{extra}}{E_{cone}}$



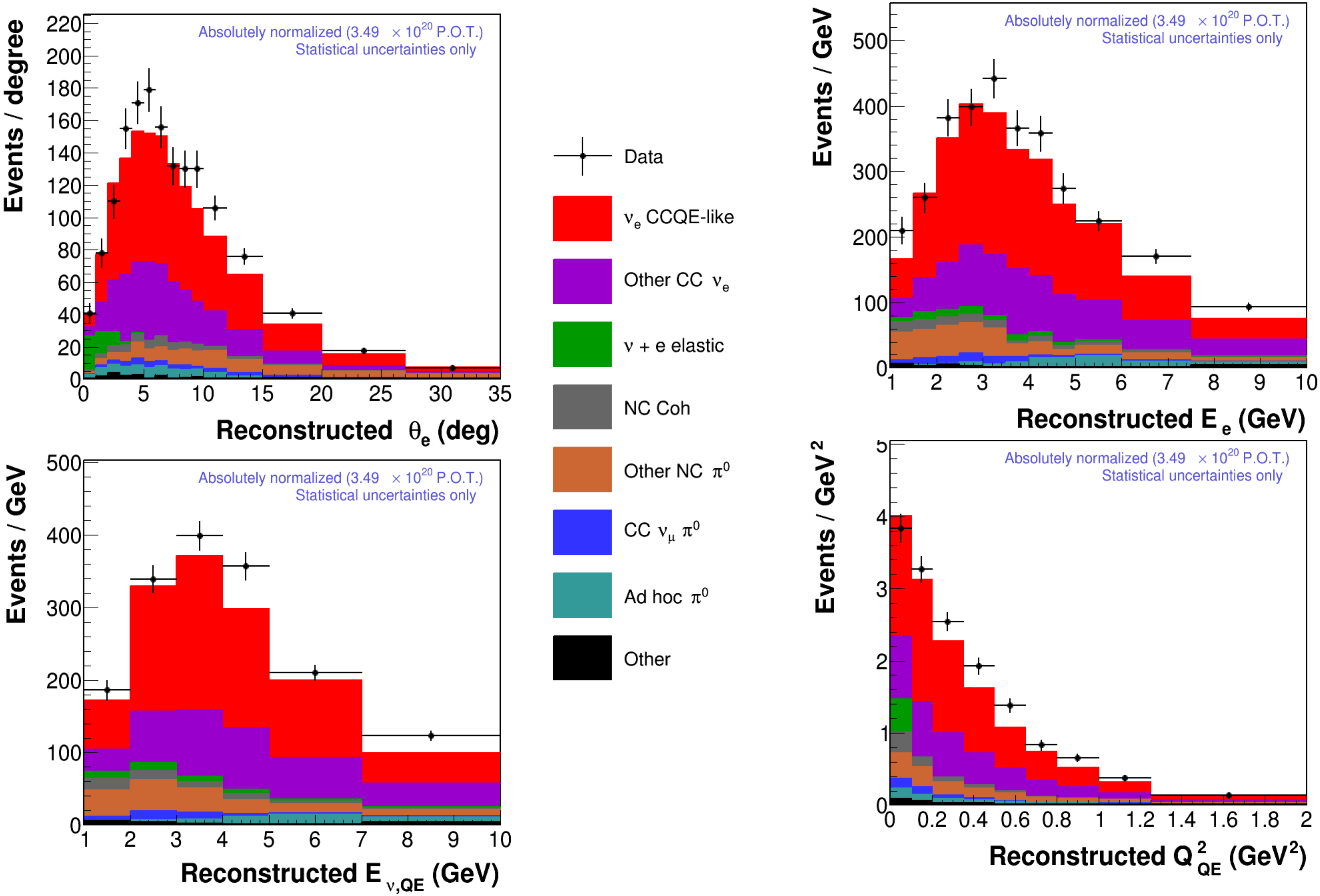
After marginalizing over all E_{vis}. Cut illustrated is around most probable value of E_{vis}= 1.25 GeV.



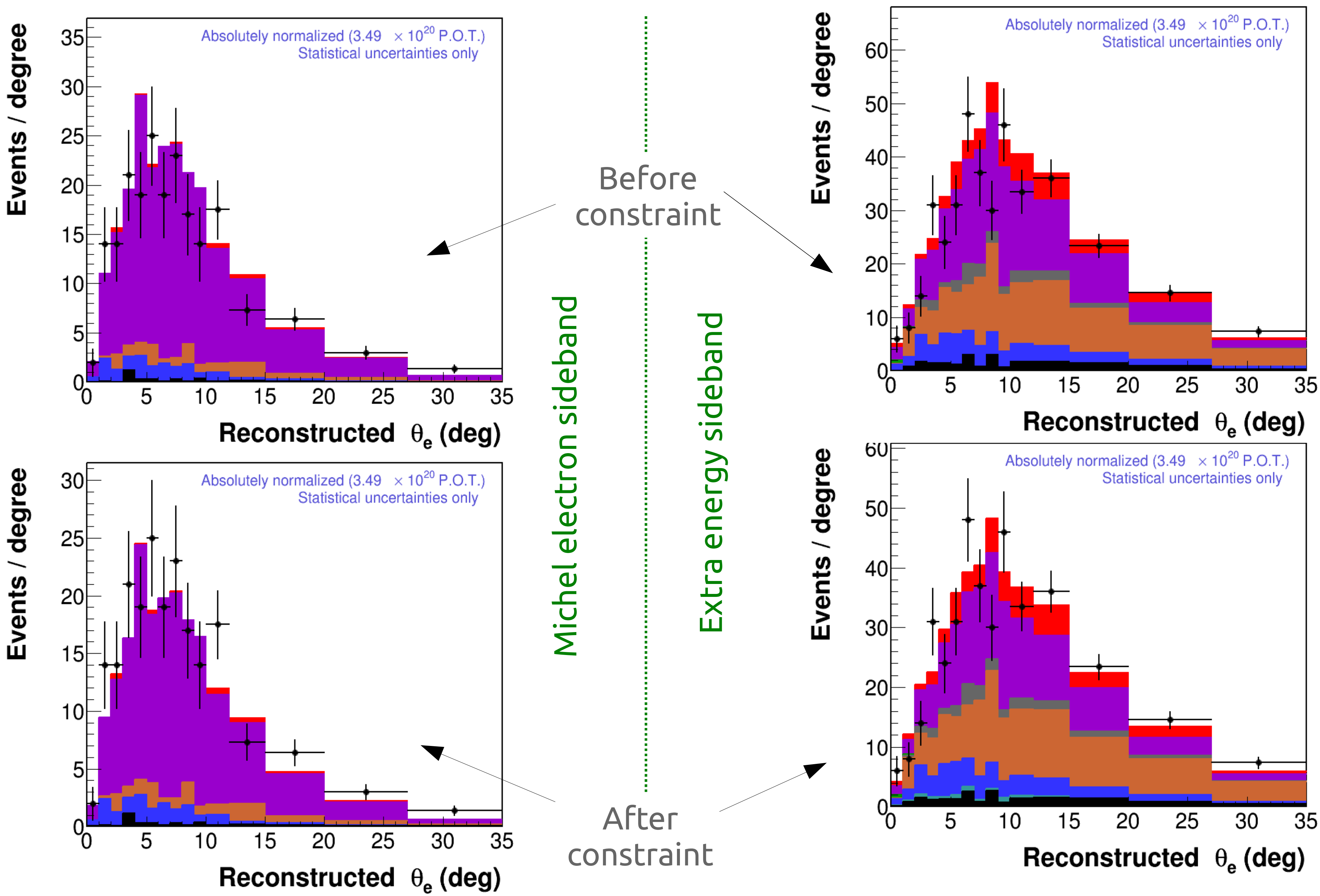
Fitting backgrounds: effect in signal region



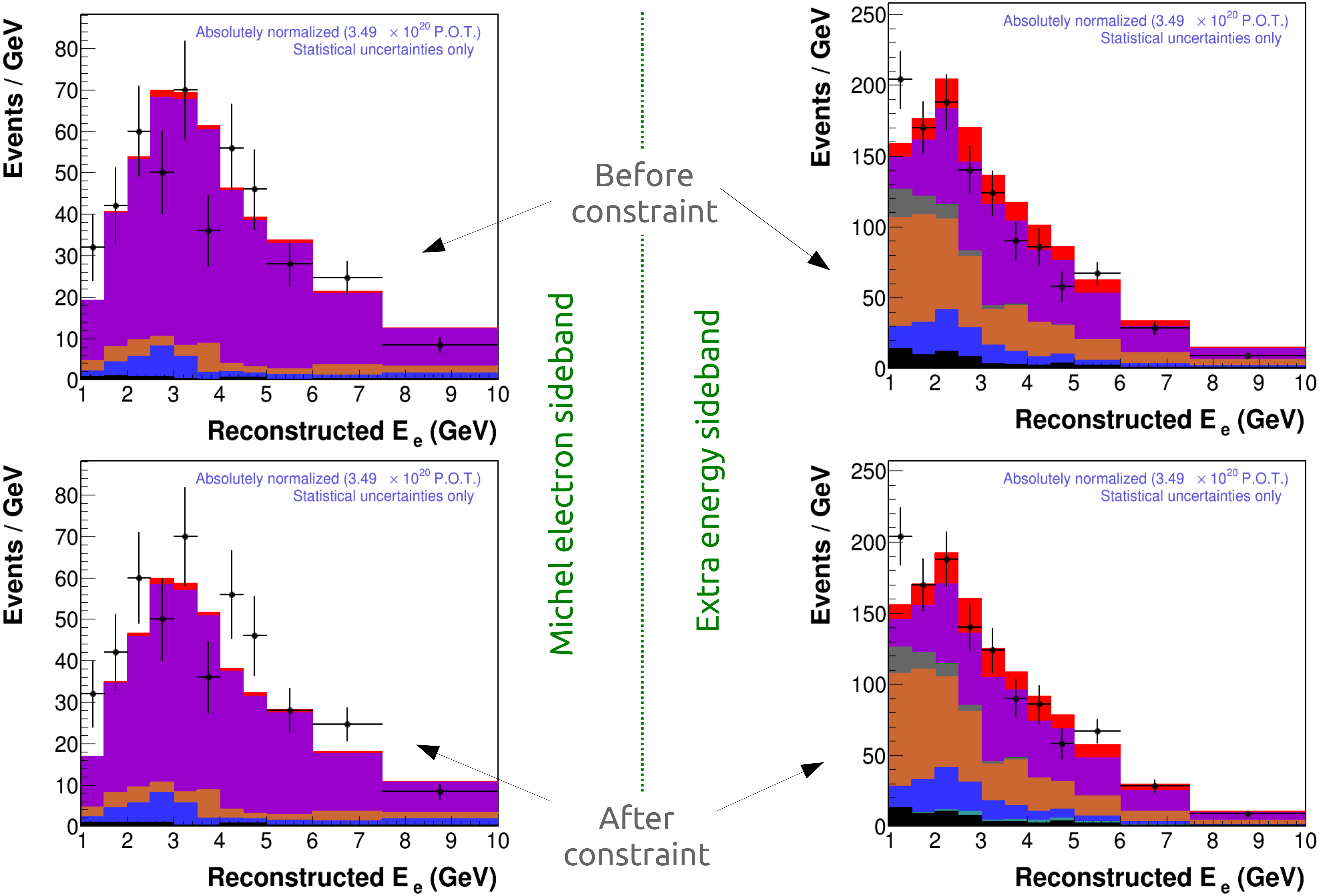
Signal region after fitting



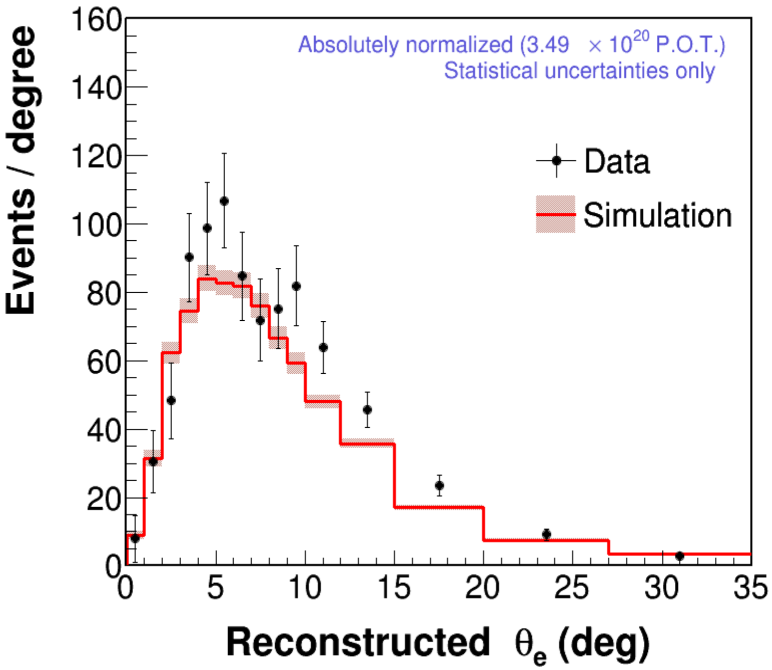
Background constraint: θ_e

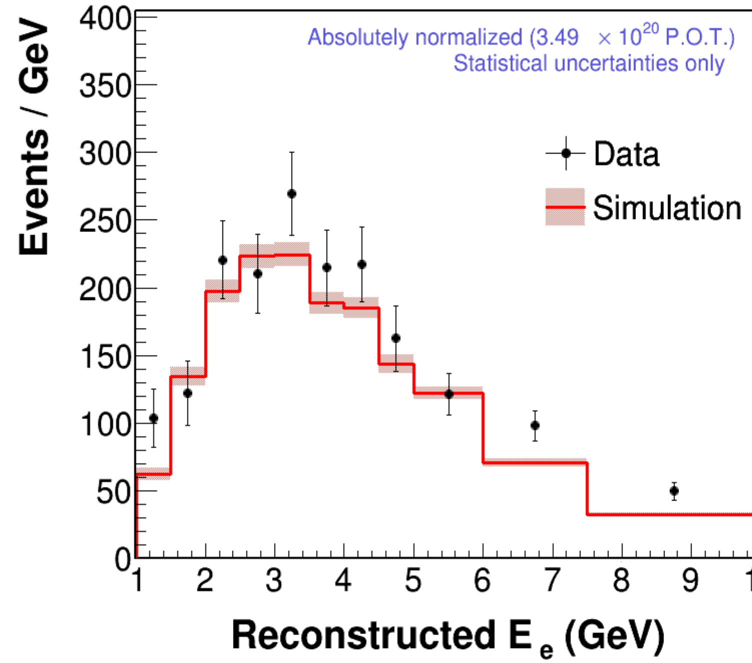


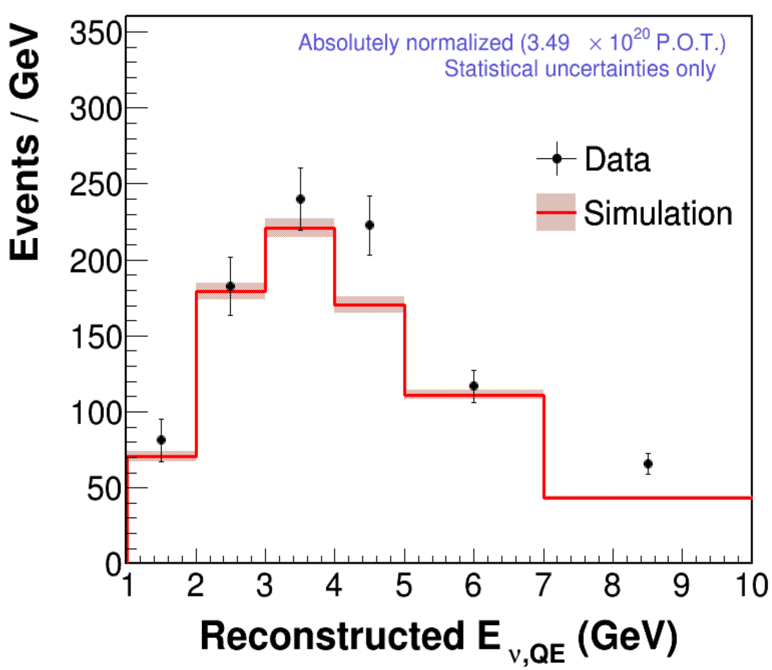
Background constraint: E_e

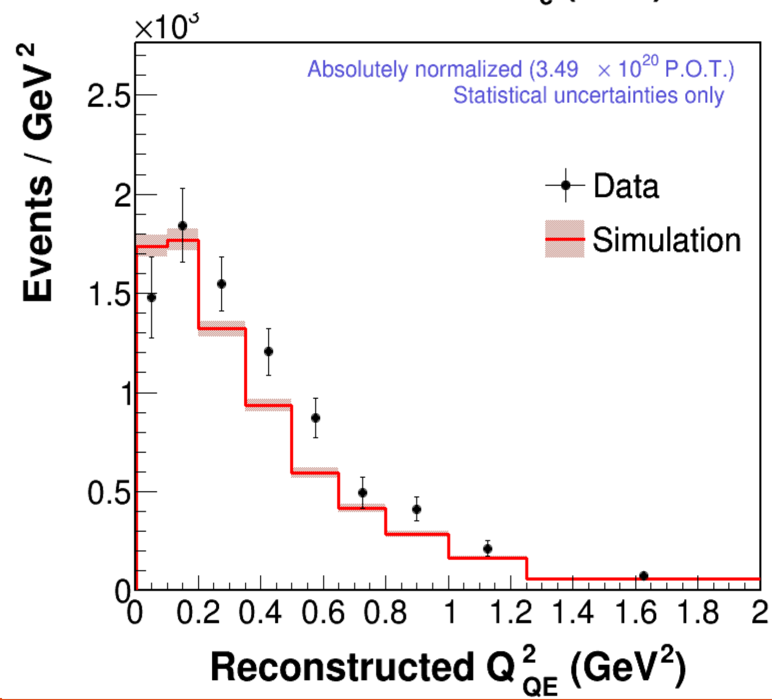


Background-subtracted distributions

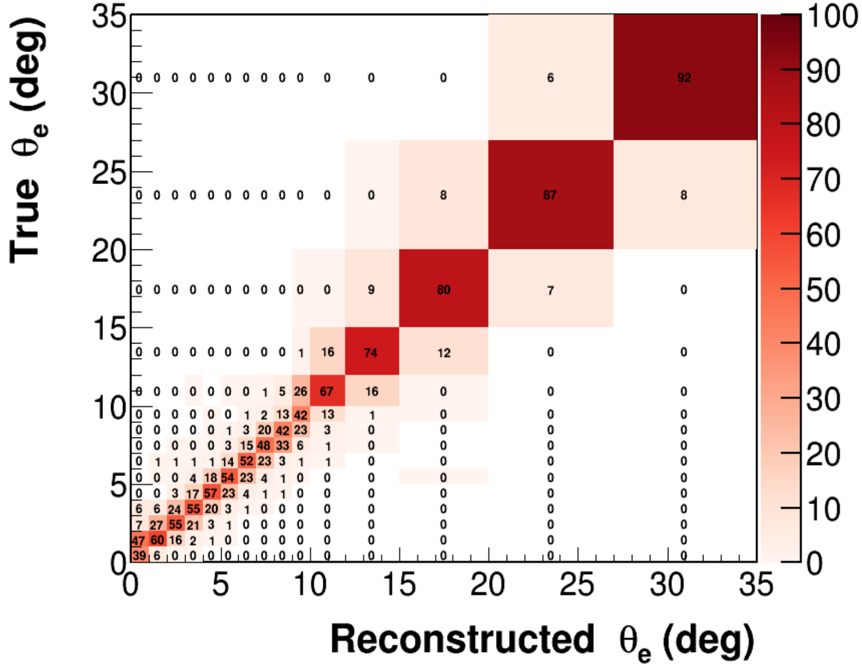


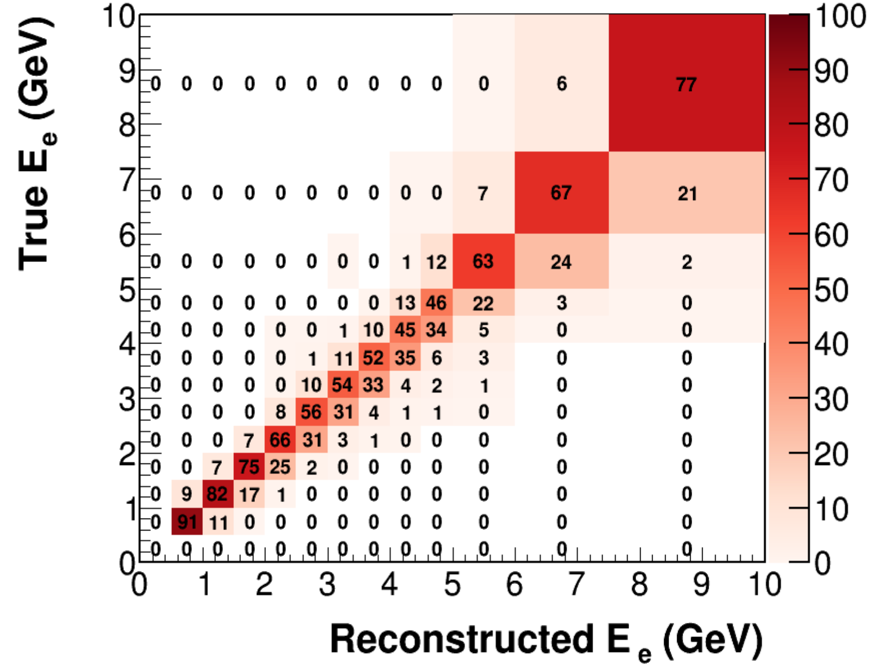


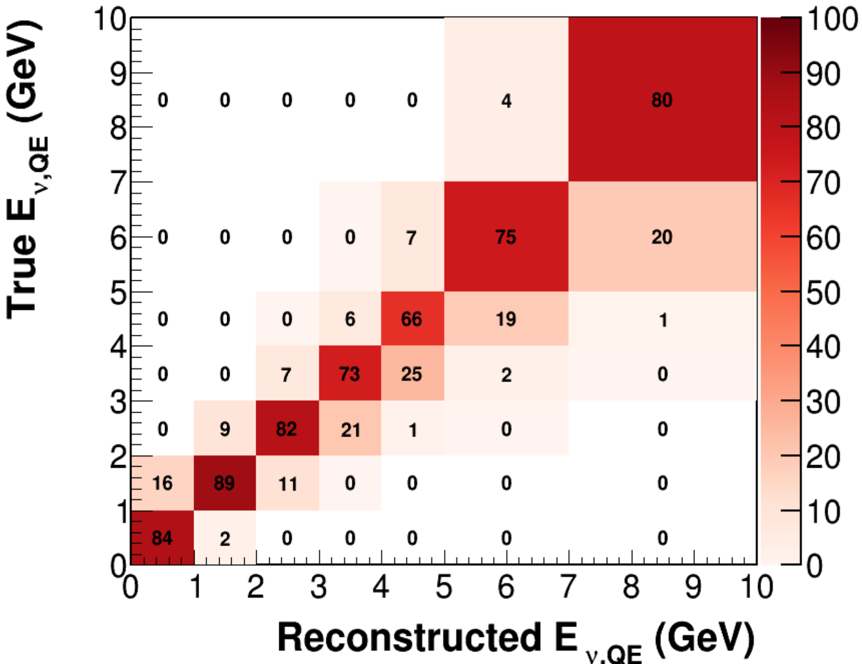


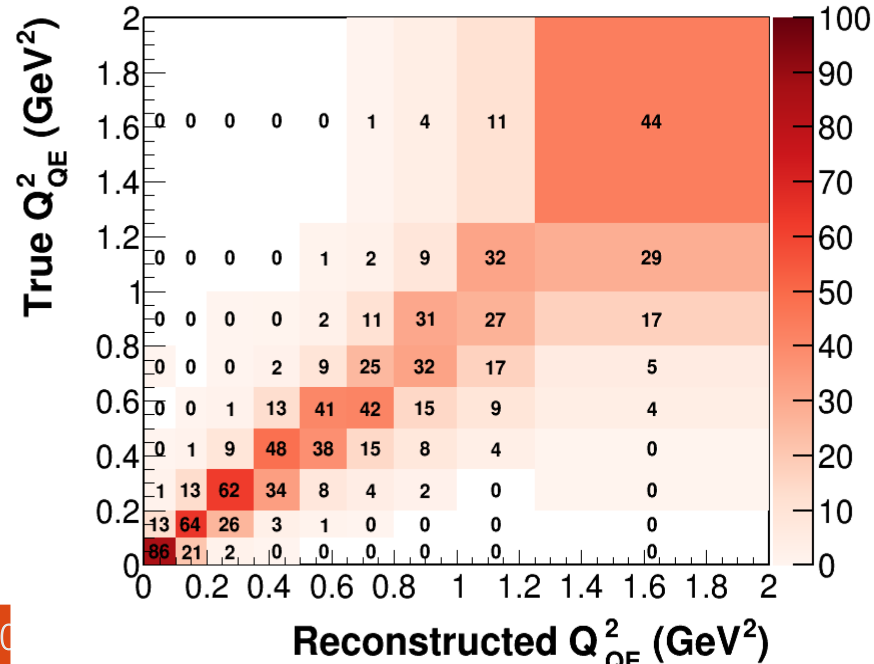


Migration matrices

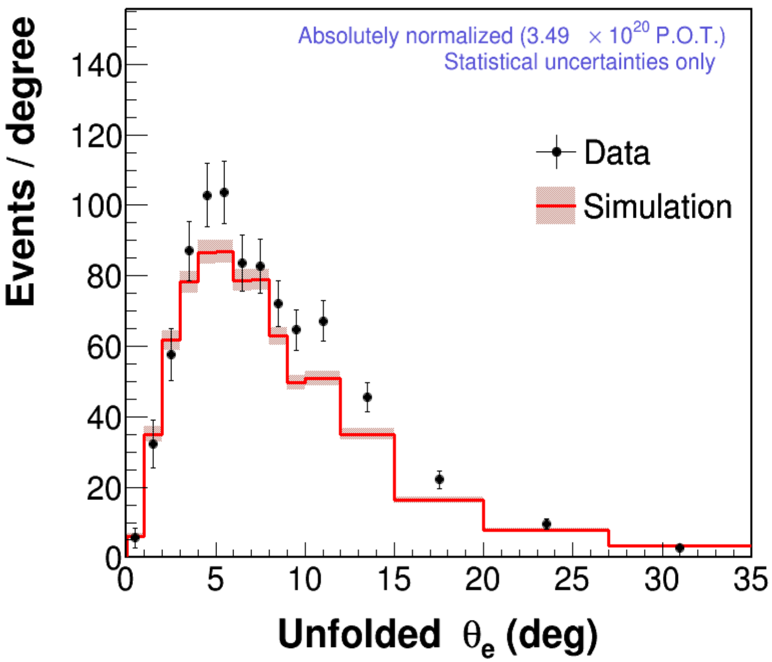


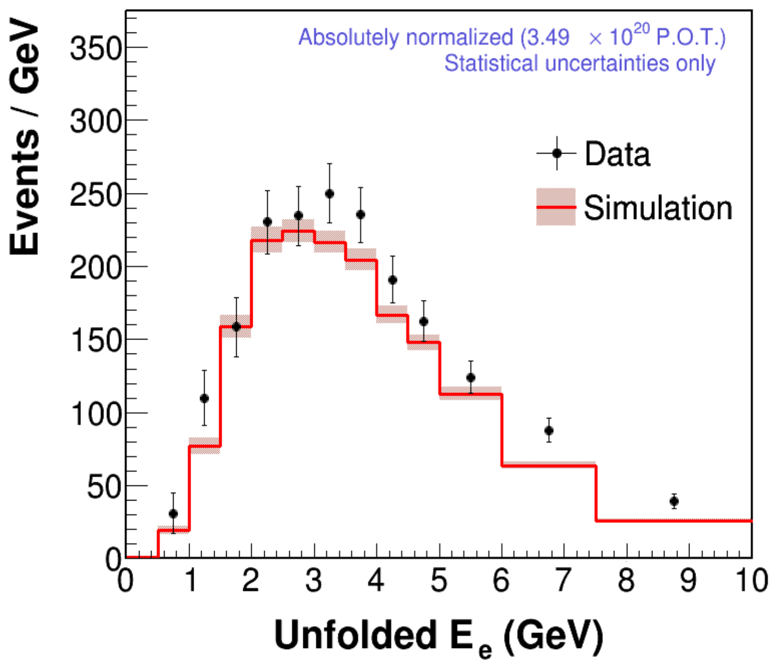


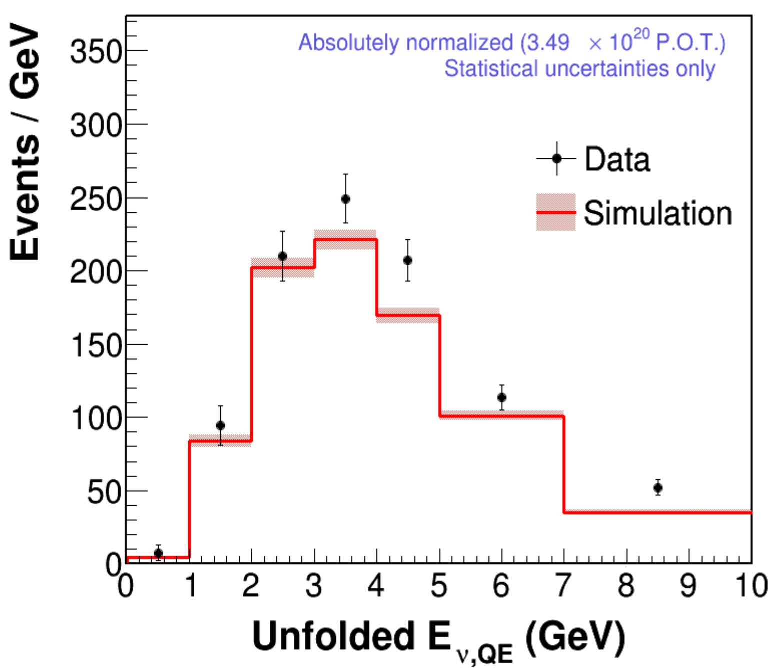


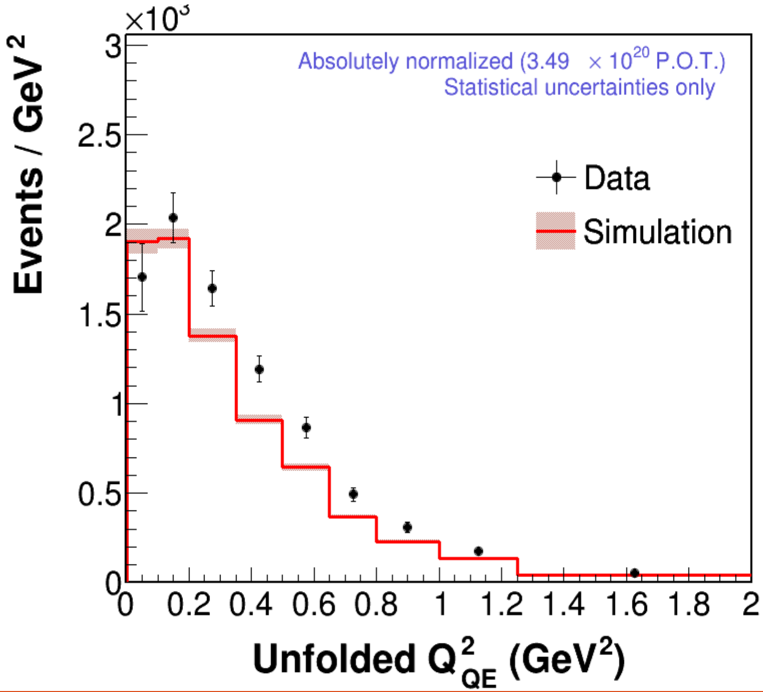


Unfolded distributions

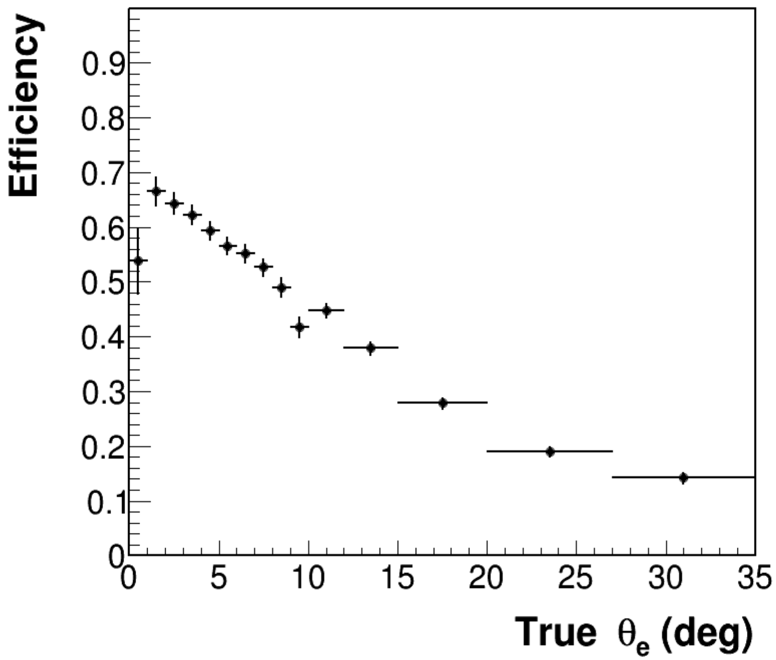


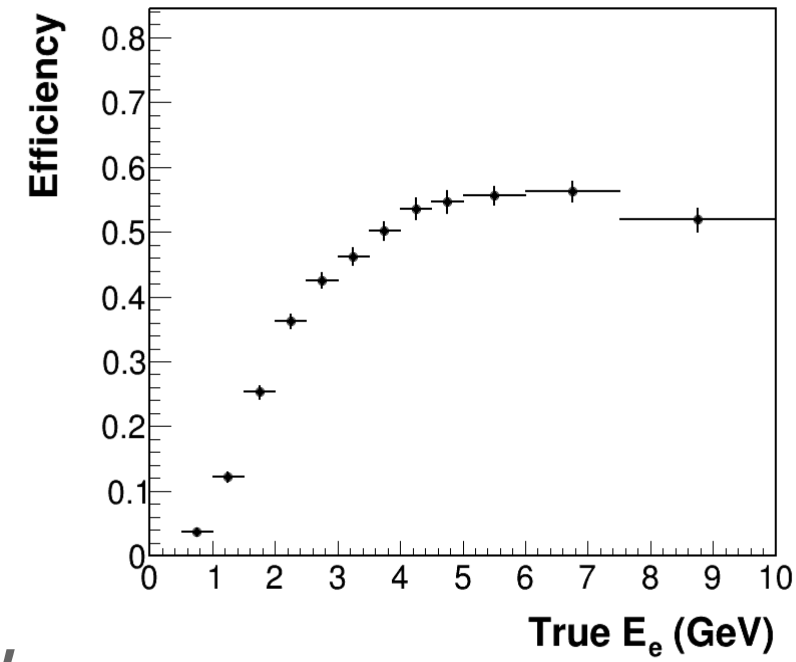




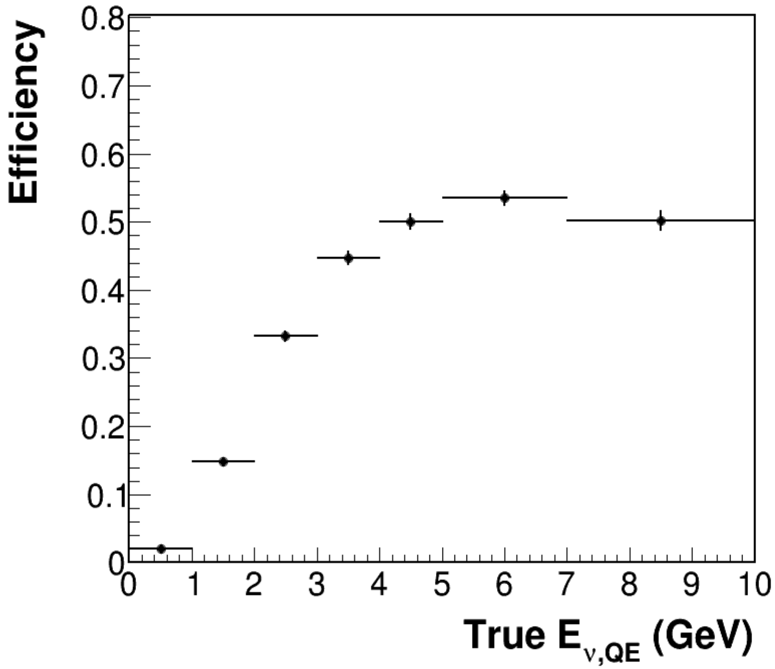


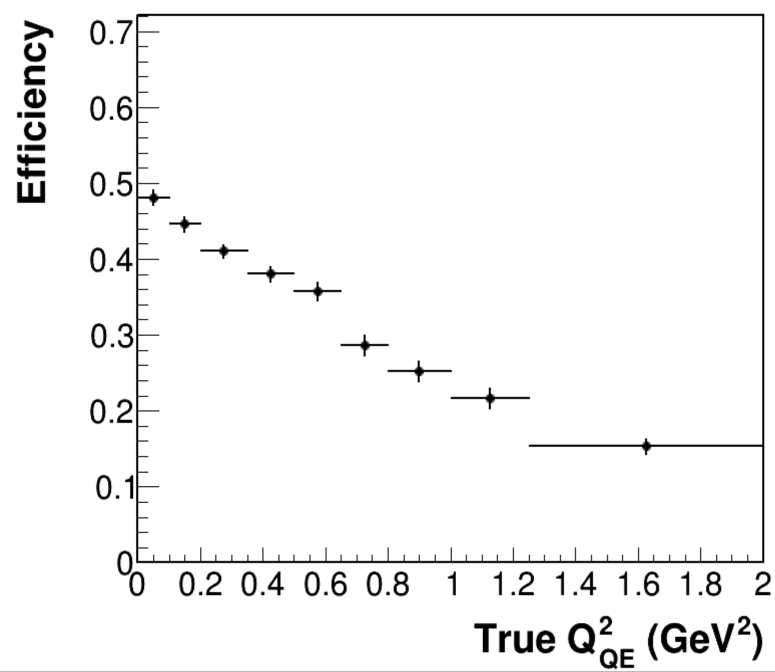
Efficiency estimates



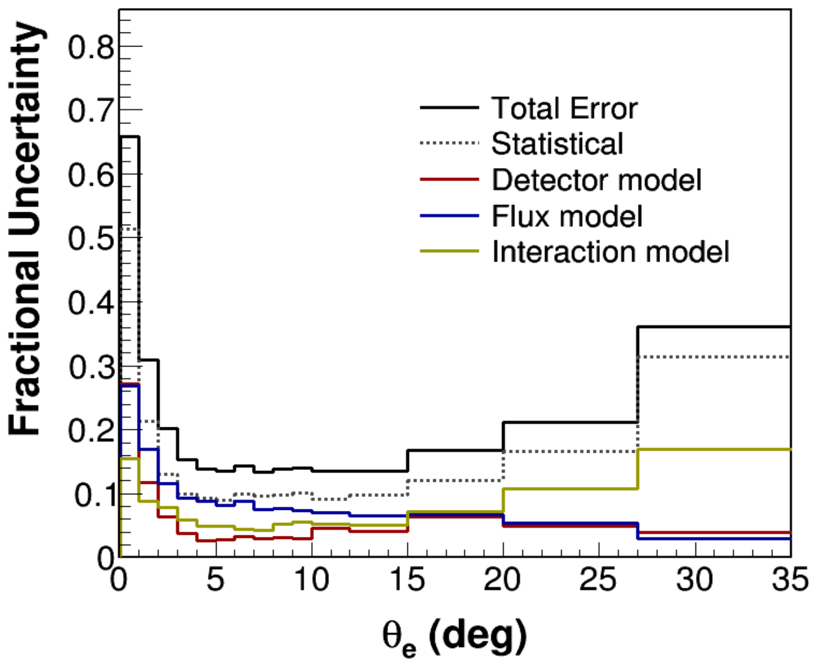


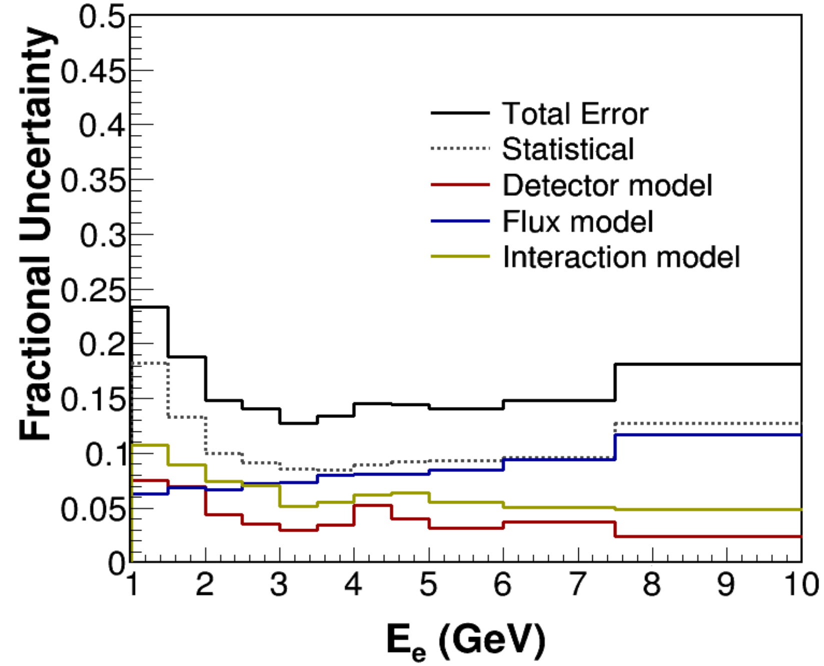
Mean selection efficiency is 35.3%.

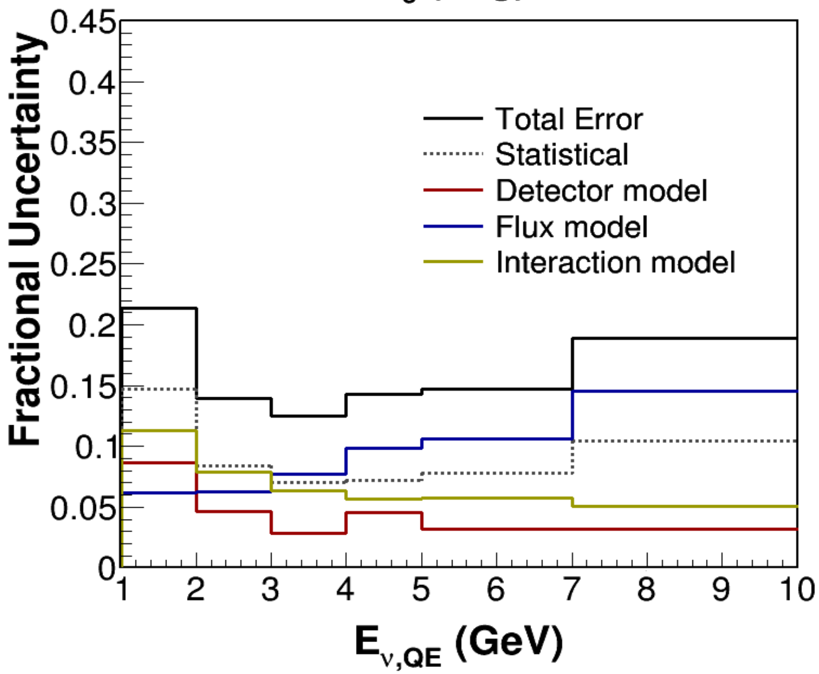


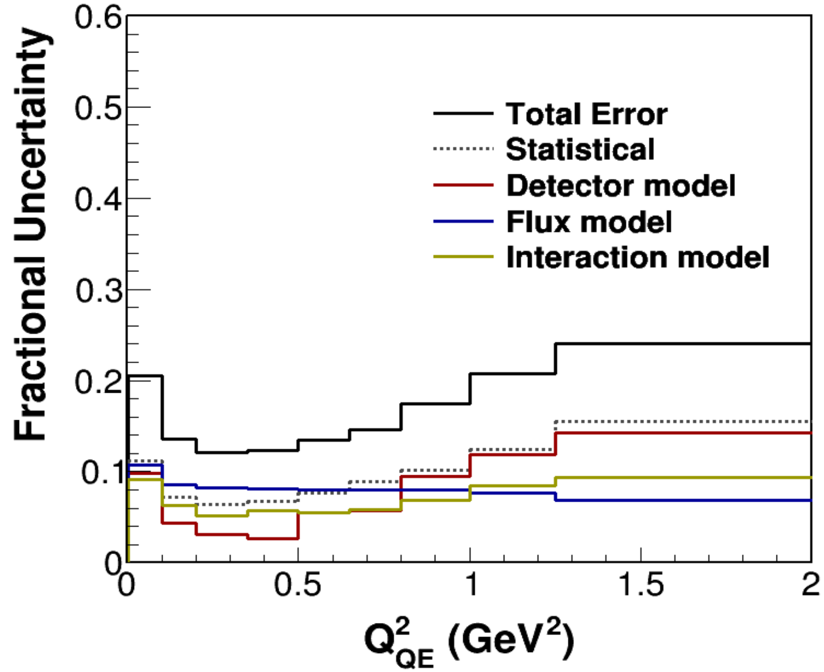


Uncertainties on cross sections

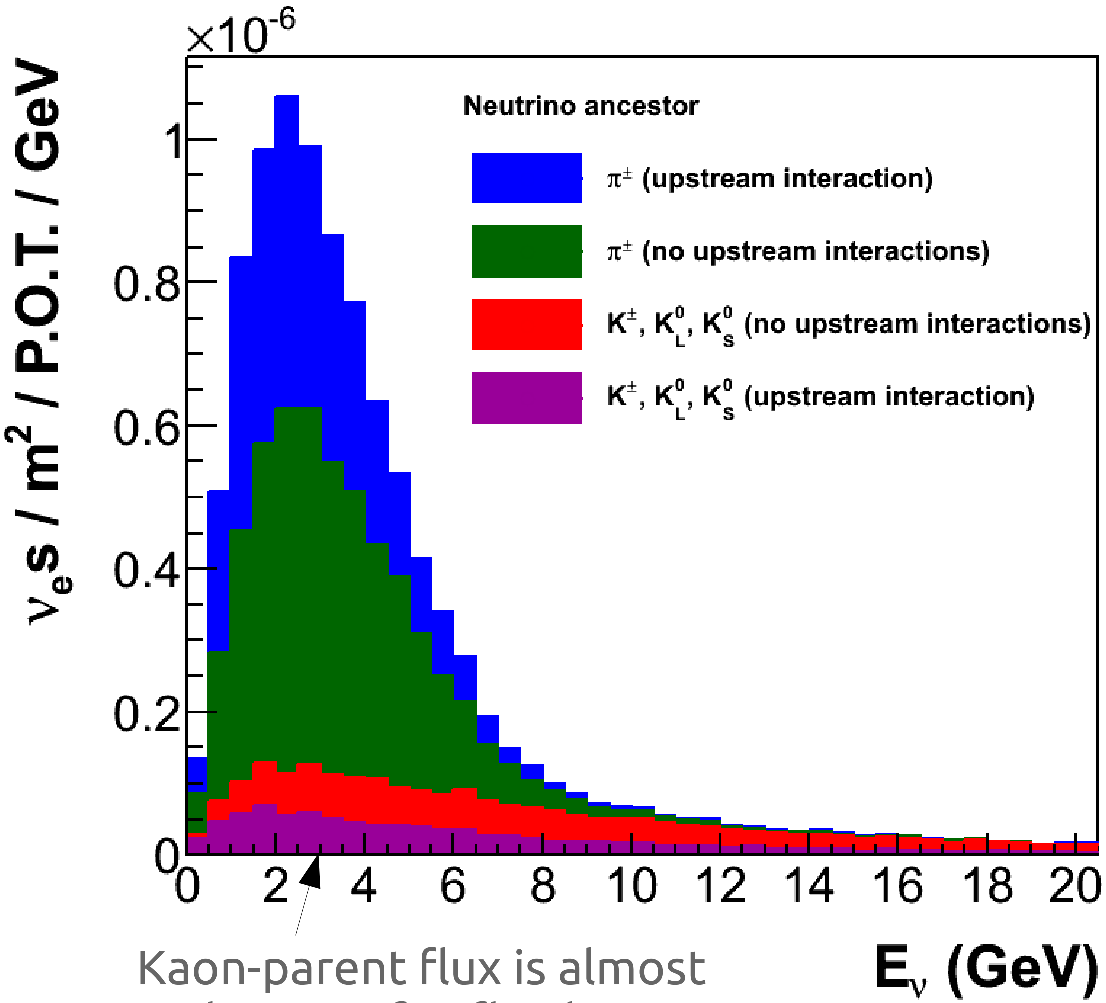




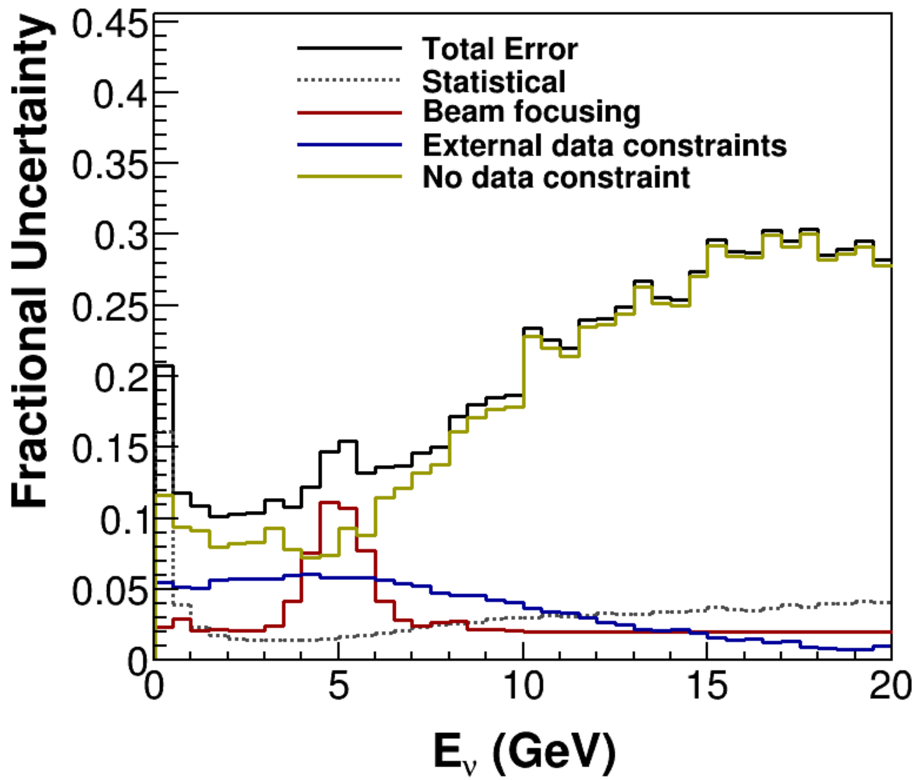




Flux prediction: ancestry

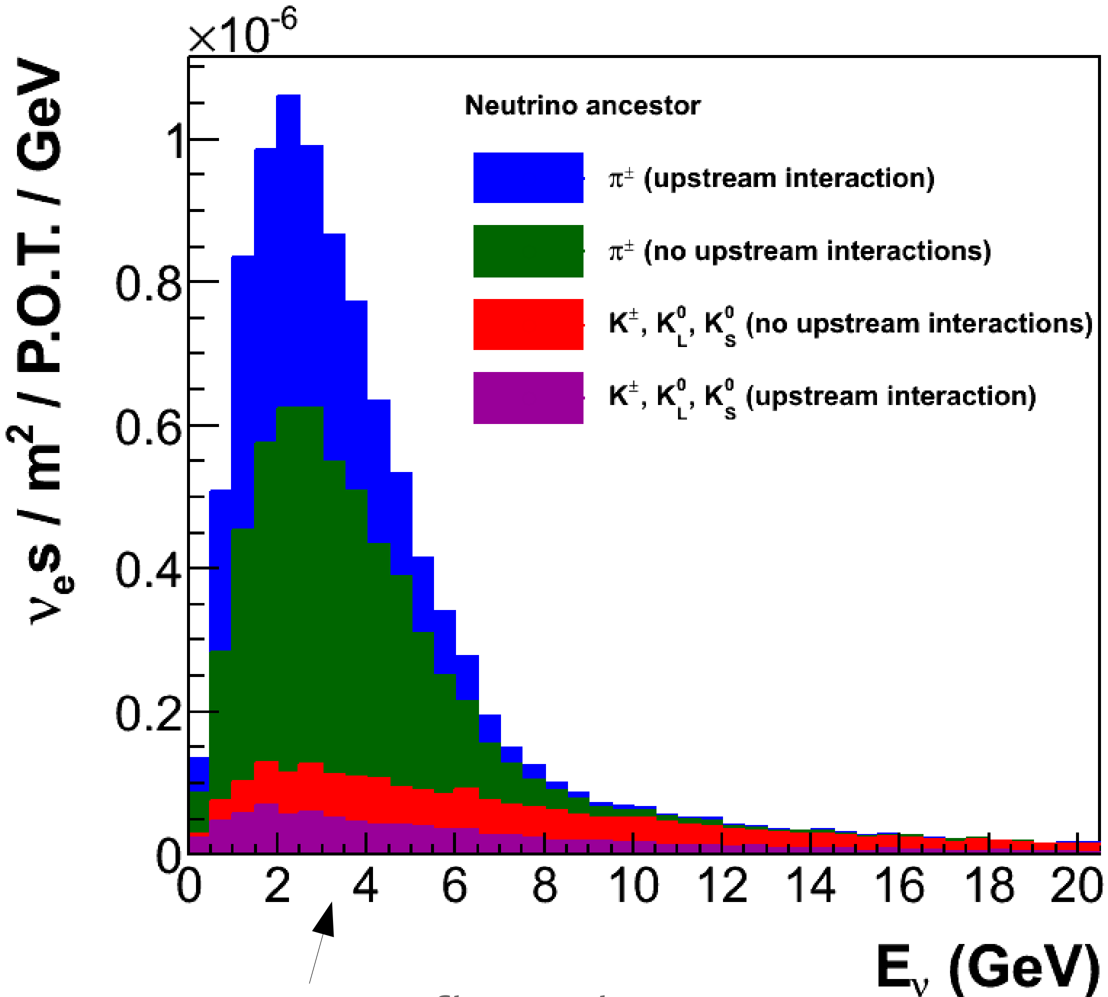


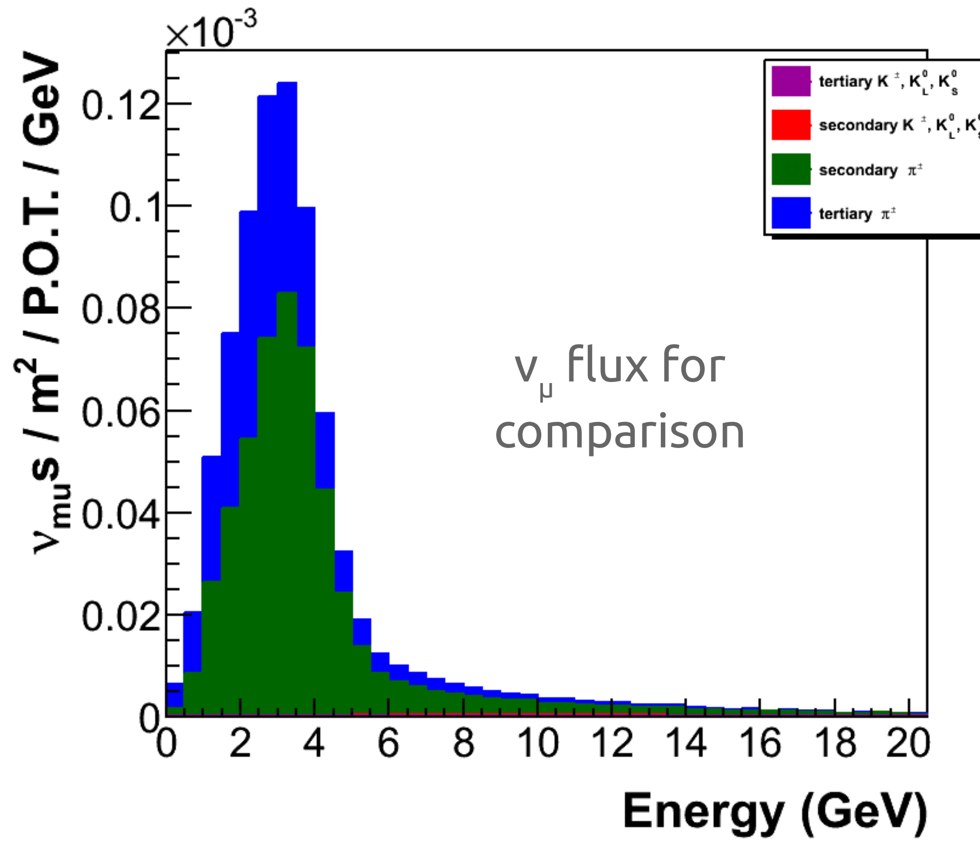
Kaon-parent flux is almost exactly 10% of ν_e flux between 0 and 10 GeV



A priori uncertainties

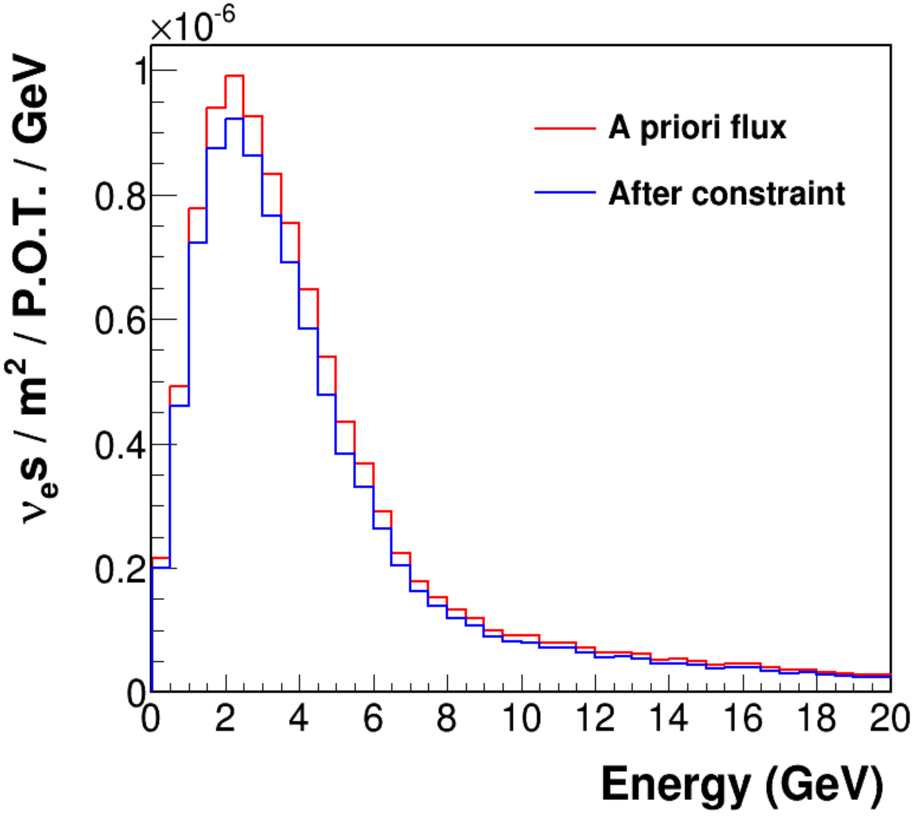
Flux prediction: ancestry

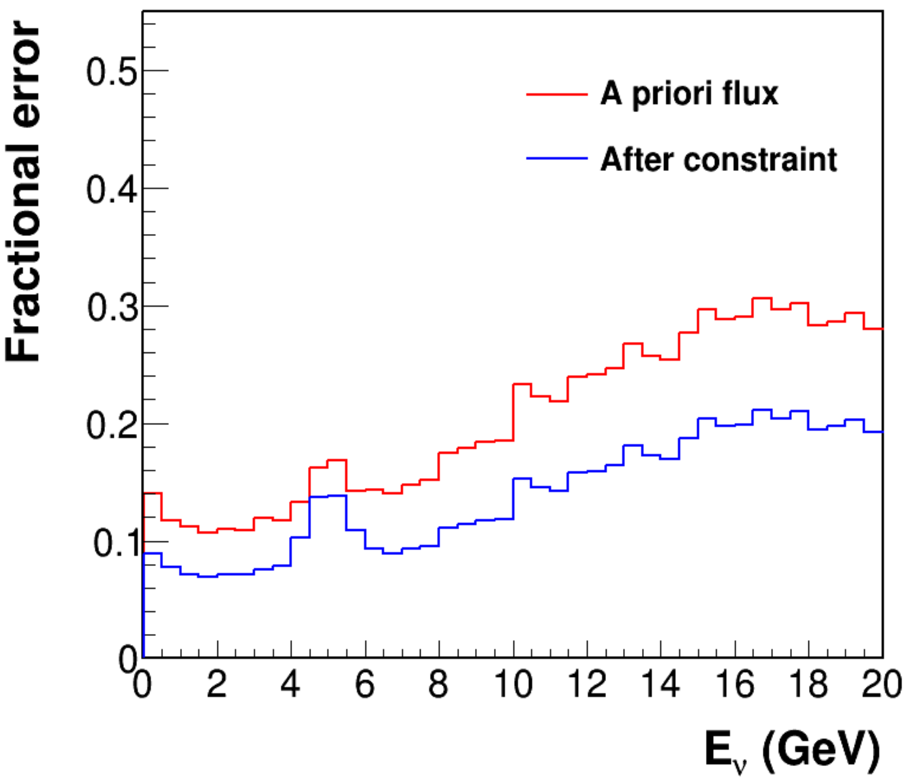




Kaon-parent flux is almost exactly 10% of ν_e flux between 0 and 10 GeV

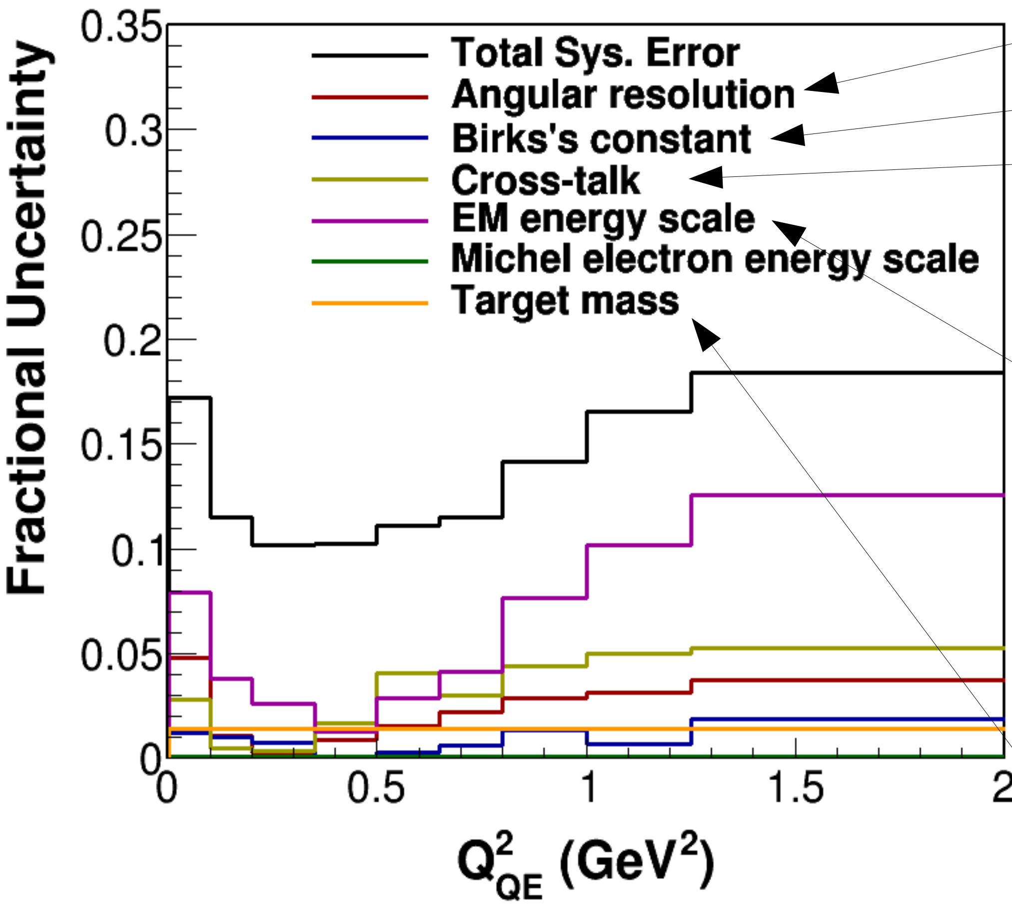
Effect of flux constraint





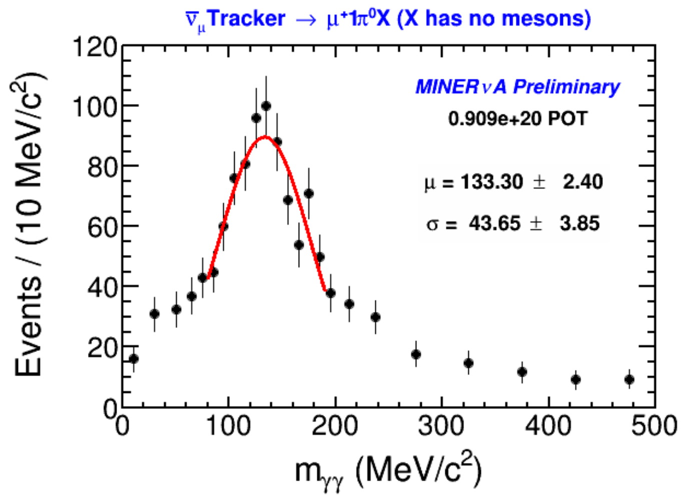
Reduction of 5-10% in prediction,
and 5-10 percentage points in predicted uncertainty as well

Detector model uncertainties



Based on studies of track reconstruction
From MINOS

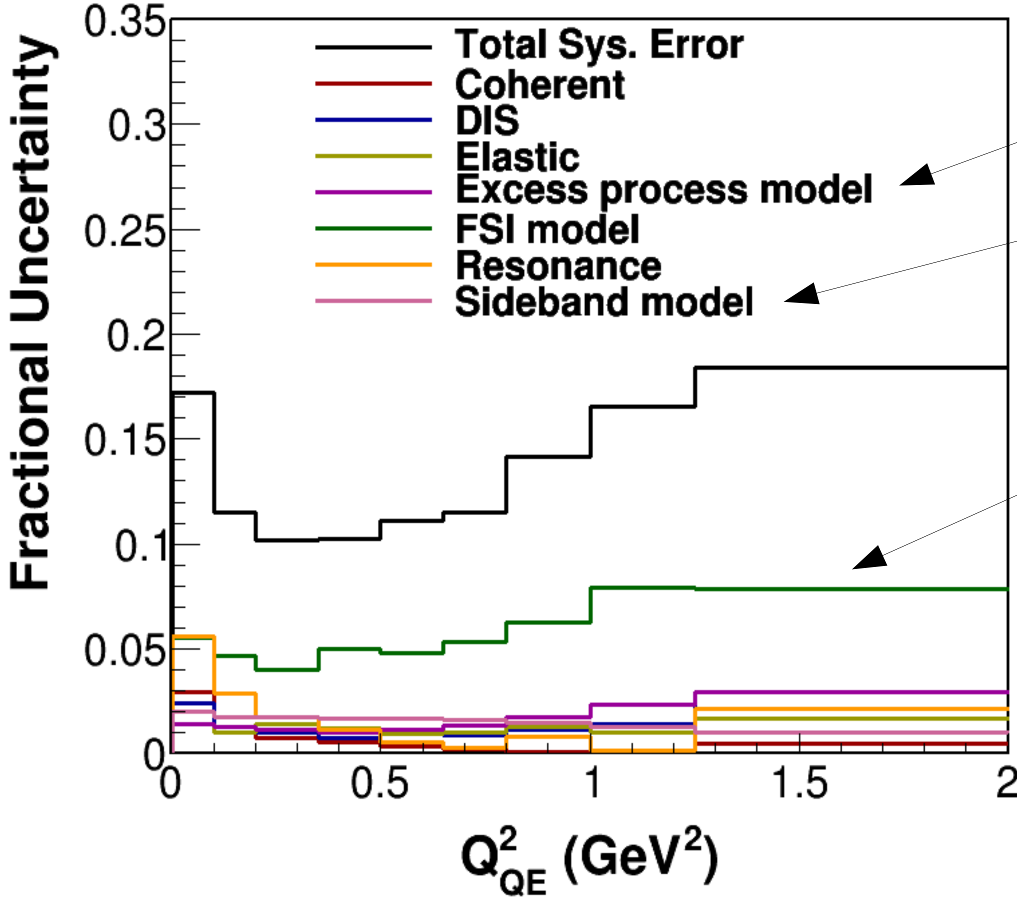
Based on bench and *in situ* measurements



1.8% EM energy scale uncertainty from fitting π^0 mass peak

Based on destructive assays of detector planes

Interaction model uncertainties

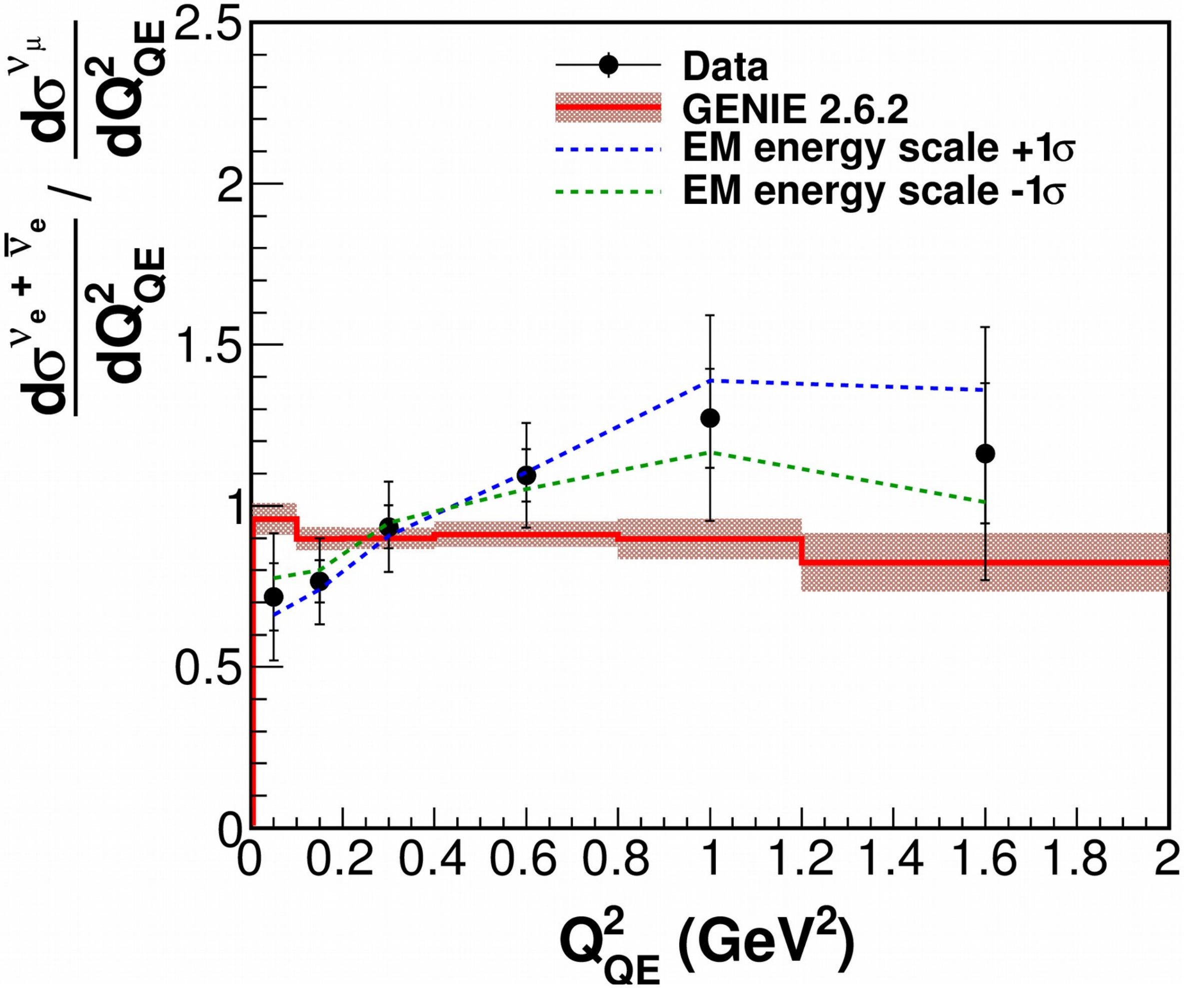


Computed by using single photon model to fit excess instead of π^0

Statistical uncertainties in sideband affect background fitting

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

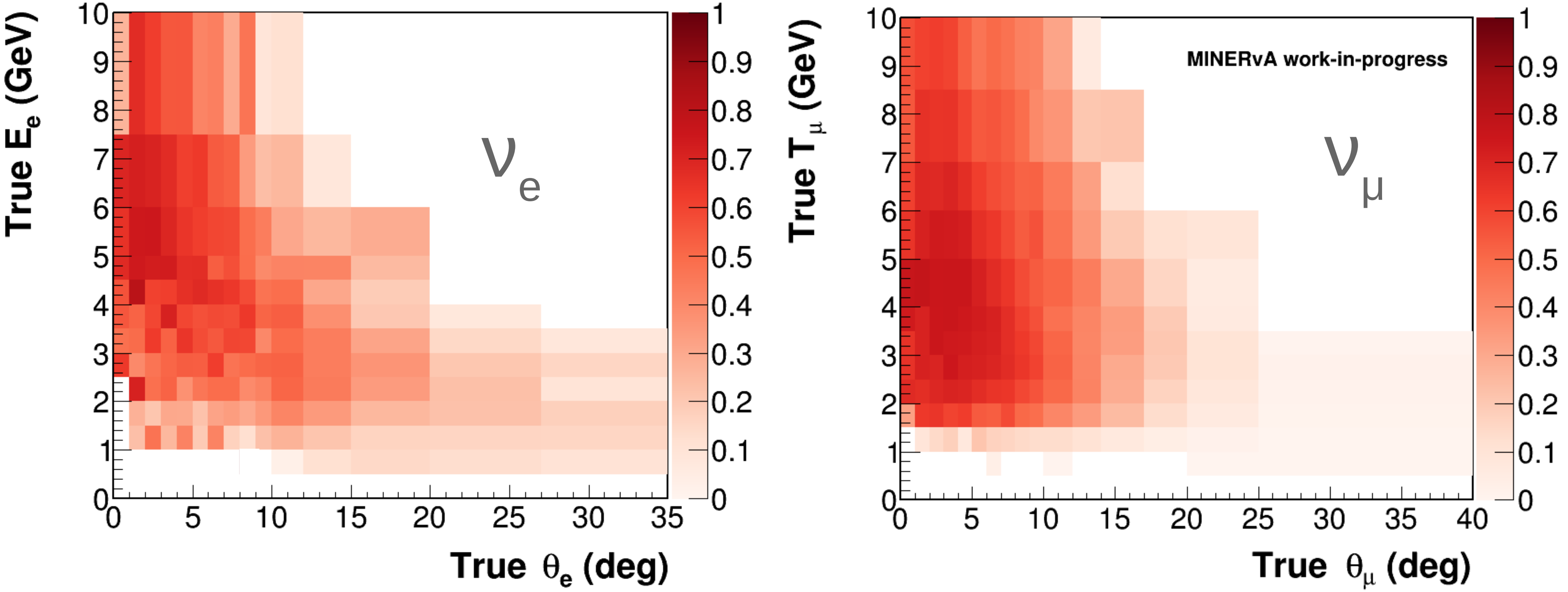
Effect of correlations in systematics



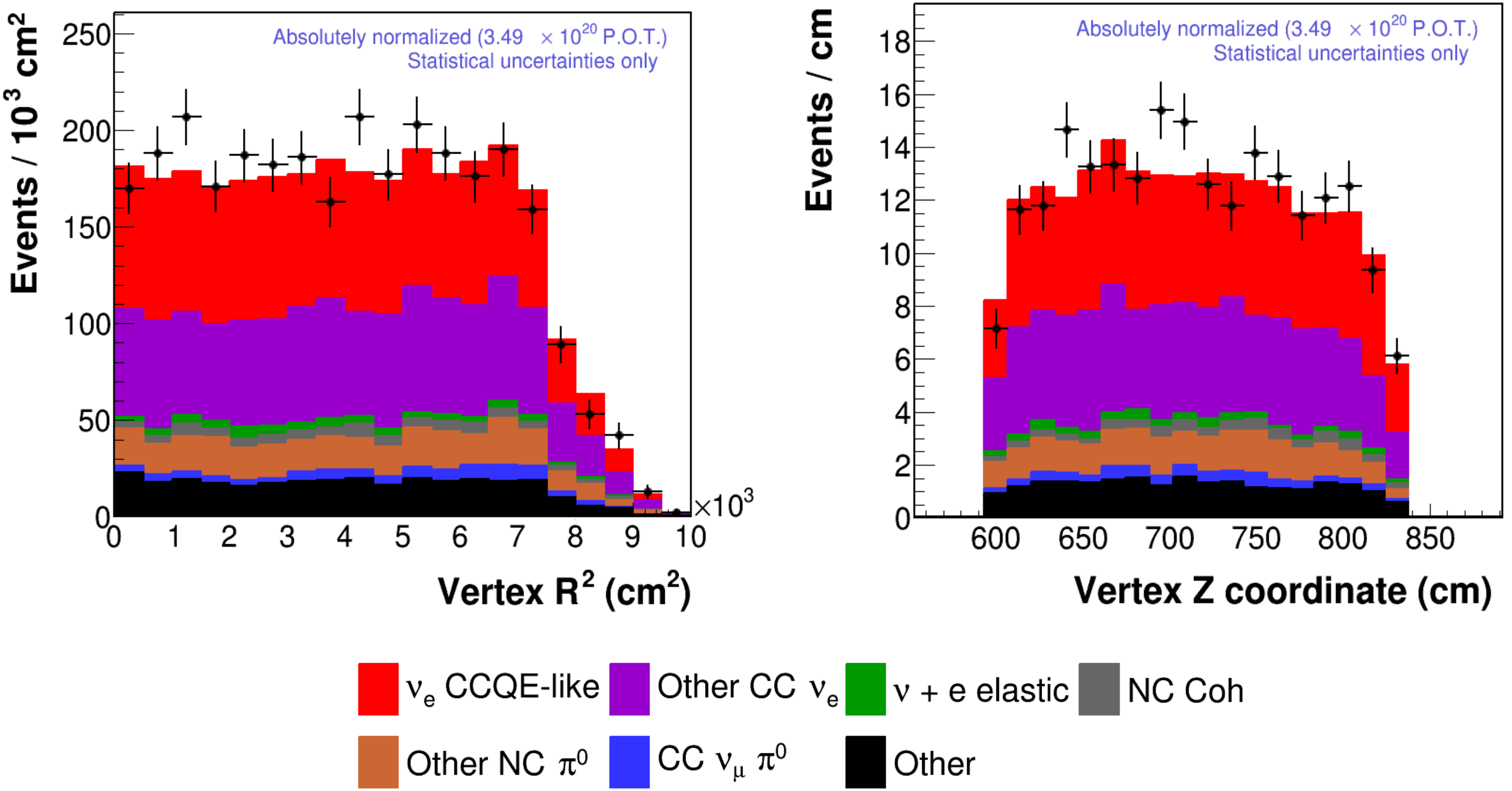
Variation in EM energy scale makes slope of data distribution much closer to agreeing with MC.

Brings net x^2 down.

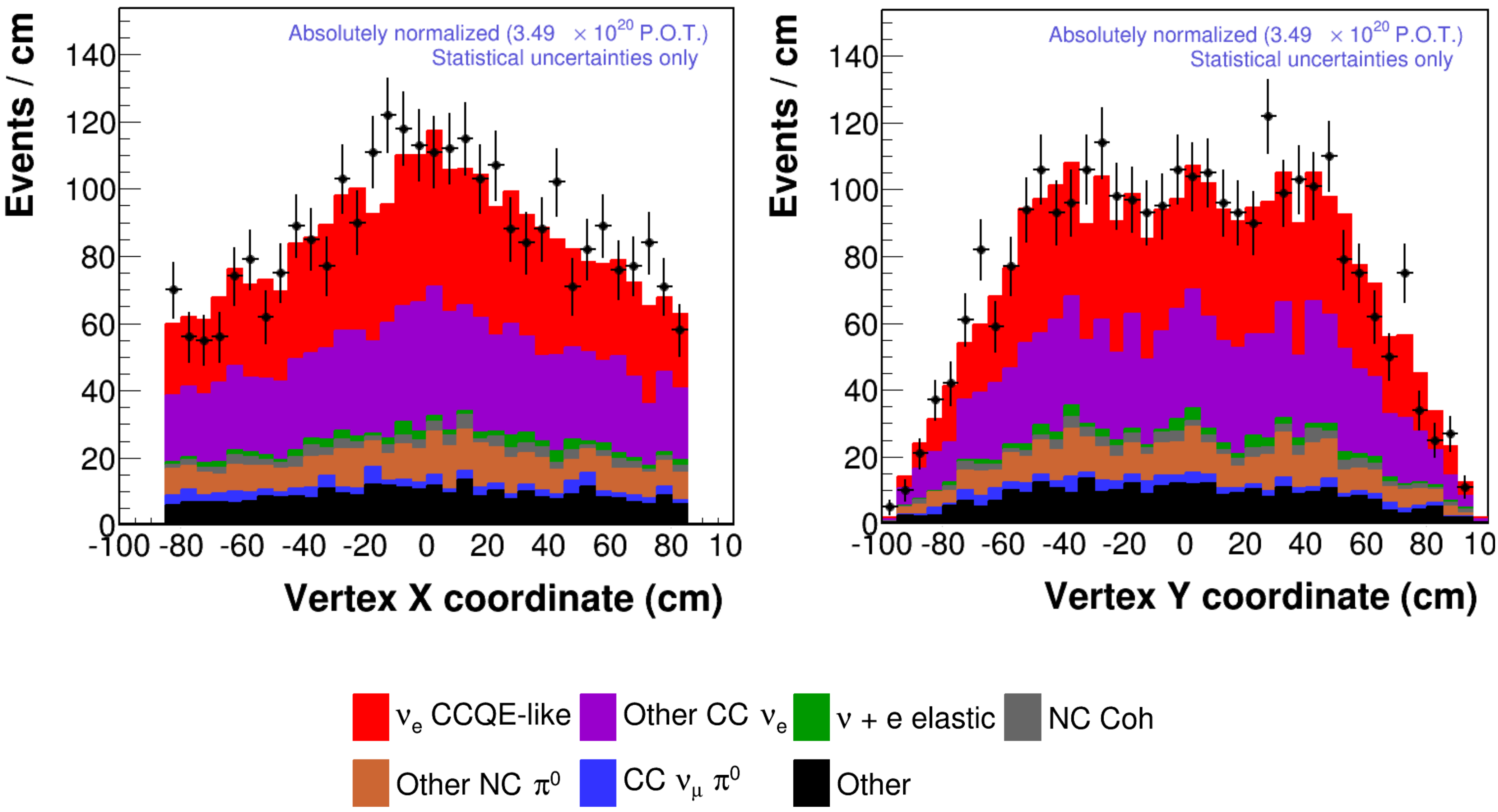
Acceptance comparison



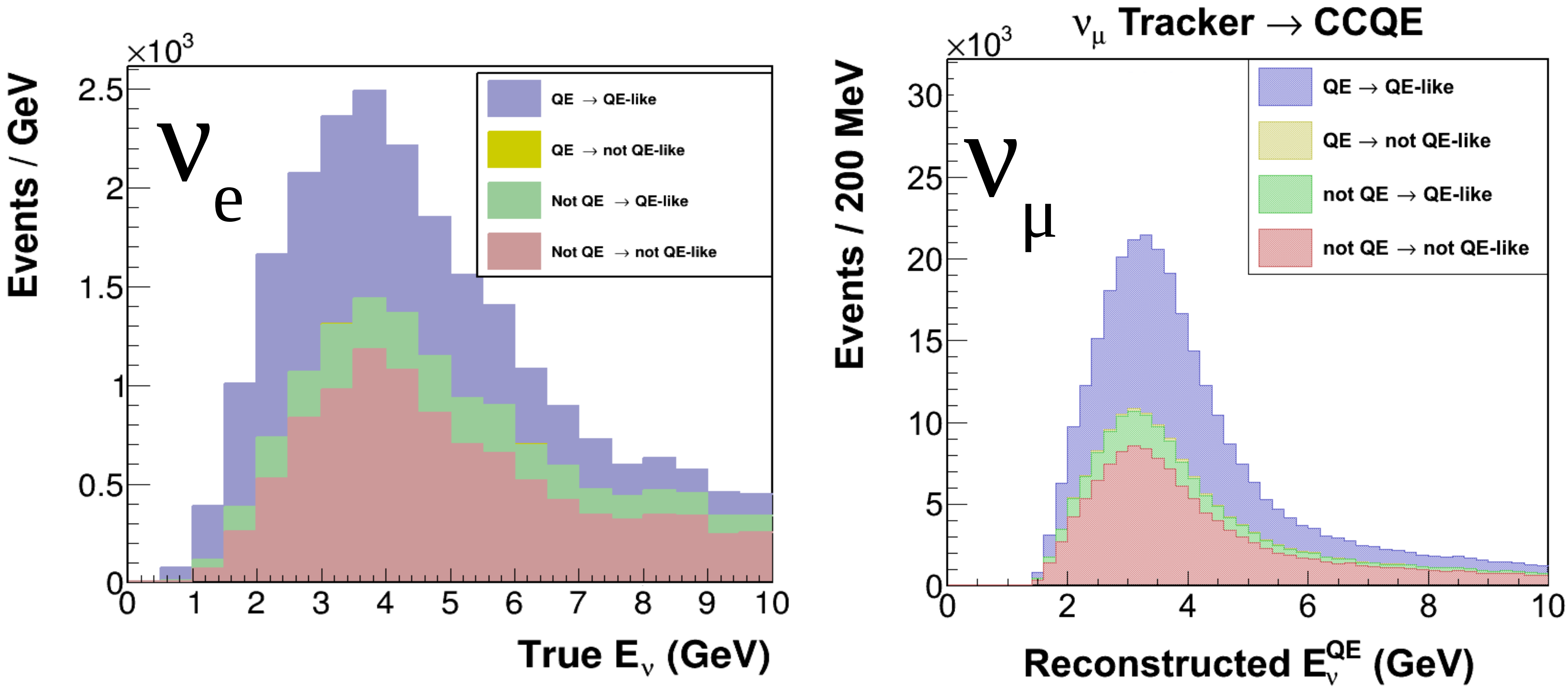
Nuisance distributions (1)



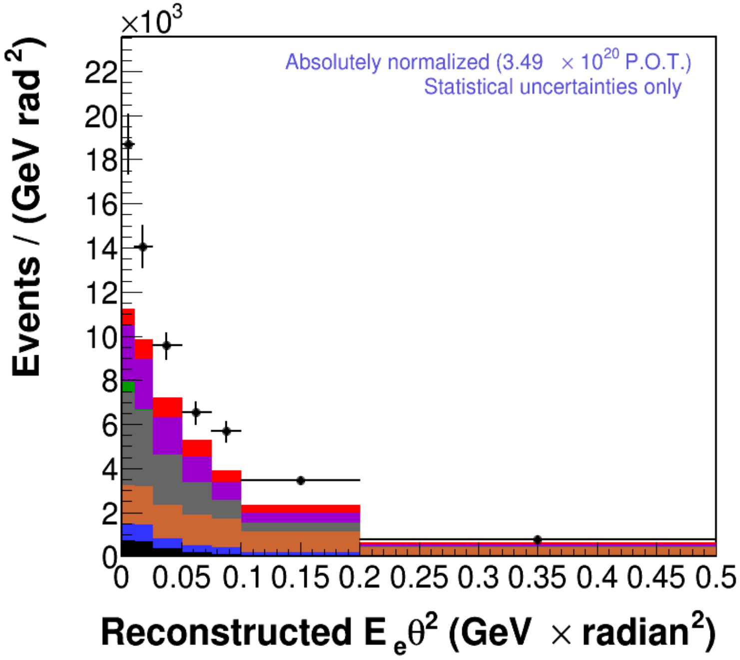
Nuisance distributions (2)



GENIE CCQE vs CCQE-like

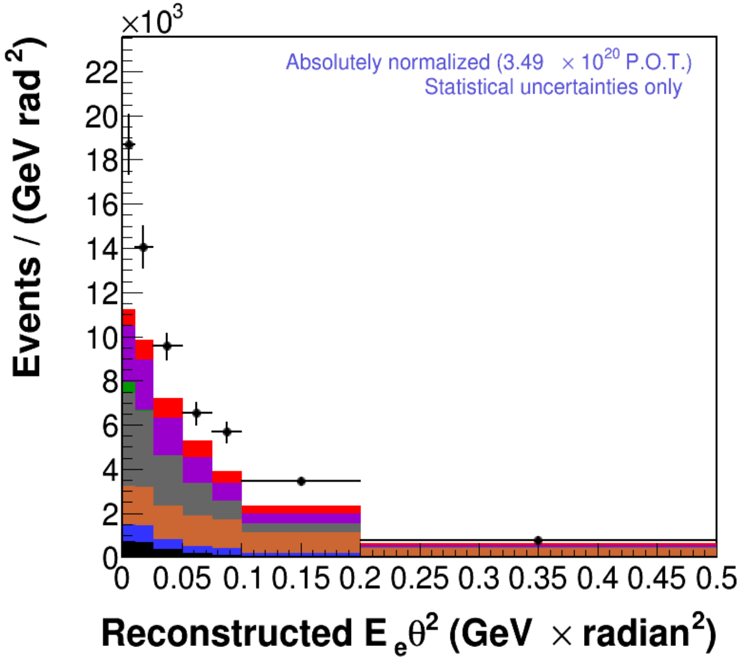


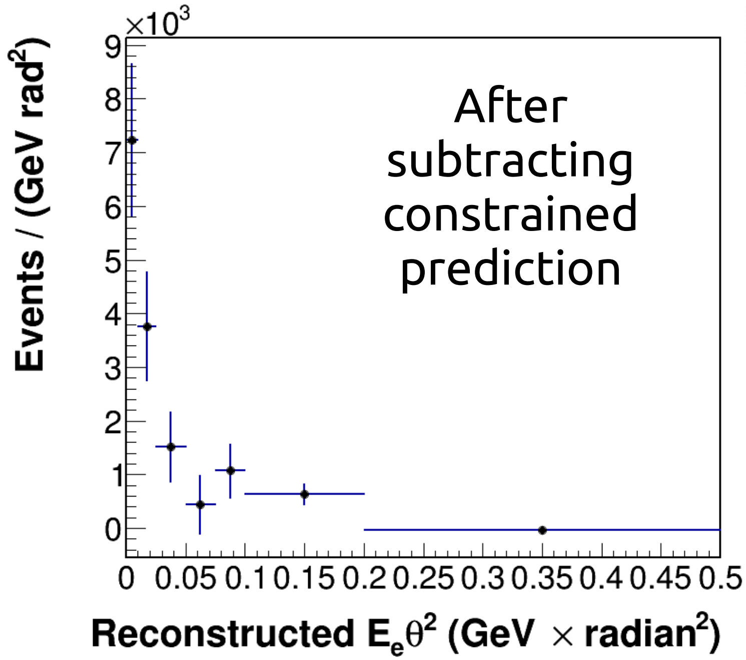
Particle identification



An invaluable tool:
shape comparisons

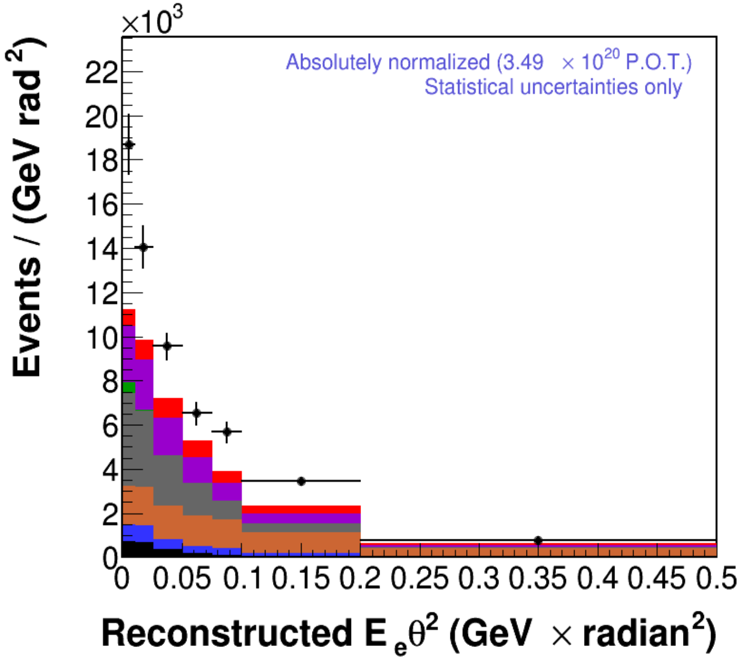
Particle identification

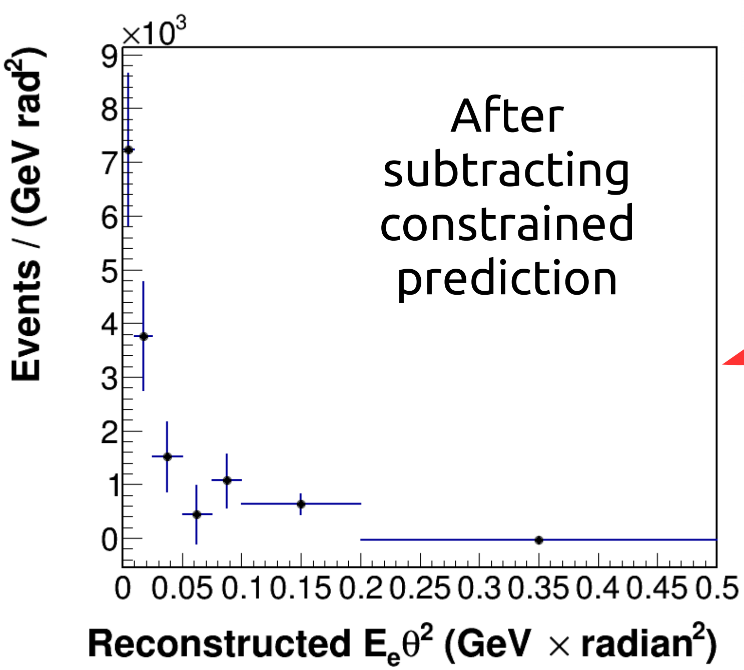




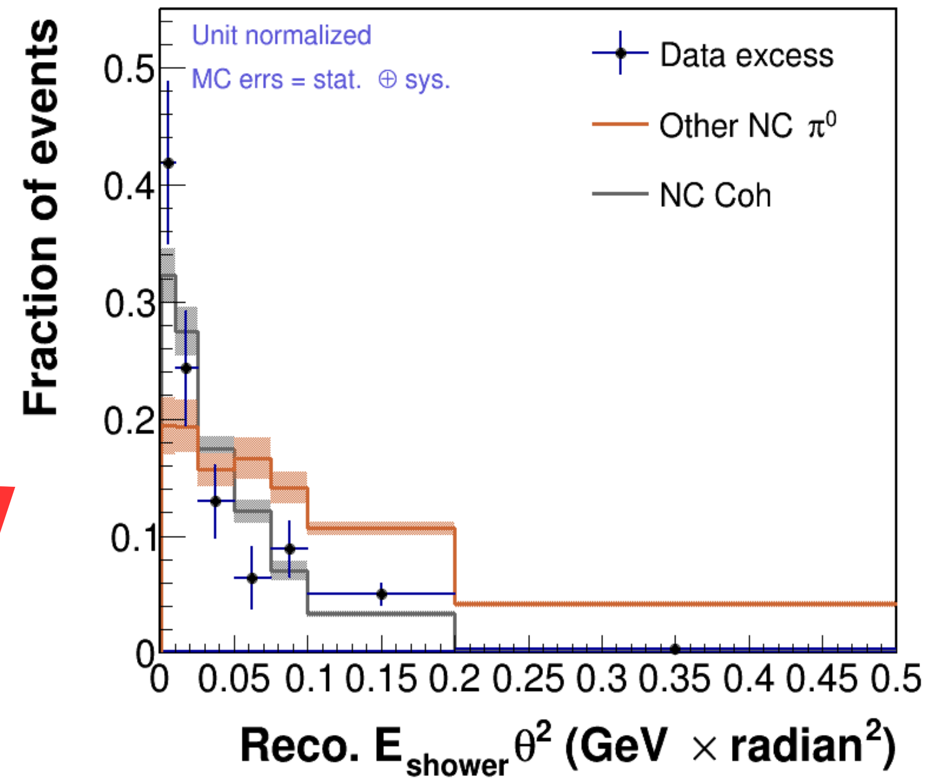
An invaluable tool:
shape comparisons

Particle identification





An invaluable tool: **shape comparisons**

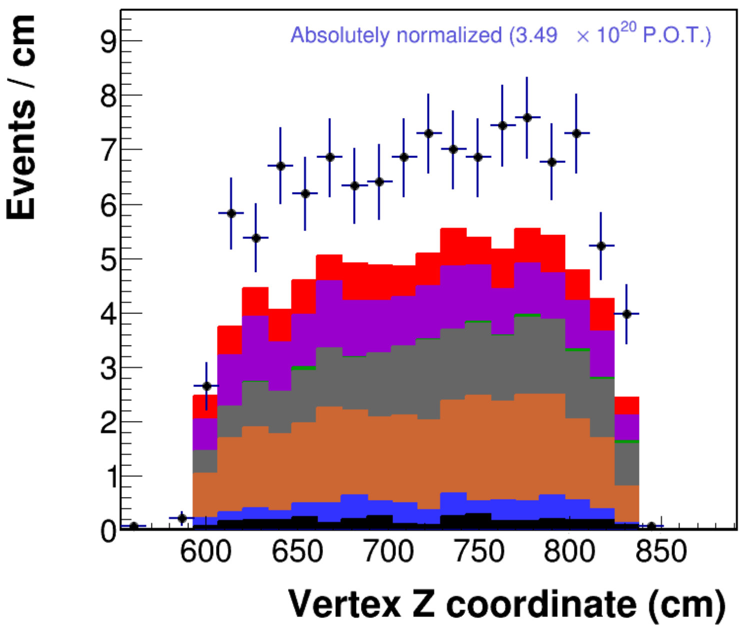


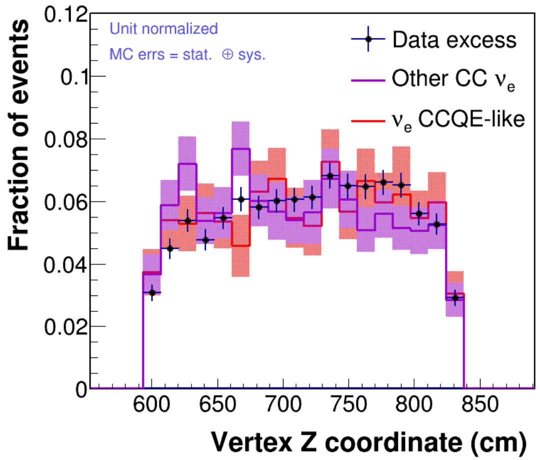
Compare data shape to model shapes

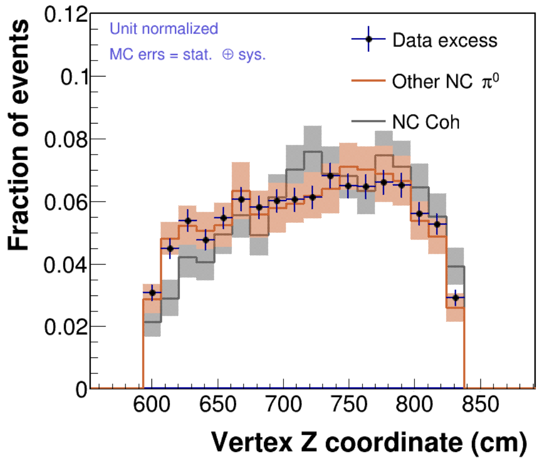
Ruling out externally-entering sources

<u>If front-entering particles responsible,</u> would expect excess to cluster around front of fiducial region.

<u>No such behavior observed.</u>

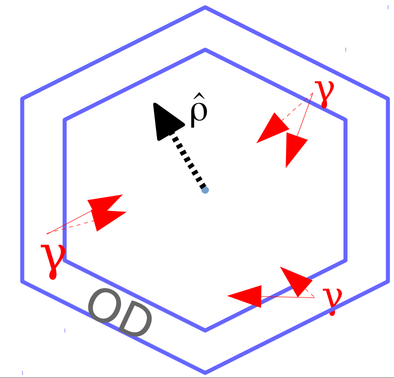


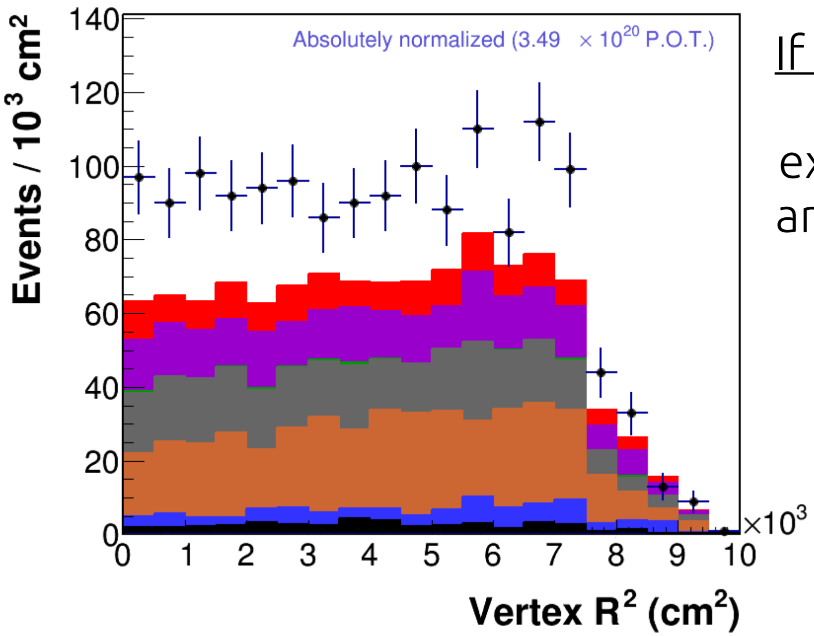




Ruling out externally-entering sources

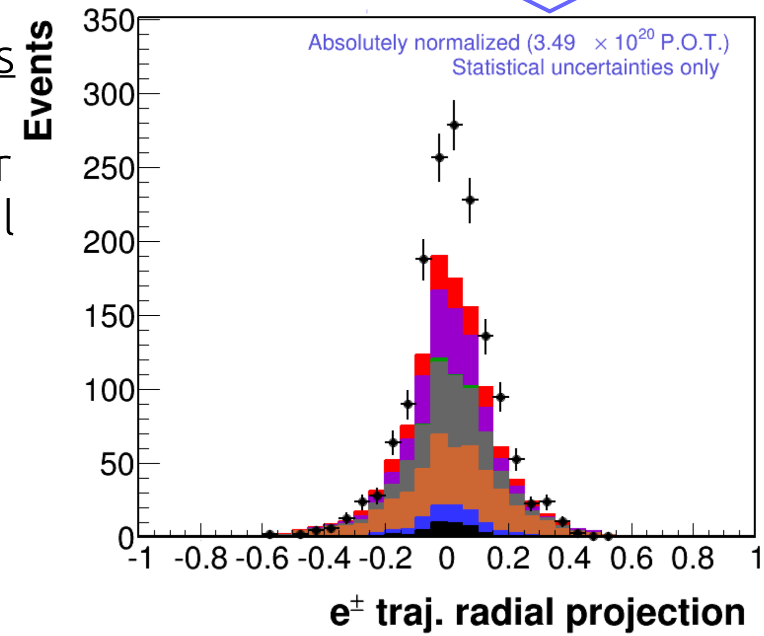
Project onto radial coordinate ρ

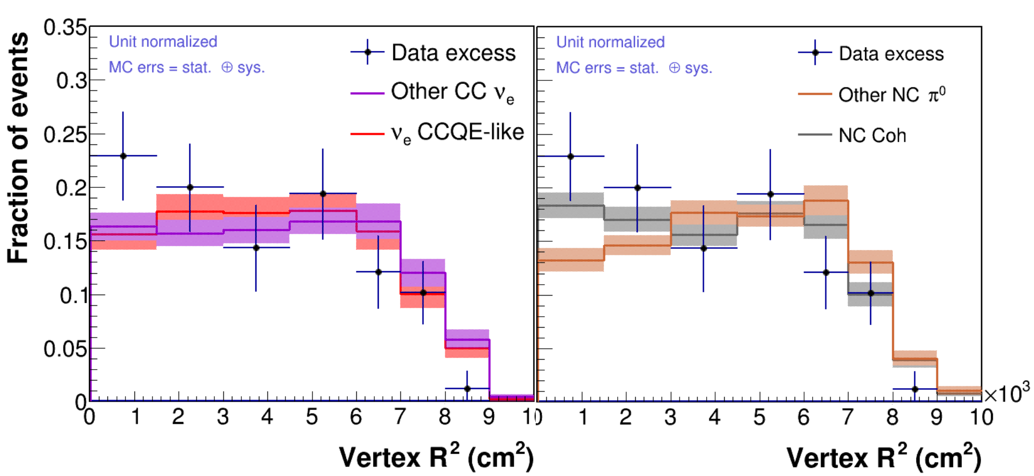


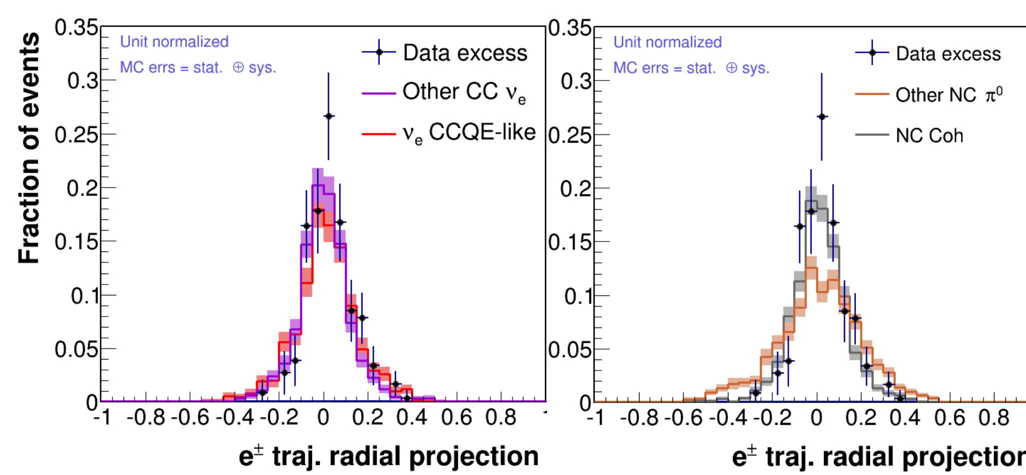


If side-entering particles responsible, would expect excess to cluster around edges of fiducial region and point inwards.

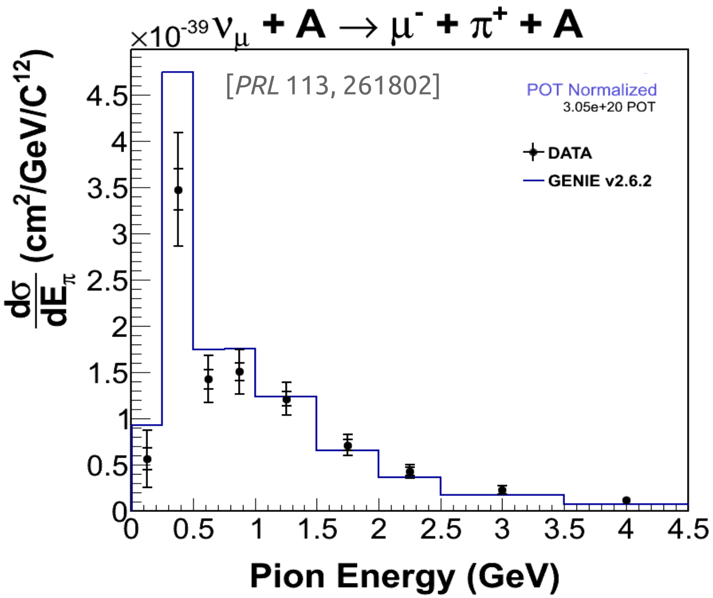
No such behavior observed.

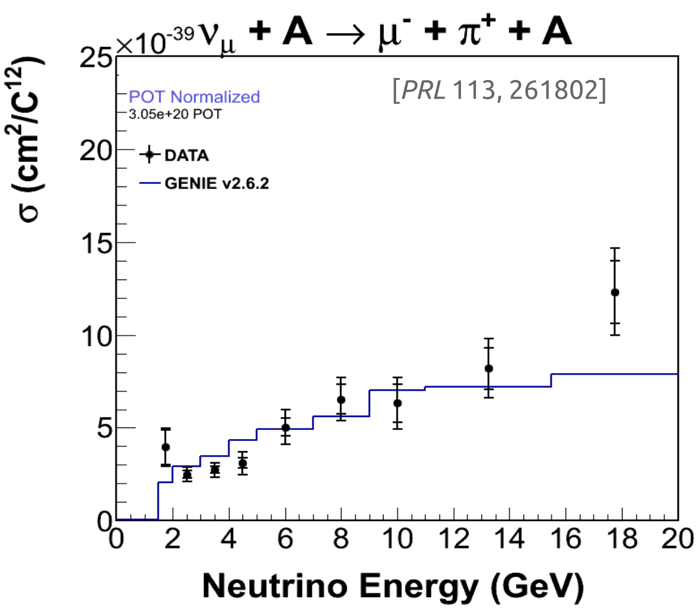


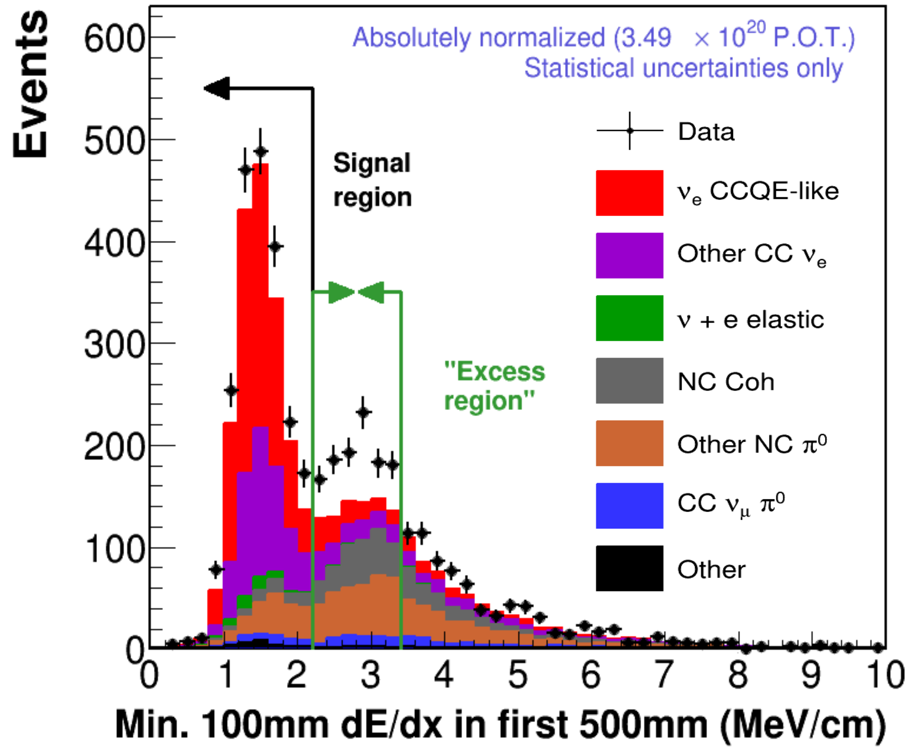




Isn't this just NC coherent?

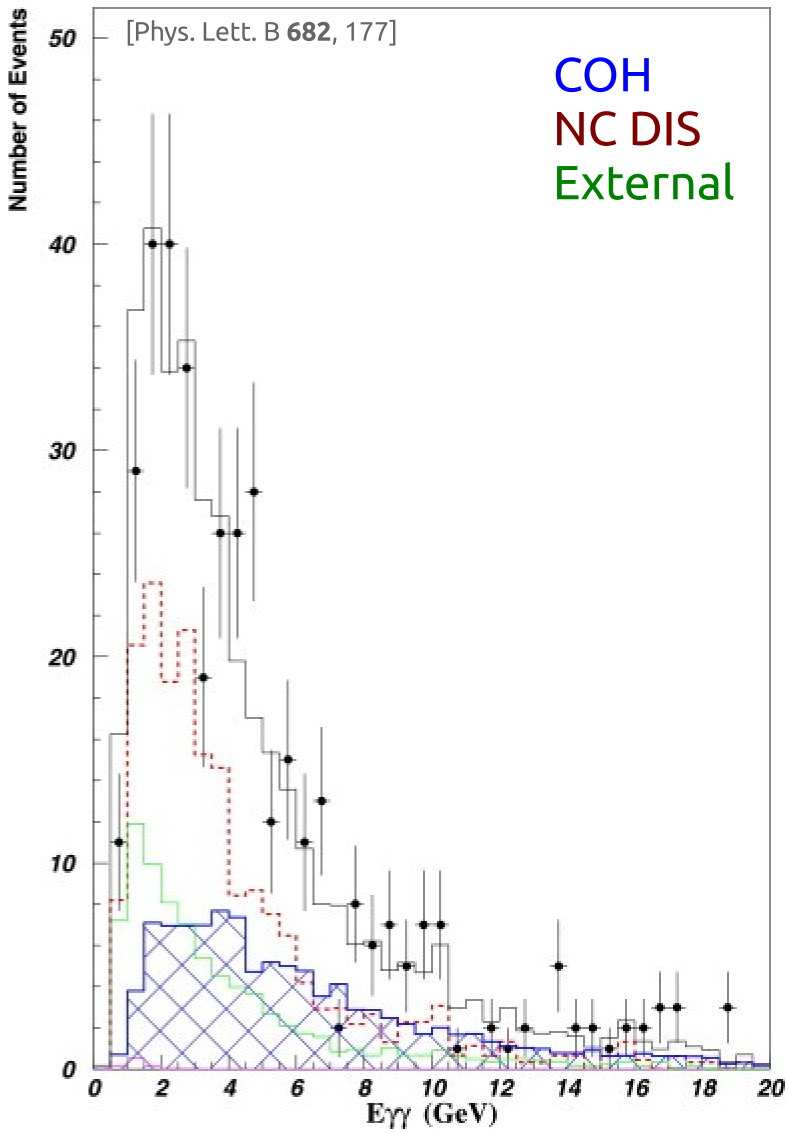




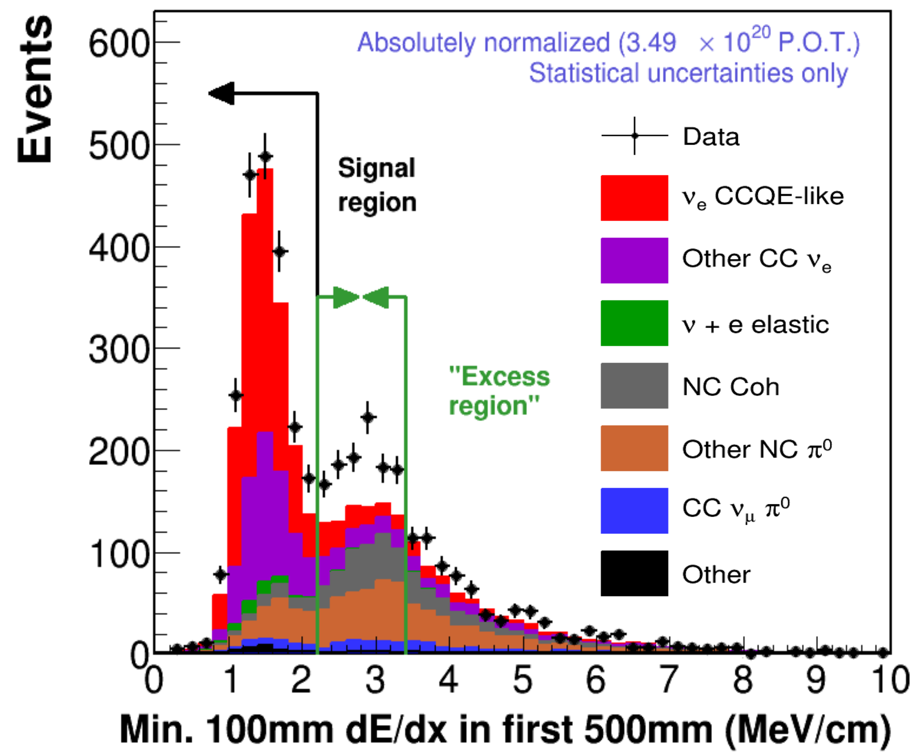


Doubling coherent to fit excess would create strong tension with MINERvA CC coherent measurement (same model produces CC and NC coherent in GENIE)

Isn't this just NC coherent?



(total π^0 energy)

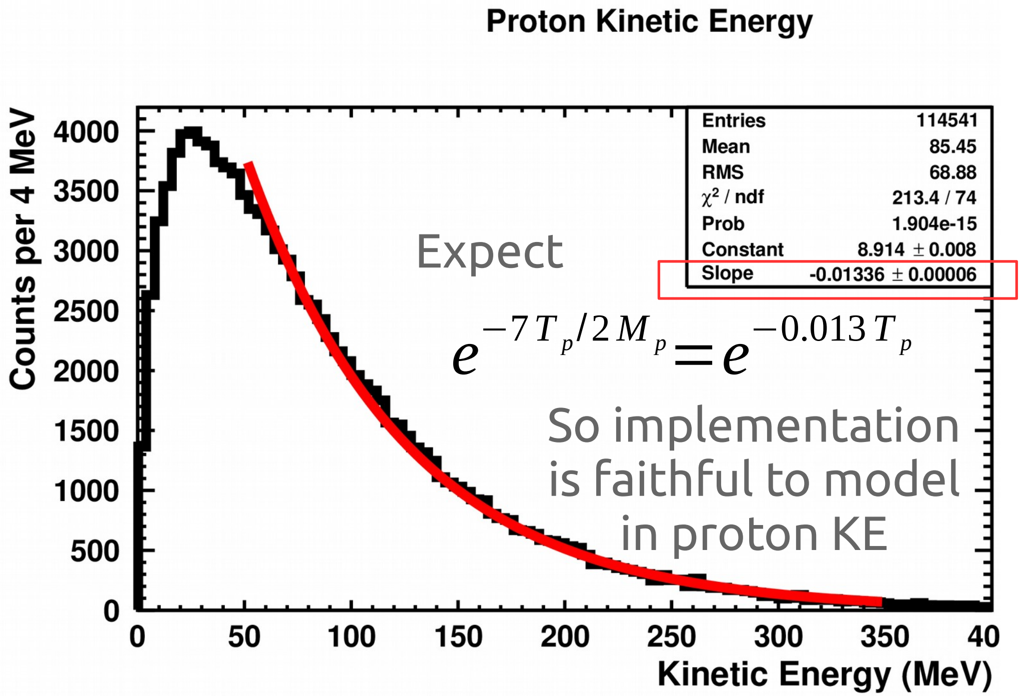


Doubling coherent to fit excess would create strong tension with NOMAD NC coherent measurement

No: not NC coherent.

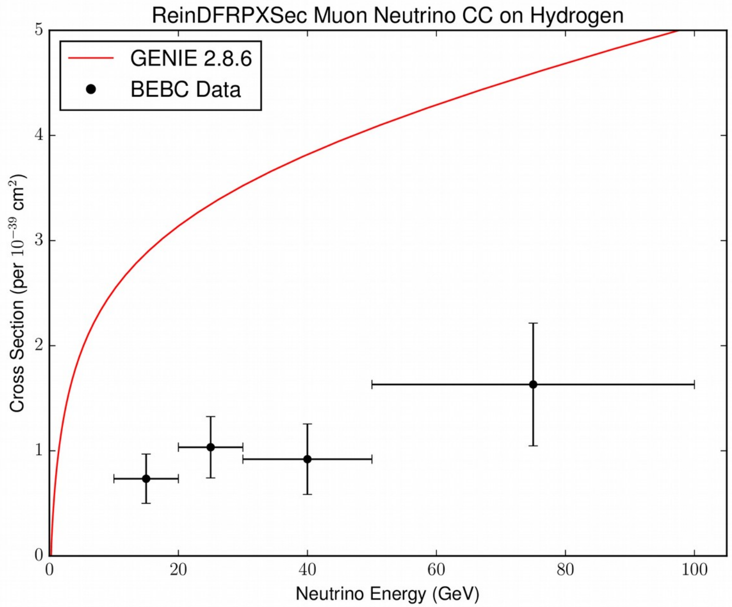
GENIE NC diffractive model

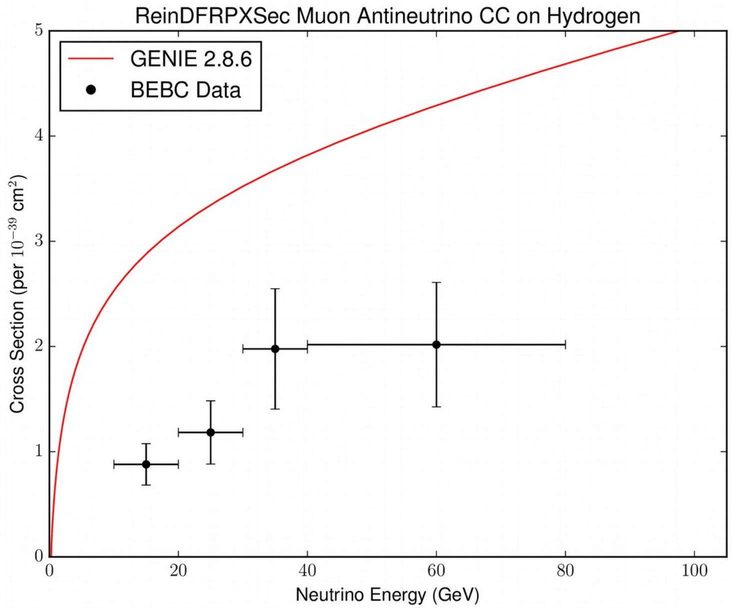
The GENIE model produces roughly the expected proton kinematics, but the charged-current version significantly over-predicts compared to what data is available (*Nucl.Phys.B* **264** 221; digitized by G. Perdue), unlike in Rein's paper



$$e^{-7T_p/2M_p} = e^{-0.013T_p}$$

So implementation is faithful to model in proton KE





Excess region scan

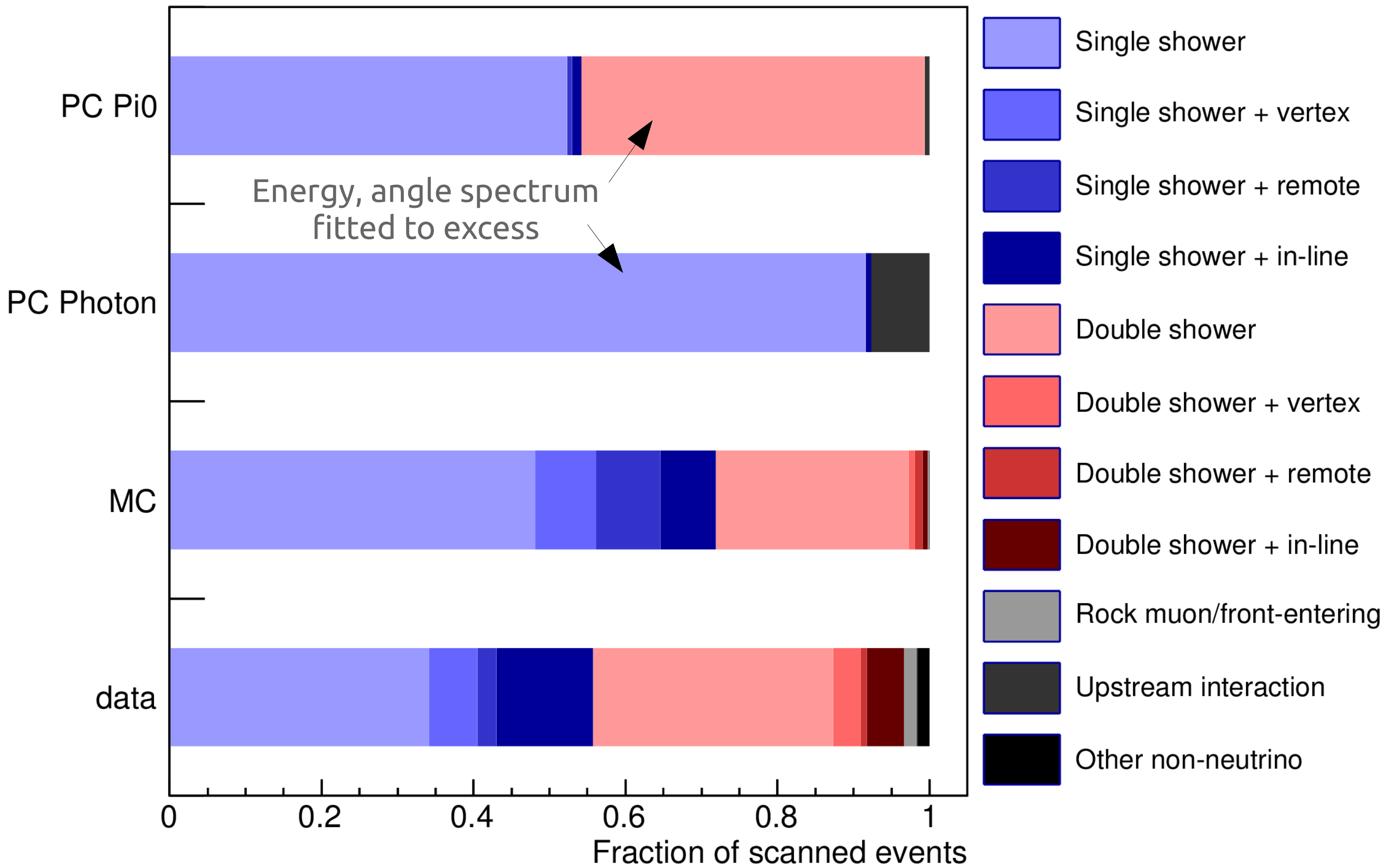
Takeaways:

- Events scanned as "double shower" are always π^0s
- π^0s frequently appear as "single showers" in the sample

Interpretation:

- Data excess region has significantly **more π^0s** than MC
- Data excess region has **more in-line activity** than MC

support our algorithmic conclusions



Category clarifications:

- "+ vertex" means activity near the shower vertex
- "+ remote" means activity away from the shower
- "+ in-line" means activity away from the shower, but upstream, in-line with the shower axis