ν-electron scattering: the MINERνA experience

S. Manly

University of Rochester

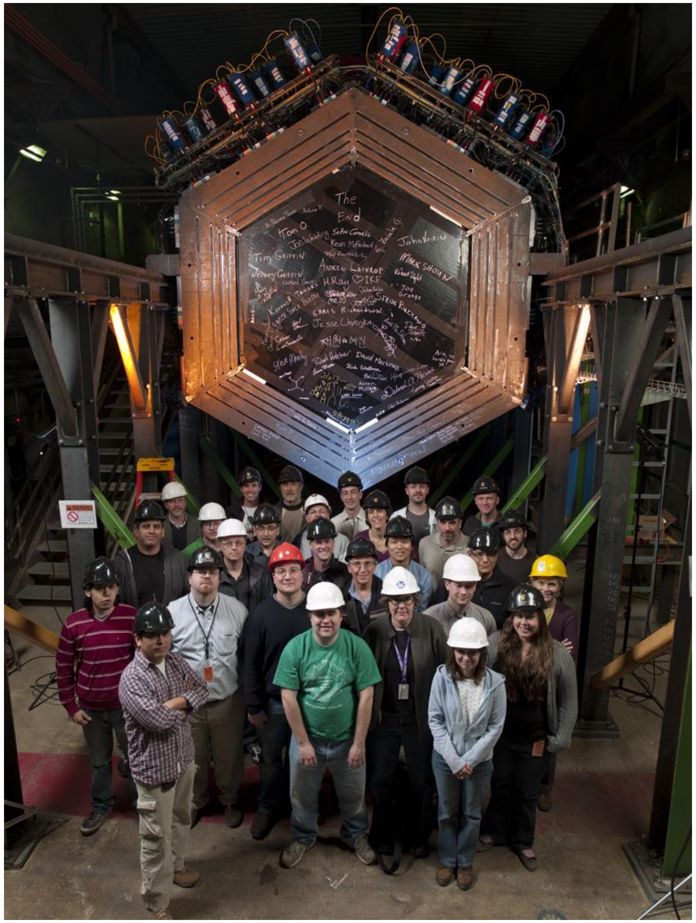
The bulk of the numbers and plots shown here come from Dr. Jaewon Park (Ph.D, University of Rochester, 2013)

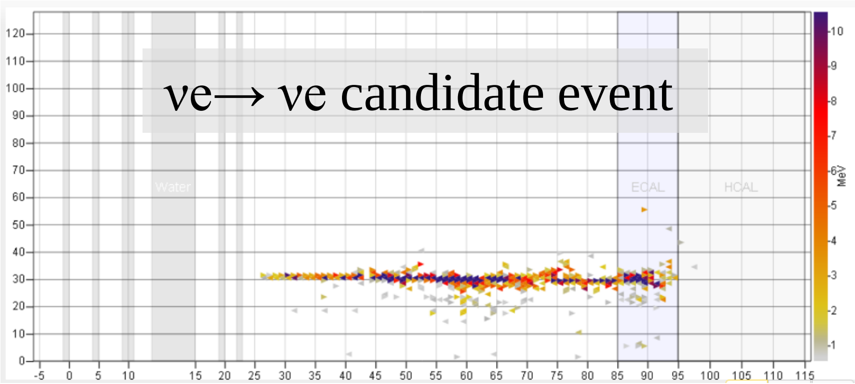
Dec. 20, 2013 FNAL Wine and Cheese and thesis (Dec. 2013)

Some important work done since then … making this a Frankenstein-ish hodge-podge of numbers, not advertised as a consistent approved set

Use with care and not for anything official

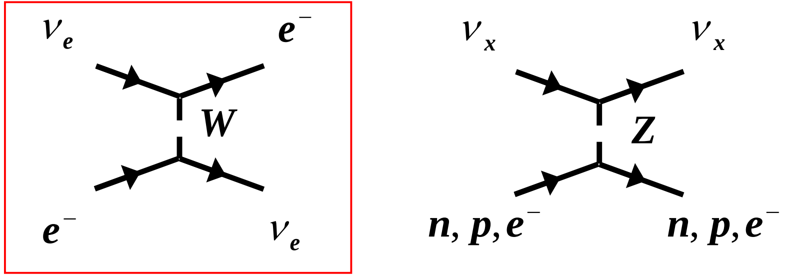
Publication coming soon




νe⟶ νe candidate event

Additional interaction for ν_e

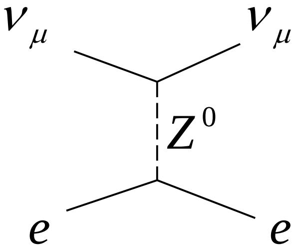
All flavor $x = e, \mu, \tau$



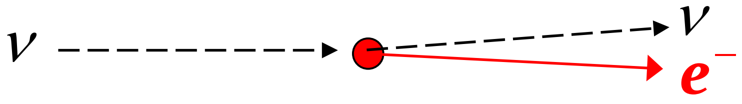
Coherent forward scatterings

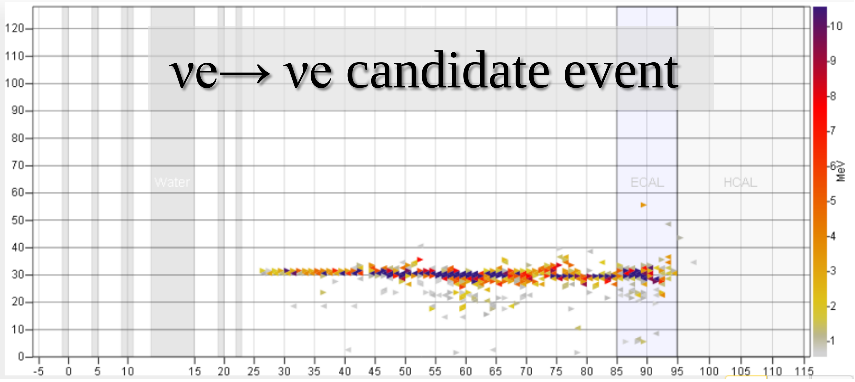
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$



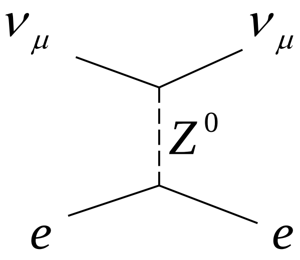
Very forward single electron final state



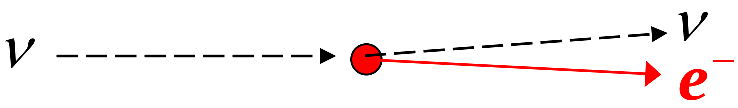


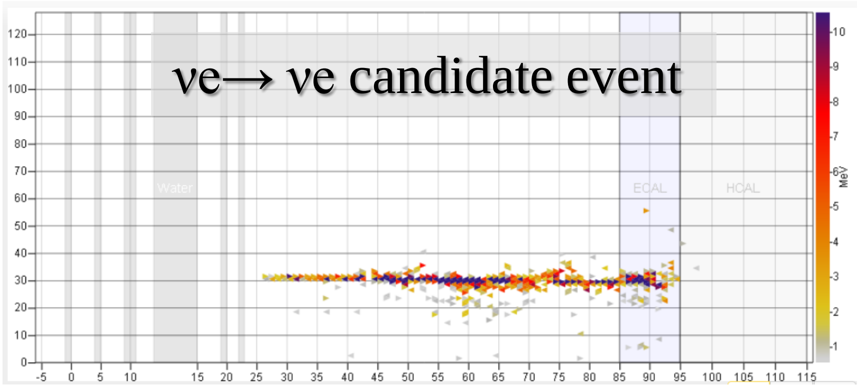
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$



Very forward single electron final state





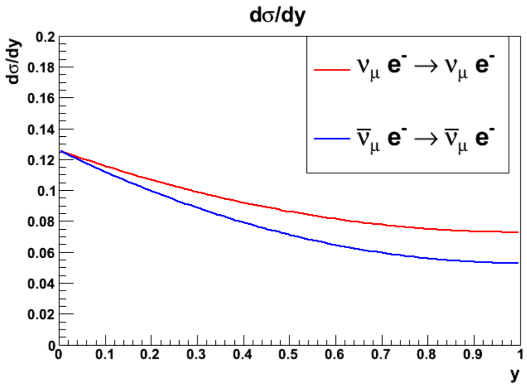
νe⟶ νe candidate event

- Standard electroweak theory. No hadronic messiness.
- Distinctive – EM, forward, no vertex activity
- Very small cross section (~1/2000 of ν-nucleon scattering)
  - Low center of mass energy due to light electron
- Good angular resolution is important to isolate the signal
- Intrinsic ν_e CC and ν_μ NC+EM (think π^0) give primary backgrounds

ν-e Scattering

$$\frac{d\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{dy} = \frac{G_F{}^2 m_e E_\nu}{2\pi}\left[\left(\frac{1}{2}-\sin^2\theta_W\right)^2 + \sin^4\theta_W(1-y)^2\right]$$

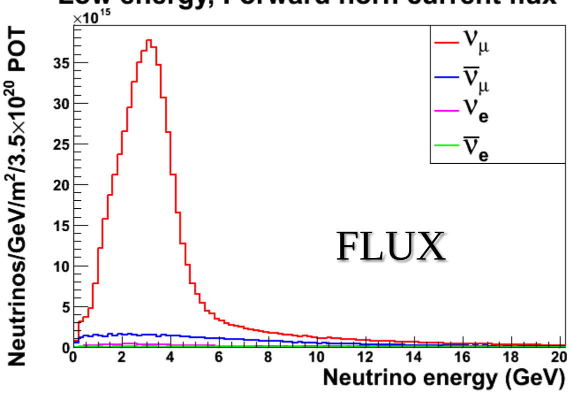
G_F and θ_W: well-known electroweak parameters

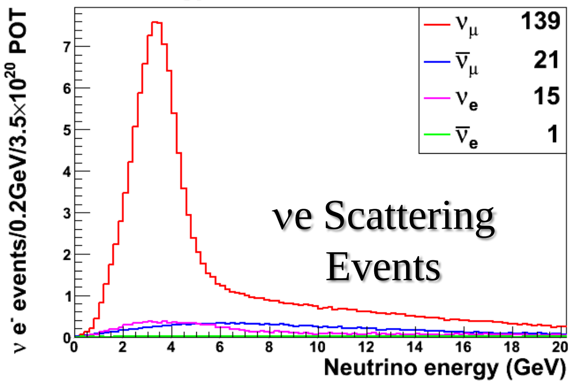


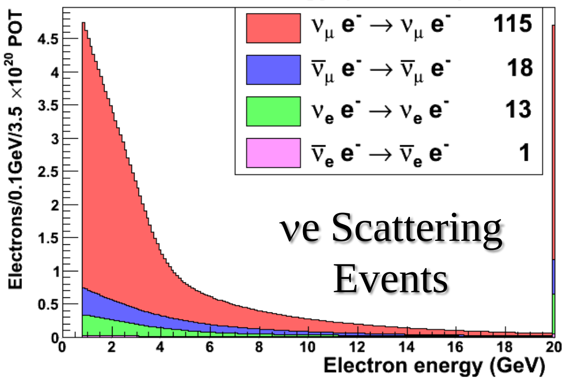
$$\sigma(\nu e) \propto E_\nu$$

$$\frac{d\sigma}{dy}$$

$$y = \frac{\text{(electron KE)}}{\text{(neutrino energy)}}$$



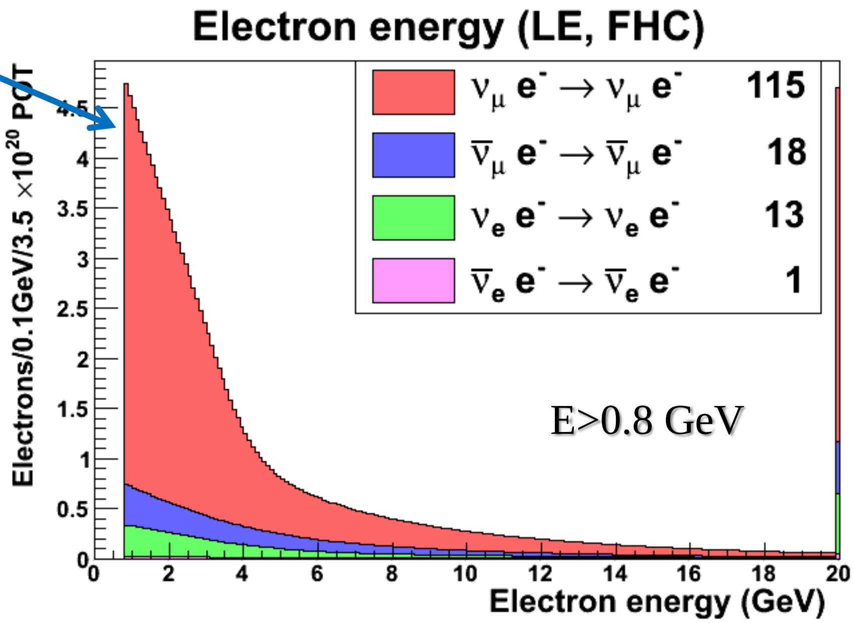




- E > 0.8 GeV
  - High background rate and tough reconstruction at low energy
- Predict 147 signal events for 3.43×10^{20} Protons On Target (POT)
  - ~100 events when you fold in (reconstruction + selection) efficiency of ~ 70%

Signal Events

E<0.8 GeV is not used
- **Large background**
- **Tough reconstruction**



- Signal is mixture of $\nu_\mu e^-, \bar{\nu}_\mu e^-, \nu_e e^-$, and $\bar{\nu}_e e^-$ in LE-FHC (neutrino beam)
- ~100 signal events for 3.43E20 POT after folding in (reconstruction + selection) efficiency of ~ 70%

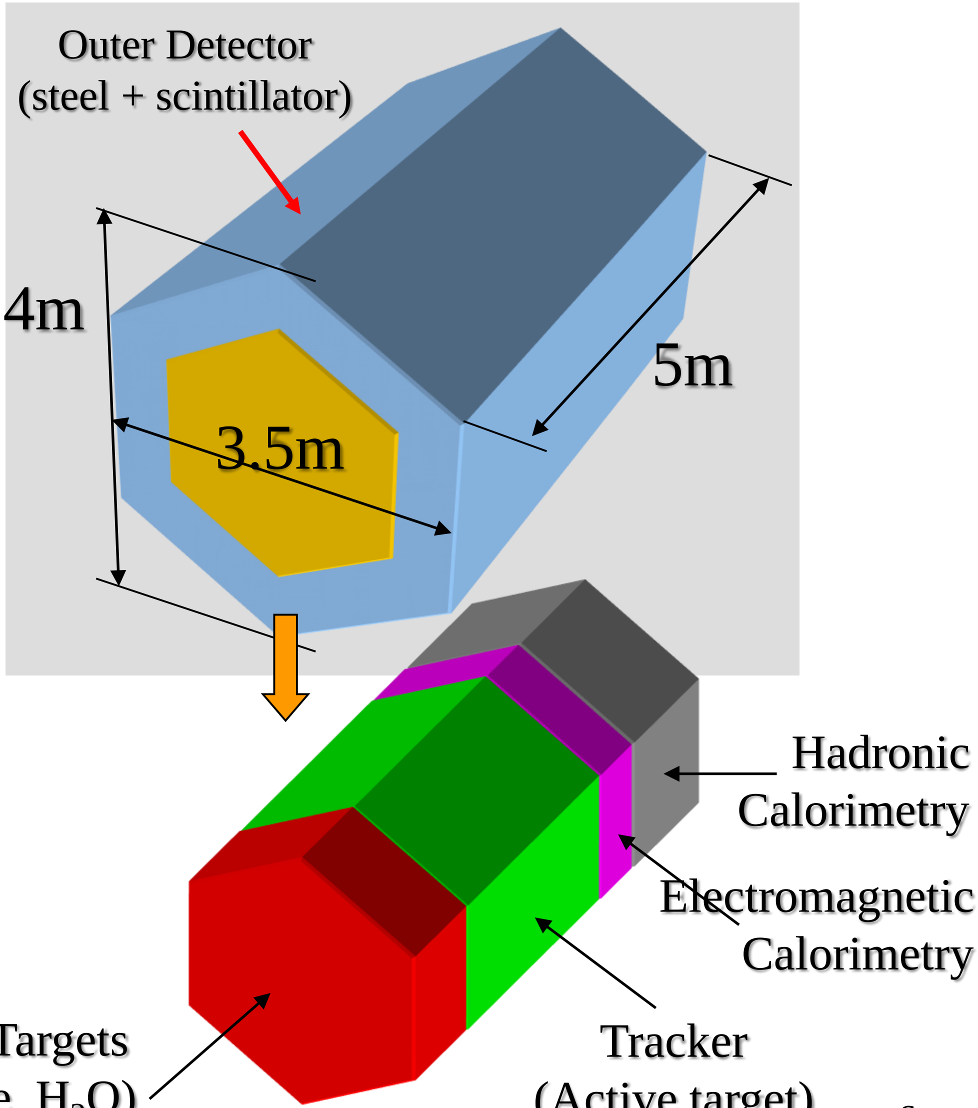
- Can't distinguish neutrino type

$$\nu_\mu e^- \text{ and } \bar{\nu}_\mu e^- : 91\%$$

$$\nu_e e^- \text{ and } \bar{\nu}_e e^- : 9\%$$

- Still useful to constrain the flux
  - Total events: Constraint for integrated flux
  - Electron spectrum: Constraint for flux shape

MINERvA Detector



Outer Detector
(steel + scintillator)

4m

3.5m

5m

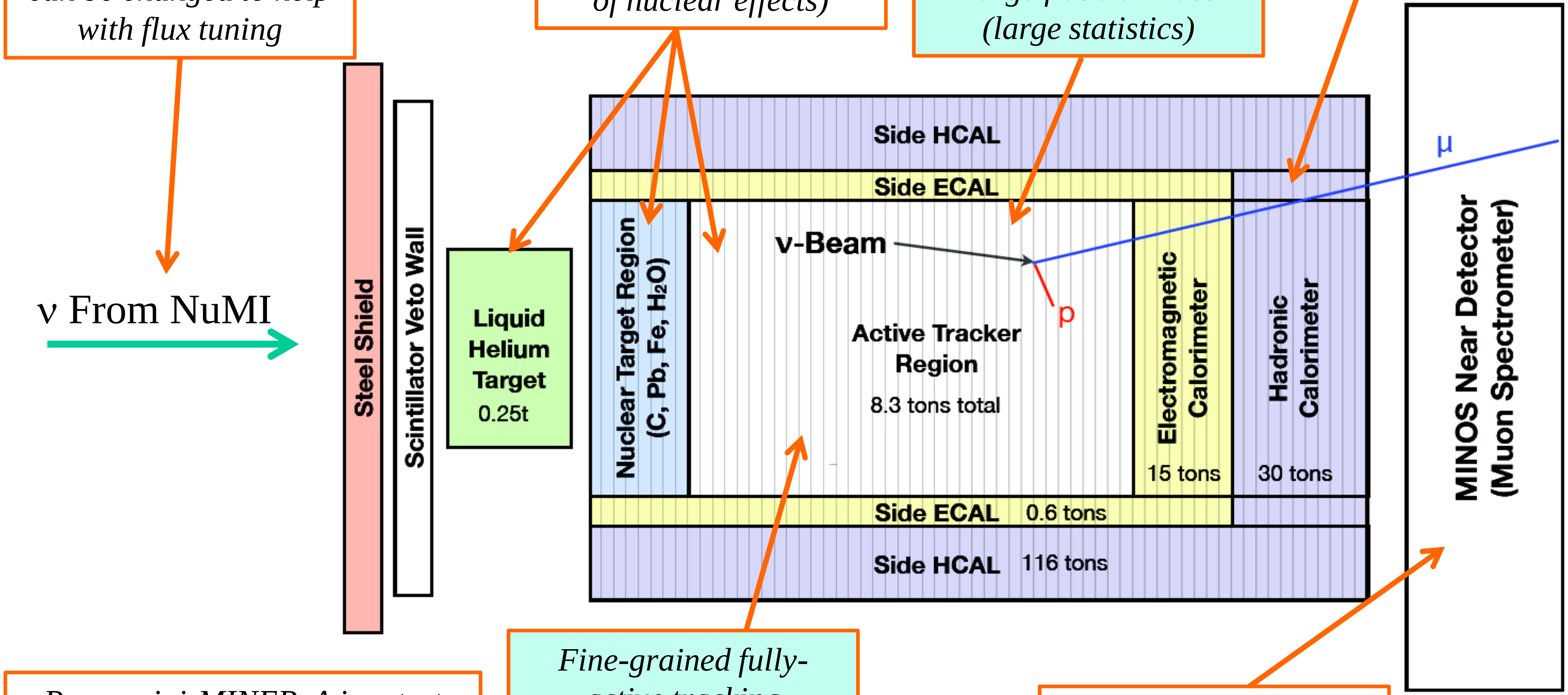
Hadronic
Calorimetry

Electromagnetic
Calorimetry

Nuclear Targets
(C, Pb, Fe, H_2O)

Tracker
(Active target)

MINERνA



Intense beam, covers interesting energy range, configuration can be changed to help with flux tuning

Nuclear targets (can explore A-dependence of nuclear effects)

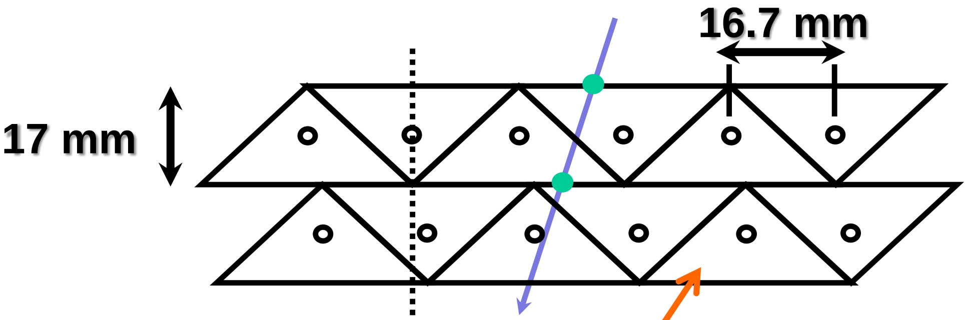
Large fiducial mass (large statistics)

Containment (particle ID and topology ID)

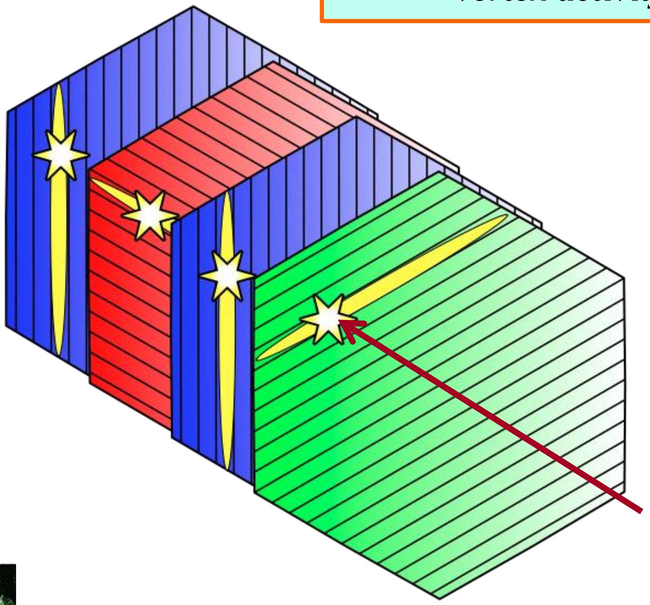
Ran a mini-MINERνA in a test beam in 2010, constrains our uncertainty in hadronic response

Fine-grained fully-active tracking (can select topologies and see vertex activity)

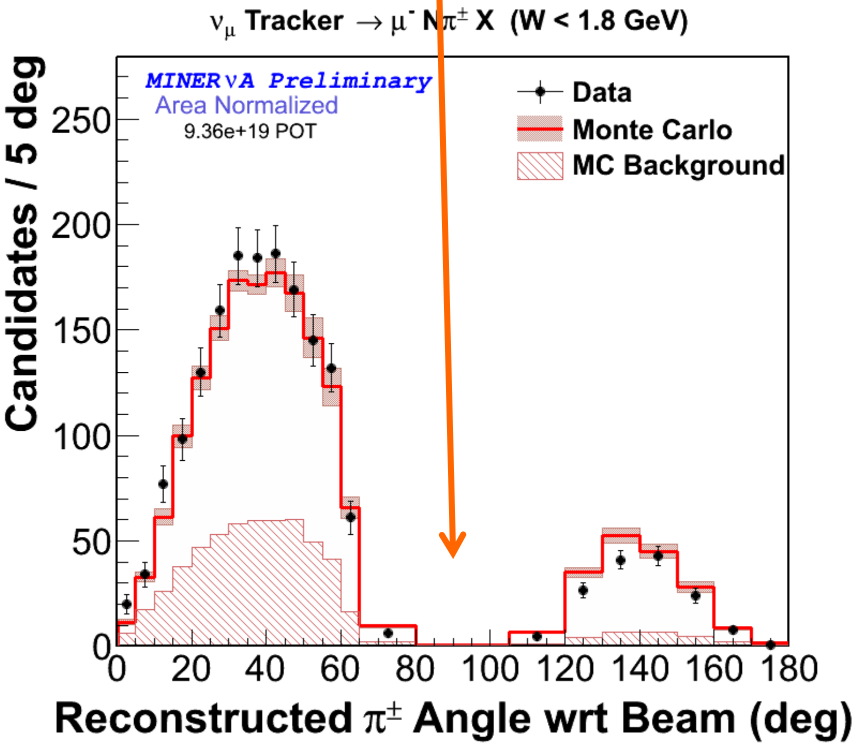
Magnetic spectrometer (momentum and sign analyze muons)



Fine-grained fully-active tracking
… but not quite a bubble chamber for looking at vertex activity

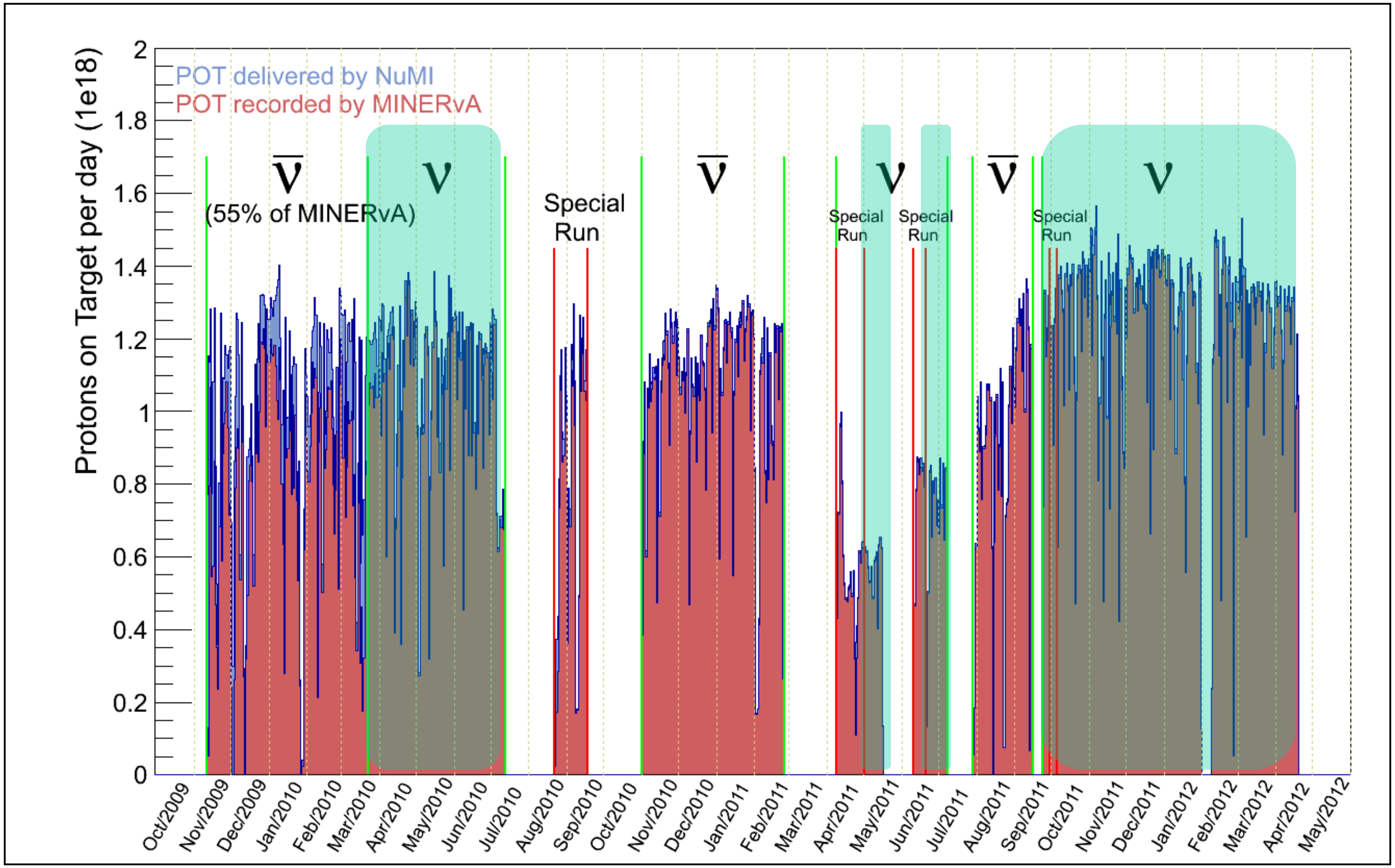


Construction of tracker gives a hole in reconstruction at 90°



ν_μ **Tracker** $\rightarrow \mu^- N\pi^\pm X$ **(W < 1.8 GeV)**

Data and Simulation Samples



MINERvA ran in three kinds of beam:

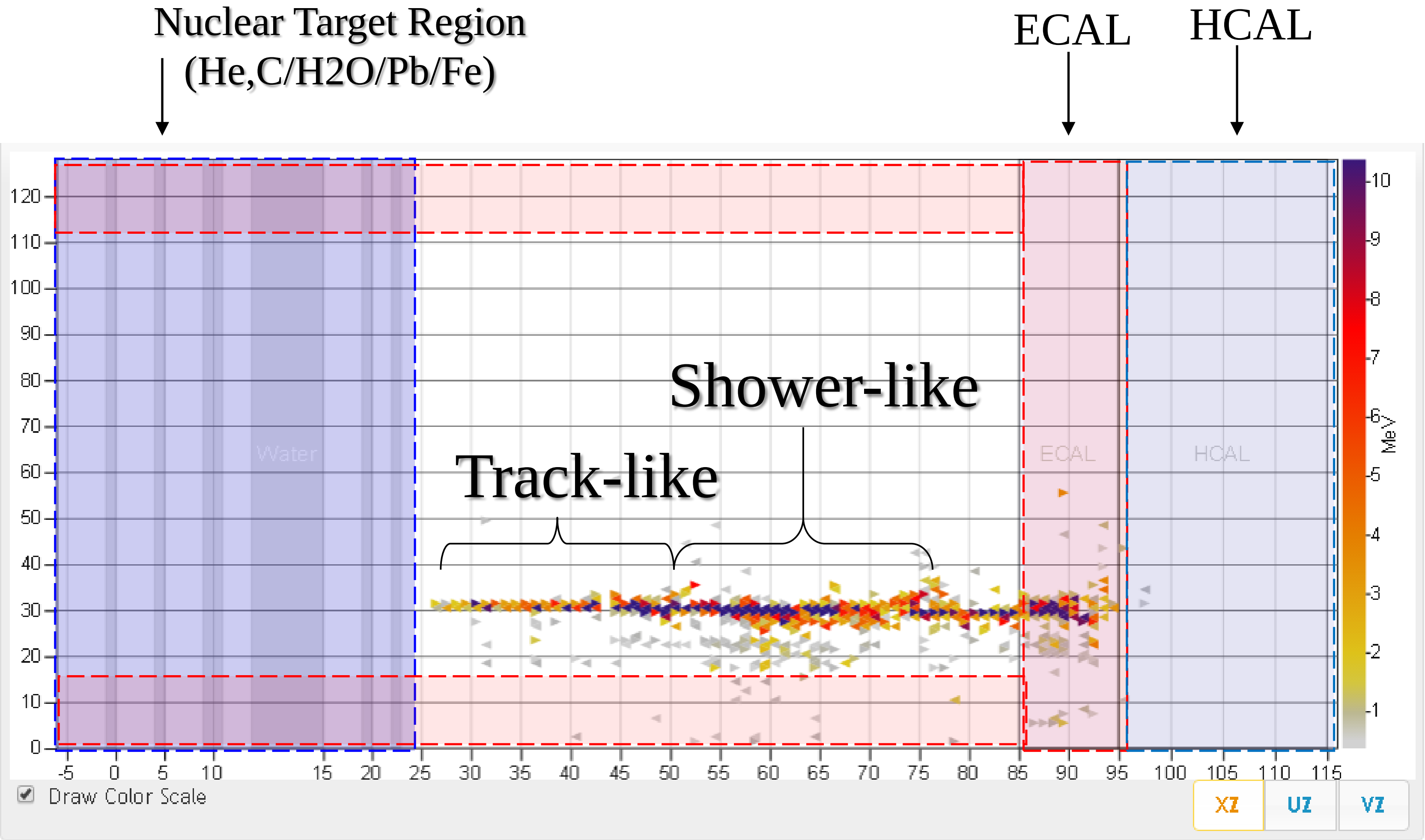
Low Energy neutrino

Low energy anti-neutrino

“Special Runs”: higher energy runs to constrain flux model

- All Low Energy neutrino data is used for the analysis: more than previous analyses shown to date (3.43×10^{20} Protons on Target)
- Time-dependent effects (calibrations, accidental activity) included in the simulation

Single Electron Reconstruction



Nuclear Target Region
(He,C/H2O/Pb/Fe)

ECAL

HCAL

Shower-like

Track-like

☑ Draw Color Scale

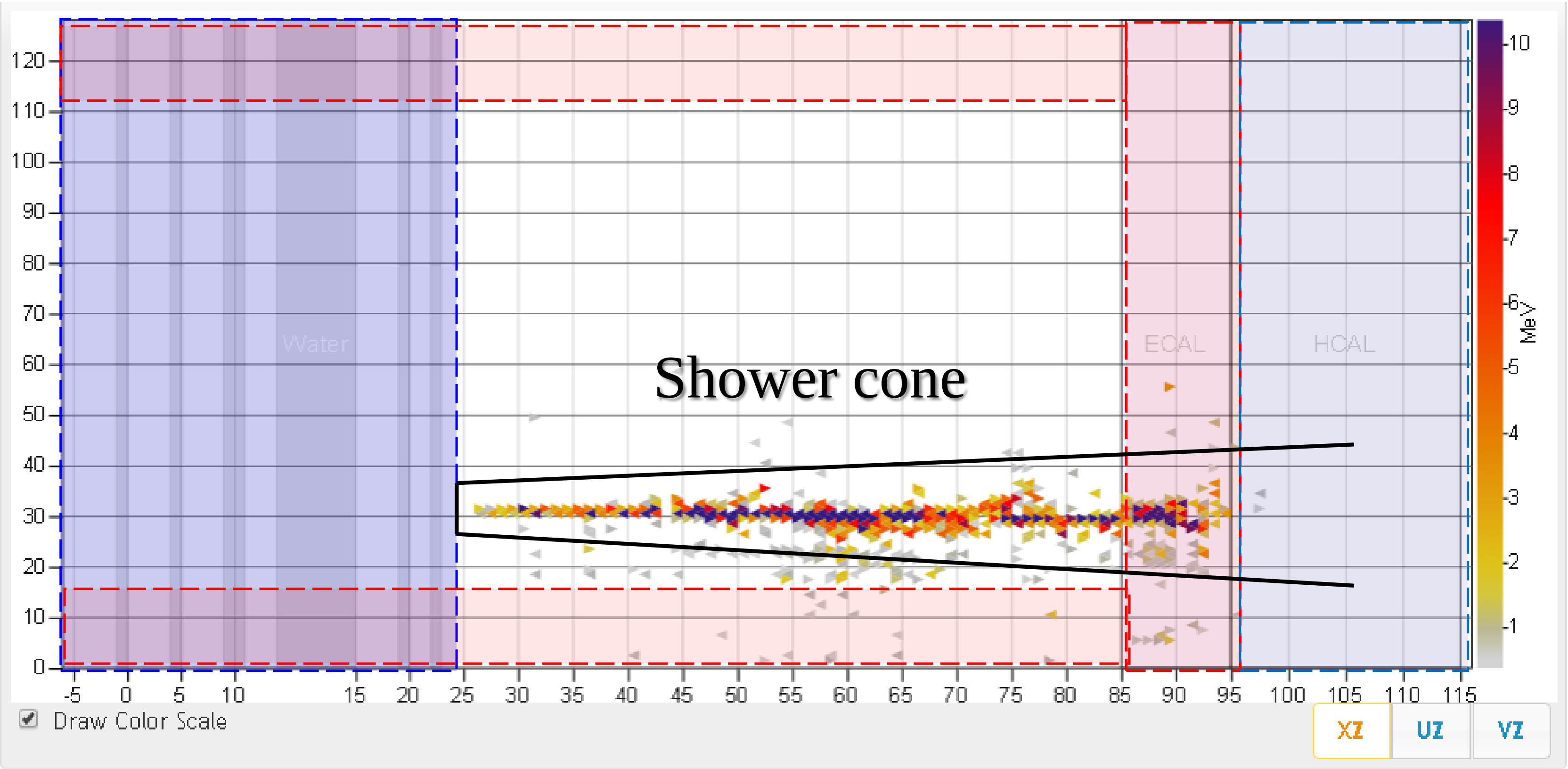
Track-like part (beginning of electron shower) gives good direction

Single Electron Reconstruction

Nuclear Target Region
(He,C/H2O/Pb/Fe)

ECAL

HCAL



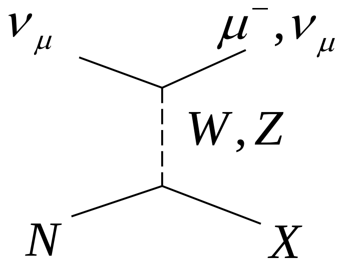
Track-like part (beginning of electron shower) gives good direction

Initial Background Rejection

- ν-e scattering is very rare, even for ν interactions:

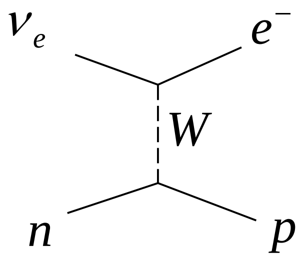
Most Events

(ν_μ Charged or neutral Current)

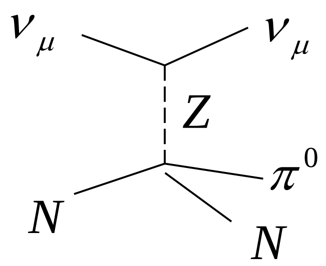


Rare but hard to reject:

ν_e Quasi-elastic (CCQE)



Coherent π^0

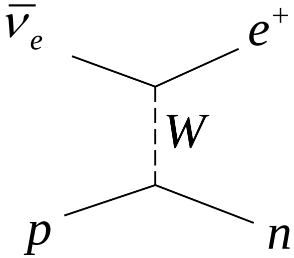


- Simple cuts can eliminate most background events while keeping high fraction of signal events
  - Obvious muon-like event rejection
  - Upstream energy rejection
    - Removes neutrino interactions upstream of detector that make μ

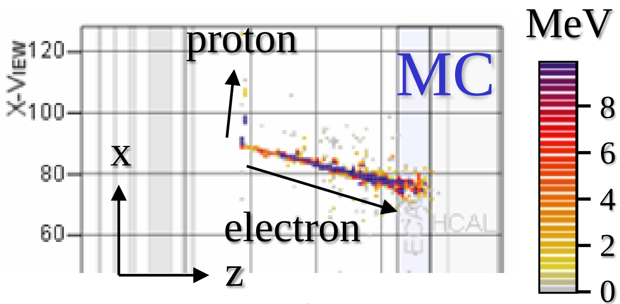
Background Events

$$\nu_e + n \rightarrow e^- + p$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Electron neutrino fraction in flux is small ~ 1%.



- If recoil nucleon is not observed, it looks similar to signal
- Angles of electron have wide spread while signal is very forward

Use Eθ² to select very forward signal

Neutral current single π⁰

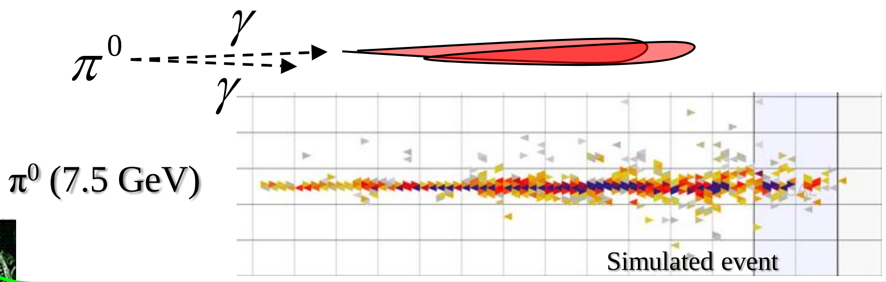
$\nu_\mu A \rightarrow \nu_\mu A \pi^0$ NC-coherent π⁰

$\nu_\mu N \rightarrow \nu_\mu N \pi^0$ NC-resonant π⁰

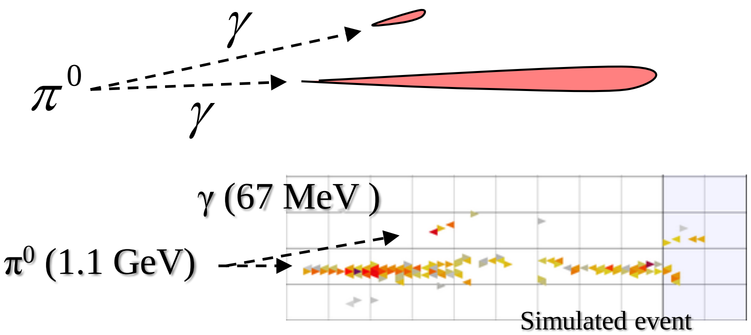
Also, photon has wide spread of angle

In addition, use dE/dx to reject

1. Small opening angle between two gammas



2. One of gammas is not observed in the detector



Kinematic Limit on Eθ^2

Mandelstam variables **Inelasticity**

$AB \rightarrow CD$

$$s = (p_A + p_B)^2$$
$$t = (p_A + p_C)^2$$
$$u = (p_A + p_D)^2$$
$$s + t + u = m_A^2 + m_B^2 + m_C^2 + m_D^2$$

$$y = \frac{p_B \cdot q}{p_B \cdot p_A}$$

$\nu e \rightarrow \nu e$

$t = \frac{s}{2}\left(1 - \cos\theta^*\right)$ $y = -\frac{1}{2}\left(1 - \cos\theta^*\right)$ in CM frame ⇨ $t = -sy$

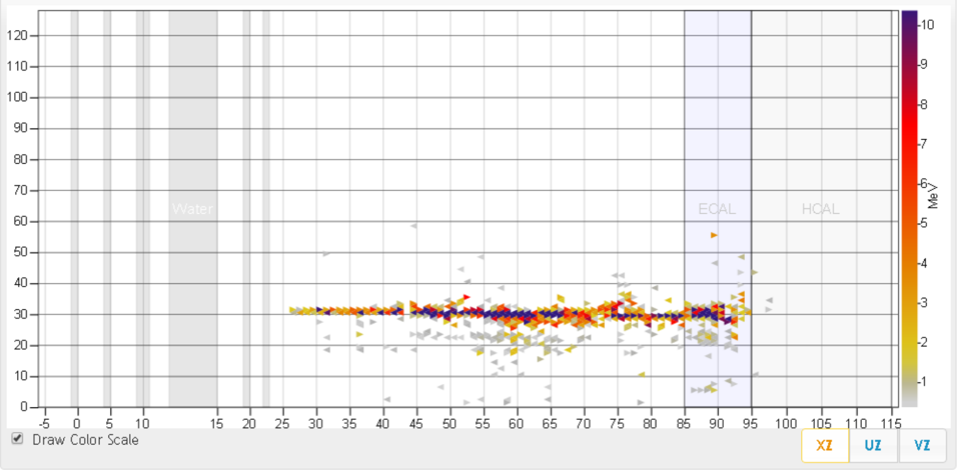
$u = -2E_\nu E_e (1 - \cos\theta)$ in lab frame

$$\boxed{\begin{aligned} & s + t = -u \\ & s(1 - y) = 2E_\nu E_e (1 - \cos\theta) \\ & 2m_e (1 - y) = E_e \theta^2 \end{aligned}}$$

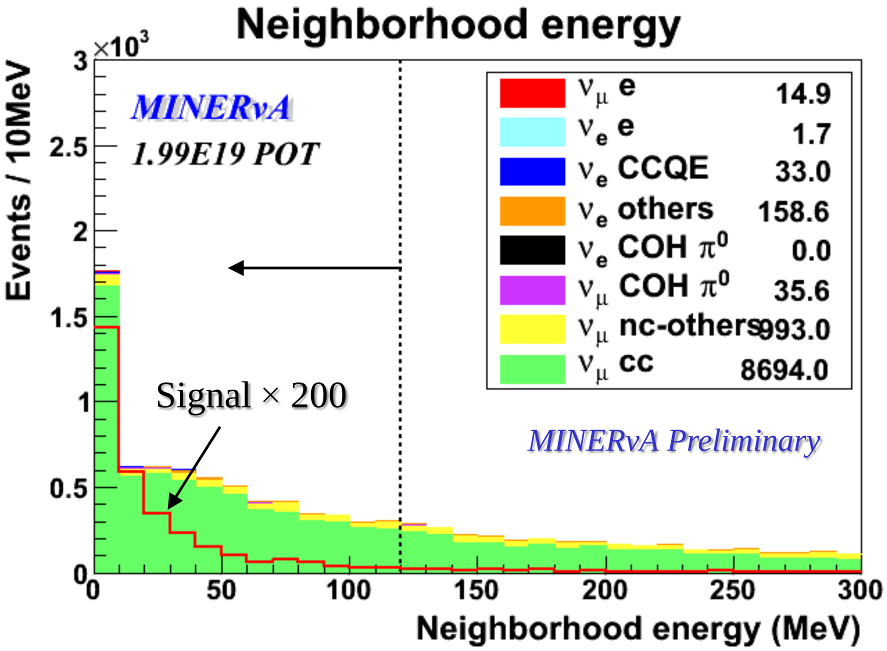
Since $0 < y < 1$, $E_e \theta^2 < 2m_e$

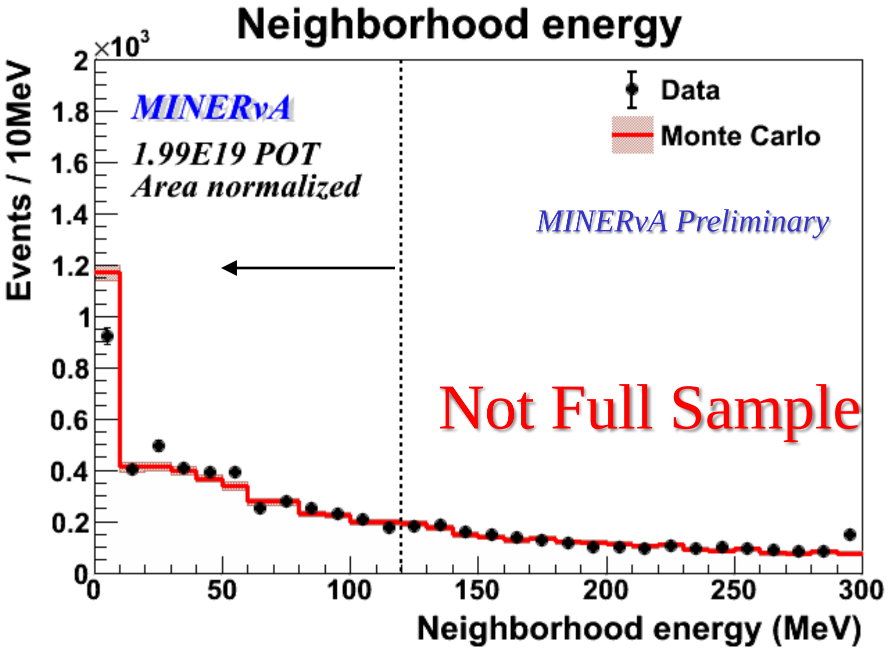
Critical for Signal

- Electron Identification
  - Must discriminate from photons
- Electron Energy Measurement
- Electron Angular Measurement



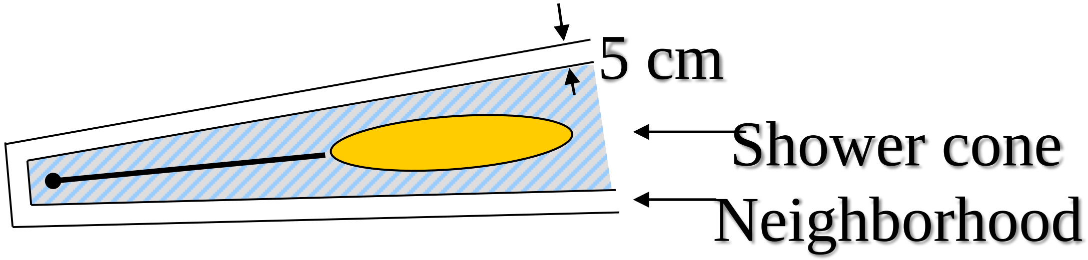
Example: Neighborhood Energy





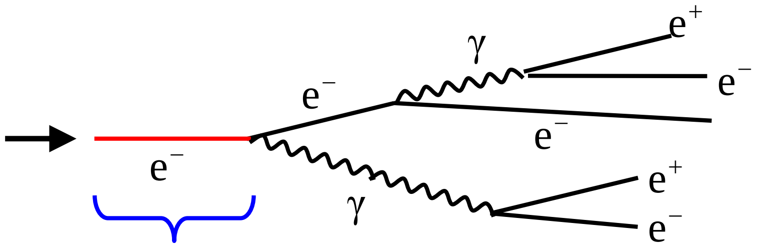
Not Full Sample

- Neighborhood energy = energy around shower cone
- Small neighborhood energy means isolated shower

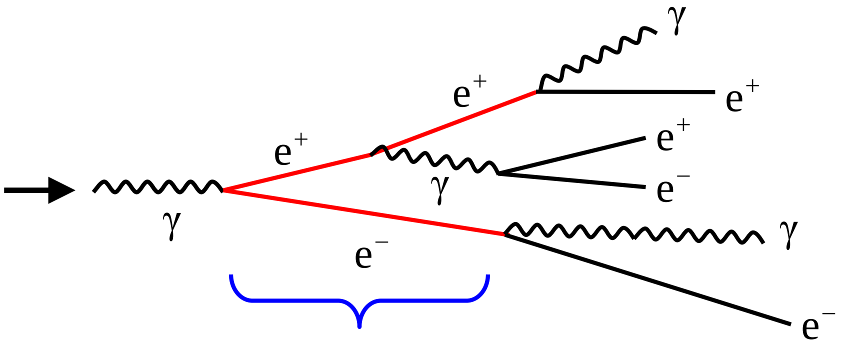


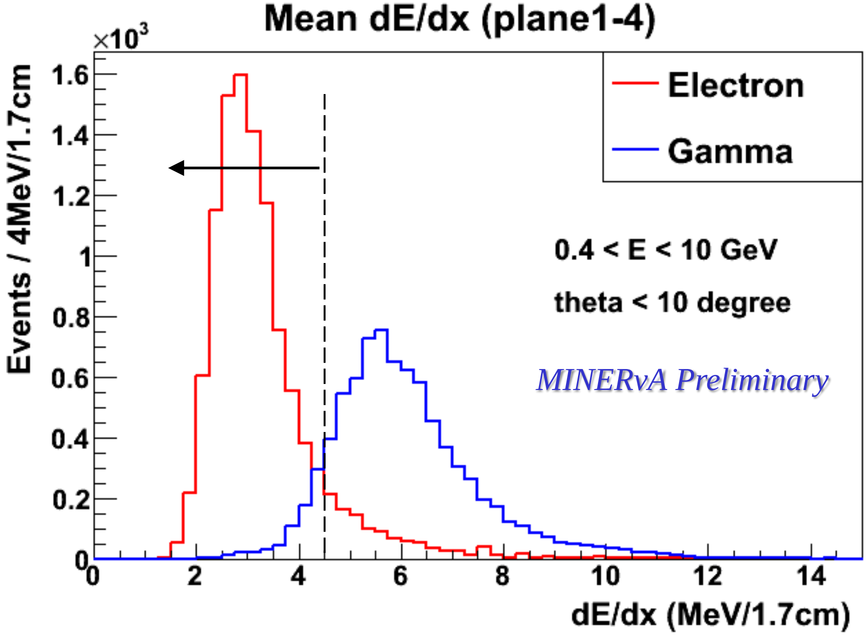
Electron Photon Discrimination using dE/dx

Electron-induced electromagnetic shower



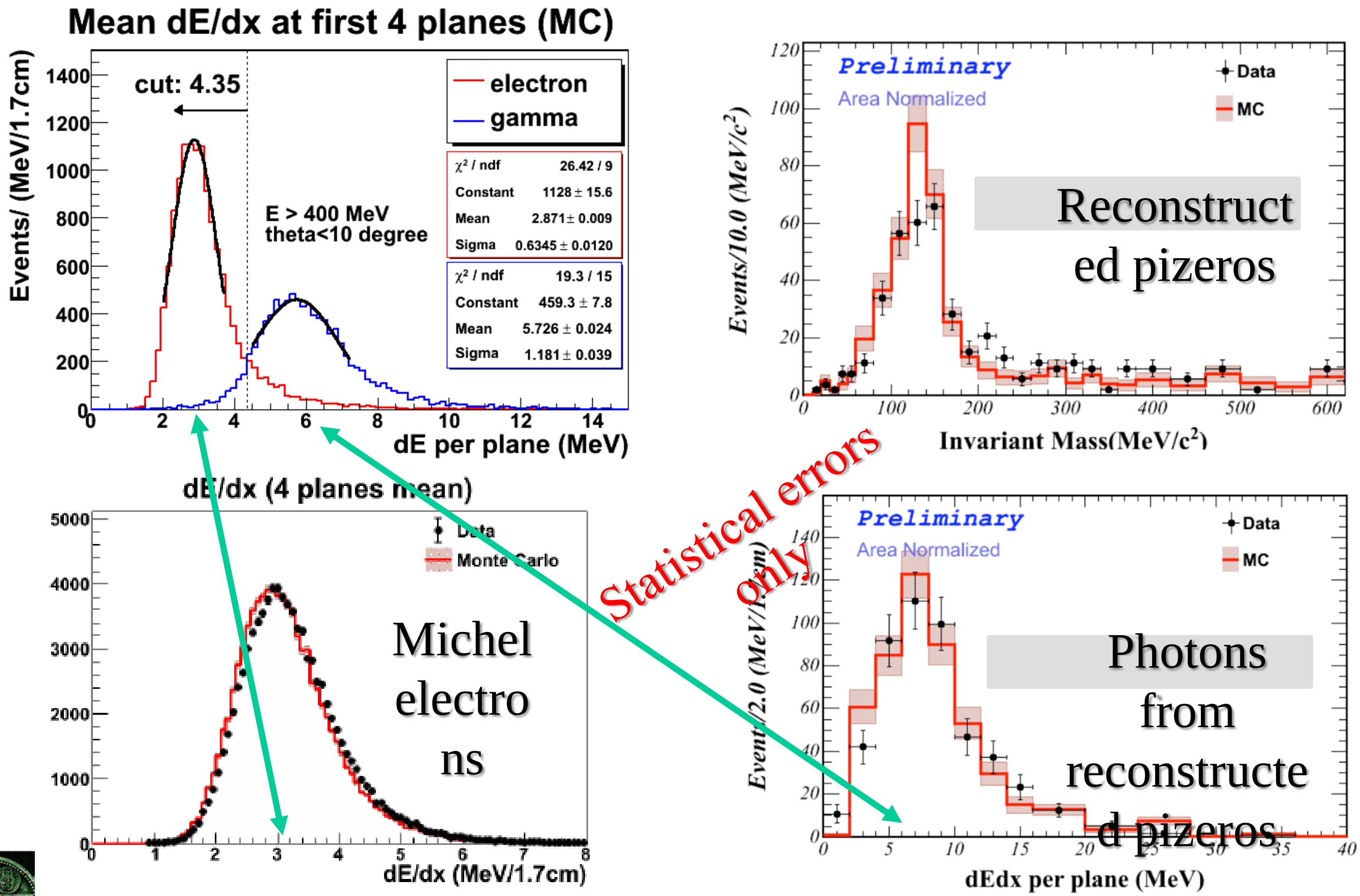
Photon -induced electromagnetic shower





- Electromagnetic shower process is stochastic
  - Electron and photon showers look very similar
- Photon shower has twice energy loss per length (dE/dx) at the beginning of shower than electron shower
  - Photon shower starts with electron and positron

Validation of e/γ separation



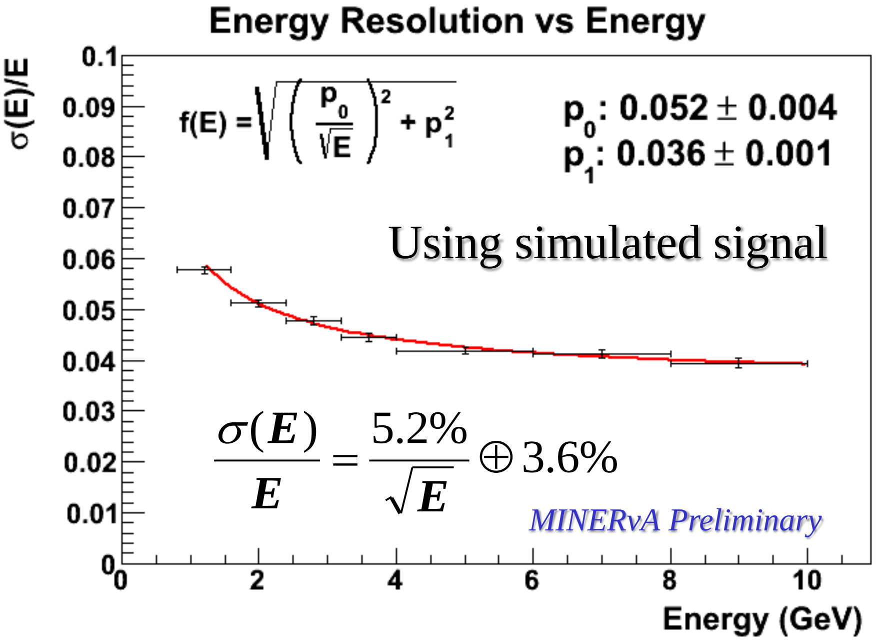
Reconstructed pizeros

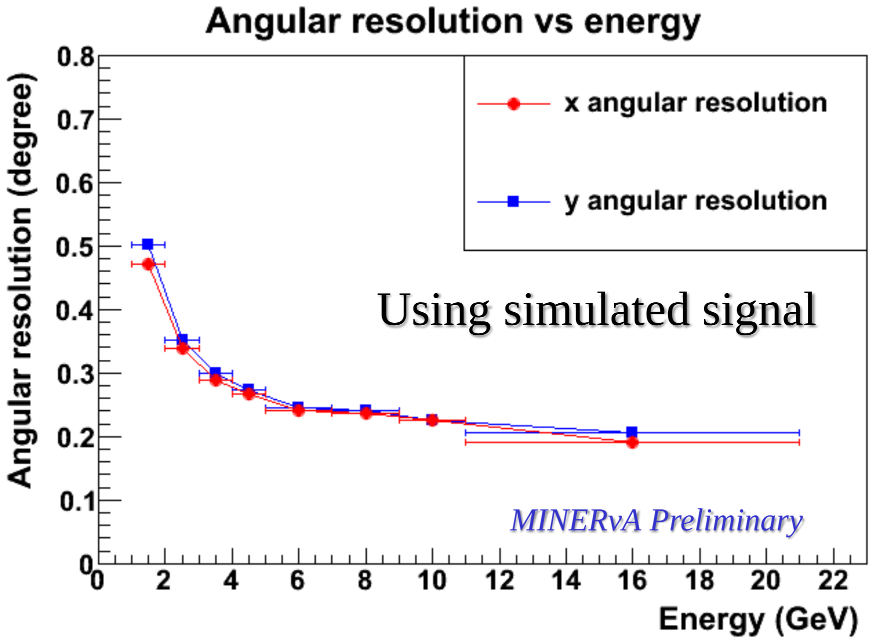
Michel electrons

Statistical errors only

Photons from reconstructed pizeros

Energy and Angle Reconstruction





- Energy resolution ~ 5%
- Projected angle resolution ~ 0.3 degree (2 sigma truncated RMS)
- Precise angle reconstruction is critical to separate *ν e* elastic scattering from background
  - Lower energy angular resolution is worse due to multiple scattering

Event Selection

Shower cone Reconstruction

→

- Electron Energy>0.8GeV
- Fiducial cut

→

Other reconstruction quality cuts

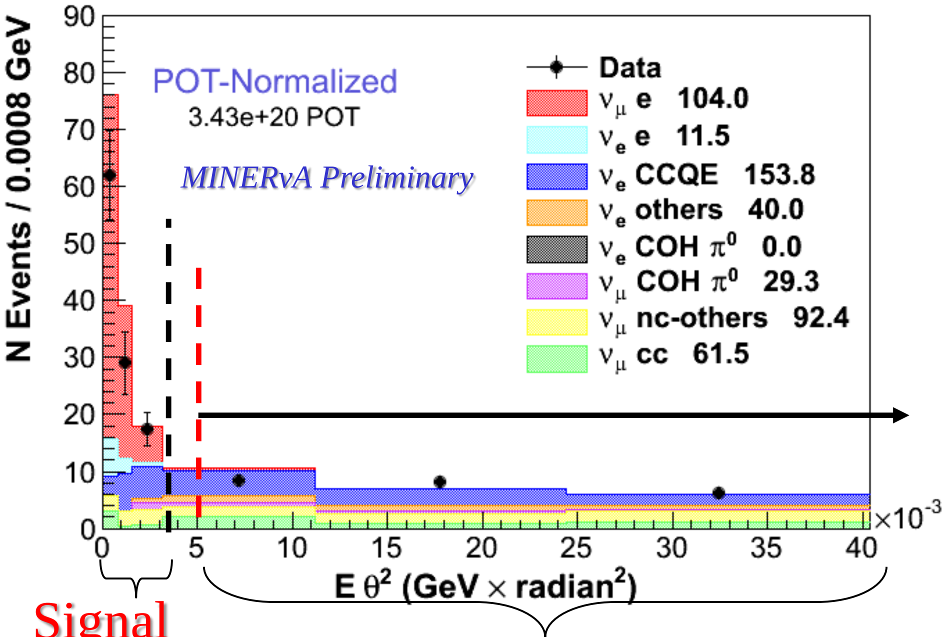
→

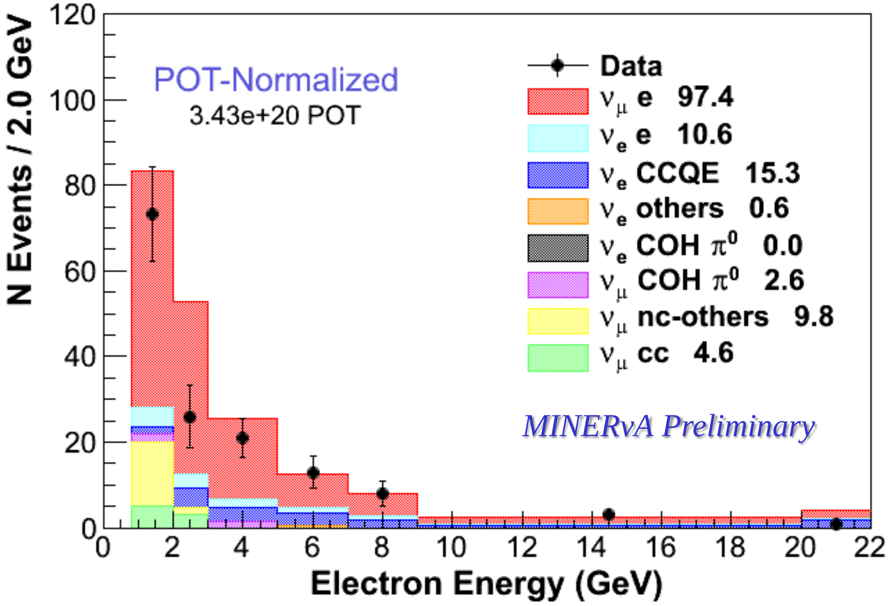
- $E\theta^2$
- dE/dx

→

Signal sample

Backgrounds after all Cuts





Signal

$E\theta^2 < 0.0032$

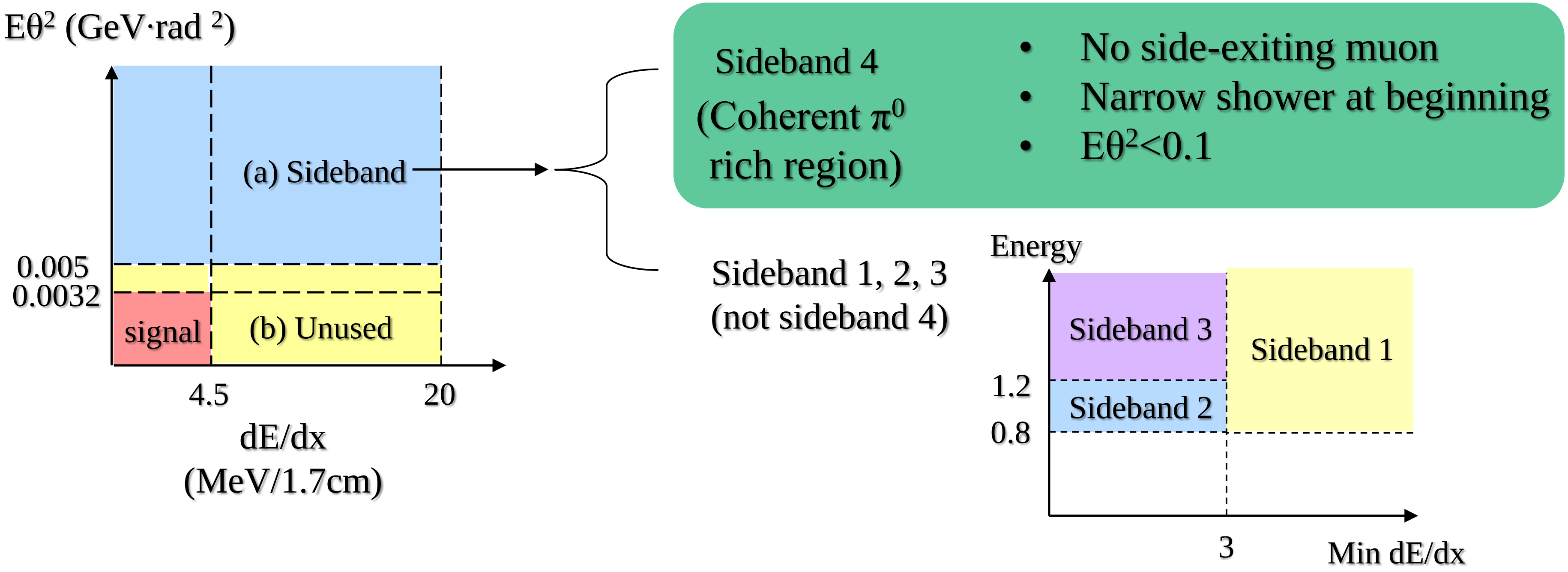
Sideband

$E\theta^2 > 0.005\,\mathrm{GeV}\cdot\mathrm{rad}^2$

Need to know energy spectrum of background

- Background prediction is affected by the flux and physics model
- Cross-section of various neutrino reactions are uncertain
- Use data-driven background tuning

4 Background Processes,
4 Sidebands (will be slightly simplified for final publication)



Sideband 4 (Coherent π^0 rich region)

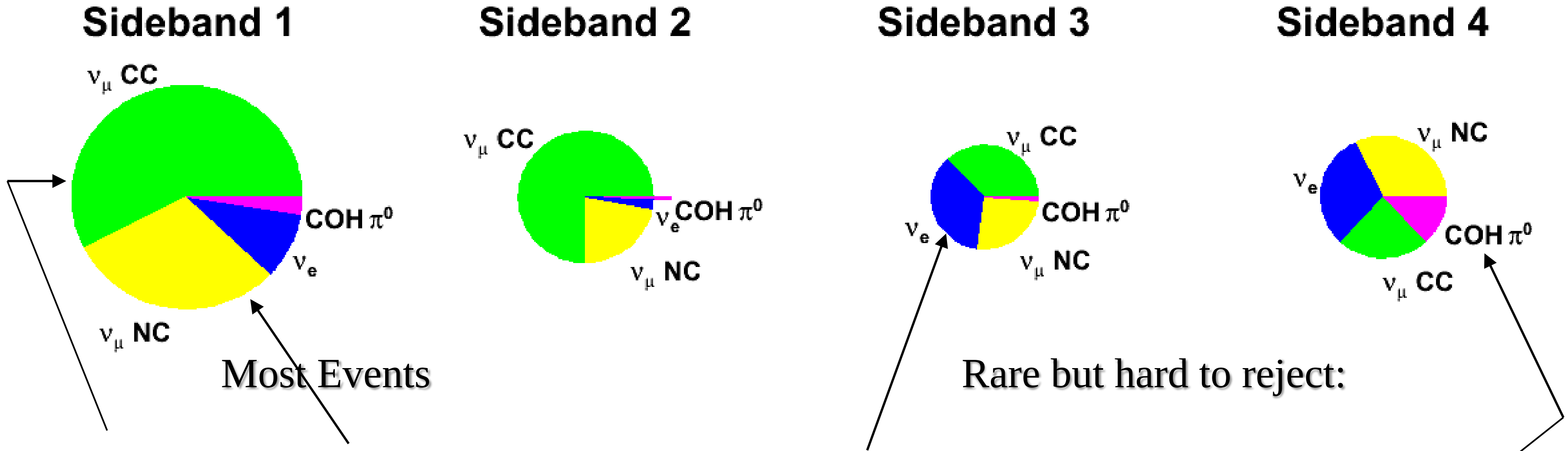
- No side-exiting muon
- Narrow shower at beginning
- $E\theta^2<0.1$

Sideband 1, 2, 3 (not sideband 4)

- Sideband = Outside of major $E\theta^2$ and dE/dx cuts
- (b) region is not used because there are not many events for tuning
- Further, cut is slightly loosened on sideband so it gets some ν_μ CC for tuning purpose

Sideband Populations

Parameter	Tuned value
ν_e	0.89 ± 0.03
COH π^0	0.92 ± 0.03
ν_μ NC	0.97 ± 0.01
ν_μ CC	0.79 ± 0.06



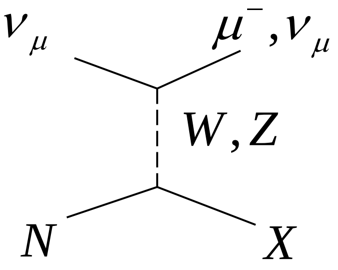
Most Events

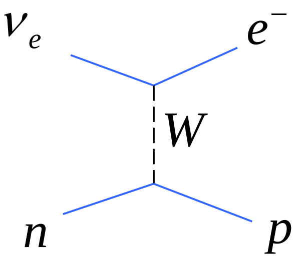
Rare but hard to reject:

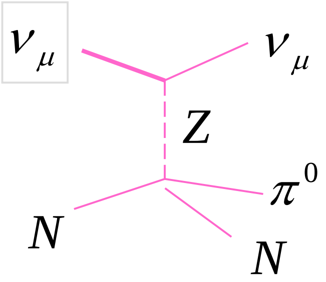
(ν_μ Charged or Neutral Current

ν_e Charged Current

Coherent π^0

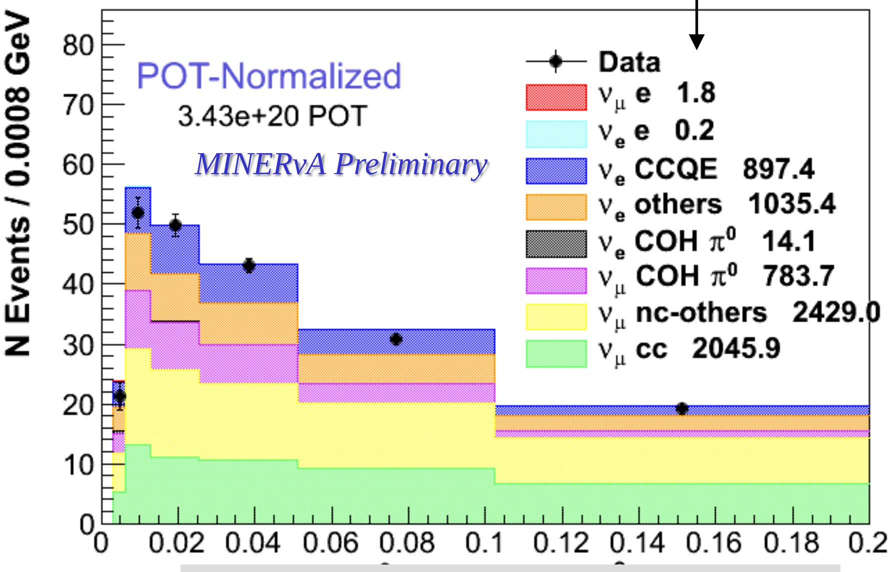




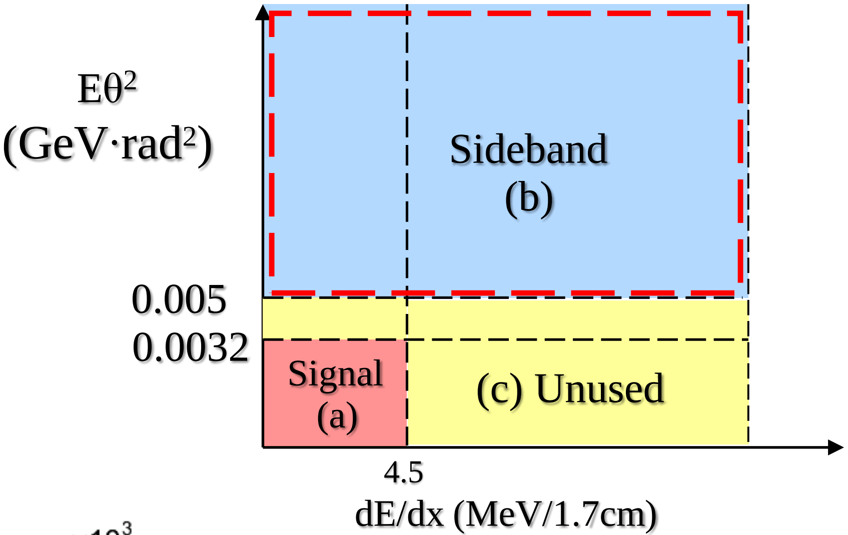


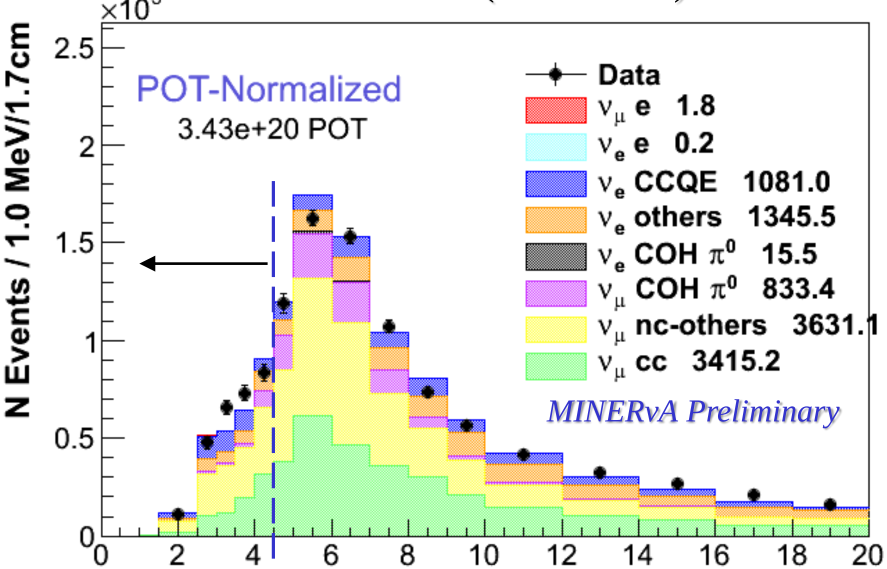
dE/dx and Eθ^2 in Sidebands after tuning

Events (Eθ^2 < 0.2)



Eθ^2 (GeV·radians ^{2})



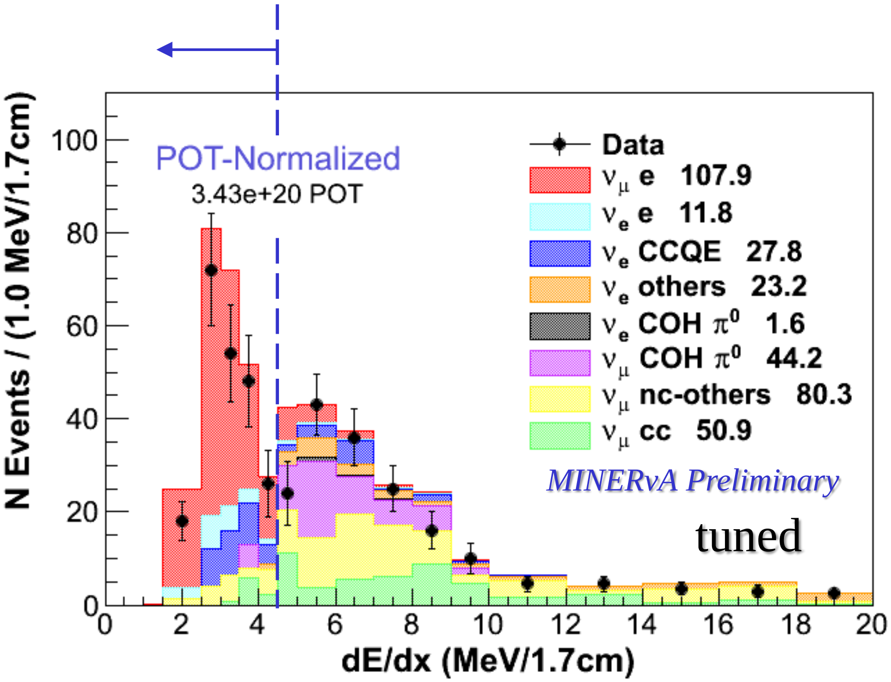


dE/dx (MeV/1.7cm)

- Both dE/dx and Eθ^2 are well simulated in the sideband region after fitting

dE/dx Cut

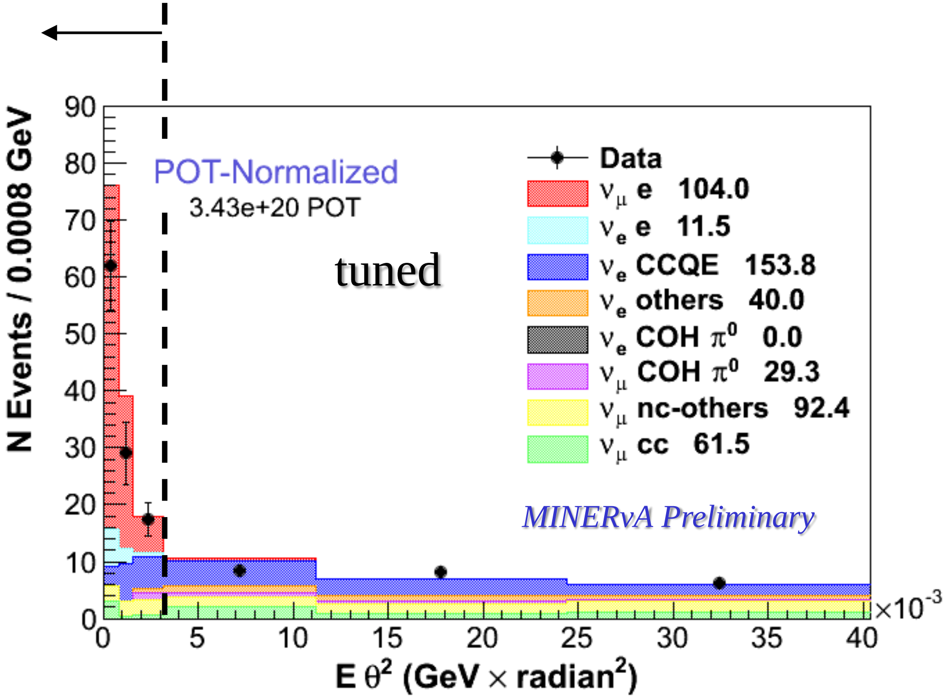
dE/dx<4.5MeV/1.7cm



tuned

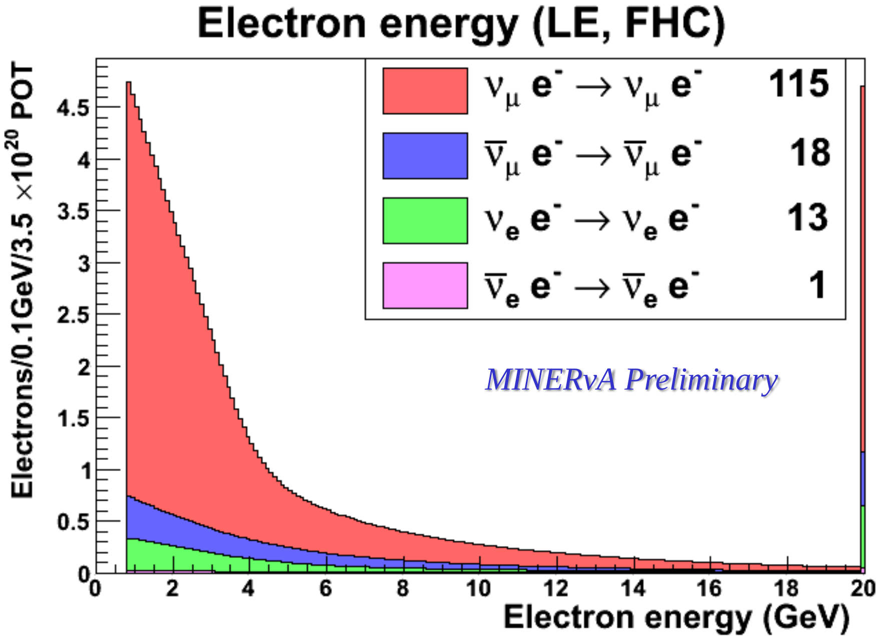
Eθ^2 Cut

$E\theta^2 < 0.0032\,\text{GeV}\cdot\text{rad}^2$

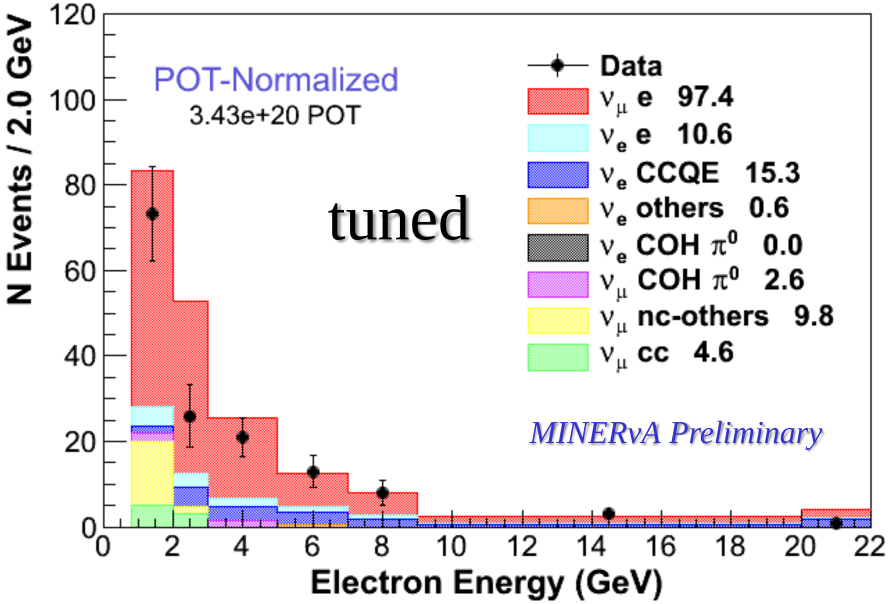


tuned

Electron Spectrum after all cuts



True electron energy
(signal only)



tuned

Reconstructed electron energy

Systematic Uncertainties

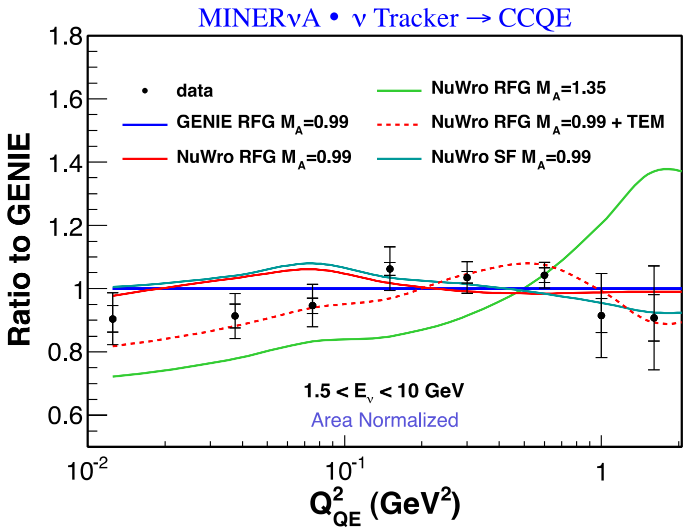
$$\Phi = \frac{N - B}{\varepsilon A \sigma}$$

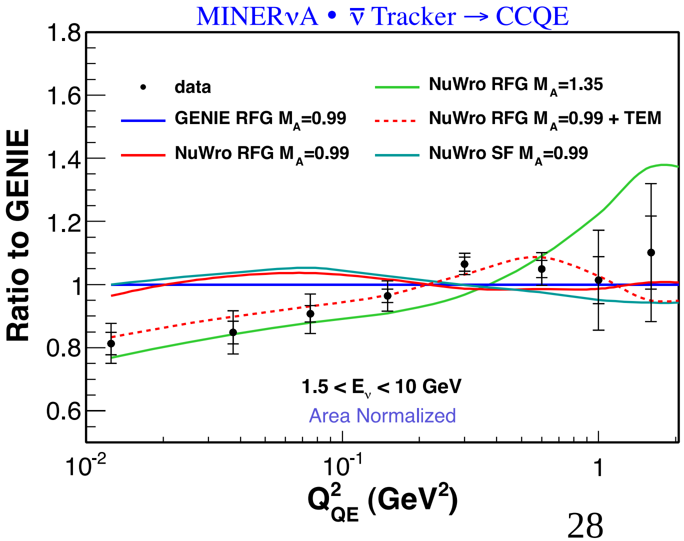
N: events in data
B: Background
ε: Efficiency
A: Acceptance
σ: signal cross section

- Error in background contribution
  - Flux uncertainties
  - Cross Section Uncertainties
- Error in efficiency and Acceptance

Uncertainty in ν_e CCQE extrapolation from sideband

- Previous MINERvA results on ν_μ Quasi-elastic process shows that momentum transfer squared (Q^2_{QE}) distribution is not what GENIE predicts *Phys. Rev. Lett. 111, 022502 (2013), Phys. Rev. Lett. 111, 022501 (2013).*
- Q^2_{QE} and $E\theta^2$ are highly correlated
- Compare ν_e background prediction $E\theta^2$ extrapolation with two different models: one is GENIE, the other is one inspired by MINERvA ν_μ data: systematic uncertainty: 3.3%





Flux and Cross Section Systematic Uncertainties on MC Background From JP W&C

Final numbers going to be something more like these:

Uncertainty Sources	MC background uncertainty [event		
	Before tuning	After tuning	
MC background events	38.9	32.9	29
MC bkg statistical	6.2	5.3	2.2
Total systematic	10.3	5.7	3.3
Flux_BeamFocus	1.1	0.2	0.9
Flux_NA49	1.8	0.3	0.14
Flux_Tertiary	7.0	1.1	0.15
GENIE	6.3	4.5	2
CCQE Shape	3.7	3.3	2.6
Total	12.1	7.8	4

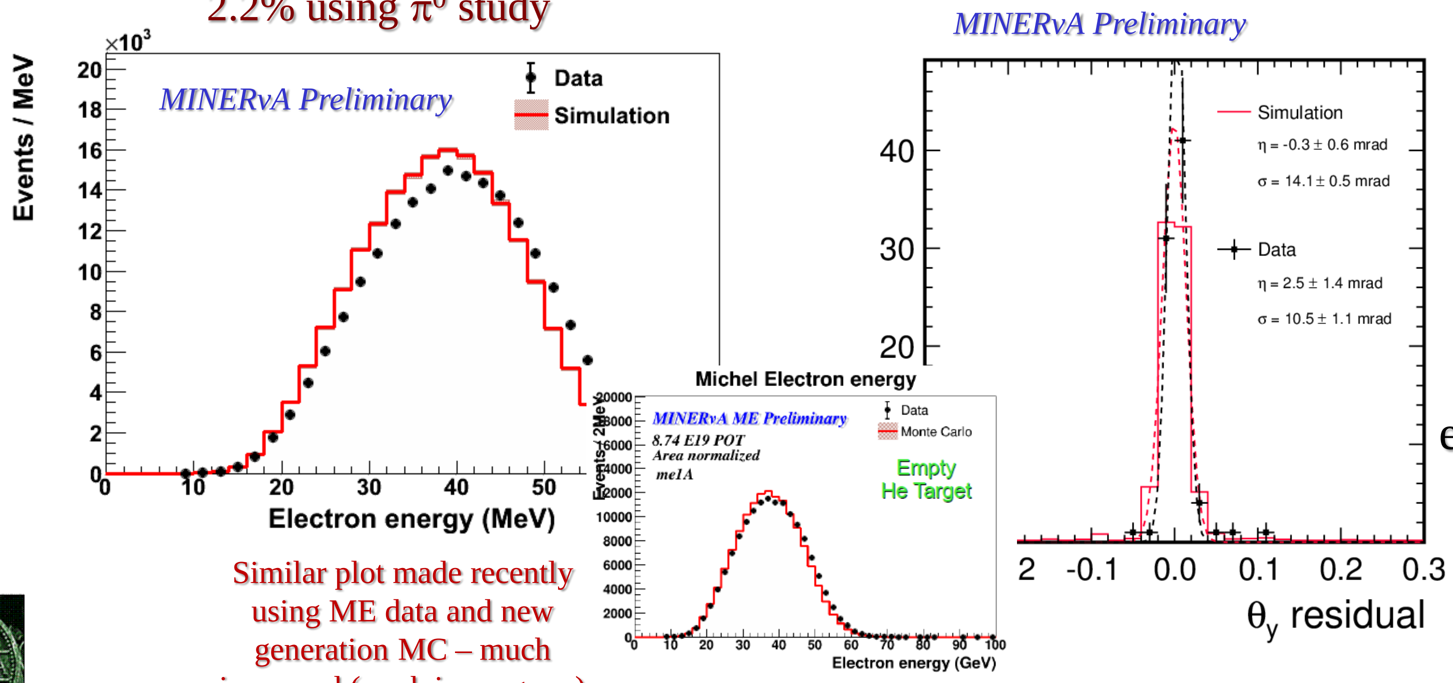
- Sideband tuning reduced systematic uncertainty on predicted background
  - Predicted background (before tuning): 38.9 ± 6.2 (stat) ± 10.3 (sys)
  - Predicted background (after tuning): 32.9 ± 5.3 (stat) ± 5.7 (sys) ±2.2±3.3
- The tuning didn’t eliminate systematic uncertainty but it gives confidence on background prediction

Reconstruction Systematic Uncertainties

- **Electromagnetic Energy Scale:** look at electrons from stopped μ decays (Michel): see agreement at 4.2% level, add as systematic uncertainty

This was shown in W&C, will improve to 2.2% using π^0 study

- Angular Alignment: look at data-simulation differences in μ angles for ν_μ CC events with low hadron energy
  - 3 (1) mrad correction in y (x)
  - uncertainty is ±1mrad



Similar plot made recently using ME data and new generation MC – much improved (work in progress)

ν_μ Charged Current Events with hadron energy<100MeV

Reconstruction Uncertainties (JP,W&C)

Source	**Uncertainty on Source**	**Systematic Uncertainty**
Beam angle uncertainty	θ_x and θ_y : ± 1 mrad	1.1% and 1.3%
Energy scale	4.2%	1.9%
EM calorimeter energy smearing	Additional energy smearing	0.0%
Absolute Electron Reconstruction Efficiency	2% based on muon studies	2.8%
All Reconstruction Uncertainties		**5.4%**
Simulation statistics (Bckgd)		6.0%
Flux (Bkgd)	Beam focusing, Beam tuning	1.3%
Cross Section (Bkgd)	GENIE, CCQE Shape	6.3%

Somewhat dated. See next slide.

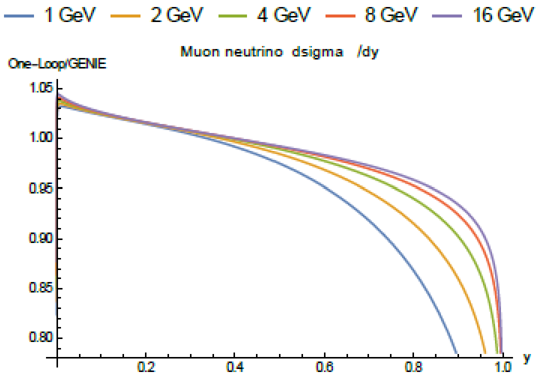
Calculation of Radiative Correction

- The radiative correction to $d\sigma/dy$ ($y=T_e/E_\nu$) was done in the early 1980s and is easy to find in the literature
- KSM Updated this calculation with recent EWK couplings with latest precision data

http://inspirehep.net/record/180251 : "Radiative Corrections to Neutrino-Lepton Scattering in the SU(2)-L x U(1) Theory", S. Sarantakos, A. Sirlinand W.J. Marciano, Nucl.Phys. B217 (1983) 84, DOI: 10.1016/0550-3213(83)90079-2

http://inspirehep.net/record/392527 : "Solar neutrinos: Radiative corrections in neutrino - electron scattering experiments", John N. Bahcall, Marc Kamionkowski and Alberto Sirlin, Phys.Rev. D51 (1995) 6146-6158,
DOI: 10.1103/PhysRevD.51.6146

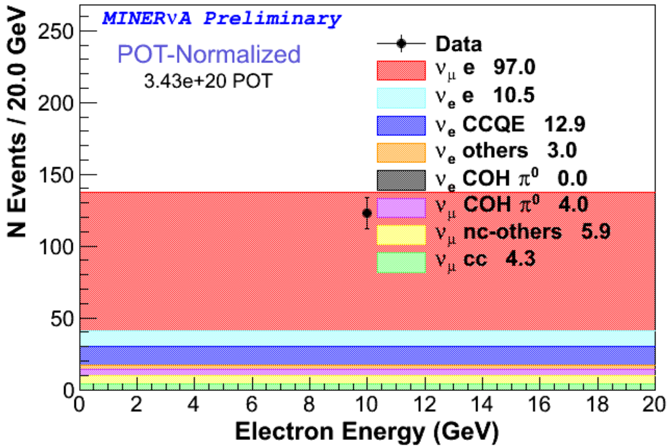
http://inspirehep.net/record/1225117 : "The Weak Neutral Current", Jens Erler, Shufang Su, Prog.Part.Nucl.Phys. 71 (2013) 119-149, DOI: 10.1016/j.ppnp.2013.03.004

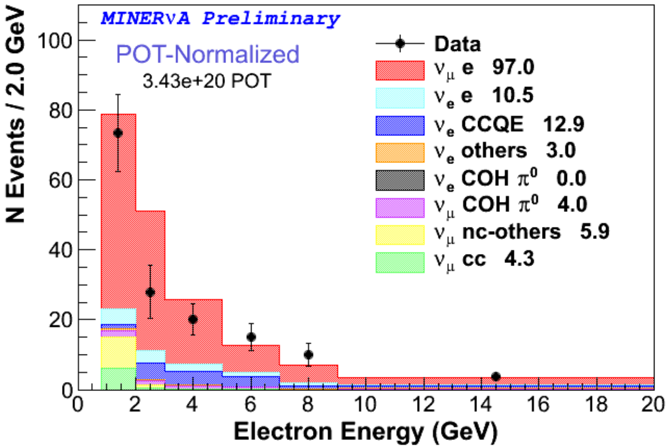


An Important Detail: You can't always get what you want ($d^3\sigma/dy/d\theta_e/dE_\gamma$)

- In principle, the radiative corrections we have are not what we want because any real photon will get added into electron energy if colinear
  - Most should be strongly colinear if energetic
- Or could veto event as a "second EM shower" if not colinear
- Is okay?
- Best study KSM can think of is to look at average energy shift of electrons. It is small compared to our energy scale uncertainty of 2% for energies with acceptance.

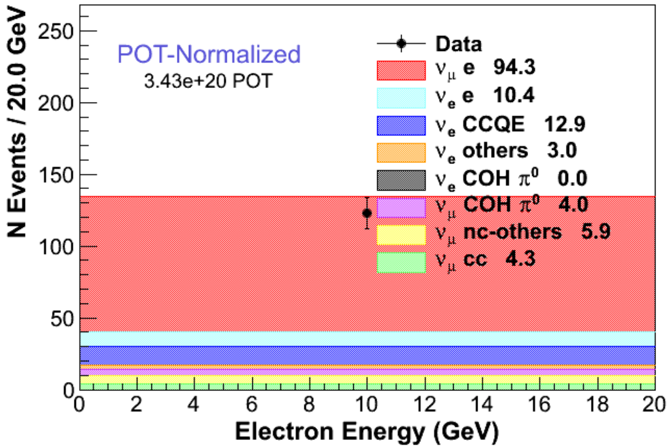
One bin and Electron Spectrum (Without Radiative Correction)

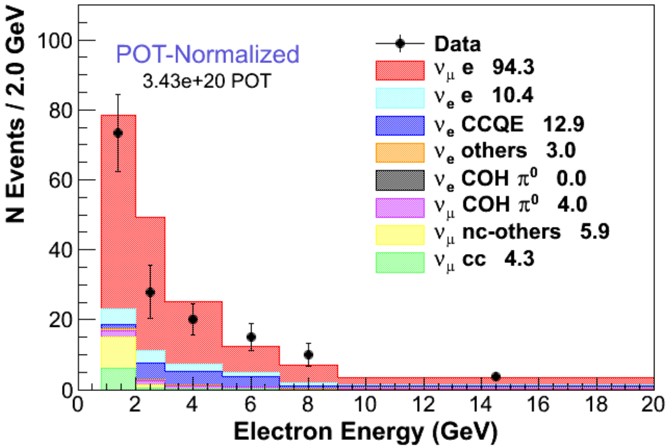




- All these plots include sideband tuning (which changes almost not at all because radiative correction only affects signal)

One bin and Electron Spectrum (With Radiative Correction)



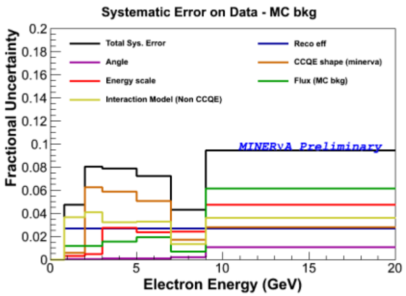


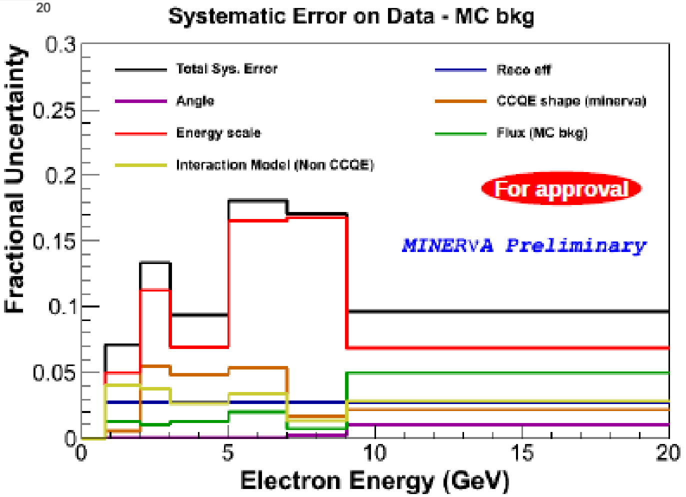
- Muon neutrino prediction: 94.3/97=0.972
- Electron neutrino prediction: 10.4/10.5=0.99

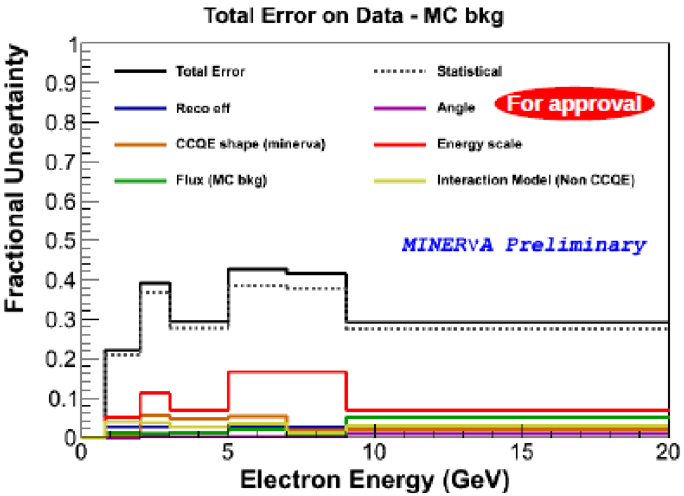
Preliminary for now. Is final or very close to final. Showing here because of relevance for this dune discussion.

Systematic Summary with New Energy Scale Uncertainty

- “CCQE shape” is from the difference between MINERvA’s measured CCQE $d\sigma/dQ^2$ and GENIE
- Interaction model is the rest of the standard GENIE suite of uncertainties, after constraints from sidebands



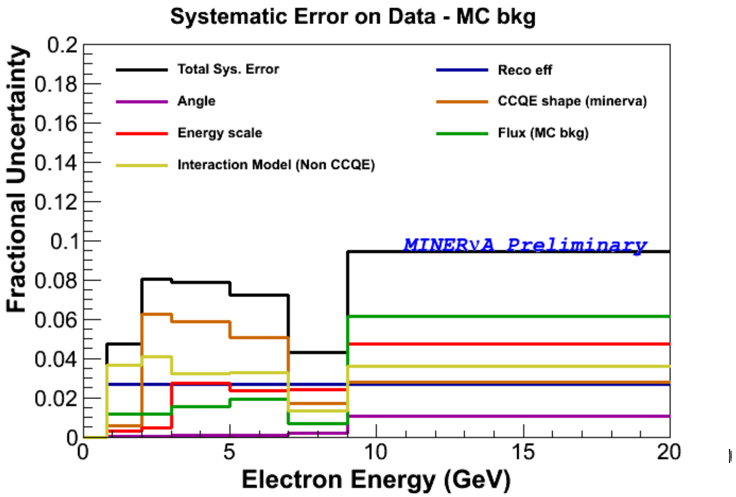


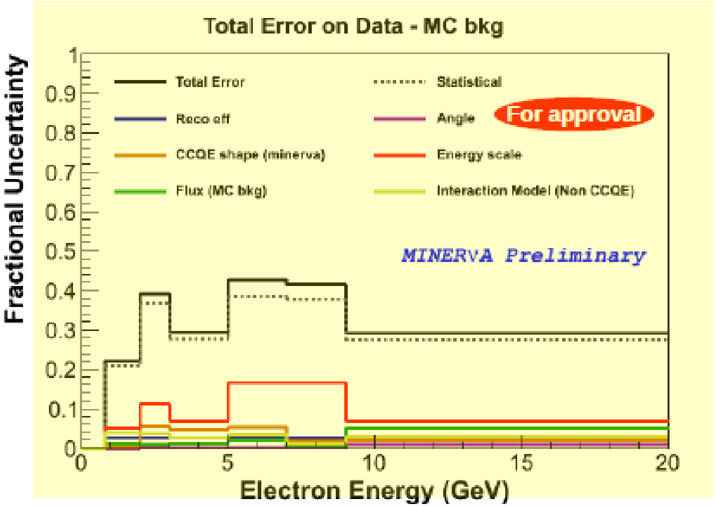


Preliminary for now. Is final or very close to final. Showing here because of relevance for this dune discussion.

Systematic Summary with New Energy Scale Uncertainty

- “CCQE shape” is from the difference between MINERvA’s measured CCQE $d\sigma/dQ^2$ and GENIE
- Interaction model is the rest of the standard GENIE suite of uncertainties, after constraints from sidebands



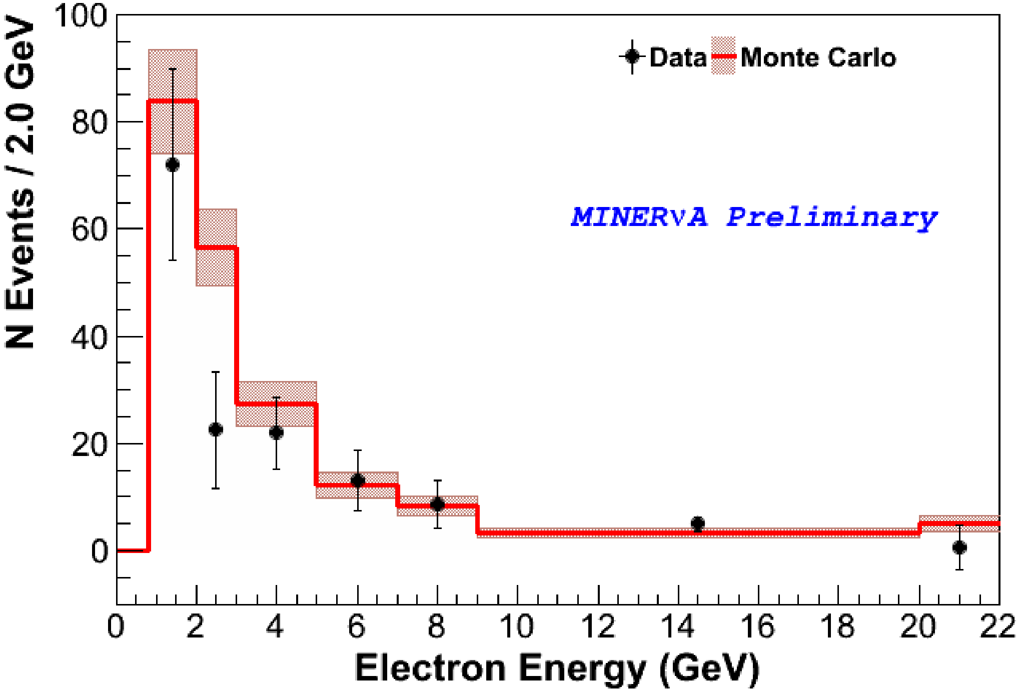


Result (shown in W&C)

- Found: 121 events before background subtraction
- ν-e scattering events after background subtraction and efficiency correction:

  123.8 ± 17.0 (stat) ± 9.1 (sys)

  total uncertainty: 15%
- Prediction from Simulation: 147.5 ± 22.9 (flux)
  - Flux uncertainty: 15.5%



Observed ν-e scattering events give a constraint on flux with similar uncertainty as current flux uncertainty, consistent with prediction

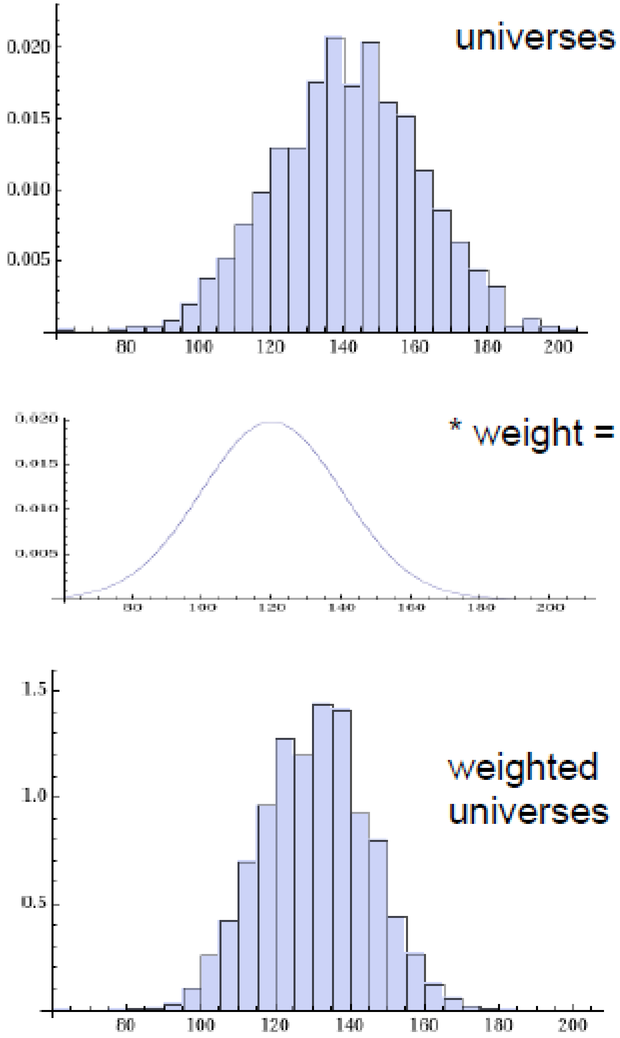
Flux constraint (JP)

- Take either the one bin or the spectrum result
- Form a weight based on consistency of a given flux universe with the neutrino-electron scattering result
- Central value and uncertainties are then estimated by the ensemble of weighted universes

Flux constraint (JP)

Take a simple toy example of a single measurement with a Gaussian *a priori* probability which seeds multi-universes

- For this toy, assumed a priori prediction was 141.2±20.1 and the measurement 120±20.2
- Preferred value shifts and uncertainty is reduced

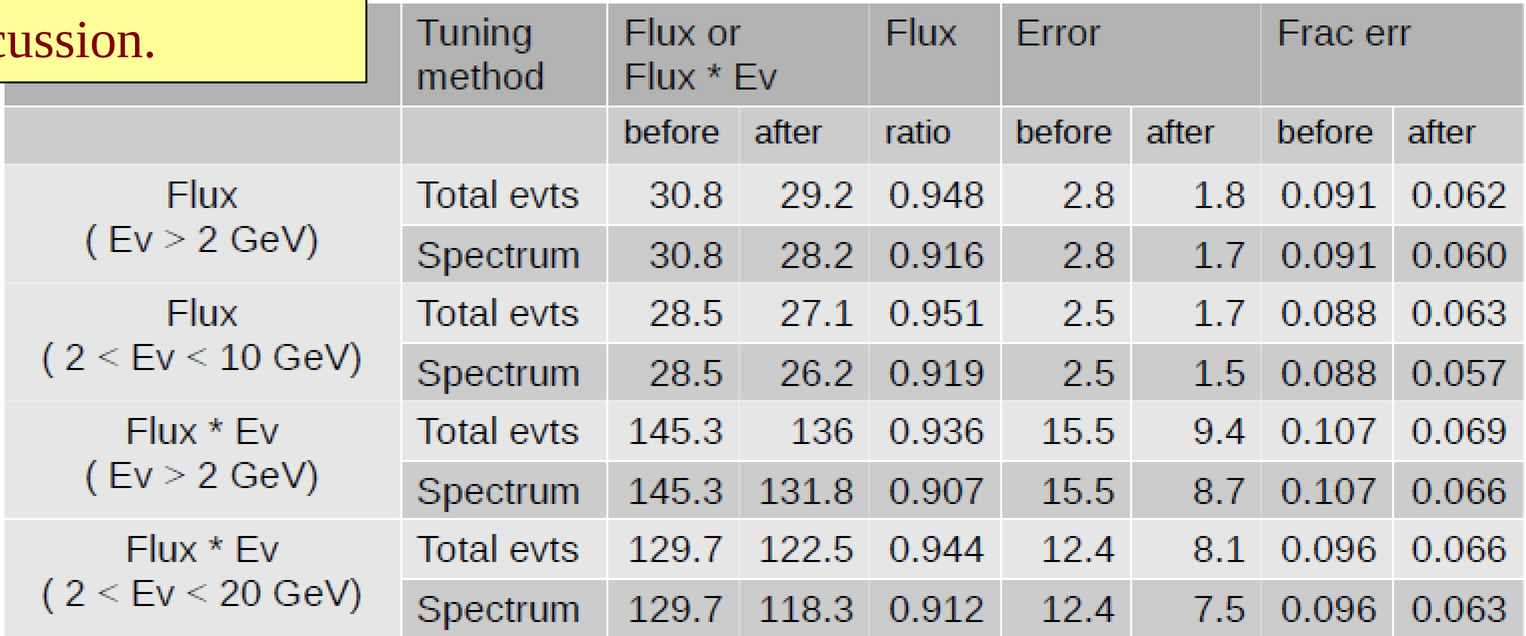


Flux constraint

- The effect of the nu-e flux constraint is analysis dependent
  - Analysis dependence on variable being constrained
  - Suppose analysis makes an E_ν cut
  - Cross-section might be a function of E_ν

Flux constraint

Preliminary for now. Is final or very close to final. Showing here because of relevance for this dune discussion.



	Tuning method	Flux or Flux * Ev		Flux	Error		Frac err	
		before	after	ratio	before	after	before	after
Flux (Ev > 2 GeV)	Total evts	30.8	29.2	0.948	2.8	1.8	0.091	0.062
	Spectrum	30.8	28.2	0.916	2.8	1.7	0.091	0.060
Flux (2 < Ev < 10 GeV)	Total evts	28.5	27.1	0.951	2.5	1.7	0.088	0.063
	Spectrum	28.5	26.2	0.919	2.5	1.5	0.088	0.057
Flux * Ev (Ev > 2 GeV)	Total evts	145.3	136	0.936	15.5	9.4	0.107	0.069
	Spectrum	145.3	131.8	0.907	15.5	8.7	0.107	0.066
Flux * Ev (2 < Ev < 20 GeV)	Total evts	129.7	122.5	0.944	12.4	8.1	0.096	0.066
	Spectrum	129.7	118.3	0.912	12.4	7.5	0.096	0.063

- Effect on flux
  - Flux (Ev>2GeV) ~ Flux (2<Ev<10GeV)
  - CV change: 0.95 (0.92 w/ spectrum tuning), error: 9% → 6%

Some lessons for DUNE

- This technique to constrain the flux works
  - ➢ Premiums on
    - ○ Statistics
    - ○ electron-photons separation
    - ○ electron energy reconstruction
    - ○ angular resolution
  - ➢ Constraint on the flux is analysis dependent
  - ➢ EM energy scale is very important, biggest MINERvA error outside of statistics
    - ○ test beam with electrons helpful?
  - ➢ MINERvA achieves approx. 70% efficiency with approx. 80% purity
  - ➢ At 3-4% level, neutrino modeling and reconst efficiency errors kick in.
  - ➢ Improvements in model *are important* … expect it to be better by DUNE time. (CCQE shape error for example)
  - ➢ Radiative correction issue needs to be cleaned up (probably okay on DUNE time scale, but …)

Effect of B field gives effect on electron reconstruction that is different from that on muons

Some lessons for DUNE

- Electrons ain’t muons
  - ➢ In both T2K and MINERvA, big effort on reconstruction of muons early in experiments while EM shower reconstruction languished somewhat (SM opinion)
  - ➢ Not arguing against priorities. Main mission of ND is muon neutrino flux constraint at start. BUT … early pressure to produce while focus on “simple” case of muon tracking caused rather muon-centric bias in the reconstruction choices that caused headaches and delays in generating good EM reconstruction
  - ➢ Unavoidable?