Neutrino Electron Scattering

Jaewon Park
University of Rochester

Flux Measurement and Determination in the Intensity Frontier Era Neutrino Beams
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Overview

- Motivation
  - Flux constraining using $\nu_\mu + e$ scattering
- Signal/Background separation
- MINERvA detector
- Single EM shower reconstruction
- e/γ Separation using dE/dx
- Small sample MC / Data comparison
- Estimated statistics in ME
- Summary

NuMI Beamline

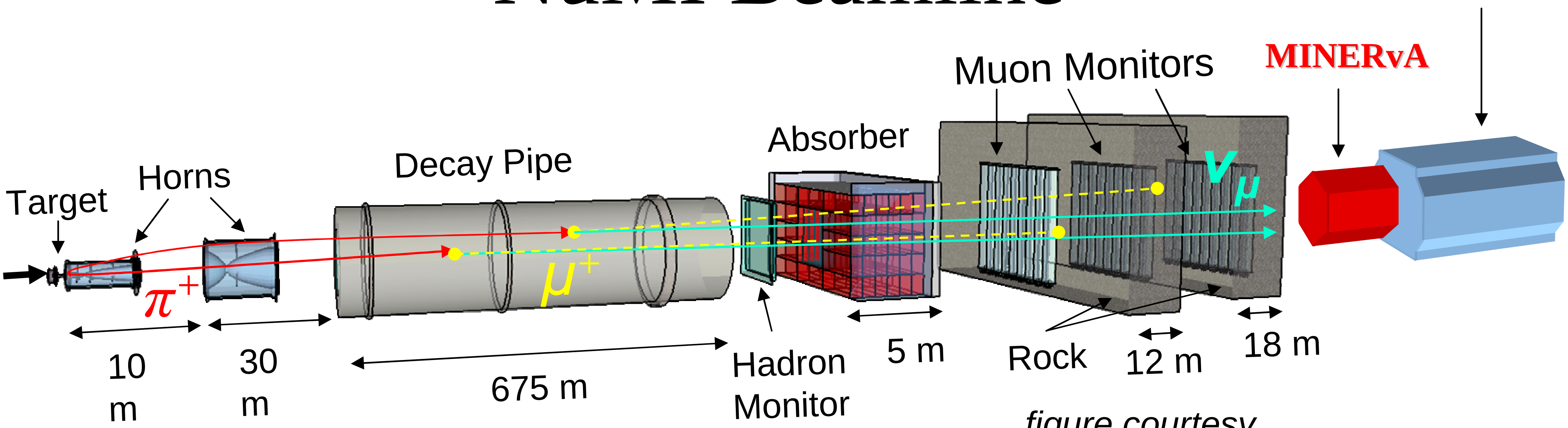
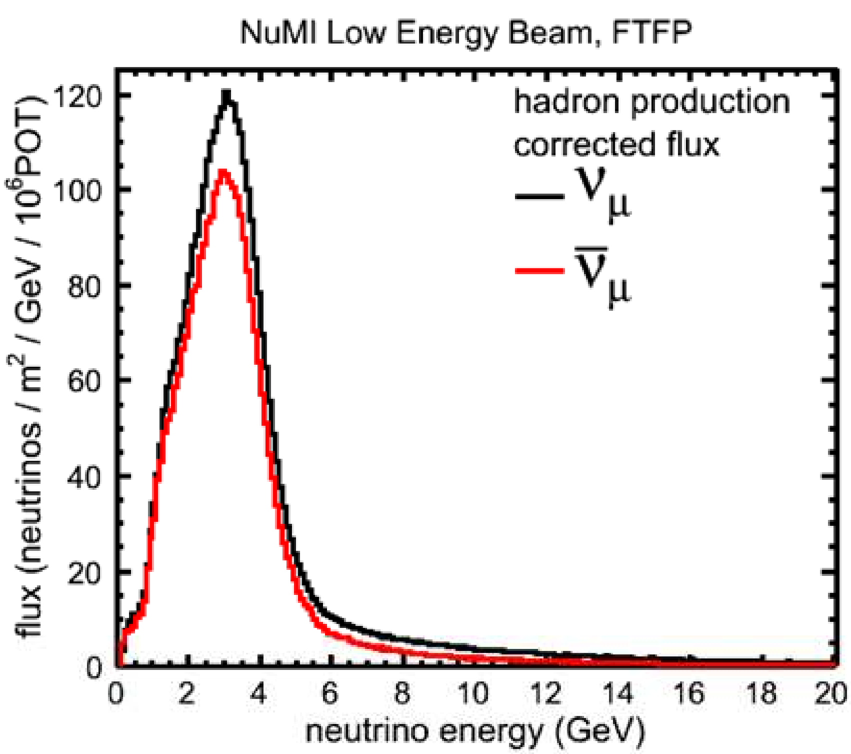
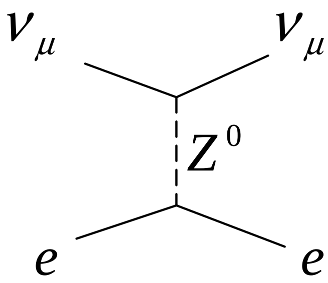


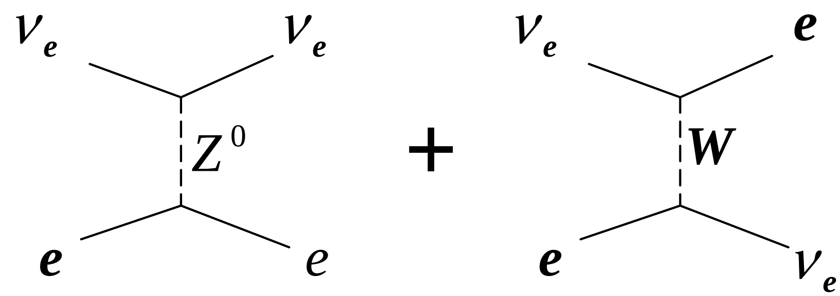
figure courtesy
Ž. Pavlović



- Movable target to configure beam energy (only low energy target)
  - ME target doesn't move
- Horn current to select sign of neutrino
  - Forward horn current: neutrino dominant beam
  - Reverse horn current: anti-neutrino dominant beam
- My study is based on
  - Low energy beam, forward horn current
  - Contamination of ν_μ, $\overline{\nu}_e$, and $\overline{\nu}_e$

Constraining flux using $\nu_\mu + e$ scattering



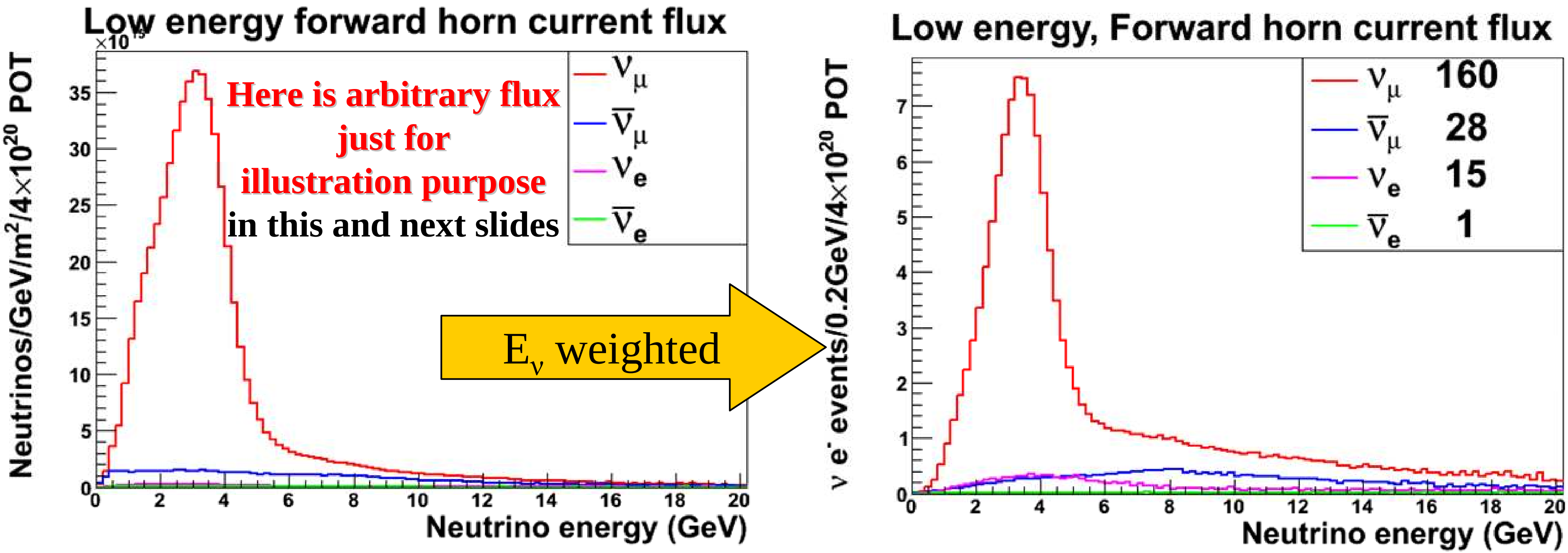


$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$
$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$

$$\nu_e + e^- \rightarrow \nu_e + e^-$$
$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

- ν + e scattering is pure leptonic process and theoretically well understood (~1% precision)
- ν scattering on light electron means small center of mass energy, consequently it has tiny cross section (~1/2000 compare to νN scattering)
- Scattering on light electron also means very small Q^2, which produces very forward electron final state
- In principle, if we measure event rate of this process, we can determine flux ($R = \Phi\sigma$)
- But it's not that simple because cross section(σ) and flux(Φ) are function of neutrino energy
- And we only measure electron energy
  - Because electron angle is really all forward within detector resolution ($E\theta^2 < 2m_e$), we don't have sensitivity to calculate neutrino energy using 2 body kinematics

Flux → Event Rate

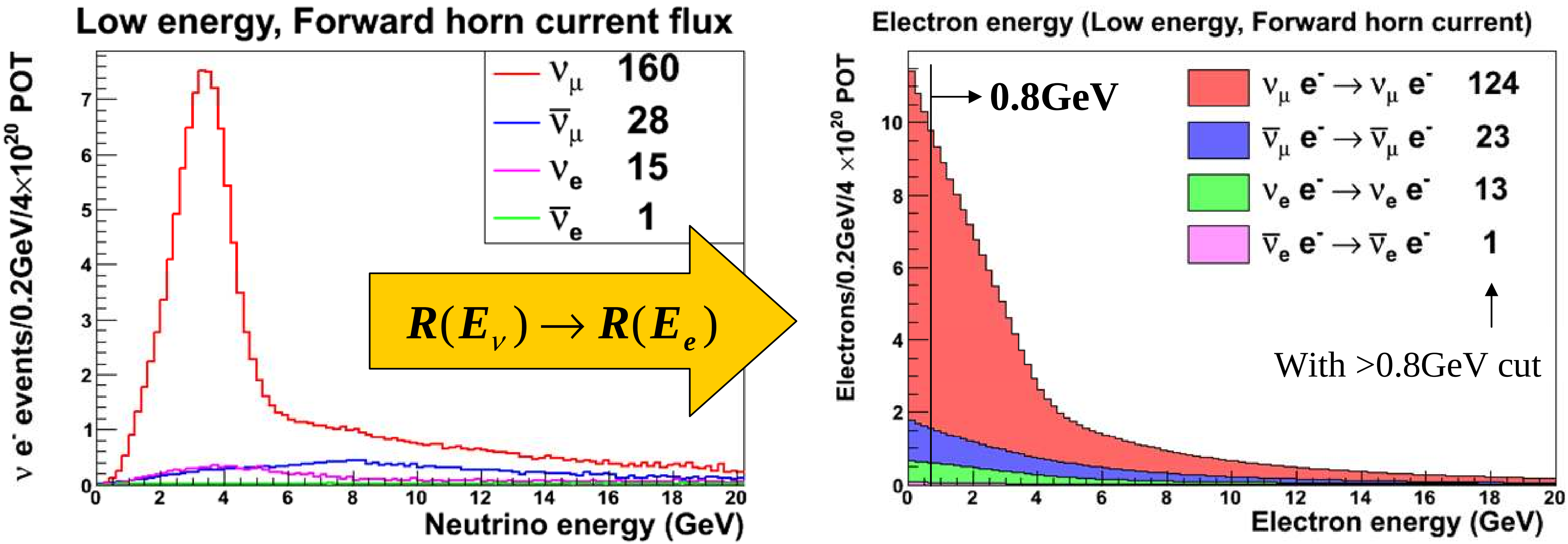


$$\sigma(\nu_\mu e^-) = \frac{G_F{}^2 s}{\pi}\left[\left(-\frac{1}{2}+\sin^2\theta_W\right)^2+\frac{1}{3}\sin^4\theta_W\right] \quad \propto E_\nu$$

$$s = 2m_e E_\nu$$

- Total cross section is proportional to beam energy
- High energy tail contribution gets bigger

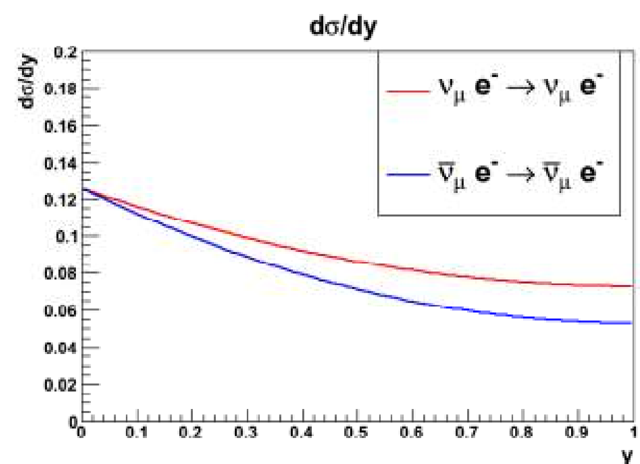
Event Rate → Electron Spectrum



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

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

$$R(E_e) = \int \Phi(E_\nu)\frac{d\sigma(E_\nu, E_e)}{dE_\nu dE_e} dE_\nu$$



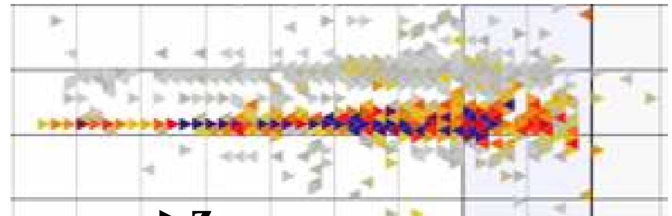
- High energy electron from high energy neutrino
- Low energy electron from both low and high energy neutrino
- Note also anti muon neutrino and electron neutrino contribution

$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ and Background Events

All MC events are shown

All can look like single electron final state

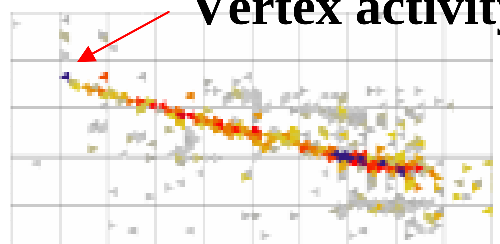
$$\nu_\mu + e \rightarrow \nu_\mu + e$$
$$\bar{\nu}_\mu + e \rightarrow \bar{\nu}_\mu + e$$



Very forward

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

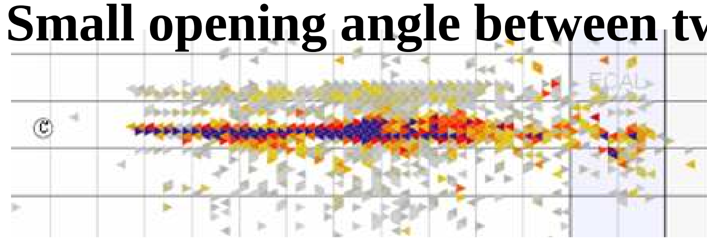
Vertex activity

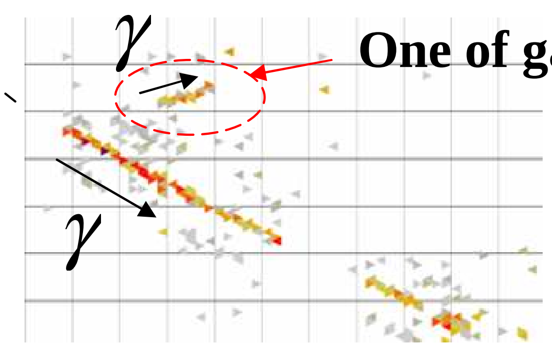


$$\nu_\mu A \rightarrow \nu_\mu A \pi^0$$
$$\nu_\mu N \rightarrow \nu_\mu N \pi^0$$

NC-coherent π^0
NC-resonant π^0

Small opening angle between two gammas





One of gamma is low energy

Background Suppression and Signal Isolation

ν_e CCQE

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

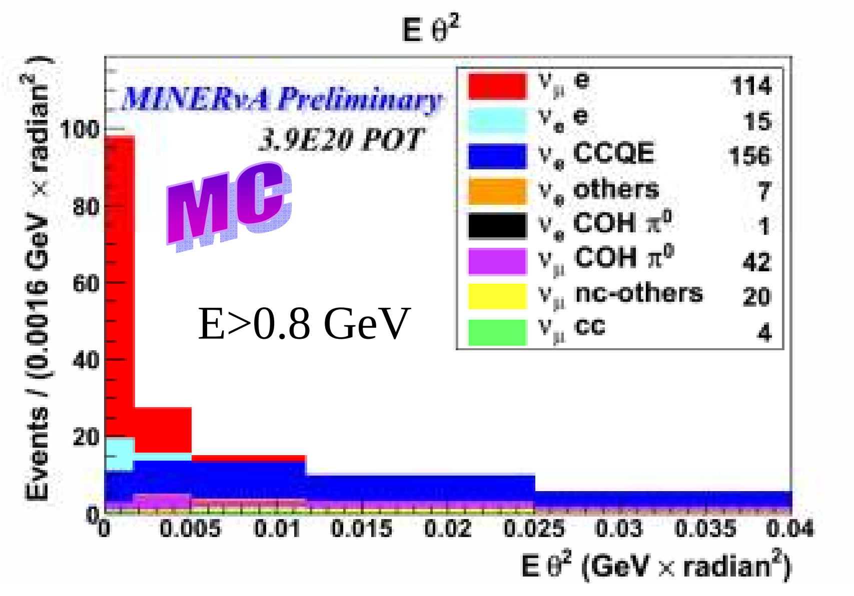
Require no or small vertex activity

NC π^0

$$\nu_\mu A \rightarrow \nu_\mu A \pi^0$$
$$\nu_\mu N \rightarrow \nu_\mu N \pi^0$$

Gamma's dE/dx at the beginning of shower is different from electron

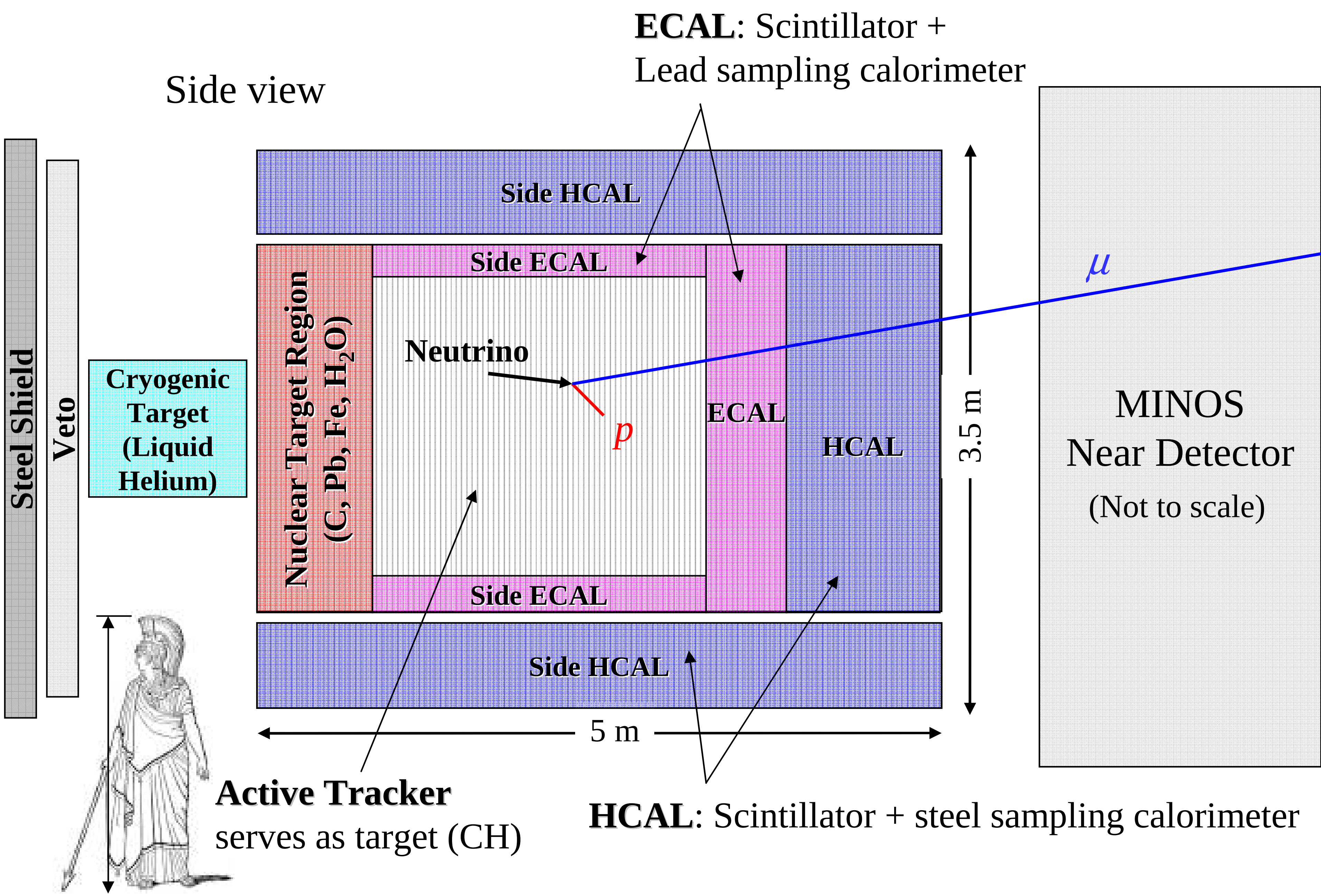
- Require EM shower energy > 0.8 GeV
  - NC background is very high at lower energy
  - Particle ID is more difficult at lower energy
- After basic background suppression, the signal is isolated using $E\theta^2$ cut



E: Energy of electron candidate
θ: Theta of electron candidates w.r.t. beam direction

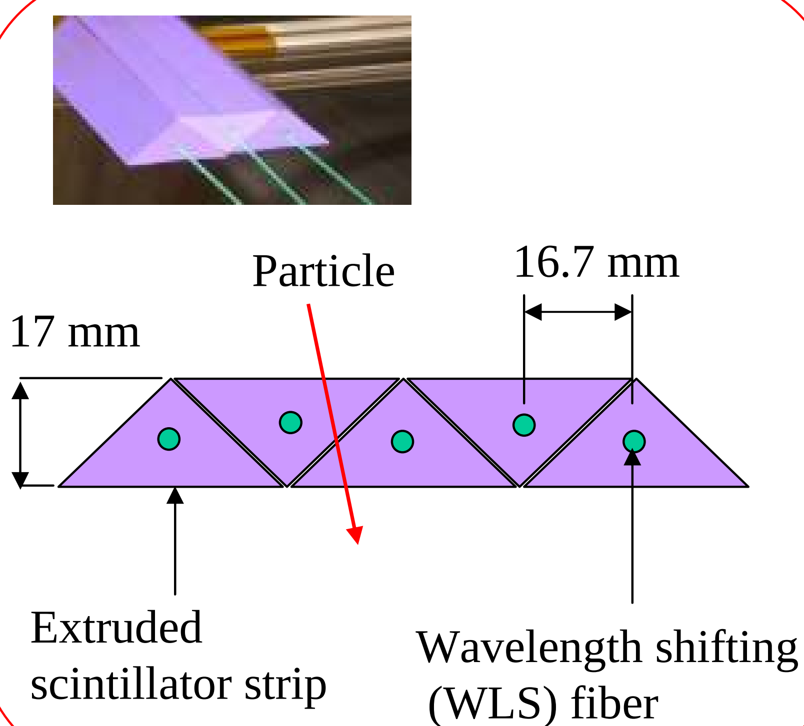
MINERνA Detector

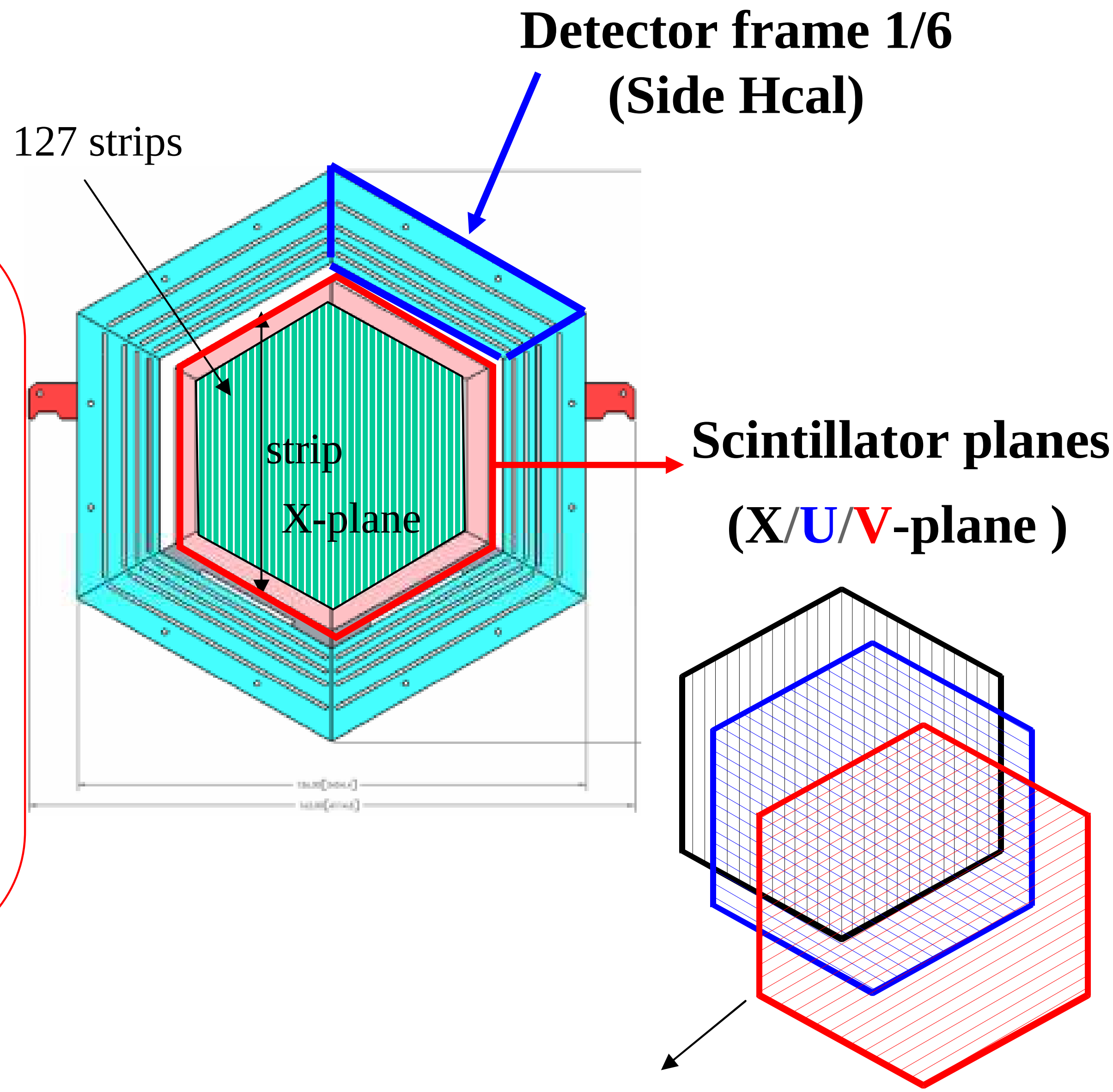
- MINERvA detector is made of a stack of "MODULES" (See next slide)



Detector Module

Scintillator plane consists of extruded scintillator strips and wavelength shifting fibers



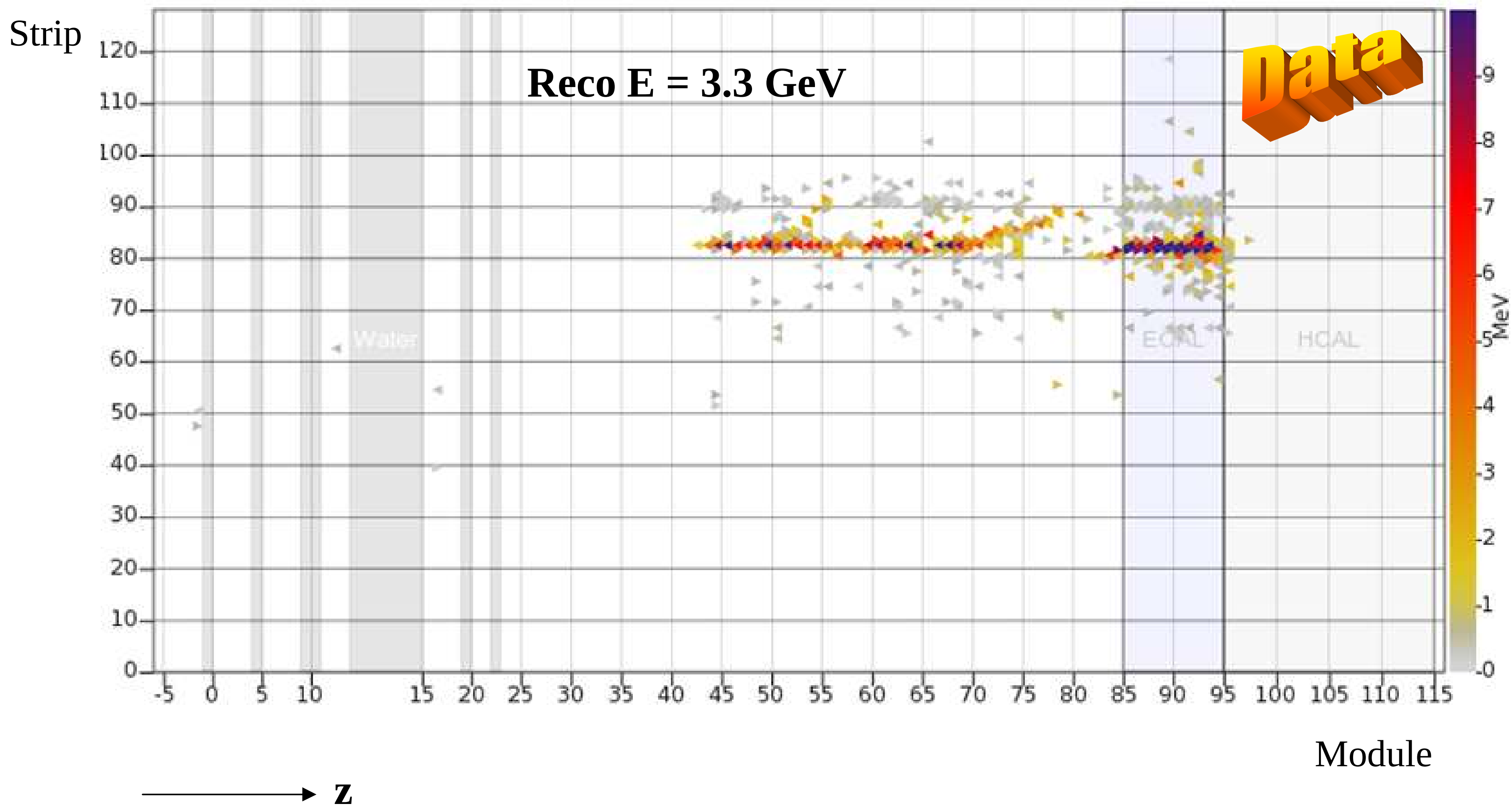


- X, U, V coordinates are combined to make 3D tracking

ν+e → ν+e Candidate Event

X-view

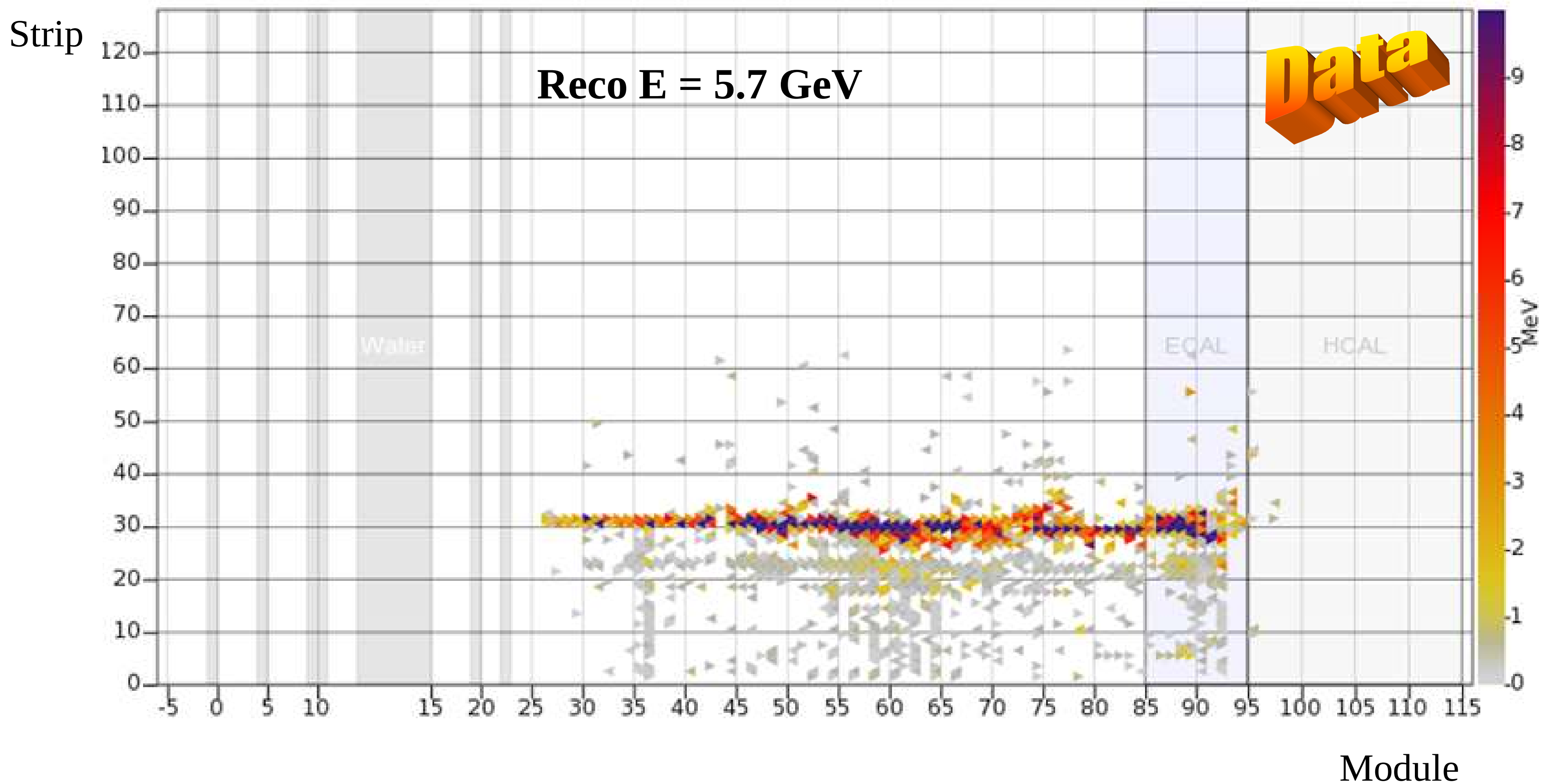
run/subrun/gate/timeslice=2017/2/219/10



ν+e → ν+e Candidate Event

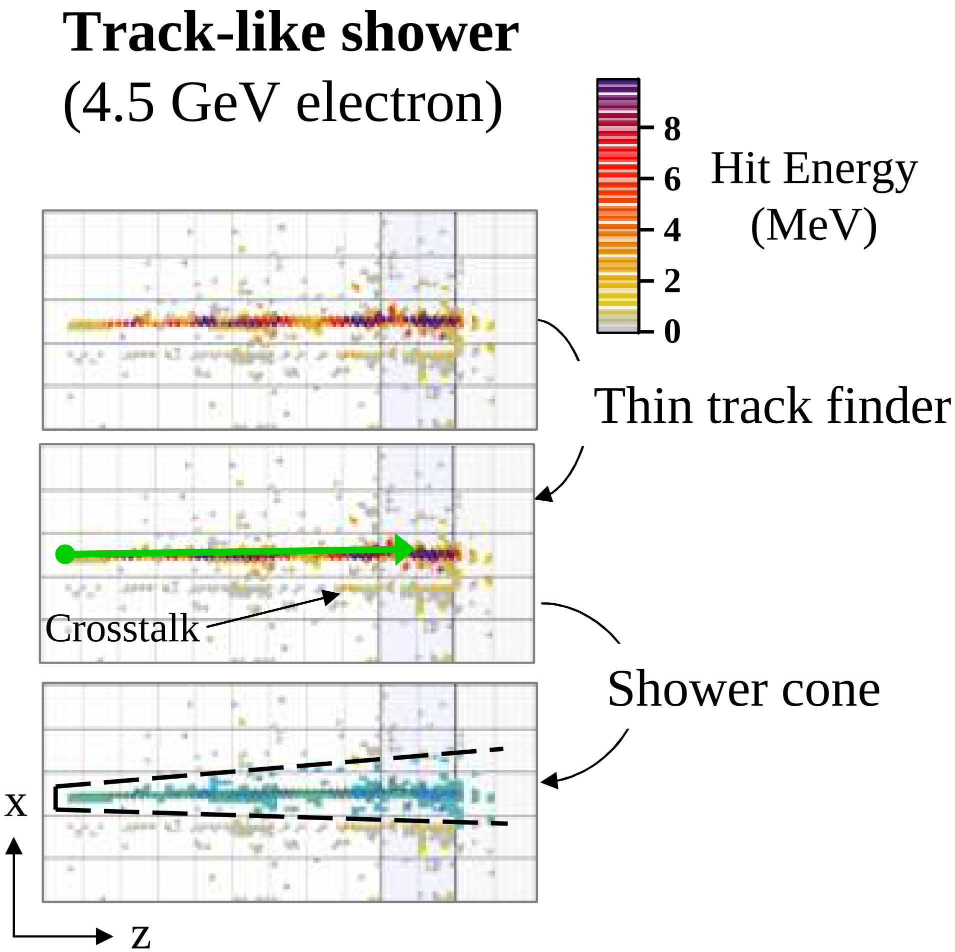
X-view

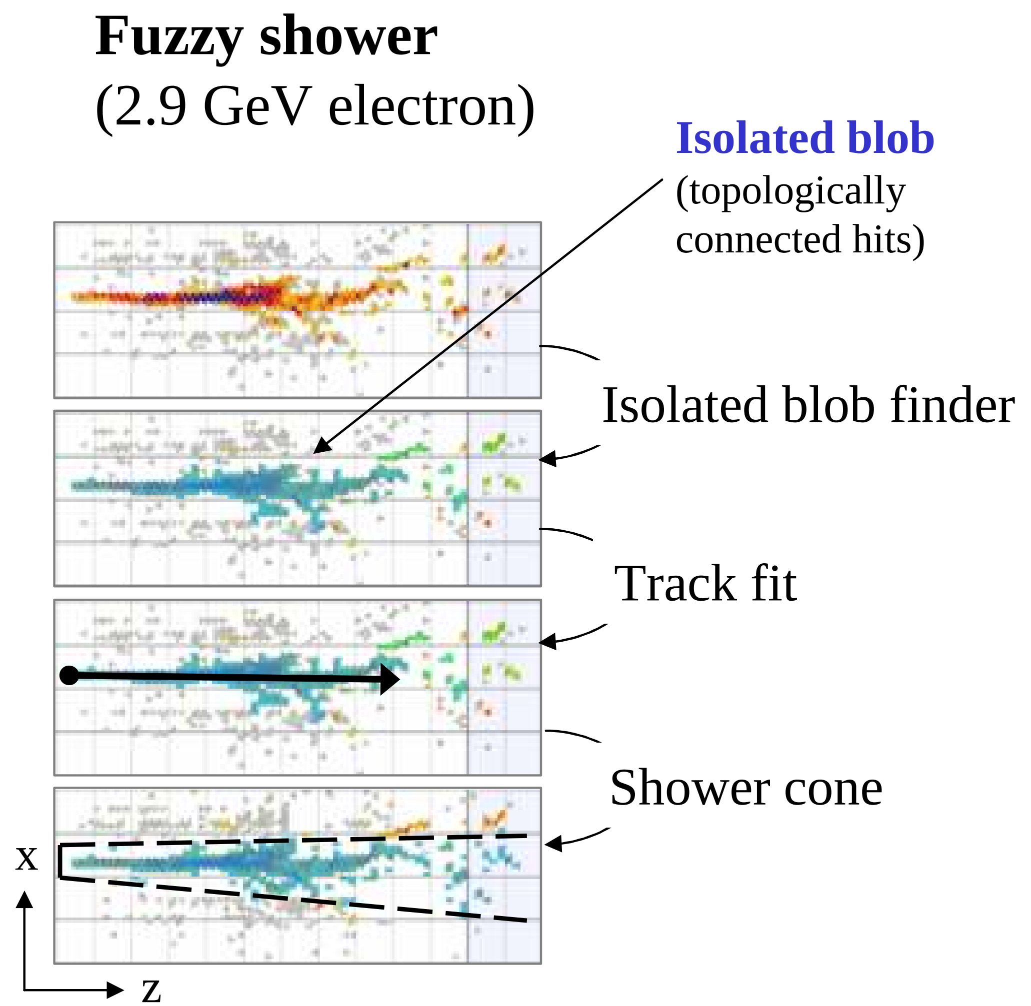
run/subrun/gate/timeslice=2157/12/1270/2



→ **z**

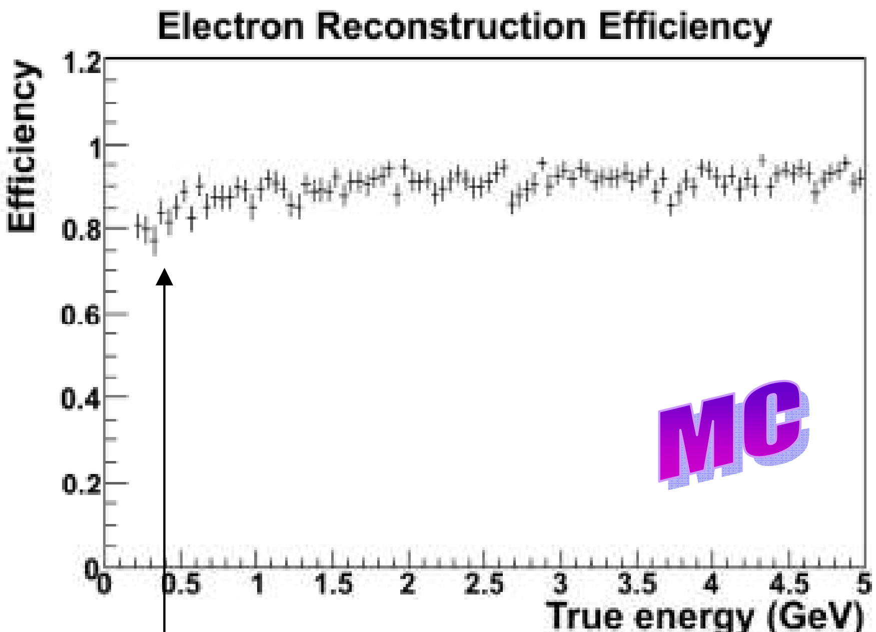
Single EM Shower Reconstruction

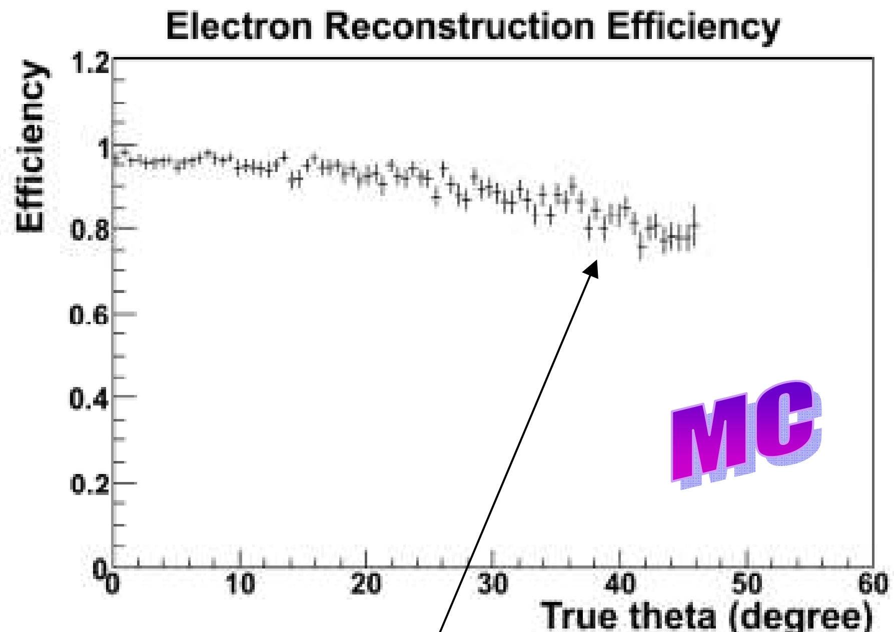


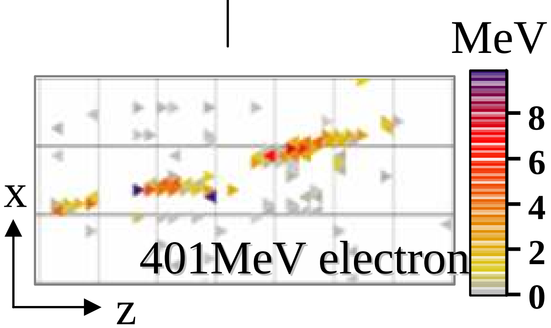


- Once vertex and direction is known, shower cone can be applied
- When (thin) track finder fails on fuzzy shower, isolated blob finder is used and then track fitter can handle fuzzy shower

MC Reconstruction Efficiency





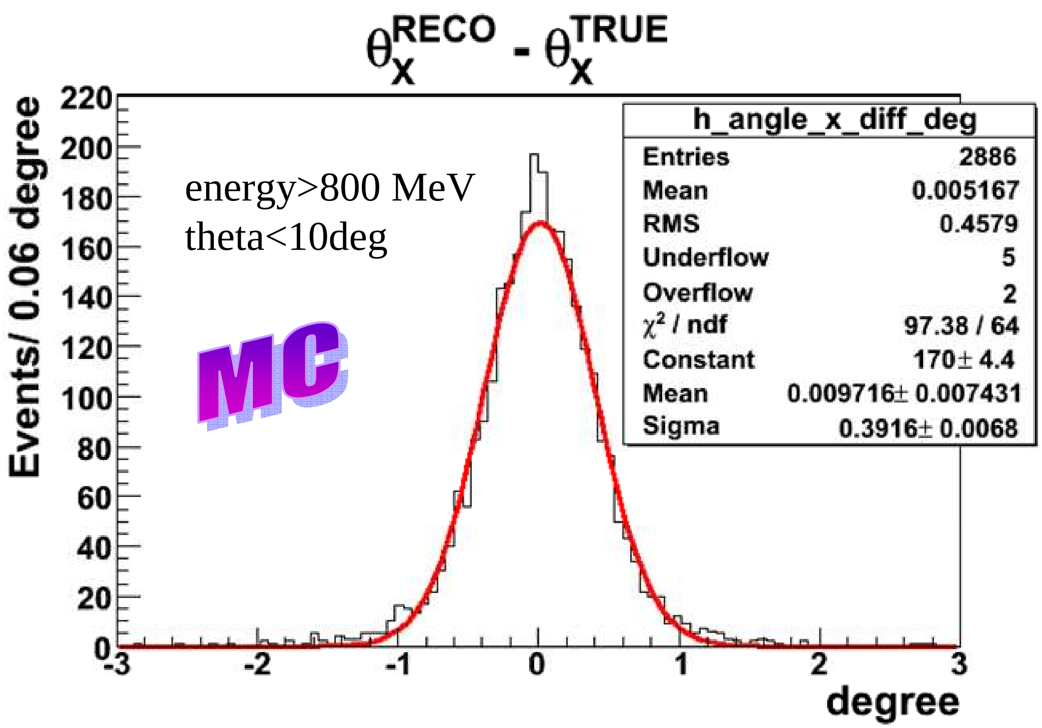


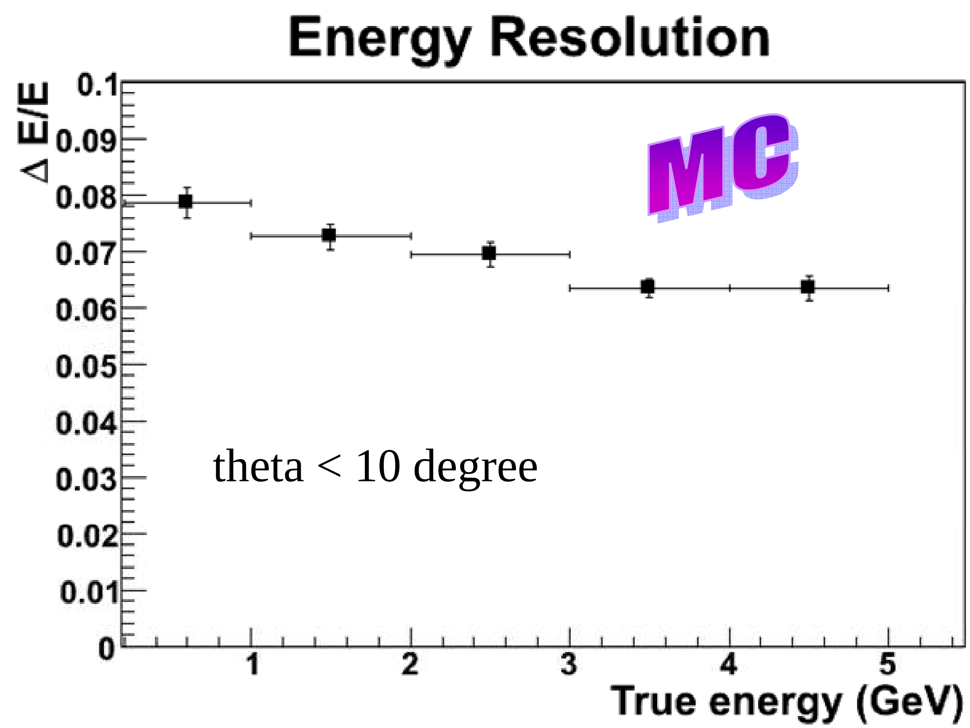
Low energy electron sometimes produces gappy shower

Big theta angle electron tends to exit to sides, which leaves less hits in tracking volume

- Single electron MC is used to calculate efficiency
  - Energy: 0.2 ~ 5 GeV, Theta: 0~45 deg
- **Reconstruction efficiency is 0.96 for small angle** (angle <10 degree, energy>400MeV)

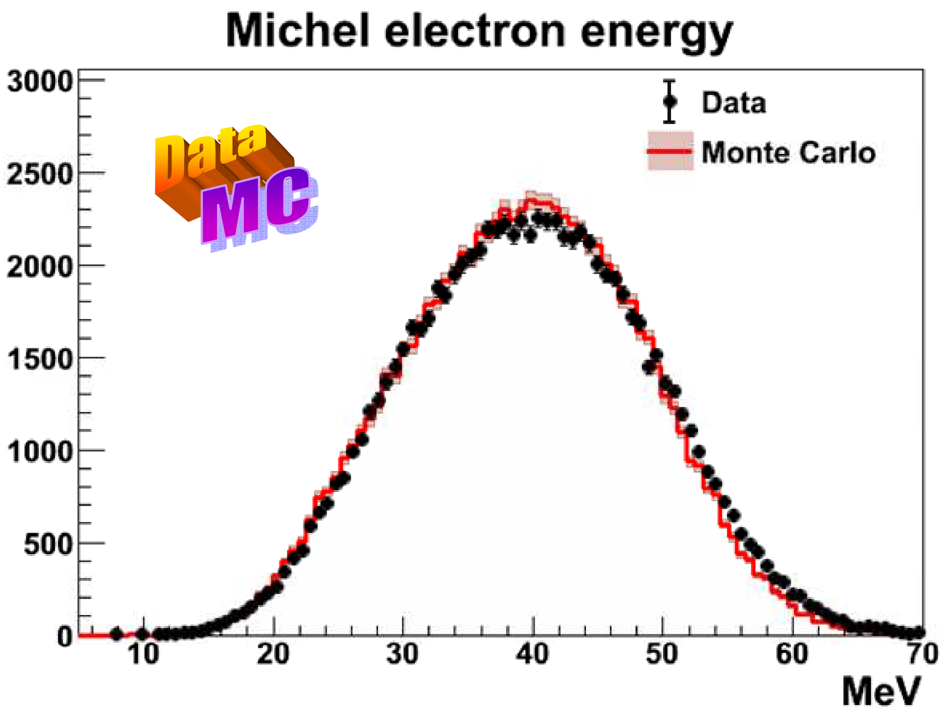
MC Angular and Energy Resolution



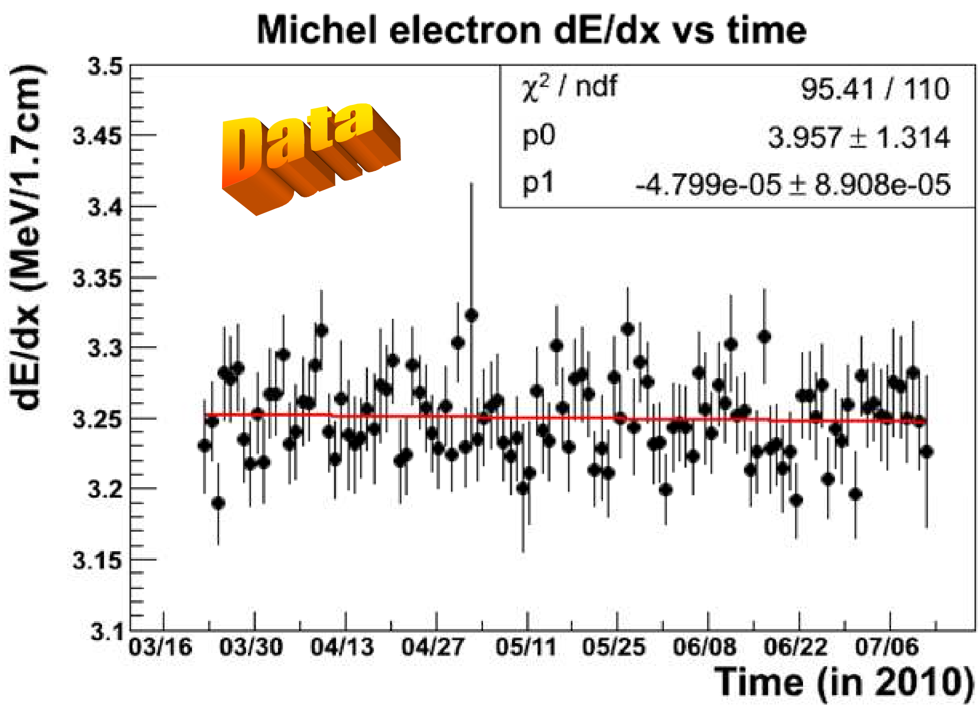


- X-angle resolution ~ 0.4 degree
- Precise angular reconstruction is critical to separate ν_μ *e* elastic scattering from ν_e CCQE
- Energy resolution: 6~ 7%

Calibration Checking using Michel electron

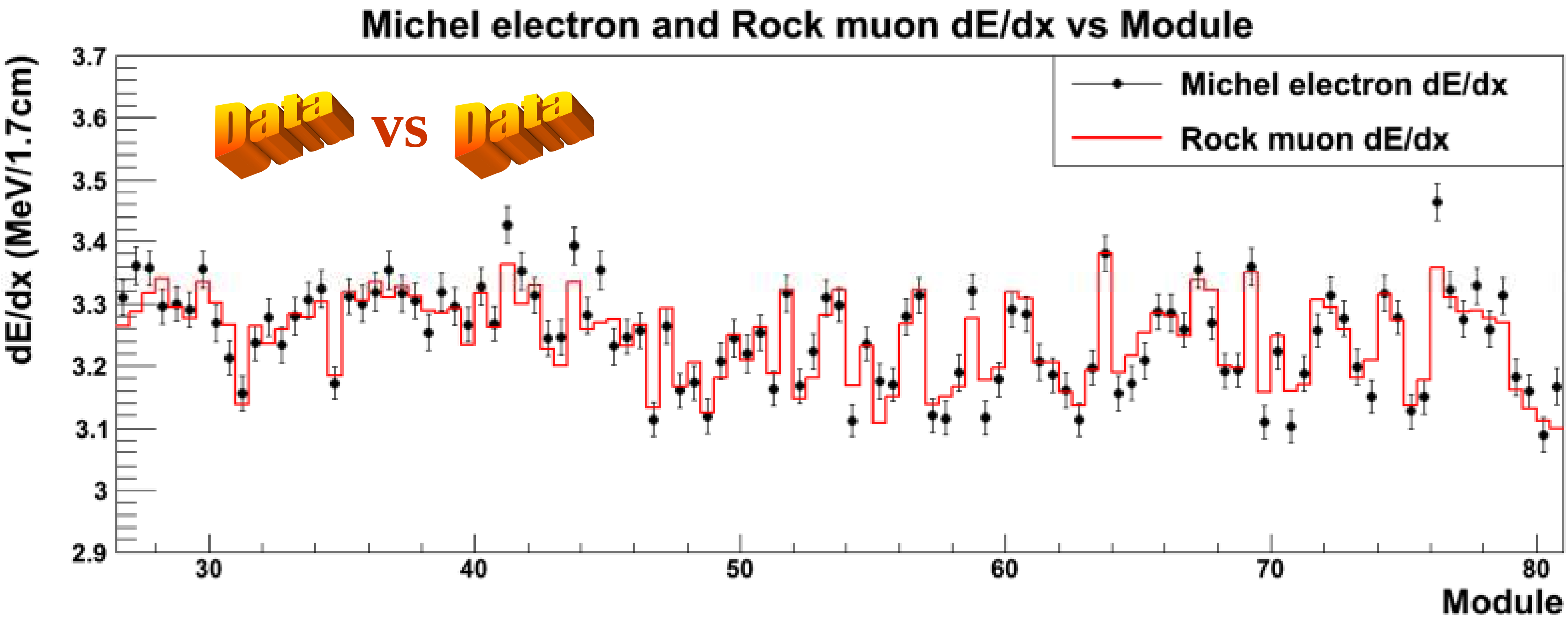


Energy scale stability



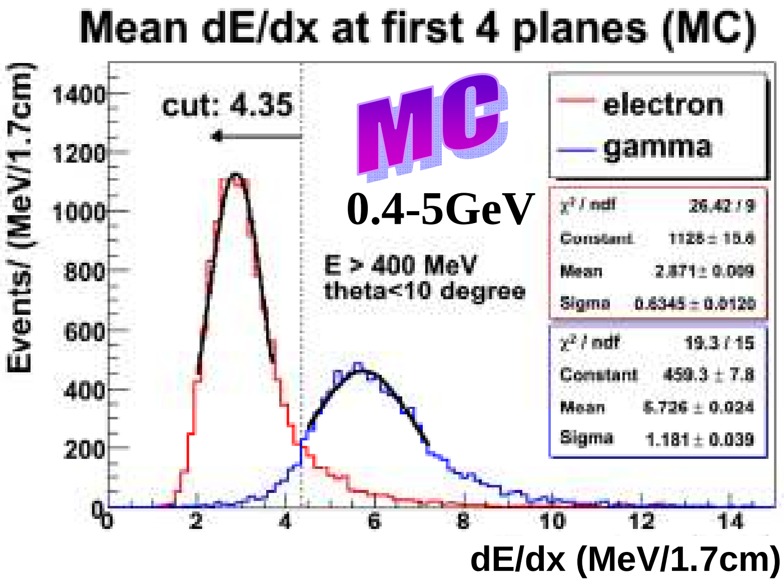
- Michel electron is produced by a muon decay and electron spectrum is predicted by well-understood theory
  - What's really seen is theory spectrum with detector energy resolution and calibration
- Michel electron is nice tool to check calibration
  - Michel energy MC/data comparison
  - EM energy scale is stable over time

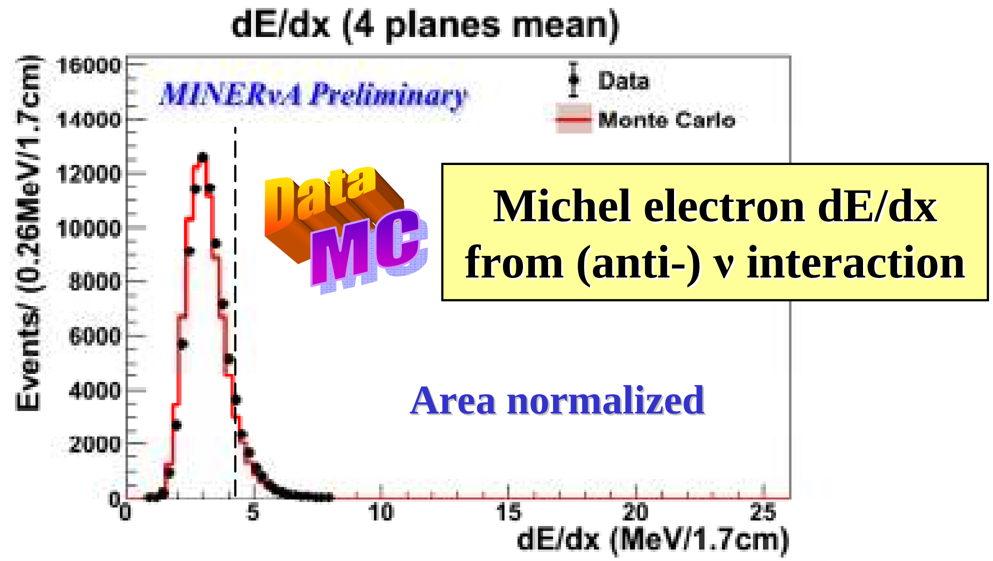
Michel electron dE/dx and Rock muon dE/dx Comparison

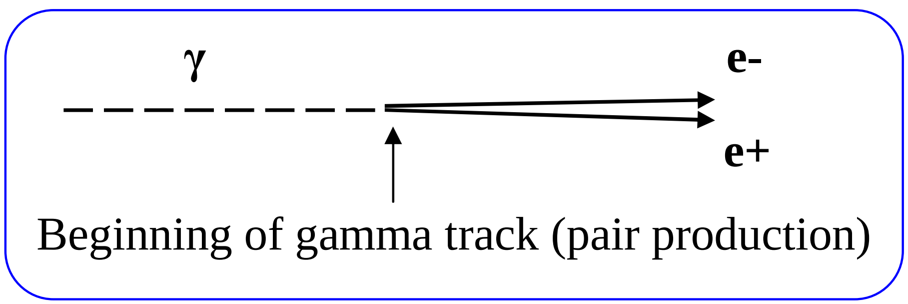


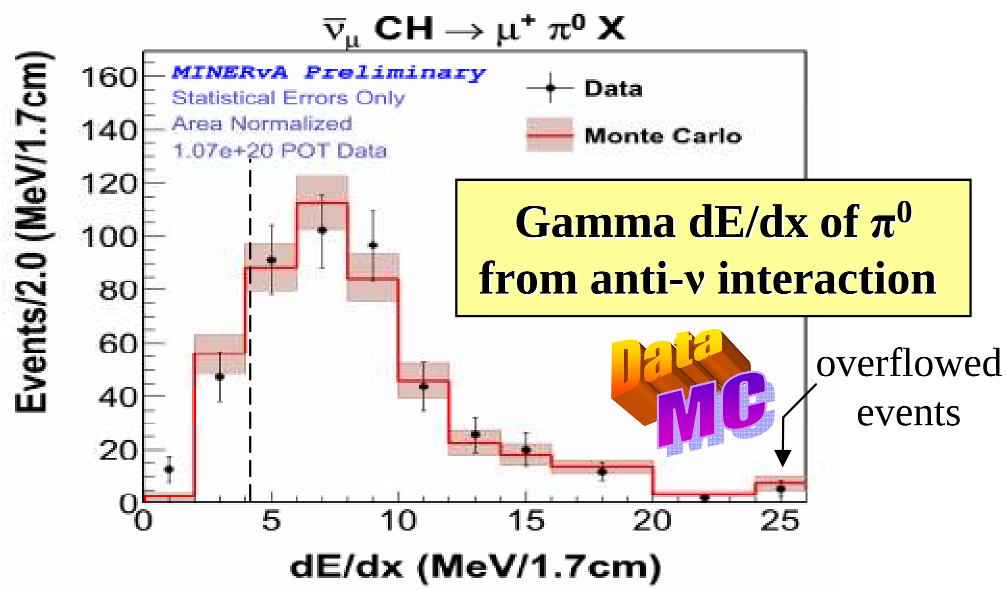
- Rock muon (muons that is produced from neutrino interaction in upstream rock) is also good source of calibration
  - Minimum ionizing particle (MIP) dE/dx is constant
- dE/dx in each plane reflects plane response
- Module to module variation is consistent between Michel electron dE/dx and muon dE/dx

dE/dx for Electron and Gamma Discrimination





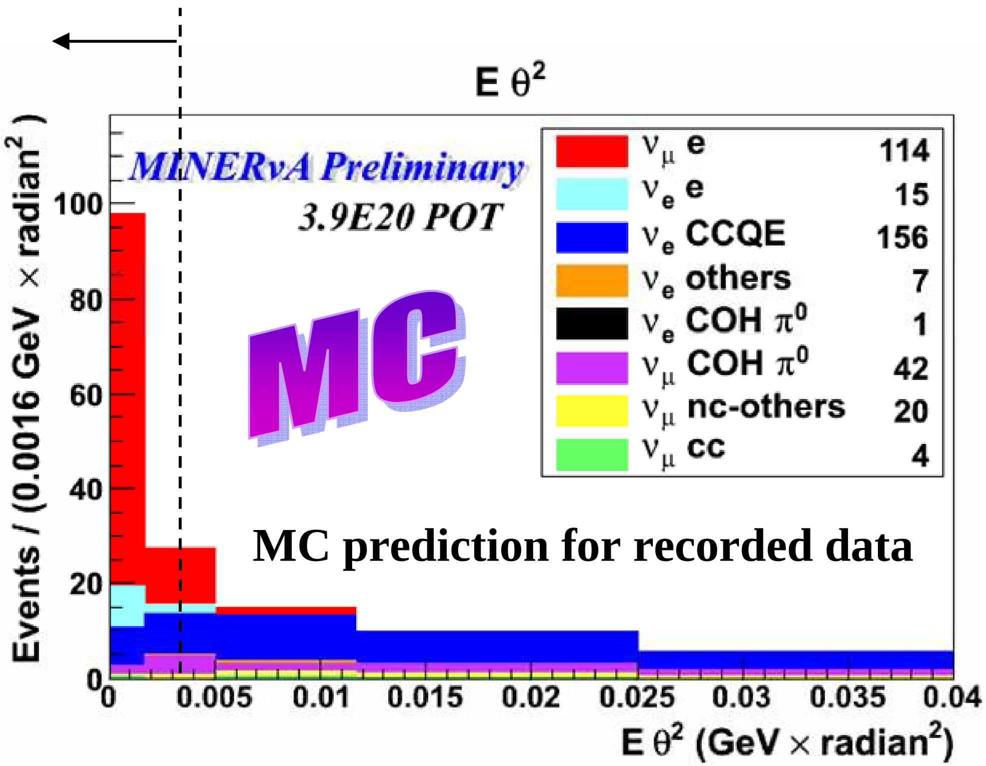




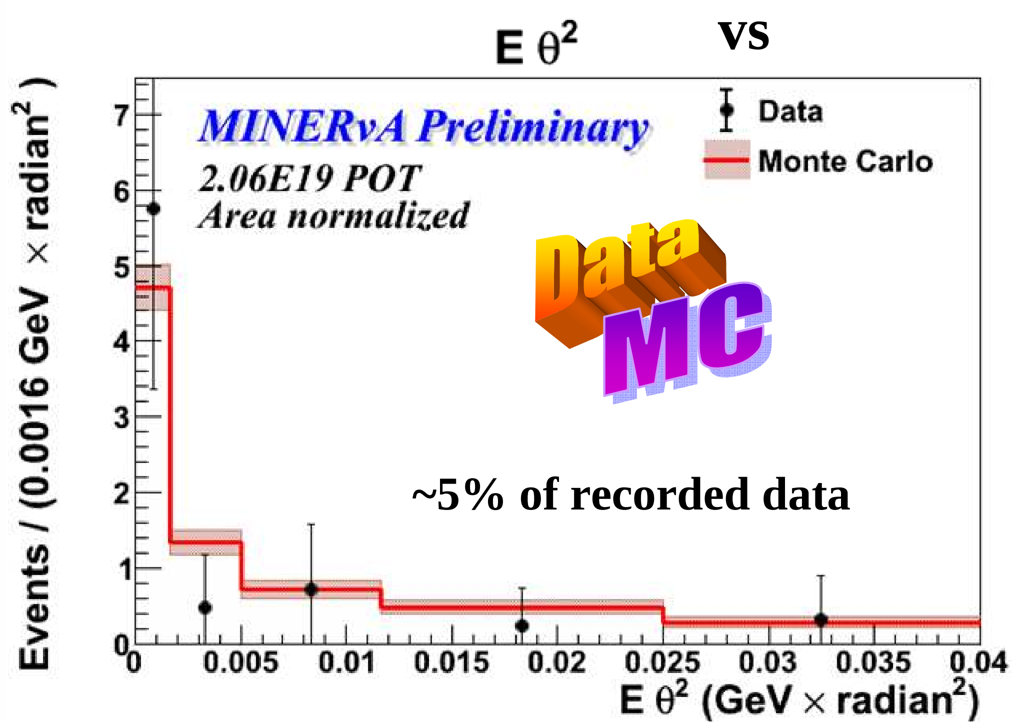
- Neutral current π^0 is decayed into energetic gamma + tiny energy gamma
- dE/dx at the beginning of shower is different for electron and gamma
  - Electron loses energy like MIP (Minimum Ionization Particle)
  - Gamma loses energy like twice MIP

Small Sample Data/MC comparison

$E\theta^2 < 0.0032$

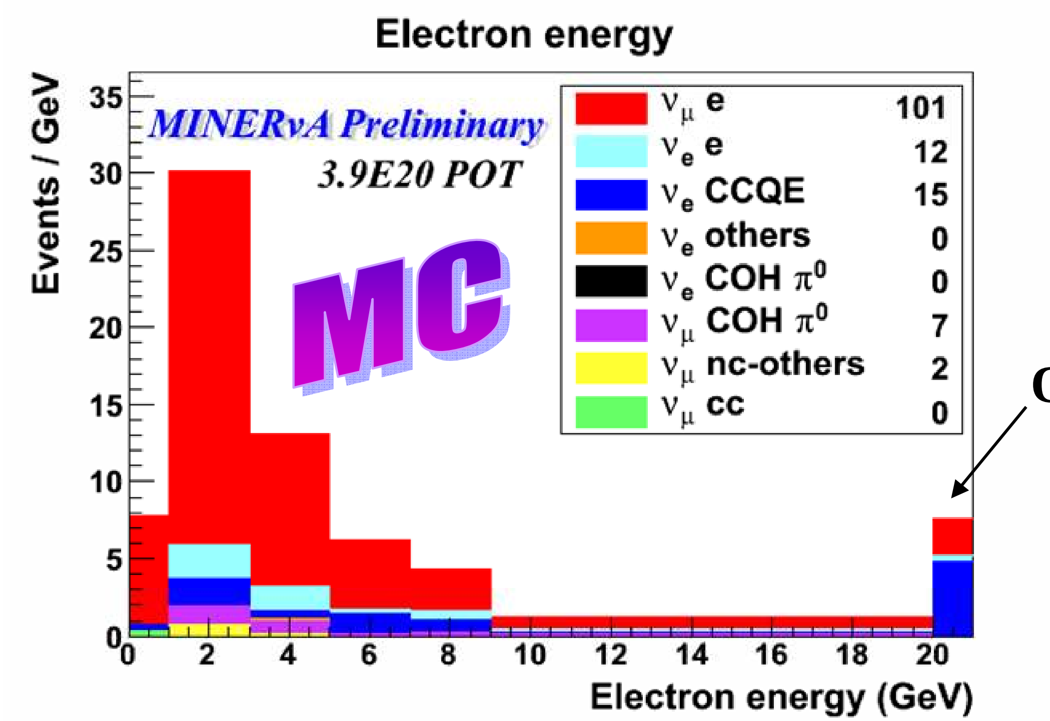


vs



- Neutrino beam, MC (left): 3.9E20 POT, data (right): 2.06E19 POT
- Small data (~ 5% to full data) is used for comparison
- Peak in low $E\theta^2$ is found in data

Electron spectrum of ν+e⁻ Elastic Scattering

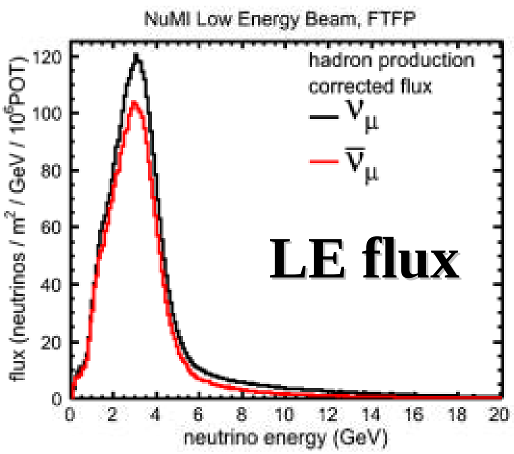


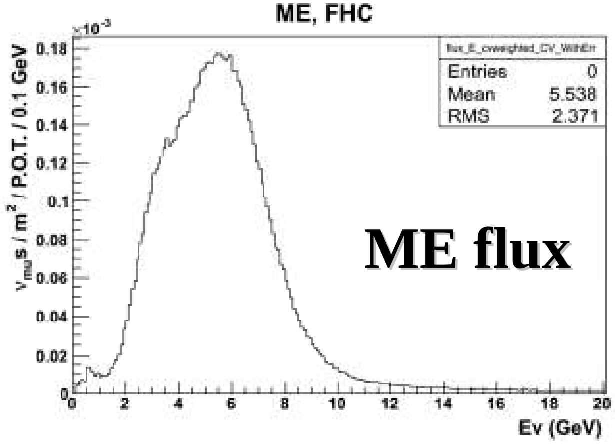
Overflowed events

- $E\theta^2<0.0032$ cut is applied to get $\nu_\mu+e^-$ rich sample
- Purity: 0.82, efficiency: 0.6
- Expected signal (**$\nu_\mu+e^-$, ν_e+e^-**) is 112 events with 24 background events for expected full data set
- It gives ~10% statistical error on absolute flux constraint

What do we expect in ME?

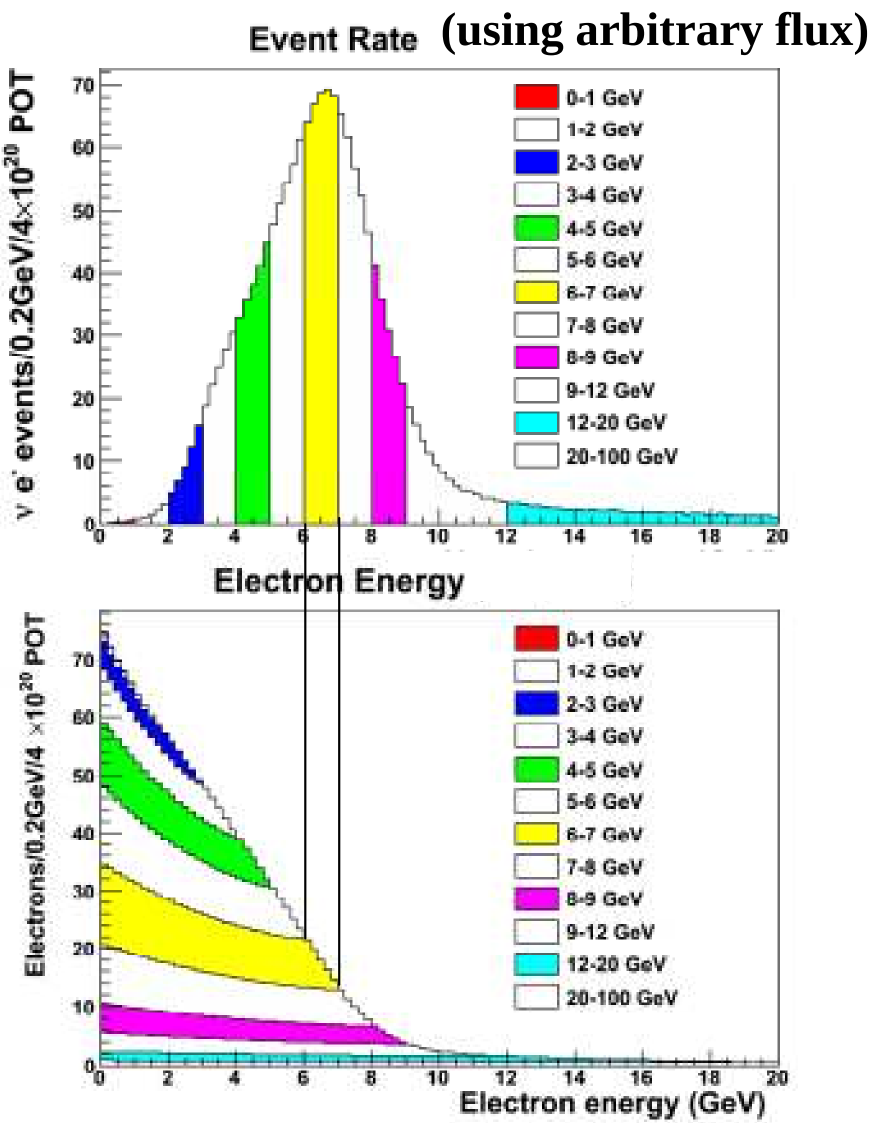
- Medium energy beam expect roughly 10 times statistics compared to low energy beam
  - Assuming:
    - low energy: 4E20 POT medium energy: 12E20 POT





- If we assume we have similar signal/background ratio as LE:
  - Signal/Background =173/47 (LE)
  - Signal/Background = 1730/470 (ME, scaled from LE)
  - Statistical error = ~2.7%

Flux Shape?



- In principle, deconvolution (electron spectrum → flux shape) is possible but it's not easy
- It's easier to compare in electron spectrum space
- Two different flux model predictions can be tested with data and we can tell which one is more consistent

Summary

- Absolute flux constraining based on $\nu_\mu + e^-$ scattering is shown useful in LE along with other methods of flux measurement
- It'll be more powerful method in higher statistics ME