Flux measurements with DUNE ND: ν+e elastic & low-ν

Chris Marshall
Lawrence Berkeley National Laboratory
Fermilab ND workshop
28 March, 2017

From 35,000 feet

- We want to measure the flux at the near detector
- Generally:

$$\Phi(E_\nu^{true}) = \frac{\int D(E_\nu^{true}, E_\nu^{reco}) N(E_\nu^{reco}) dE_\nu^{reco}}{\epsilon(E_\nu^{true})\sigma(E_\nu^{true})}$$

- Ideally, identify a subsample with known σ(E) and simple, well-understood energy smearing matrix ***D***
- Alternatively, use two samples:

  1) Known absolute σ(E)

  2) Known σ(E) *shape*, simple matrix ***D***

Sample 1: ν+e elastic scattering

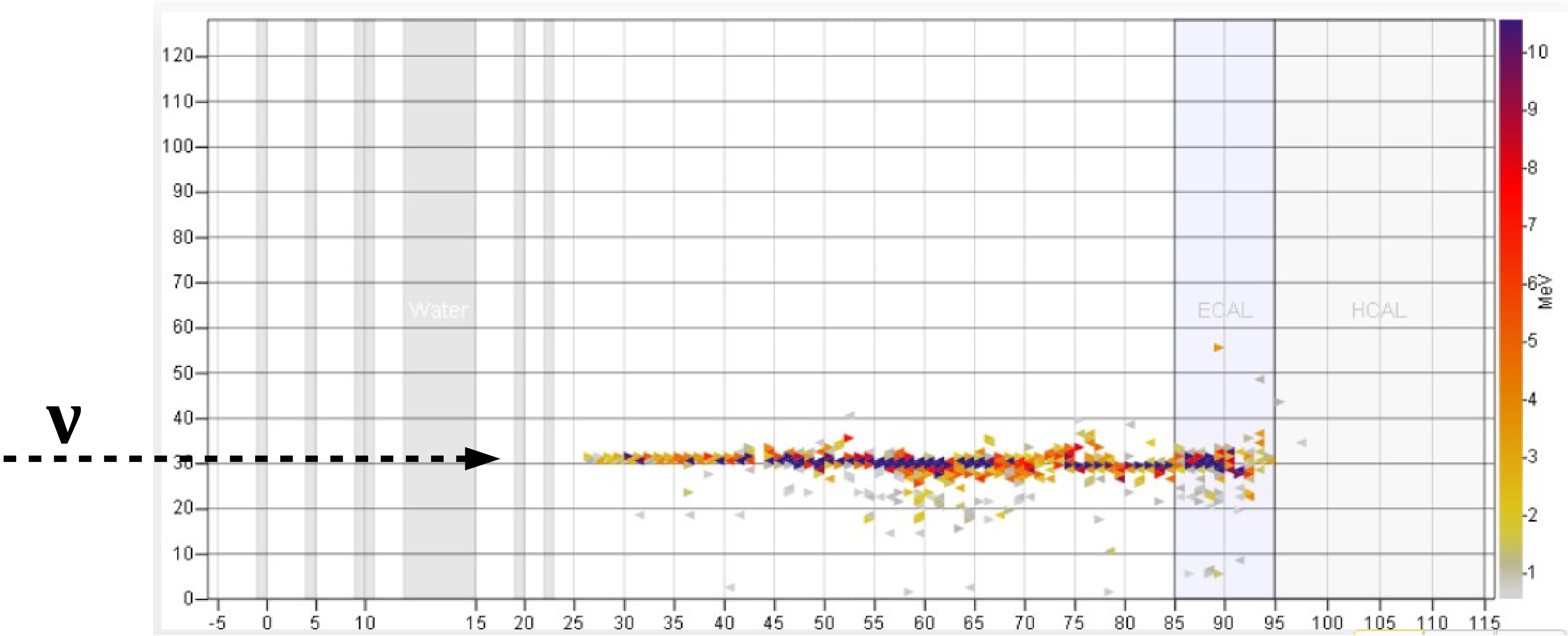
- Purely electroweak process with known cross section*:

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

- No nuclear effects!
- Straightforward measurement of total flux
- Theoretically possible to measure Φ(E), but extracting *y* is very challenging
  - More on this later

*radiative corrections need to be calculated and implemented in GENIE

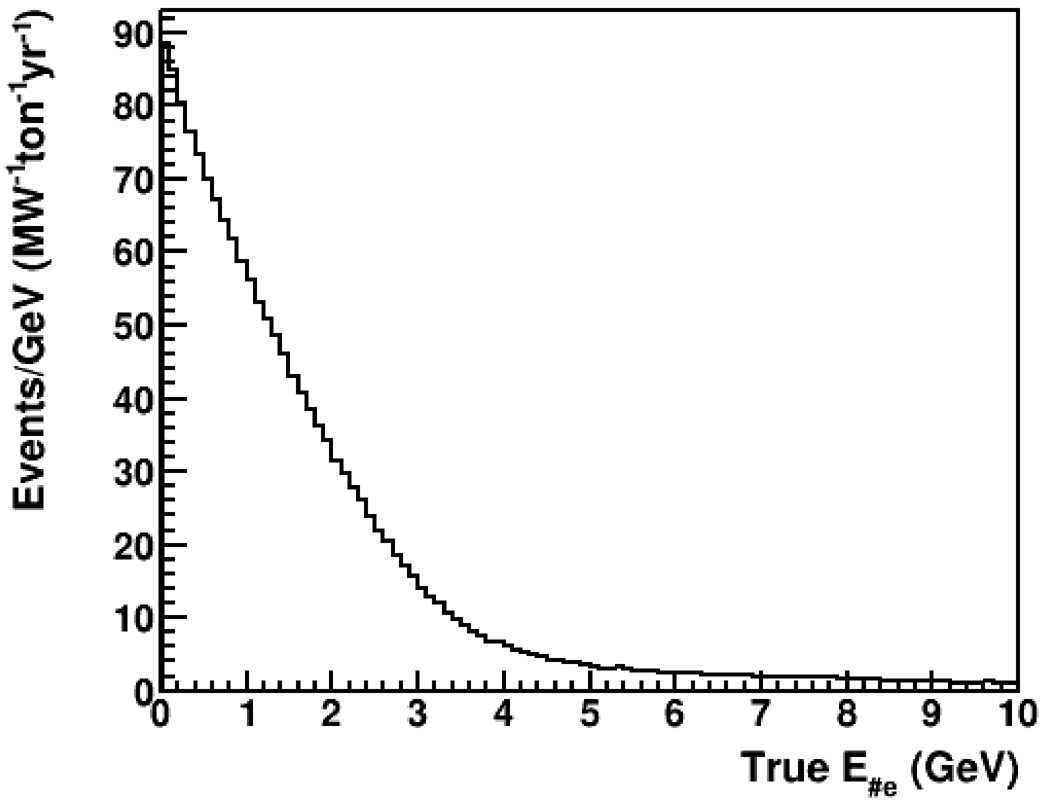
ν+e scattering



- Example from MINERvA shown
- Signal is very forward electron and no other activity
- $E_e\theta^2 = 2m_e(1\text{-}y) < 2m_e$

ν+e signal spectrum

80GeV 3-horn optimized flux
Ar target @ 574m

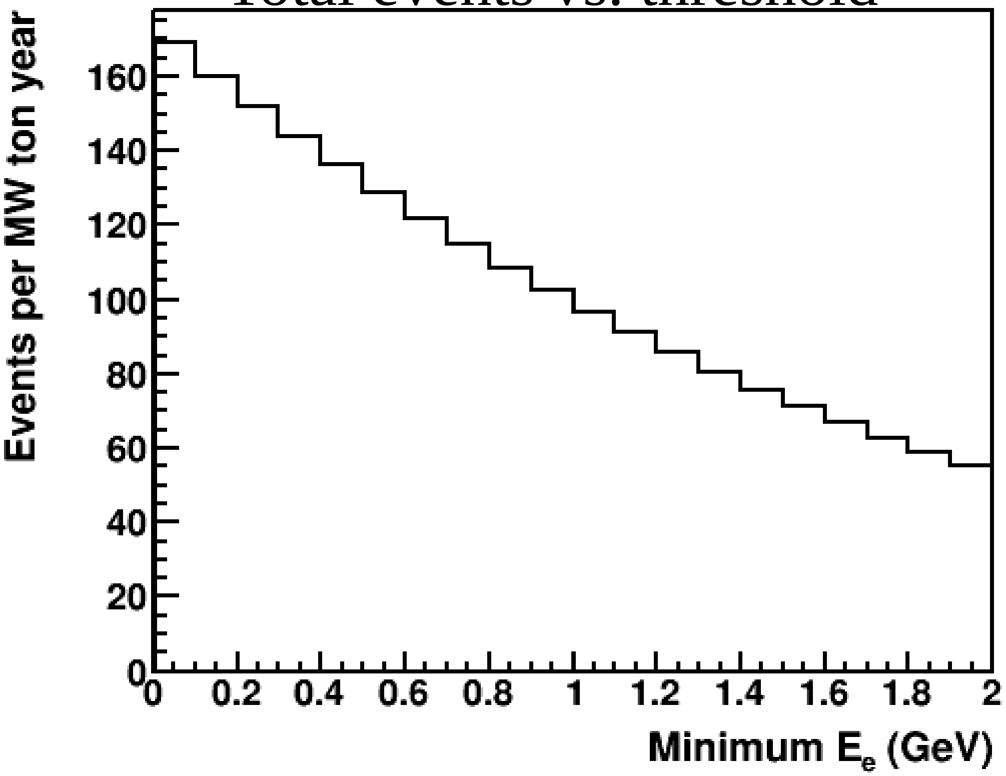


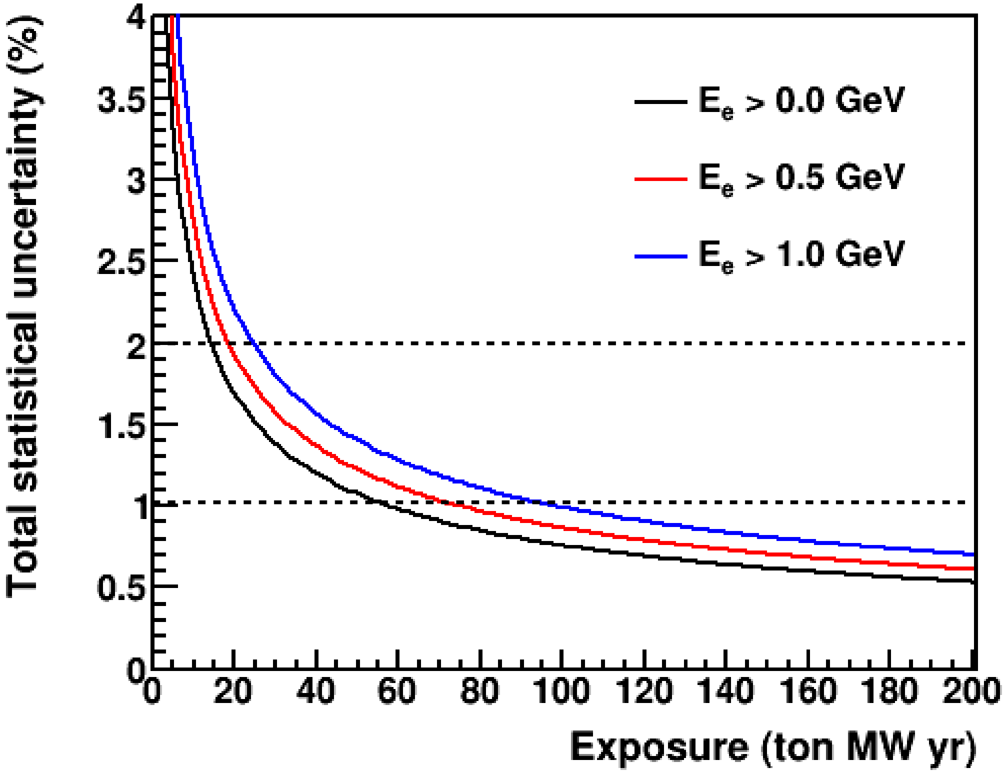
- Spectrum falls with electron energy
- Reconstruction will be very challenging at very low energies, and there will be some minimum shower energy
- In MINERvA this was 0.8 GeV, but DUNE ND should do better

ν+e event rate in DUNE flux

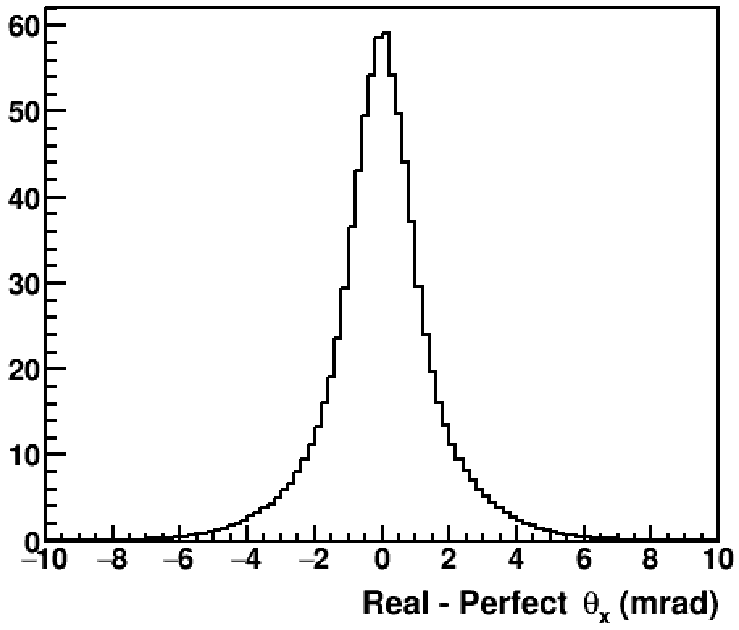
80GeV 3-horn optimized flux
Ar target @ 574m
Step function efficiency

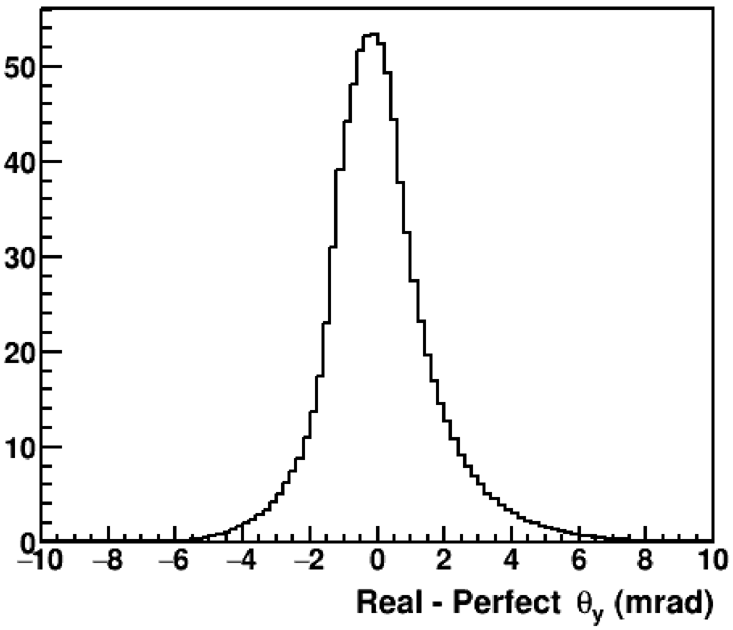
Total events vs. threshold





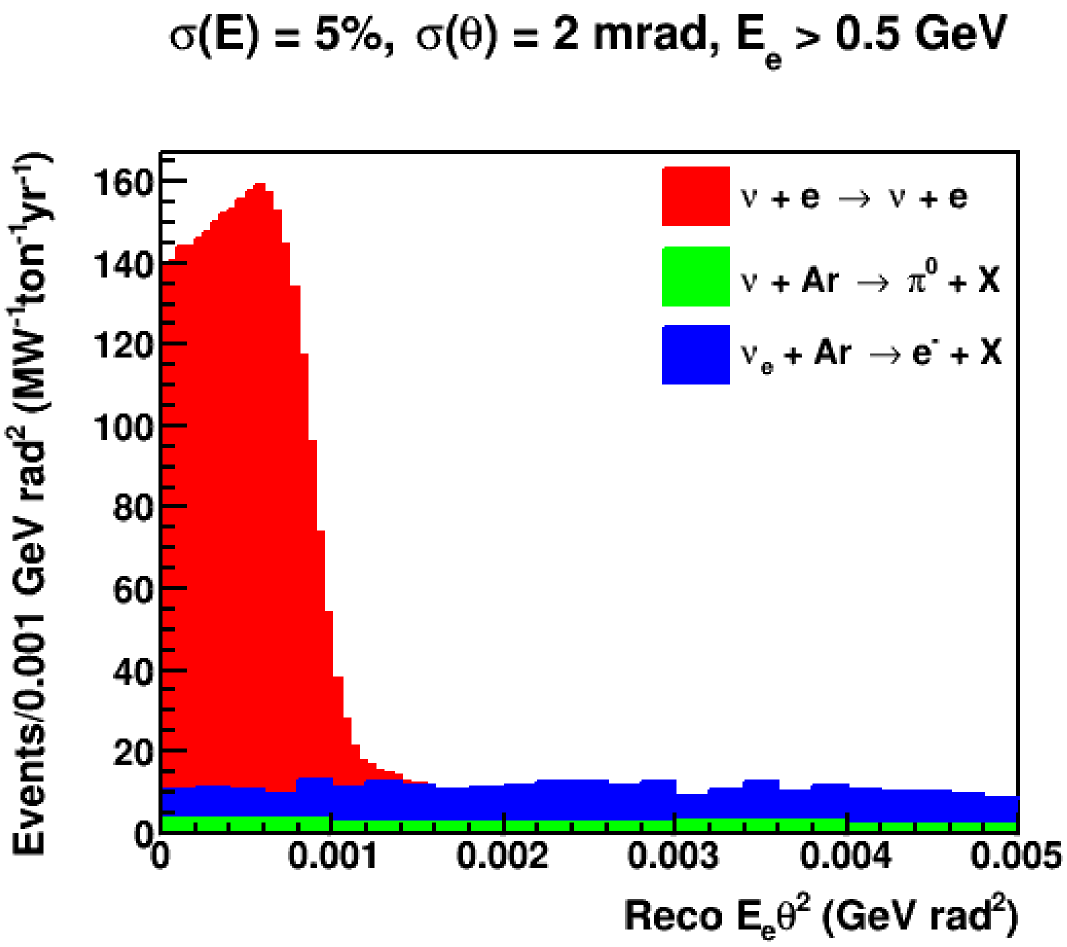
Beam angle at 574m





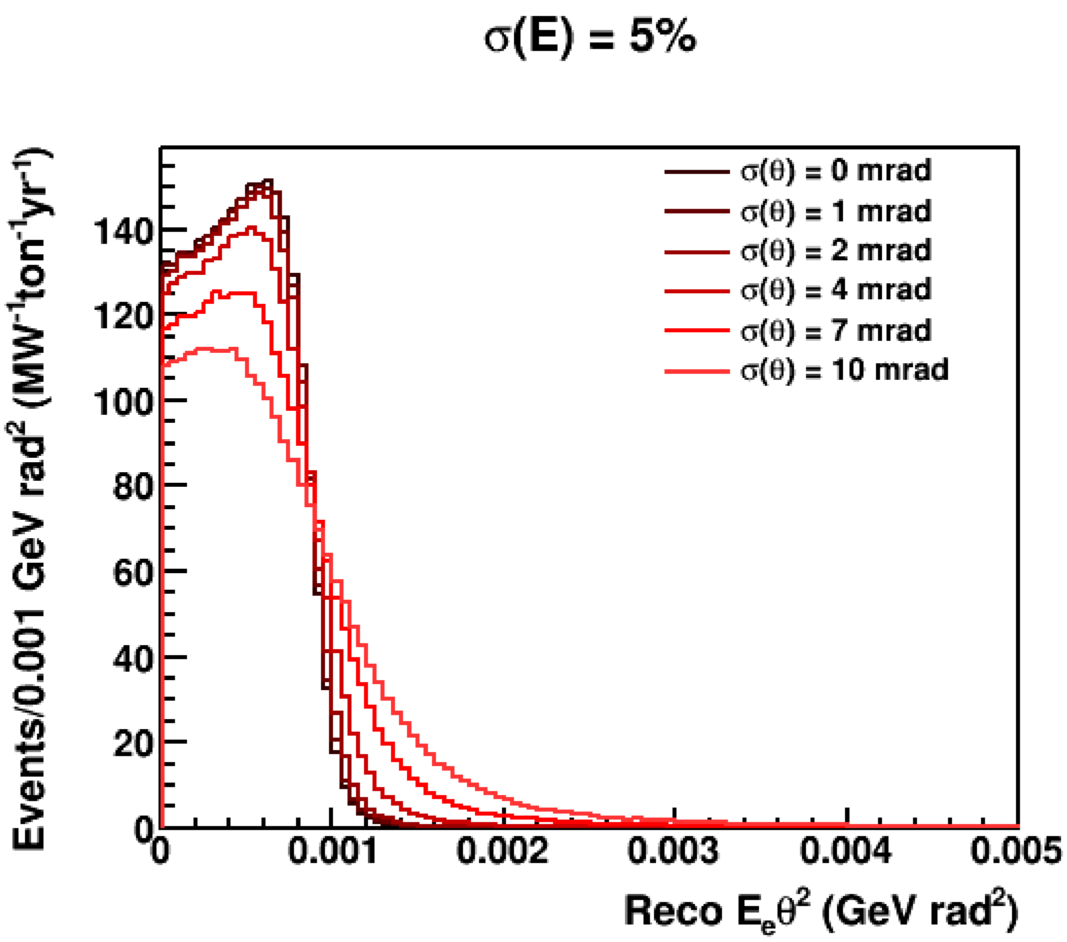
- “Perfect” is if you knew the incoming neutrino direction exactly event-by-event
- “Real” is correcting for the mean beam angle only

ν+e background



- Background events with Σ(charged hadron KE + EM total E) < 20 MeV
- π^0 events have second photon energy < 50 MeV, or photon opening angle < 2 mrad
- Assumes 10x rejection of γ (green), FGT CDR claims 100x

$E\theta^2$ cut in DUNE



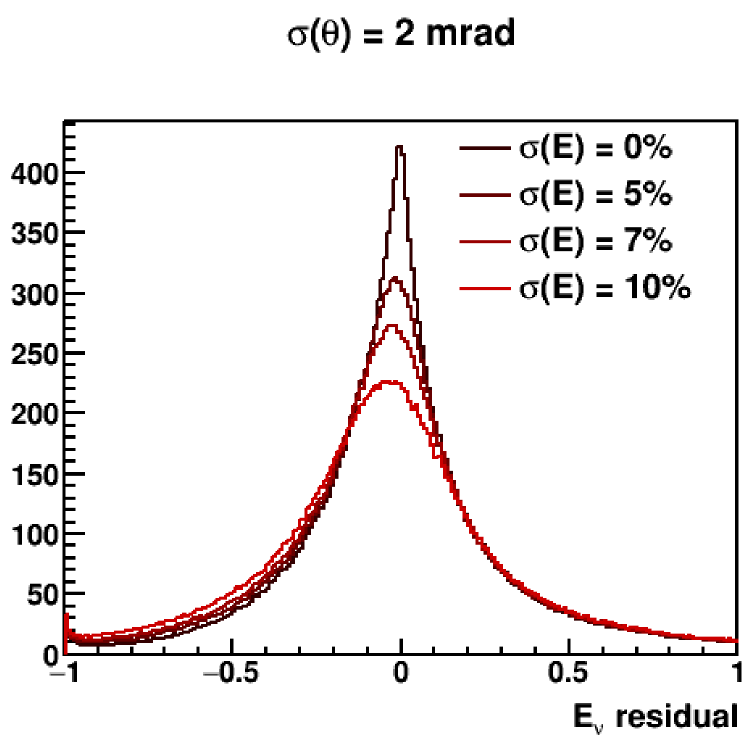
- For 0.5 GeV threshold
- Not very sensitive to electron energy resolution
- For < 4mrad angular resolution, can cut at 0.0015 and reduce background by a factor of 2 compared to MINERvA

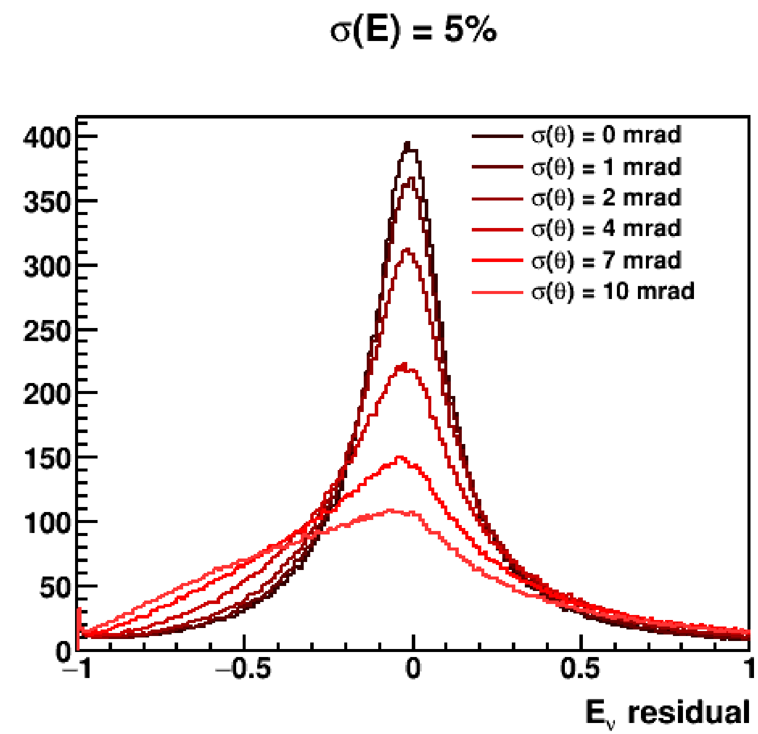
Potential for shape information

- 2-body scattering
- For known neutrino direction, can reconstruct neutrino energy from lepton kinematics
- Requires excellent angular resolution

$$E_\nu = \frac{E_e}{1 - \frac{E_e(1-\cos\theta)}{m}} \approx \frac{E_e}{1 - \frac{E_e\theta^2}{2m}}$$

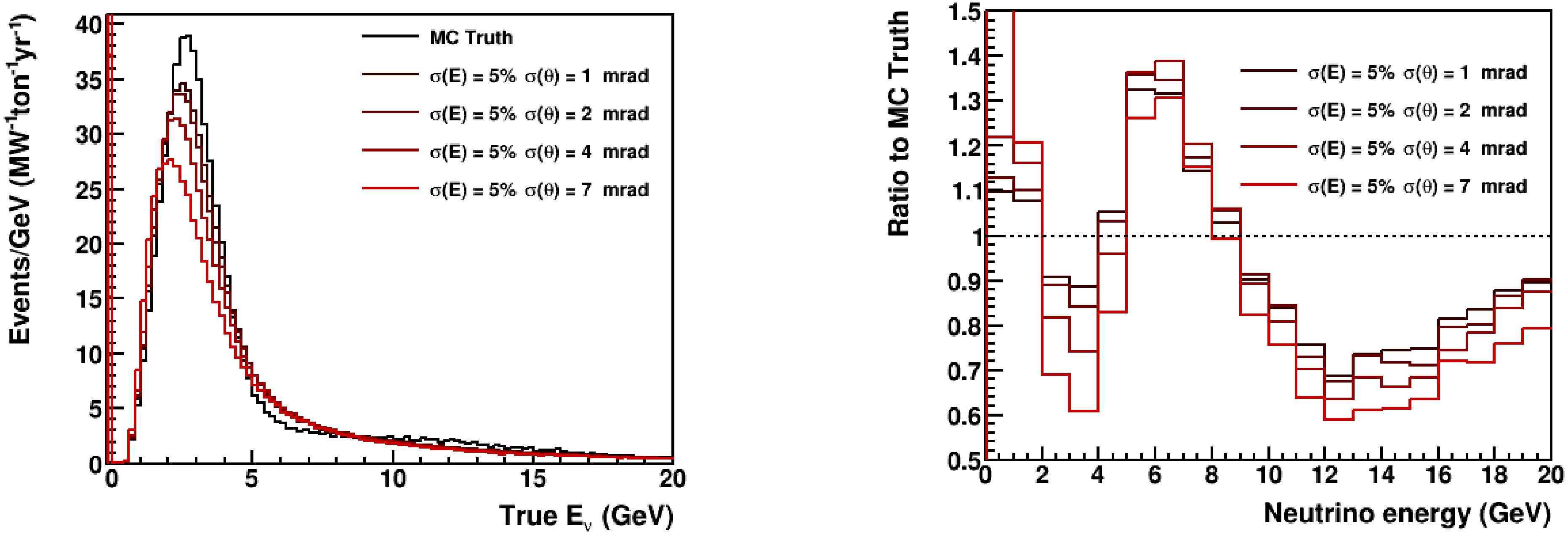
Neutrino energy residuals





- (Reco – True)/True neutrino energy
- Left: varying electron energy resolution
- Right: varying electron angle resolution

Reconstructed neutrino energy



- y reconstructs negative when $E\theta^2 > 2\ m_e$
- Even with ~2mrad angular resolution, there are ~20% corrections to the spectrum

ν+e conclusions

- 1% statistical uncertainty in ~100 ton MW yrs at 574m
- Background systematic of ~0.5% is realistic with expected improvements to generators
- Need $<$ 0.6% uncertainty on efficiency to get to 1% systematic
- 5% energy resolution and 4-7 mrad angular resolution is good enough for rate measurement
- Shape is difficult, even with 1-2 mrad angular resolution
- At 360m, intrinsic neutrino direction dispersion roughly doubles

Sample 2: Charged-current low-ν

- Differential cross section can be written as:

$$\frac{d\sigma}{d\nu} = A + B\frac{\nu}{E} - C\frac{\nu^2}{2E^2} \qquad \lim_{\frac{\nu}{E}\to 0}\frac{d\sigma}{d\nu} = A$$

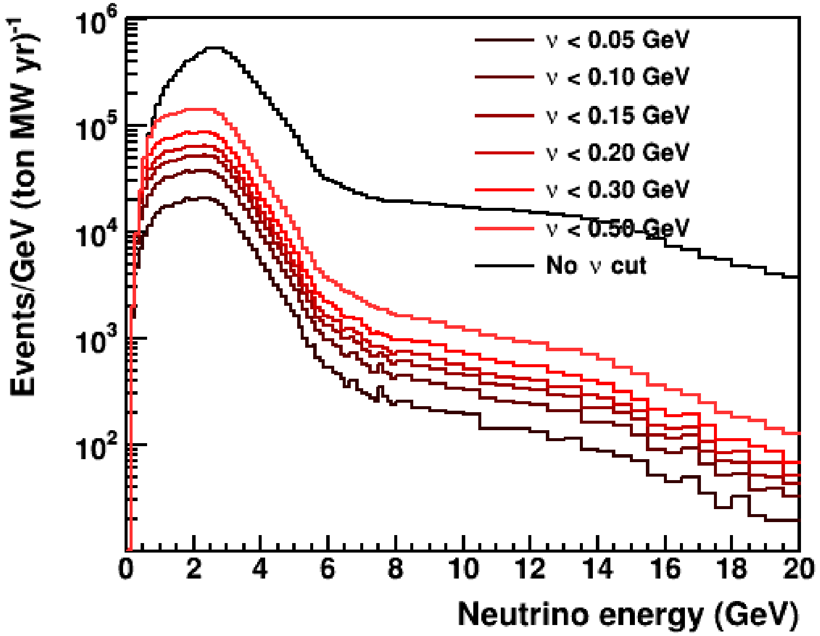
- A, B, and C are integrals of structure functions
- $\nu = E_{had} = E_{\nu} - E_{lep}$
- In practice, the low-ν sample is defined with some finite cut ν0 << E_{ν}

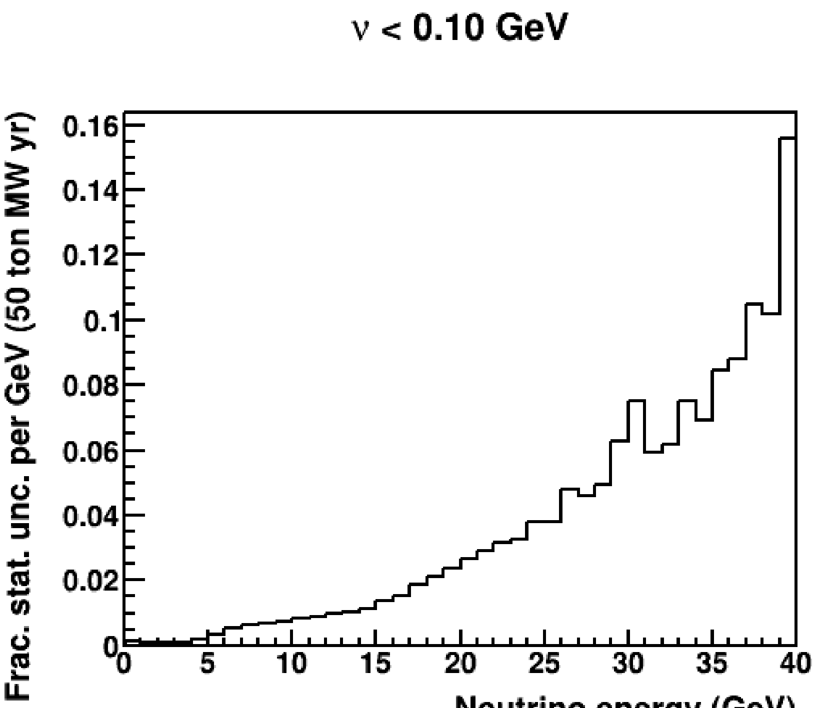
$$S(E) = \frac{\sigma(E)^{\nu<\nu_0}}{\sigma(E)^{\nu\to 0}} = \frac{\sigma(E)^{\nu<\nu_0}}{\sigma(E\to\infty)^{\nu<\nu_0}}$$

Low-ν analysis

- Used by CCFR, NuTeV, NOMAD, MINOS, MINERνA
- Challenging at low neutrino energy, because ν/E must be small
- MINOS, MINERνA used variable ν cut to increase statistics at higher E_ν, with additional systematics
- Signal is forward muon, very little else
- Systematics to worry about:
  - Theoretical correction for B and C terms
  - Hadronic energy resolution smearing events into or out of low-ν sample, especially neutrons
  - Muon energy resolution

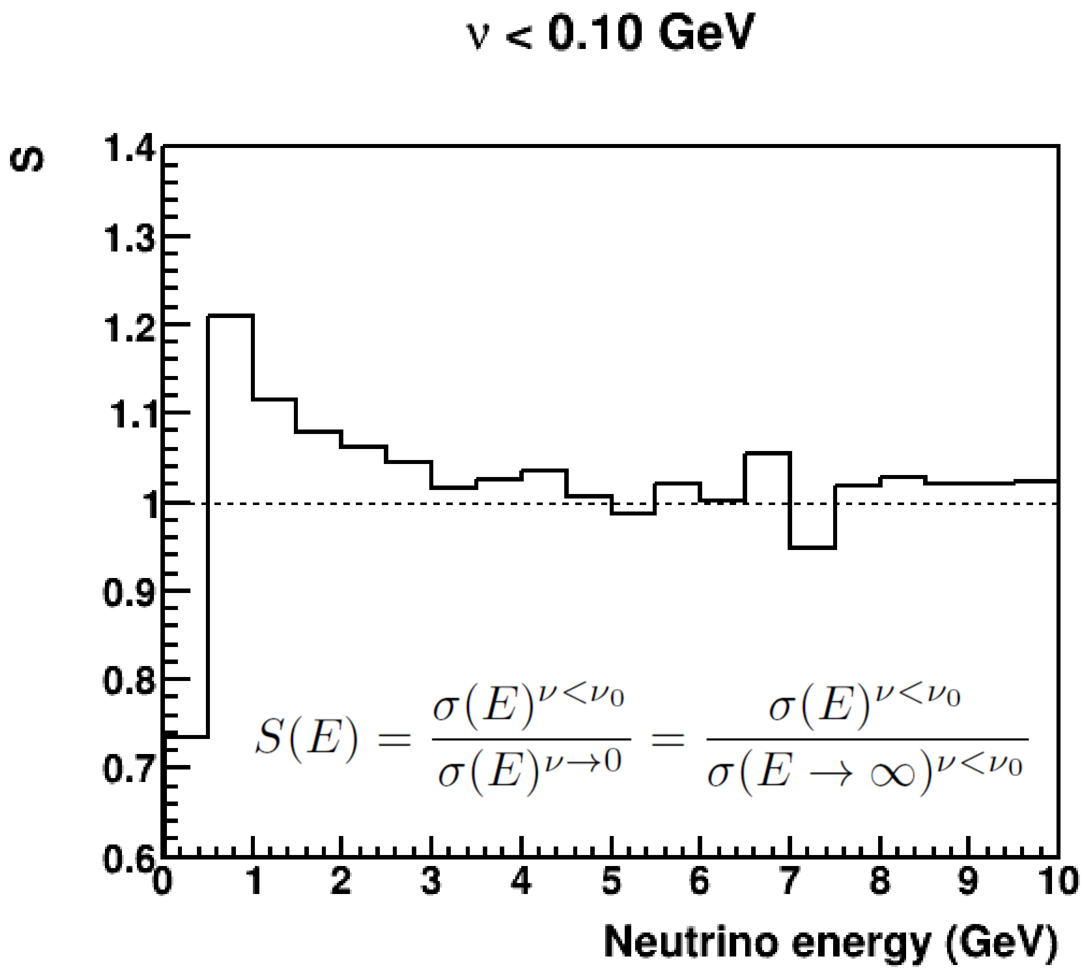
Low-ν statistics

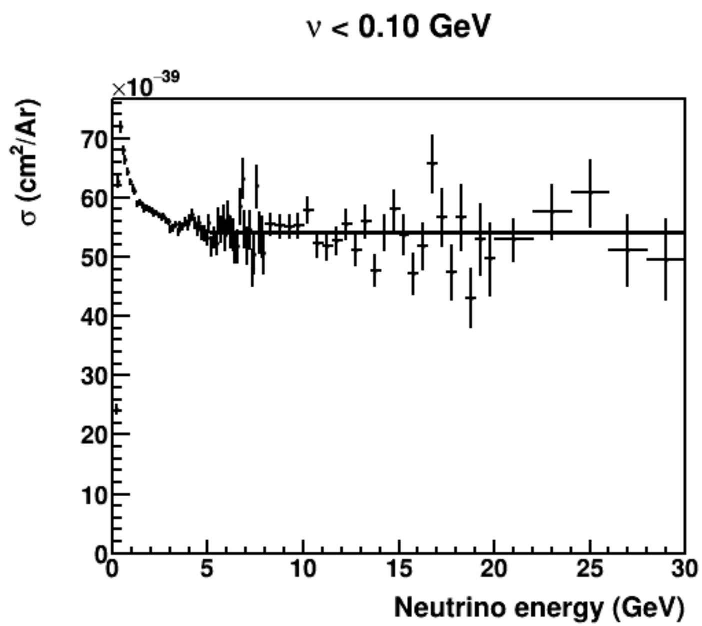




- High statistics – few 100s of events per GeV per ton MW year in the tail with ν < 100 MeV
- 50 ton MW yr exposure gives ~1-2% statistical uncertainty per GeV in the tail
- Low-ν sample will be systematics dominated in DUNE

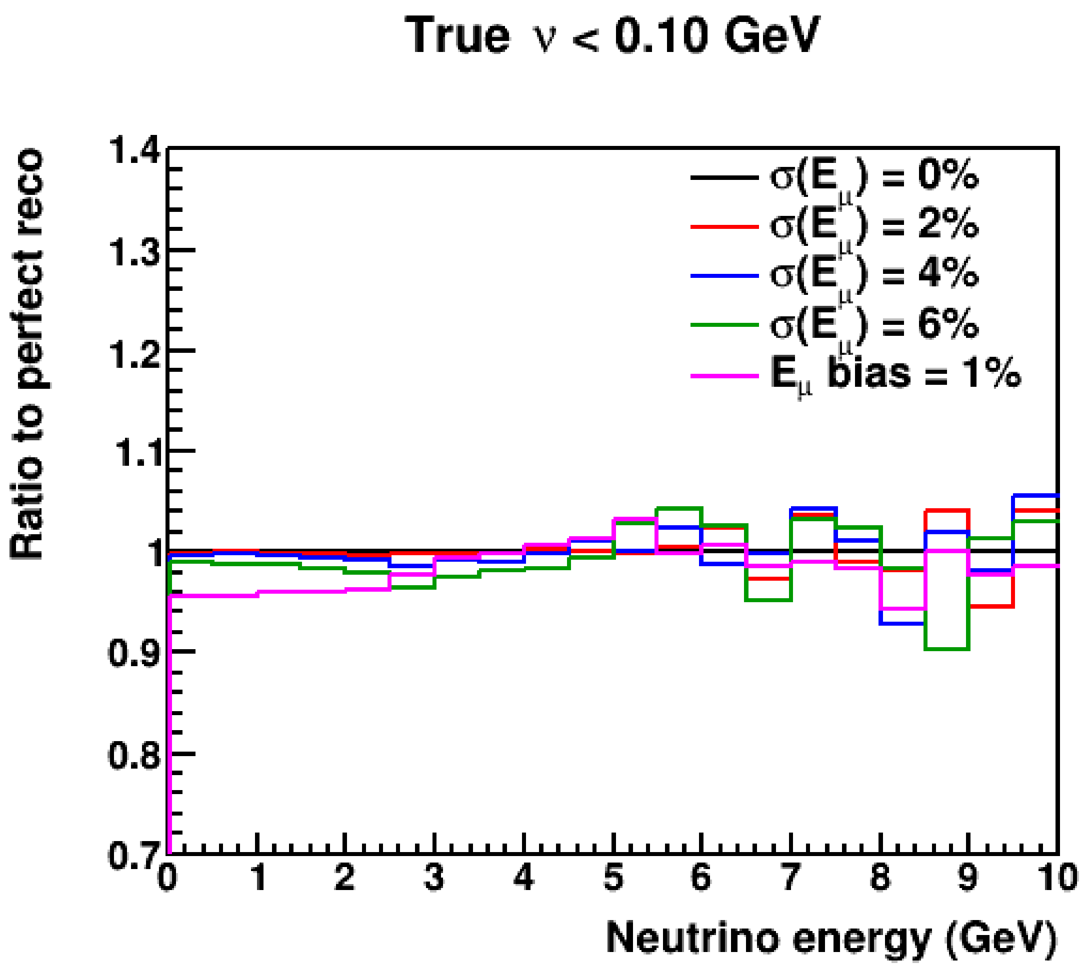
Theoretical correction





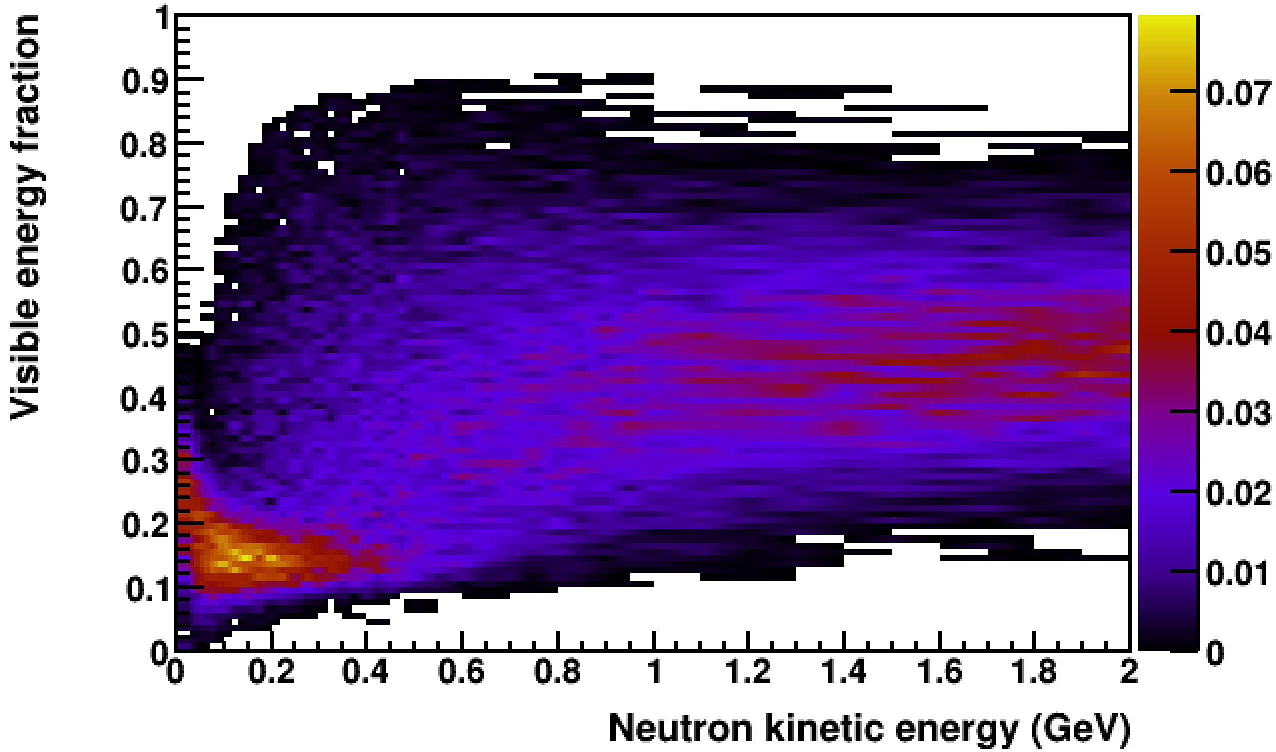
- Event distribution divided by flux prediction and high-energy cross section
- 10% correction at 1 GeV

Muon reconstruction



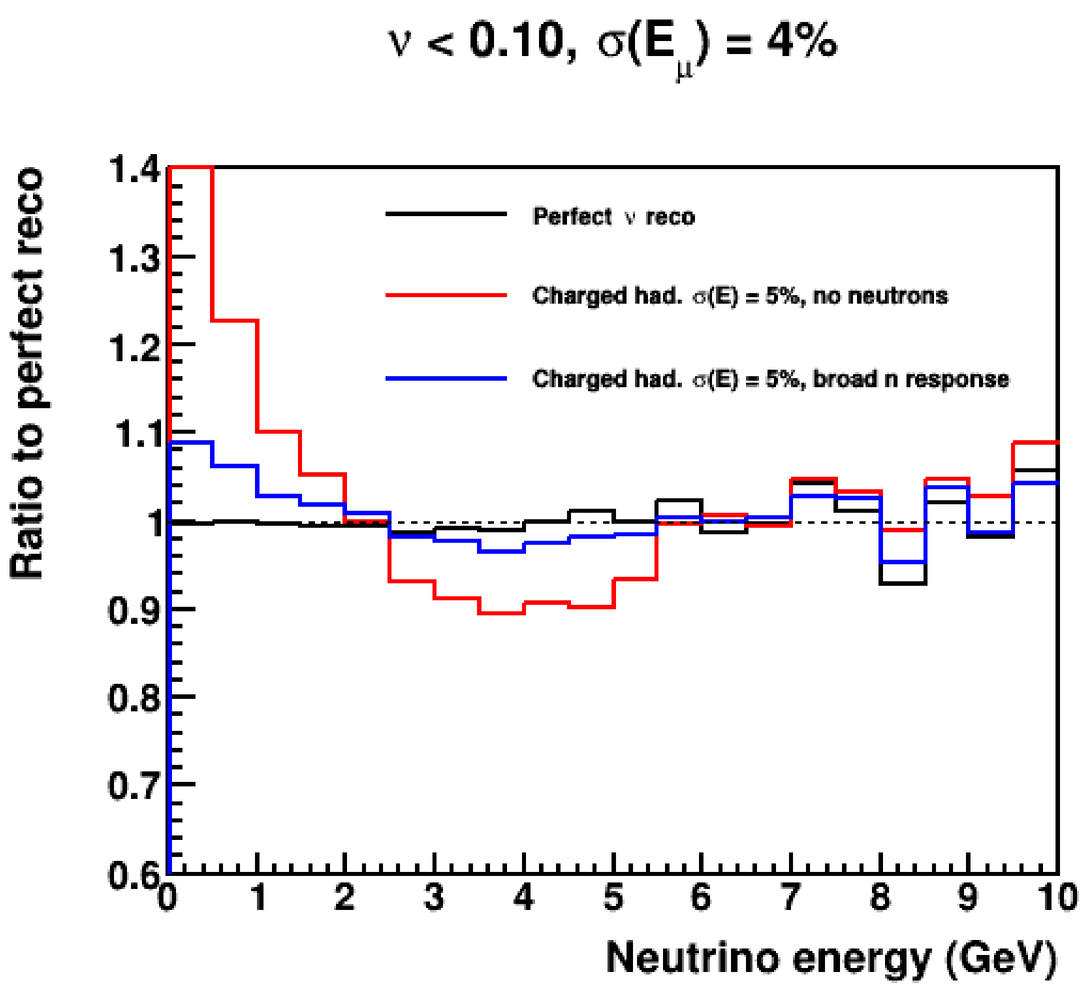
- Muon energy resolution of 4-6% gives 1-2% dip in the peak due to smear-out
- Energy scale bias of 1% is a 4% effect from 1-2 GeV
- No acceptance effects simulated – perfect acceptance is assumed

Neutrons



- Simulate neutrons in LAr in Geant4 at different initial energies
- Visible energy is all charged particle deposits, mostly due to knock-out protons

Hadron reconstruction



- Charged hadron reconstruction is a small effect
- Neutrons give a ~20% shape between 1-4 GeV
- For ~3% shape error, need uncertainty on neutron response to be < 15%

Low-ν conclusions

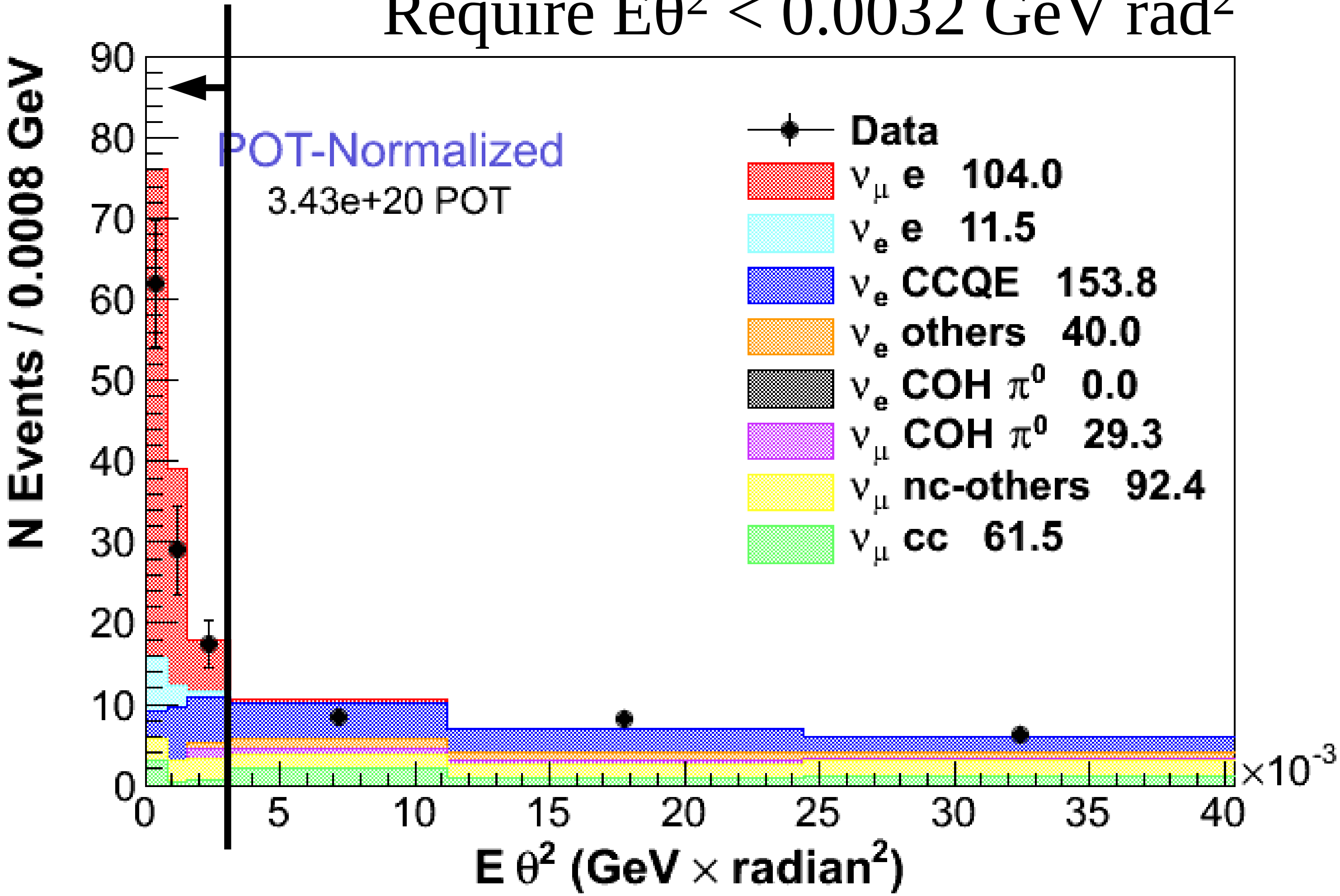
- Sufficiently high statistics to use flat ν < 0.1 GeV cut
- Theoretical correction is ~10% in oscillation region
- For 3% shape uncertainty, need:
  - Uncertainty on theory correction < 20%
  - Uncertainty on muon energy scale normalization < 1%
  - Uncertainty on neutron response < 15%

Backups

- There are hundreds of interesting plots in the zip files associated with this talk

MINERvA $E\theta^2$ cut

Require $E\theta^2 < 0.0032$ GeV rad^2



MINERvA

ν+e systematics

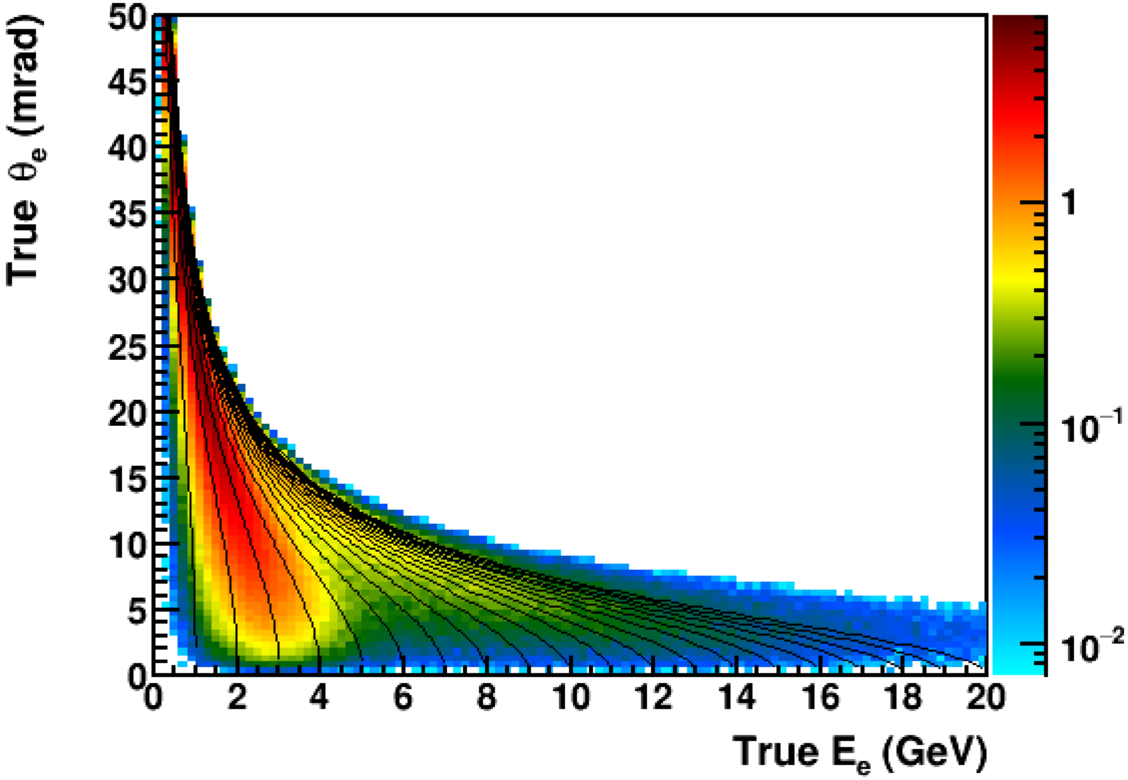
- MINERvA LE measurement (124 events) had 5.1% systematic with 12.2% statistical uncertainty
- Leading systematics are background prediction (ν_e CCQE Q^2 shape, NC π^0), and detector (efficiency vs. electron energy)
- Must reduce:
  - Background uncertainties
  - Detector uncertainties

Source	Fractional Uncertainty
Flux (simulated background)	0.2%
GENIE (not including CCQE)	2.3%
CCQE shape	3.1%
Beam angle	0.2%
Electromagnetic energy scale	1.8%
Reconstruction Efficiency	2.7%
Total Systematic Uncertainty	5.1%
Statistical Uncertainty	12.2%

ν+e background systematics

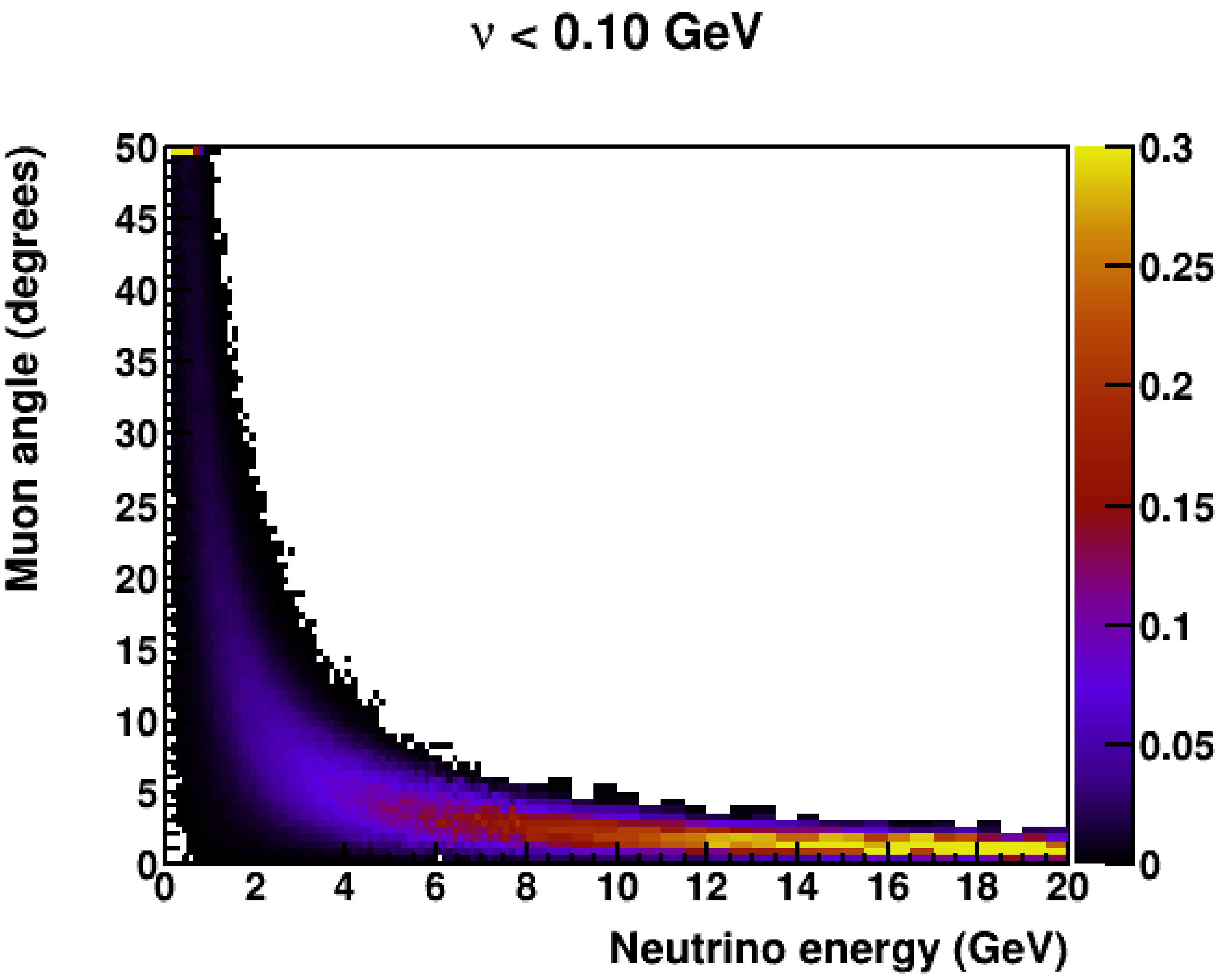
- 90% sample purity with $E\theta^2 < 0.0015$
  - Background reduced by ~2x compared to MINERvA
- Need uncertainty on ν_e CCQE extrapolation from mid-$E\theta^2$ sideband reduced by ~2x compared to MINERvA to get background uncertainty < 0.5%
  - Doable with improved models for 2p2h, etc.
- If detector is magnetized, NC π^0 should be negligible
- For 1% total systematic, need uncertainty on efficiency < 0.6%

Energy vs. angle



- Lines of constant neutrino energy
- Beam angle smearing only – perfect detector

Acceptance



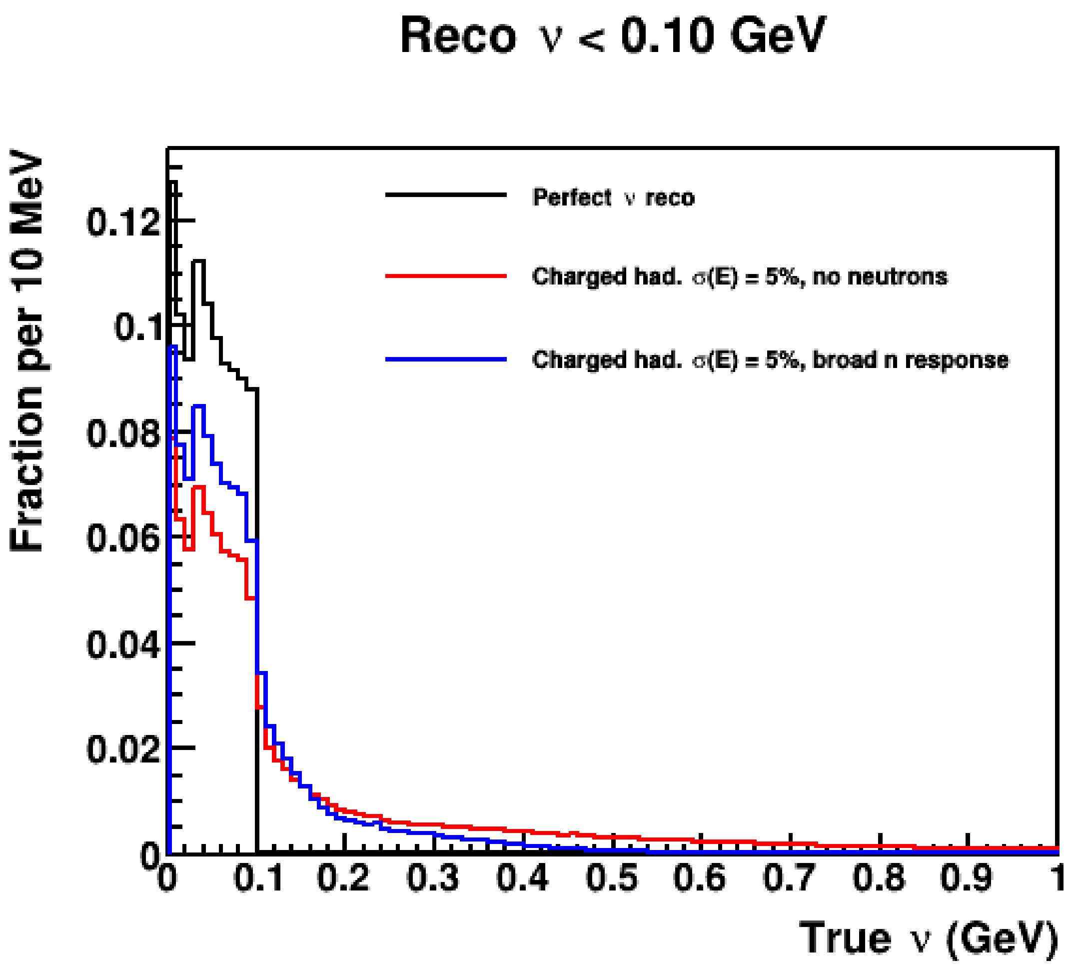
- Column-normalized to unity
- Very forward for $E_\nu > 2$ GeV
- Down to 1 GeV muon angle goes up to ~45 degrees

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

Detector effects

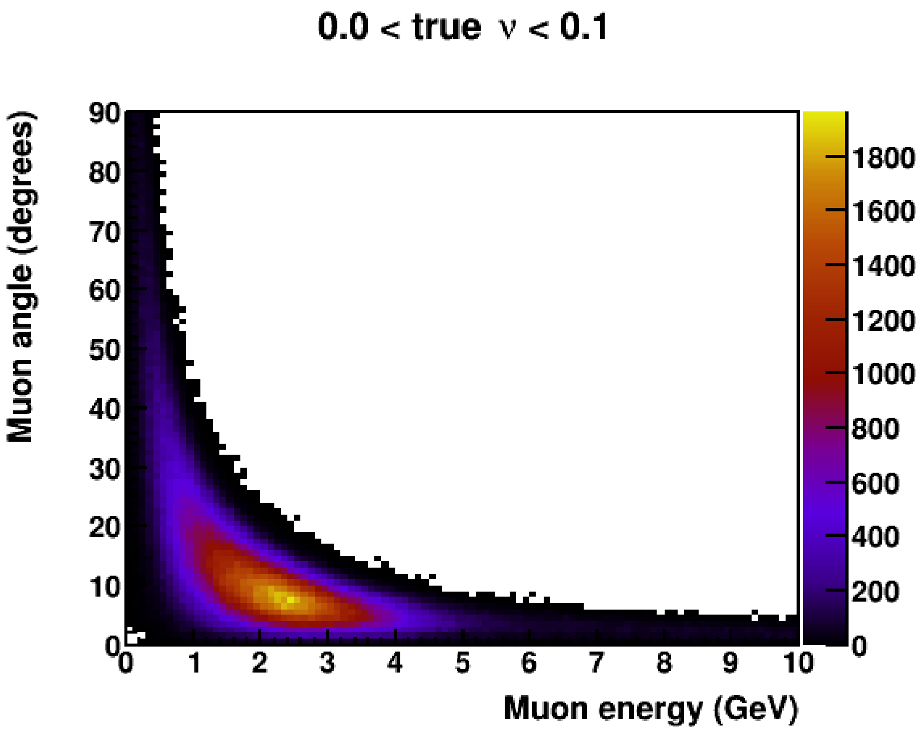
- Used fast MC to study these detector effects:
  - Finite muon energy resolution
  - Muon energy scale bias
  - ν reconstruction: $\sigma(p) = 5\%$ for p/π, $\pi^\pm$ KE only, no neutrons
  - Add neutrons based on Geant4 LAr study
- Plot event rate / (flux prediction * high-energy cross section * S)
- Takes out all cross section effects – result is 1.0 for perfect detector

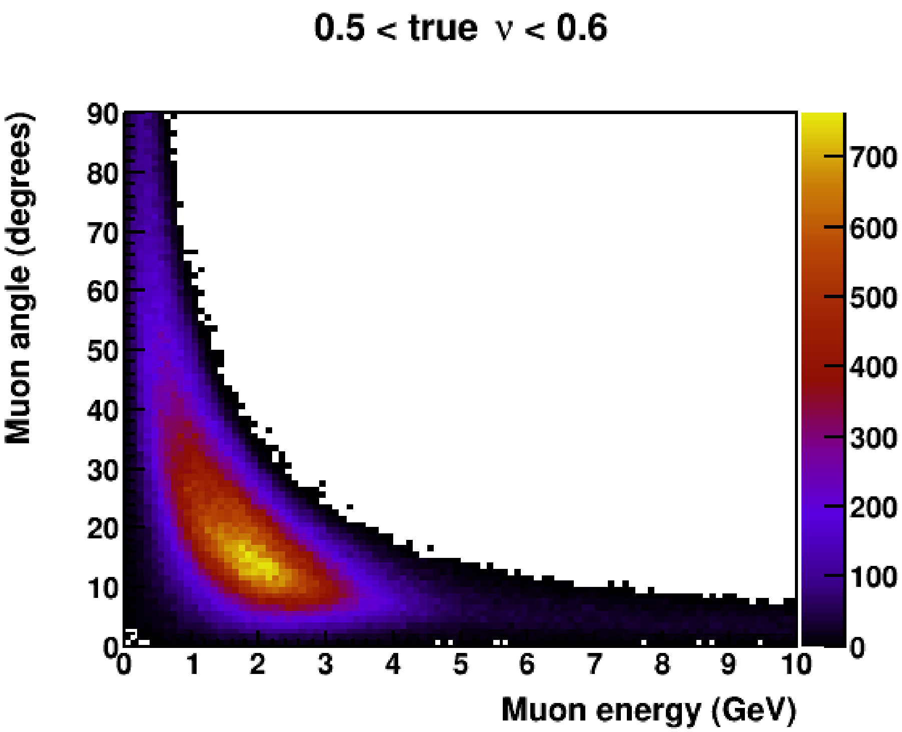
Hadron reconstruction



- For cut on reco $\nu < 0.1$ GeV, true ν distributions for different assumptions
- Red loses all neutron energy
- Blue keeps energy based on previous slide

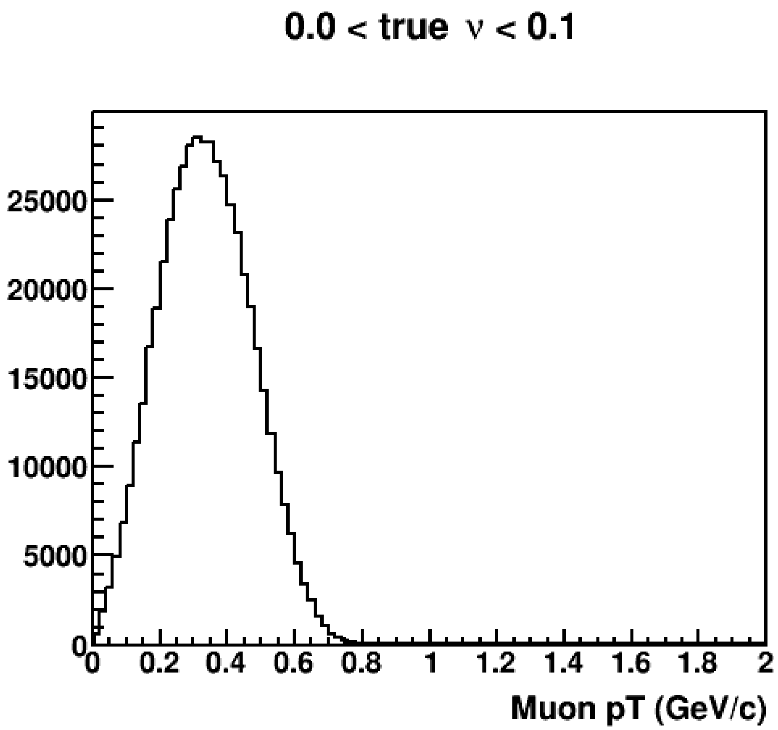
Muon kinematics

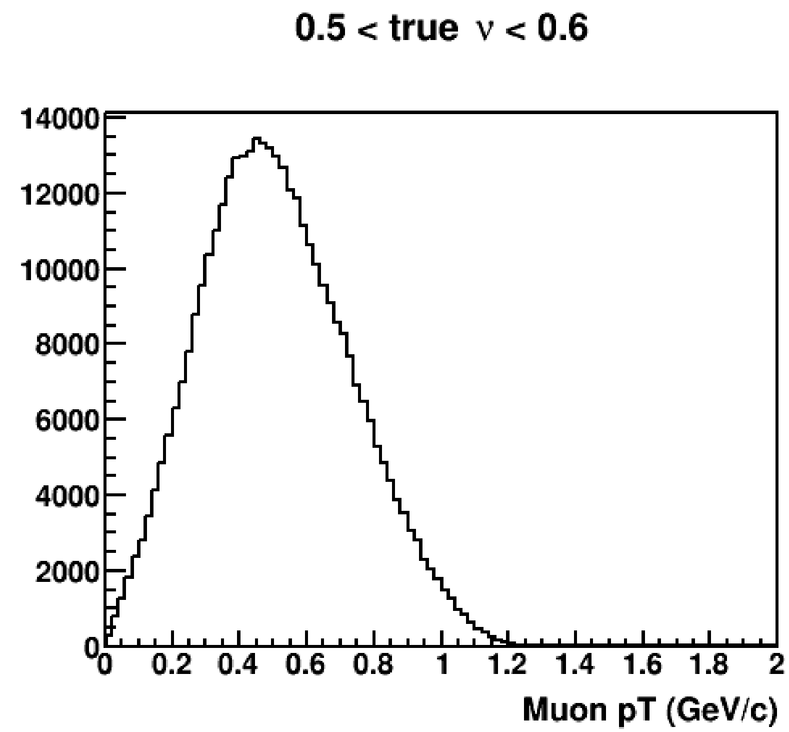




- To first order, for low-ν sample, reco $E_\nu \approx E_\mu$
- Could you reject high-energy neutrons with missing p_T?

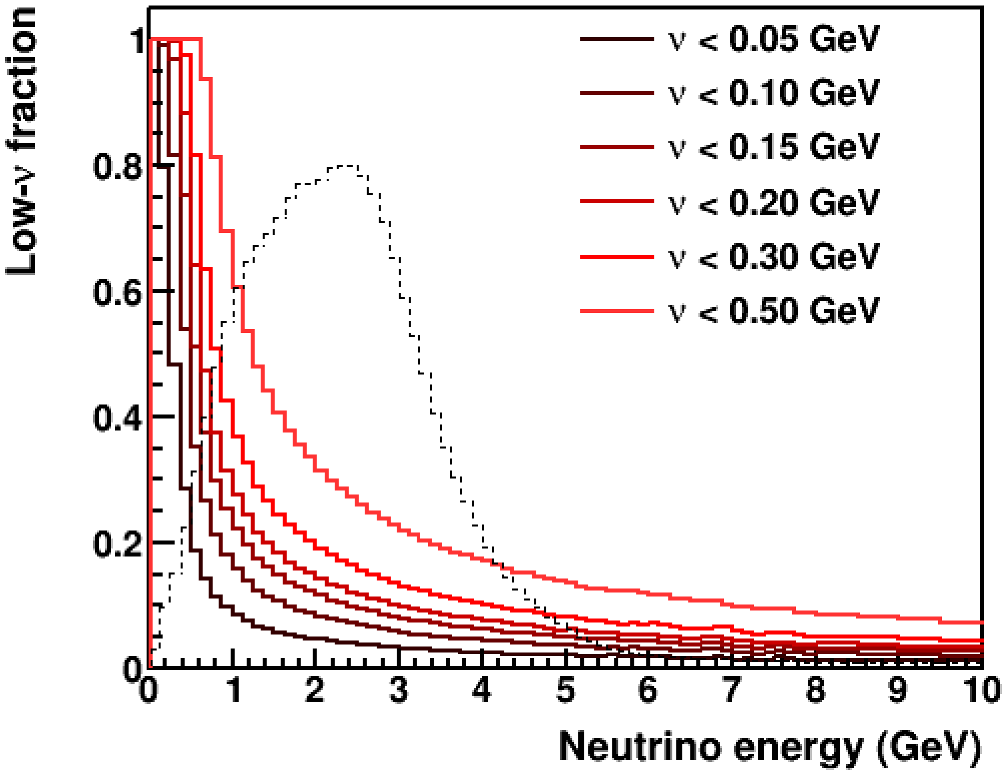
Muon kinematics





- Could reject events with muon p_T above ~0.7 GeV, but that would only reject ~20% of events with missed neutrons and true ν ~ 0.5 GeV

Low-ν fraction



- Fit every event once
- Use separate low-ν sample that is not used to constrain ν-Ar cross sections
- For ν < 0.1 GeV, low-ν sample is 5-10% of CC sample in DUNE flux