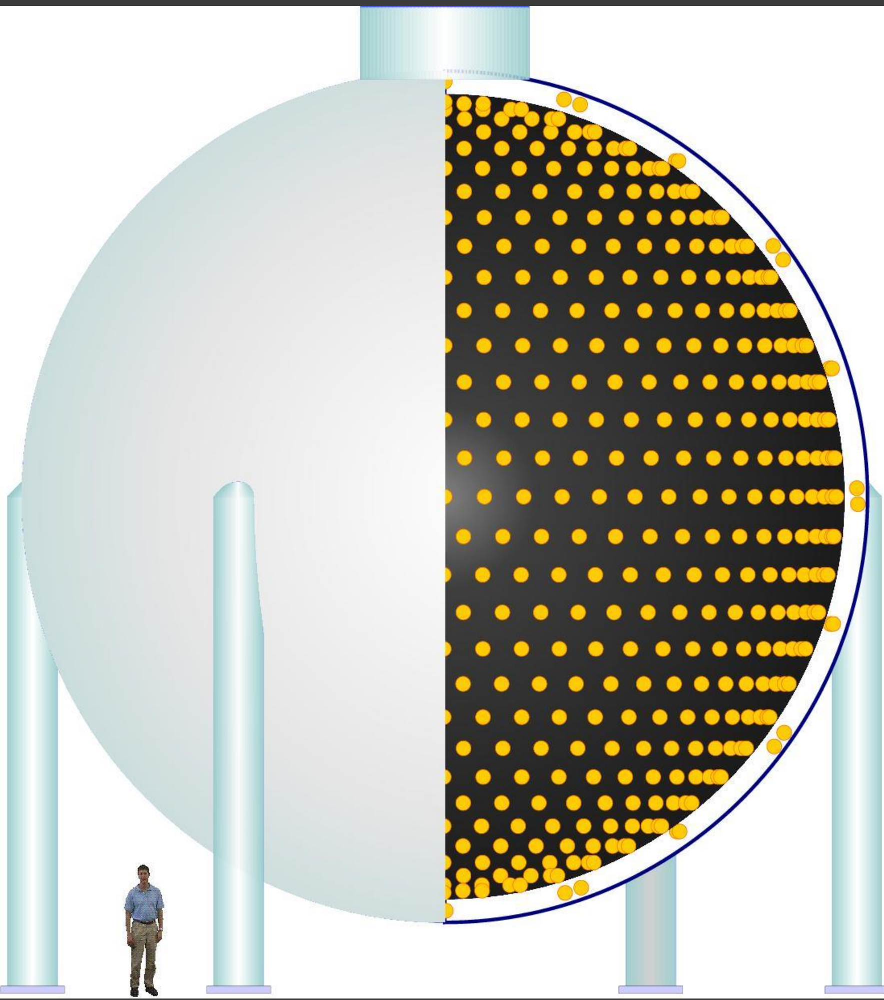
MiniBooNE Reconstruction Overview

M. Tzanov
Louisiana State University

FroST-II Workshop, Mainz, Germany
October 22-24, 2016

The MiniBooNE Detector



A. A. Aguilar-Arevalo et al., NIM A599, 28 (2009)

- 541 meters downstream of target
- 3 meter overburden
- 12 meter diameter sphere

  (10 meter “fiducial” volume)

  - Filled with 800 t

    of pure mineral oil (CH_2)

    (Fiducial volume: 450 t)

  - 1280 inner phototubes,

    240 veto phototubes

LOUISIANA STATE UNIVERSITY

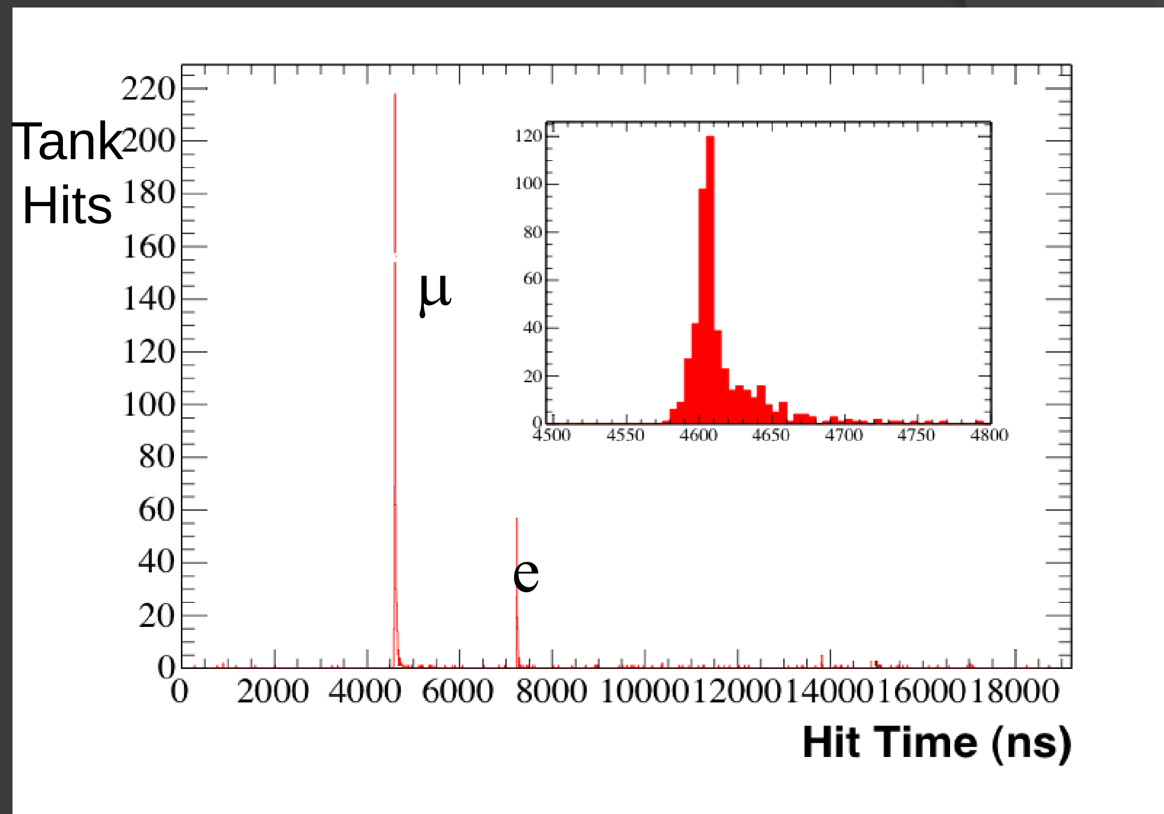
Subevents

A 19.2 μs beam trigger window

- encompasses the 1.6 μs spill
- starts 4 μs before the beam

Subevent:
Multiple hits within a ~100 ns window form "subevents"

Most events are from ν_μ CC interactions (ν+n $\rightarrow$ μ+p) with characteristic two "subevent" structure from stopped $\mu \rightarrow \nu_\mu \nu_e e$



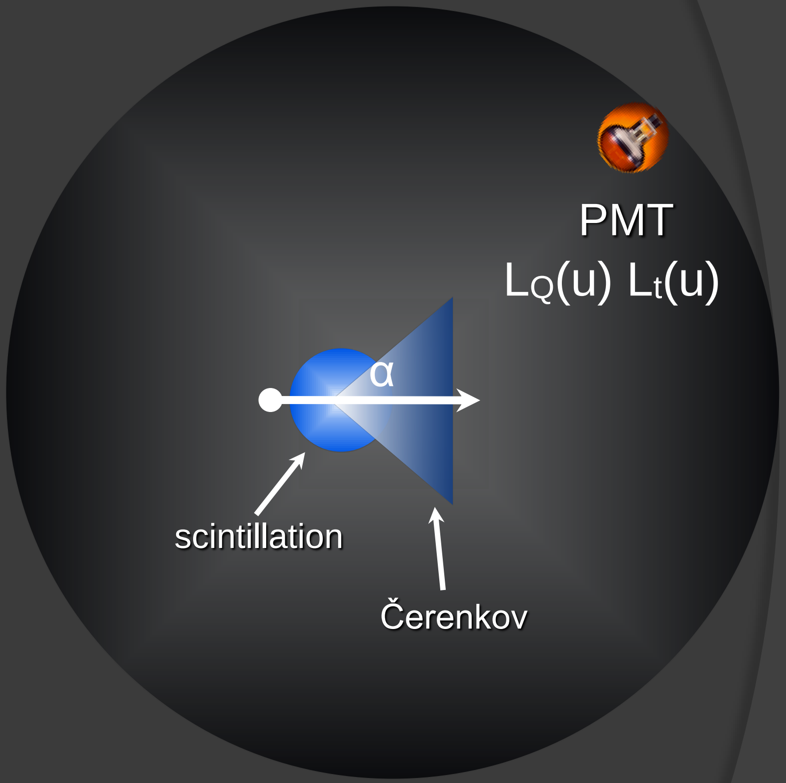
LSU
LOUISIANA STATE UNIVERSITY

Track Reconstruction

- A particle is parametrized as a "track" in the oil.
  - Vertex: (x,y,z)
  - Time: (t)
  - Direction: (θ,φ)
  - Kinetic energy: (E)

- At each point of the track scintillation and Čerenkov light is produced. This depends on the type of particle.

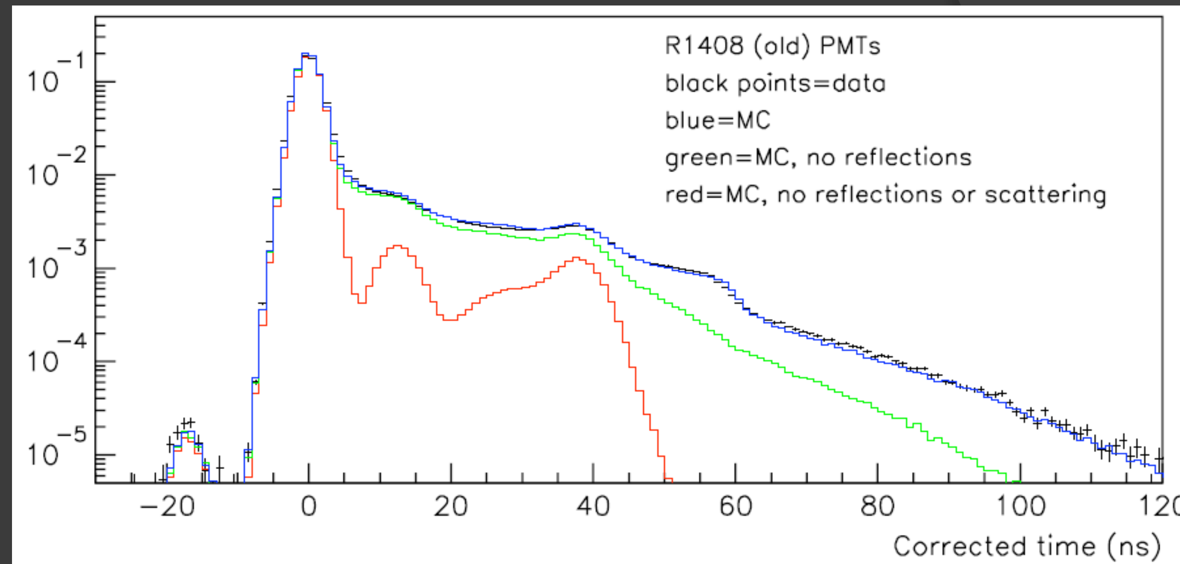
- This light propagates through the mineral oil to the PMTs.

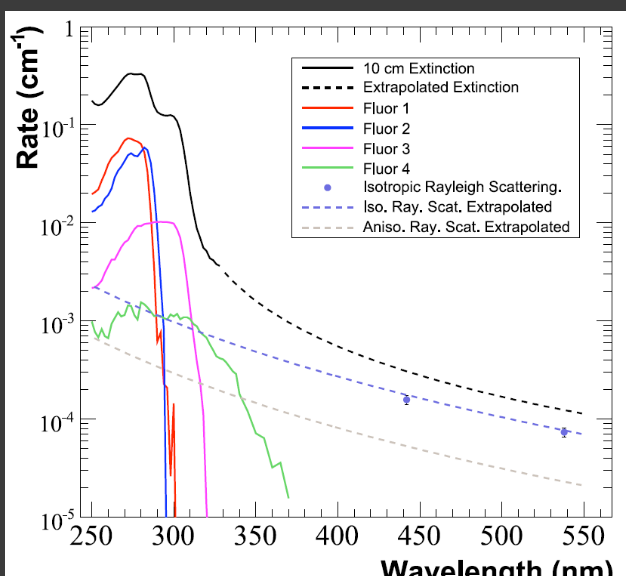


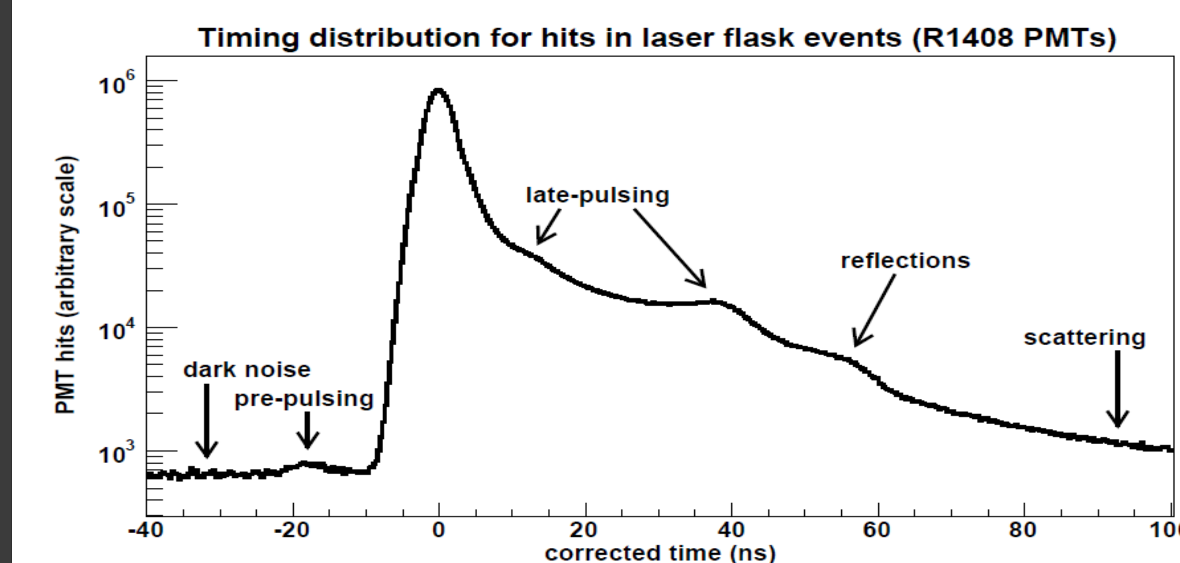
R.B. Patterson et al., Nucl. Instrum. Meth. A608, 206 (2009)

Optical Model

For the first 2-3 years MB was mainly an experiment in optics.

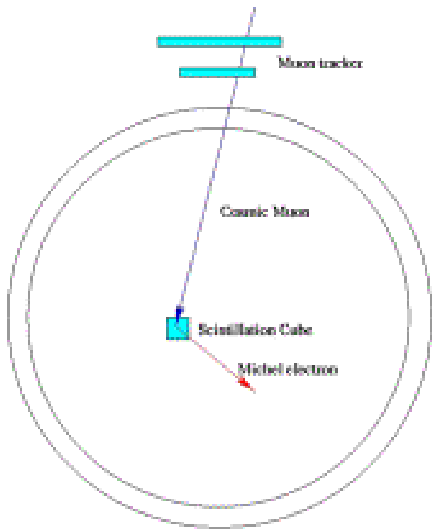


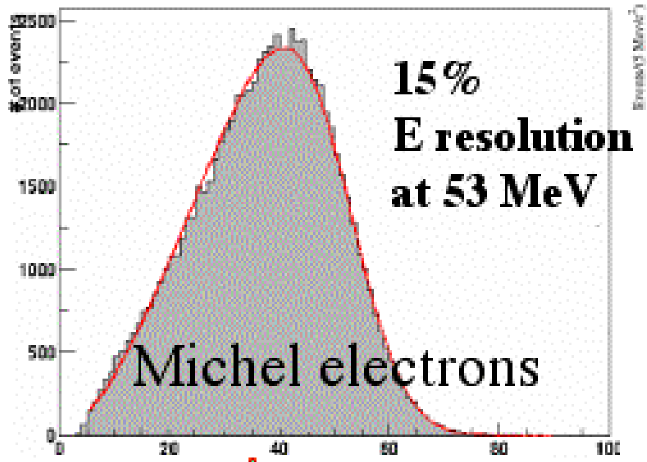


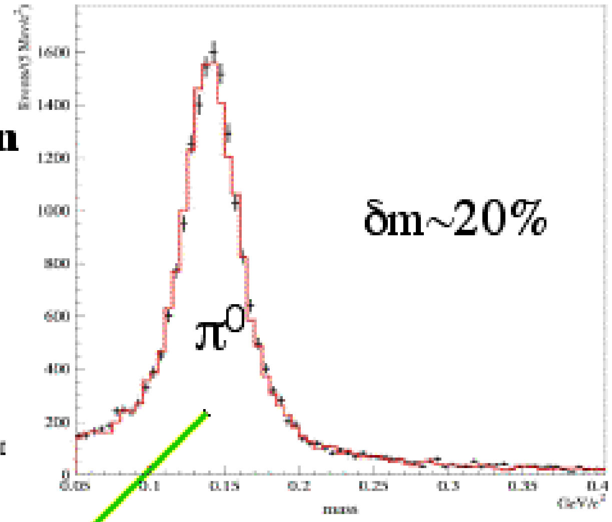


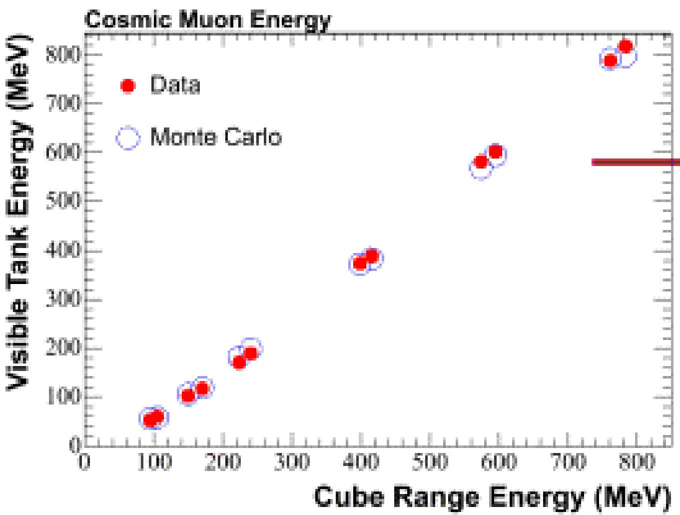
Detector Callibration

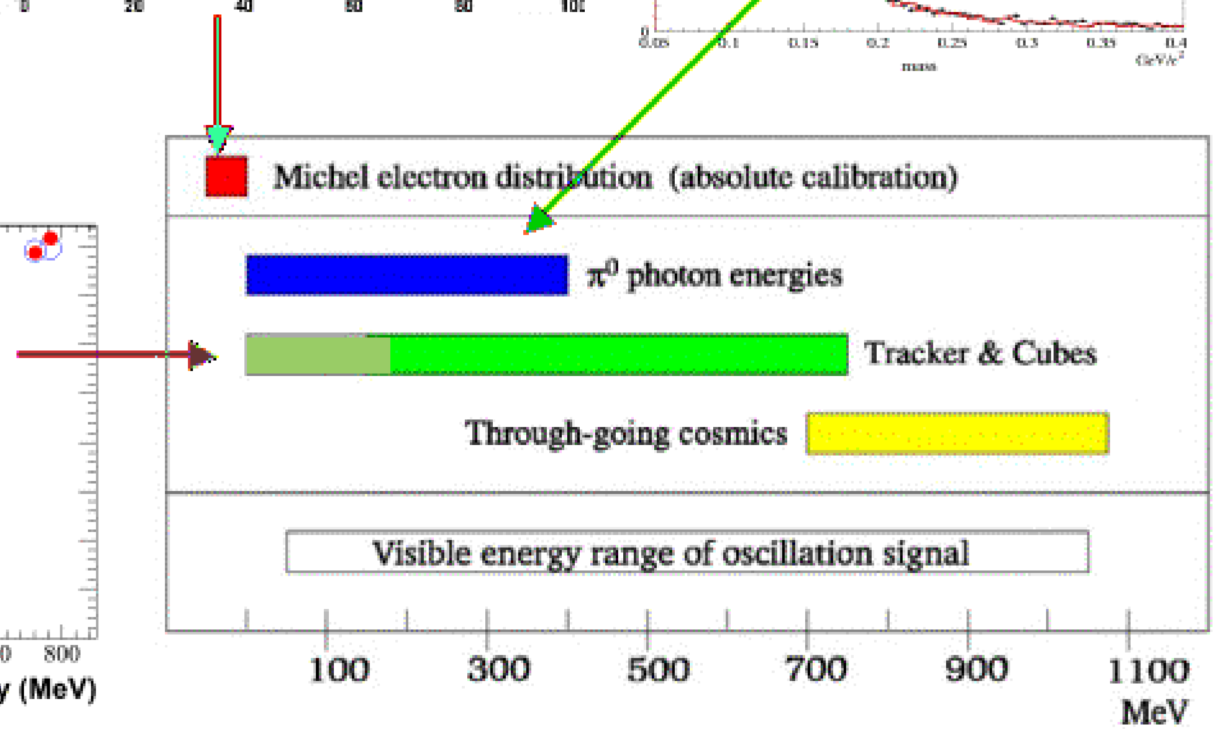
Tracker system











Track Fitting - Likelihood

$$\mathcal{L}(\mathbf{x}) = \prod_{i=1}^{N_{unhit}} \mathcal{P}_i(\text{unhit};\mathbf{x}) \prod_{j=1}^{N_{hit}} \mathcal{P}_j(\text{hit};\mathbf{x}) f(q_j;\mathbf{x}) f(t_j;\mathbf{x})$$

$$-\log(\mathcal{L})(\mathbf{x}) = F_q(\mathbf{x}) + F_t(\mathbf{x})$$

$$F_q(\mathbf{x}) = -\sum_{i=1}^{N_{unhit}} \log(\mathcal{P}_i(\text{unhit};\mathbf{x})) - \sum_{j=1}^{N_{hit}} \log(\mathcal{P}_j(\text{hit};\mathbf{x}) f(q_j;\mathbf{x})),$$

$$F_t(\mathbf{x}) = -\sum_{j=1}^{N_{hit}} \log(f(t_j;\mathbf{x})).$$

$$\mathcal{P}(\text{hit};\mu(\mathbf{x})) = 1 - \mathcal{P}(\text{unhit};\mu(\mathbf{x})) = 1 - e^{-\mu}.$$

L – likelihood.

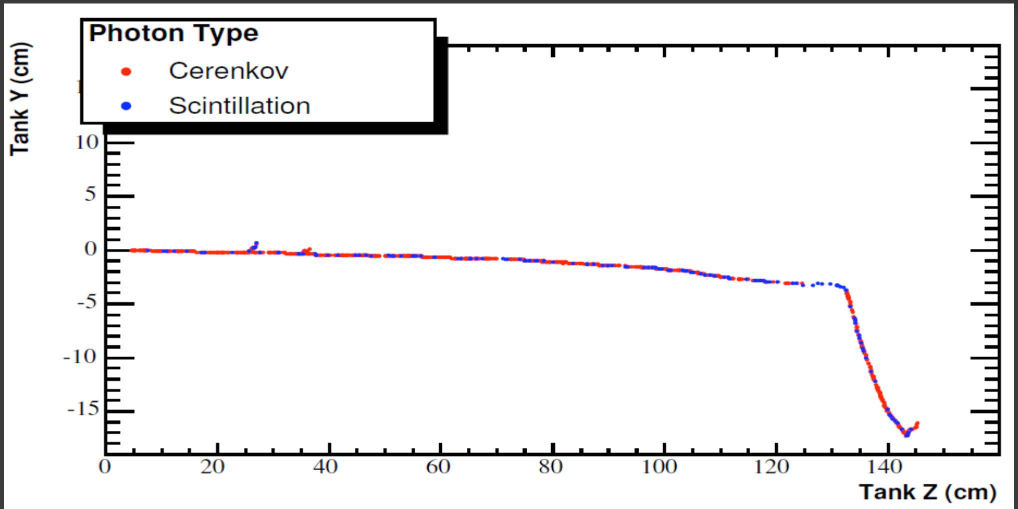
P_i(unhit;**x**) – probability a tube i to be unhit given **x**.

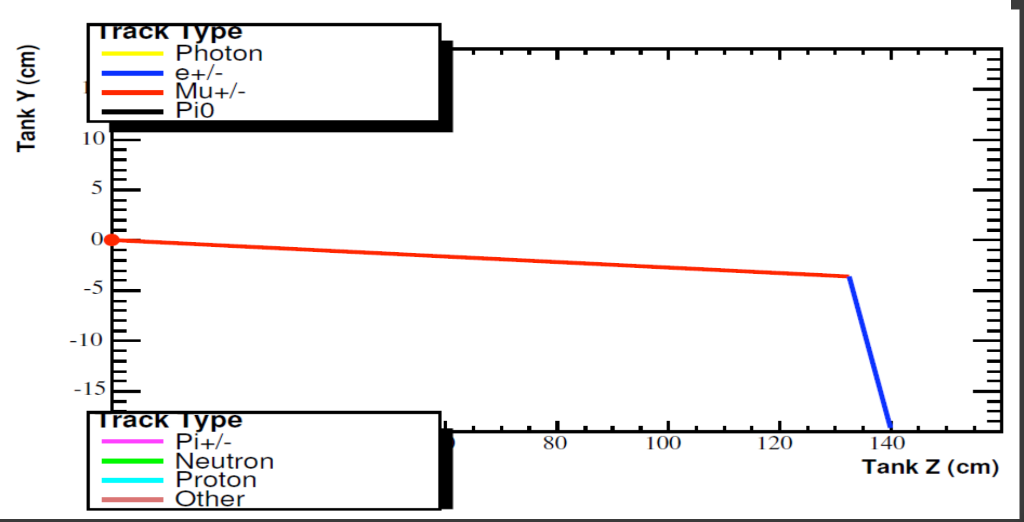
f(q_j;**x**) - charge PDF for PMT j.

f(t_j;**x**) - time PDF for PMT j.

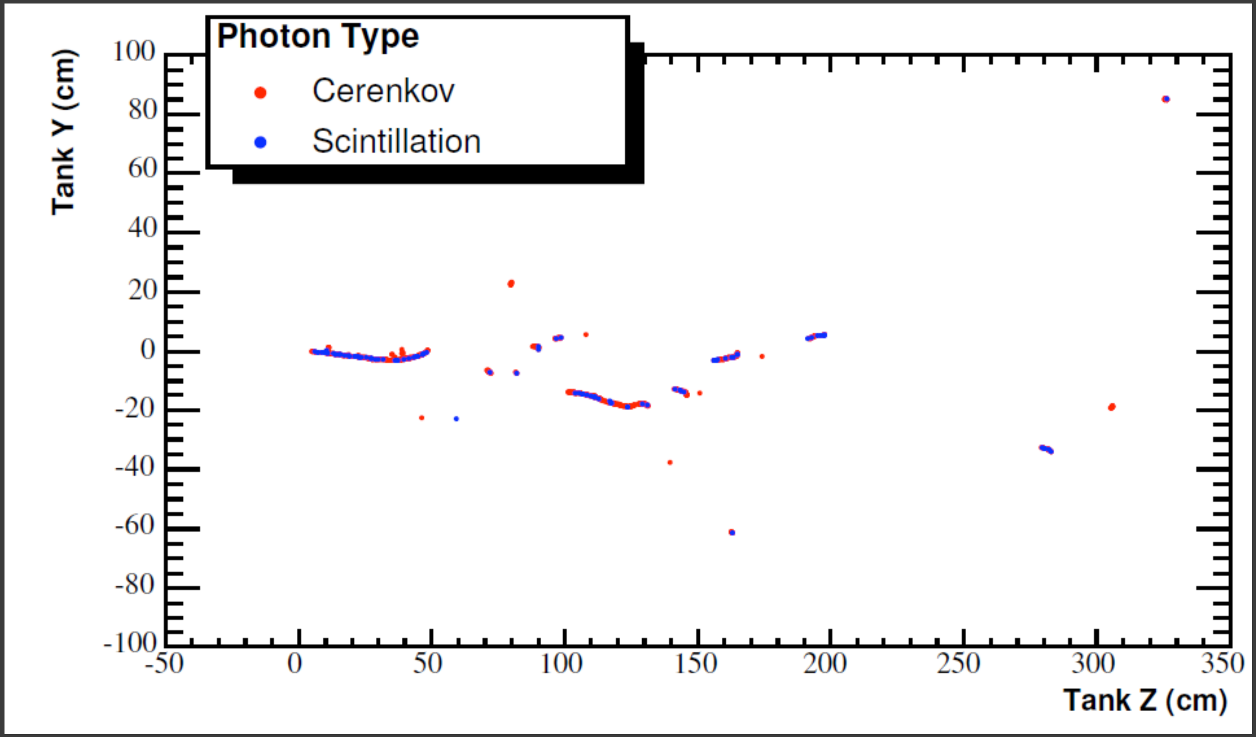
LSU LOUISIANA STATE UNIVERSITY

Photon Emission Along the Track - Muon





Photon Emission Along the Track - Electron

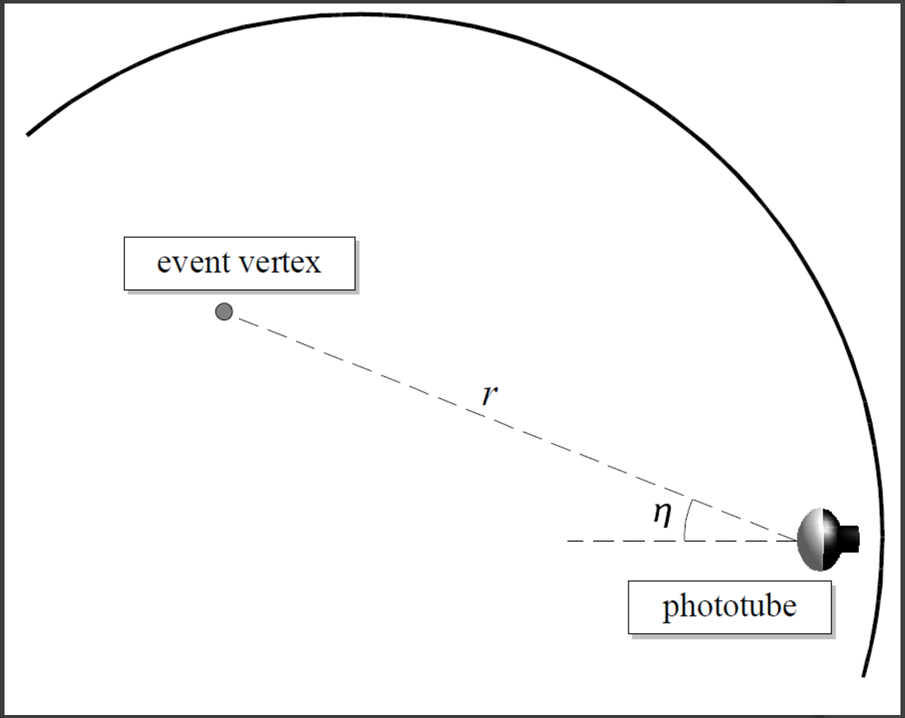


M. Wilking Thesis

Track Fitting – Predicted Charge Point Source

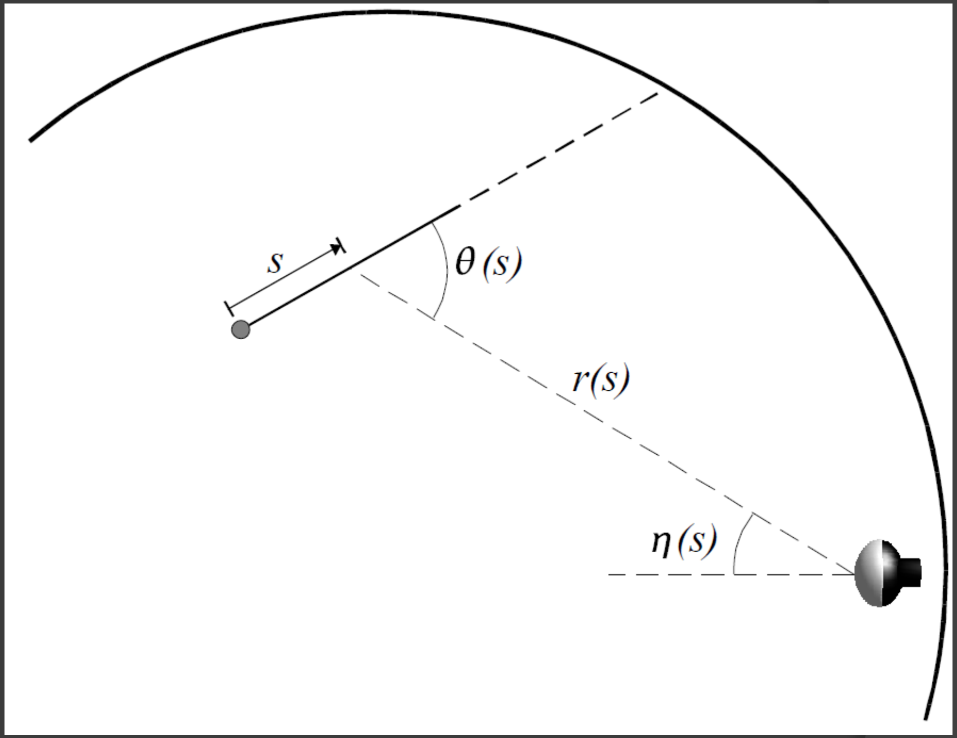
$$\mu = \Phi\,\Omega(r)\,T(r)\,\epsilon(\eta)$$

μ - predicted charge
Φ – light yield
Ω – solid angle PMT
T – transition
ε - acceptance



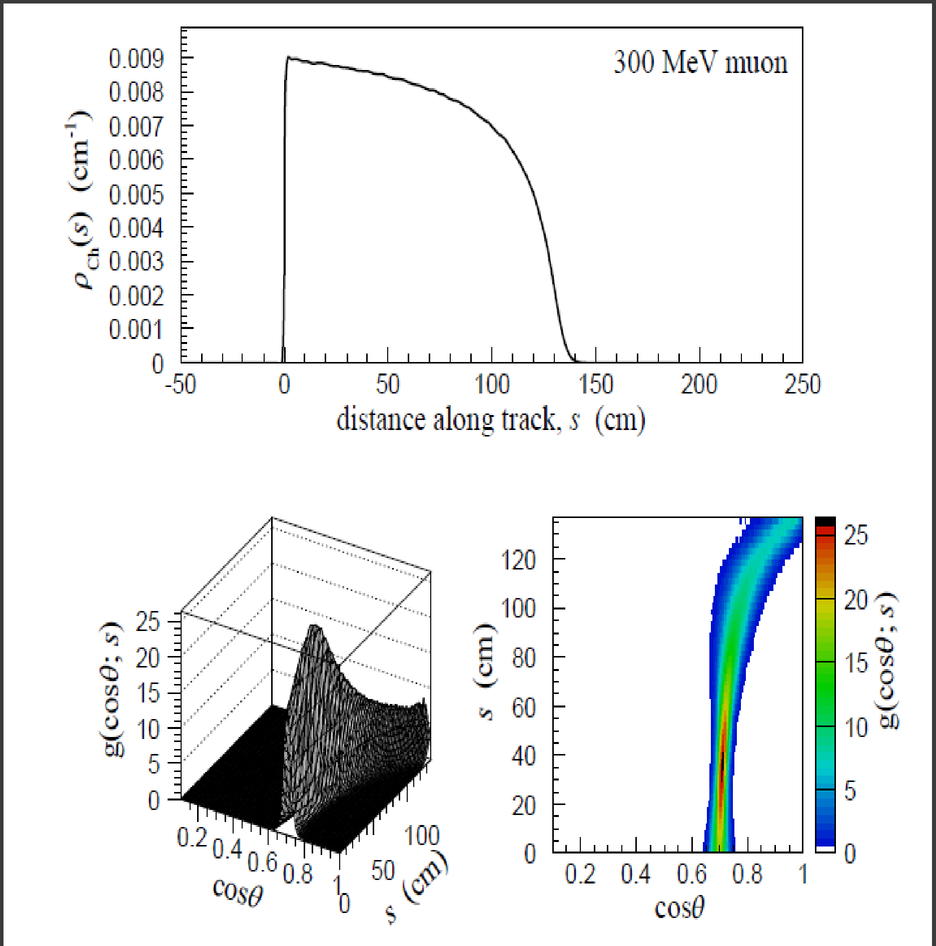
Track Fitting – Predicted Charge Extended Track Directional

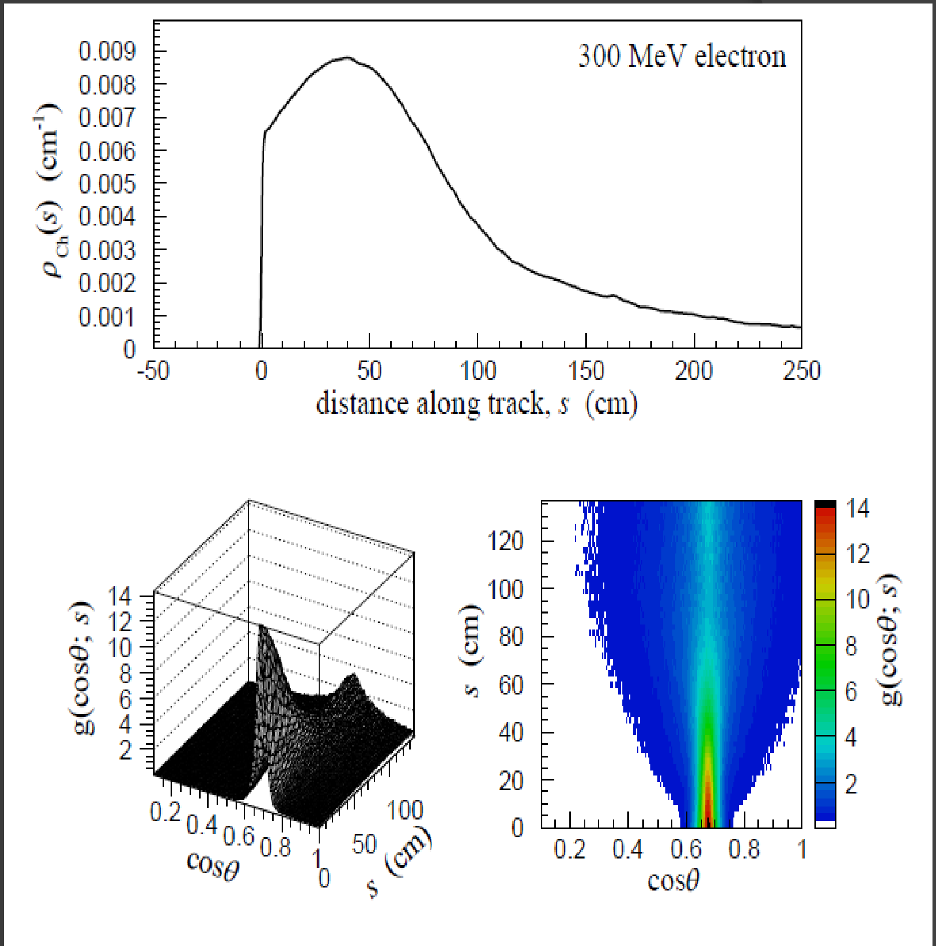
$$\mu_{\rm Ch} = \Phi_{\rm Ch} \int_{-\infty}^{\infty} ds\, \rho_{\rm Ch}(s)\, \Omega(s)\, T_{\rm Ch}(s)\, \epsilon(s)\, g(\cos\theta(s); s)$$



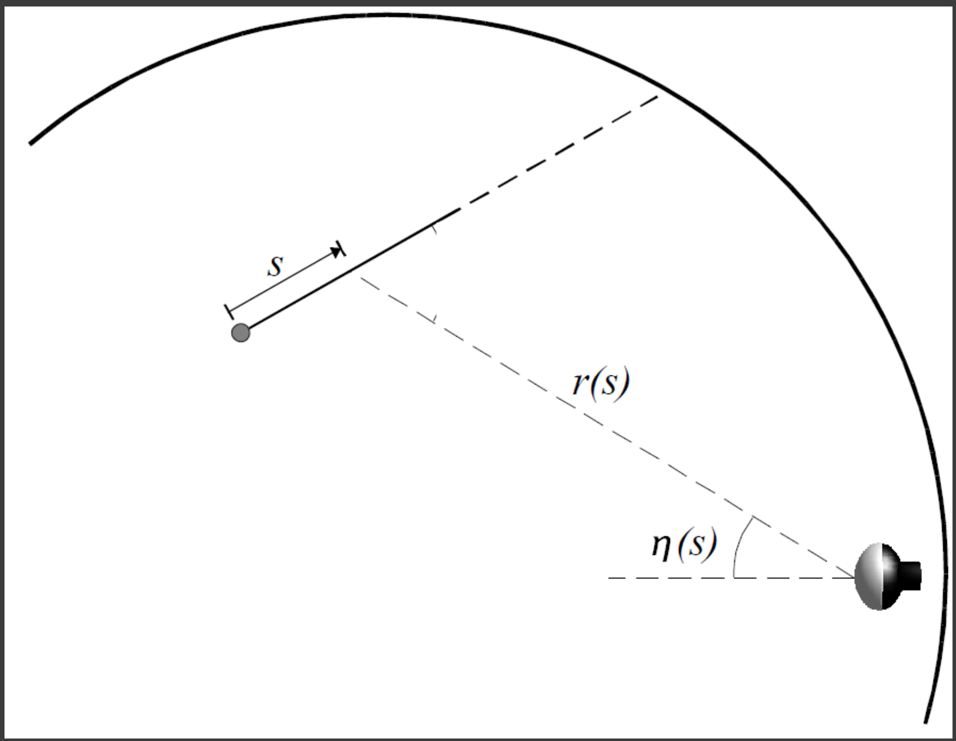
g(cos θ(s);s) – angular emission profile

Emission Profile - Cherenkov



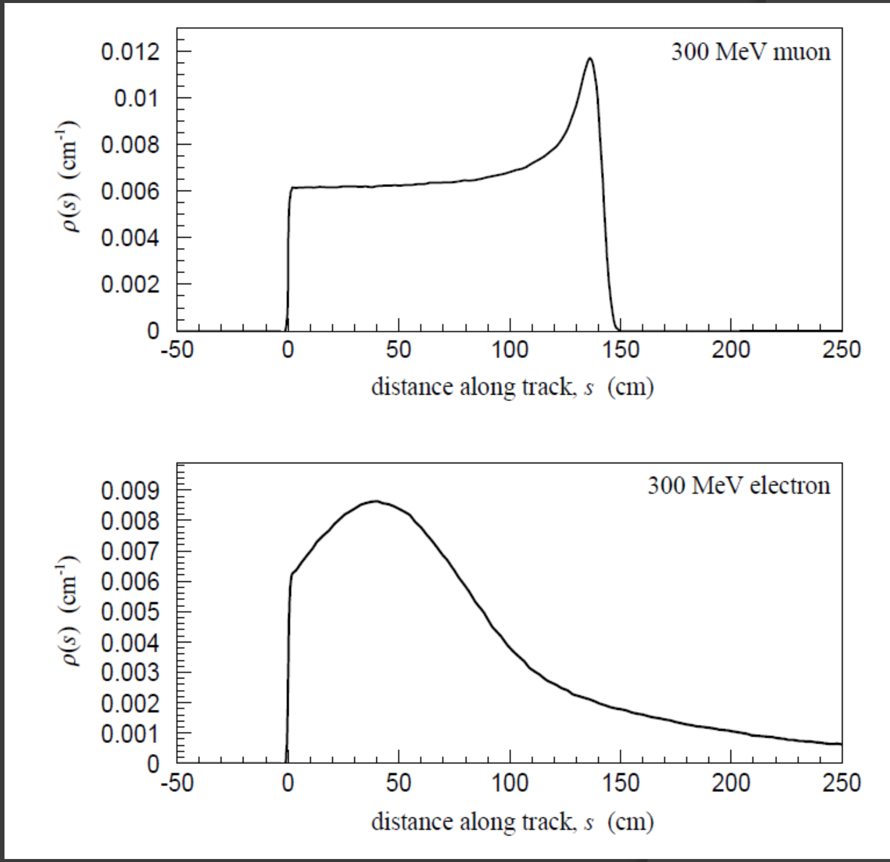


Track Fitting – Predicted Charge Extended Track



$$\mu_{\rm sci} = \Phi_{\rm sci} \int_{-\infty}^{\infty} ds\ \rho_{\rm sci}(s)\, \Omega(s)\, T_{\rm sci}(s)\, \epsilon(s)$$

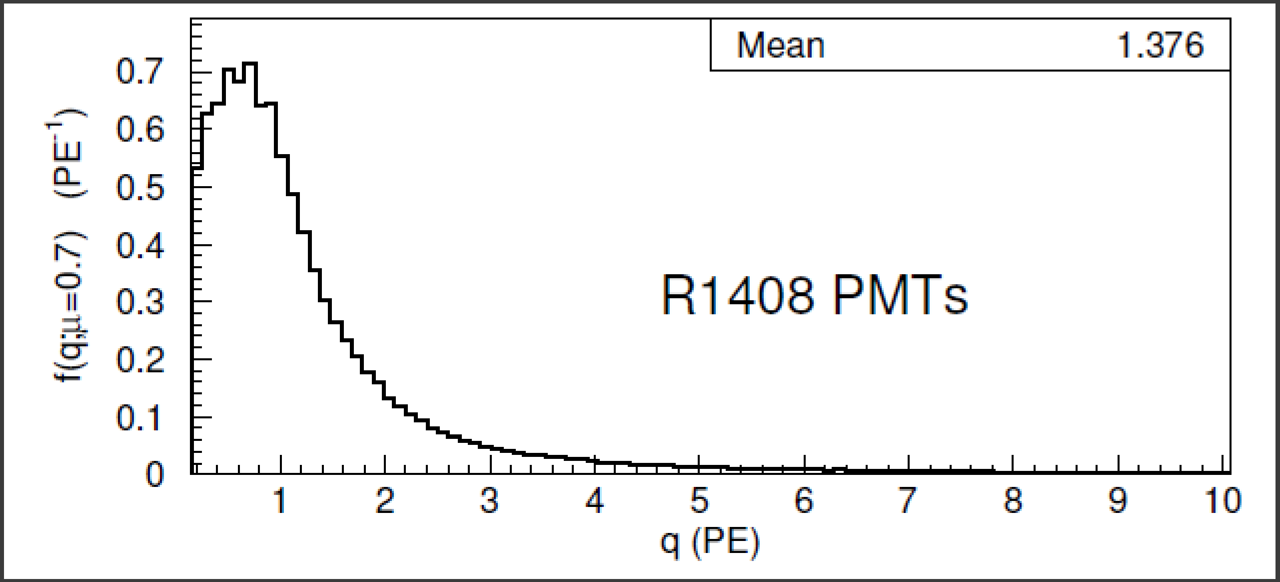
ρ(s) normalized to 1



LSU LOUISIANA STATE UNIVERSITY

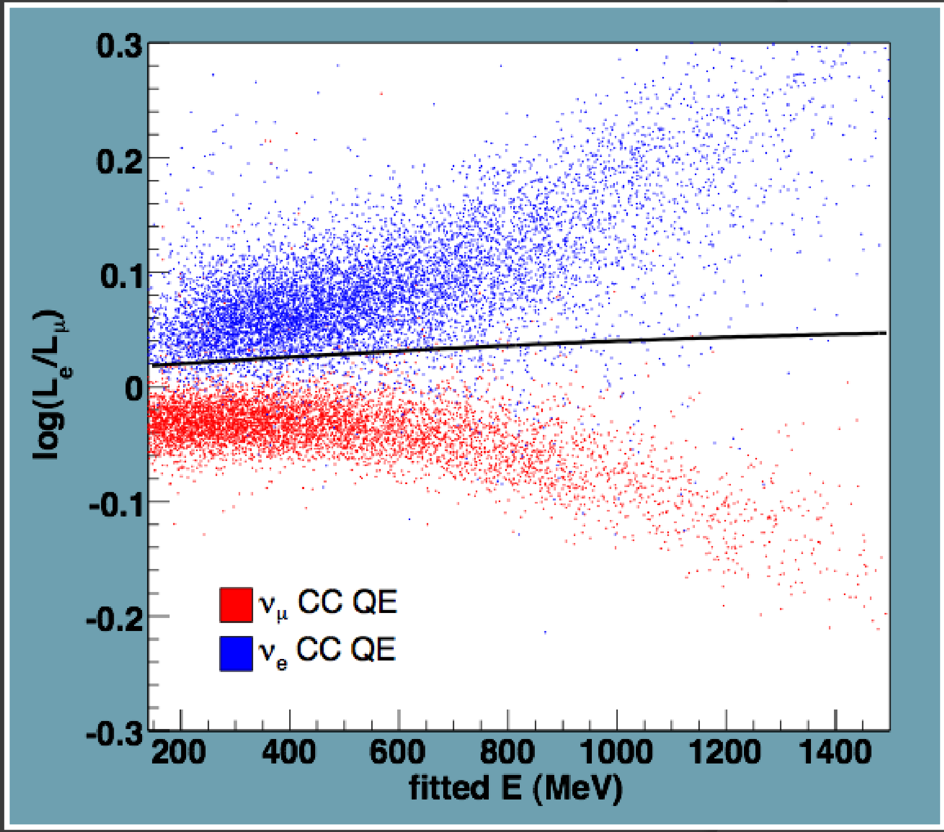
Charge PDF

Measured by *in-situ* laser with control light output.

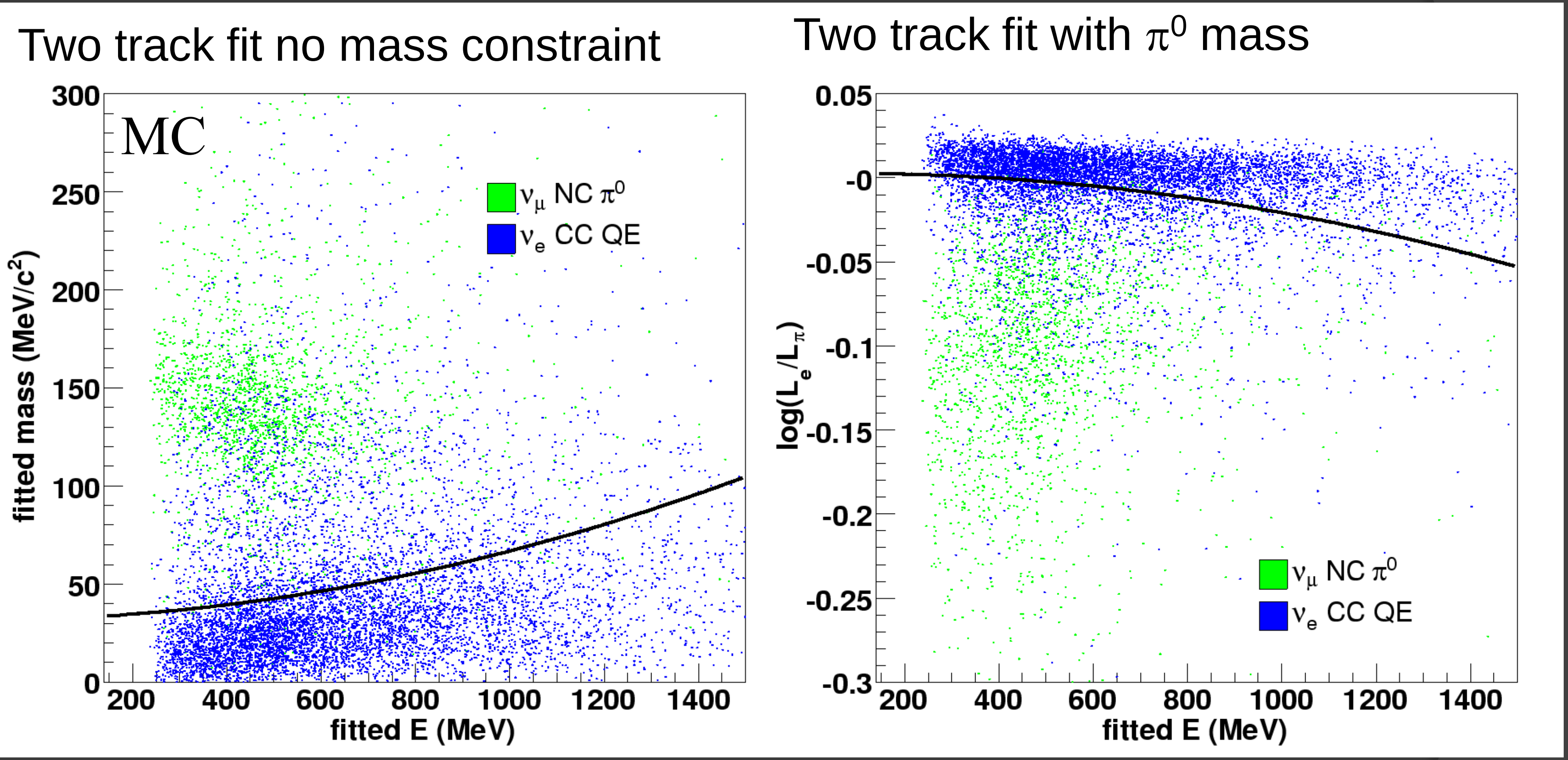


Track-Based Analysis
Rejecting Muon-like Events

- Single track fit to muon and electron hypothesis
- $\log(L_\varepsilon/L_\mu)>0$ selects electron hypothesis.
- The cut is a quadratic function with energy, optimizing oscillation sensitivity.
- Separation is clean at high energies where muon-like events are long.



Track-based Analysis Rejecting π^0 Events



- Cuts are quadratic functions chosen to maximize $\nu_\mu \rightarrow \nu_e$ sensitivity.

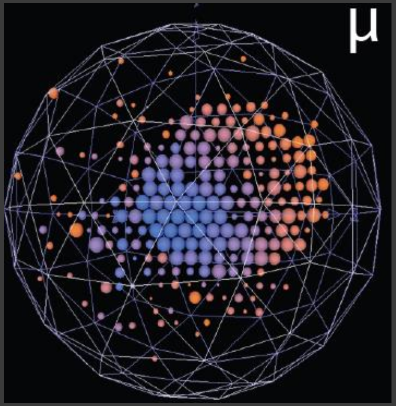
Log(L_e/L_π)>0 – electron hypothesis fits better.

ν_μ CCπ^0 Challenges

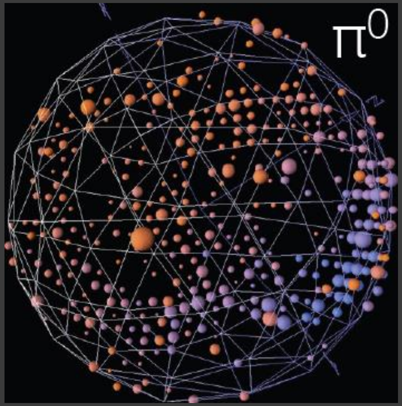
- CC π^0 is tagged by one stopped muon decay electron (also CCQE signature).
- CC π^0 is a small fraction (6%) in sample dominated by CCQE events 63%

Sample	Events	Fraction
total MC	267007	100%
CCQE	168723	63%
CCπ0	16504	6%
CCπ+	66268	25%

- Overlapping rings make reconstruction more difficult.

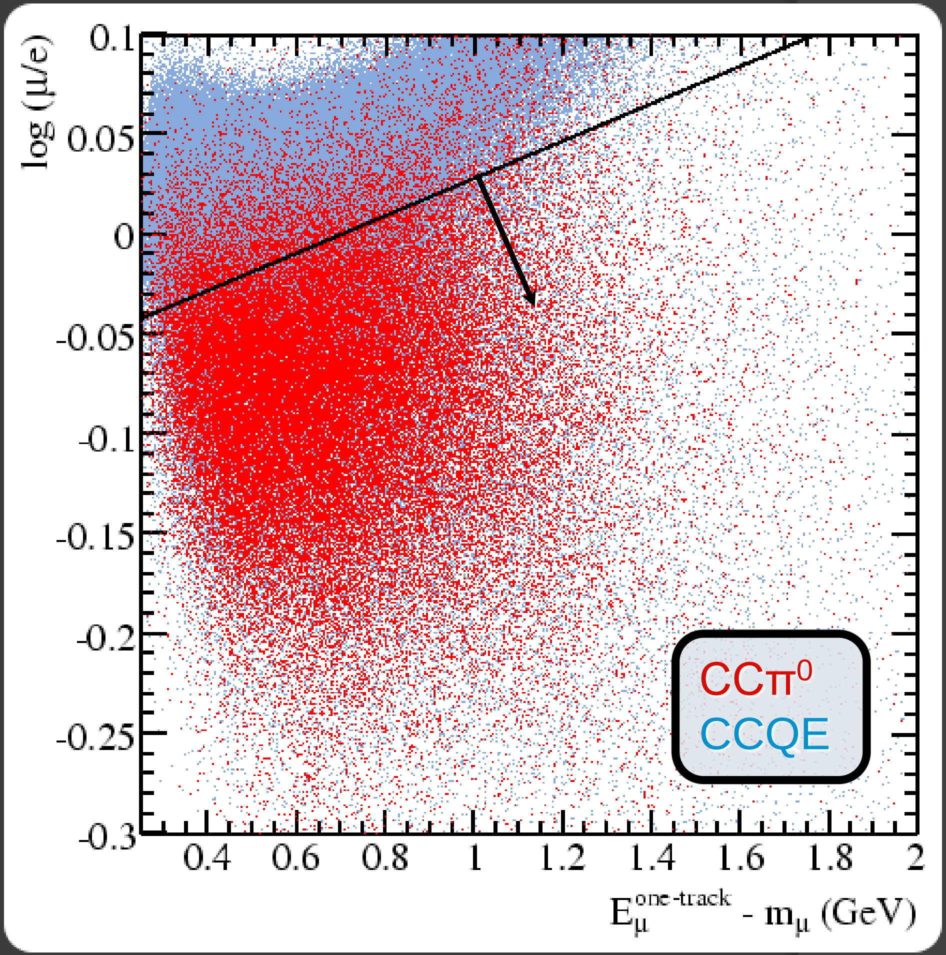


+



Pre-filtering before the fit

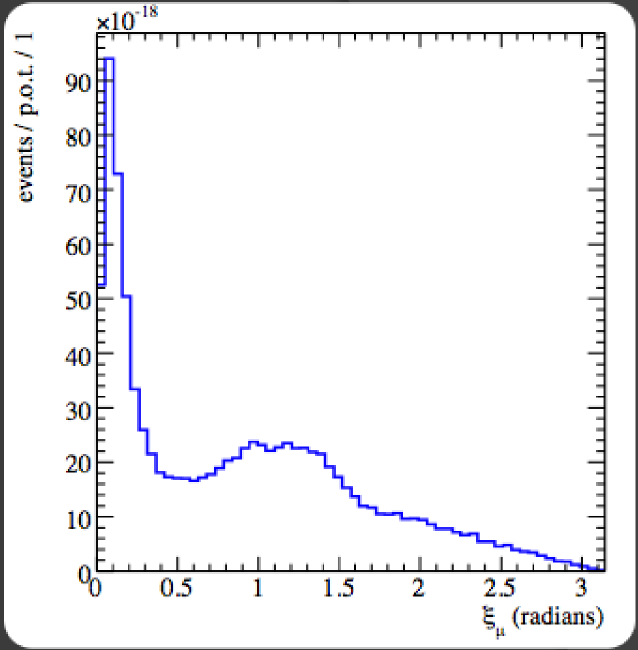
- 2 subevents.
- Tank hits > 200 (1st subevent)
  Tank hits < 200 (2nd subevent)
  Veto hits < 6 (both subevents)
- We need to reduce the two-subevent sample down to something more manageable before the fitter is run.
- A one-track likelihood ratio cut vs one-track energy reduces CCQE events by 98% while keeping 86% of $CC\pi^0$ events.

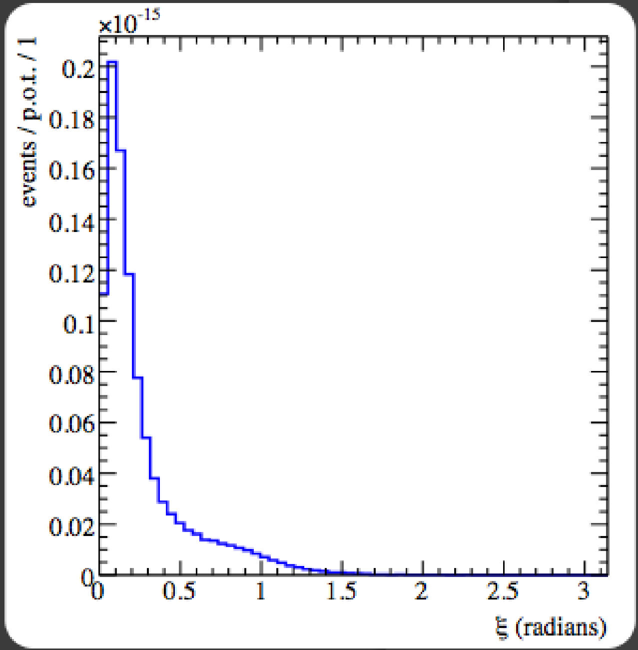


R. Nelson Thesis

Three-track fitting

- We start with a muon hypothesis.
- Measure the angle vs the true muon.
- That fit only finds the true muon ~1/3rd of the time.
- However, it does a good job of finding one of the three rings.

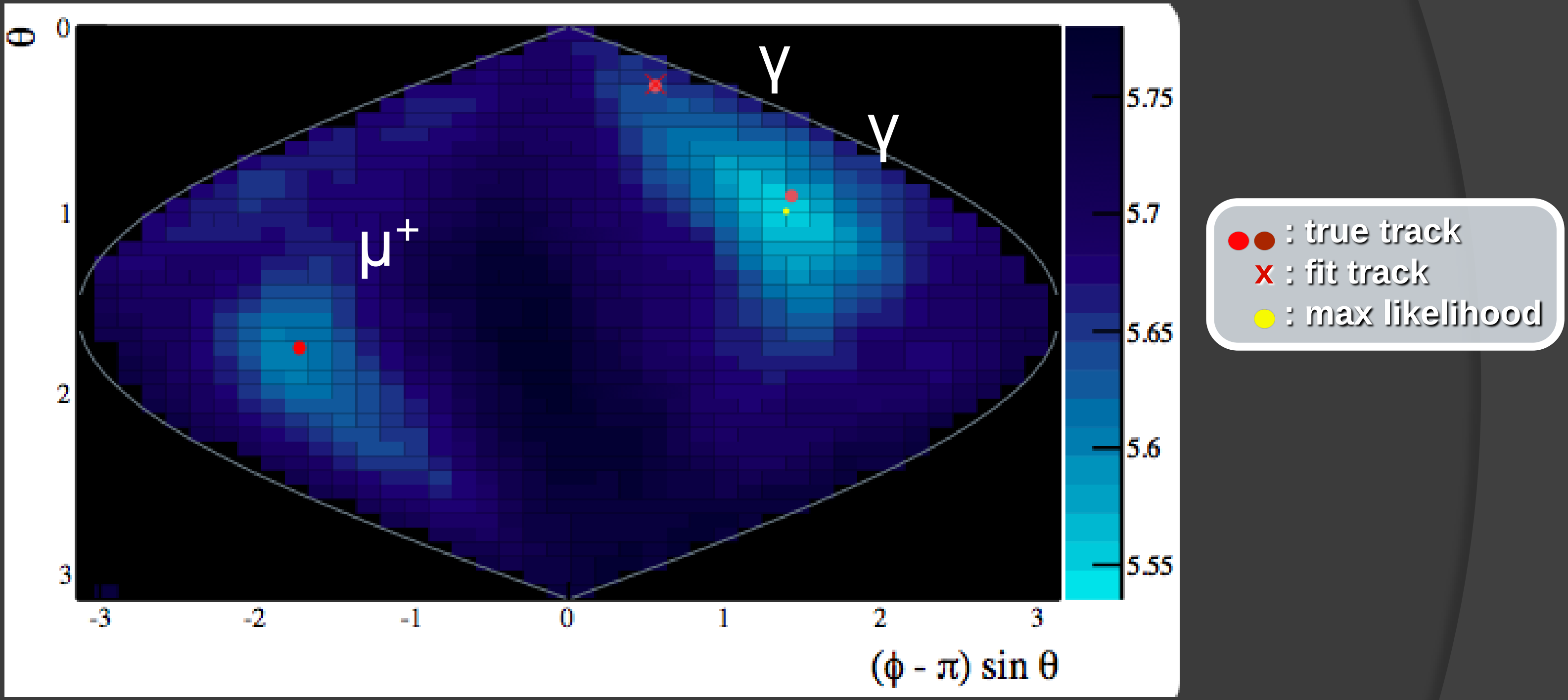




LOUISIANA STATE UNIVERSITY

Reconstructing CCπ^0 events

- Fixing the one-track muon fit in the likelihood function, we scan (in solid angle) for a second track.

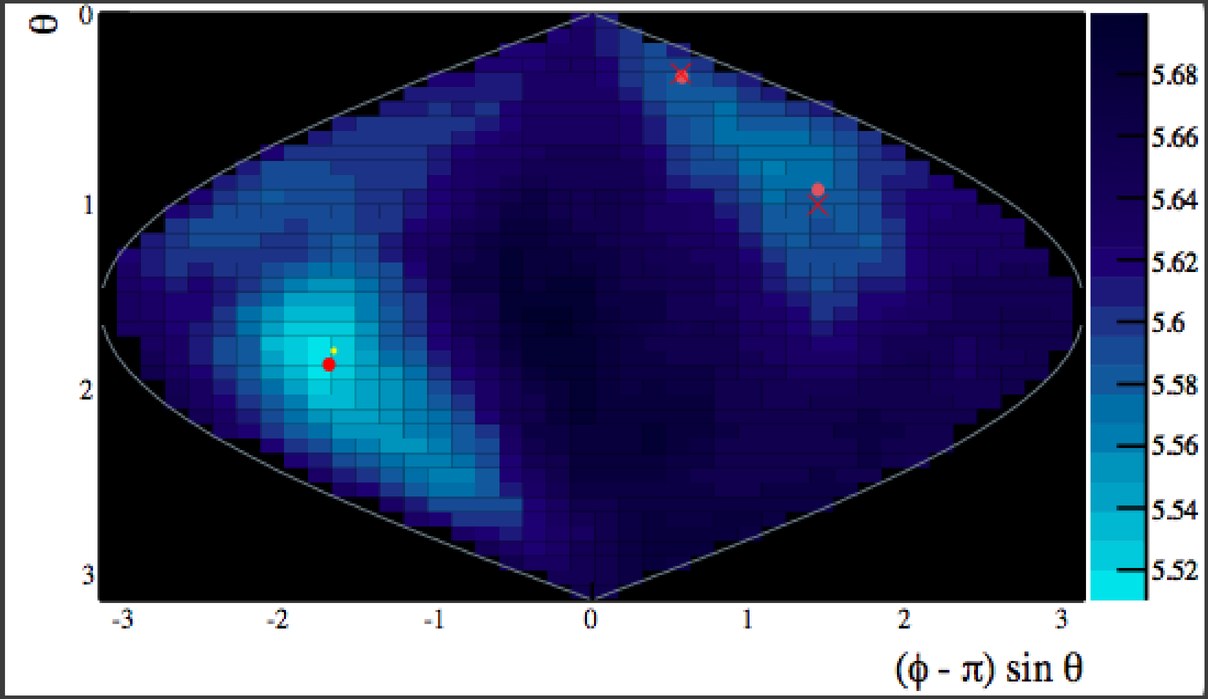


- The one track fit found one of the photons in this event.
- The scan found the second photon.
- After this scan, both tracks are allowed to float in a two-track fit.

R. Nelson Thesis

Reconstructing CCπ^0 events

- Both tracks are fixed in the likelihood function. A third track is scanned for in all directions of solid angle.



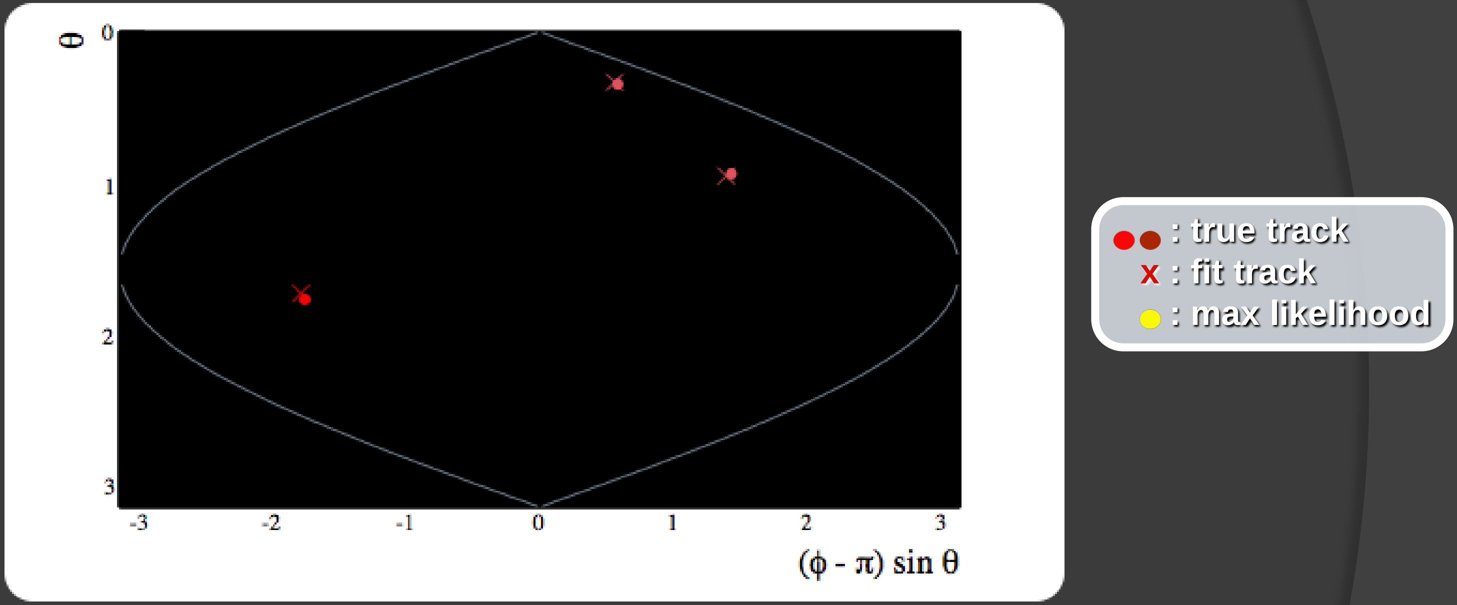
- The two-track fit dimmed likelihood around the second photon, and brightened the likelihood around the muon.
- The scan found the muon in this event.

LOUISIANA STATE UNIVERSITY

R. Nelson Thesis

Reconstructing CCπ^0 events

- For all three possible particle configurations, additional three-track fits are performed. Swapping out two of the tracks for photons.



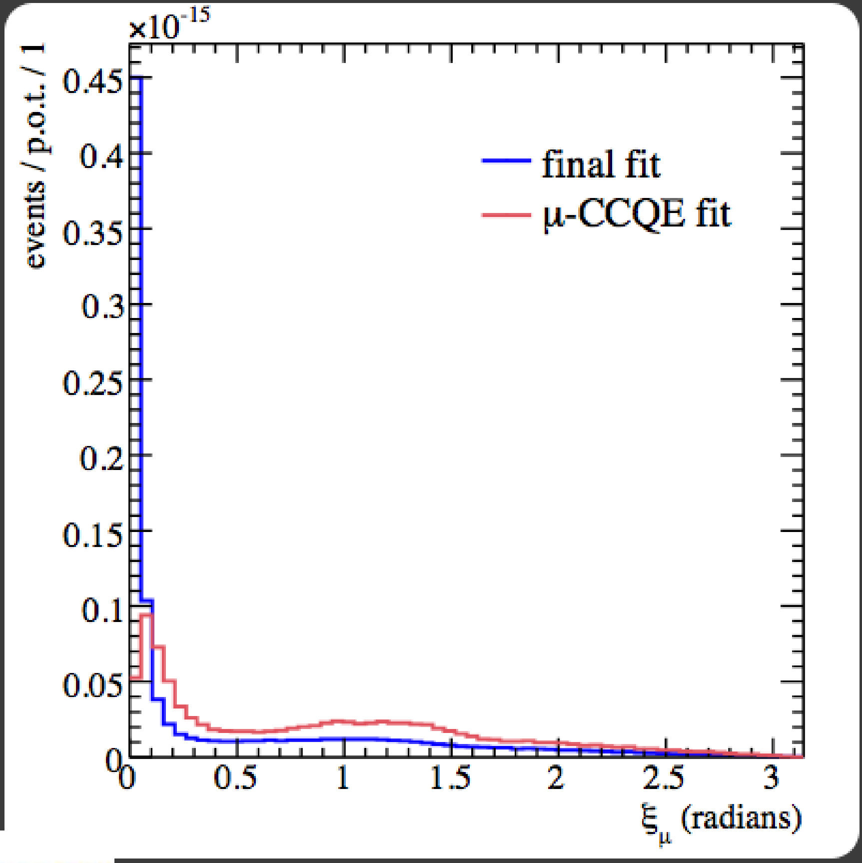
- **Particle ID is performed by combining the fit likelihood and the direction to the 2nd subevent vertex (muon decay) vs the assumed muon in the fit as an additional likelihood.**

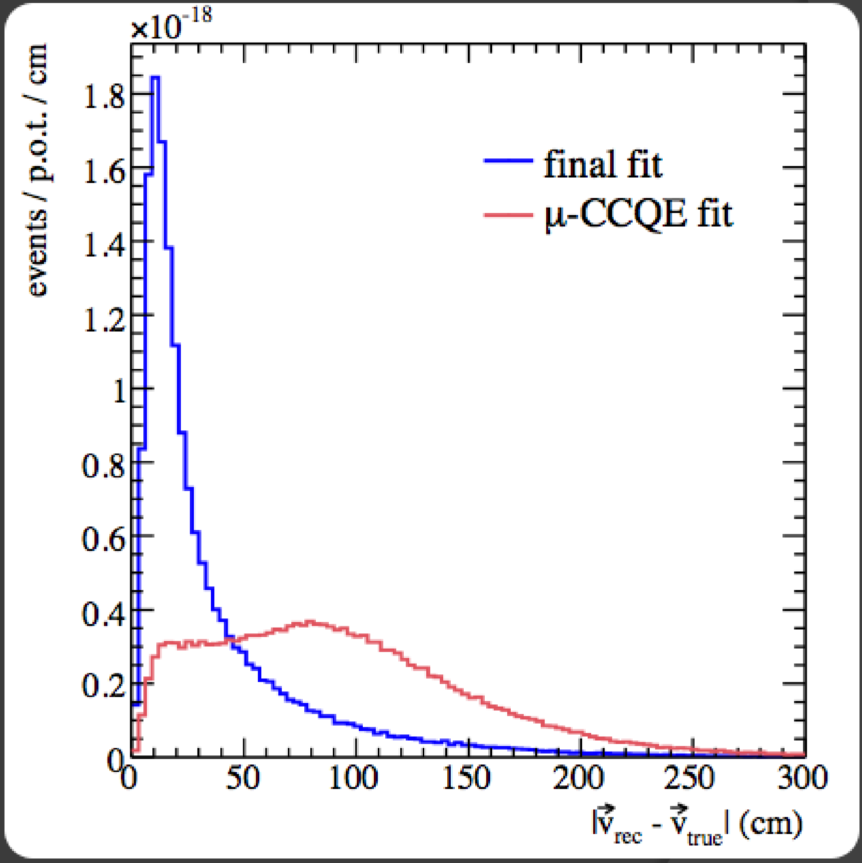
- The three-track fit has identified all three particles (μ,γ,γ) in this event.

R. Nelson Thesis

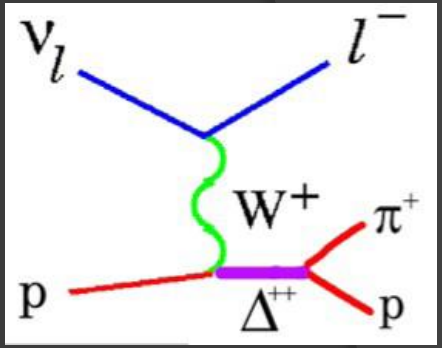
Muon angle and event vertex

- The fitter has significantly improved the muon angular reconstruction.
- The event vertex has significantly improved.





ν_μ CC π^+ Reconstruction- a Step Further

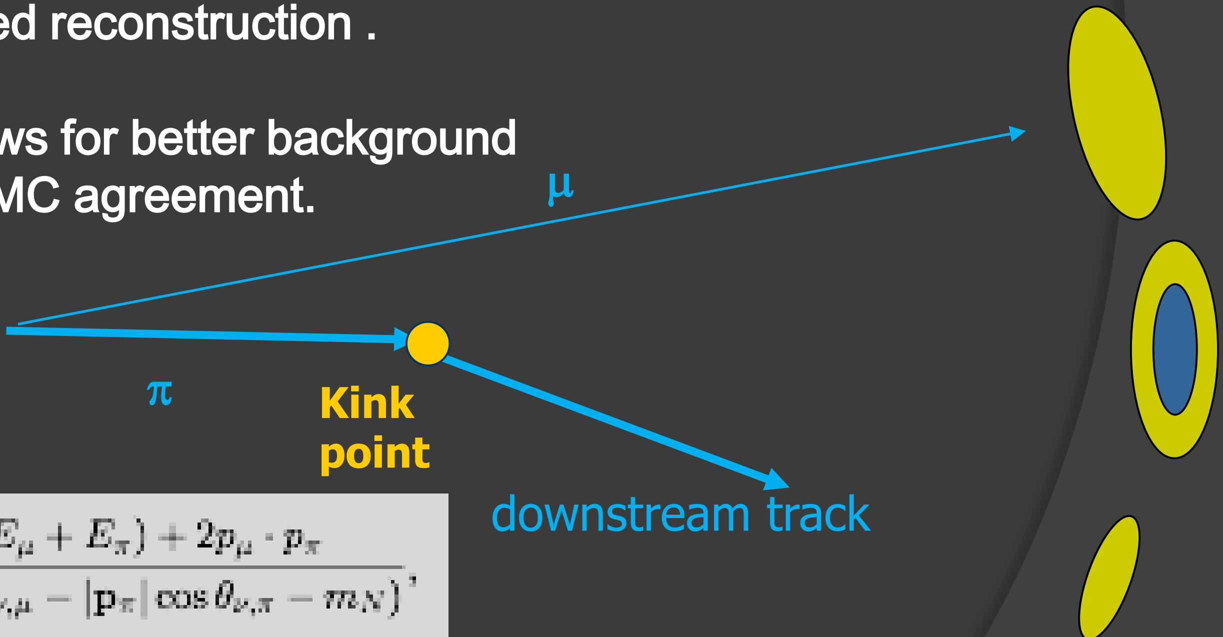


- We can reconstruct the whole event if we reconstruct both μ and π kinematics (assuming neutrino direction and target nucleon at rest).

- Need to reconstruct the pion – kinked fitter.

- Developed CCπ^+ dedicated reconstruction .

- Better reconstruction allows for better background rejection and better data MC agreement.



$$E_\nu = \frac{m_\mu^2 + m_\pi^2 - 2m_N(E_\mu + E_\pi) + 2\mathbf{p}_\mu \cdot \mathbf{p}_\pi}{2\left(E_\mu + E_\pi - |\mathbf{p}_\mu|\cos\theta_{\nu,\mu} - |\mathbf{p}_\pi|\cos\theta_{\nu,\pi} - m_N\right)},$$

M. Wilking Thesis

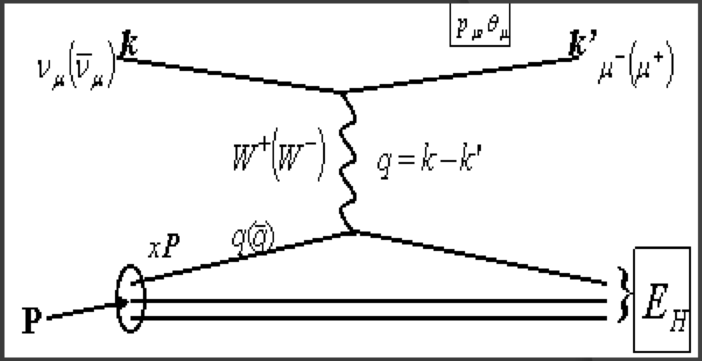
LOUISIANA STATE UNIVERSITY

CC Inclusive Event Reconstruction

New event reconstruction for MiniBooNE

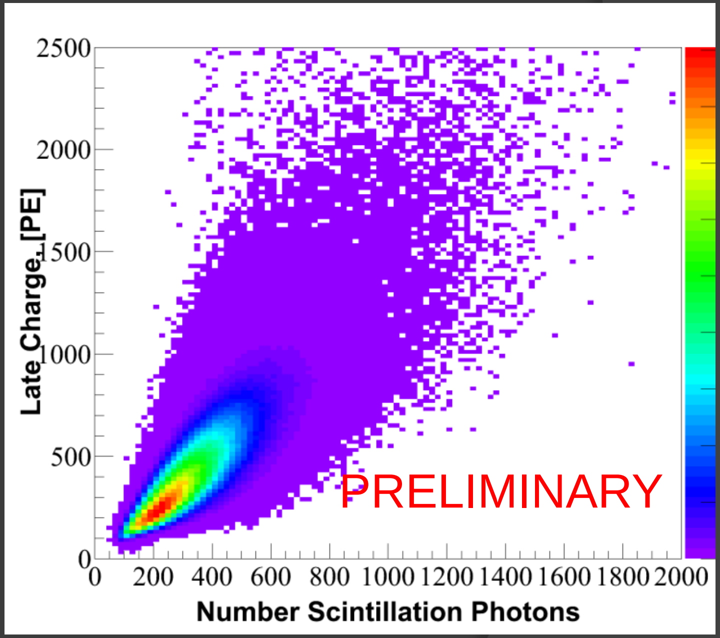
- Muon kinematics from 2-track likelihood fit:

  Second ring of the fit absorbs the bias due to second most prominent ring.



- Neutrino energy – MiniBooNE detector as calorimeter.

  Small scintillation light component produces late hits in the event. The charge of the late hits is used as a measure of the neutrino energy.



Fully reconstruct the lepton vertex – no assumptions for the target!!!

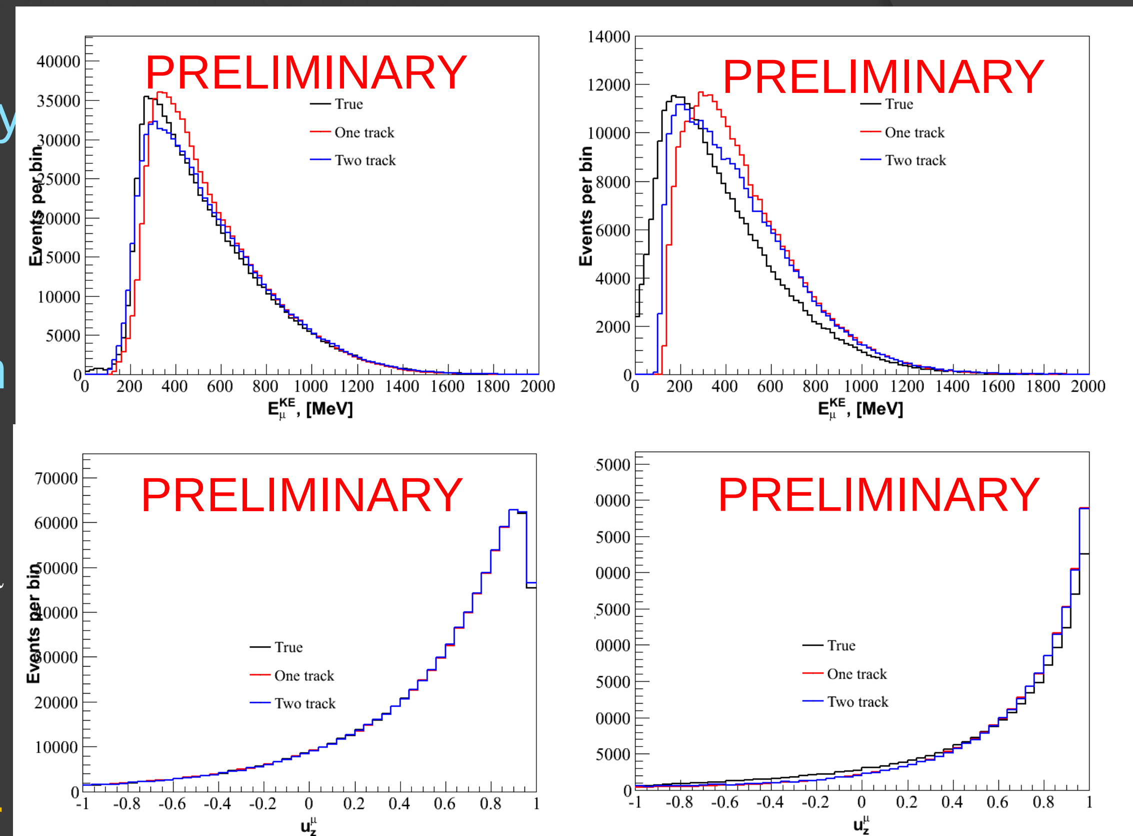
Plots are from MC

Muon Kinematics Reconstruction Performance

2-track fit improves significantly reconstruction of the muon kinetic energy compared to one track fit. Muon kinetic energy resolution is about 5%.

T_μ

u_z^μ



CCQE

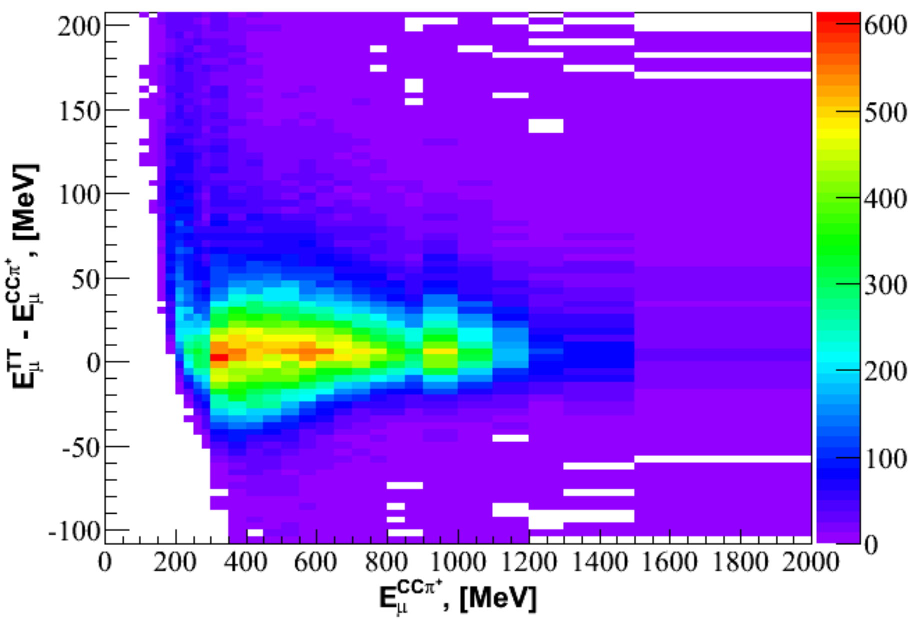
CCπ+

No significant improvement for the muon angle. Muon angle resolution is better than 1°.

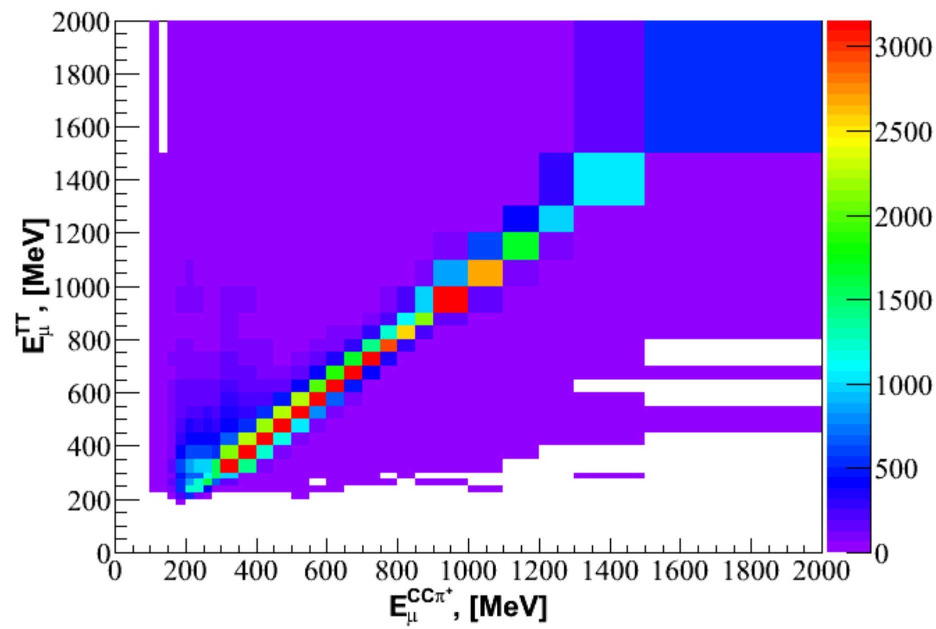
Plots are from MC.

CC Inclusive Reconstruction – CCπ^+ Sample

Event-by-event difference

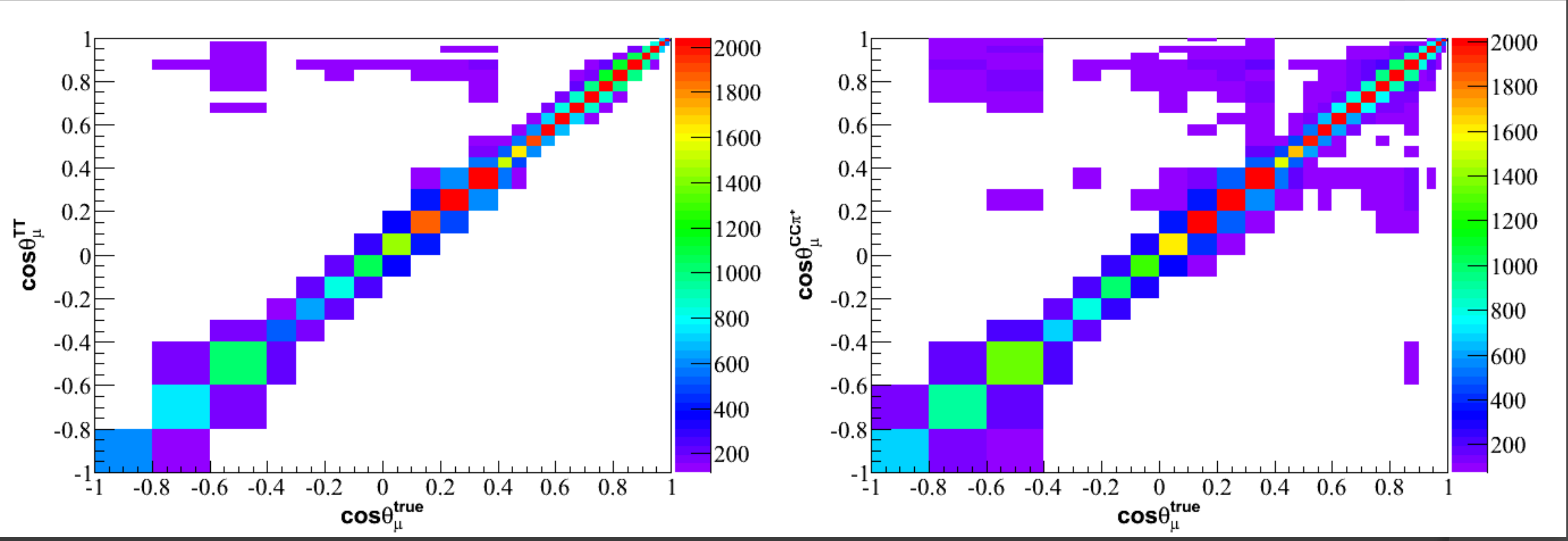


TT vs CCπ fitter



CC Inclusive Reconstruction – CCπ^+ Sample

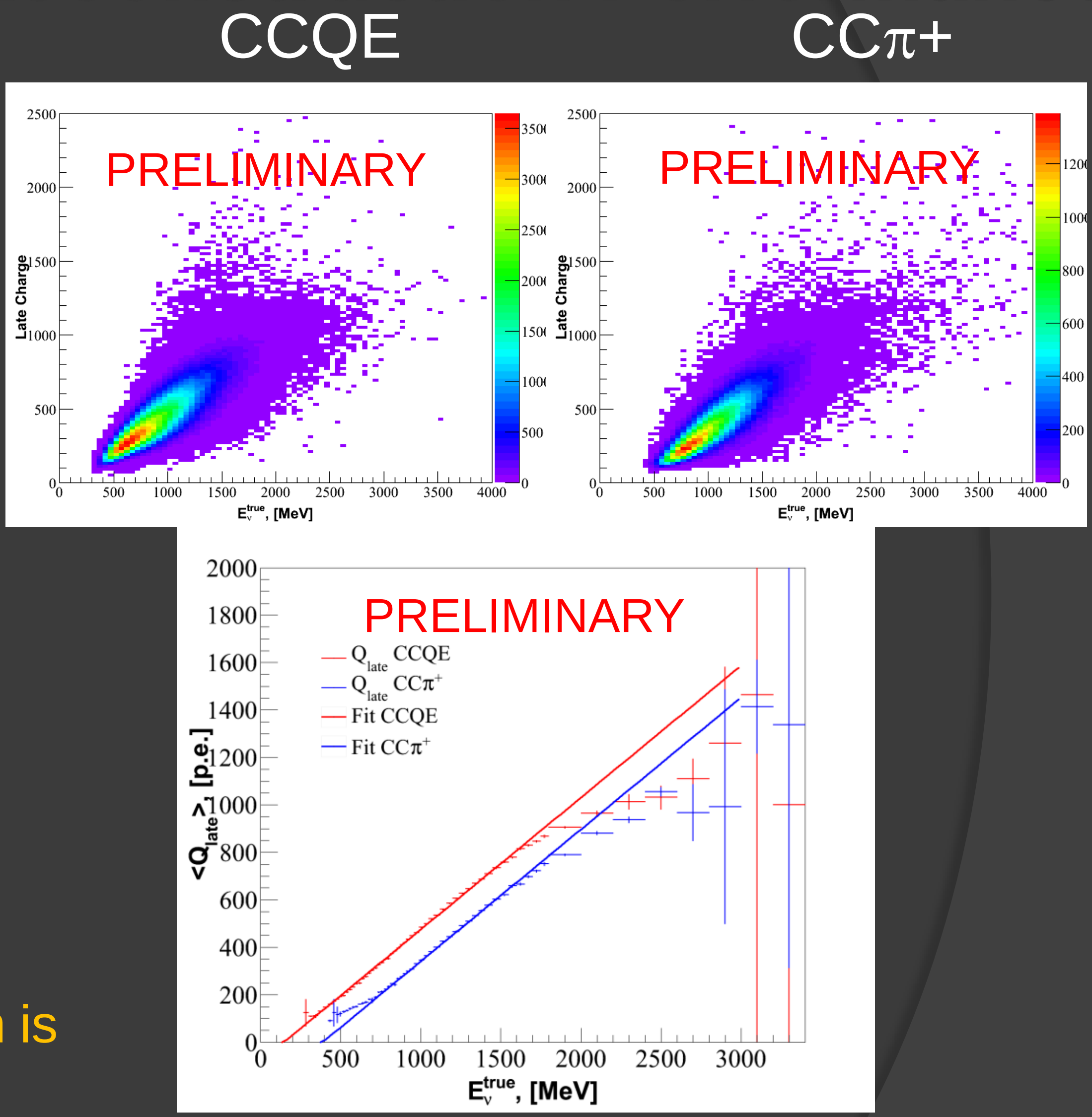
Uz Rec vs Uz true



Two Track Fit

CCπ Fit

Neutrino Energy Reconstruction Performance



Neutrino energy reconstruction is obtained from the late light charge which is linearly correlated with the true neutrino energy.

The parameters of the reconstruction come from a linear fit to both CCQE and $CC\pi^+$ enhanced samples. the slope parameter is the same in both cases while the Intercept is different.

Energy reconstruction resolution is about 18%.

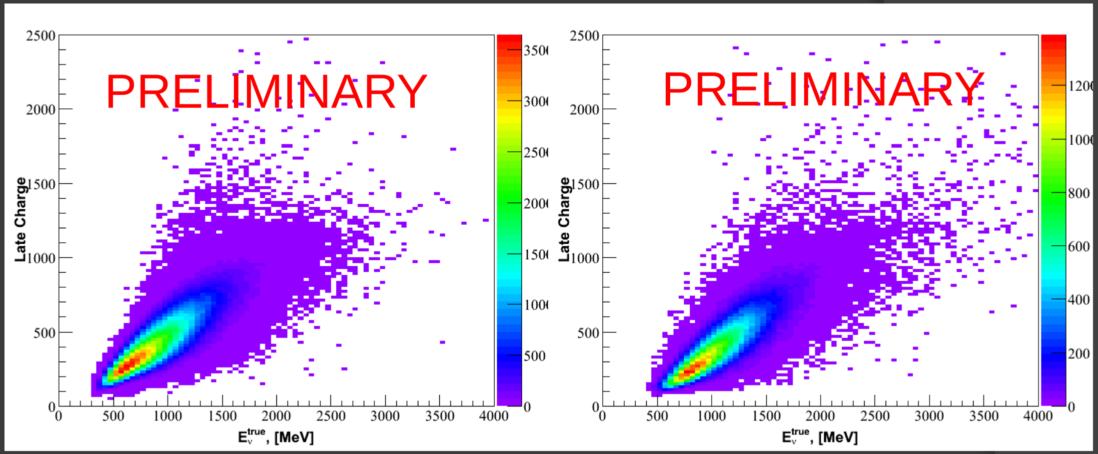
Plots are from MC.

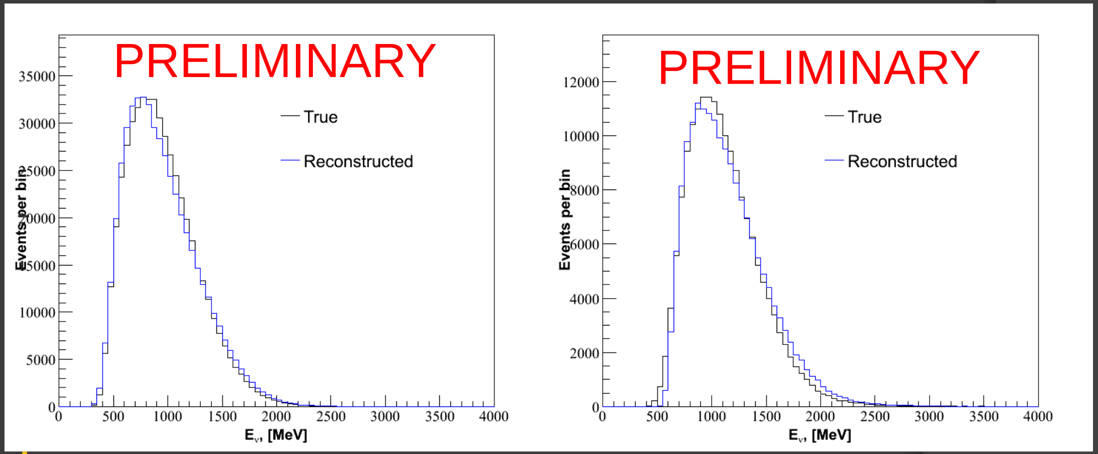
Neutrino Energy Reconstruction Performance

Neutrino energy reconstruction is obtained from the late light charge which is linearly correlated with the true neutrino energy.

The parameters of the reconstruction come from a linear fit to both CCQE and $CC\pi^+$ enhanced samples. the slope parameter is the same in both cases while the Intercept is different.

Energy reconstruction resolution is about 18%.





CCQE

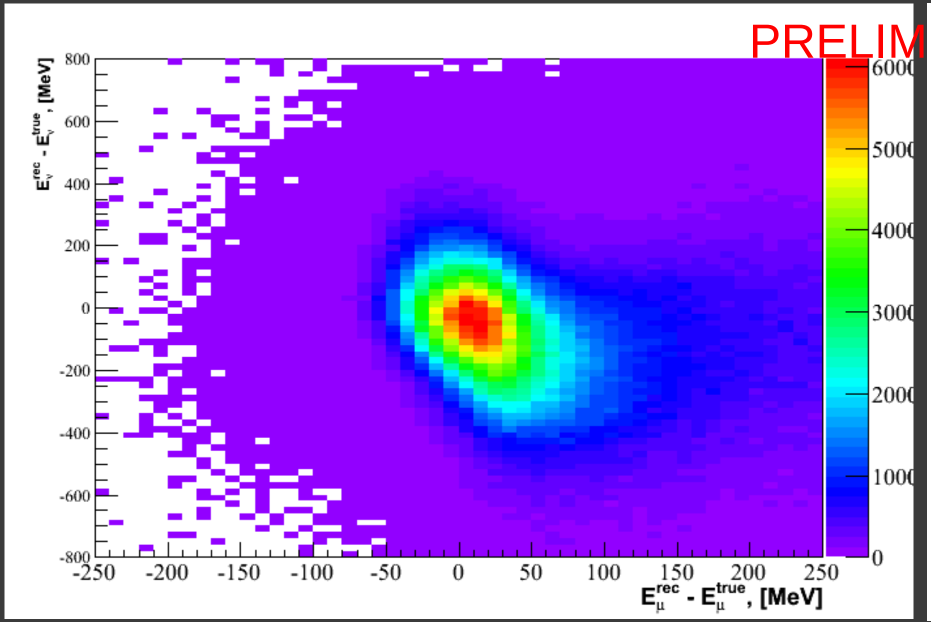
$CC\pi+$

Plots are from MC.

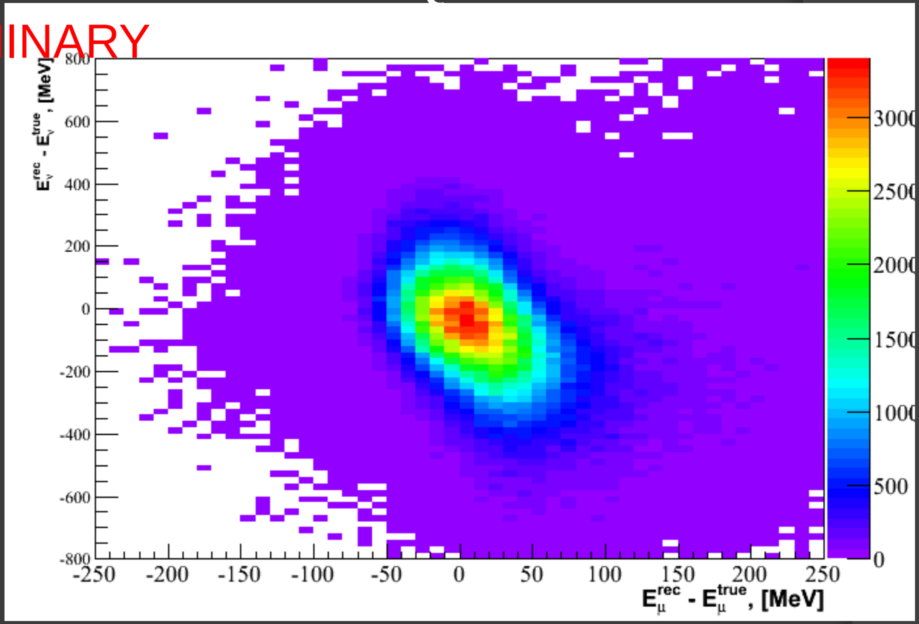
LOUISIANA STATE UNIVERSITY

Reconstruction Correlation

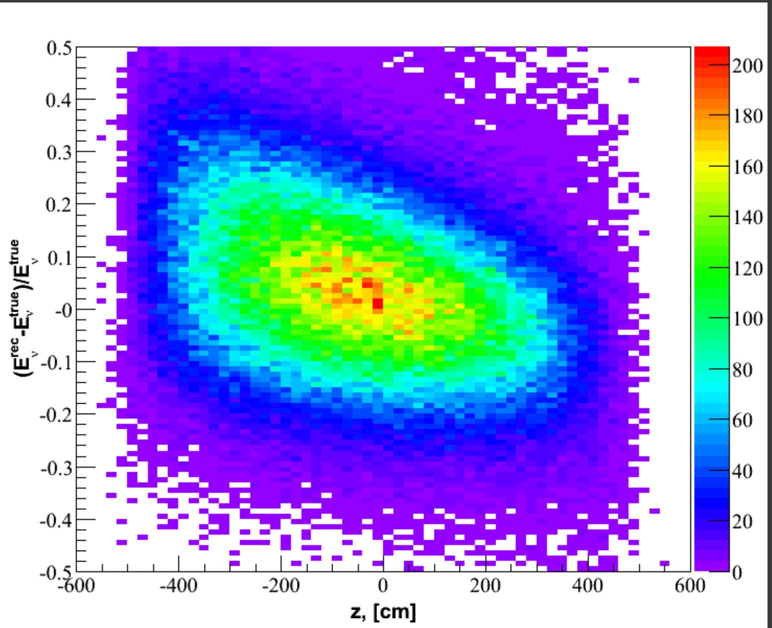
All SE

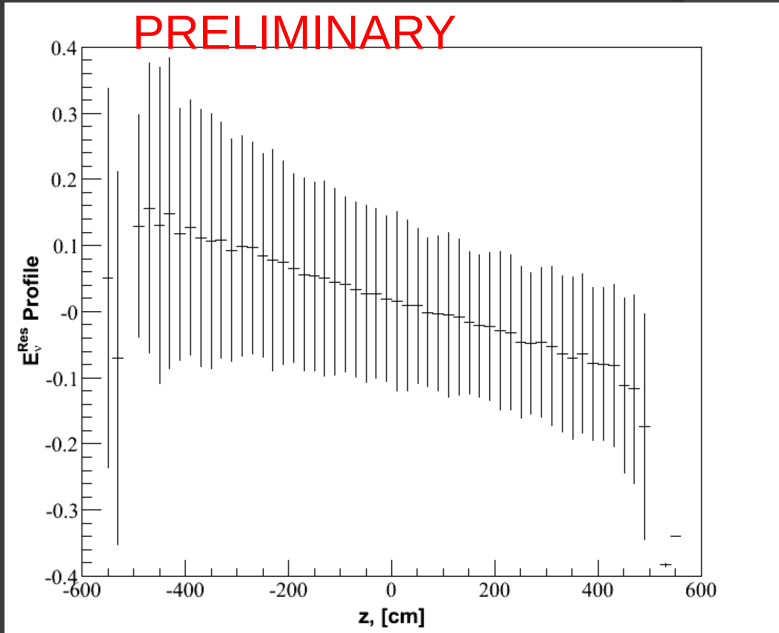


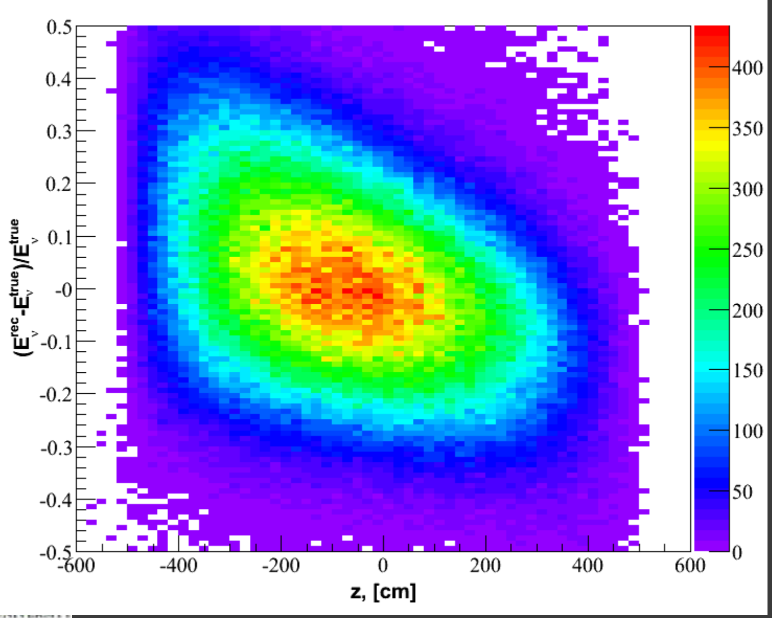
CCQE

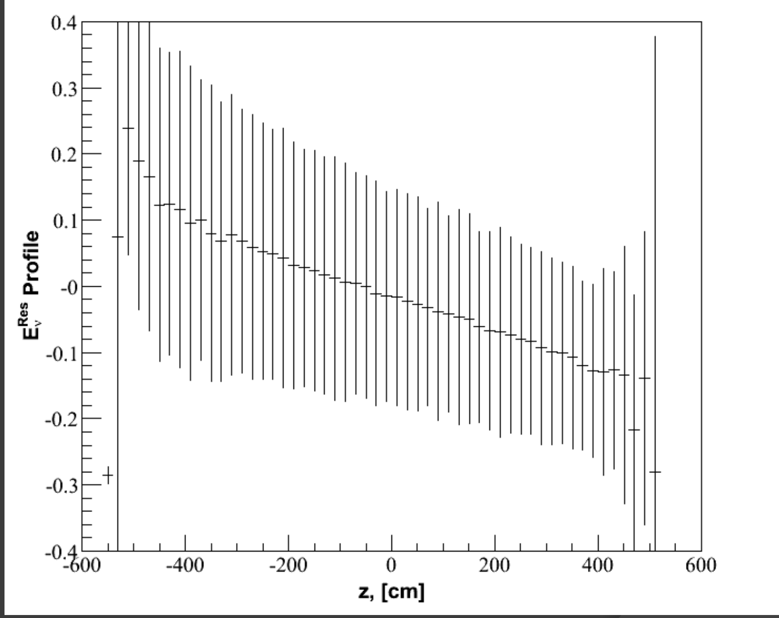


CC Inclusive Reconstruction – E_ν Resolution









Summary

This reconstruction has been successfully applied to SK

The MB reconstruction depends on the “optical” model

Requires very good understanding of the optical properties

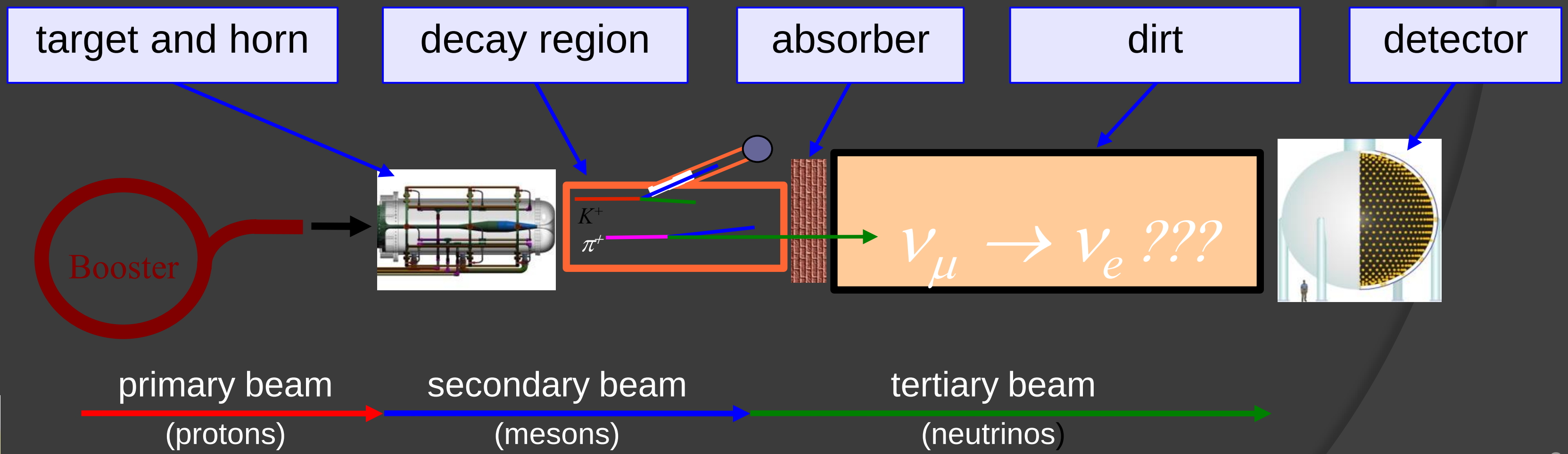
Requires good coverage and good time resolution

Either separate the sci/cer light and/or save the waveforms.

MiniBooNE Experiment – E898 at Fermilab

Test of LSND within the context of $\nu_\mu \rightarrow \nu_e$ appearance only is an essential first step:

- Keep the same L/E
- Higher energy and longer baseline – E=0.5 – 1 GeV; L=500m
- Different beam
- Different oscillation signature ν_μ–>ν_e
- Different systematics
- Antineutrino-capable beam



Neutrino Flux Prediction

- GEANT4 based Monte Carlo simulates the neutrino flux in MiniBooNE beamline,
- high purity ν_μ beam – 99%, small ν_e component – intrinsic ν_e
  - background for ν_e appearance

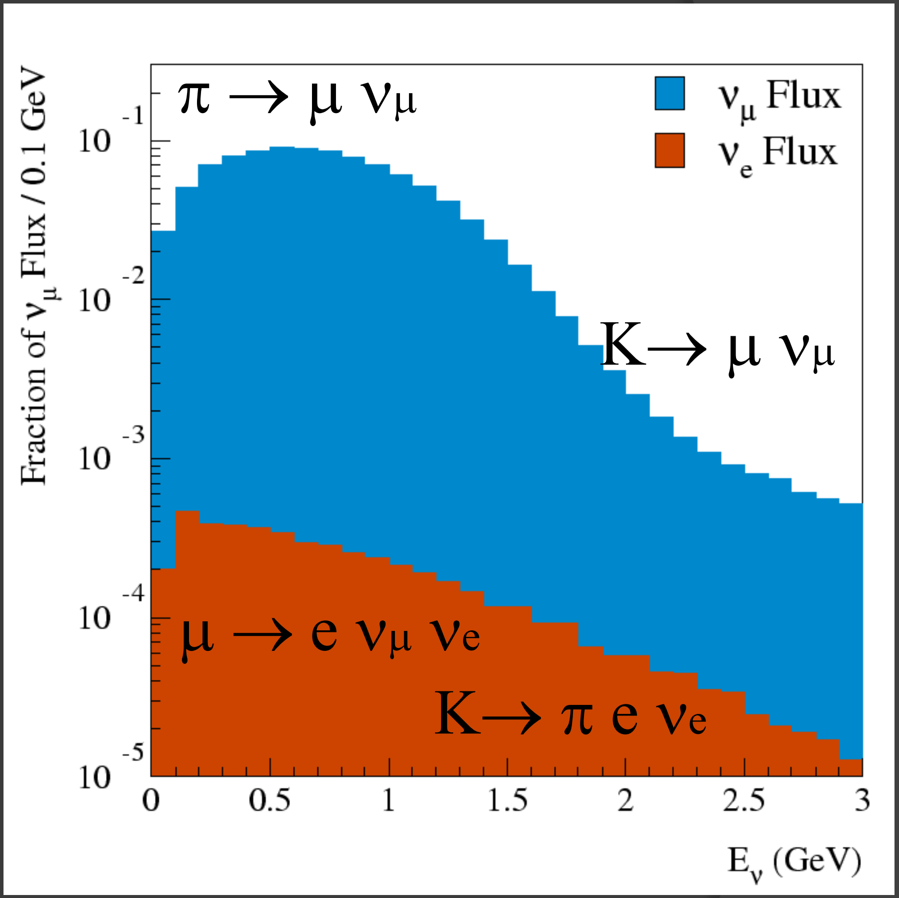
  $\nu_\mu \to \nu_e$, $\nu_e/\nu_\mu = 0.5\%$
- "Intrinsic" ν_e + $\bar{\nu}_e$ sources:

  $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ (52%)

  $K+ \to \pi^0 e^+ \nu_e$ (29%)

  $K^0 \to p\ e\ \nu_e$ (14%)

  Other (5%)
- Antineutrino content: 6%

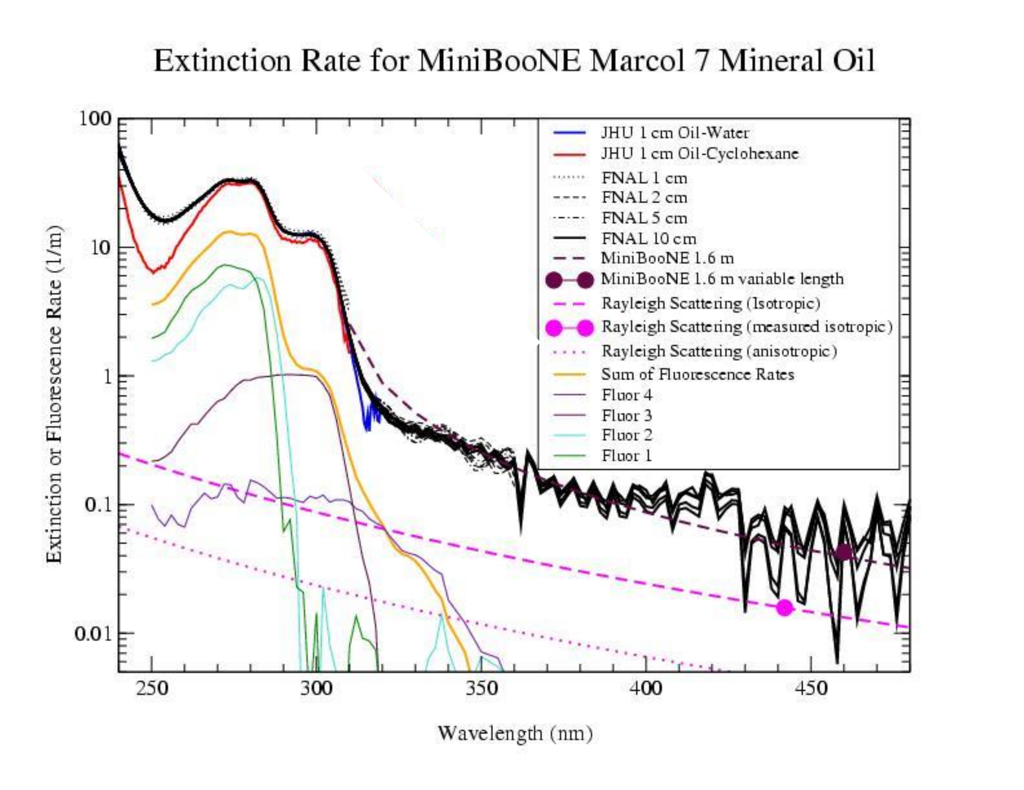


Detector "Optical" Model

Primary light sources

- Cherenkov
  - Emitted promptly, in cone known wavelength distribution
- Scintillation
  - Emitted isotropically
  - Several lifetimes, emission modes
  - Studied oil samples using Indiana Cyclotron test beam
  - Particles below Cherenkov threshold still scintillate

We have developed 39-parameter "Optical Model" based on internal calibration and external measurement



Optical properties of oil, detectors:

- Absorption (attenuation length >20m at 400 nm)
- Rayleigh and Raman scattering
- Fluorescence
- Reflections