First Results from MiniBooNE

April 11, 2007

William Louis, Janet Conrad

for the MiniBooNE Collaboration

The MiniBooNE Collaboration

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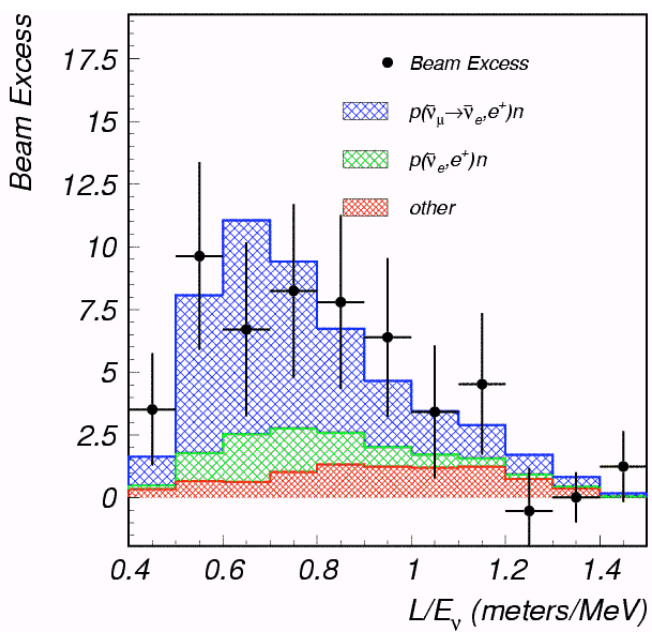
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

- Introduction
- The Neutrino Beam
- Events in the Detector
- Two Independent Analyses
- Errors, Constraints and Sensitivity
- Initial Results

MiniBooNE was approved in 1998,
with the goal of addressing the LSND anomaly:

an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam,
87.9 ± 22.4 ± 6.0 (3.8σ)

which can be interpreted as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations:



Points -- LSND data
Signal (blue)
Backgrounds (red, green)

LSND Collab, PRD 64, 112007

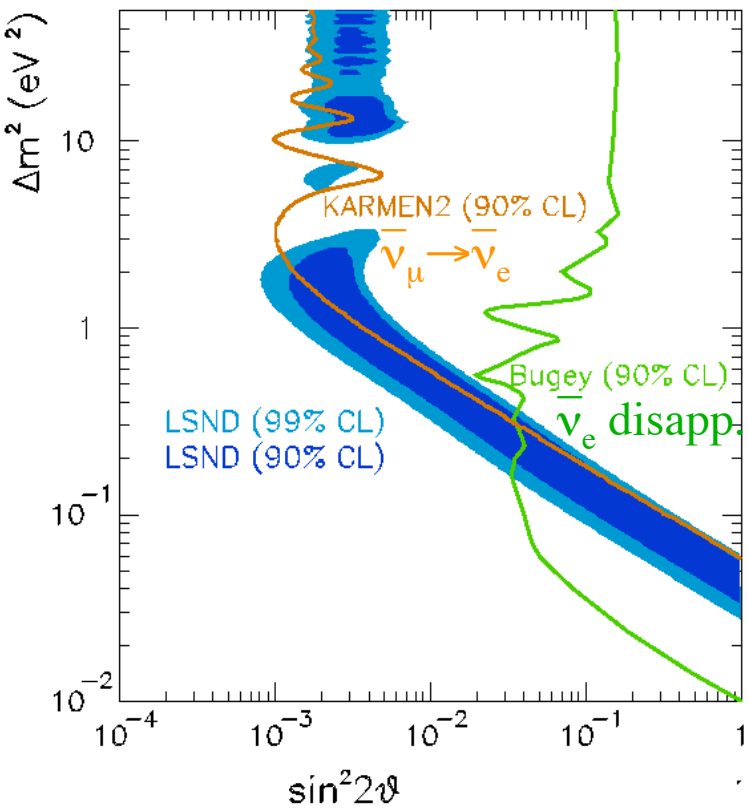
Within a $\nu_\mu \rightarrow \nu_e$ appearance model

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

mixing angle

squared mass difference

$\frac{\text{travel distance}}{\text{energy}}$ of the neutrinos



This model allows comparison to other experiments:

Karmen2

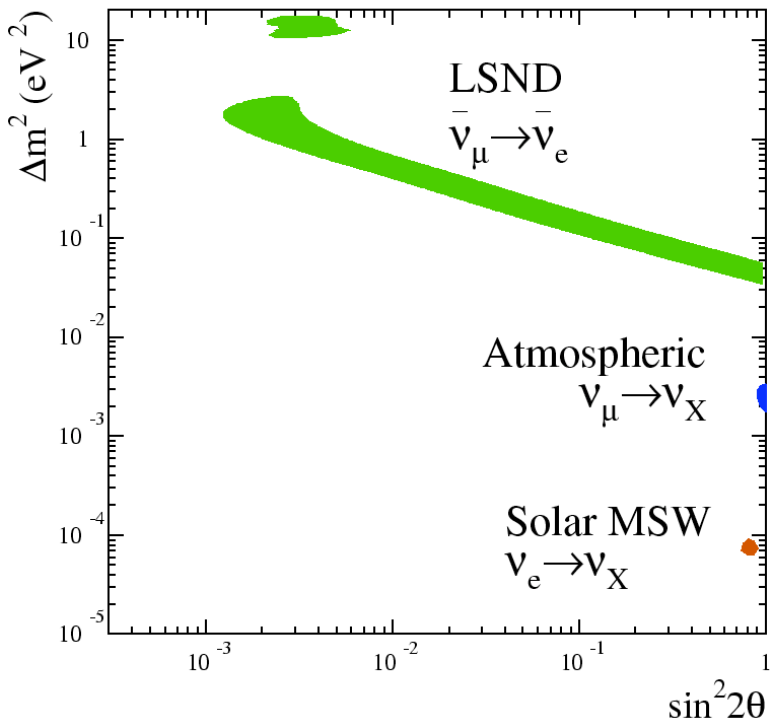
Bugey

Joint analysis with Karmen2:
64% compatible

Church, et al., PRD 66, 013001

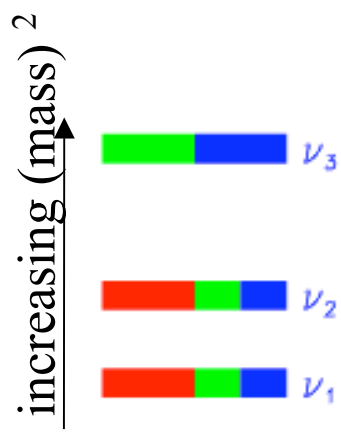
This is a simplistic interpretation.

$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$



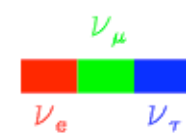
A 3 neutrino picture requires

$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$



$$\Delta m_{23}^2 = m_2^2 - m_3^2$$

$$\Delta m_{12}^2 = m_1^2 - m_2^2$$



The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics

However a test of LSND within the context of $\nu_\mu \rightarrow \nu_e$ appearance (no disappearance) is an essential first step:

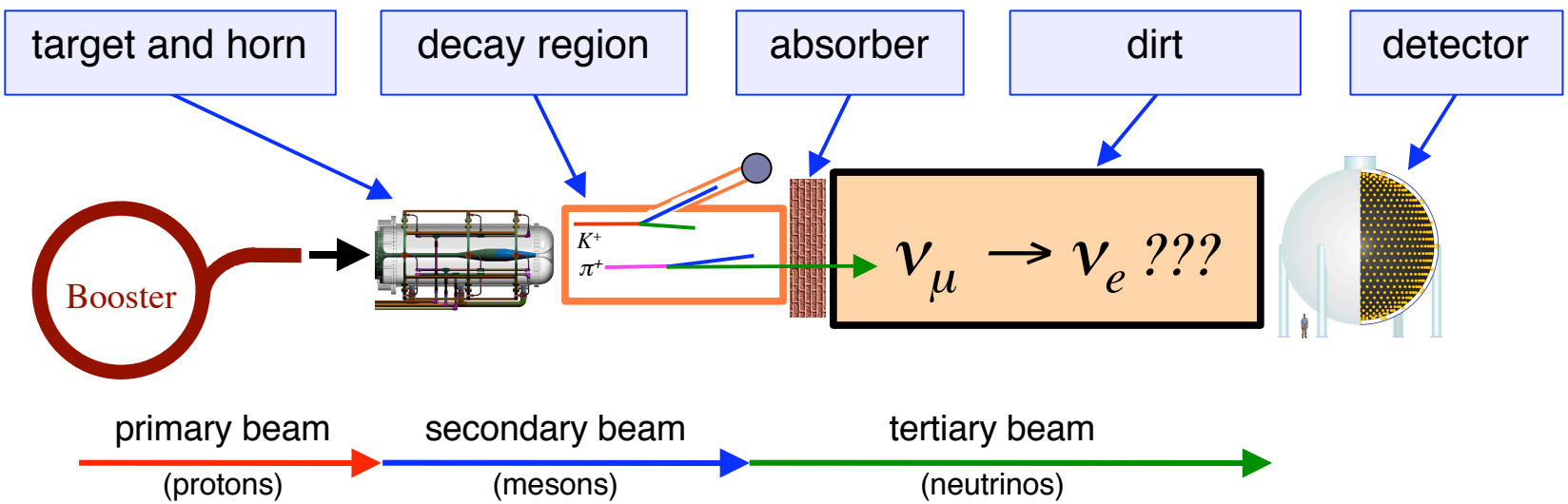
- This is the simplest model which explains LSND.

- This model allows cross comparison with published
  oscillation results from LSND and
  other relevant past experiments (e.g. Karmen)

MiniBooNE's Design Strategy...

Keep L/E same
while changing systematics, energy & event signature

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$$



Order of magnitude
higher energy (~500 MeV)
than LSND (~30 MeV)

Order of magnitude
longer baseline (~500 m)
than LSND (~30 m)

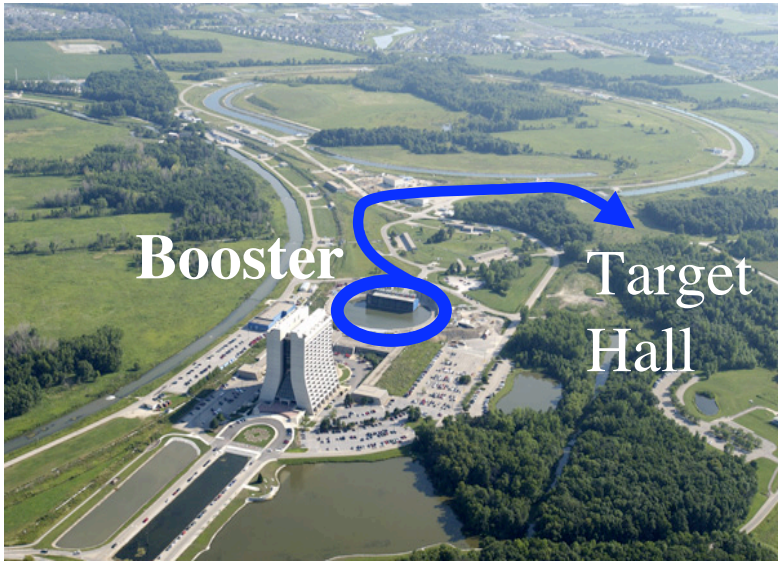
Today we report MiniBooNE's initial results on testing the LSND anomaly:

- A generic search for a ν_e excess in our ν_μ beam,
- An analysis of the data within a $\nu_\mu \rightarrow \nu_e$ appearance context

This was a blind analysis.
The box was opened on March 26, 2007

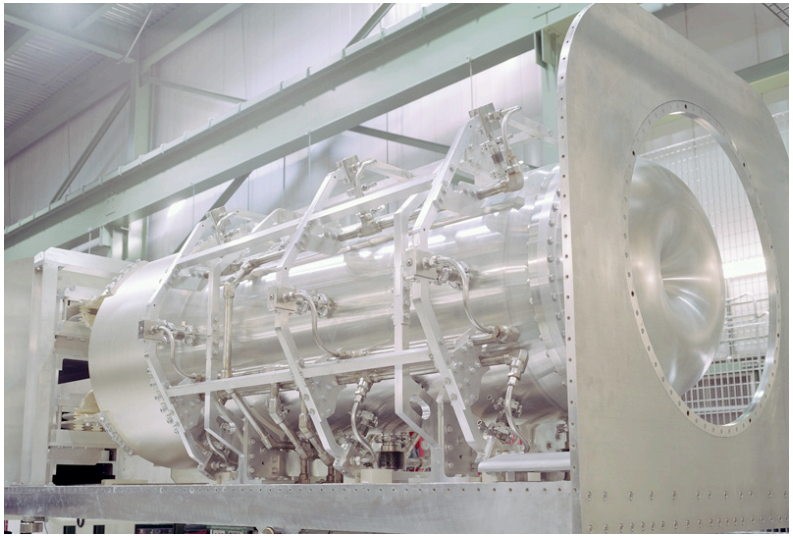
Two independent analyses were performed.
The primary analysis was chosen based on $\nu_\mu \rightarrow \nu_e$ sensitivity, prior to unblinding.

The Neutrino Beam



MiniBooNE extracts beam from the 8 GeV Booster

Delivered to a 1.7 λ Be target



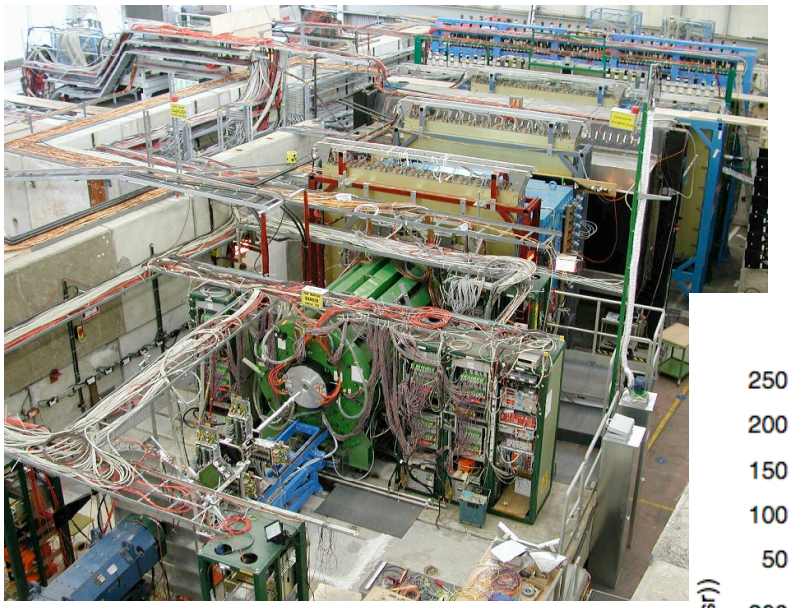
4×10^{12} protons per 1.6 μs pulse delivered at up to 5 Hz.

6.3×10^{20} POT delivered.

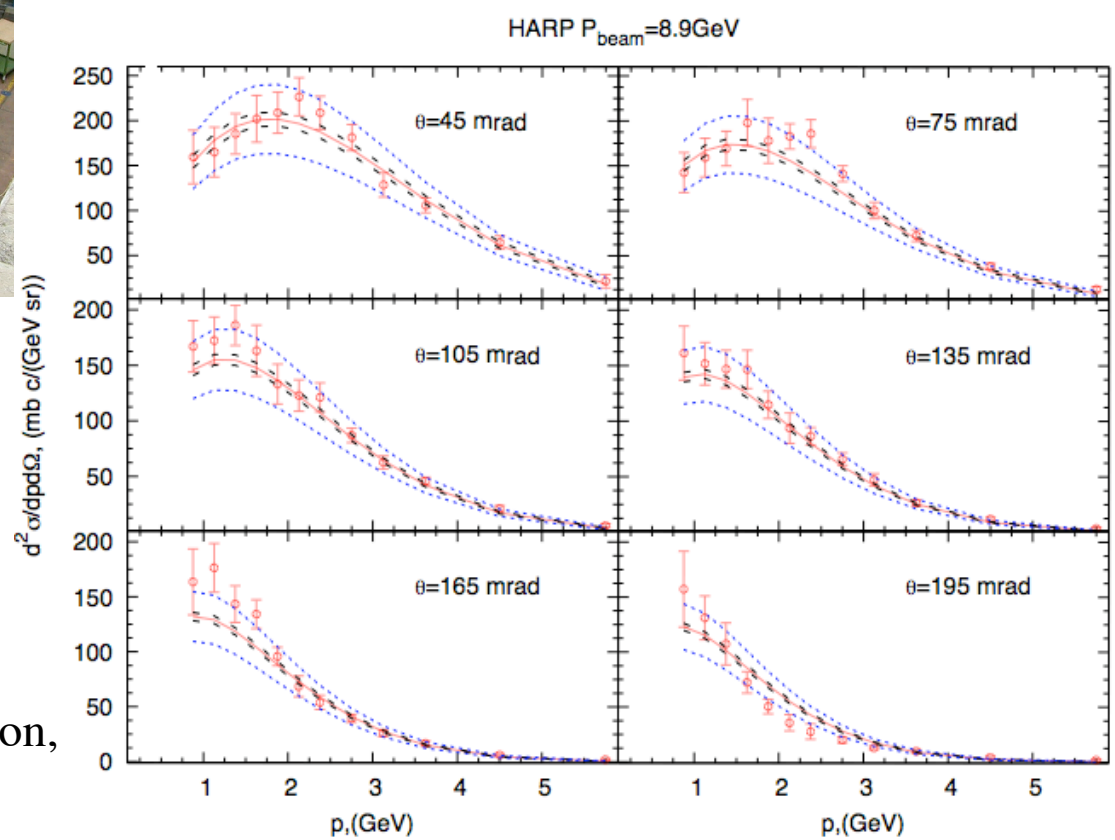
Results correspond to $(5.58 \pm 0.12) \times 10^{20}$ POT

within a magnetic horn (2.5 kV, 174 kA) that (increases the flux by ×6)

Modeling Production of Secondary Pions



- HARP (CERN)
  - 5% λ Beryllium target
  - 8.9 GeV proton beam momentum



Data are fit to a Sanford-Wang parameterization.

HARP collaboration, hep-ex/0702024

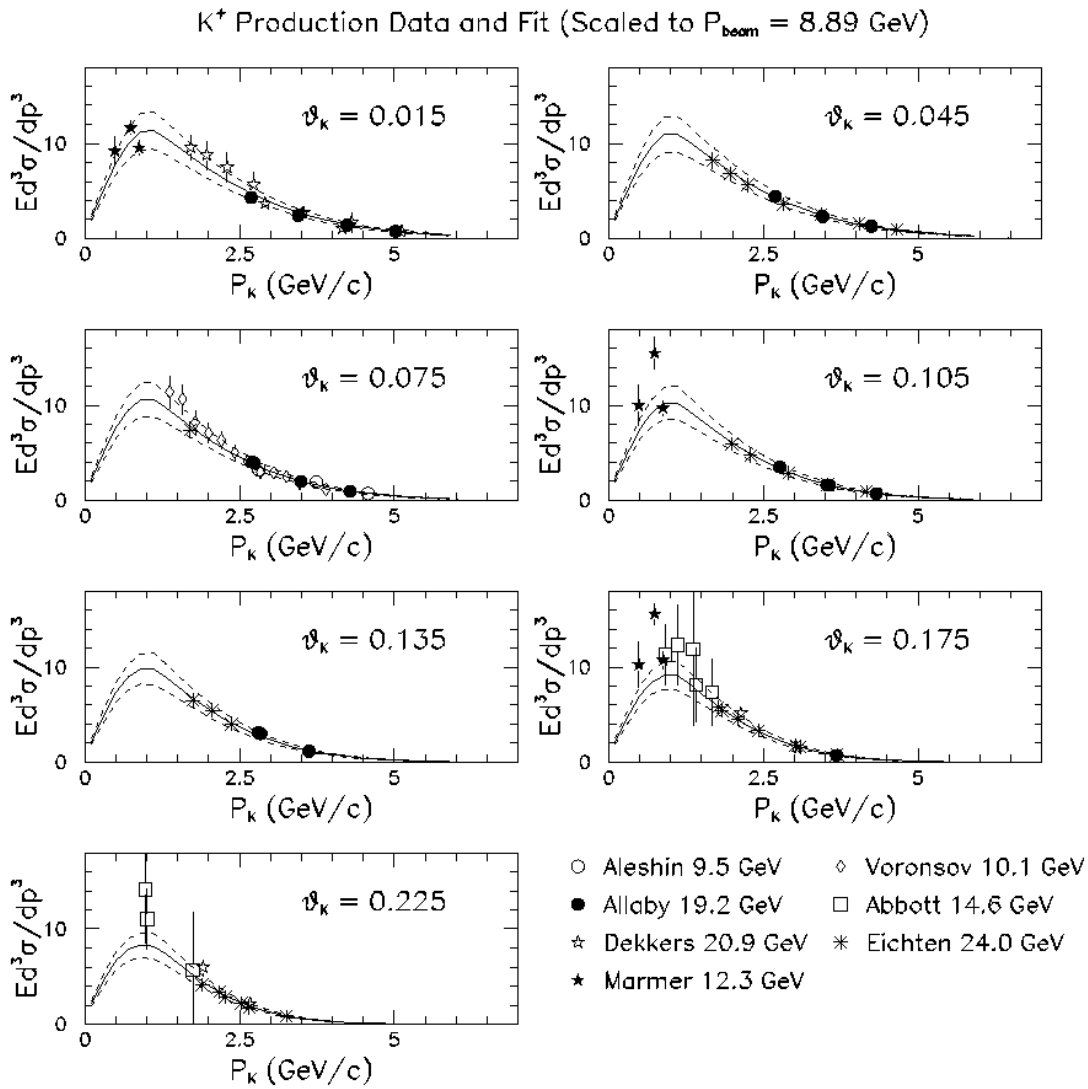
Modeling Production of Secondary Kaons

K^+ Data from 10 - 24 GeV. Uses a Feynman Scaling Parameterization.

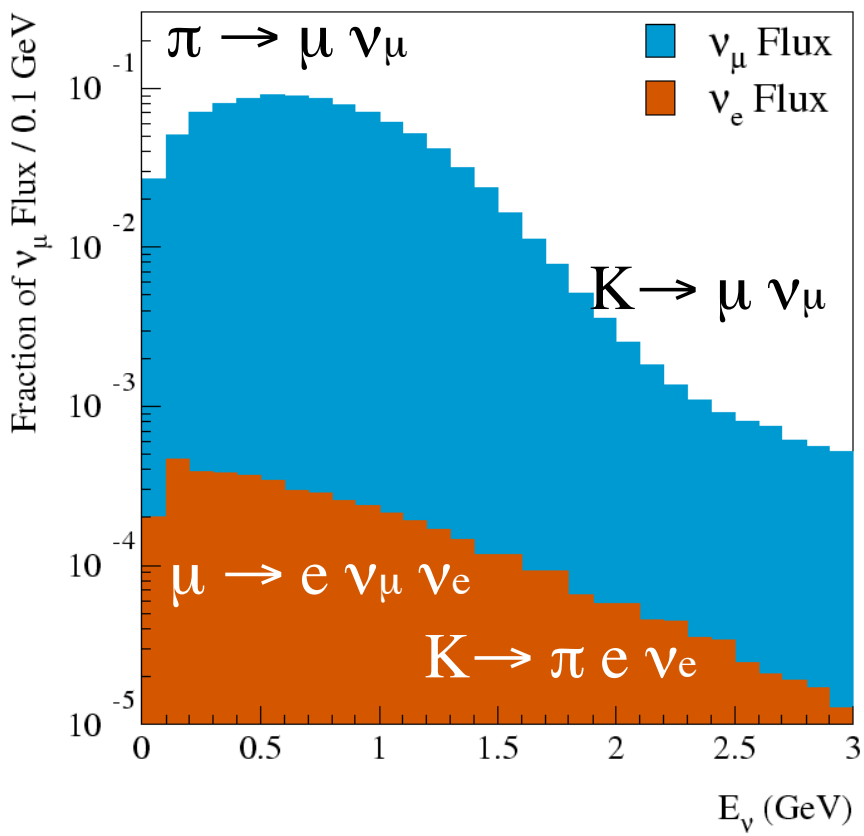
data -- points
dash --total error
(fit ⊕ parameterization)

K^0 data are also parameterized.

In situ measurement of K^+ from LMC agrees within errors with parameterization



Neutrino Flux from GEANT4 Simulation



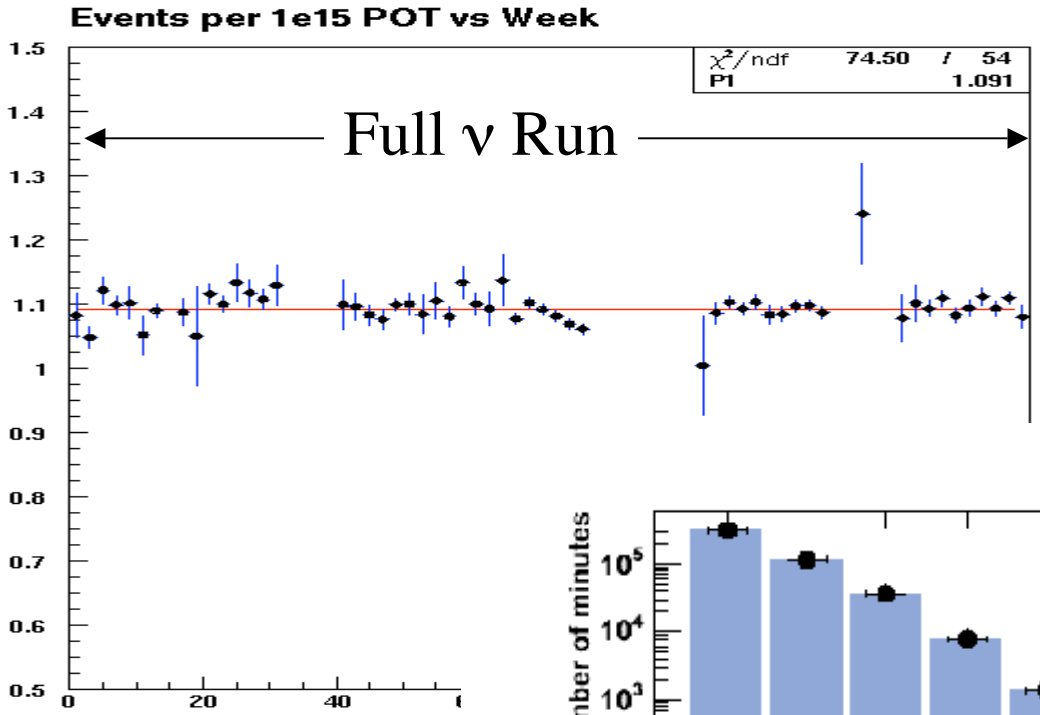
$\nu_e/\nu_\mu = 0.5\%$

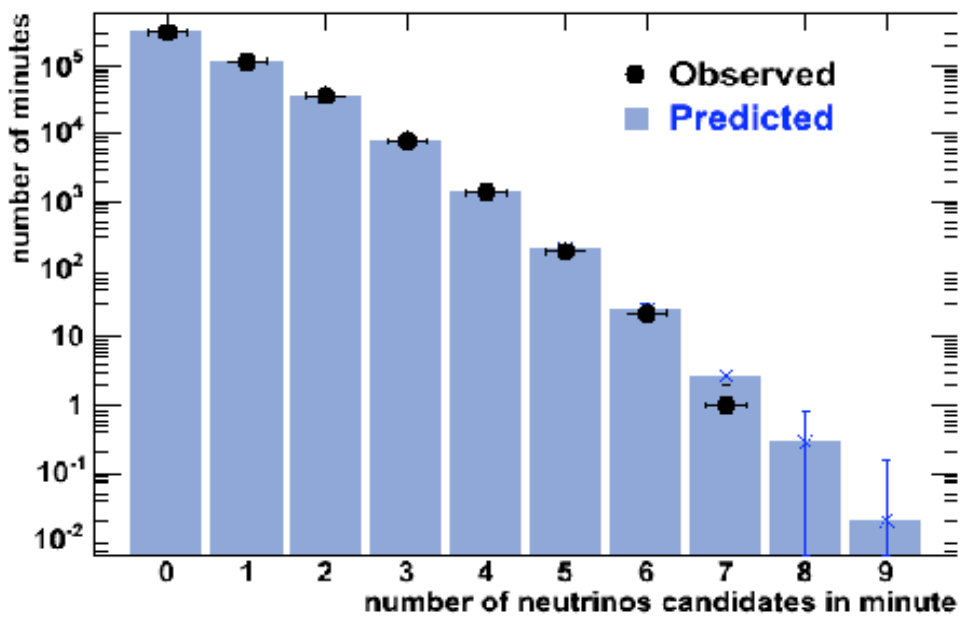
Antineutrino content: 6%

"Intrinsic" $\nu_e + \bar{\nu}_e$ sources:

$\mu^+ \rightarrow e^+\ \bar{\nu}_\mu\ \nu_e$	(52%)
$K^+ \rightarrow \pi^0\ e^+\ \nu_e$	(29%)
$K^0 \rightarrow \pi\ e\ \nu_e$	(14%)
Other	(5%)

Stability of running:

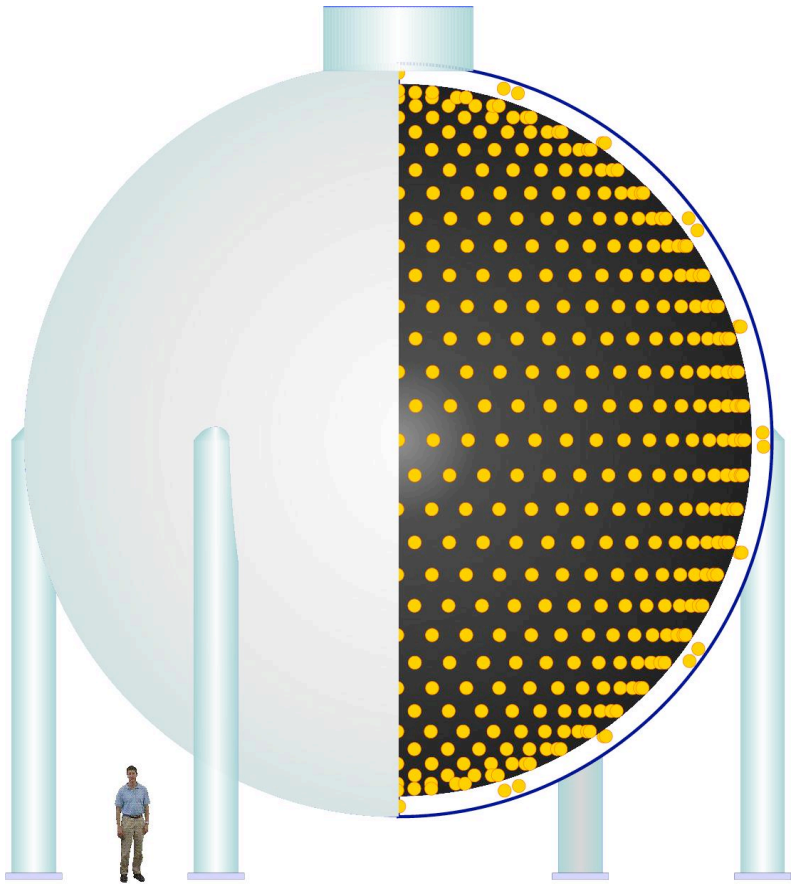




Observed and expected events per minute

Events in the Detector

The MiniBooNE Detector



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

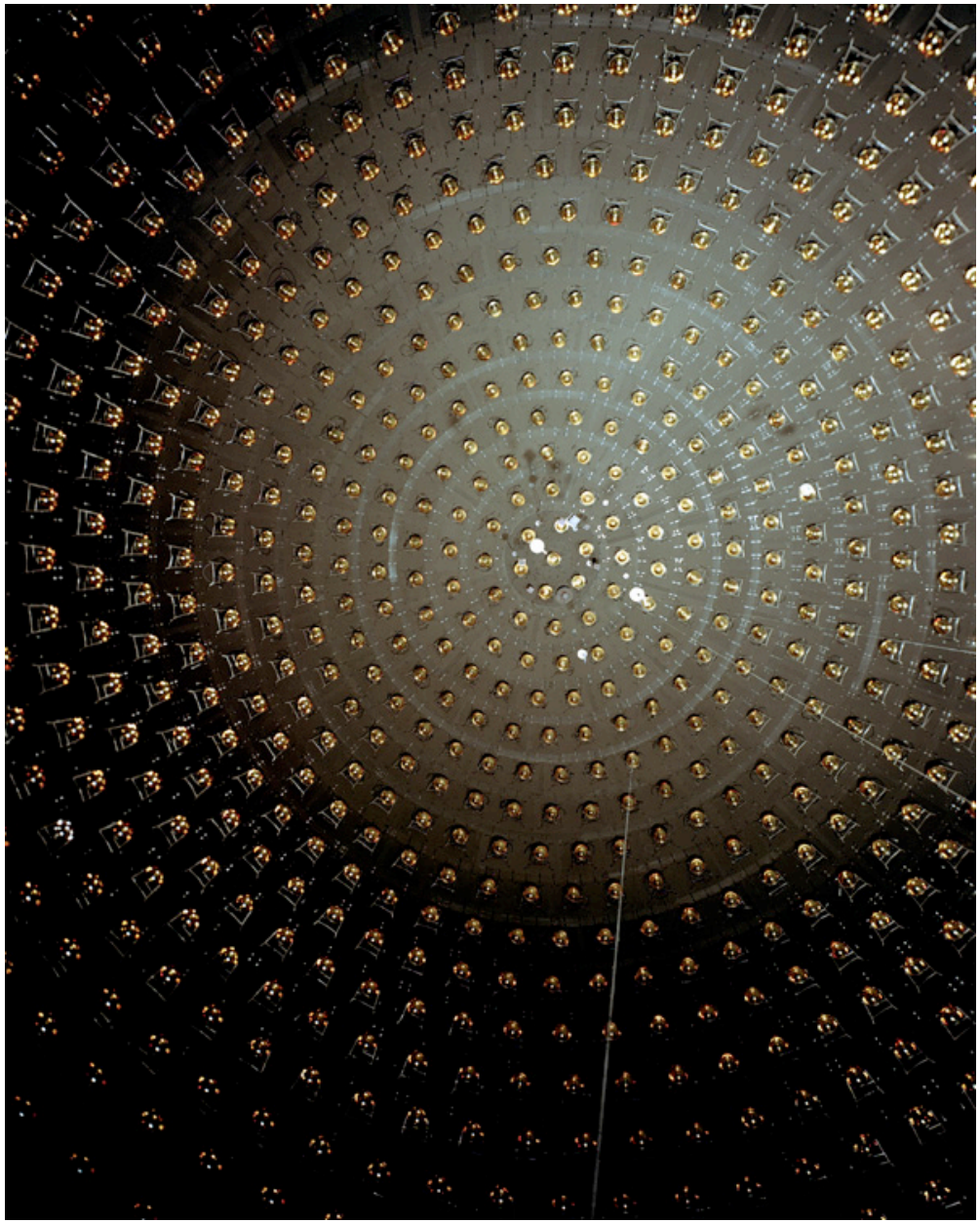
  (10 meter "fiducial" volume)

  - Filled with 800 t

    of pure mineral oil (CH_2)

    (Fiducial volume: 450 t)
  - 1280 inner phototubes,

    240 veto phototubes
  - Simulated with a GEANT3 Monte Carlo



10% Photocathode coverage

Two types of
Hamamatsu Tubes:
R1408, R5912

Charge Resolution:
1.4 PE, 0.5 PE

Time Resolution
1.7 ns, 1.1ns

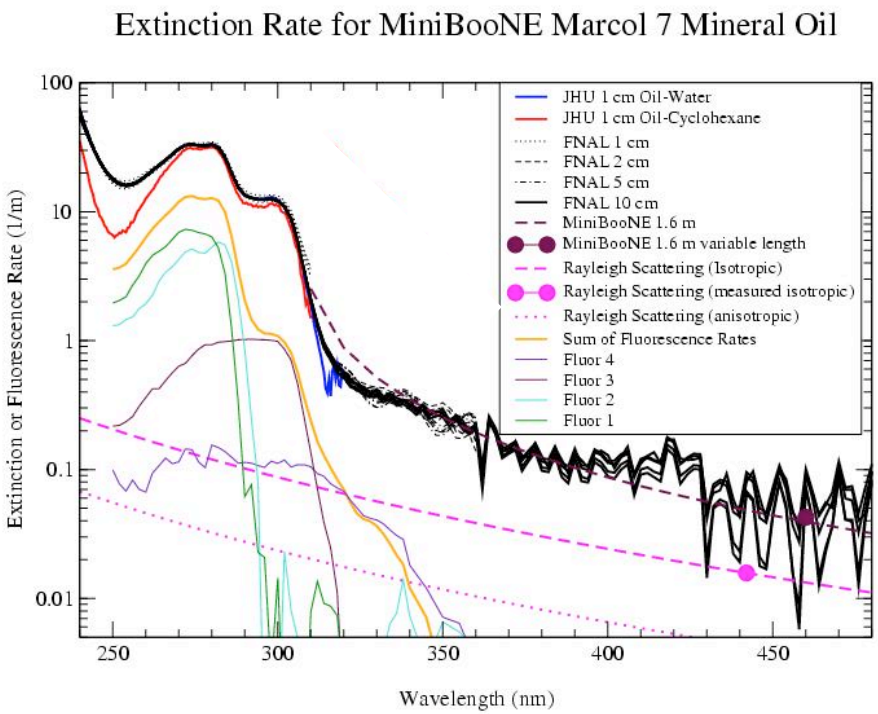
Optical Model

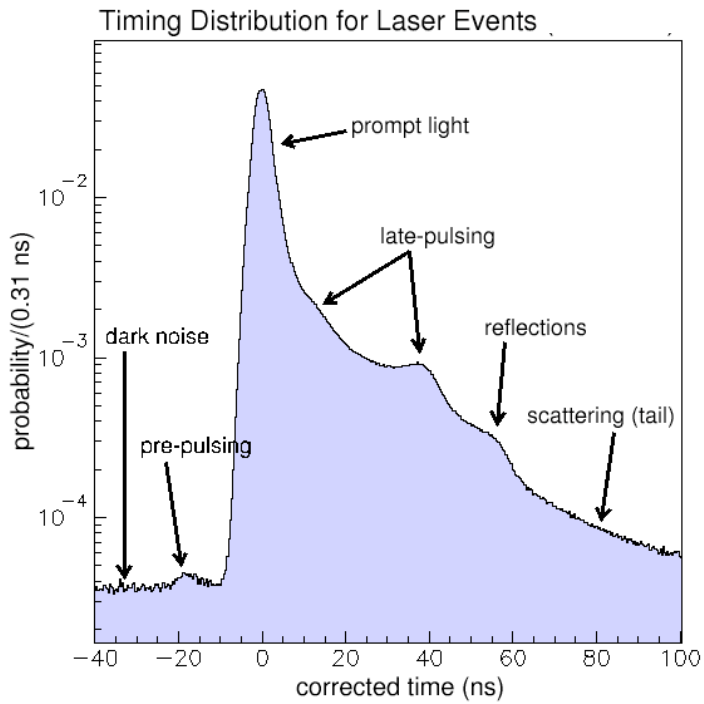
Attenuation length: >20 m @ 400 nm

Detected photons from

- Prompt light (Cherenkov)
- Late light (scintillation, fluorescence) in a 3:1 ratio for β~1

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



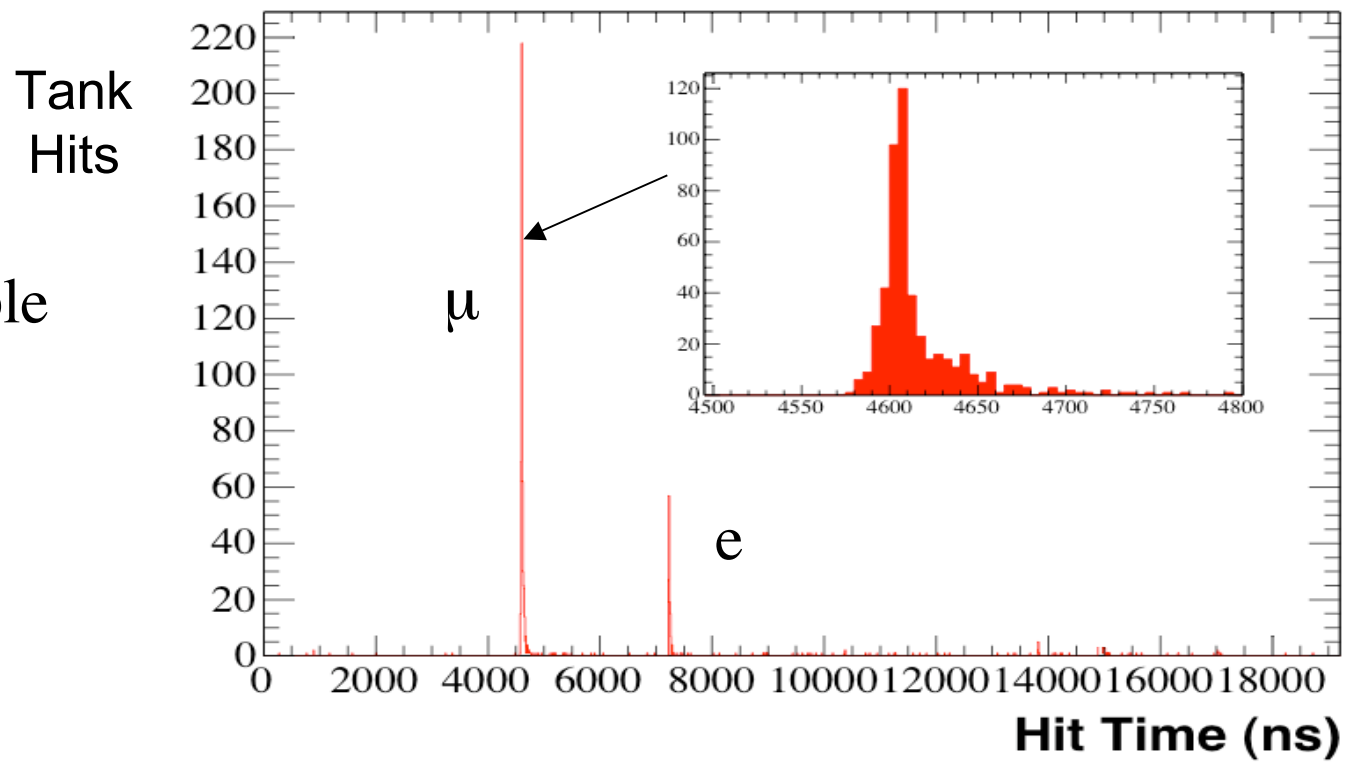


A 19.2 μs beam trigger window encompasses the 1.6 μs spill

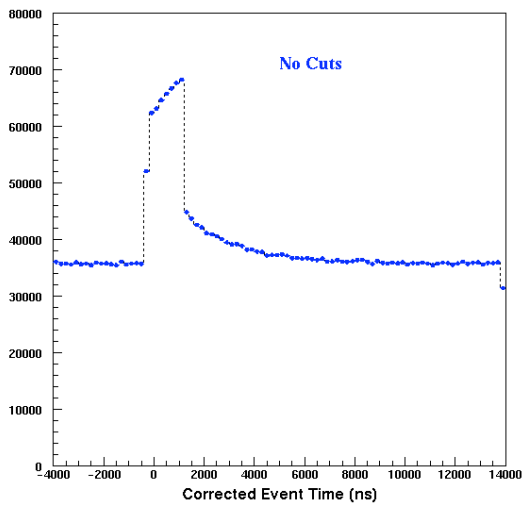
Multiple hits within a ~100 ns window form "subevents"

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

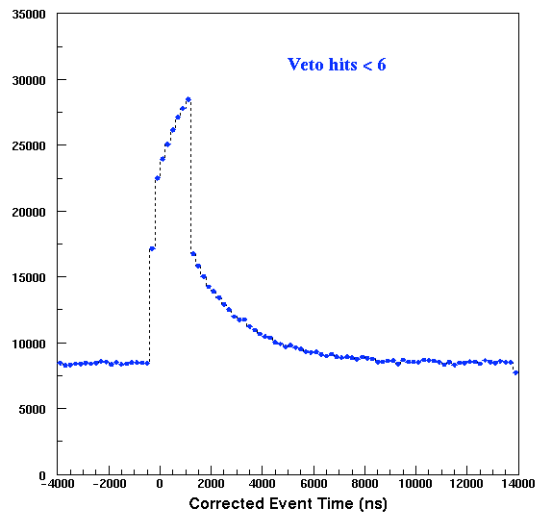
Example Event



Progressively introducing cuts on the time window:

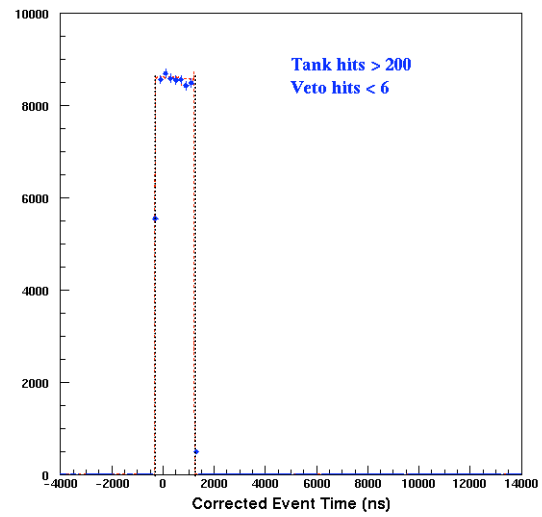


Raw data



Veto<6 removes through-going cosmics

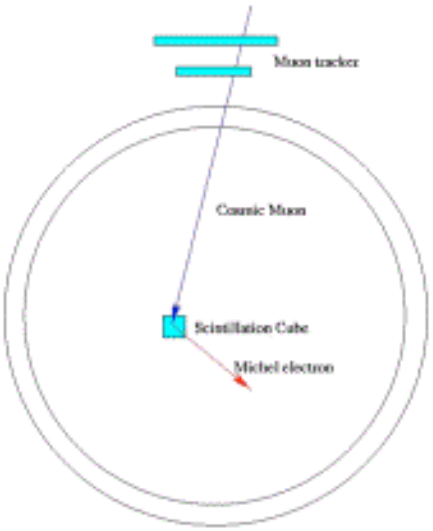
This leaves " Michel electrons" ($\mu \rightarrow \nu_\mu \nu_e e$) from cosmics

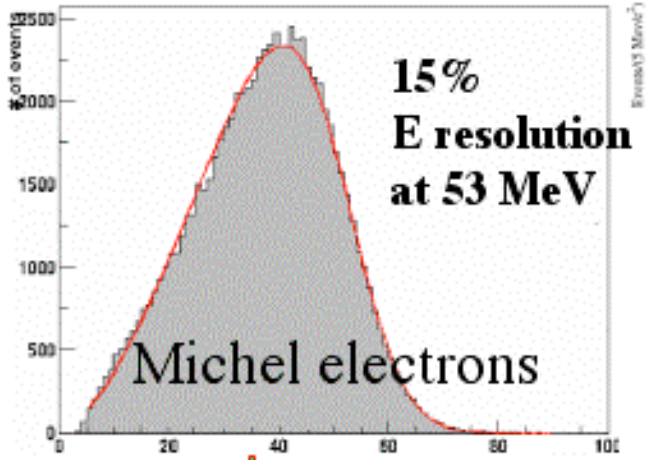


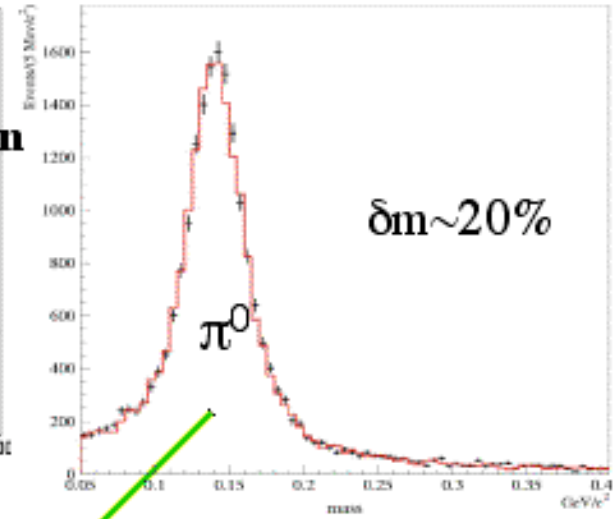
Tank Hits > 200 (equivalent to energy) removes Michel electrons, which have 52 MeV endpoint

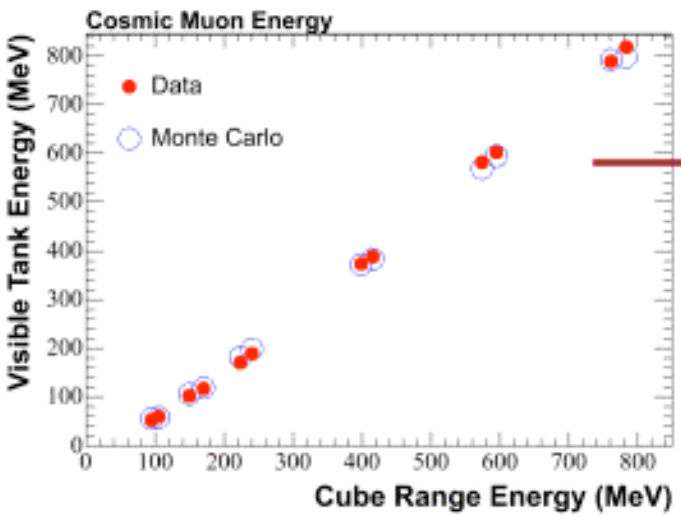
Calibration Sources

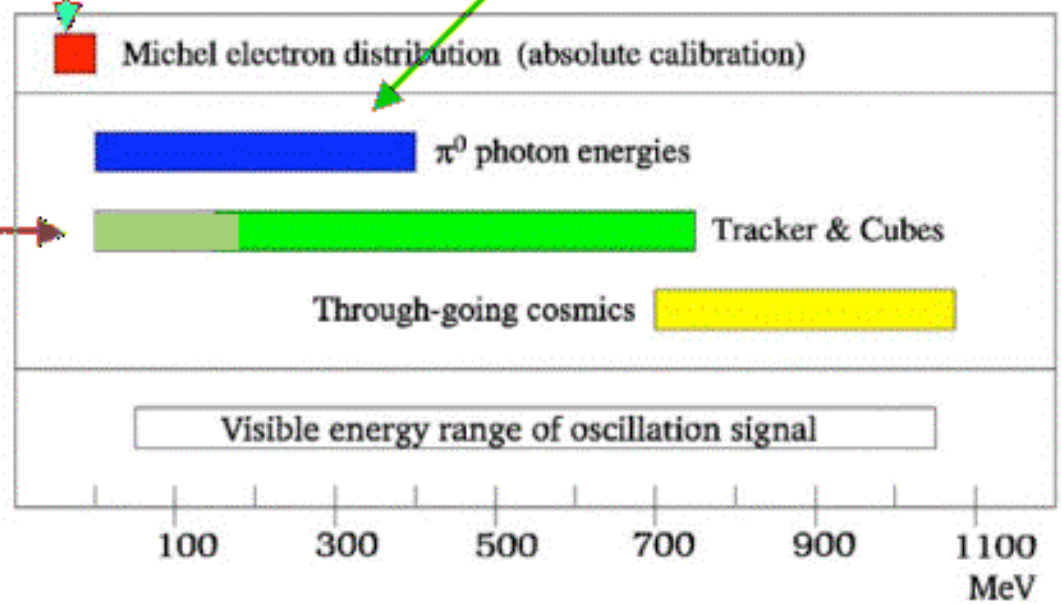
Tracker system





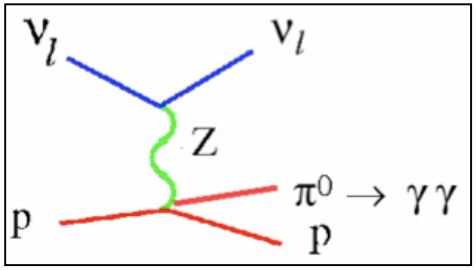


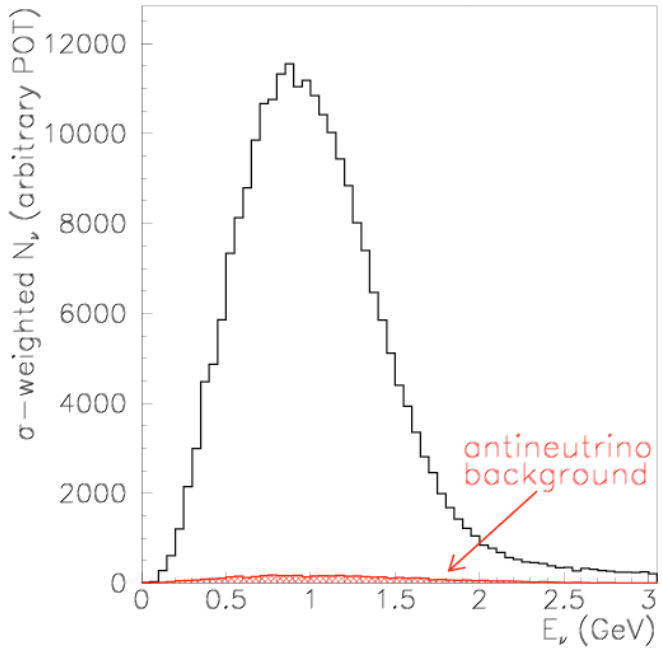




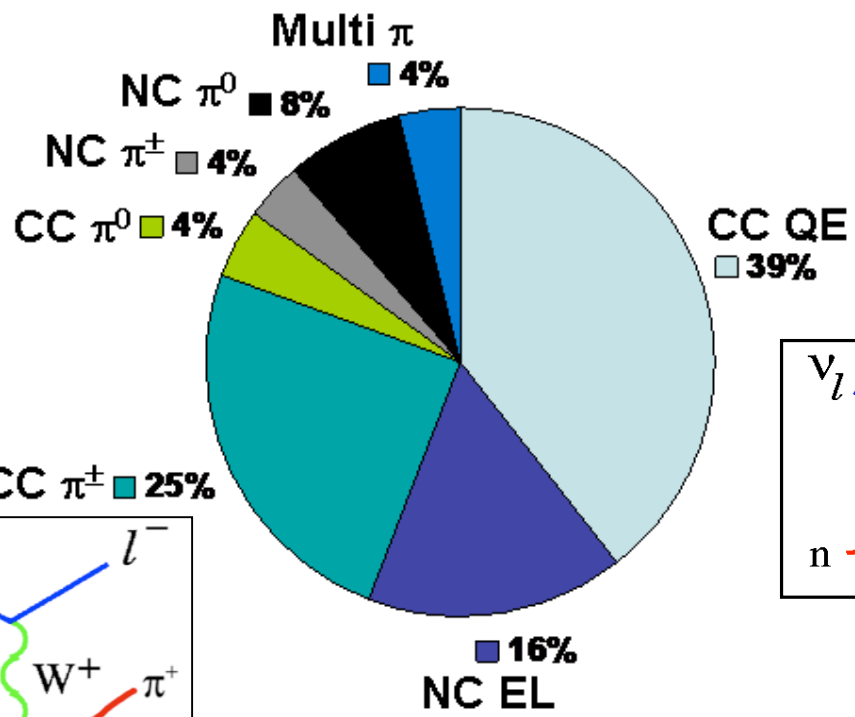
Predicted event rates before cuts (NUANCE Monte Carlo)

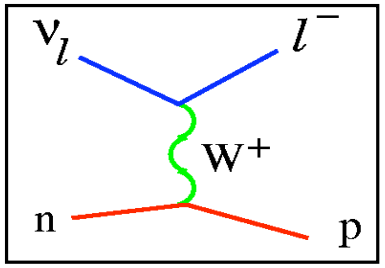
D. Casper, NPS, 112 (2002) 161

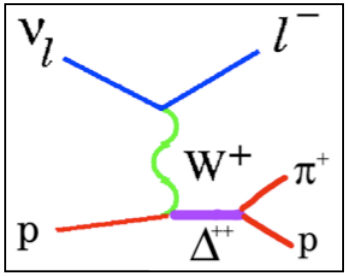




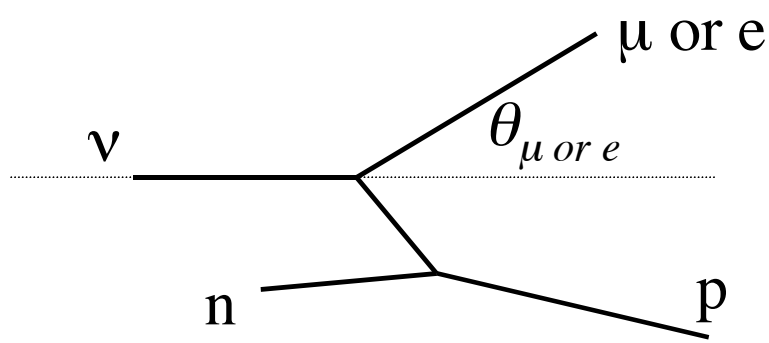
Event neutrino energy (GeV)







CCQE
(Charged Current Quasi-Elastic)

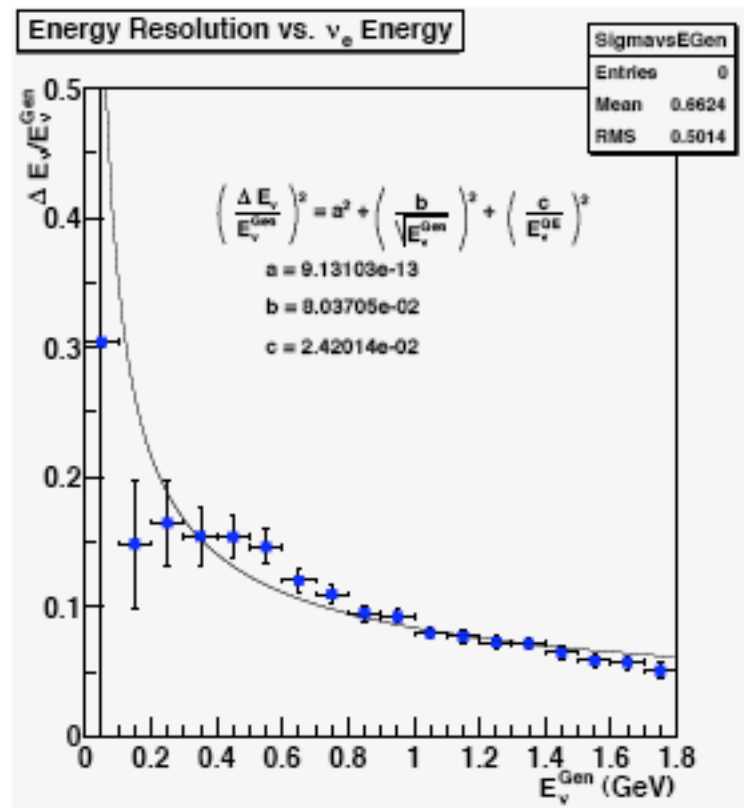


39% of total

- Events are "clean" (few particles)
- Energy of the neutrino can be reconstructed

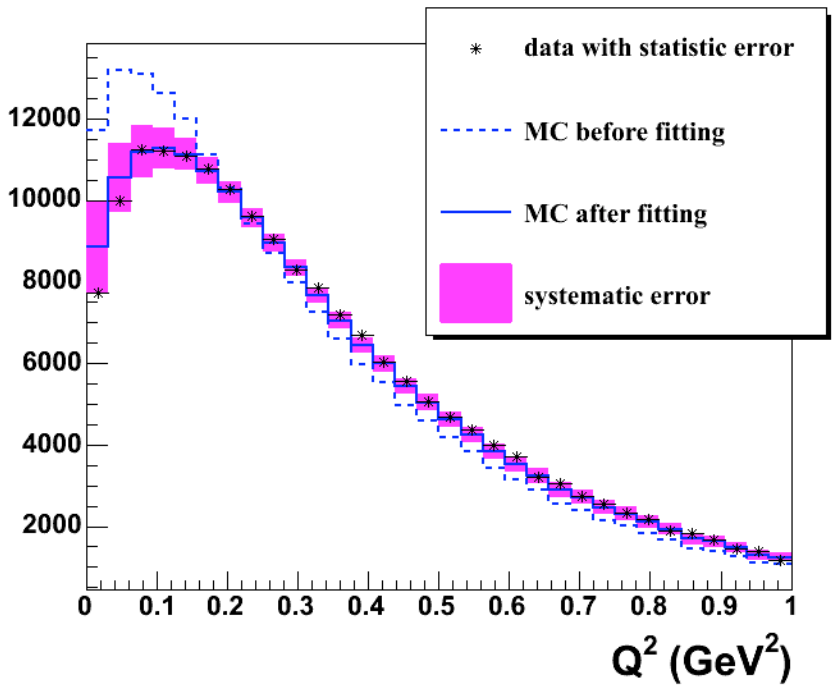
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$

Reconstructed from:
Scattering angle
Visible energy ($E_{visible}$)



An oscillation signal is an excess of ν_e events as a function of E_ν^{QE}

NUANCE Parameters:



Model describes CCQE ν_μ data well

From Q^2 fits to MB ν_μ CCQE data:

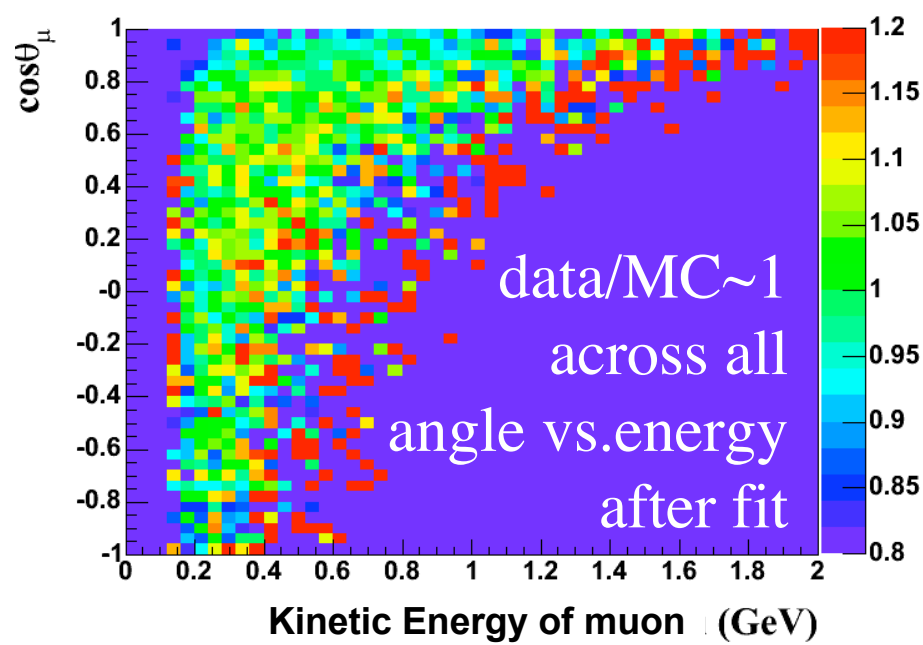
M_A^{eff} -- effective axial mass

E_{lo}^{SF} -- Pauli Blocking parameter

From electron scattering data:

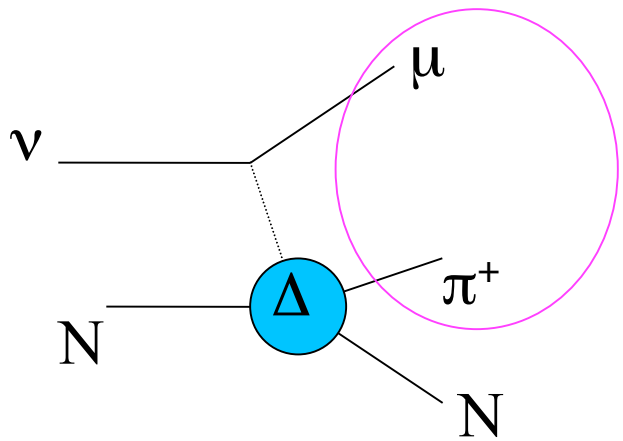
E_b -- binding energy

p_f -- Fermi momentum



Events producing pions

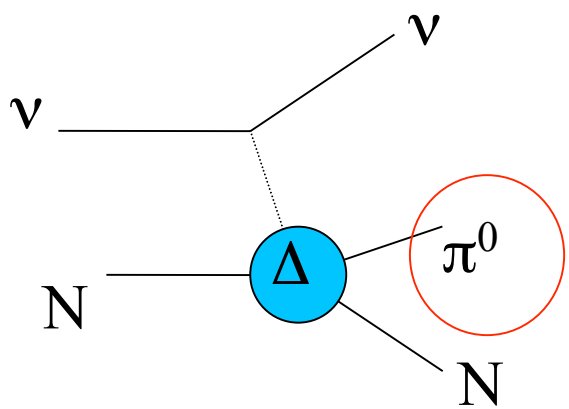
25%



$CC\pi^+$

Easy to tag due to 3 subevents. Not a substantial background to the oscillation analysis.

8%



$NC\pi^0$

The π^0 decays to 2 photons, which can look "electron-like" mimicking the signal...

(also decays to a single photon with 0.56% probability)

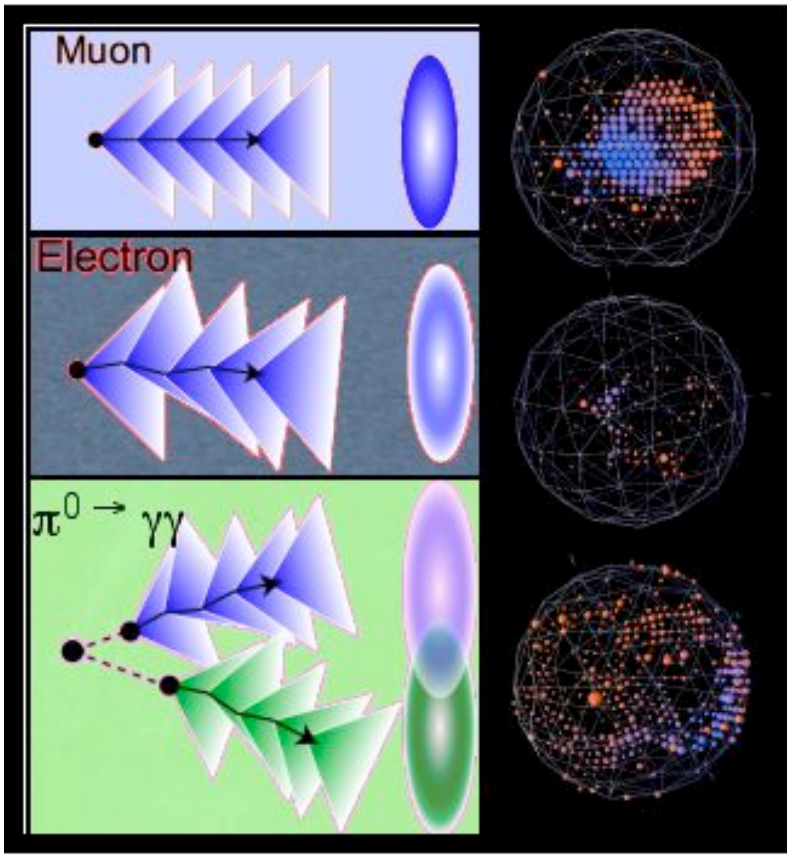
<1% of π^0 contribute to background.

The types of particles these events produce:

Muons:
Produced in most CC events.
Usually 2 subevent or exiting.

Electrons:
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent

π^0s:
Can form a background if one photon is weak or exits tank.
In NC case, 1 subevent.



Two Independent Analyses

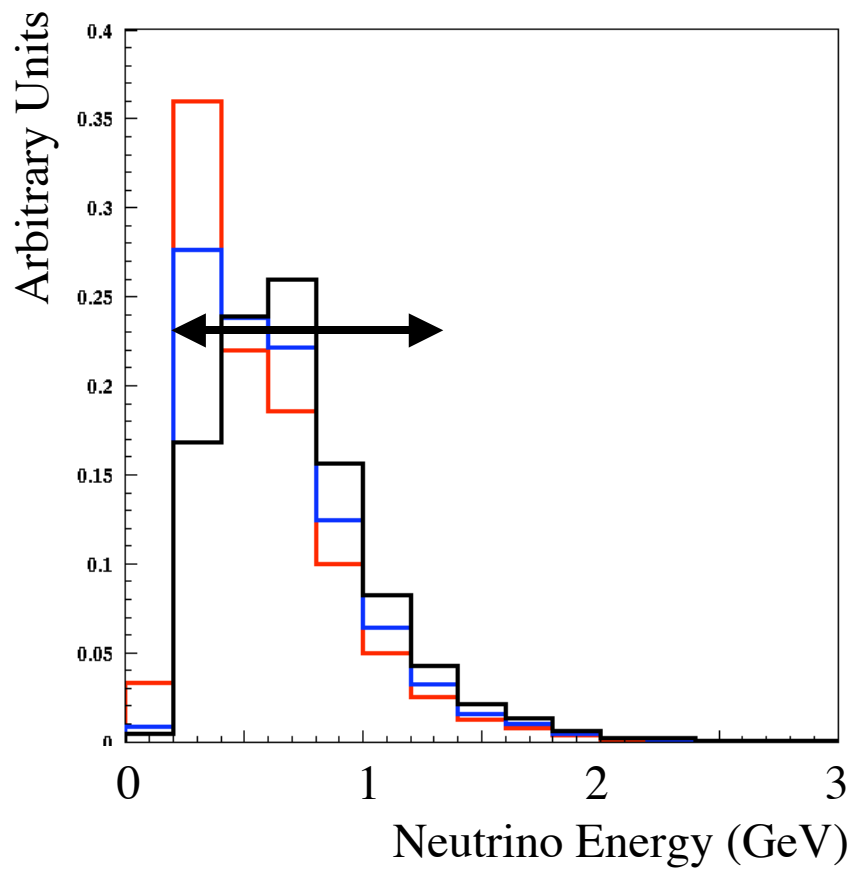
The goal of both analyses:

<u>minimize background</u> &
<u>maximize signal</u> efficiency.

"Signal range" is approximately
300 MeV < E_ν^{QE} < 1500 MeV

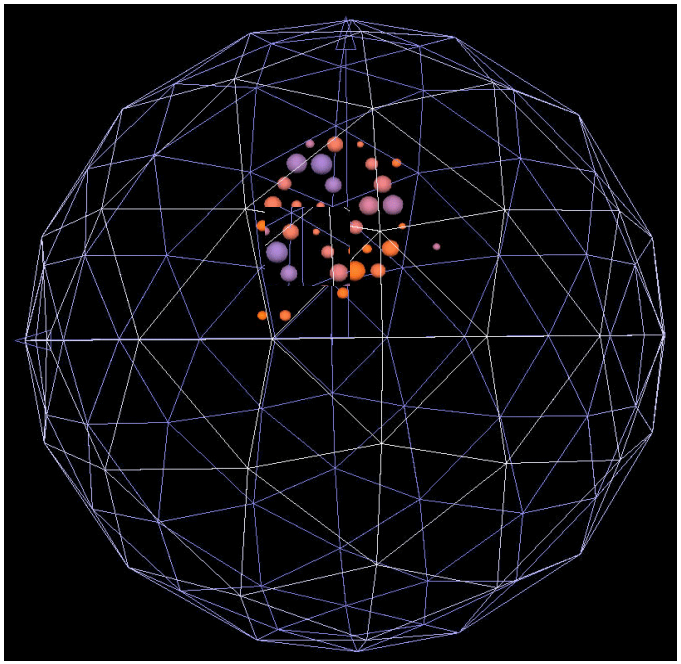
One can then either:

- look for a total excess
  ("counting expt")
- fit for both an excess and
  energy dependence
  ("energy fit")



MiniBooNE signal examples:
Δm^2=0.4 eV^2
Δm^2=0.7 eV^2
Δm^2=1.0 eV^2

Open Data for Studies:



MiniBooNE is searching
for a small but distinctive
event signature

In order to maintain blindness,
Electron-like events were sequestered,
Leaving ~99% of the in-beam events available for study.

Rule for cuts to sequester events: $<1\sigma$ signal outside of the box

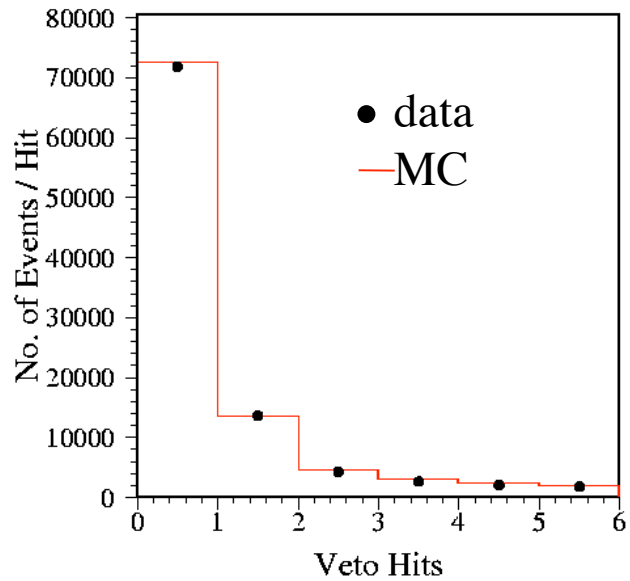
Low level information which did not allow particle-id
was available for all events.

Both Algorithms and all analyses presented here share “hit-level pre-cuts”:

Only 1 subevent

Veto hits < 6

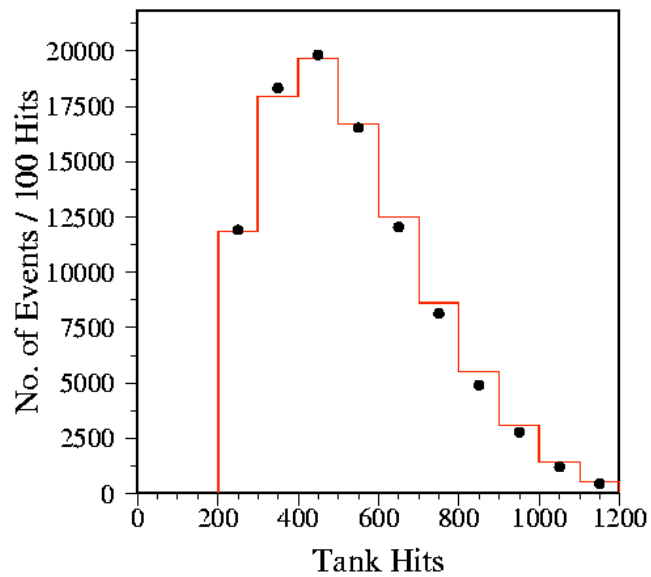
Tank hits > 200



And a radius precut:

R<500 cm

(where reconstructed R is algorithm-dependent)



Analysis 1: "Track-Based" (TB) Analysis

Philosophy:

Uses detailed, direct reconstruction of particle tracks,
and ratio of fit likelihoods to identify particles.

This algorithm was found to have the better
sensitivity to $\nu_\mu \rightarrow \nu_e$ appearance.
Therefore, before unblinding,
this was the algorithm chosen for the "primary result"

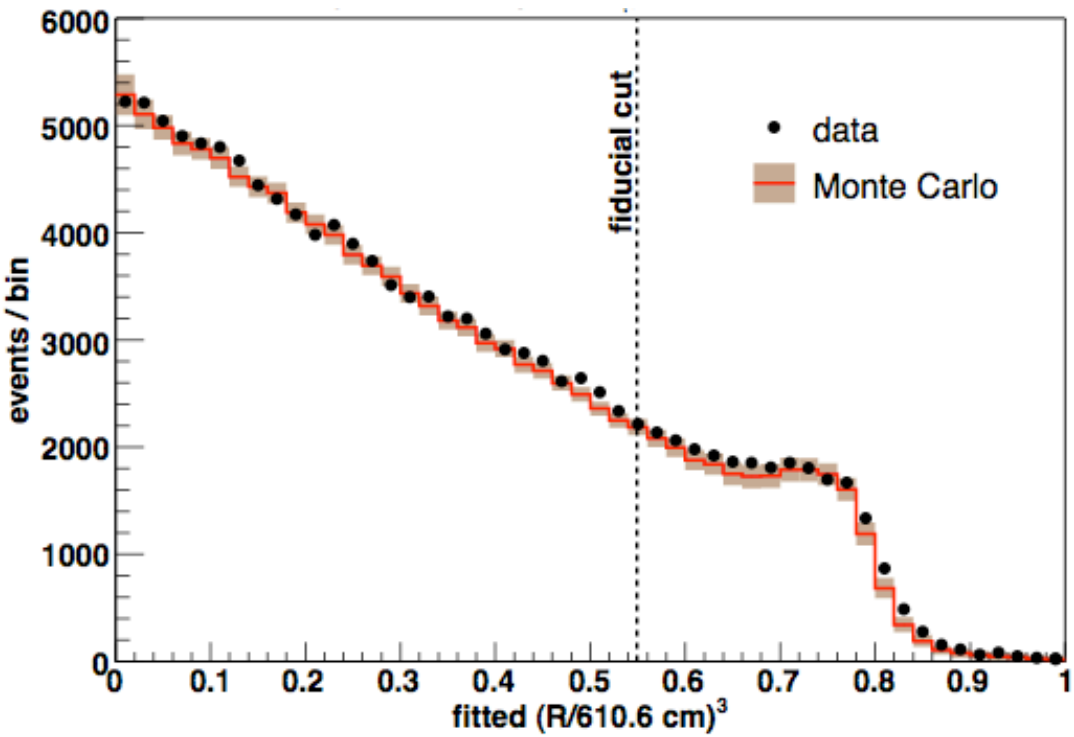
Each event is characterized by 7 reconstructed variables:

vertex *(x,y,z)*, time, energy, and direction $(\theta,\phi) \Leftrightarrow (U_x, U_y, U_z)$.

Resolutions: vertex: 22 cm

direction: 2.8°

energy: 11%

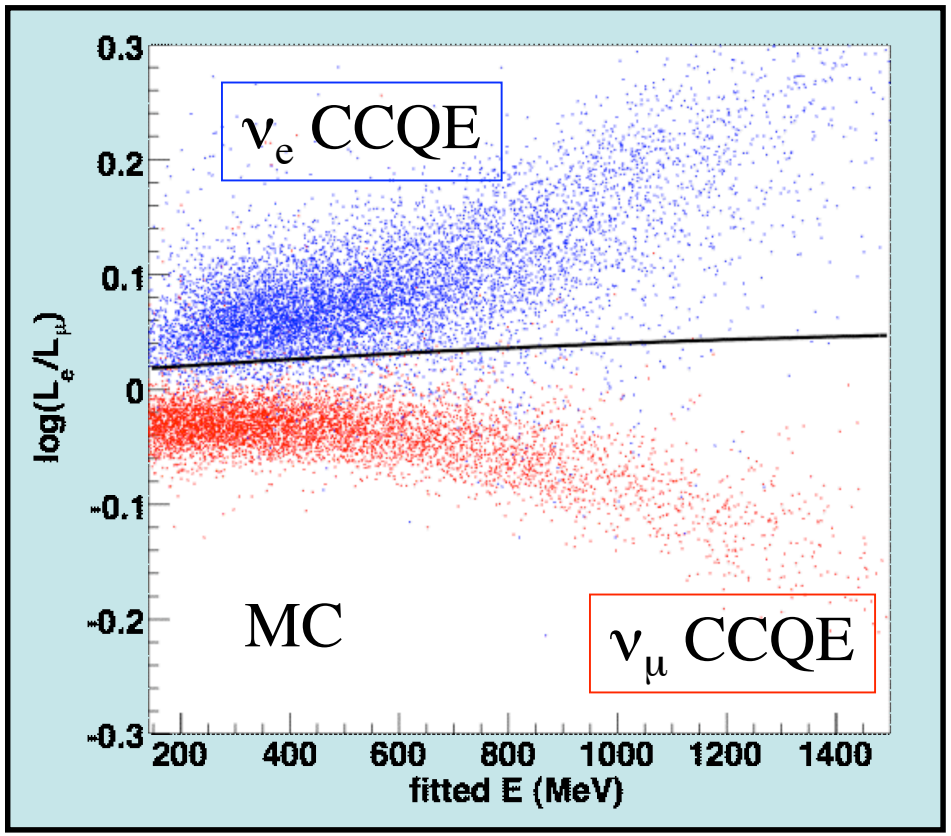


ν_μ CCQE events

2 subevents
Veto Hits<6
Tank Hits>200

Rejecting "muon-like" events
Using $\log(L_e/L_\mu)$

$\log(L_e/L_\mu)>0$ favors electron-like hypothesis



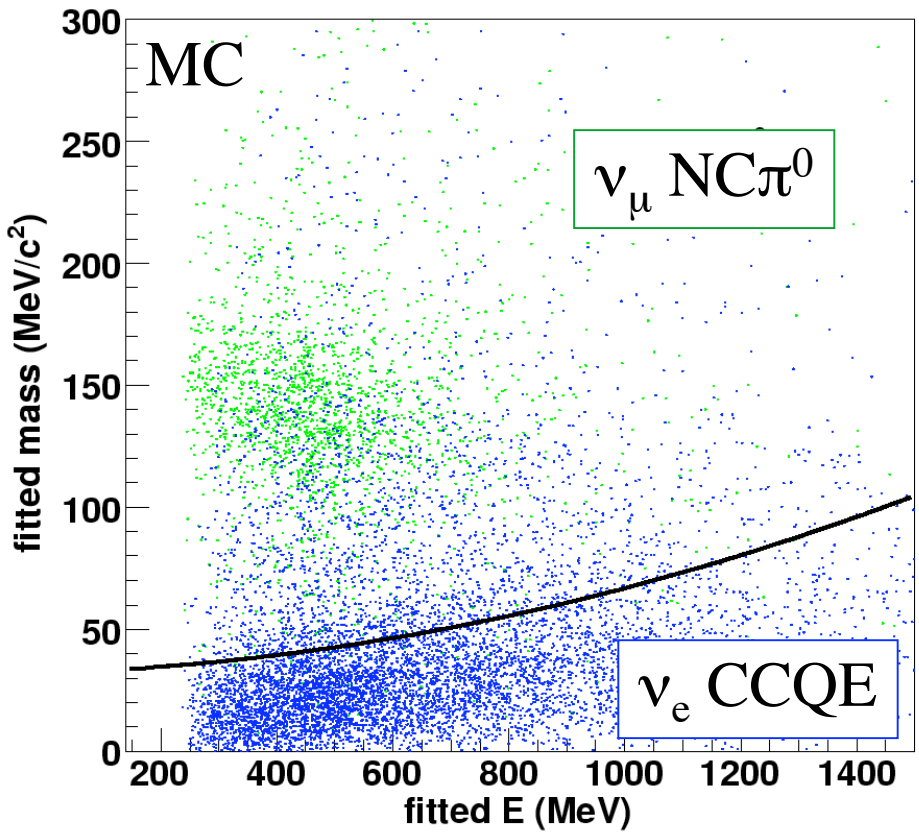
Note: photon conversions are electron-like.
This does not separate e/π^0.

Separation is clean at high energies where muon-like events are long.

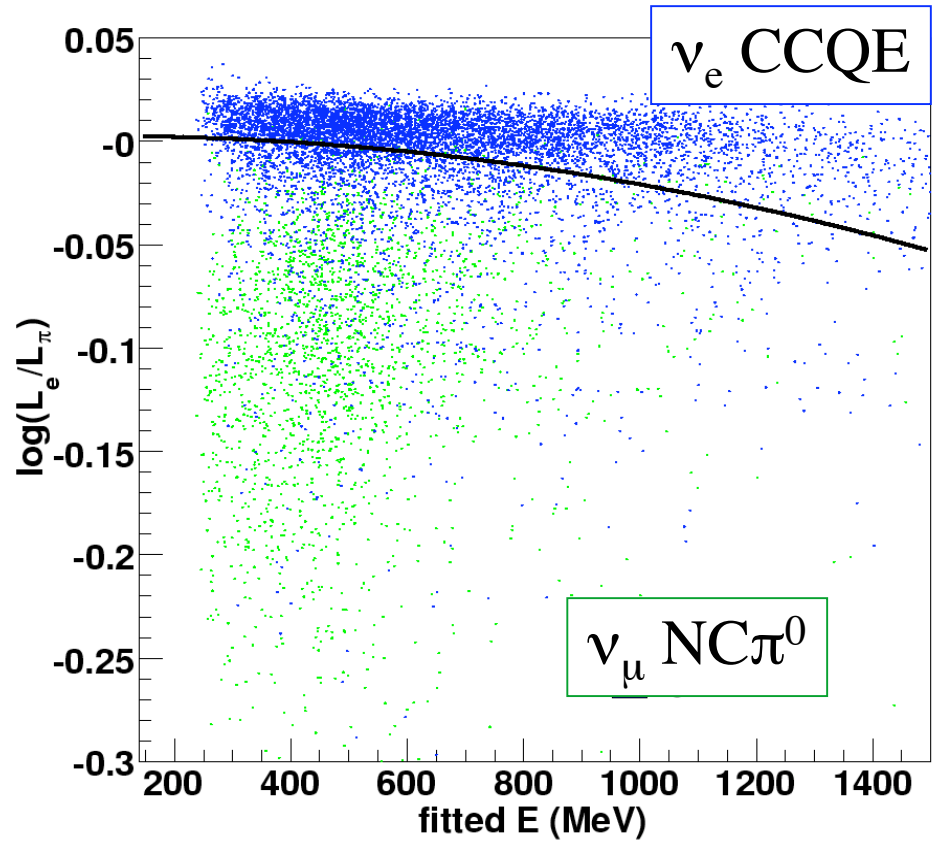
Analysis cut was chosen to maximize the $\nu_\mu \rightarrow \nu_e$ sensitivity

Rejecting "π^0-like" events

Using a mass cut



Using $\log(L_e/L_\pi)$



Cuts were chosen to maximize $\nu_\mu \rightarrow \nu_e$ sensitivity

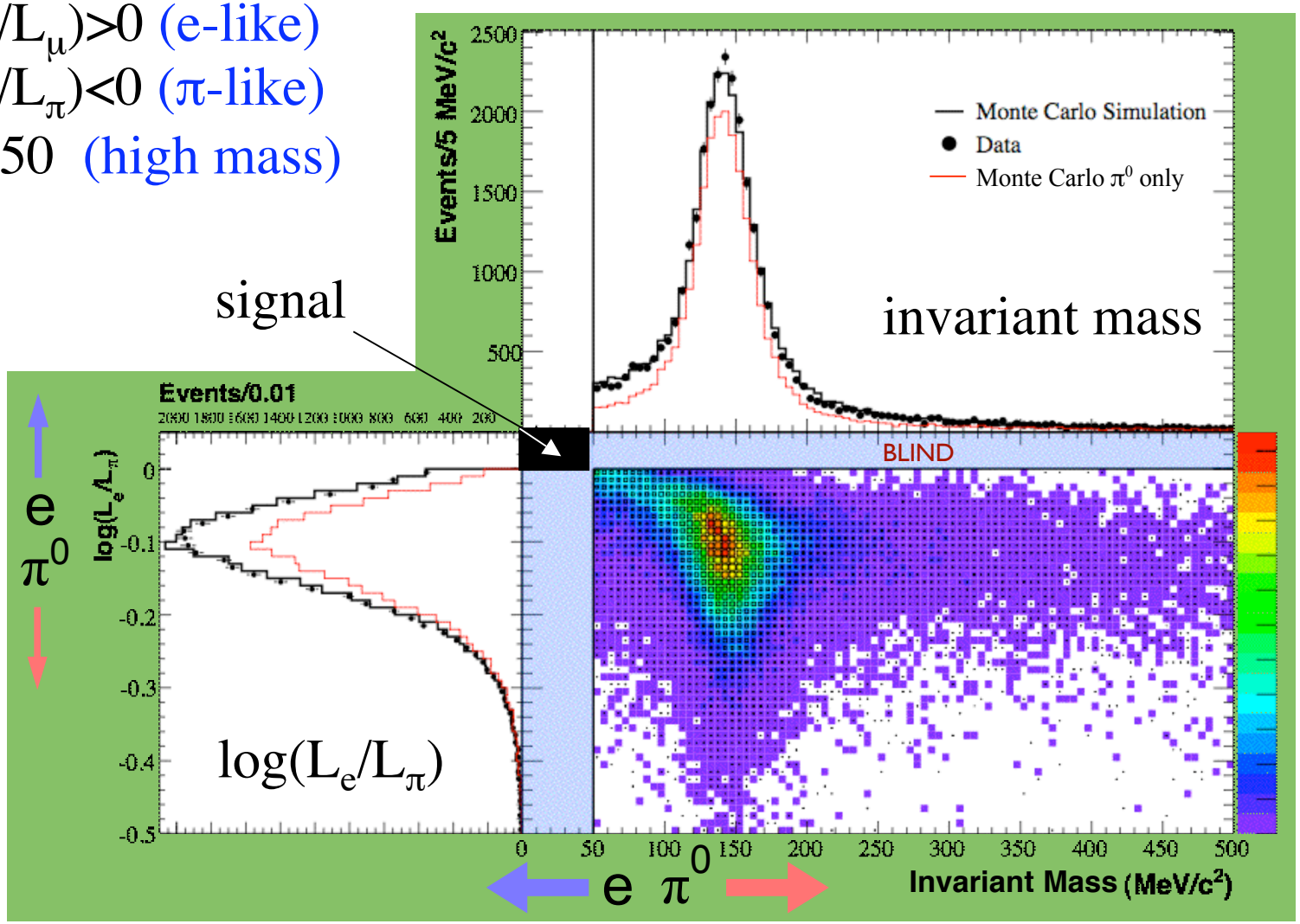
Testing e-π^0 separation using data

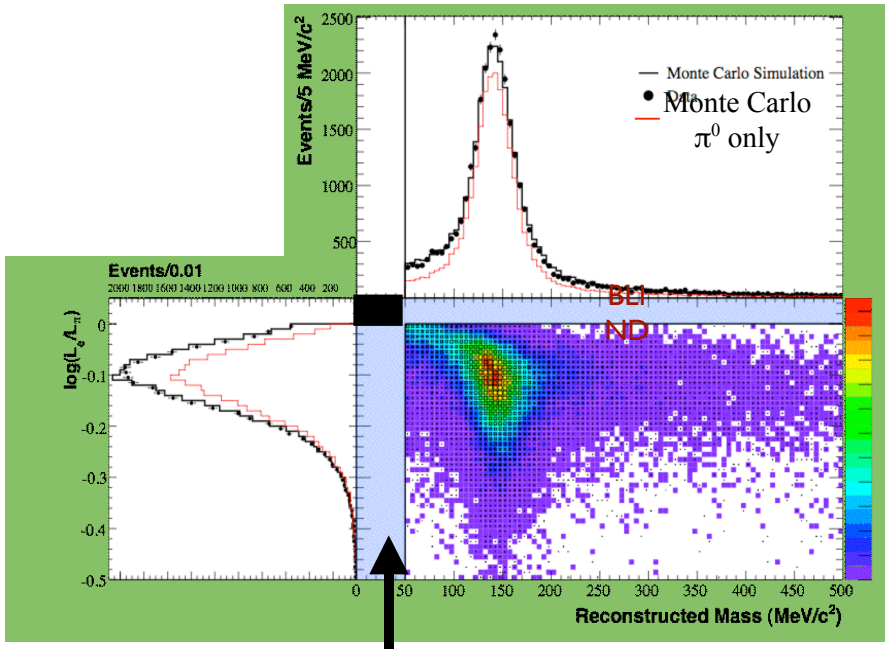
1 subevent

$\log(L_e/L_\mu)>0$ (e-like)

$\log(L_e/L_\pi)<0$ (π-like)

mass>50 (high mass)





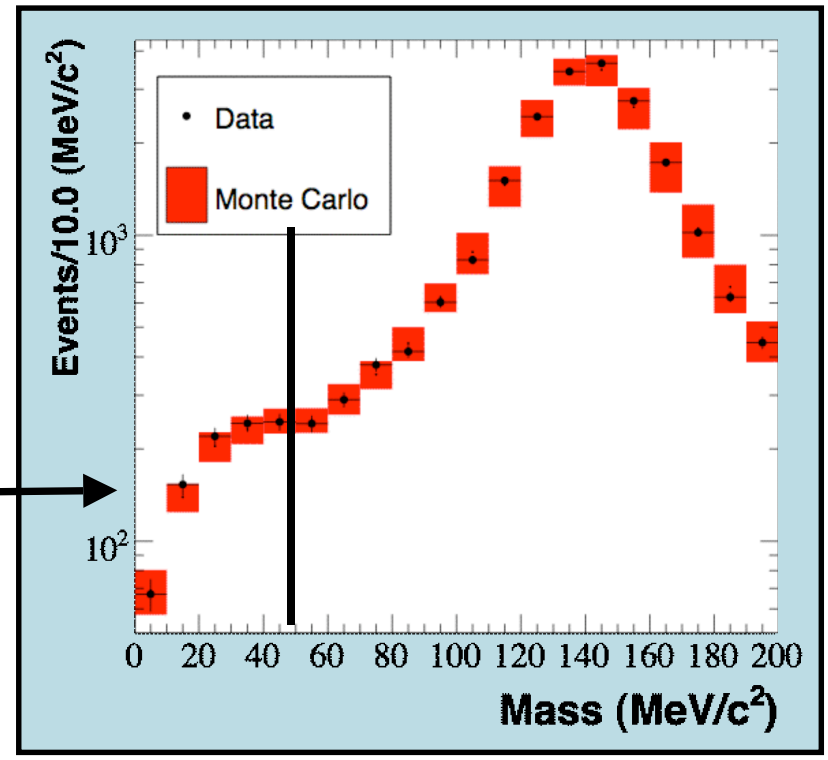
1 subevent

$\log(L_e/L_\mu)>0$ (e-like)

$\log(L_e/L_\pi)<0$ (π-like)

mass<200 (low mass)

Next: look here....



χ^2 Prob for mass<50 MeV ("most signal-like"): 69%

Summary of Track Based cuts

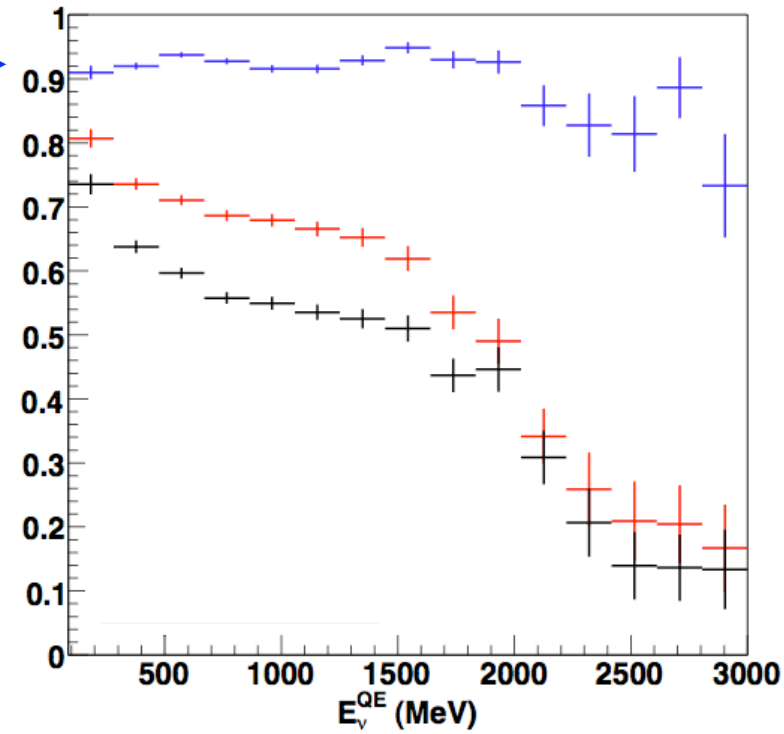
"Precuts" +

$\mathrm{Log}(L_e/L_\mu)$

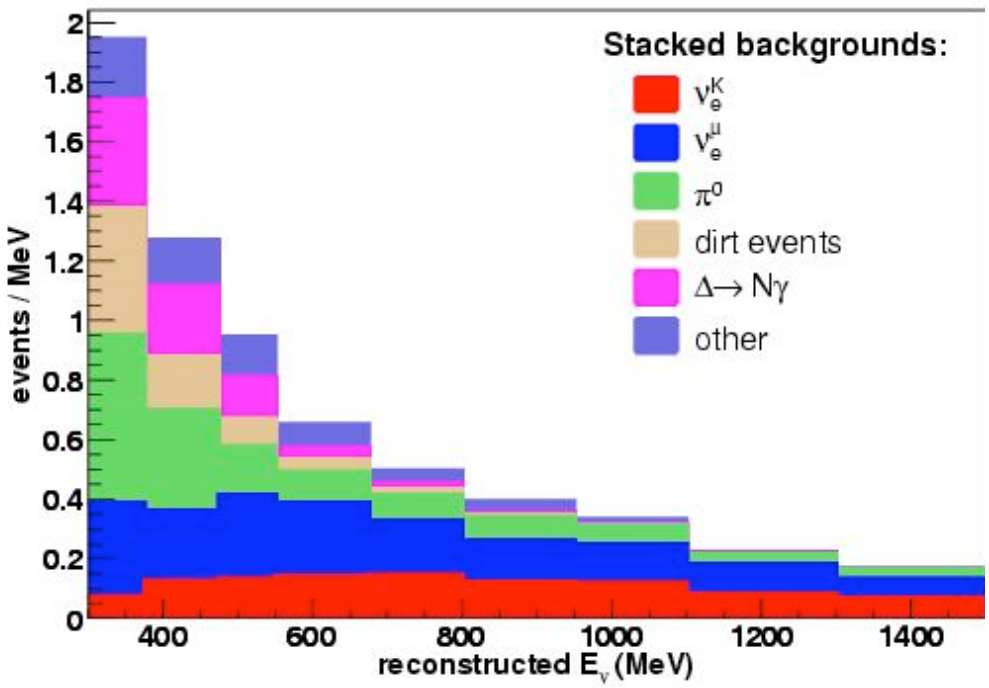
+ $\mathrm{Log}(L_e/L_\pi)$

+ invariant mass

Efficiency:



Backgrounds after cuts



Analysis 2: Boosted Decision Trees (BDT)

Philosophy:

Construct a set of low-level analysis variables
which are used to make a series of cuts to
classify the events.

This algorithm represents an independent cross check
of the Track Based Analysis

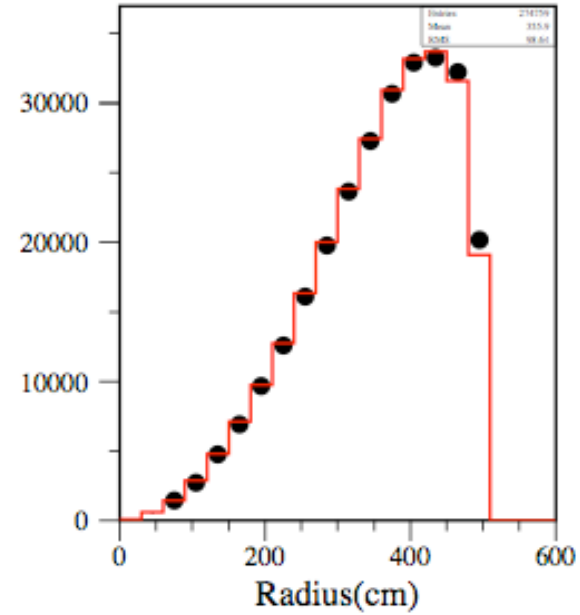
Step 1:
Convert the "Fundamental information" into "Analysis Variables"

Analysis variables	*Fundamental information from PMTs* Hit Position	Charge	Hit Timing
Energy	√	√	
Time sequence		√	√
Event shape	√	√	√
Physics	√	√	√

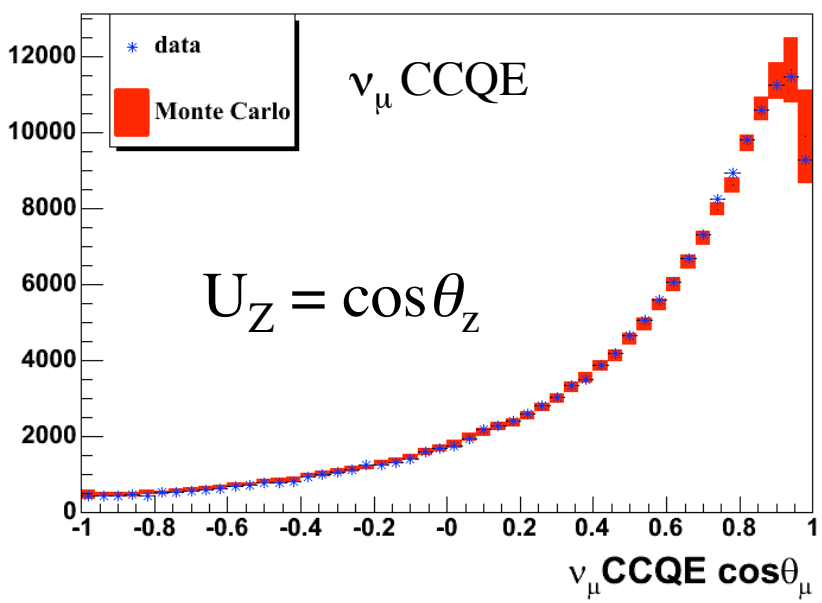
"Physics" = π^0 mass, E_ν^{QE}, etc.

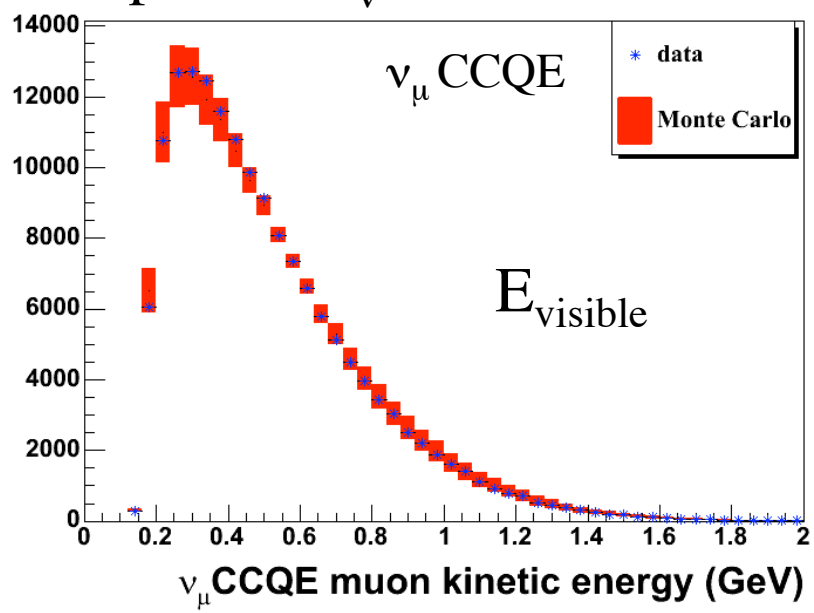
Examples of "Analysis Variables"

Resolutions:
vertex: 24 cm
direction: 3.8°
energy 14%



Reconstructed quantities which are inputs to E_ν^{QE}



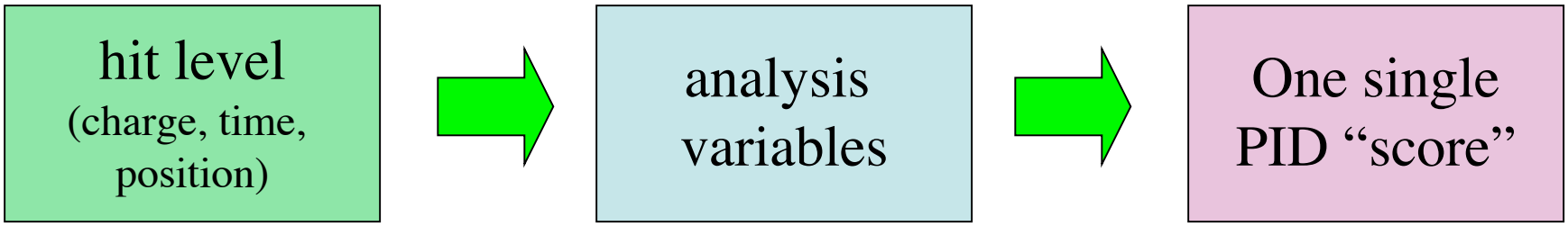


Step 2: Reduce Analysis Variables to a Single PID Variable

Boosted Decision Trees

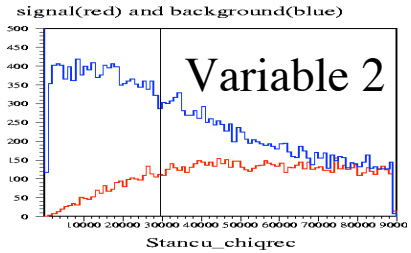
"A procedure that combines many weak classifiers to form a powerful committee"

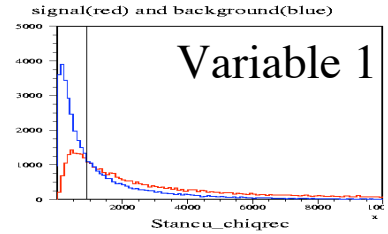
Byron P. Roe, *et al.*, NIM A543 (2005) 577.



A Decision Tree

(sequential series of cuts based on MC study)





(N_{signal}/N_{bkgd})

bkgd-like

signal-like

9755/23695

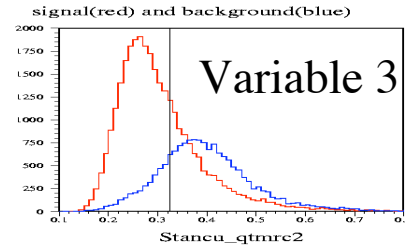
bkgd-like

sig-like

1906/11828

7849/11867

30,245/16,305



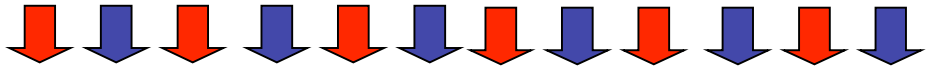
sig-like

bkgd-like

20455/3417

9790/12888

etc.

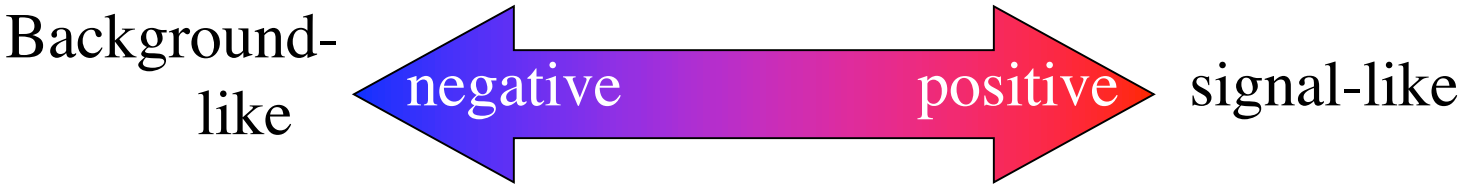


This tree is one of many possibilities...

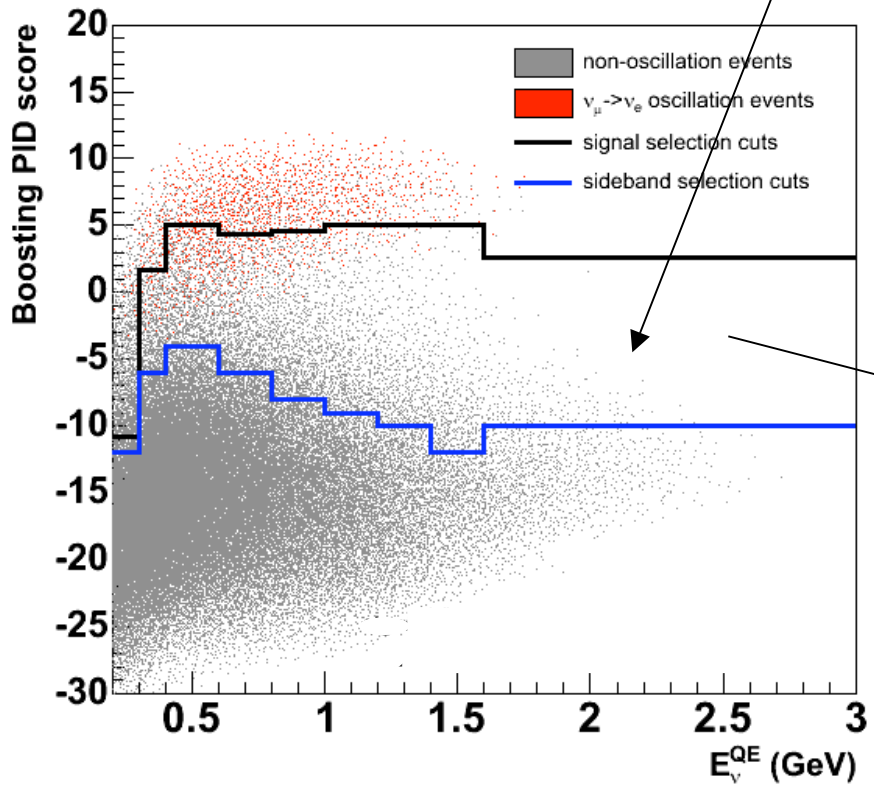
A set of decision trees can be developed,
each re-weighting the events to enhance
identification of backgrounds misidentified
by earlier trees (“boosting”)

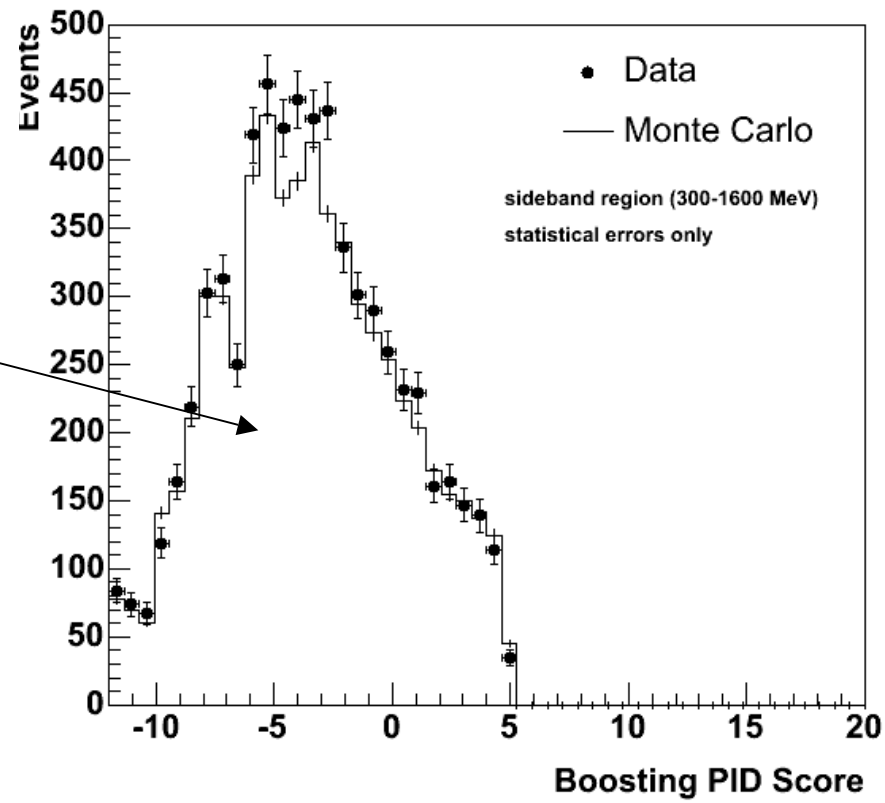
For each tree, the data event is assigned
+1 if it is identified as signal,
-1 if it is identified as background.

The total for all trees is combined into a “score”



BDT cuts on PID score as a function of energy.
We can define a "sideband" just outside of the signal region





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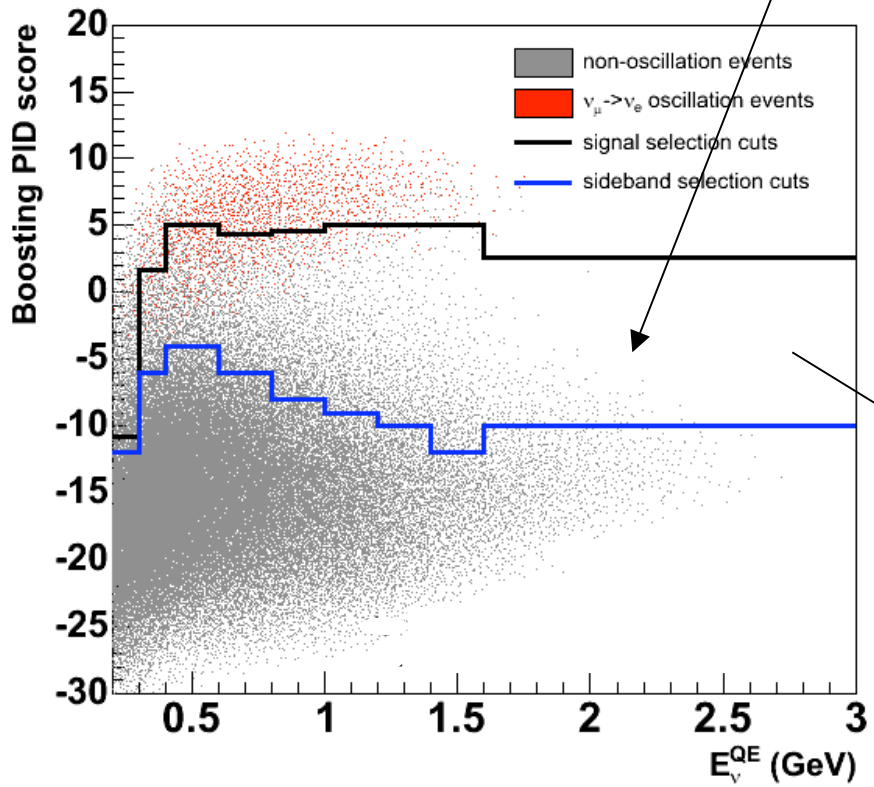
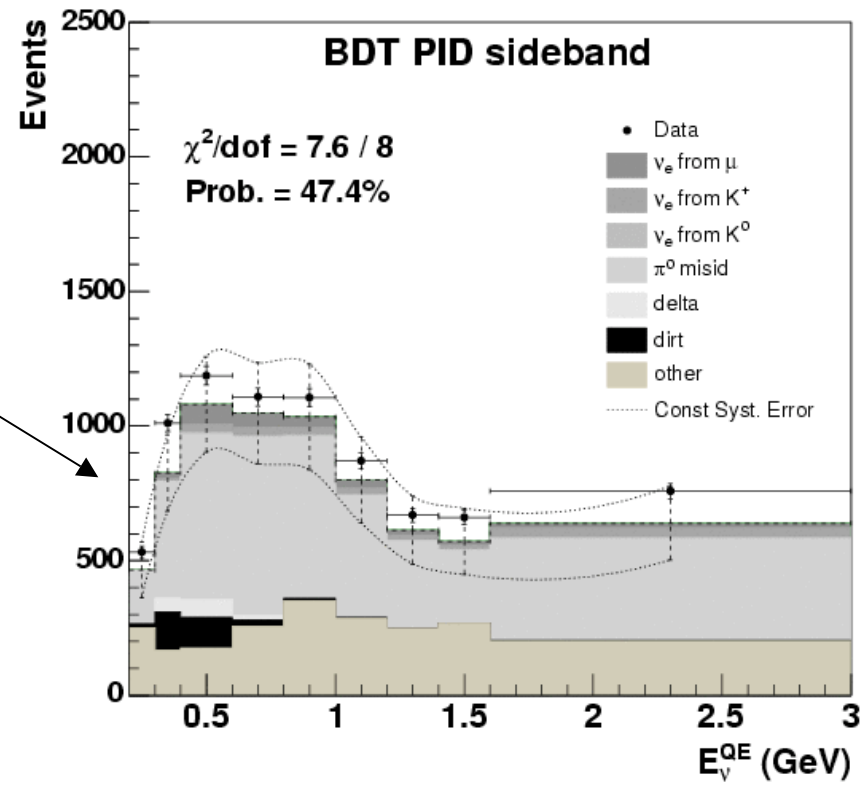
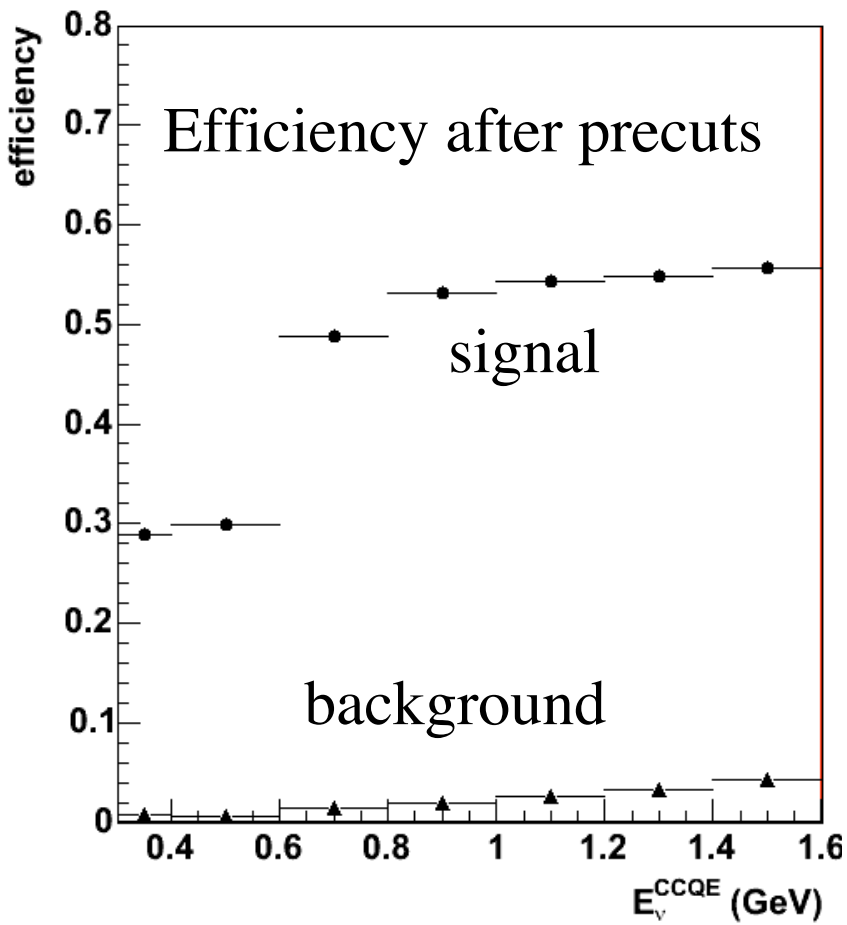
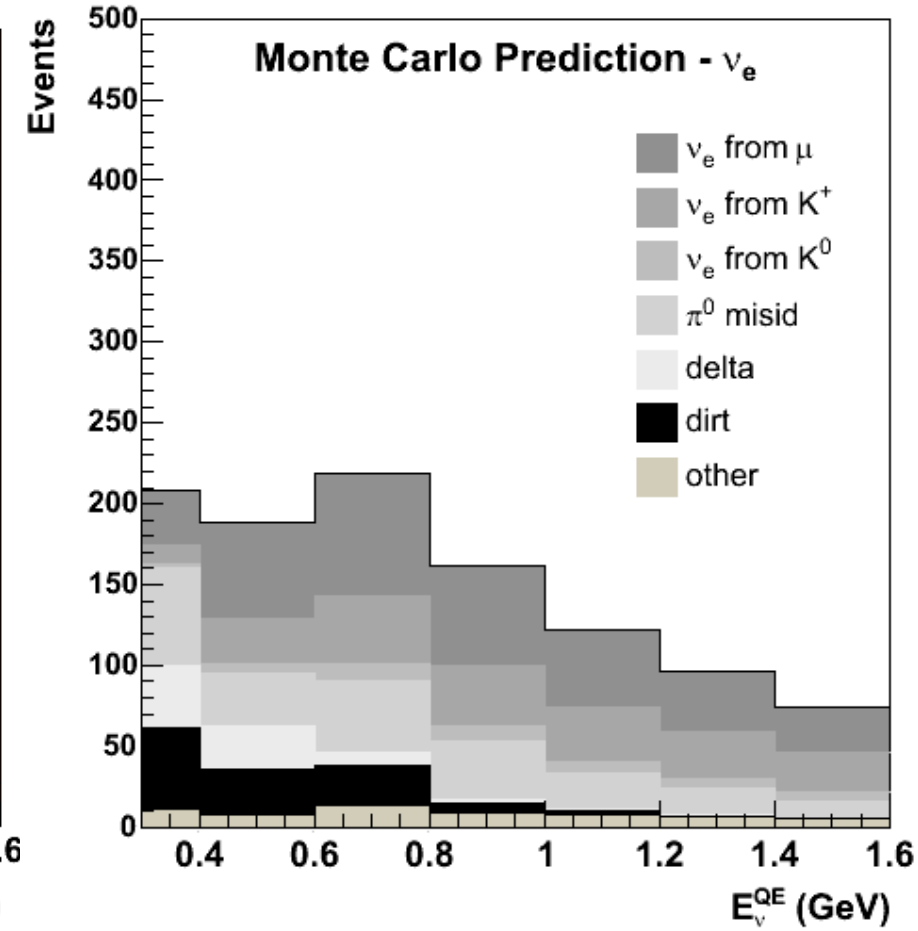




BDT Efficiency and backgrounds after cuts:

Analysis cuts on PID score as a function of Energy





Errors, Constraints and Sensitivity