First Oscillation Results From MiniBooNE

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Outline

- Neutrino oscillations.
- MiniBooNE experiment.
- Oscillation analysis.
- First oscillation result.
- Future.

Neutrino Oscillations – Two Flavor

Simple Oscillation Model

- Two neutrinos
- Massive, but masses are non-degenerate
- Mass eigenstates ν_1, ν_2 not the same as flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- Time evolution of the quantum mechanical state

$$|\nu_1\rangle \to e^{-im_1 t}|\nu_1\rangle \quad (\hbar = c = 1)$$

- Flavor eigenstate is a superposition of mass eigenstates

$$|\psi(0)\rangle = |\nu_e\rangle = |\nu_1\rangle\cos\theta + |\nu_2\rangle\sin\theta$$

- After traveling certain time changes flavor

$$|\psi(t)\rangle = e^{-m_1 t}|\nu_1\rangle\cos\theta + e^{-m_2 t}|\nu_2\rangle\sin\theta$$

Neutrino Oscillations Probability

Probability of flavor change is given by:

$$P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

- L is the distance (km)
- E is the energy (GeV)
- $\Delta m^2 = m^2_1 - m^2_2$ (eV^2/c^4)
- θ is the mixing angle

For any number neutrino flavors we have

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \qquad (\alpha, \beta \ldots)\ \textit{flavors} \qquad (i, j \ldots)\ \textit{masses}$$

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) = \quad & \delta_{\alpha\beta} \\ & -4\Sigma_{i>j}\Re(\mathcal{U}) \sin^2[1.27\Delta m^2_{ij}(L/E)] \\ & +2\Sigma_{i>j}\Im(\mathcal{U}) \sin^2[2.54\Delta m^2_{ij}(L/E)] \end{aligned}$$

where $\mathcal{U} \equiv U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}$

where $U_{\alpha i}$ is a unitary matrix which can be parameterized by three mixing angles and a phase in the case of three neutrino flavors.

Neutrino Oscillations Evidence

Atmospheric neutrinos

- Discovery of oscillations (SuperK), 1998 (muon disappearance only)
  ν_μ disappearance assuming ν_μ -> ν_τ
- Disappearance confirmed in long-baseline accelerator experiments (K2K, MINOS).

$$\Delta m^2 \approx (2-3)\times 10^{-3}\, eV^2/c^4 \qquad \sin^2 2\theta \approx 1$$

Solar neutrinos

- Deficit in the ν_e flux has been long standing problem. ν_e disappearance
- Sudbury Neutrino Observatory (SNO) observed neutral/charged current ratio, confirming flavor mixing as the solution to solar neutrino “problem”.
- KamLAND observed disappearance of reactor antineutrinos: confirmed oscillations and resolved an ambiguity in Δm^2.

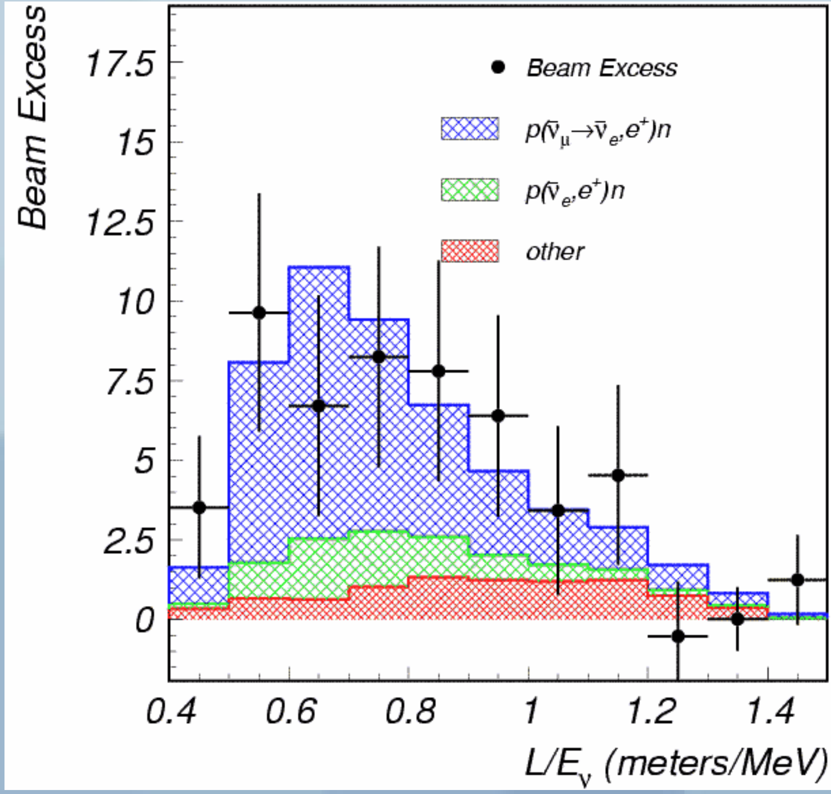
$$\Delta m^2 \approx 10^{-4}\, eV^2/c^4 \qquad \sin^2 2\theta \approx 0.8$$

LSND Experiment

Liquid Scintillator Neutrino Detector at Los Alamos Meson Physics Facility (LAMPF) accelerator

- Neutrino source: stopped pion and muon decays
- Search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations

- L = 30 m, E = 30-53 MeV



Observed excess:

- 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 Oscillation Signal

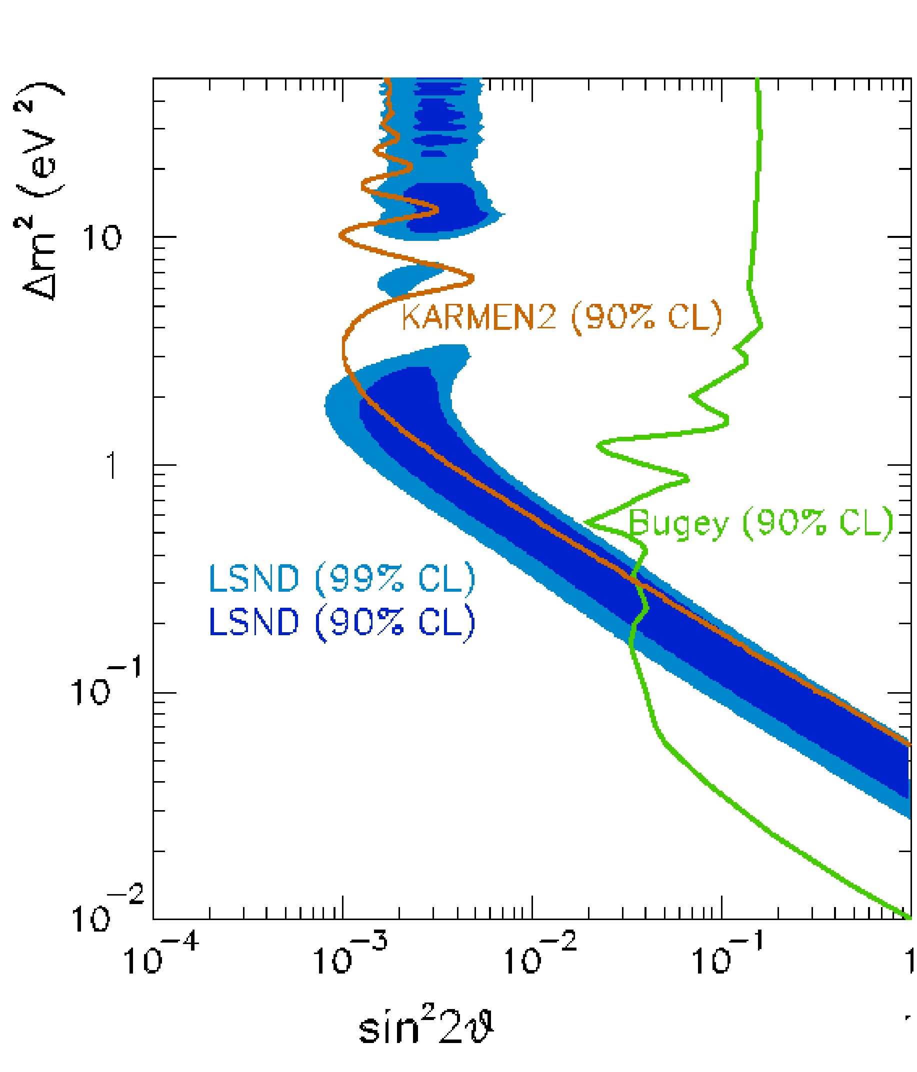
LSND observed excess in the context of two-neutrino oscillation:

$$P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) = (2.5 \pm 0.6_{stat} \pm 0.4_{syst}) \times 10^{-3}$$

Comparison with KARMEN and **Bugey** given the same oscillation model

Joint analysis with Karmen2:
64% compatible

Church, et al., PRD 66, 013001



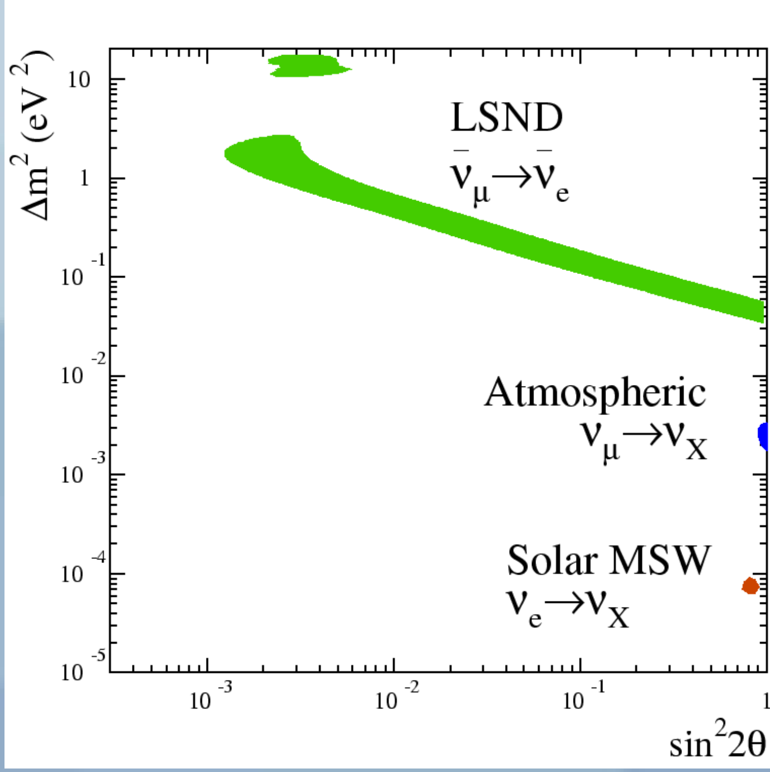
Neutrino Oscillations – Current Status

In three neutrino model two Δm^2 constrain the third:

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

LSND	$\Delta m^2 > 0.1\text{eV}^2$	$\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$
Atmos.	$\Delta m^2 \approx 2 \times 10^{-3}\text{eV}^2$	$\nu_\mu \leftrightarrow \nu_?$
Solar	$\Delta m^2 \approx 10^{-4}\text{eV}^2$	$\nu_e \leftrightarrow \nu_?$

- 3 neutrino masses can not reconcile an order of magnitude difference in the 3 Δm^2.



Is there fourth neutrino?

- Z^0 boson resonance width measurements is consistent with only 3 weakly interacting neutrinos.

Possible solutions

- Sterile neutrino sector.
- Discover one of the three is not oscillations

MiniBooNE Experiment – E898 at Fermilab

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

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

MiniBooNE Collaboration

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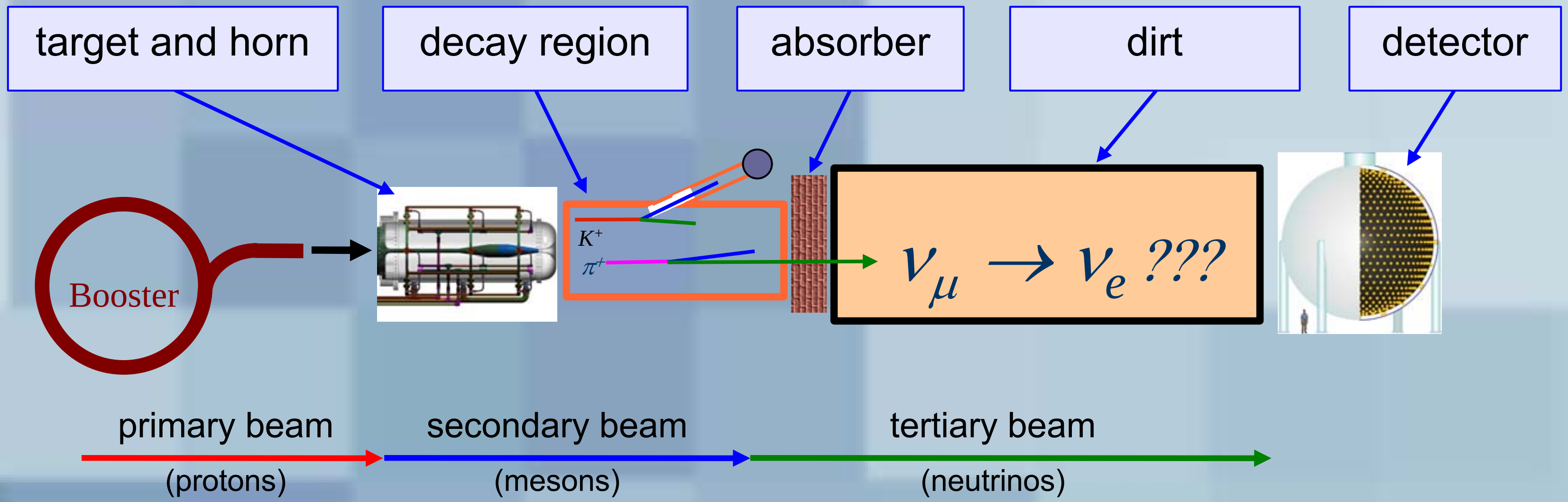
Fermi National Accelerator Laboratory
Indiana University
Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary’s University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

MiniBooNE Layout

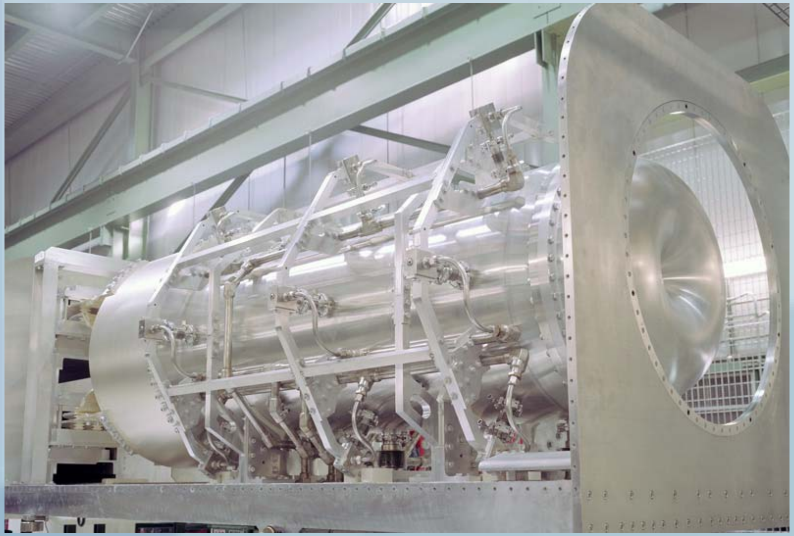


Proton Beam
- 8 GeV protons from Booster
  into MiniBooNE beamline

Secondary Beam
- Mesons from protons striking Be target
  Focused by horn and monitored by Little Muon Counter

Neutrino Beam (~0.5-1 GeV)
- Neutrinos from meson decay in 50 m pipe
  Pass through 450 m dirt (and oscillate?) to reach detector

Booster and Magnetic Horn

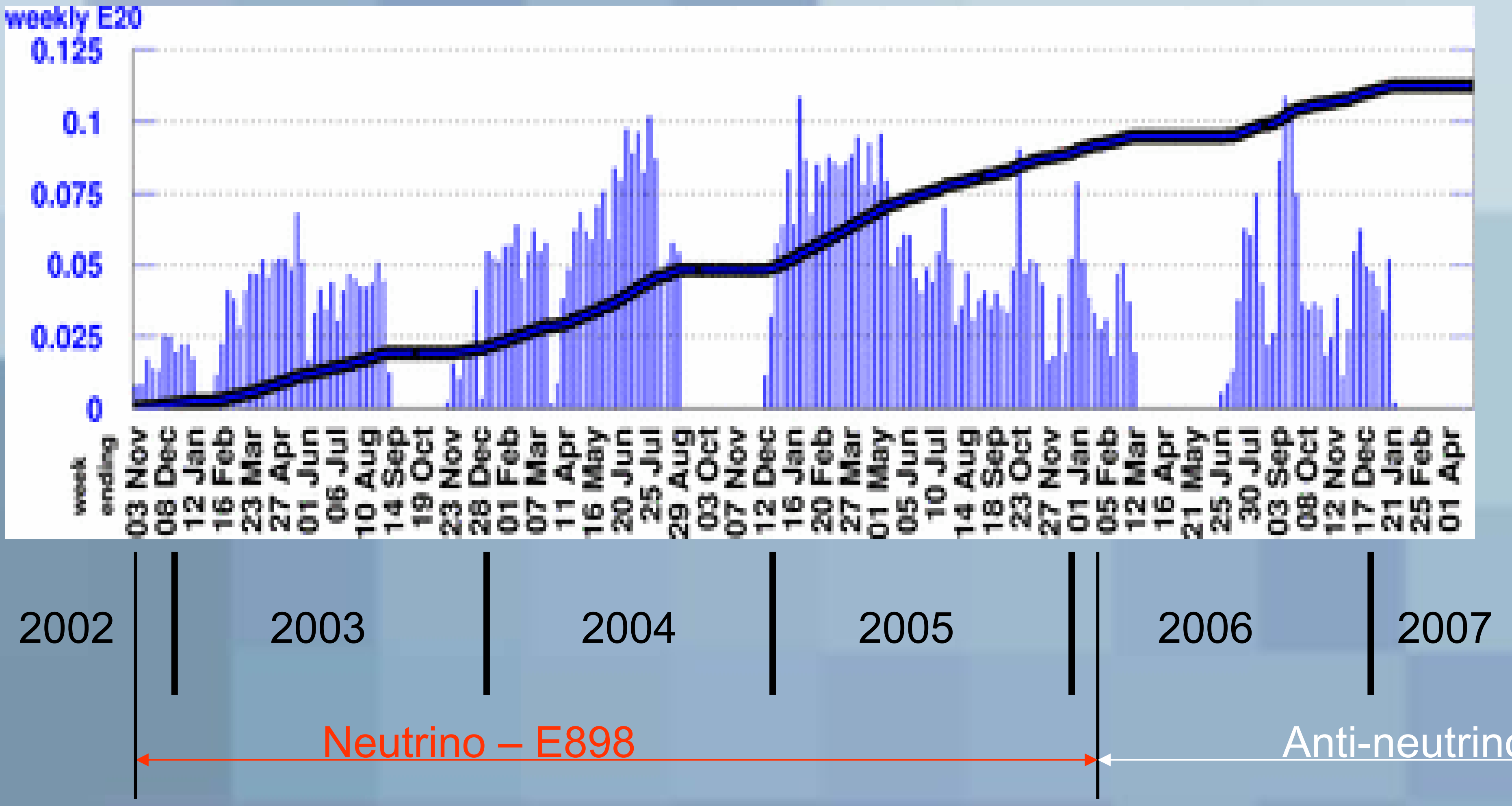


- MiniBooNE extracts beam from the 8 GeV Booster
- 4×10^{12} protons per 1.6 μs pulse delivered at up to 5 Hz.

6.3×10^{20} POT delivered.

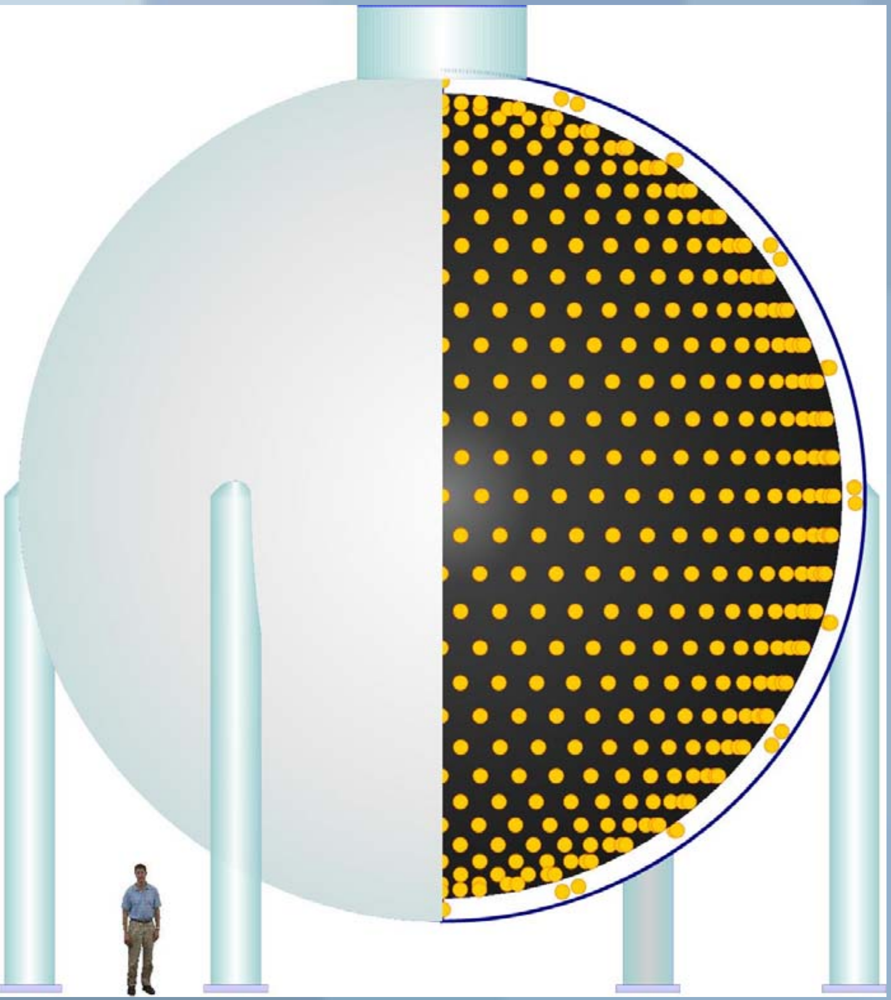
Delivered to a 1.7λ Be target inserted into a magnetic horn (2.5 kV, 174 kA) that (increases the flux by $\times 6$)

Beam Delivery



First oscillation result uses the 2002-2005 E898 data set (5.7E20 pot).

The MiniBooNE Detector



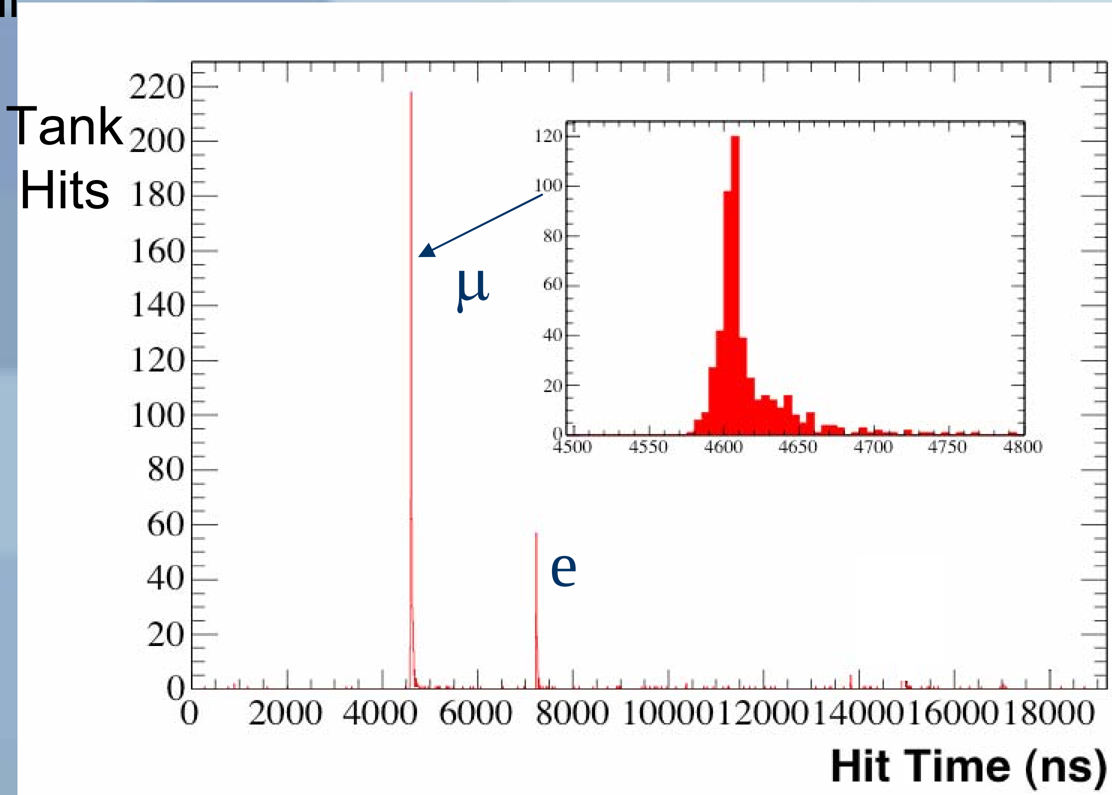
- 541 meters downstream of target
- 3 meter overburden
- 12 meter diameter sphere
  (10 meter “fiducial” volume)
- Filled with 800 t
  of pure mineral oil (CH_2)
  (Fiducial volume: 450 t)
- 1280 inner phototubes,
  240 veto phototubes

Subevents

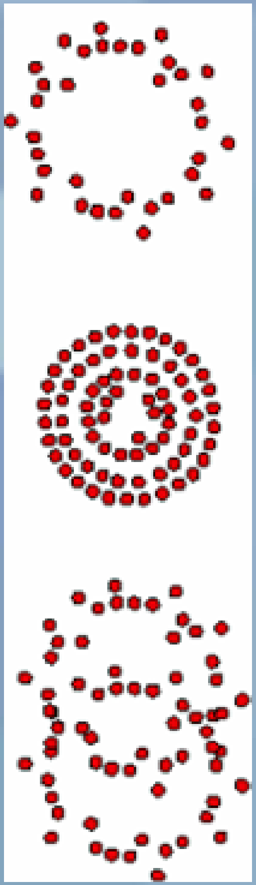
A 19.2 μs beam trigger window
- encompasses the 1.6 μs spill
- starts 4 μs before the beam

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 $\mu \rightarrow \nu_\mu \nu_e e$



Event Topologies in MiniBooNE Detector



Electron/photon event – fuzzy ring
- short track, large scattering
- γ converts and looks like electrons

Muon event
- long track, small scattering

π^0 event – two fuzzy rings

Oscillation Analysis

- Neutrino flux model.
- Neutrino cross sections model.
- Detector response model.
- Particle ID and reconstruction
- Systematic errors and checks
- Oscillation fit

Neutrino Flux Prediction

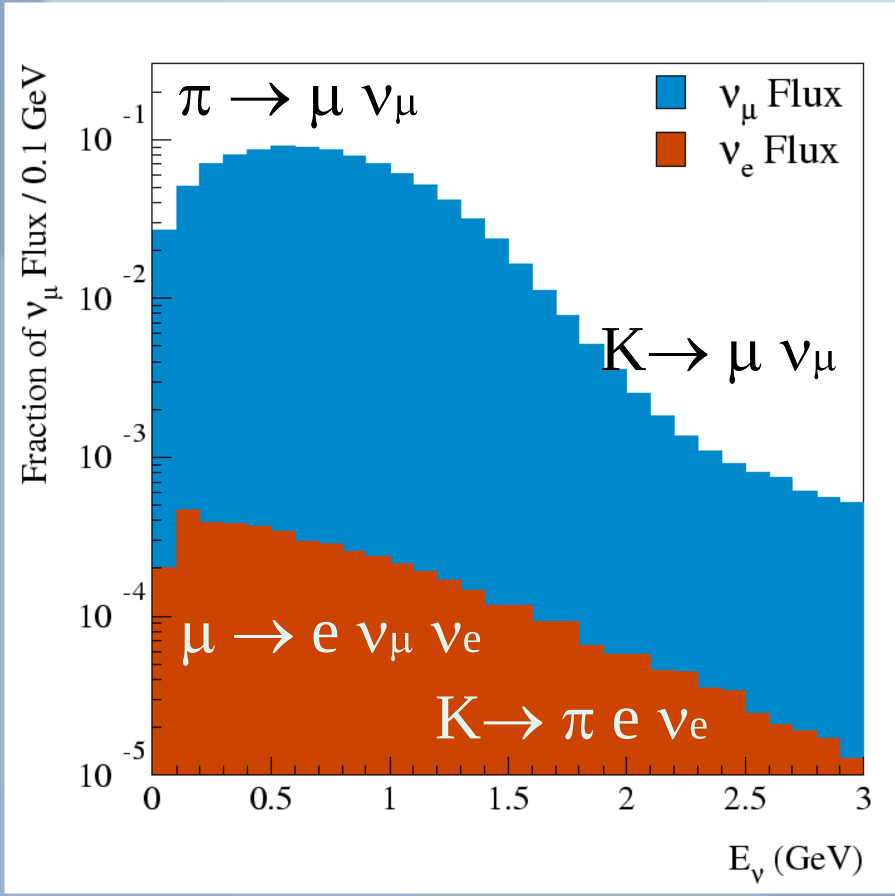
- GEANT4 based Monte Carlo simulates the neutrino flux in MiniBooNE beamline,
- high purity ν_μ beam – 99%, small ν_e component – intrinsic ν_e
  - background for ν_e appearance

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

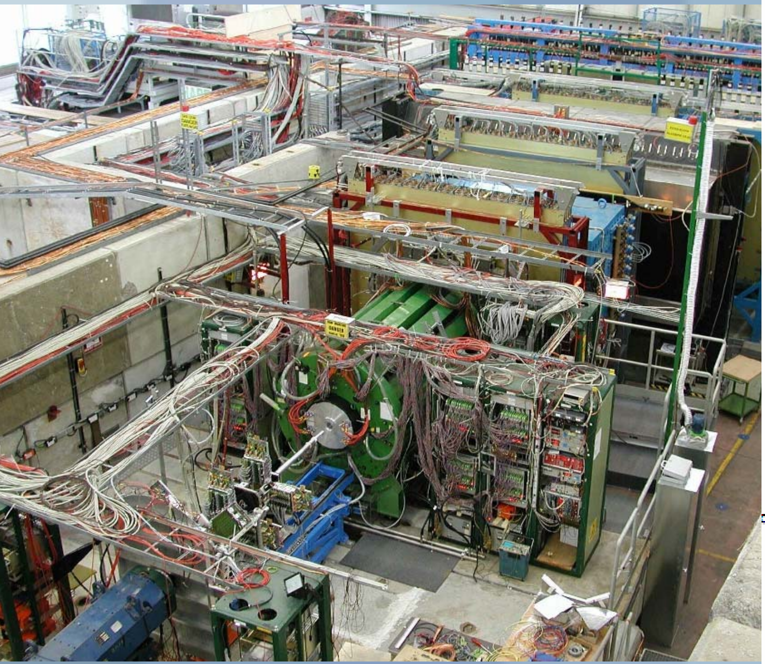
- "Intrinsic" ν_e + $\bar{\nu}_e$ sources:

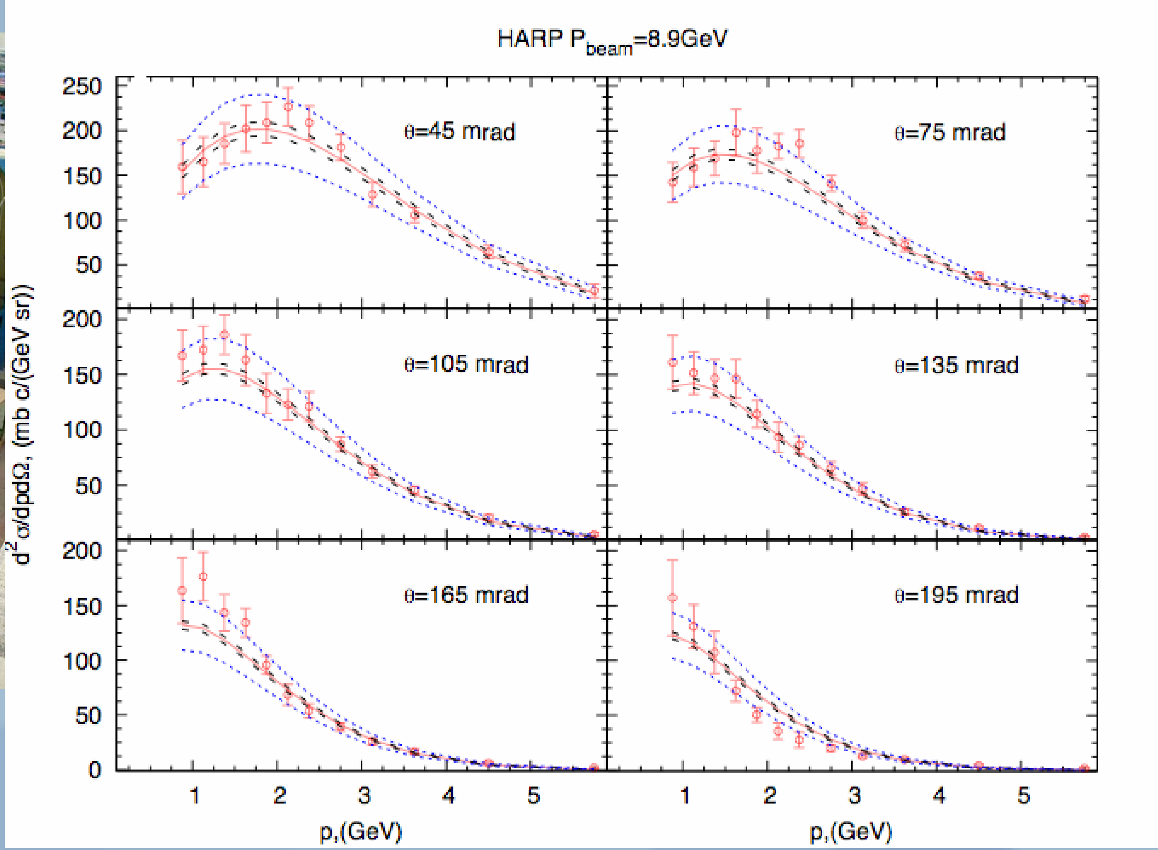
$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$	(52%)
$K+ \to \pi^0 e^+ \nu_e$	(29%)
$K^0 \to p\ e\ \nu_e$	(14%)
Other	(5%)

- Antineutrino content: 6%



π^+ Production Cross Section from HARP





π^+ production cross section is parameterized from a fit to HARP π^+ production cross section, using the standard Sanford-Wang parameterization.

HARP collaboration,
hep-ex/0702024

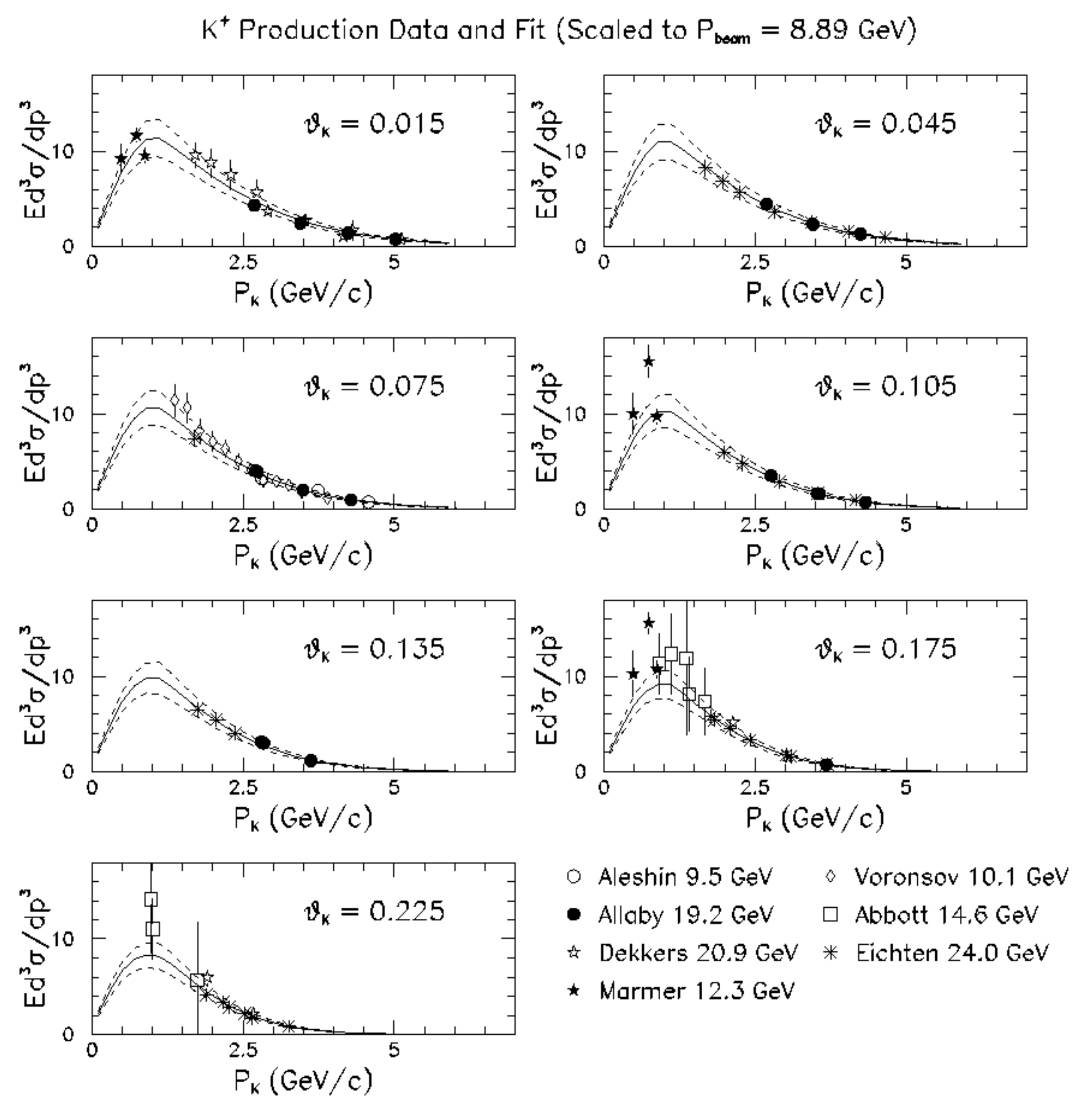
HARP (CERN) measured the π^+ production cross section

- 5% λ Beryllium target
- 8.9 GeV proton beam momentum

K Production Cross Section

- K^+ production cross section is parameterized from a fit to external data with beam momentum from 10-24 GeV.
- Feynman Scaling function is used parameterization.
- SW parameterization was also used and it's completely covered by the FS uncertainty.

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



- K^0 cross section is also parameterized from external data using SW.

In-situ Cross Check of K^+ Model: Little Muon Counter

LMC :

• off-axis muon spectrometer viewing the decay pipe at 7º.

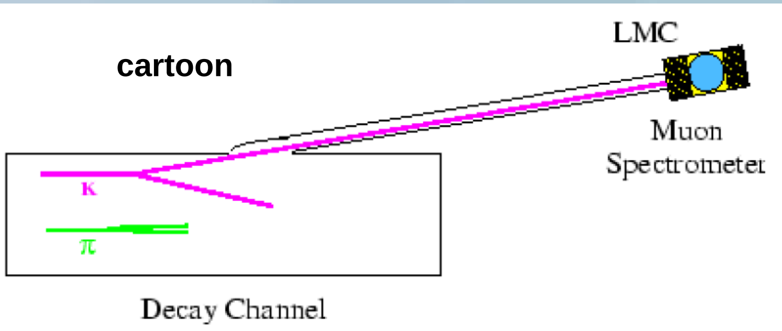
• High-p_T μ's come from K^+ decays;
Low-p_T μ's come from π^+ decays

• Effective |p| separation at this angle.

• clear separation of μ from π and K^+,

• High K/ π ratio,

• Most π's have too high energy to produce μ at this angle.

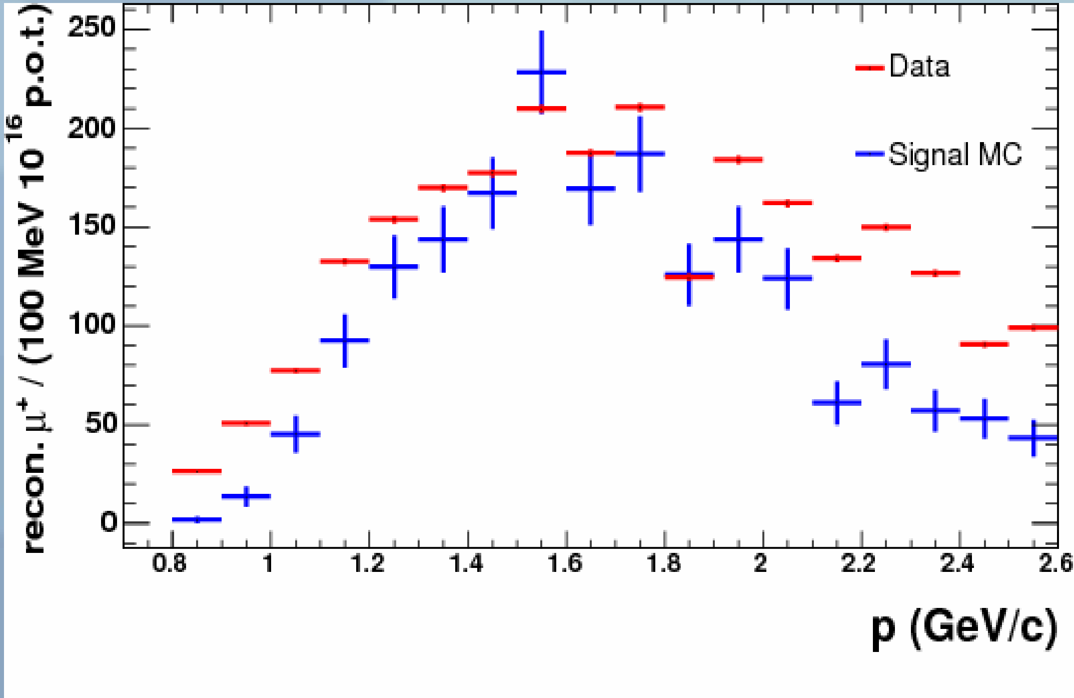


K^+ Production Limit from LMC

Constraint on the K^+ flux normalization:

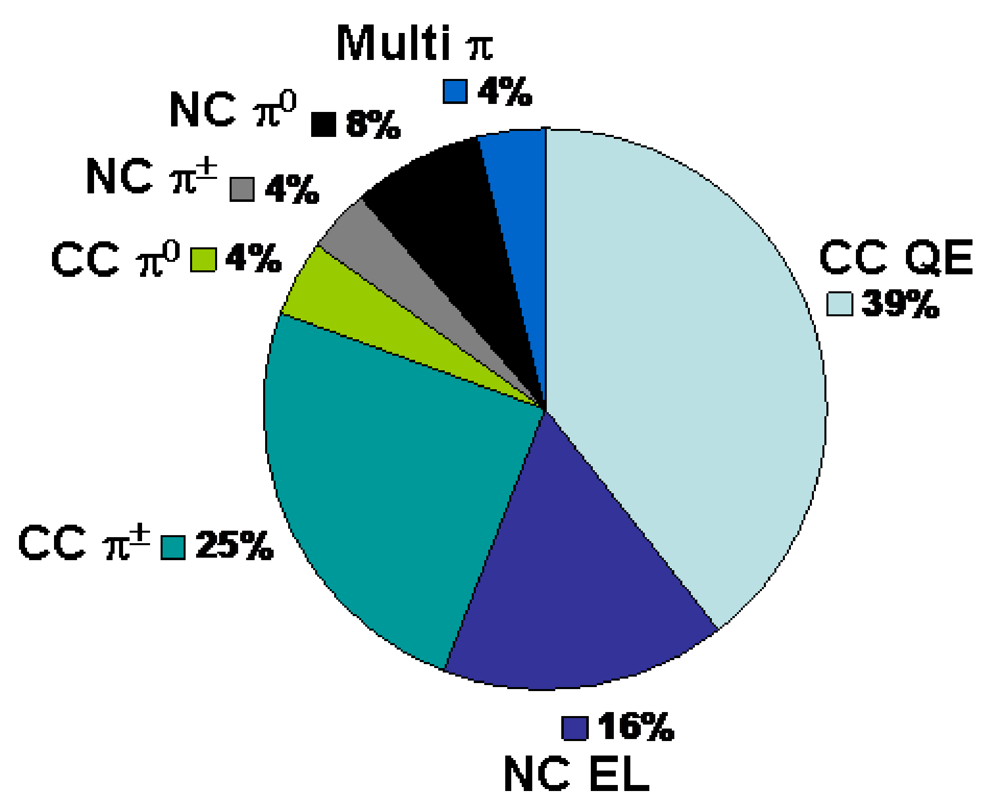
- MC simulates π and K decays.
- No hadronic interaction backgrounds simulated.
- Plot shows data vs MC for well-identified muons in a region where we expect low backgrounds.

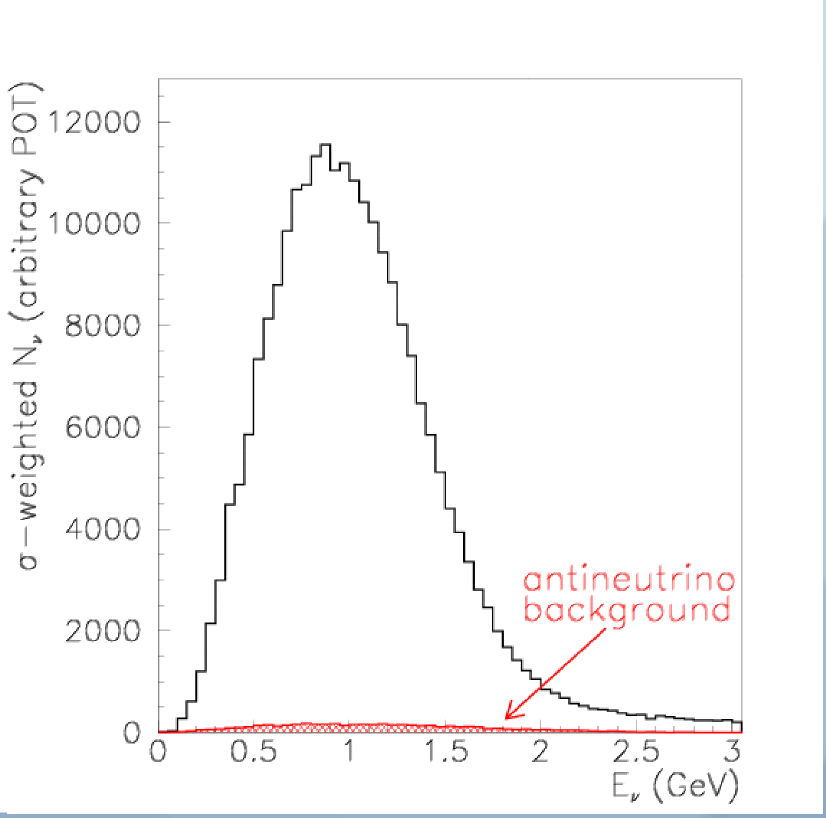
The upper limit on the K^+ flux normalization is 1.32.



Neutrino Cross Section Model - NUANCE

D. Casper, NPS, 112 (2002) 161





Predicted event type fractions.

Predicted neutrino energy spectrum

Charge Current Quasielastic

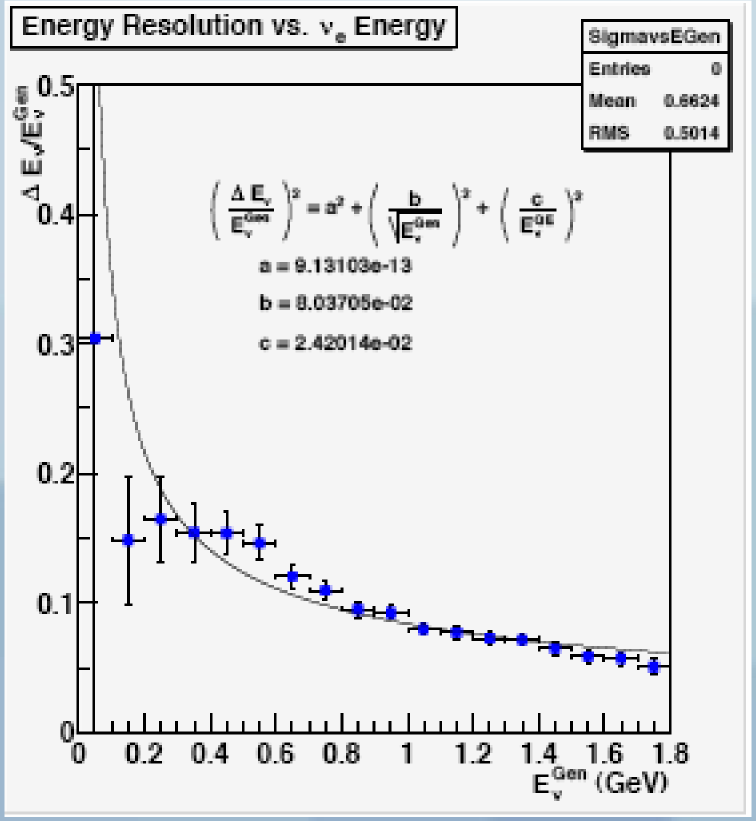
Golden mode for oscillation search

$$\nu_\mu n \rightarrow \mu^- p$$

- Clean signature in the detector.
- Neutrino energy is reconstructed from the reconstructed momentum and angle of the charged lepton.

$$E_\nu^{CCQE} = \frac{m_N E_l - \frac{1}{2} m_l^2}{m_N - E_l + p_l \cos\theta_l}$$

$$Q^2 = -2E_\nu (E_\mu - p_l \cos\theta_l) + m_l^2$$



- Nuclear target
- Nucleon is not excited

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

Tuning the Cross Section Model - QE

Default NUANCE model QE Q^2 distr. shows discrepancy with data.

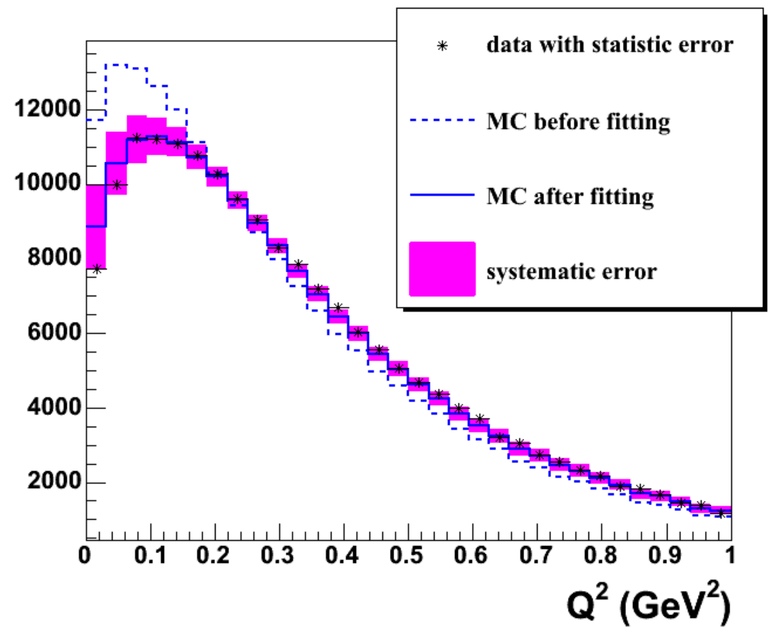
- reported by K2K (1kt) as well

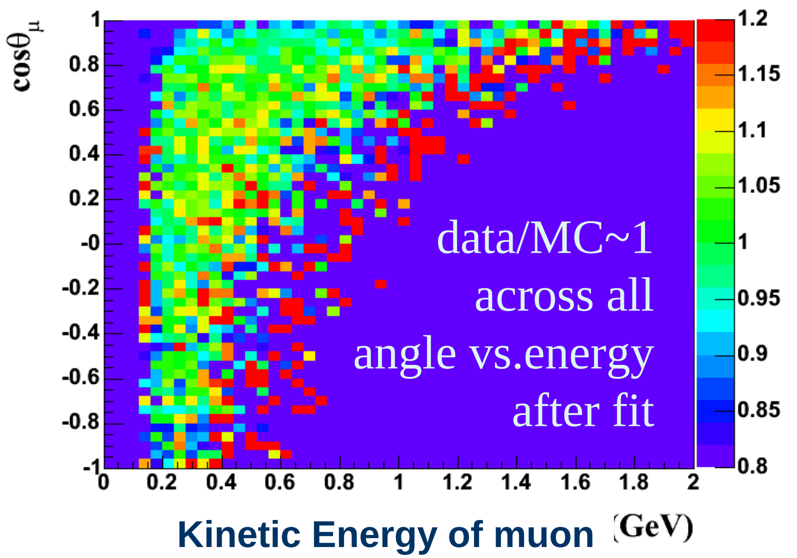
From Q^2 fits to MB ν_μ CCQE data:

- M_A^{eff} -- effective axial mass
- E_{lo}^{SF} -- Pauli Blocking parameter

From electron scattering data:

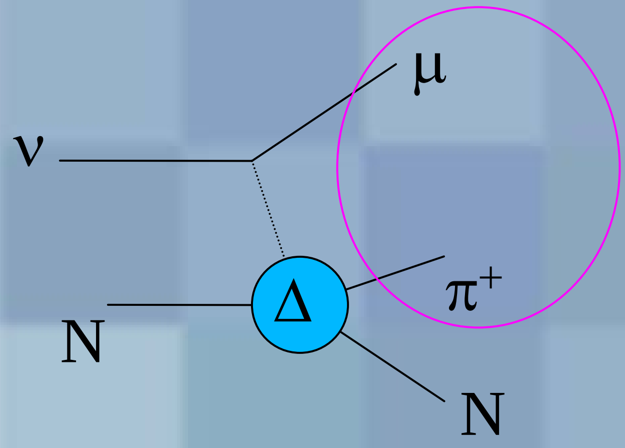
- E_B -- binding energy
- p_F -- Fermi momentum





Δ Resonance Production

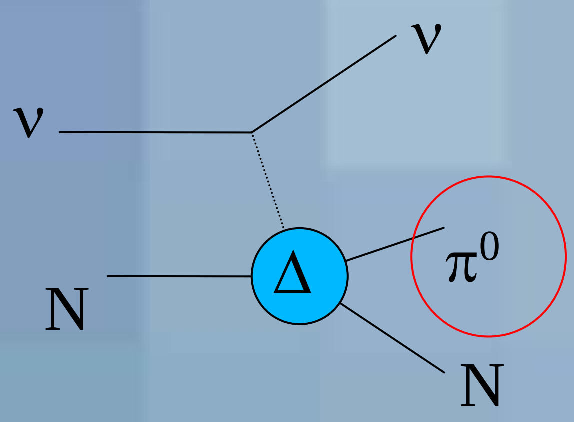
25%



$CC\pi^+$

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...

<1% of π^0 contribute to background.

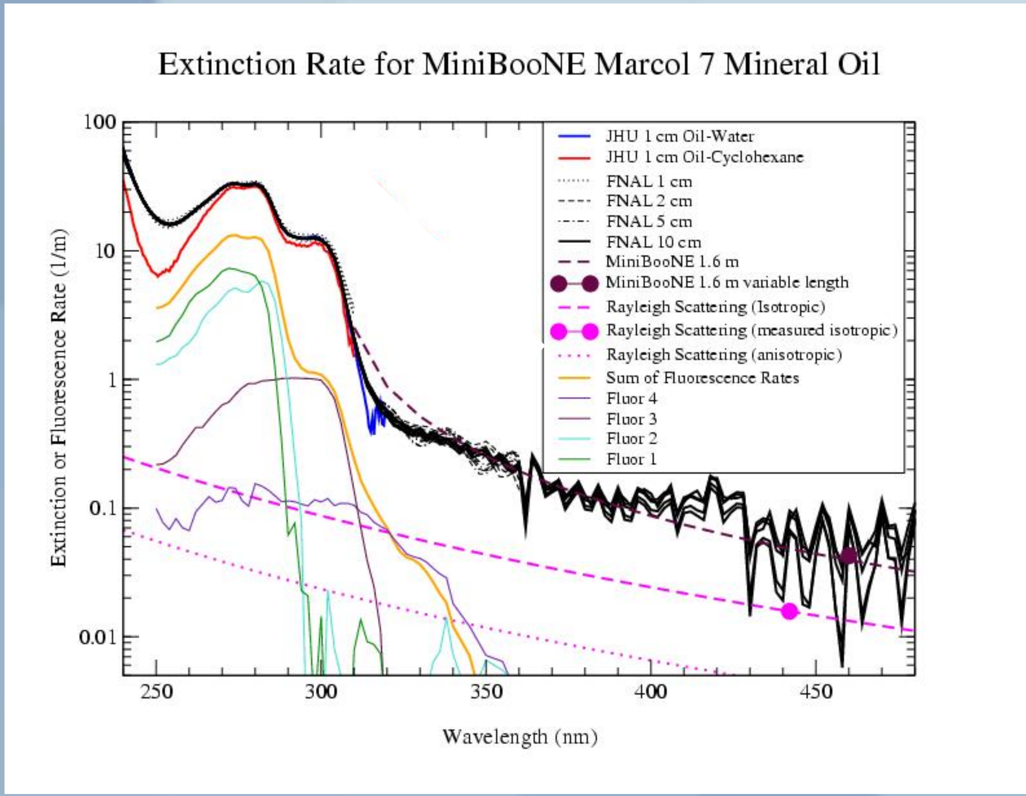
(also decays to a single photon with 0.56% probability)

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

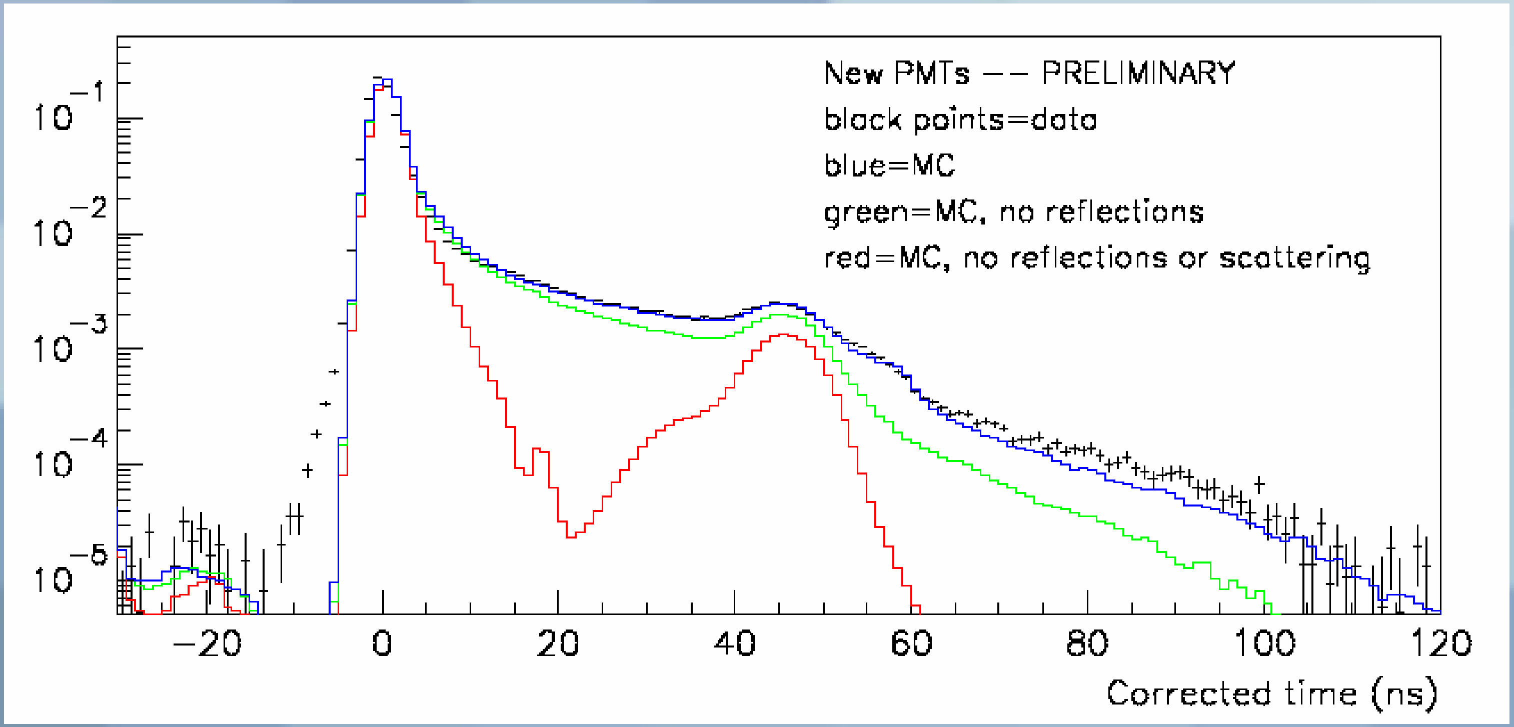
We have developed
39-parameter
"Optical Model"
based on internal calibration
and external measurement



Optical properties of oil, detectors:

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

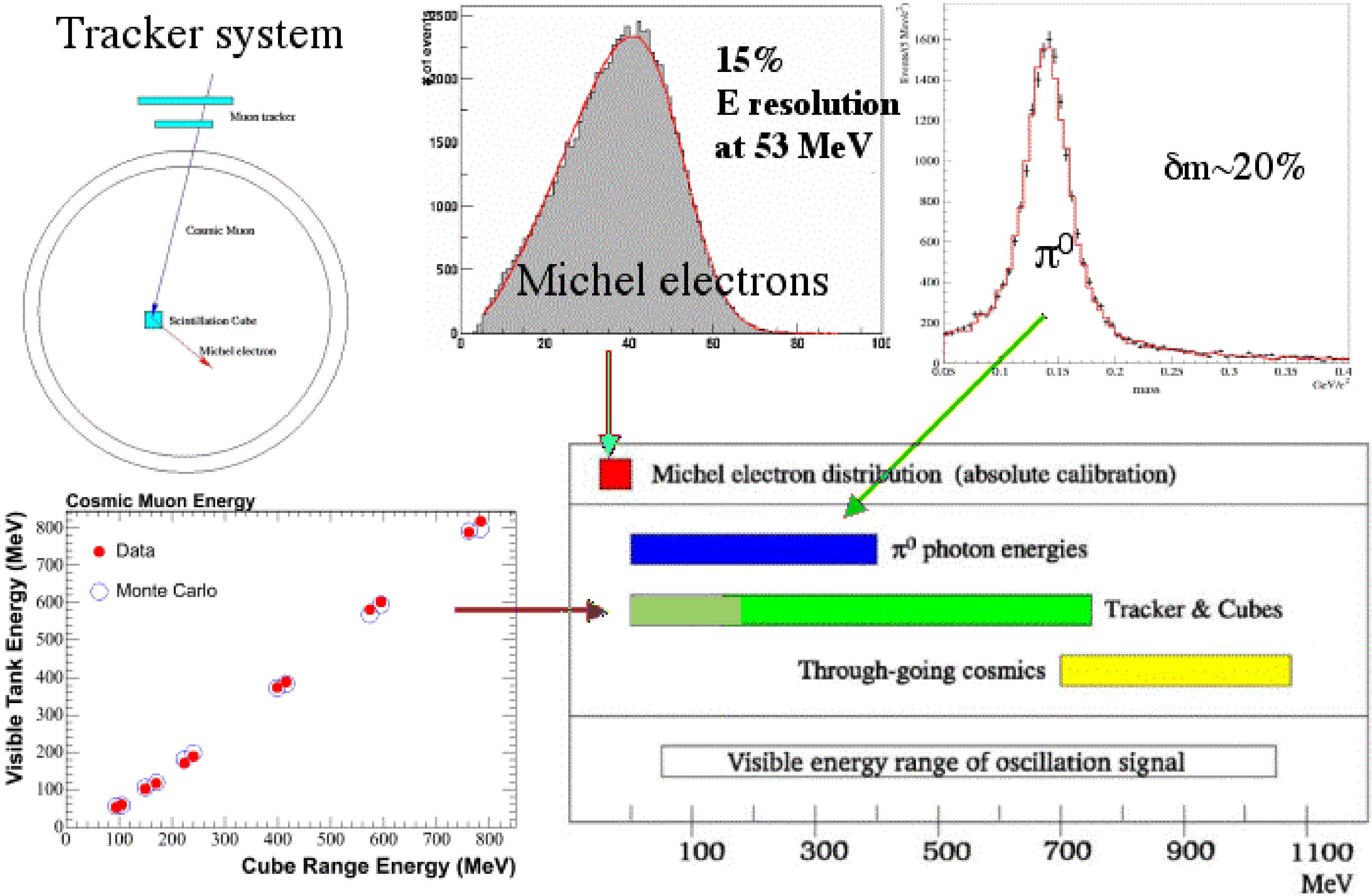
Detector “Optical” Model



Timing distribution for PMT hits

- Calibration laser source inside tank
- Monte Carlo with full optical model describes most of the timing structure

Detector Callibration



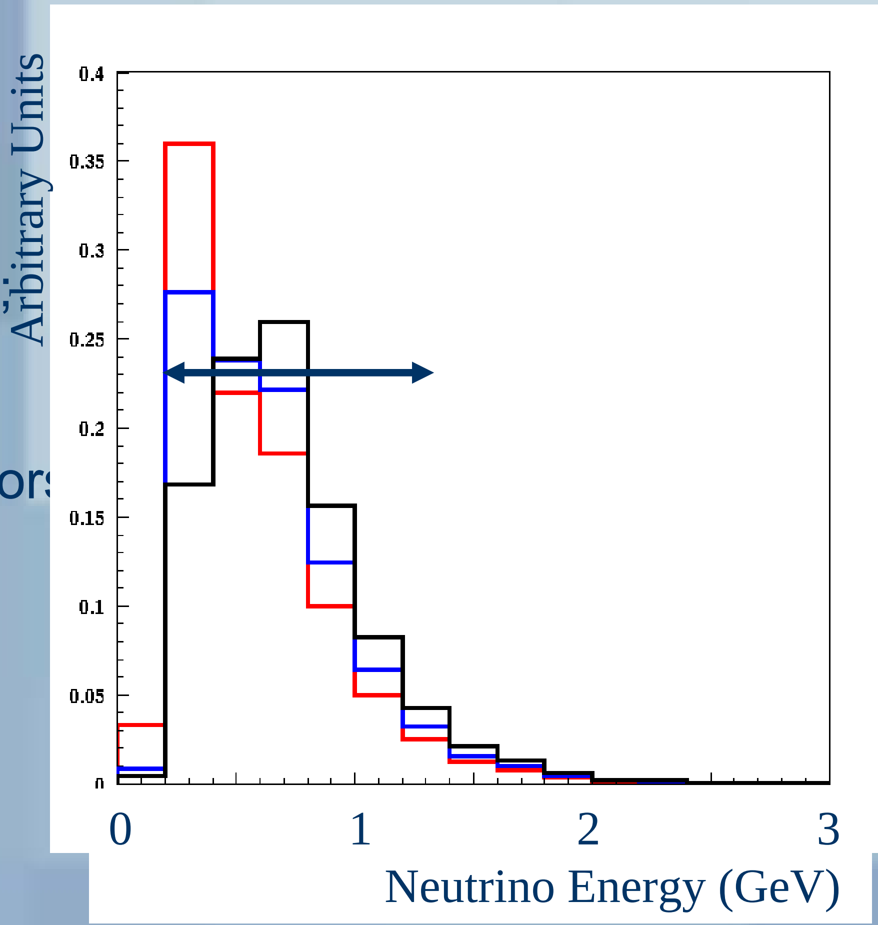
Events Reconstruction and Particle ID

Two parallel approaches to PID analysis:

Track/likelihood-based (TB) analysis:
- detailed reconstruction of particle tracks;
- PID from ratio of fit likelihoods for different particle hypotheses.
- Less vulnerable to detector modeling errors

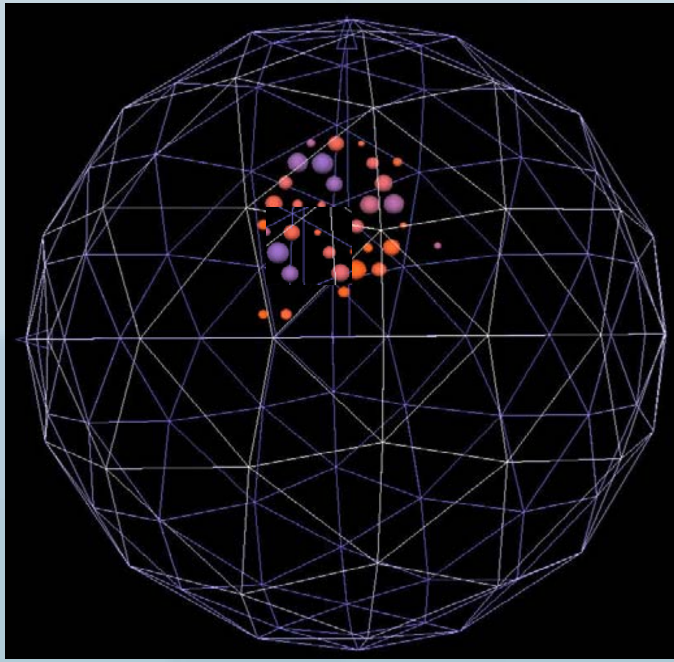
Boosted decision trees (BDT):
- algorithmic approach, able to extract particle ID information from larger set of lower-level event variables.
- Better signal/background, but more sensitive to detector modeling.

Signal energy range is approximately $0.3<E_{\nu}^{QE}<1.5$ GeV.



MiniBooNE signal examples:
$\Delta m^2=0.4$ eV^2
$\Delta m^2=0.7$ eV^2
$\Delta m^2=1.0$ eV^2

Blind Analysis



MiniBooNE is searching for a small but distinctive event signature.

Blind region:
- Electron-like events were sequestered
    - about 1% of the in-beam events.

The rest 99% of in beam events
- At the beginning highly restrictive.

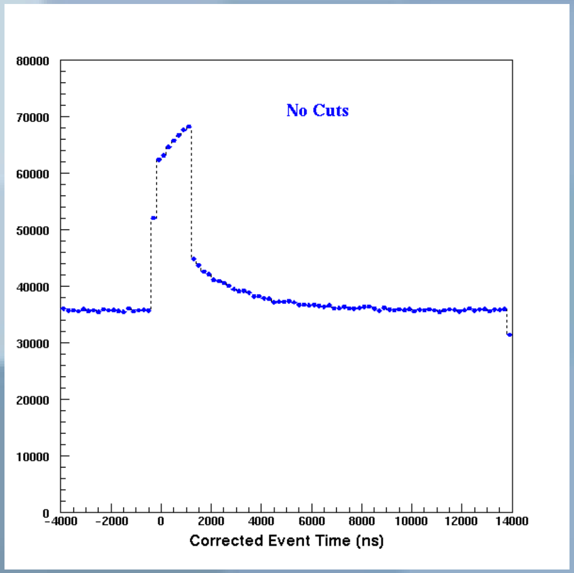
- Rule for cuts to sequester events:
  <1σ signal outside of the box

- Look closer and closer to the box as the PID and MC became more and more trustworthy.

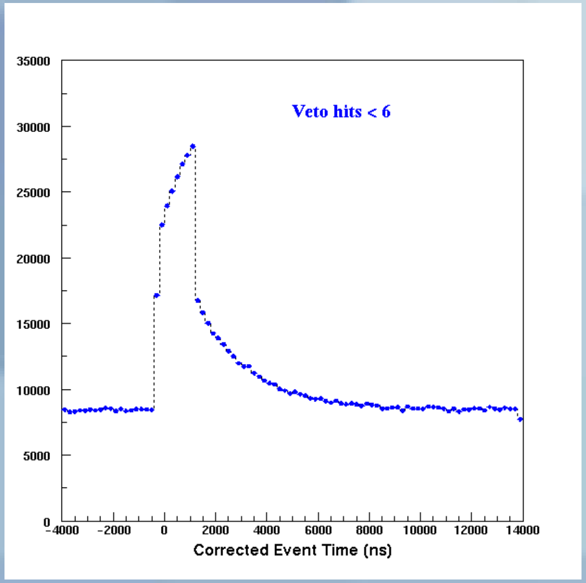
Finally box was opened in series of steps.

Eliminating Cosmic Background

Progressively introducing cuts on the time window:

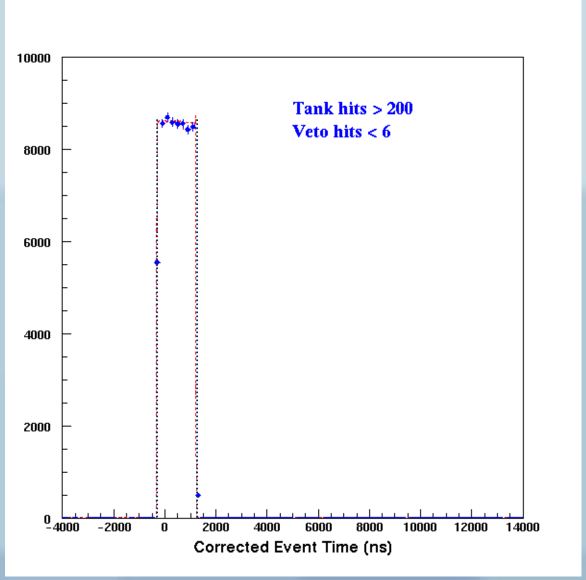


Raw data



Veto<6 removes through-going cosmics

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



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

Analysis Precuts

Precuts:

Only 1 subevent

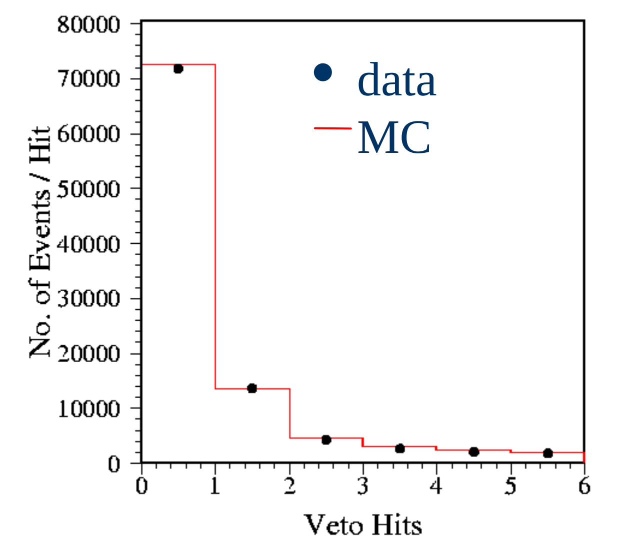
Veto hits < 6

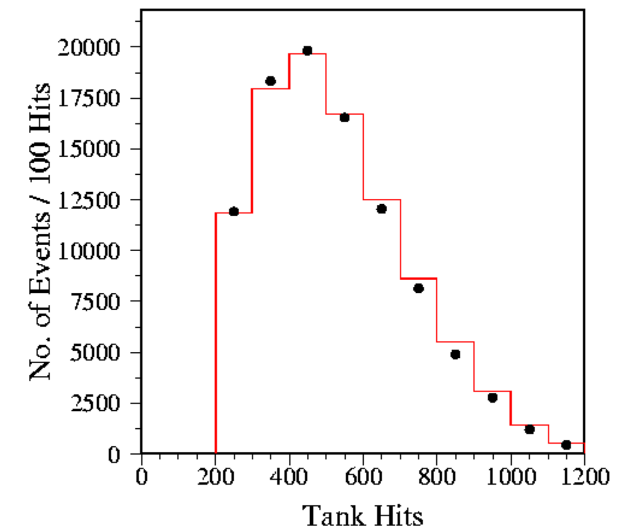
Tank hits > 200

And a radius precut:

R<500 cm

(where reconstructed R is algorithm-dependent)



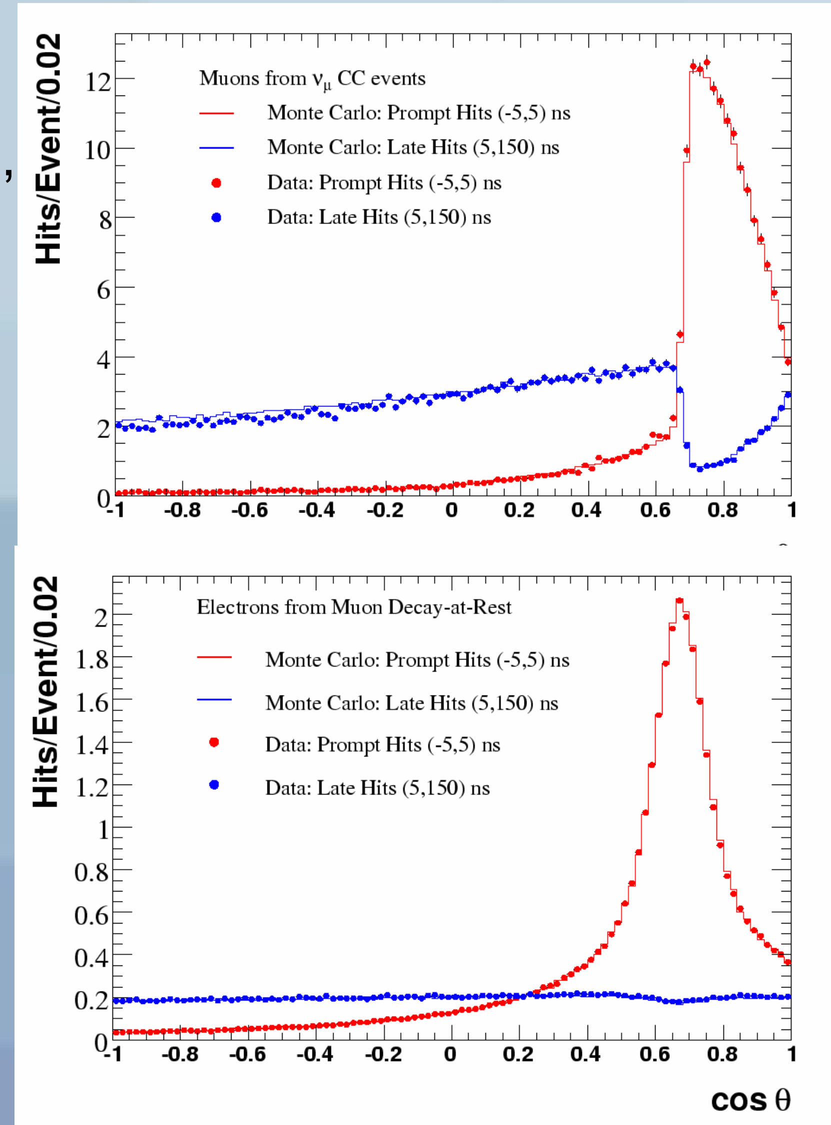


Track-Based Analysis

Detailed analytical calculation of the average number of photo-electrons (PE) for each tube, given the optical properties of the detector and the particle parameters.

Accounts for:

- Non-uniform light source.
- Prompt light (Cherenkov, scattering)
- Delayed light (scintillation, fluorescence)
- Indirect light (scattering, reflection
- Angular profile of the produced light.



Predicts the probability for each tube to be "hit" based on the calculated average number PE.

Track-Based Analysis Likelihood Fit

A single track (μ,e) is parameterized with 7 parameters

- (x^0, y^0, z^0, T^0) (initial vertex and time)
- E^0 – energy
- (θ^0, ϕ^0) – direction

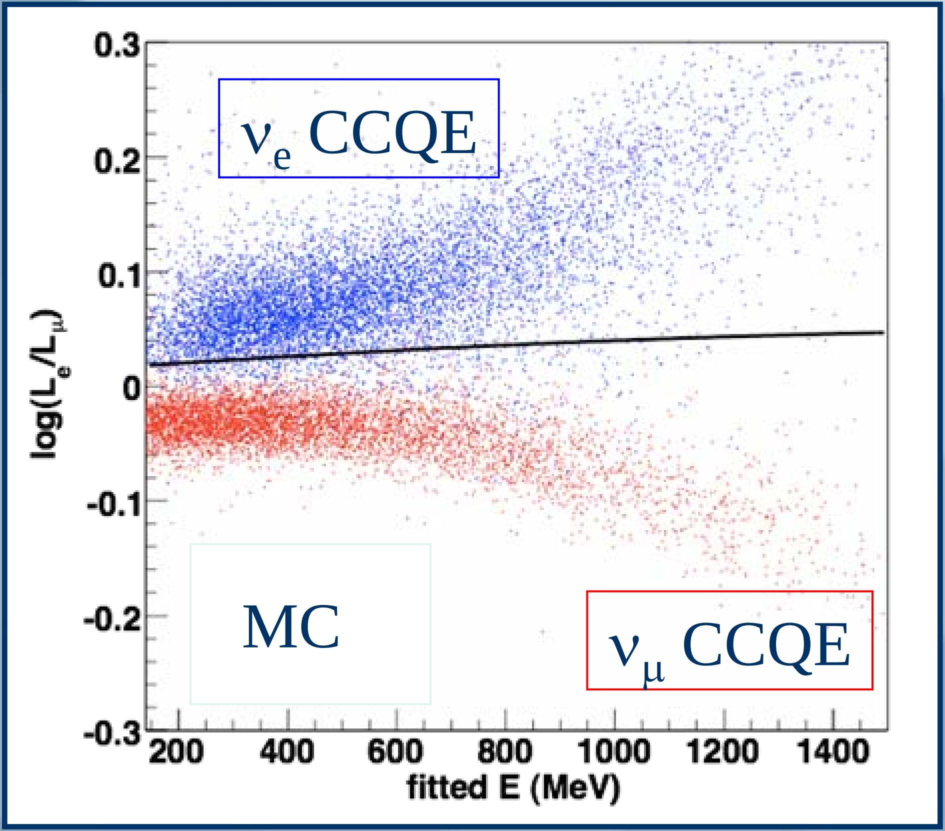
Two track fit to π^0 hypothesis includes additionally:

- γ_1, γ_2 conversion lengths.
- energy and direction of γ_2.
- with and without π^0 mass constraint.

Perform likelihood fits to each event with different particle hypothesis (μ, e, π^0 -> 2 γ with and without π^0 mass constraint) varying the parameters.

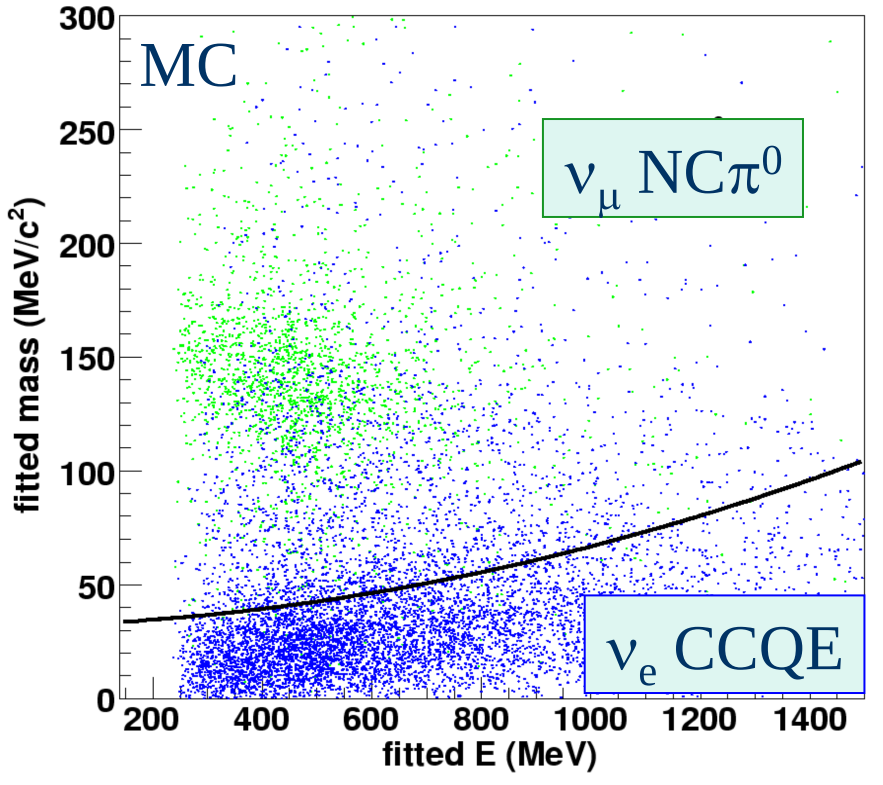
Track-Based Analysis
Rejecting Muon-like Events

- 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.

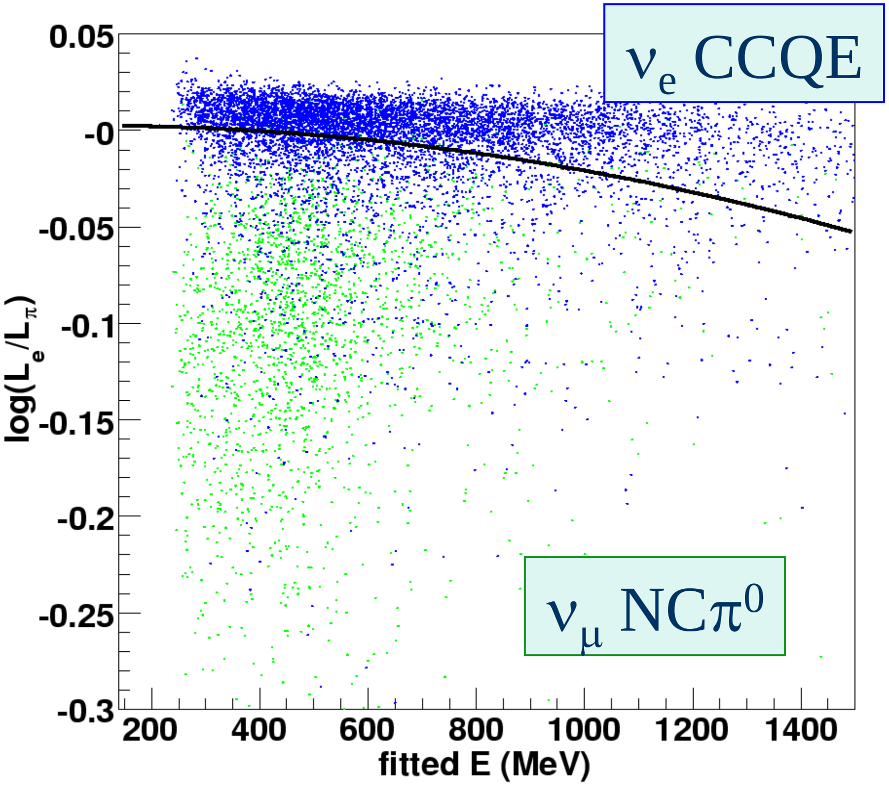


Track-based Analysis Rejecting π^0 Events

Two track fit no mass constraint



Two track fit with π^0 mass

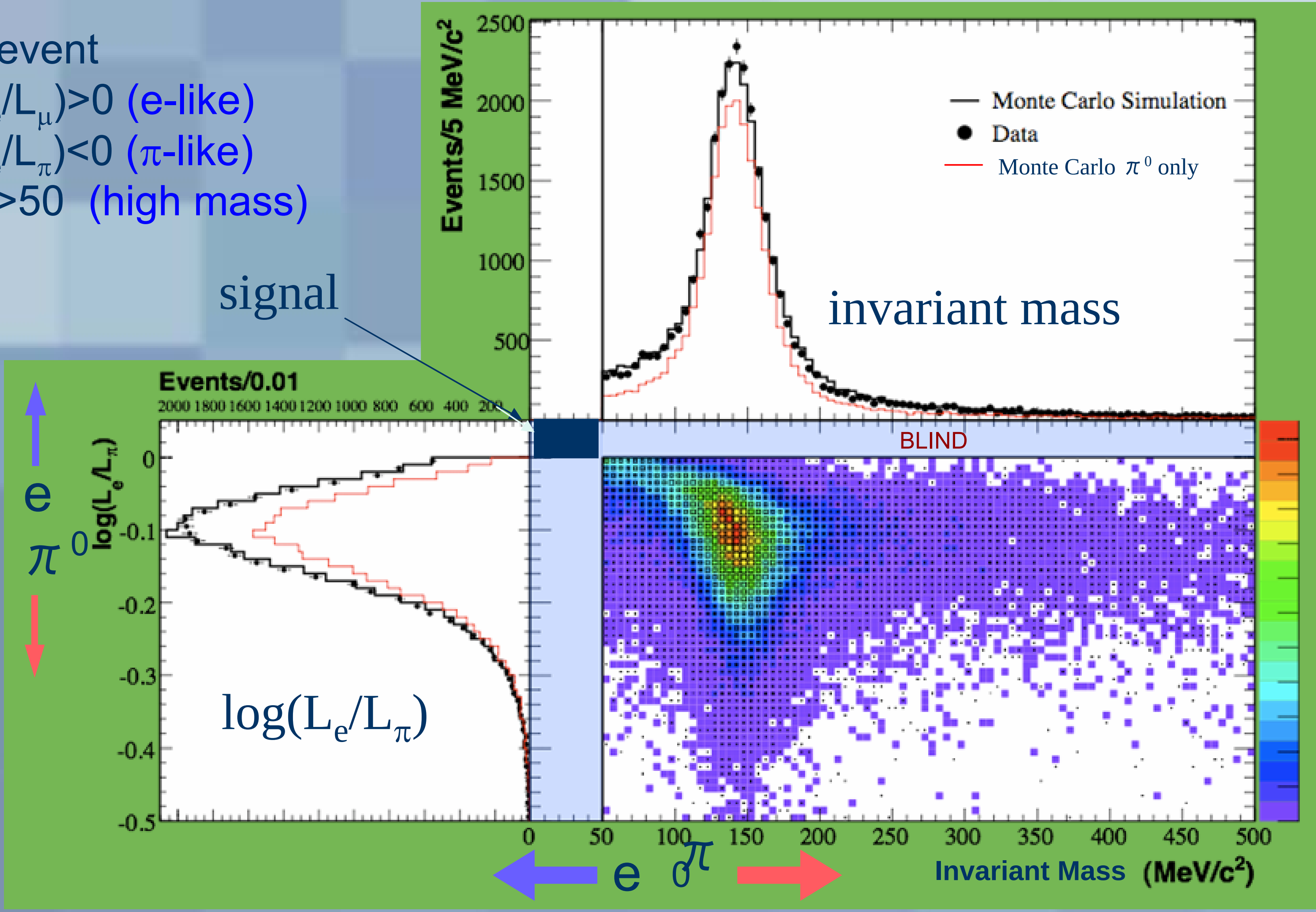


- Cuts are quadratic functions chosen to maximize $\nu_\mu \rightarrow \nu_e$ sensitivity.

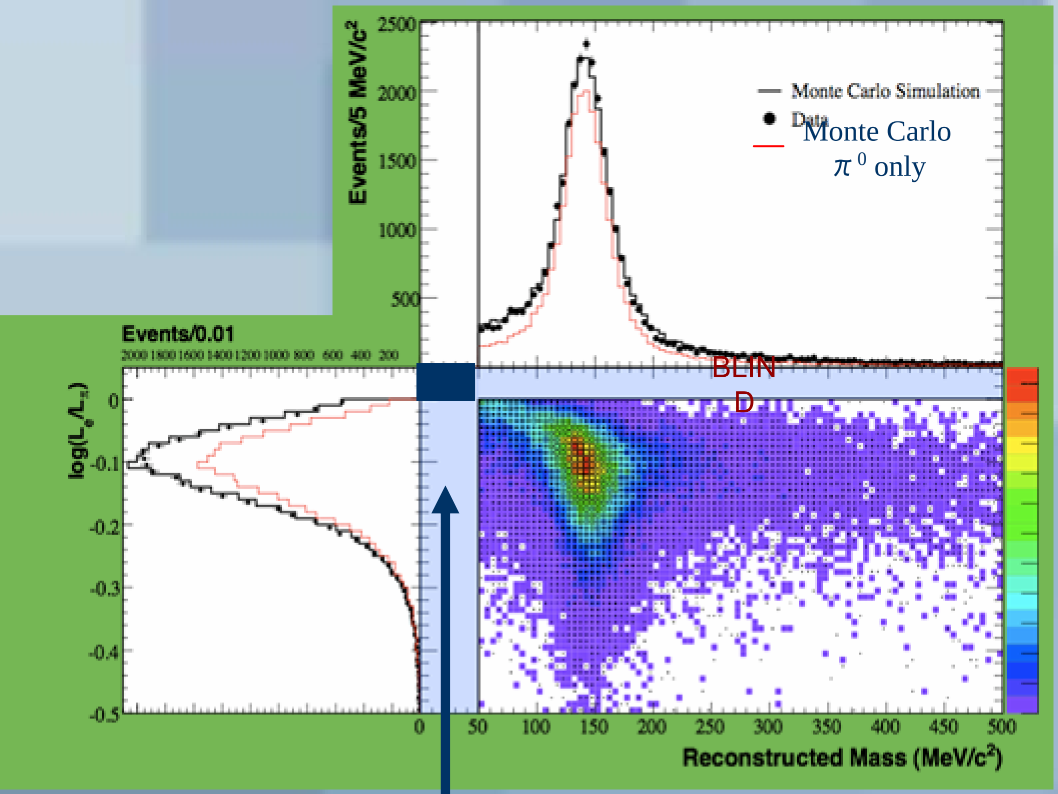
  Log(L_e/L_π)>0 – electron hypothesis fits better.

Track-Based Analysis
Test of e/π^0 Separation

1 subevent
log(L_e/L_μ)>0 (e-like)
log(L_e/L_π)<0 (π-like)
mass>50 (high mass)



Track-Based Analysis
Checking the Sidebands

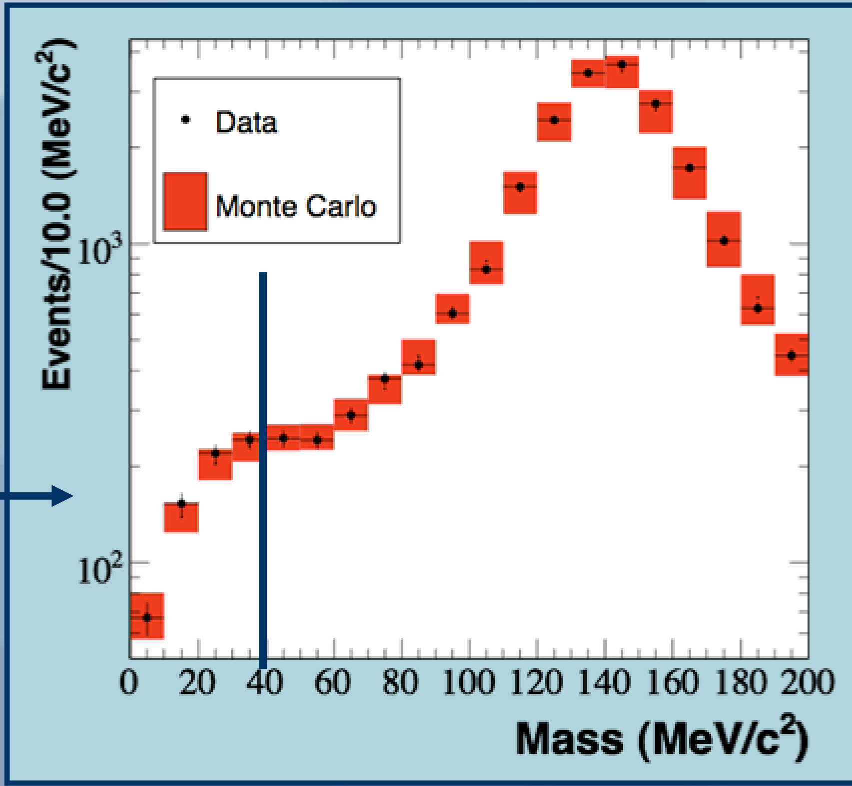


1 subevent

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

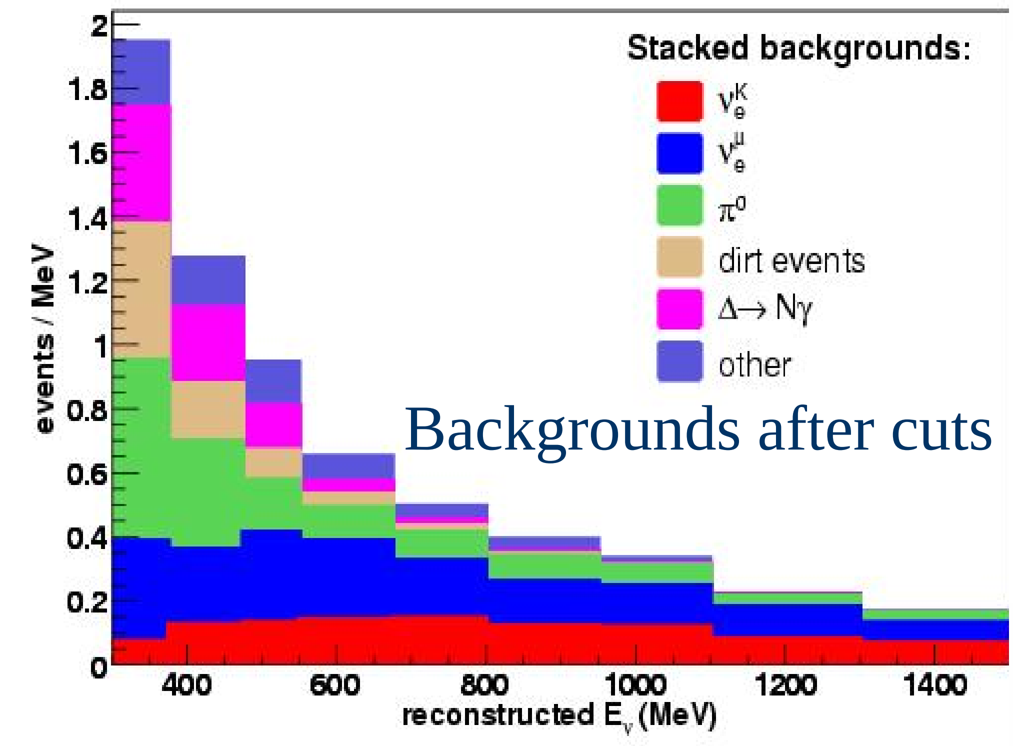
$\log(L_e/L_\pi)<0$ (π-like)

mass<200 (low mass)

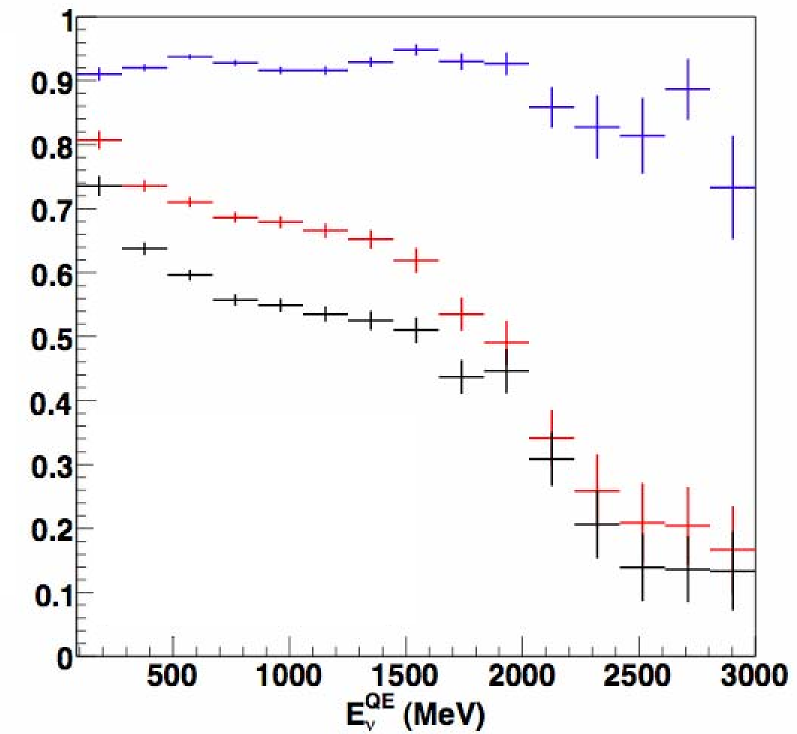


χ^2 Prob for mass<50 MeV
("most signal-like"): 69%

Track-Based Analysis
Signal Efficiency and Predicted Background



Efficiency:



"Precuts" +
$Log(L_e/L_\mu)$ +
$Log(L_e/L_\pi)$ +
Invariant mass

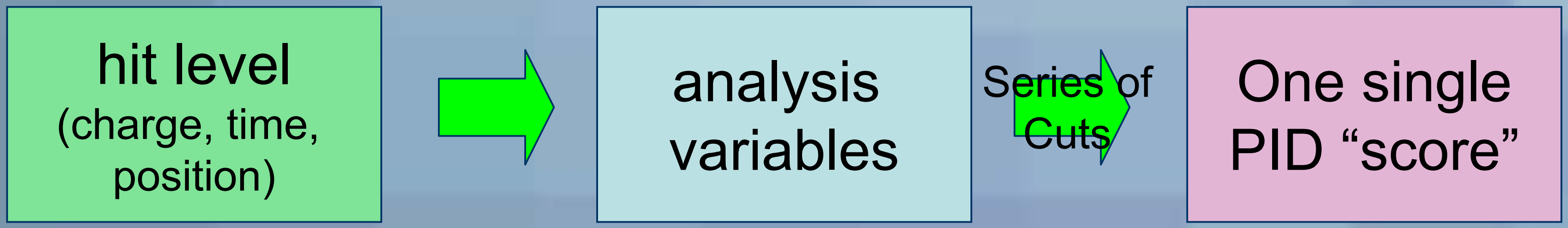
Boosted Decision Tree Analysis (BDT)

- An algorithm optimized to combine many weakly discriminating variables into one that provides powerful separation
  B. Roe et al., Nucl. Inst. Meth. ***A543*** *577 (2005)*

- Idea: Go through all analysis variables and find best variable and value to split a Monte Carlo data set.

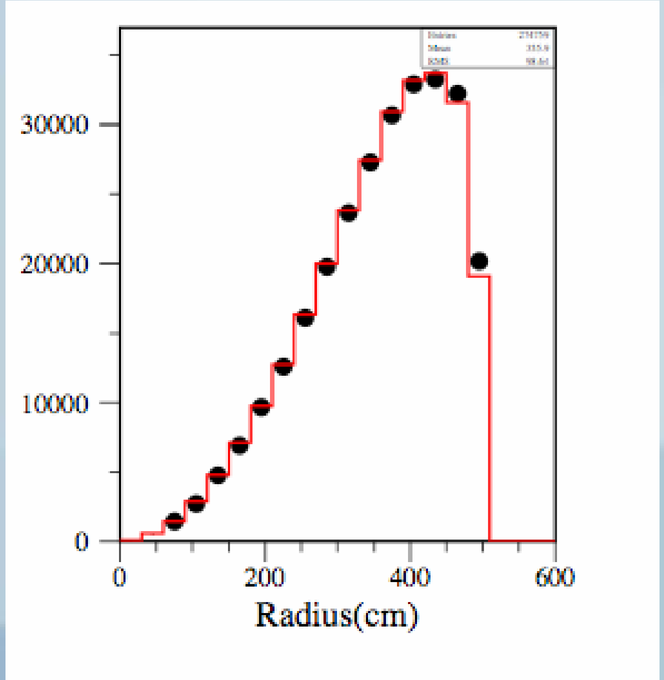
    - For each of the two subsets repeat the process

    - Proceeding in this way, a "decision tree" is built, whose final nodes are called leaves

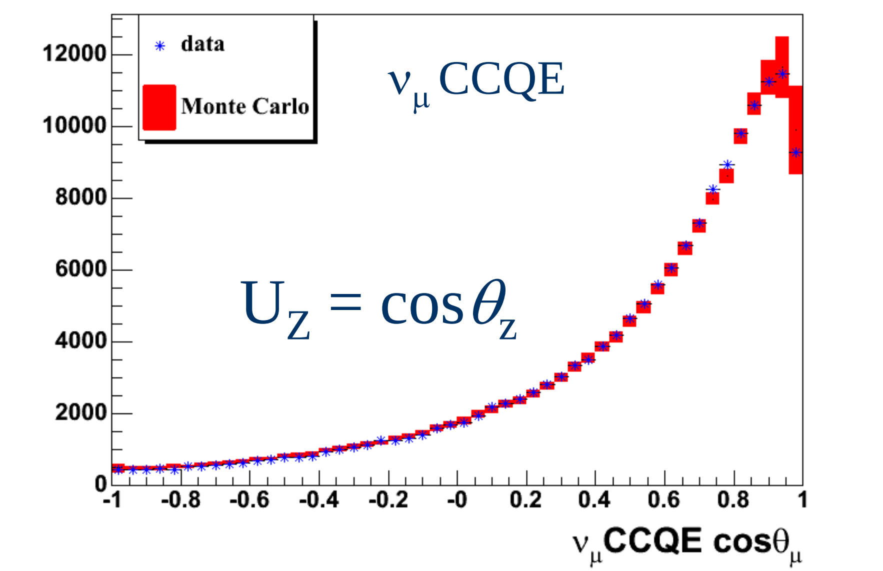


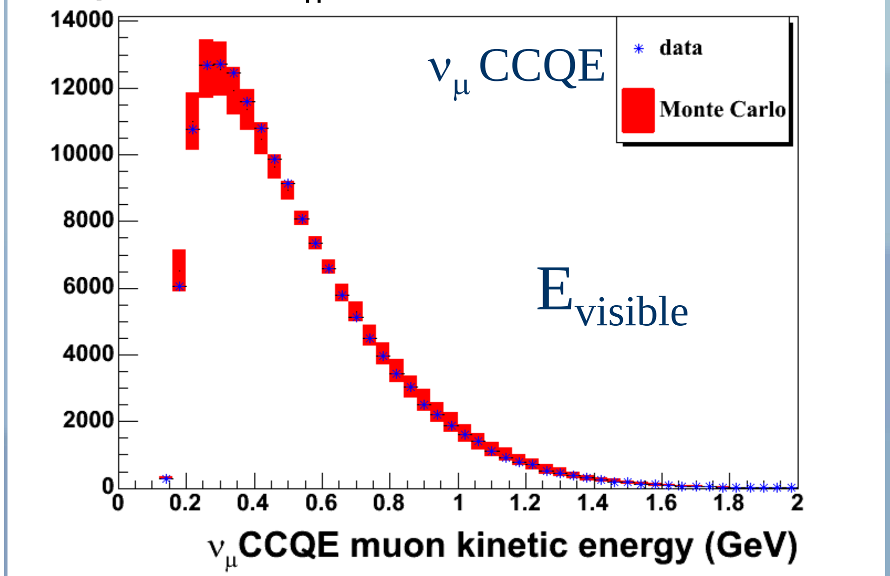
Boosted Decision Tree Analysis Variable

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

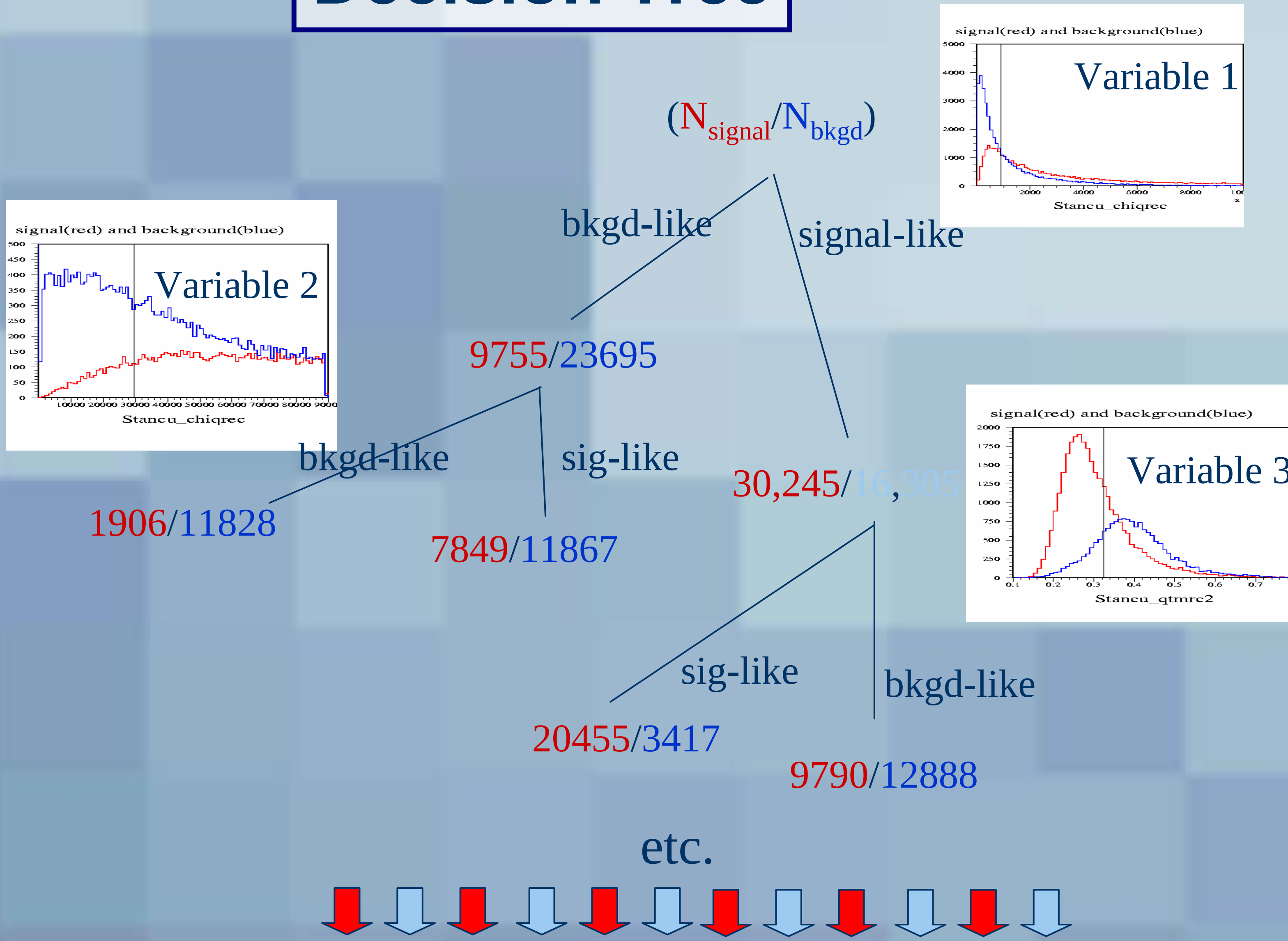


Reconstructed quantities which are inputs to E_n^{QE}





Decision Tree



This tree is one of many possibilities...

Boosted Decision Tree

- 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.

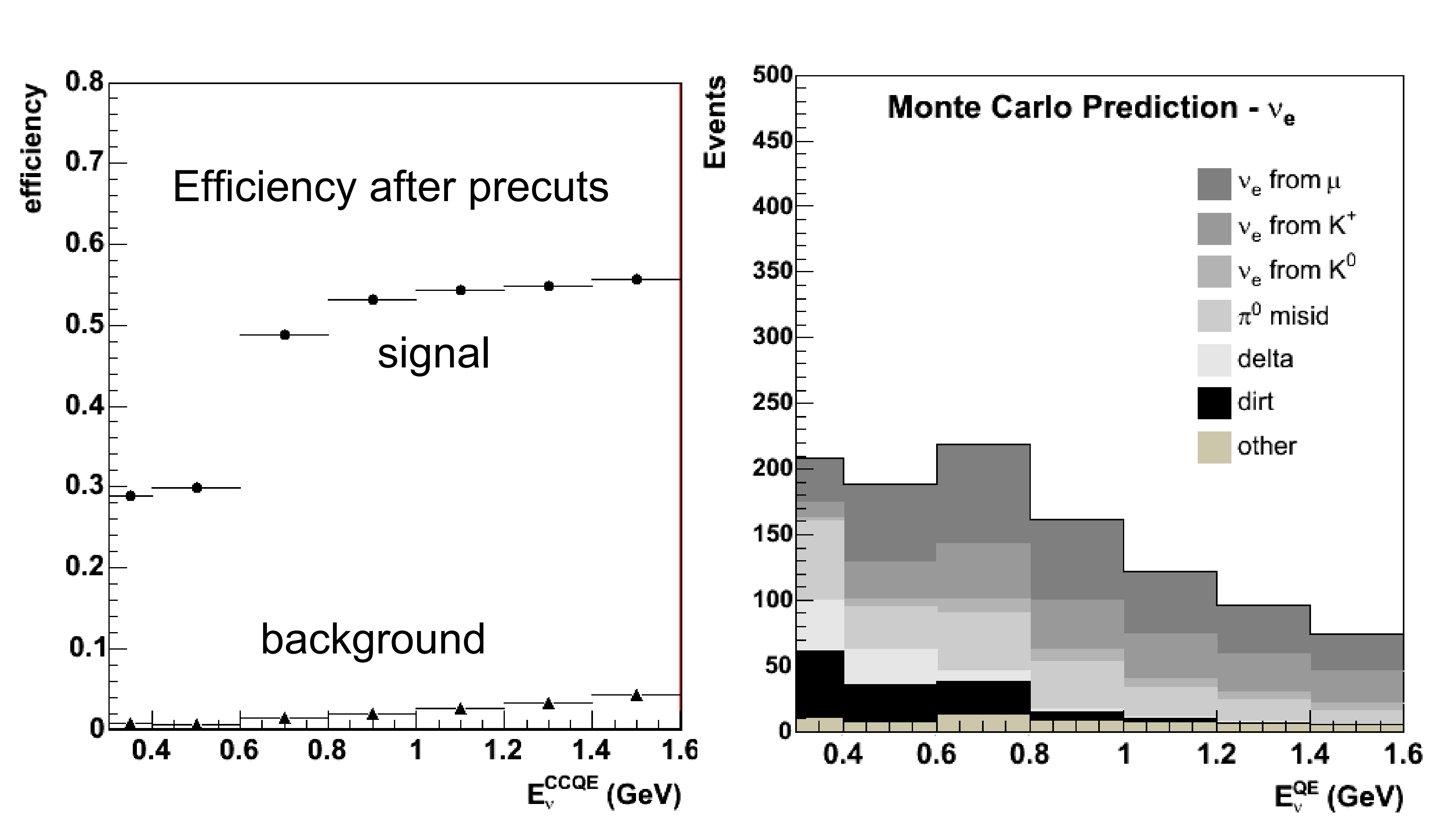
The total for all trees is combined into a "score"

Background-like

Signal-like

Background and Signal Efficiency of BDT

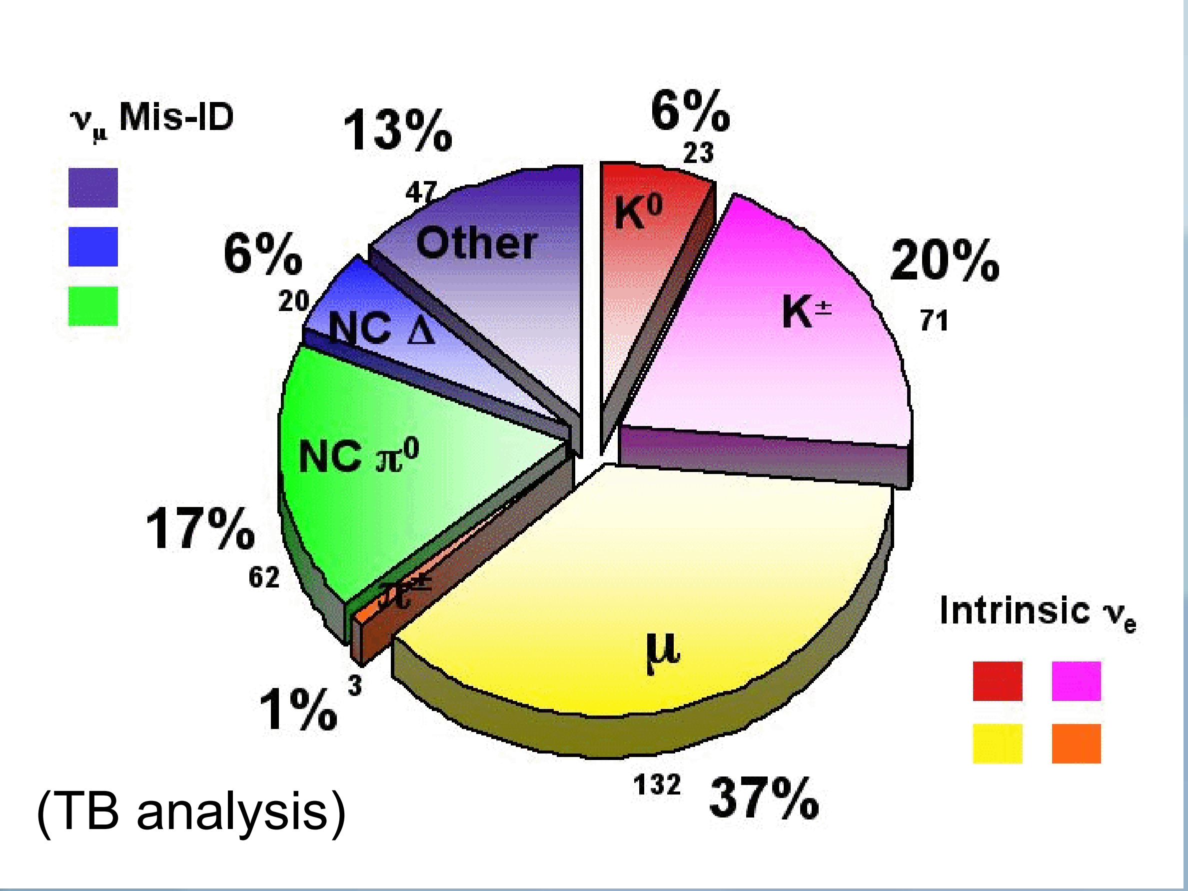
Analysis cuts on PID score as a function of Energy



Uncertainties, Constraints and Sensitivity

Background Components

We have two categories of backgrounds:

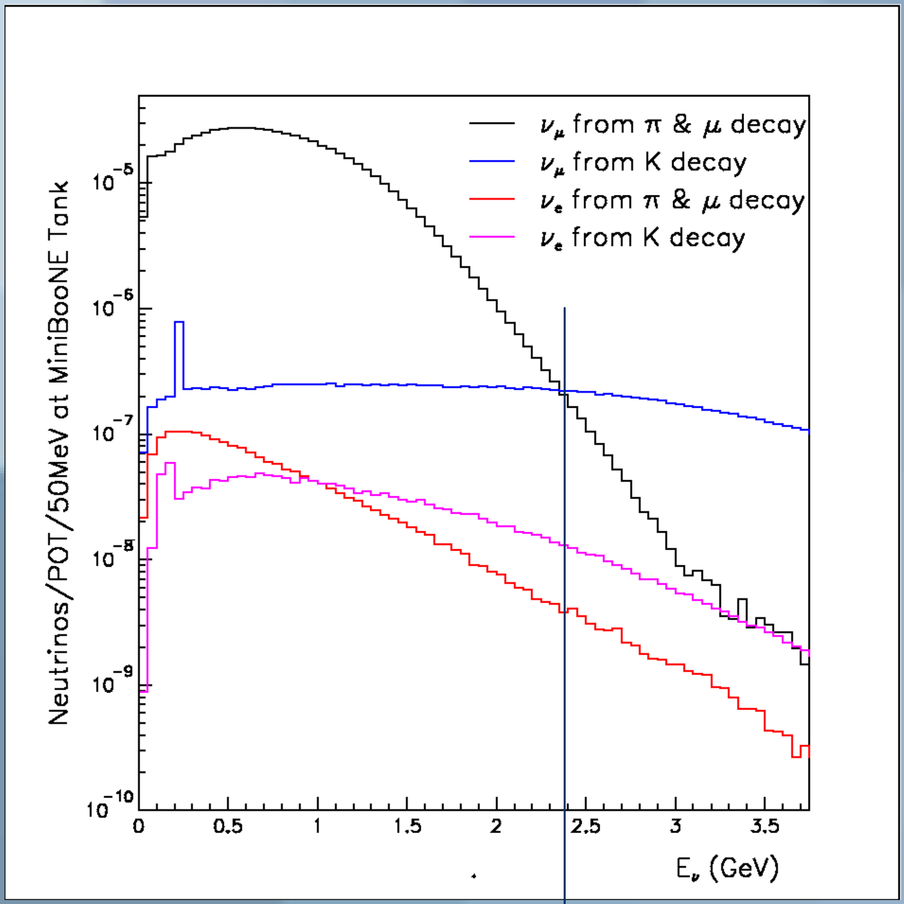


Predictions of the backgrounds are among the nine sources of significant error in the analysis

Systematic Uncertainties

Source of Uncertainty On ν_e background	Track Based /Boosted Decision Tree error in %	Checked or Constrained by MB data	Further reduced by tying ν_e to ν_μ
Flux from π^+/μ^+ decay	6.2 / 4.3	√	√
Flux from K^+ decay	3.3 / 1.0	√	√
Flux from K^0 decay	1.5 / 0.4	√	√
Target and beam models	2.8 / 1.3	√	
ν-cross section	12.3 / 10.5	√	√
NC π^0 yield	1.8 / 1.5	√	
External interactions ("Dirt")	0.8 / 3.4	√	
Optical model	6.1 / 10.5	√	√
DAQ electronics model	7.5 / 10.8	√	

High Energy Constraint of K⁺



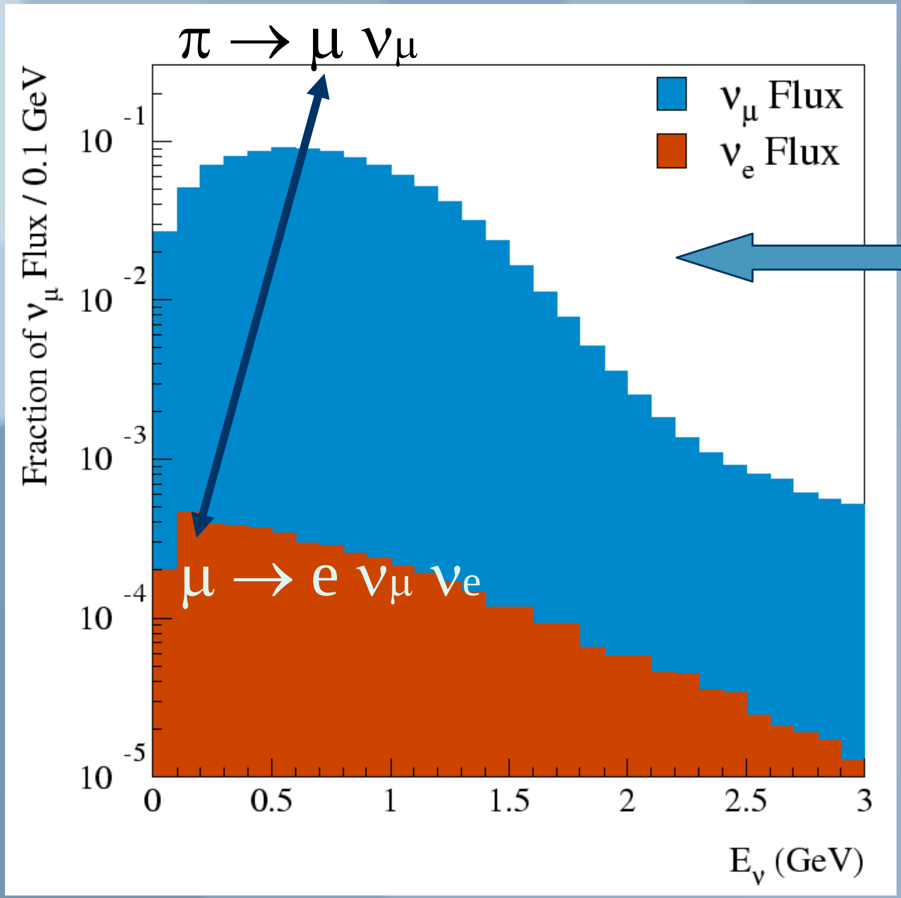
- Kaon decay has much higher *Q*-value than pion decay
- Kaons produce higher energy neutrinos
- Particularly true for two-body $K^+ \rightarrow \mu + \nu_\mu$

- High energy ν_μ events provide constraint to the kaon flux that produces ν_e background

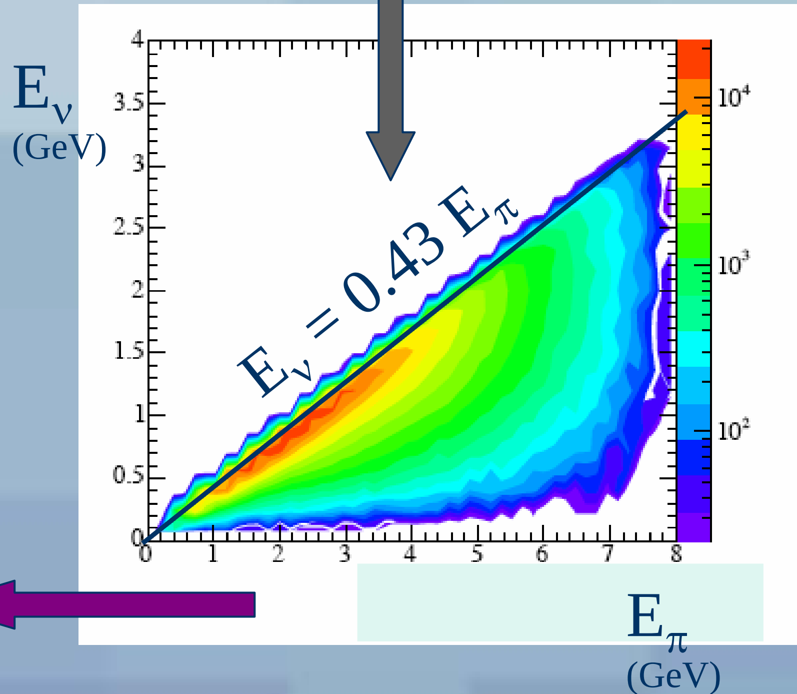
Dominated by π decay

Dominated by *K* decay

ν_μ Constraint on Intrinsic ν_e from π+ Decay Chains

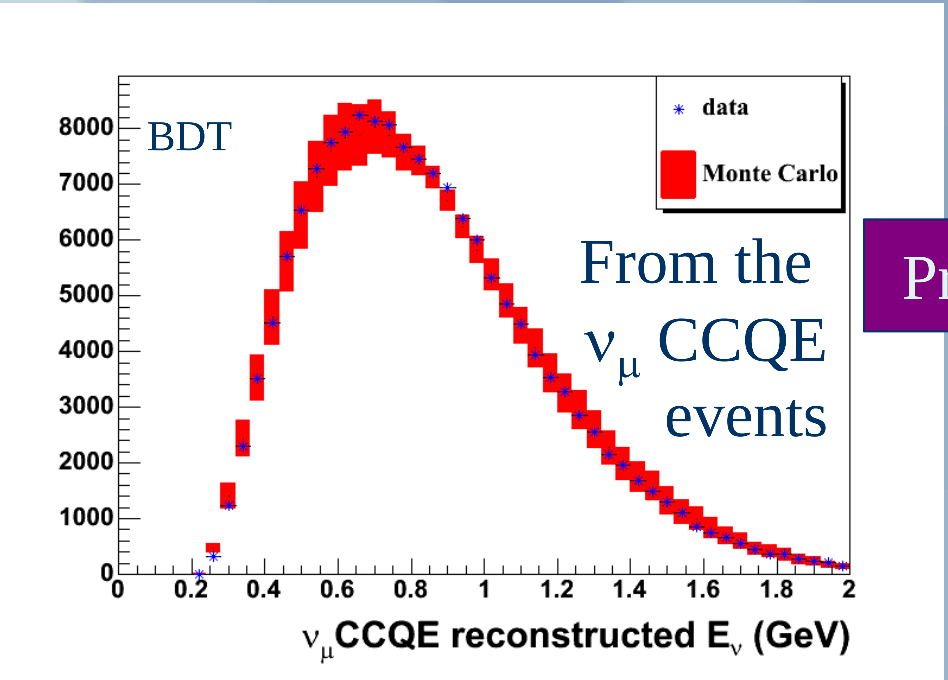


- Measure the ν_μ flux
- Kinematics allows connection to the π flux



- Once the π flux is known, the μ flux is determined

ν_μCCQE Sample



Predict

Normalization
& energy dependence
of both background
and signal

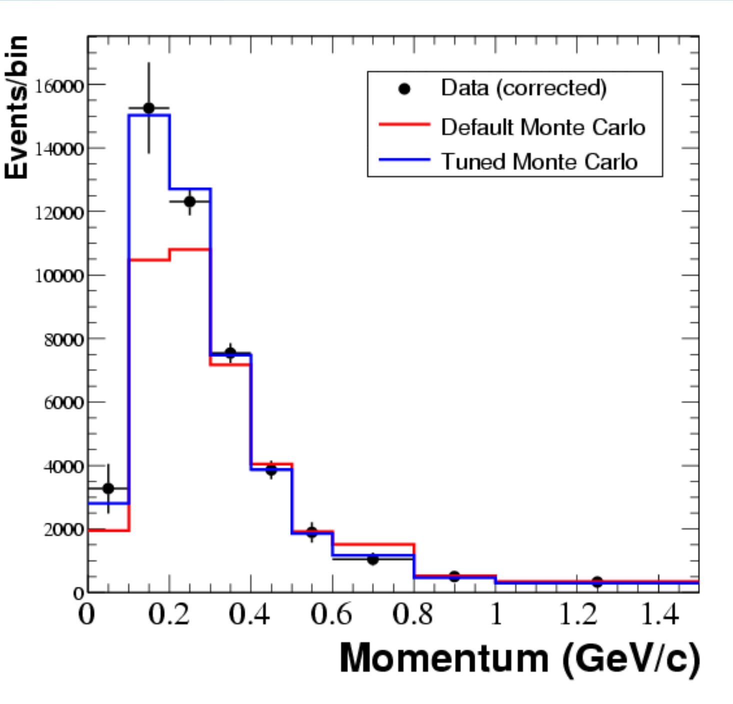
Data/MC	Boosted Decision Tree:	1.22 ± 0.29
	Track Based:	1.32 ± 0.26

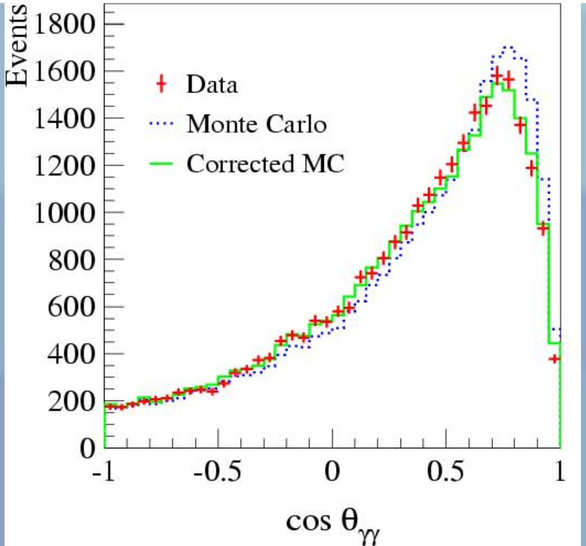
Tying the ν_e background and signal prediction to the ν_μ flux constrains this analysis to a strict $\nu_\mu \rightarrow \nu_e$ appearance-only search

Constraining NC Δ Resonance

- Fully reconstructed π^0 events sample constrains the total NC Δ rate.
- Re-weight the MC π^0 using the measured momentum distribution and total rate.
- Reduces the uncertainty of the π^0 mis-ID/misreconstructed background.
- It constrains also $\Delta \to N\gamma$

Reweighting improves agreement in other variables, e.g.⇒

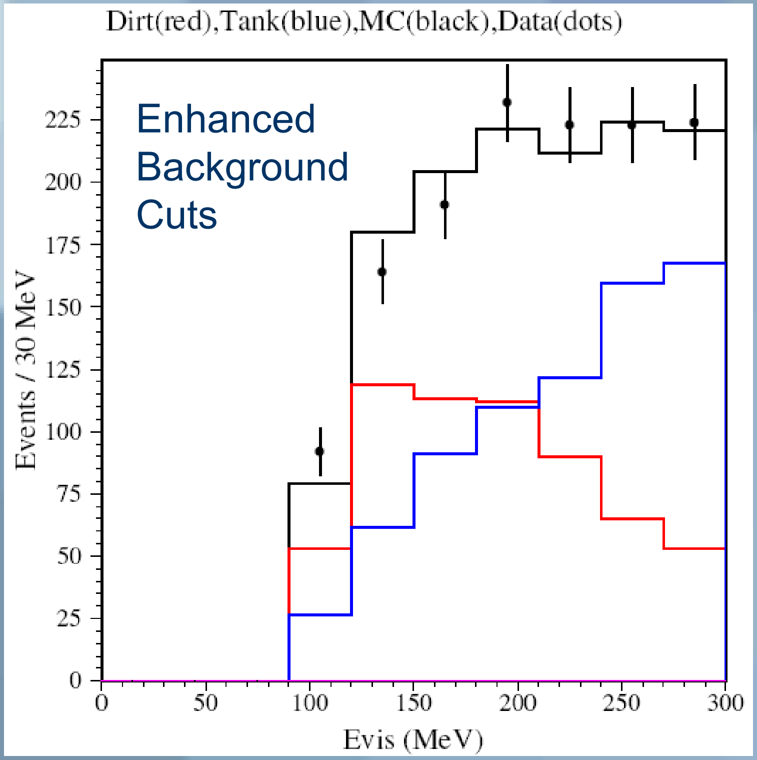


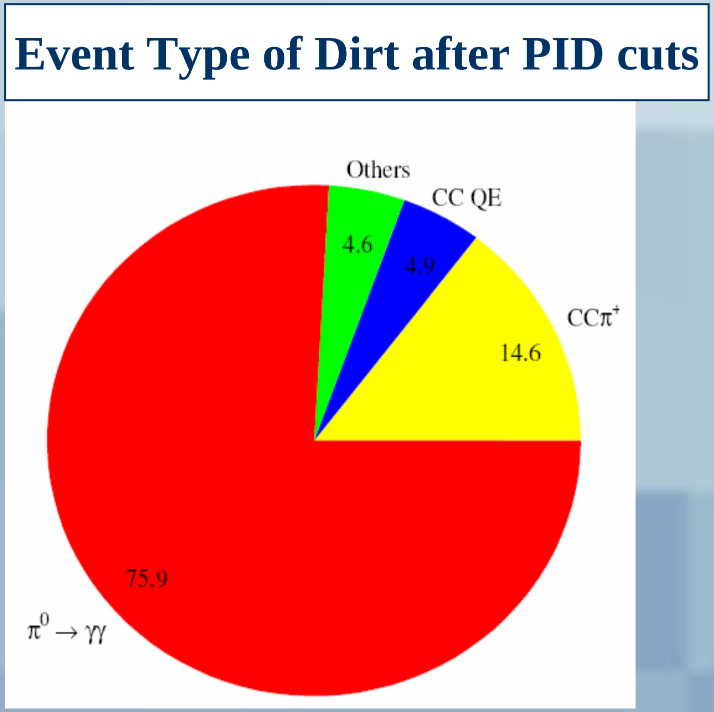


External Backgrounds

"Dirt" Events

ν interactions outside of the detector $N_{data}/N_{MC} = 0.99 \pm 0.15$





Cosmic Rays: Measured from out-of-beam data: 2.1 ± 0.5 events

Other Single Photon Sources

Neutral Current: $\nu + N \to \nu + N + \gamma$ negligible

From Efrosinin, hep-ph/0609169,
calculation checked by Goldman, LANL

Charged Current < 6 events @ 95% CL

$$\nu + N \to \mu + N' + \gamma$$

where the presence of the γ leads to mis-identification

Use events where the μ is tagged by the michel e^-,
study misidentification using BDT algorithm.

Predicted Background Content (TB)

Process	Number of Events
ν_μ CCQE	10
$\nu_\mu e \rightarrow \nu_\mu e$	7
Miscellaneous ν_μ Events	13
NC π^0	62
NC $\Delta \rightarrow N\gamma$	20
NC Coherent & Radiative γ	< 1
Dirt Events	17
ν_e from μ Decay	132
ν_e from K^+ Decay	71
ν_e from K^0_L Decay	23
ν_e from π Decay	3
Total Background	358
0.26% $\nu_\mu \rightarrow \nu_e$	(example signal) 163

Applying ν_μCCQE Constraint

Two Approaches

TB: Reweight MC prediction to match measured ν_μ result (accounting for systematic error correlations)

BDT: include the correlations of ν_μ to ν_e in the error matrix:

$$\chi^2 = \left(\Delta_i^{\nu_e} \quad \Delta_i^{\nu_\mu} \right) \begin{pmatrix} M_{ij}^{e,e} & M_{ij}^{e,\mu} \\ M_{ij}^{\mu,e} & M_{ij}^{\mu,\mu} \end{pmatrix}^{-1} \begin{pmatrix} \Delta_j^{\nu_e} \\ \Delta_j^{\nu_\mu} \end{pmatrix}$$

$$\text{where } \Delta_i^{\nu_e} = \text{Data}_i^{\nu_e} - \text{Pred}_i^{\nu_e}(\Delta m^2, \sin^2 2\theta) \text{ and } \Delta_i^{\nu_\mu} = \text{Data}_i^{\nu_\mu} - \text{Pred}_i^{\nu_\mu}$$

Systematic (and statistical) uncertainties are included in $(M_{ij})^{-1}$

(i,j are bins of E_ν^{QE})

Cross Section Uncertainties

(Many are common to ν_μ and ν_e and cancel in the fit)

M_A^{QE}, e_{lo}^{sf}	6%, 2% (stat + bkg only)	determined from MiniBooNE ν_μ QE data
QE σ norm	10%	
QE σ shape	function of E_ν	
ν_e/ν_μ QE σ	function of E_ν	

NC π^0 rate	function of π^0 mom	determined from MiniBooNE ν_μ NC π^0 data
M_A^{coh}, coh σ	±25%	
$\Delta \rightarrow N\gamma$ rate	function of γ mom + 7% BF	

E_B, p_F	9 MeV, 30 MeV	determined from other experiments
Δs	10%	
$M_A^{1\pi}$	25%	
$M_A^{N\pi}$	40%	
DIS σ	25%	

Error Propagation – Optical Model

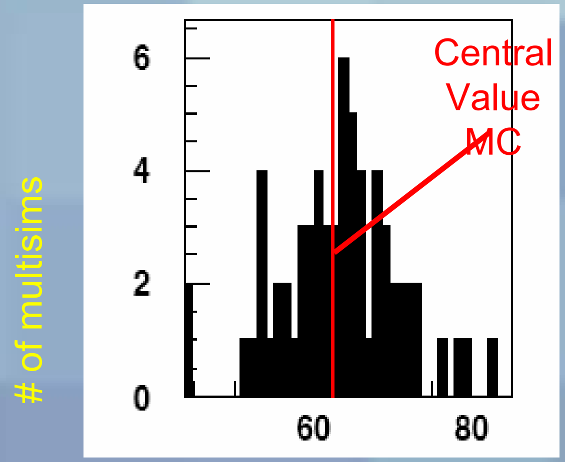
- Optical model depends on 39 parameters such as absorption, scintillation, fluorescence behavior.

- Use “Multisim” technique to estimate error: vary the parameters according to a full covariance matrix, and run 70 full GEANT Monte Carlo “experiments” to map the space of detector responses to the parameters.

- Space of output results is used to produce error matrix for the oscillation candidate histogram

Example of multisim outputs in a single osc. bin:

70 Optical Model multisims



events passing signal cuts in bin $500<E_\nu^{QE}<600$ MeV

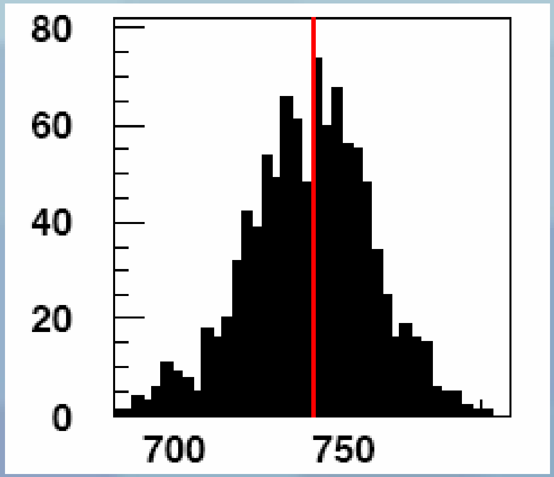
Error Propagation - Other

- Flux and neutrino cross-section parameter variations do not affect the hit distributions for a given event, only the probability of that event occurring in the first place

- Rather than repeating hit-level MC, determine effect of varying by mocking up 1000 multisims by reweighting the same MC events: reduced MC statistics error and greatly reduced CPU usage.

- Similar procedure to produce error matrix for the oscillation candidate histogram

Example of multisim outputs in a single osc. bin:



Error Matrix Calculation

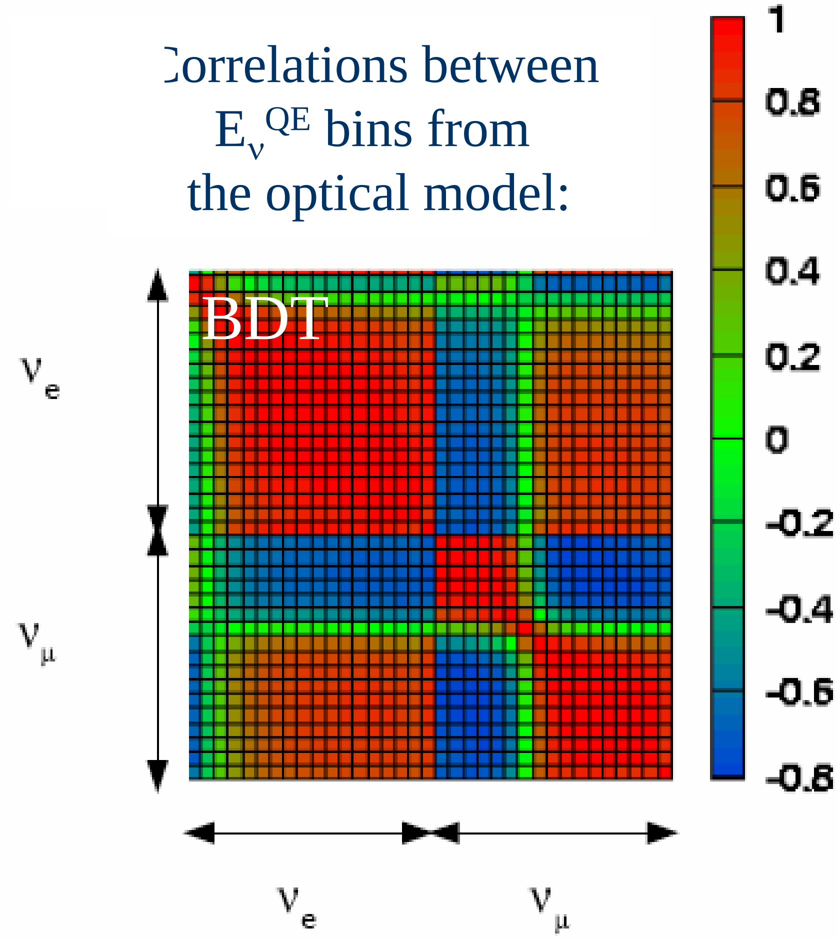
$$E_{ij} \approx \frac{1}{M} \sum_{\alpha=1}^{M} \left(N_i^{\alpha} - N_i^{MC}\right)\left(N_j^{\alpha} - N_j^{MC}\right)$$

- N is number of events passing cuts
- MC is standard monte carlo
- α represents a given multisim
- M is the total number of multisims
- i,j are E_{ν}^{QE} bins

Total error matrix
is sum from each source.

TB: ν_e-only total error matrix
BDT: ν_{μ}-ν_e total error matrix

Correlations between E_{ν}^{QE} bins from the optical model:



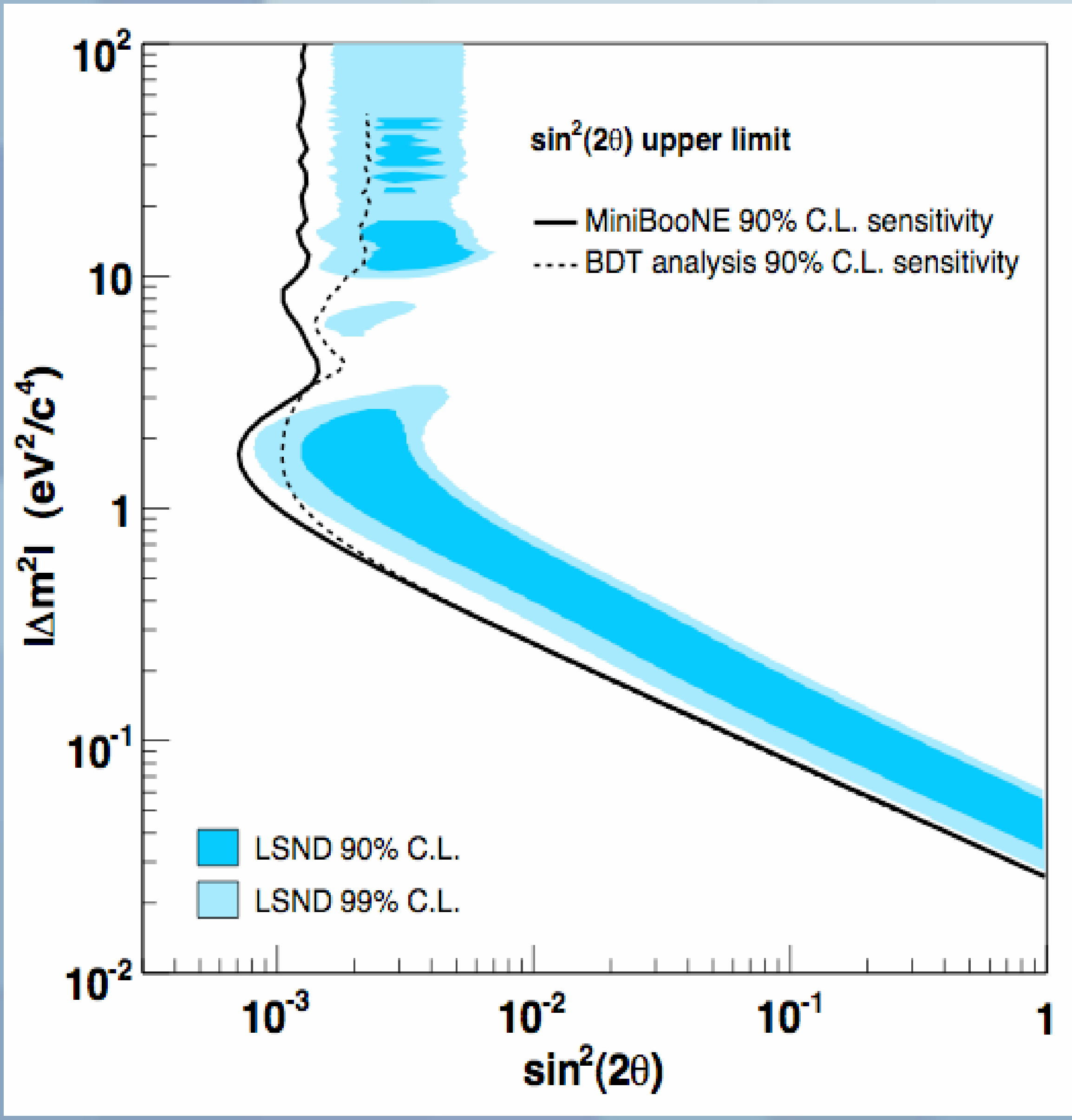
MiniBooNE Sensitivity

- Track-based analysis has slightly better sensitivity to 2-neutrino oscillations.

- Therefore it's the PRIMARY MiniBooNE result.

This is the culmination of the analysis

Next step: UNBLINDING Procedure in steps.



Set using $\Delta\chi^2=1.64$ @ 90% CL

First Oscillation Results

The Box Opening

Unblinding Steps

After applying all analysis cuts:

1. Fit sequestered data to an oscillation hypothesis, returning no fit parameters. Return the χ^2 of the data/MC comparison for a set of diagnostic variables.

2. Open up the plots from step 1. The Monte Carlo has unreported signal. Plots chosen to be useful diagnostics, without indicating if signal was added.

3. Report the χ^2 for a fit to E_ν^{QE}, without returning fit parameters.

4. Compare E_ν^{QE} in data and Monte Carlo, returning the fit parameters.
   At this point, the box is open (March 26, 2007)

Box Opening - Step 1

Return the χ^2 of the data/MC comparison for
a set of diagnostic variables

12 variables are tested for TB
46 variables are tested for BDT

All analysis variables were returned with good probability except...

Track Based analysis χ^2 Probability of $E_{visible}$ (not E_ν^{QE}) fit: 1%

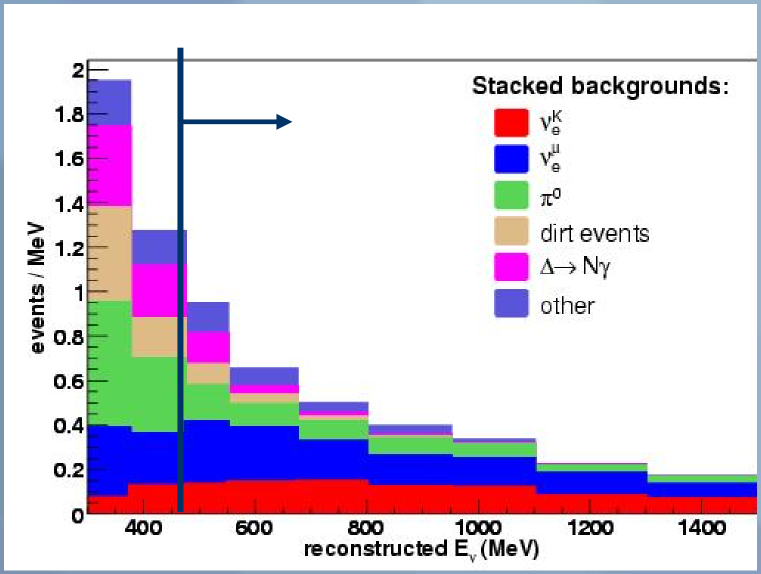
This probability was sufficiently low
to merit further consideration

Setting Low Energy Cut

In the Track Based analysis

- We re-examined our background estimates using sideband studies.
  $\Rightarrow$ *We found no evidence of a problem*

- However, knowing that backgrounds rise at low energy,
  We tightened the cuts for the oscillation fit:



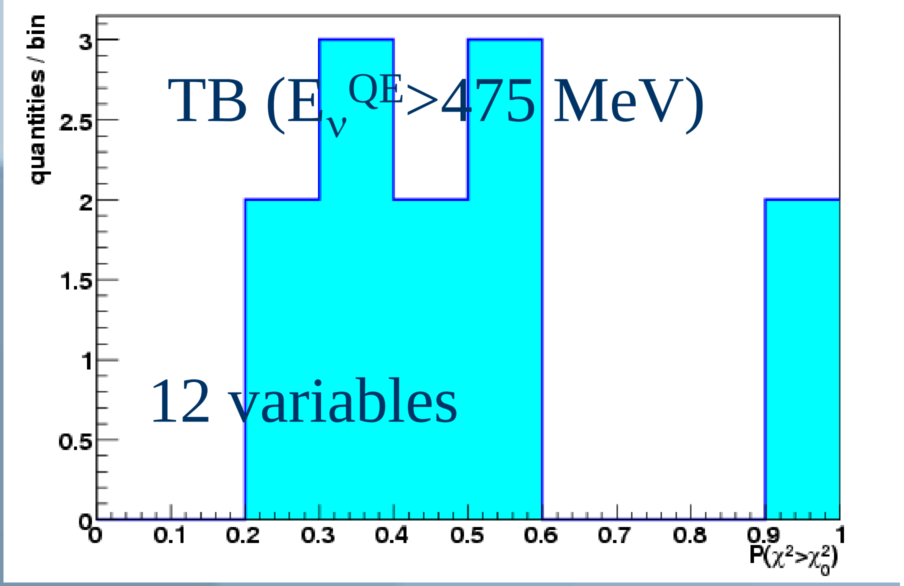
$E_\nu^{QE} > 475$ MeV

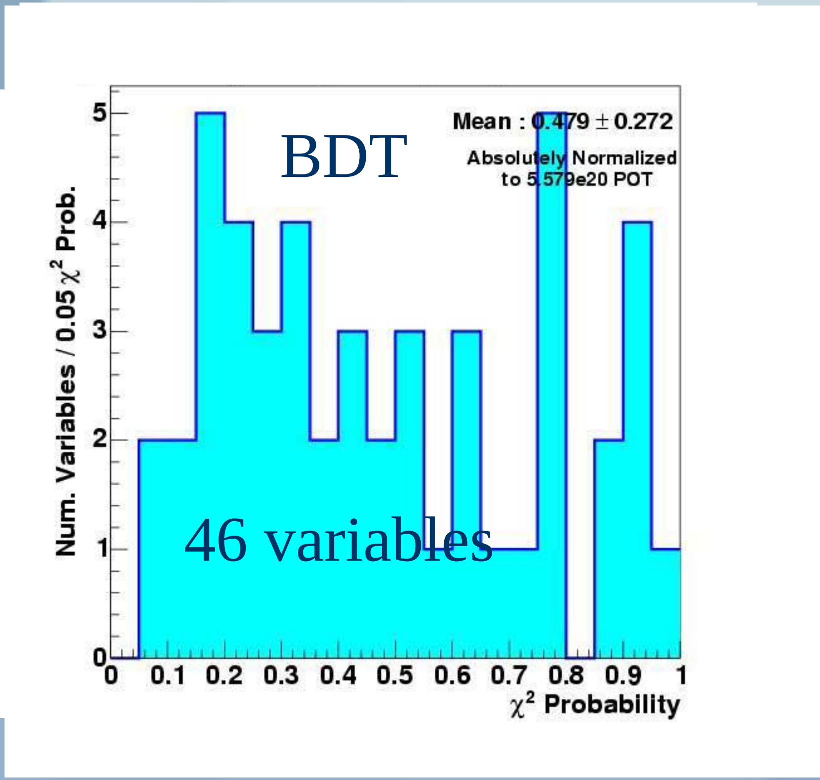
We agreed to report events over the original full range:
$E_\nu^{QE} > 300$ MeV

Box Opening - Step 1

Return the χ^2 of the data/MC comparison for a set of diagnostic variables

χ^2 probabilities returned:



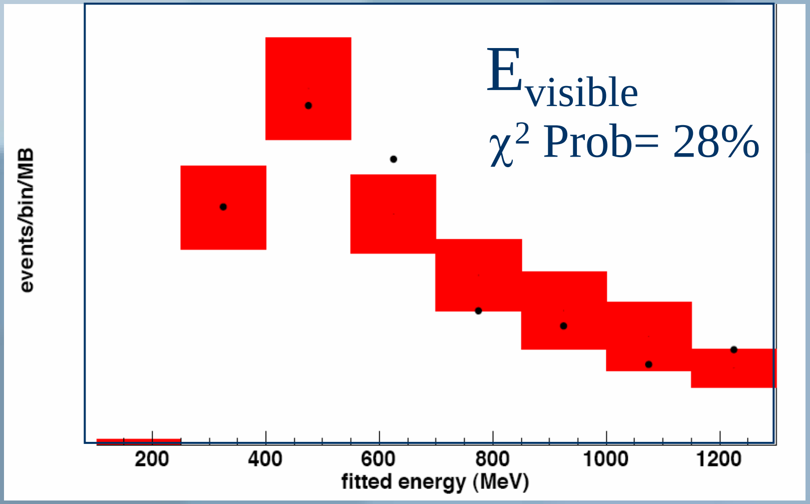


Parameters of the oscillation fit were not returned.
$E_{visible}$ probability is OK.

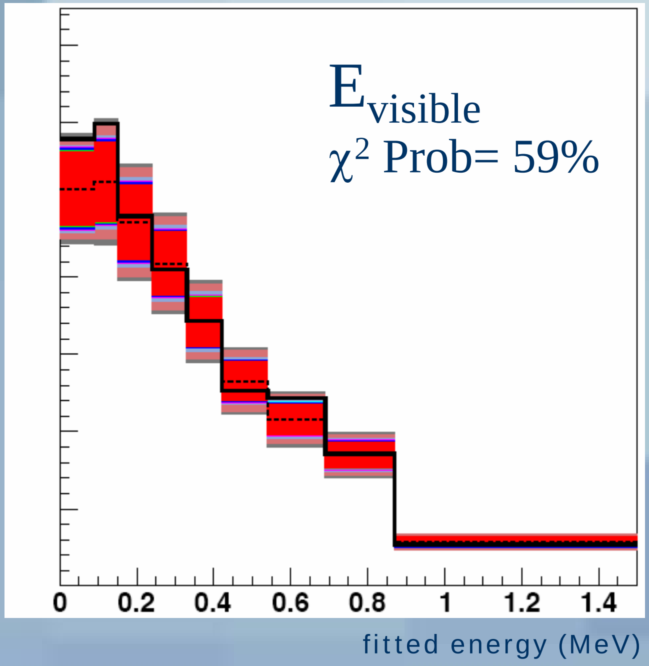
Box Opening - Step 2

Open up the plots from step 1 for approval.

Examples of what we saw:



TB (E_ν^{QE}>475 MeV)



BDT

MC contains fitted signal at unknown level

Box Opening - Step 3

Report the χ^2 for a fit to E_ν^{QE} across full energy range

TB (E_ν^{QE}>475 MeV) χ^2 Probability of fit: 99%
BDT analysis χ^2 Probability of fit: 52%

Leading to...

Step 4

Open the box...

Counting Experiment

The Track-based $\nu_\mu \rightarrow \nu_e$ Appearance-only Result:

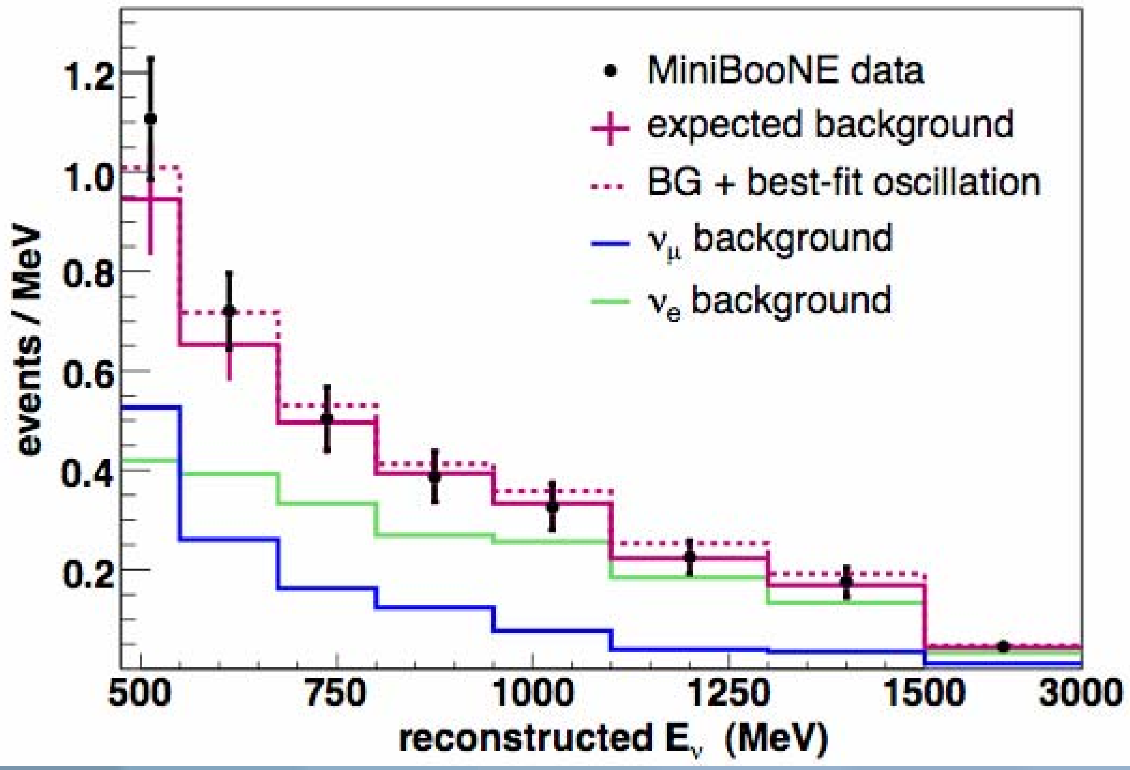
Counting Experiment: $475 < E_\nu^{QE} < 1250$ MeV

data: 380 events
expectation: 358 $\pm$19 (stat) $\pm$ 35 (sys) events

significance:
0.55 σ

Energy Fit

Track Based energy dependent fit results:
Data are in good agreement with background prediction.



Error bars are diagnonals of error matrix.

Fit errors for >475 MeV:
Normalization 9.6%
Energy scale: 2.3%

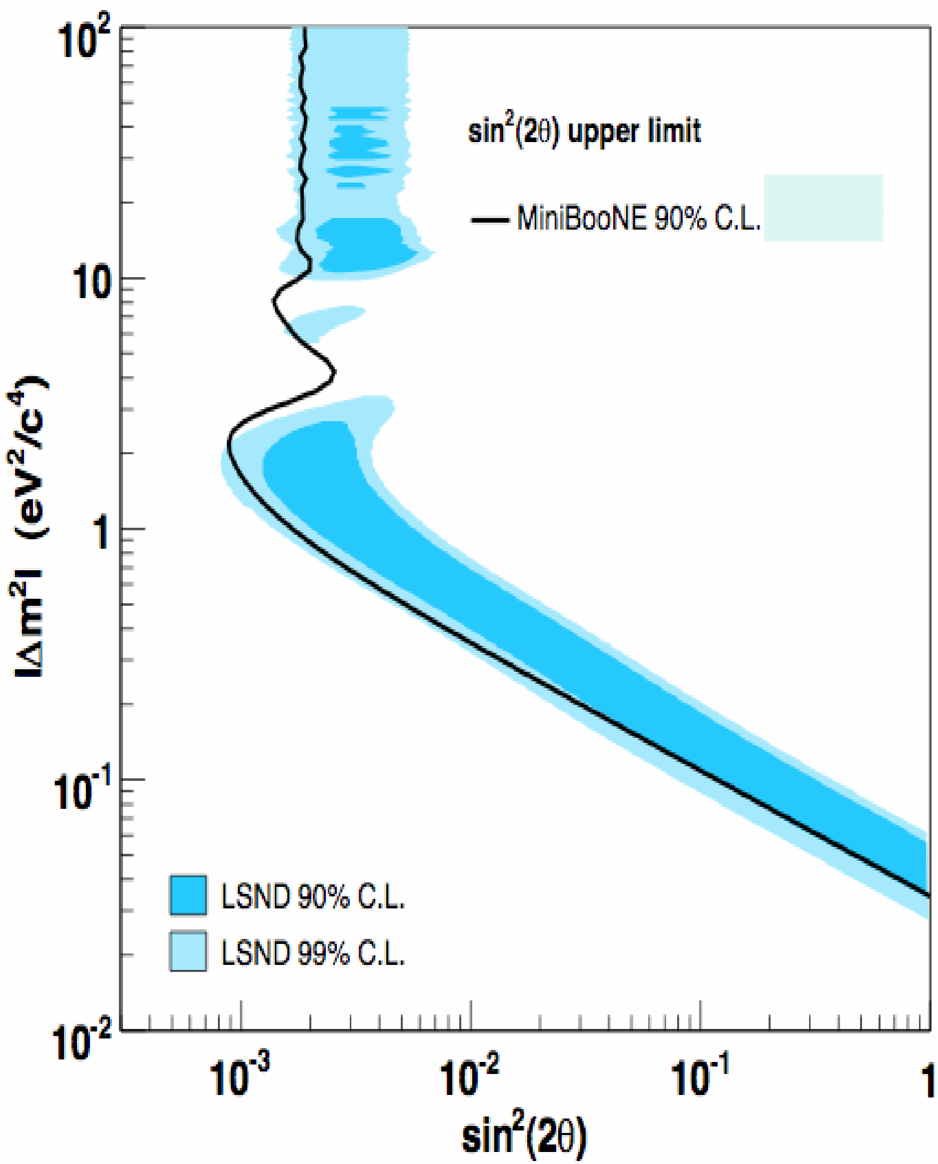
Best Fit (dashed): $(\sin^2 2\theta, \Delta m^2) = (0.001, 4\ eV^2)$

Oscillation Limit

- The result of the $\nu_\mu \rightarrow \nu_e$ appearance-only analysis is a <u>limit</u> on oscillations.

  - χ^2 probability, null hypothesis: 93%

Energy fit: $475 < E_\nu^{QE} < 3000$ MeV



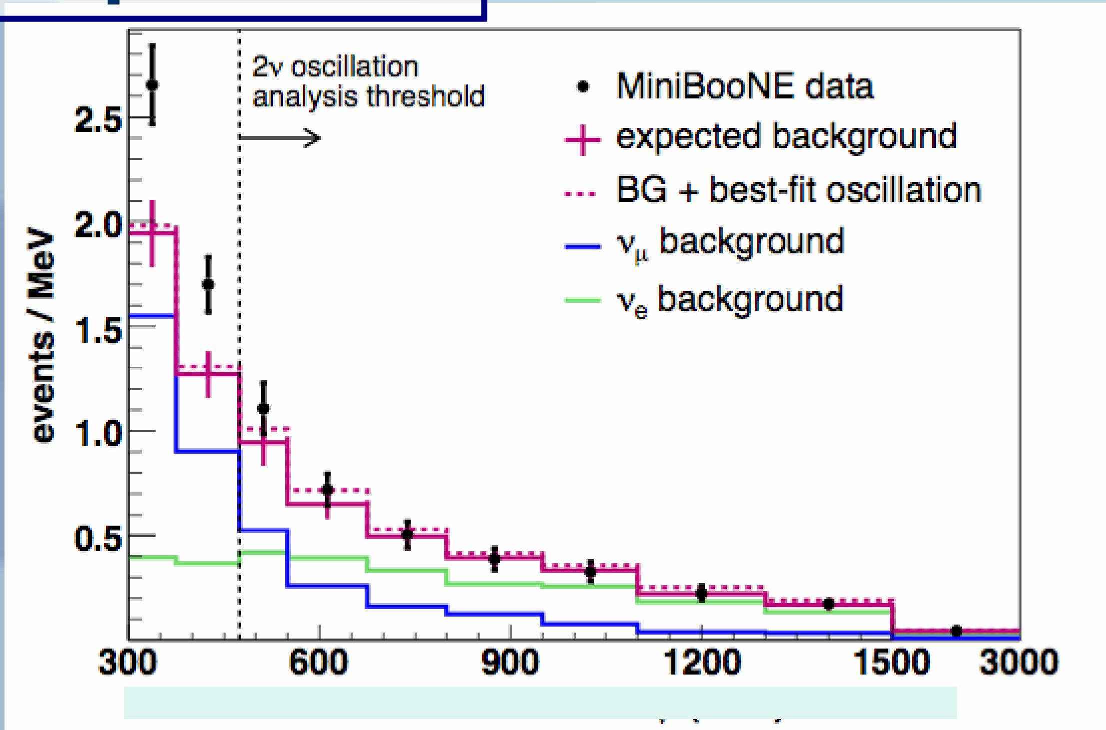
Full Spectrum

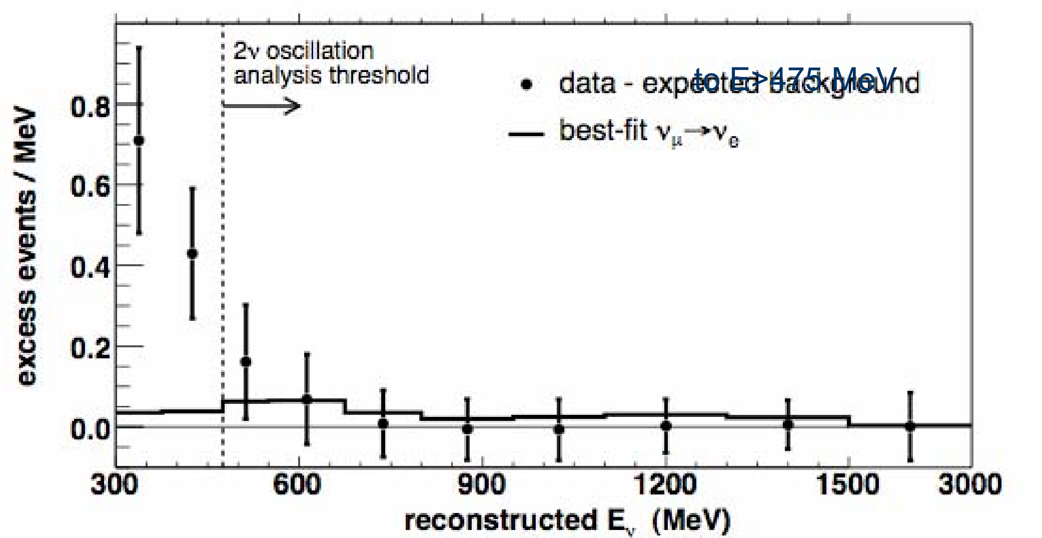
As planned before opening the box....
Report the full range:
$300 < E_\nu^{QE} < 3000$ MeV

96 ± 17 ± 20 events above background,
for $300 < E_\nu^{QE} < 475$ MeV

Deviation: 3.7σ

Background-subtracted:



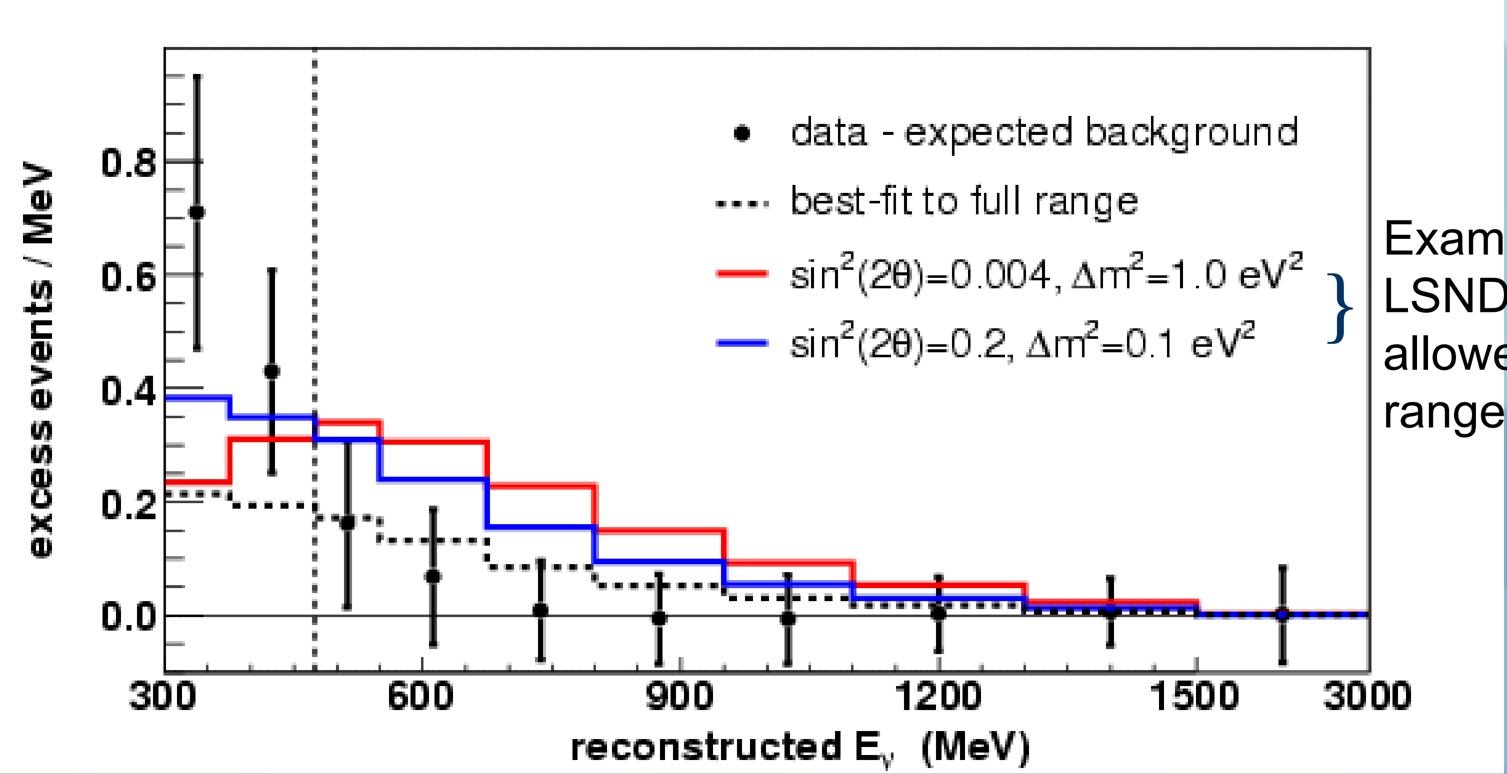


Energy Fit to Full Spectrum

Fit to the > 300 MeV range:

Best Fit (dashed): $(\sin^2 2\theta, \Delta m^2) = (1.0, 0.03\ \text{eV}^2)$

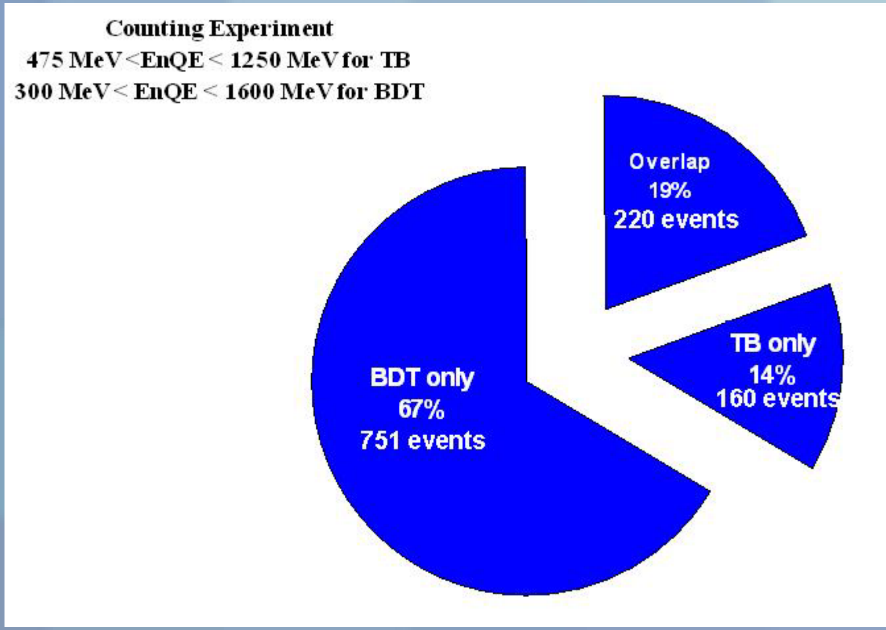
χ^2 Probability: 18%



} Examples in LSND allowed range

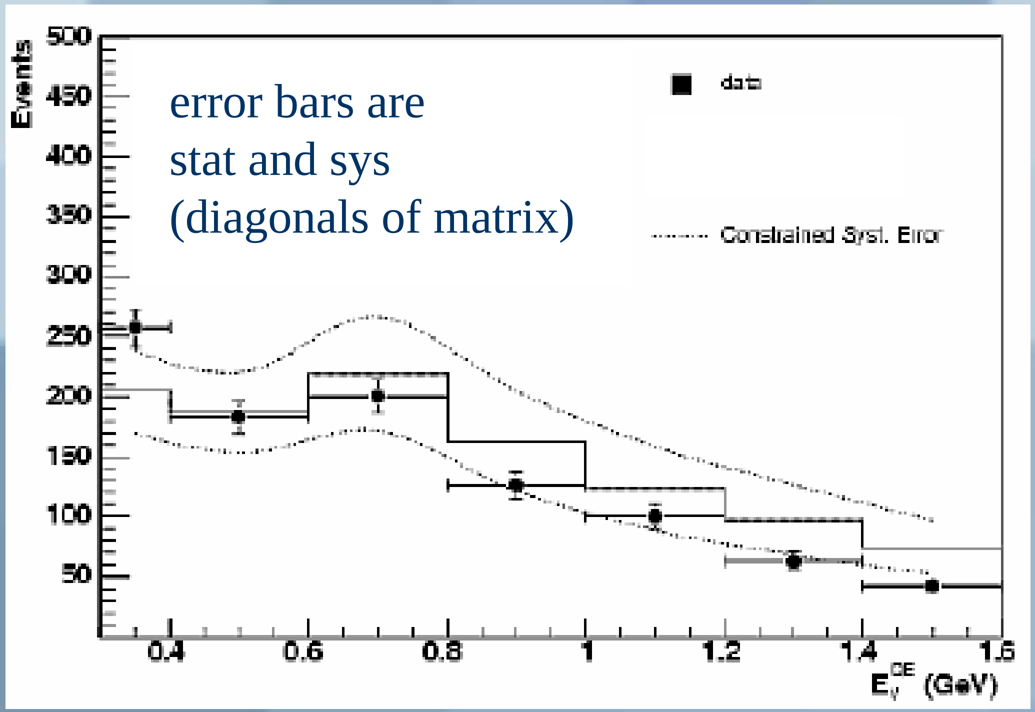
BDT Counting Experiment

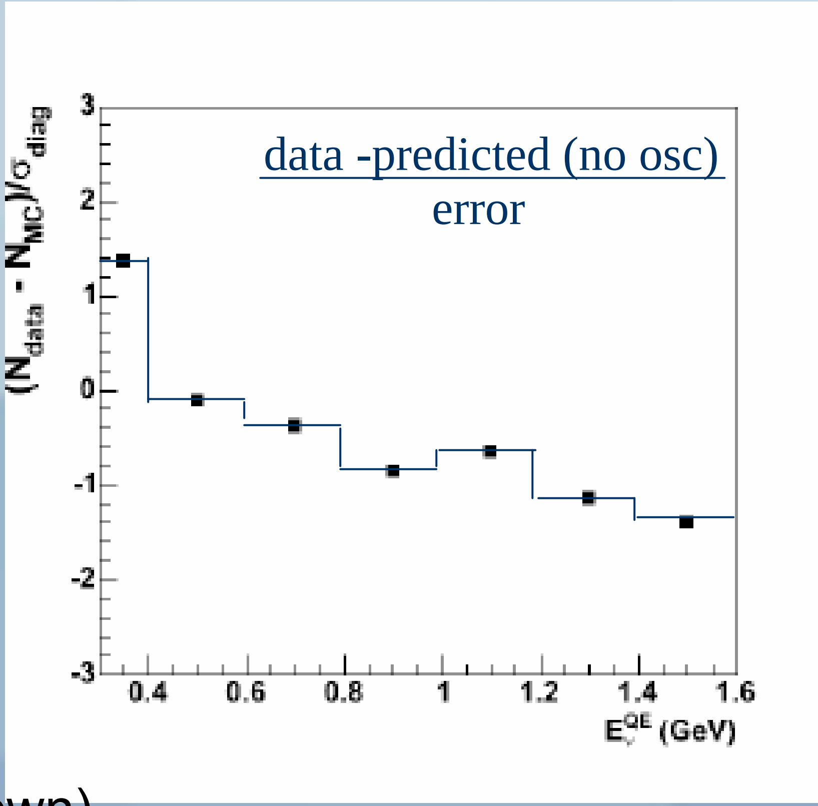
Counting Experiment: $300<E_\nu^{QE}<1600$ MeV
data: 971 events
expectation: 1070 ±33 (stat) ± 225 (sys) events
significance: –0.38 σ



BDT Energy Fit to Full Spectrum

Boosted Decision Tree E_ν^{QE} data/MC comparison:





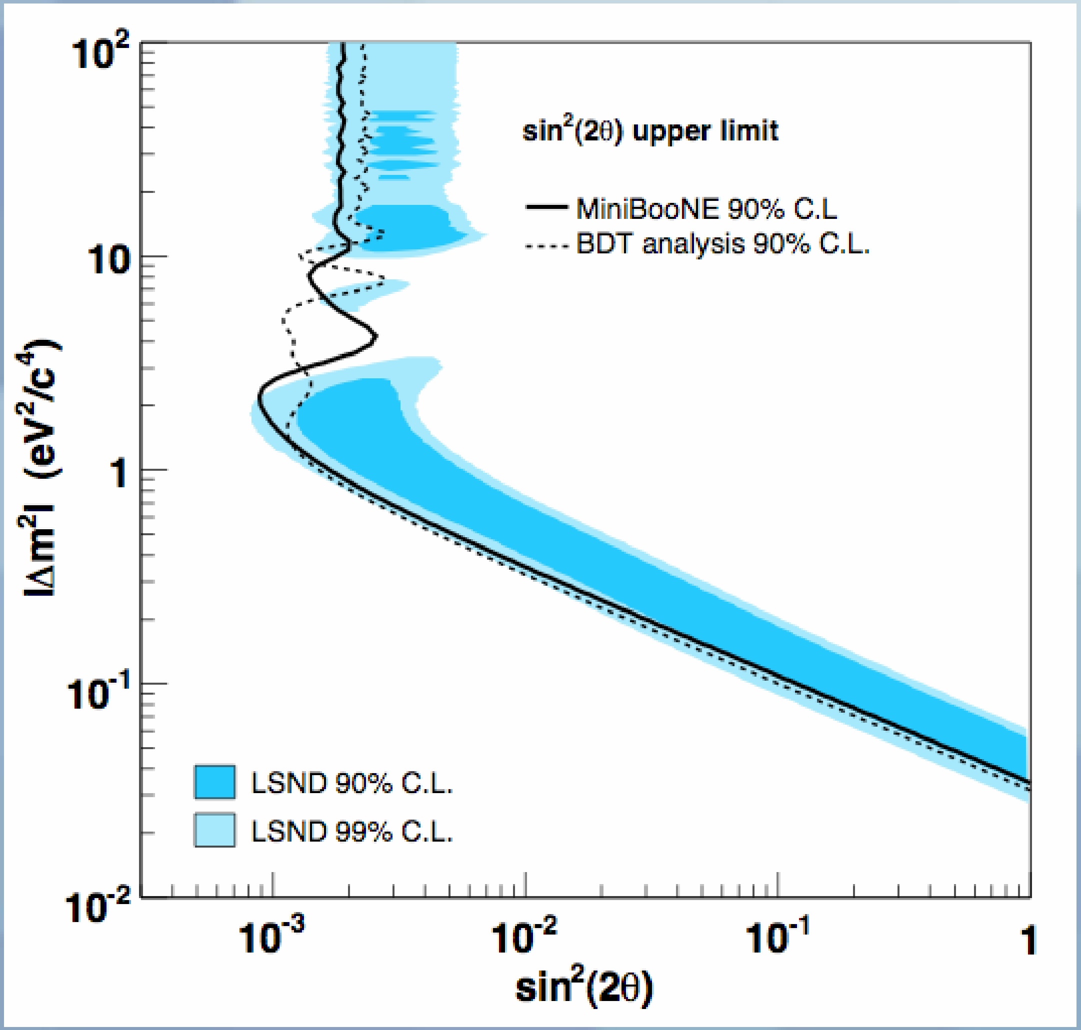
(sidebands used for constraint not shown)

Comparison of the Limits

- Energy-fit analysis:
  solid: TB
  dashed: BDT

- Independent analyses
  are in good agreement.

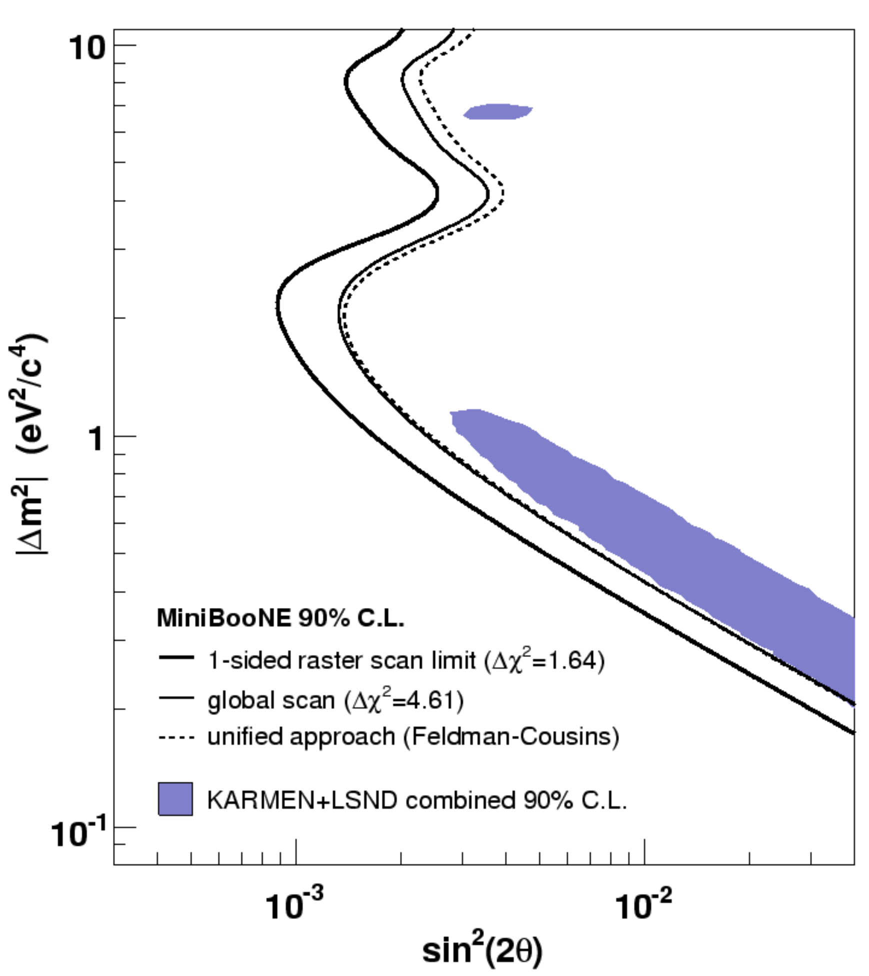
TB is still the primary analysis



Different Limit Definitions

1) There are various ways to present limits:
   - Single sided raster scan (historically used, presented here)
   - Global scan
   - Unified approach (most recent method)

2) This result must be folded into an LSND-Karmen joint analysis.



Church, et al., PRD 66, 013001

We will present a full joint analysis soon.

MiniBooNE-LSND Compatibility Test

$$\chi_0^2 = \frac{(z_{MB} - z_0)^2}{\sigma_{MB}^2} + \frac{(z_{LSND} - z_0)^2}{\sigma_{LSND}^2}$$

- For each Δm^2, determine the MB and LSND measurement:

  $z_{MB} \pm \delta z_{MB}$, $z_{LSND} \pm \delta z_{LSND}$

  where $z = \sin^2(2\theta)$ and δz is the 1σ error

- For each Δm^2, form χ^2 between MB and LSND measurement

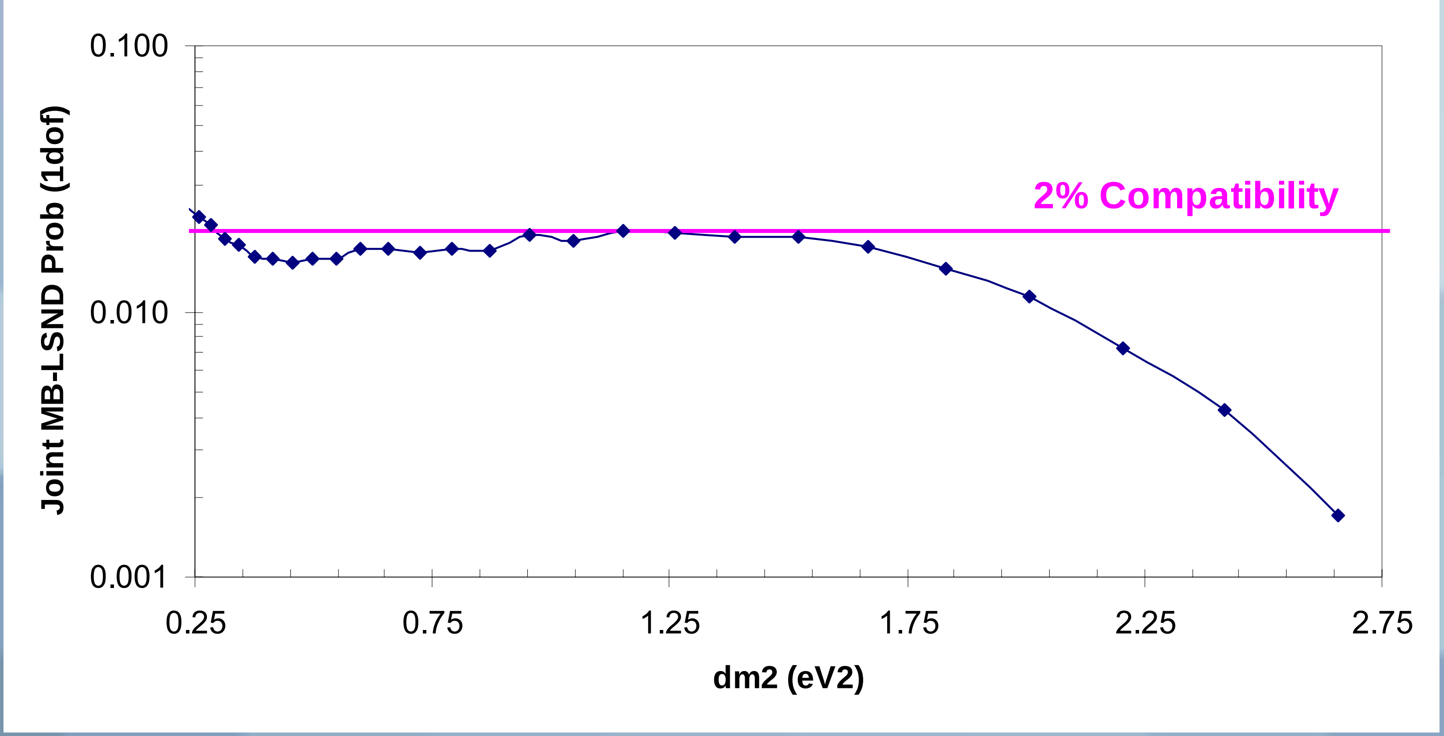
- Find z_0 that minimizes χ^2

  (weighted average of two measurements) and this gives χ^2_{min}

- Find probability of χ^2_{min} for 1 dof;

  this is the joint compatibility probability for this Δm^2

MiniBooNE-LSND Compatibility



MiniBooNE is incompatible with a $\nu_\mu \rightarrow \nu_e$ appearance only interpretation of LSND at 98% CL

Future

Many more papers supporting this analysis will follow,
in the very near future:

ν_μ CCQE production
π^0 production
MiniBooNE-LSND-Karmen joint analysis

We are pursuing further analyses of the neutrino data,
including...

an analysis which combines TB and BDT,
more exotic models for the LSND effect.

MiniBooNE is presently taking data in antineutrino mode.

Conclusions

- The observed reconstructed energy distribution is inconsistent with a $\nu_\mu \rightarrow \nu_e$ appearance-only model
- Therefore we set a limit on ν_μ->ν_e appearance

- Data show discrepancy vs. background at low energies, but spectrum is inconsistent with two-neutrino oscillation.