First Results from MiniBooNE

Byron Roe
for the MiniBooNE Collaboration

The MiniBooNE Collaboration

A. A. Aguilar-Arevalo, A. O. Bazarko, S. J. Brice, B. C. Brown,
L. Bugel, J. Cao, L. Coney, J. M. Conrad, D. C. Cox, A. Curioni,
Z. Djurcic, D. A. Finley, B. T. Fleming, R. Ford, F. G. Garcia,
G. T. Garvey, J. A. Green, C. Green, T. L. Hart, E. Hawker,
R. Imlay, R. A. Johnson, P. Kasper, T. Katori, T. Kobilarcik,
I. Kourbanis, S. Koutsoliotas, J. M. Link, Y. Liu, Y. Liu,
W. C. Louis, K. B. M. Mahn, W. Marsh, P. S. Martin, G. McGregor,
W. Metcalf, P. D. Meyers, F. Mills, G. B. Mills, J. Monroe,
C. D. Moore, R. H. Nelson, P. Nienaber, S. Ouedraogo,
R. B. Patterson, D. Perevalov, C. C. Polly, E. Prebys, J. L. Raaf,
H. Ray, B. P. Roe, A. D. Russell, V. Sandberg, R. Schirato,
D. Schmitz, M. H. Shaevitz, F. C. Shoemaker, D. Smith, M. Sorel,
P. Spentzouris, I. Stancu, R. J. Stefanski, M. Sung, H. A. Tanaka,
R. Tayloe, M. Tzanov, M. O. Wascko, R. Van de Water, D. H. White,
M. J. Wilking, H. J. Yang, G. P. Zeller, E. D. Zimmerman

University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle University
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

74 people, 16 Institutions

Michigan MiniBooNE People

- Prof. Byron P. Roe
- Assis. Res. Sci. Hai-jun Yang (2003-present)
  (PI LANL/DOE grant 2005-now)
- Res. Fellow Jun Cao (2001-2003)
  (now at IHEP, Beijing)
- Res. Fellow Yan Liu (2002-2004)
  (now at Henry Ford Hospital, Detroit)
- 7 REU students since 2001

Some Major Michigan Contributions to MiniBooNE

- Event reconstruction and about ½ particle ID variables used
- Particle ID based on Boosted Decision Trees (3 NIM papers)
- Identifying and mitigating “dirt events”, a major background
- Muon monitoring in hadron shield
- Helping understand secondary particles in beamline
- Work on fluxes of neutrinos at detector
- Statistical problems (multisims, non-gaussian behavior, etc.– 2 Phys. Rev. and 1 NIM paper)
- 38 of the 223 MiniBooNE technical notes

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

Neutrino Oscillations

- Direct measurements have difficulty probing small neutrino masses

  $\Rightarrow$ *Use neutrino oscillations*

- If we postulate:
  - Neutrinos have (different) mass
  - The ***Weak Eigenstates*** are a mixture of ***Mass Eigenstates***

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

Then a pure ν_μ beam at t=0, will develop a ν_e component with time.

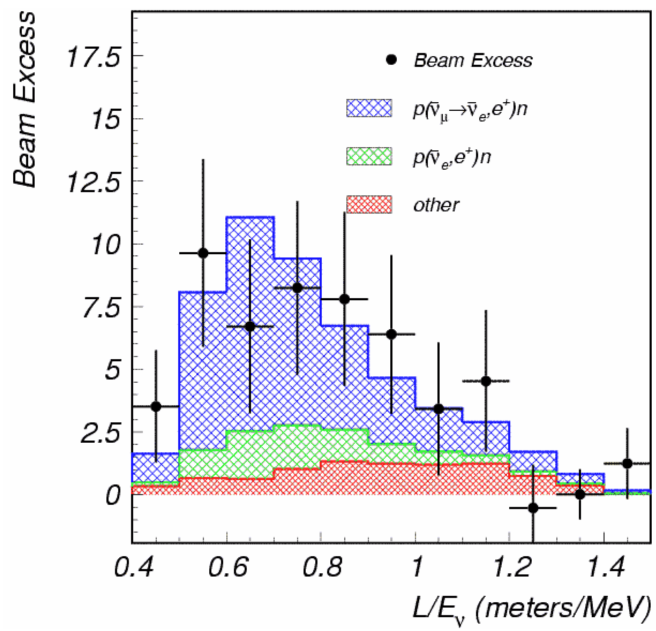
The Probability for Oscillations...

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

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

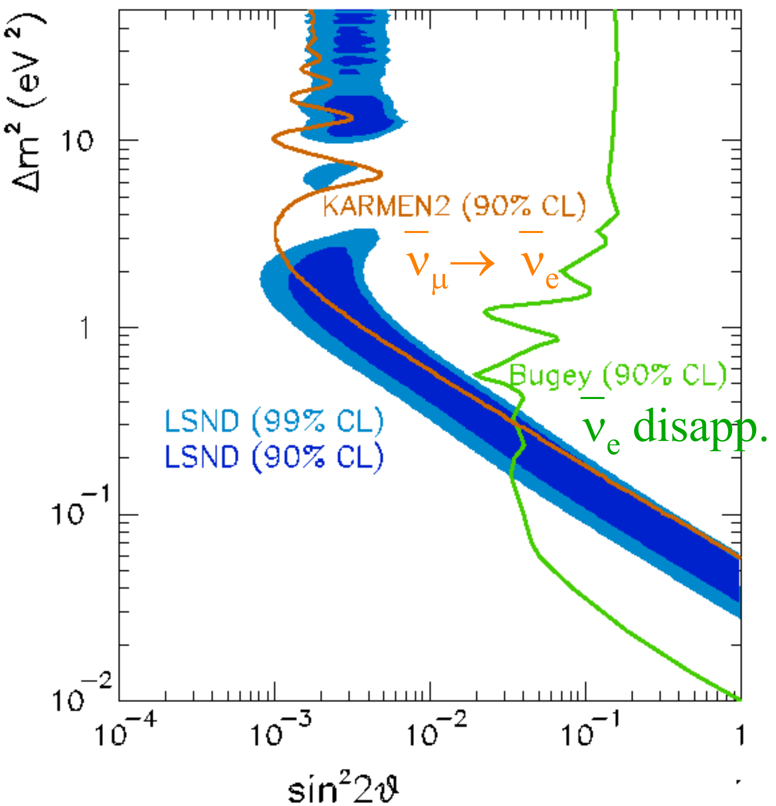
Within a $\nu_\mu \to \nu_e$ appearance model

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

mixing angle

squared mass difference

travel distance / energy of the neutrinos



This model allows comparison to other experiments:

Karmen2

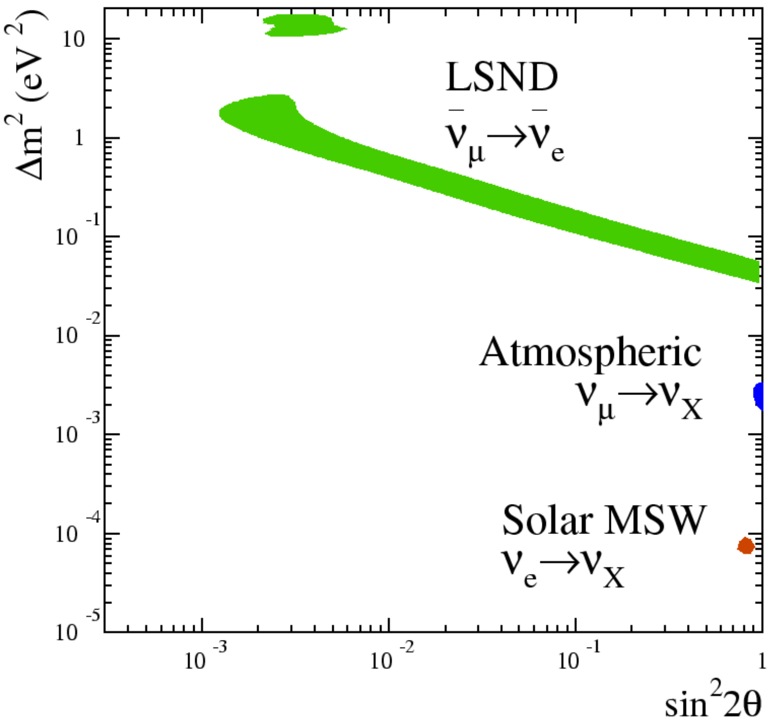
Bugey

Joint analysis with Karmen2:
64% compatible

Church, et al., PRD 66, 013001

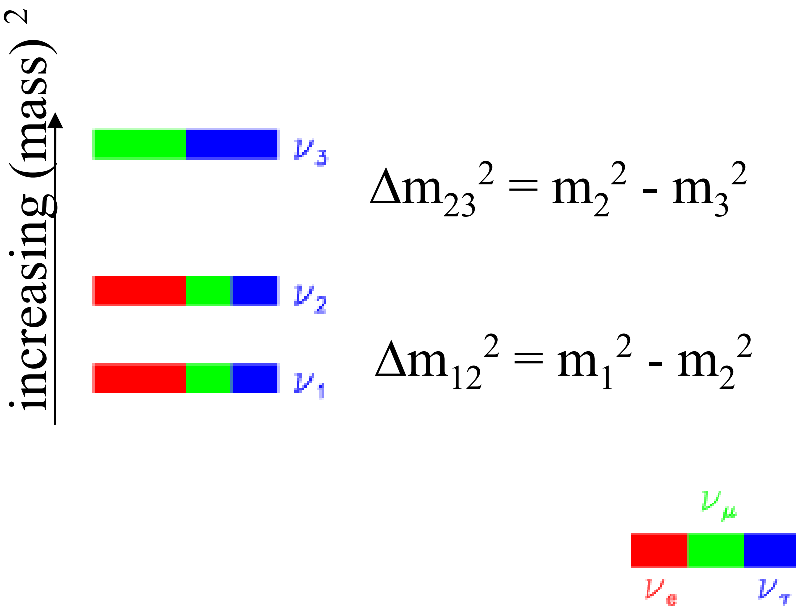
This is a simplistic interpretation.

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



A 3 neutrino picture requires

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



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:

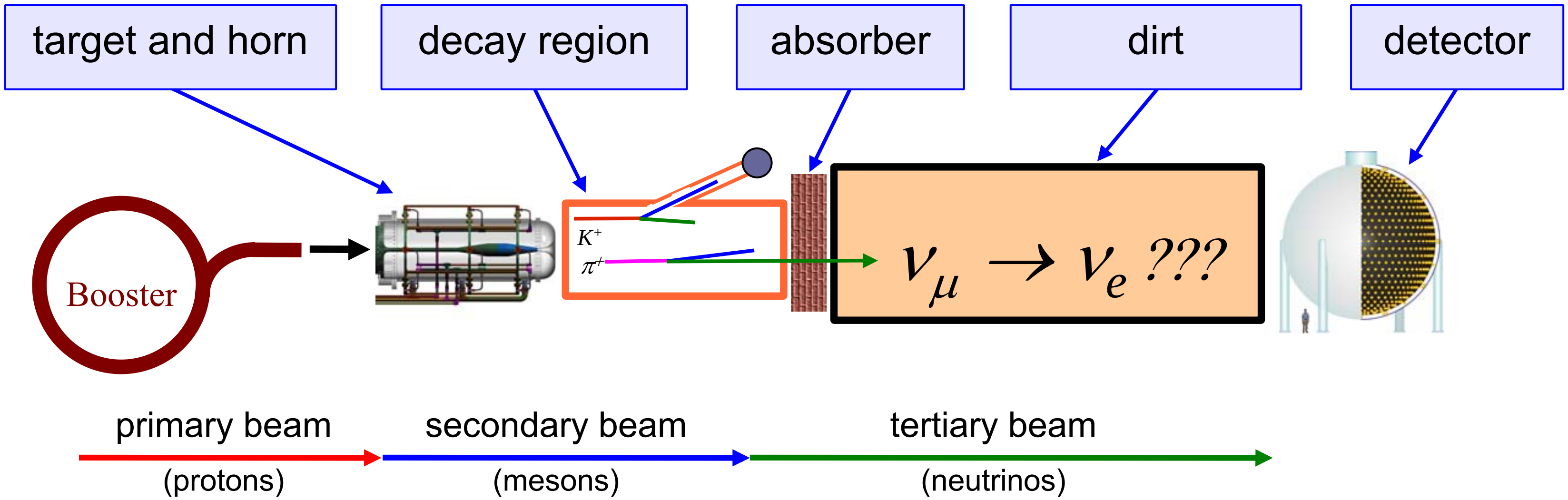
- This is the simplest model which explains LSND.

- 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

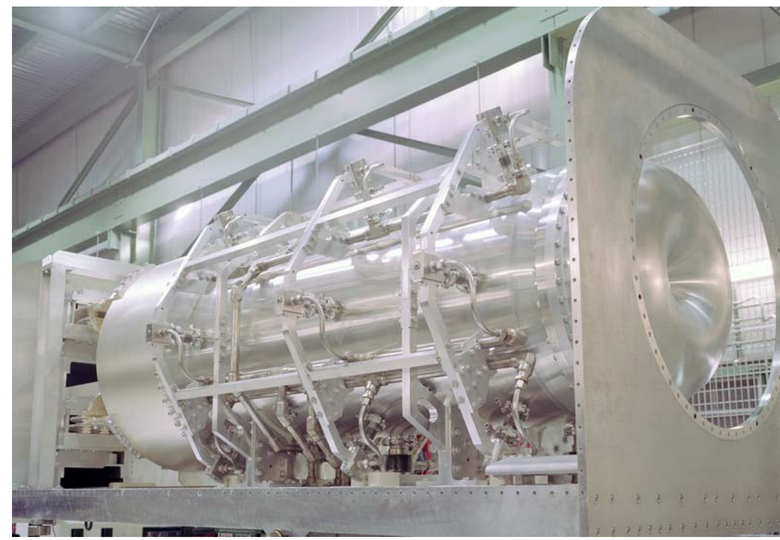
This was a blind analysis.
The box was opened on March 26, 2007

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



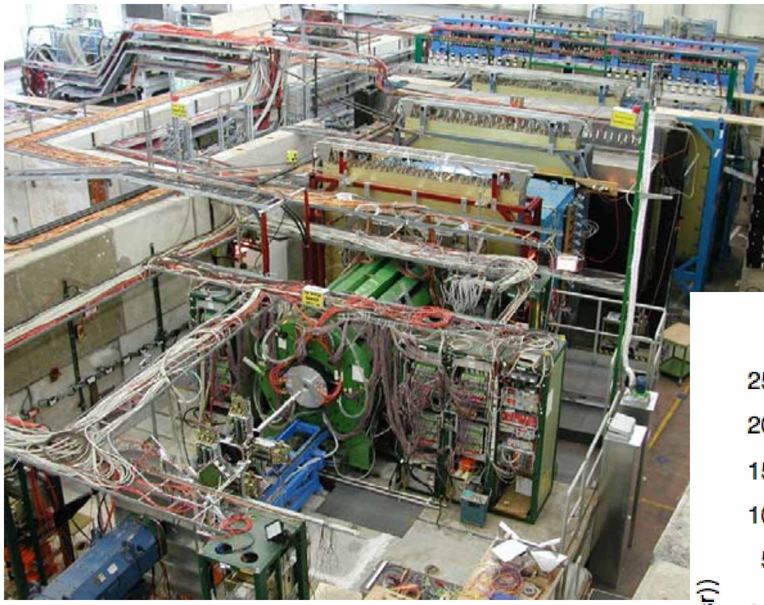
4 $\times 10^{12}$ protons per 1.6 μs pulse delivered at up to 5 Hz.

6.3 $\times 10^{20}$ POT delivered.

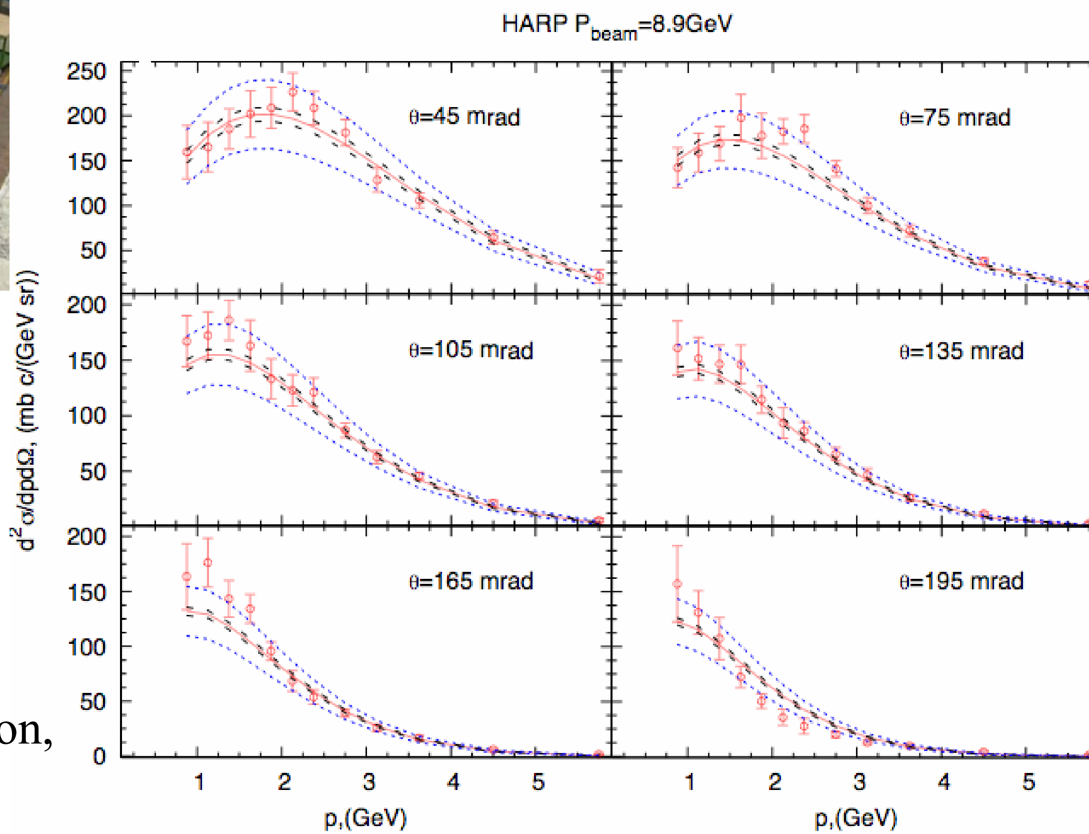
Results correspond to (5.58±0.12) $\times 10^{20}$ POT

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

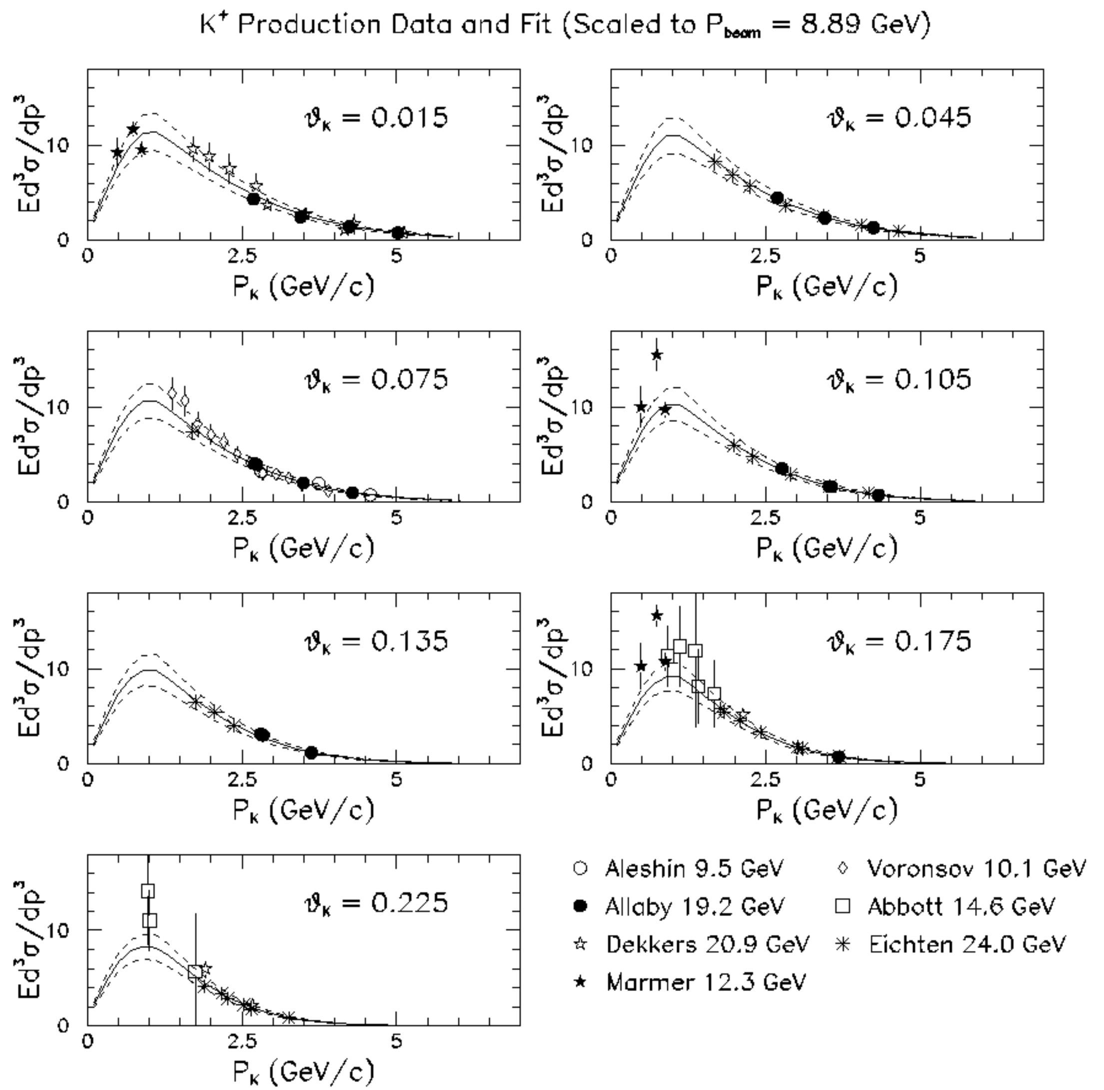
Modeling Production of Secondary Kaons

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

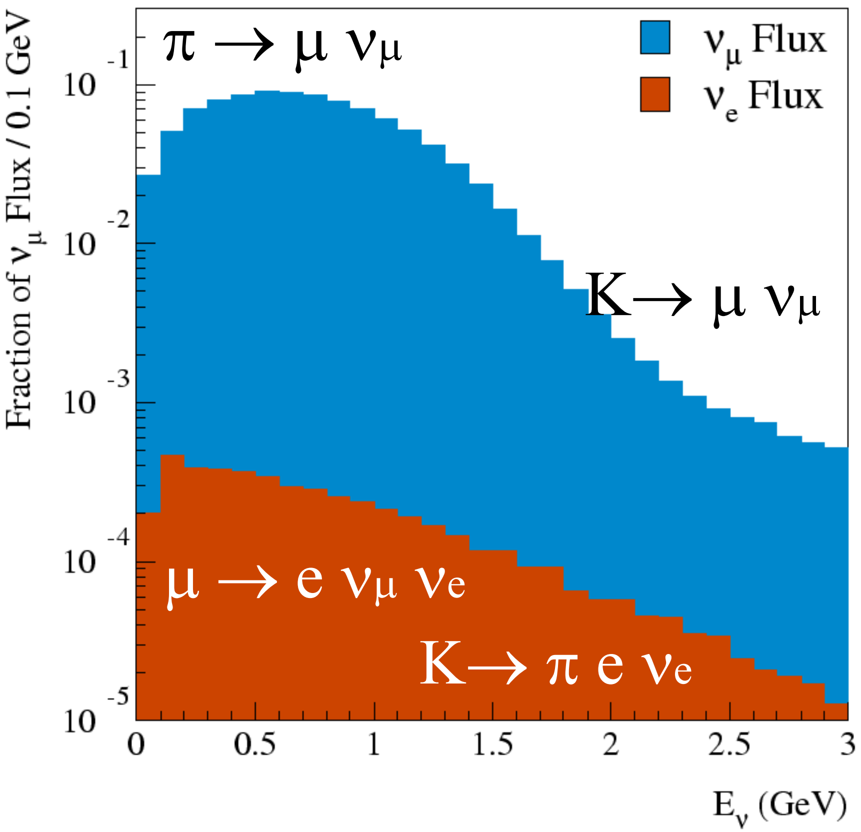
data -- points
dash --total error
(fit ⊕ parameterization)

K^0 data are also parameterized.

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



Neutrino Flux from GEANT4 Simulation



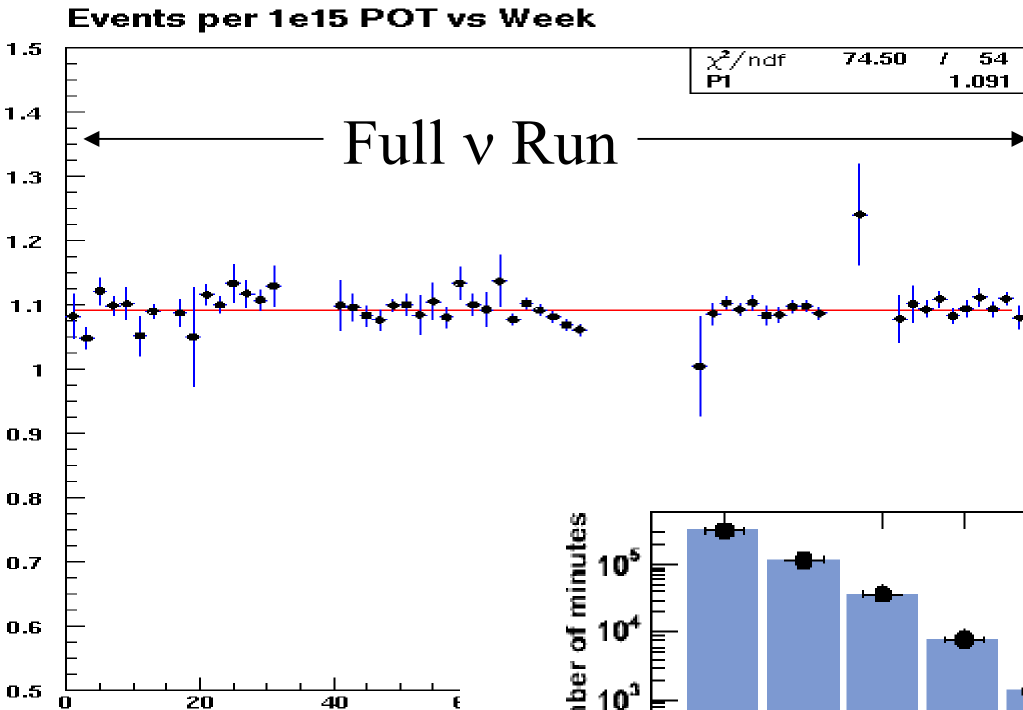
"Intrinsic" $\nu_e + \bar{\nu}_e$ sources:

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

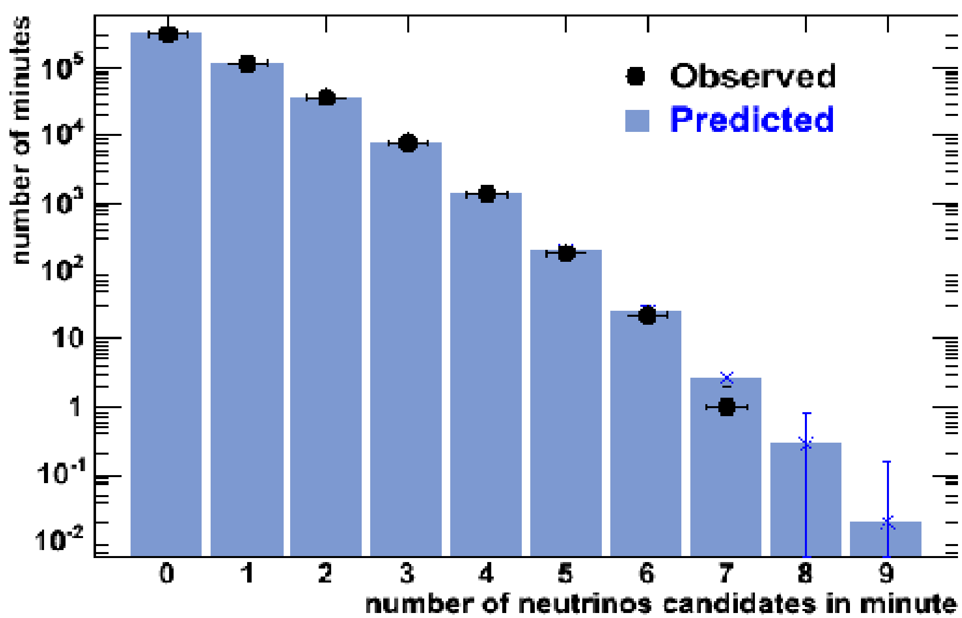
$\nu_e/\nu_\mu = 0.5\%$

Antineutrino content: 6%

Stability of running:

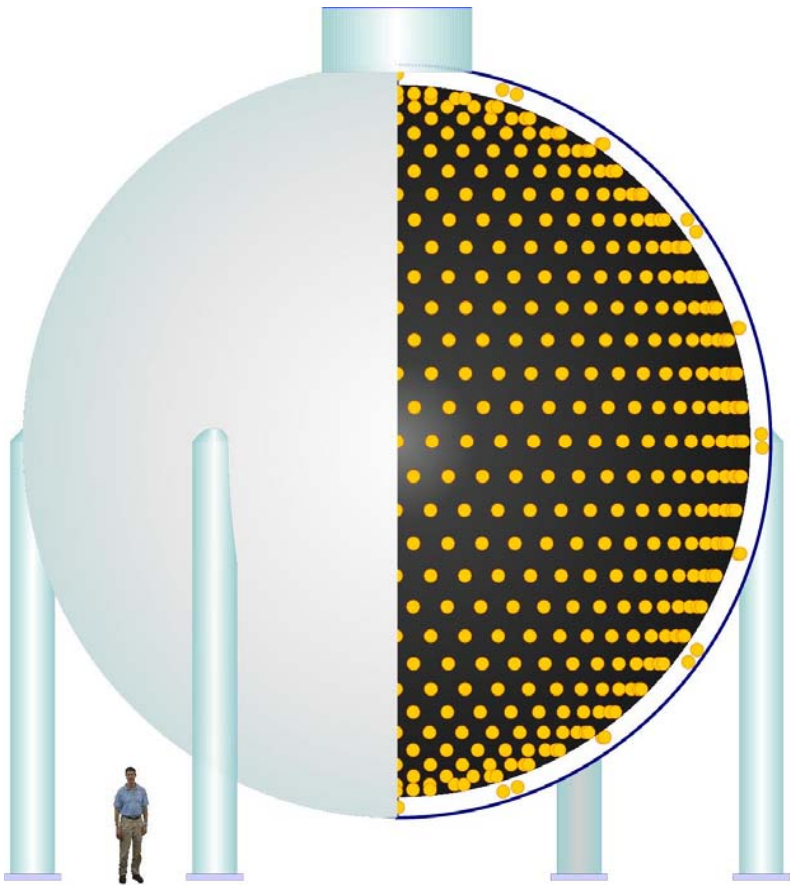


Observed and expected events per minute



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

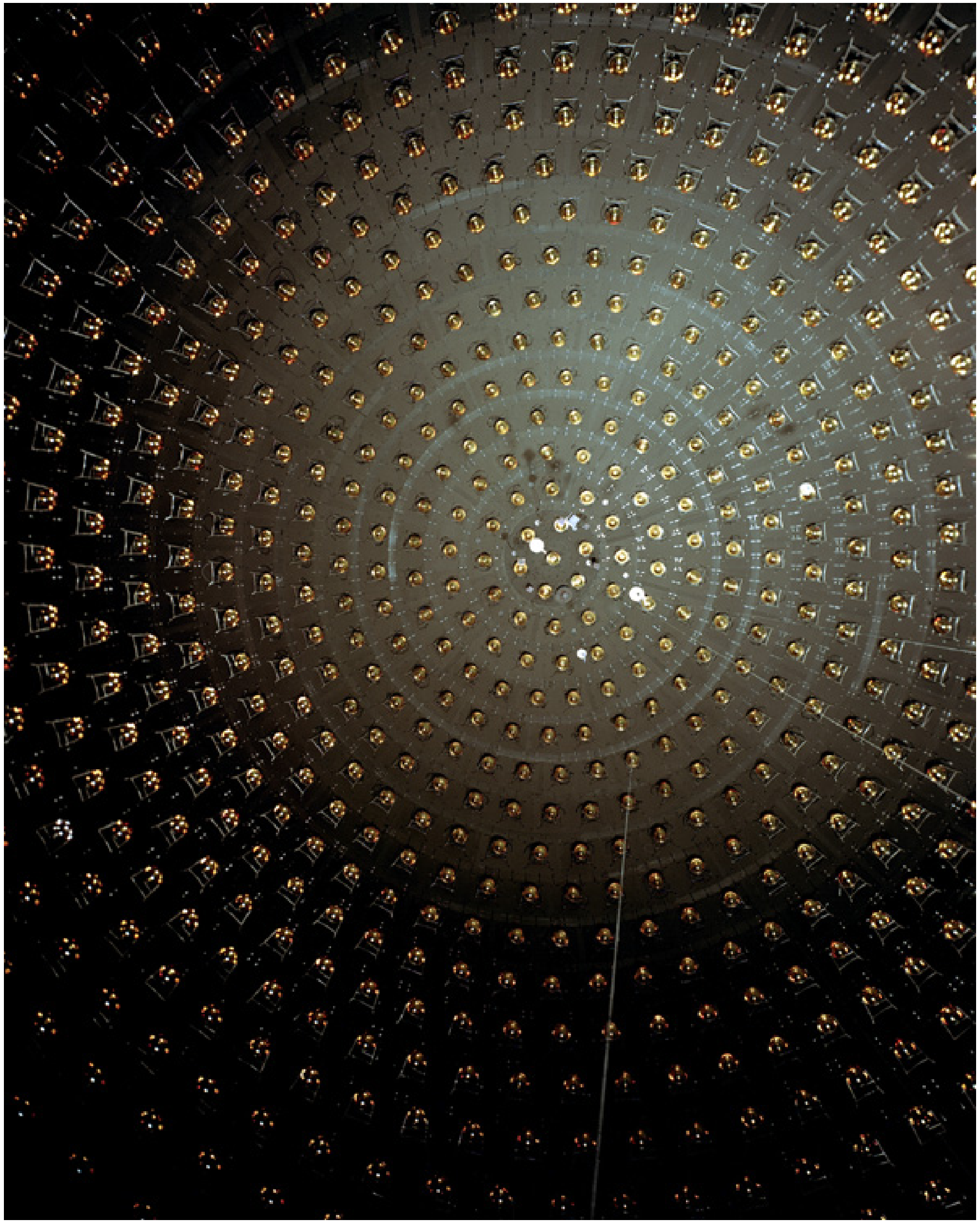
    of pure mineral oil (CH_2)

    (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

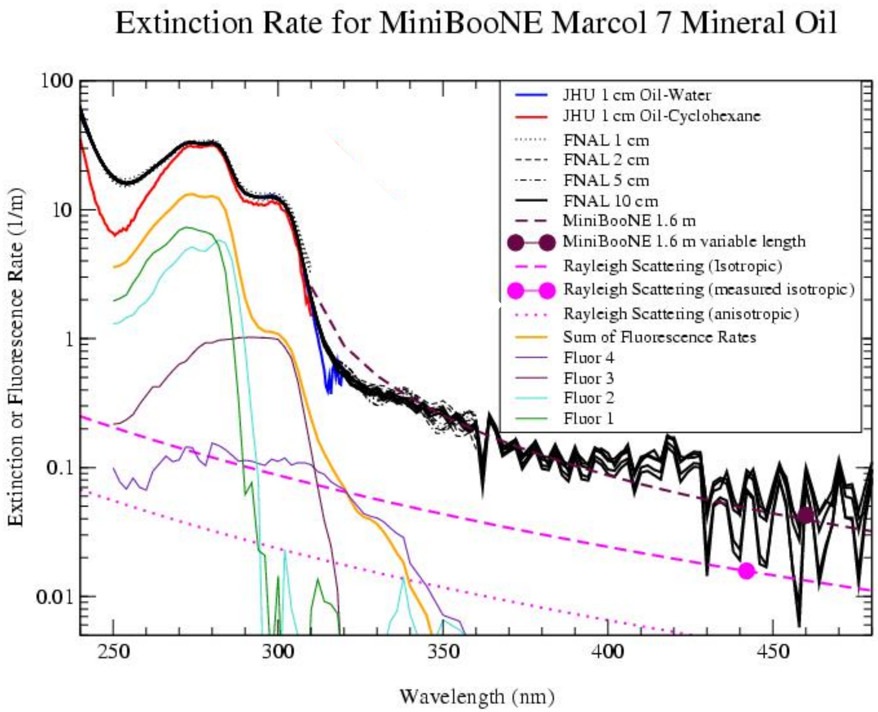
Detected photons from

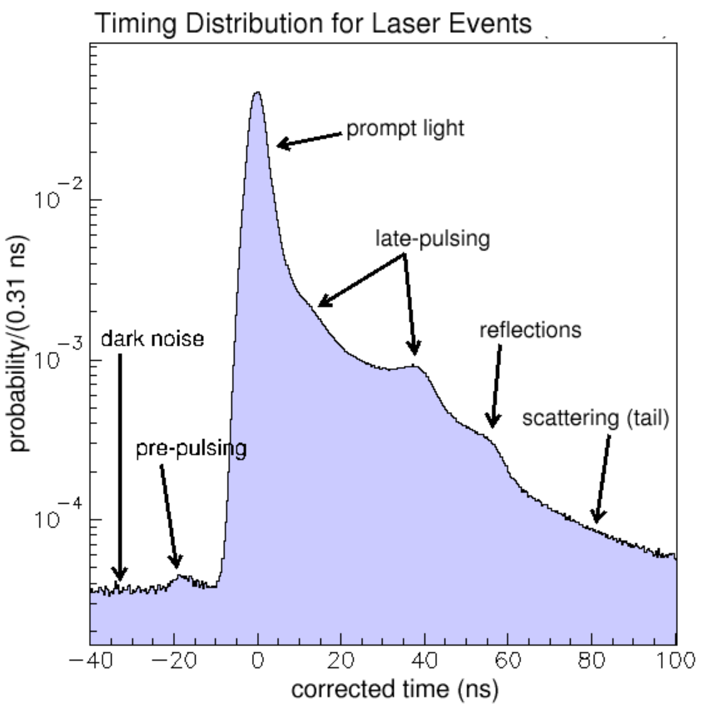
• Prompt light (Cherenkov)

• 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



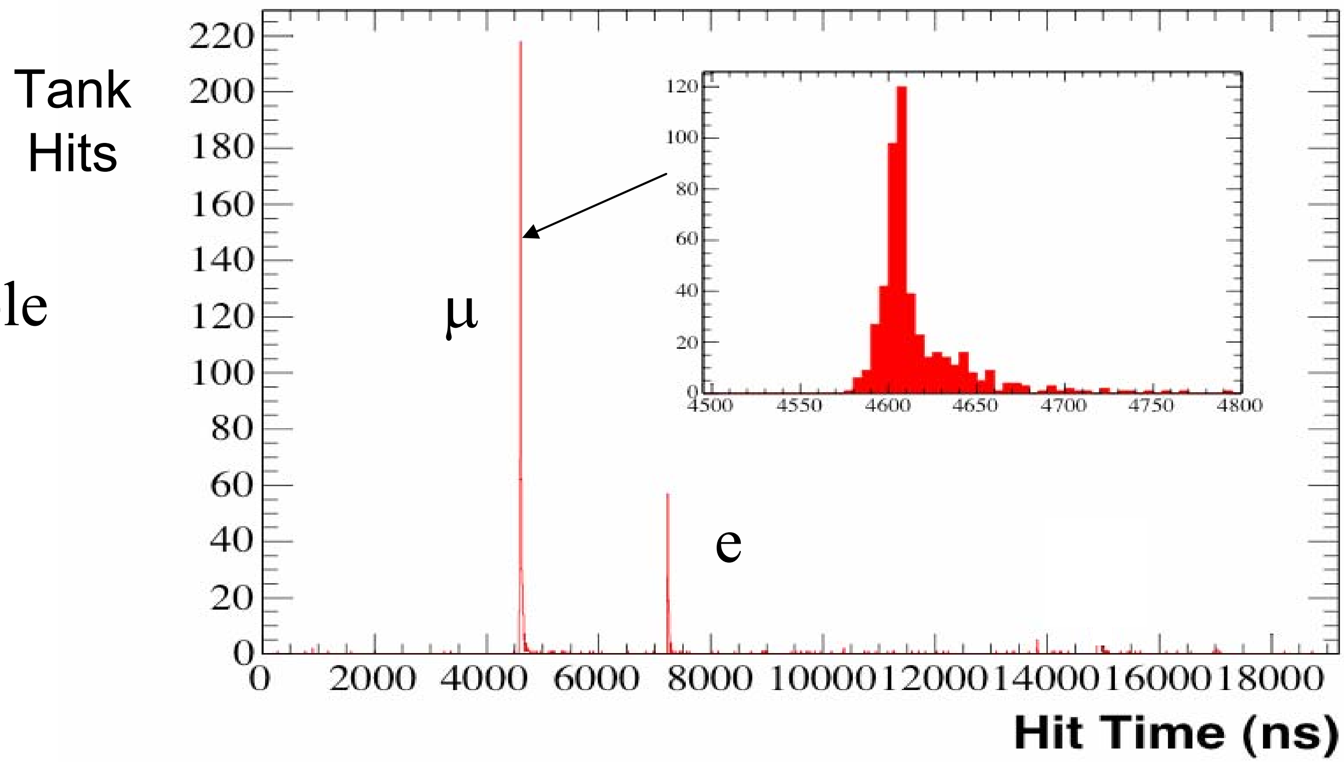


A 19.2 μs beam trigger window encompasses the 1.6 μs spill

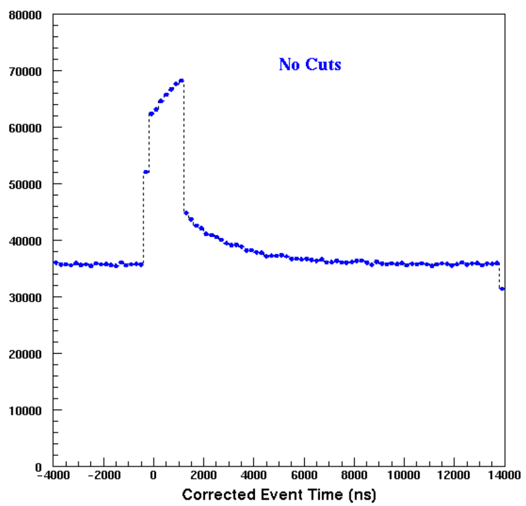
Multiple hits within a ~100 ns window form "subevents"

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

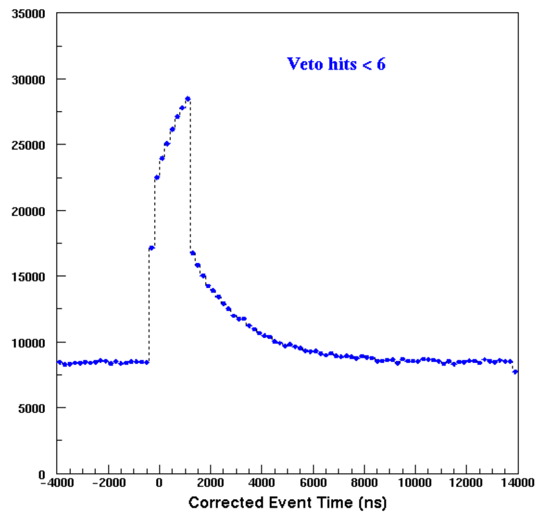
Example
Event



Progressively introducing cuts on the time window:

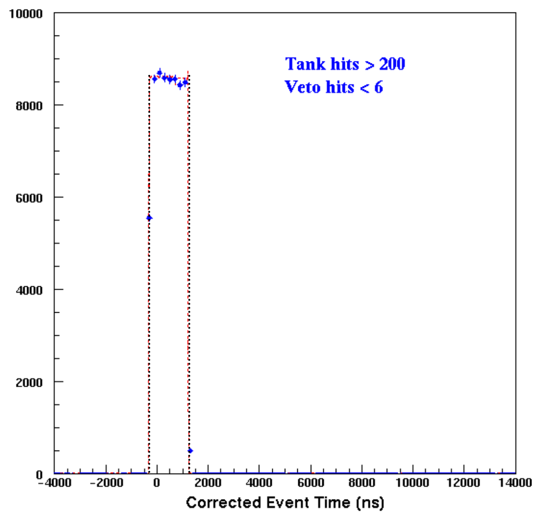


Raw data



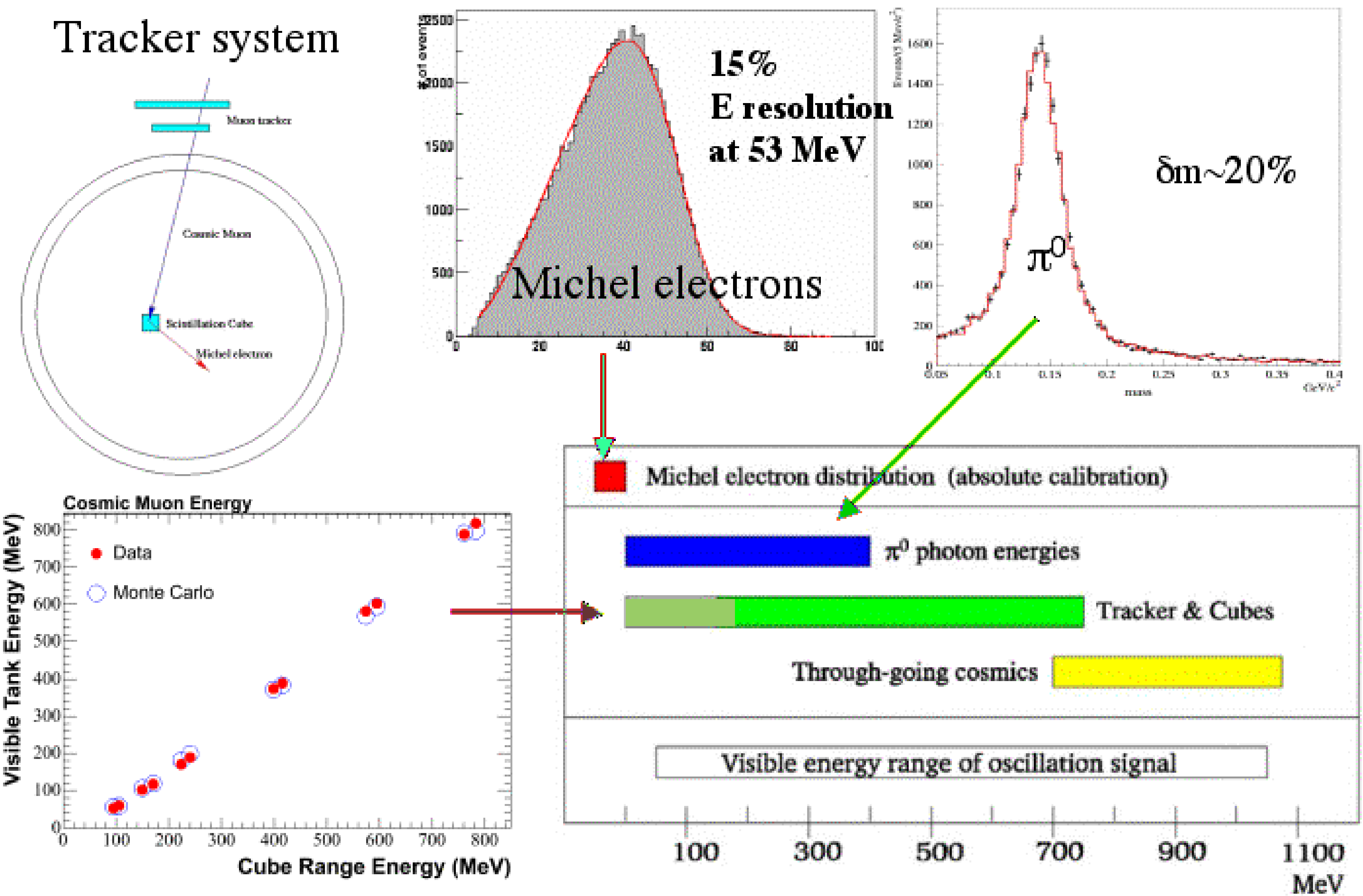
Veto<6 removes through-going cosmics

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



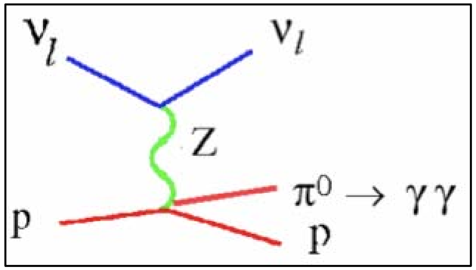
Tank Hits > 200 (equivalent to energy) removes Michel electrons, which have 52 MeV endpoint

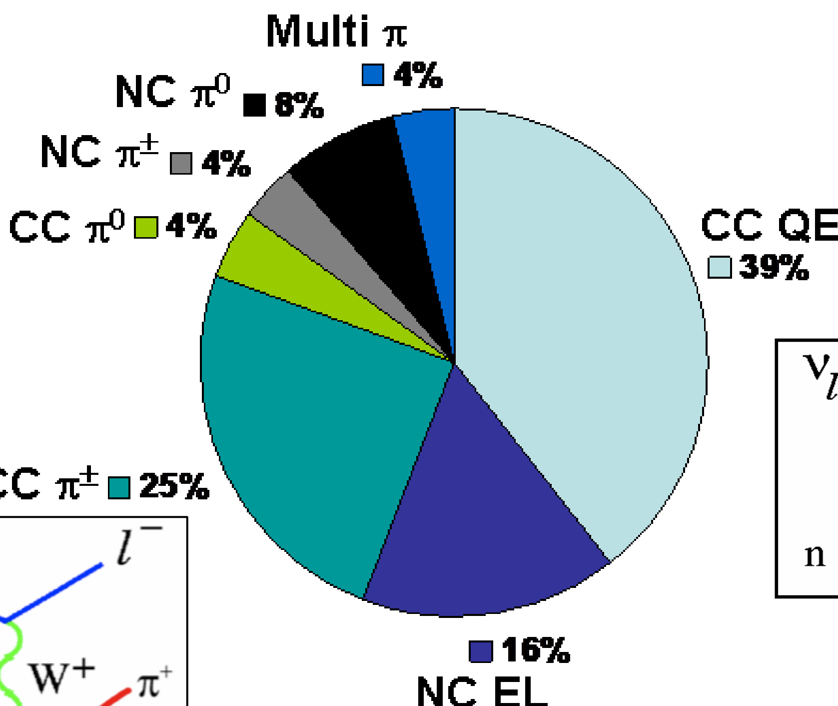
Calibration Sources

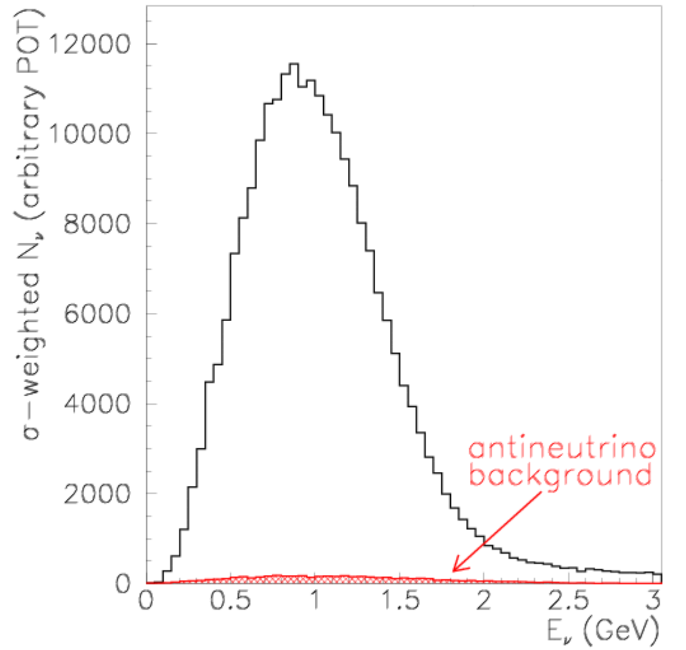


Predicted event rates before cuts (NUANCE Monte Carlo)

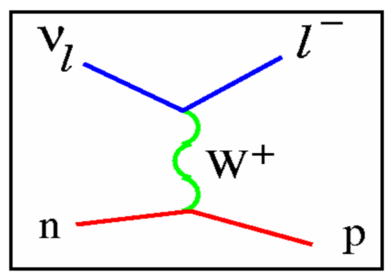
D. Casper, NPS, 112 (2002) 161

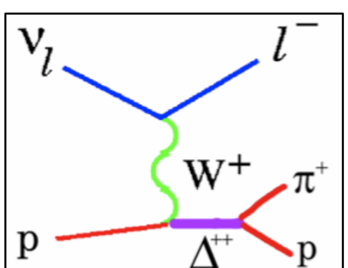






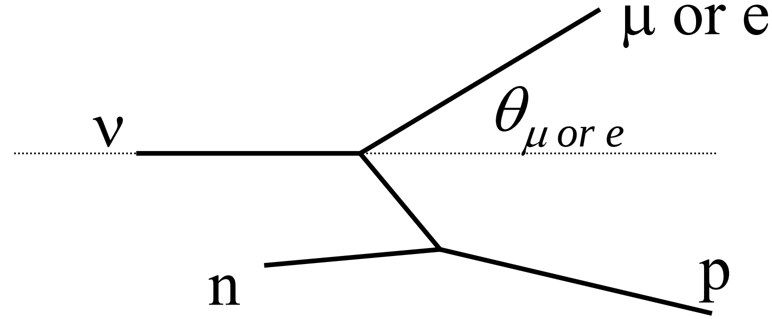
Event neutrino energy (GeV)





CCQE

(Charged Current Quasi-Elastic)

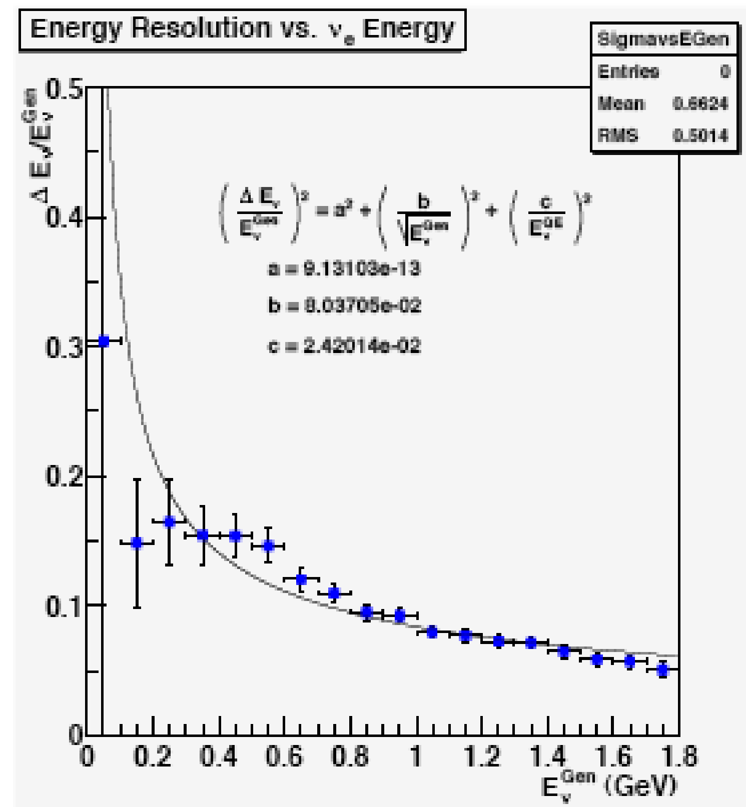


39% of total

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

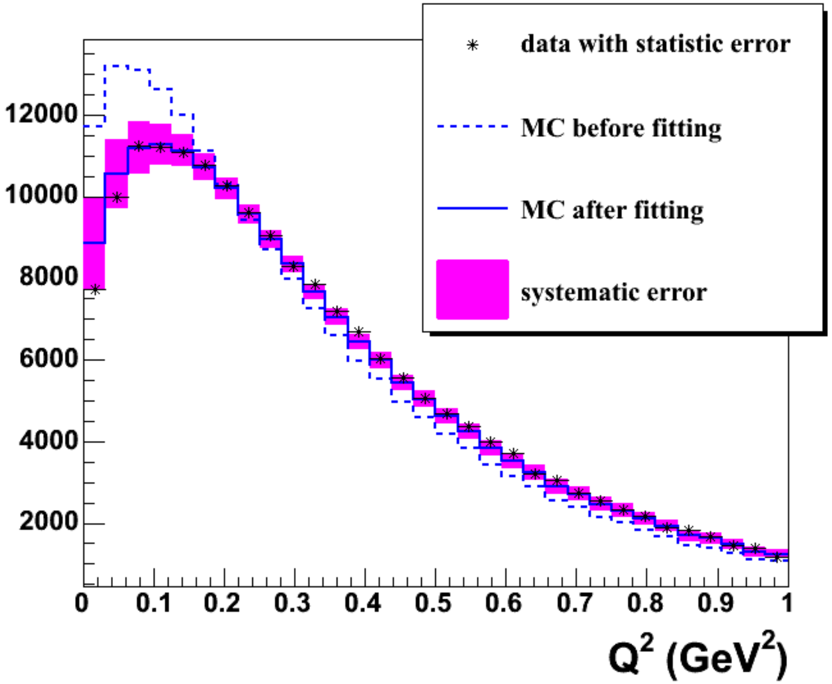
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}cos\theta_\ell}$$

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:



From Q^2 fits to MB ν_μ CCQE data:

M_A^{eff} -- effective axial mass

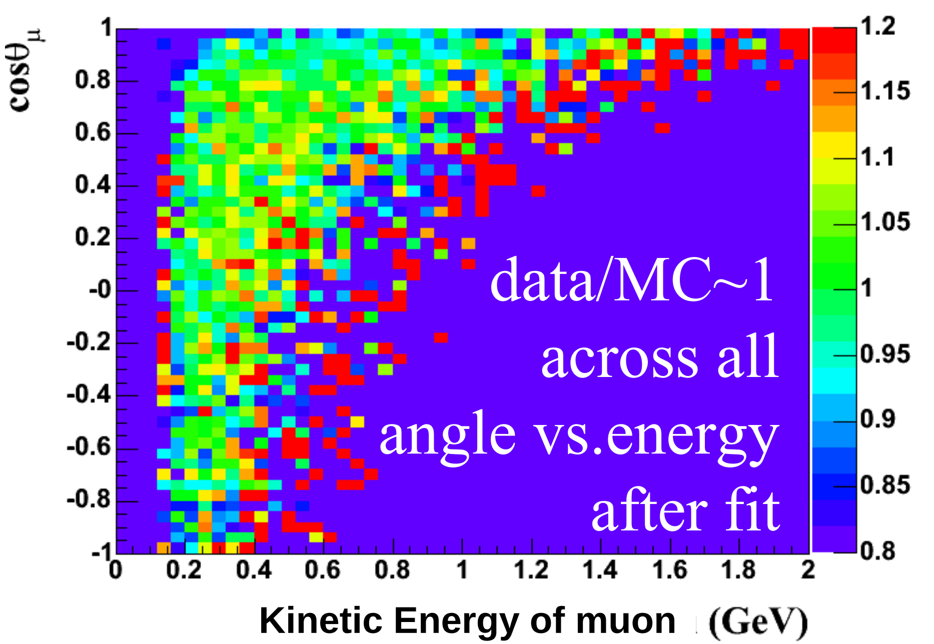
E_{lo}^{SF} -- Pauli Blocking parameter

From electron scattering data:

E_b -- binding energy

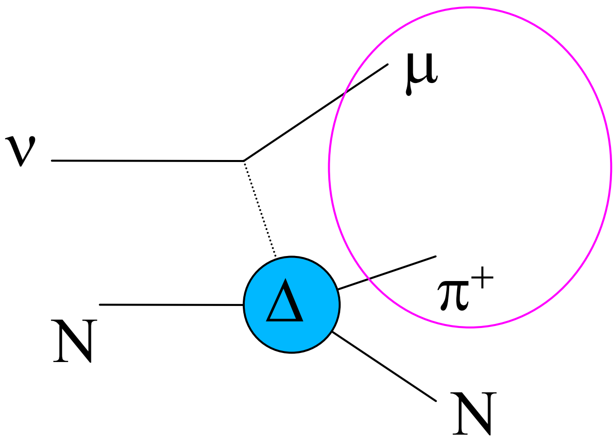
p_f -- Fermi momentum

Model describes CCQE ν_μ data well



Events producing pions

25%

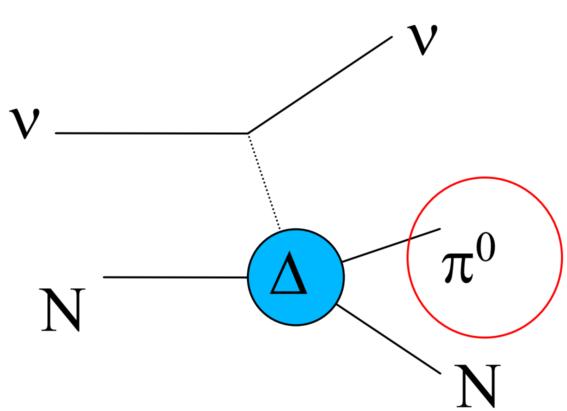


CCπ$^+$

Easy to tag due to 3 subevents.

Not a substantial background to the oscillation analysis.

8%



NCπ^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)

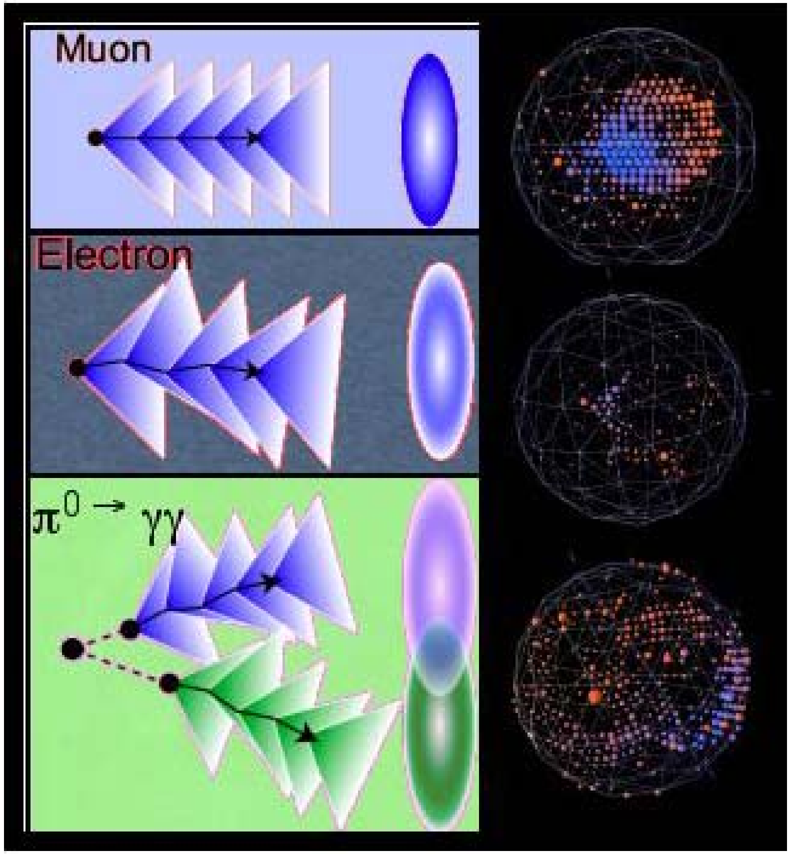
<1% of π^0 contribute to background.

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

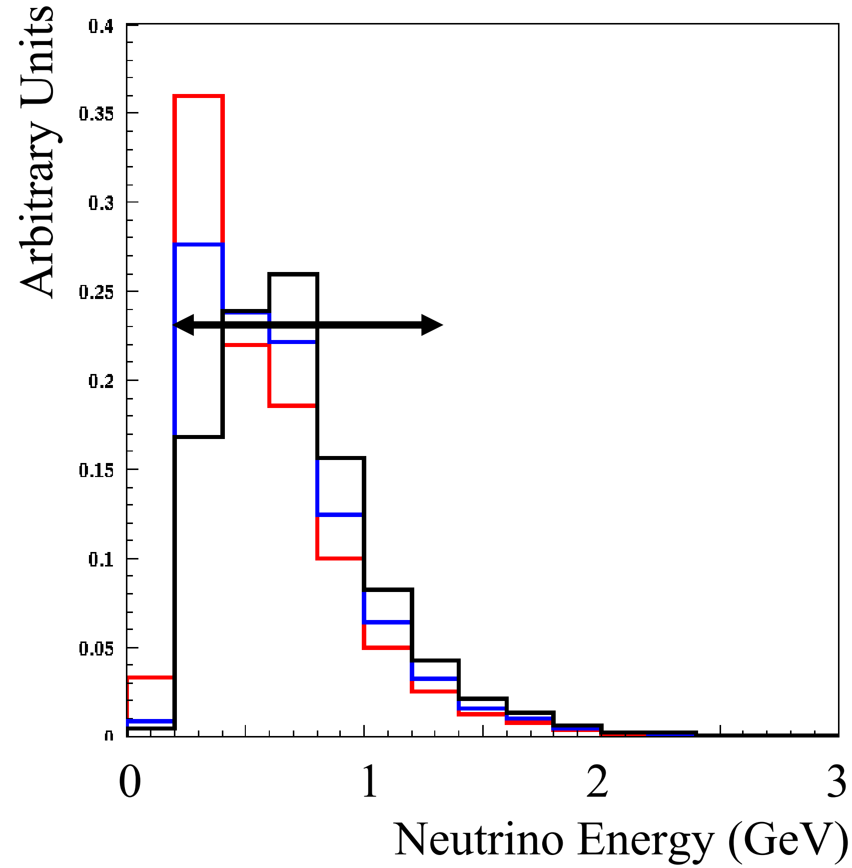
The goal of both analyses:

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

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

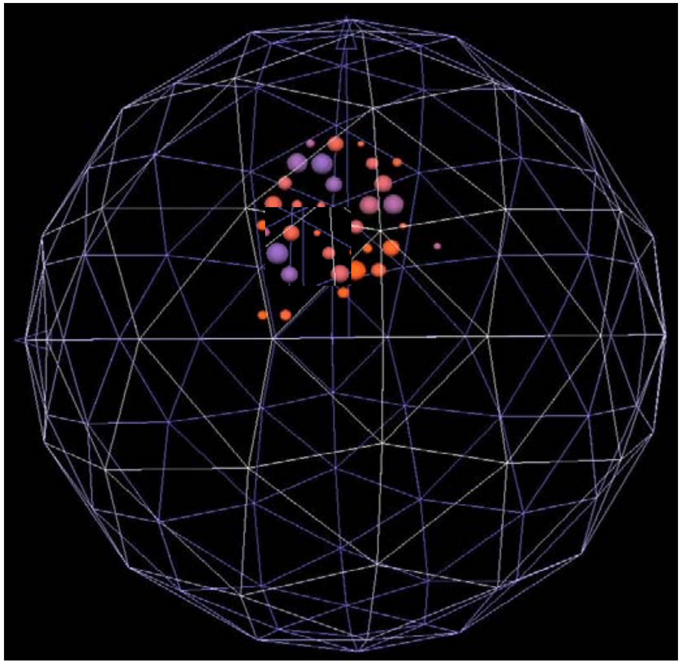
One can then either:

- 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

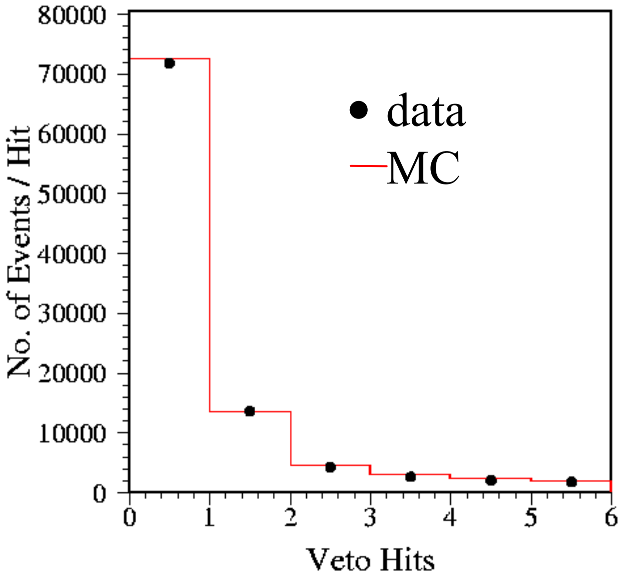
Low level information which did not allow particle-id was available for all events.

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

Only 1 subevent

Veto hits < 6

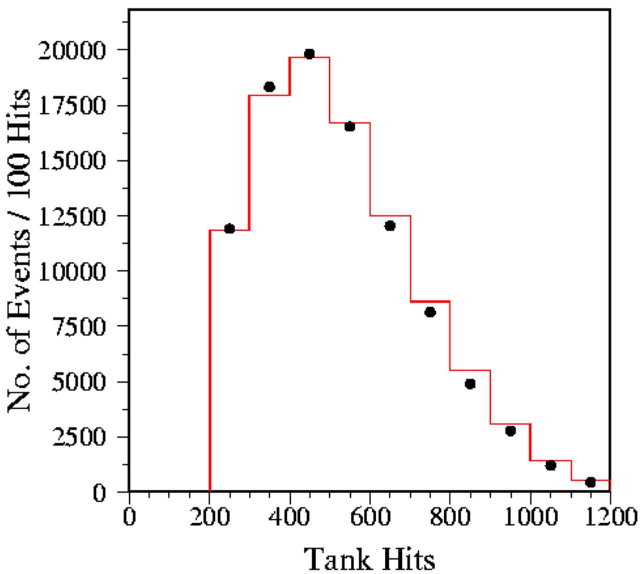
Tank hits > 200



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"

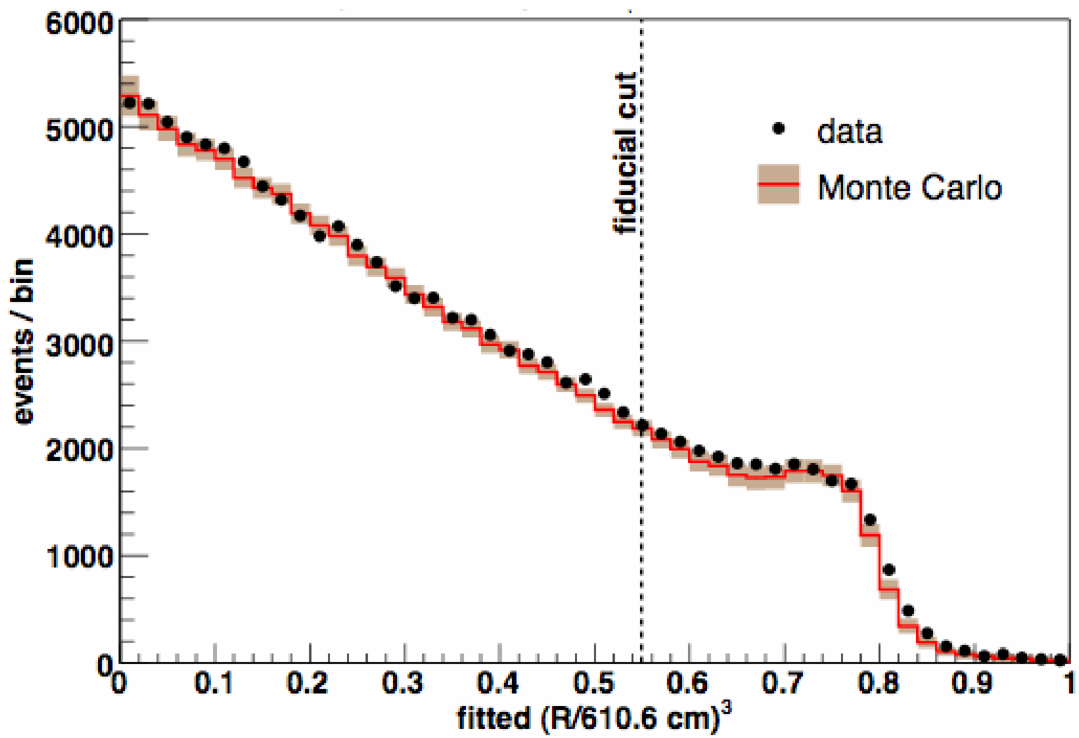
Each event is characterized by 7 reconstructed variables:

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

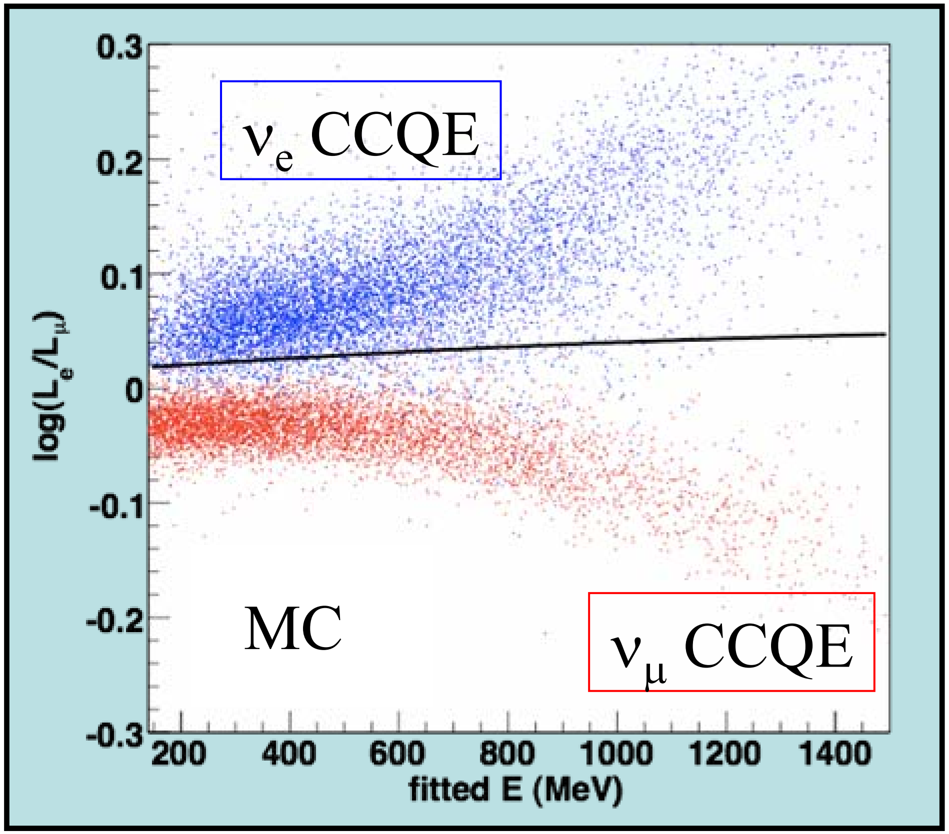
2 subevents

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



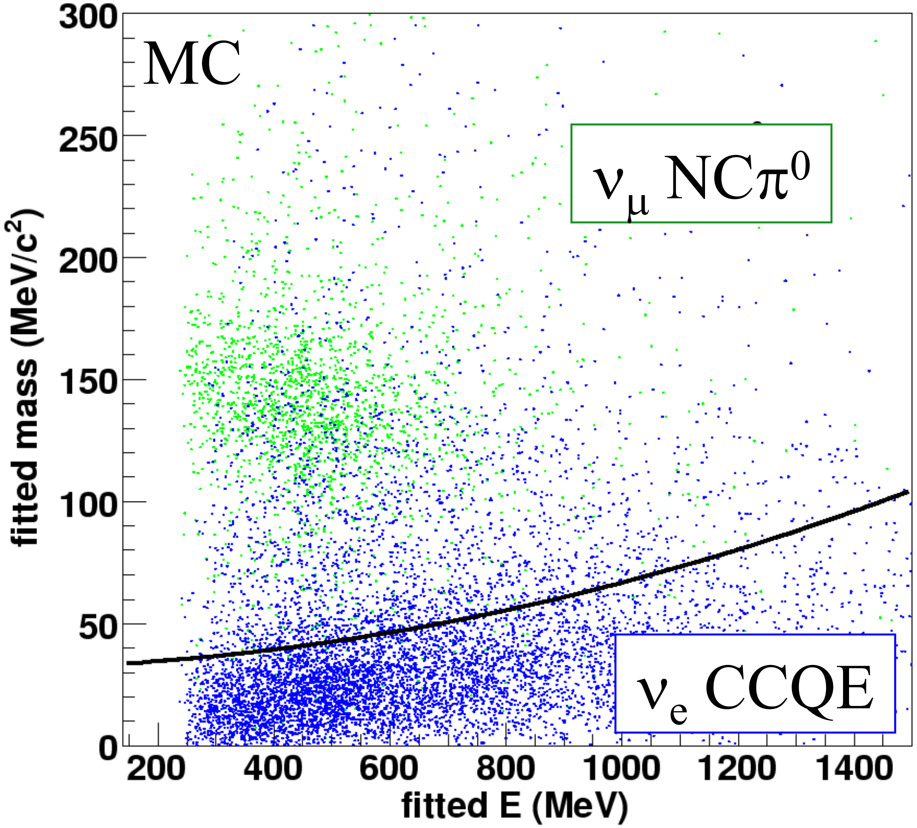
Note: photon conversions are electron-like.
This does not separate e/π^0.

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

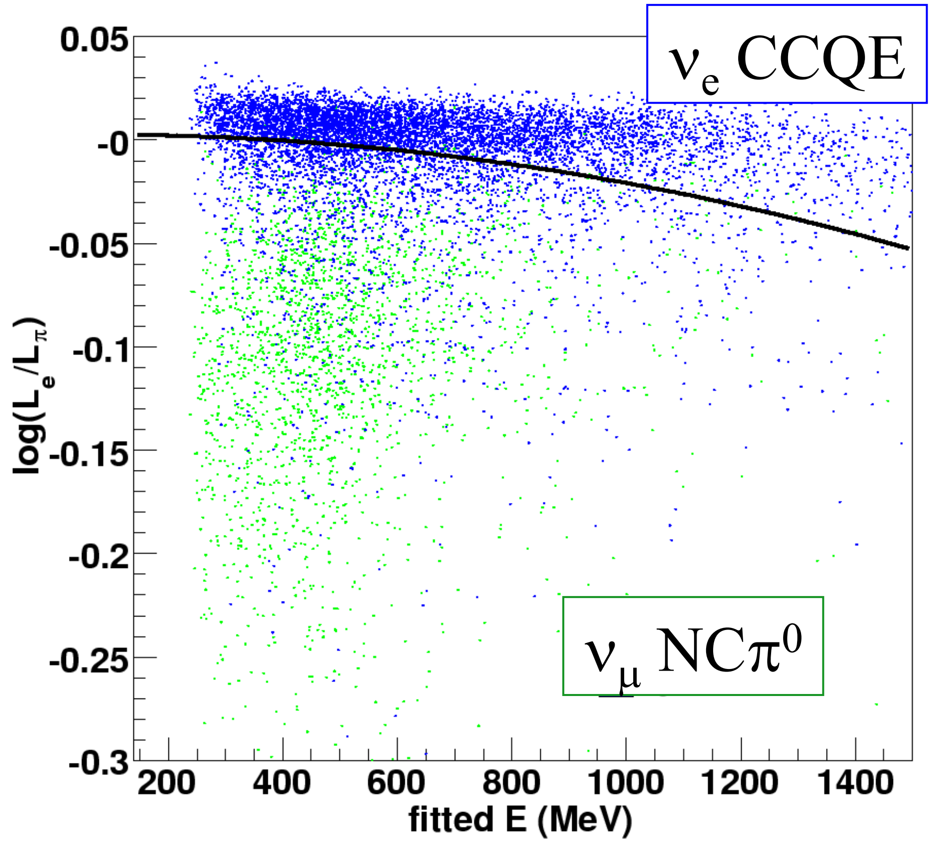
Analysis cut was chosen to maximize the $\nu_\mu \rightarrow \nu_e$ sensitivity

Rejecting "π^0-like" events

Using a mass cut



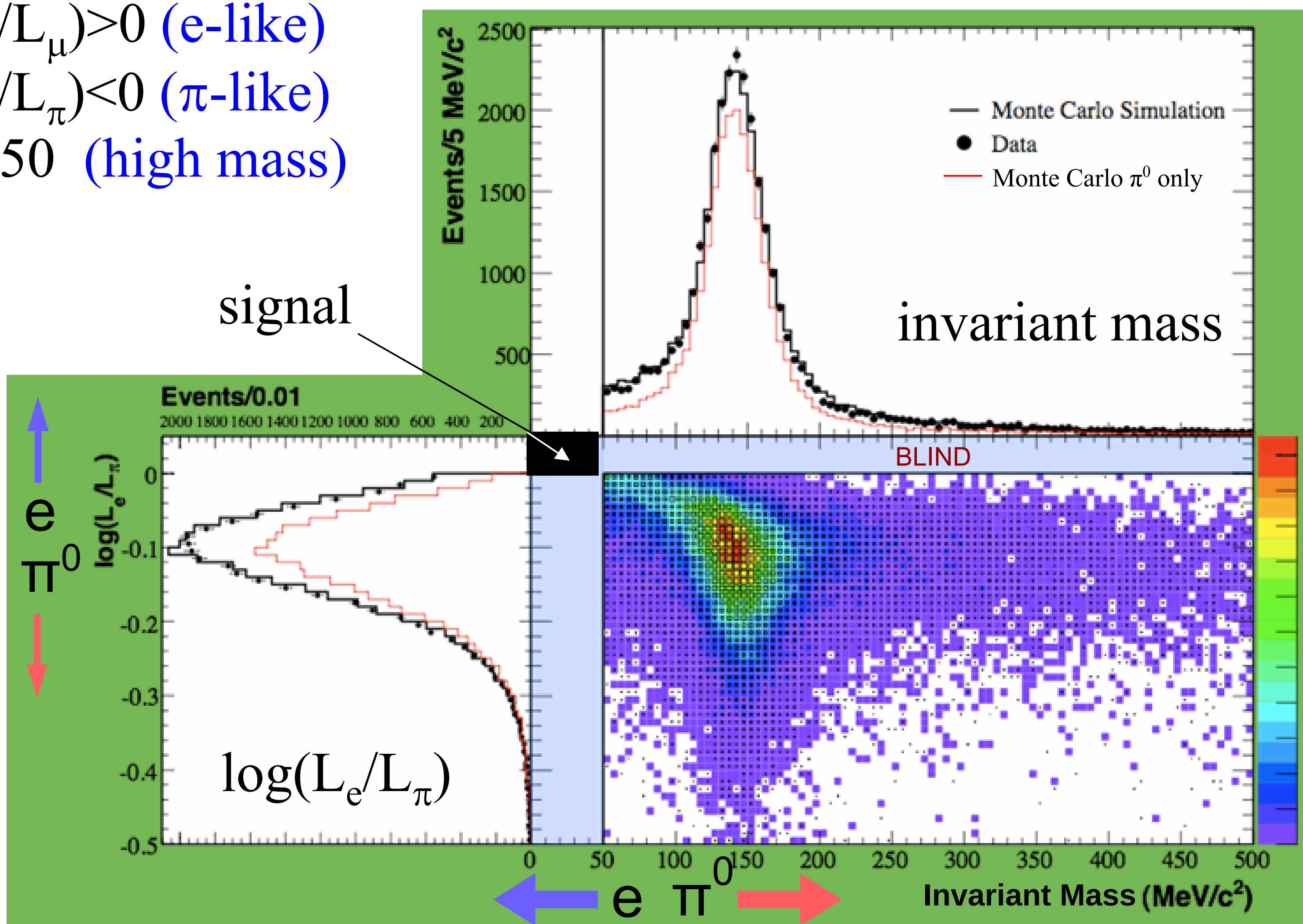
Using $\log(L_e/L_\pi)$

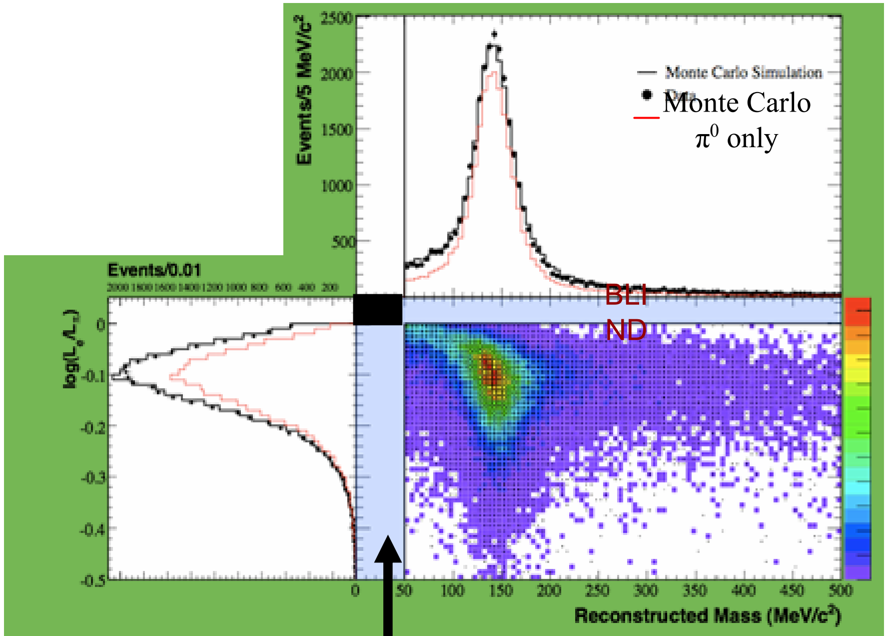


Cuts were chosen to maximize $\nu_\mu \rightarrow \nu_e$ sensitivity

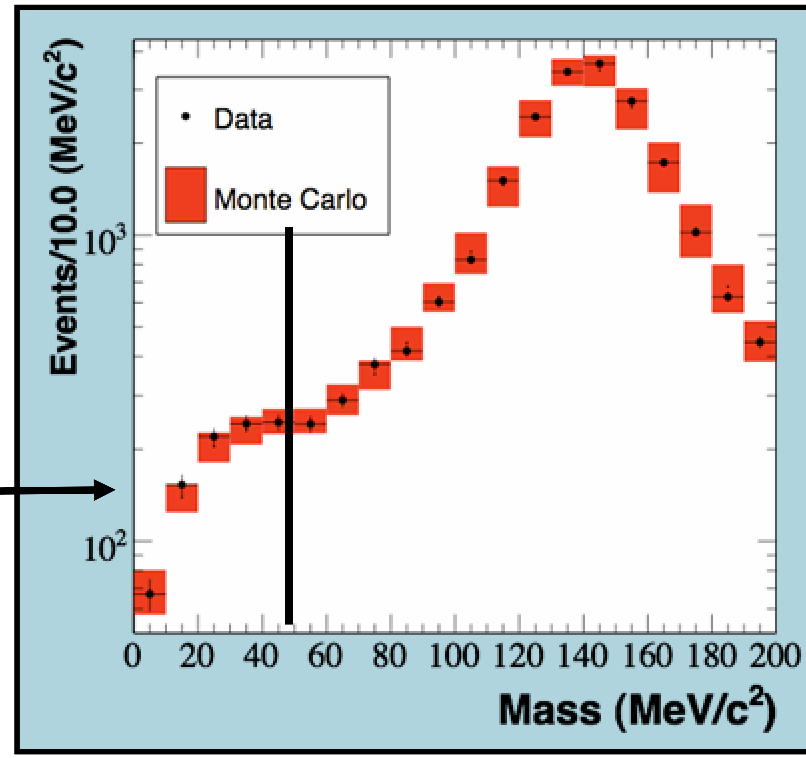
Testing e-π^0 separation using data

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

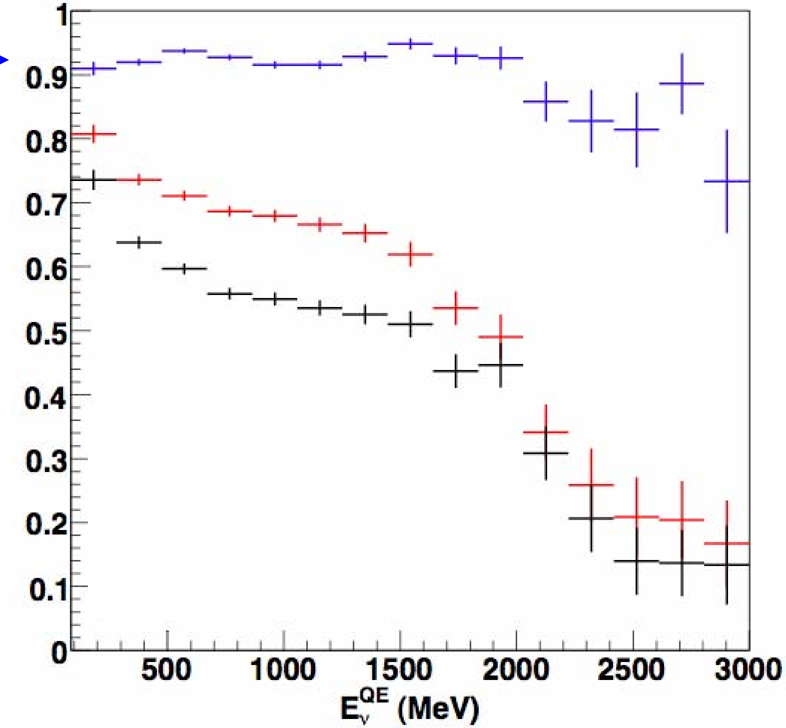
"Precuts" +

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

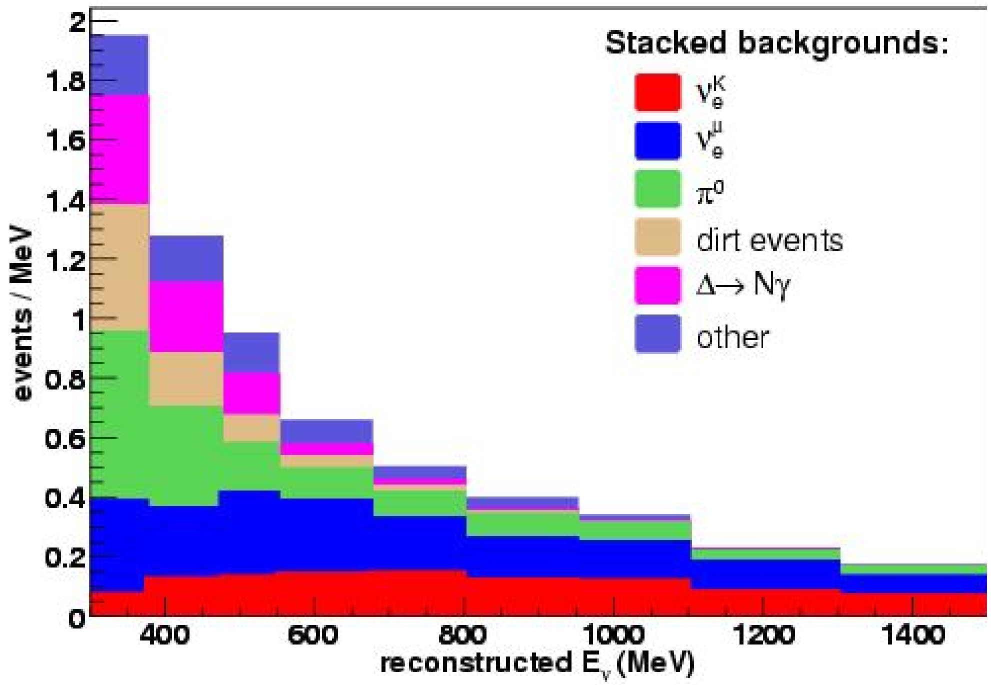
$+ \text{Log}(L_e/L_\pi)$

\+ invariant mass

Efficiency:



Backgrounds after cuts



Efficiency for 1000 MeV, ~35% (14% including precuts)

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

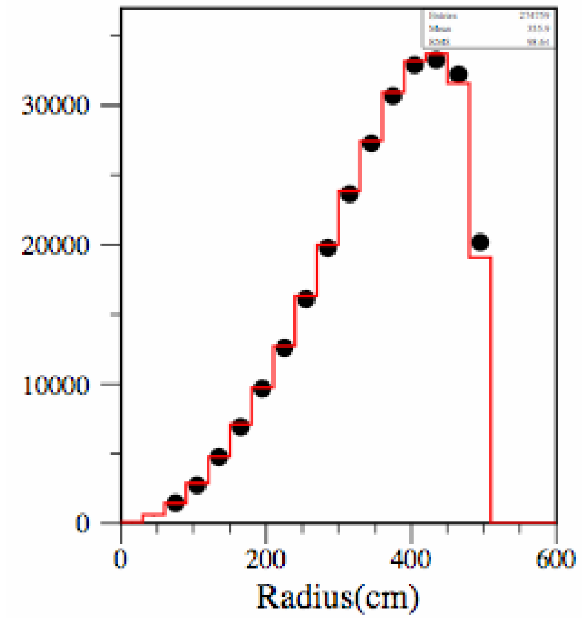
Step 1:
Convert the "Fundamental information" into "Analysis Variables"

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

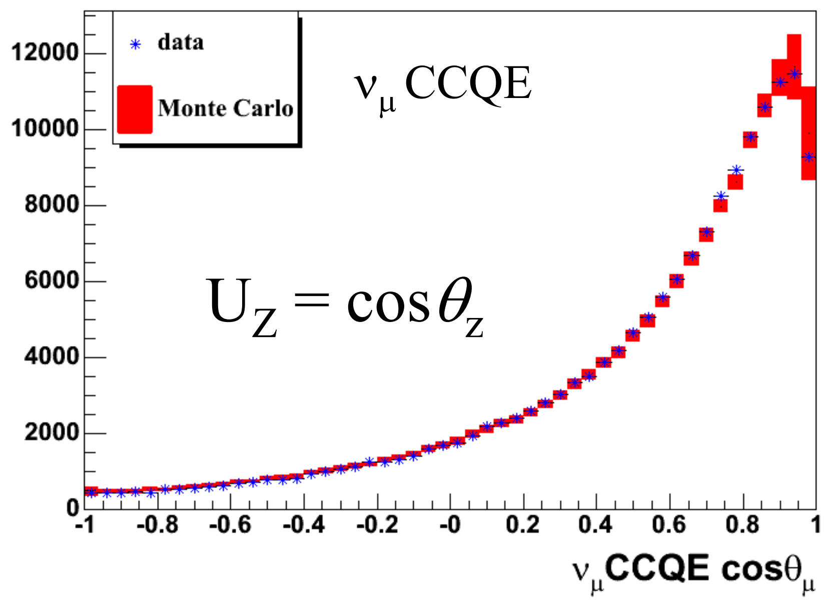
"Physics" = π^0 mass, E_ν^{QE}, etc.

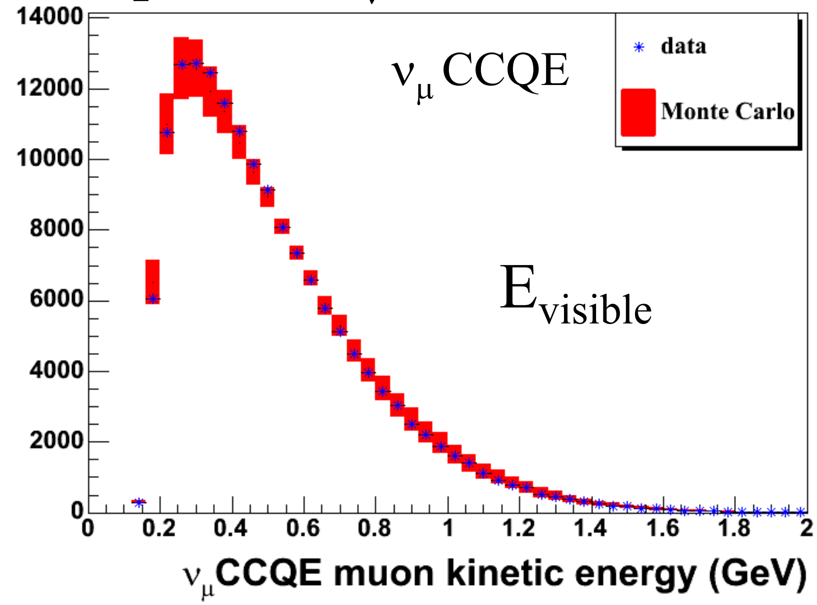
Examples of "Analysis Variables"

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



Reconstructed quantities which are inputs to E_ν^{QE}



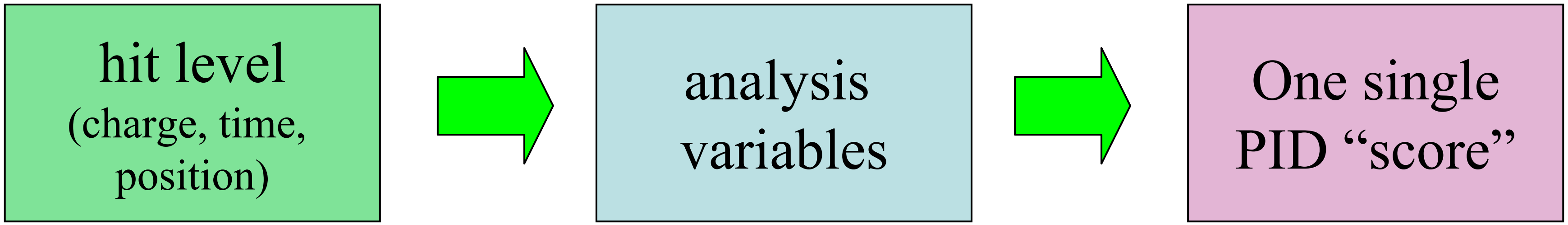


Step 2: Reduce Analysis Variables to a Single PID Variable

Boosted Decision Trees

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

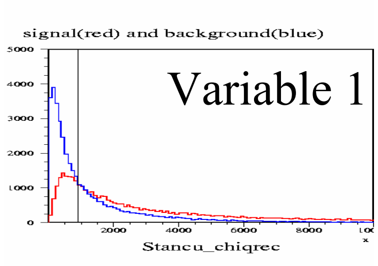
Byron P. Roe, *et al.*, NIM A543 (2005) 577.



A Decision Tree

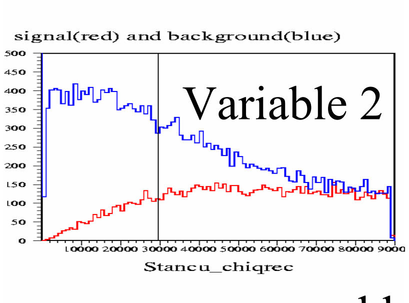
(sequential series of cuts based on MC study)

(N_{signal}/N_{bkgd})



bkgd-like

signal-like

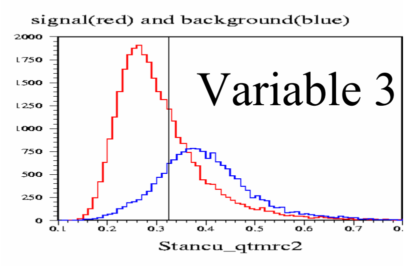


9755/23695

bkgd-like

sig-like

30,245/16,305



1906/11828

7849/11867

sig-like

bkgd-like

20455/3417

9790/12888

etc.

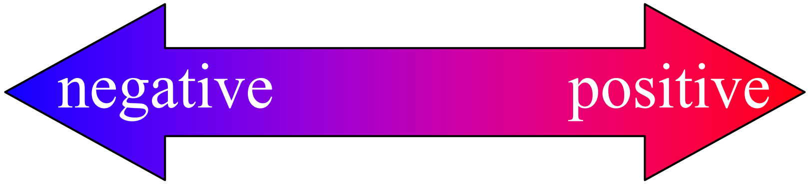
This tree is one of many possibilities...

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”

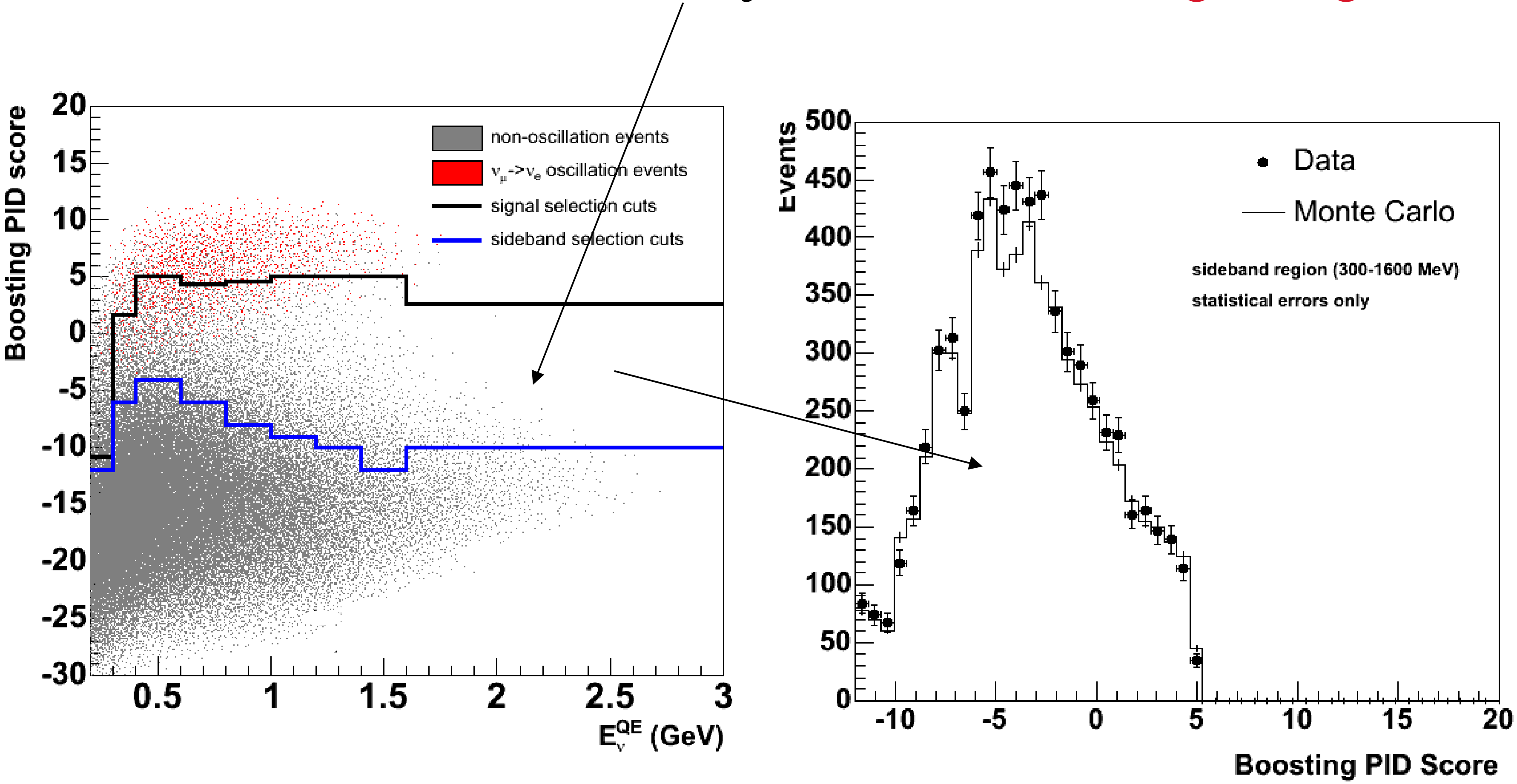
Background-like



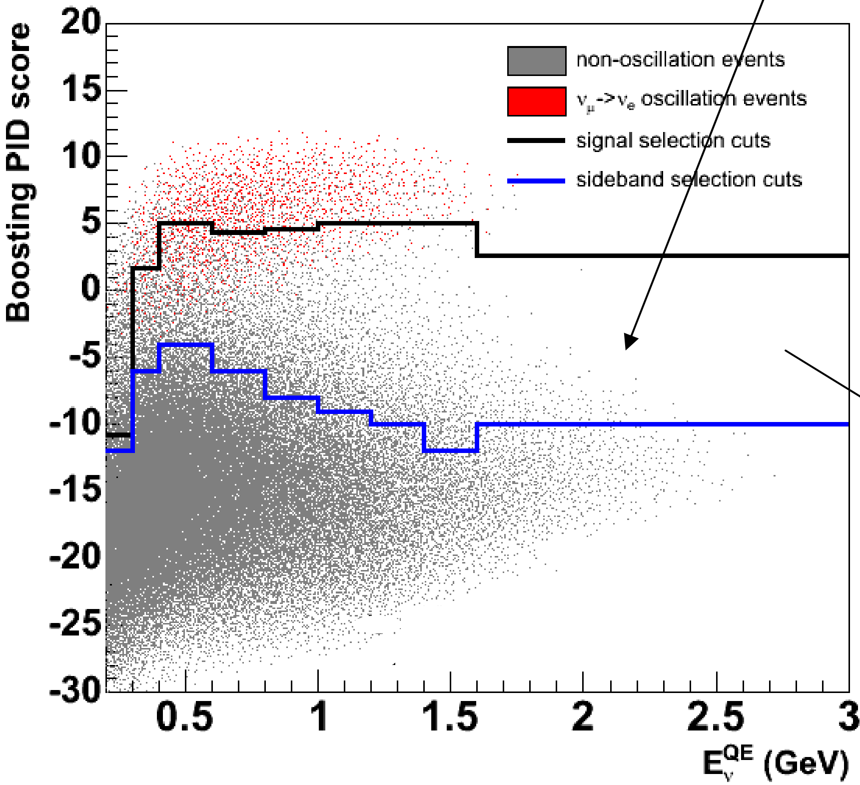
signal-like

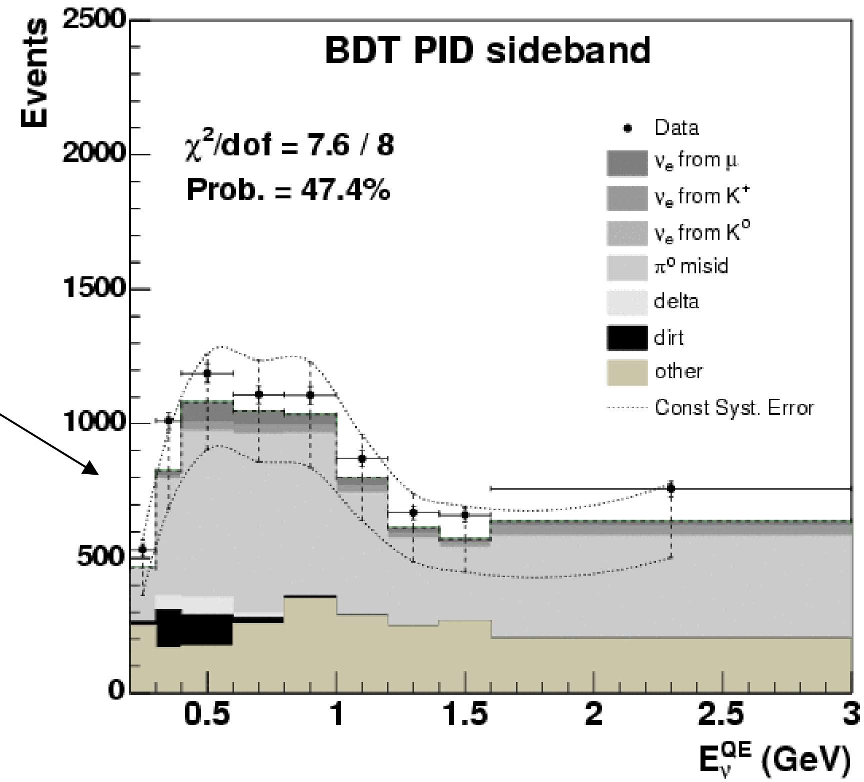
BDT cuts on PID score as a function of energy.

We can define a “sideband” just outside of the signal region



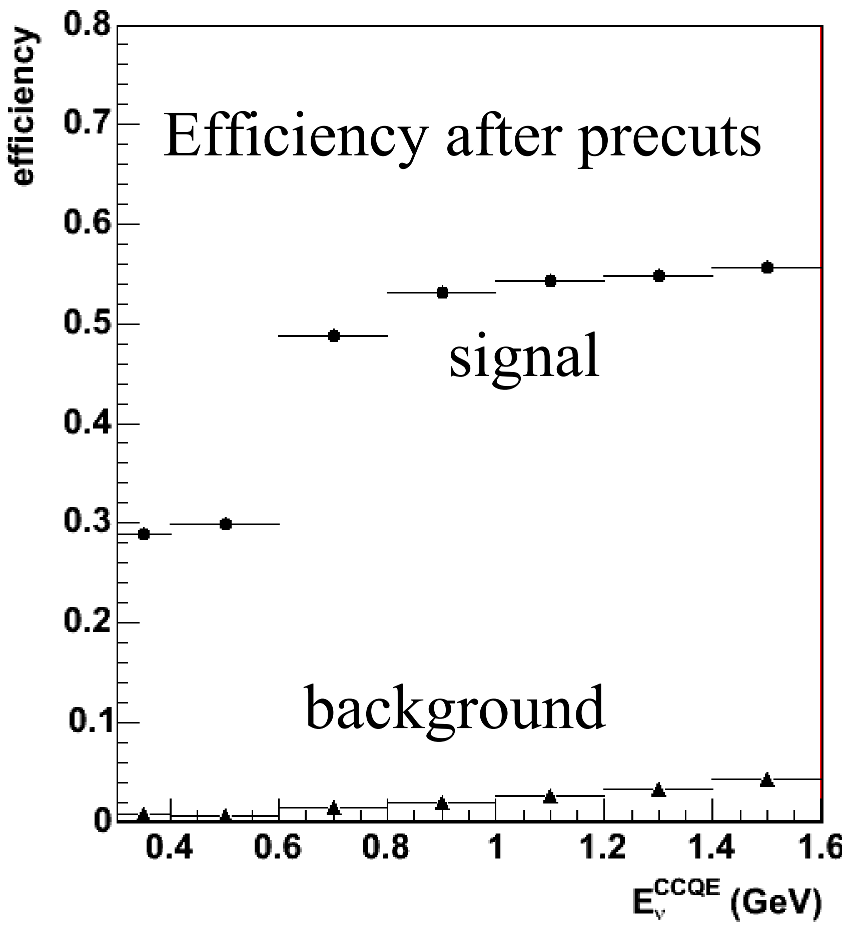
BDT cuts on PID score as a function of energy.
We can define a "sideband" just outside of the signal region

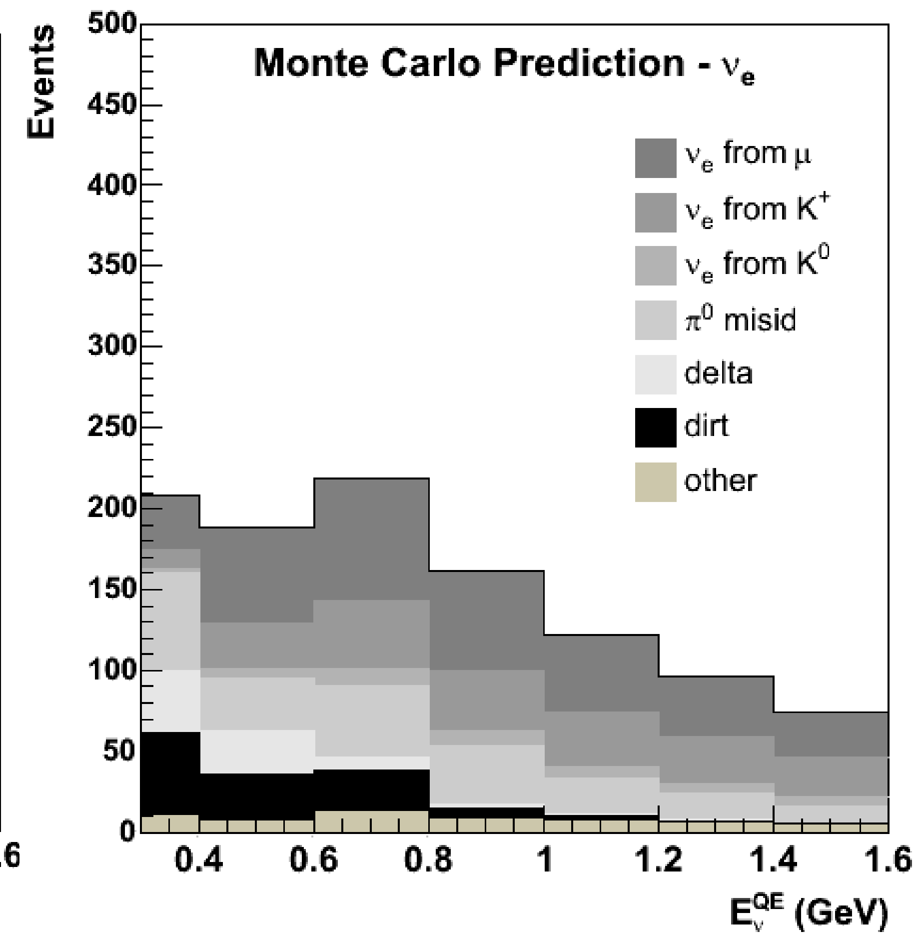




BDT Efficiency and backgrounds after cuts:

Analysis cuts on PID score as a function of Energy

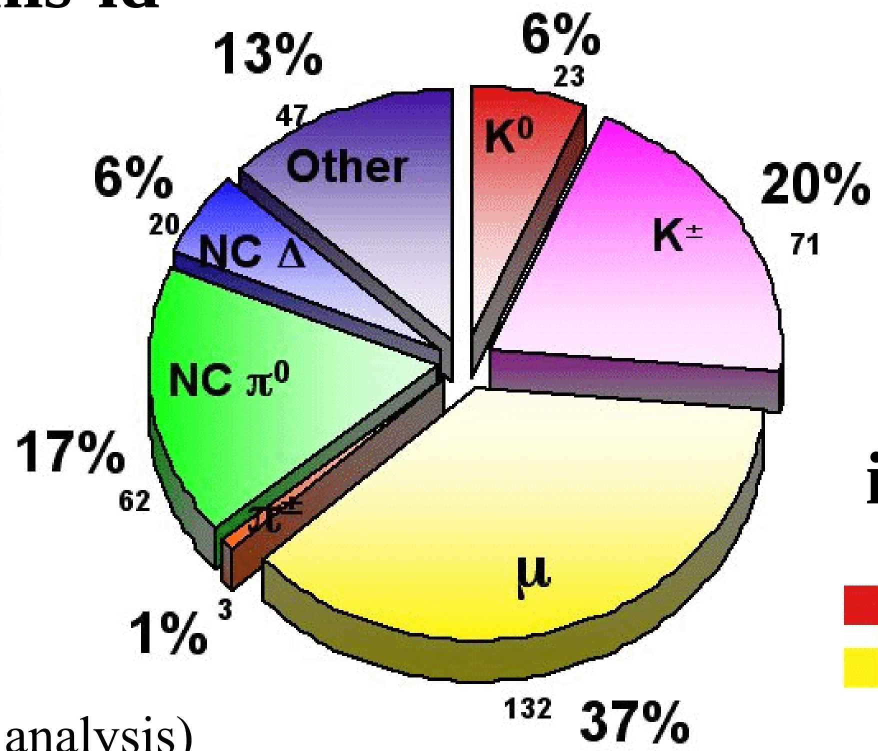




Errors, Constraints and Sensitivity

We have two categories of backgrounds:

ν_μ mis-id

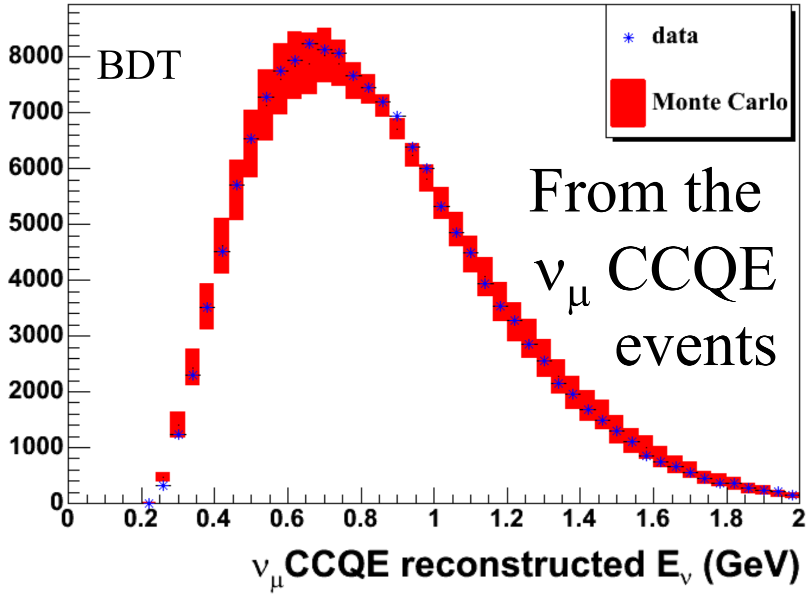


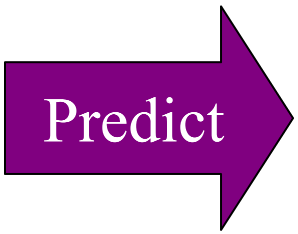
intrinsic ν_e

(TB analysis)

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

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	√	



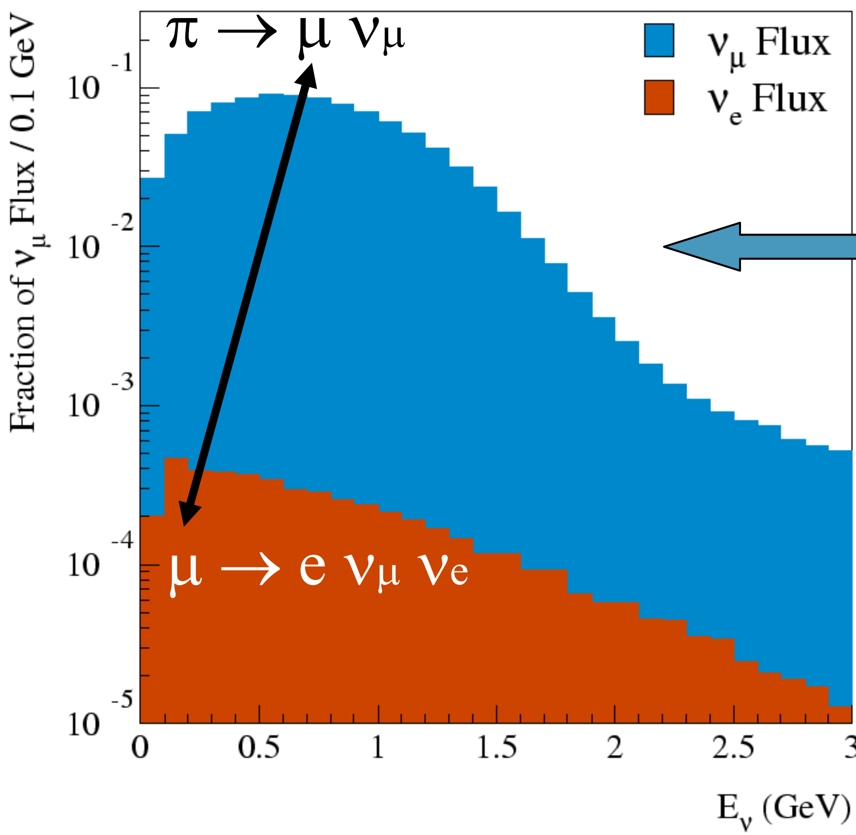


Normalization
& energy dependence
of both background
and signal

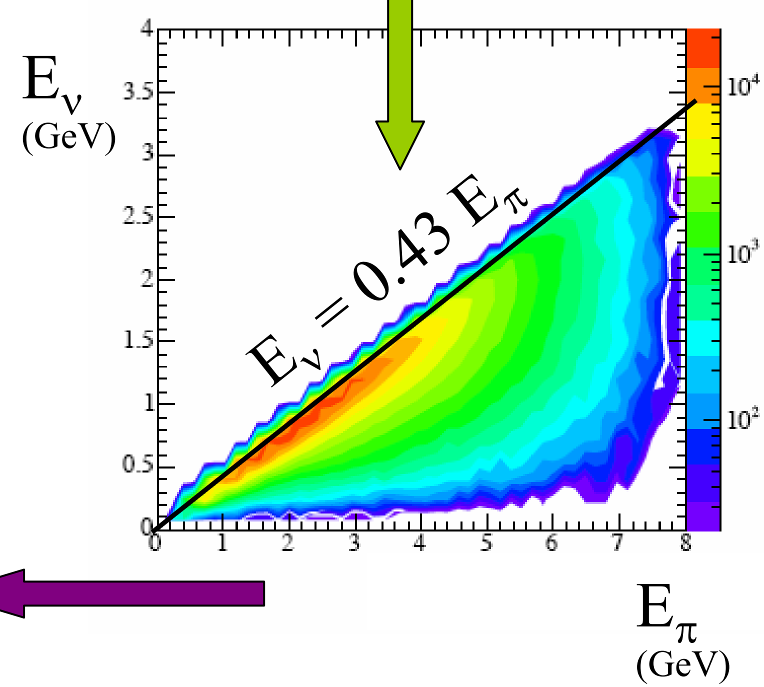
Data/MC Boosted Decision Tree: 1.22 ± 0.29
Track Based: 1.32 ± 0.26

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

ν_μ constraint on intrinsic ν_e from π^+ decay chains

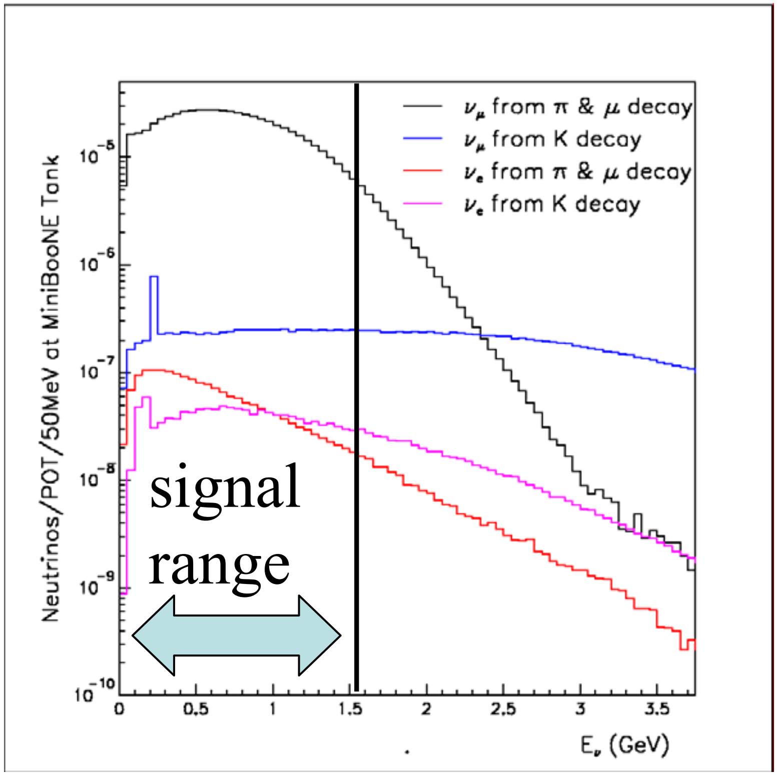


- Measure the ν_μ flux
- Kinematics allows connection to the π flux

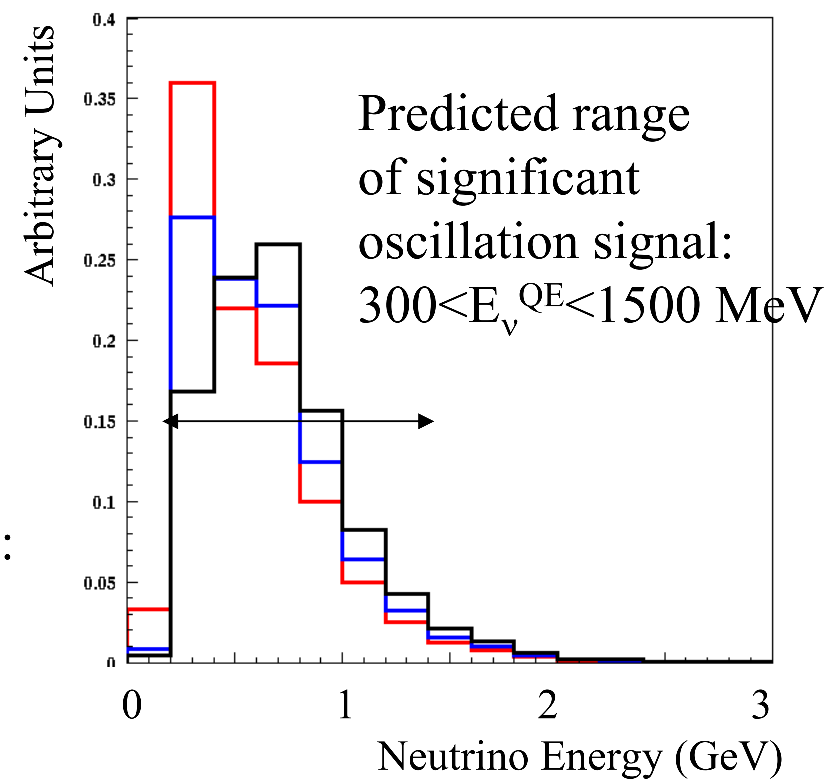


- Once the π flux is known, the μ flux is determined

K^+ and K^0 decay backgrounds



At high energies, above "signal range" ν_μ and ν_e events are largely due to kaon decay



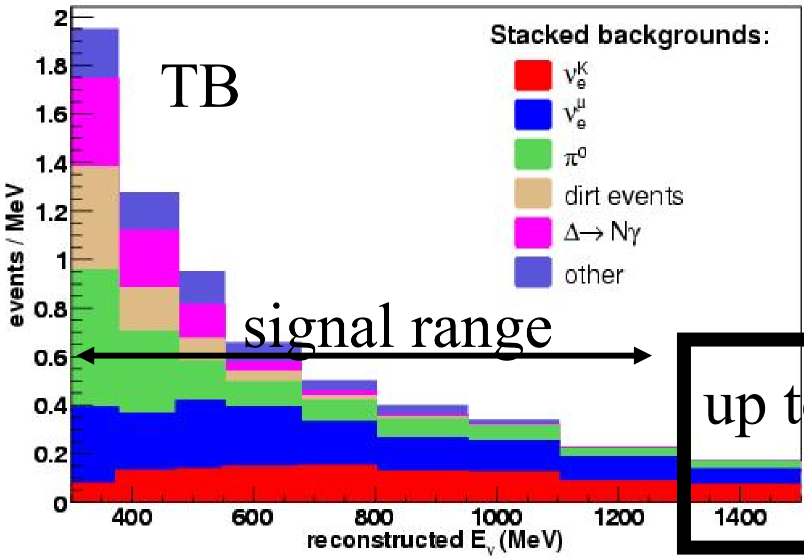
Signal examples:

$\Delta m^2=0.4$ eV^2

$\Delta m^2=0.7$ eV^2

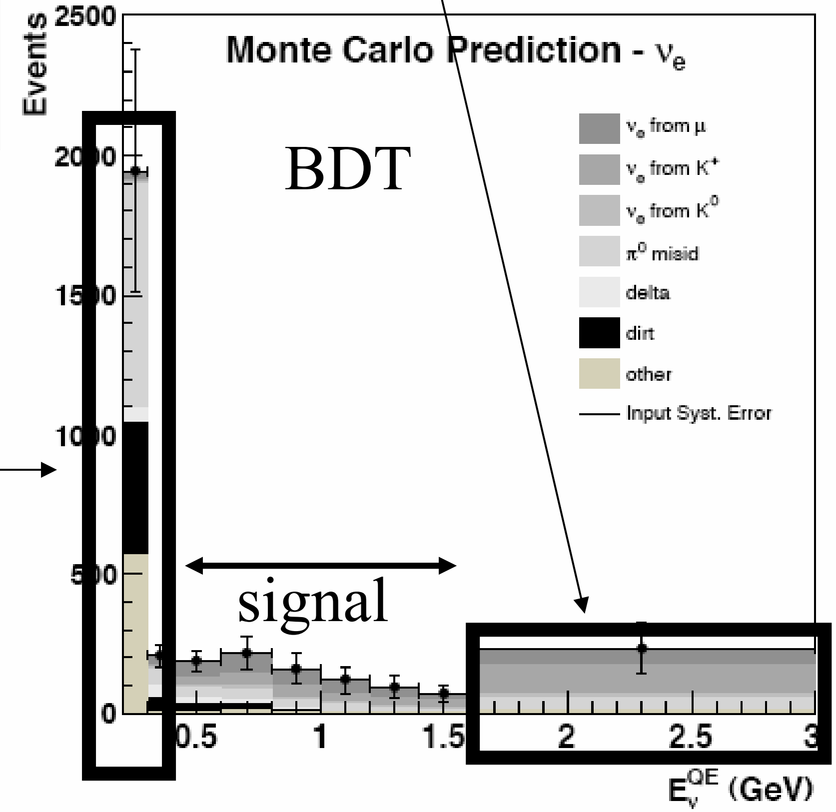
$\Delta m^2=1.0$ eV^2

Use of low-signal/high-background energy bins



up to 3000 MeV

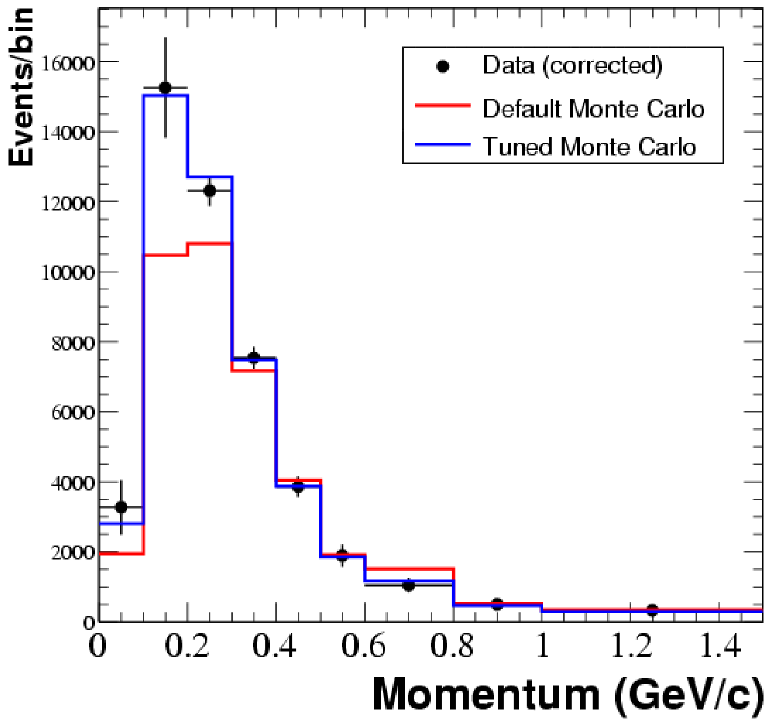
In both analyses, high energy bins constrain ν_e background



In Boosted Decision Tree analysis:
Low energy bin
($200 < E_\nu^{QE} < 300$ MeV)

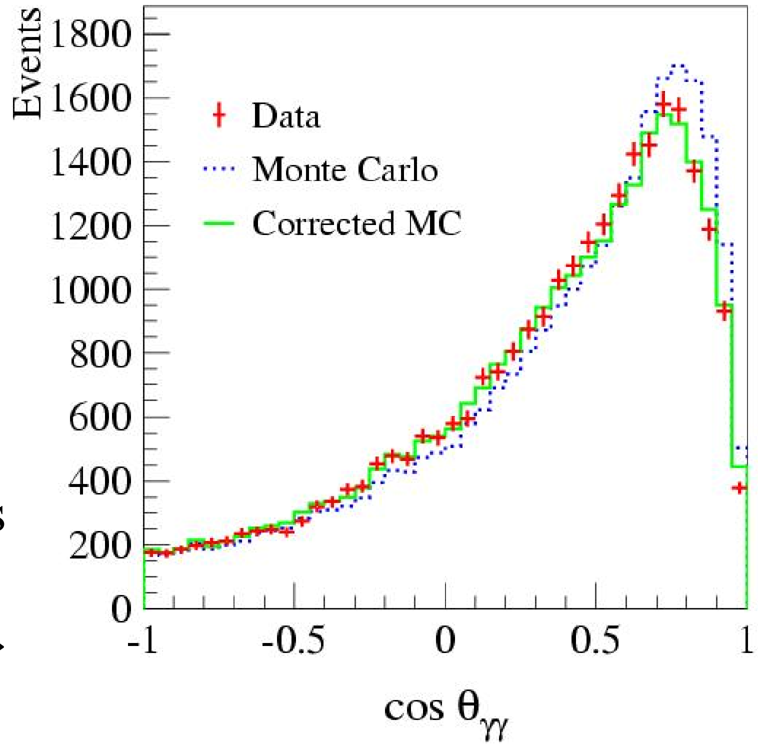
constrains ν_μ mis-ids:
π^0, $\Delta \rightarrow N\gamma$, dirt ...

We constrain π^0 production using data from our detector



This reduces the error on predicted mis-identified π^0s

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



Because this constrains the Δ resonance rate, it also constrains the rate of $\Delta \rightarrow N\gamma$

Other Single Photon Sources

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

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

Charged Current < 6 events @ 95% CL

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

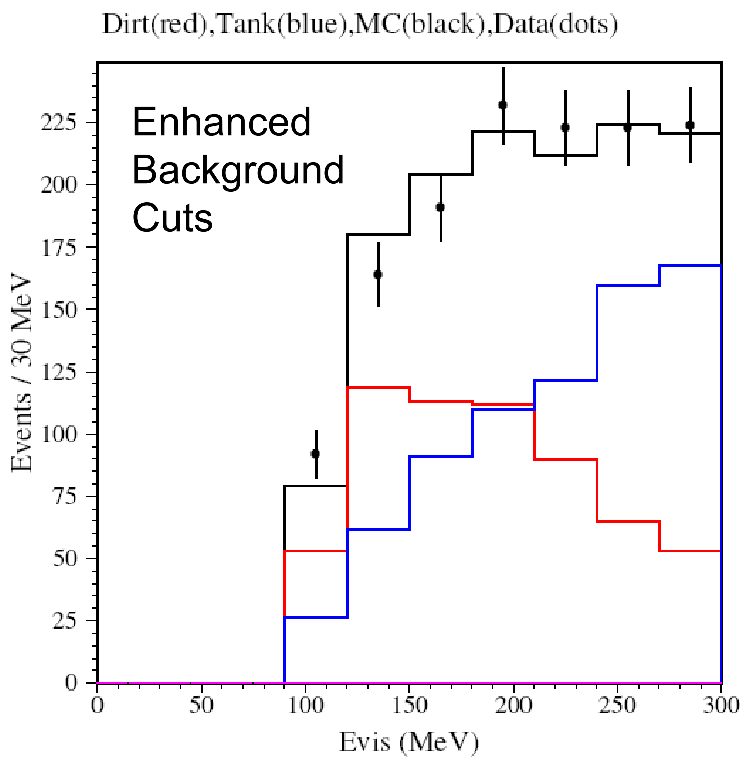
where the presence of the γ leads to mis-identification

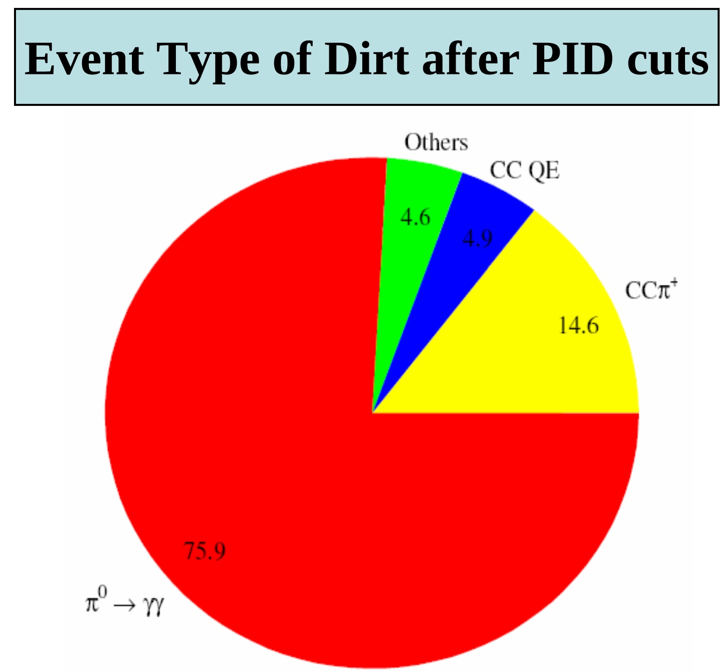
Use events where the μ is tagged by the michel e^-,
study misidentification using BDT algorithm.

External Sources of Background

"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

Summary of predicted backgrounds for the final MiniBooNE result (Track Based Analysis):

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

Handling uncertainties in the analyses:

What we begin with...	... what we need
For a given source of uncertainty, Errors on a wide range of parameters in the underlying model	For a given source of uncertainty, Errors in bins of E_ν^{QE} and information on the correlations between bins

How the constraints enter...

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:

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

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

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

(i,j are bins of E_ν^{QE})

Example: 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	

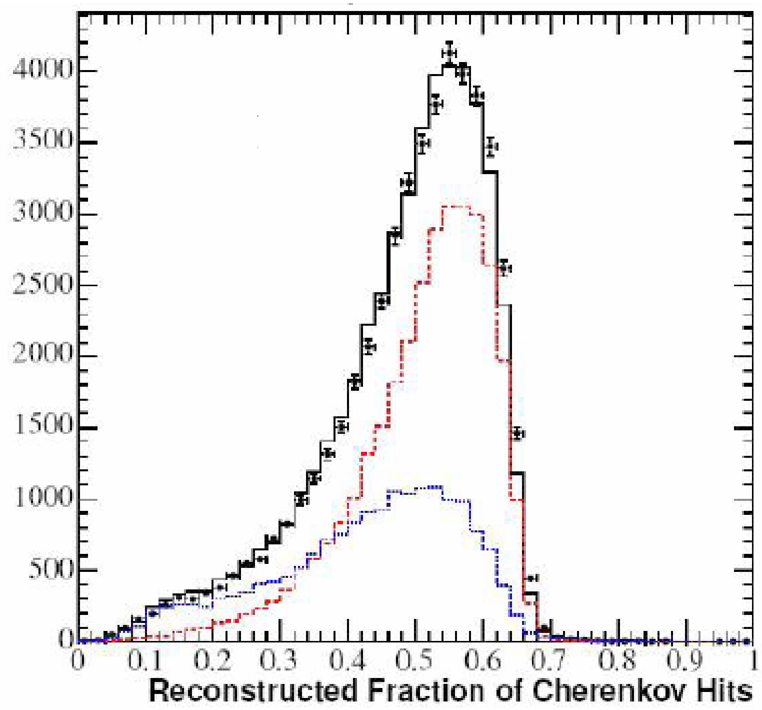
NC π^0 rate	function of π^0 mom	determined from MiniBooNE ν_μ NC π^0 data
M_A^{coh}, coh σ	±25%	
$\Delta \rightarrow N\gamma$ rate	function of γ mom + 7% BF	

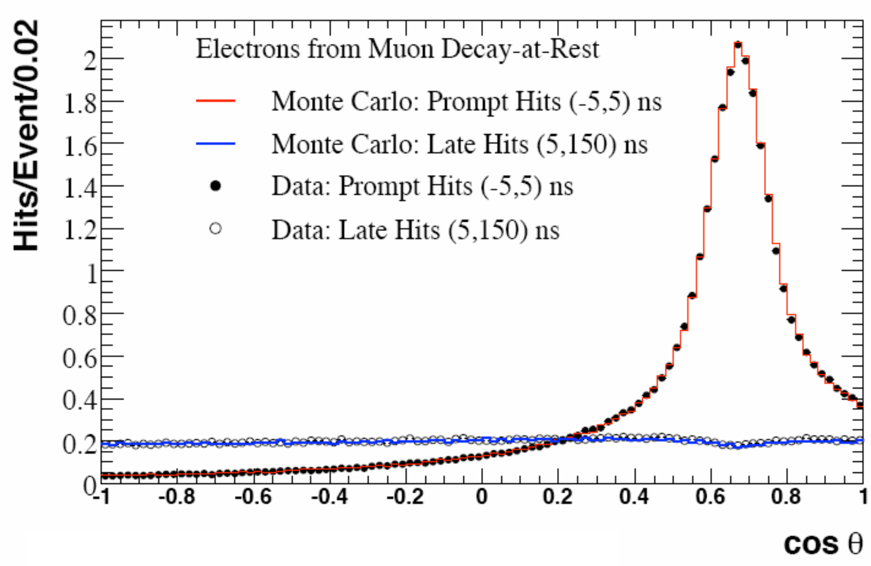
E_B, p_F	9 MeV, 30 MeV	determined from other experiments
Δs	10%	
$M_A^{1\pi}$	25%	
$M_A^{N\pi}$	40%	
DIS σ	25%	

Example:
Optical Model Uncertainties

39 parameters must be varied

Allowed variations are set by the Michel calibration sample





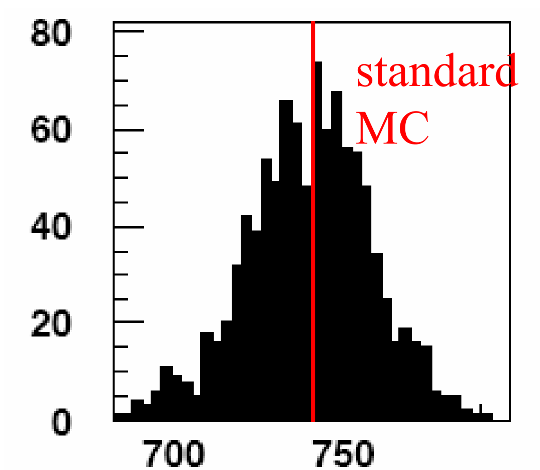
To understand allowed variations, we ran 70 hit-level simulations, with differing parameters.

⇒"Multisims"

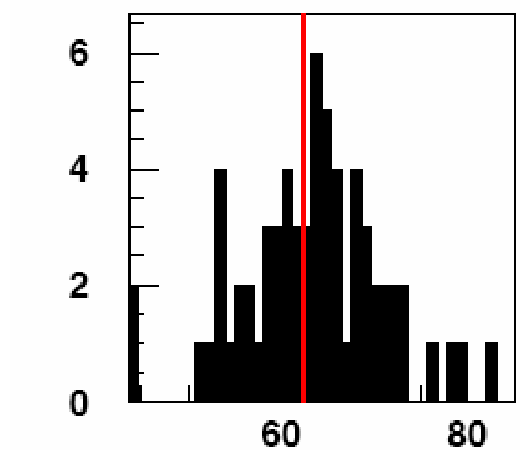
Using Multisims to convert from errors on parameters to errors in E_ν^{QE} bins:

For each error source,
"Multisims" are generated within the allowed variations by reweighting the standard Monte Carlo.
In the case of the OM, hit-level simulations are used.

1000 multisims for K^+ production



70 multisims for the Optical Model



number of multisims

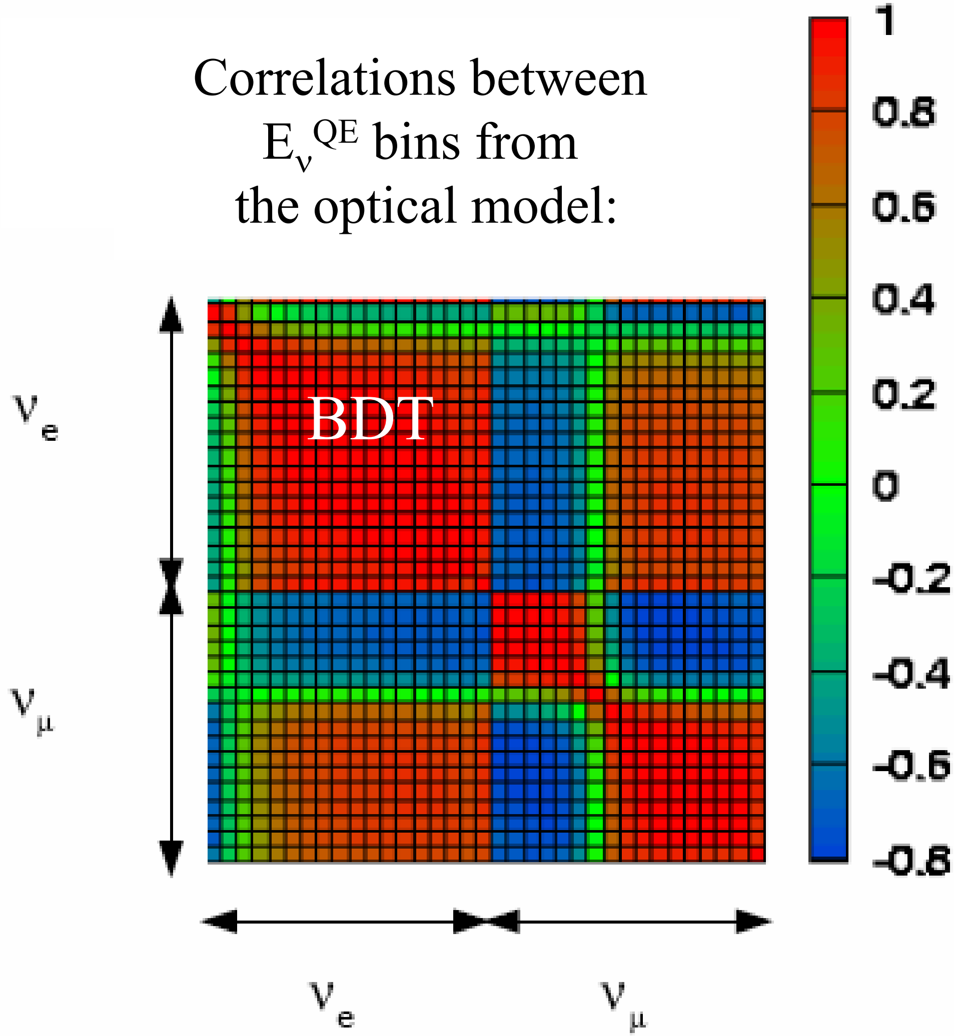
Number of events passing cuts in bin $500<E_\nu^{QE}<600$ MeV

Error Matrix Elements:

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

- 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

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



Total error matrix is sum from each source.

TB: ν_e-only total error matrix
BDT: ν_μ-ν_e total error matrix

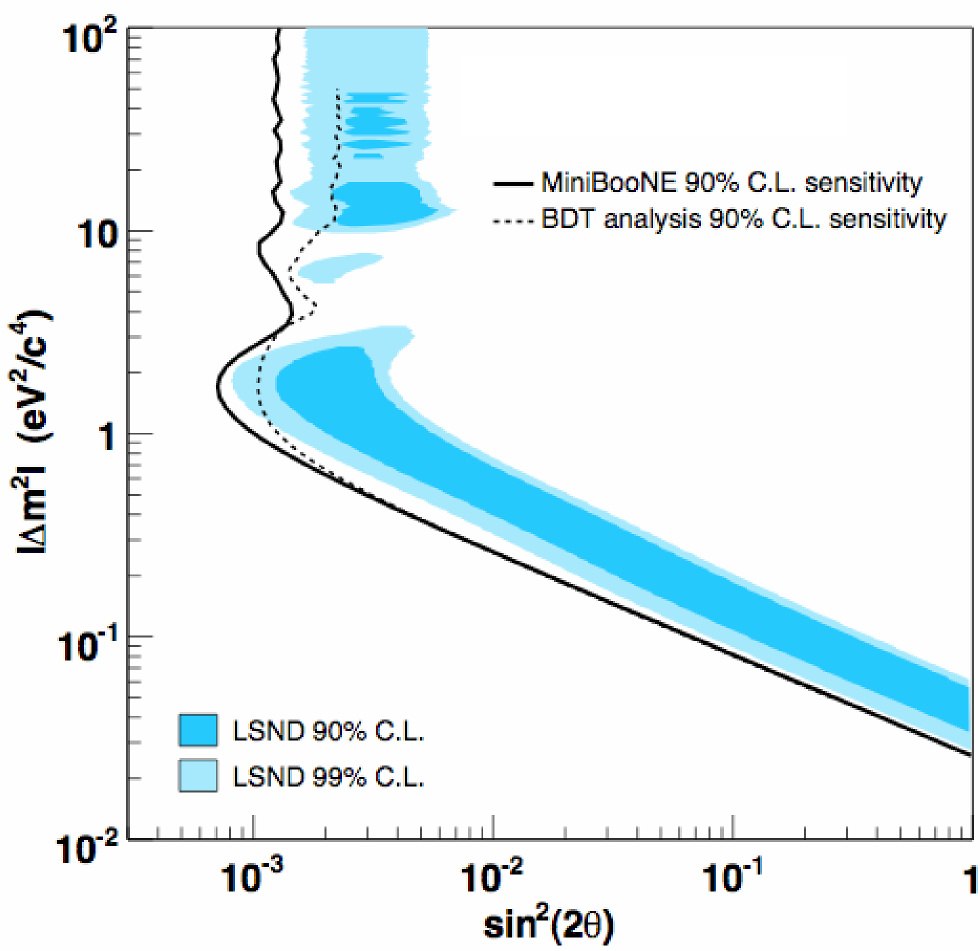
As we show distributions in E_ν^{QE},
keep in mind that error bars are
the diagonals of the error matrix.

The effect of correlations between E_ν^{QE} bins
is not shown,

however E_ν^{QE} bin-to-bin correlations
improve the sensitivity to oscillations,
which are based on an energy-dependent fit.

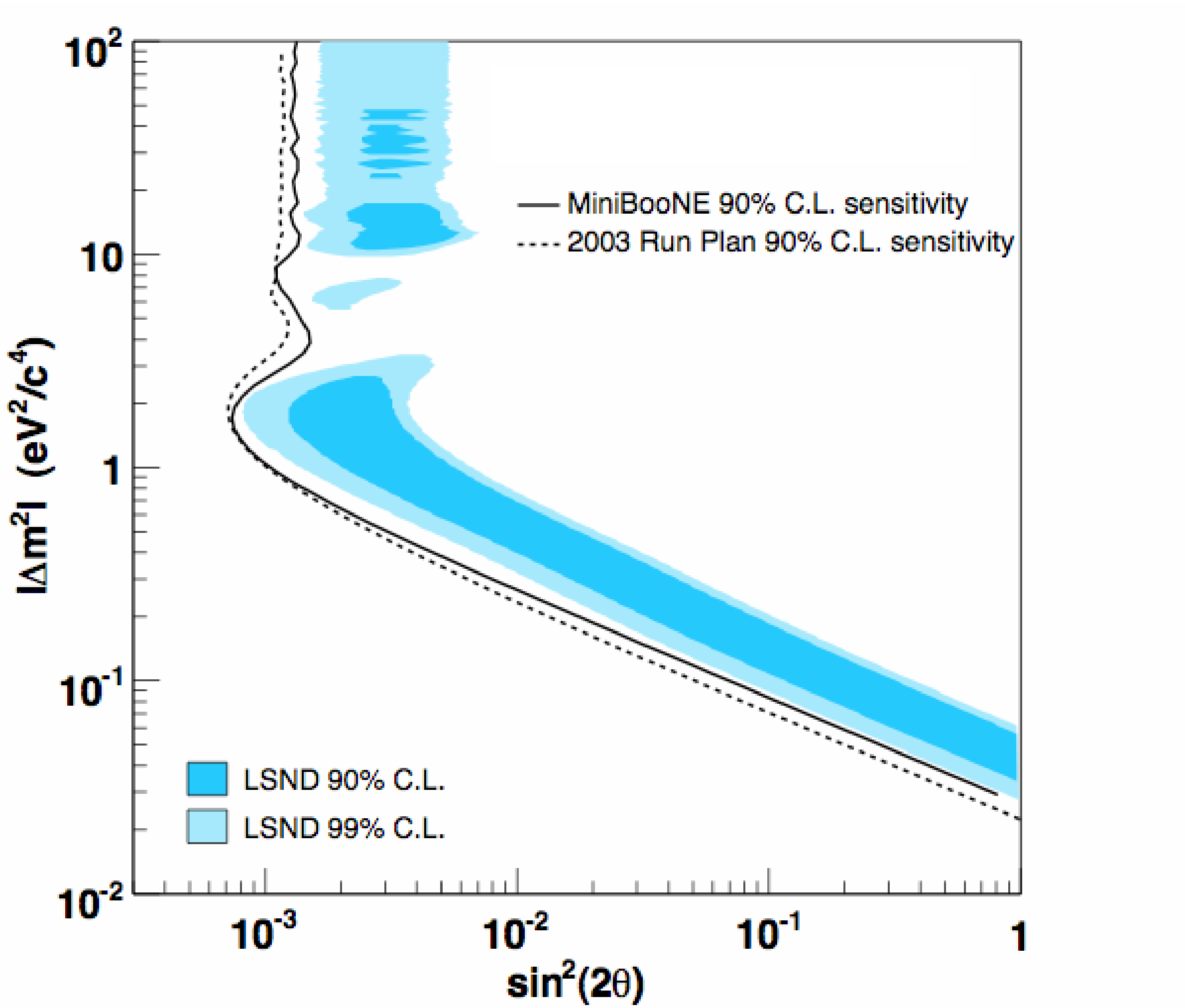
Sensitivity of the two analyses

The Track-based sensitivity is better,
thus this becomes the pre-determined default algorithm



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

Comparison to sensitivity goal for 5E20 POT determined by Fermilab PAC in 2003



The Initial Results

The Box Opening

Box Opening Procedure

Progress cautiously,
in a
step-wise fashion

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)

5. Present results two weeks later.

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 $E_{visible}$ fit: 1%

This probability was sufficiently low to merit further consideration

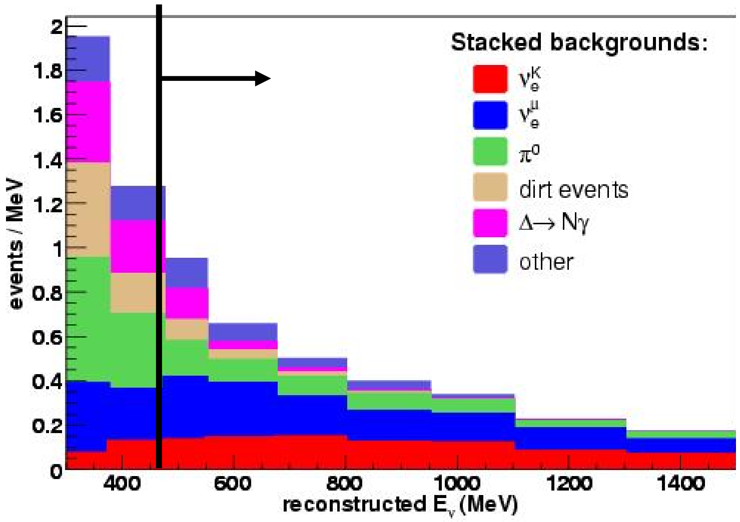
In the Track Based analysis

- We re-examined our background estimates using sideband studies.

  ⇒ *We found no evidence of a problem*

- However, knowing that backgrounds rise at low energy,

  We tightened the cuts for the oscillation fit:

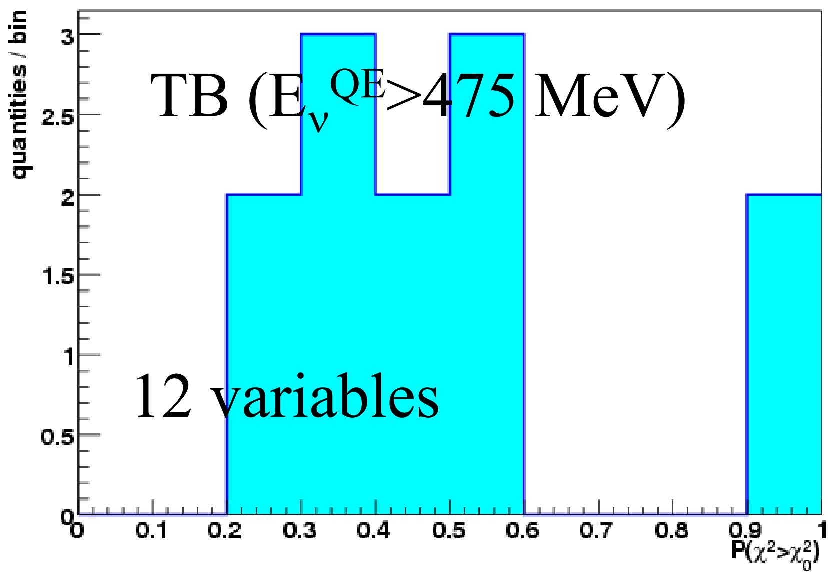


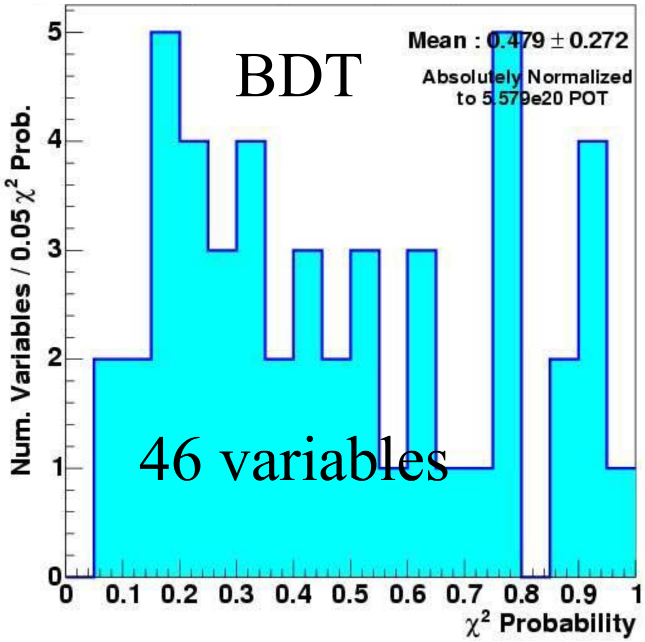
$E_\nu^{QE} > 475$ MeV

We agreed to report events over the original full range: $E_\nu^{QE} > 300$ MeV, Step 1: again!

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

χ^2 probabilities returned:



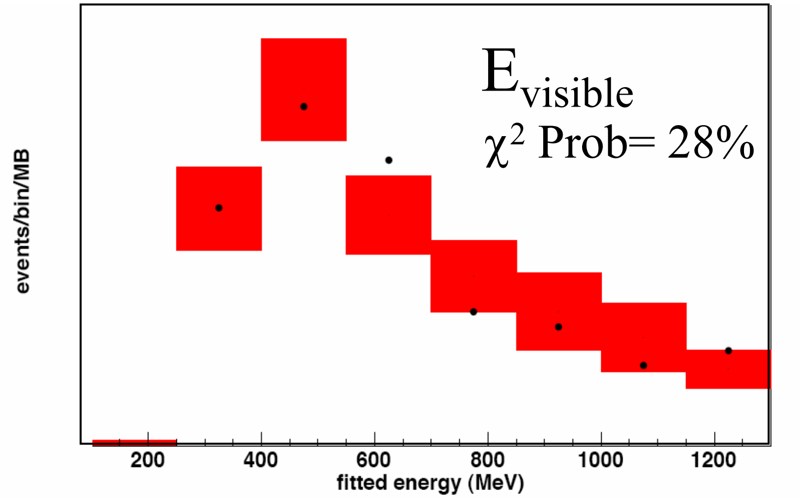


Parameters of the oscillation fit were not returned.

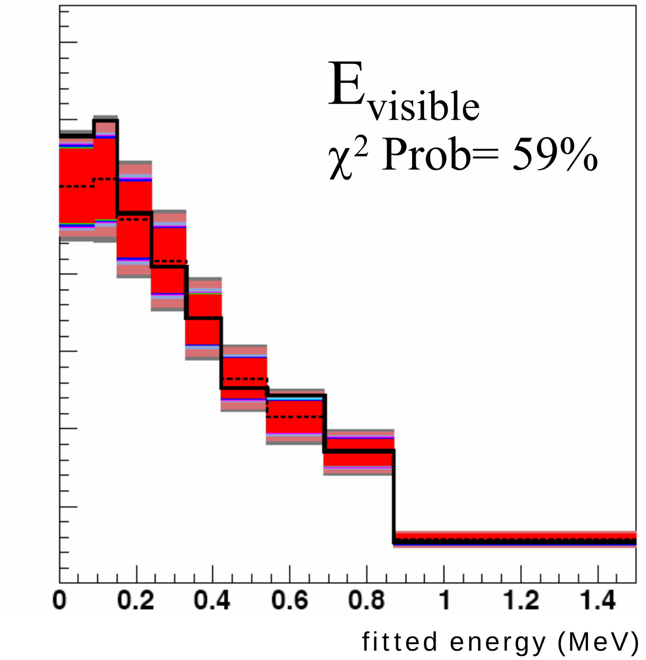
Step 2

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

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...

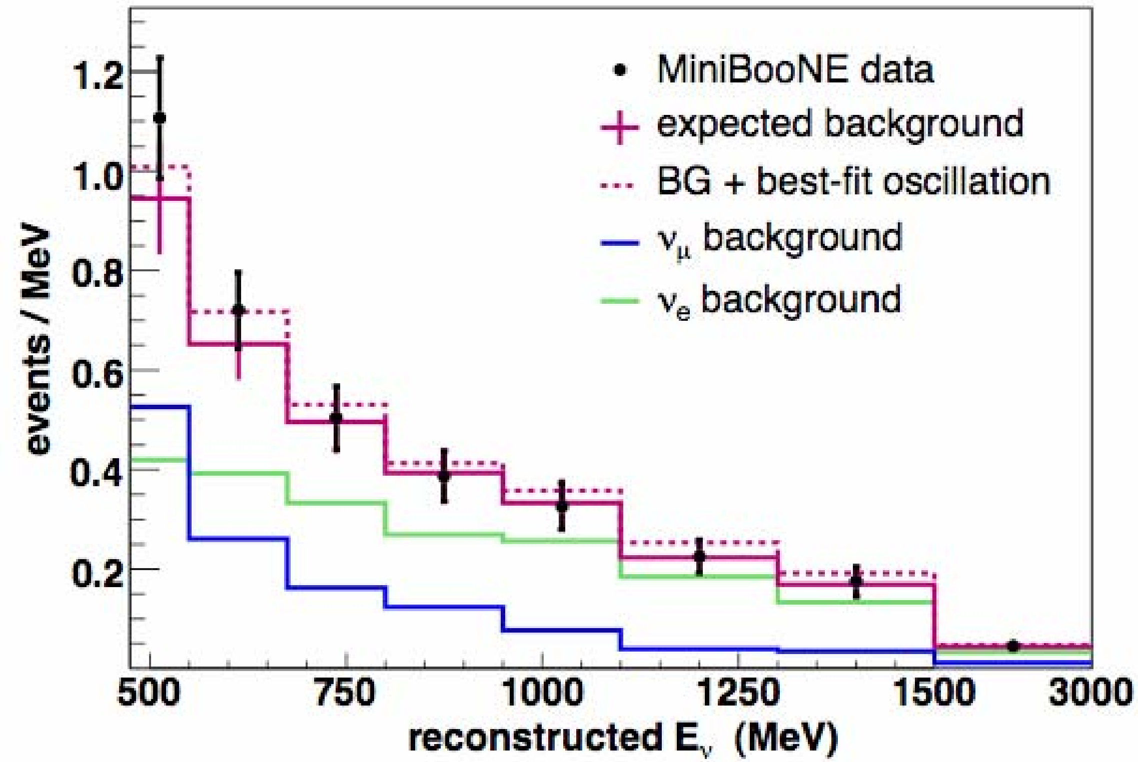
The Track-based $\nu_\mu \to \nu_e$ Appearance-only Result:

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

data: 380 events
expectation: 358 ±19 (stat) ± 35 (sys) events
(sys/stat = 1.8)

significance: 0.55 σ

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

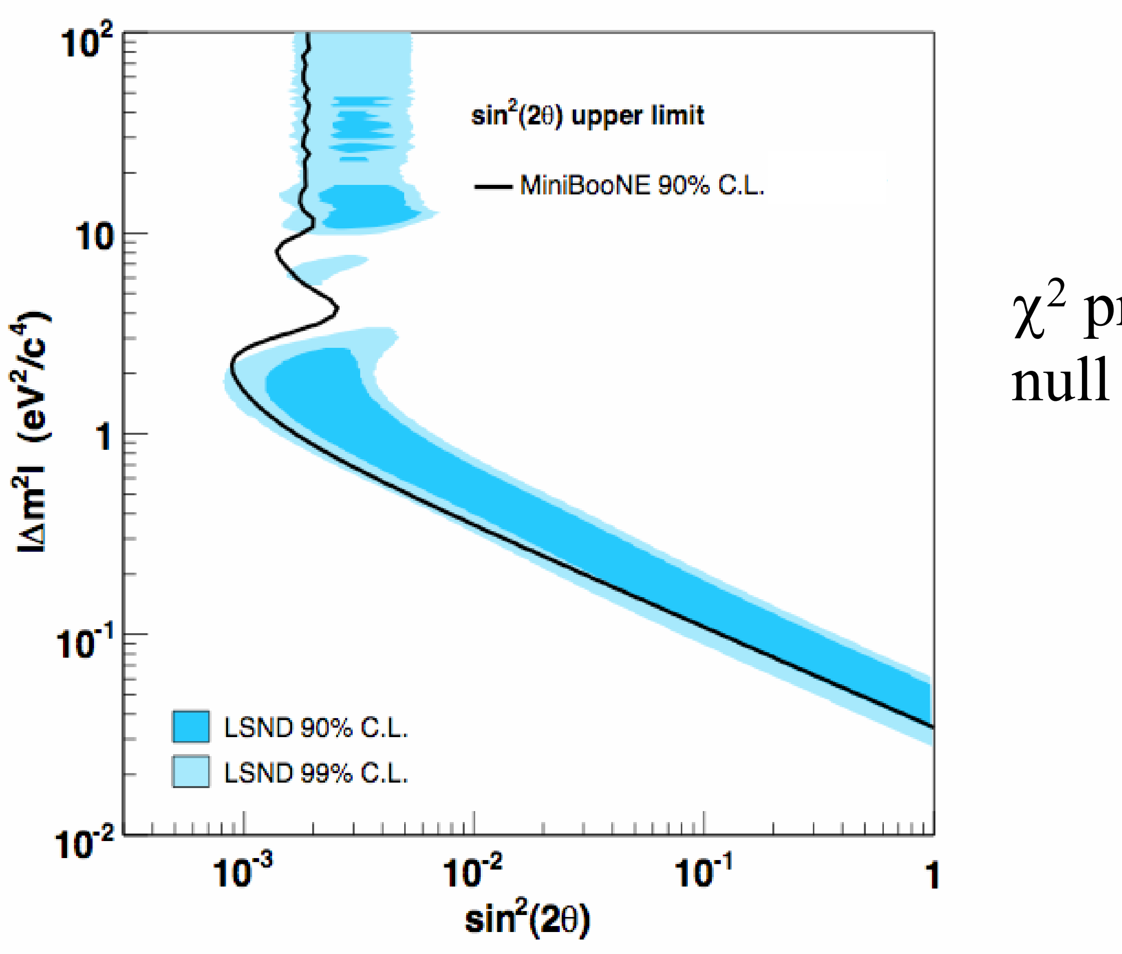


Error bars are diagnonals of error matrix.

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

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

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



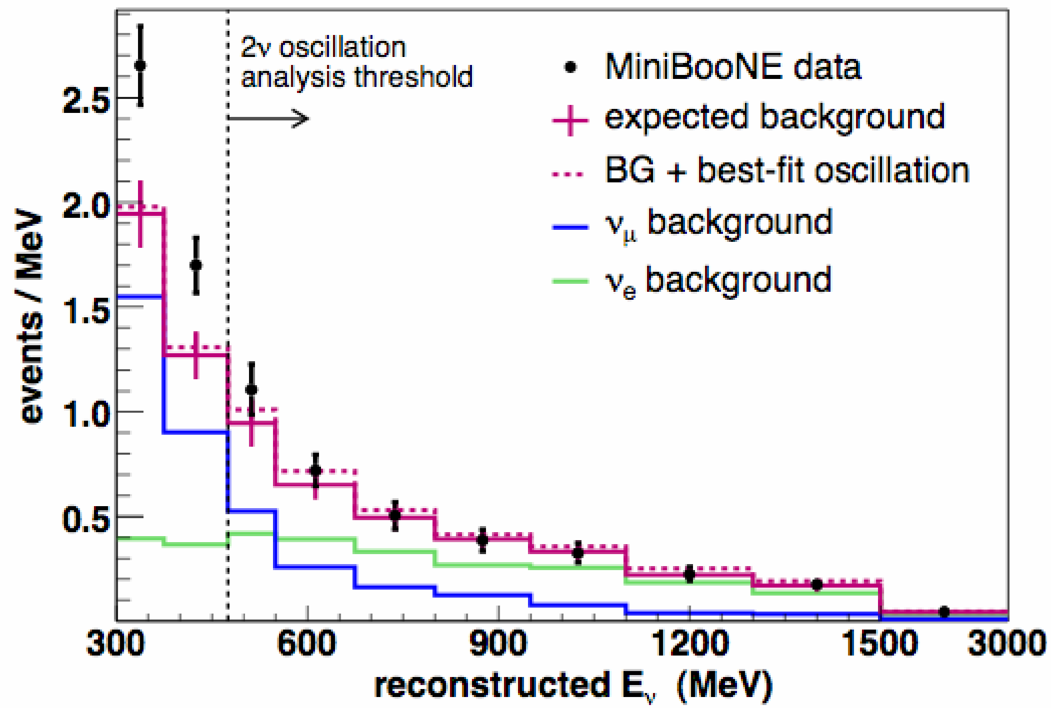
χ^2 probability,
null hypothesis: 93%

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

As planned before opening the box....

Report the full range:

$300<E_\nu^{QE}<3000$ MeV

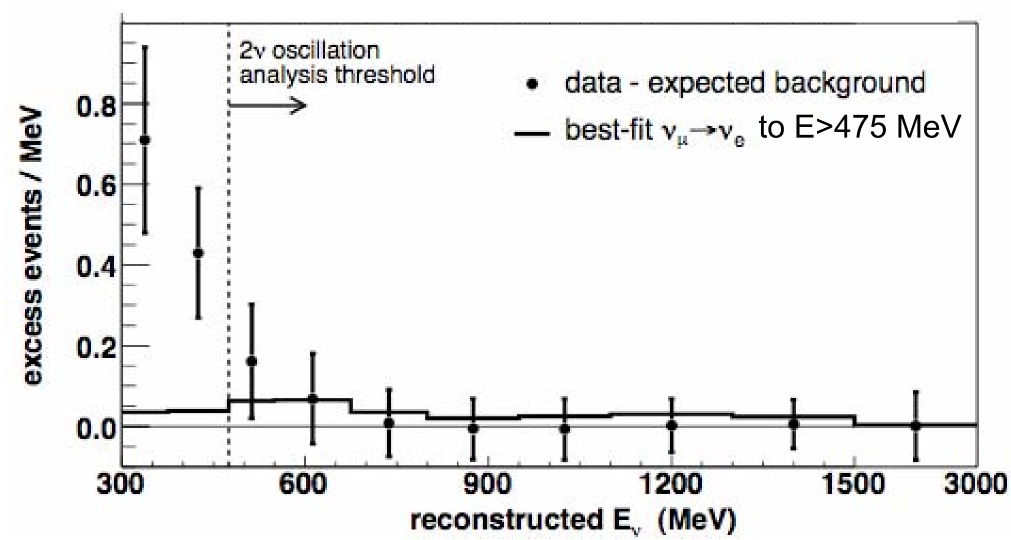


96 ± 17 ± 20 events above background,

for $300<E_\nu^{QE}<475$MeV

Deviation: 3.7σ

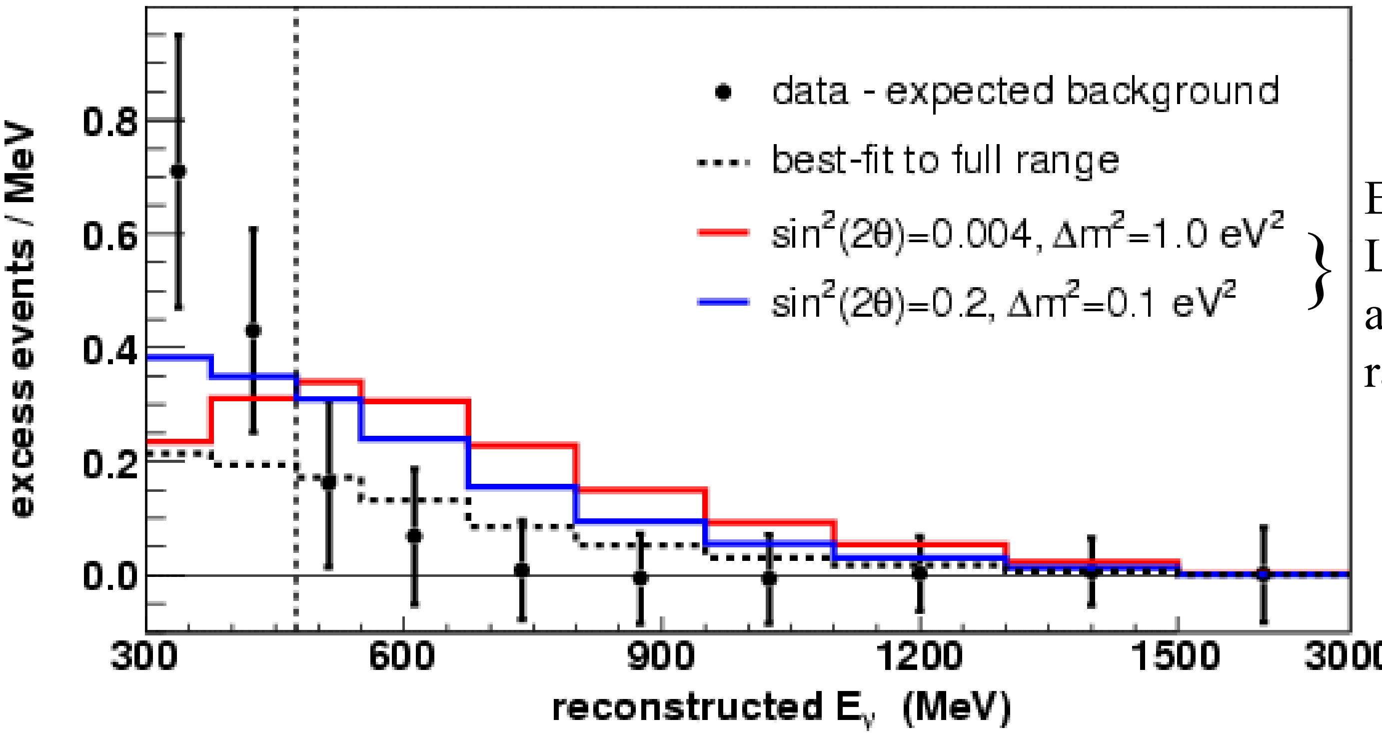
Background-subtracted:



Fit to the > 300 MeV range:

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

χ^2 Probability: 18%



Examples in LSND allowed range

This is interesting, but requires further investigation

⇒ A two-neutrino appearance-only model systematically disagrees with the shape as a function of energy.

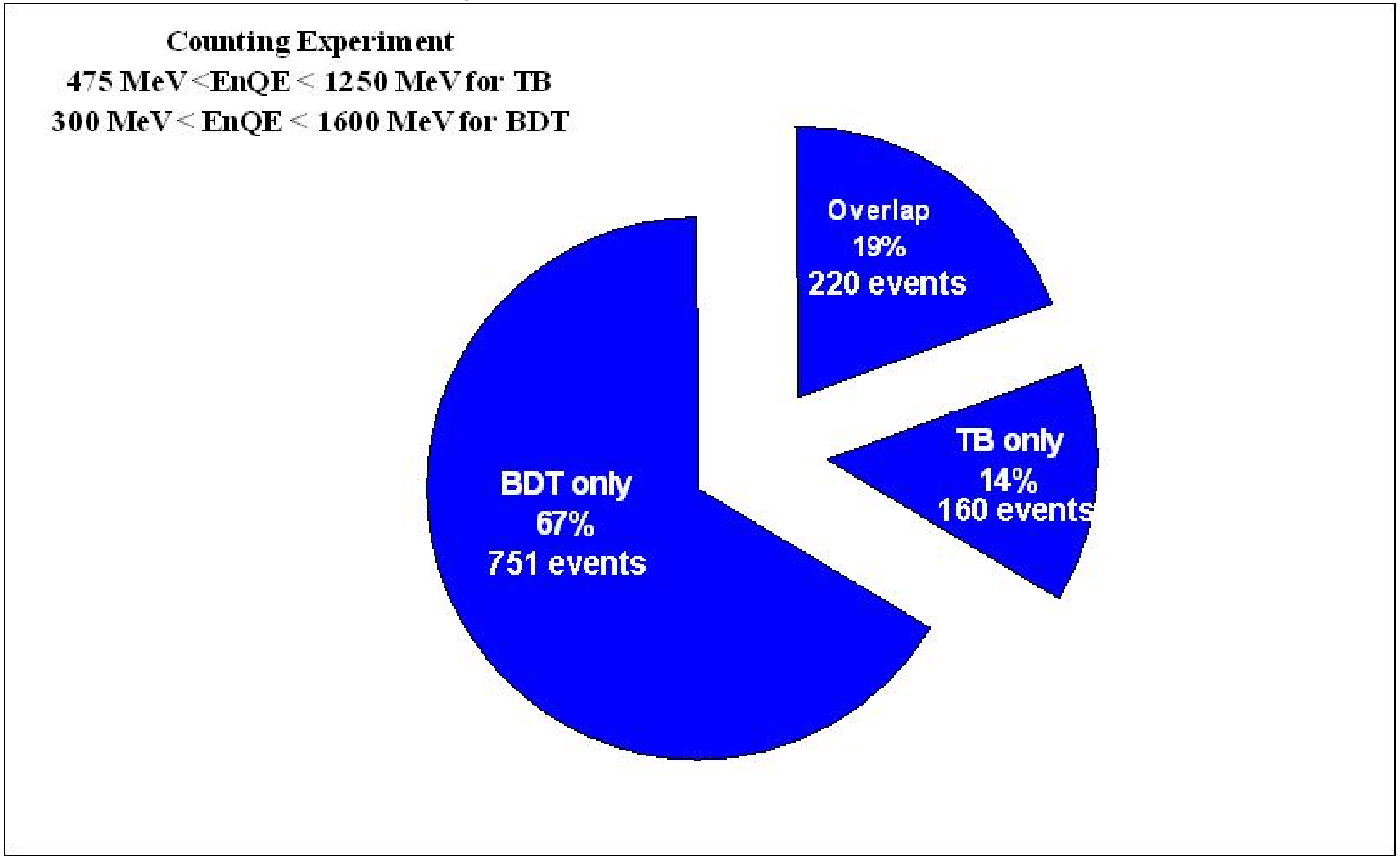
⇒ We need to investigate non-oscillation explanations, including unexpected behavior of low energy cross sections. *This will be relevant to future* $\nu_\mu \rightarrow \nu_e$ *searches*

This will be addressed by MiniBooNE and SciBooNE

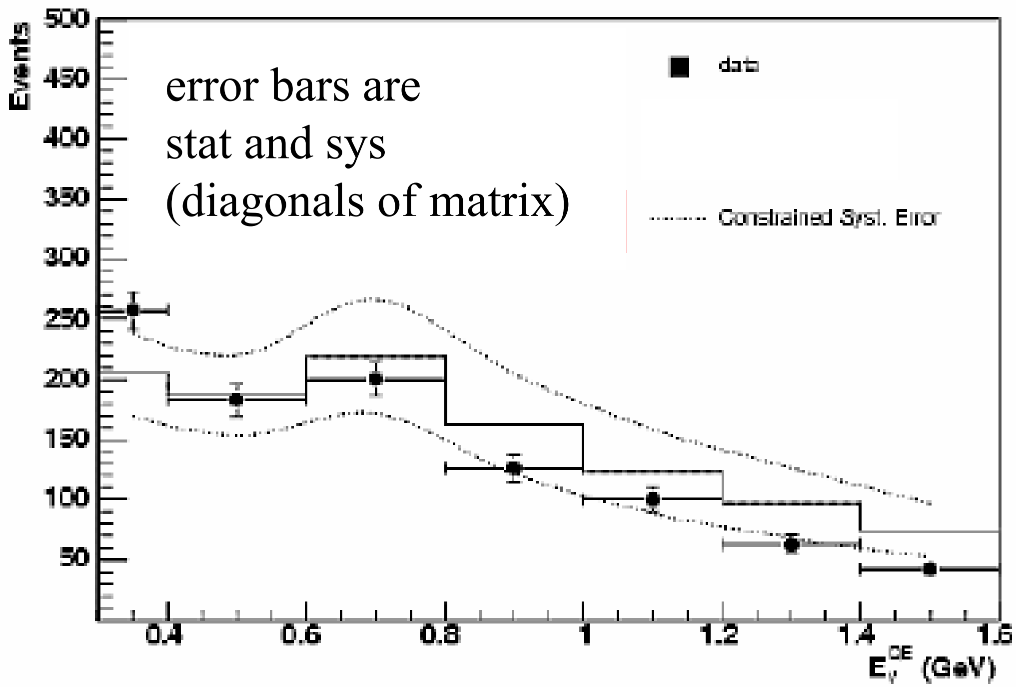
Boosted Decision Tree Analysis

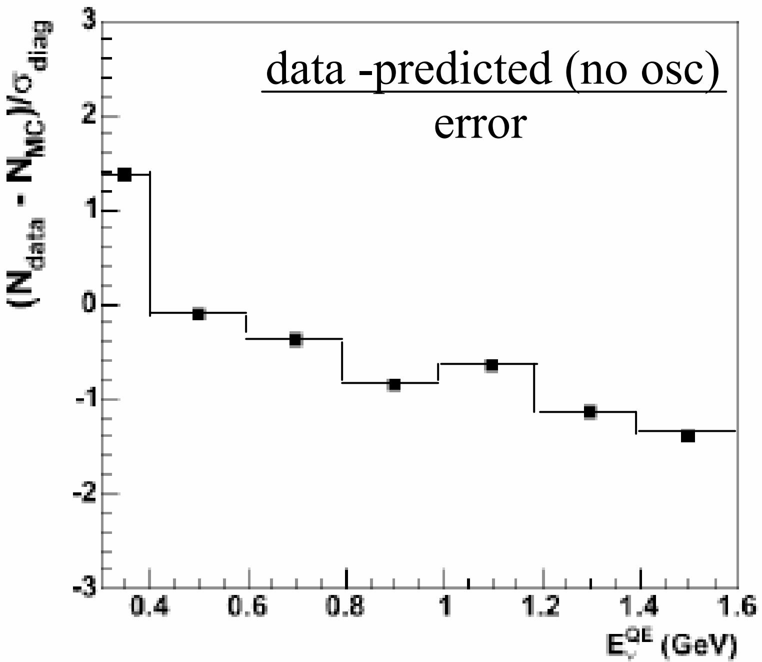
Counting Experiment: 300<E_ν^{QE}<1600 MeV
data: 971 events
expectation: 1070 ±33 (stat) ± 225 (sys) events
Sys/stat = 6.8

significance: –0.38 σ



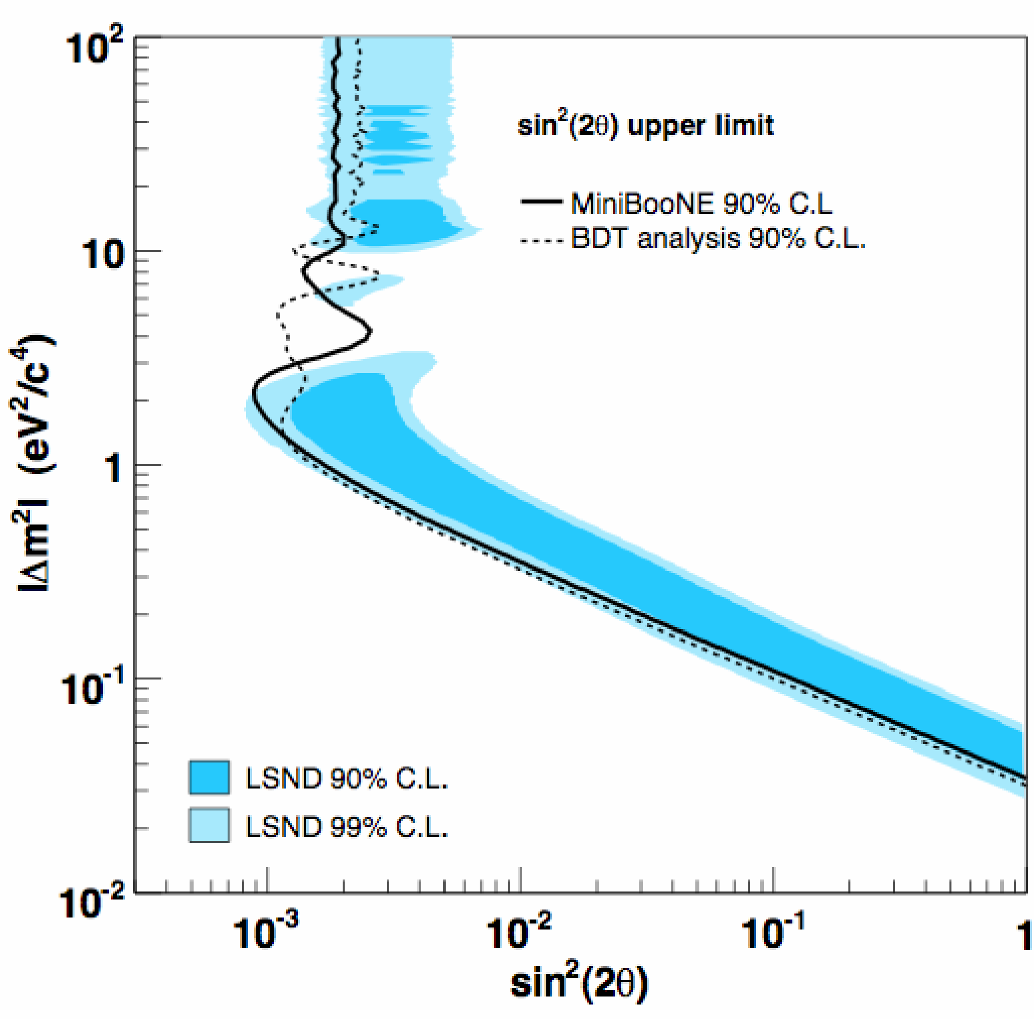
Boosted Decision Tree E_ν^{QE} data/MC comparison:





(sidebands used for constraint not shown)

Boosted Decision Tree analysis shows no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations.



Energy-fit analysis:
solid: TB
dashed: BDT

Independent analyses are in good agreement.

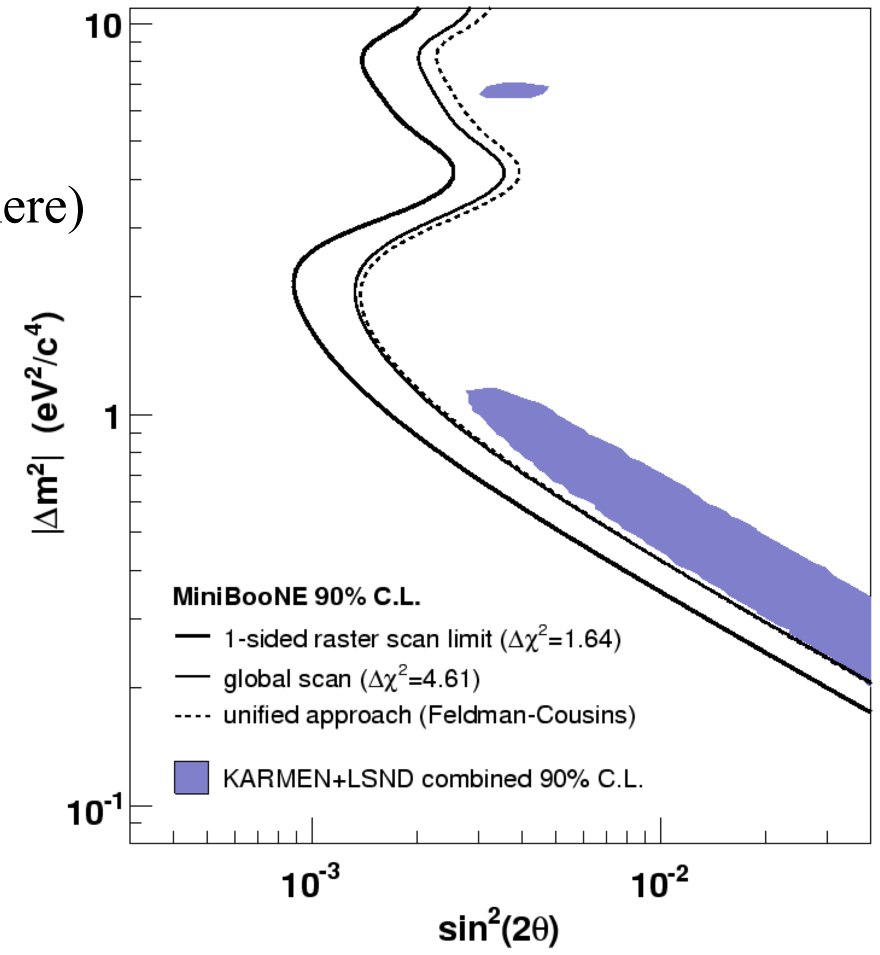
Two points on interpreting our limit

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.

A 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

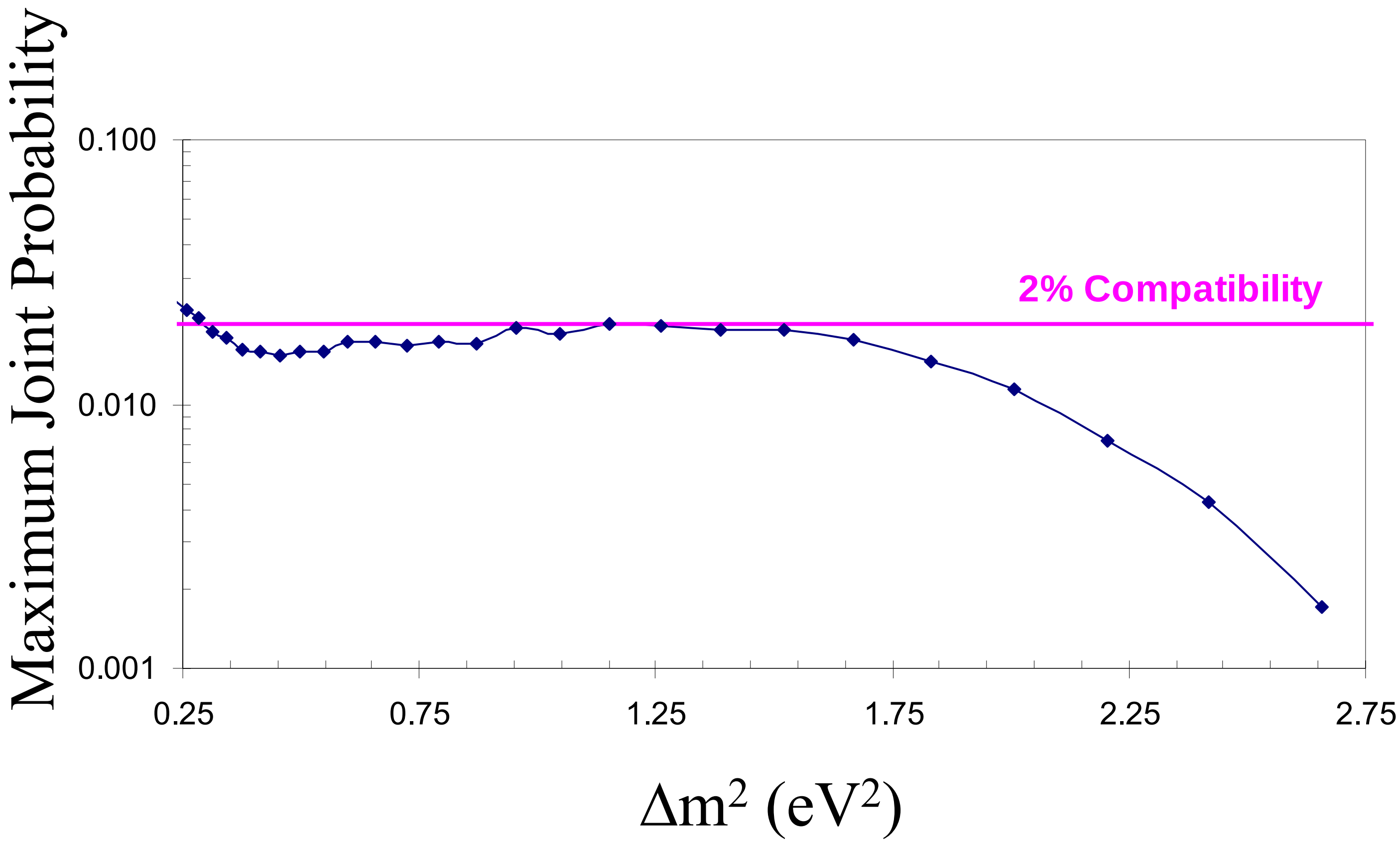
- For each Δm^2, form χ^2 between MB and LSND measurement

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

Plans:

A paper on this analysis has been posted to the "archive"
and to the MiniBooNE webpage.

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.

Improvements in sensitivity

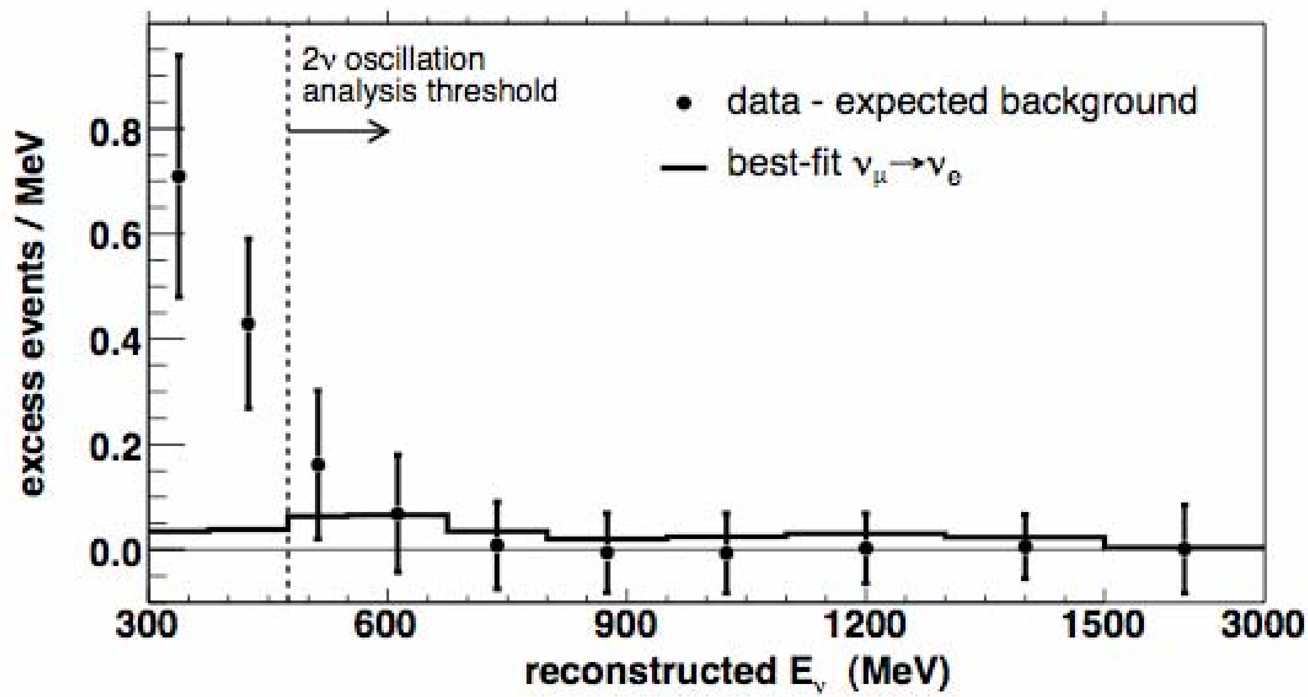
- Use the TB reconstruction to get BDT variables
- Re-examine systematic errors
- Use boosting value in fit, not as just a cut

Conclusions

Our goals for this first analysis were:

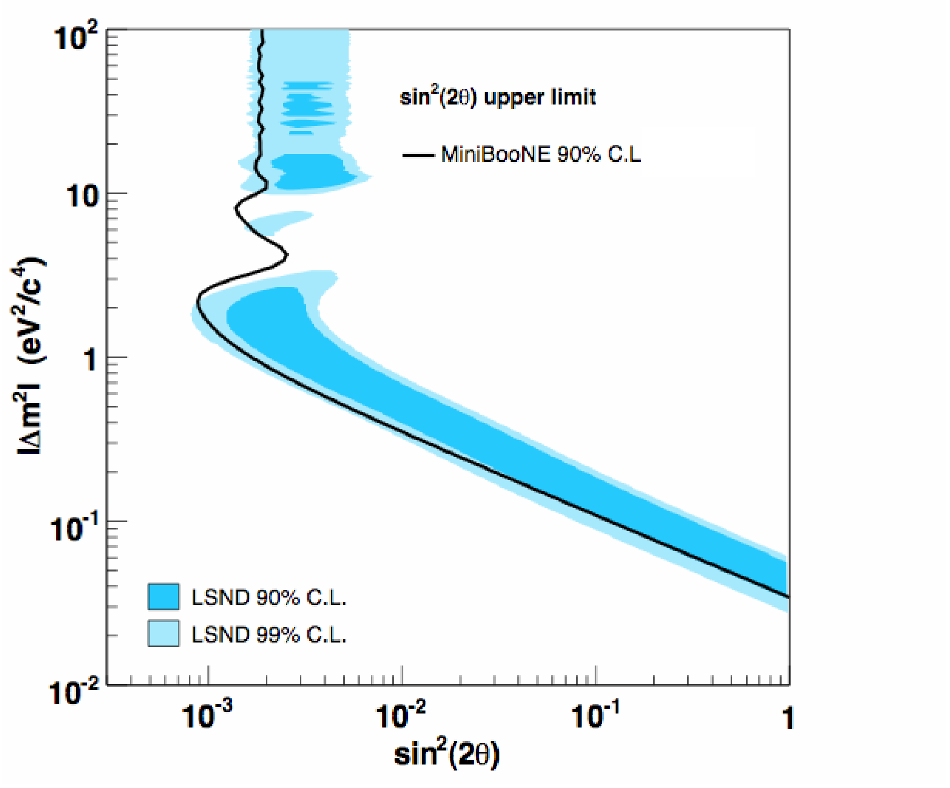
- A generic search for a ν_e excess in our ν_μ beam,
- An analysis of the data within a $\nu_\mu \rightarrow \nu_e$ appearance-only context

Within the energy range defined by this oscillation analysis, the event rate is consistent with background.



The observed low energy deviation is under investigation.

The observed reconstructed energy distribution is inconsistent with a $\nu_\mu \rightarrow \nu_e$ appearance-only model



Therefore we set a limit on $\nu_\mu \rightarrow \nu_e$ appearance

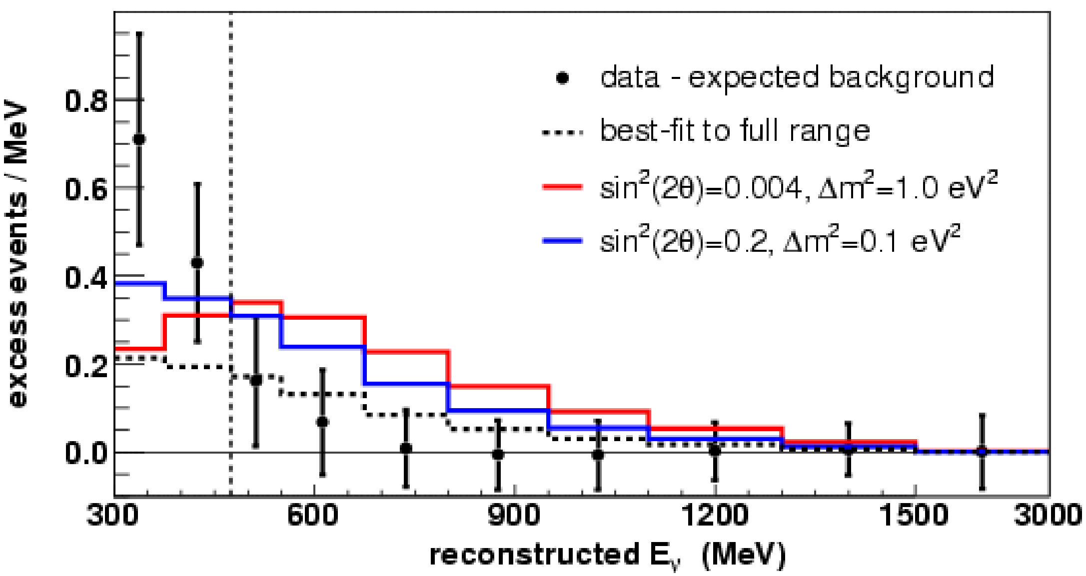
BACKUP

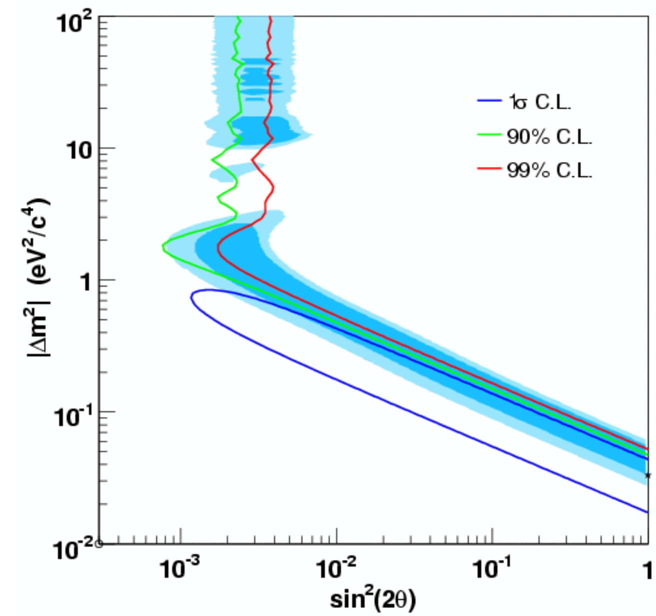
We Thank:

DOE and NSF

The Fermilab Divisions and Staff

Fit to the >300 Energy Range:



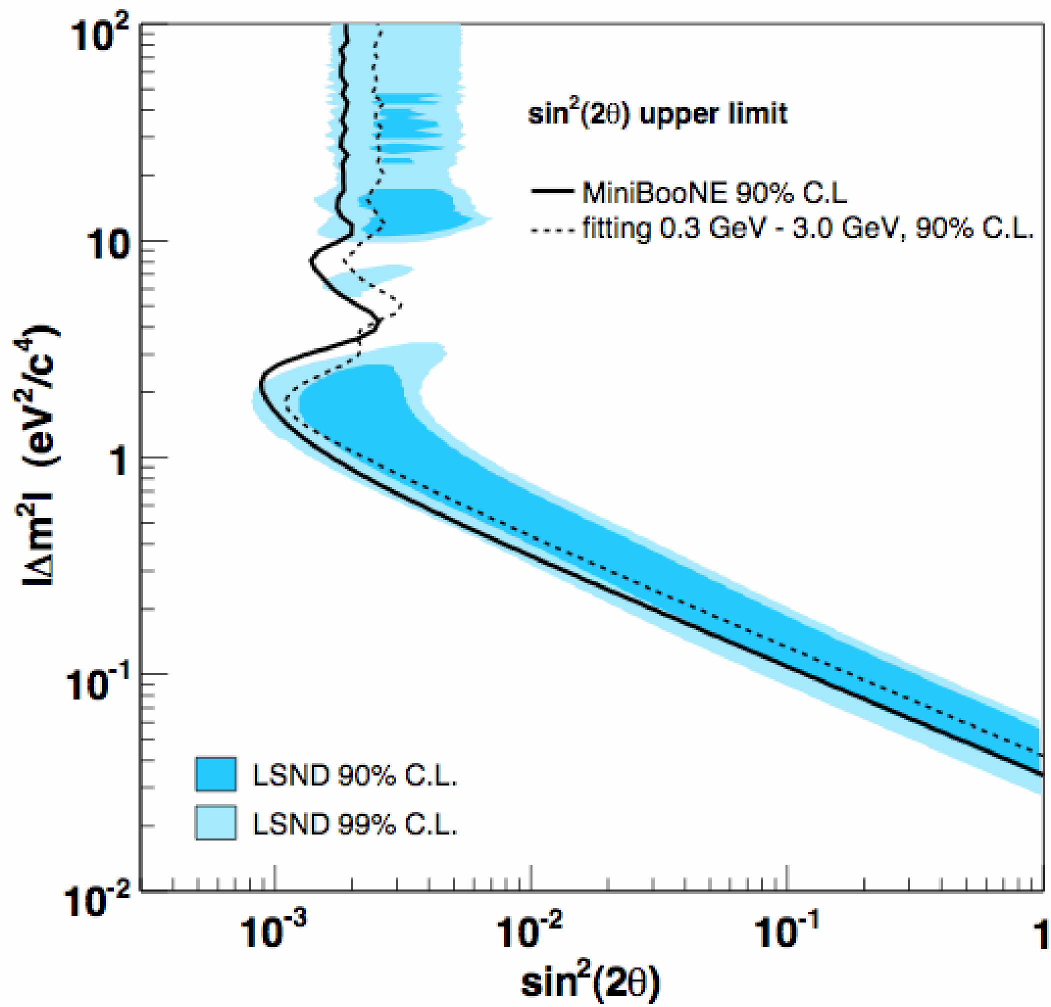


Best Fit (dashed): $(\sin^2 2\theta, \Delta m^2) = (1.0, 0.03\ \text{eV}^2)$

χ^2 Probability: 18%

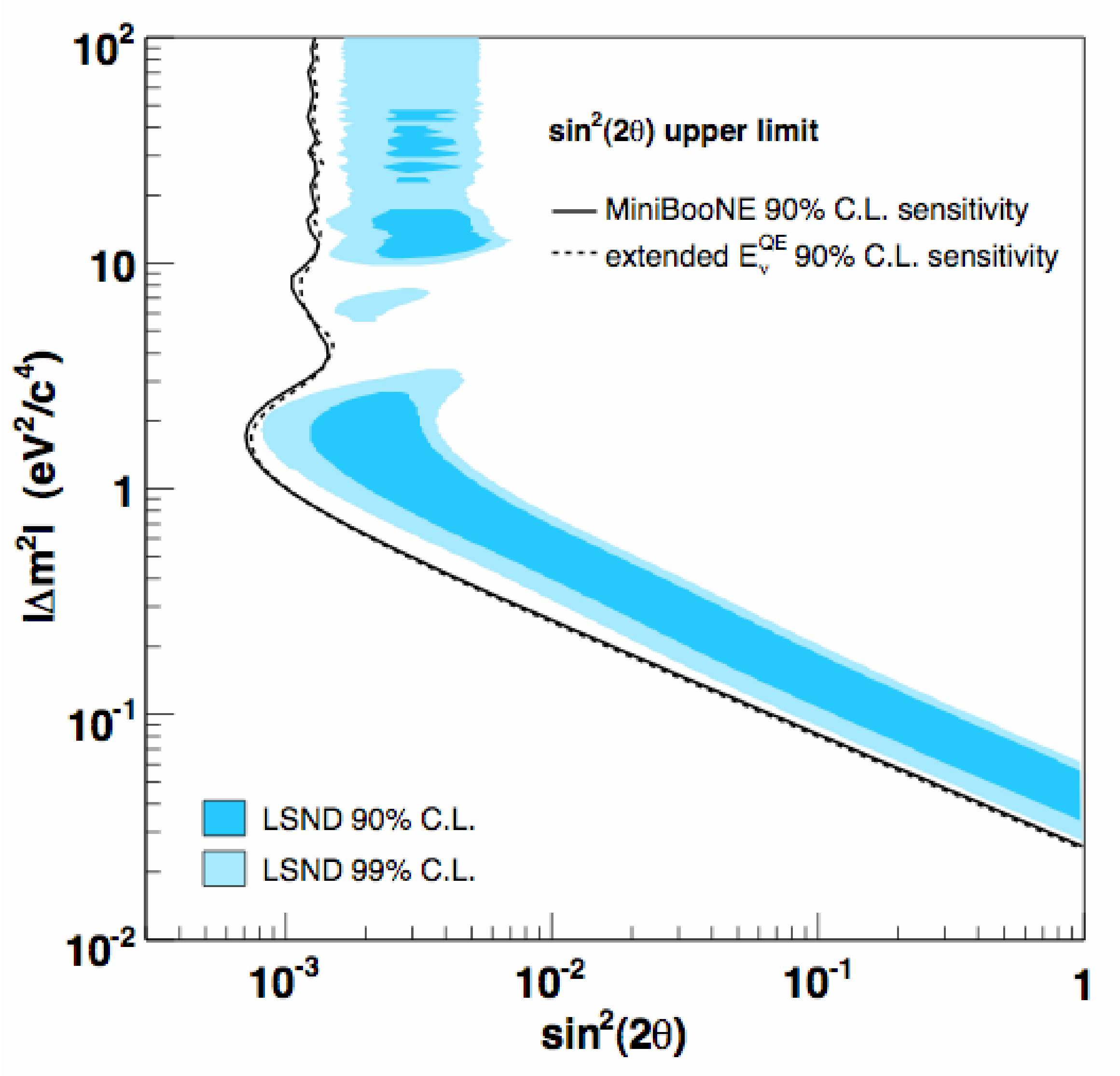
While the χ^2 is acceptable, there is a systematic shift in the energy dependence from the appearance-only model.

If the Track-based Analysis lower energy cut was 300 MeV rather than 450 MeV



solid: > 475 MeV
dashed: >300 MeV

Sensitivity for E_ν^{QE}>475 MeV and > 300 MeV



Normalization:

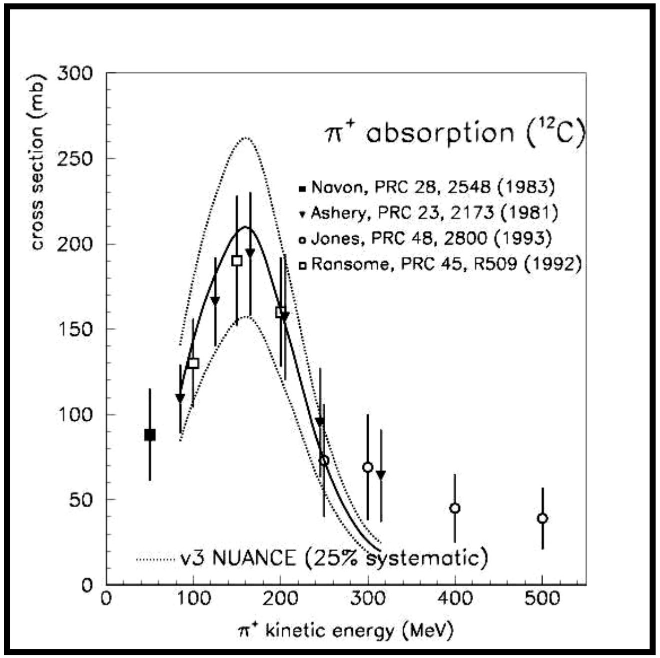
In our Run Plan, we reported a 1.5 data/MC normalization factor.
A series of corrections led to the present ratio of 1.2

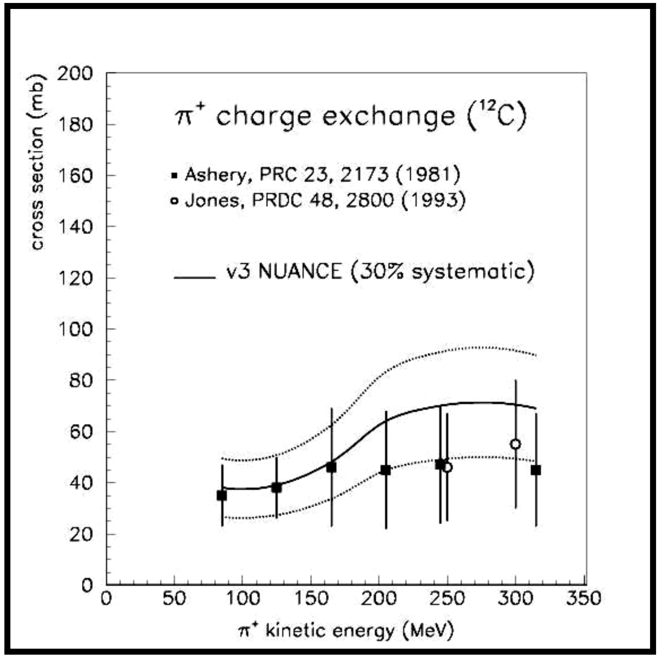
The important changes to the rate prediction were:

+17.5% from modeling beam optics to reflect measurement
+16.2% from HARP π^+ measurement and p-Be cross-sections
+3.1% from CCQE cross section tuning (M_A^{eff}, e_{lo}^{sf}, E_b, p_f)
–3.5% from adjustments to the inelastic cross section
–6.0% from secondary reinteractions in beamline

Final State Interaction Uncertainties (pion absorption and charge exchange) are from external data:

- π absorption 25%
  (inside target nucleus)
- π charge exchange 30%
  (inside target nucleus)
- $\Delta N \rightarrow NN$ rate 100%
- π^+ absorption 25%
  (in transit thru CH_2, wrt GCALOR)
- π^+ charge exchange 50%
  (in transit thru CH_2, wrt GCALOR)





Blindness and Algorithm Development

To test the algorithms, define specific event sets ("boxes") with $< 1\sigma$ signal in an energy-based analysis

Initial Boxes:

0.25% random sample -- an unbiased cross check

michel electrons -- electron subevents from cosmic rays

CCQE -- ν_μ CCQE events used to constrain the flux

CCπ+ -- ν_μ CC production with π+ used to constrain cross section

NCπ0 -- ν_μ neutral pion production used

ν-e elastic -- electron events for MC comparison

"dirt" -- External-to-tank neutrino events putting energy in the tank, used to measure rate from entering background.

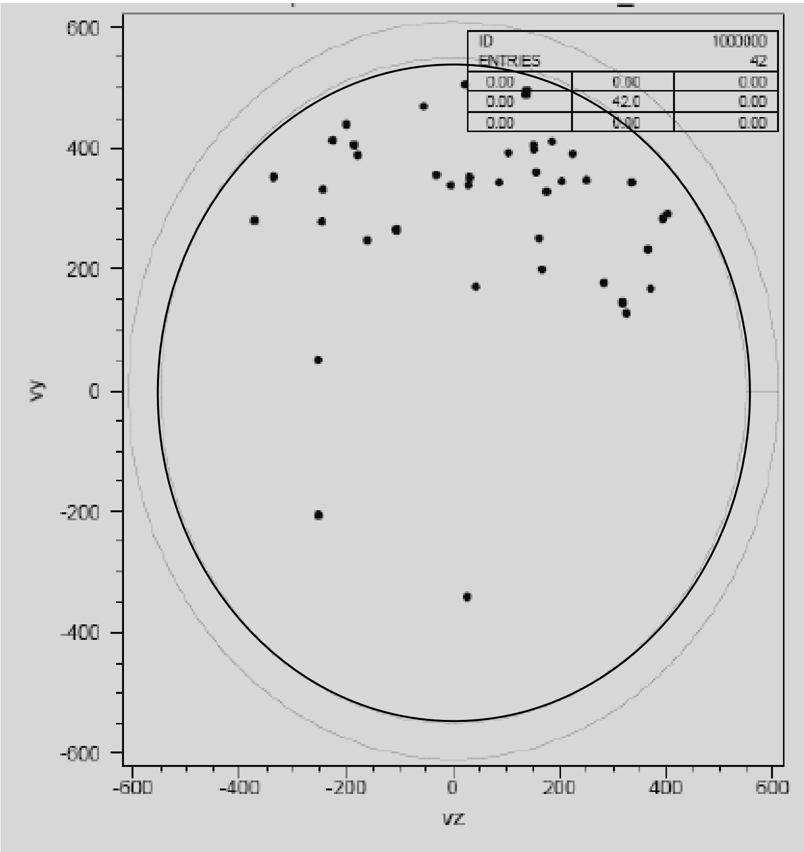
High Energy Events -- all events with energy that is above the 90% CL signal region, E_ν>1.4 GeV, used as a cross-check

Second Step: All-but-signal box -- explicitly sequester the signal

Cosmic Rays

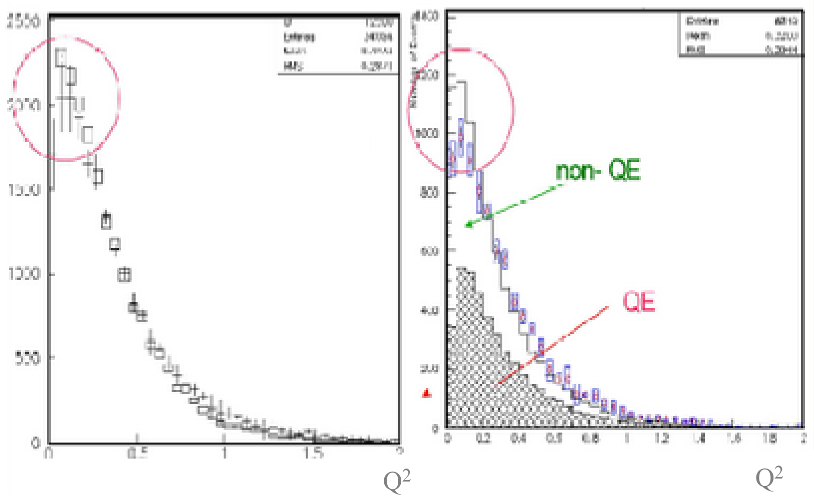
Measured from our strobe data, using BDT analysis:
2.1 ± 0.5 events in the beam window

Loosening the cut, these events populate upper region of tank

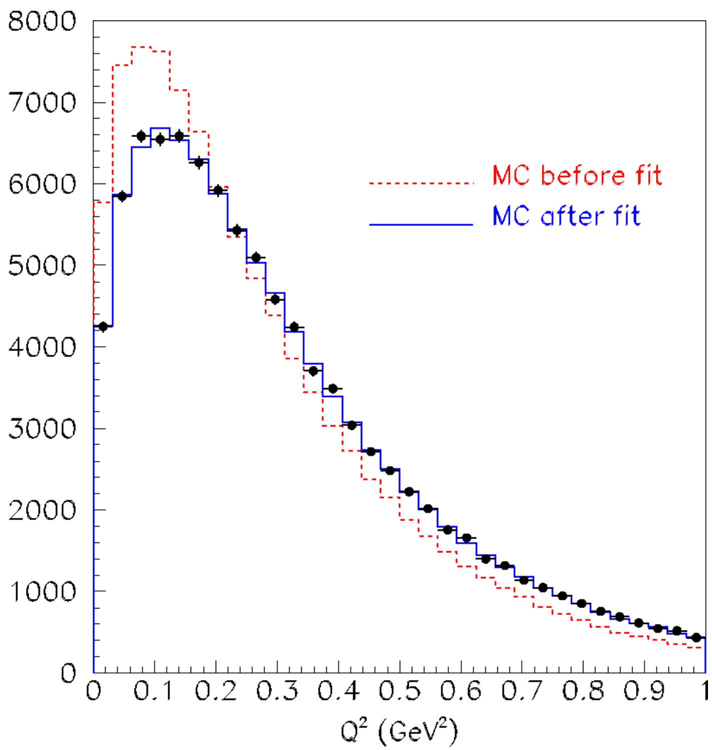


For nuclear targets there has been a mystery in the Q^2 distribution...

K2K
H_2O
“1kt”
detector



K2K
Carbon
“SciFi”
detector

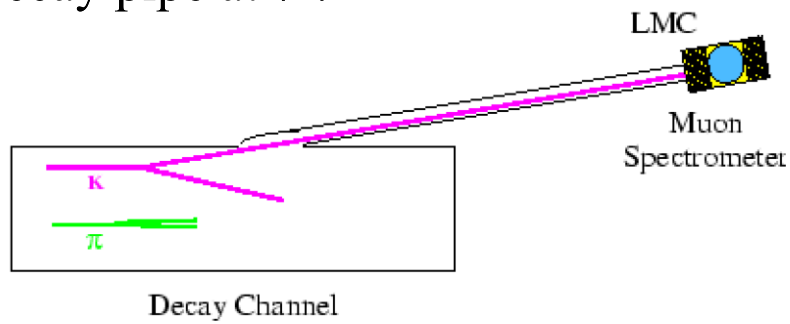


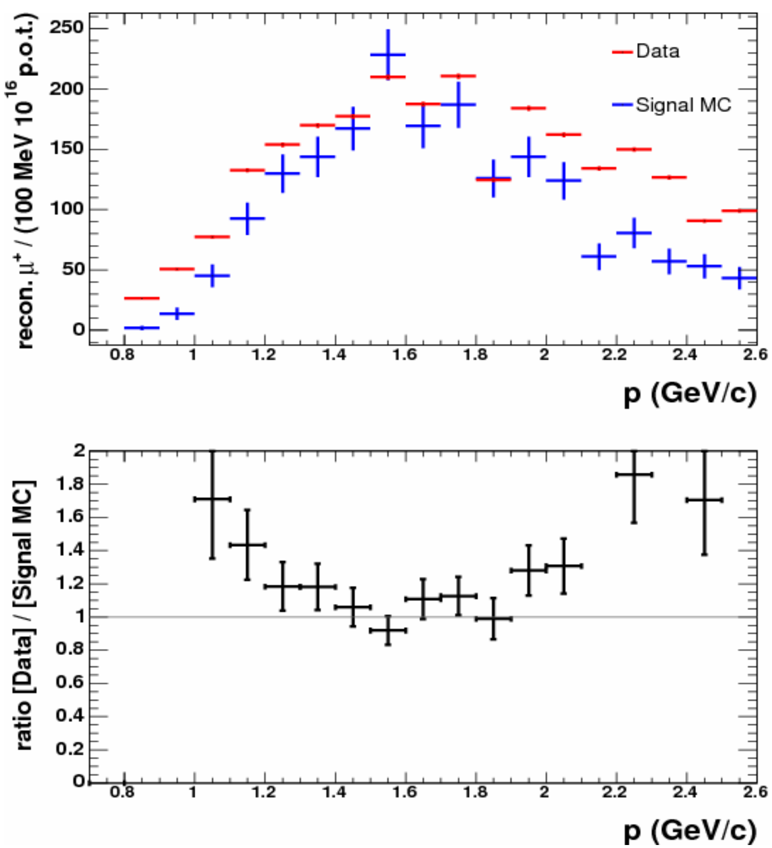
MiniBooNE sees this effect too

We can fit our data
if we adjust parameters
in our nuclear model
including “Pauli Blocking”
(accounting for energy level differences
when converting C to N)

In-situ cross check of K^+ model: LMC (Little Muon Counter):

- 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.





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.