First Results from MiniBooNE

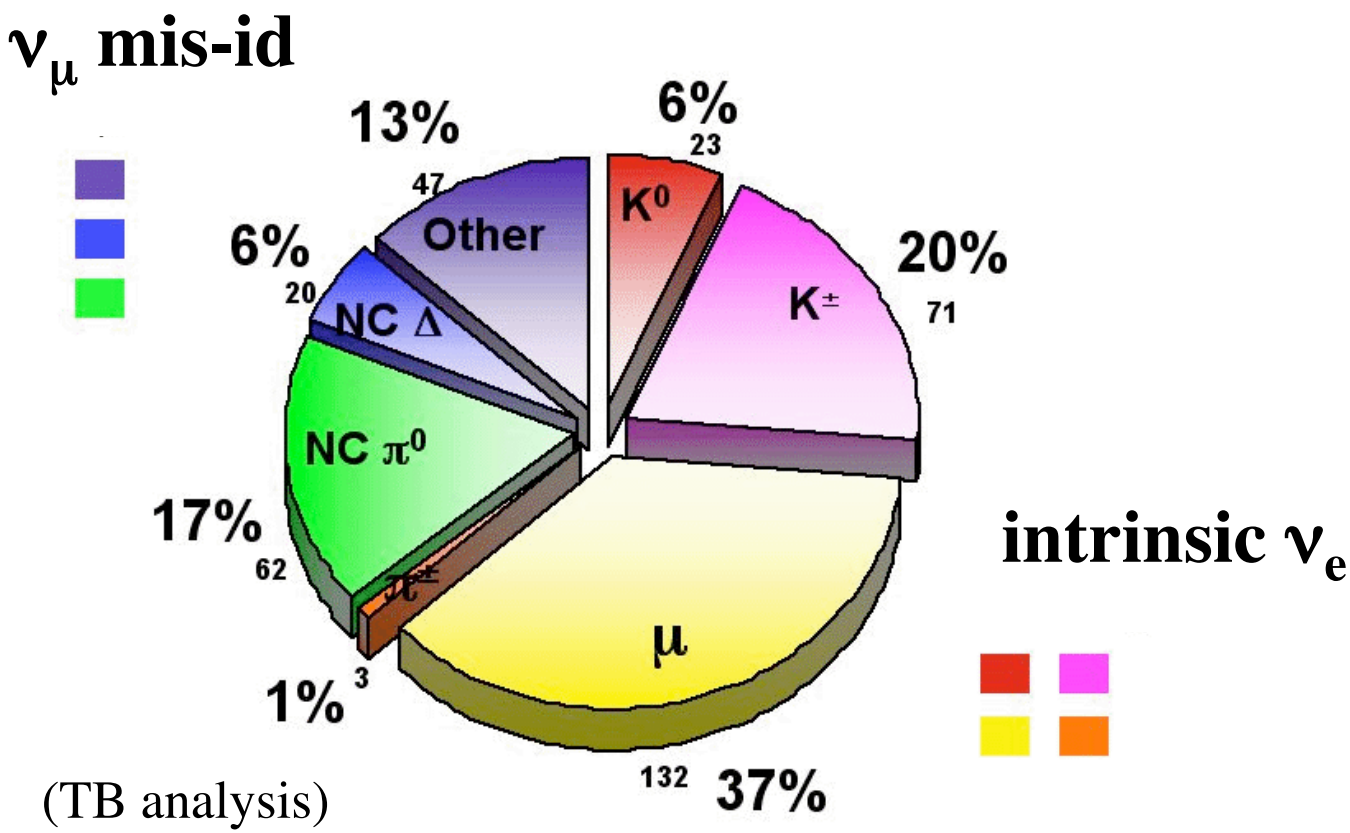
April 11, 2007

William Louis, Janet Conrad

for the MiniBooNE Collaboration

Errors, Constraints and Sensitivity

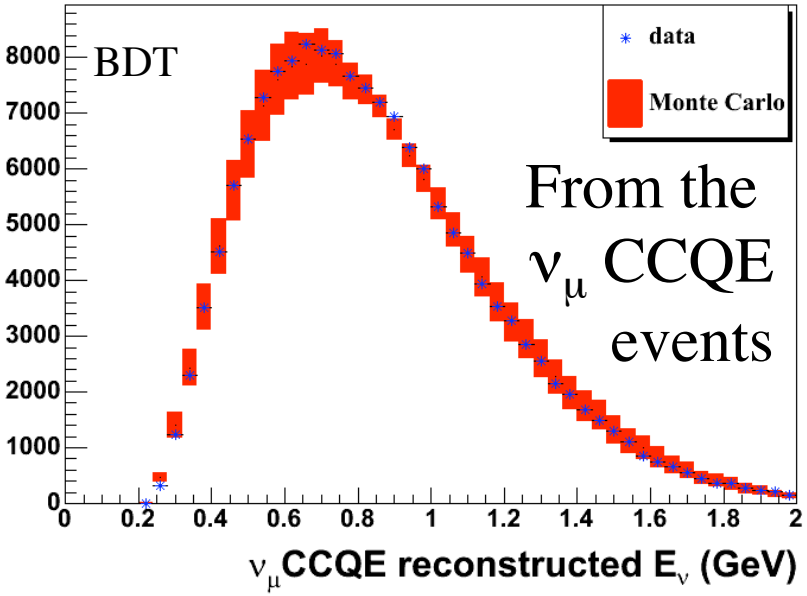
We have two categories of backgrounds:



(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	√	



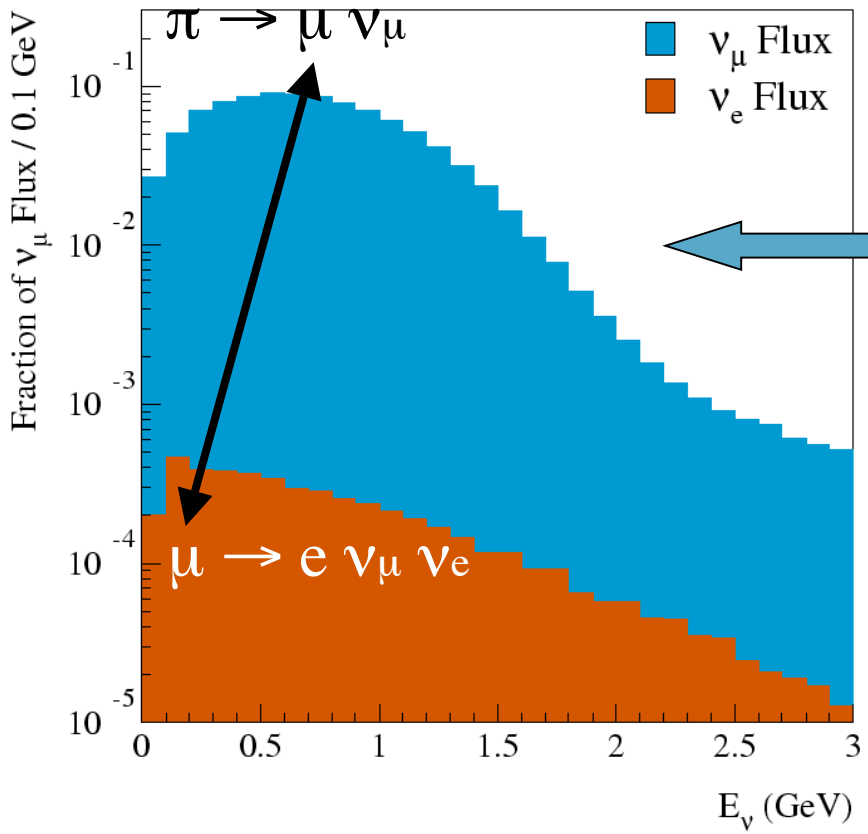
Predict

Normalization
& energy dependence
of both background
and signal

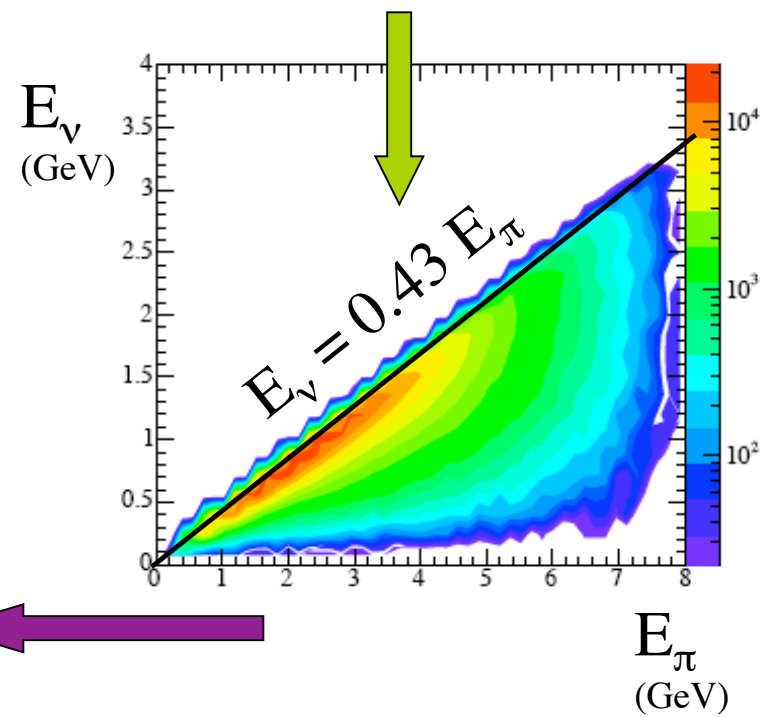
Data/MC Boosted Decision Tree: 1.22 ± 0.29
Track Based: 1.32 ± 0.26

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

ν_μ constraint on intrinsic ν_e from π^+ decay chains

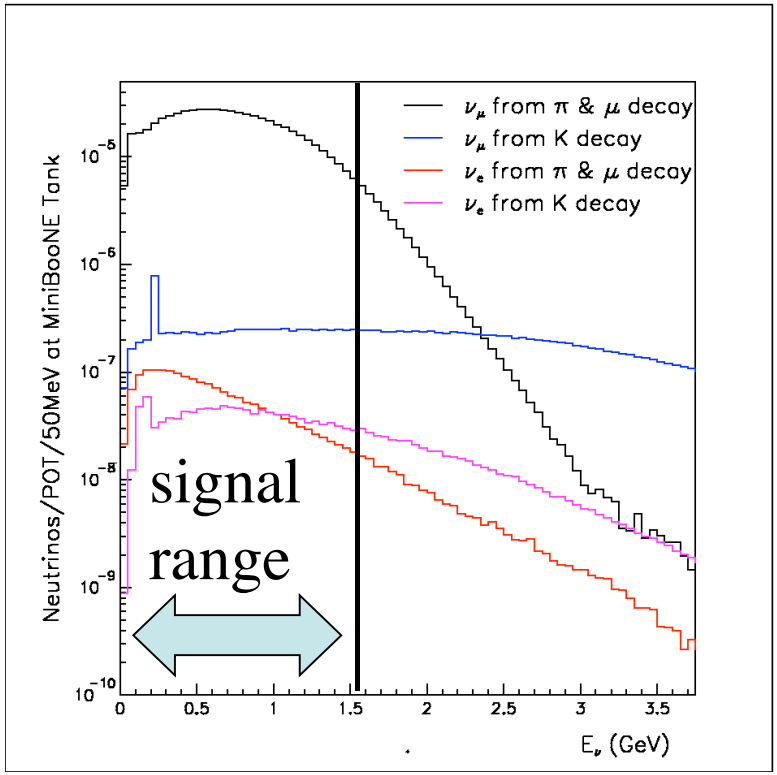


- Measure the ν_μ flux
- Kinematics allows connection to the π flux

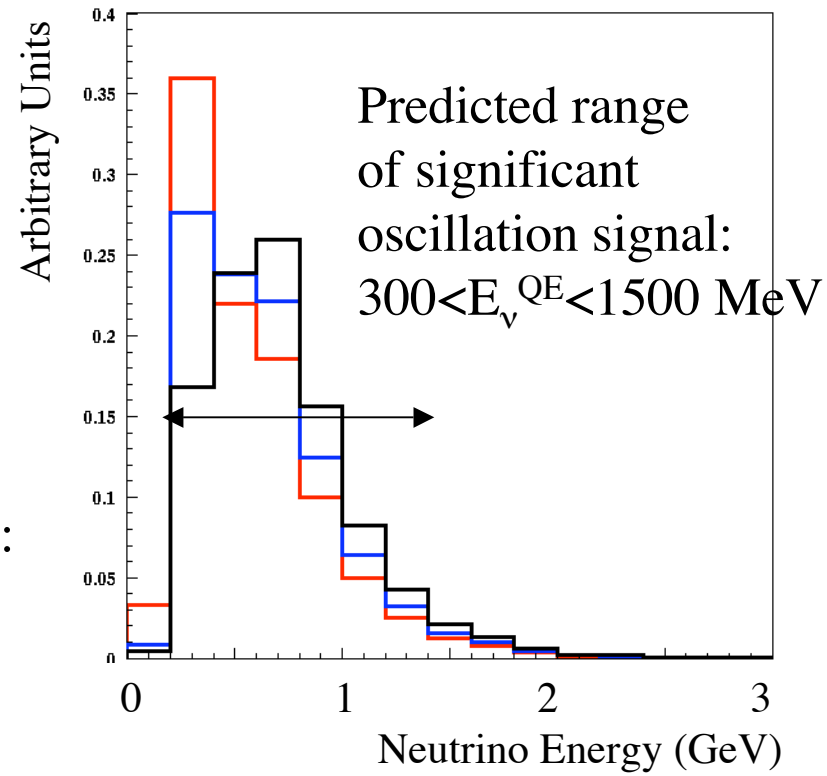


- Once the π flux is known, the μ flux is determined

K^+ and K^0 decay backgrounds

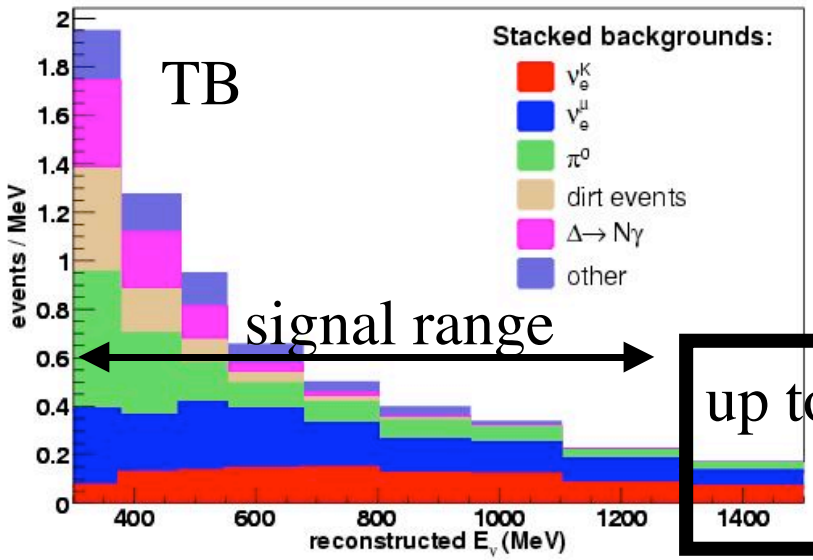


At high energies,
above "signal range"
ν_μ and "ν_e -like" events are
largely due to kaon decay



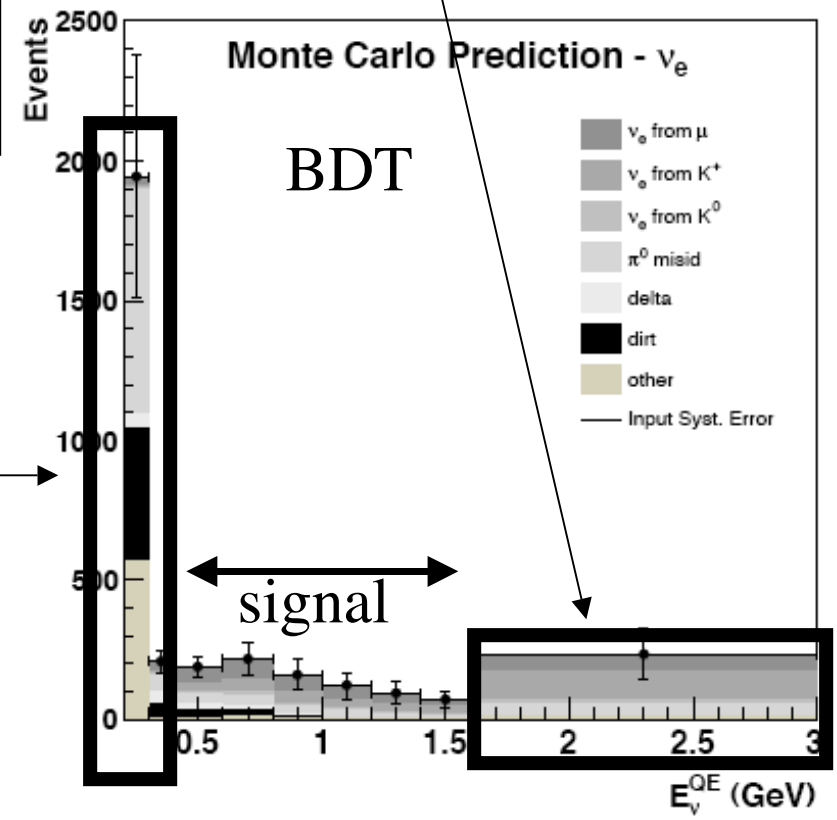
Signal examples:
$\Delta m^2=0.4$ eV^2
$\Delta m^2=0.7$ eV^2
$\Delta m^2=1.0$ eV^2

Use of low-signal/high-background energy bins



up to 3000 MeV

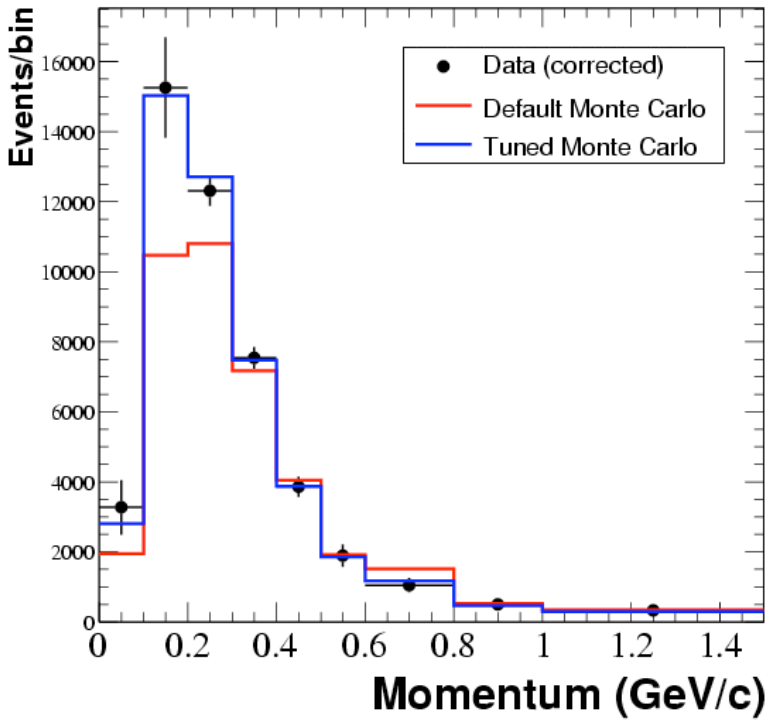
In both analyses, high energy bins constrain ν_e background



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

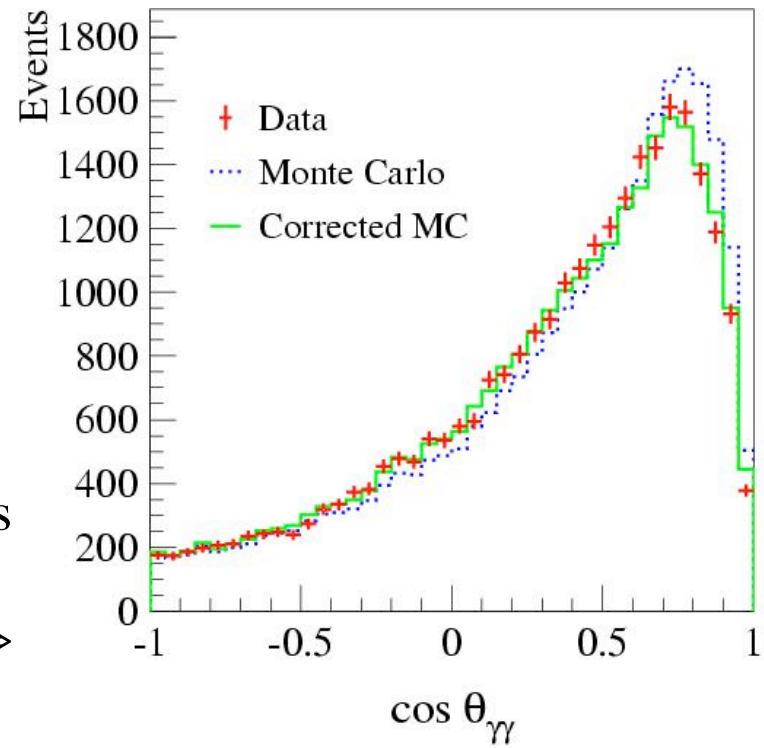
constrains ν_μ mis-ids:
π^0, $\Delta \rightarrow N\gamma$, dirt ...

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 Δ→Nγ

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

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

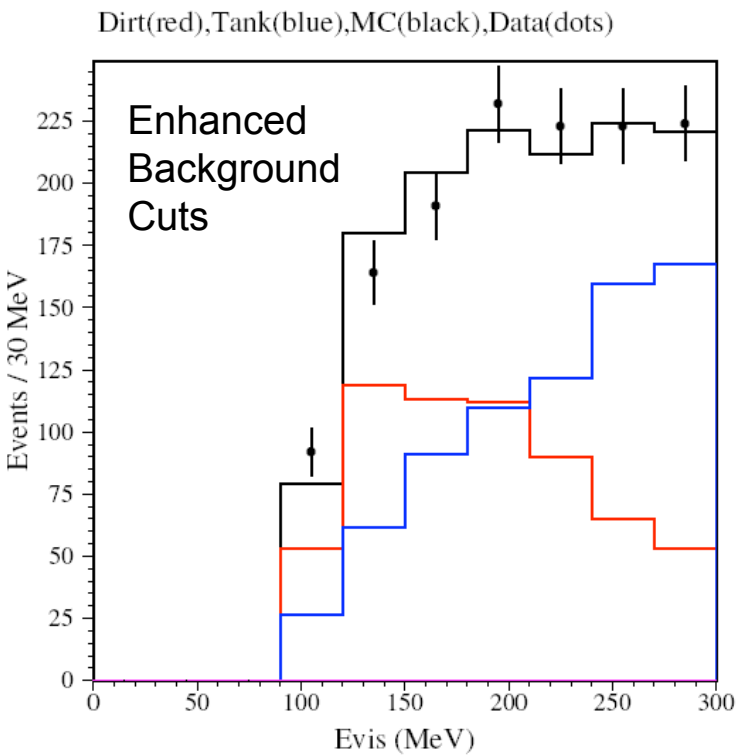
where the presence of the γ leads to mis-identification

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

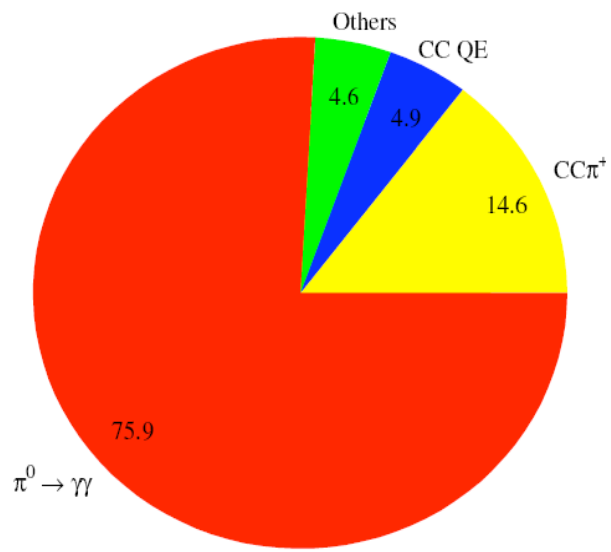
External Sources of Background

"Dirt" Events

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



Event Type of Dirt after PID cuts



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_L^0 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...

For a given source
of uncertainty,

Errors on a wide range
of parameters
in the underlying model

... what we need

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

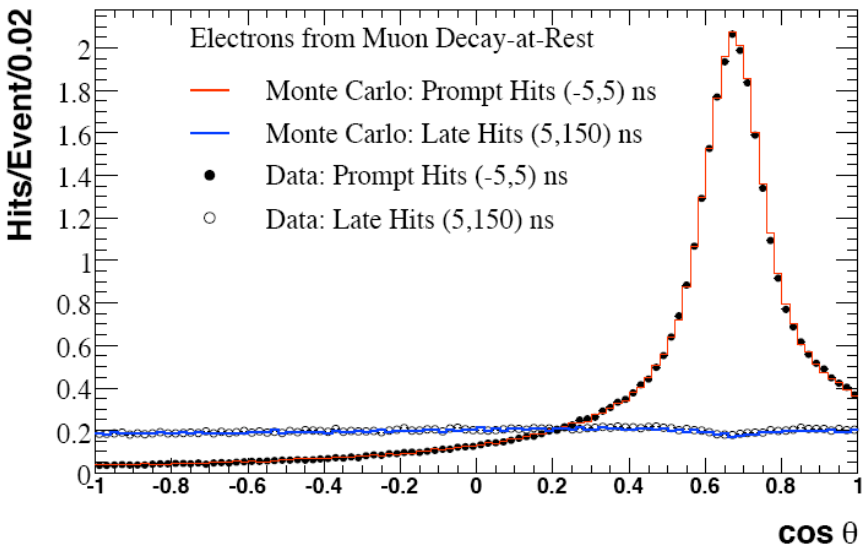
(Many are common to ν_μ and ν_e and cancel in the fit)

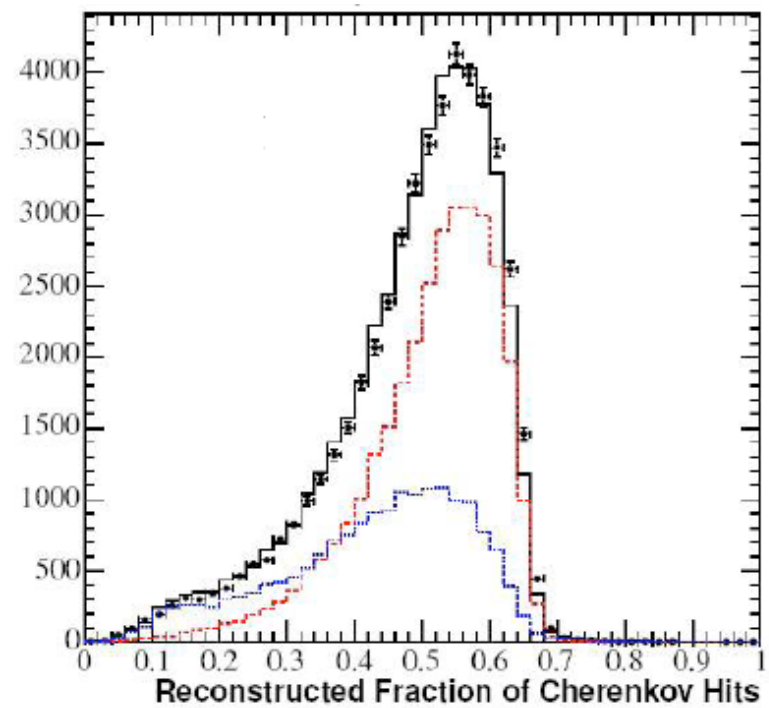
M_A^{QE}, e_{lo}^{sf}	6%, 2% (stat + bkg only)	determined from MiniBooNE ν_μ QE data
QE σ norm	10%	
QE σ shape	function of E_ν	
ν_e/ν_μ QE σ	function of E_ν	
NC π^0 rate	function of π^0 mom	determined from MiniBooNE ν_μ NC π^0 data
M_A^{coh}, coh σ	±25%	
$\Delta \rightarrow N\gamma$ rate	function of 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,

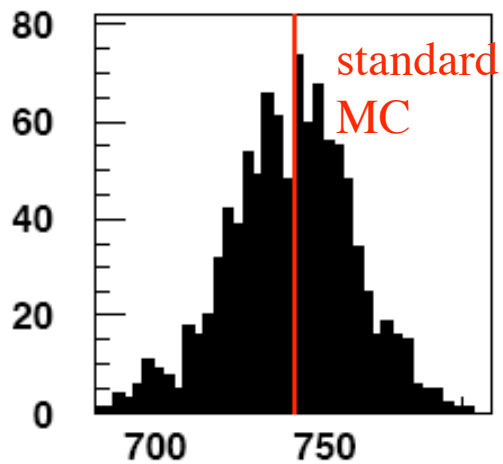
"Multisims" are generated within the allowed variations by reweighting the standard Monte Carlo.

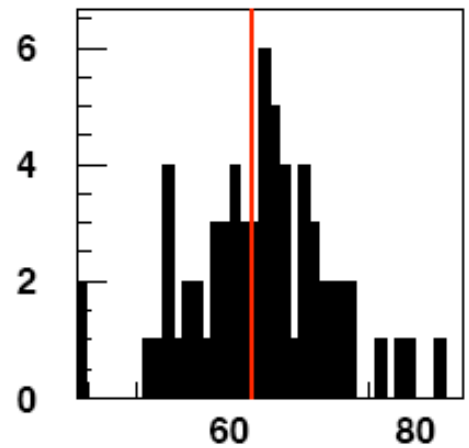
In the case of the OM, hit-level simulations are used.

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:

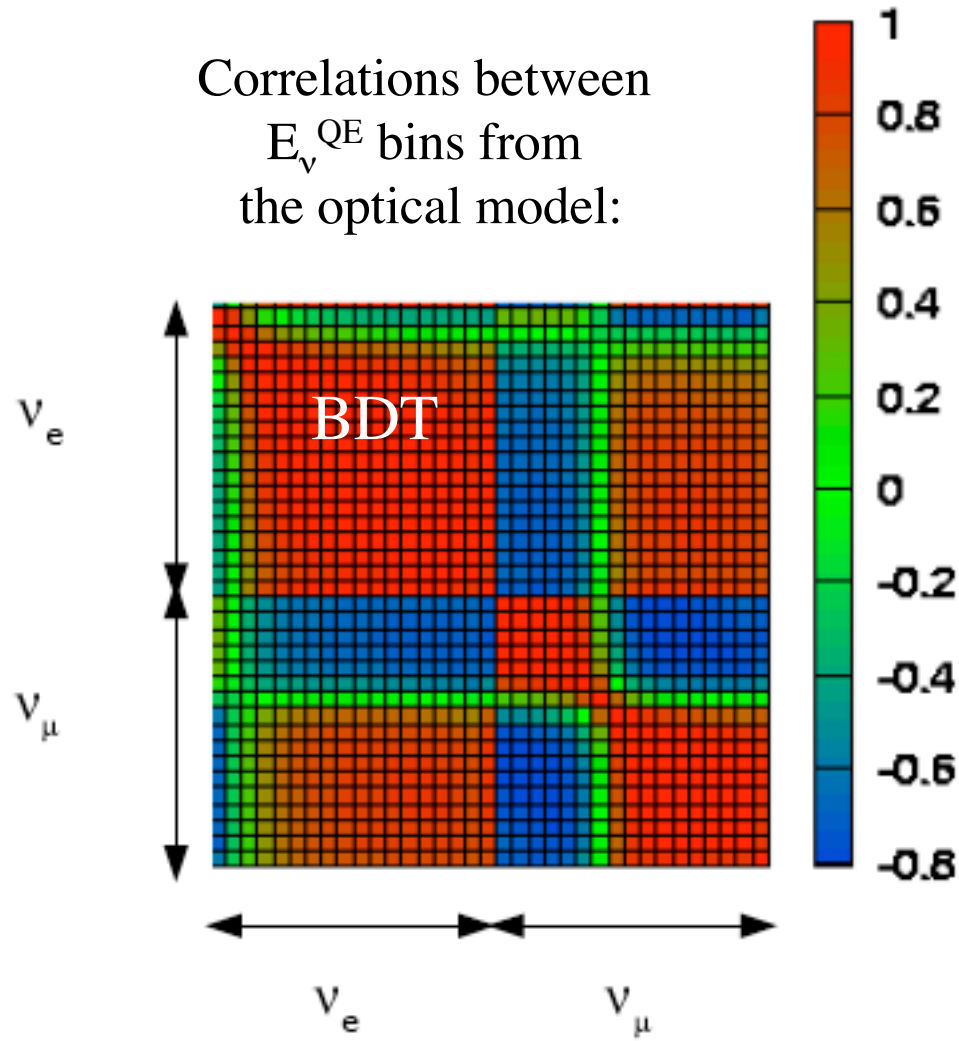
$$E_{ij} \approx \frac{1}{M}\sum_{\alpha=1}^{M}\left(N_i^{\alpha} - N_i^{MC}\right)\left(N_j^{\alpha} - N_j^{MC}\right)$$

- 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

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:



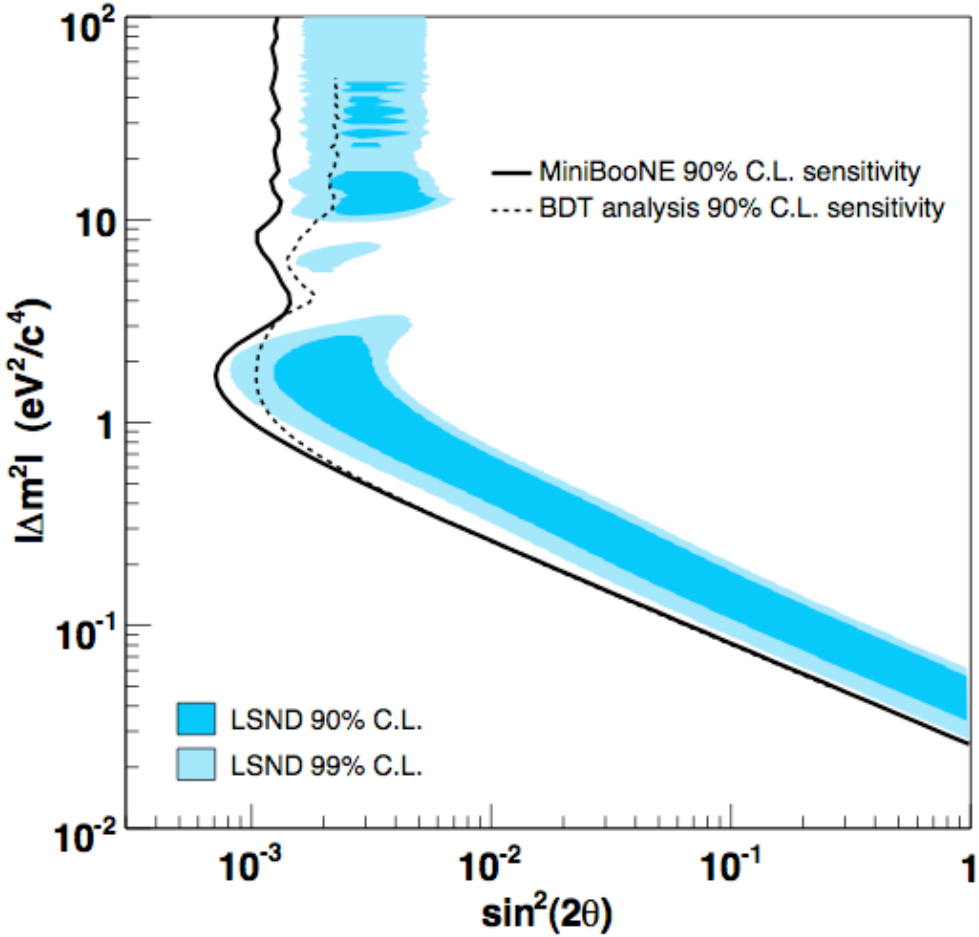
As we show distributions in E_ν^{QE},
keep in mind that error bars are
the diagonals of the error matrix.

The effect of correlations between E_ν^{QE} bins
is <u>not</u> shown,

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

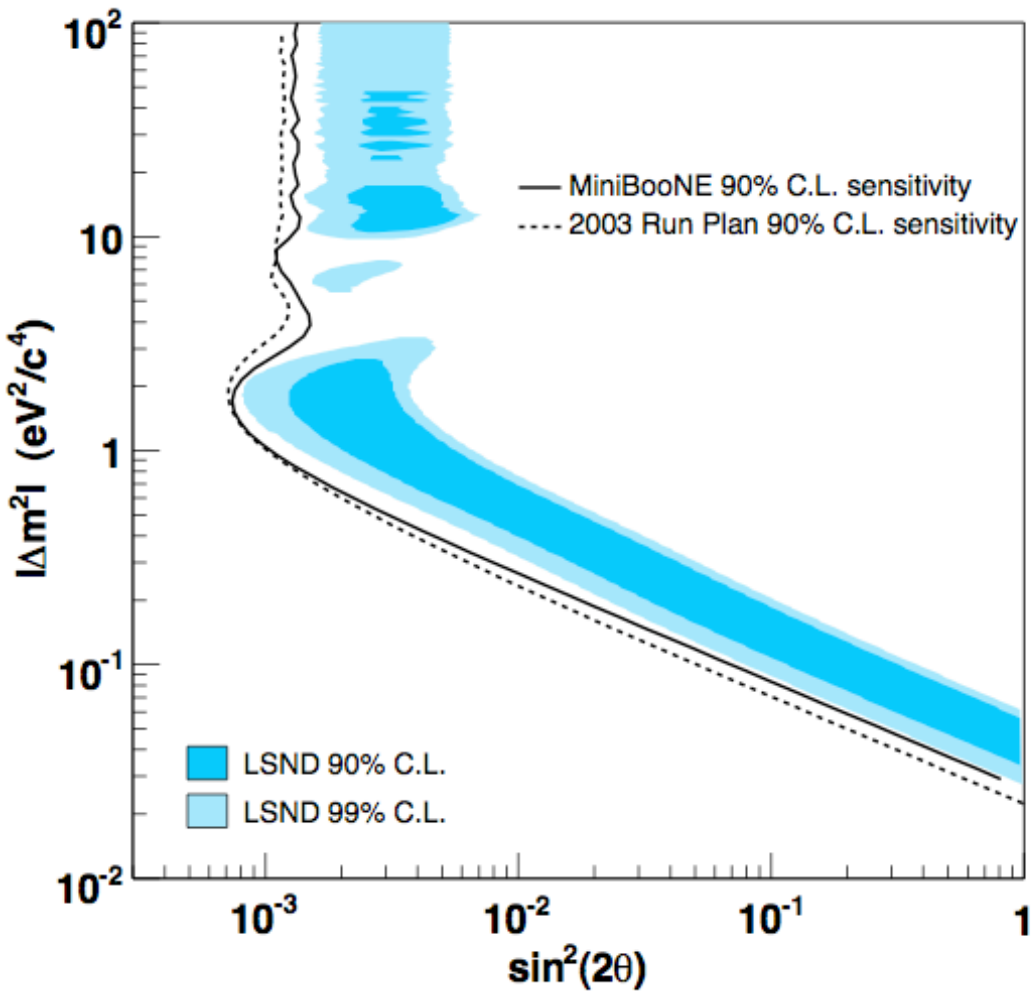
Sensitivity of the two analyses

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...

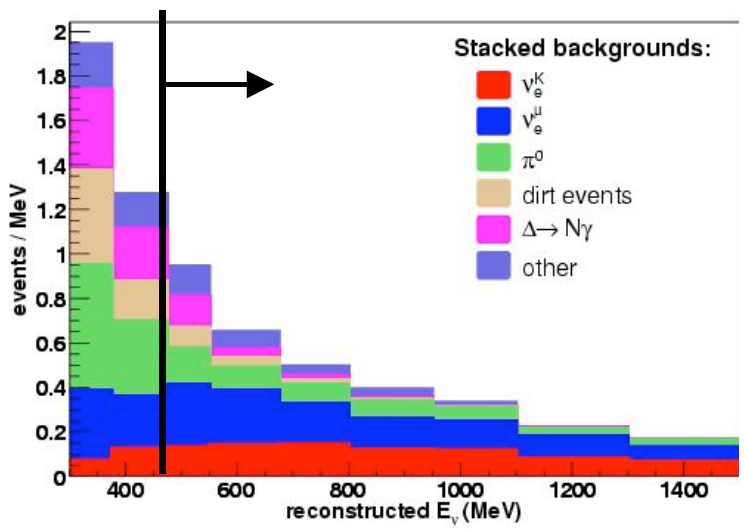
Track Based analysis χ^2 Probability of $E_{visible}$ fit: 1%

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:



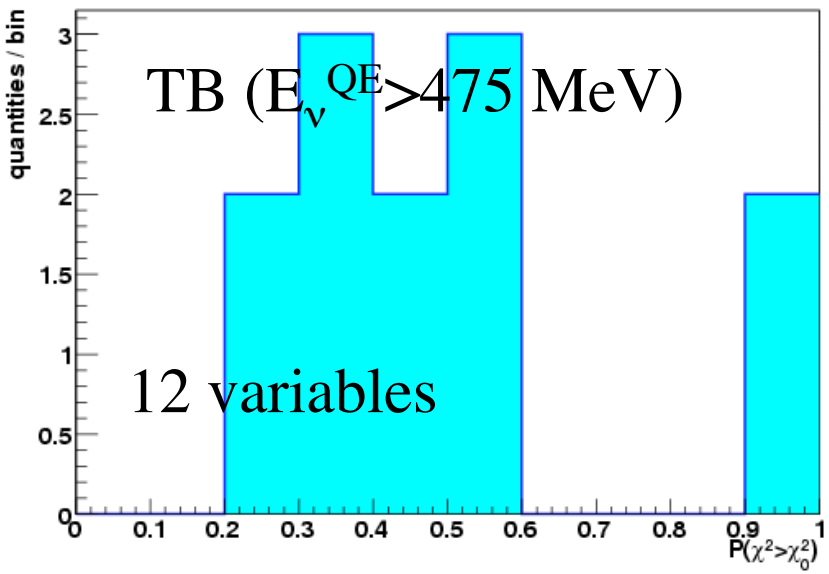
$E_\nu^{QE} > 475$ MeV

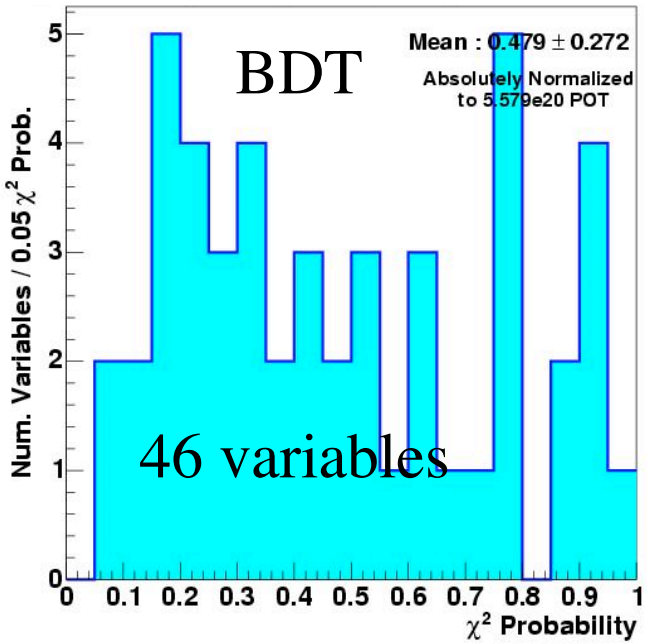
We agreed to report events over the original full range: $E_\nu^{QE} > 300$ MeV,

Step 1: again!

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

χ^2 probabilities returned:



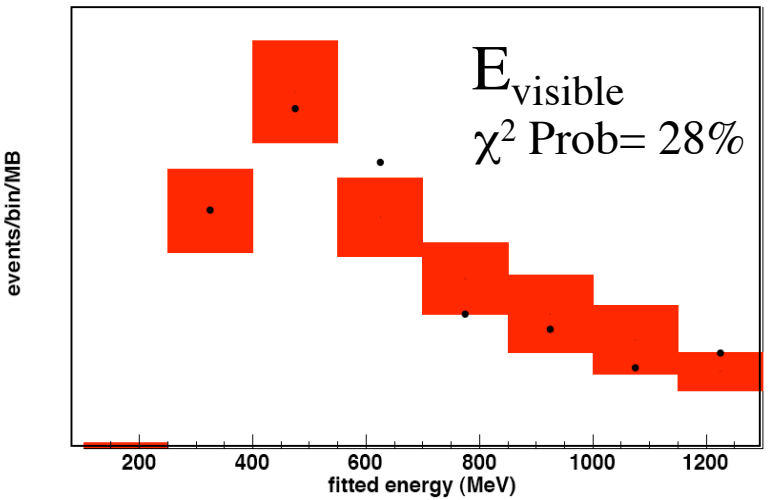


Parameters of the oscillation fit were not returned.

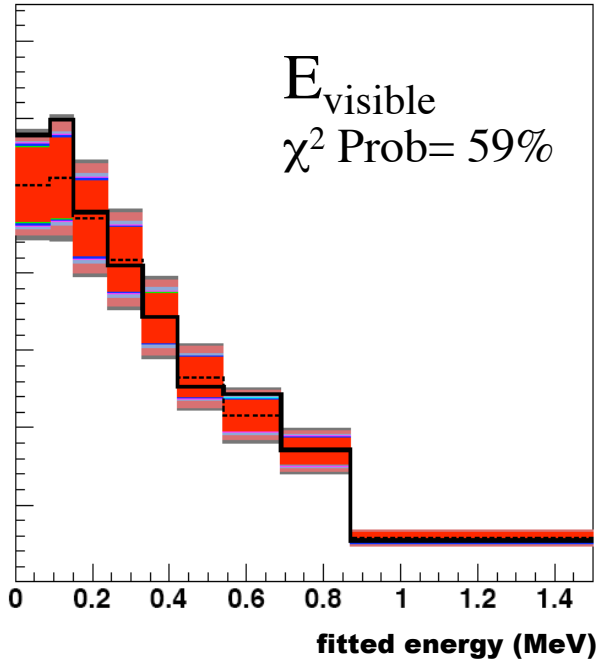
Step 2

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...

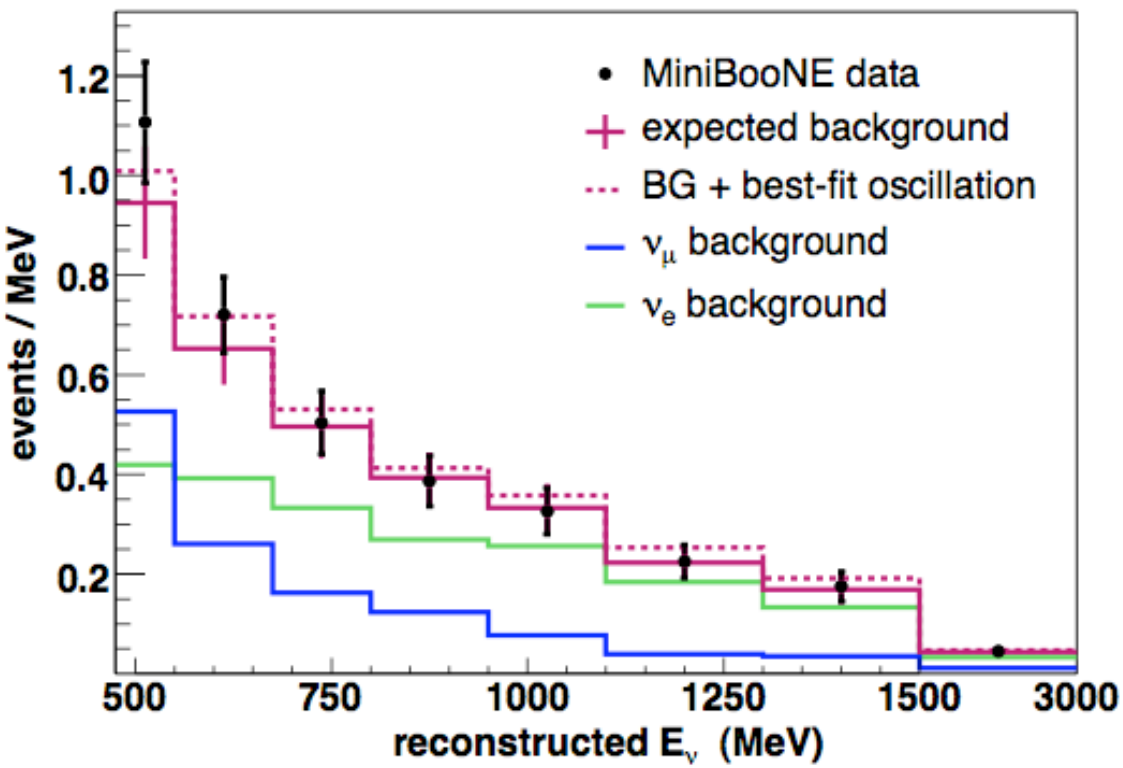
The Track-based $\nu_\mu \rightarrow \nu_e$ Appearance-only Result:

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

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

significance:
0.55 σ

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

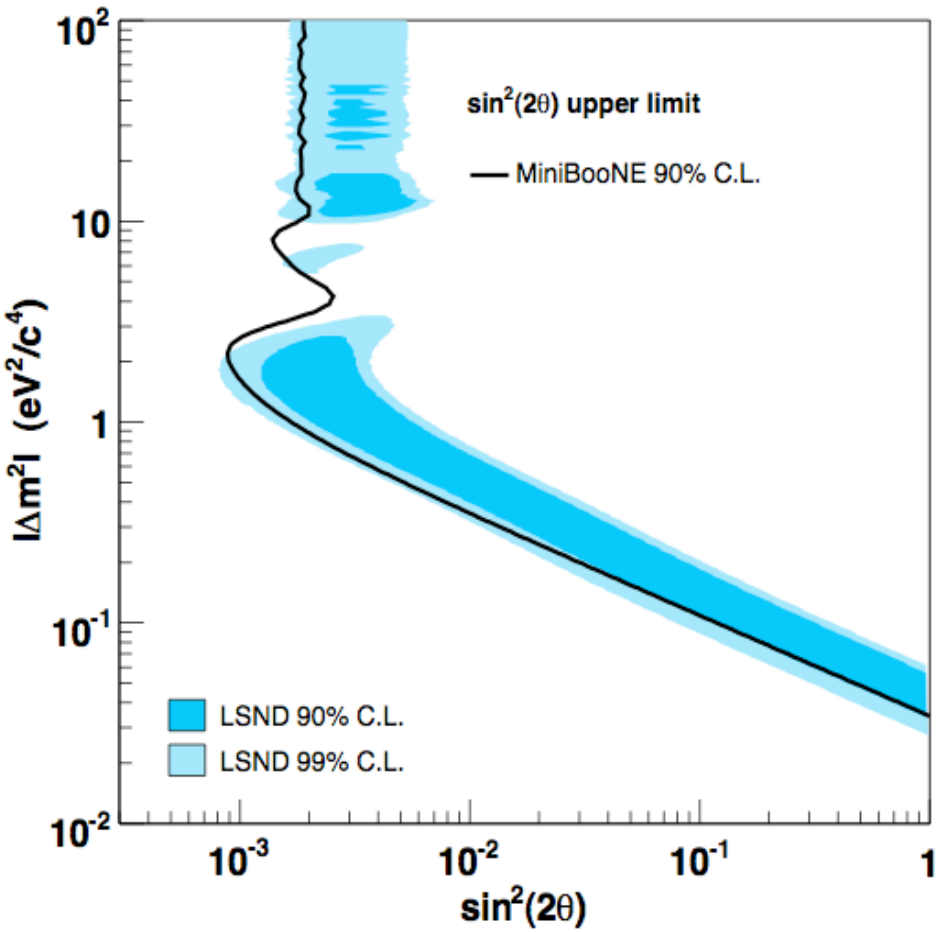


Error bars are diagnonals of error matrix.

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

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

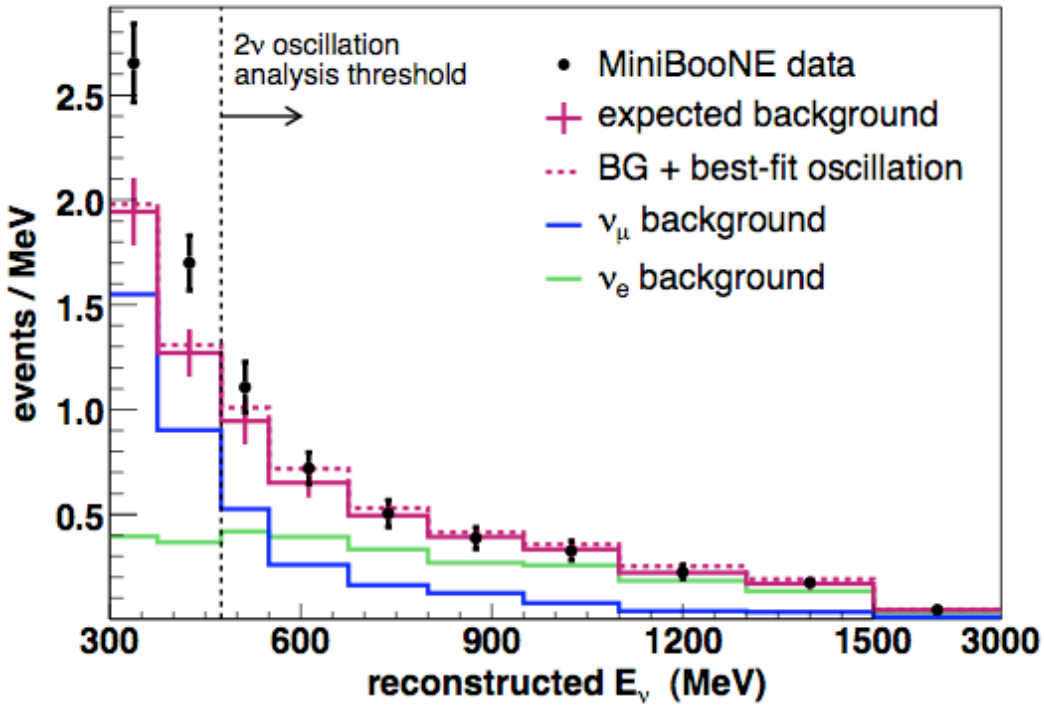
The result of
the $\nu_\mu \rightarrow \nu_e$ appearance-only analysis
is a <u>limit</u> on oscillations:



χ^2 probability,
null hypothesis: 93%

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

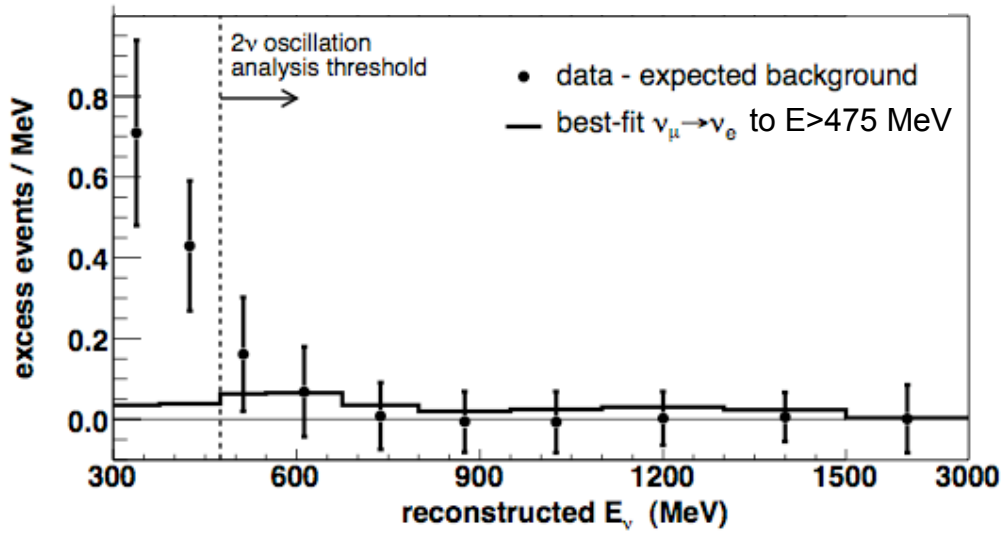
As planned before opening the box....
Report the full range:
$300<E_\nu^{QE}<3000$ MeV



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

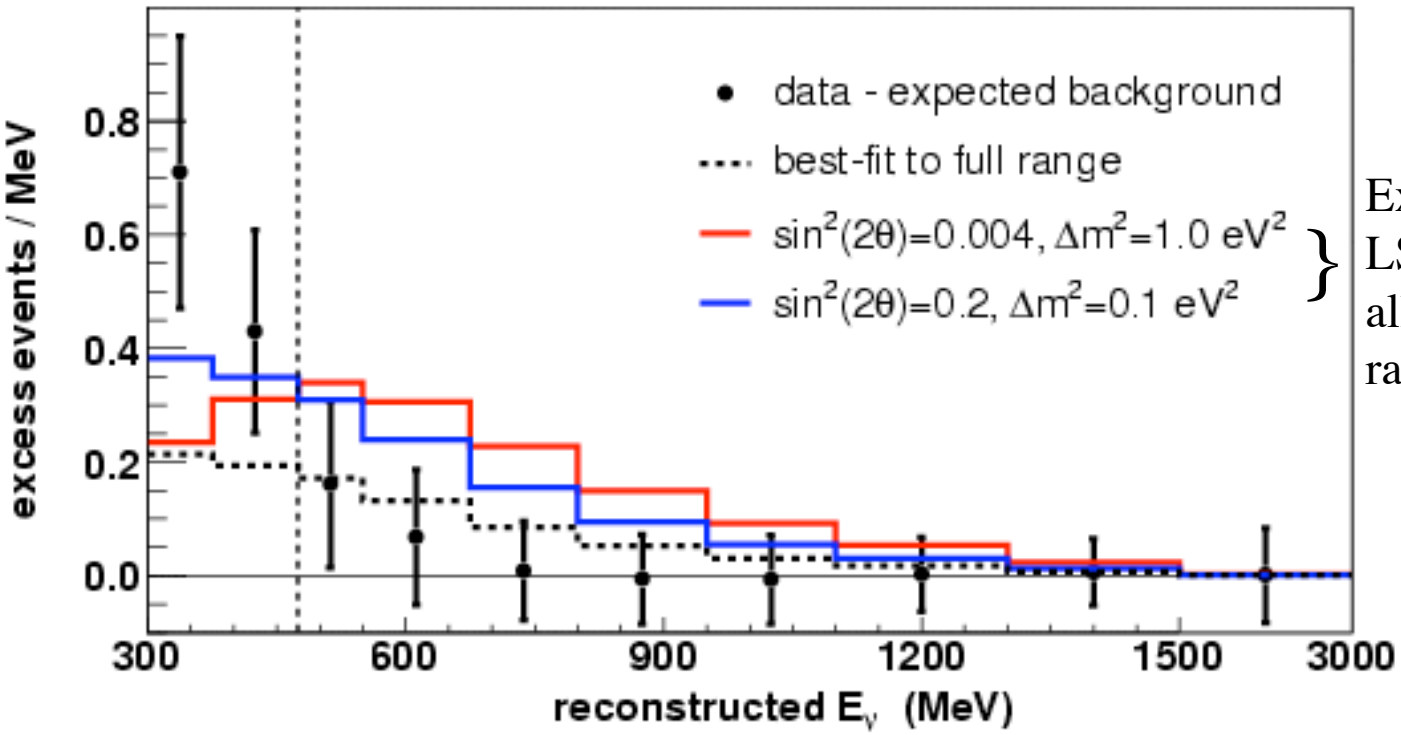
Deviation: 3.7σ

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

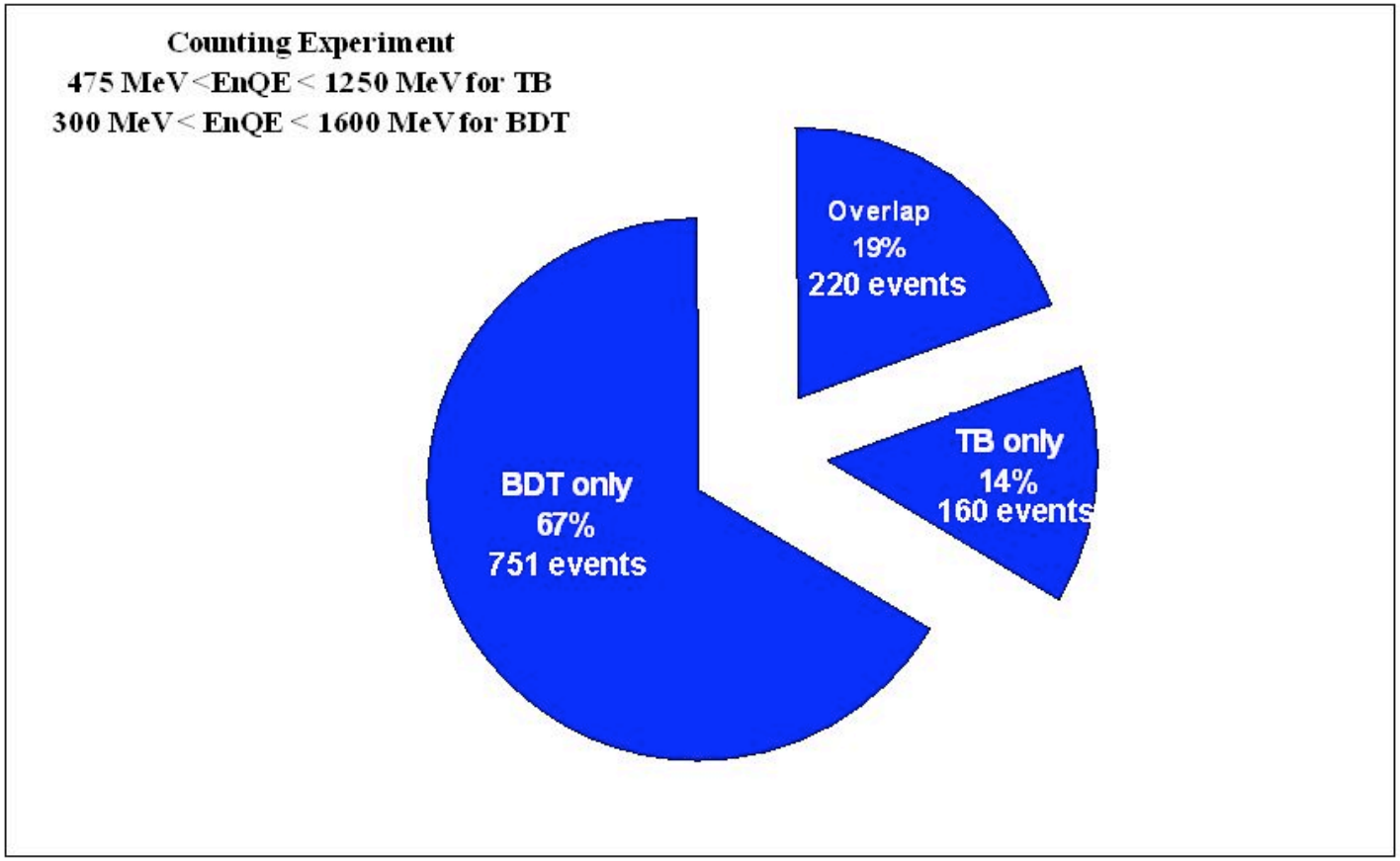
⇒ A two-neutrino appearance-only model systematically disagrees with the shape as a function of energy.

⇒ 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*

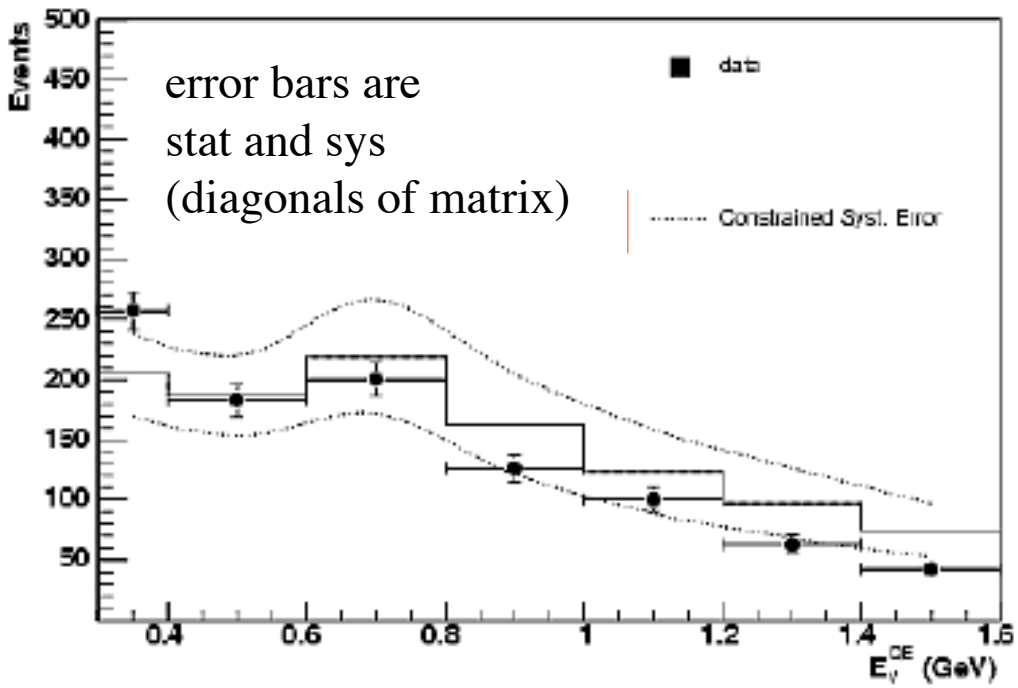
This will be addressed by MiniBooNE and SciBooNE

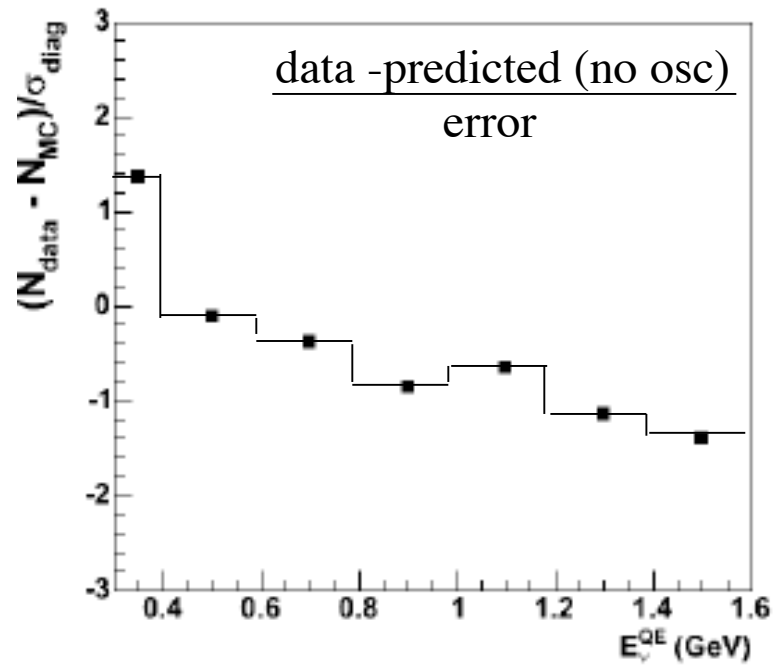
Boosted Decision Tree Analysis

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



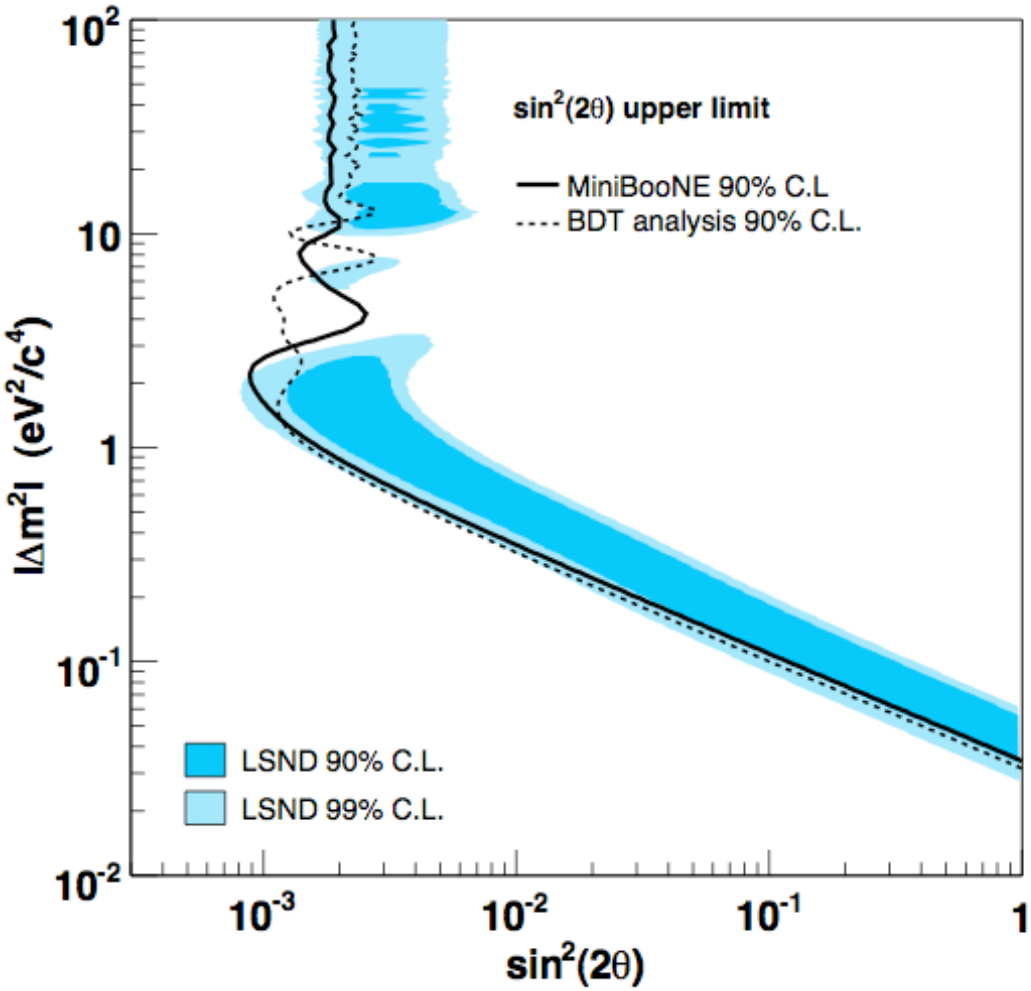
Boosted Decision Tree E_ν^{QE} data/MC comparison:





(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.

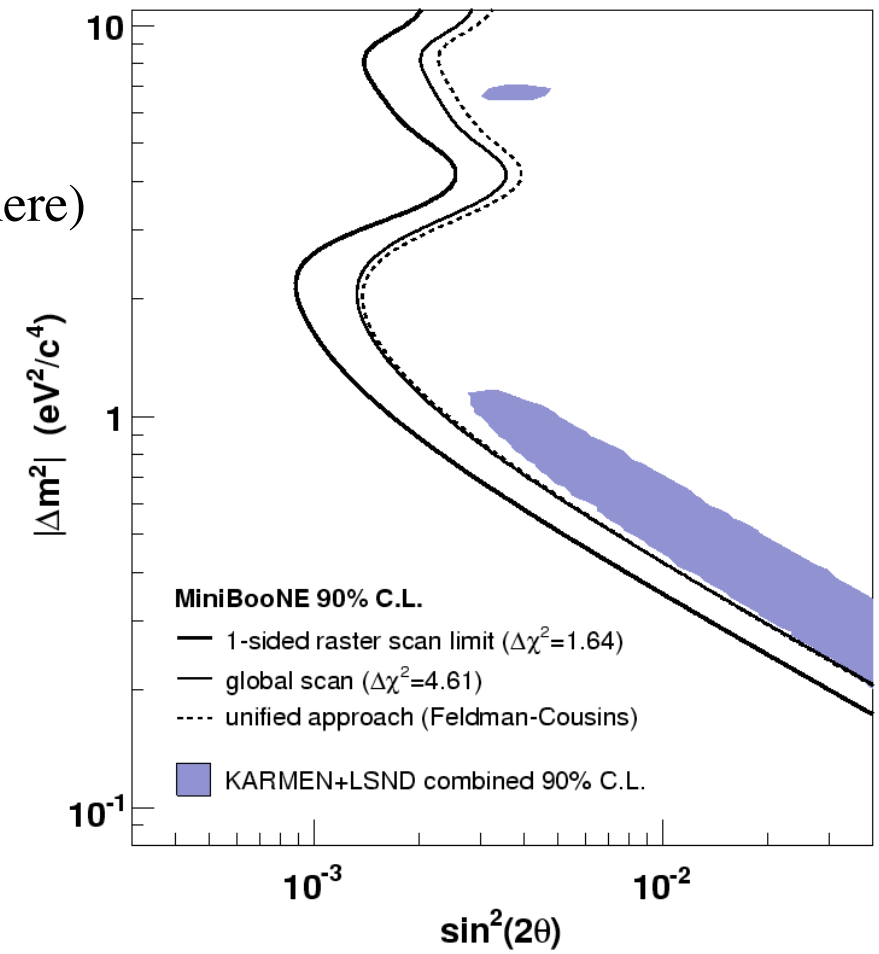
Two points on interpreting our limit

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

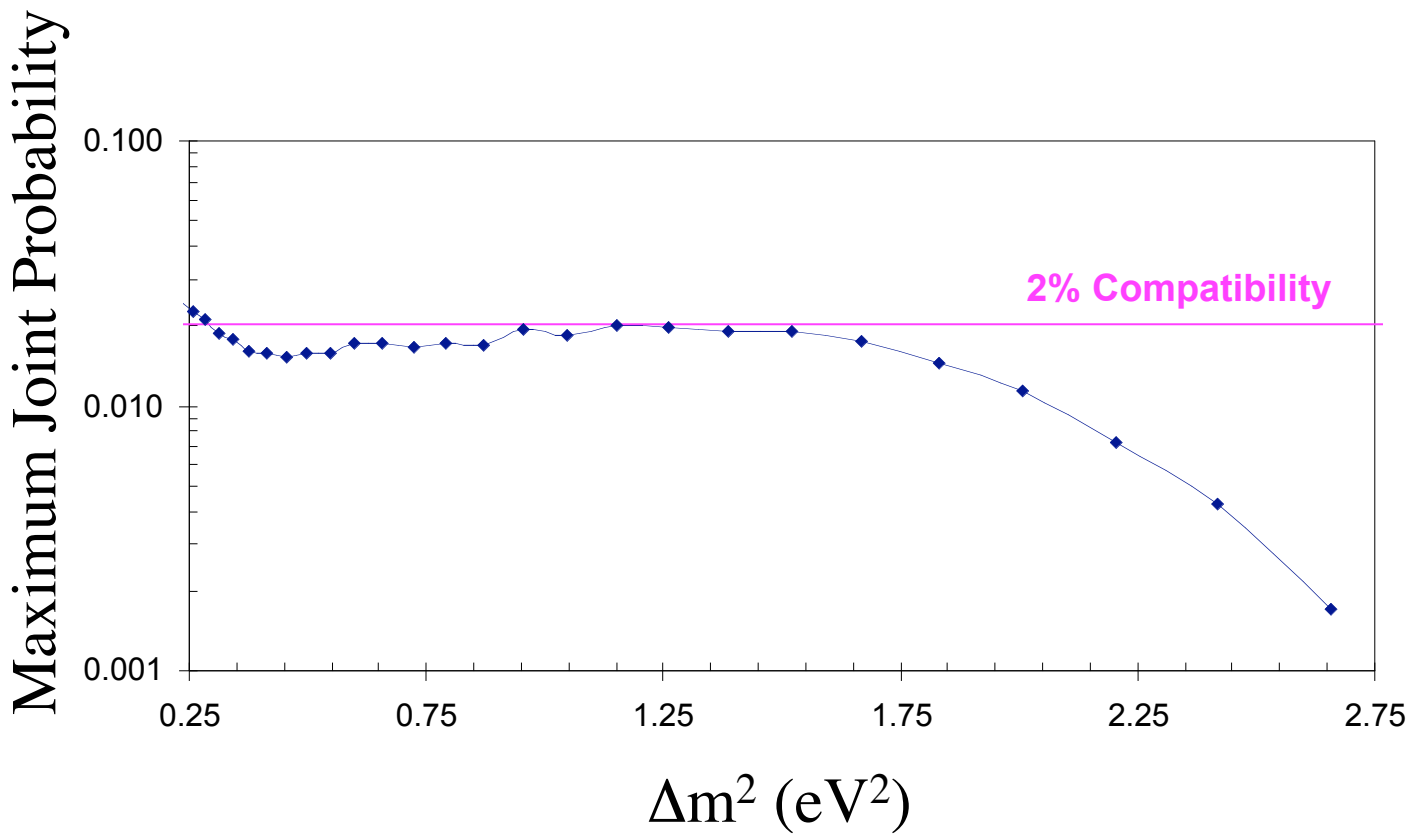
- For each Δm^2, form χ^2 between MB and LSND measurement

- 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 will be posted to the "archive"
and to the MiniBooNE webpage after 5 CT today.

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.

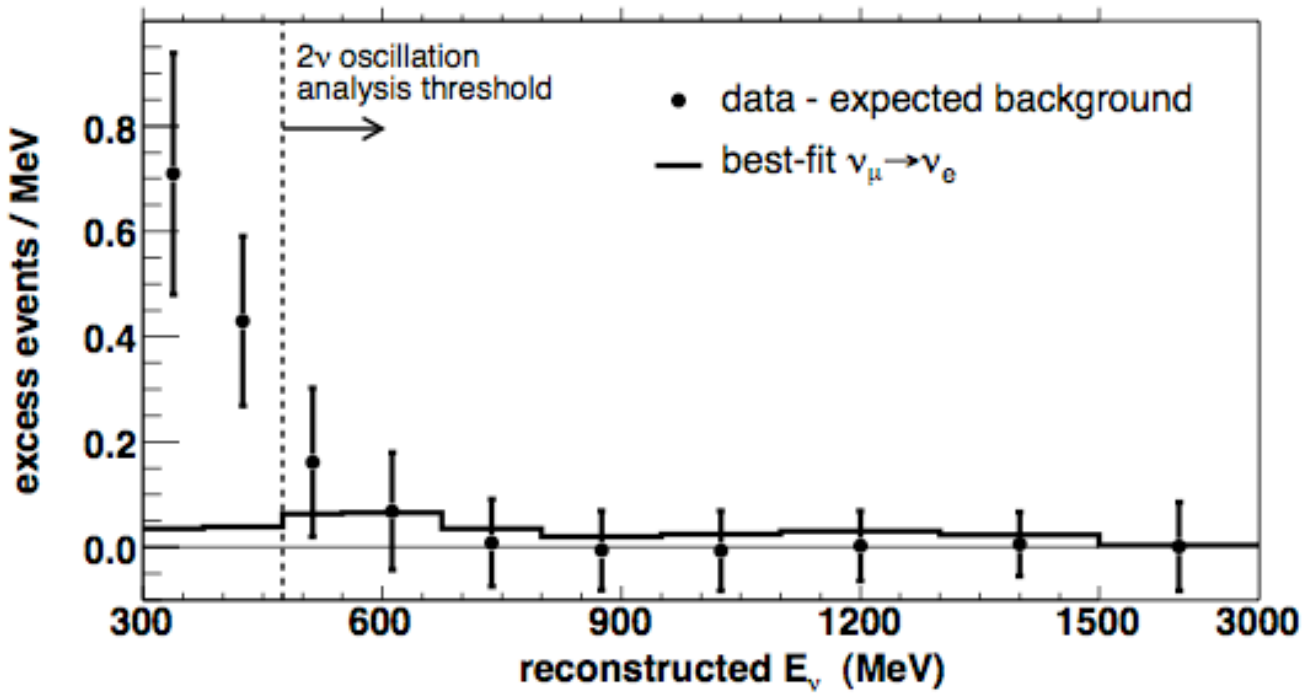
MiniBooNE is presently taking data in antineutrino mode.

Conclusions

Our goals for this first analysis were:

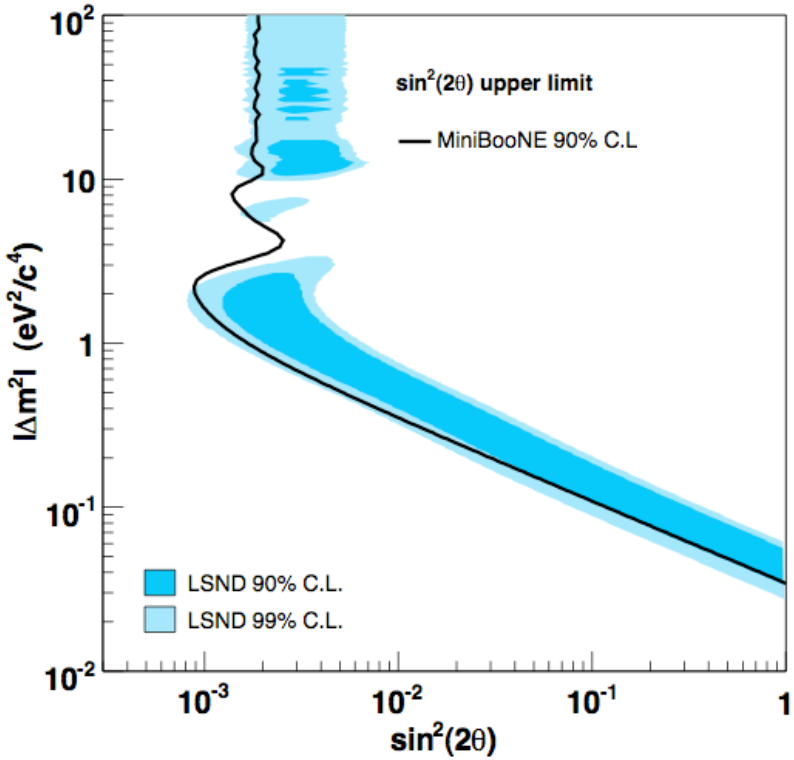
- A generic search for a ν_e excess in our ν_μ beam,
- An analysis of the data within a $\nu_\mu \rightarrow \nu_e$ appearance-only context

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

We Thank:

DOE and NSF

The Fermilab Divisions and Staff