Results from MiniBooNE

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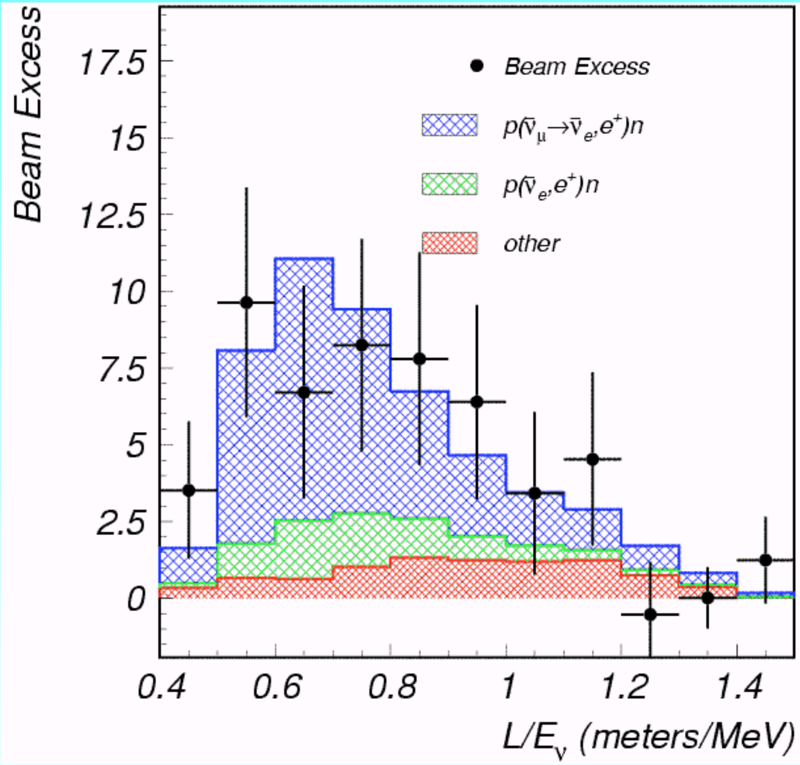
Outline of the talk

- Physics case & Results
- Description of MiniBooNE: beam, detector, interactions in MiniBooNE
- Signal & Background
- Analysis
- Results (again)
- Conclusions

Physics case

LSND



LSND reported an excess of $\bar{\nu}_e$ (87.9±22.4±6) which was interpreted as $\bar{\nu}_\mu$ -> $\bar{\nu}_e$ oscillation with **.25%** probability

PRD 64, 112007 (2001)

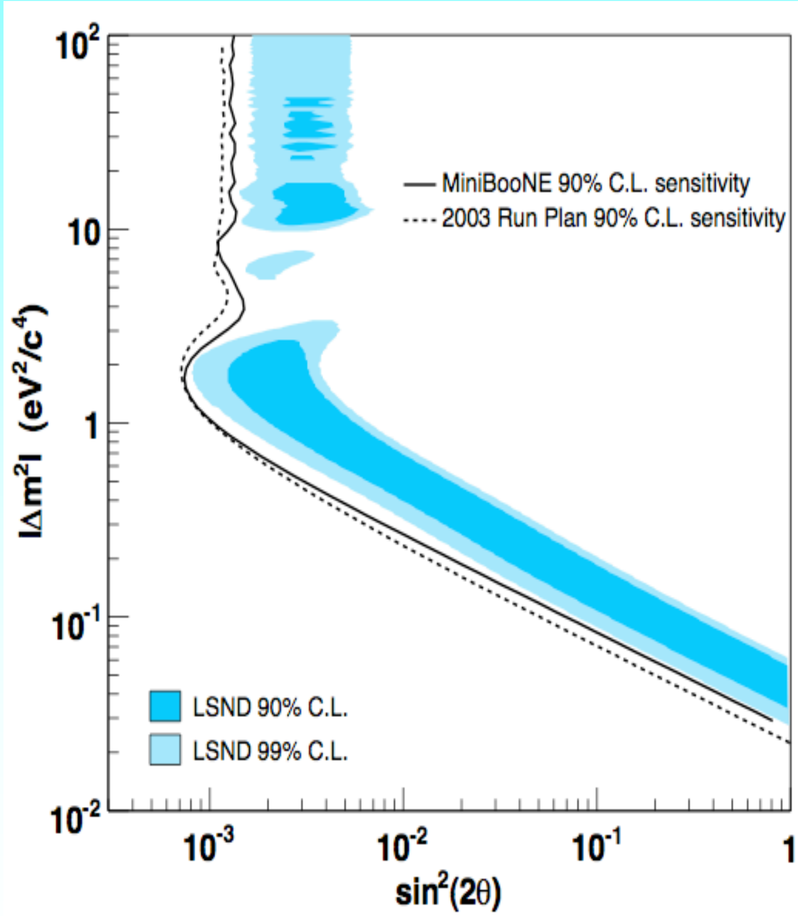
$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2 2\theta \, \sin^2(1.27 \, \Delta m^2 \, L/E)$

more exotic non-oscillation interpretations also possible

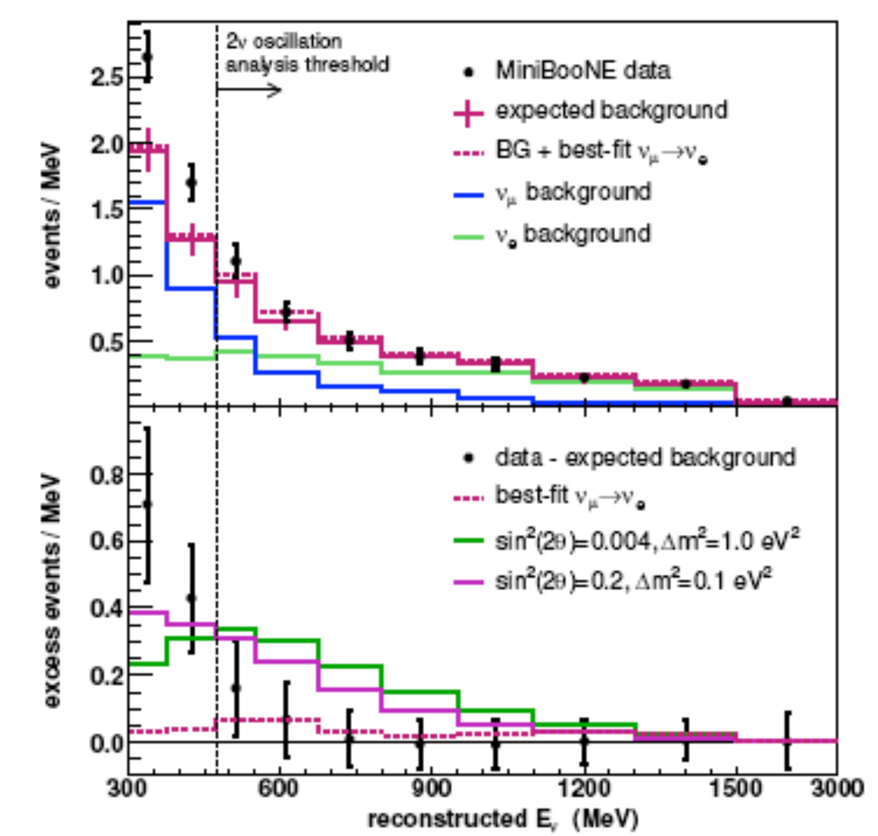
Before MiniBooNE, no independent experiment has been able to clearly confirm or disprove this result

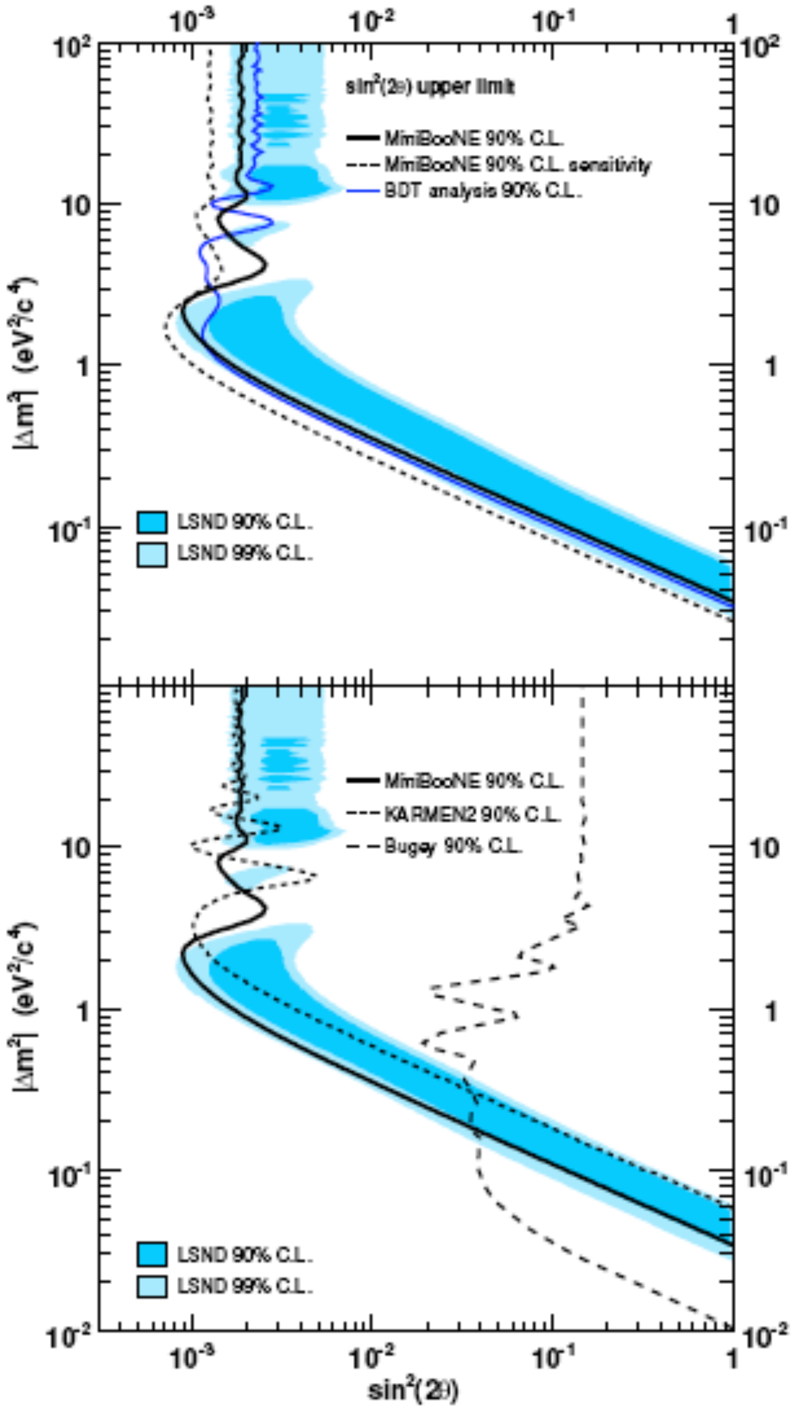
MiniBooNE

- MiniBooNE was designed to definitely check the LSND result in terms of neutrino oscillations
- MiniBooNE has the same L/E of LSND (~0.6 km/GeV) with different L and different E, and different systematic errors and experimental challenges



Results from MiniBooNE





MiniBooNE

MiniBooNE - The People

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(The MiniBooNE Collaboration)

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MiniBooNE - Beam

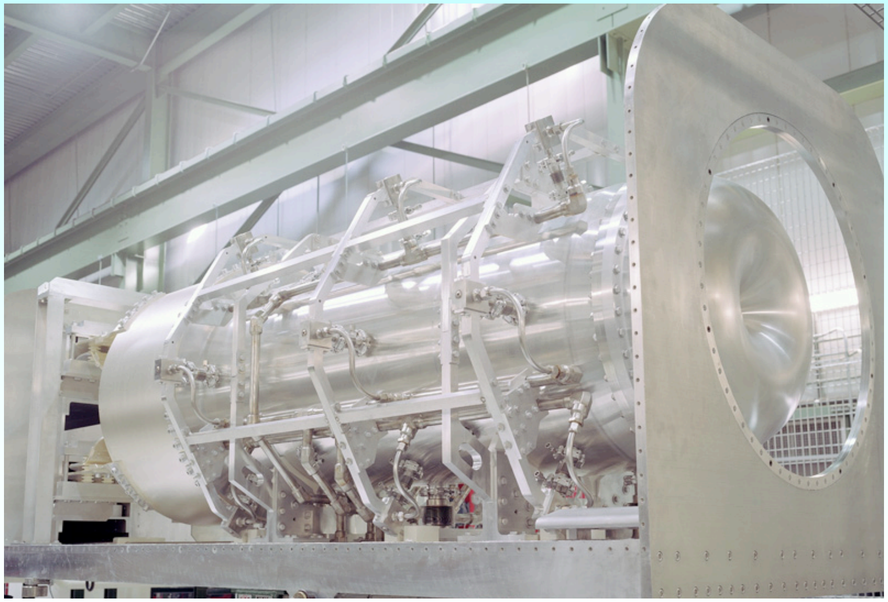
MiniBooNE extracts beam from the 8 GeV Booster

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

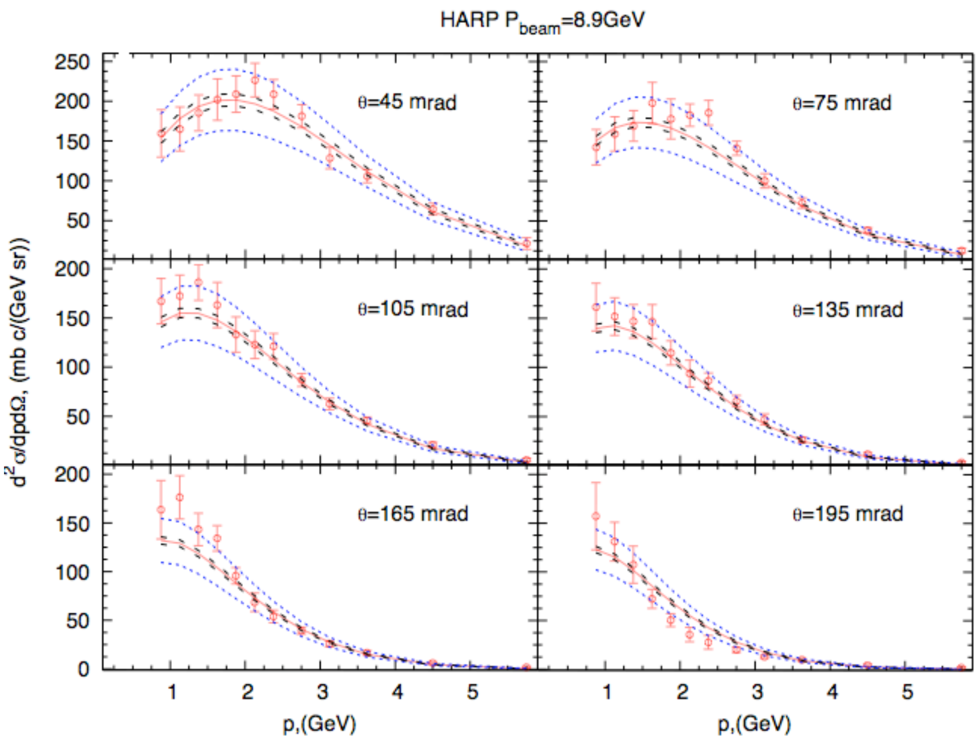
6.3×10^{20} POT delivered

Results correspond to $(5.58\pm0.12)\times10^{20}$ POT

Protons hit a Be target (1.7 λ) placed within a magnetic horn (2.5 kV, 174 kA) that increases the neutrino flux by x6



MINIBOONE - BEAM



Modeling the secondary pions:

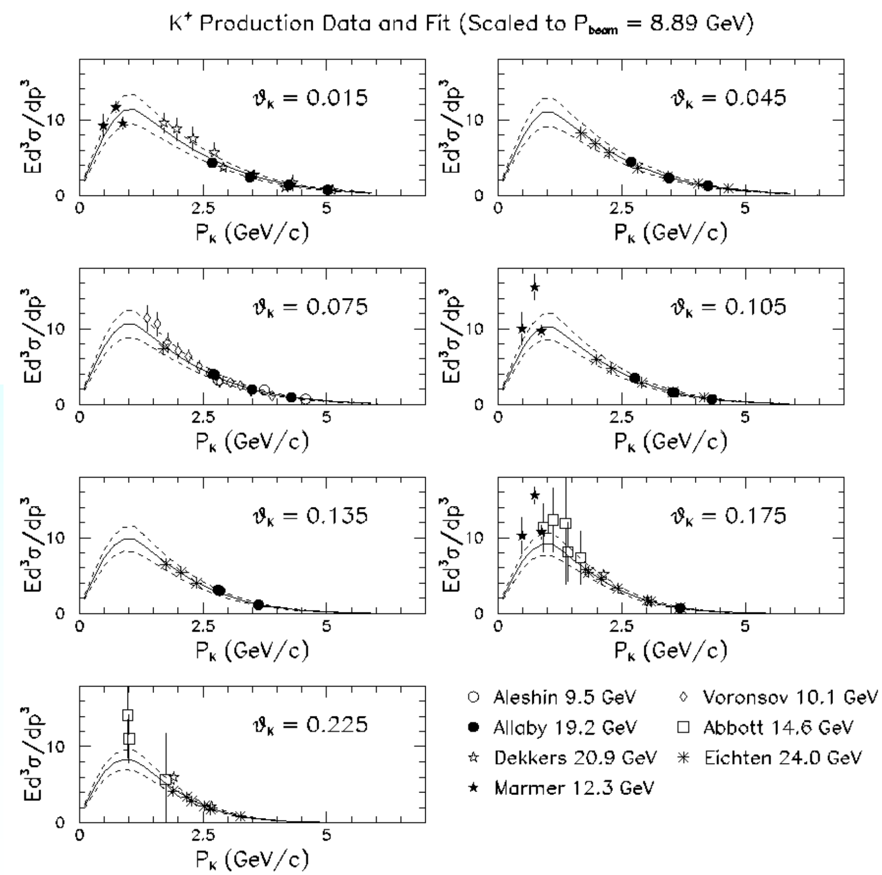
HARP data (5% λ of Be, 8.9 GeV Protons)

Sanford-Wang parameterization

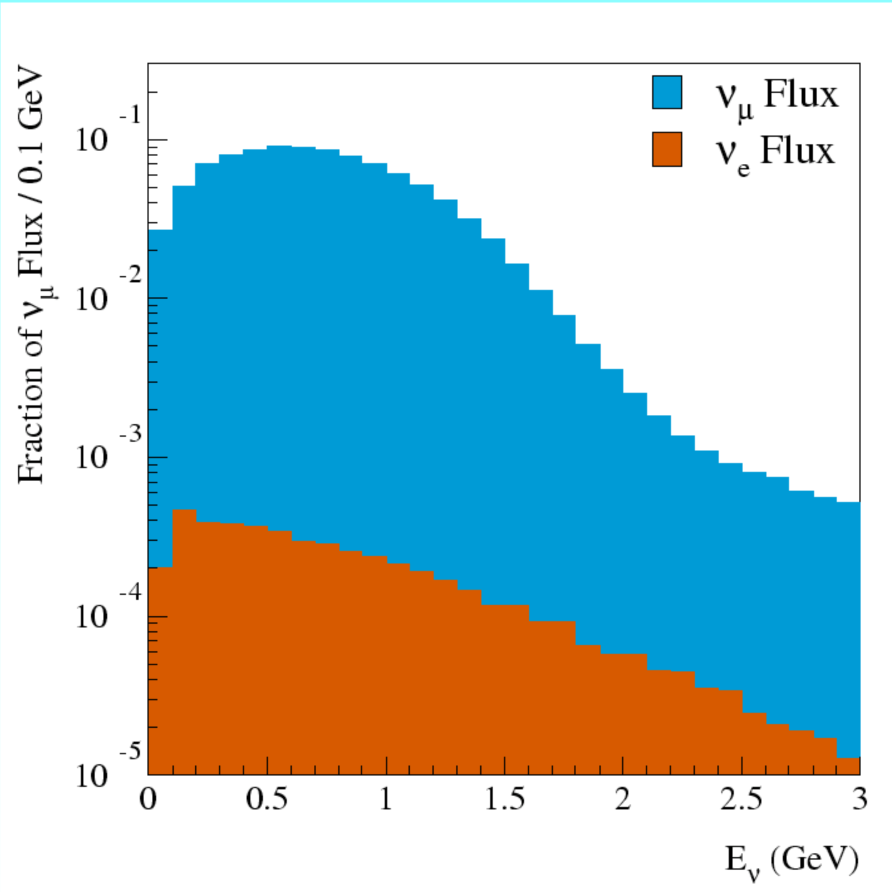
and the secondary kaons:

K^+ data 10-24 GeV

Feynman scaling inspired parameterization



MiniBooNE - Beam



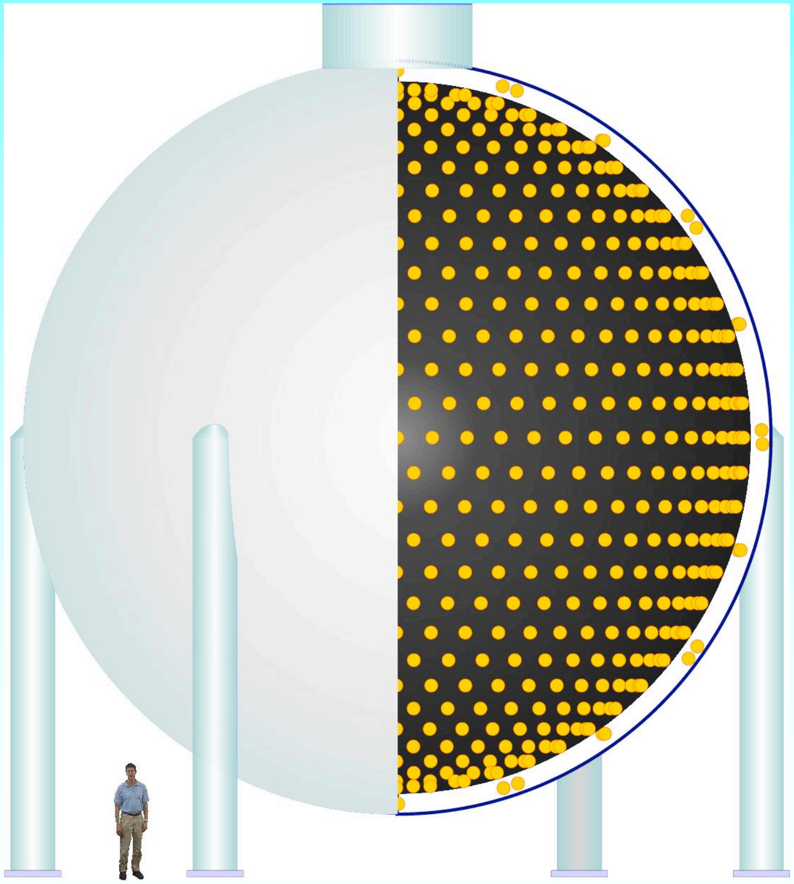
Neutrino flux from GEANT4 simulation:

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

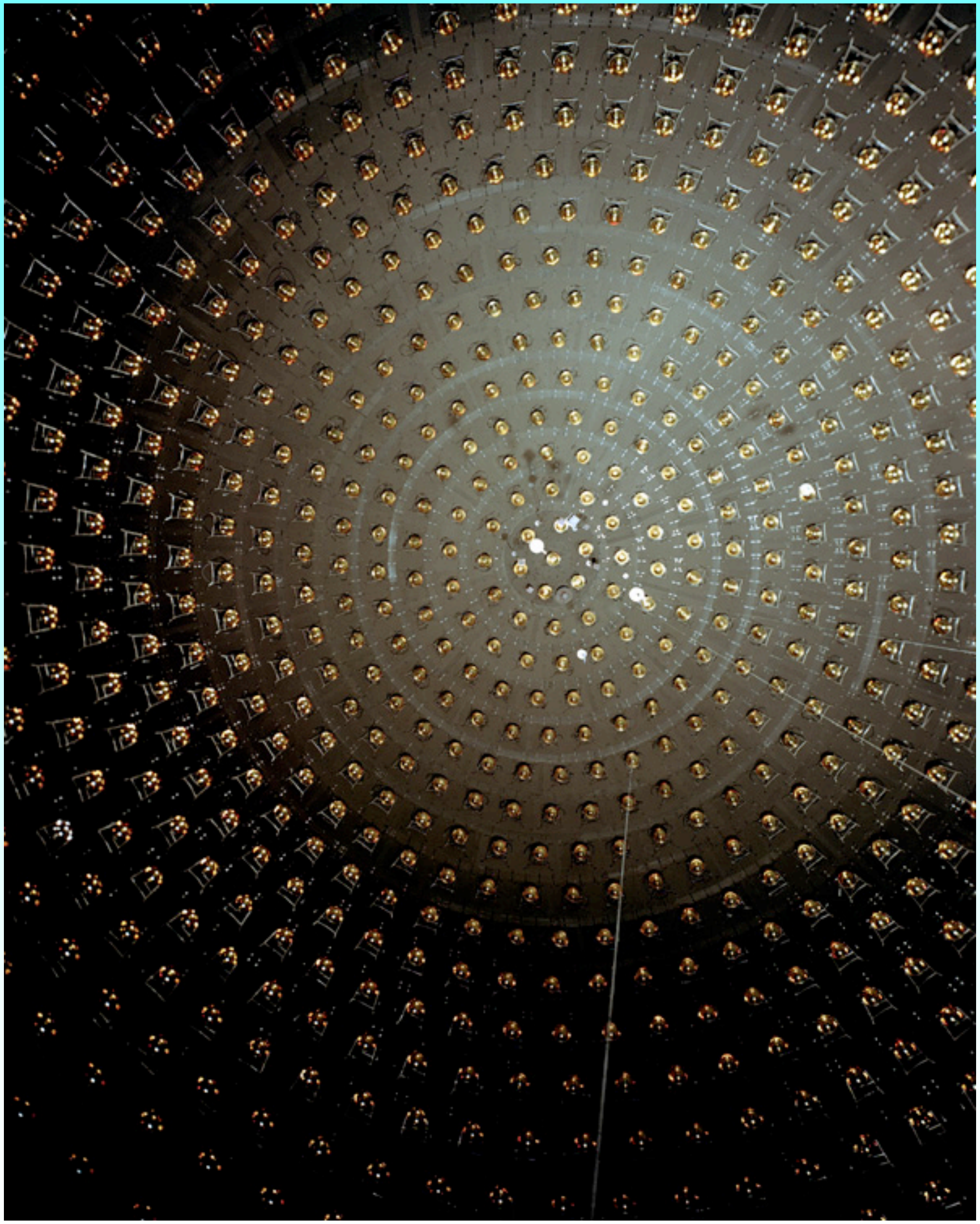
- $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ (52%)
- $K^+ \to \pi^0 e^+ \nu_e$ (29%)
- $K^0 \to \pi e \nu_e$ (14%)
- Other (5%)

ν_e/ν_μ = 0.5%

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

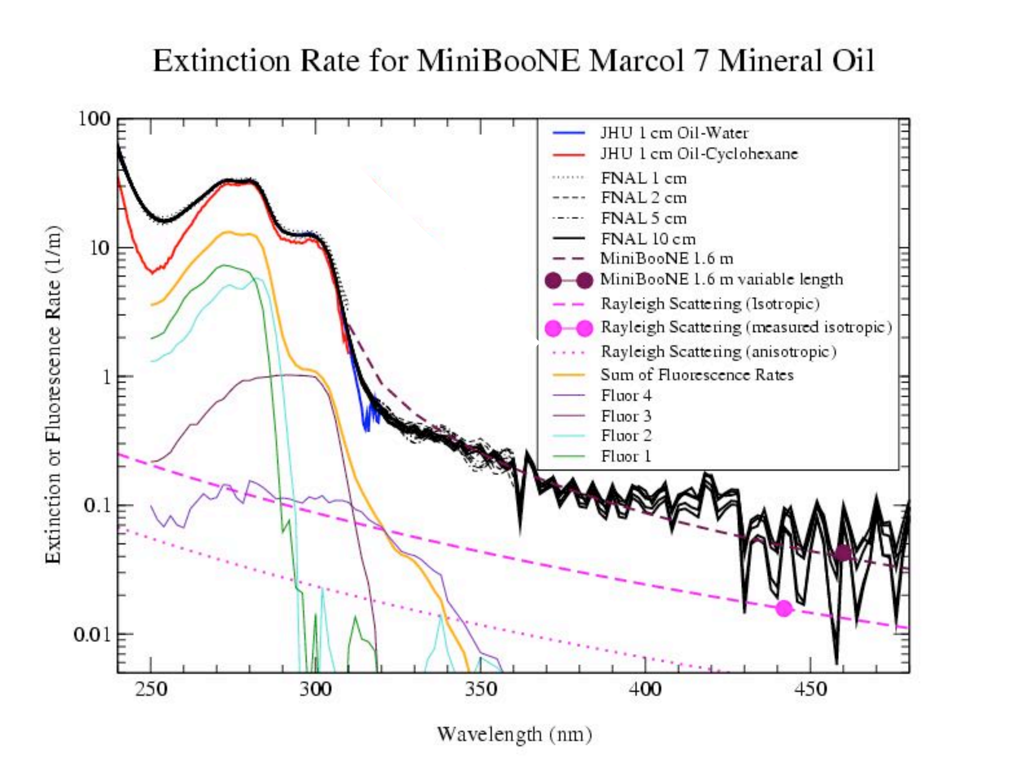
Attenuation length: >20 m @ 400 nm

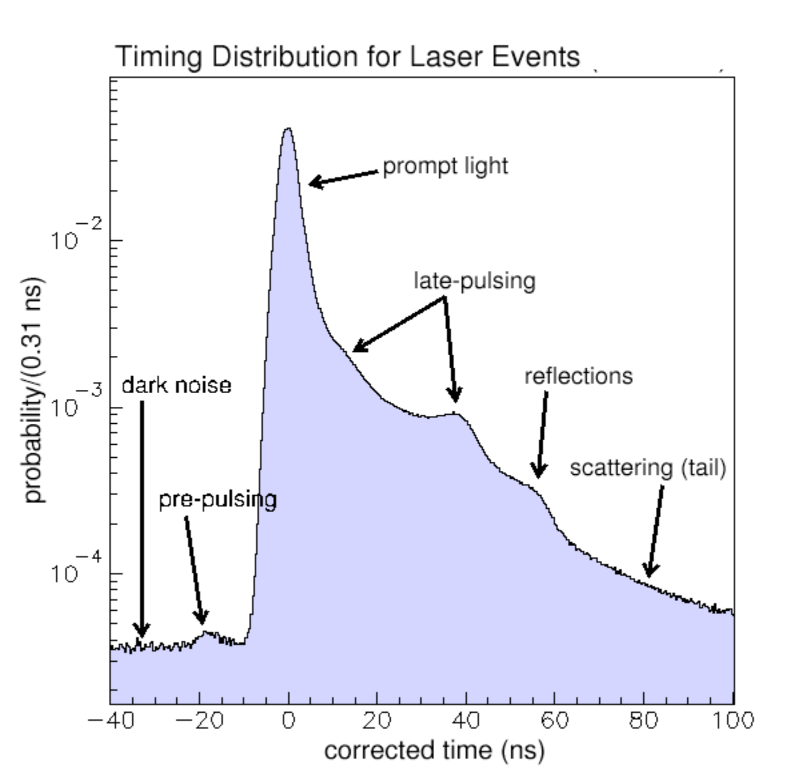
Detected photons from

- 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



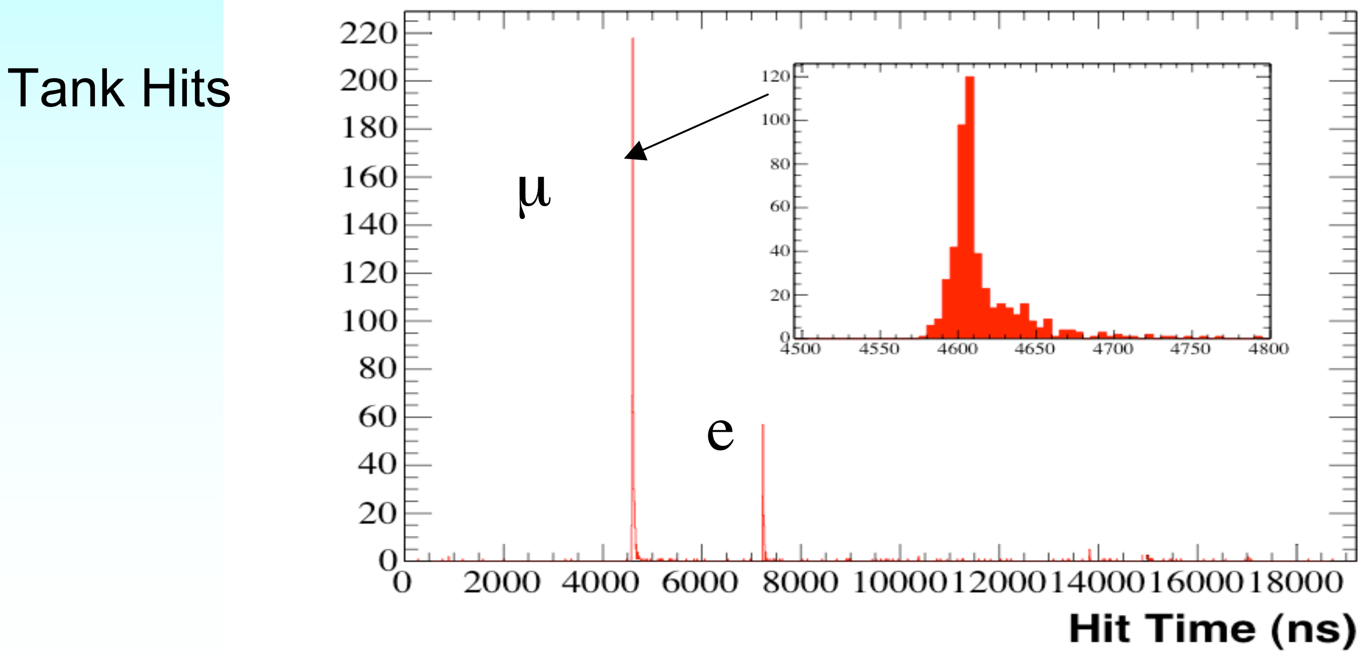


Events in MiniBooNE

19.2 μs beam trigger window encompasses the 1.6 μs spill

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

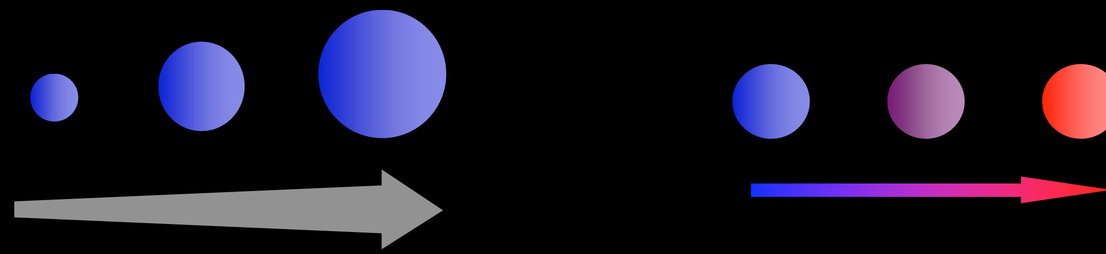
Most events are from ν_μ CC interactions with characteristic two "subevent" structure from stopped $\mu \rightarrow \nu_\mu \nu_e e$

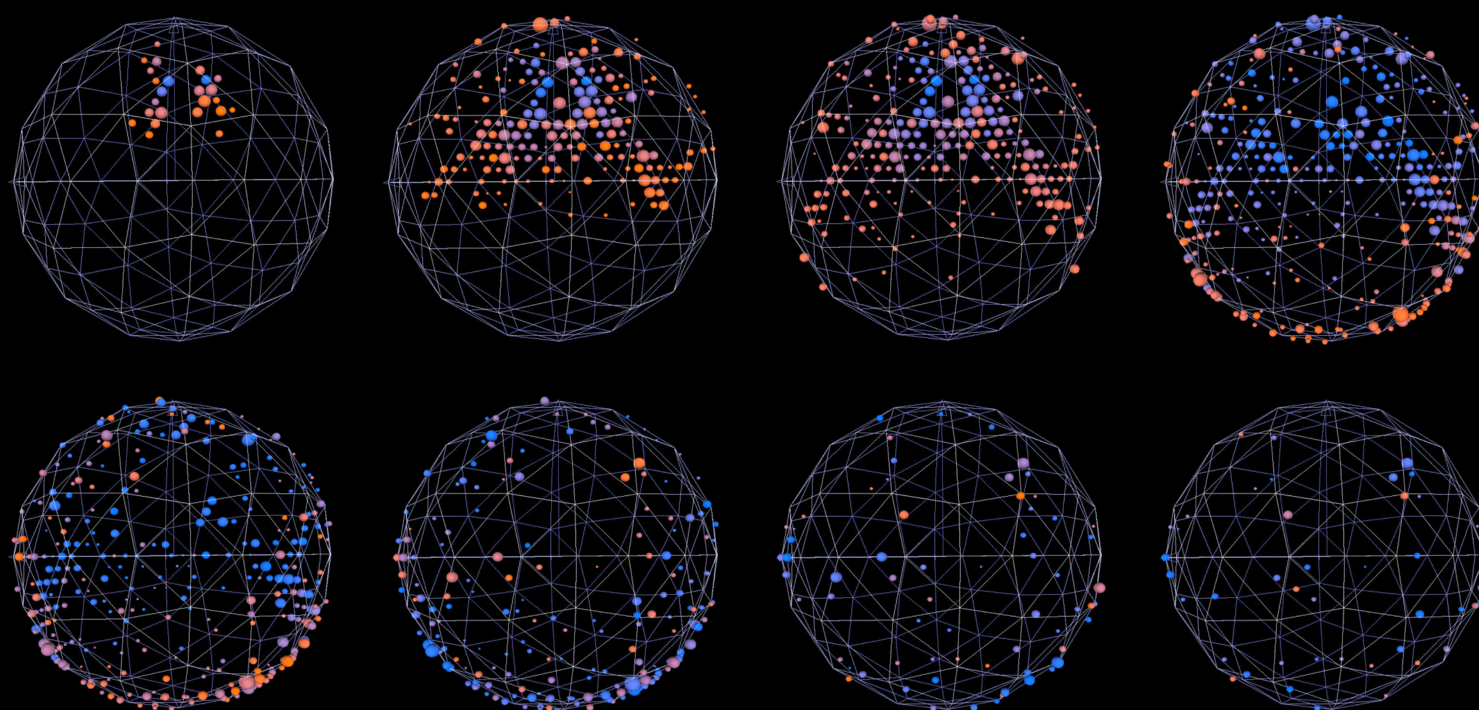


Example of Cerenkov Rings: A stopping cosmic ray

Charge (Size)

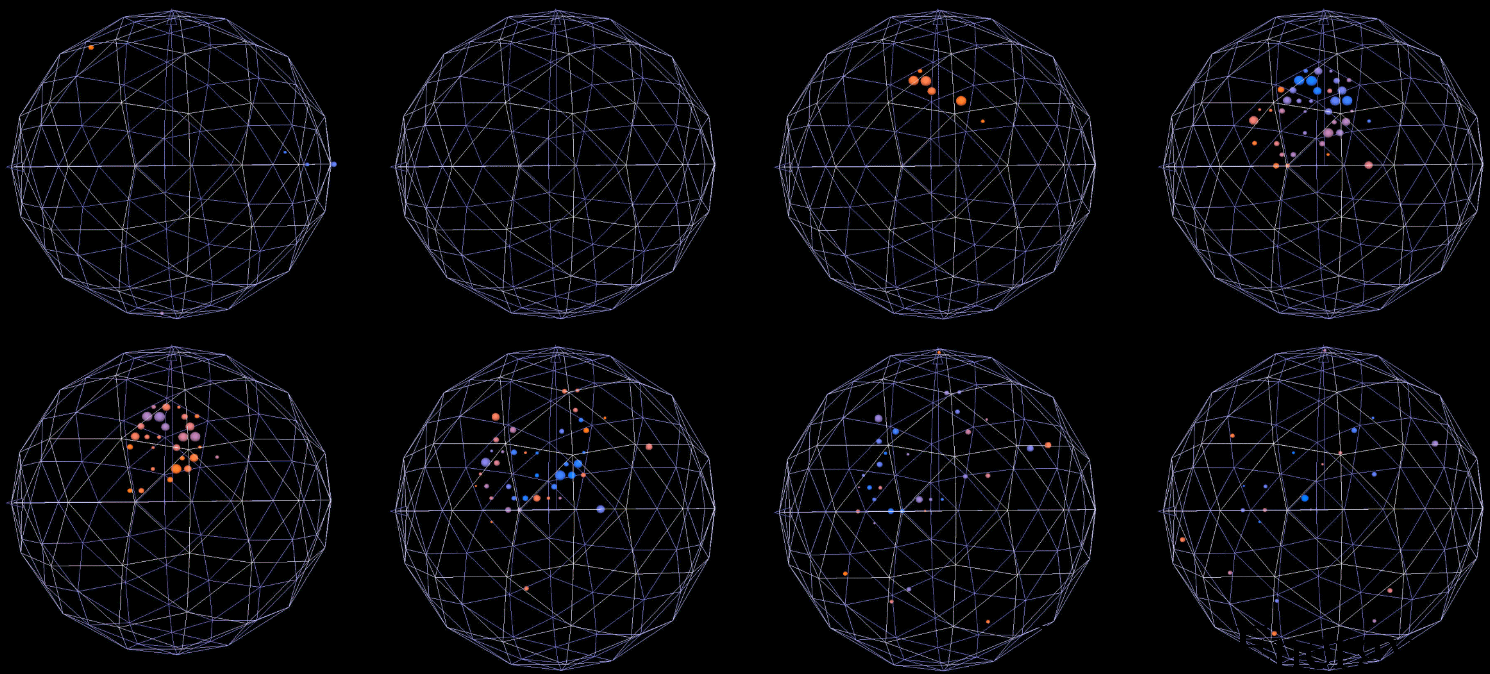
Time (Color)





First the muon enters the tank and stops...

Later a the Michel electron is observed



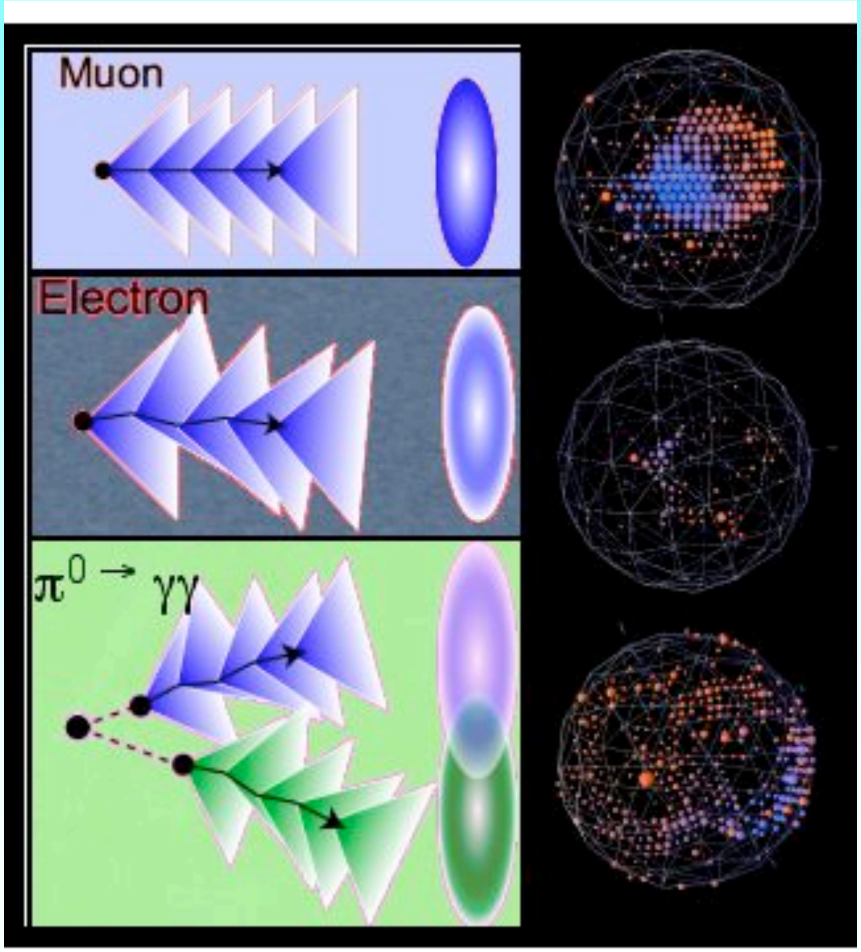
Michel electrons provide   muon tags and calibration

Events in MiniBooNE

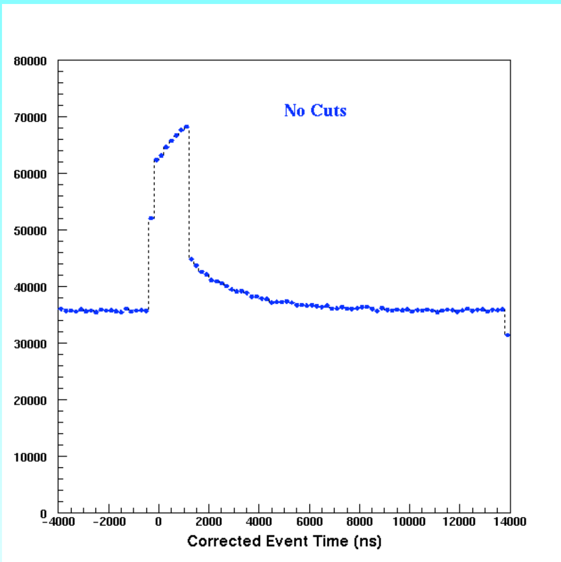
Muons:
Produced in most CC events.
Usually 2 subevent or exiting.

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

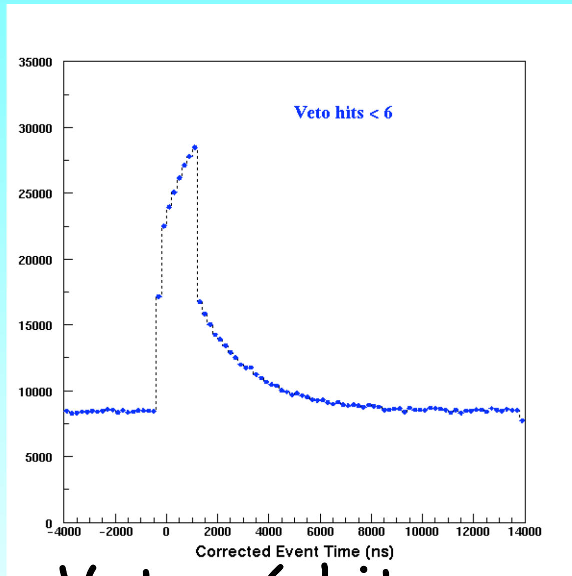
π^0s:
Can form a background if one photon is weak or exits tank.
In NC case, 1 subevent.



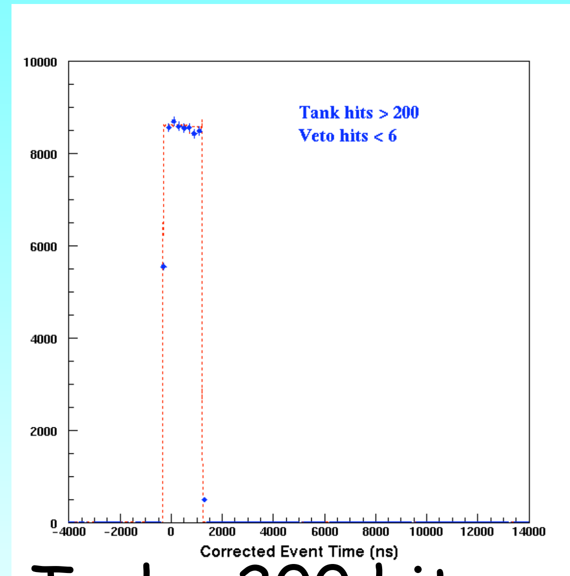
Events in MiniBooNE



Raw data



Veto < 6 hits

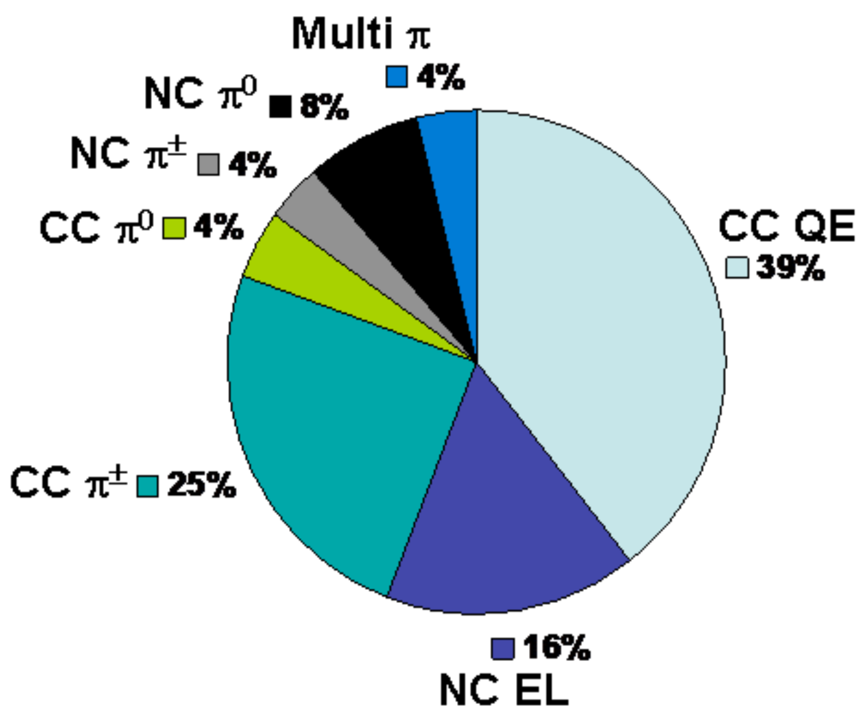


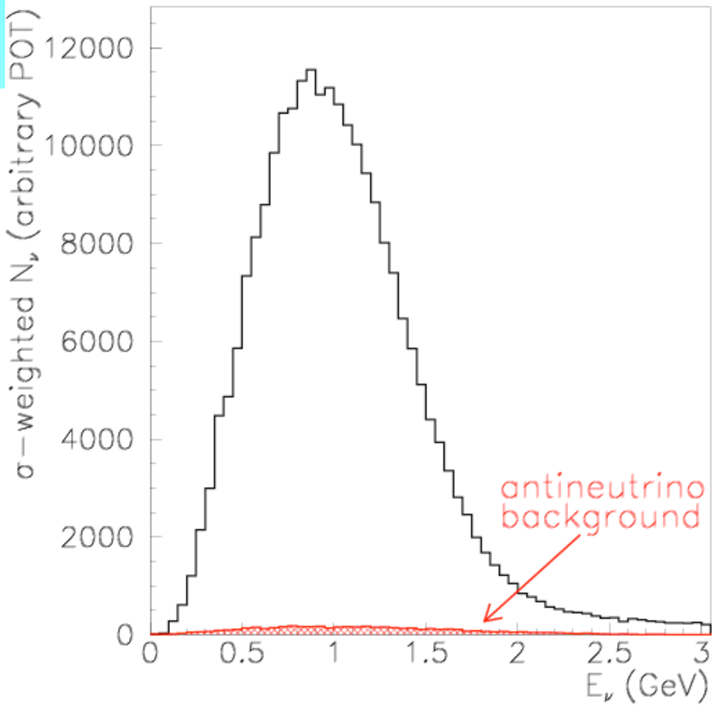
Tank > 200 hits

Energy scale from Michel electrons (53 MeV E_{max}), gamma from π^0 decay (up to ~400 MeV), cosmic muons from "tracker & cubes" (up to ~800 MeV), through going muons (1 GeV and higher)

Predicted event rates before cuts (NUANCE Monte Carlo)

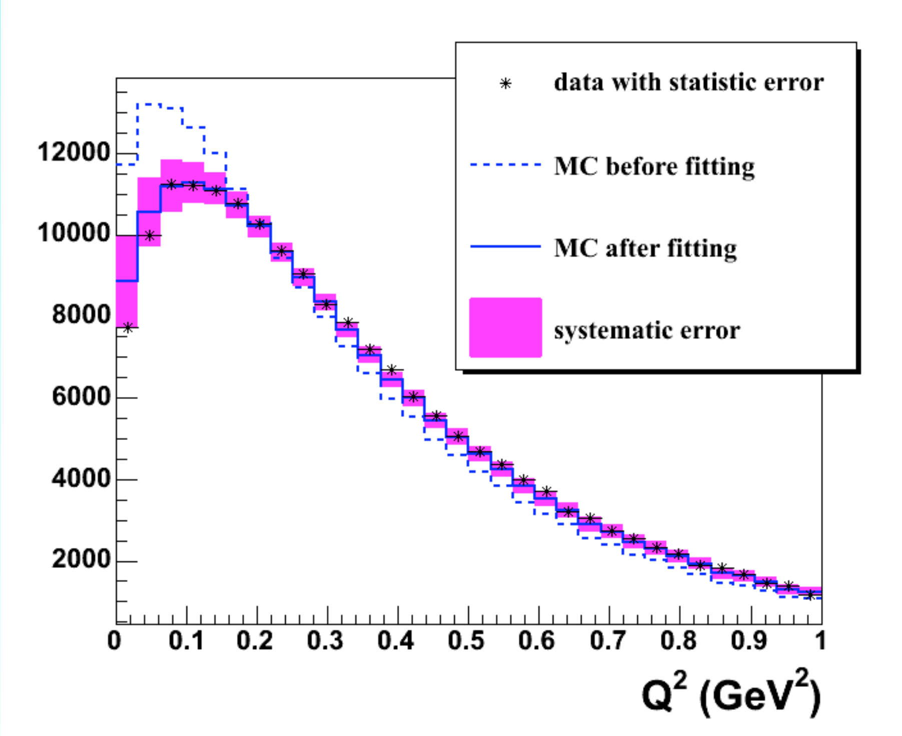
D. Casper, NPS, 112 (2002) 161





Event neutrino energy (GeV)

NUANCE Parameters:

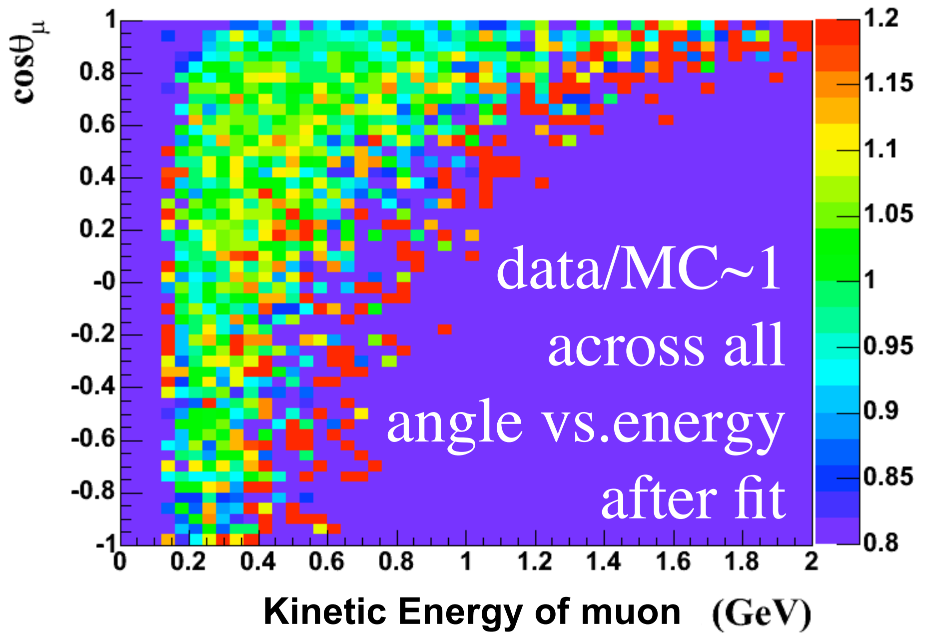


From Q^2 fits to MiniBooNE CCQE data:

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

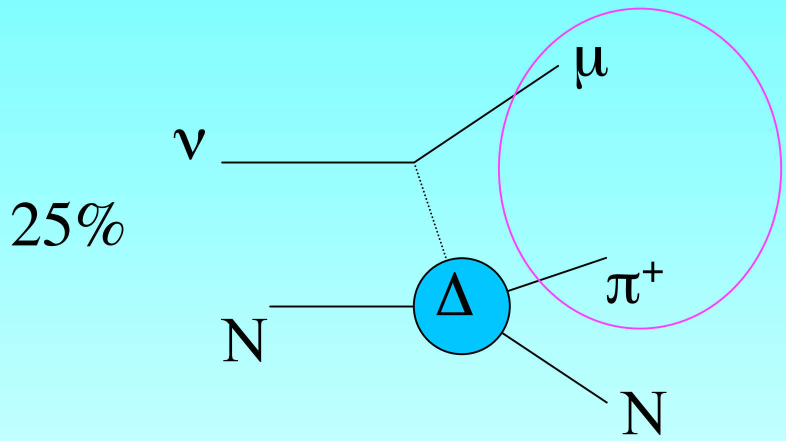
From electron scattering data:

- E_b -- binding energy
- p_f -- Fermi momentum

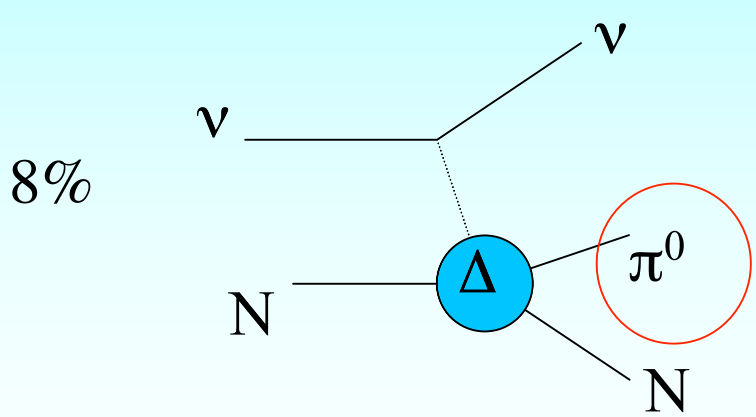


Model describes CCQE ν_μ data well

Events producing pions

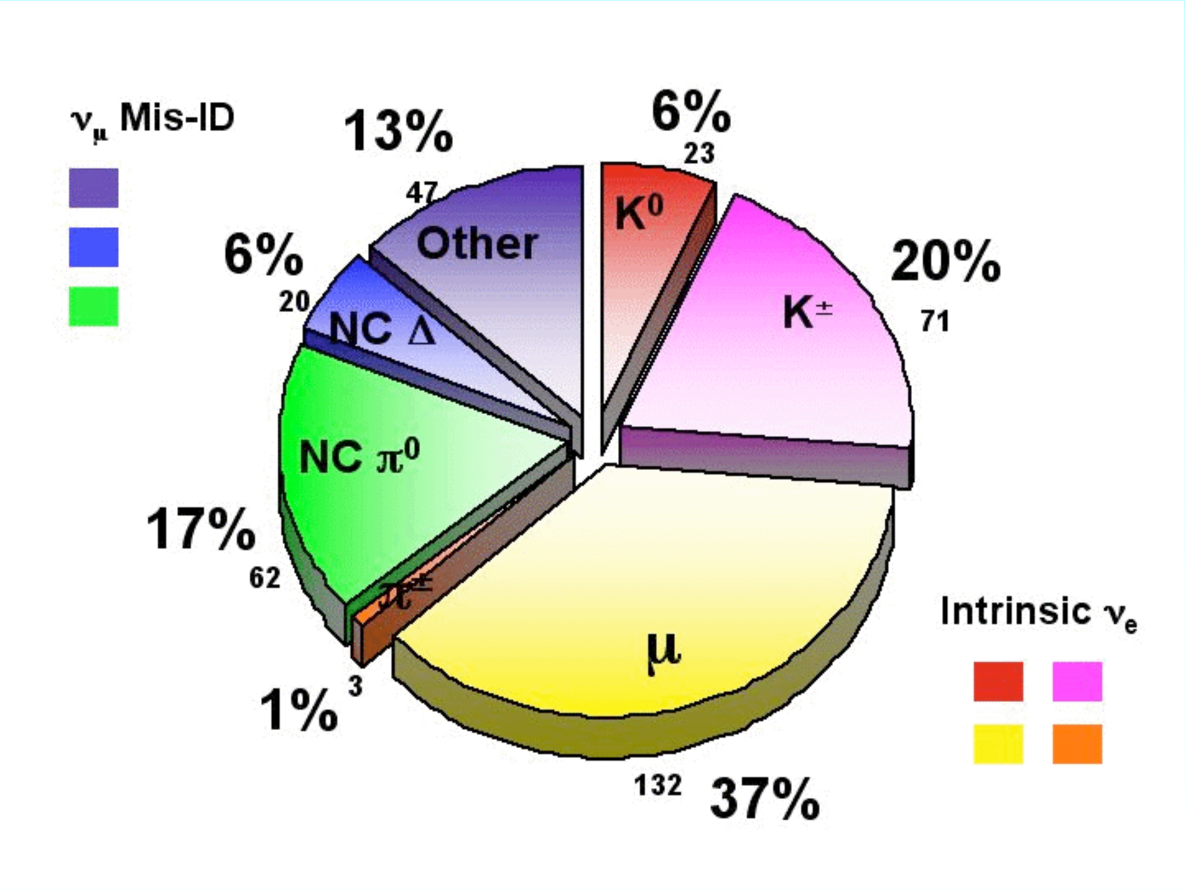


CCπ⁺: Easy to tag due to 3 subevents. Not a substantial background to the oscillation analysis.



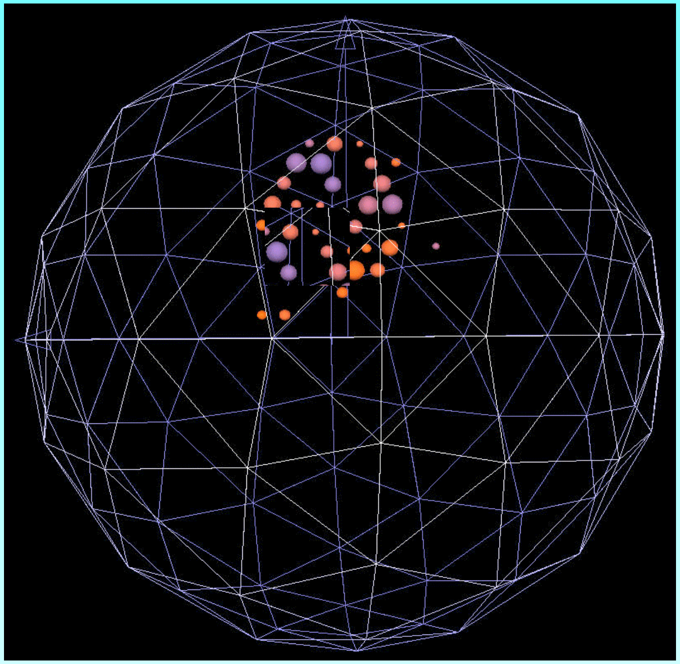
NCπ^0: The π^0 decays to 2 photons, which can look electron-like mimicking the signal (also decays to a single photon with 0.56% probability)

MiniBooNE - Signal & Background



ANALYSIS

MiniBooNE searches 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.

Two Separate Analysis:

1. **Track Based (TB) analysis:**

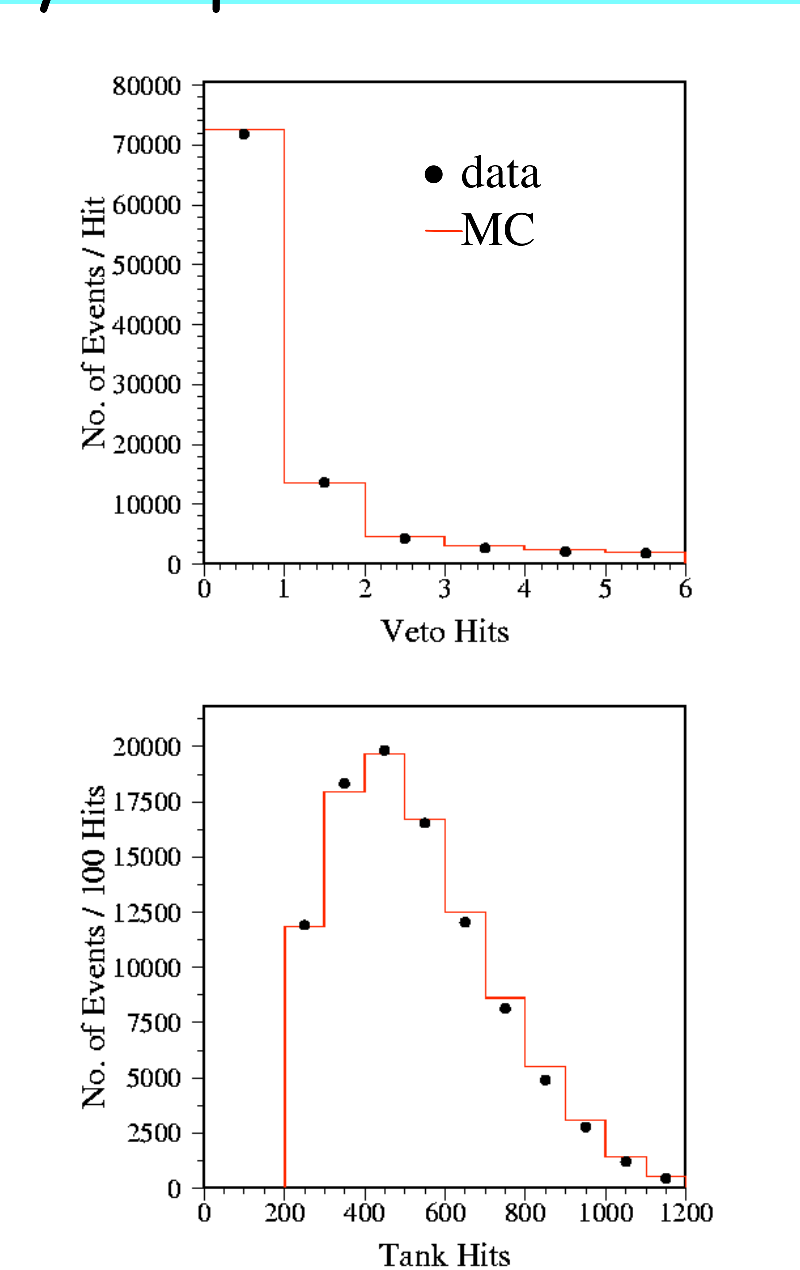
   Uses detailed, direct reconstruction of particle tracks, and ratio of fit likelihoods to identify particles. Better sensitivity, PRIMARY RESULTS

2. **Boosted Decision Tree (BDT) analysis:** Construct a set of low-level analysis variables which are used to make a series of cuts to classify the events. Independent cross check of the TB analysis.

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

only 1 sub-event
veto hits < 6
tank hits > 200

and a radius precut **R<500 cm** (where reconstructed R is algorithm-dependent)



TB Analysis

Each event is characterized by 7 reconstructed variables: vertex (x,y,z), time, energy, and direction (Ux, Uy, Uz i.e. 2 angles)

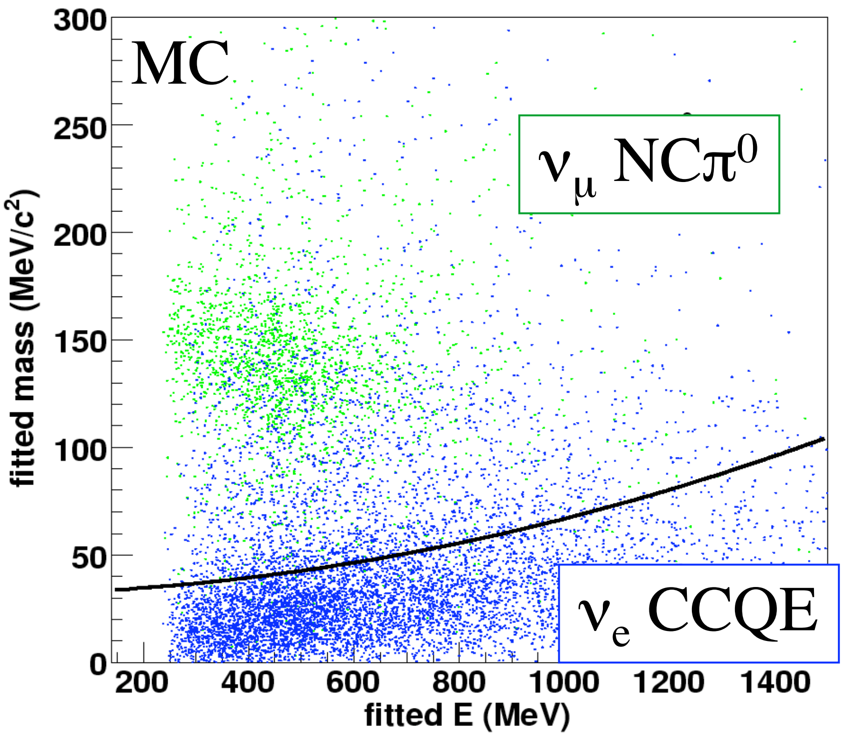
Resolutions: vertex: 22 cm, direction: 2.8°, energy: 11%

Reject muon-like events using a cut on $\log(L_e/L_\mu)$, optimized vs. energy to maximize the sensitivity

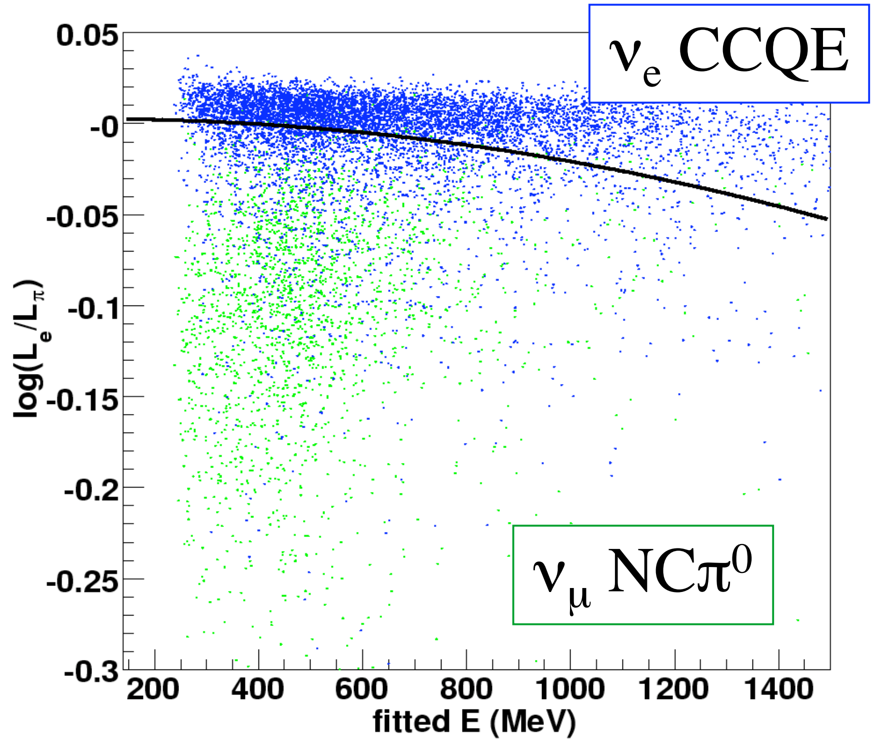
Reject π^0-like events using a "mass cut" and a $\log(L_e/L_\pi)$ cut, again optimized vs. energy

TB Analysis: 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

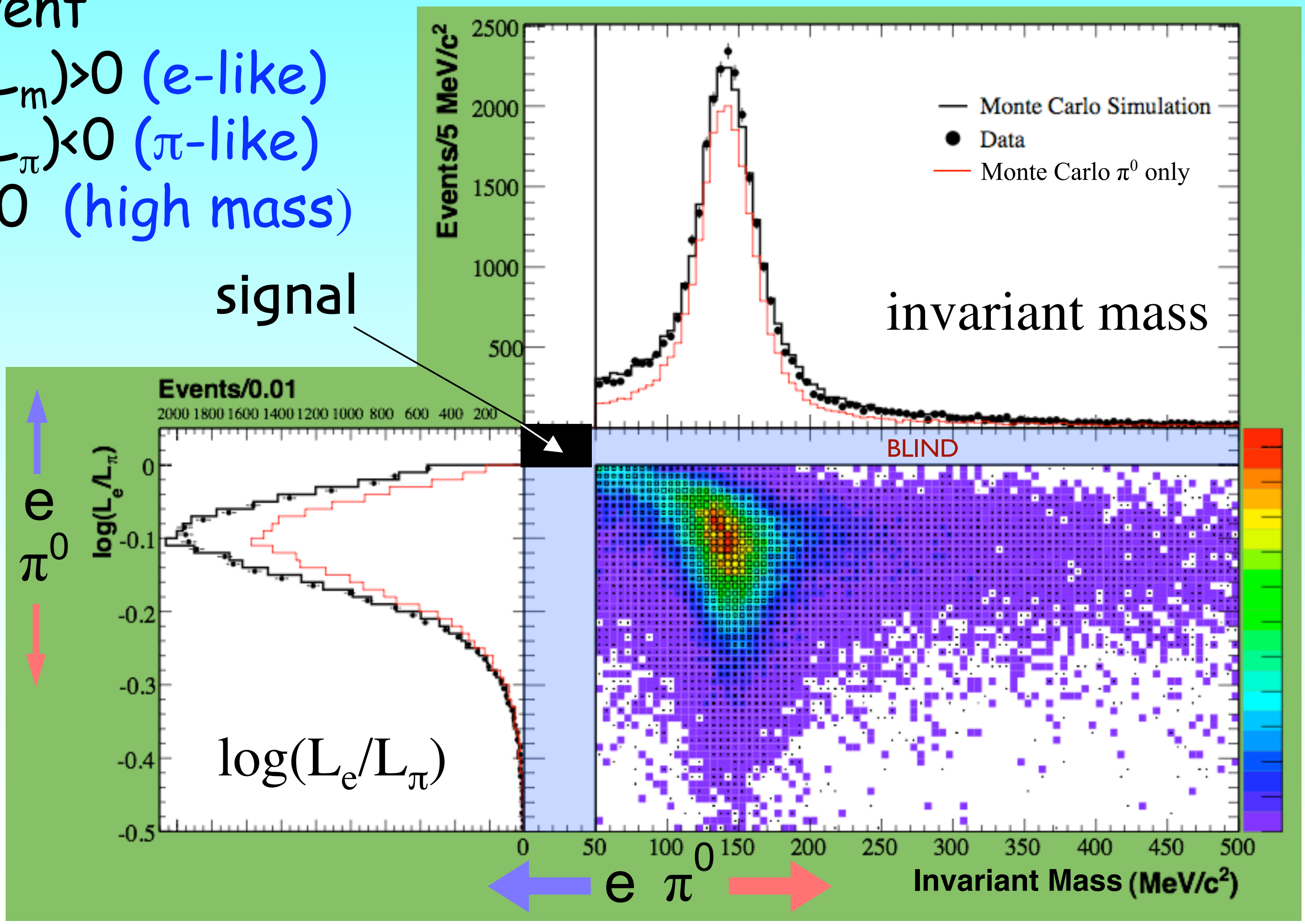
Testing e- π^0 separation using data

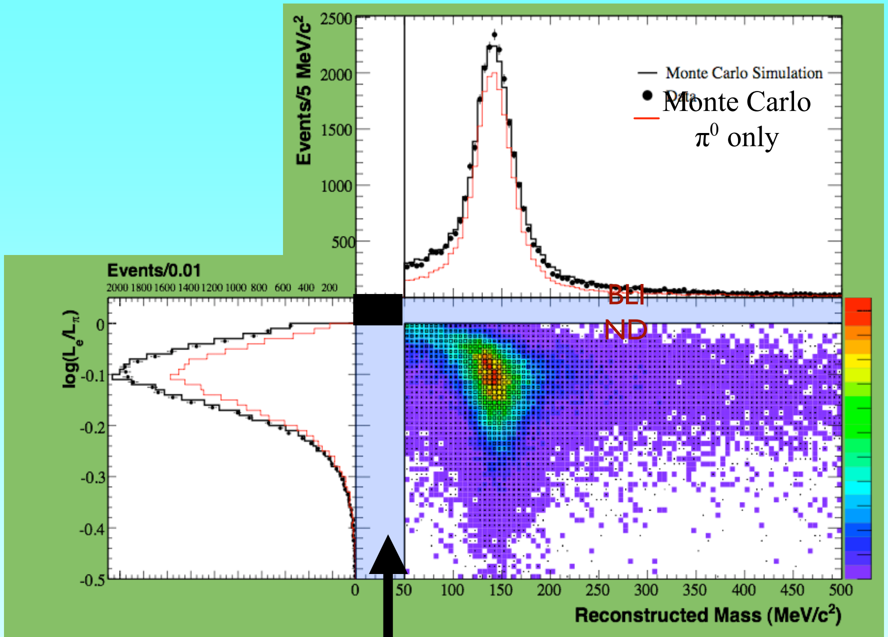
1 subevent

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

$\log(L_e/L_\pi)<0$ (π-like)

mass>50 (high mass)





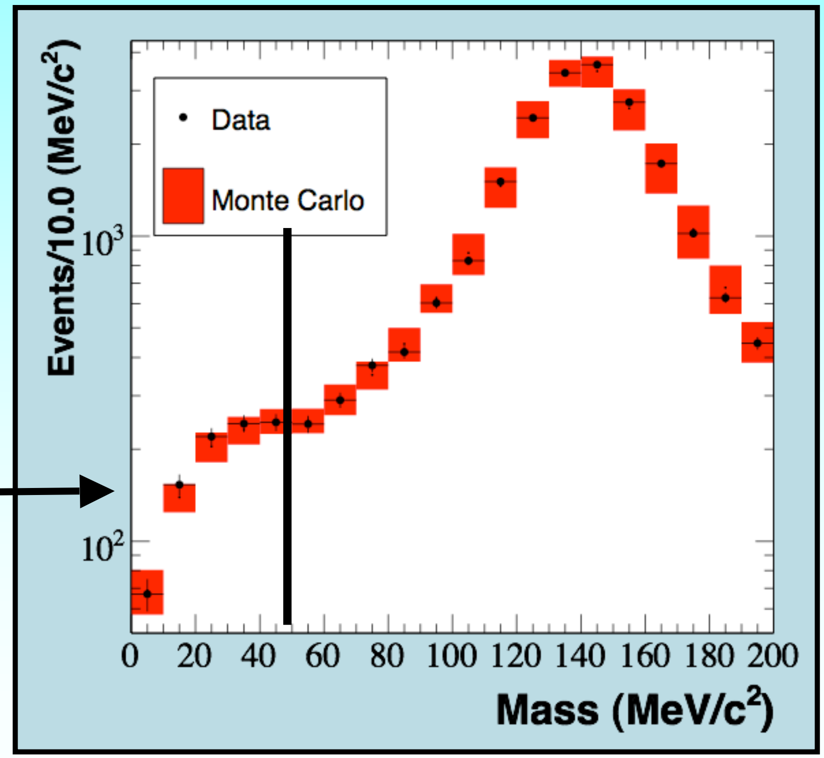
1 subevent

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

$\log(L_e/L_\pi)<0$ (π-like)

Mass<200 (high mass)

Next: look here...



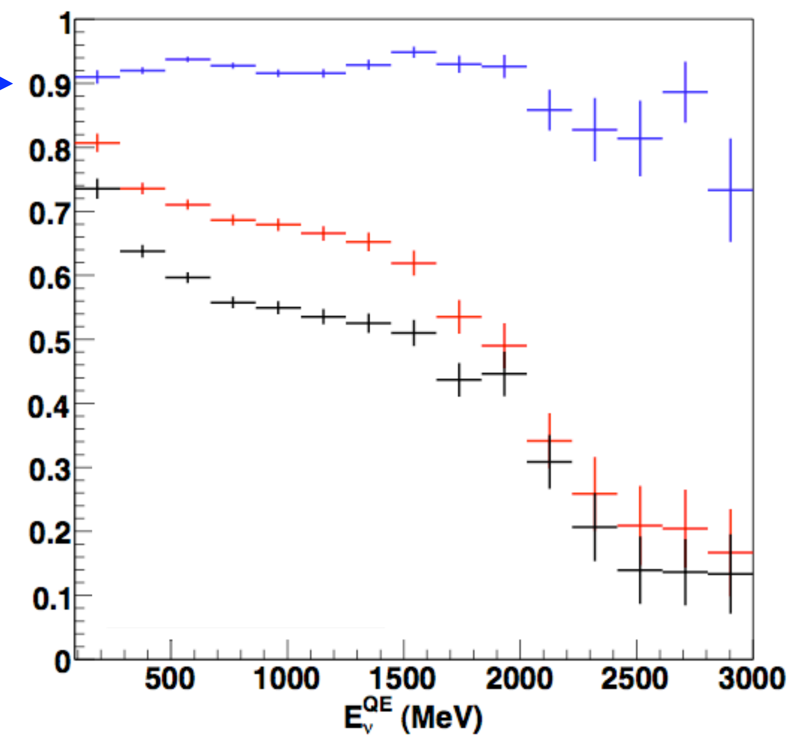
χ^2 probability for mass<50 MeV ("most signal-like"): 69%

SUMMARY OF TRACK BASED CUTS

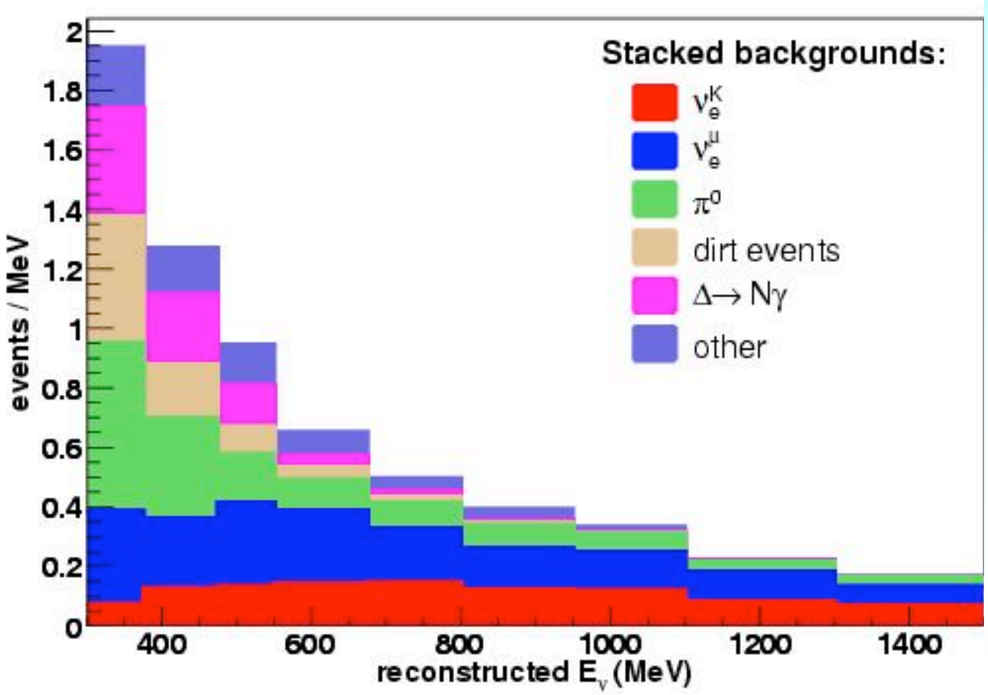
Precuts

+ $Log(L_e/L_\mu)$
+ $Log(L_e/L_\pi)$
+ invariant mass

Efficiency:



Backgrounds after cuts



BDT Analysis

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

Fundamental information from PMTs

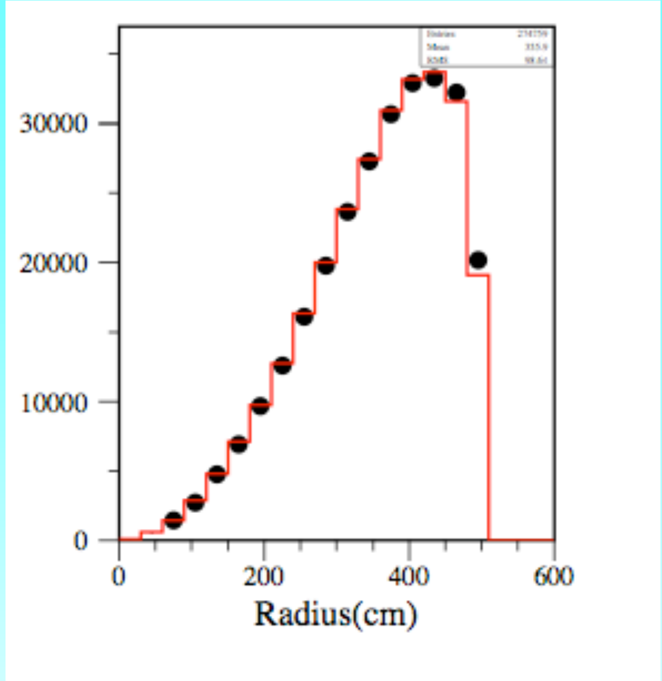
Analysis variables

	Hit position	Charge	Hit timing
Energy	✖	✖	
Time sequence		✖	✖
Event shape	✖	✖	✖
Physics	✖	✖	✖

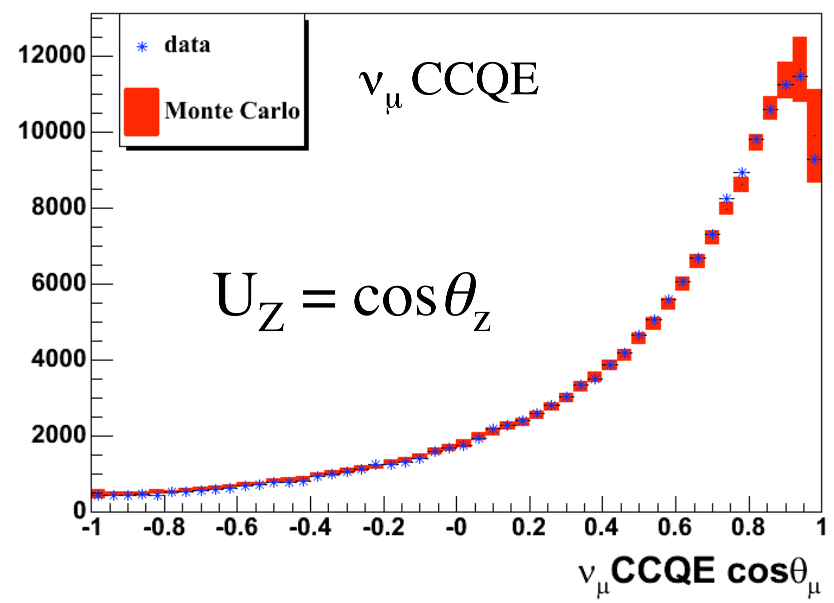
Physics -> π^0 mass, E_ν^{QE}, etc.

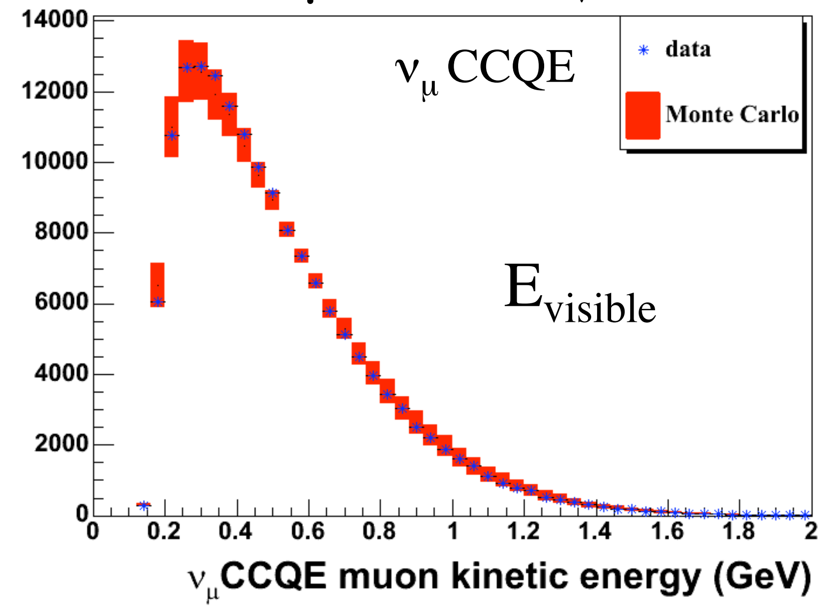
Analysis Variables:

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

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

hit level (charge, time, position)	→	analysis variables	→	One single PID "score"

A decision tree:

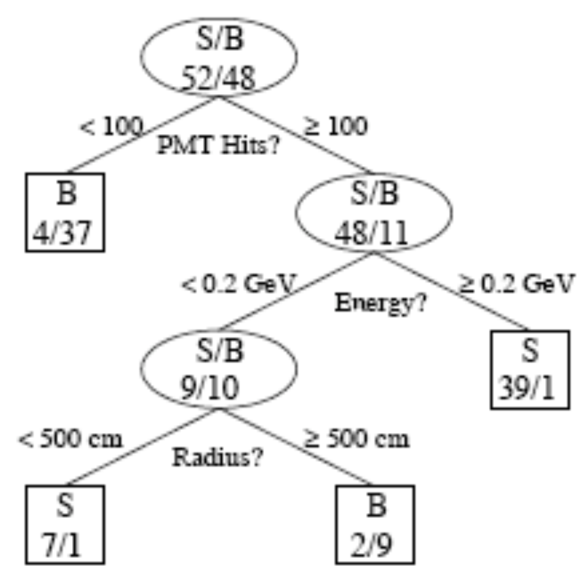


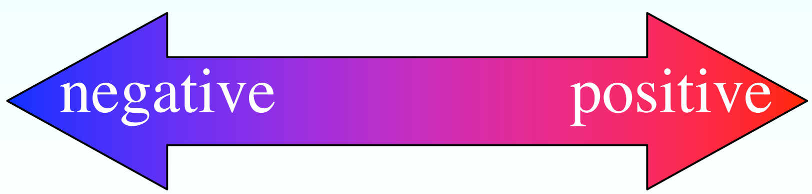
Figure 1: Schematic of a decision tree.

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.

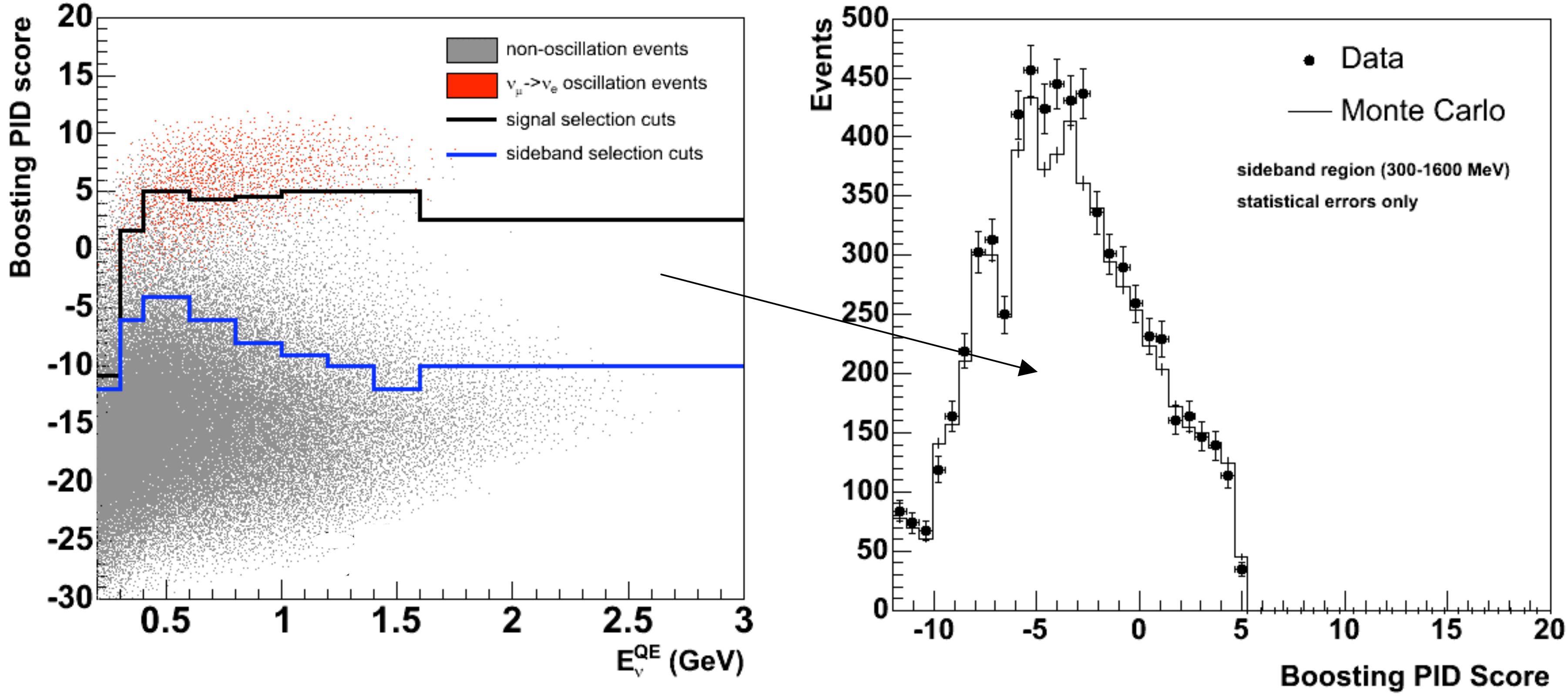
The total for all trees is combined into a score

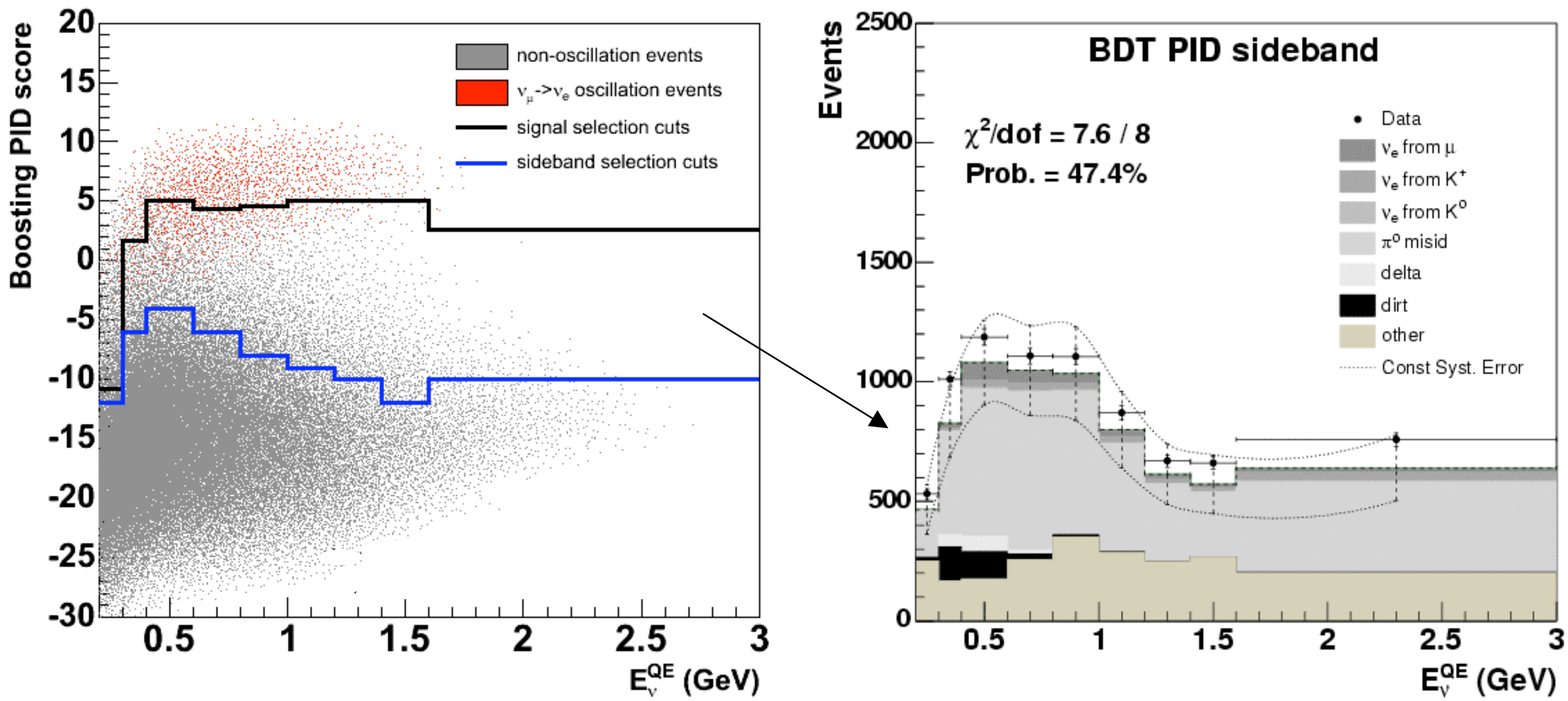
Background-like



signal-like

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

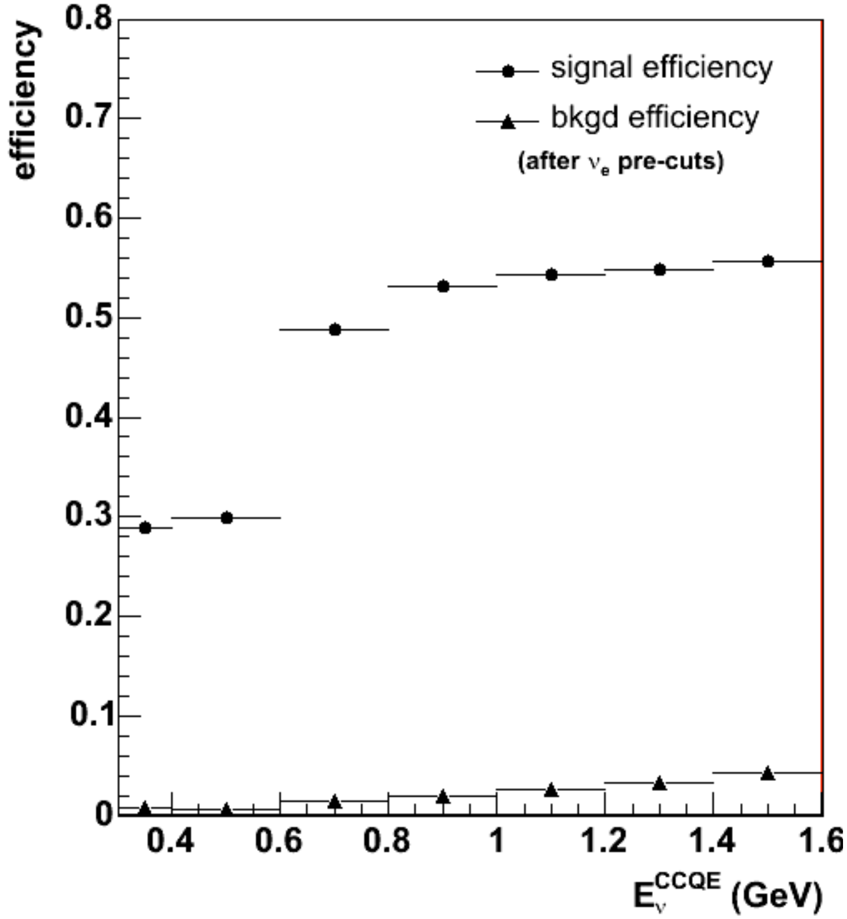


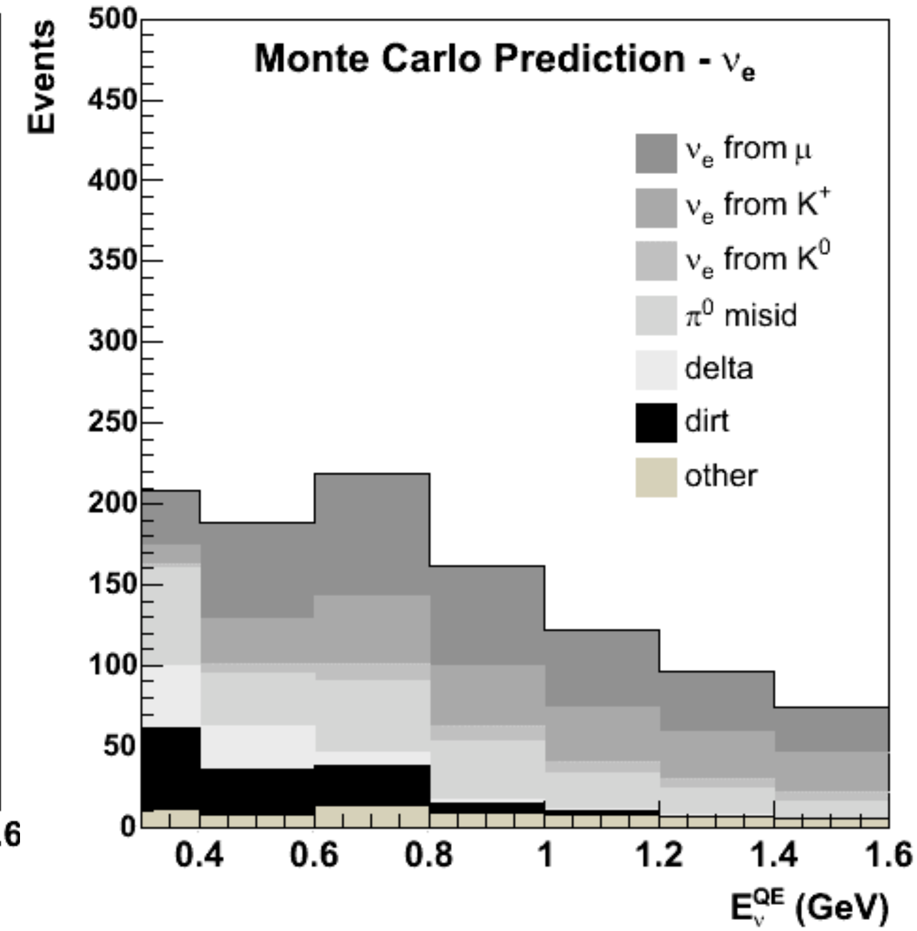


Boosting PID score
non-oscillation events
νμ->νe oscillation events
signal selection cuts
sideband selection cuts
E_ν^QE (GeV)
Events
BDT PID sideband
χ²/dof = 7.6 / 8
Prob. = 47.4%
Data
νe from μ
νe from K+
νe from K0
π0 misid
delta
dirt
other
Const Syst. Error

BDT Efficiency and Backgrounds after cuts

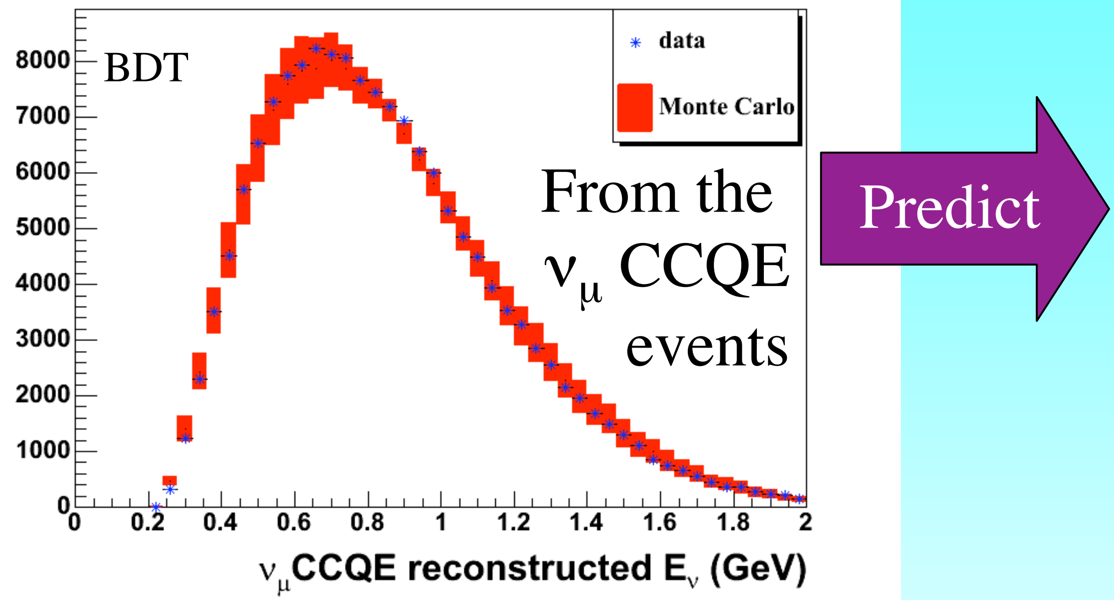
Analysis cuts on PID score as a function of Energy





SIGNAL, BACKGROUND, SENSITIVITY

Source of Uncertainty On ν_e background	TB %	BDT %	Checked / constrained by data	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 & beam models	2.8	1.3	✖	
Neutrino xsec	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	✖	

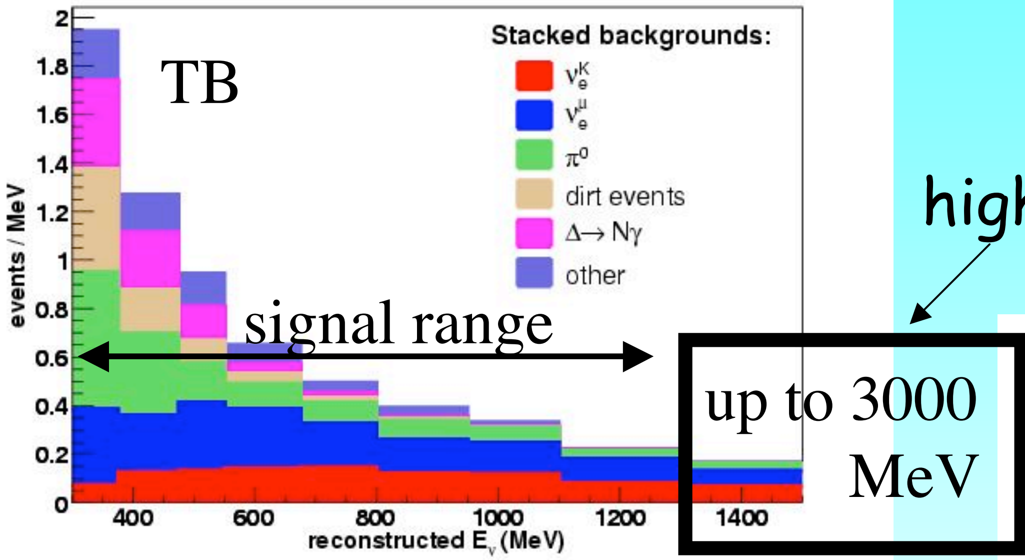


Normalization & energy dependence of both background and signal

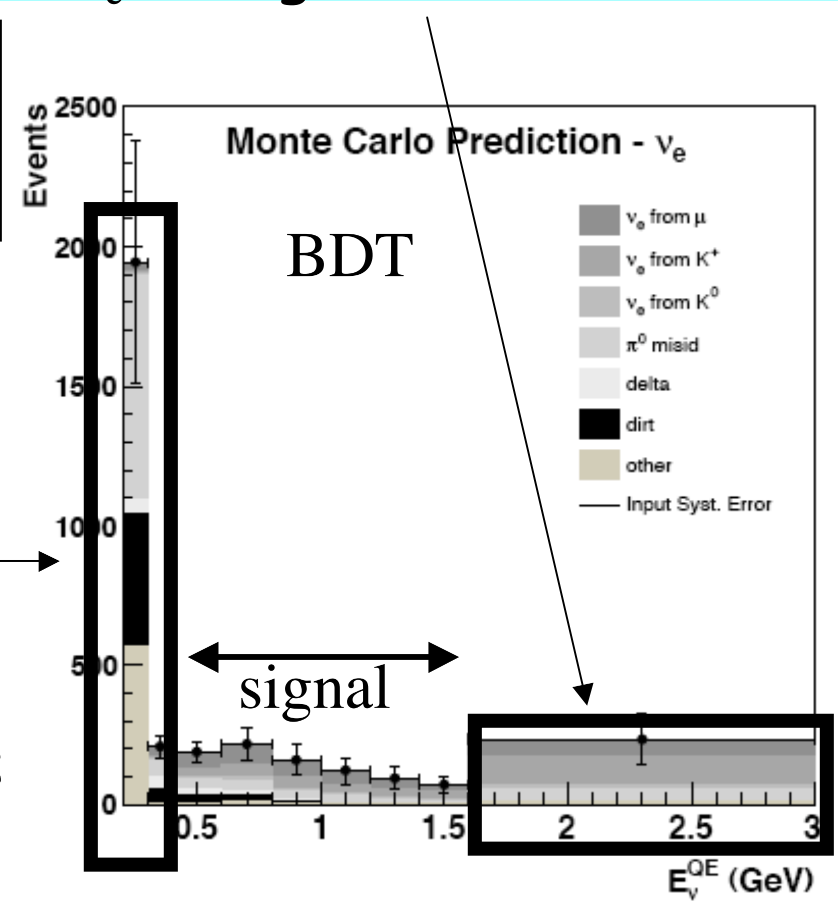
Data/MC	Boosted Decision Tree:	1.22 ± 0.29
	Track Based:	1.32 ± 0.26

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

Use of low-signal/high-background energy bins



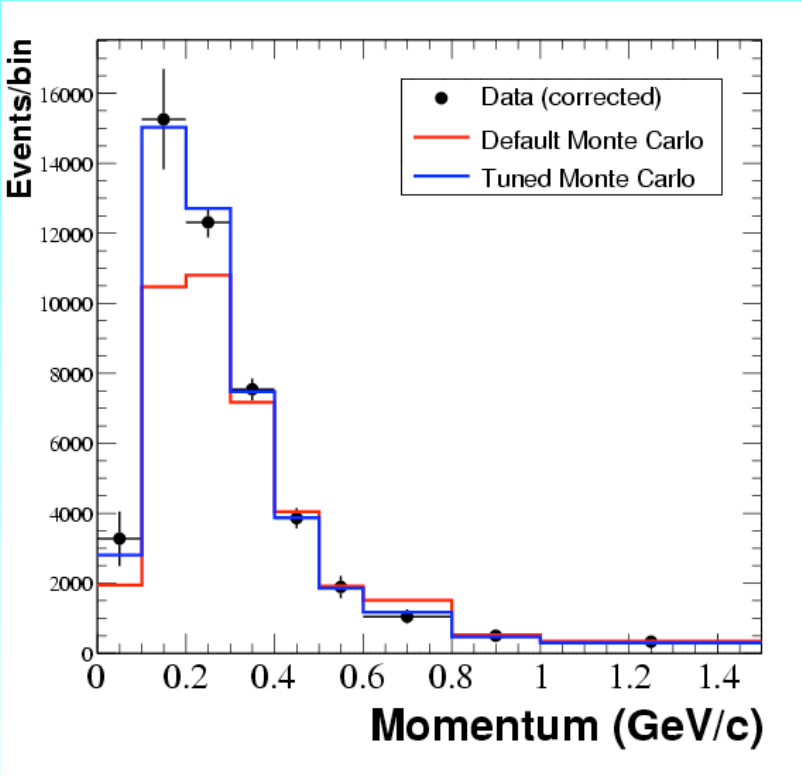
In both analyses, high energy bins constrain ν_e background



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

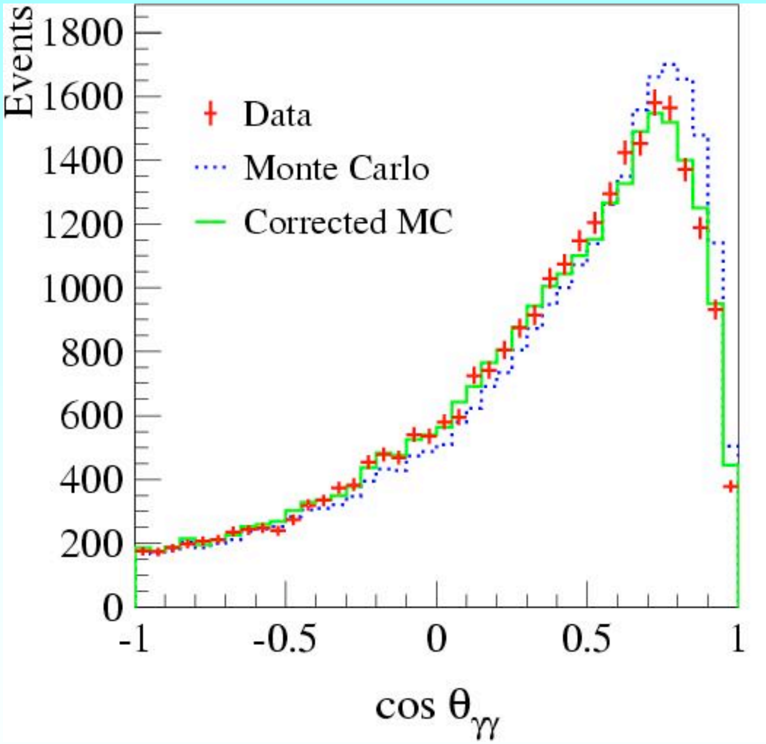
constrains ν_μ mis-ids: π^0, $\Delta \rightarrow N\gamma$, dirt ...

constrain π^0 production using MiniBooNE data



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

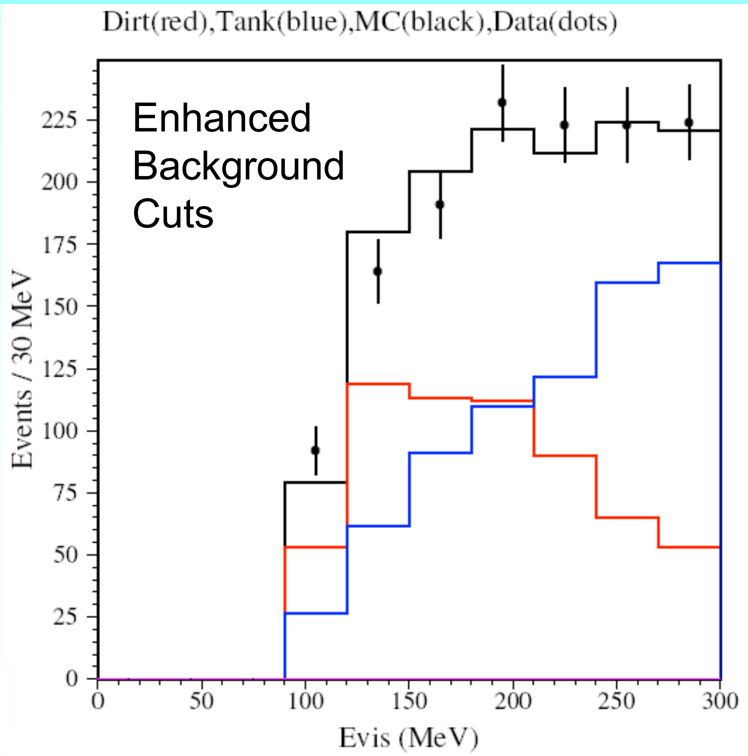
Re-weighting improves agreement in other variables, e.g.

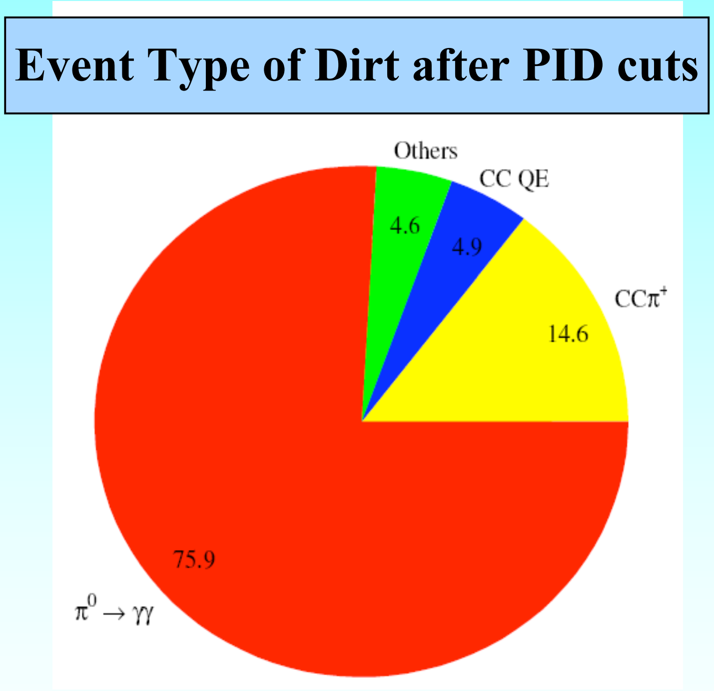


Because this constrains the Δ resonance rate, it also constrains the rate of $\Delta \rightarrow N\gamma$

External Sources of Background

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

Table 1: The estimated number of events with systematic error in the $475 < E_\nu^{QE} < 1250$ MeV energy range from all of the significant backgrounds, together with the estimated number of signal events for 0.26% $\nu_\mu \to \nu_e$ transmutation, after the complete event selection.

Process	Number of Events
ν_μ CCQE	10 ± 2
$\nu_\mu e \to \nu_\mu e$	7 ± 2
Miscellaneous ν_μ Events	13 ± 5
NC π^0	62 ± 10
NC $\Delta \to N\gamma$	20 ± 4
NC Coherent & Radiative γ	< 1
Dirt Events	17 ± 3
ν_e from μ Decay	132 ± 10
ν_e from K^+ Decay	71 ± 26
ν_e from K^0_L Decay	23 ± 7
ν_e from π Decay	3 ± 1
Total Background	358 ± 35
0.26% $\nu_\mu \to \nu_e$	163 ± 21

Handling Uncertaintes in the Analyis

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

Two approaches in introducing the constraints:

TB: re-weight 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 $(M_{ij})^{-1}$

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)
QE σ norm	10%
QE σ shape	function of E_ν
ν_e/ν_μ QE σ	function of E_ν

determined from MiniBooNE ν_μ QE data

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

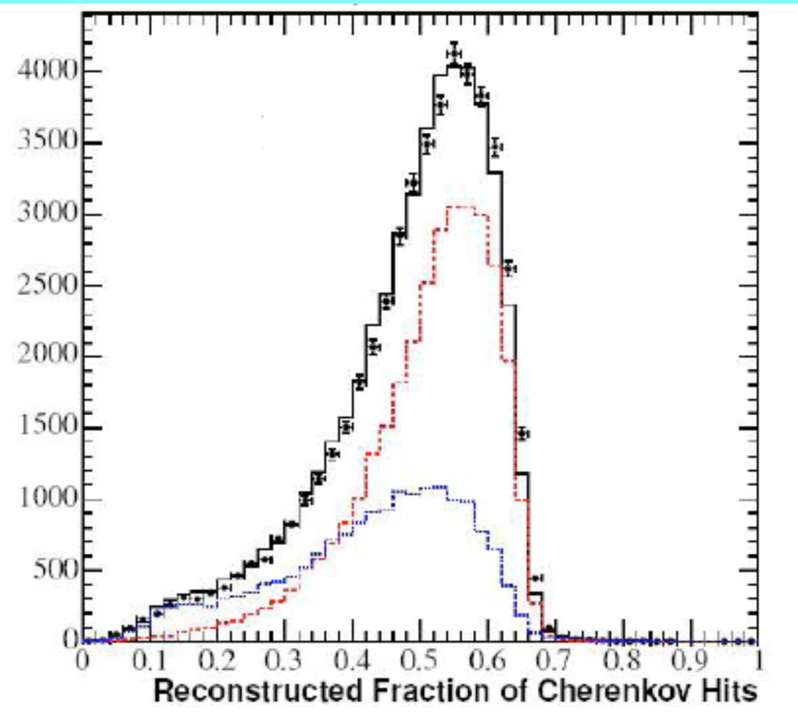
determined from MiniBooNE ν_μ NC π^0 data

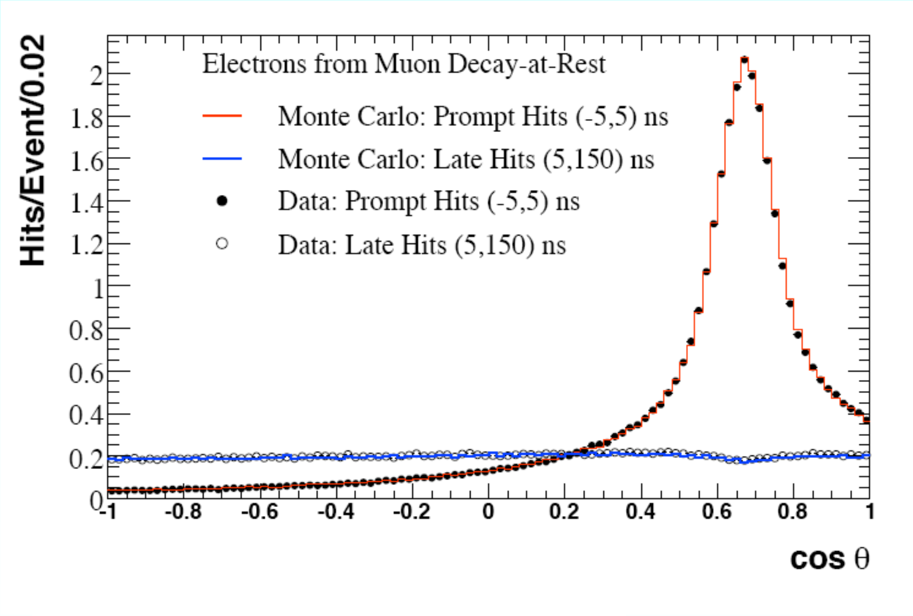
E_B, p_F	9 MeV, 30 MeV
Δs	10%
$M_A^{1\pi}$	25%
$M_A^{N\pi}$	40%
DIS σ	25%

determined from other experiments

Example: Optical Model Uncertainties

39 parameters must be varied, allowed variations are set by the Michel electron calibration sample





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

"Multisims"

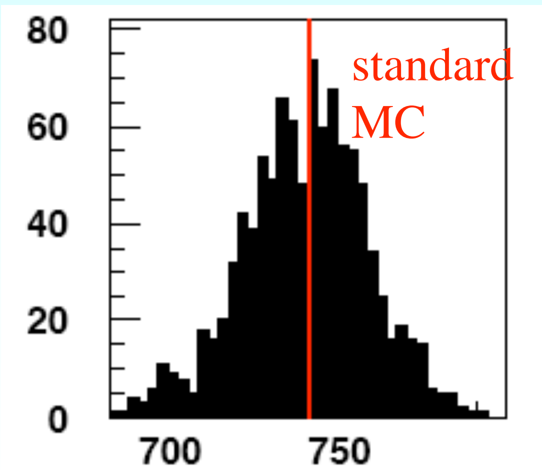
Using Multisims to convert from errors on parameters to errors in E_ν^{QE} bins:

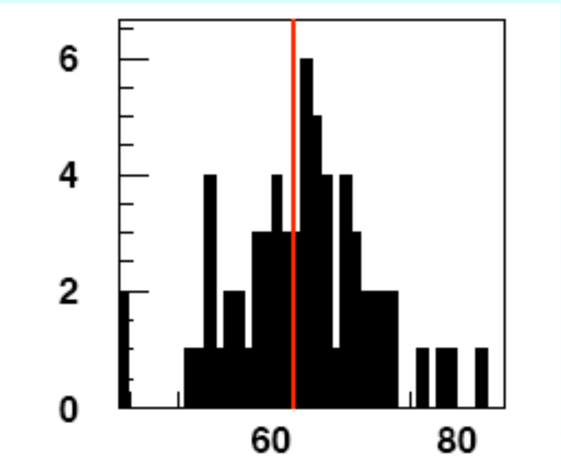
For each error source, Multisims are generated within the allowed variations by re-weighting the standard Monte Carlo.
In the case of the OM, hit-level simulations are used.

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:

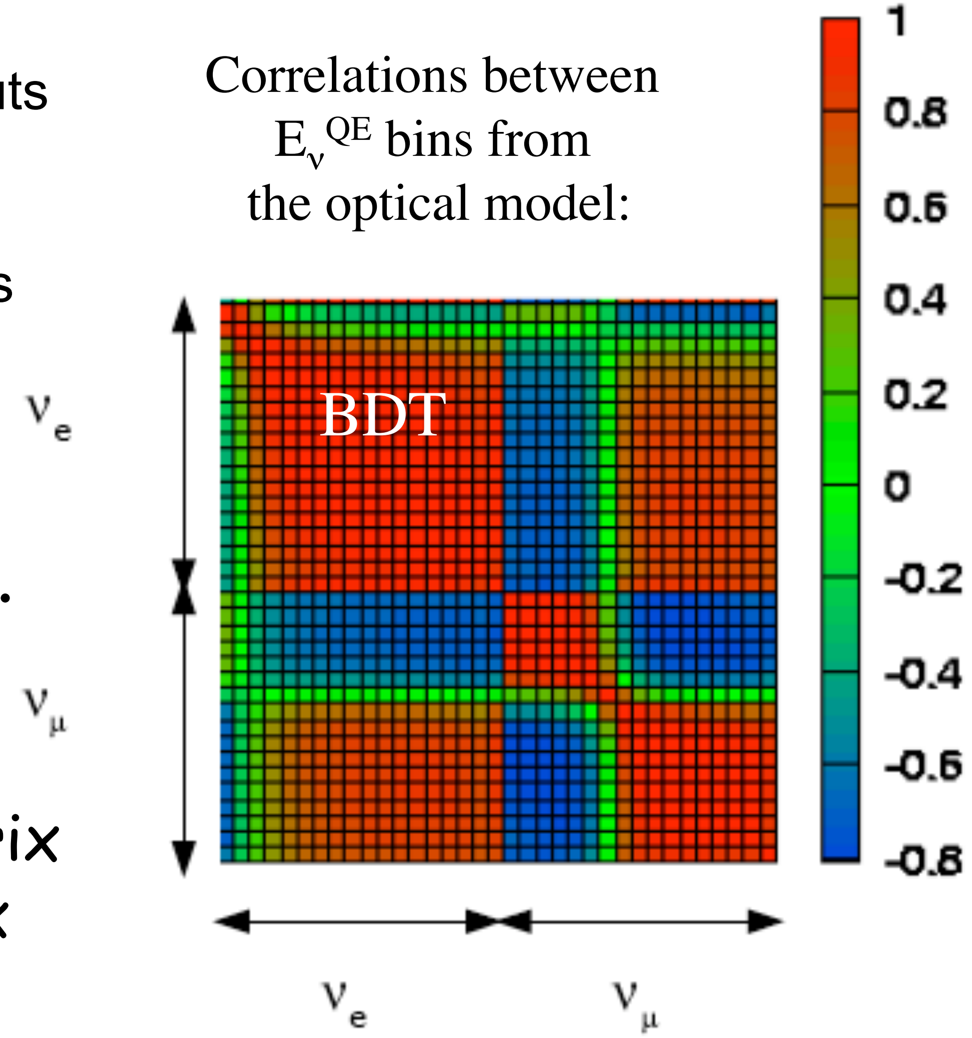
$$E_{ij} \approx \frac{1}{M}\sum_{\alpha=1}^{M}\left(N_i^{\alpha}-N_i^{MC}\right)\left(N_j^{\alpha}-N_j^{MC}\right)$$

- 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.

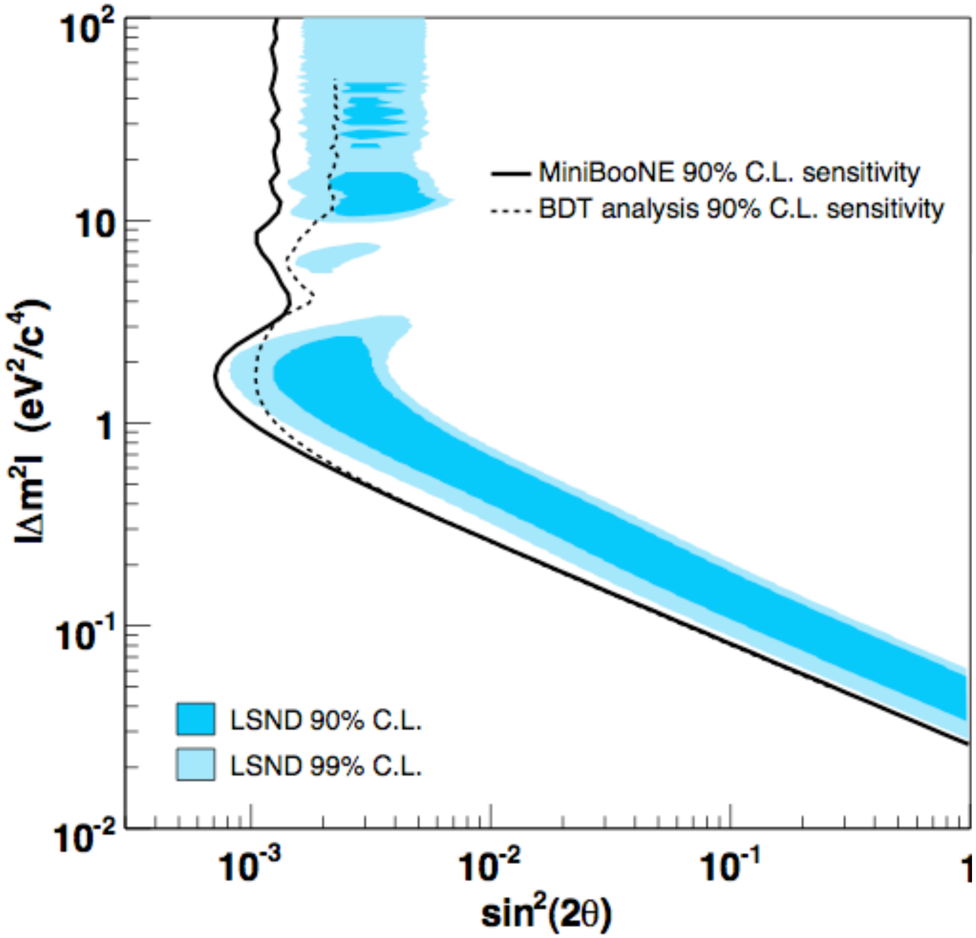
TB : ν_e only total error matrix
BDT: ν_μ-ν_e total error matrix

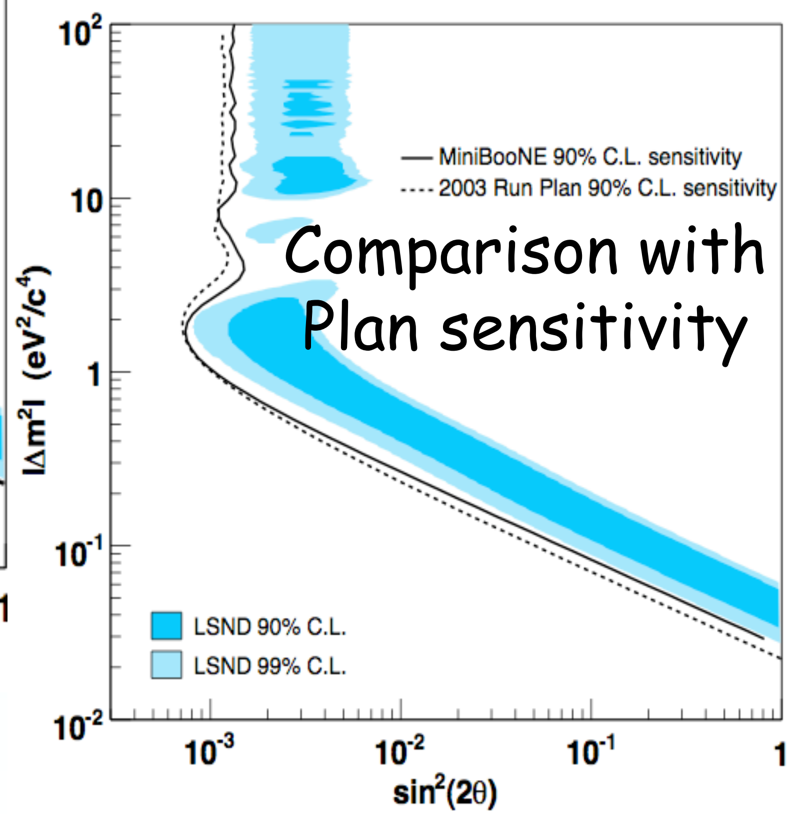
Correlations between E_ν^{QE} bins from the optical model:



Sensitivity

The track based analysis has better sensitivity, therefore it becomes the default analysis (prior to opening the box)





Comparison with Run Plan sensitivity

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

RESULTS

Box Opening Procedure

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:

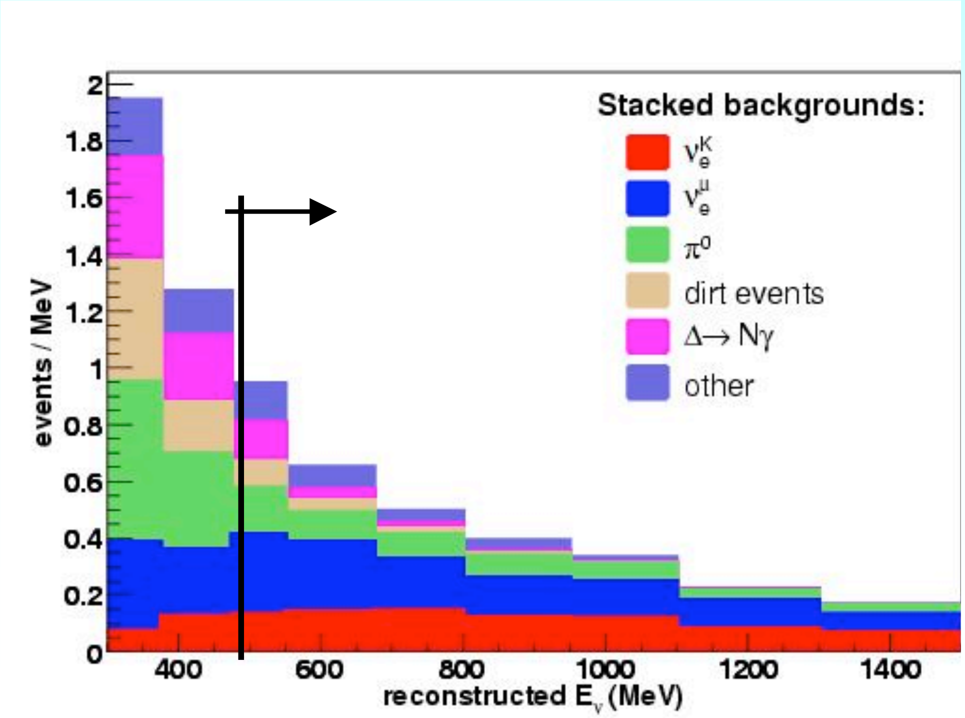
- 12 variables are tested for TB
- 46 variables are tested for BDT

All analysis variables were returned with good probability except TB analysis χ^2 probability of $E_{visible}$ fit: 1%

This probability was sufficiently low to merit further consideration

Looked at unsigned fractional discrepancies for $E_{visible}$; re-examined background estimates from sideband studies and found no evidence of a problem. However, knowing that **1.** Backgrounds rise at low energy and **2.** Sensitivity changes very little, we tightened the cuts for the oscillation fit:

E_ν^{QE} > 475 MeV

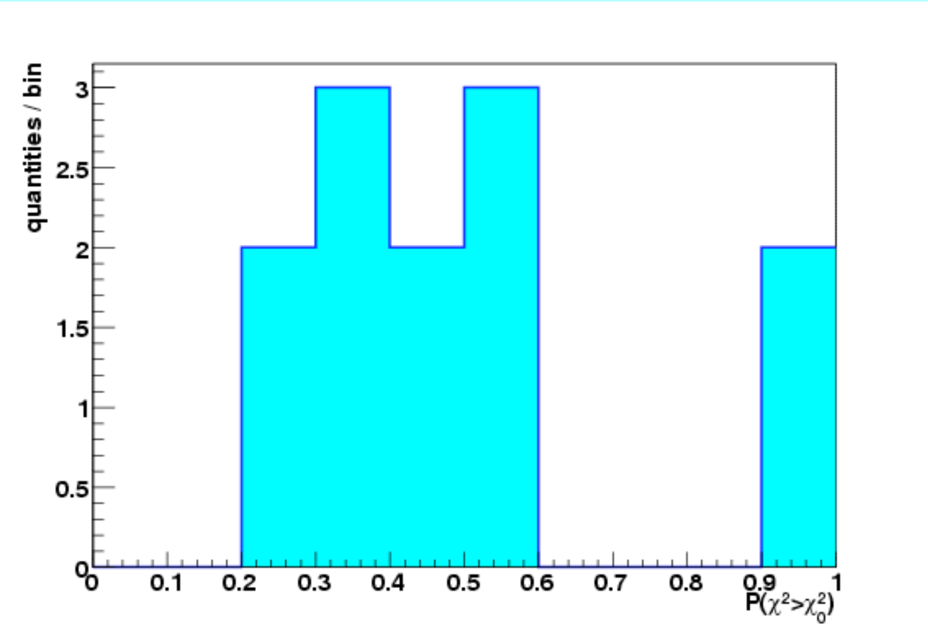


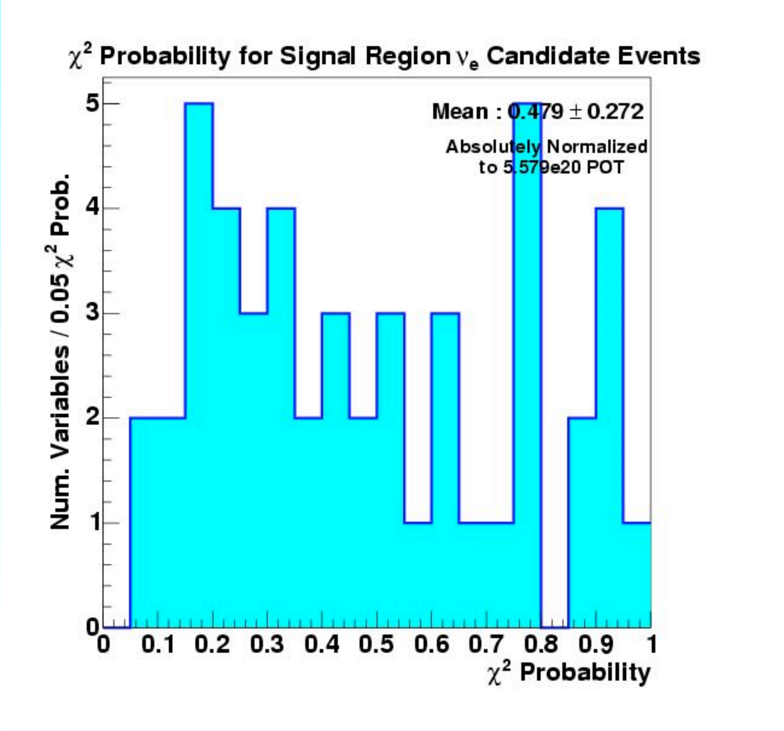
We agreed to report events over the original energy range (E_ν^{QE} > 300 MeV)

STEP 1 AGAIN

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

χ^2 probabilities returned:





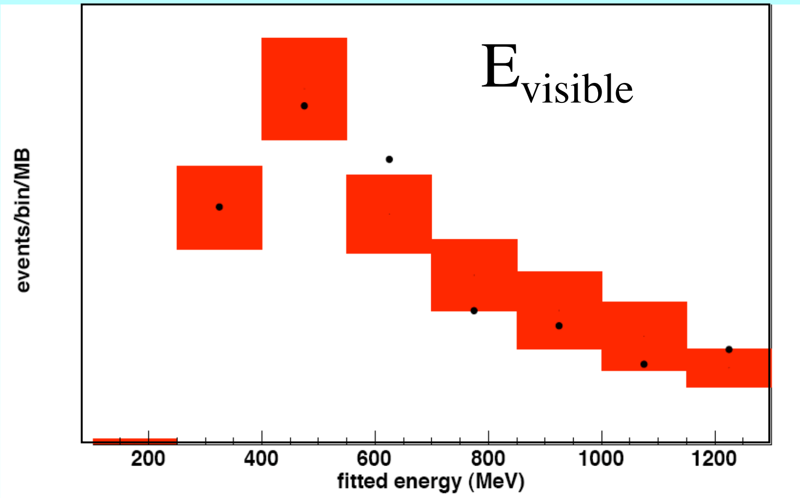
Parameters of the oscillation fit were not (yet) returned.

STEP 2

Open up the plots from step 1 for approval

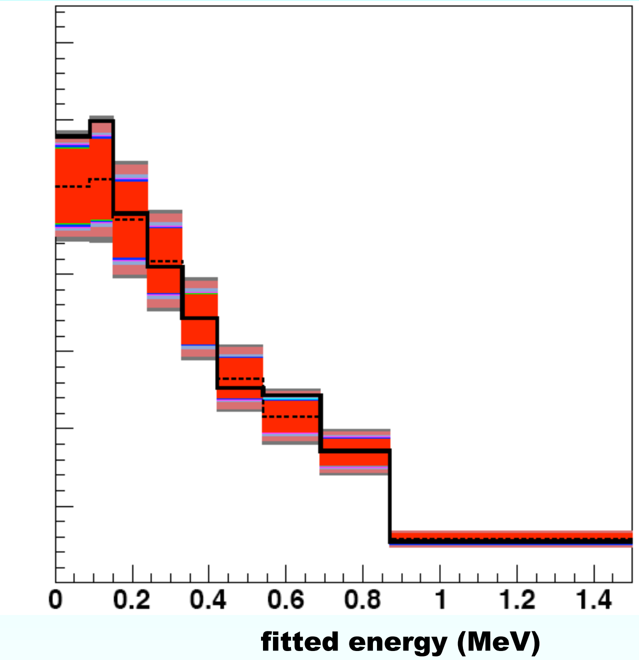
Examples of what we saw: $E_{visible}$

χ^2 probability = 28%



TB (E_ν^{QE} >475 MeV)

χ^2 probability = 59%



BDT

MC contains fitted signal at unknown level

STEP 3

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

TB analysis χ^2 Probability of fit: 99%

BDT analysis χ^2 Probability of fit: 52%

LEADING TO STEP 4: OPEN THE BOX

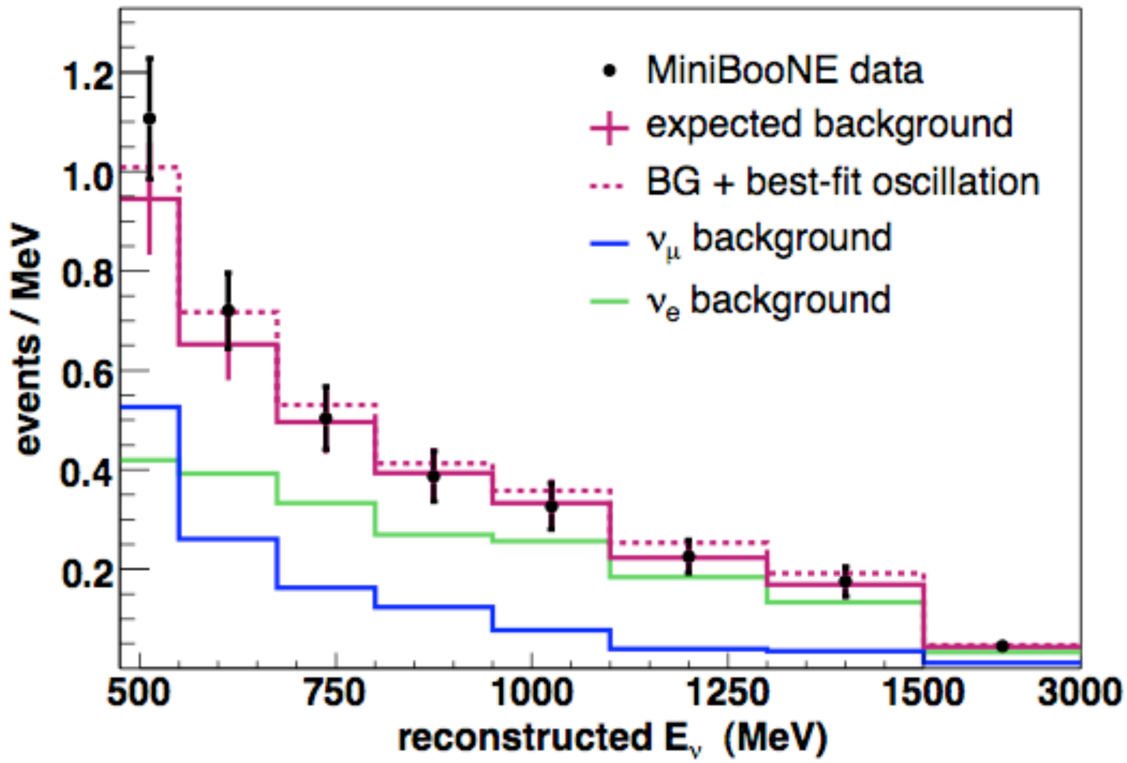
Result of the Track-Based Analysis ($\nu_\mu \rightarrow \nu_e$ hypothesis)

Counting Experiment: 475< E_ν^{QE} <1250 MeV

DATA: 380 events
EXPECTATION: 358 ±19 (stat) ± 35 (sys)

significance: 0.55 σ

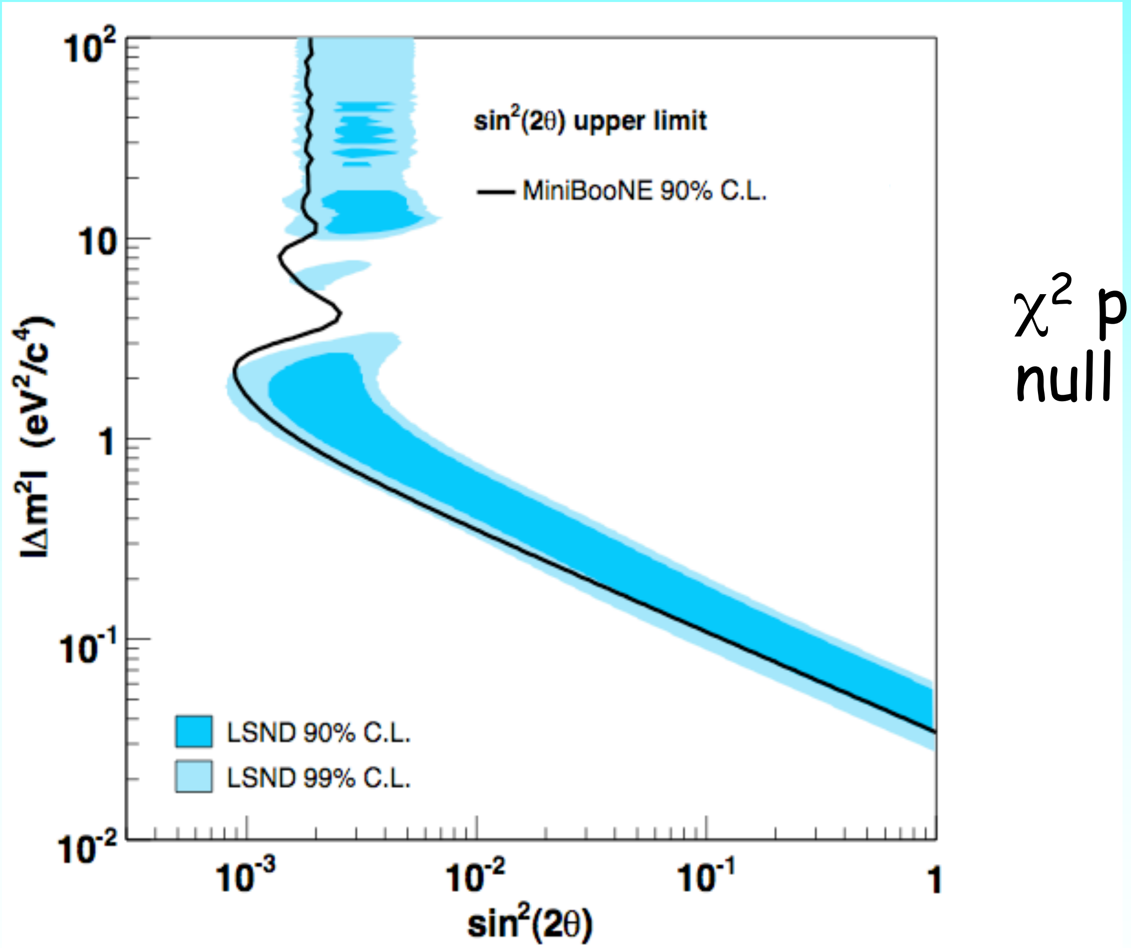
Track Based energy dependent fit results: data are in good agreement with prediction for background.



Error bars are diagonals of error matrix.

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

The analysis under the $\nu_\mu \rightarrow \nu_e$ hypothesis sets a limit on oscillations:



χ^2 probability,
null hypothesis: 93%

Energy fit: 475 MeV< E_ν^{QE} <3000 MeV

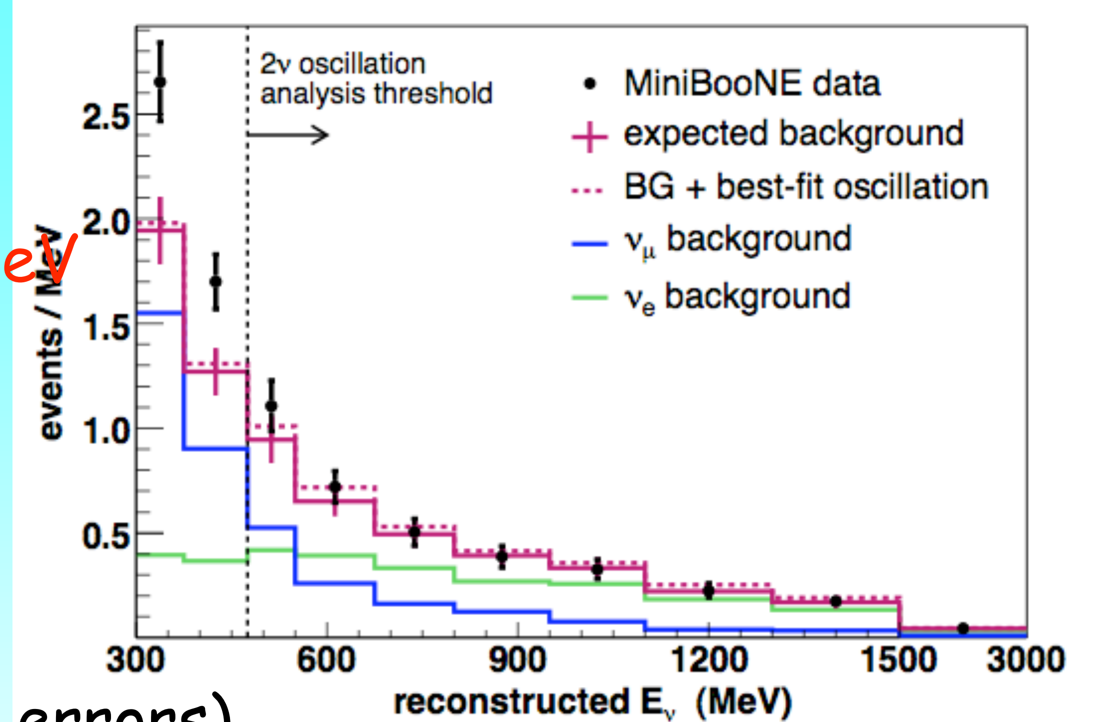
As planned before opening the box...

Report the full range:

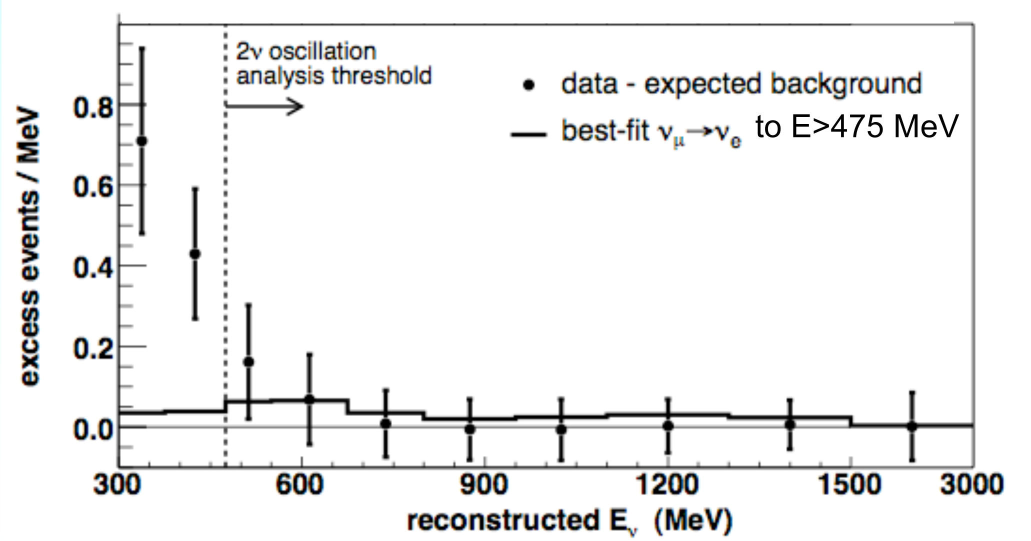
300 MeV < E_ν^{QE} < 3000 MeV

96 ± 17 ± 20 events above background, for 300< E_ν^{QE} <475MeV

Deviation: 3.7σ (diagonal errors)

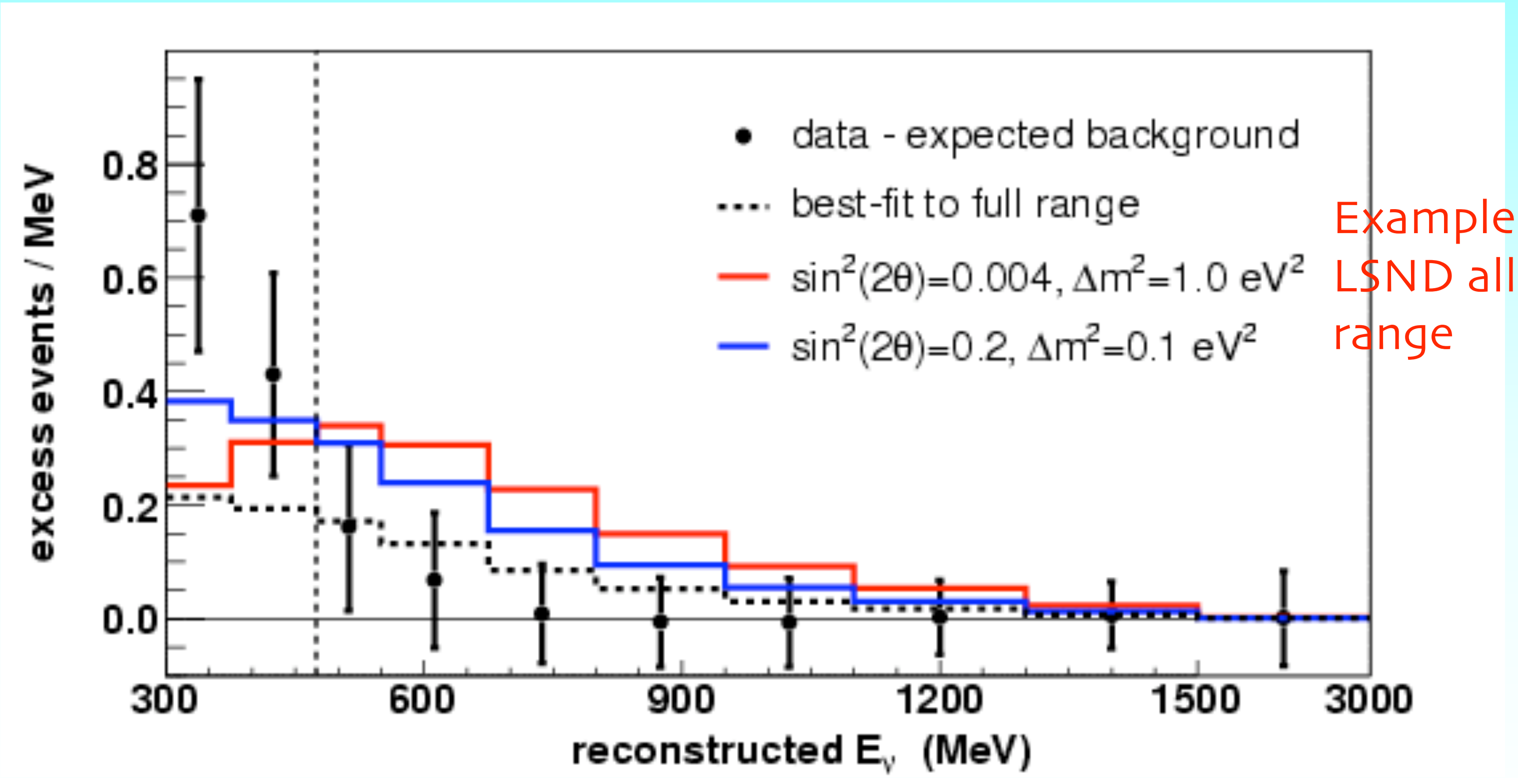


Background-subtracted:



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

Low E excess is interesting and requires further (on-going at this very moment) investigation

- The $\nu_\mu \rightarrow \nu_e$ hypothesis systematically disagrees with the shape as a function of energy

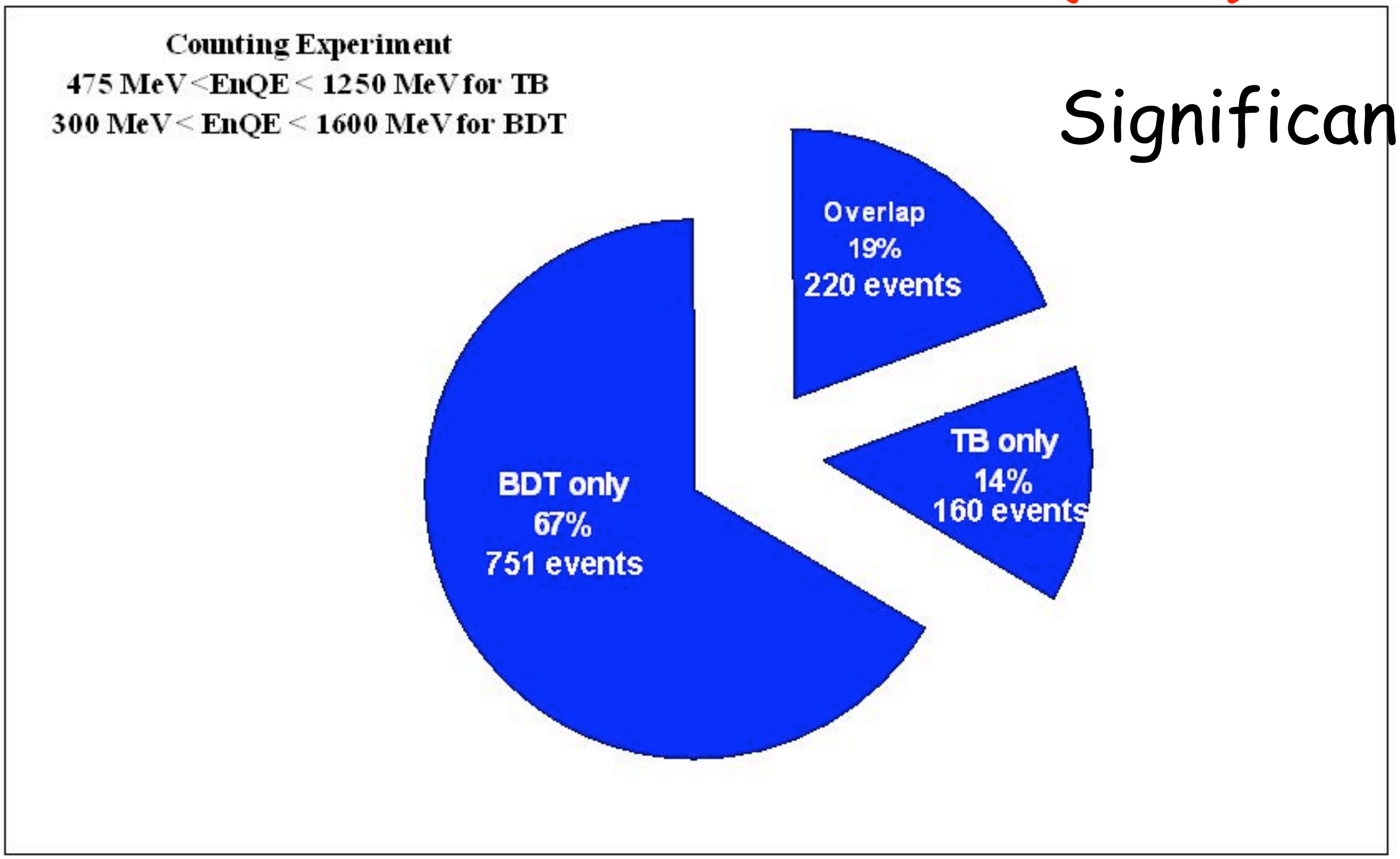
- We need to investigate non-oscillation explanations, including instrumental/analysis effects and unexpected behavior of low energy cross sections. Some of this may be relevant to future $\nu_\mu \rightarrow \nu_e$ searches

Boosted Decision Tree Analysis

Counting Experiment: 300< E_ν^{QE} <1600 MeV

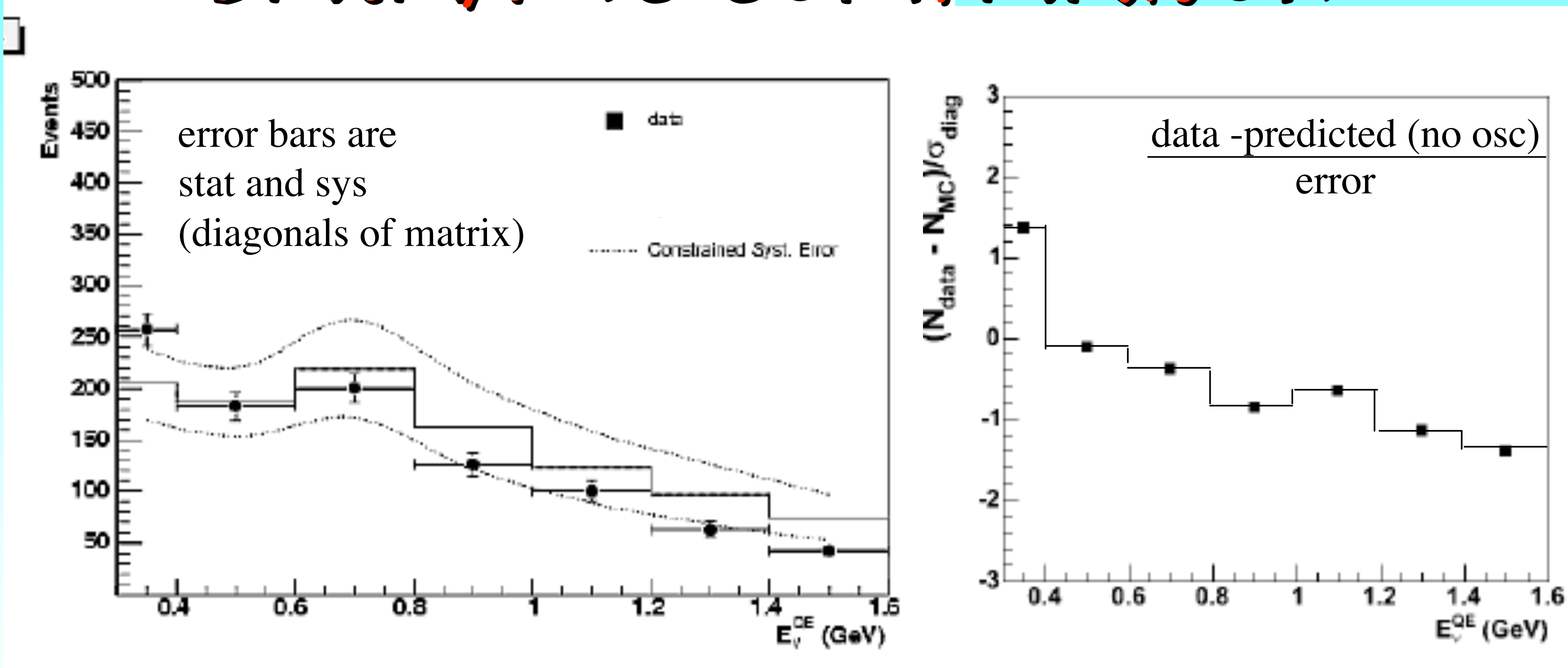
DATA: 971 events

EXPECTATION: 1070 ±33 (stat) ± 225 (sys)

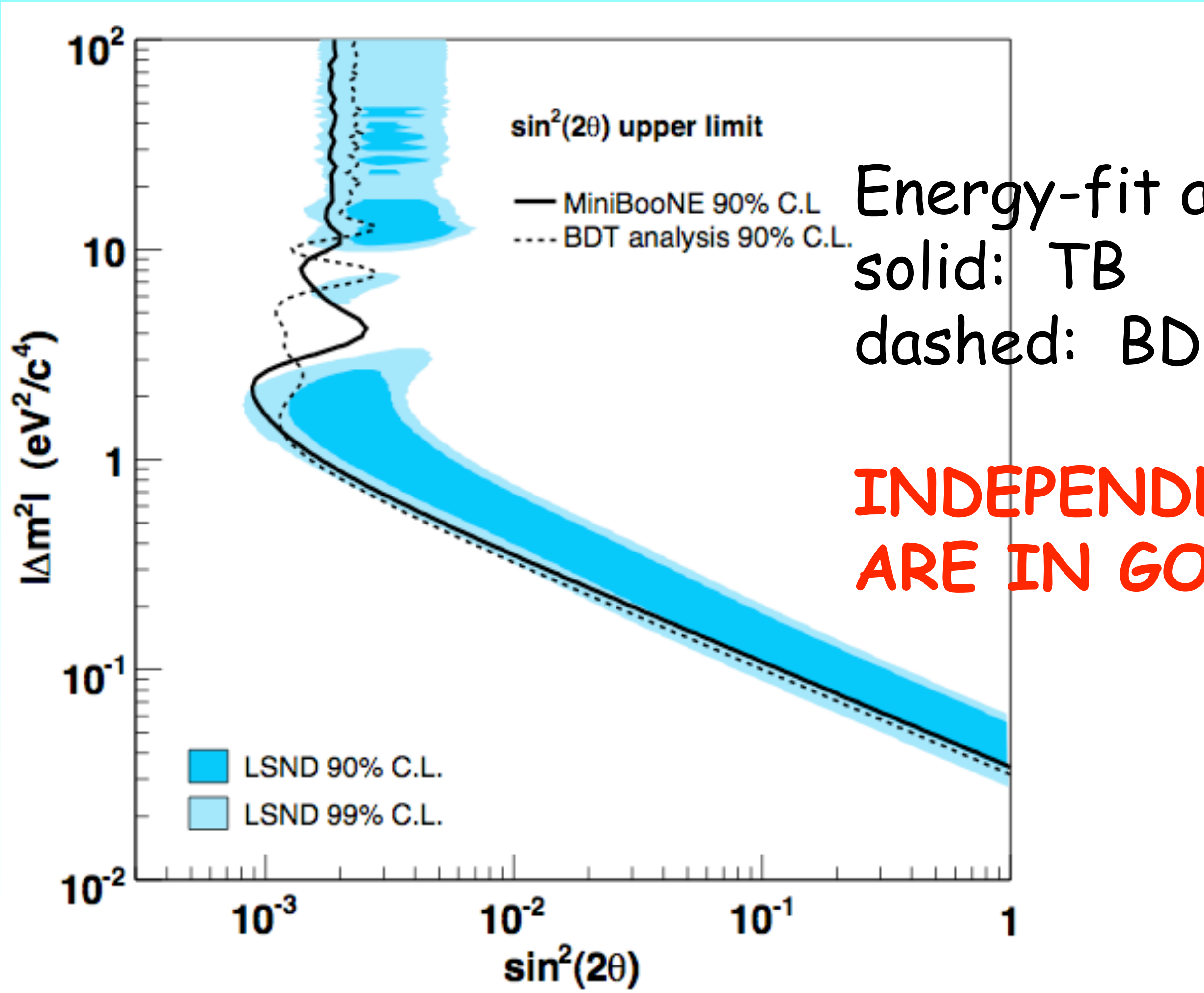


Significance: -0.38 σ

Boosted Decision Tree E_ν^{QE} Data/MC Comparison



Boosted Decision Tree analysis shows no evidence for $\nu_\mu \rightarrow \nu_e$ oscillations



Energy-fit analysis:
solid: TB
dashed: BDT

INDEPENDENT ANALYSIS ARE IN GOOD AGREEMENT

OUTLOOK & CONCLUSIONS

- MiniBooNE has completed its first analysis, looking for an excess of ν_e in a predominantly ν_μ beam
- The data were further analyzed looking for $\nu_\mu \rightarrow \nu_e$ oscillations under a 2-neutrino approximation
- In the energy range defined for the oscillation analysis there is no significant excess of ν_e and $\nu_\mu \rightarrow \nu_e$ oscillations are ruled out in the LSND region
- The observed excess at low energy is presently unexplained and is under investigation

- The first result is available on the archive arXiv:0704.1500 [HEP-EX] (submitted to PRL)
- The data will be available on-line very soon
- Several analyses are under way to extend the oscillation search beyond the 2-neutrino approximation
- Including possible exotic interpretation of LSND
- More analyses studying neutrino cross-sections (CC QE, resonant and coherent processes, etc.) with unprecedented high statistics are presently being completed