A Search for $\nu_\mu \rightarrow \nu_e$ Oscillations in the ~1Δm^2 eV^2 region at MiniBooNE

Workshop on ***N***ext Generation ***N***ucleon Decay
and ***N***eutrino Detectors
Hamamatsu, Japan
October 2-5, ***2007***

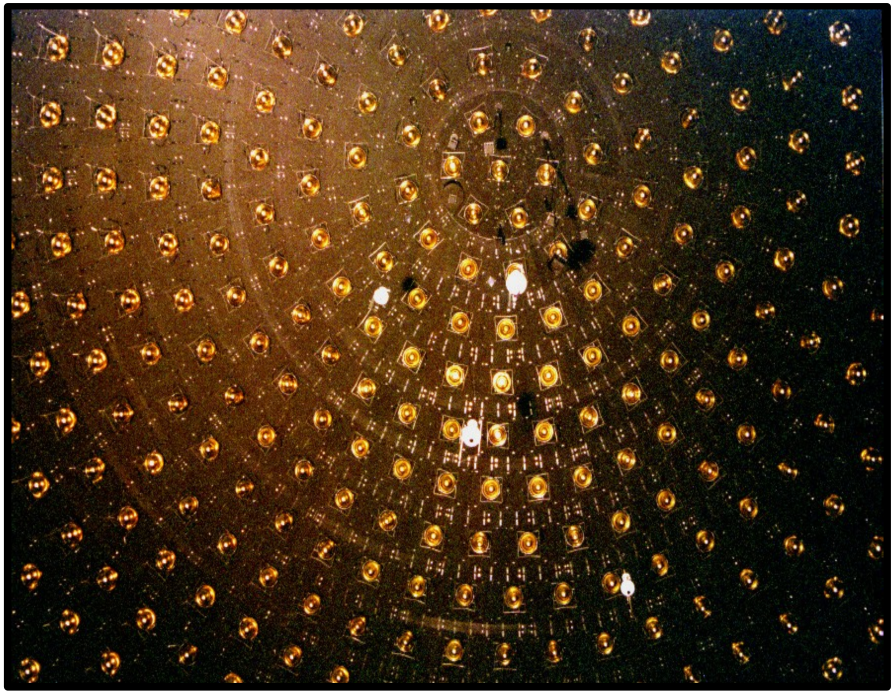
Dave Schmitz
Columbia University

on behalf of the
MiniBooNE Collaboration

O
u
t
l
i
n
e

A Search for $\nu_\mu \rightarrow \nu_e$ Oscillations in the ~1Δm^2 eV^2 region at MiniBooNE

- Motivation for this oscillation search
- Overview of the MiniBooNE design and analysis strategy
- The oscillation analysis
- The oscillation results
- Future outlook
- Summary



The MiniBooNE Collaboration

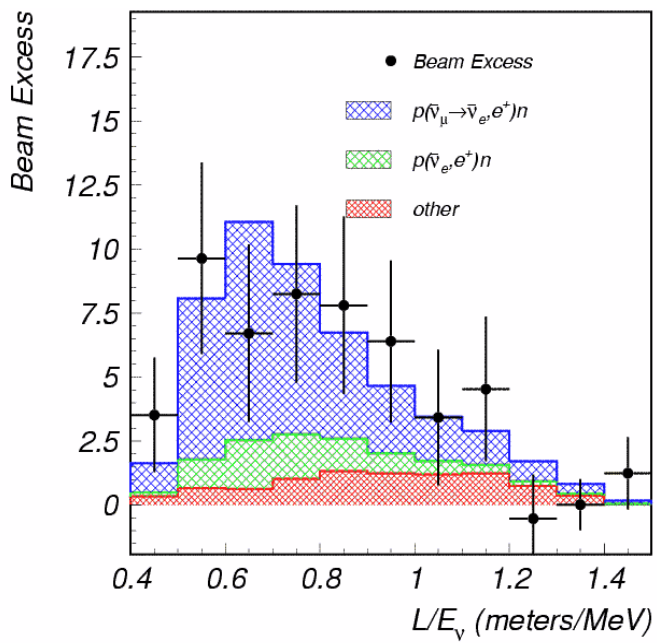
A. A. Aguilar-Arevalo, A. O. Bazarko, S. J. Brice, B. C. Brown, L. Bugel, J. Cao, L. Coney, J. M. Conrad, D. C. Cox, A. Curioni, Z. Djurcic, D. A. Finley, B. T. Fleming, R. Ford, F. G. Garcia, G. T. Garvey, J. A. Green, C. Green, T. L. Hart, E. Hawker, R. Imlay, R. A. Johnson, P. Kasper, T. Katori, T. 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

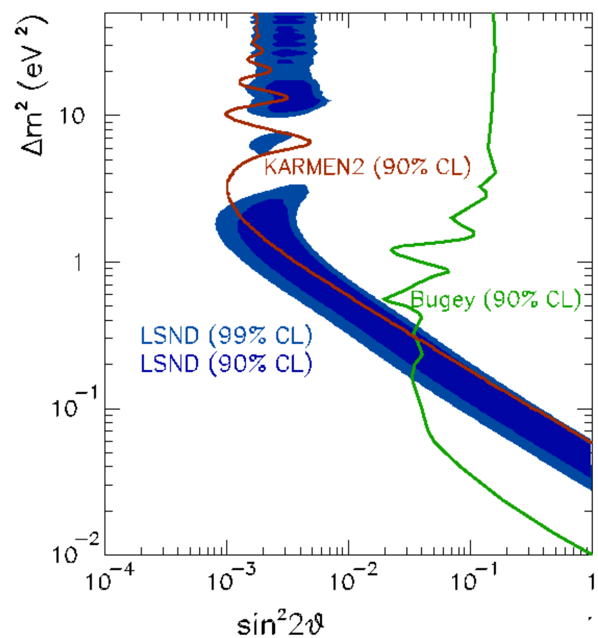
University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle University
Fermilab
Indiana University
Los Alamos National Laboratory
Louisiana State University
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Western Illinois University
Yale University

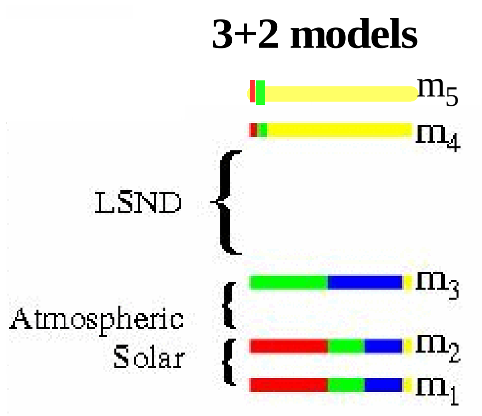
The LSND Signal as Oscillations

Motivation

- LSND looked for an excess of $\overline{\nu}_e$ in a $\overline{\nu}_\mu$ beam
- Found an 87.9 ± 22.4 ± 6.0 (3.8σ) $\overline{\nu}_e$ event excess above background
- Interpreted as 2 flavor oscillations, implies an oscillation probability of (0.264 +- 0.067 +- 0.045)%







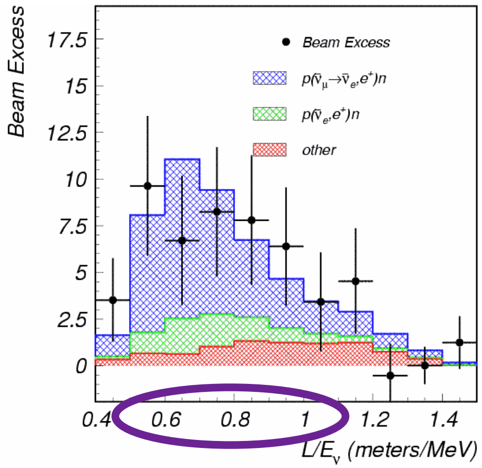
- LSND plus atmospheric and solar mass splittings typically interpreted as indication of additional "sterile" neutrinos
- ***But LSND requires confirmation. . .***

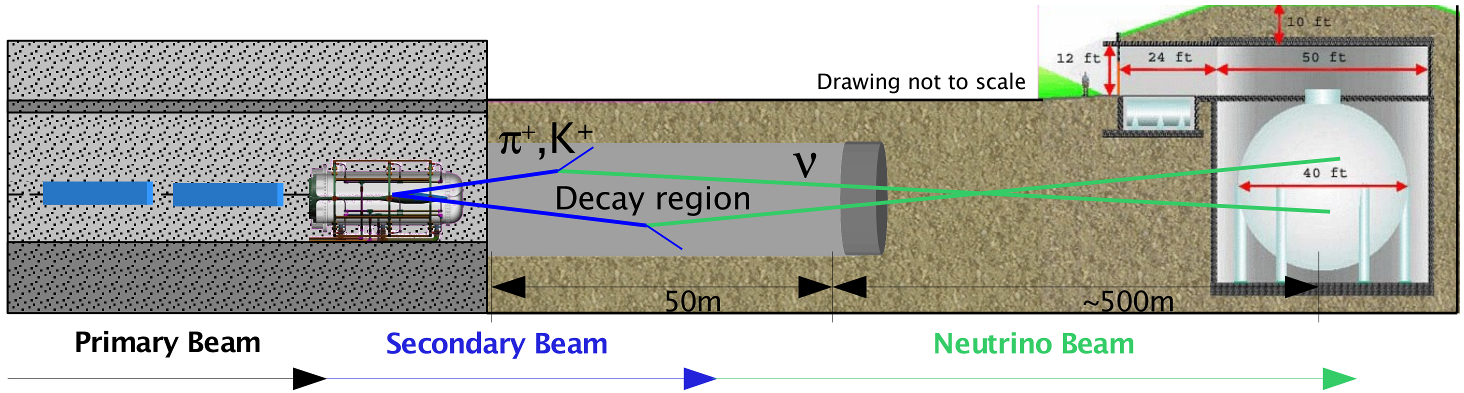
(Sorel, Conrad, and Shaevitz, PRD 70 (2004) 073004 (hep-ph/0305255)
Karagiorgi et al., PRD75 (2007) 013011 (hep-ph/0609177)

MiniBooNE Design

- If the LSND excess is due to oscillations, then the effect should be preserved for a ***fixed ratio of baseline length, L and neutrino energy, E***

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2 \frac{L}{E}\right)$$





<E> ~ 0.5-1.0 GeV

<L> ~ 0.540 km

$$\frac{\langle L \rangle}{\langle E \rangle} \approx 0.5 - 1.0$$

- 8 GeV protons from Fermilab Booster focused on to a 1.7λ beryllium target
  - 174 kA focusing horn
  - 5.58E20 p.o.t. in neutrino mode
  - changed to anti-neutrino mode in Jan, 2006
- π and K decay to produce neutrinos with mean energy ~0.7 GeV
- 800T pure mineral oil detector
  - 1280 8” photomultiplier tubes
  - 240 optically isolated tubes in a veto region
  - detect Cherenkov and scintillation light produced in neutrino interactions

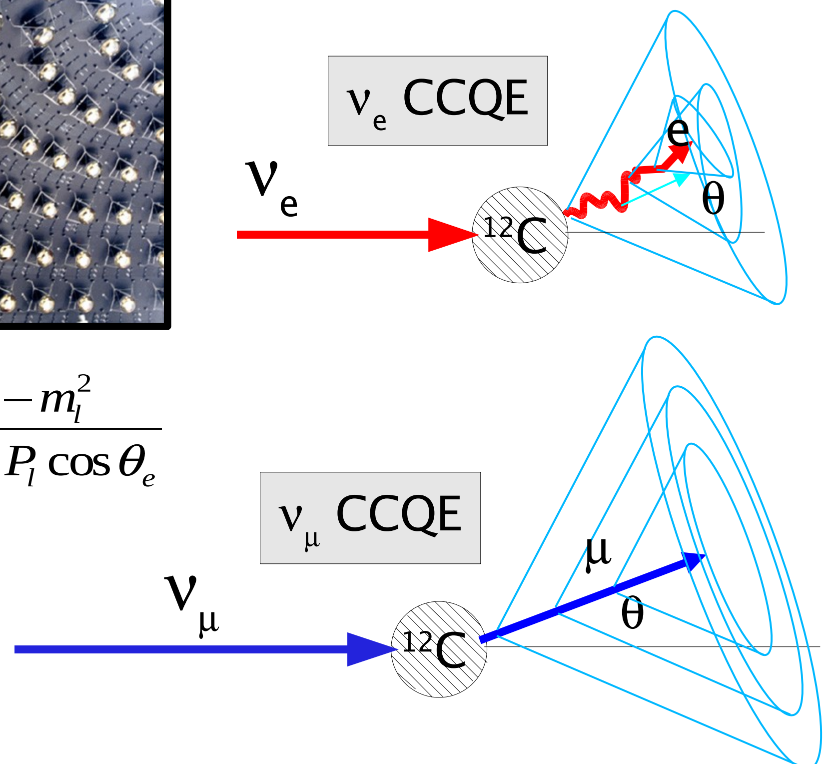
Beam composition and detection scheme completely different from LSND,* but *sensitive to the same oscillation space because of L/E

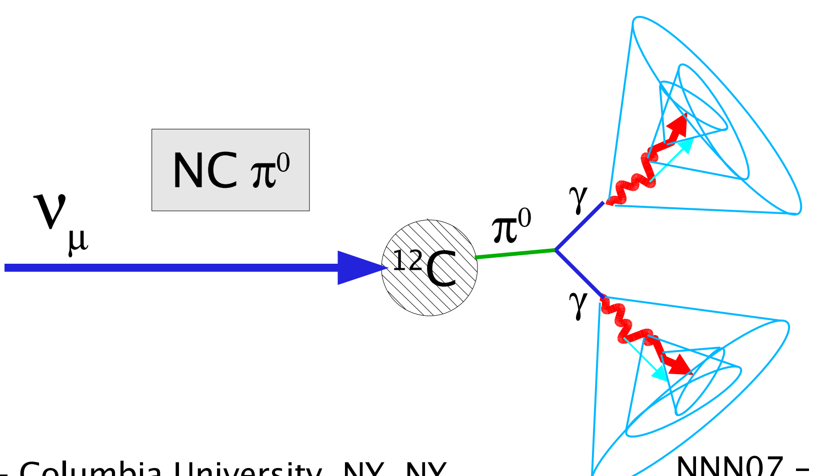
Exp Overview

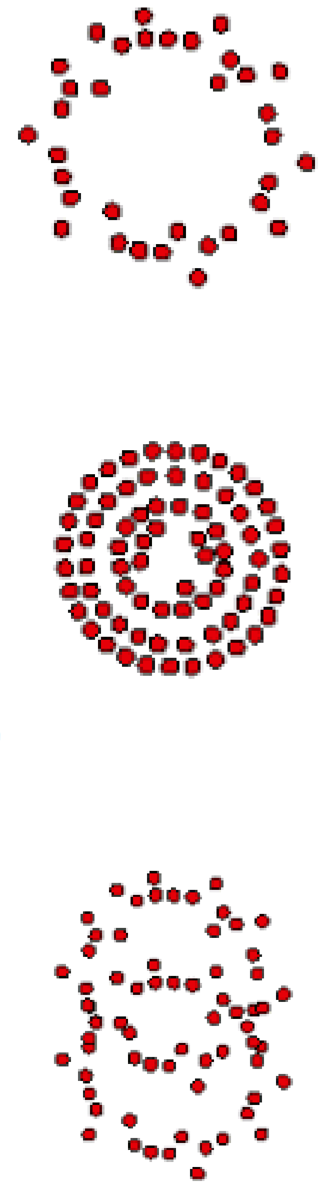
MiniBooNE Design

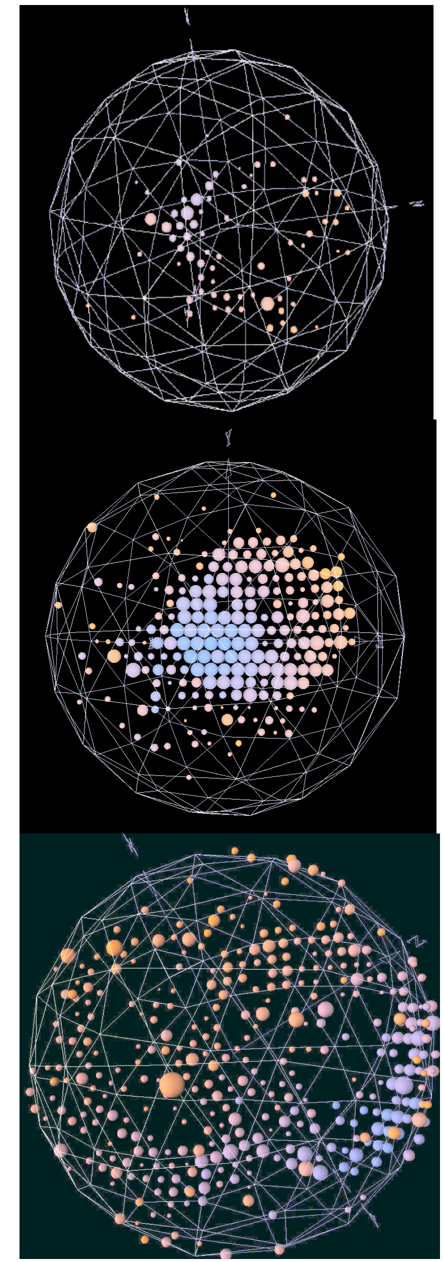
- After cuts, MiniBooNE must be able to find $O(100s)$ ν_e CCQE interactions in a sea of $O(100Ks)$ ν_μ interactions

$$E_\nu^{QE} = \frac{1}{2}\frac{2ME_l - m_l^2}{M - E_l + P_l \cos\theta_e}$$

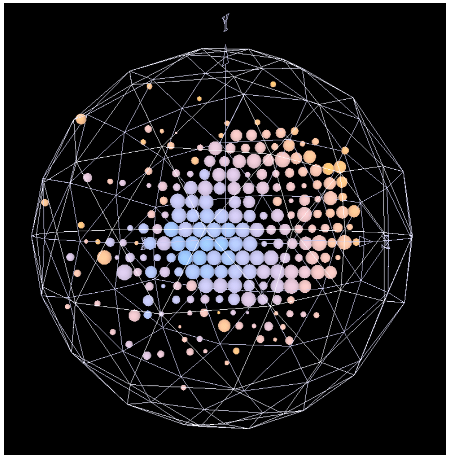


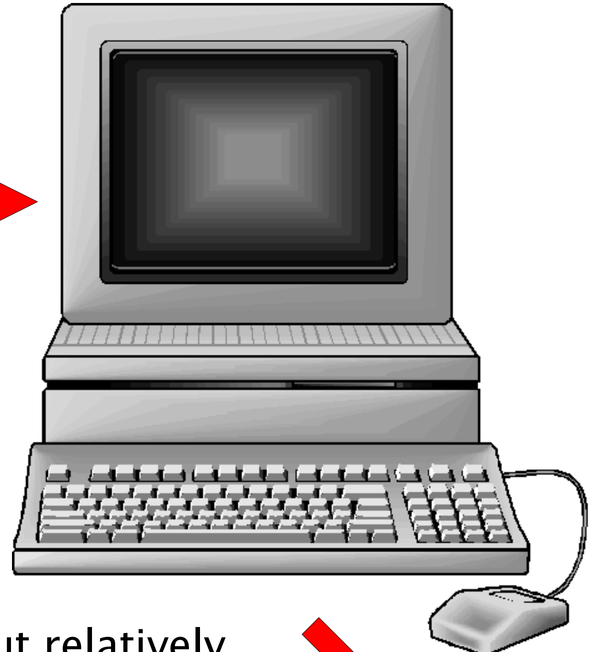




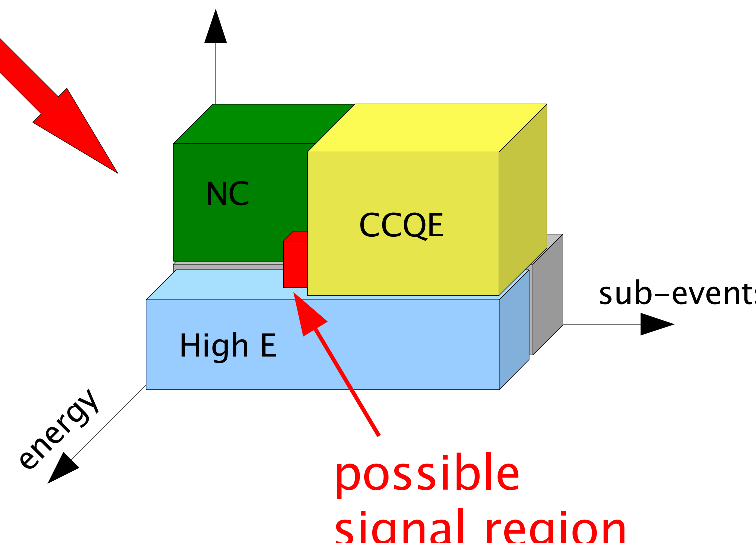


A Note on Blindness



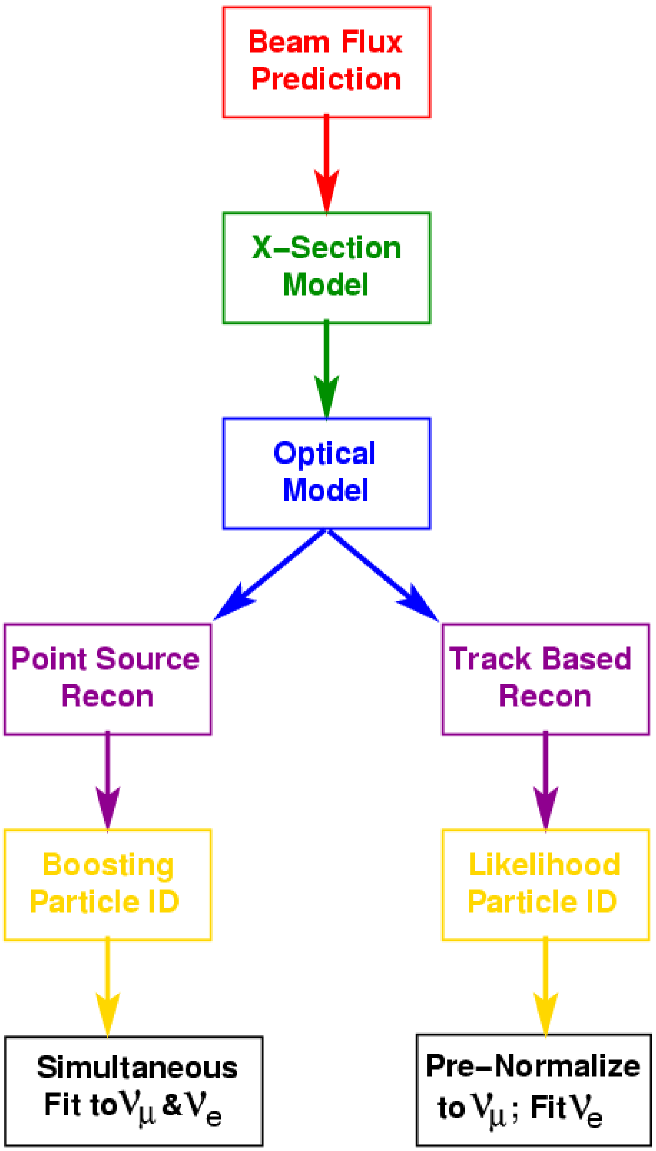


- The MiniBooNE signal is small but relatively easy to isolate
- As data is collected it is classified into 'boxes'
- For boxes to be opened to analysis they must be shown to have a signal < 1σ
- In the end, ***99% of the data were available prior to unblinding***...necessary to understand errors
- All systematics, PID selections and fitting procedures had to be finalized before opening (literally just “push the button”)



Osc Analysis

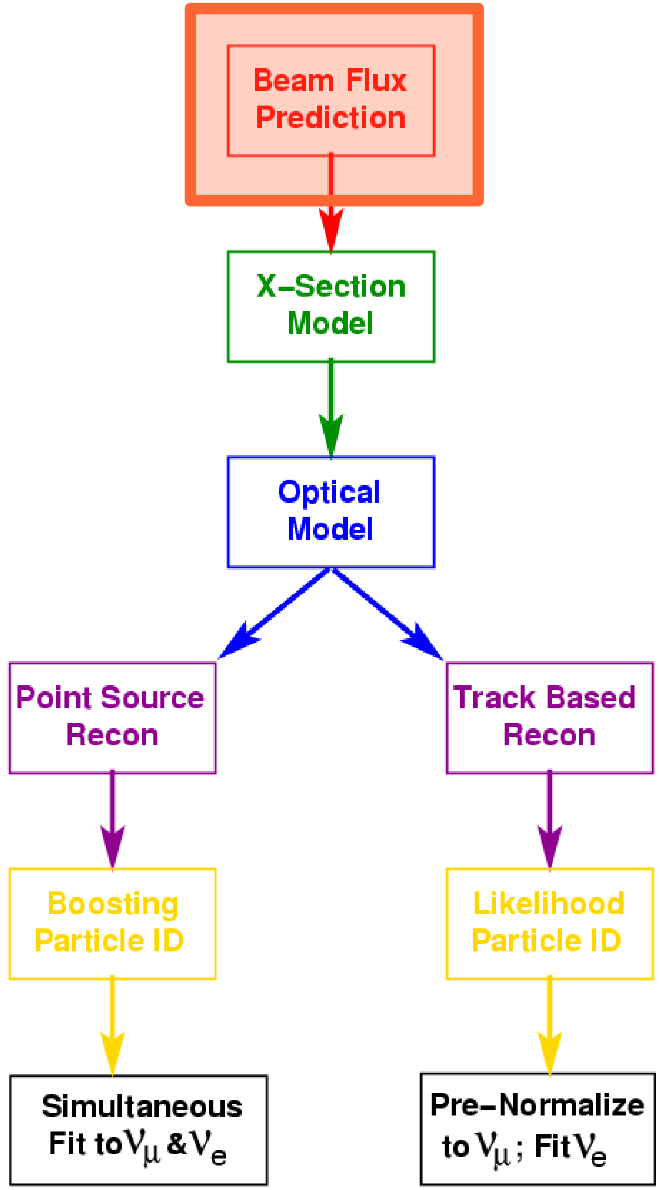
The Oscillation Analysis



- GEANT4 simulation of Booster neutrino beam line
  Uses **meson production** cross-sections as input
- **NUANCE** neutrino interaction code used to predict rate and kinematics of ν interactions
- Detector modeled by a GEANT3 simulation with an added 35 parameter "**optical model**" to describe the production, absorption and propagation of light within the tank
- Two **event reconstruction** packages (energy, position, direction) which start from PMT signals
- Two algorithms for **event classification** (ν_μ CCQE, ν_e CCQE, π^0)
- Two approaches to apply the ν_μ/ν_e ratio constraint and **fit for oscillation signal**

The Oscillation Analysis

Osc Analysis

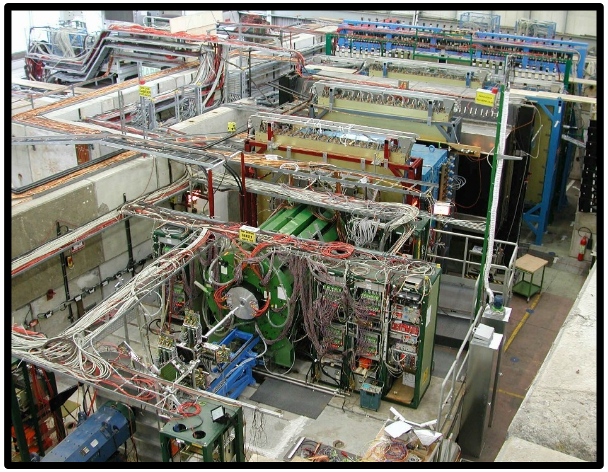


- GEANT4 simulation of Booster neutrino beam line
  Uses **meson production** cross-sections as input
- **NUANCE** neutrino interaction code used to predict rate and kinematics of ν interactions
- Detector modeled by a GEANT3 simulation with an added 35 parameter "**optical model**" to describe the production, absorption and propagation of light within the tank
- Two **event reconstruction** packages (energy, position, direction) which start from PMT signals
- Two algorithms for **event classification** (ν_μ CCQE, ν_e CCQE, π^0)
- Two approaches to apply the ν_μ/ν_e ratio constraint and **fit for oscillation signal**

O
s
c

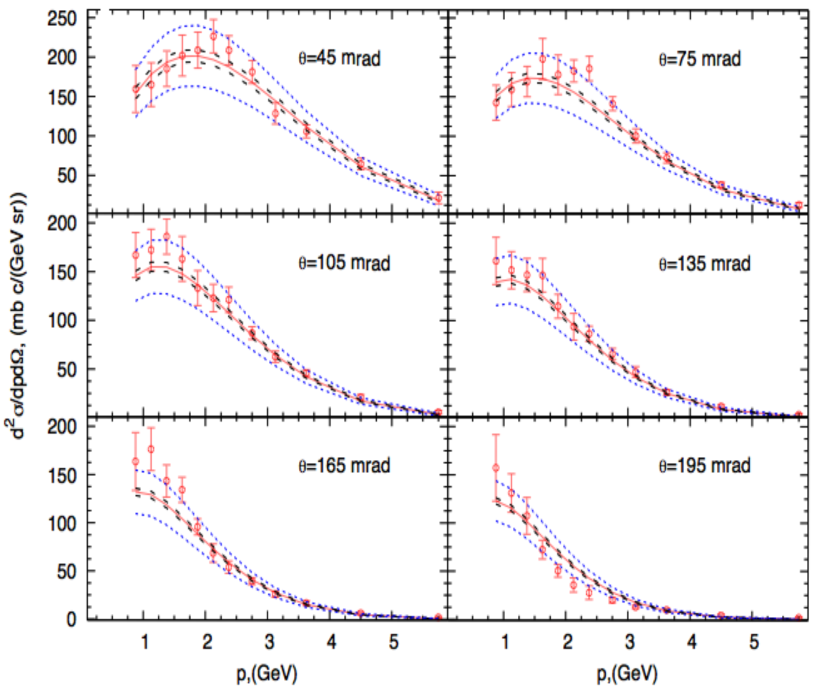
A
n
a
l
y
s
i
s

Neutrino Flux Prediction

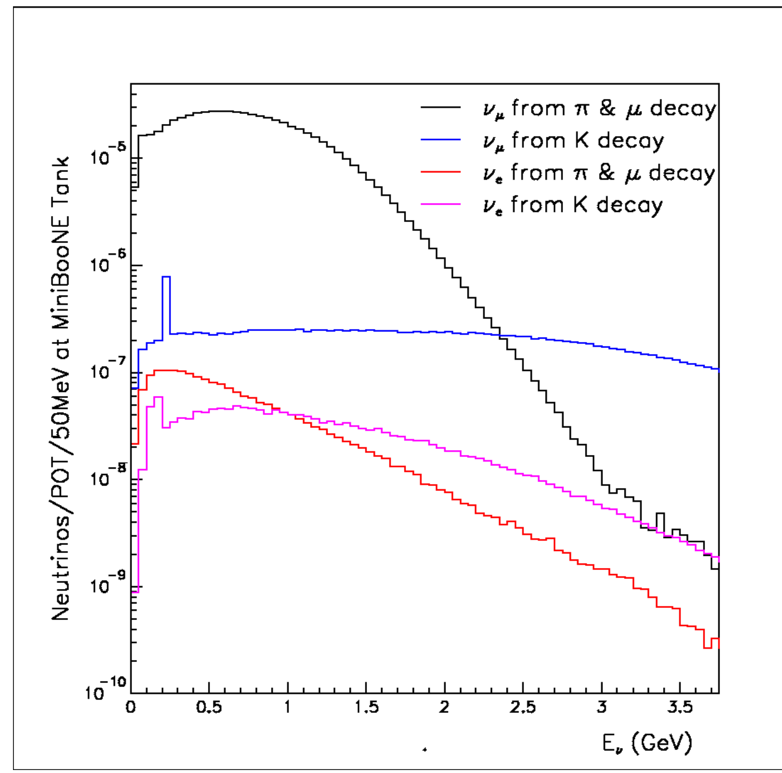


- Hadron production measurements from the ***HARP*** and ***E910*** experiments constrain π^+ and π^- production which yield muon neutrino fluxes
- Similar fits performed to available kaon production data for muon and electron flux prediction
- the largest source of intrinisic ν_e (~52%), ***ν_e from muon decay,*** heavily constrained by MiniBooNE ν_μ event rates

HARP π^+ production data



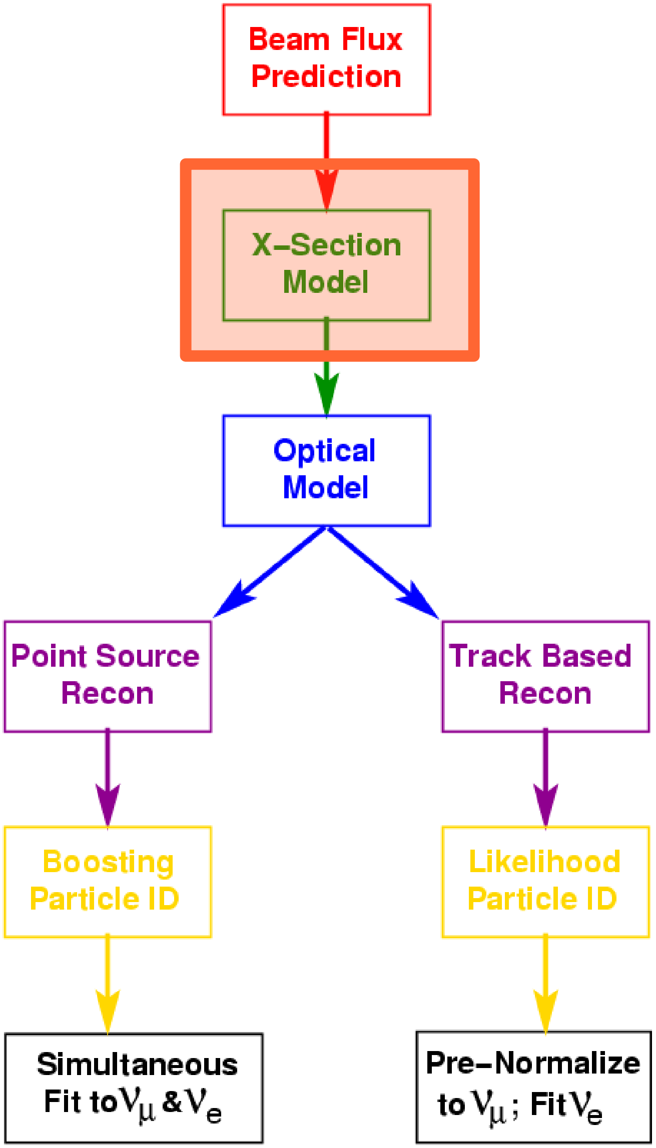
ν_μ	~93%
$\bar{\nu}_\mu$	~6%
ν_e	~0.6%
$\bar{\nu}_e$	<0.1%



M.G. Catanesi et al "Measurement of the production cross-section of positive pions in the collision of 8.9 GeV/c protons on beryllium." Euro. Phys. J C 52:29-53 (2007)

Neutrino Cross-section Model

Osc Analysis

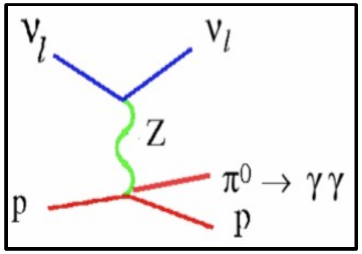


- armed with an input flux, neutrino interactions are simulated using the **NUANCE** neutrino event generator software
- the most important exclusive channel for the MiniBooNE oscillation search is the **charged–current quasi–elastic** interaction
- NUANCE models CCQE events using the relativistic Fermi gas model of Smith and Moniz as a framework
- the next most critical exclusive channels are the **neutral current production of π^0's**
- NUANCE uses the resonant and coherent π^0 production models of Rein and Sehgal

→ D. Casper, "The nuance Neutrino Physics Simulation, and the Future", Proceedings of NUINT01 workshop (2001)
→ R.A. Smith, E.J Moniz, "Neutrino Reactions on Nuclear Targets" Nucl.Phys.B43:605 (1972) Erratum–ibid.B101:547 (1975)
→ D. Rein, L.M. Sehgal, "Coherent pi0 production in neutrino reactions" Nucl.Phys.B223:29 (1983)
→ D. Rein, L.M. Sehgal, "Neutrino Excitation Of Baryon Resonances And Single Pion Production" Annals.Phys.1333:79 (1980)

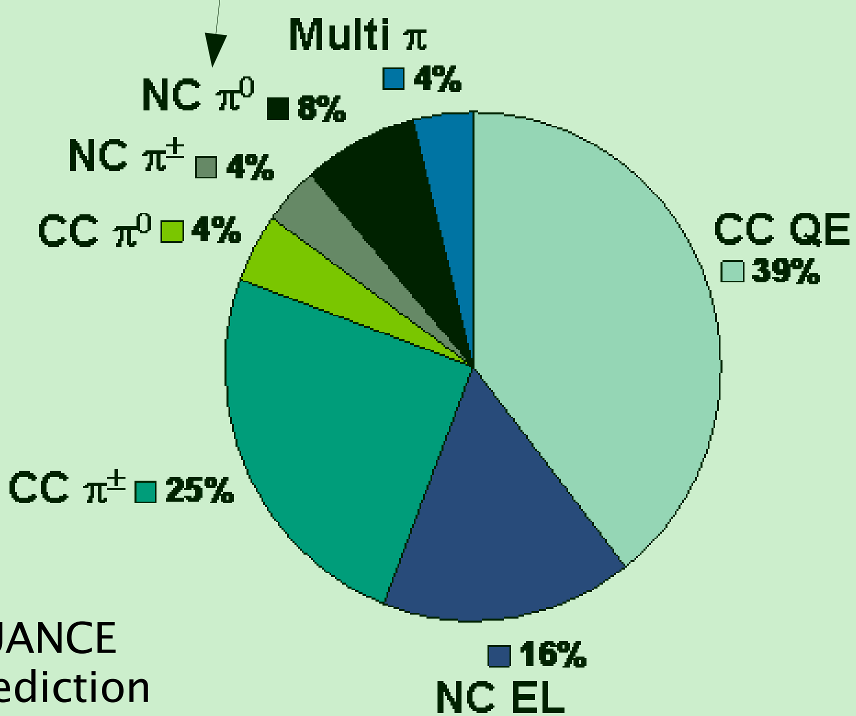
Neutrino Cross-section Model

- largest mis-ID background in ν_e event sample
- NUANCE cross-section model ***tuned to observed π^0 rate***

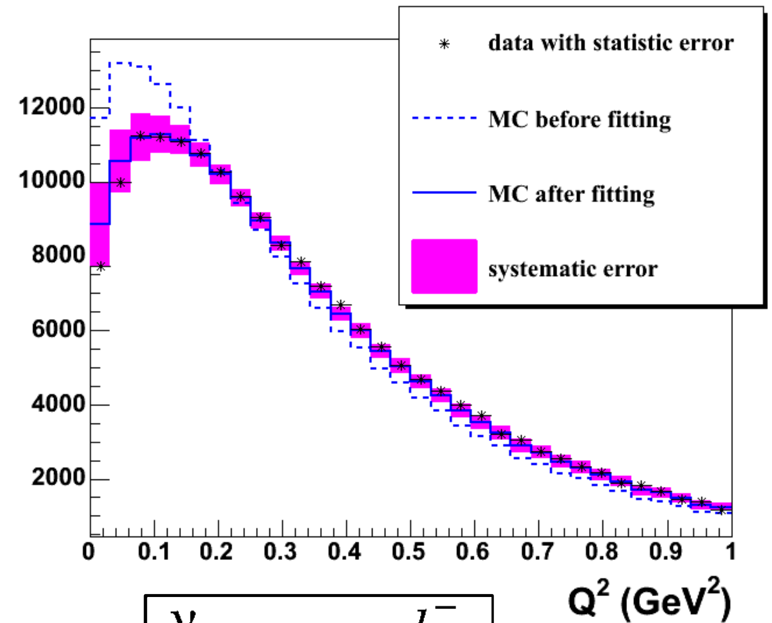


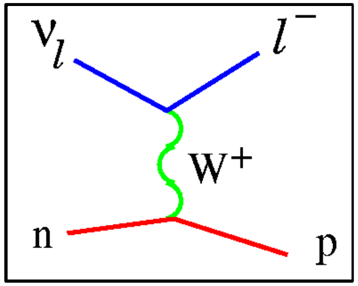
NC π^0

ν_μ



NUANCE prediction





CCQE

- by far the largest event sample (~200,000)
- NUANCE cross-section model ***tuned to observed ν_μ CCQE rate***
- only ν_μ - ν_e differences are due to lepton mass effects, m_μ vs. m_e

A.A. Aguilar-Arevalo et al., "Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon", arXiv:0706.0926 [hep-ex], submitted to PRL

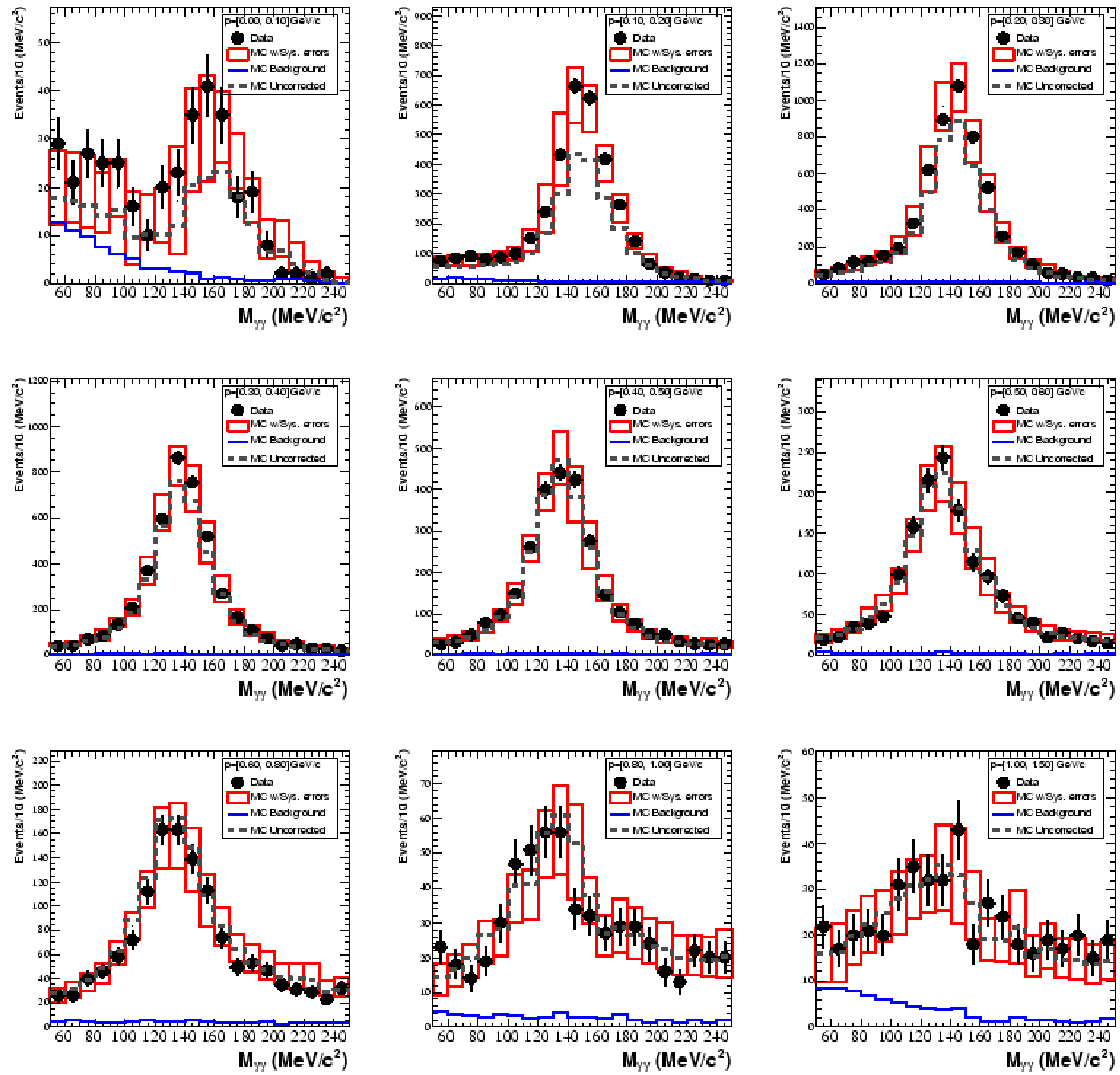
Osc Analysis

Neutrino Cross-section Model

constraining the NC π^0 background with data

- 90%+ pure π^0 sample (mainly $\Delta \rightarrow N\pi^0$)
- Measure rate as function of pion momentum
- Default MC underpredicts rate at low momentum
- analysis reaches 1.5 GeV

Invariant mass distributions in momentum bins



Data with statistical errors

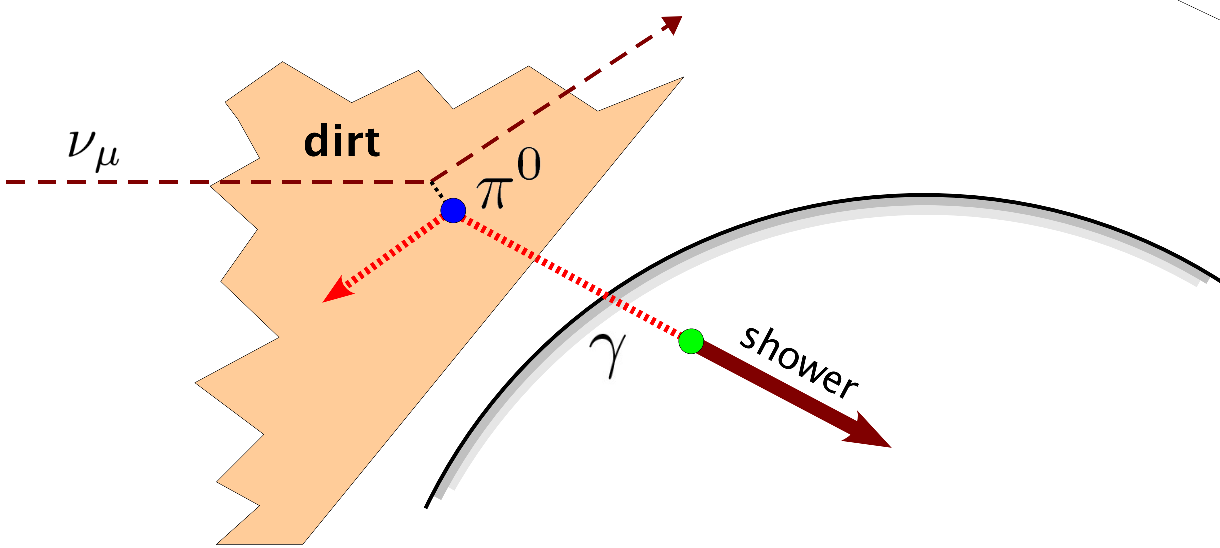
MC with systematic errors

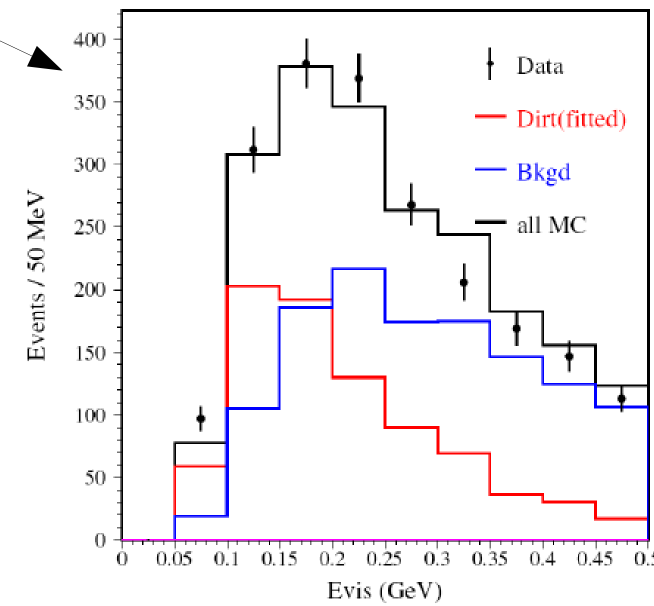
MC before tuning

Neutrino Cross-section Model

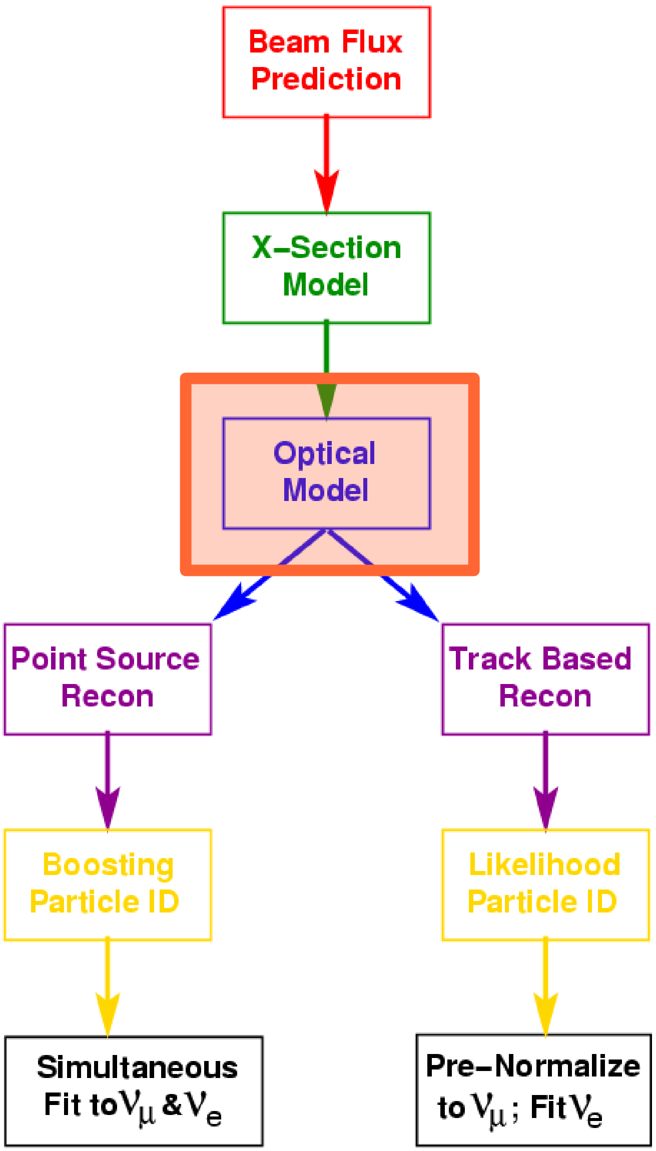
other important mis-ID backgrounds

- Δ radiative decay, ***Δ→Nγ***, rate can be constrained by π^0 rate measurement
  - most of the NC-π^0 production is resonant production (through the Δ)
  - the branching ratio for the radiative decay is known
- ***"dirt"*** events are beam induced (so come in the beam time window), but the neutrino interacted outside of the tank (most from π^0s).
  - low energy background.
  - simulation is verified by using a dirt enhanced sample (close to the tank edge, moving inward)





Detector Response Model



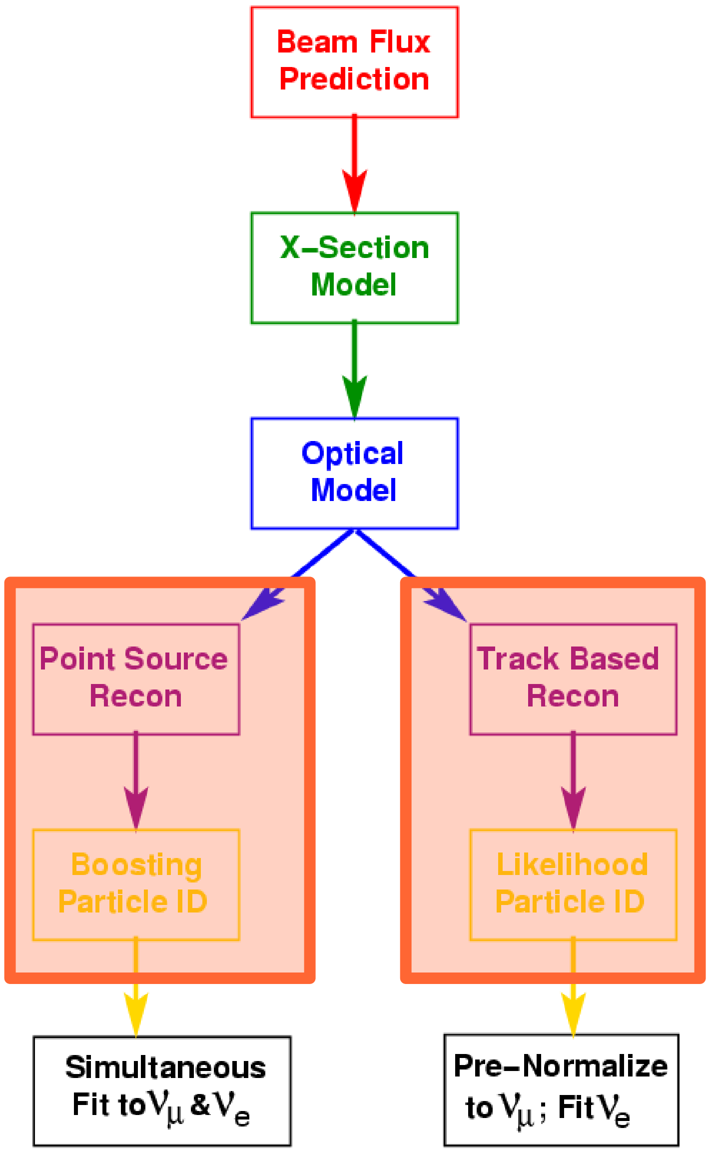
MiniBooNE detector :
- 12 m diameter sphere
- 950,000 liters of mineral oil
- 1280 photomultiplier tubes
- 240 optically isolated tubes in a veto region

- detector modeled by a GEANT3 simulation with an added ***"optical model"*** to describe the production, absorption and propagation of light within the tank

- OM parameters can be tuned by studying :
  - **external measurements**
  - **Michel electrons in the tank**
  - **cosmic rays in the tank**
  - **NC events in the tank**
  - **calibration lasers inside the tank**

- lacking the ultimate energy calibration source (i.e. 1 GeV electron gun), we must calibrate the model very carefully with sources we do have to gain confidence we model the detector properly
  - **Michel decay endpoint at 53 MeV**
  - **reconstructed π^0 mass**
  - **scintillator cubes and muon hodoscope calibration system**

Event Reconstruction & PID



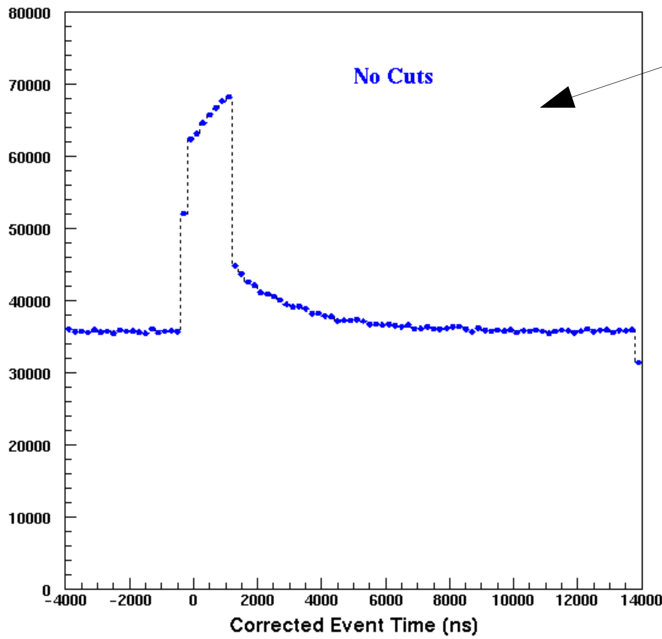
- At this point, the oscillation analysis splits down independent paths providing a ***powerful cross–check*** of the results after un–blinding

- The analyses have different background predictions and different sensitivities to the various systematics

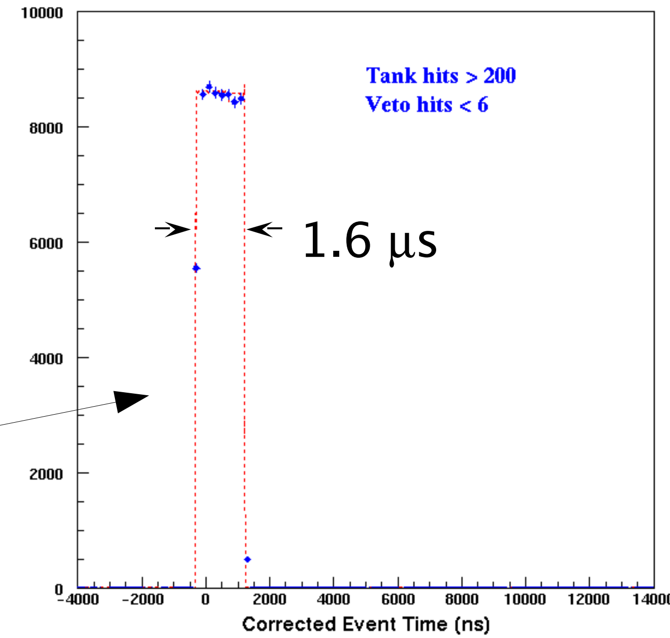
- In the end, the track based reconstruction + Likelihood PID was slightly more sensitive to 2–ν oscillations and is the base line analysis published in **Phys. Rev. Lett. 98, 231801 (2007)**

Osc Analysis

Oscillation Analysis Pre-cuts



trigger window, no cuts



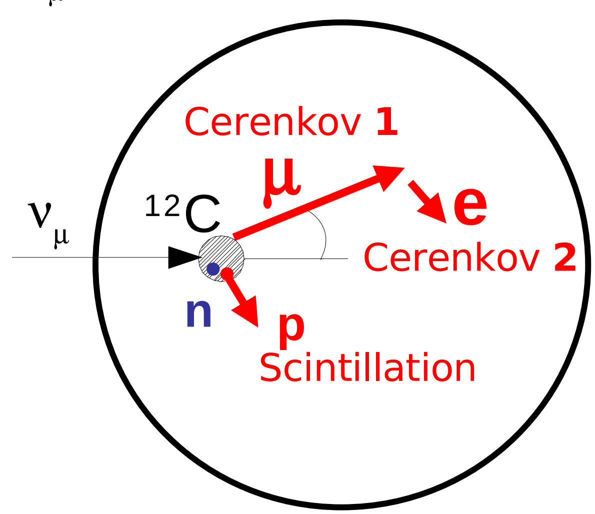
Beam Window

remove cosmic μ and decay e

PMT hits in veto < 6

PMT hits in tank > 200

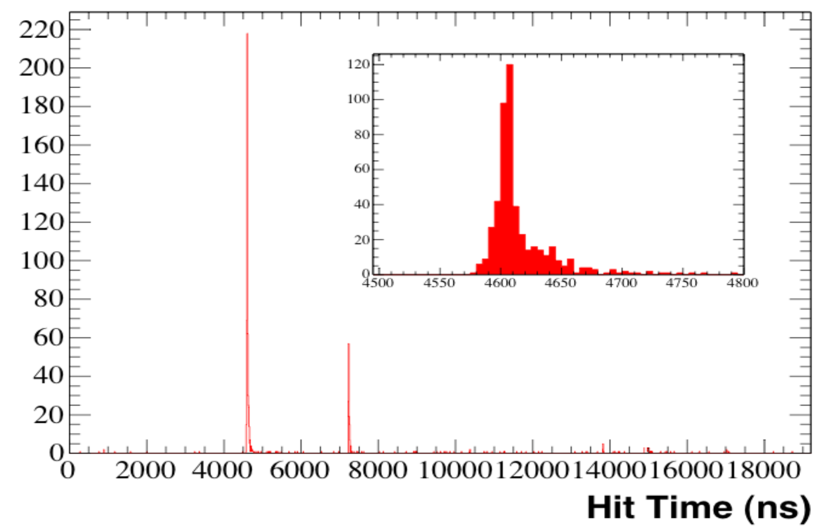
ν_μ CCQE: $\nu_\mu + n \rightarrow p + \mu^-$



Sub-events

remove >90% of beam induced ν_μ CCQE events (largest event category)

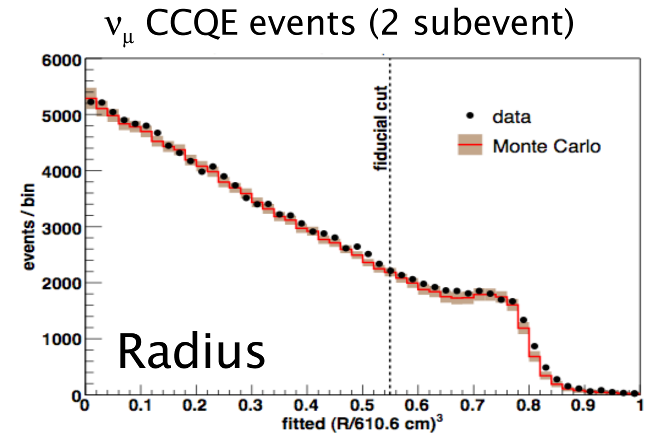
Sub-events == 1

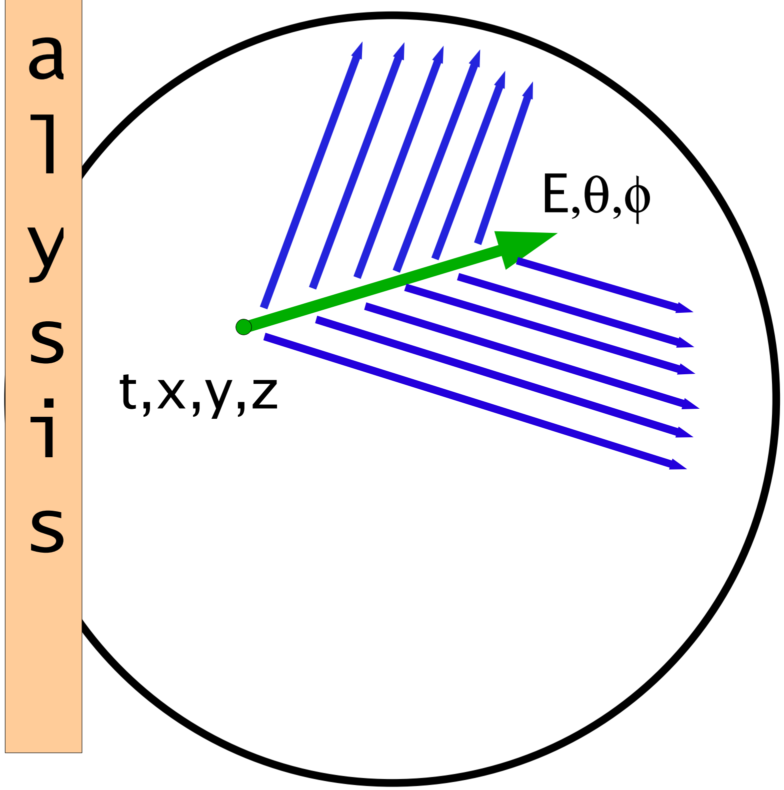


Osc Analysis

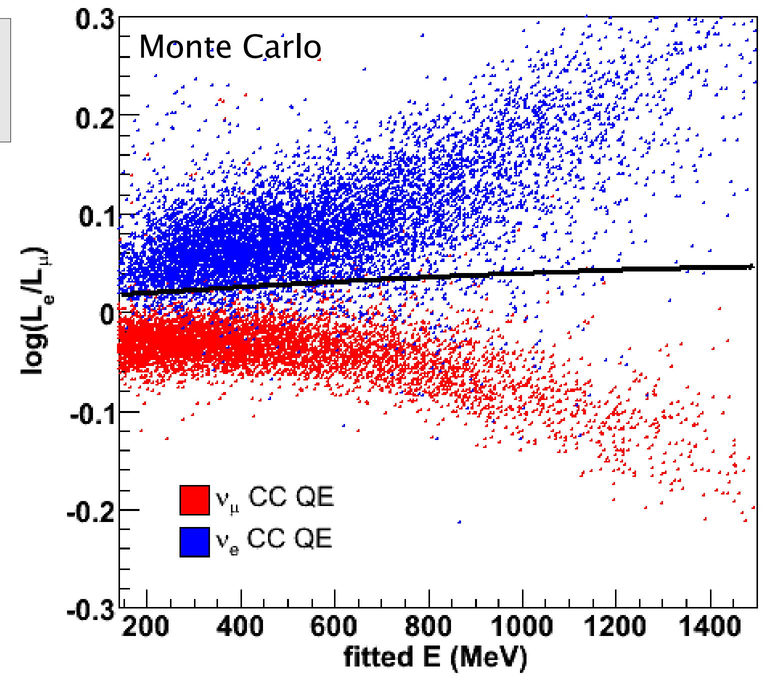
Track Based Rec + Likelihood PID

- construct sophisticated ***Q and T PDFs*** for different event types
- fit each event for 7 track parameters under a ***muon and electron hypothesis***
- construct the Likelihood ratio ***$log(L_e/L_\mu)$***
- extend fit to include ***2 electron-like tracks***
- construct the ***invariant mass $M_{\gamma\gamma}$***
- construct the Likelihood ratio ***$log(L_e/L_\pi)$***





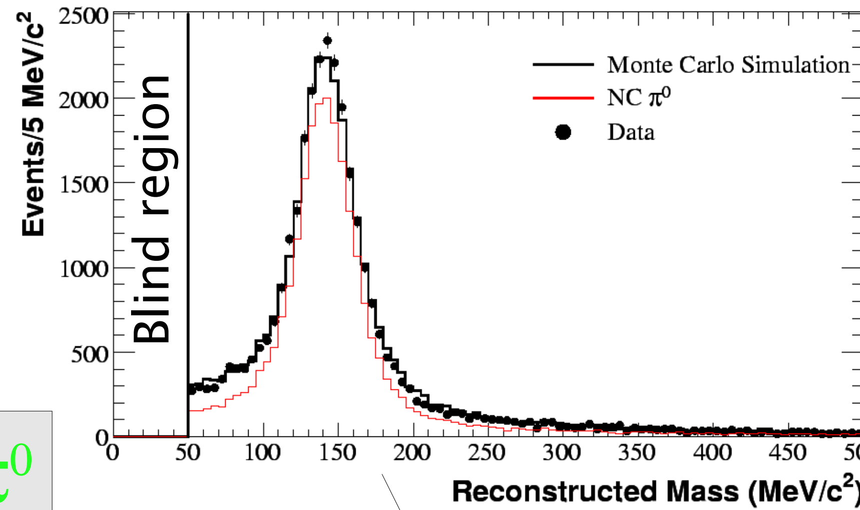
e μ

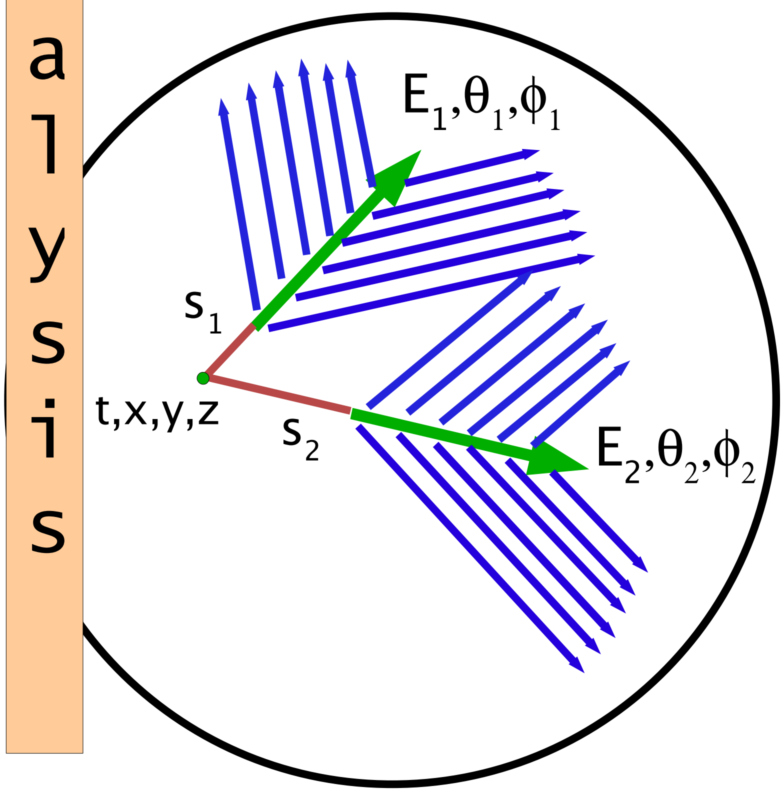


Track Based Rec + Likelihood PID

Osc Analysis

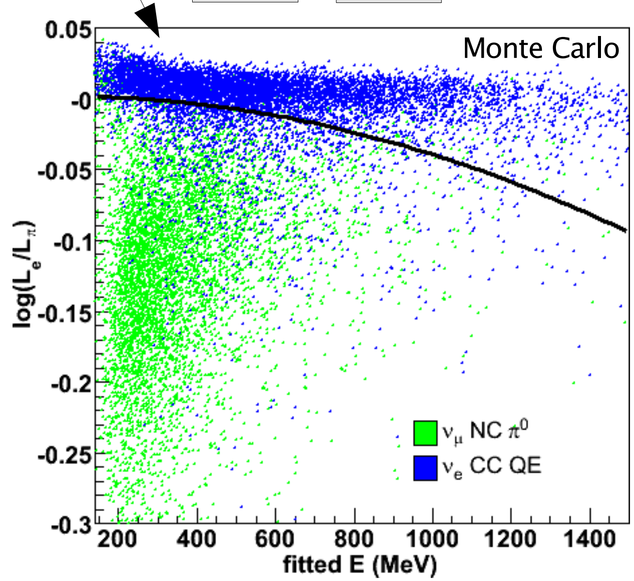
- construct sophisticated ***Q and T PDFs*** for different event types
- fit each event for 7 track parameters under a ***muon and electron hypothesis***
- construct the Likelihood ratio $\log(L_e/L_\mu)$
- extend fit to include ***2 electron-like tracks***
- construct the ***invariant mass*** $M_{\gamma\gamma}$
- construct the Likelihood ratio $\log(L_e/L_\pi)$

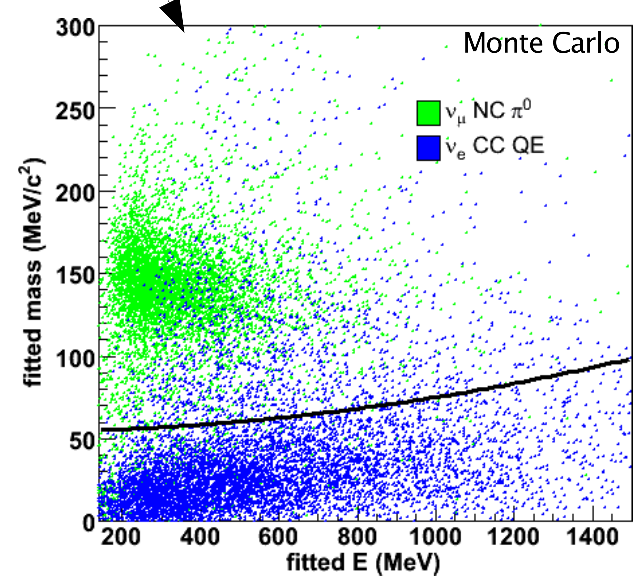




e

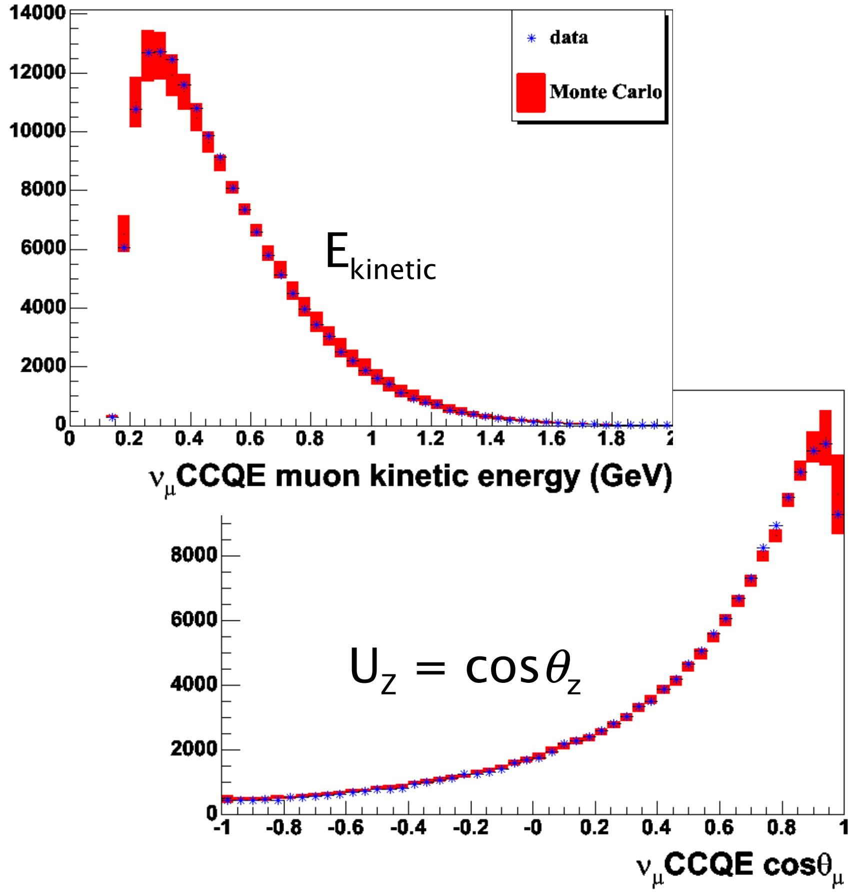
π^0

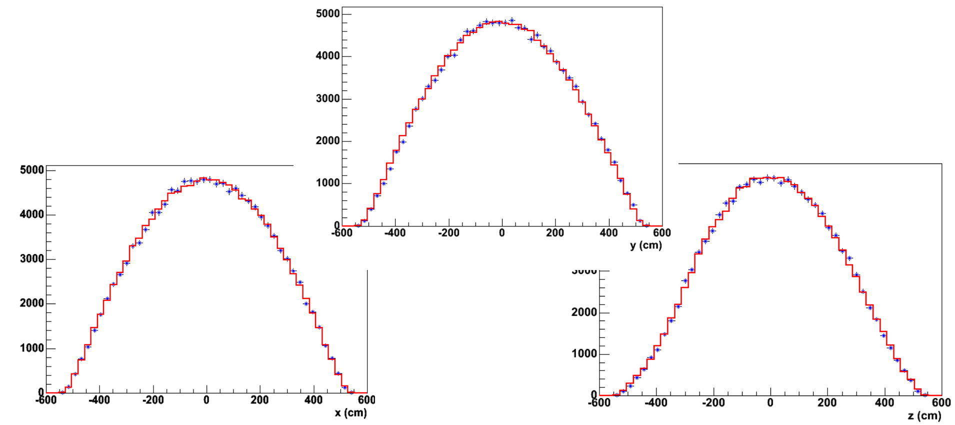


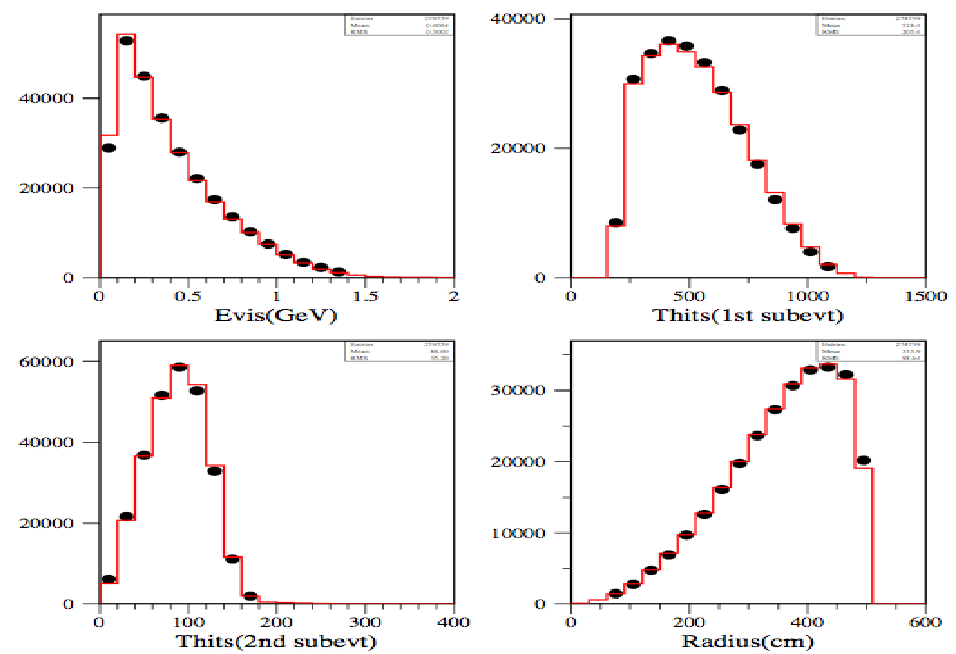


Point Source Rec + Boosting PID

- construct a large number of low and high level variables from PMT data :
  - → ***low-level*** (number of hit PMTs, fraction of early to late light, . . .)
  - → ***high-level*** (Q^2, U_z, fit Likelihoods, . . .)
  - → ***topology*** (charge in annuli, isotropic light, . . .)







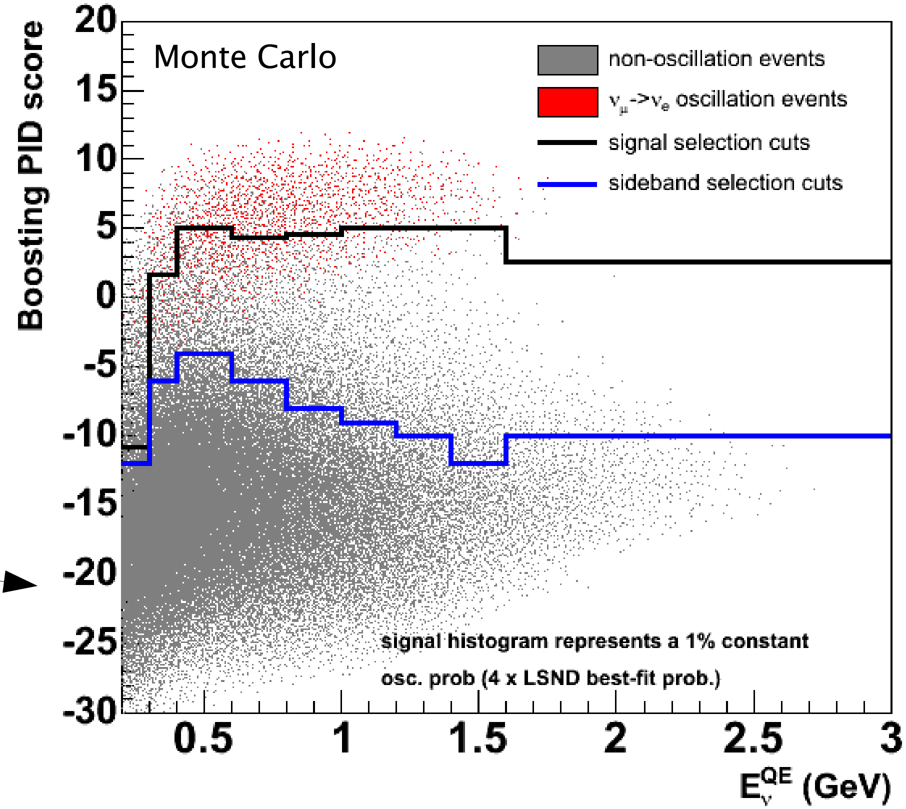
Point Source Rec + Boosting PID

- construct a large number of low and high level variables from PMT data :
  - *low-level* (number of hit PMTs, fraction of early to late light, . . .)
  - *high-level* (Q^2, U_z, fit Likelihoods, . . .)
  - *topology* (charge in annuli, isotropic light, . . .)

osc

non-osc

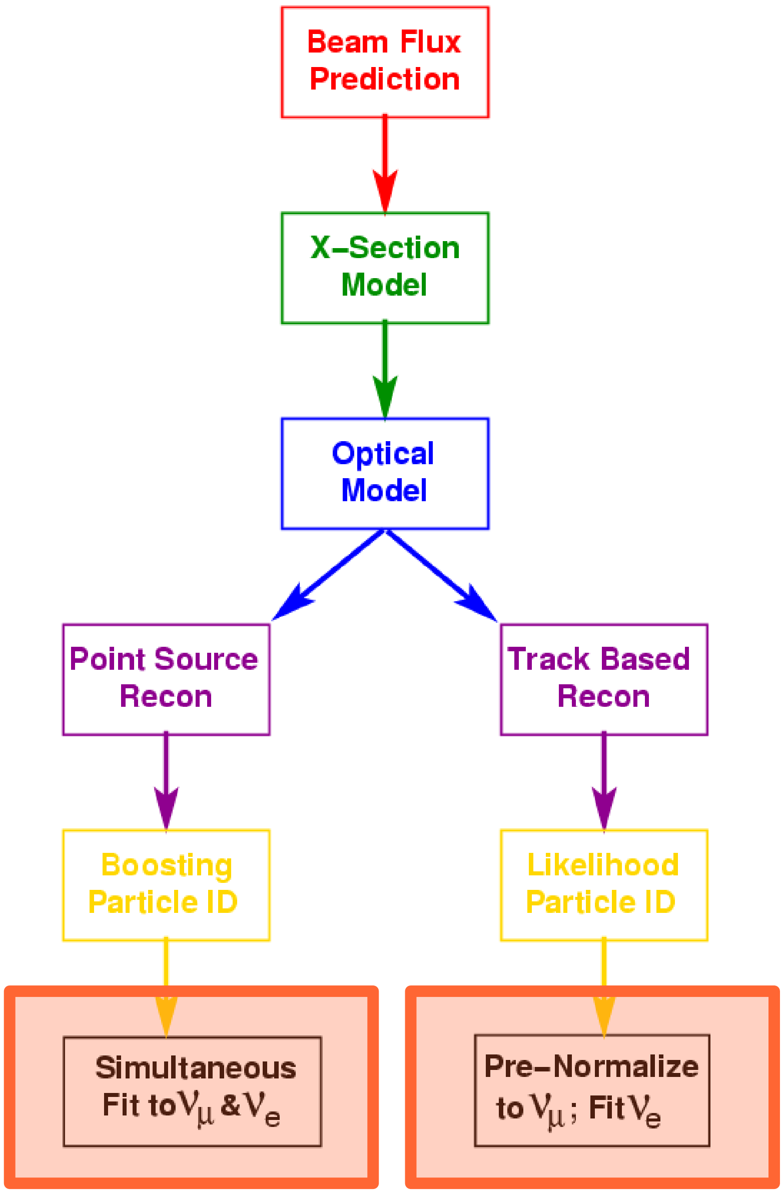
- A total of 172 such variables were used as input for the Boosted Decision Tree algorithm
- All 172 were checked for agreement within errors in 5 important 'boxes' (ν_μ CCQE, NC π^0, NC-elastic, Michel decay e, 10% closed)
- BDT is a technique involving the weighting and combining of many decision trees into a ***single output classifier***



H. Yang, B. Roe, J. Zhu, "Studies of Boosted Decision Trees for MiniBooNE Particle Identification", Nucl.Instrum.Meth.A555; 370-385 (2005)
B. Roe ***et. al.*** "Boosted Decision Trees as an Alternative to Artificial Neural Networks for Particle Identification" Nucl.Instrum.Meth.A543; 577-584 (2005)

Oscillation Signal Fit

Osc Analysis



- Two methods were also developed for applying the ***constraint on (flux)*** x ***(cross-section)*** provided by the observed ν_μ-CCQE events

- **Pre-Normalize and fit ν_e**
  - predicted ν_e distribution and errors are reweighted according to information from the ν_μ sample
  - $N_{\nu e}$ x $N_{\nu e}$ covariance matrix constructed for the ν_e distribution and used in signal fit

- **Simultaneous fit to ν_μ and ν_e**
  - construct a single, large covariance matrix $(N_{\nu e}+N_{\nu\mu})$ x $(N_{\nu e}+N_{\nu\mu})$
  - matrix includes correlations within the ν_e distribution as well as between ν_μ and ν_e
  - ν_μ and ν_e bins contribute to a total χ^2 in the fit for a signal

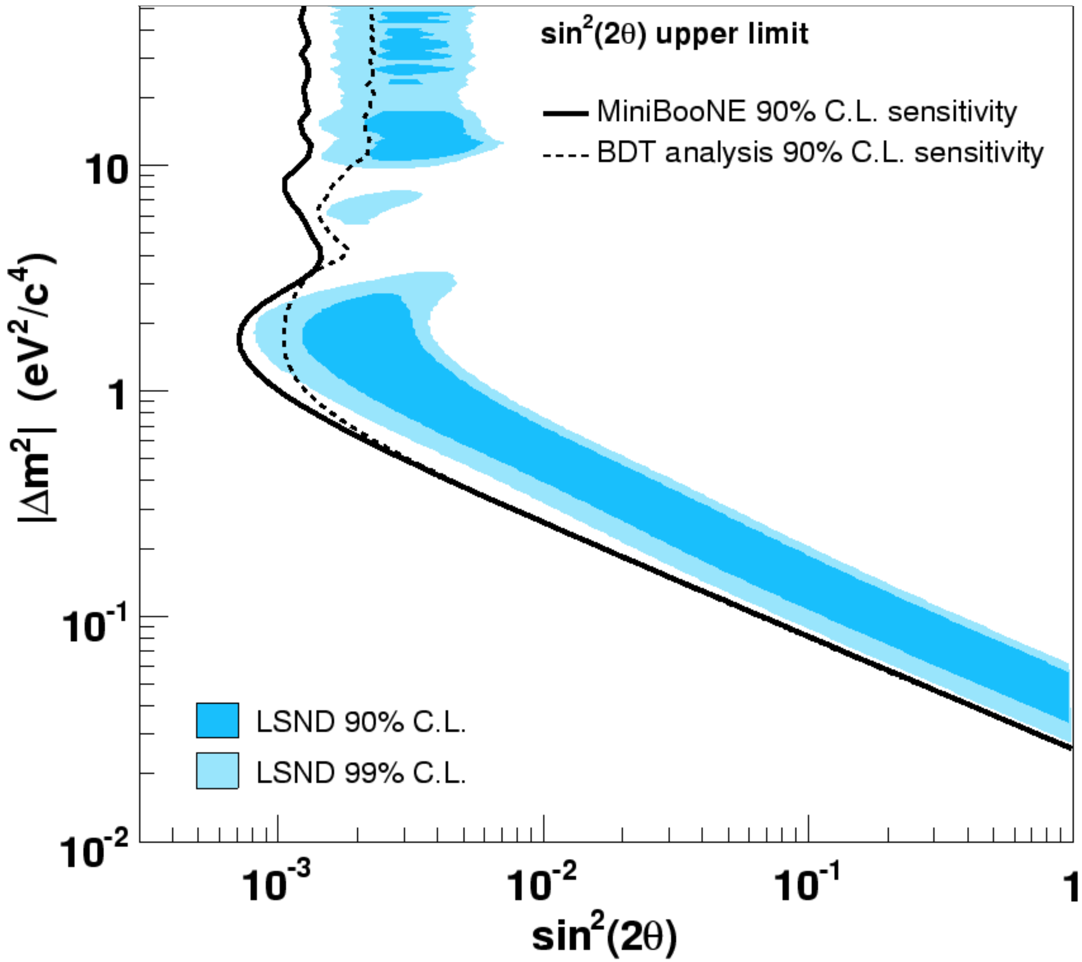
Final Error Budget and Sensitivity

Source of uncertainty on ν_e background	TBL/BDT error in %	Constrained by MB 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	√	
ν cross-section	12.3 / 10.5	√	√
NC π^0 yield	1.8 / 1.5	√	
Dirt interactions	0.8 / 3.4	√	
Optical model	6.1 / 10.5	√	√
DAQ electronics model	7.5 / 10.8	√	

- errors come from common uncertainties in flux, cross-section and detector models
- all sources have been constrained by MiniBooNE data
- several errors reduced by applying constraint from ν_μ data set
- TBL and BDT analyses are ***quite different :***
  - BDT better signal to background ratio
  - TBL less sensitive to systematics
  - about 50% event overlap in the two selections

Final Error Budget and Sensitivity

Osc Analysis



- sensitivities are determined from simulation only
- ***before unblinding*** :
  - all systematics must be finalized
  - all PID selections must be finalized
  - ***TBL*** chosen as base line result based on better sensitivity at high Δm^2
- then. . . nothing left to do. . .but ***open the box!!***

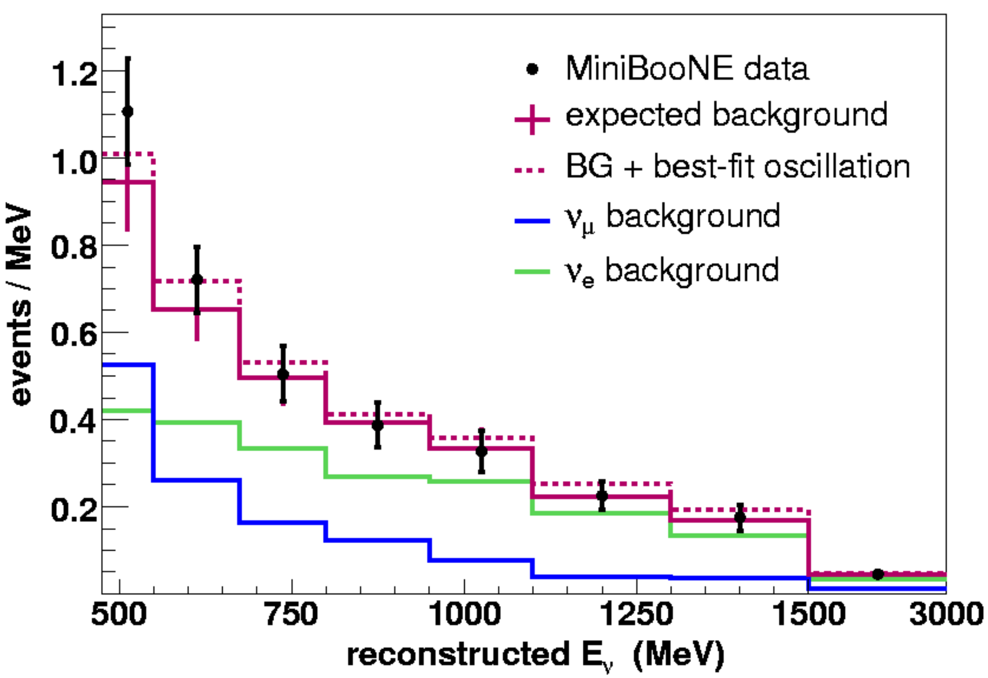
- TBL and BDT analyses are ***quite different*** ***: yet have similar sensitivities to oscillations***
  - BDT better signal to background ratio
  - TBL less sensitive to systematics
  - about 50% event overlap in the two selections

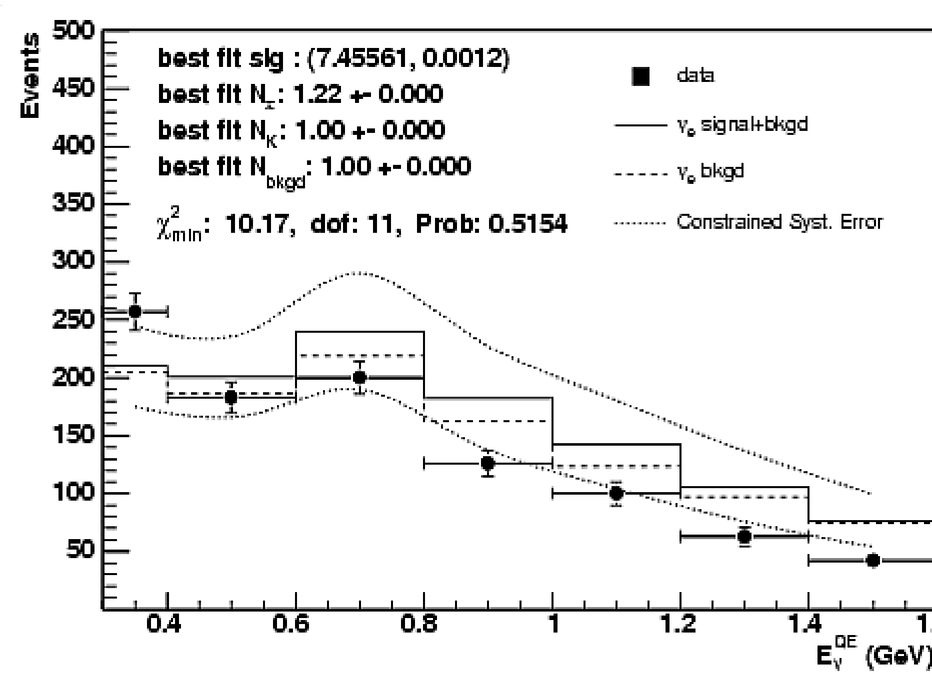
$\nu_\mu \rightarrow \nu_e$ Oscillation Results

- begin with ***counting experiment only*** and sum up ν_e candidate events in an energy range

TBL	BDT
475 MeV < E_ν < 1250 MeV	**300 MeV < E_ν < 1600 MeV**
prediction : $358 \pm 35(\text{syst})$	prediction : $1069 \pm 225(\text{syst})$
data : $380 \pm 19(\text{stat})$	data : $971 \pm 31(\text{stat})$
significance : $+0.55\sigma$	significance : -0.38σ

- perform ***energy spectrum fit*** – predicted signal shape is different from backgrounds





Osc Analysis

$\nu_\mu \rightarrow \nu_e$ Oscillation Results

- begin with ***counting experiment only*** and sum up ν_e candidate events in an energy range

TBL

475 MeV < E_ν < 1250 MeV

prediction : $358 \pm 35(\text{syst})$

data : $380 \pm 19(\text{stat})$

significance : $+0.55\sigma$

BDT

300 MeV < E_ν < 1600 MeV

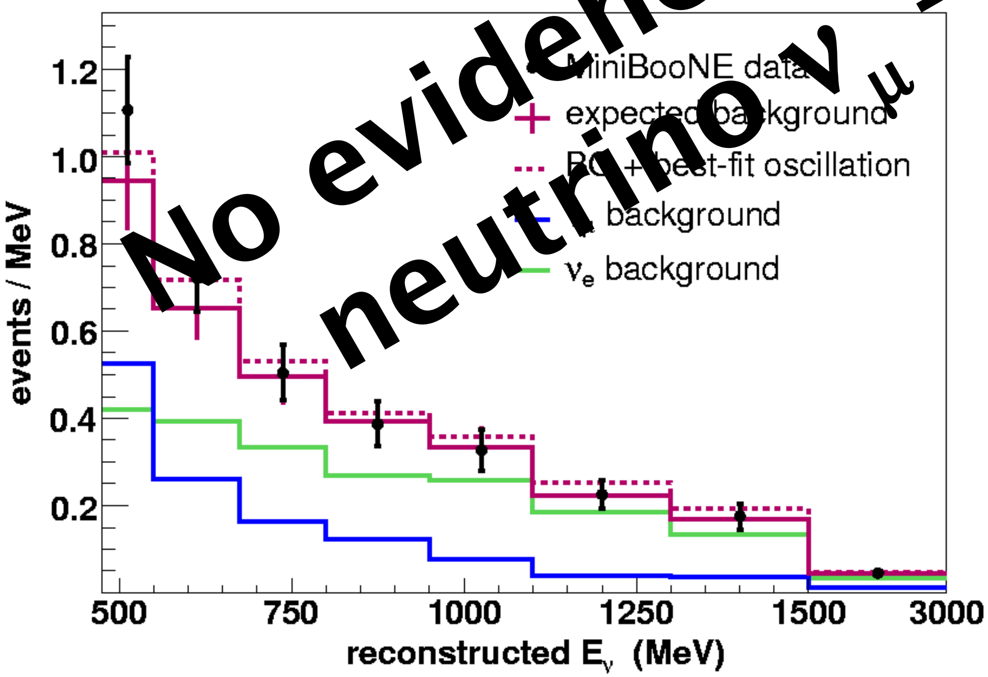
prediction : $1069 \pm 225(\text{syst})$

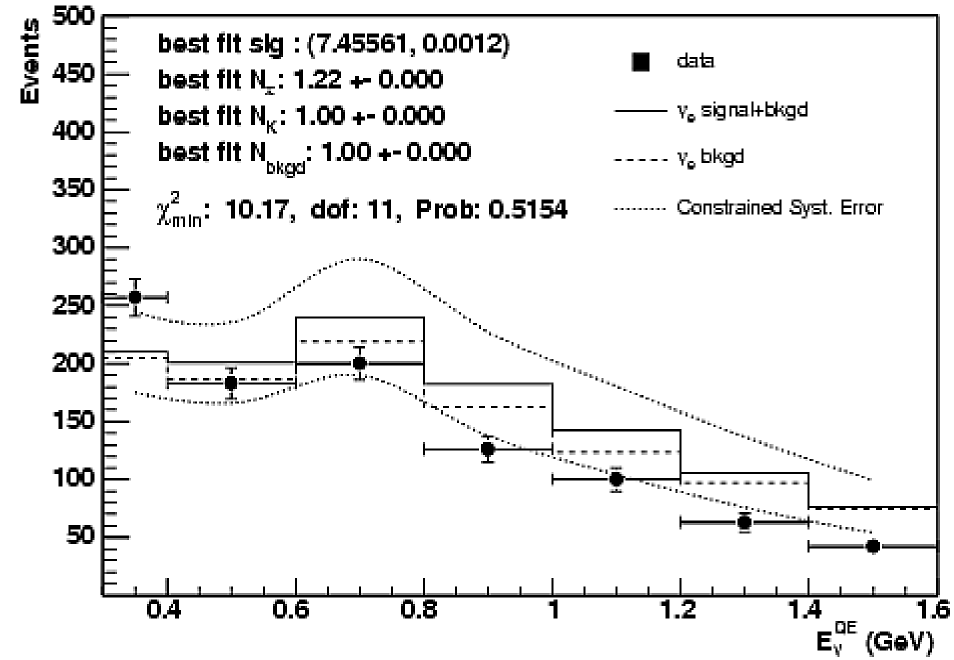
data : $971 \pm 31(\text{stat})$

significance : -0.38σ

No evidence seen for direct two neutrino $\nu_\mu \rightarrow \nu_e$ oscillations

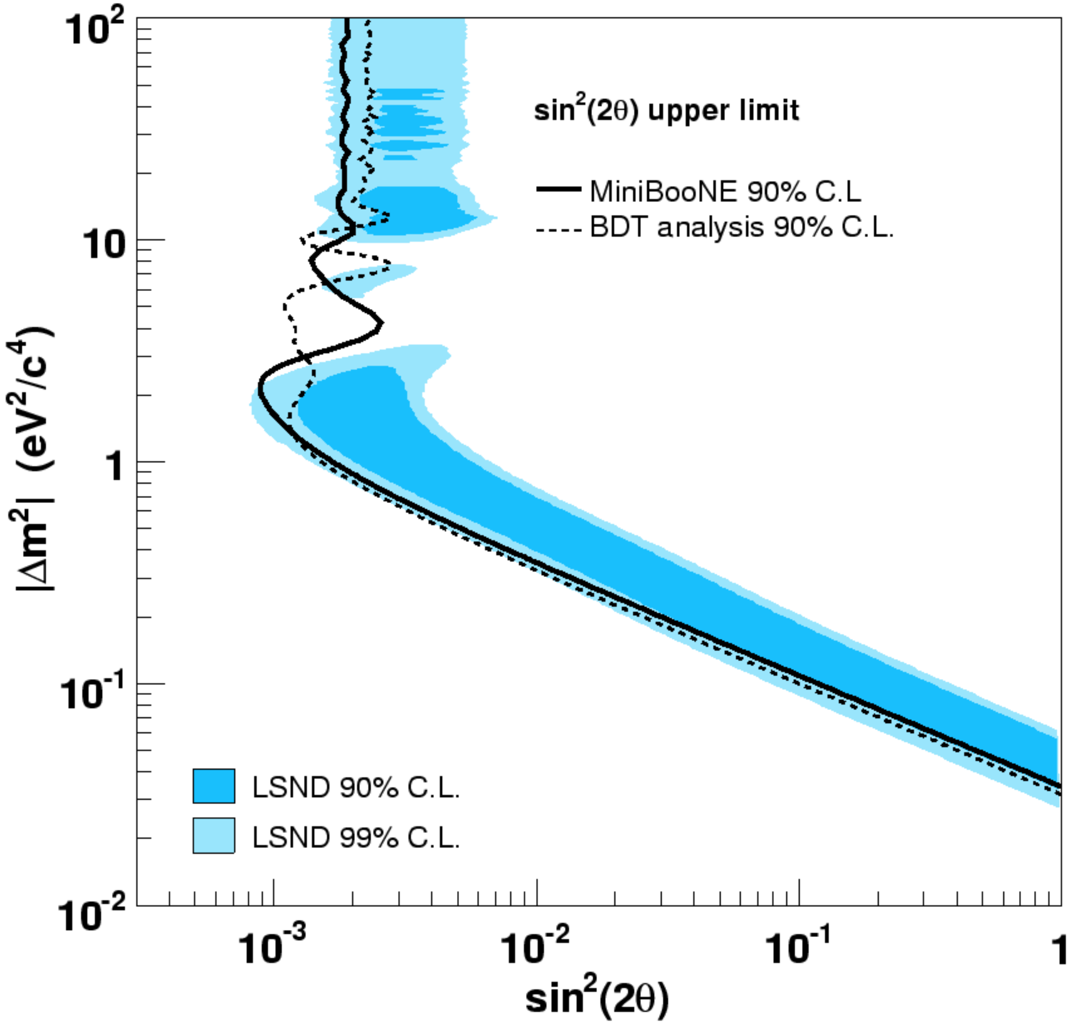
- perform ***energy spectrum fit*** – predicted signal shape is different from backgrounds



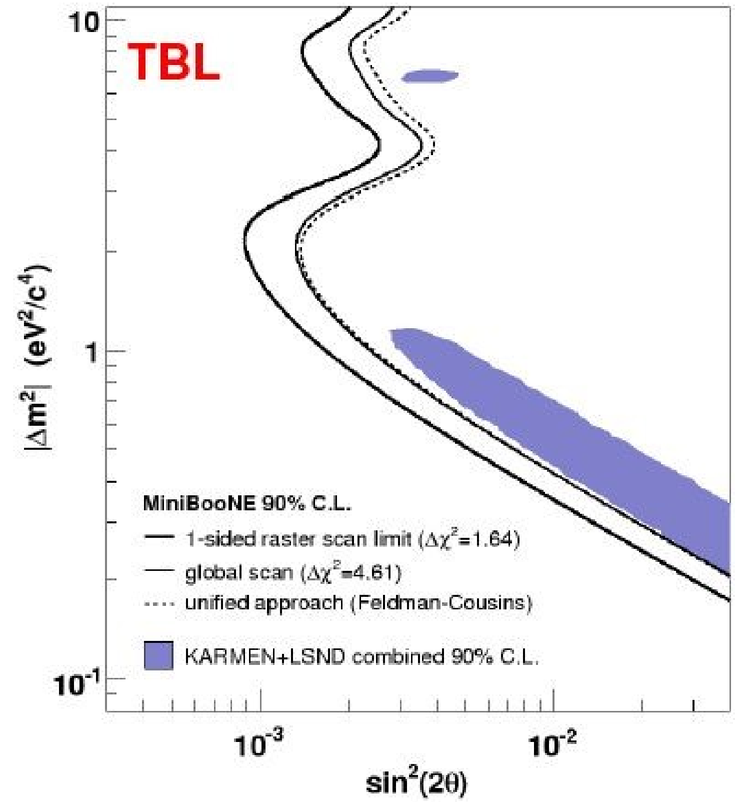


$\nu_\mu \rightarrow \nu_e$ Oscillation Results

Osc Analysis



- so a limit is set on this interpretation of the excess seen by LSND
- MiniBooNE and LSND incompatible at a 98% CL for all Δm^2 under a 2ν mixing hypothesis
- two independent analyses are in good agreement



Future Outlook

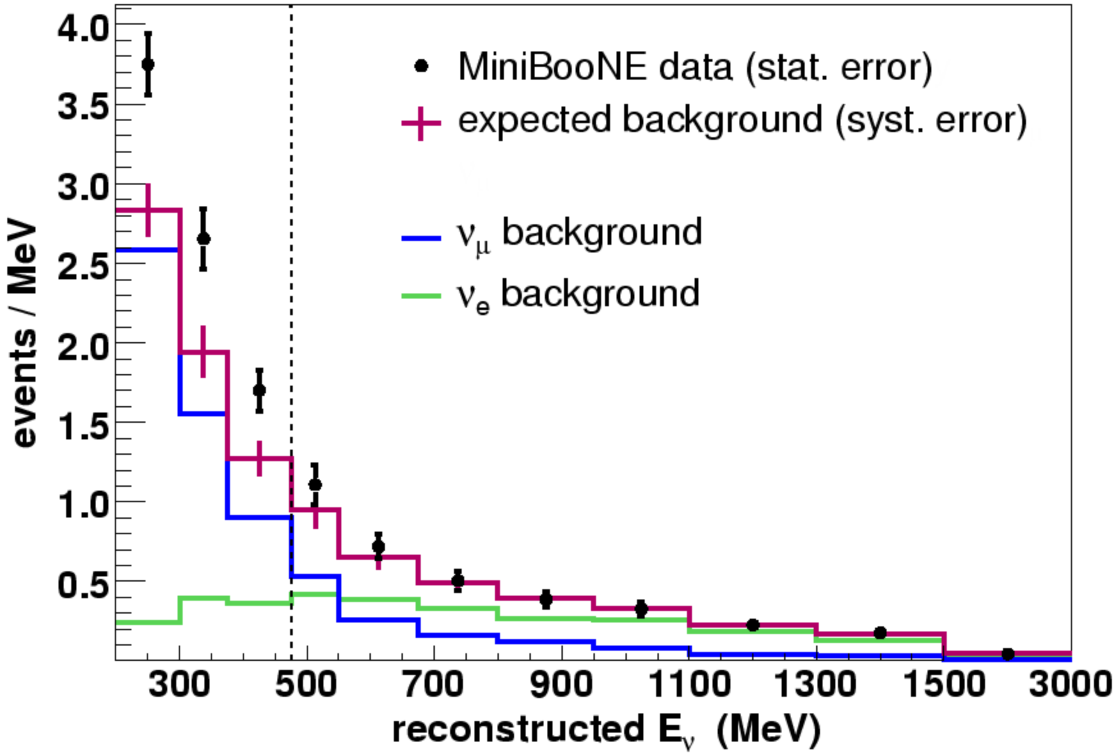
Low Energy Discrepancy

- direct oscillations governed by

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2 \frac{L}{E}\right)$$

would have peaked in the 500–1000 MeV region. Our data agrees well with the expectation in this region.

- However, an excess of events is seen below 475 MeV



Future Outlook

Low Energy Discrepancy

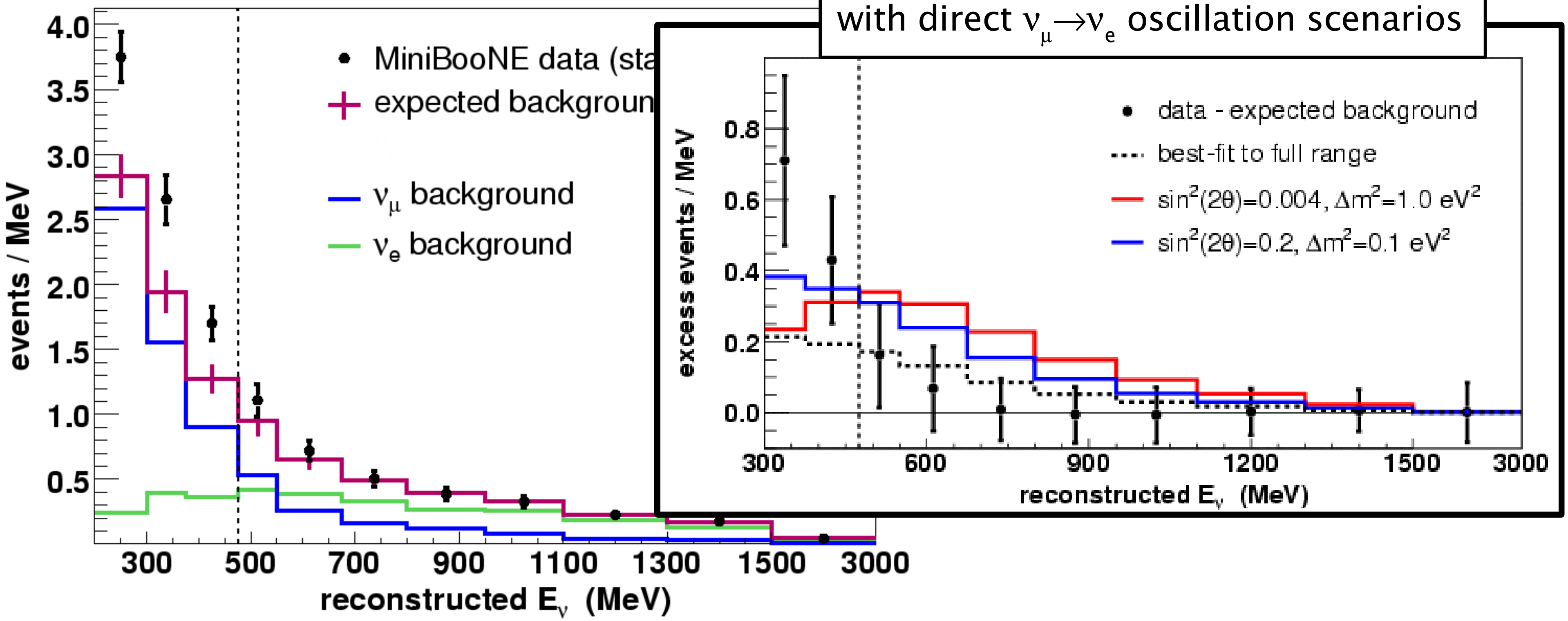
- direct oscillations governed by

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2 \frac{L}{E}\right)$$

would have peaked in the 500–1000 MeV region. Our data agrees well with the expectation in this region.

- However, an excess of events is seen below 475 MeV

shape of discrepancy not compatible with direct $\nu_\mu \rightarrow \nu_e$ oscillation scenarios



Future Outlook

Low Energy Discrepancy

E_ν^{QE} [MeV]	200-300	300-475	475-1250	
total background	284±25	274±21	358±35	(syst. error)
ν_e intrinsic	26	67	229	
ν_μ induced	258	207	129	
NC π^0	115	76	62	
NC $\Delta \rightarrow N\gamma$	20	51	20	
Dirt	99	50	17	
other	24	30	30	
Data	375±19	369±19	380±19	(stat. error)
Data-MC	91±31	95±28	22±40	(stat+syst)

- NC π^0 largest
- Dirt background significant
- NC $\Delta \rightarrow N\gamma$ falling off
- Intrinsic ν_e negligible

- Backgrounds all have similar rates:
  - NC π^0
  - Dirt bkgnd
  - NC $\Delta \rightarrow N$
  - Intrinsic ν_e

- Intrinsic ν_e largest background

lower energy bins **oscillation analysis region**

Low Energy Discrepancy

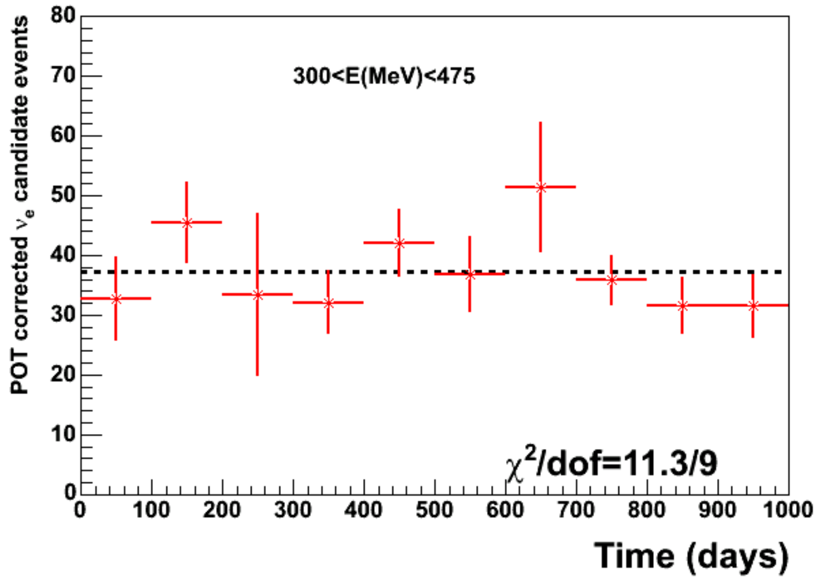
Future Outlook

- *investigating possible explanations:*
  - detector anomalies or reconstruction problems
  - incorrect estimation of a background
  - missing background
  - new physics including exotic oscillation scenarios, neutrino decay, Lorentz violation

No Detector anomalies found

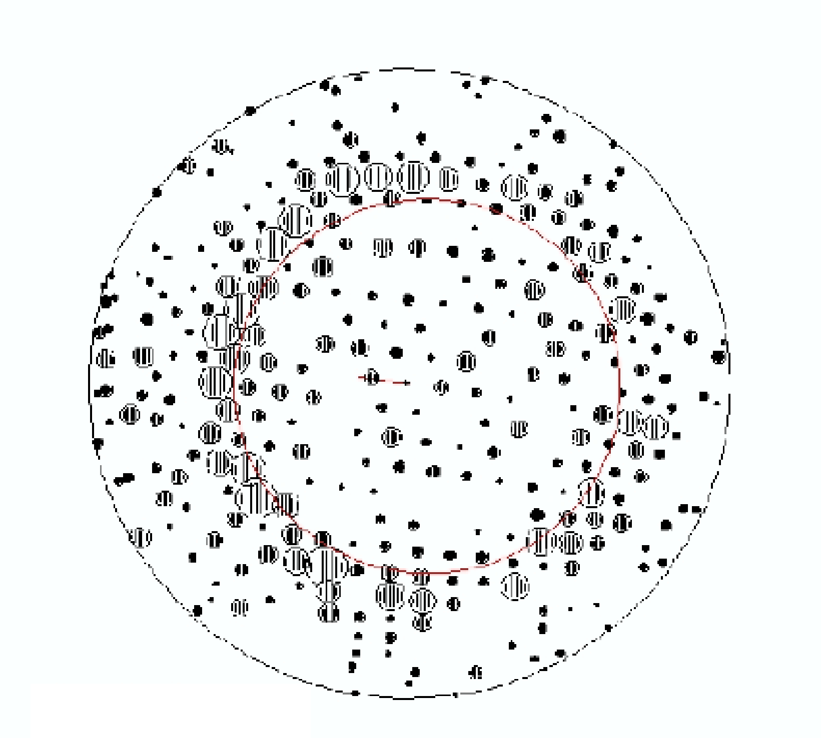
– Example: rate of electron candidate events is constant (within errors) over course of run

event/POT vs day, 300<Enu<475 MeV



No Reconstruction problems found

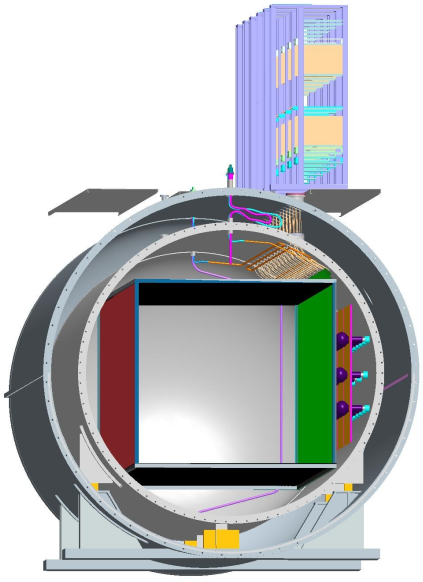
– All low-E electron candidate events have been examined via event displays, consistent with 1-ring events



Future Outlook

Future Run/Analysis Plans

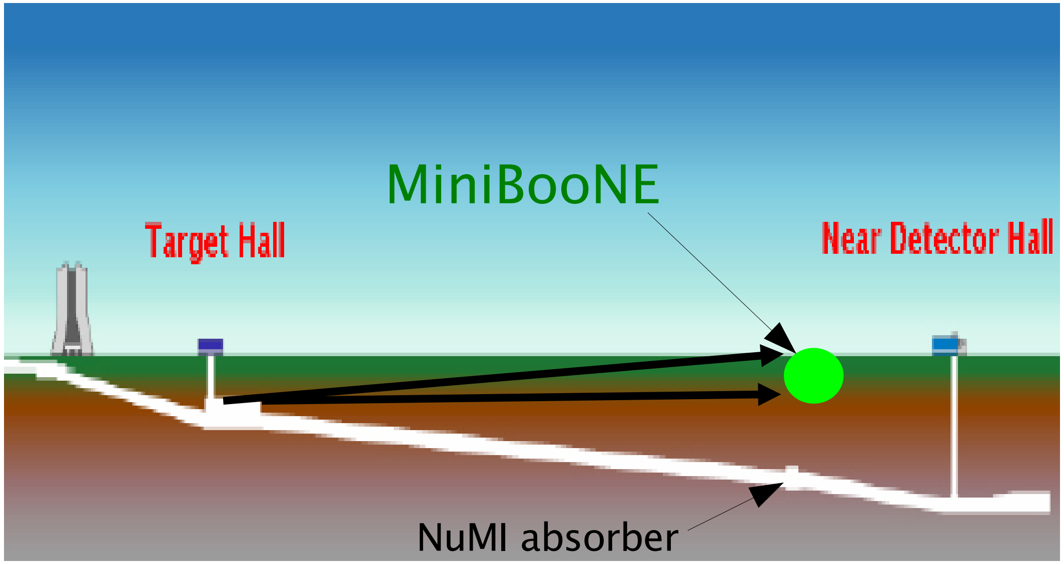
- Working on several ***publications*** in support of and extensions on this analysis
  - ν_μ CCQE paper submitted to PRL
  - NC π^0 background measurement
  - combined TBL/BDT analysis
  - combined LSND-MiniBooNE-KARMEN oscillation analysis
  - others. . .
- Continue to re-examine low E backgrounds and significance of ***low E excess***
- MiniBooNE currently running in ***antineutrino mode*** and is proposing to run in this mode for several more years
  - important antineutrino low energy cross-sections not measured before
  - another low energy data set
  - direct test of LSND
- Neutrino events in MiniBooNE from ***NuMI beam***
- ***SciBooNE*** currently running in BNB
- ***MicroBooNE, a 70 ton LArTPC detector***, has been proposed for BNB to study low energy
  - sensitive at low energies
  - e/γ separation
  - ~80% efficiency
  - low backgrounds



MicroBooNE

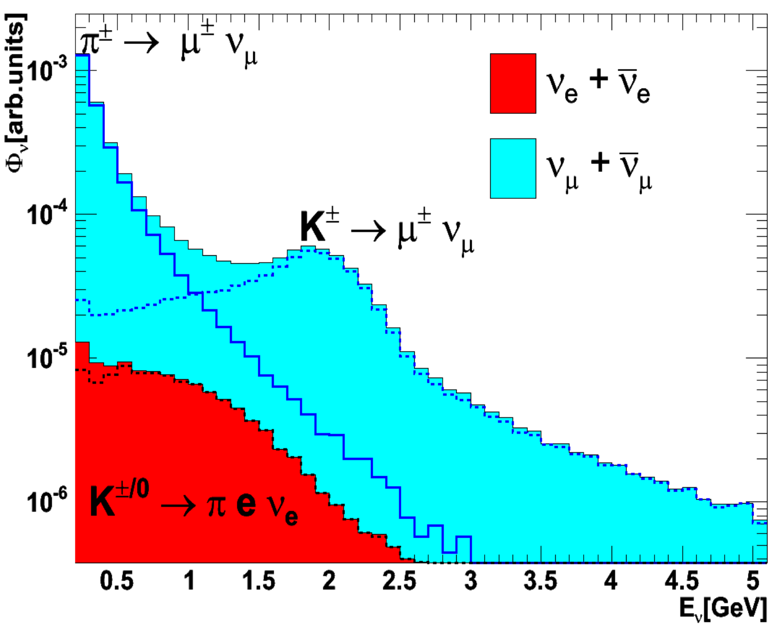
Future Outlook

NuMI → MiniBooNE



- can events from NuMI provide any insight on low energy excess seen from BNB?
- beam contains enhanced (~x10) ν_e component from kaon decays
- L/E is similar to standard MB (750m/1.25 GeV)

NuMI → MB flux prediction



BNB → MB

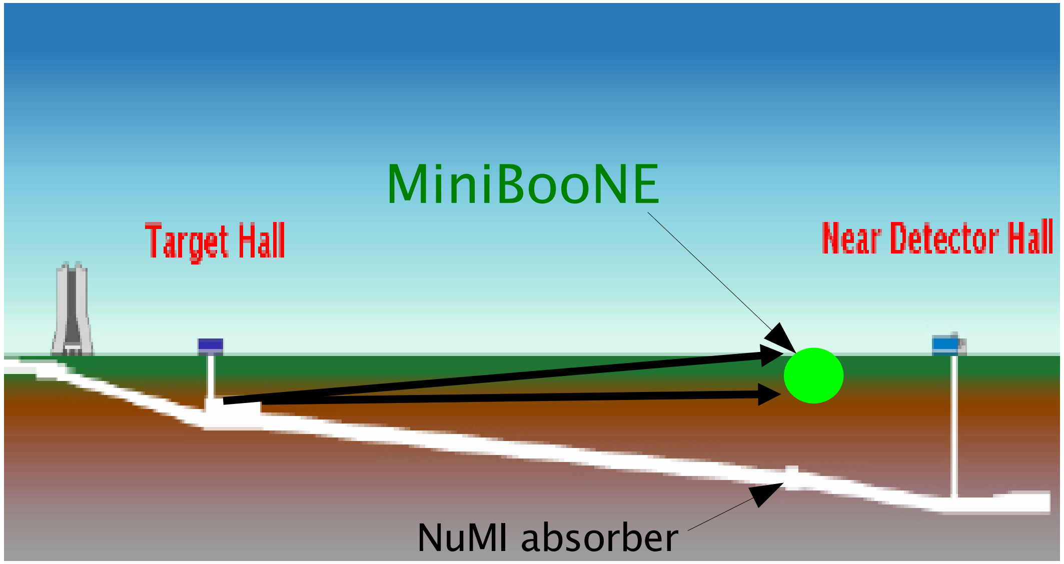
ν_μ	93%
$\bar{\nu}_\mu$	6%
ν_e	0.6%
$\bar{\nu}_e$	<0.1%

NuMI → MB

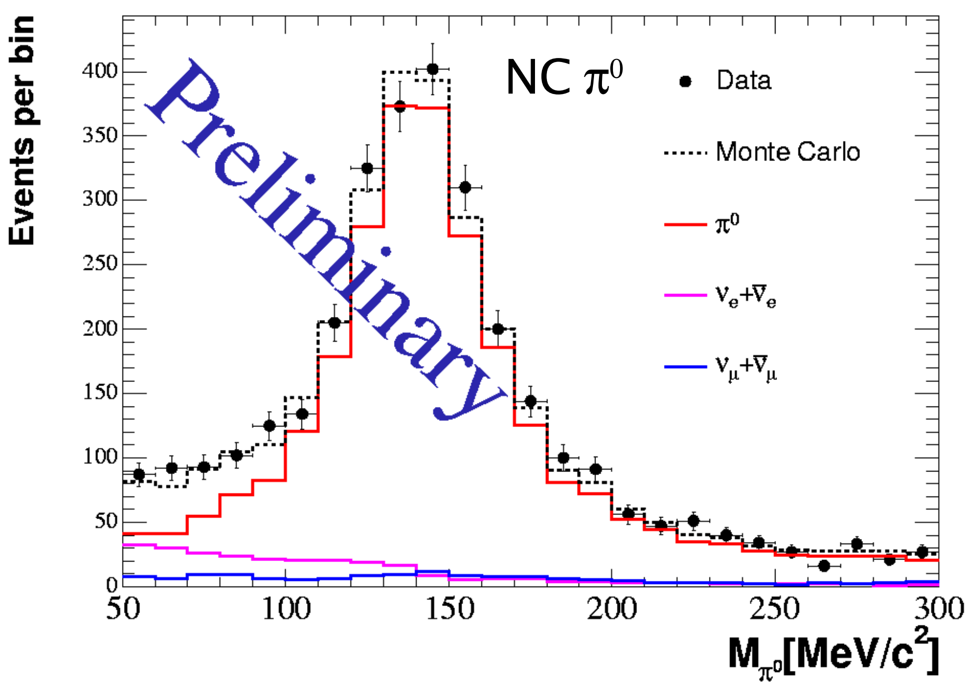
ν_μ	81%
$\bar{\nu}_\mu$	13%
ν_e	5%
$\bar{\nu}_e$	1%

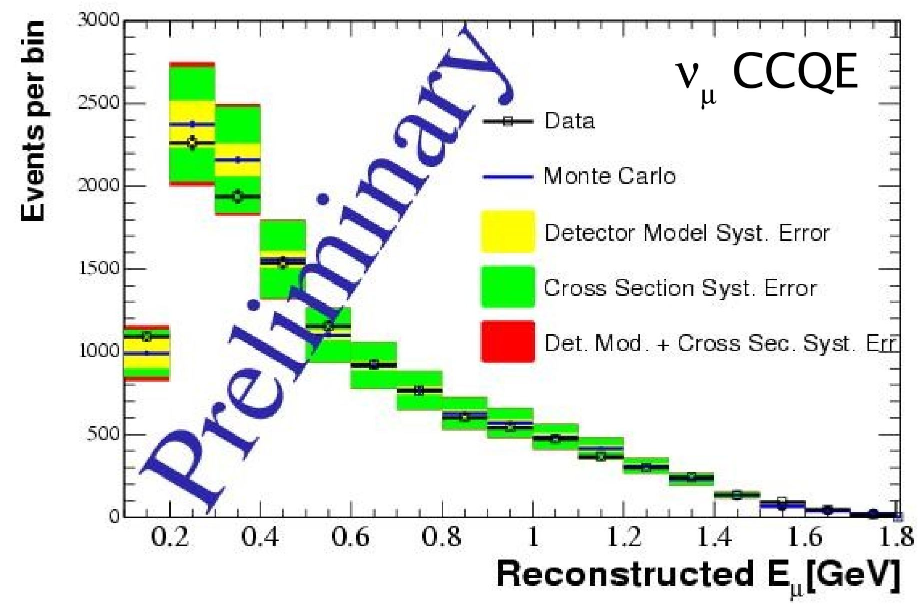
Future Outlook

NuMI → MiniBooNE



- can events from NuMI provide any insight on low energy excess seen from BNB?
- beam contains enhanced (~x10) ν_e component from kaon decays
- L/E is similar to standard MB (750m/1.25 GeV)
- nice agreement seen in ν_μ–CCQE and π^0 events
- ***ν_e analysis coming soon***





Summary

S u m m a r y

- **First results from MiniBooNE have seen no evidence for the two neutrino direct $\nu_\mu \rightarrow \nu_e$ oscillation interpretation of the LSND result**

(Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500v2 [hep-ex])

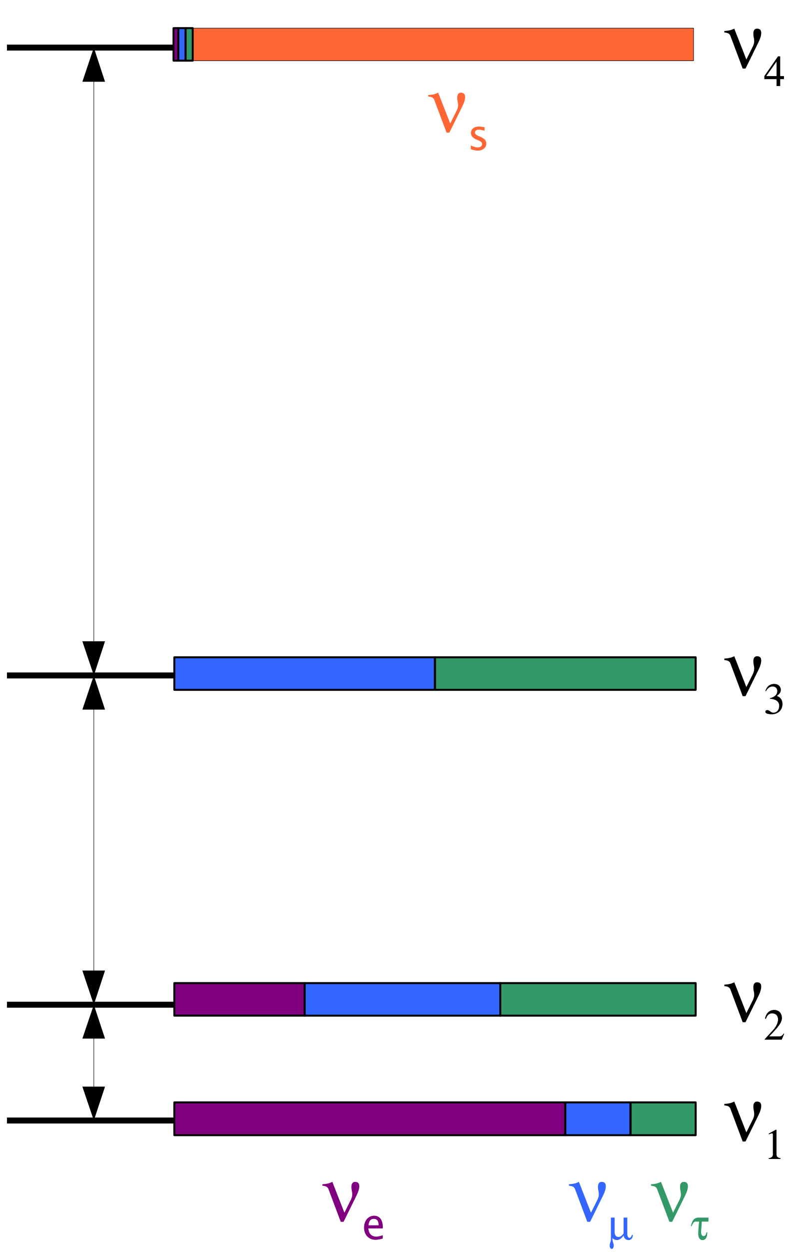
- An excess of events is seen between 200-475 MeV in the ν_e distribution and is still being investigated/interpreted
- Look for electron result from NuMI $\rightarrow$ MB neutrino beam in ~November
- Currently collecting antineutrino data

Backup Slides

M o t i v a t i o n

Neutrino Oscillations

- 'Simplest' explanation is a 4th (or more) neutrino that is mostly "sterile"
- But there are other exotic, beyond the SM solutions as well, for example:
  - Sterile neutrinos ***hep-ph/0305255***
  - Neutrino decay ***hep-ph/0602083***
  - Lorentz/CPT violation ***hep-ex/0506067***
  - Extra dimensions ***hep-ph/0504096***
- But these interpretations are not the subject of this presentation
- **First, the large Δm^2 oscillation must be confirmed. . .**



Motivation

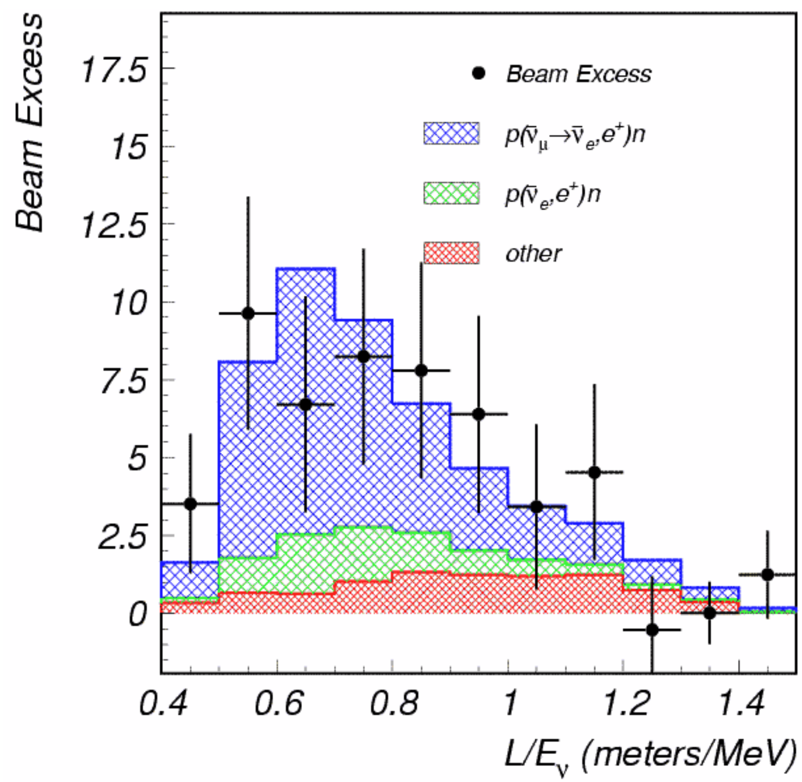
The LSND Signal as Oscillations

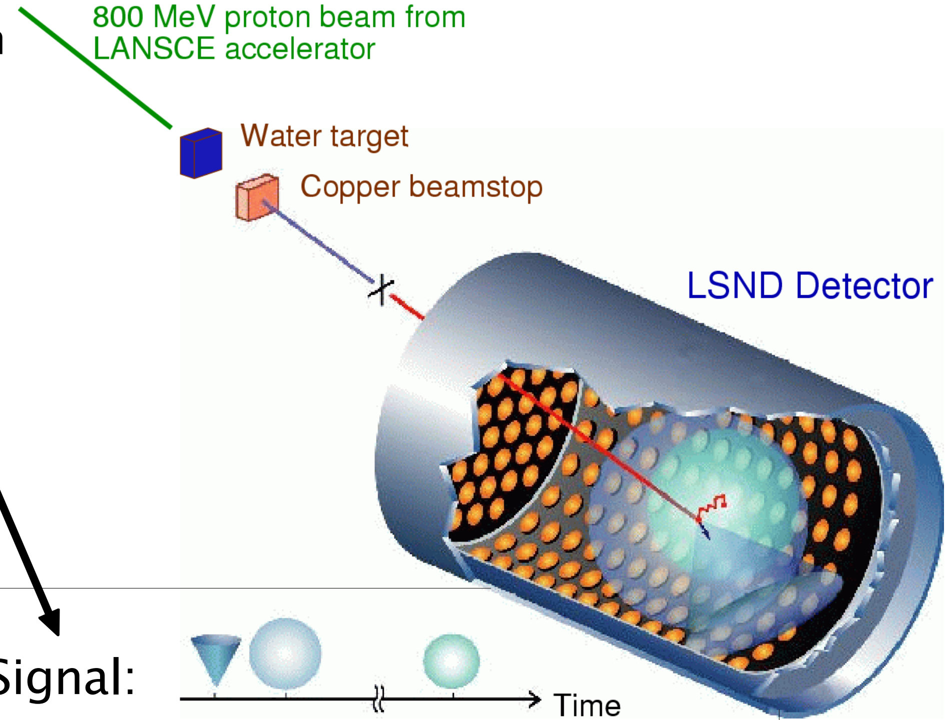
- LSND looked for an excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam

Beam: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu \overset{?}{\Rightarrow} \bar{\nu}_e$

- Found an 87.9 ± 22.4 ± 6.0 (3.8σ) $\bar{\nu}_e$ event excess above background





Signal:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + p \rightarrow d + \gamma_{2.2\,MeV}$$

- If interpreted as 2 flavor oscillations, implies an oscillation probability of

(0.264 +- 0.067 +- 0.045)%

The LSND Signal as Oscillations

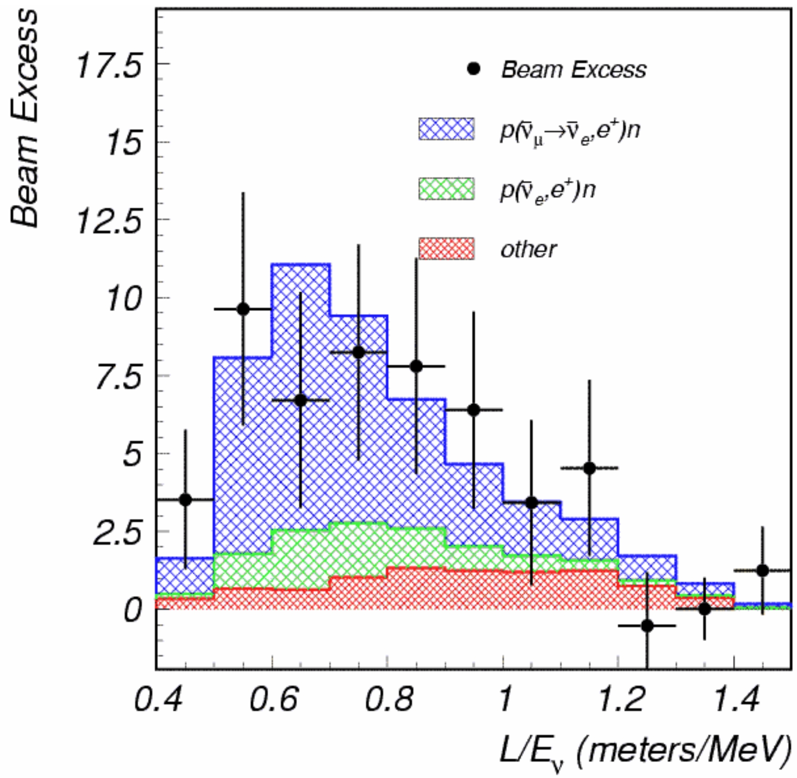
Motivation

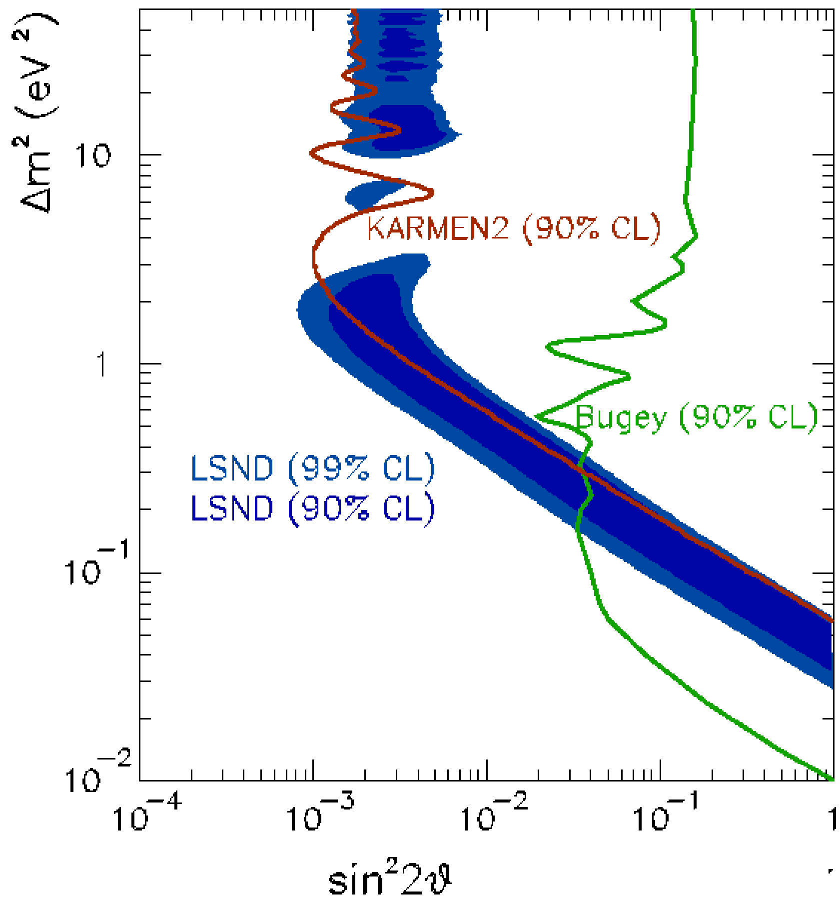
- LSND looked for an excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam

Beam: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\quad\quad \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \overset{?}{\Rightarrow} \bar{\nu}_e$

- Found an 87.9 ± 22.4 ± 6.0 (3.8σ) $\bar{\nu}_e$ event excess above background





- If interpreted as 2 flavor oscillations, implies an oscillation probability of

(0.264 +- 0.067 +- 0.045)%

MiniBooNE Analysis

Exp Overview

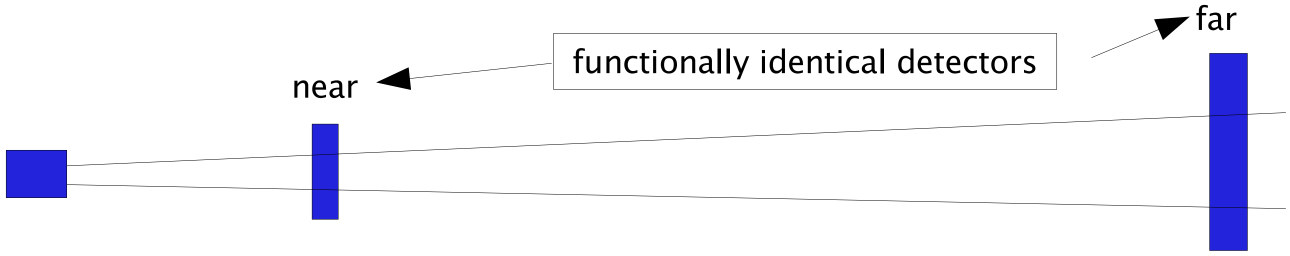
- MiniBooNE will look for an excess of ν_e events (~0.25% of ν_μ) above the predicted ν_e background (~0.6% of ν_μ) and ν_μ mis-identifications

- What makes MiniBooNE different from other accelerator neutrino experiments (K2K, MINOS, etc.)?
  - MiniBooNE is a **short baseline** experiment. The neutrino energies are very similar.
  - The expected **oscillation probability is much much smaller** than the “solar” and “atmospheric” oscillations. **[0.25% vs. maximal !!]**
  - MiniBooNE has only **one detector**, not the standard “near/far” comparison that the long baseline oscillation measurements are based on.
- What effects do these features have on an analysis
  - The baseline is not technically important. It just means we search in a different Δm^2 region. . . and we can walk the neutrinos' path during a lunch break
  - MiniBooNE is an **appearance** experiment. The others, to date, are largely disappearance measurements
  - instead of a “near/far” ratio we tie together the expected rates of $\boldsymbol{\nu_\mu/\nu_e}$.

Exp Overview

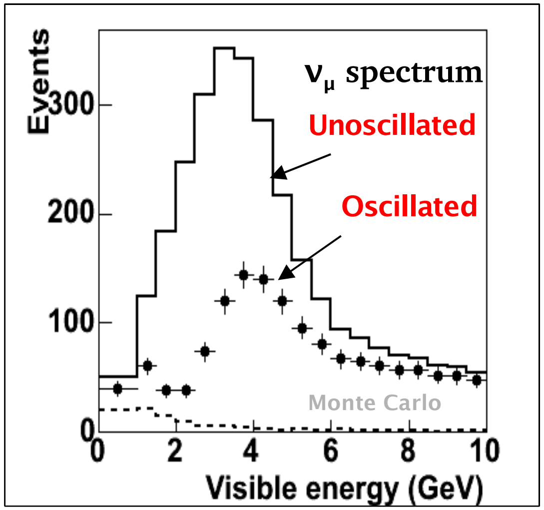
MiniBooNE Analysis

long baseline, two detector disappearance experiment



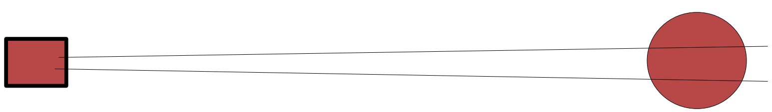
here you see the **unoscillated ν_μ flux**

here you see the **oscillated ν_μ flux**



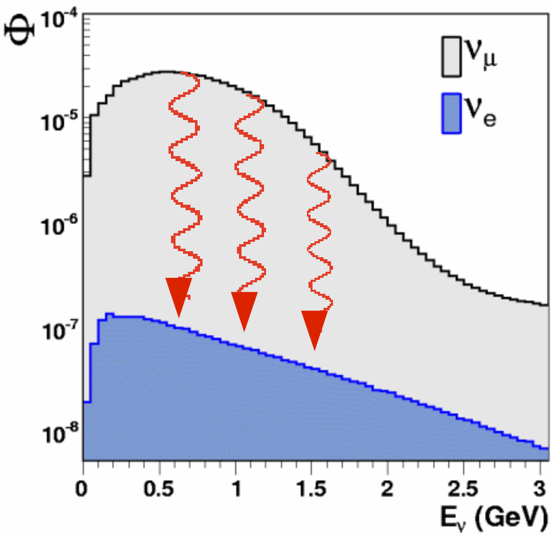
plot shamelessly stolen from MINOS collaboration

short baseline, one detector appearance experiment



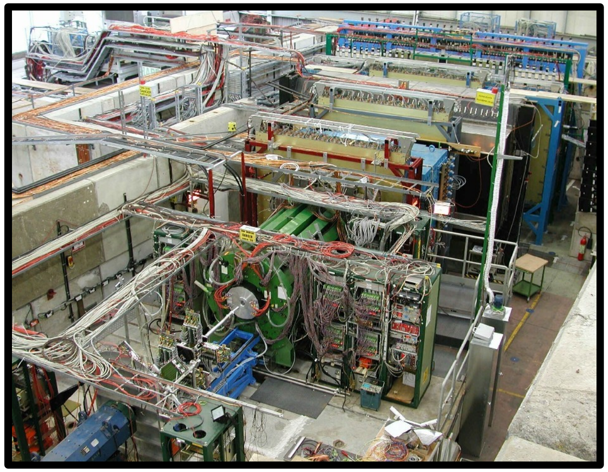
here you also see the oscillated ν_μ flux **appearing as ν_e**

here you see a ν_μ flux that is only 0.25% oscillated **effectively unoscillated ν_μ**



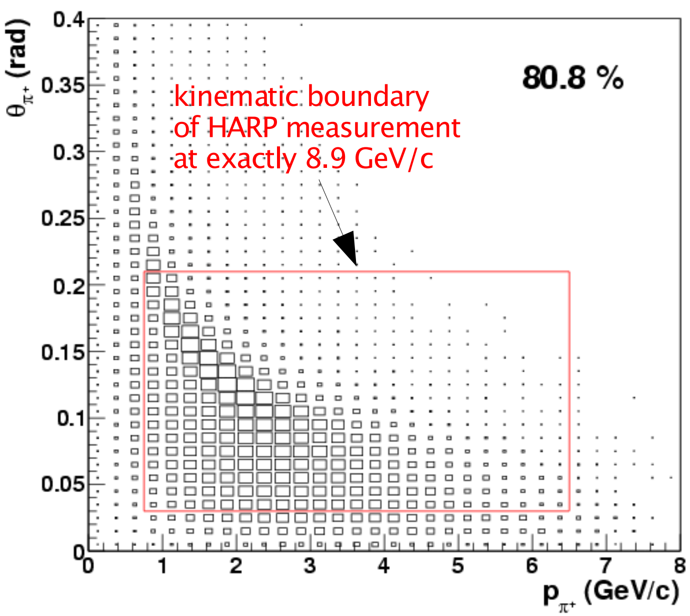
Osc Analysis

Neutrino Flux Prediction



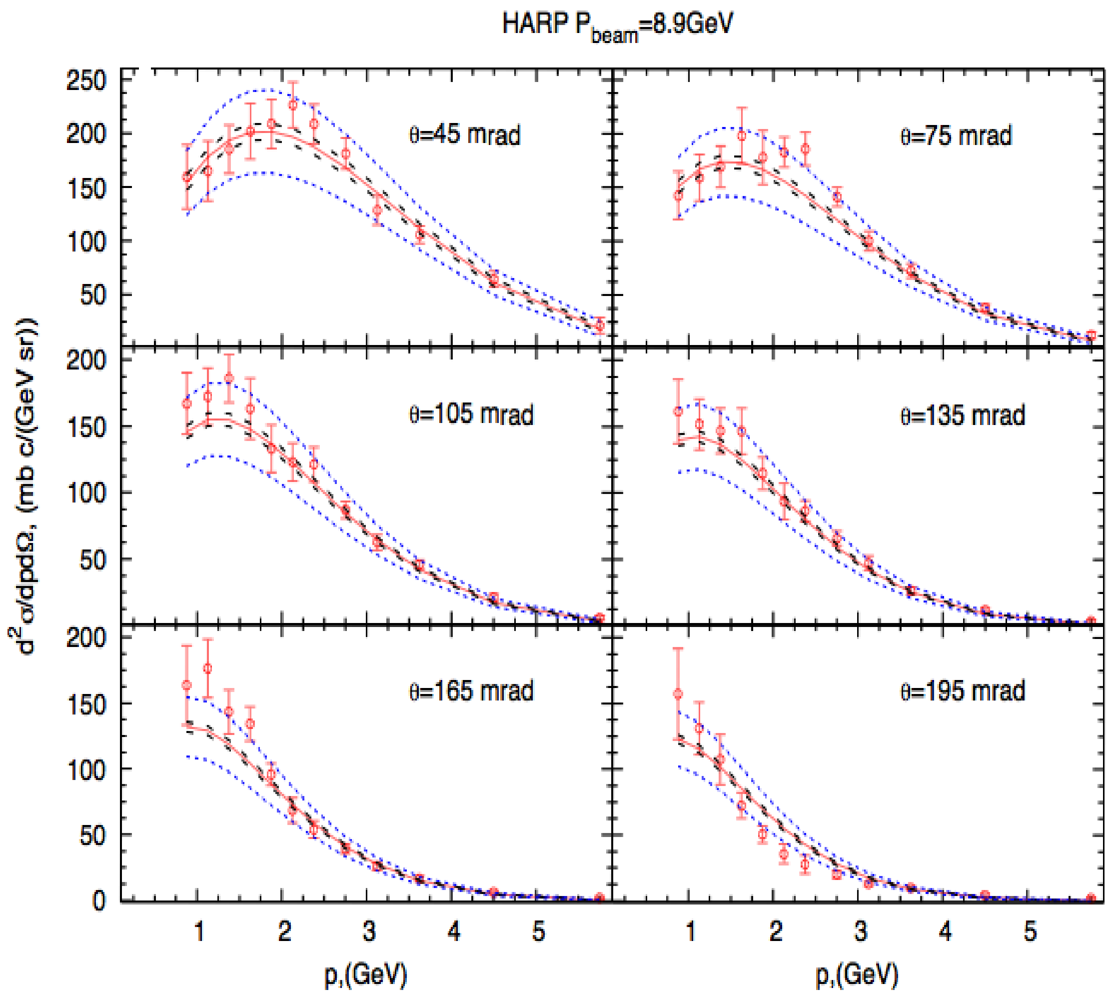
$$p + Be \rightarrow \pi^{+} \rightarrow \nu_{\mu}$$

- black boxes are the distribution of π^+ which decay to a ν_μ that **passes through the MiniBooNE detector**



- Hadron production measurements from the **HARP** and **E910** experiments constrain π^+ and π^- production which yield muon neutrino fluxes

- Similar fits performed to available kaon production data



M.G. Catanesi et al "Measurement of the production cross-section of positive pions in the collision of 8.9 GeV/c protons on beryllium." Euro. Phys. J C 52:29-53 (2007)

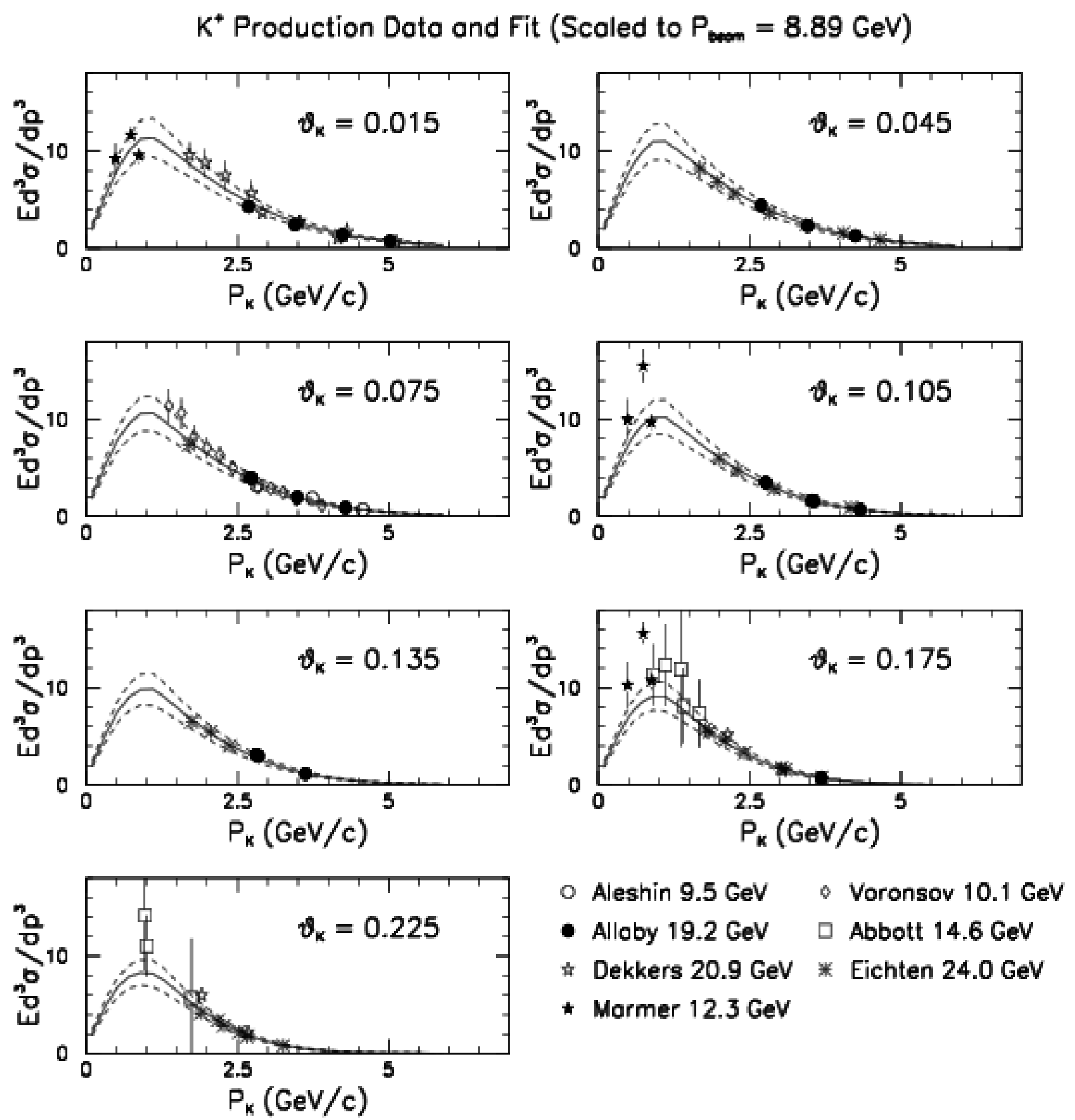
Neutrino Flux Prediction

Osc Analysis

- intrinsic electron neutrinos come from **kaon decays** or the decay of muons coming from pions

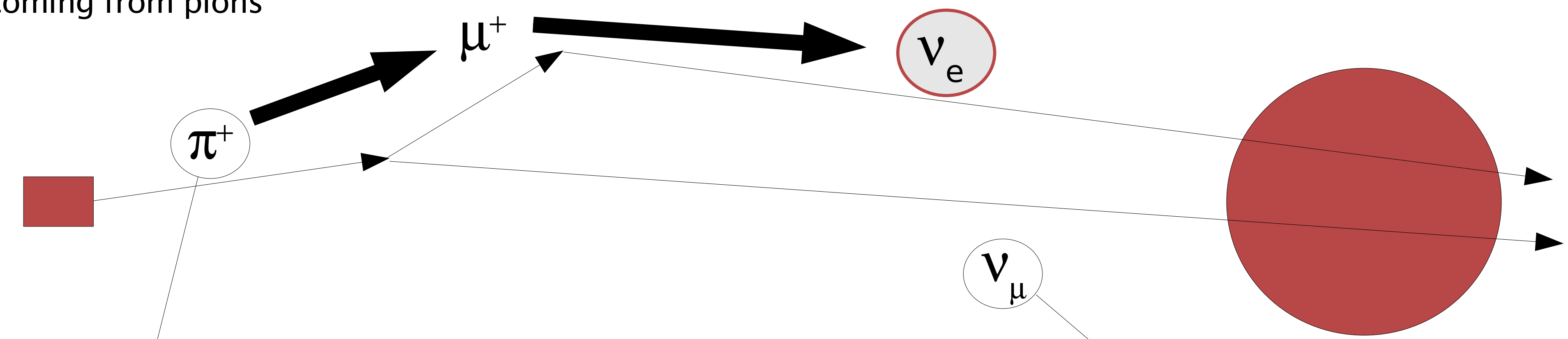
$$p + Be \rightarrow K^{+} \rightarrow \nu_{\mu}/\nu_{e}$$

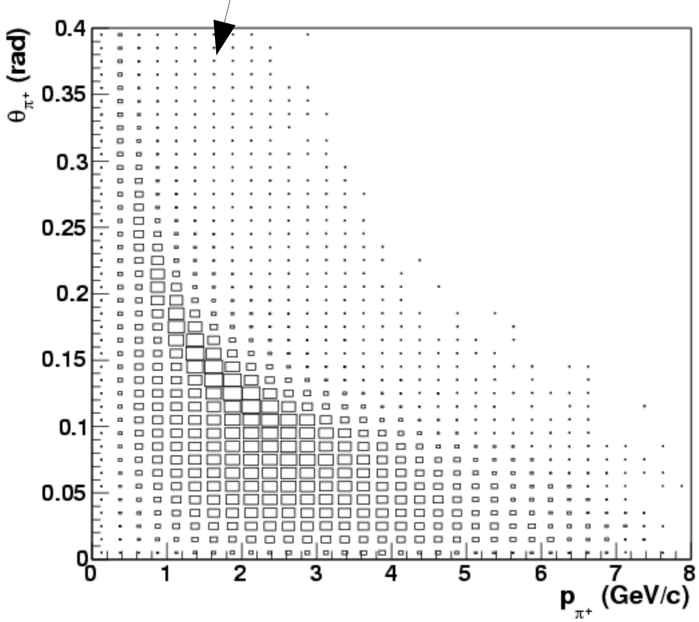
- K^+ data from 10 – 24 GeV/c proton beams
- parameterization based on principles of Feynman scaling developed by MiniBooNE collaborators. Working on a paper.
- plots show data scaled to 8.9 GeV/c beam momentum with parameterization and 1σ excursions
- K^0 also parameterized, but present a much smaller background than K^+

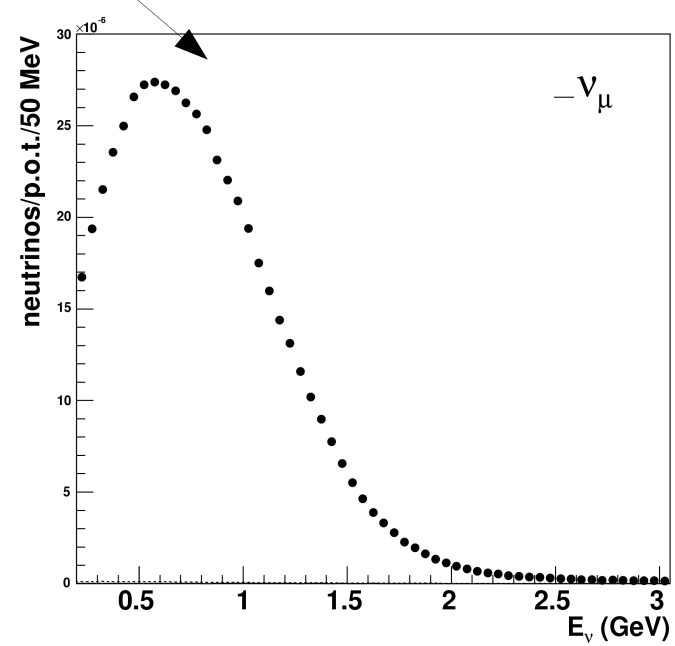


Constraining ν_e from μ decay

- intrinsic electron neutrinos come from kaon decays or the **decay of muons** coming from pions

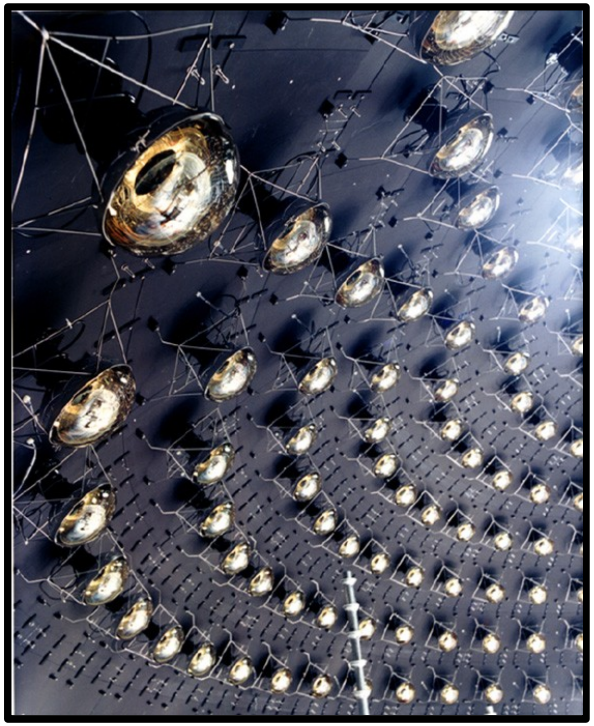






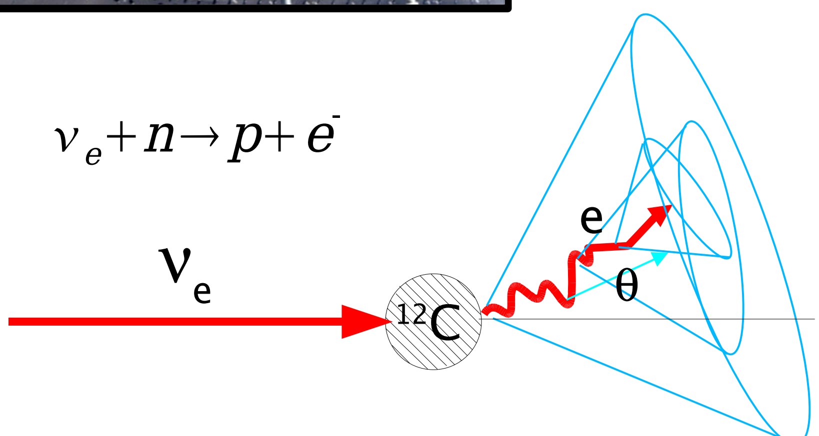
*note: same technique would apply to tiny signal from $\pi^+ \rightarrow \nu_e$

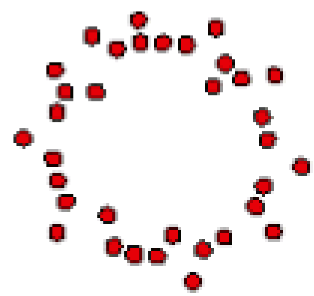
MiniBooNE Tank Events

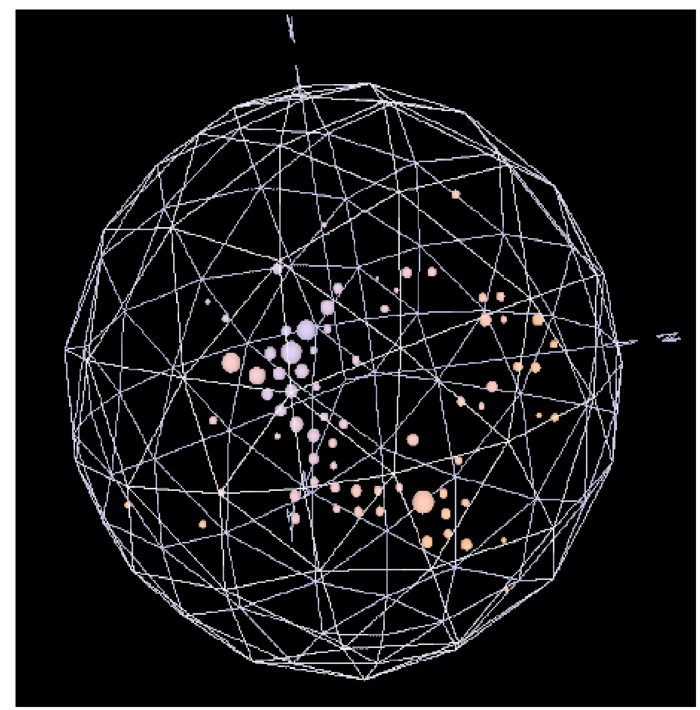


- After cuts, MiniBooNE must be able to find O(100s) ν_e CCQE interactions in a sea of O(100Ks) ν_μ interactions
  - **electrons:**
    - electrons create **fuzzy rings** due to multiple scattering
    - several hundred CCQE events from **intrinsic ν_e** produced in the beamline from muon and kaon decays are expected
    - these **intrinsics are irreducible** at the event level
    - **energy spectrum** of intrinsics differs from oscillation signal

$$\nu_e + n \rightarrow p + e^-$$



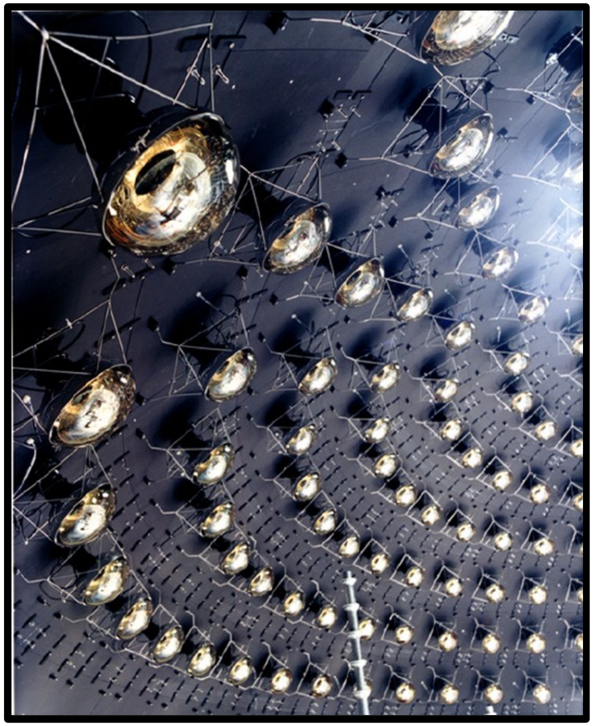




$$E_\nu^{QE} = \frac{1}{2}\frac{2ME_l - m_l^2}{M - E_l + P_l\cos\theta_e}$$

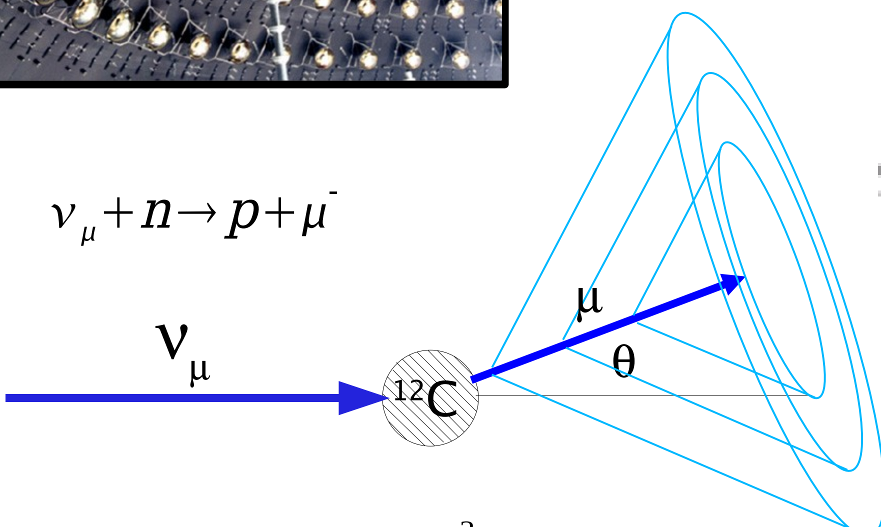
Exp Overview

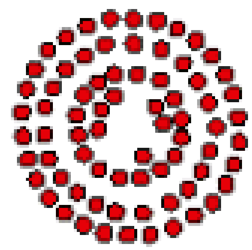
MiniBooNE Tank Events

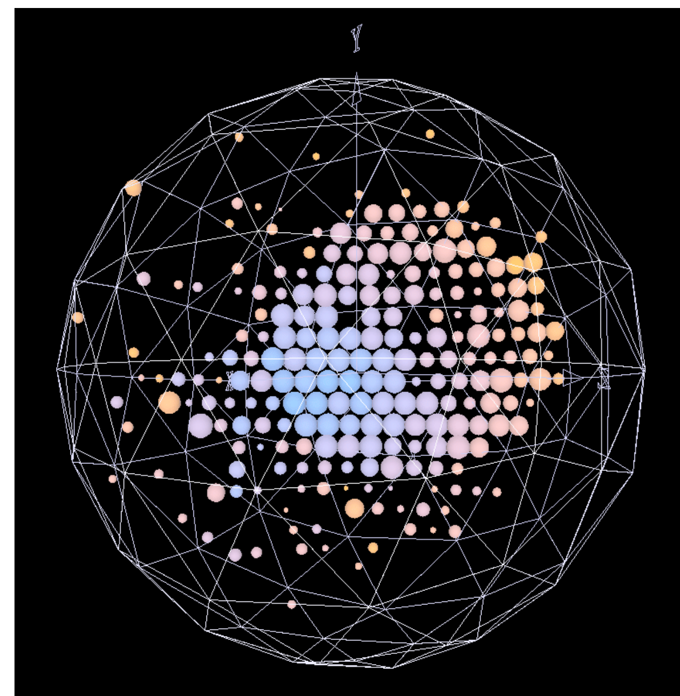


- After cuts, MiniBooNE must be able to find O(100s) ν_e CCQE interactions in a sea of O(100Ks) ν_μ interactions
  - **muons:**
    - muons create **sharp, filled-in rings**
    - event classification algorithms must reject >**99%** ν_μ CCQE events
    - most CCQE can be removed by **2nd sub-event** (more later)
    - where muon is captured or electron not seen can use **topology**

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



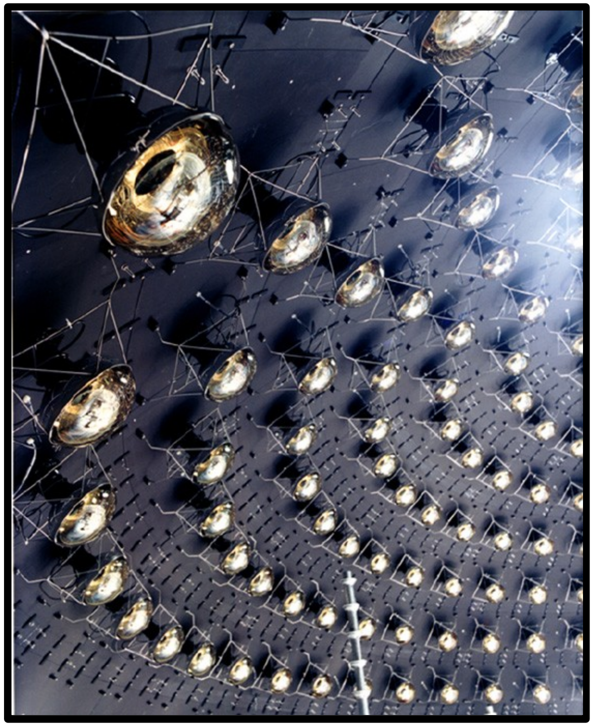




$$E_\nu^{QE} = \frac{1}{2} \frac{2ME_l - m_l^2}{M - E_l + P_l \cos\theta_e}$$

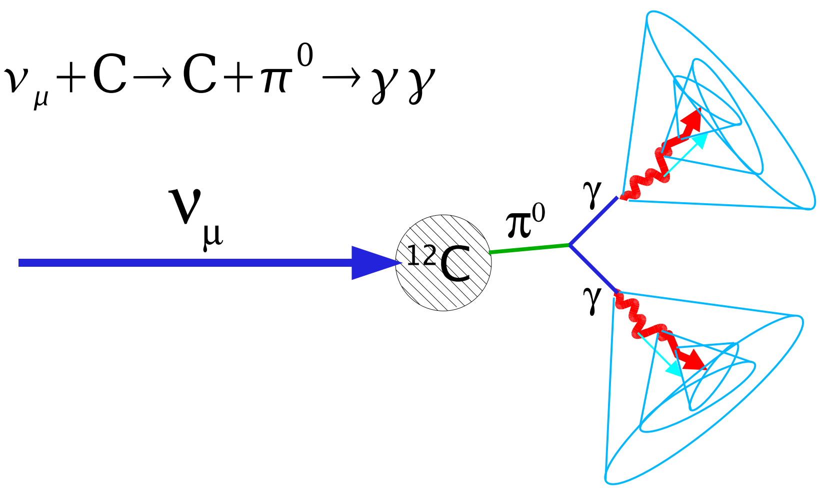
Exp Overview

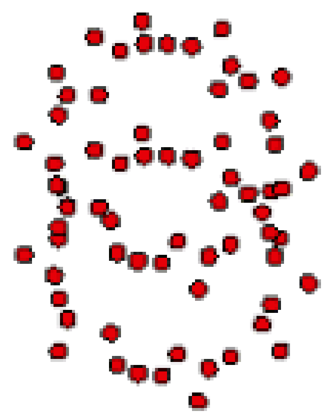
MiniBooNE Tank Events

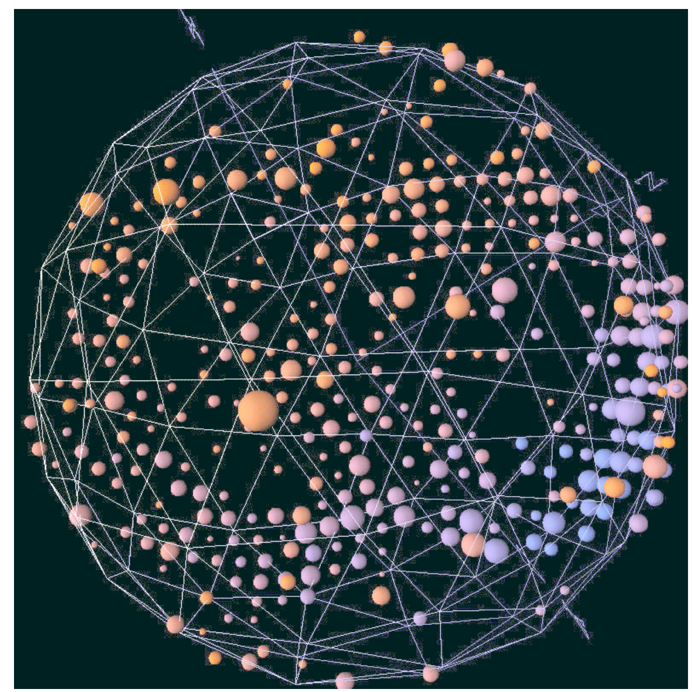


- After cuts, MiniBooNE must be able to find O(100s) ν_e CCQE interactions in a sea of O(100Ks) ν_μ interactions
  - **neutral pions:**
    - π^0s create **two fuzzy, electron-like rings**
    - most π^0 can be removed by **two ring fit**
    - background comes from asymmetric decays where reconstruction cannot resolve both rings (kinematics)

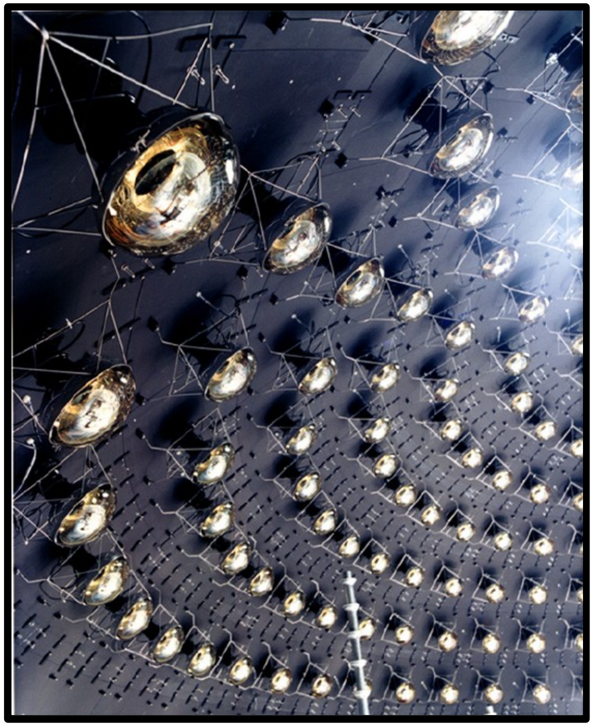
$$\nu_\mu + C \rightarrow C + \pi^0 \rightarrow \gamma\gamma$$





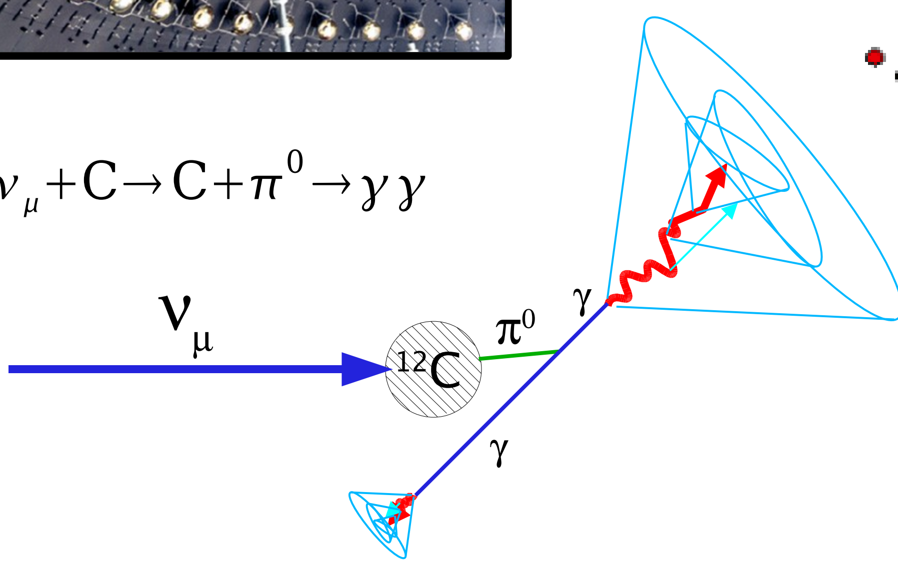


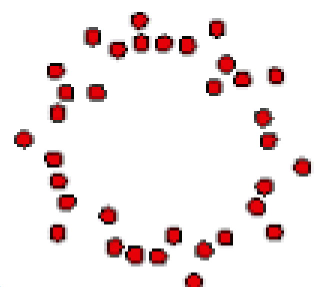
MiniBooNE Tank Events

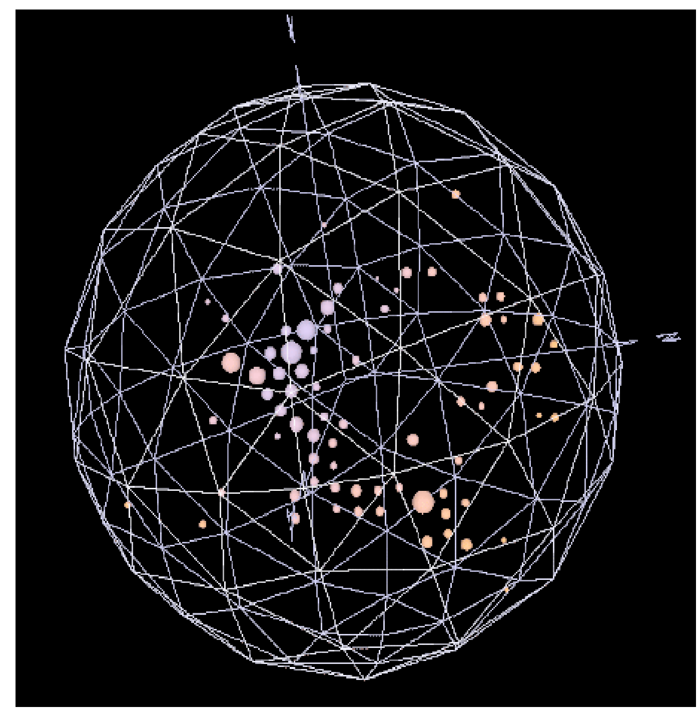


- After cuts, MiniBooNE must be able to find O(100s) ν_e CCQE interactions in a sea of O(100Ks) ν_μ interactions
  - **neutral pions:**
    - π^0s create **two fuzzy, electron-like rings**
    - most π^0 can be removed by **two ring fit**
    - background comes from **asymmetric decays** where reconstruction cannot resolve both rings (kinematics)

$$\nu_\mu + C \rightarrow C + \pi^0 \rightarrow \gamma\gamma$$



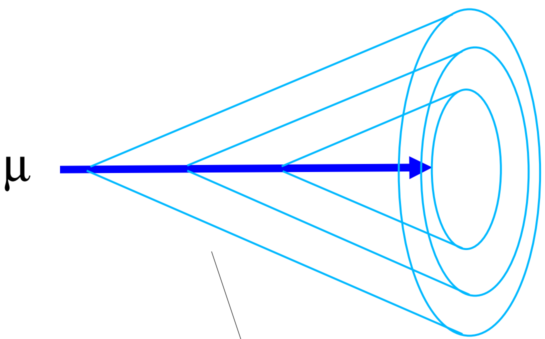


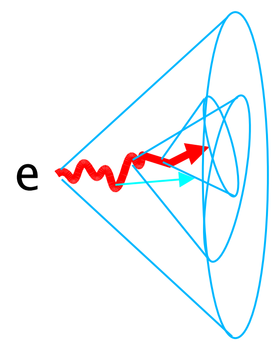


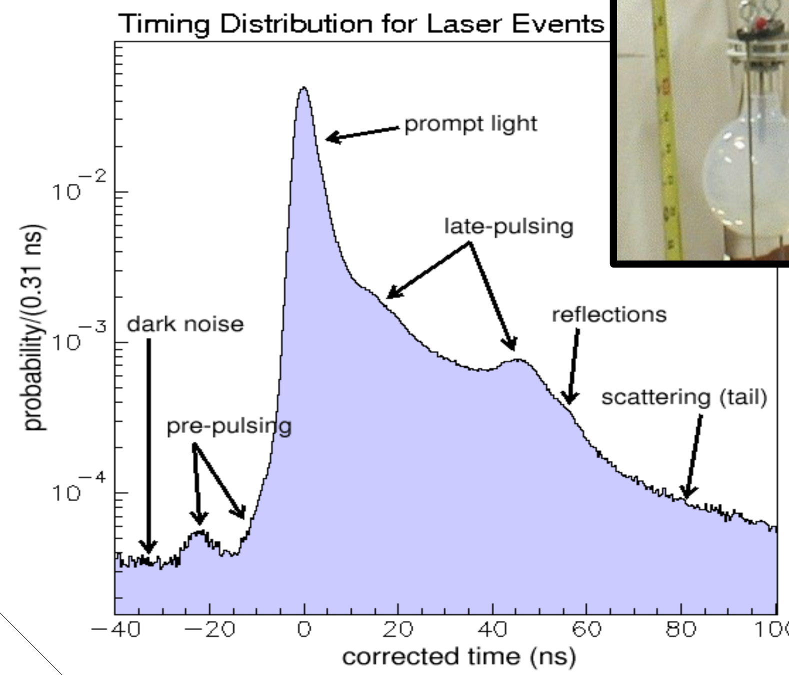
Osc Analysis

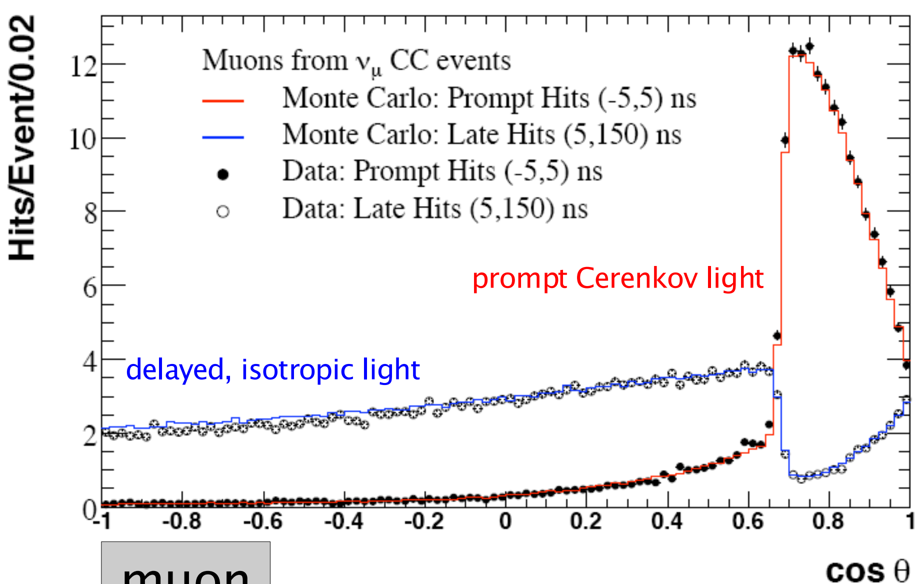
Detector Response Model

- Optical model is quite complex
  - Cherenkov, scintillation, fluorescence
  - PMT Q/t response
  - Scattering, reflections, prepulses
  - Overall, about 40 non-trivial parameters

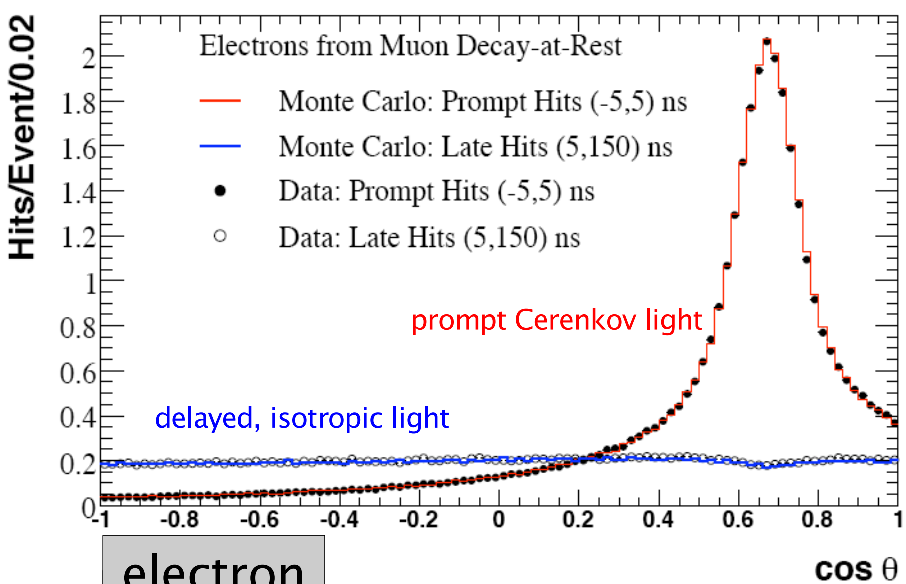








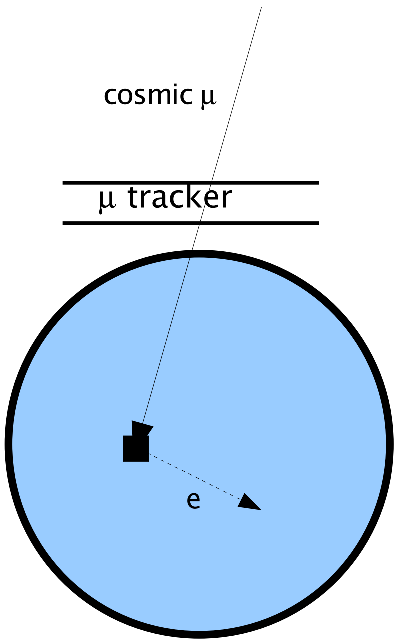
muon



electron

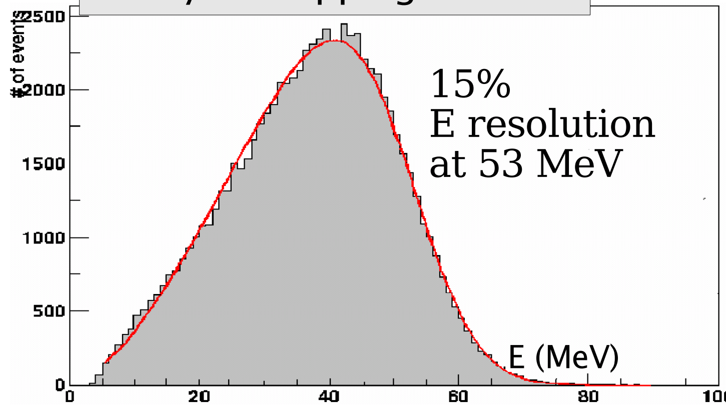
Detector Response Model

Osc Analysis

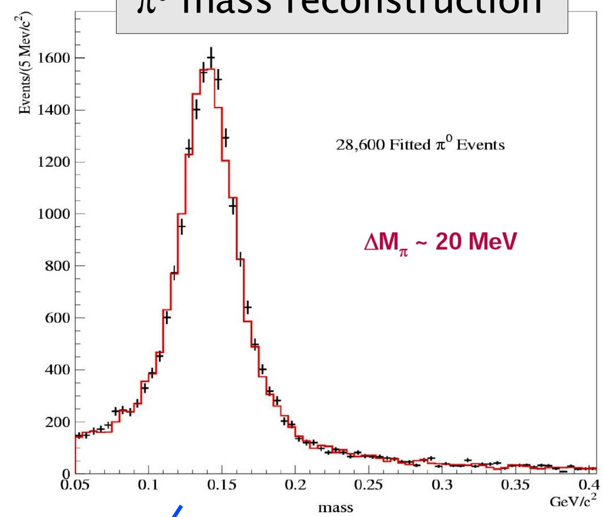


energy calibration

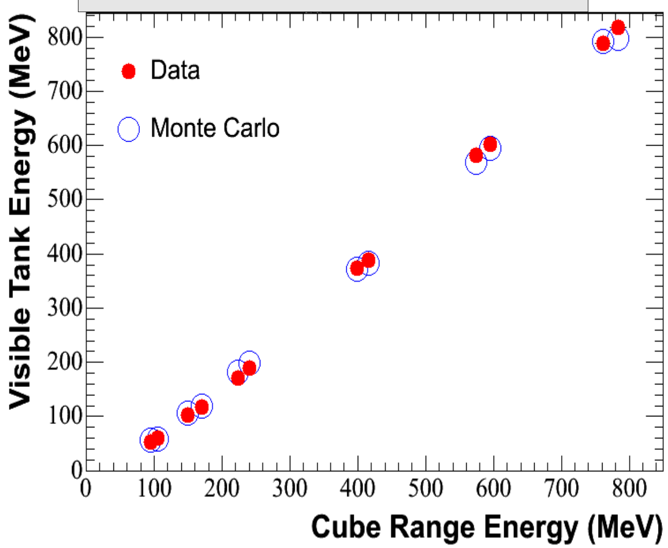
Michel electrons from the decay of stopping muons

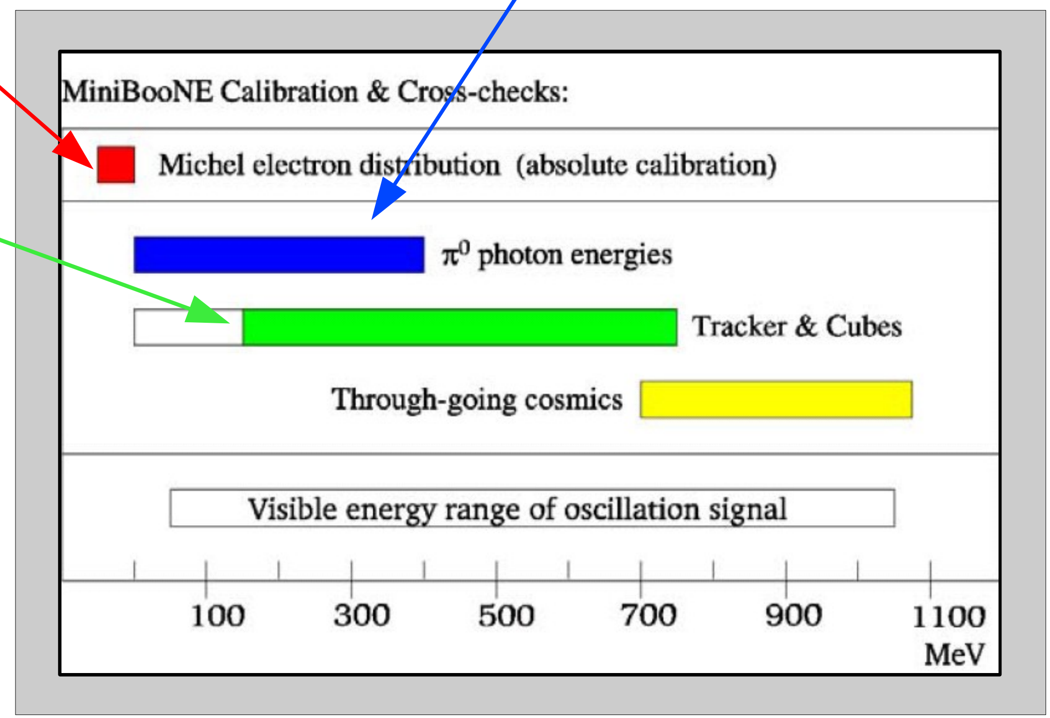


π^0 mass reconstruction



Cosmic muons stopping in scintillator cubes

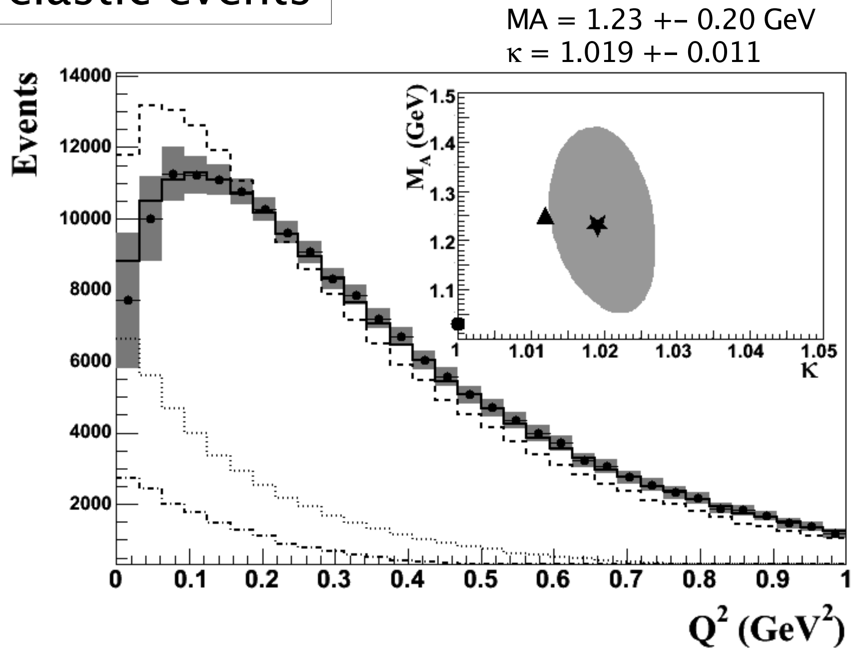




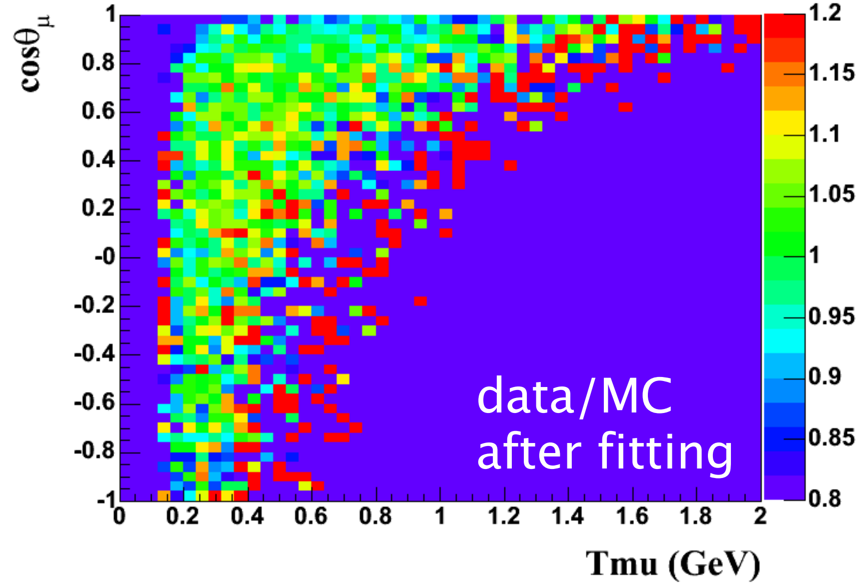
Neutrino Cross-section Model

charged-current quasi-elastic events

- A deficit is seen in the data for low values of the momentum transfer, Q^2
- **Solution:** use ν_μ data sample to adjust available parameters in present model to reproduce data. only ν_μ - ν_e differences are due to lepton mass effects, m_μ vs. m_e
- Model describes CCQE data well

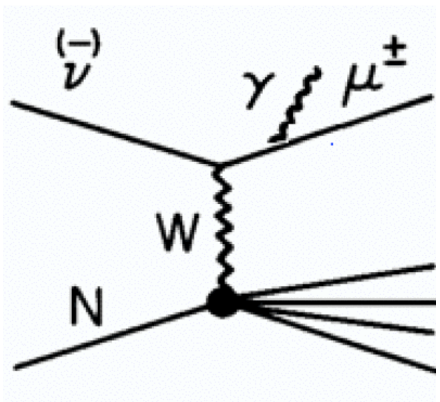


- From Q^2 fits to MiniBooNE ν_μ CCQE data:
  - M_A^{eff} -- effective axial mass
  - E_{lo}^{SF} -- Pauli Blocking parameter
- From electron scattering data:
  - E_b -- binding energy
  - p_f -- Fermi momentum

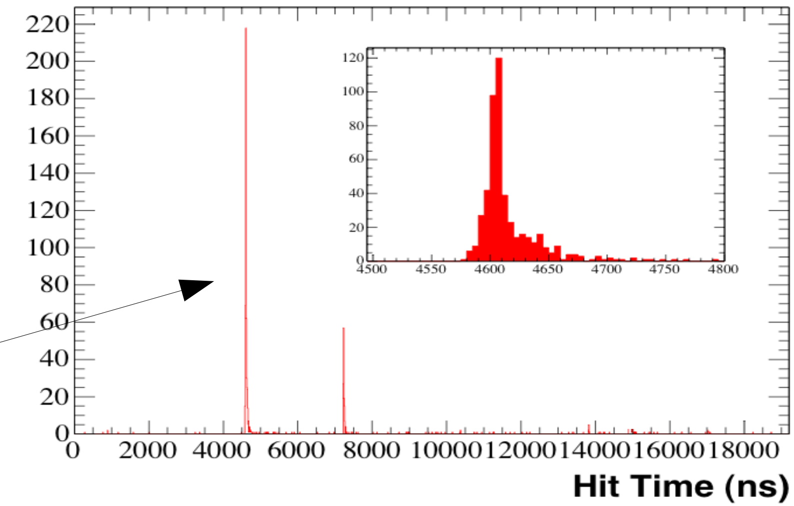


A.A. Aguilar-Arevalo et al., "Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon", arXiv:0706.0926 [hep-ex], submitted to Phys. Rev. Lett.

Muon bremsstrahlung

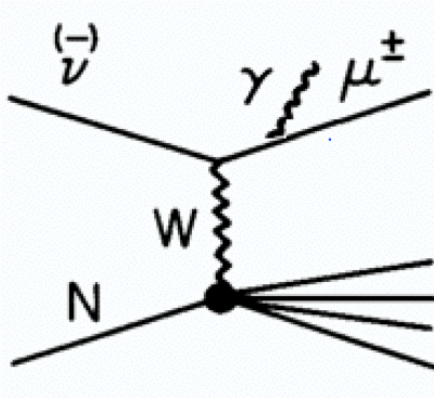


- muon radiates a hard photon
- rate for this effect calculated by Efrosinin (arXiv:hep-ph/0609169v1) and more recently by Bodek (arXiv:0709.4004v2 [hep-ex])

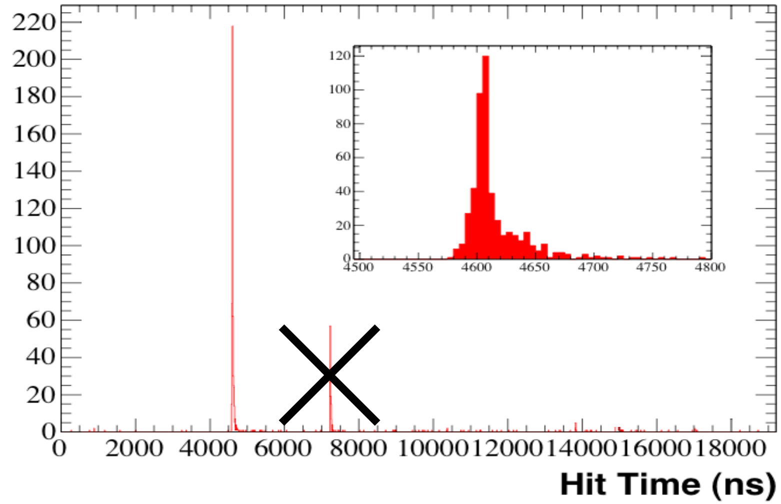


- the relevant question for MiniBooNE, however, is ***do these events look like electrons in our detector?***
- can use the two sub-event sample to answer:
  - start with 2 sub-event CCQE sample, erase 2^{nd} sub-event and run PID on first sub-event only
  - start with 2 sub-event CCQE sample, move 2^{nd} sub-event in time to overlap the first sub-event (e/γ directly on top of μ)

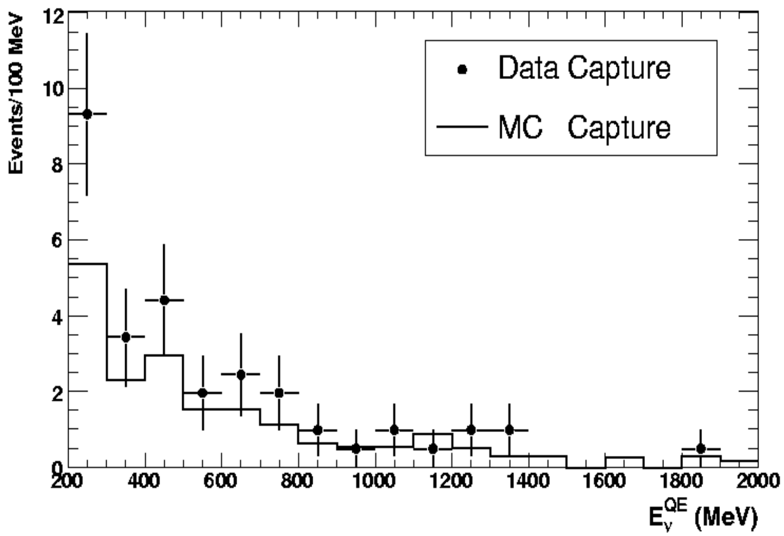
Muon bremsstrahlung



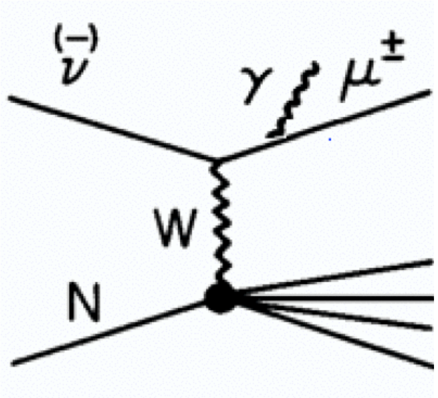
- muon radiates a hard photon
- rate for this effect calculated by Efrosinin (arXiv:hep-ph/0609169v1) and more recently by Bodek (arXiv:0709.4004v2 [hep-ex])



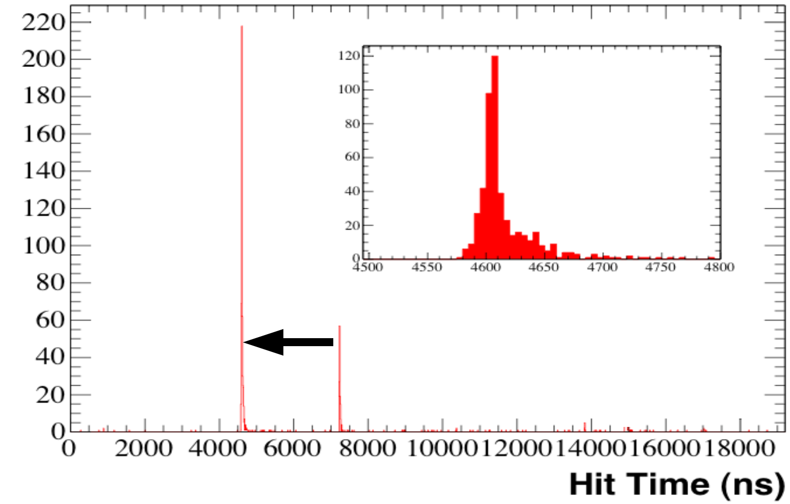
- the relevant question for MiniBooNE, however, is ***do these events look like electrons in our detector?***
- can use the two sub-event sample to answer:
  - start with 2 sub-event CCQE sample, erase 2nd sub-event and run PID on first sub-event only
  - start with 2 sub-event CCQE sample, move 2nd sub-event in time to overlap the first sub-event (e/γ directly on top of μ)



Muon bremsstrahlung



- muon radiates a hard photon
- rate for this effect calculated by Efrosinin (arXiv:hep-ph/0609169v1) and more recently by Bodek (arXiv:0709.4004v2 [hep-ex])



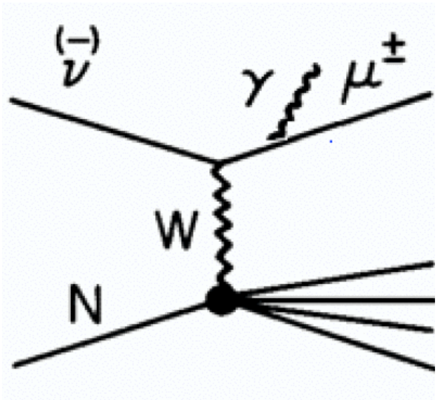
- the relevant question for MiniBooNE, however, is ***do these events look like electrons in our detector?***
- can use the two sub-event sample to answer:
  - start with 2 sub-event CCQE sample, erase 2nd sub-event and run PID on first sub-event only
  - start with 2 sub-event CCQE sample, move 2nd sub-event in time to overlap the first sub-event (e/γ directly on top of μ)

out of 10,000 events, the numbers passing ν_e cuts are:

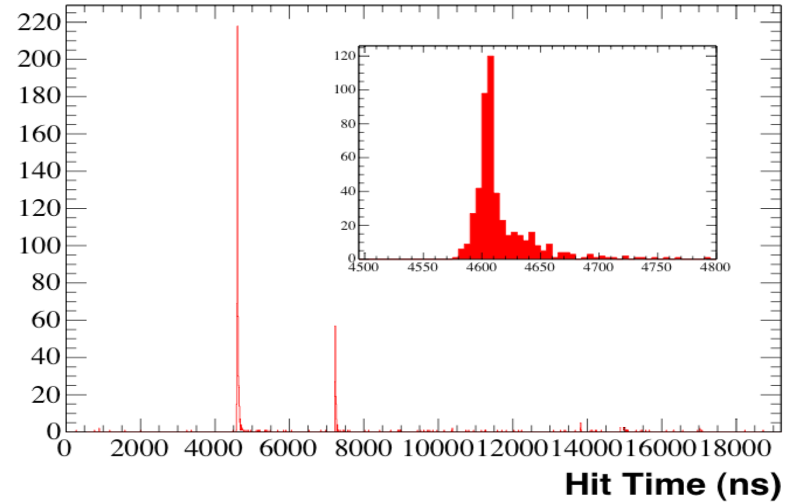
28 Data
32 Monte Carlo

Osc Analysis

Muon bremsstrahlung



- muon radiates a hard photon
- rate for this effect calculated by Efrosinin (arXiv:hep-ph/0609169v1) and more recently by Bodek (arXiv:0709.4004v2 [hep-ex])



- the relevant question for MinibooNE, however, is ***do these events look like electrons in our detector?***
- can use the two sub-event sample to answer:
  - start with 2 sub-event CCQE sample, erase 2nd sub-event and run PID on first sub-event only
  - start with 2 sub-event CCQE sample, move 2nd sub-event in time to overlap the first sub-event (e/γ directly on top of μ)
- conclusion: ***these events still look very muon-like and the small rate for mis-ID is well predicted by the Monte Carlo***

Osc Analysis

Event Reconstruction & PID

- Each tank event is just a collection of low level PMT-hit information for each tube that recorded a signal

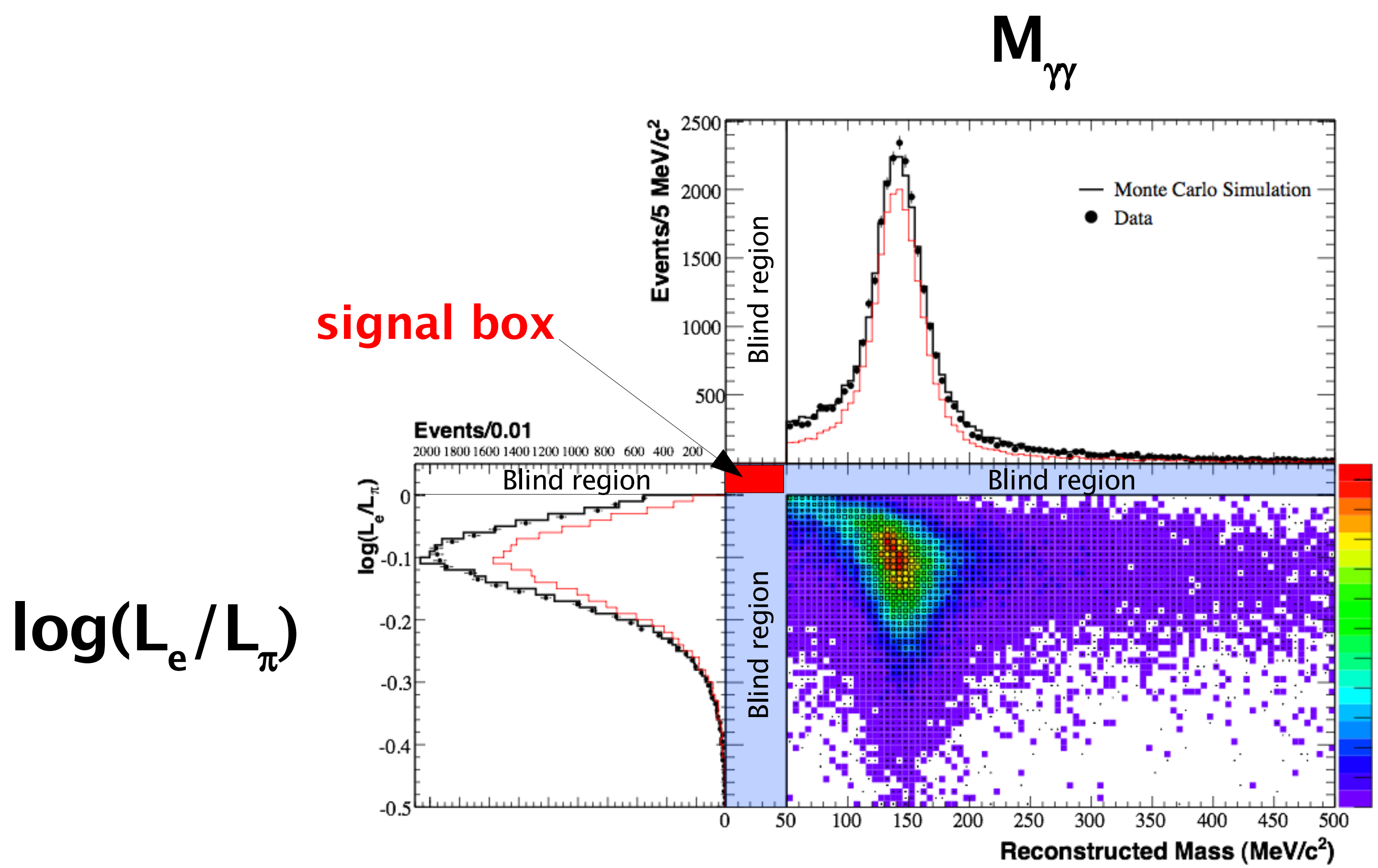
charge, Q
time, t
position, $\vec{x}$

- We employ two approaches to extract particle information from these data :
  1. **Track Based** reconstruction + **Likelihood PID**
     - treats particles in the tank as extended tracks and carefully considers dE/dx effects
     - extremely tenacious fit. . . π^0 (2 ring) fitter takes ~8 minutes per event!
     - PID algorithm based on Likelihood ratios of different particle hypotheses
  2. **Point Source** reconstruction + **Boosted Decision Tree PID**
     - treats particles more like point-sources and is less careful about dE/dx
     - fit not nearly as tenacious about getting out of local minima, particularly with π^0 fit
     - reconstruction runs nearly 10 times faster
     - to compensate for the more simple fitting procedure a more advanced PID algorithm (Boosted Decision Trees) is required to improve ν_e selection

resolutions	**TB**	**PS**
vertex	22 cm	24 cm
direction	2.8 deg	3.8 deg
energy	11%	14%

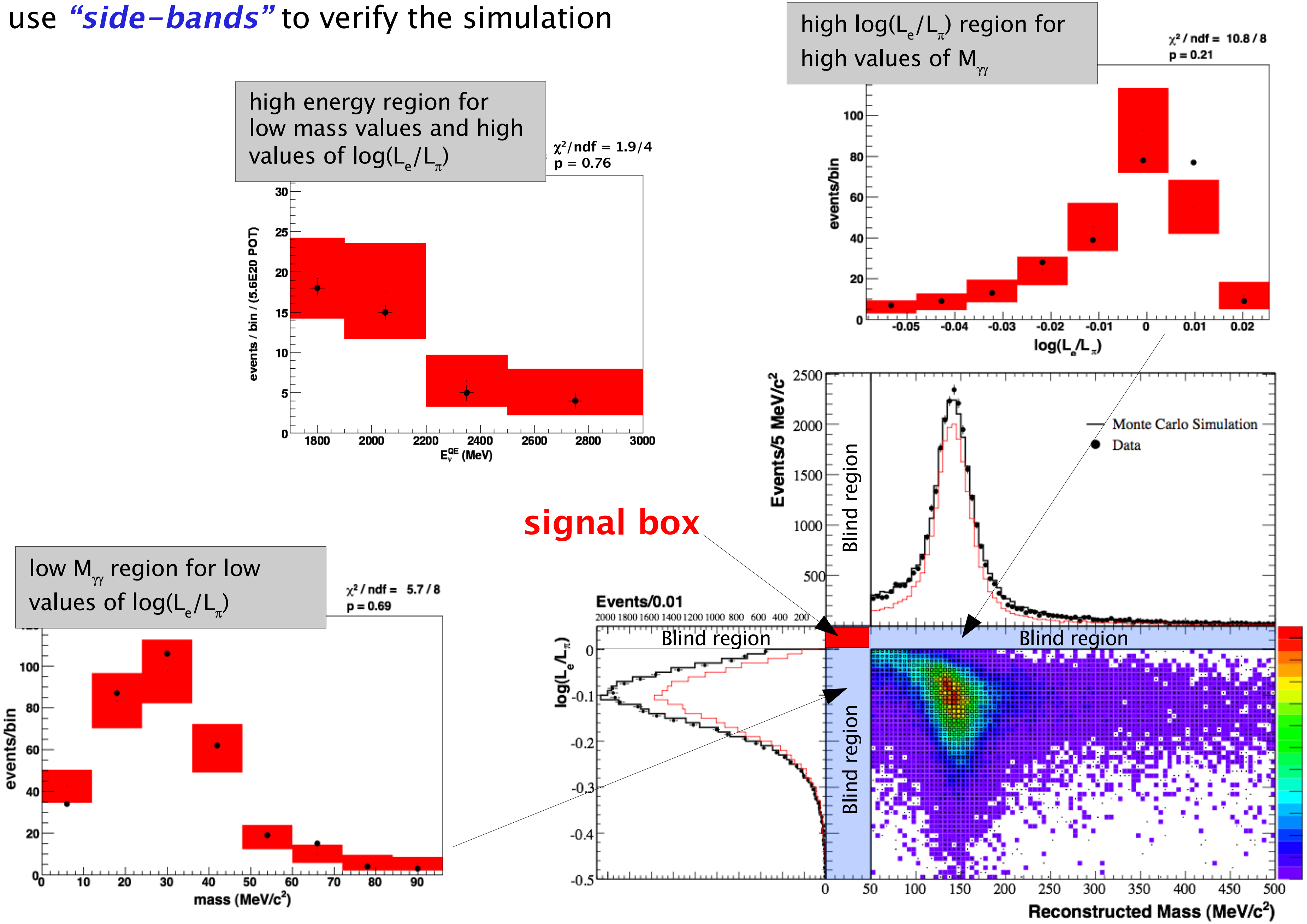
Verifying Sidebands (Likelihood PID)

- cannot compare data and Monte Carlo for PID variables within the signal region (blindness)
- use ***"side-bands"*** to verify the simulation
- apply $\log(L_e/L_\mu)$ cut and check side-bands in e/π^0 separation variables



Verifying Sidebands (Likelihood PID)

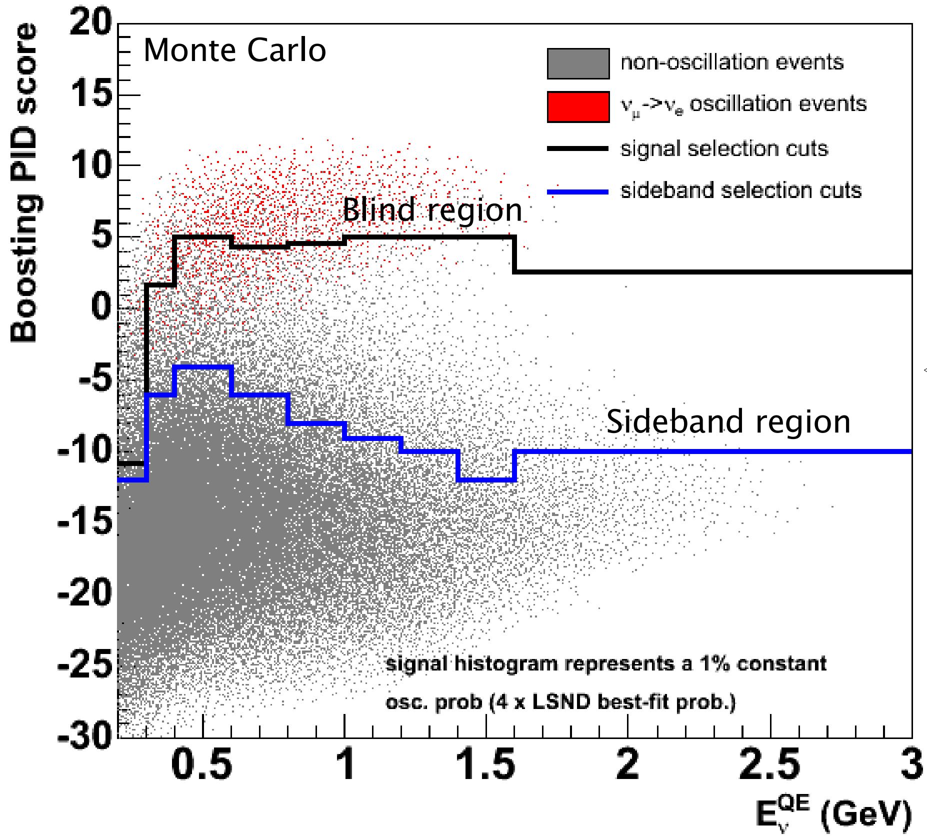
- use ***"side-bands"*** to verify the simulation

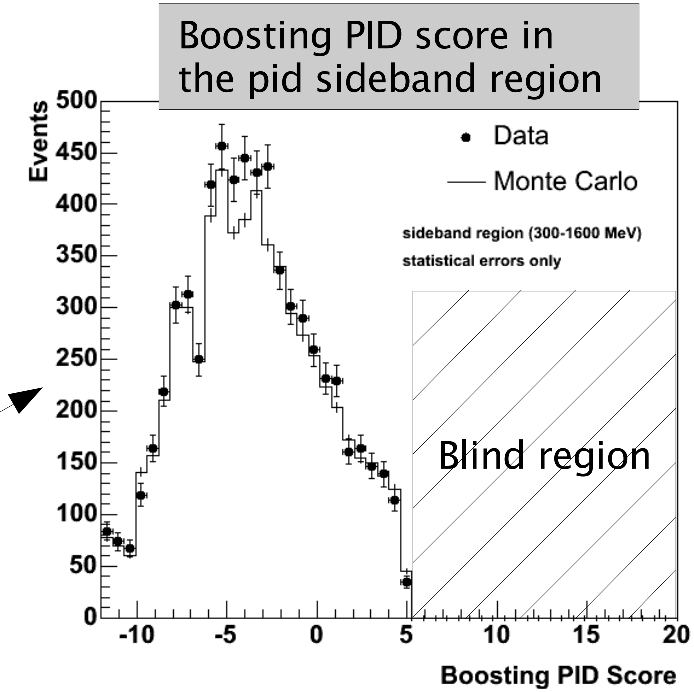


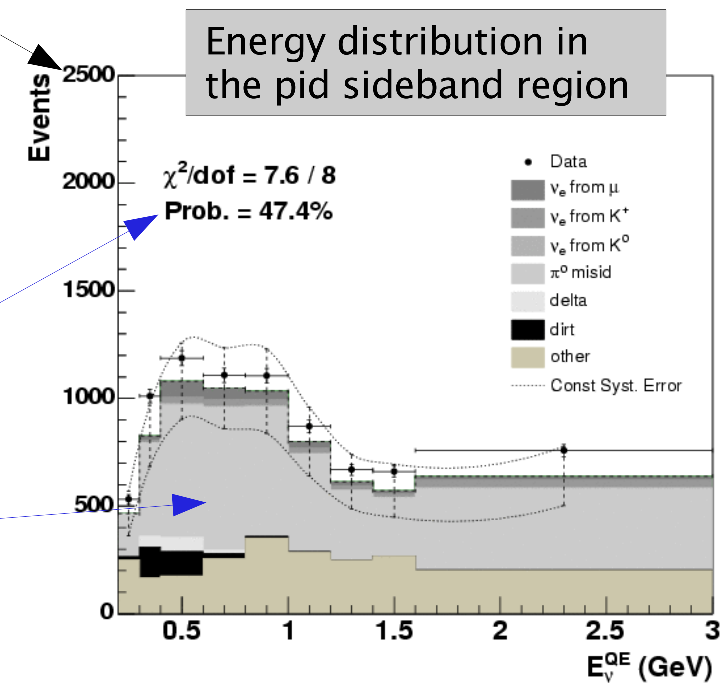
Osc Analysis

Verifying Sidebands (Boosting PID)

- just as with Likelihood variables use ***"side-bands"*** to verify the simulation







- good agreement within systematic errors
- sideband dominated by π^0 events

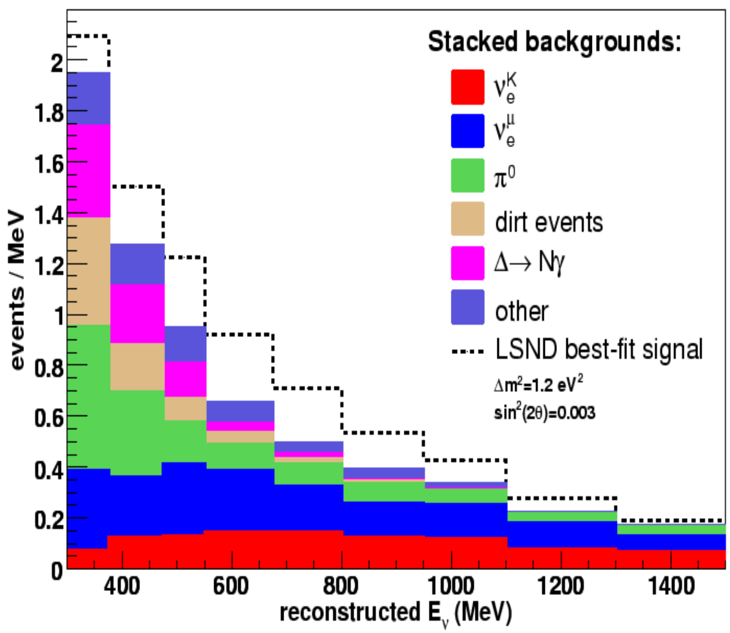
Osc Analysis

Background Predictions in Signal Region

TBL

475 MeV – 1250 MeV	
ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
	358
LSND $\nu_\mu \rightarrow \nu_e$	126

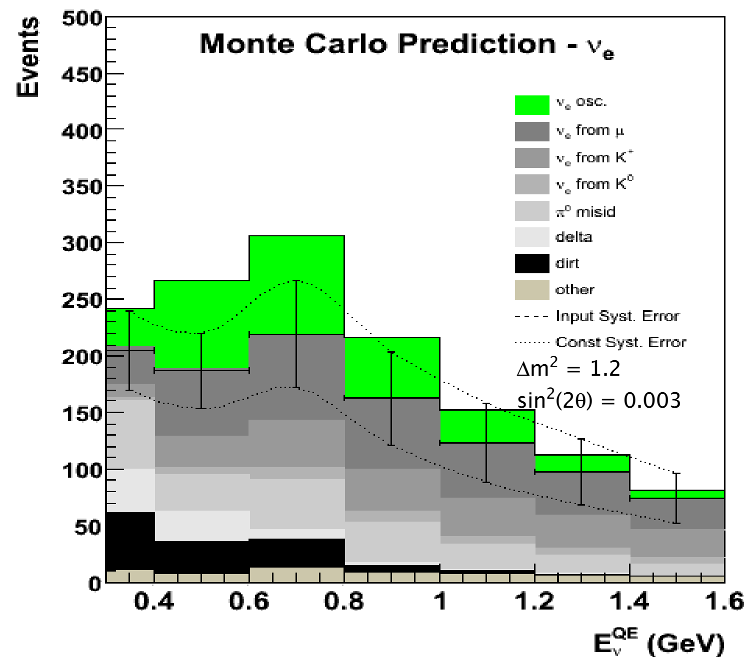
$$\frac{S}{\sqrt{B}} = 6.7$$



BDT

300 MeV – 1600 MeV	
ν_e^K	253
ν_e^μ	343
π^0	224
dirt	117
$\Delta \rightarrow N\gamma$	78
other	54
	1069
LSND $\nu_\mu \rightarrow \nu_e$	273

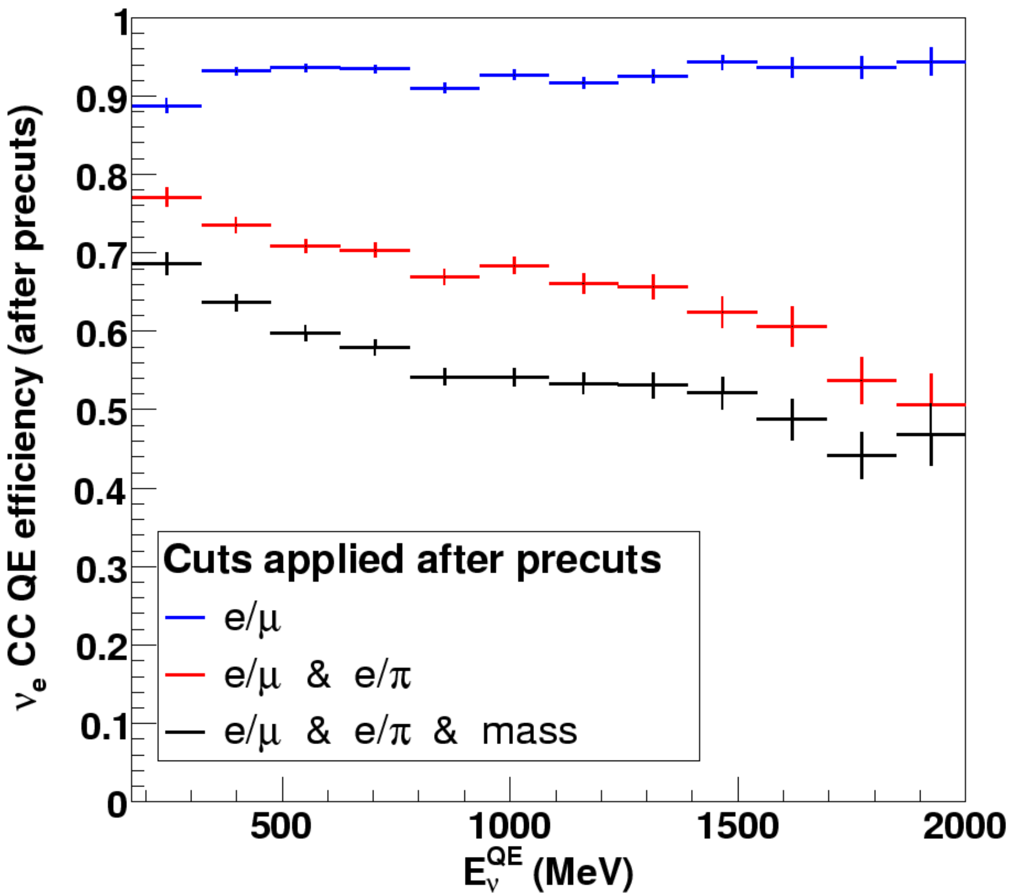
$$\frac{S}{\sqrt{B}} = 8.3$$



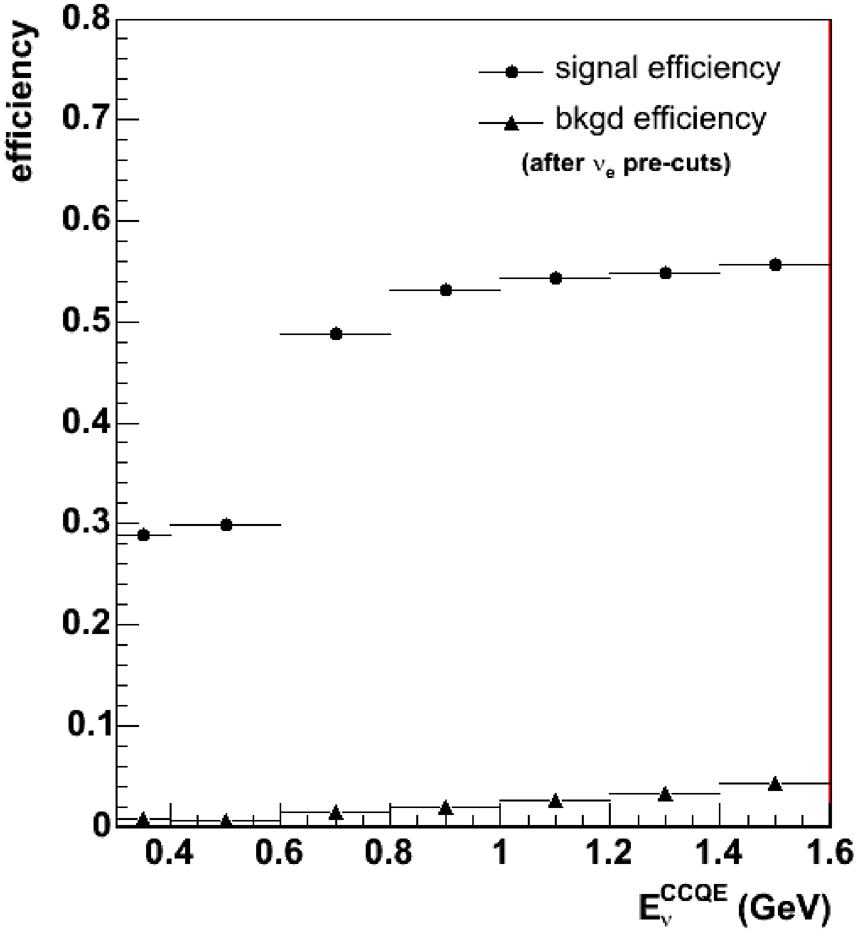
Osc Analysis

Signal Efficiency

TBL



BDT



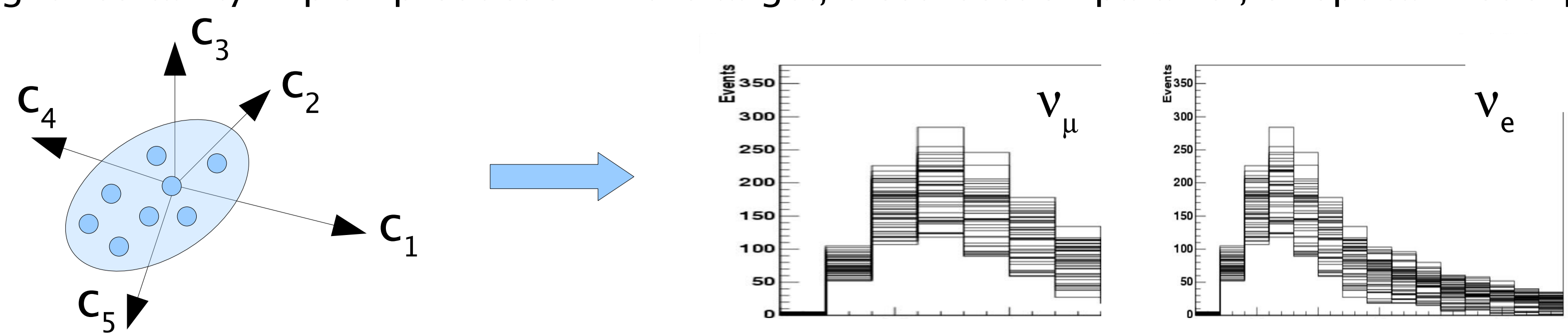
Osc Analysis

Constructing the Error Matrix

- Total error matrix is sum of ***9 systematic error matrices*** and ***statistical errors***

$$E_{ij}^{\text{total}} = E_{ij}^{\pi^+} + E_{ij}^{K^+} + E_{ij}^{K^0} + E_{ij}^{\text{beam}} + E_{ij}^{\text{xsec}} + E_{ij}^{\pi^0\text{-rate}} + E_{ij}^{\text{dirt-rate}} + E_{ij}^{\text{daq model}} + E_{ij}^{\text{optical model}}$$

- Need to map uncertainty in ***systematic source parameters*** to uncertainty in neutrino energy distribution, E_ν^{CCQE}
  - e.g. uncertainty in pion production in the target, cross-section params., or optical model params.



- Individual error matrices constructed using ***multisim approach :***
  - A multisim is a random draw from an underlying parameter that is considered allowed, where allowed means the draw does not violate internal or external constraints
  - correlations among input parameters are considered - imagine Cherenkov and scintillation as independent sources of light, but the Michel energy must be conserved
  - flux and cross-sections are produced from re-weighting. Optical model multisims require generation of full hit-level Monte Carlo

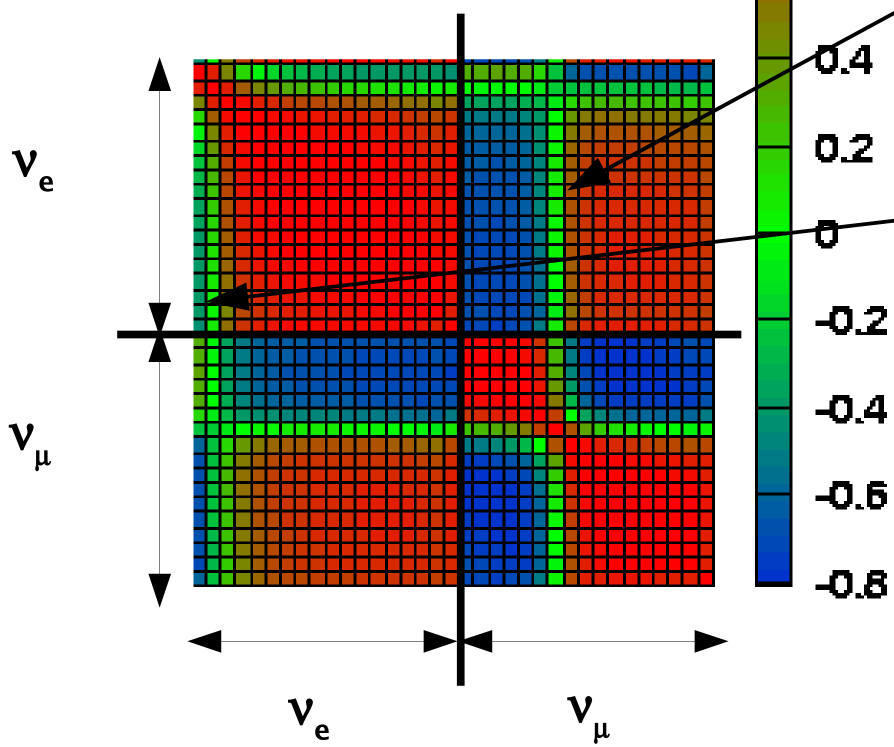
$$E_{ij}^{\alpha} = \frac{1}{M-1} \sum_{m=1}^{M} (N_i^m - N_i^{MC})(N_j^m - N_j^{MC})$$

Constructing the Error Matrix

- Total error matrix is sum of ***9 systematic error matrices*** and ***statistical errors***

$$E_{ij}^{\text{total}} = E_{ij}^{\pi^+} + E_{ij}^{K^+} + E_{ij}^{K^0} + E_{ij}^{\text{beam}} + E_{ij}^{\text{xsec}} + E_{ij}^{\pi^0\text{-rate}} + E_{ij}^{\text{dirt-rate}} + E_{ij}^{\text{daq model}} + E_{ij}^{\text{optical model}}$$

Ex: Optical Model correlations



- energy shift in ν_μ spectrum correlated with ν_e
- small correlations between LE and HE ν_e bins and signal region
- things like cross-section and flux can be fully correlated (mostly a pure normalization error)

Osc Analysis

The Fit for Oscillations

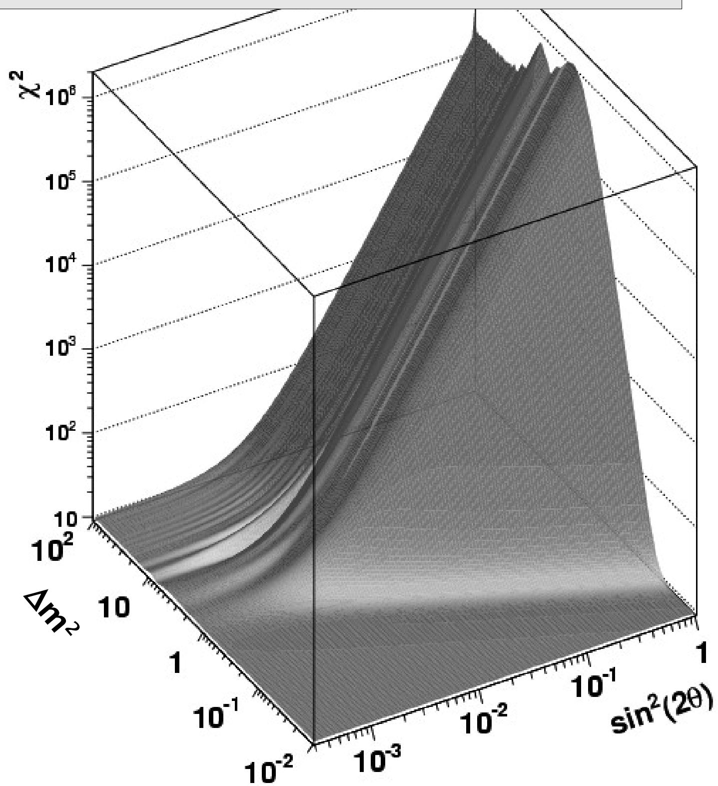
- In the ***combined fit used for the BDT selected events*** the χ^2 has contributions from the ν_μ and ν_e distributions.

$$\chi^2 = \left([N^{\nu_e}_{\mathrm{data}} - N^{\nu_e}_{\mathrm{MC}}]_i \;\; [N^{\nu_\mu}_{\mathrm{data}} - N^{\nu_\mu}_{\mathrm{MC}}]_i \right) \begin{pmatrix} E_{ij}^{\nu_e,\nu_e} & E_{ij}^{\nu_e,\nu_\mu} \\ E_{ij}^{\nu_\mu,\nu_e} & E_{ij}^{\nu_\mu,\nu_\mu} \end{pmatrix} \begin{pmatrix} [N^{\nu_e}_{\mathrm{data}} - N^{\nu_e}_{\mathrm{MC}}]_j \\ [N^{\nu_\mu}_{\mathrm{data}} - N^{\nu_\mu}_{\mathrm{MC}}]_j \end{pmatrix}$$

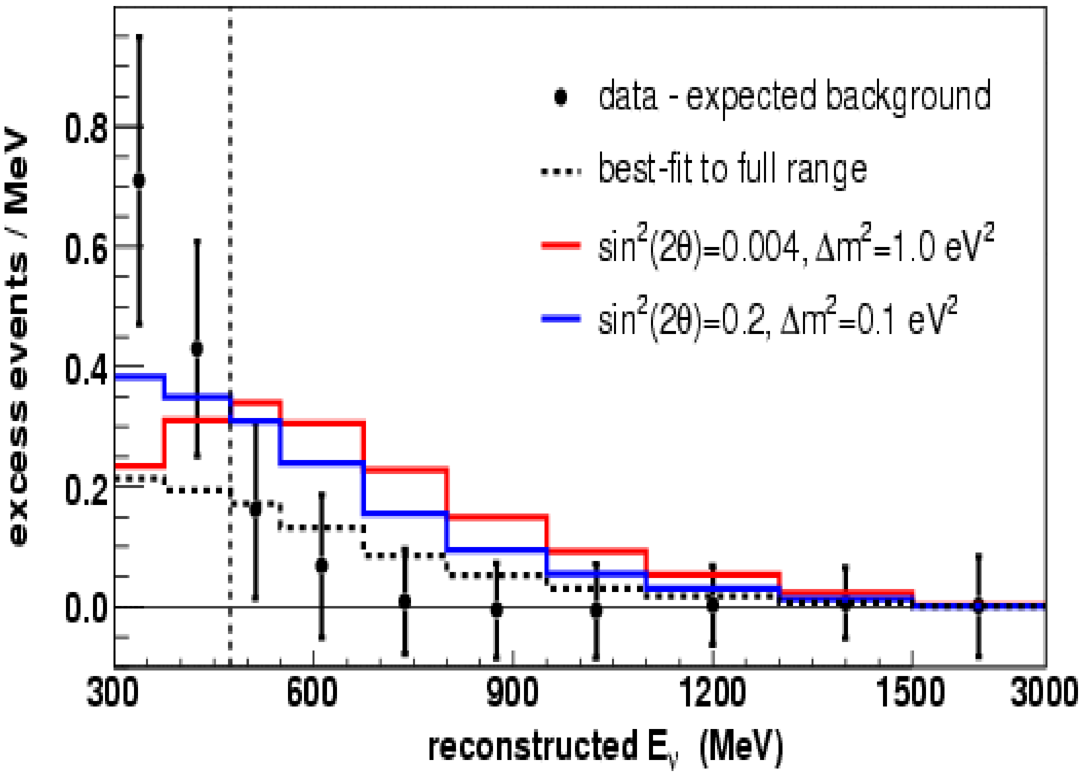
- the ν_e prediction depends on the oscillation signal being tested. . .

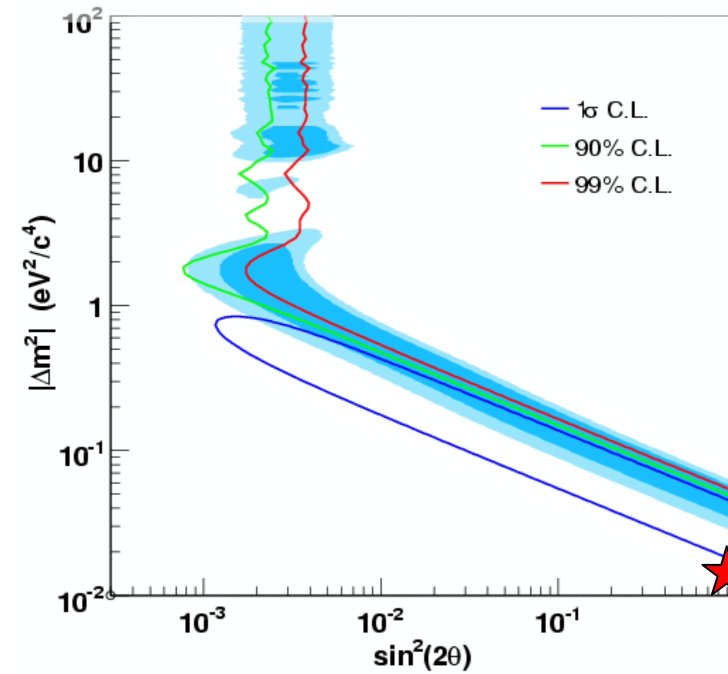
$$N^{\nu_e}_{\mathrm{MC},i} \equiv N^{\nu_e}_{\mathrm{MC},i}(\Delta m^2, \sin^2(2\theta))$$

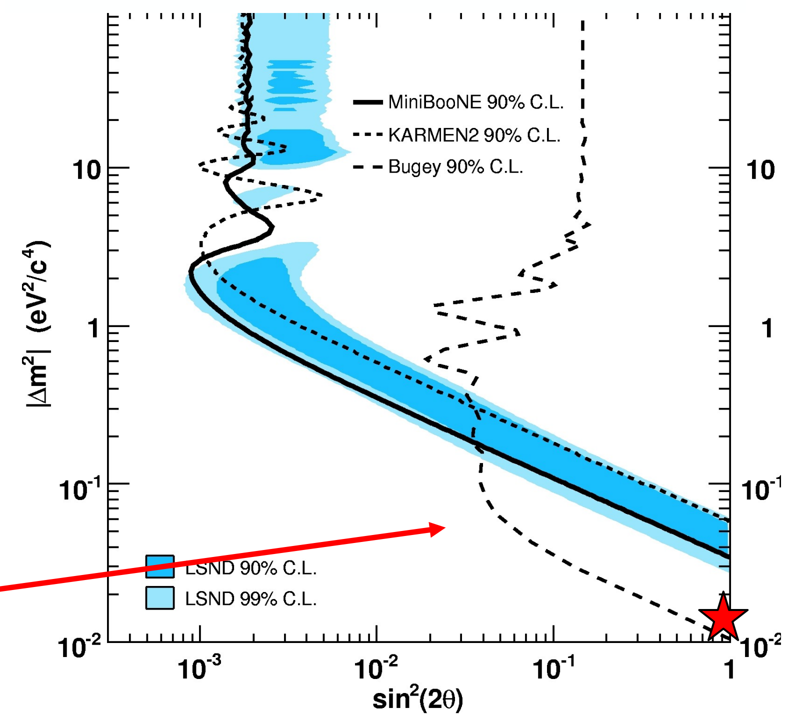
. . . and a χ^2 surface can be mapped



2-ν Oscillation Fits for 300 – 3000 MeV







Best Fit (dashed):
$(\sin^2 2\theta, \Delta m^2) = (1.0, 0.03\ eV^2)$
χ^2 Probability: 18%

This best fit is not probable but also ruled out by the Bugey and Chooz reactor experiment.