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

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

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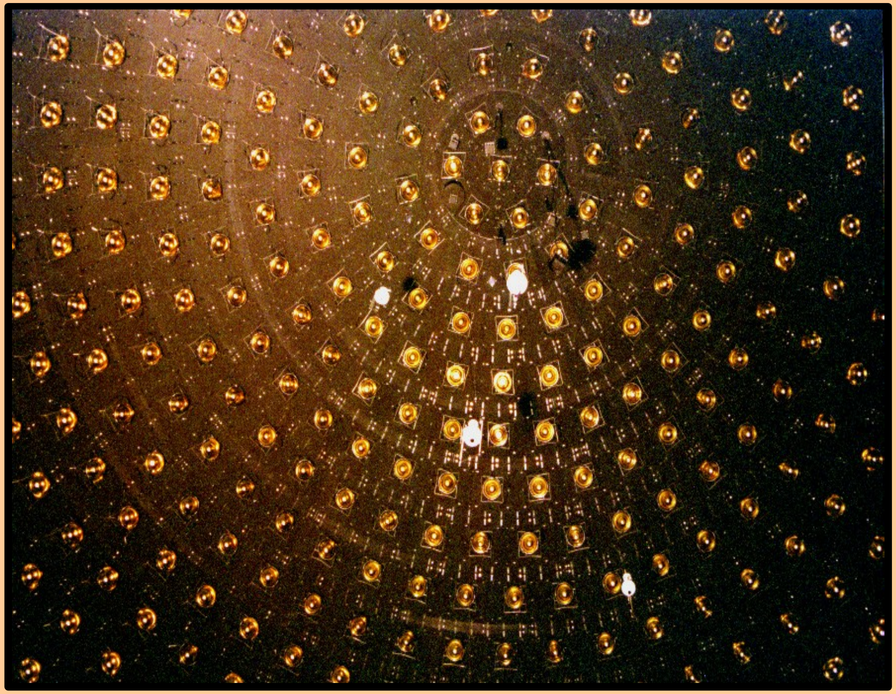
- Introduction and motivation for this oscillation search
- Overview of the MiniBooNE design and analysis strategy
- The oscillation analysis
- The oscillation results
- Future outlook
- Summary



The MiniBooNE Collaboration

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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

Introduction

Neutrino Oscillations

- ν oscillations first postulated by Pontecorvo in ***1957***, based on analogy to kaons.
- Non-zero mass means mass eigenstates ≠ flavor eigenstates:

flavor states participating in standard weak interactions with charged lepton partners

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mixing matrix describing mass state content of flavor states

mass states

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mixing matrix describing mass state content of flavor states

mass states

- Different ν masses allow for changes in lepton flavor composition as ν propagates:

$$\boxed{P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | \nu_\alpha(L)\rangle\right|^2} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[1.27\Delta m^2_{ij} L/E]$$
$$+2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[2.54\Delta m^2_{ij} L/E]$$

- $\mathbf{U_{xy}}$: elements of mixing matrix
- $\mathbf{\Delta m_{ij}^2 \equiv m_i^2 - m_j^2}$: mass squared splitting between states
- $\mathbf{L}$: the travel path-length of the neutrino
- $\mathbf{E}$: the energy of the neutrino

Neutrino Oscillations

I n t r o d u c t i o n

- ν oscillations first postulated by Pontecorvo in ***1957***, based on analogy to kaons.
- Non-zero mass means mass eigenstates ≠ flavor eigenstates:

Simplified case of direct 2 neutrino oscillations

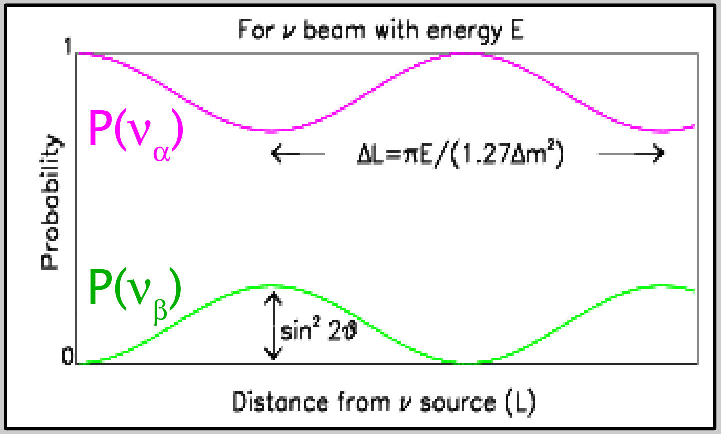
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos(\theta_{ij}) & \sin(\theta_{ij}) \\ -\sin(\theta_{ij}) & \cos(\theta_{ij}) \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

determines shape of oscillation probability as function of E (or L)

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta_{ij}) \sin^2\left(1.27 \Delta m_{ij}^2 \frac{L}{E}\right)$$

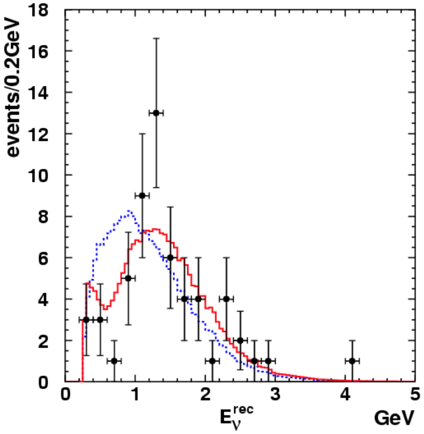
determines amplitude for oscillation ~ probability



Neutrino Oscillations

- ***First*** experimental evidence was seen in 1968 by R. Davis in the detection of solar neutrinos
  - observed ~1/3 as many ν_e from the sun as expected
  - disappearance $\nu_e \rightarrow \nu_x$
  - $\Delta m^2 \sim 7\text{x}10^{-5}$ eV^2
  - later confirmed by SNO (solar), Super-K (solar) and KamLAND (reactor)

- Then a ***different*** mixing was seen in neutrinos from the atmosphere
  - observed ~1/2 as many upward going ν_μ as downward going
  - disappearance $\nu_\mu \rightarrow \nu_x$
  - $\Delta m^2 \sim 2\text{x}10^{-3}$ eV^2
  - later confirmed by MINOS (accelerator) and K2K (accelerator)



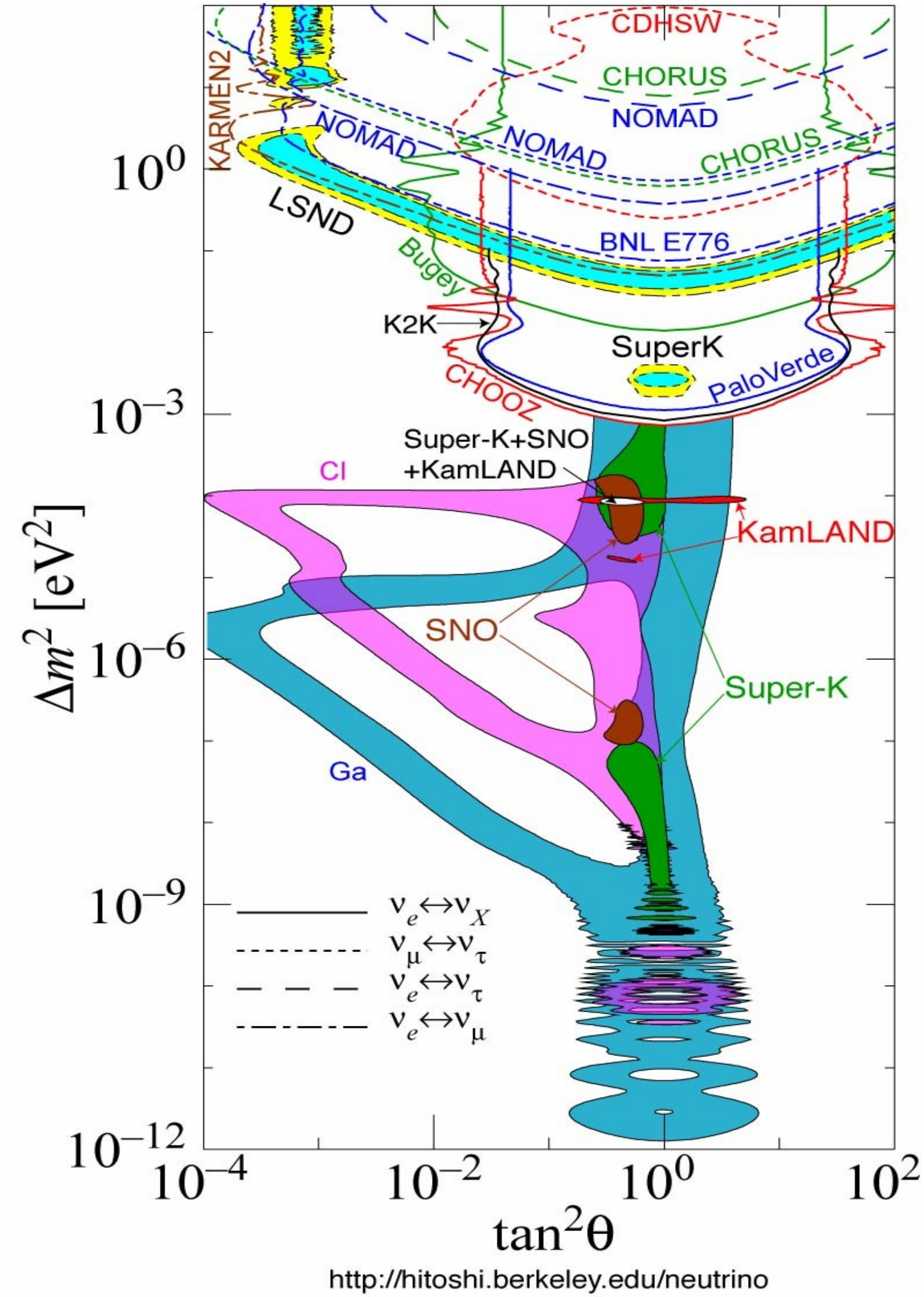
- A ***third*** mixing was seen by the LSND experiment at Los Alamos
  - observed a small excess off $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam
  - appearance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - $\Delta m^2 \sim 10^0$ eV^2
  - later experiments reduced allowed regions, but never confirmed

Only experimental evidence for physics beyond the Standard Model !!!

Neutrino Oscillations

Introduction

- Many experiments
- Resulting in an extremely crowded neutrino oscillation landscape!!
- This wild compilation of allowed regions and limits can, fortunately, be summed up pretty concisely by the observation of ***three unique Δm^2 regions:***



Introduction

Neutrino Oscillations

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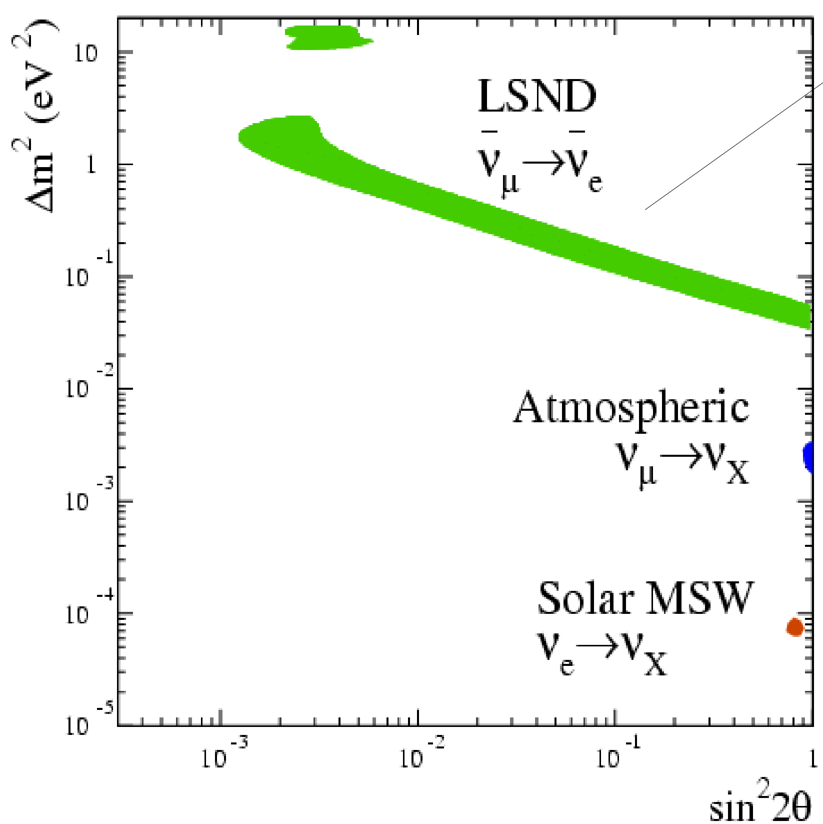
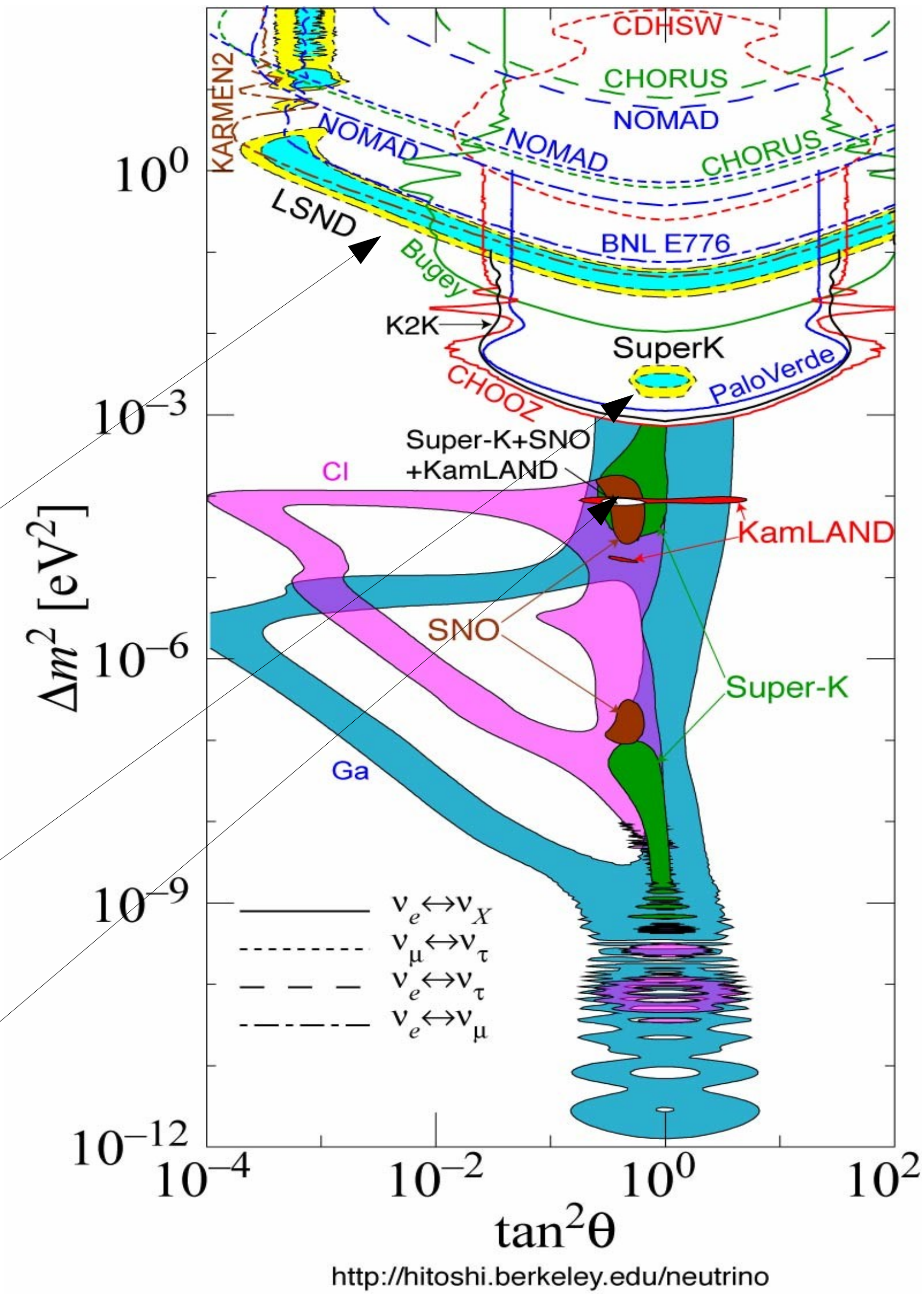
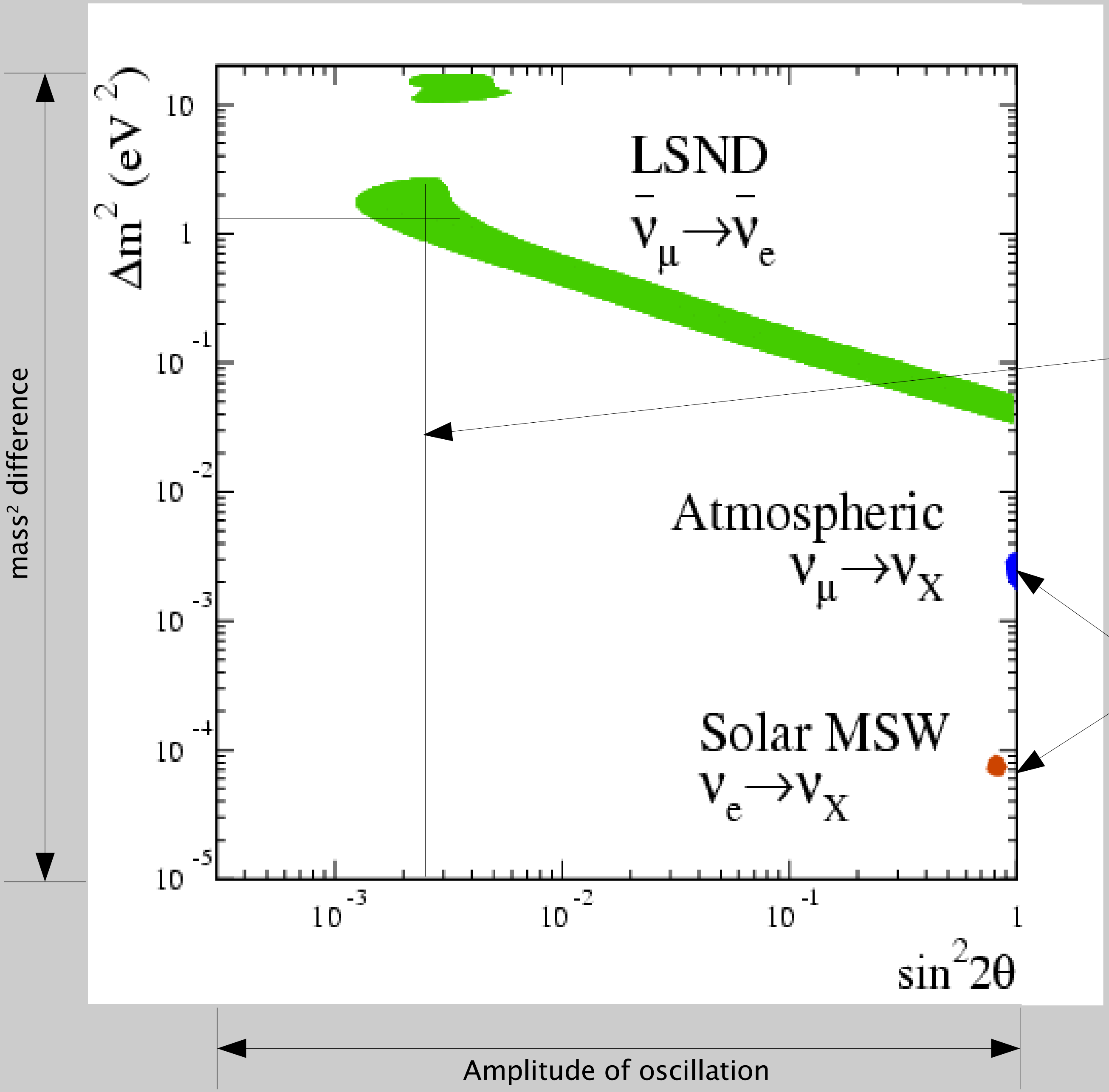




Neutrino Oscillations

Introduction



Δm^2_{LSND}~0.1–1 eV^2

best fit mixing
is tiny (~0.26%)

Δm^2_{atm}~2.4x10^{-3} eV^2

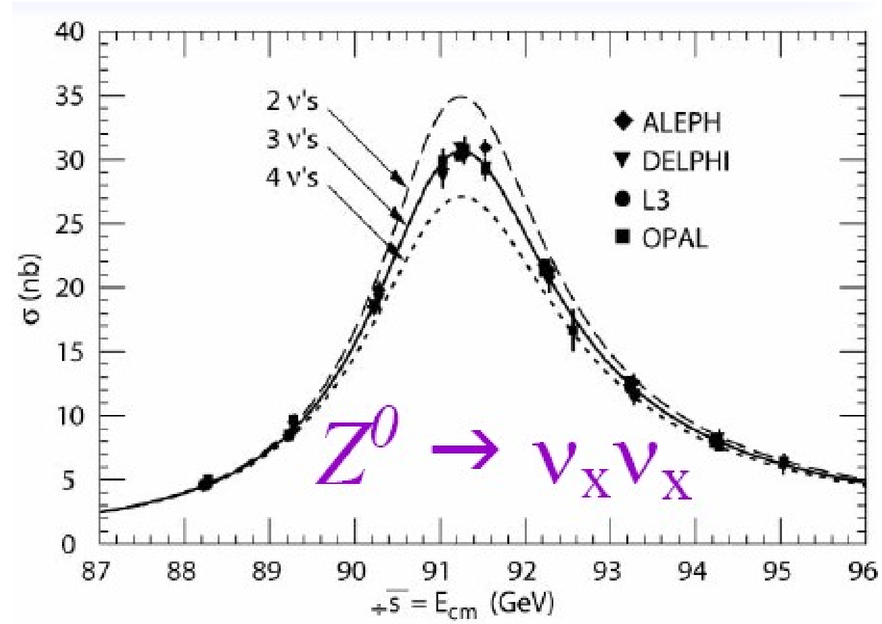
~maximal mixing (>80%)

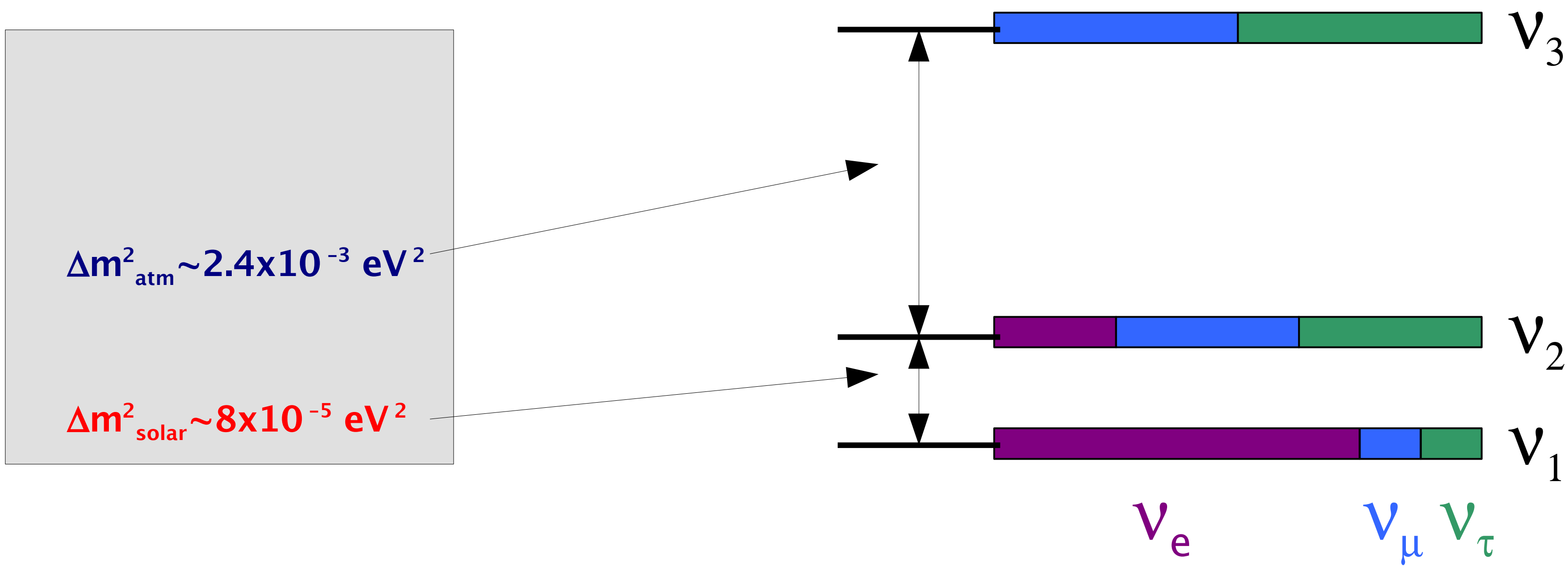
Δm^2_{solar}~8x10^{-5} eV^2

Neutrino Oscillations

- Width of the Z implies 2.994 +– 0.012 light neutrino flavors
- And two independent mass splittings fit very nicely into this picture

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





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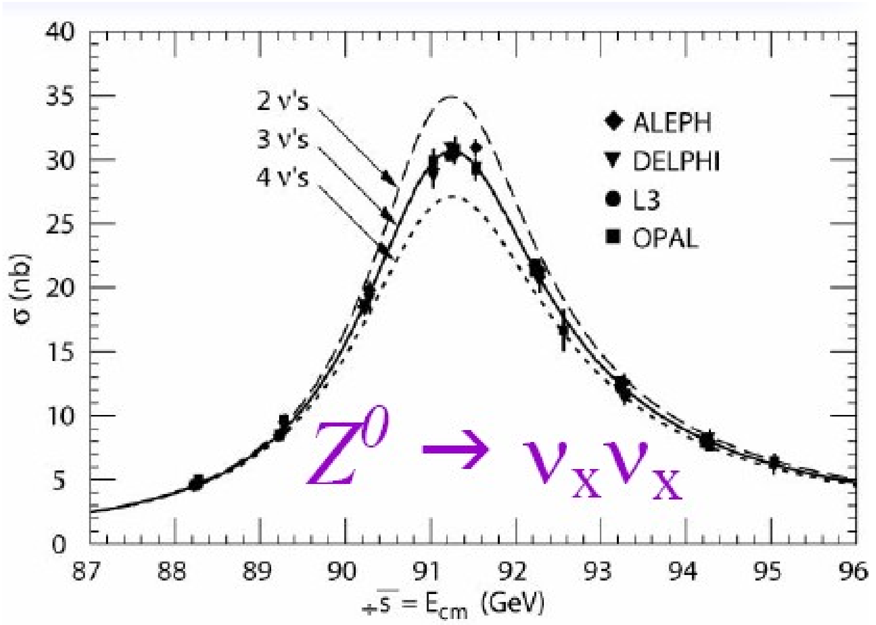


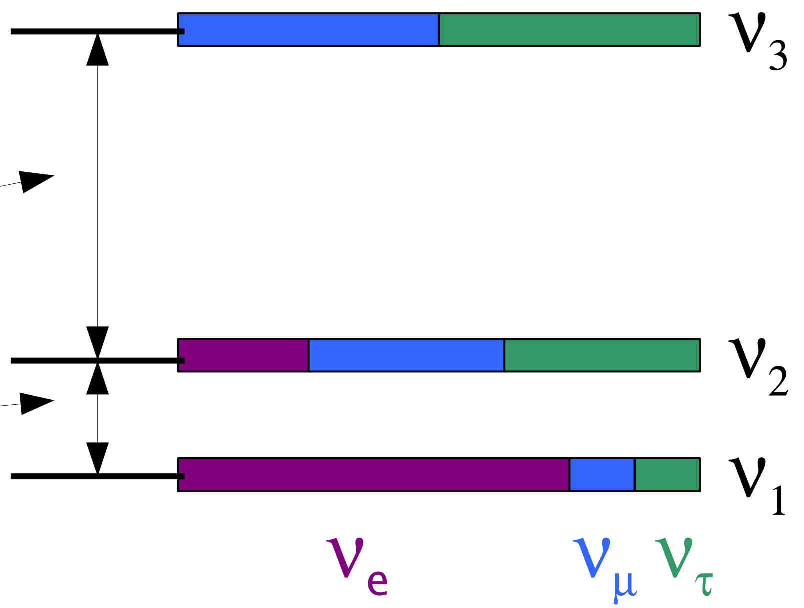
$\Delta m^2_{LSND} \sim 0.1-1\ eV^2$

$\neq$

$\Delta m^2_{atm} \sim 2.4x10^{-3}\ eV^2$

$+$

$\Delta m^2_{solar} \sim 8x10^{-5}\ eV^2$



- But what to do with a third, independent neutrino mass splitting?

Neutrino Oscillations

- 'Simplest' explanation is a 4th (or more) neutrino that is mostly "sterile" (non-interacting)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s_1} \\ \cdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \cdots \end{pmatrix}$$

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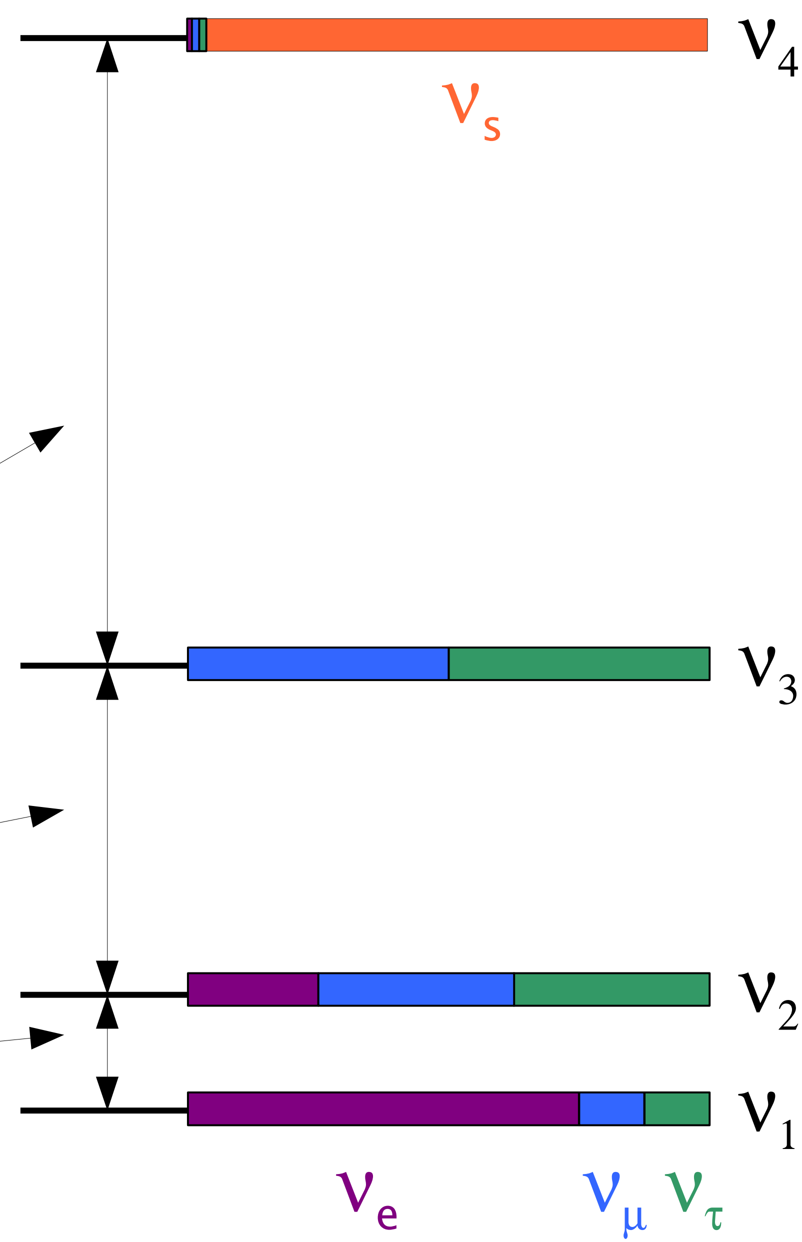
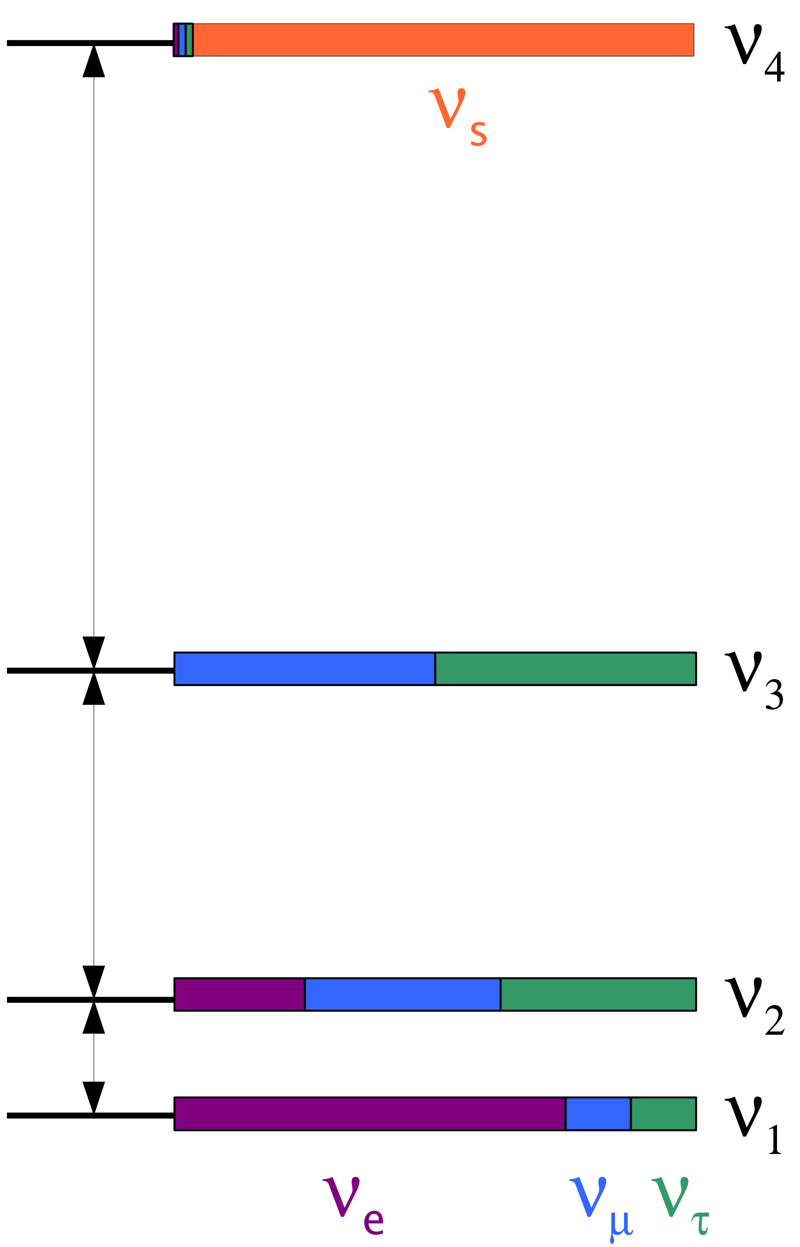


I n t r o d u c t i o n

Neutrino Oscillations

- 'Simplest' explanation is a 4th (or more) neutrino that is mostly “sterile” (non–interacting)
- 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. . .***

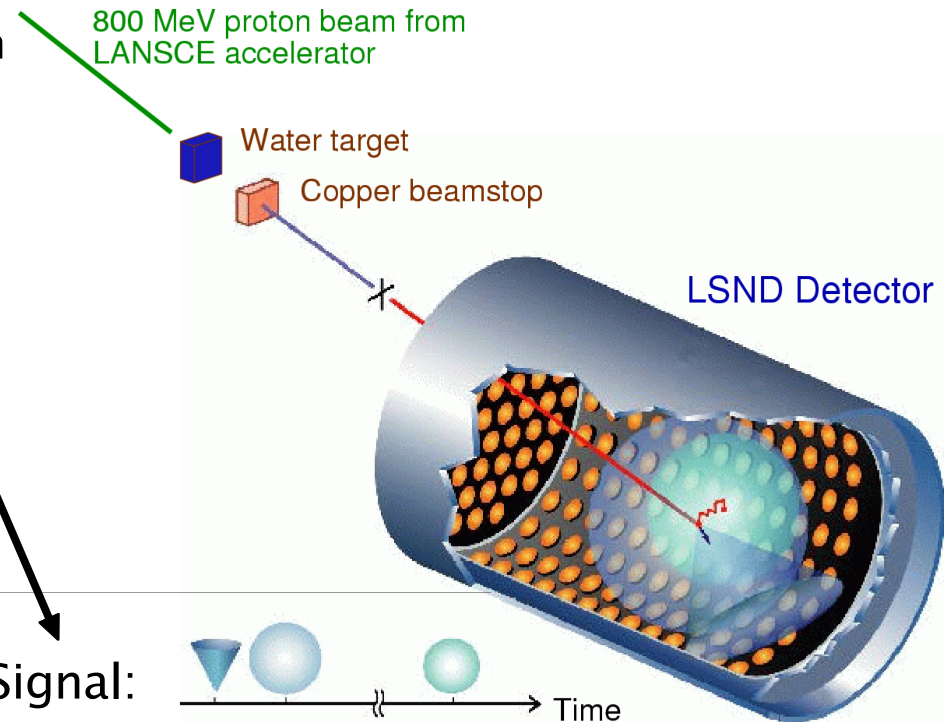


The LSND Signal as Oscillations

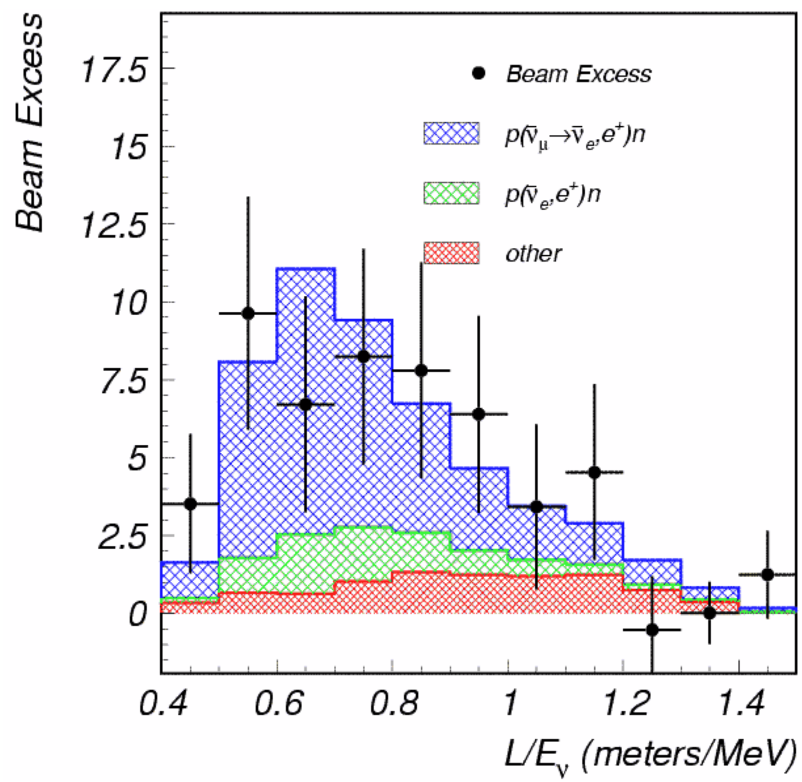
- LSND looked for an excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam

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:

Time

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

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

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

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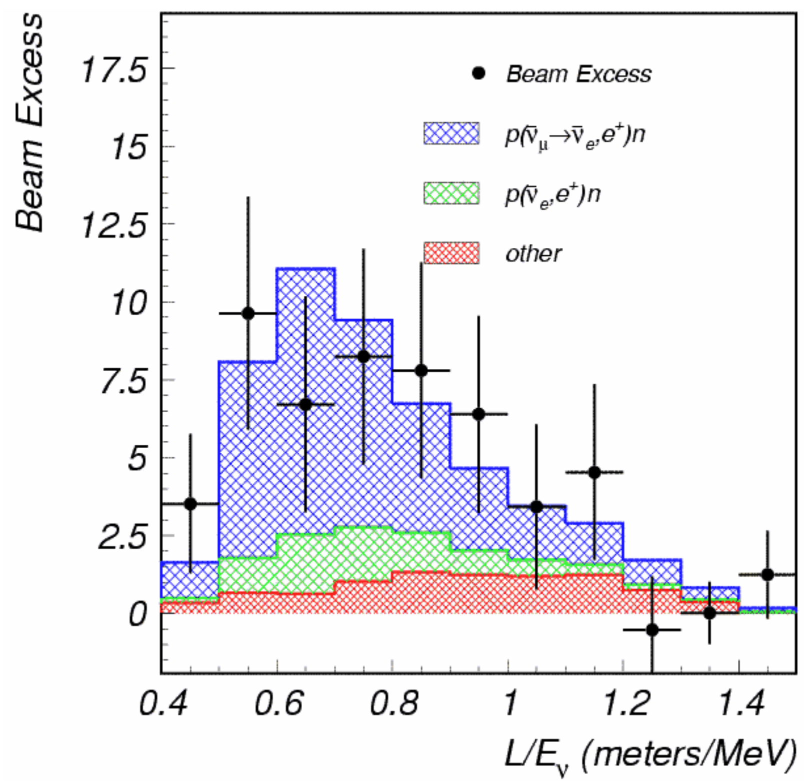
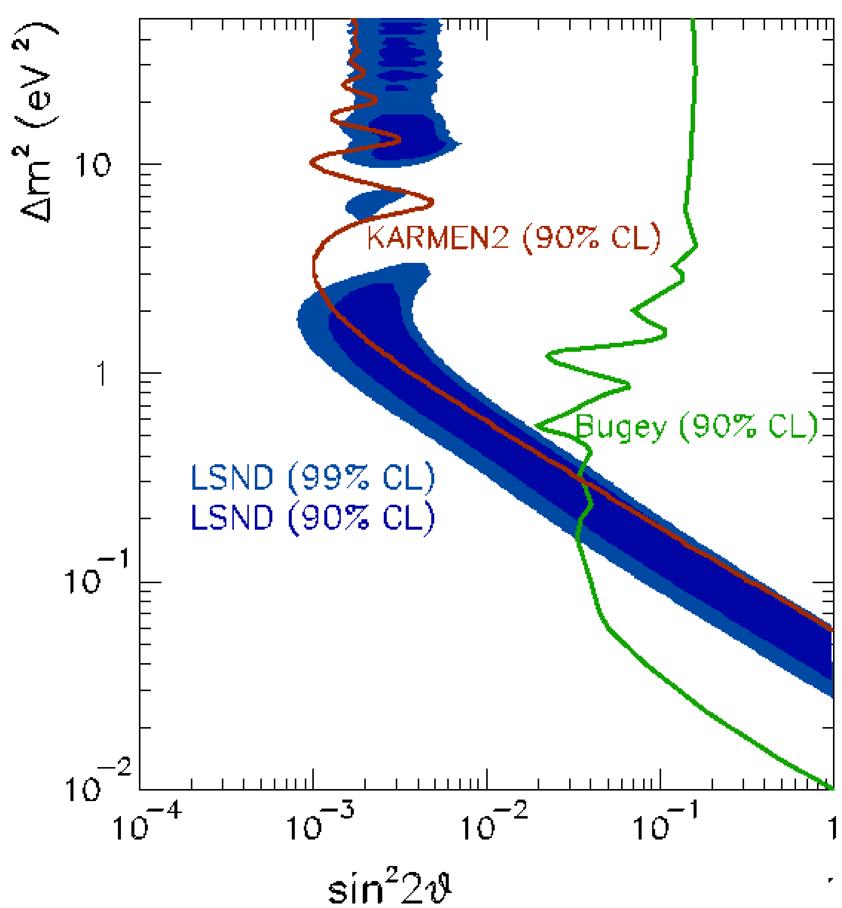




- If interpreted as 2 flavor oscillations, implies an oscillation probability of

(0.264 +- 0.067 +- 0.045)%

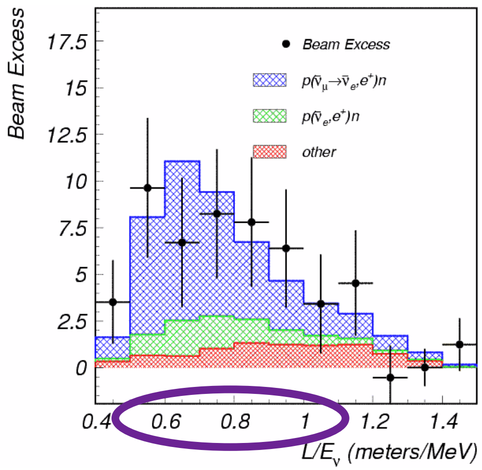
Overview of the MiniBooNE design and analysis strategy

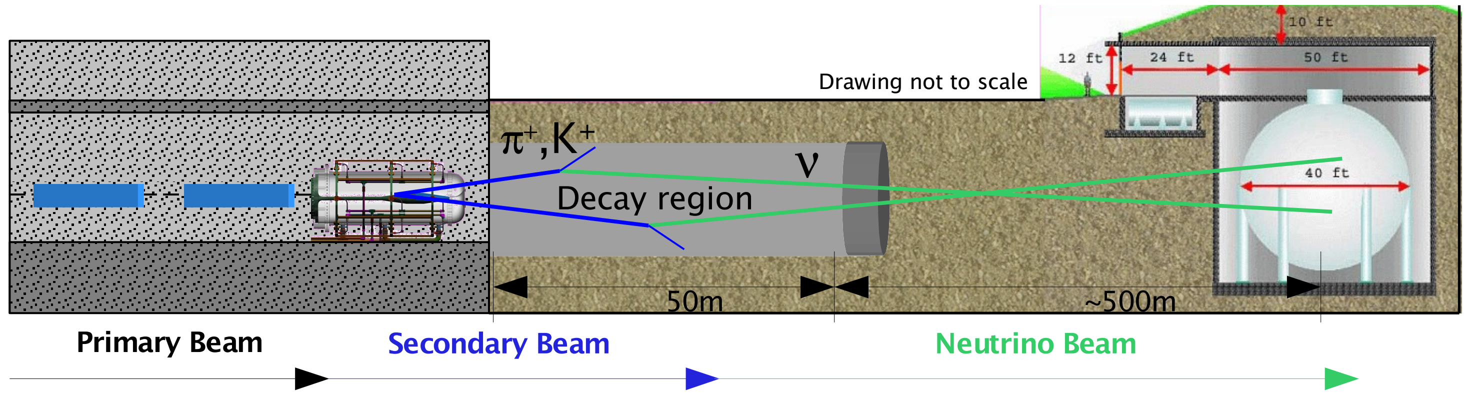
Exp Overview

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

$$\frac{<L>}{<E>} \approx 0.5-1.0$$

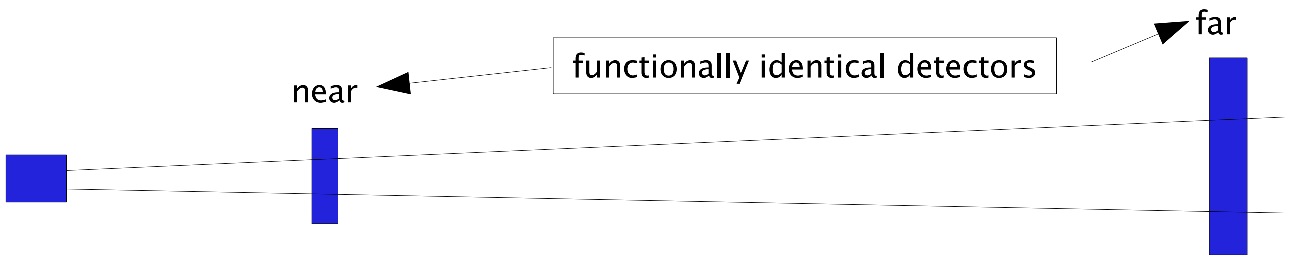
- 8 GeV protons from Fermilab Booster focused on to a 1.7λ beryllium target
  - 174 kA focusing horn
  - 5.58E20 p.o.t. in neutrino mode
  - changed to anti-neutrino mode in Jan, 2006
- π and K decay to produce neutrinos with mean energy ~0.7 GeV
- 800T pure mineral oil detector
  - 1280 8" photomultiplier 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

MiniBooNE Analysis

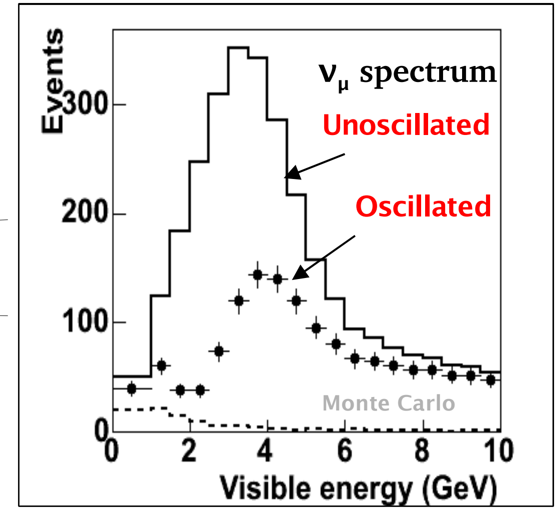
Exp Overview

long baseline, two detector disappearance experiment



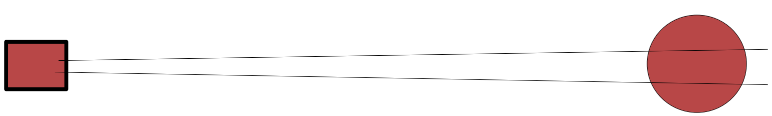
here you see the
unoscillated ν_μ flux

here you see the
oscillated ν_μ flux



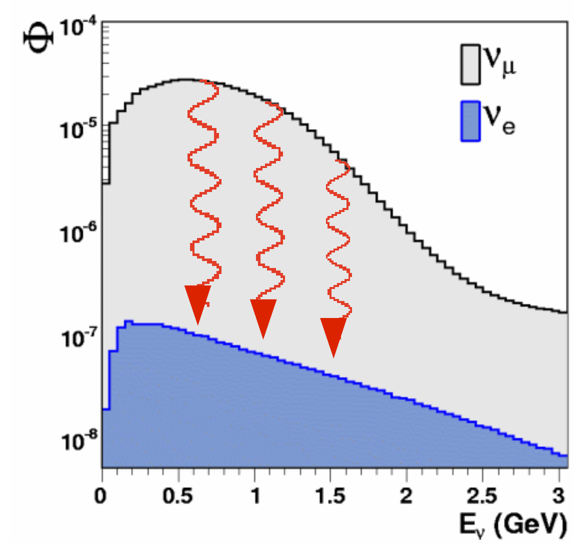
plot shamelessly stolen from MINOS collaboration

short baseline, one detector appearance experiment



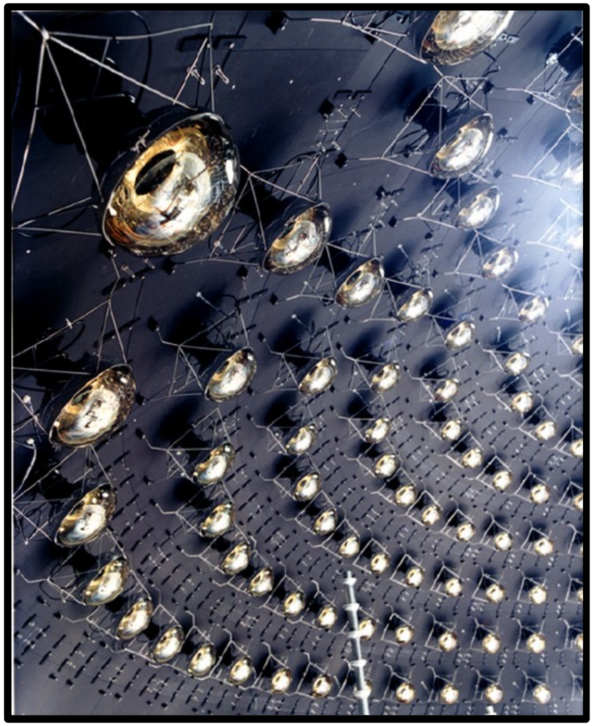
here you also see the
oscillated ν_μ flux
appearing as ν_e

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



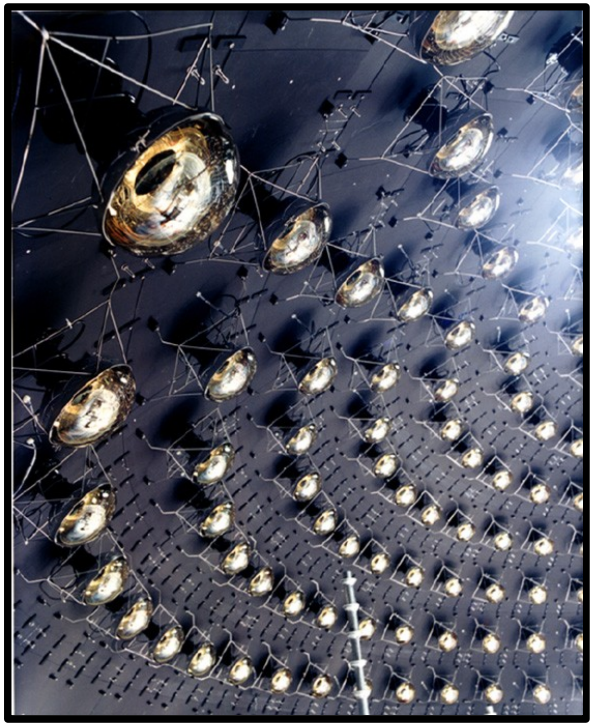
MiniBooNE will look for an excess of ν_e events (~0.25% of ν_μ) above the predicted ν_e background (~0.6% of ν_μ) and ν_μ mis-identifications

MiniBooNE Tank Events



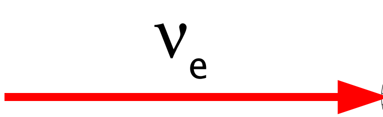
- After cuts, MiniBooNE must be able to find O(100s) ν_e CCQE interactions in a sea of O(100Ks) ν_μ interactions
  - the three most important types of particles in the tank are ***electrons, muons*** and π^0

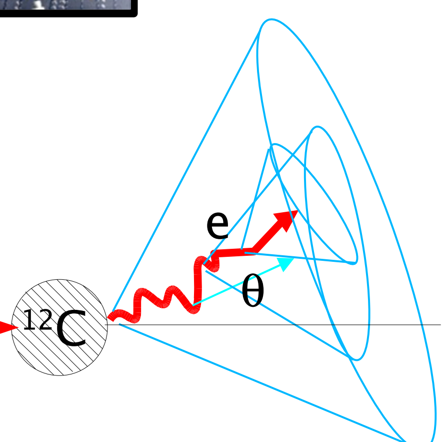
MiniBooNE Tank Events

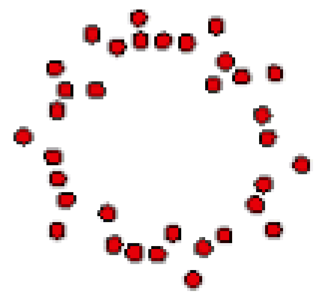


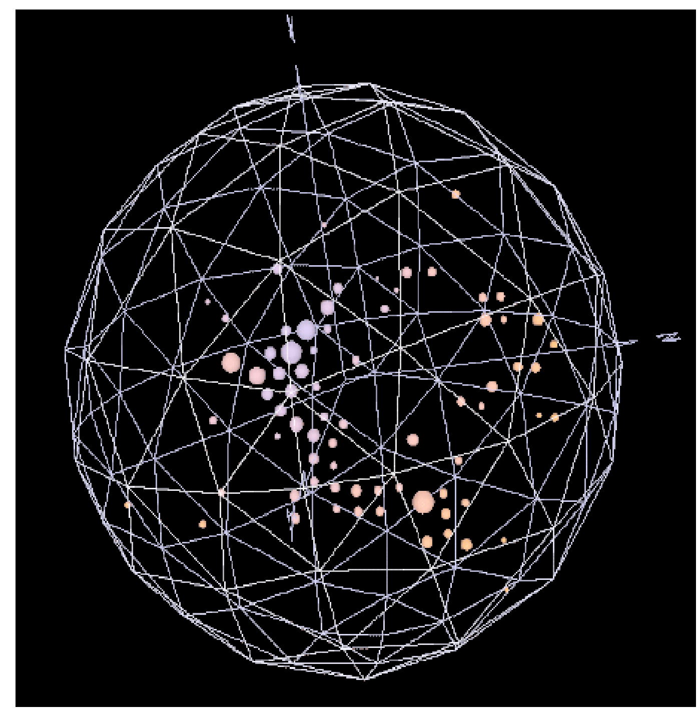
- After cuts, MiniBooNE must be able to find O(100s) ν_e CCQE interactions in a sea of O(100Ks) ν_μ interactions
  - ***electrons:***
    - electrons create **fuzzy rings** due to multiple scattering
    - several hundred CCQE events from **intrinsic ν_e** produced in the beamline from muon and kaon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

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





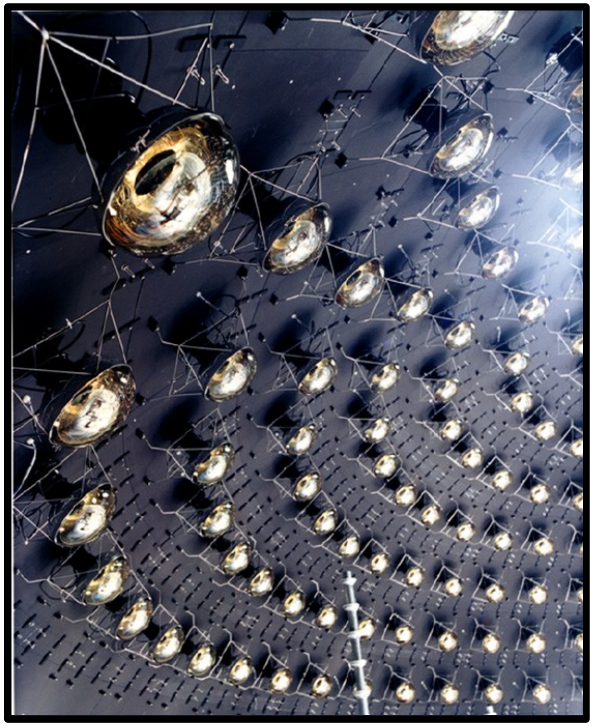




$$E_\nu^{QE} = \frac{1}{2}\frac{2ME_l - m_l^2}{M - E_l + P_l \cos\theta_e}$$

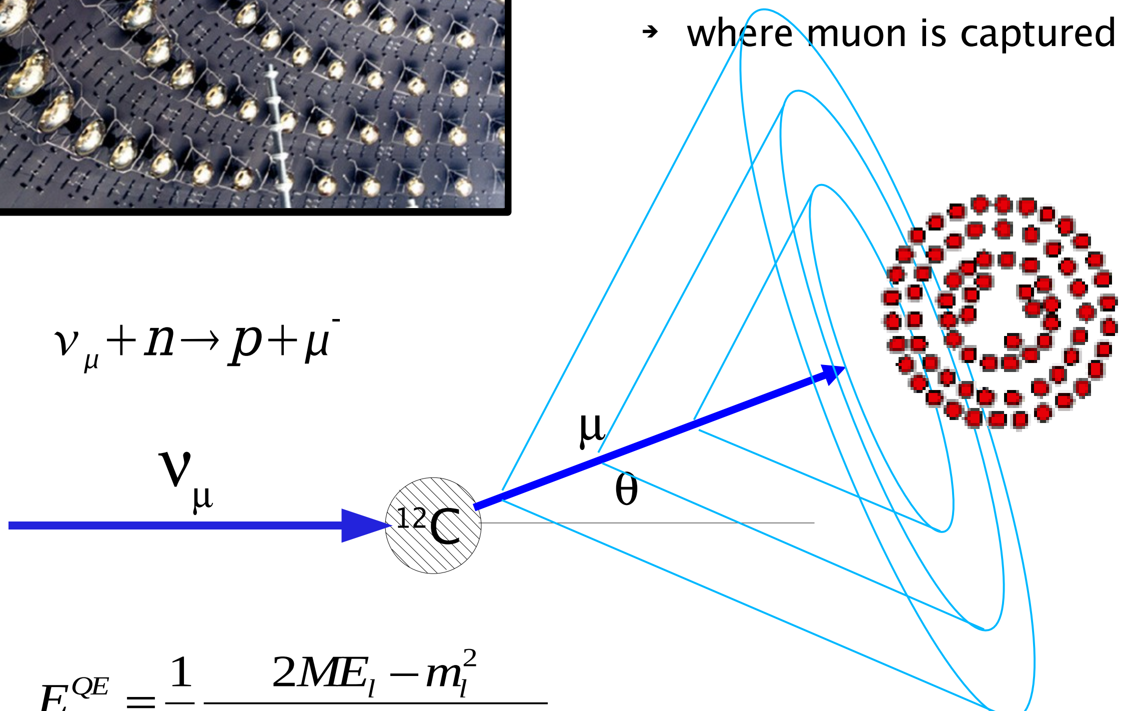
Exp Overview

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**

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



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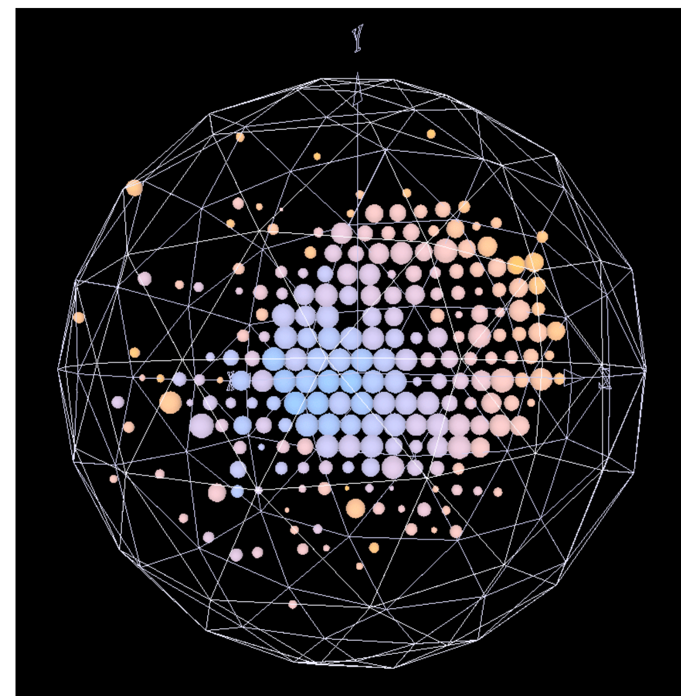
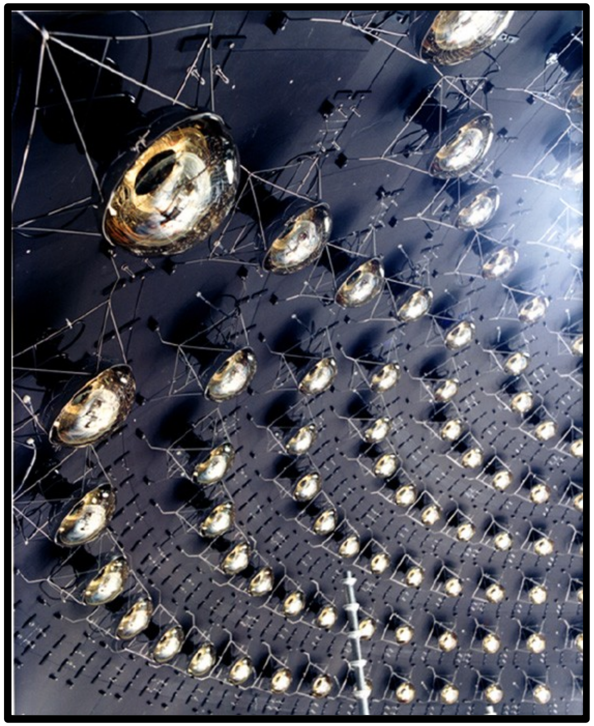


MiniBooNE Tank Events



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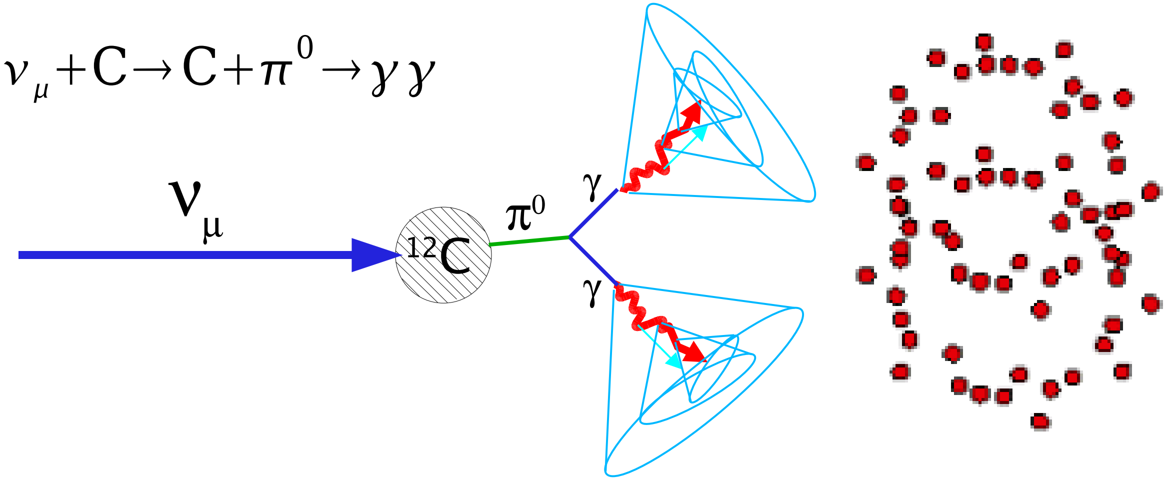
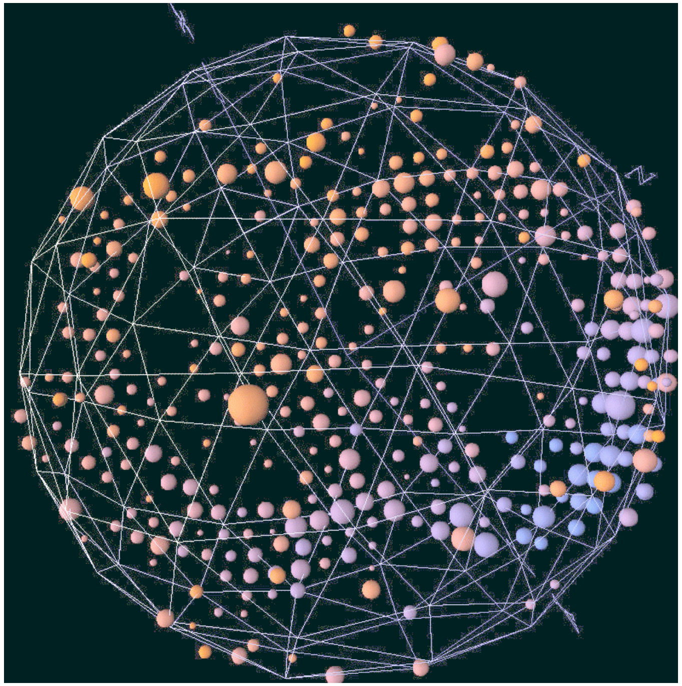
  - ***neutral pions:***
    - π^0s create **two fuzzy, electron-like rings**
    - most π^0 can be removed by **two ring fit**

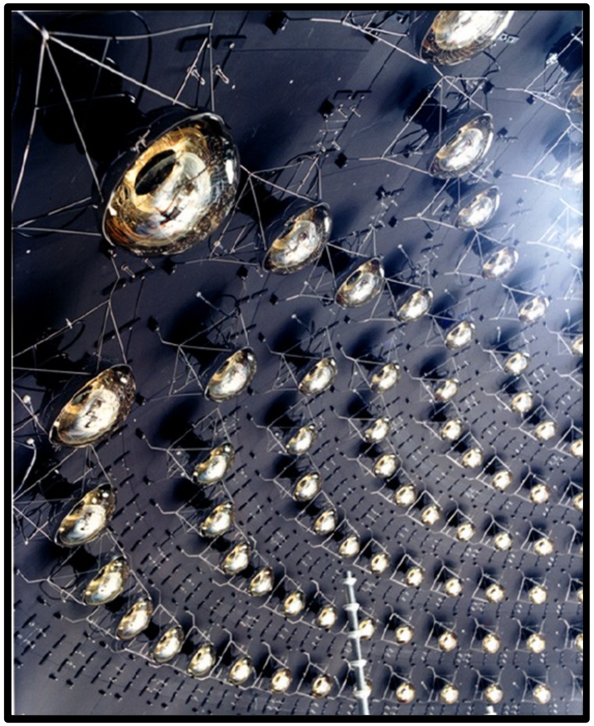
$$\nu_\mu + C \rightarrow C + \pi^0 \rightarrow \gamma\gamma$$





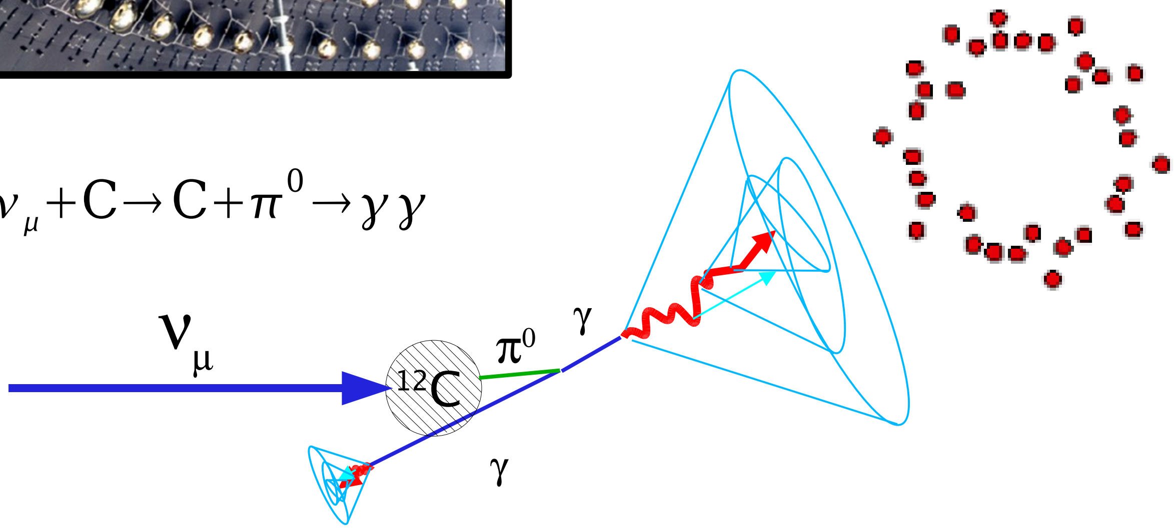
Exp Overview

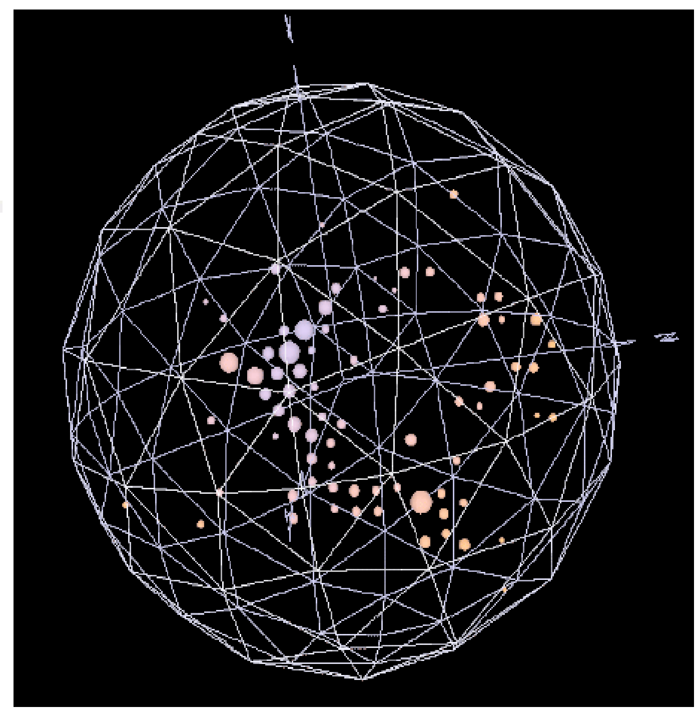
MiniBooNE Tank Events



- 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)

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

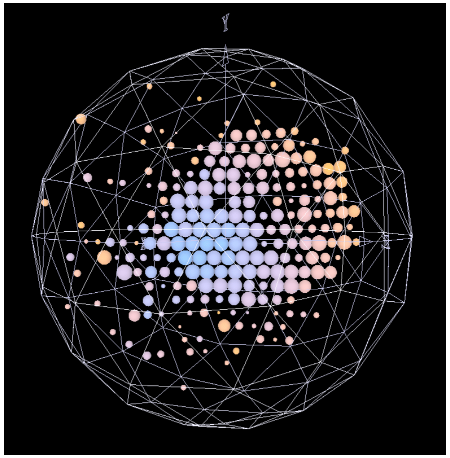


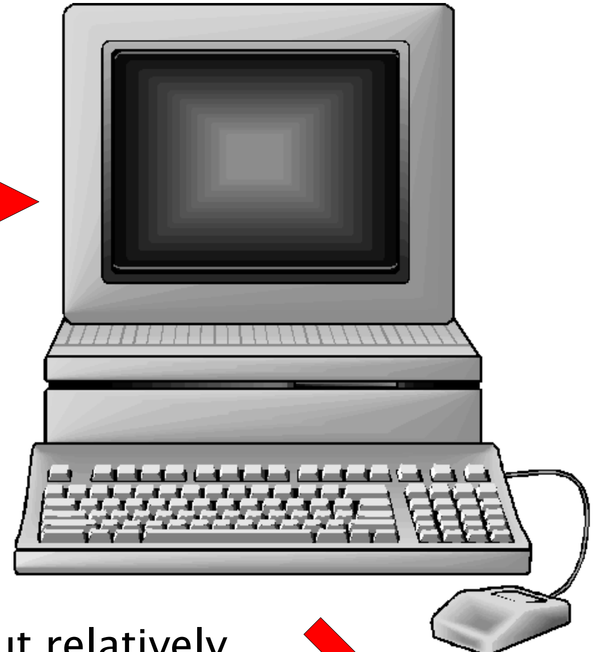


The Oscillation Analysis

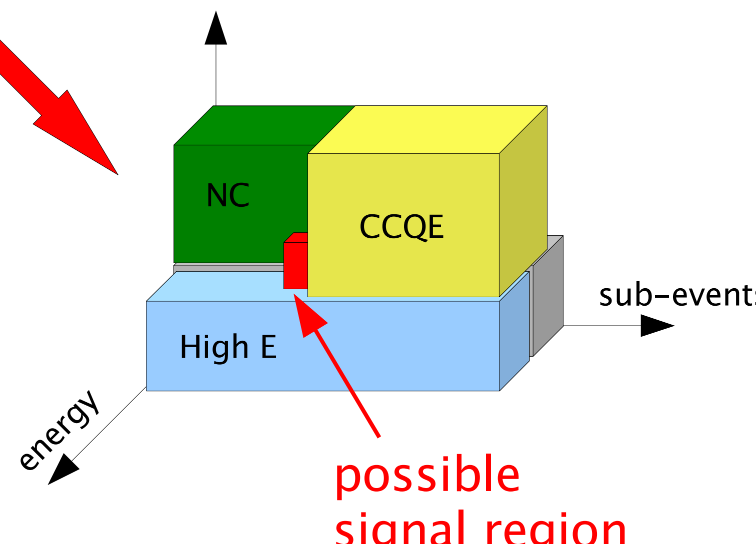
Osc Analysis

A Note on Blindness

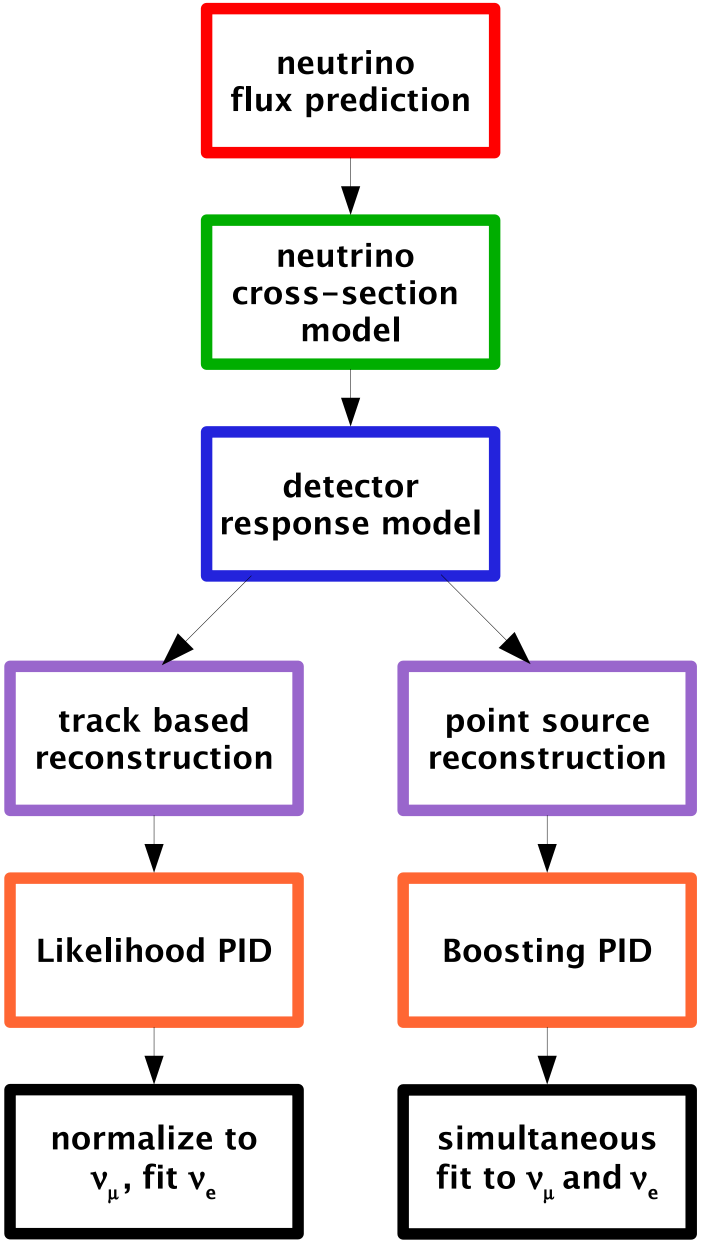




- The MiniBooNE signal is small but relatively easy to isolate
- As data is collected it is classified into 'boxes'
- For boxes to be opened to analysis they must be shown to have a signal < 1σ
- In the end, ***99% of the data were available prior to unblinding***...necessary to understand errors
- All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



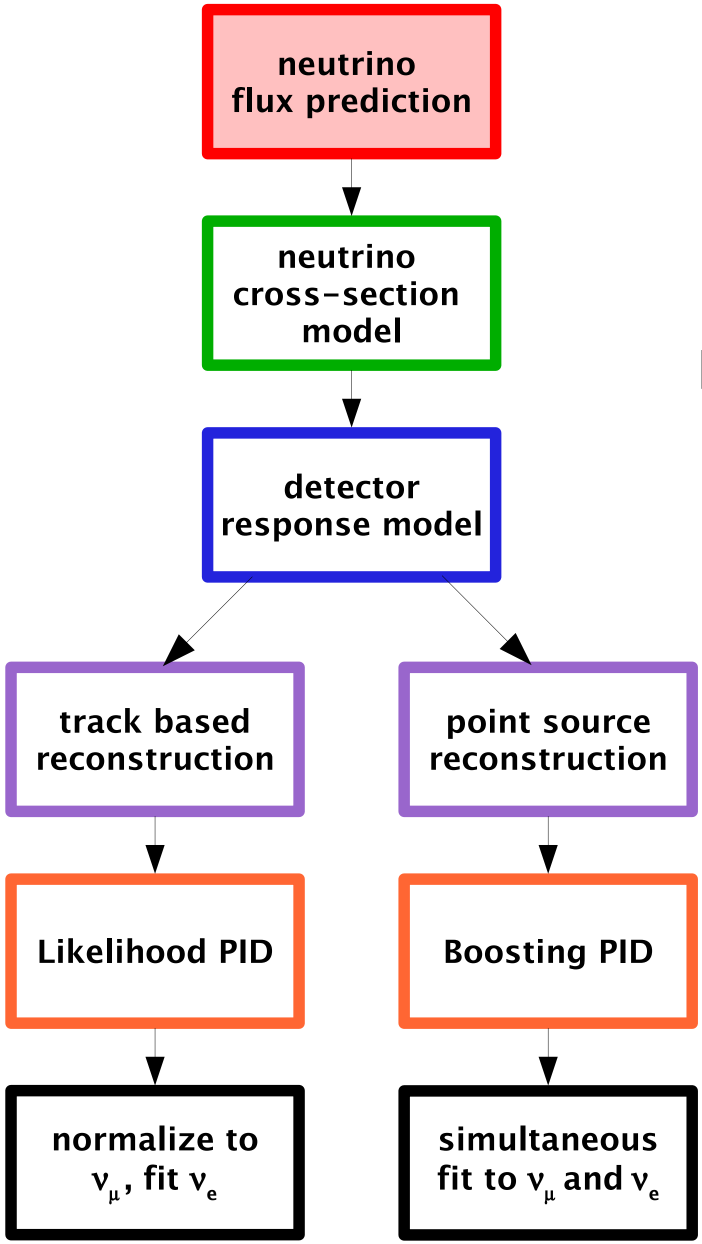
Oscillation Analysis

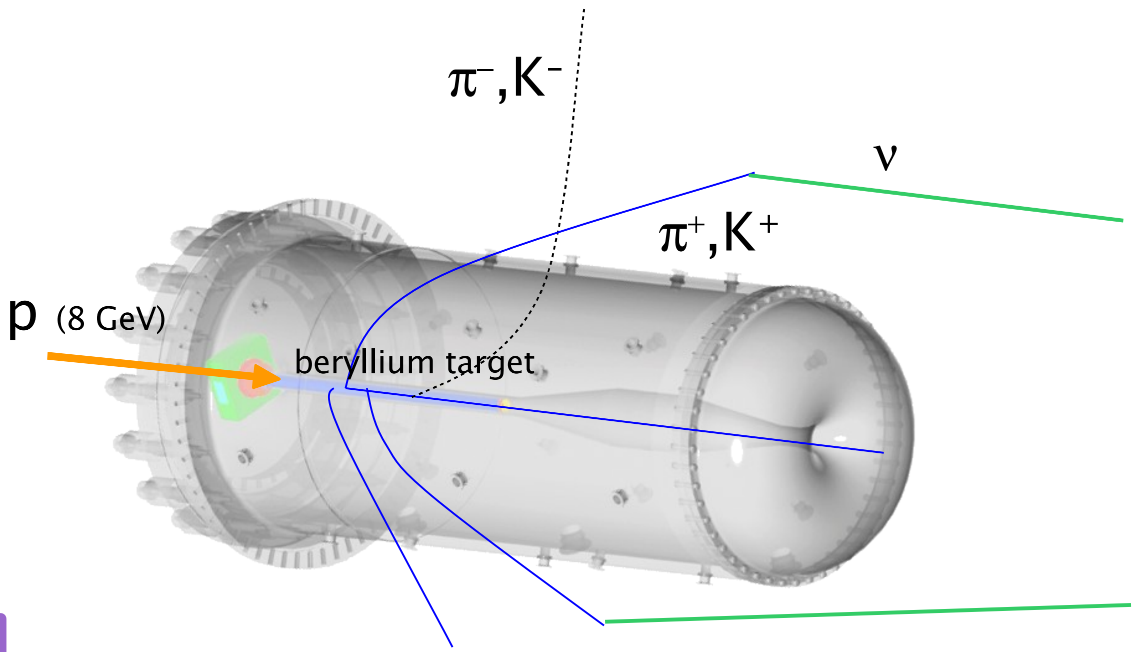


- **GEANT4** simulation of Booster neutrino beam line
- **NUANCE** neutrino interaction code tuned to MB data
- **GEANT3** simulation with an added "**optical model**"
- Two **event reconstruction** packages
- Two algorithms for **event classification**
- Two approaches to apply the ν_μ/ν_e ratio constraint and **fit for oscillation signal**

Oscillation Analysis

Osc Analysis

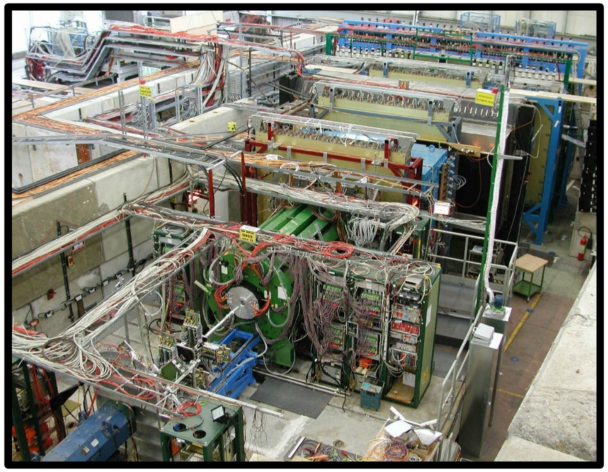




miniboone horn
rendering
Bartoszek Engineering

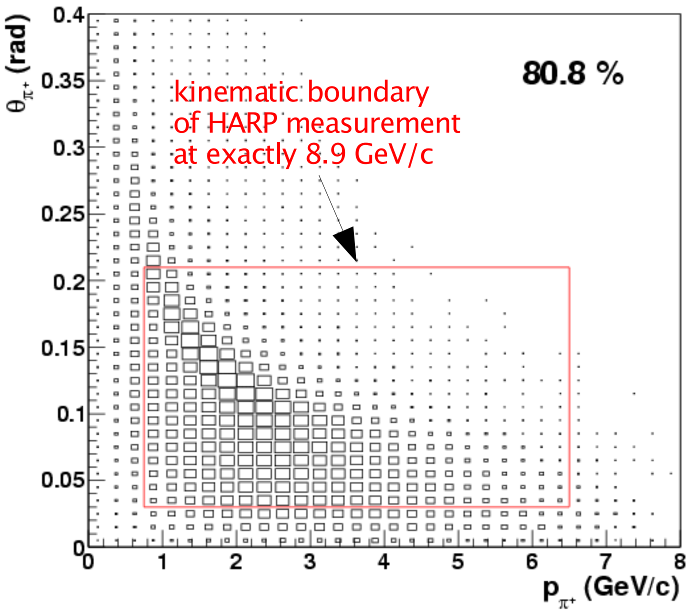
Osc Analysis

Neutrino Flux Prediction

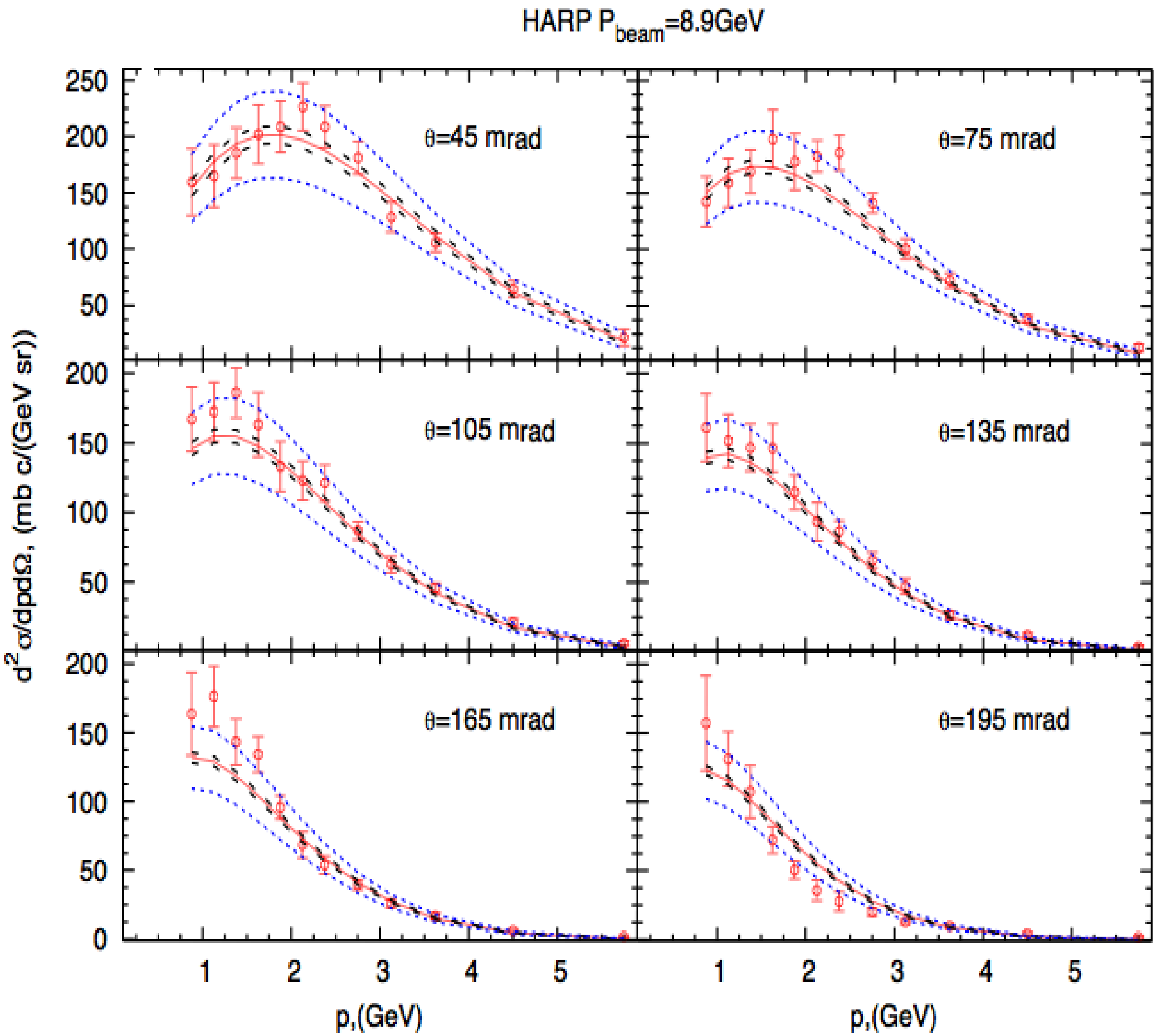


$$p + Be \rightarrow \pi^+ \rightarrow \nu_\mu$$

- 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



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)

Osc Analysis

Neutrino Flux Prediction

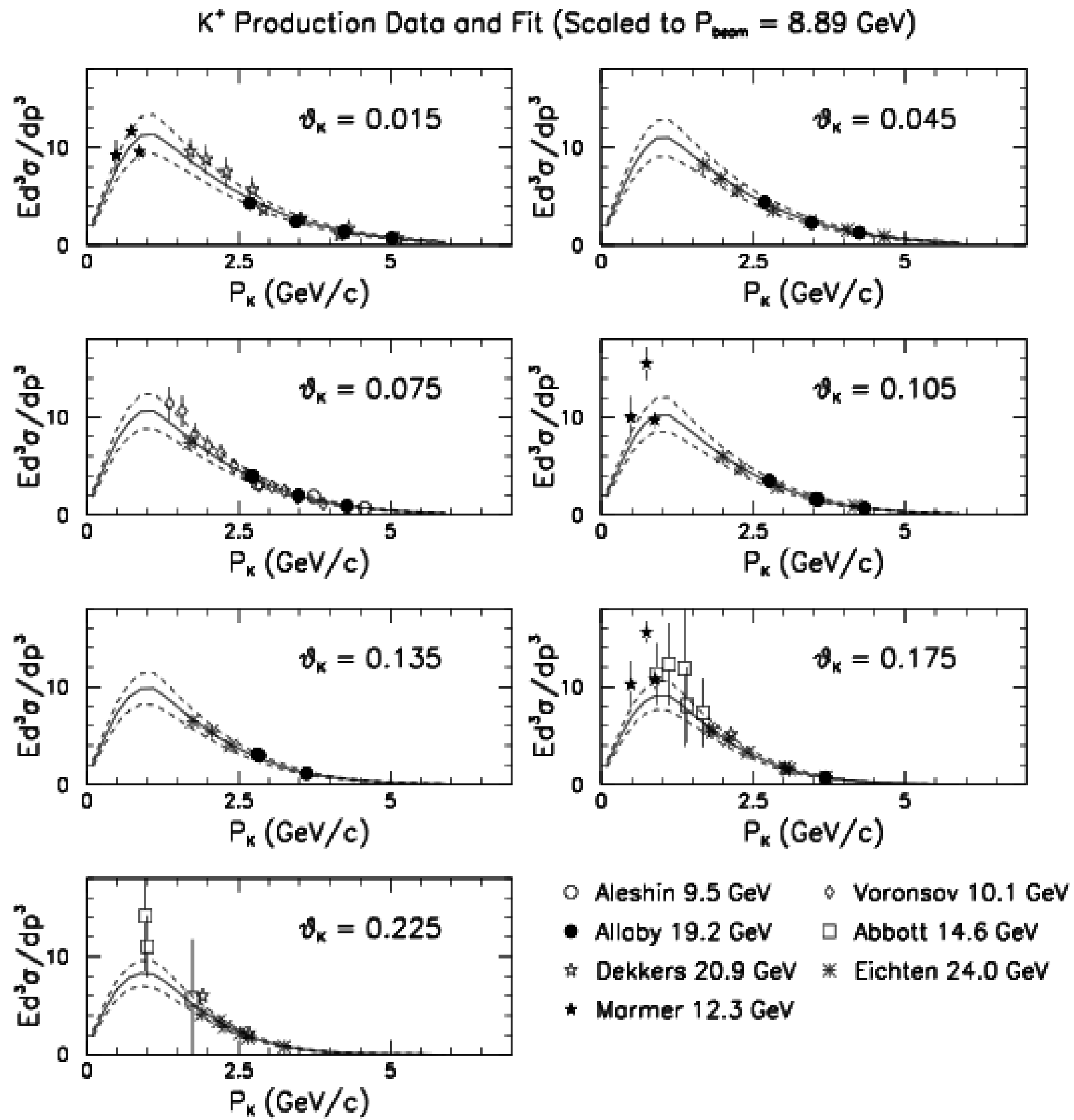
- intrinsic electron neutrinos come from **kaon decays** or the decay of muons coming from pions

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

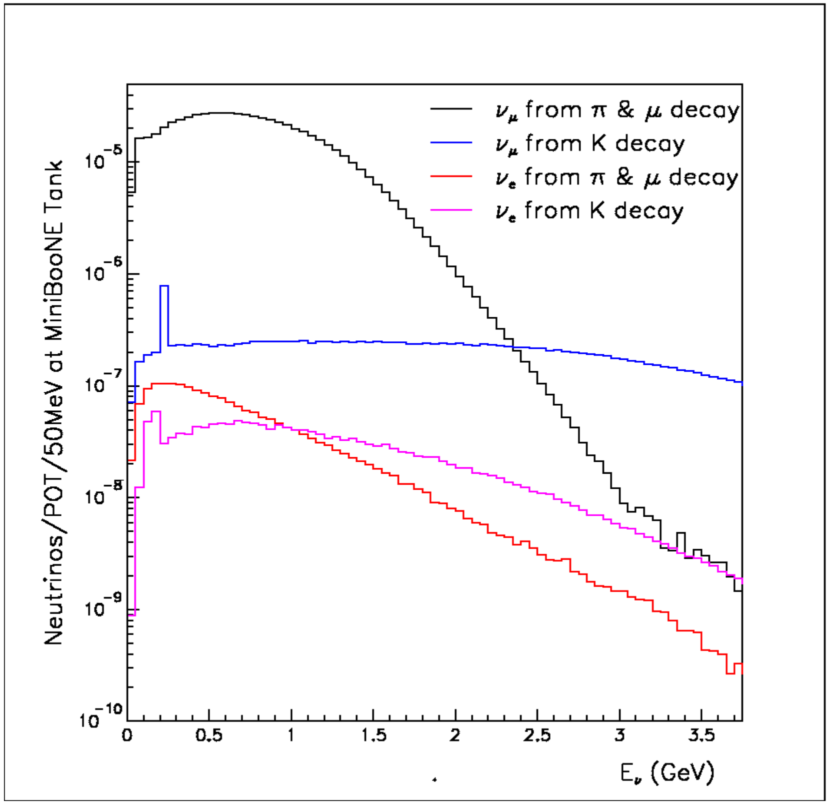
- K^{+} data from 10 – 24 GeV/c proton beams

- 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^{+}



Neutrino Flux Prediction

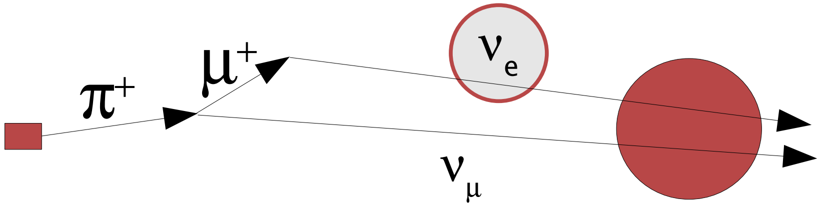


ν_μ	~93%
$\bar{\nu}_\mu$	~6%
ν_e	~0.6%
$\bar{\nu}_e$	<0.1%

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

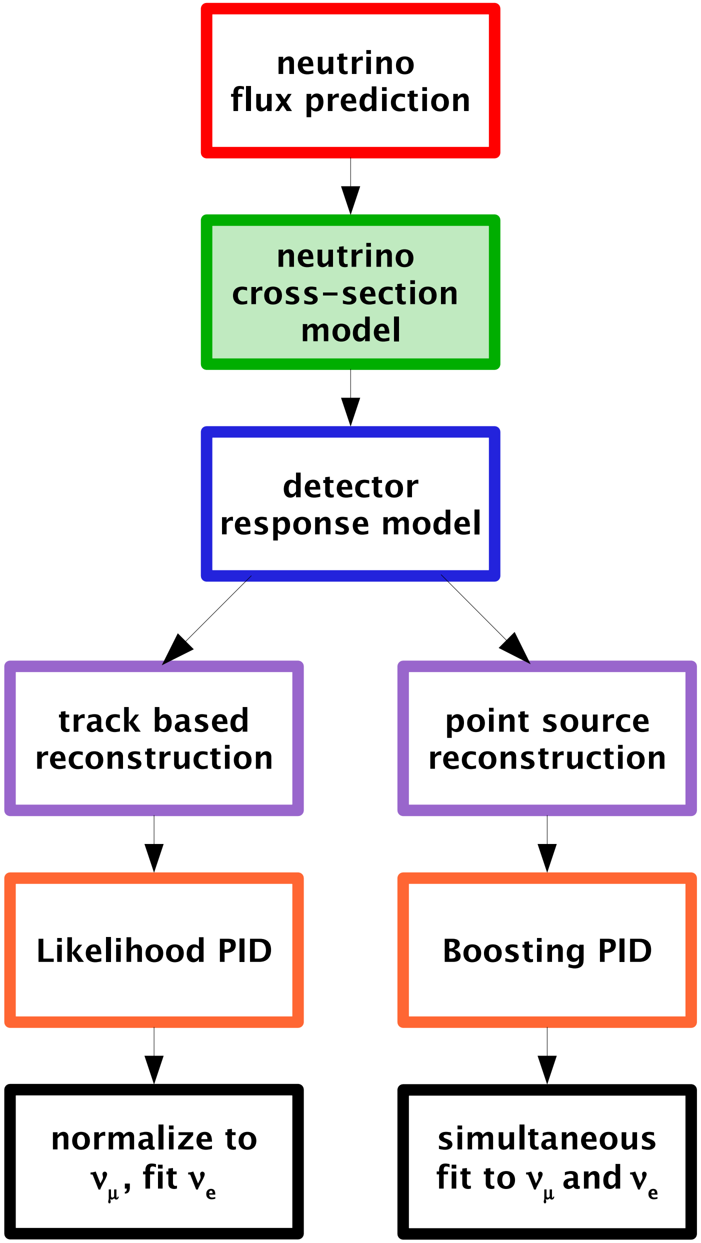
- $\mu^+ \rightarrow e^+ \nu_\mu \nu_e$ (52%)
- $K^+ \rightarrow \pi^0 e^+ \nu_e$ (29%)
- $K^0 \rightarrow \pi e \nu_e$ (14%)
- Other (5%)

largest source of intrinsic ν_e are tied directly to ν_μ event rate through π^+ production in target



Osc Analysis

Neutrino Cross-section Model



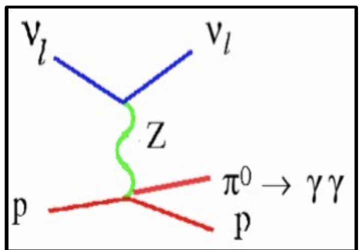
- armed with an input flux, neutrino interactions are simulated using the **NUANCE** neutrino event generator software
- exclusive channels are handled separately and use differing, appropriate models
- the most important exclusive channel for the MiniBooNE oscillation search is the **charged-current 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)

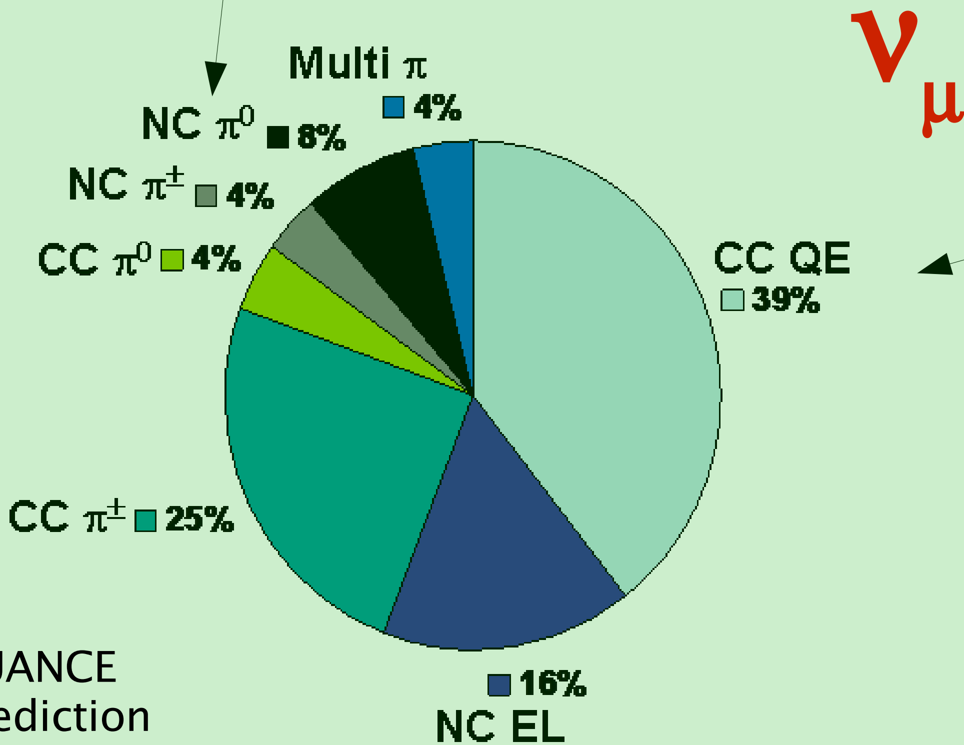
Osc Analysis

Neutrino Cross-section Model

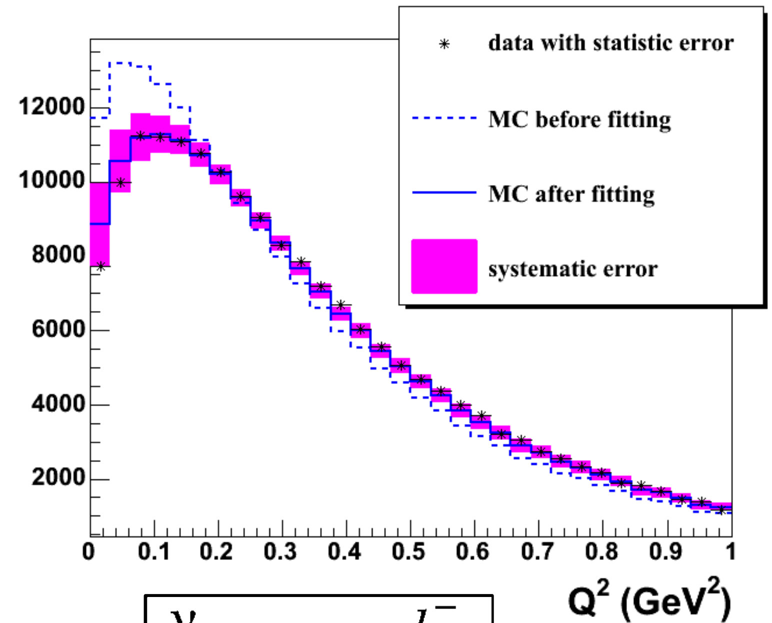
- largest mis-ID background in ν_e event sample
- NUANCE cross-section model ***tuned to observed π^0 rate***

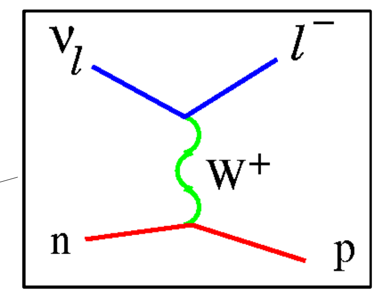


NC π^0



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

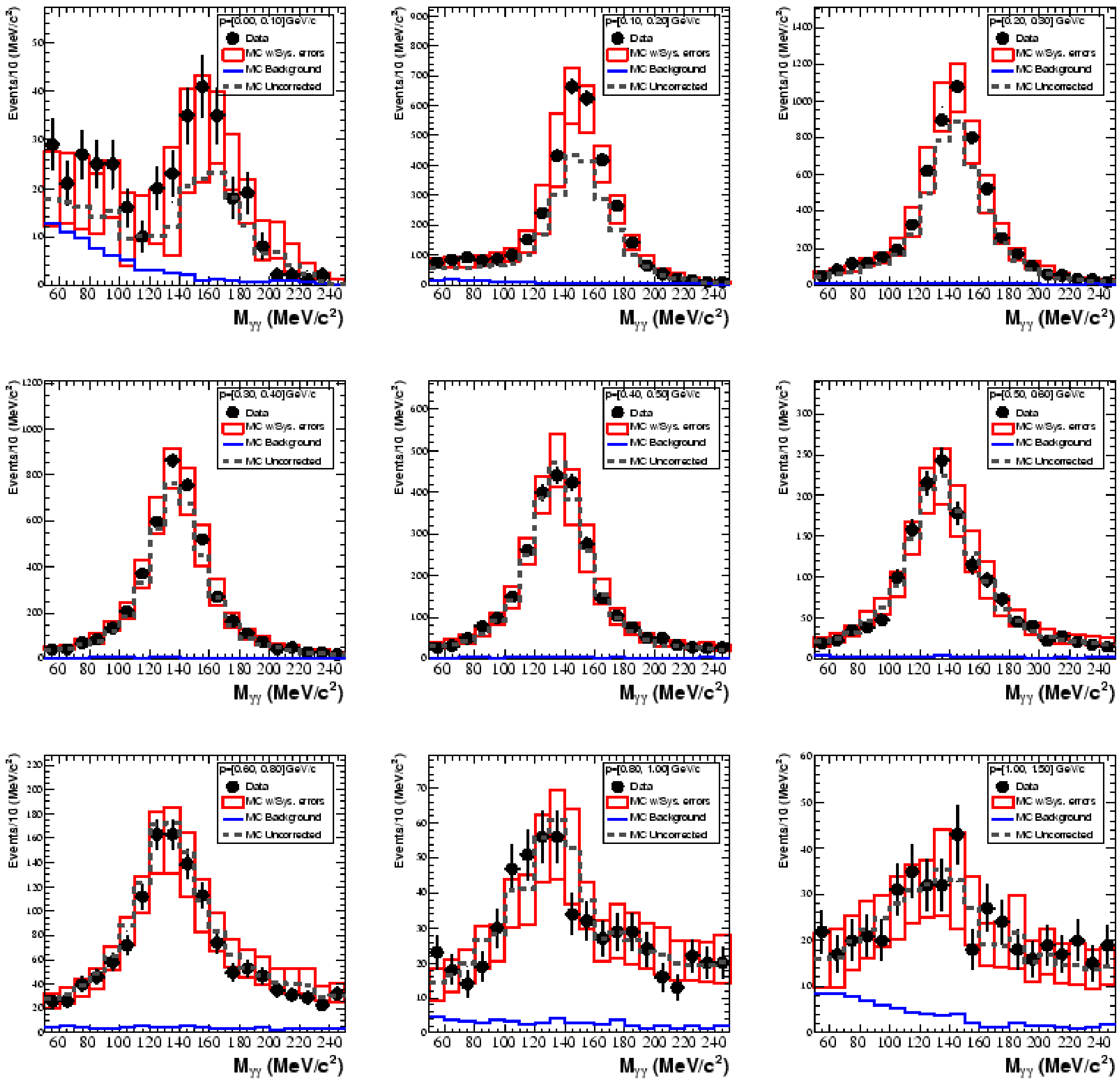
Osc Analysis

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

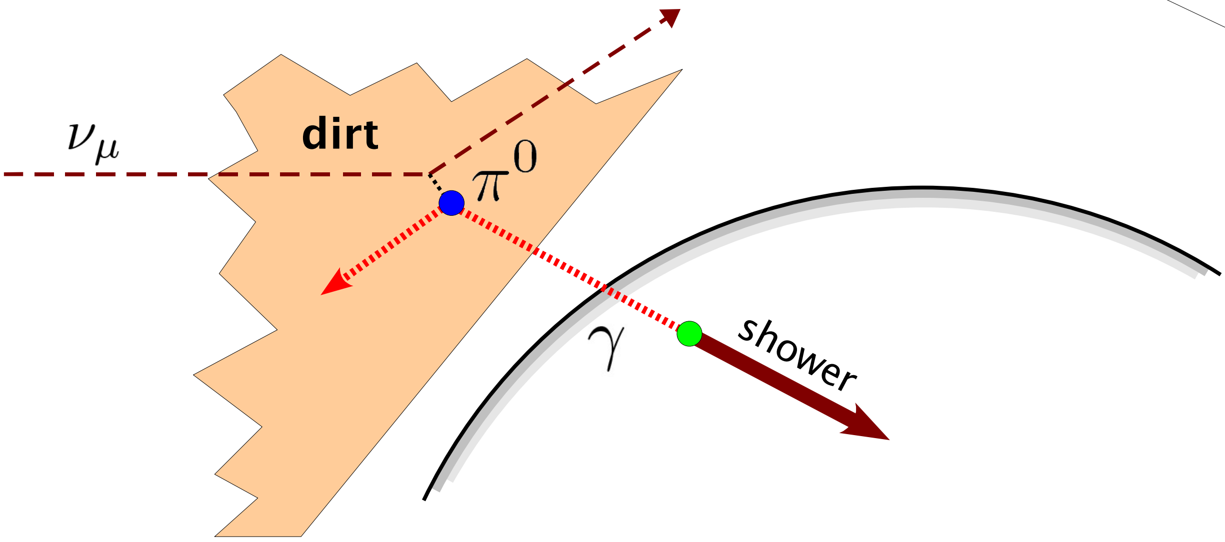
MC with systematic errors

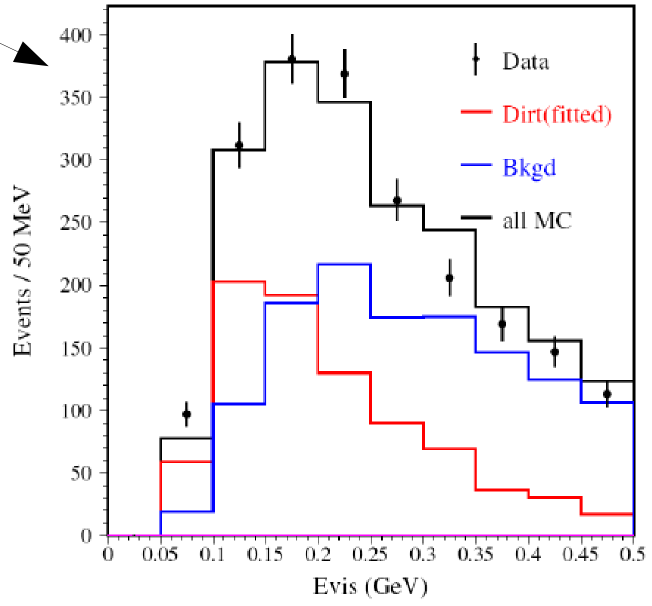
MC before tuning

Neutrino Cross-section Model

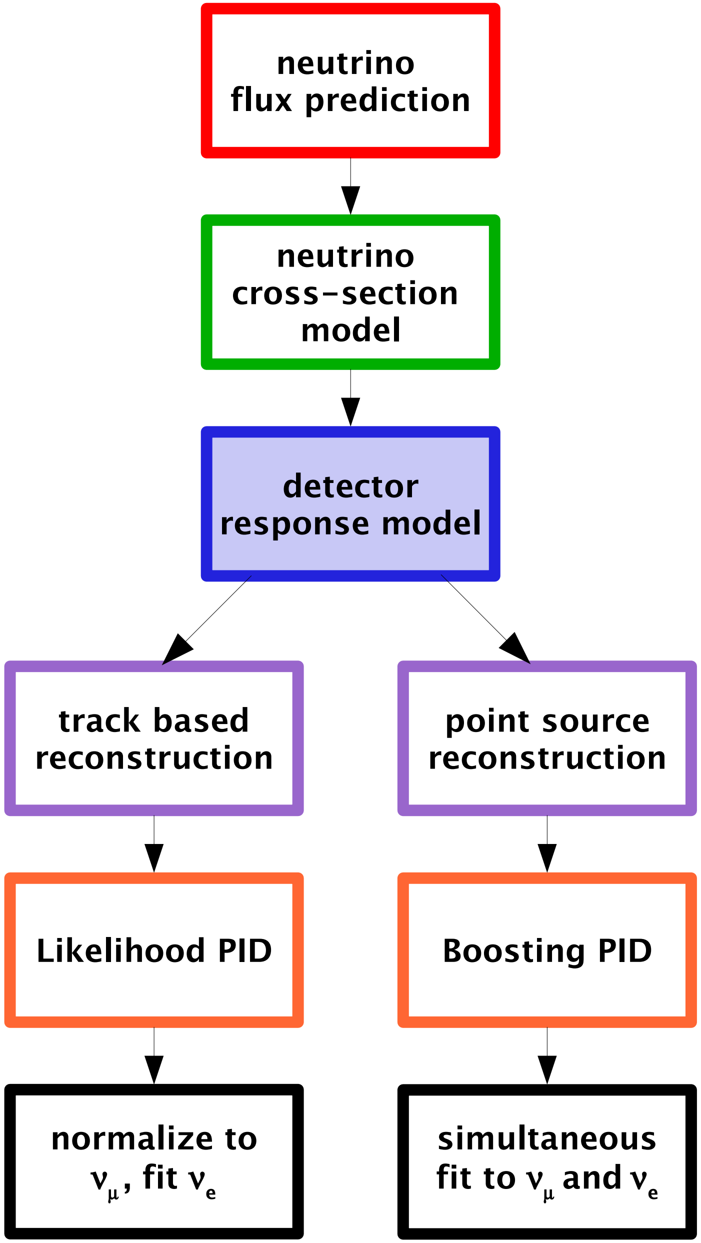
other important mis-ID backgrounds

- 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

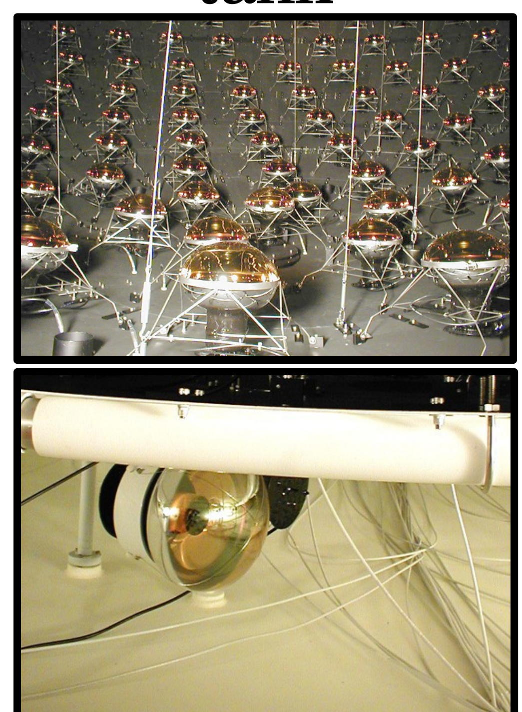


MiniBooNE detector :

- 12 m diameter sphere
- 800T 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

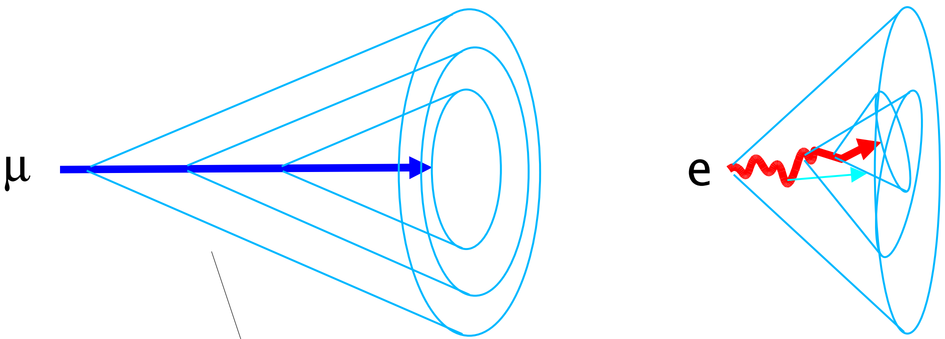
tank

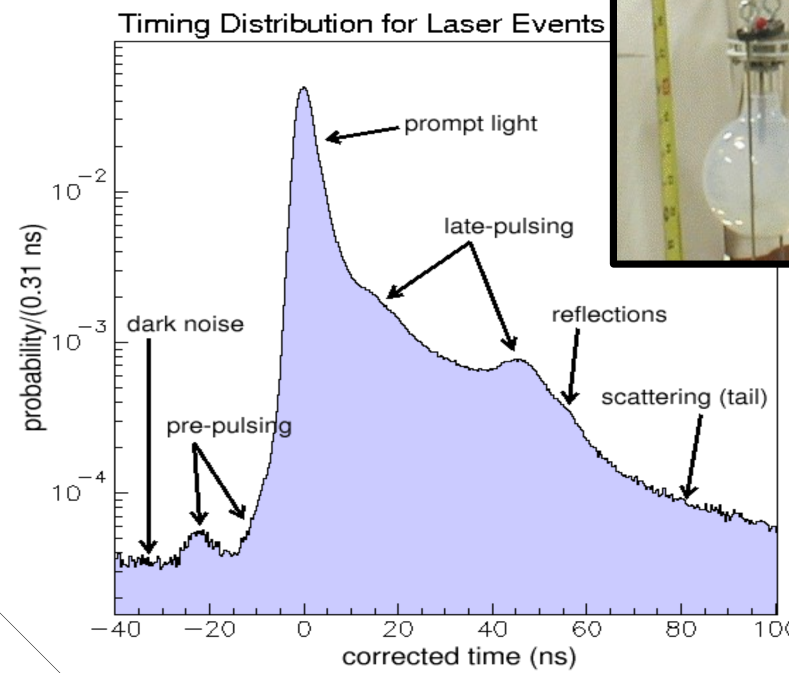


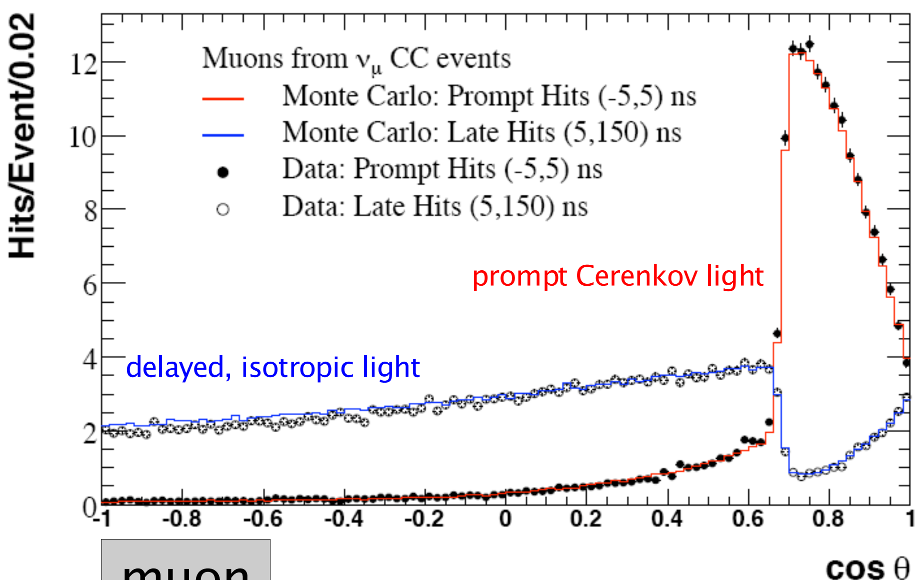
veto region

Detector Response Model

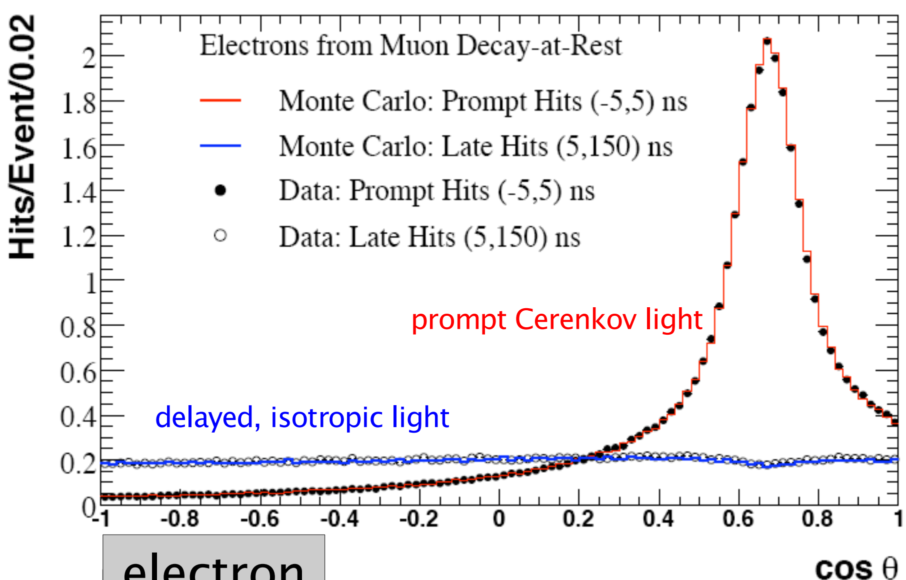
- Optical model is quite complex
  - Cherenkov, scintillation, fluorescence
  - PMT Q/t response
  - Scattering, reflections, prepulses
  - Overall, about 40 non-trivial parameters





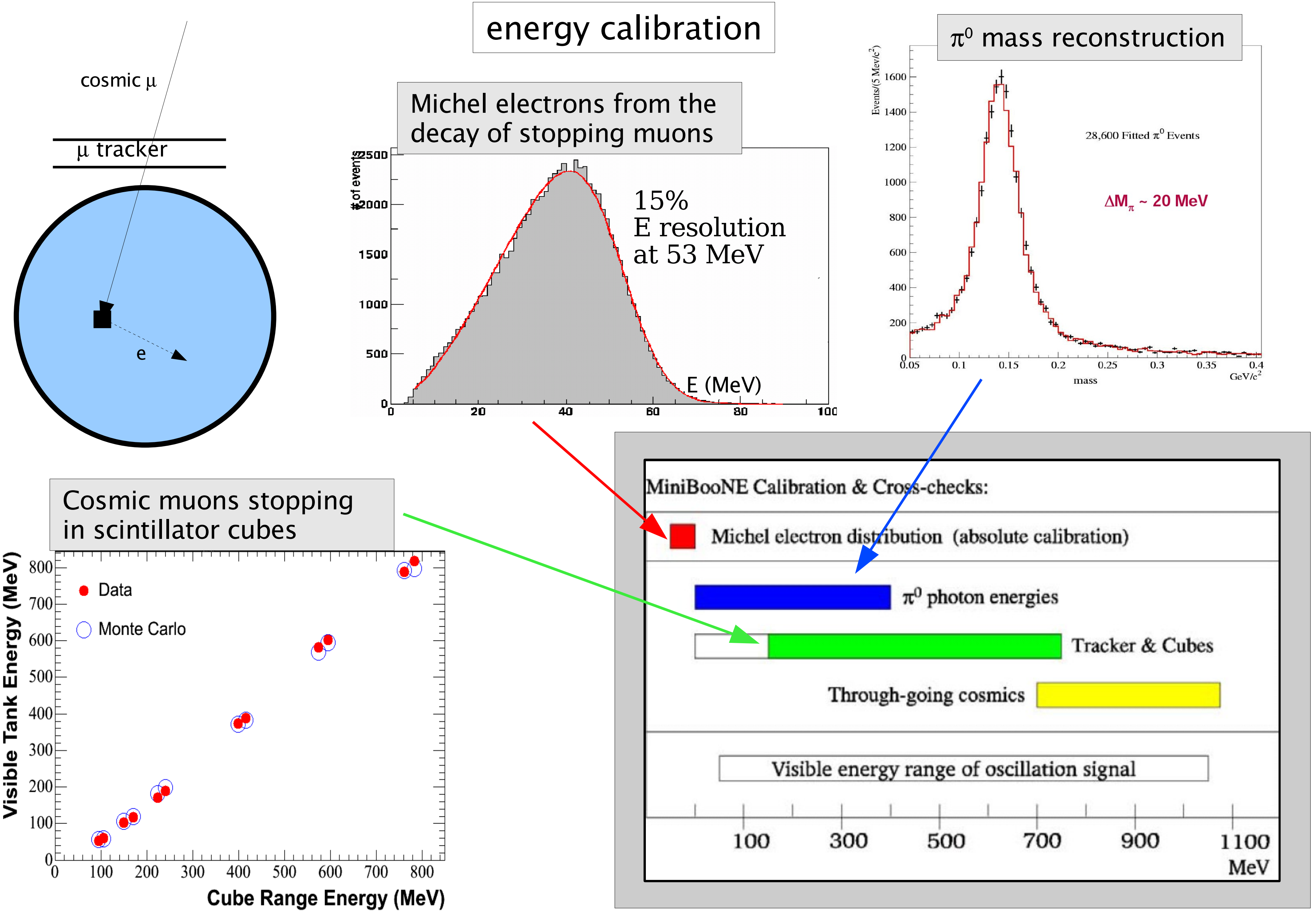


muon



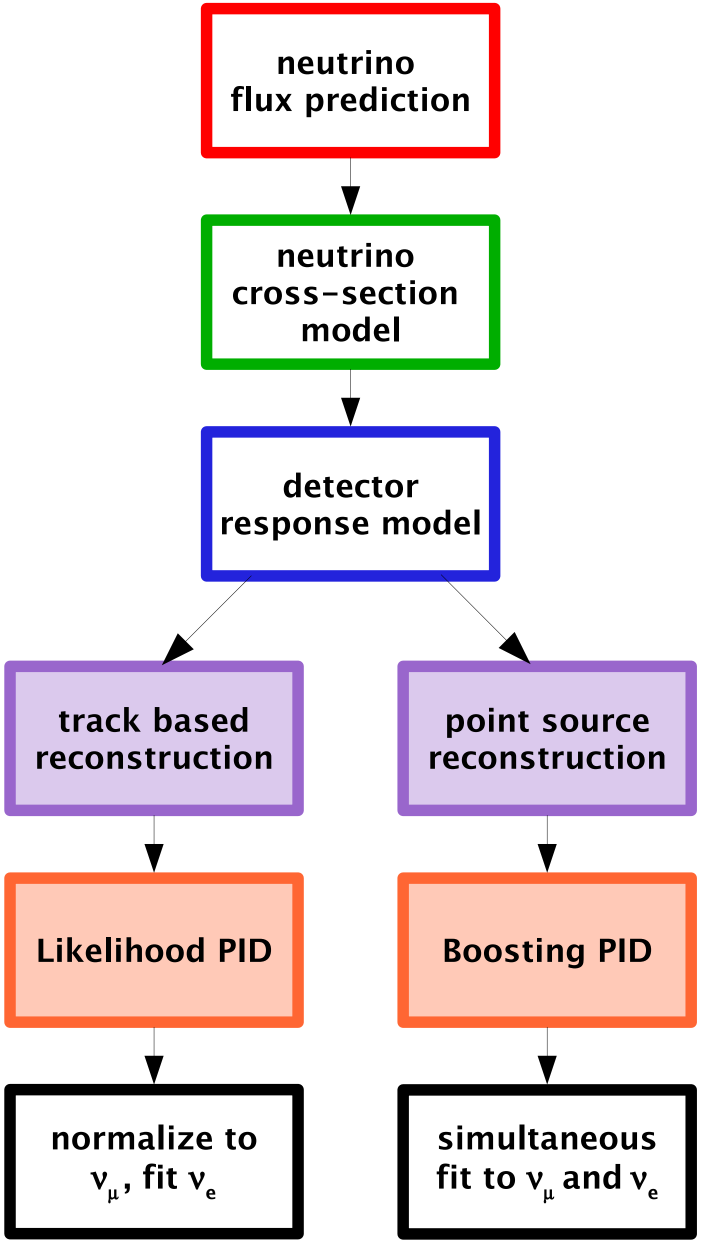
electron

Detector Response Model



Osc Analysis

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

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 :

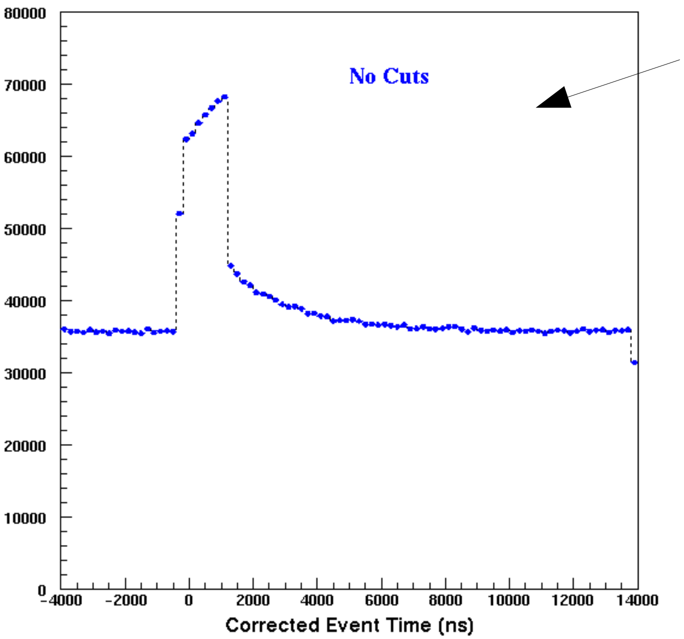
1. **Track Based** reconstruction + **Likelihood PID**
   - treats particles in the tank as extended tracks and carefully considers dE/dx effects
   - extremely tenacious fit. . . π^0 (2 ring) fitter takes ~8 minutes per event!
   - PID algorithm based on Likelihood ratios of different particle hypotheses

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

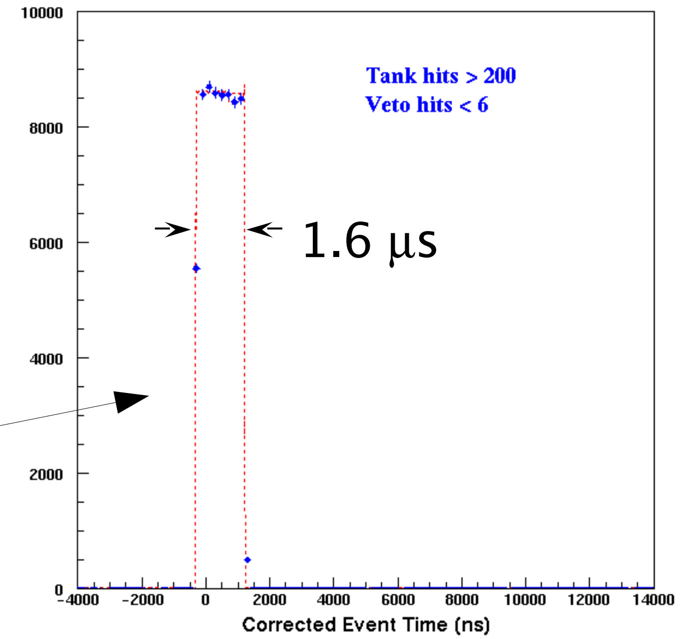
resolutions	**TB**	**PS**
vertex	22 cm	24 cm
direction	2.8 deg	3.8 deg
energy	11%	14%

Oscillation Analysis Pre-cuts

Osc Analysis



trigger window, no cuts



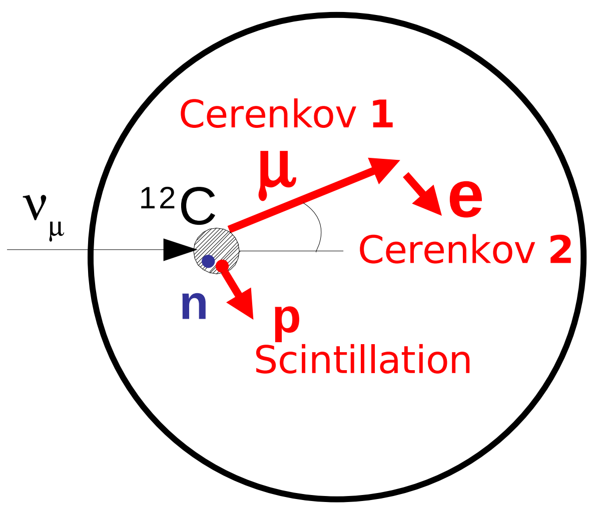
Beam Window

remove cosmic μ and decay e

PMT hits in veto < 6

PMT hits in tank > 200

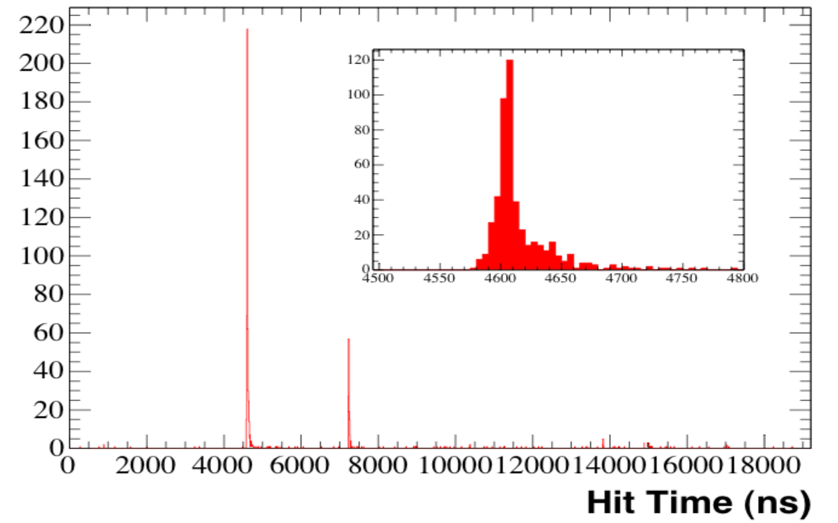
ν_μ CCQE: $\nu_\mu + n \rightarrow p + \mu^-$



Sub-events

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

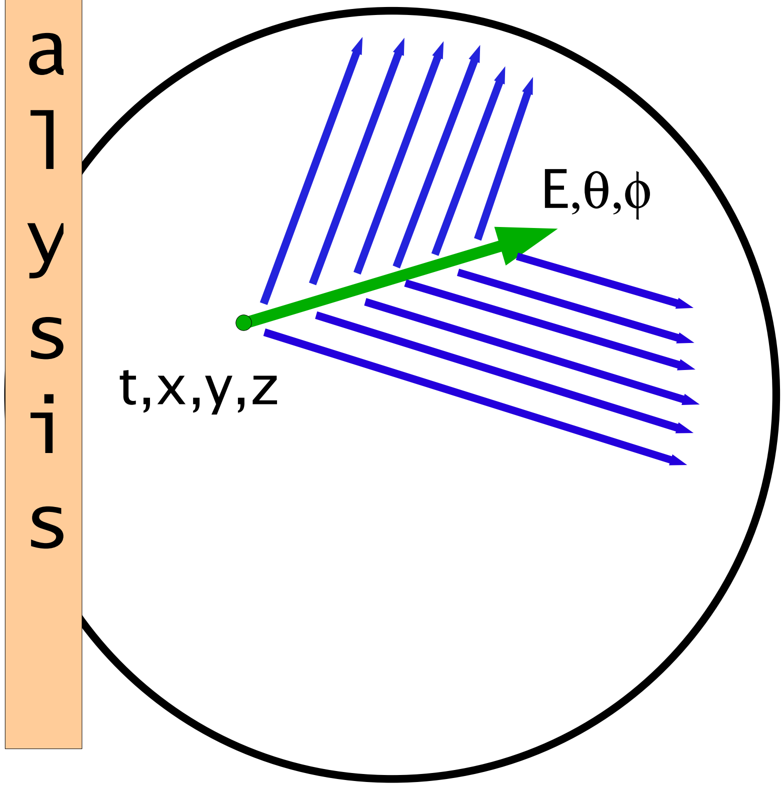
Sub-events == 1



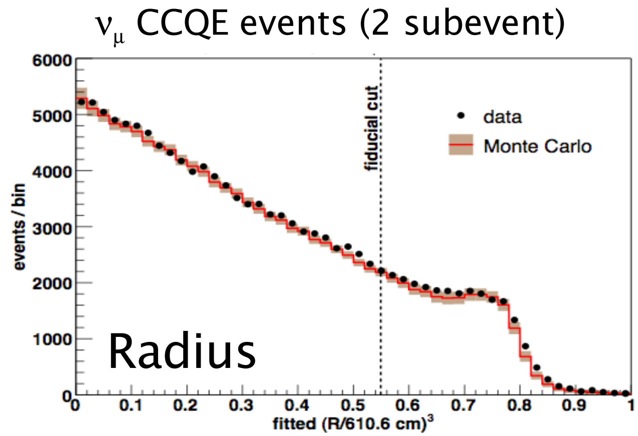
Track Based Rec + Likelihood PID

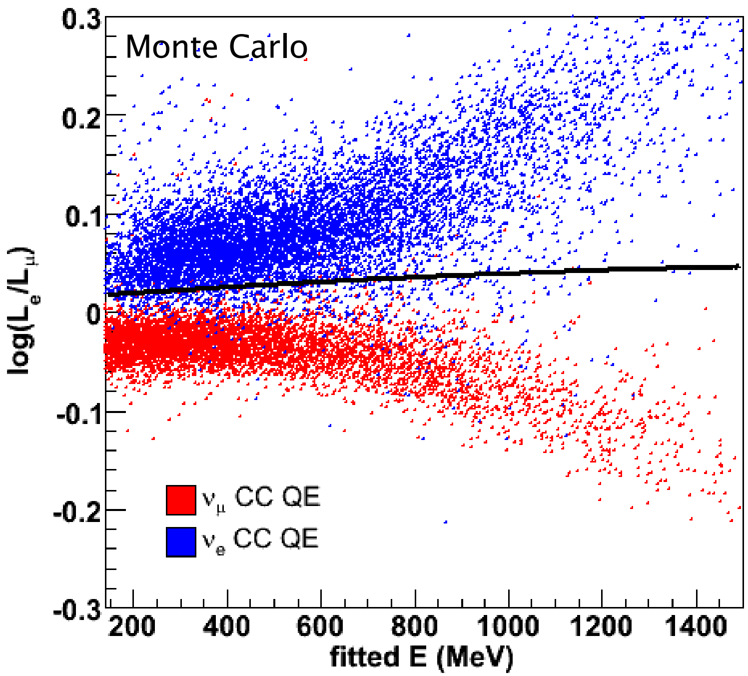
Osc Analysis

- 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 μ





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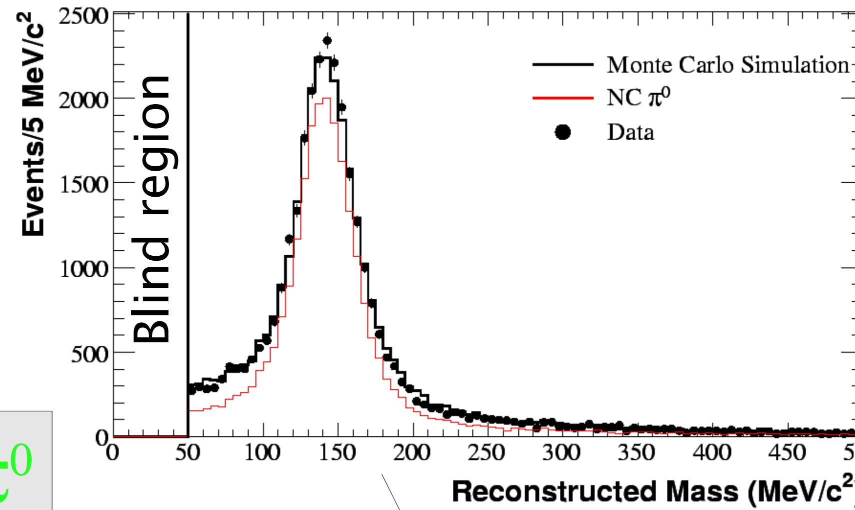
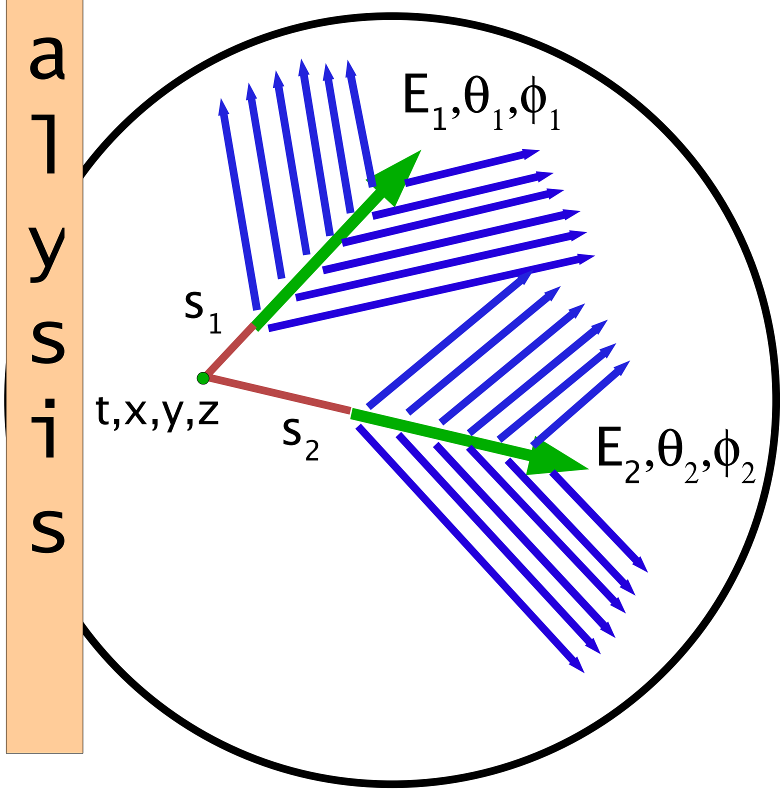
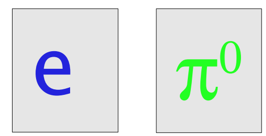
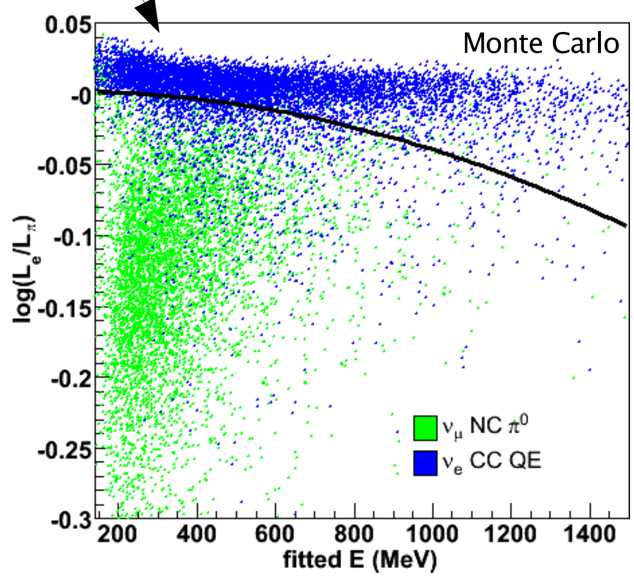
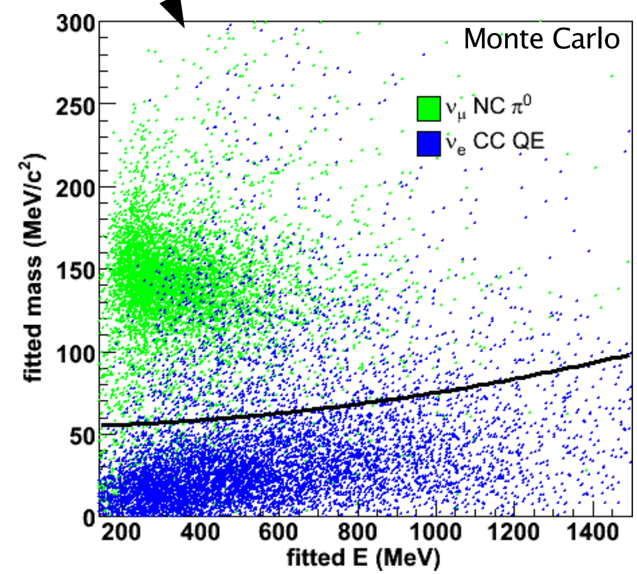






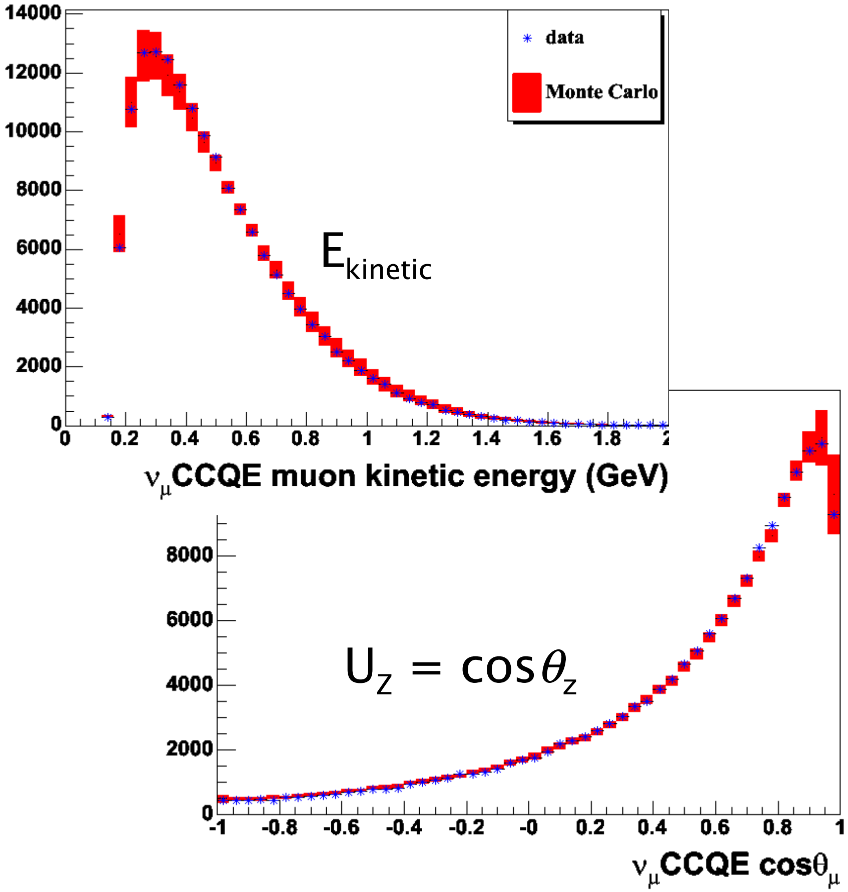


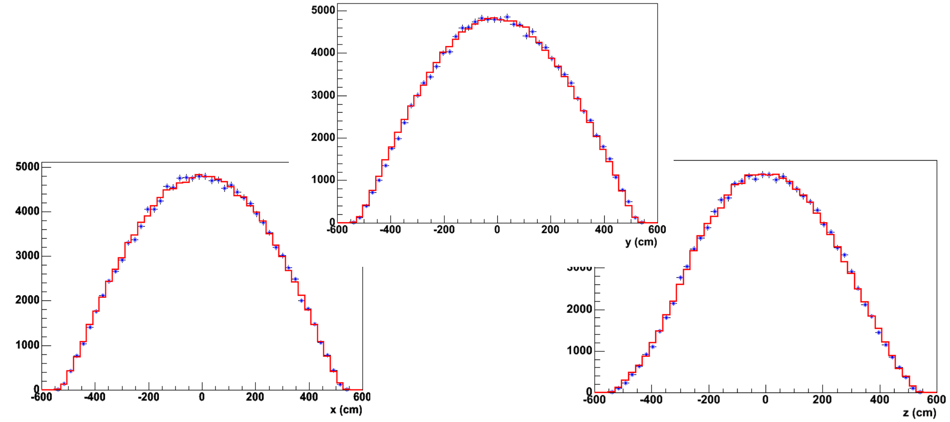


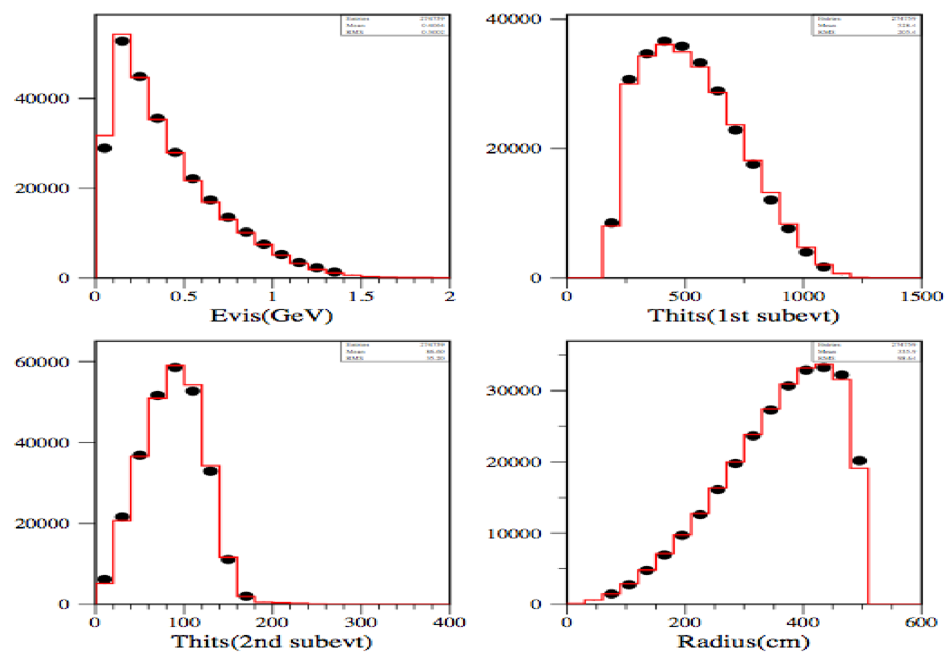
Osc Analysis

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

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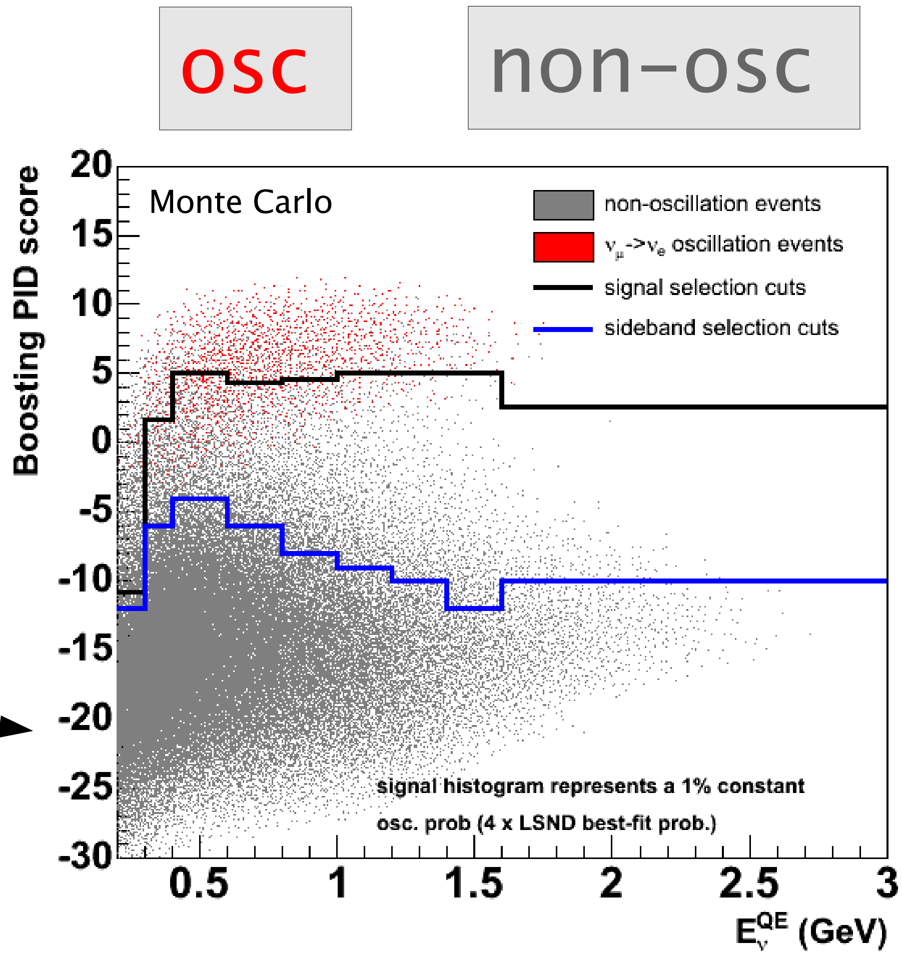
  - *low-level* (number of hit PMTs, fraction of early to late light, . . .)
  - *high-level* (Q^2, U_z, fit Likelihoods, . . .)
  - *topology* (charge in annuli, isotropic light, . . .)

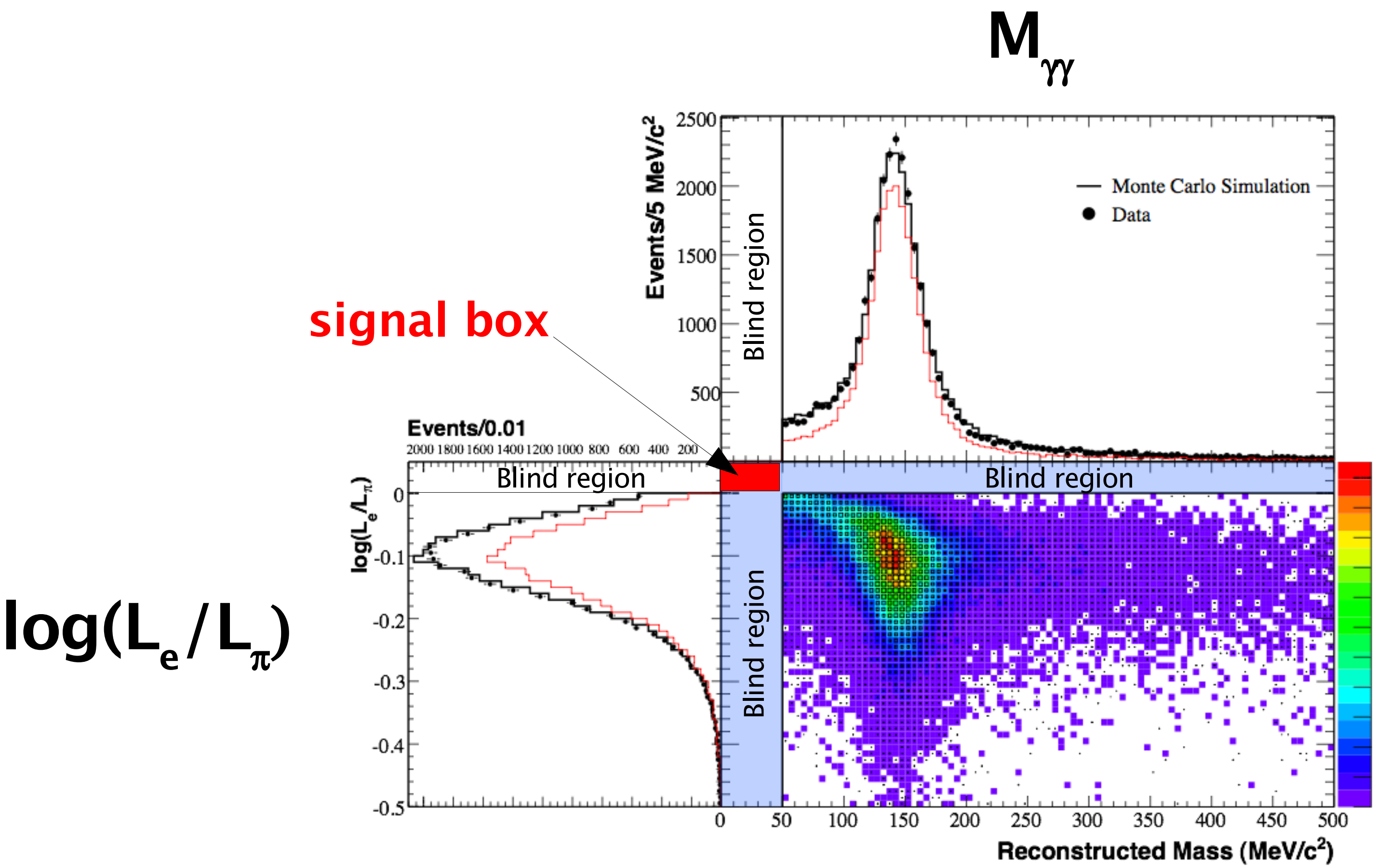
- A total of 172 such variables were used as input for the Boosted Decision Tree algorithm
- All 172 were checked for agreement within errors in 5 important 'boxes' (ν_μ CCQE, NC π^0, NC-elastic, Michel decay e, 10% closed)
- BDT is a technique involving the weighting and combining of many decision trees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

Verifying Sidebands (Likelihood PID)

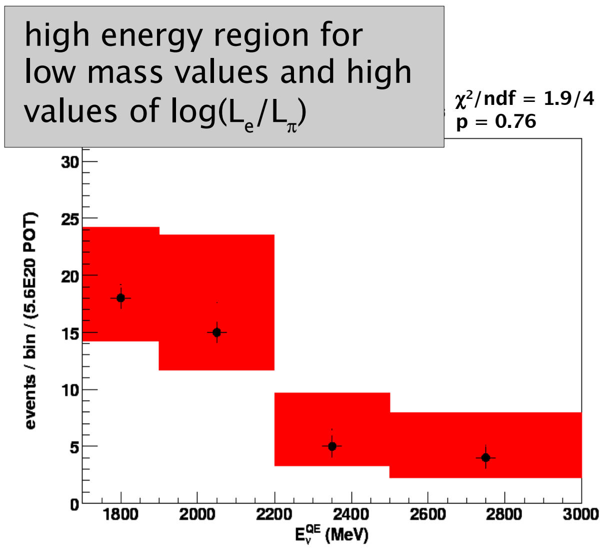
- cannot compare data and Monte Carlo for PID variables within the signal region (blindness)
- use ***"side-bands"*** to verify the simulation
- apply $\log(L_e/L_\mu)$ cut and check side-bands in e/π^0 separation variables

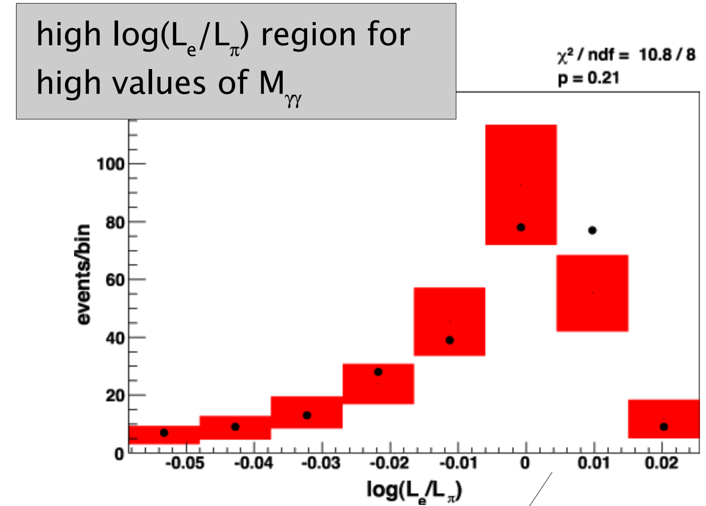


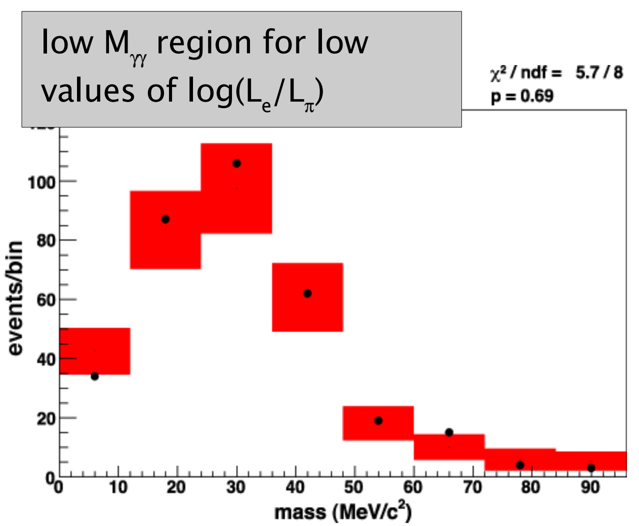
D. Schmitz - Columbia University, NY, NY

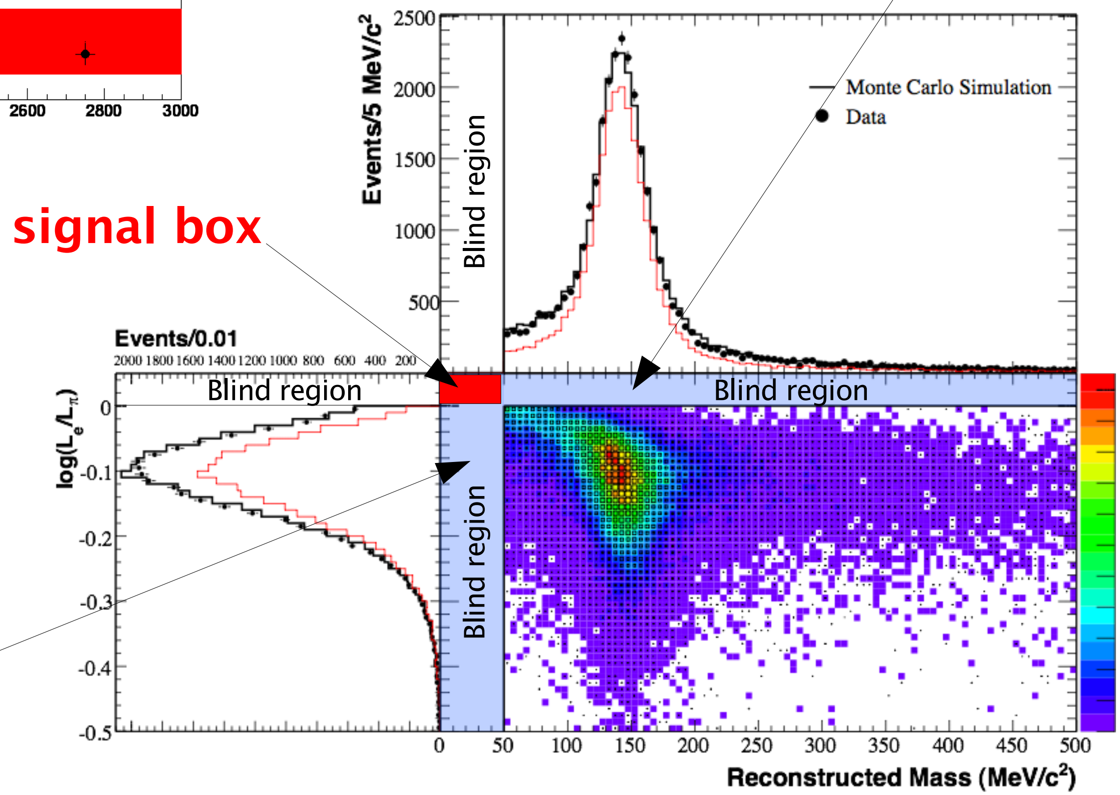
Verifying Sidebands (Likelihood PID)

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



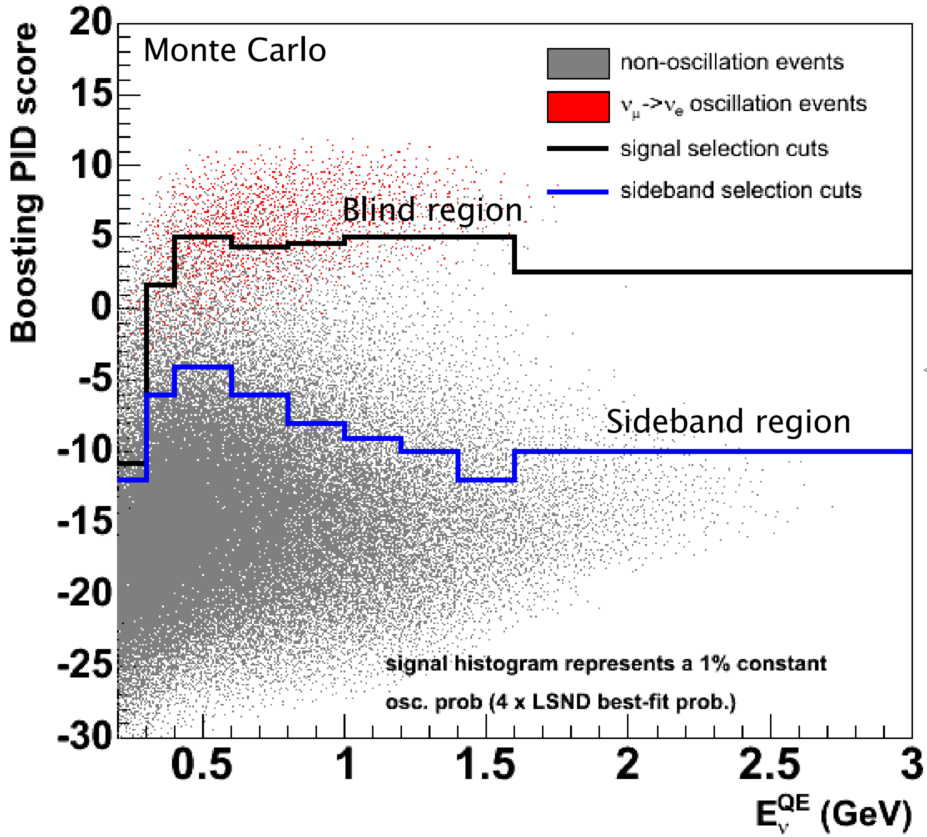


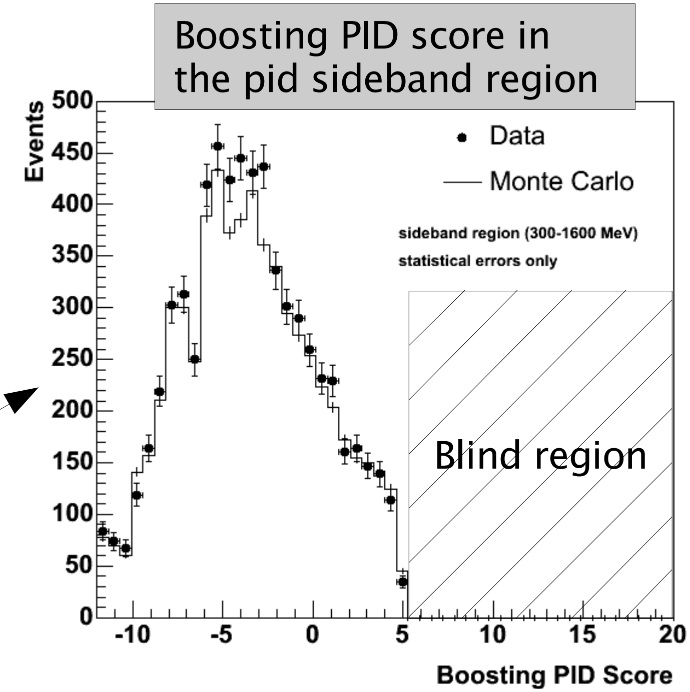


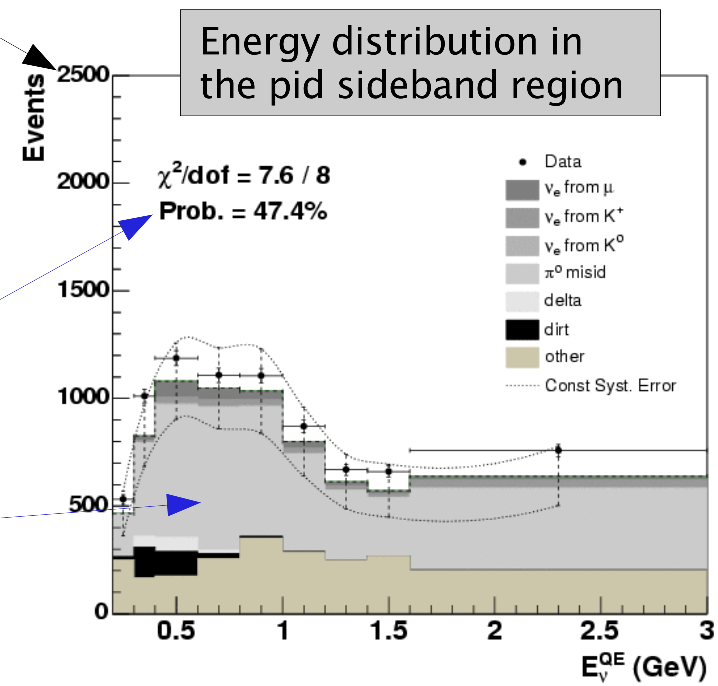


Verifying Sidebands (Boosting PID)

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

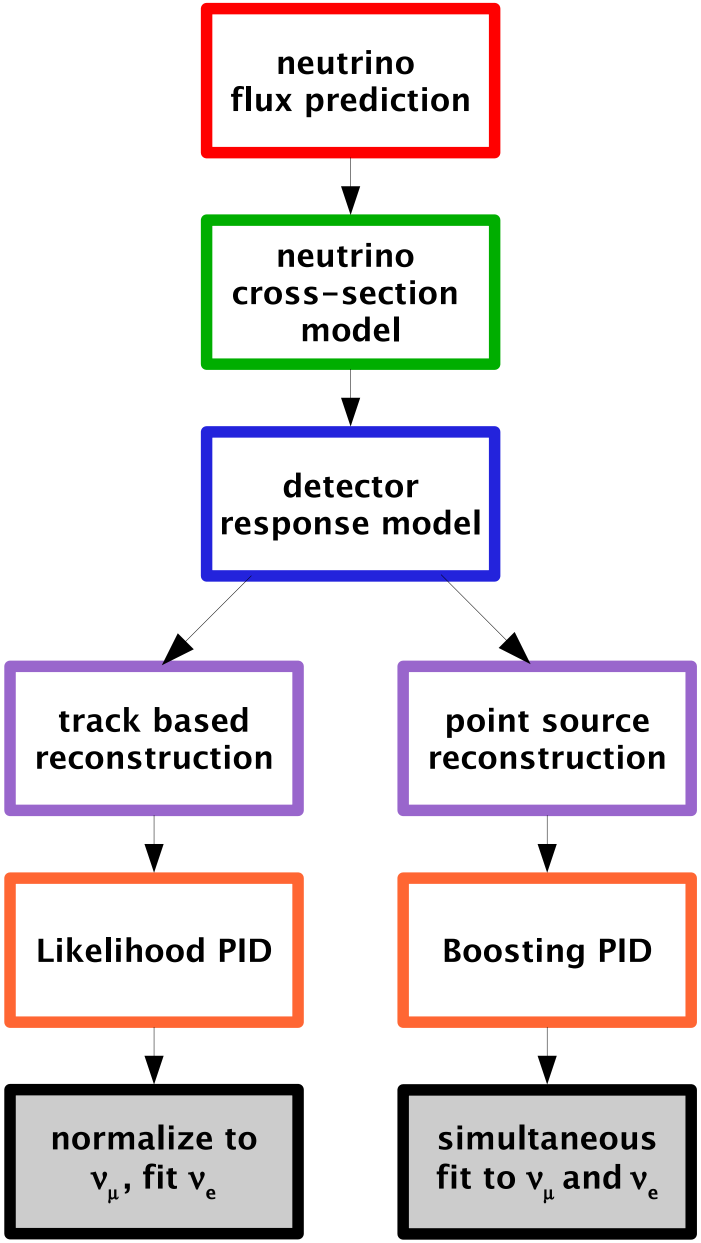






- good agreement within systematic errors
- sideband dominated by π^0 events

Oscillation Signal Fit



- 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
  - only ν_e bins contribute to signal fit χ^2

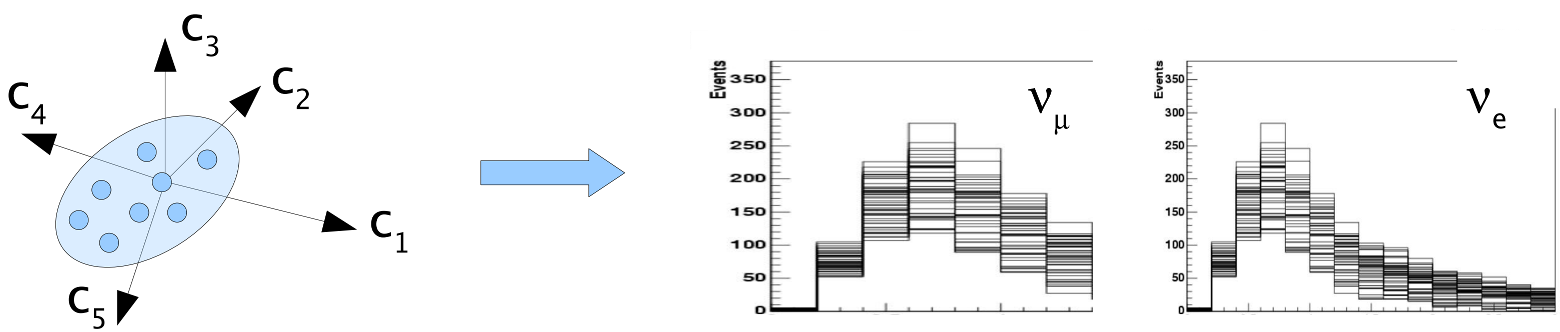
- **Simultaneous fit to ν_μ and ν_e**
  - construct a single, large covariance matrix $(N_{\nu e}+N_{\nu\mu})$ x $(N_{\nu e}+N_{\nu\mu})$
  - matrix includes correlations within the ν_e distribution as well as between ν_μ and ν_e
  - ν_μ and ν_e bins contribute to a total χ^2 in the fit for a signal

Constructing the Error Matrix

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

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

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



- Individual error matrices constructed using ***multisim approach :***
  - A multisim is a random draw from underlying parameters
  - correlations among input parameters are considered
  - 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

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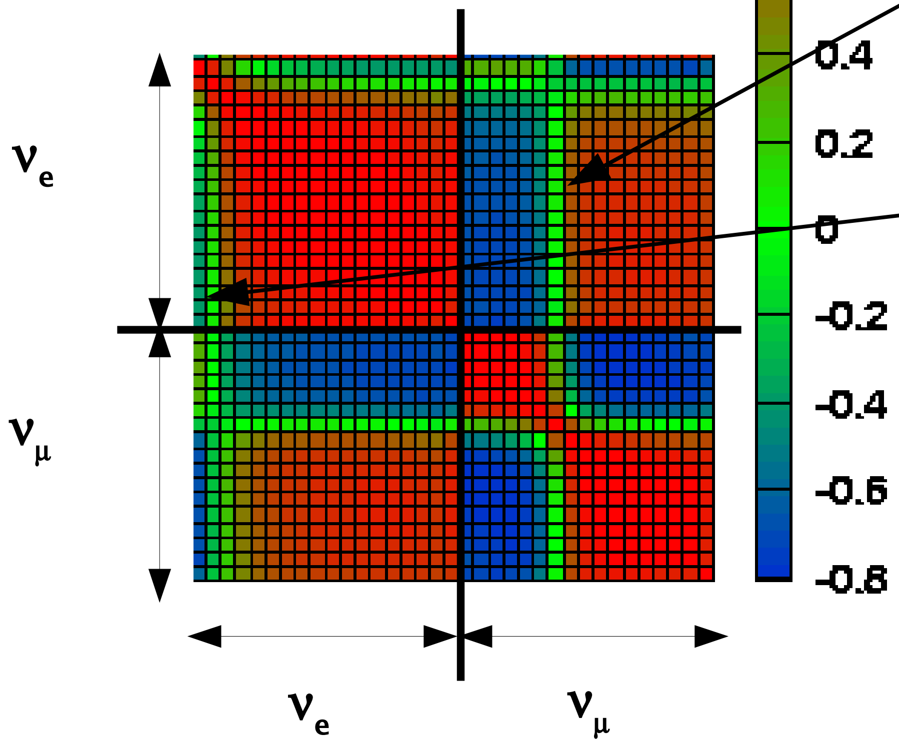
Ex: Optical Model correlations



- 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

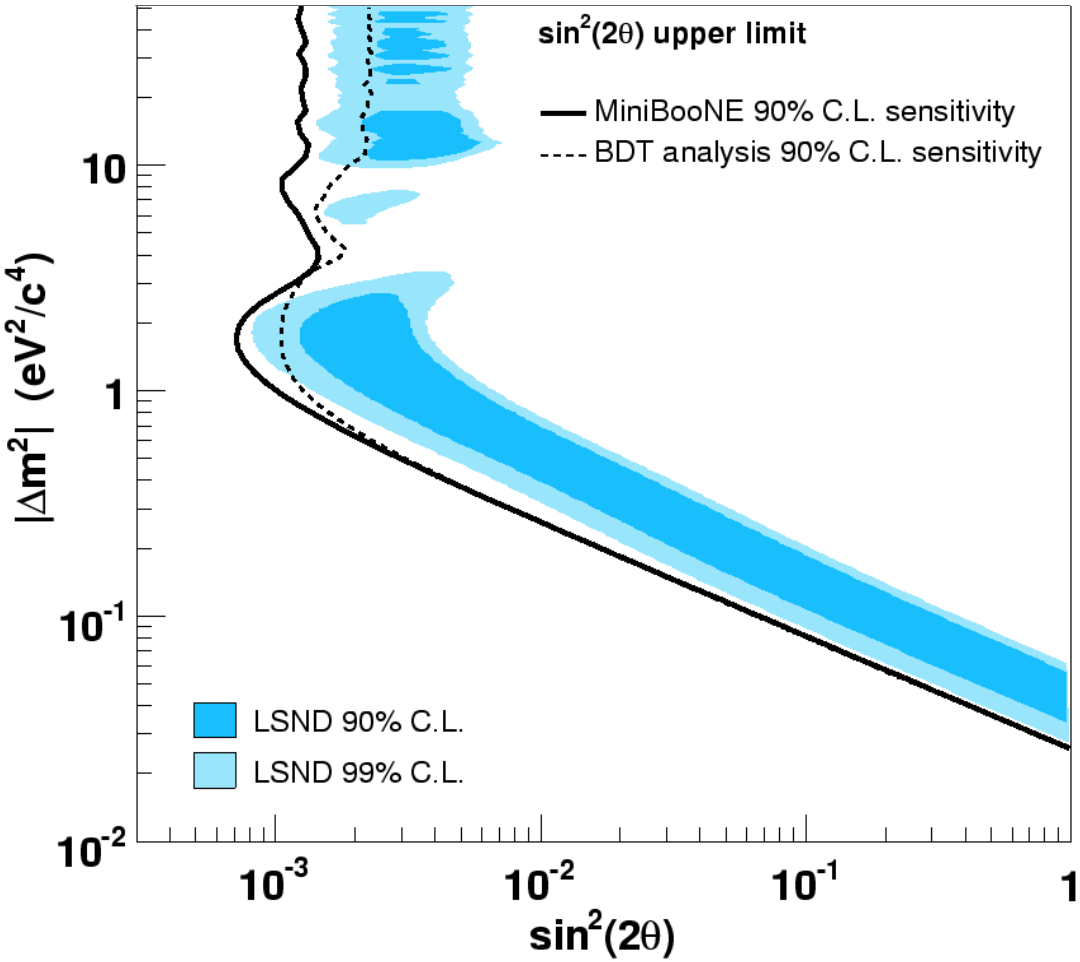
Final Error Budget and Sensitivity

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

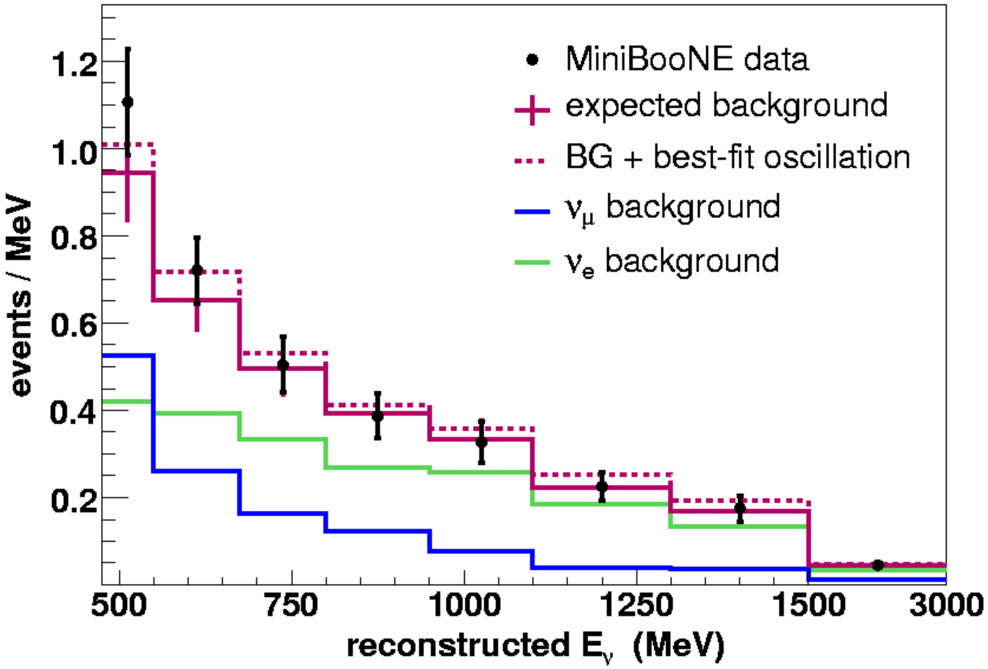
The Oscillation Results

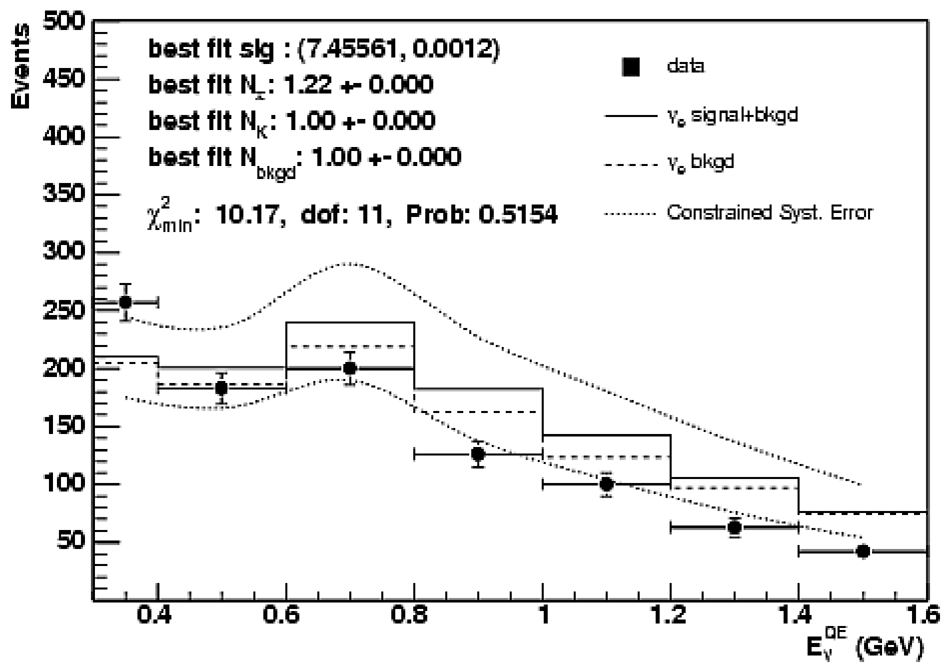
$\nu_\mu \rightarrow \nu_e$ Oscillation Results

• 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





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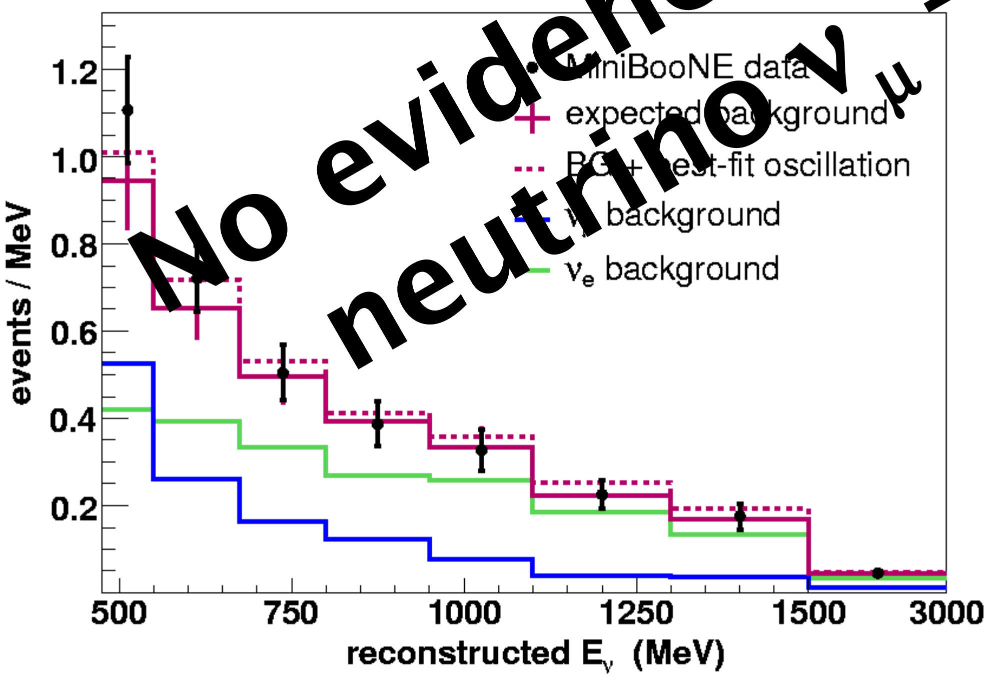
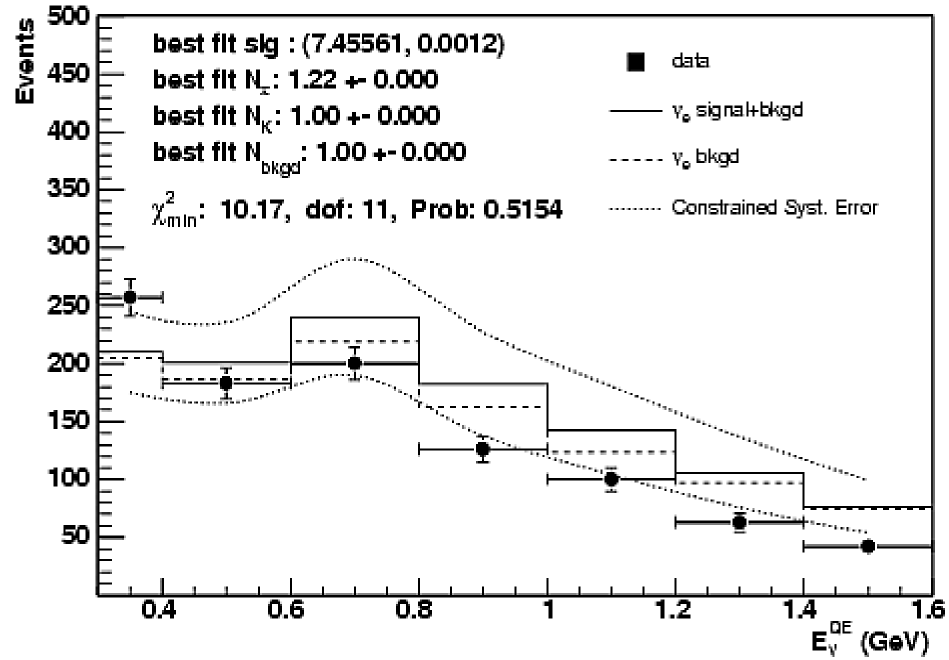
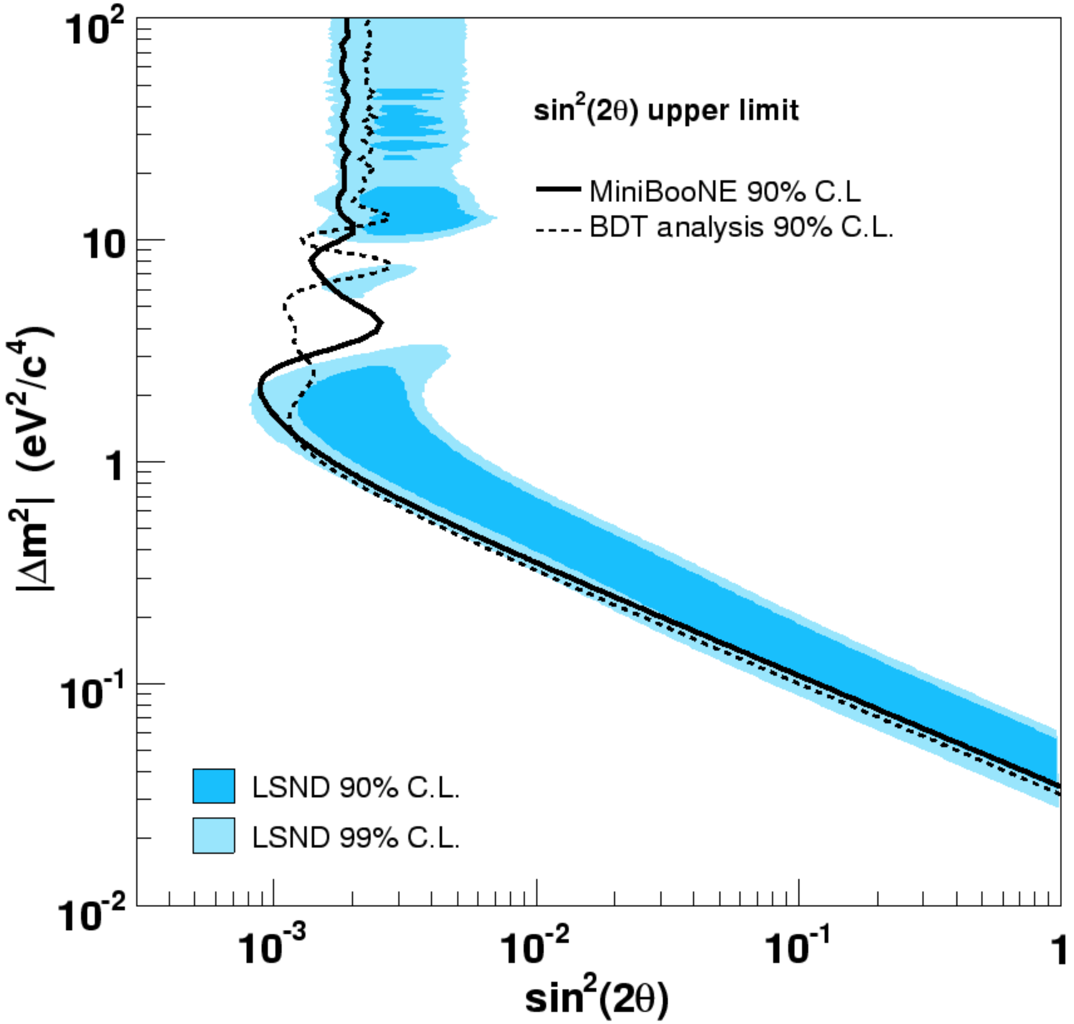
No evidence seen for direct two neutrino $\nu_\mu \rightarrow \nu_e$ oscillations

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

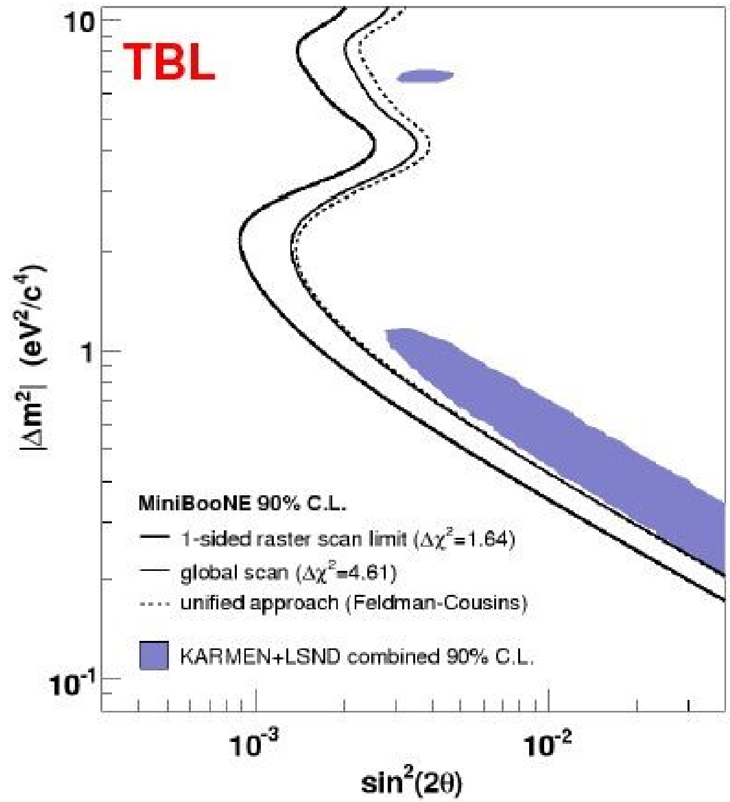




$\nu_\mu \rightarrow \nu_e$ Oscillation Results



- 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



Beyond the Oscillation Search

F u t u r e O u t l o o k

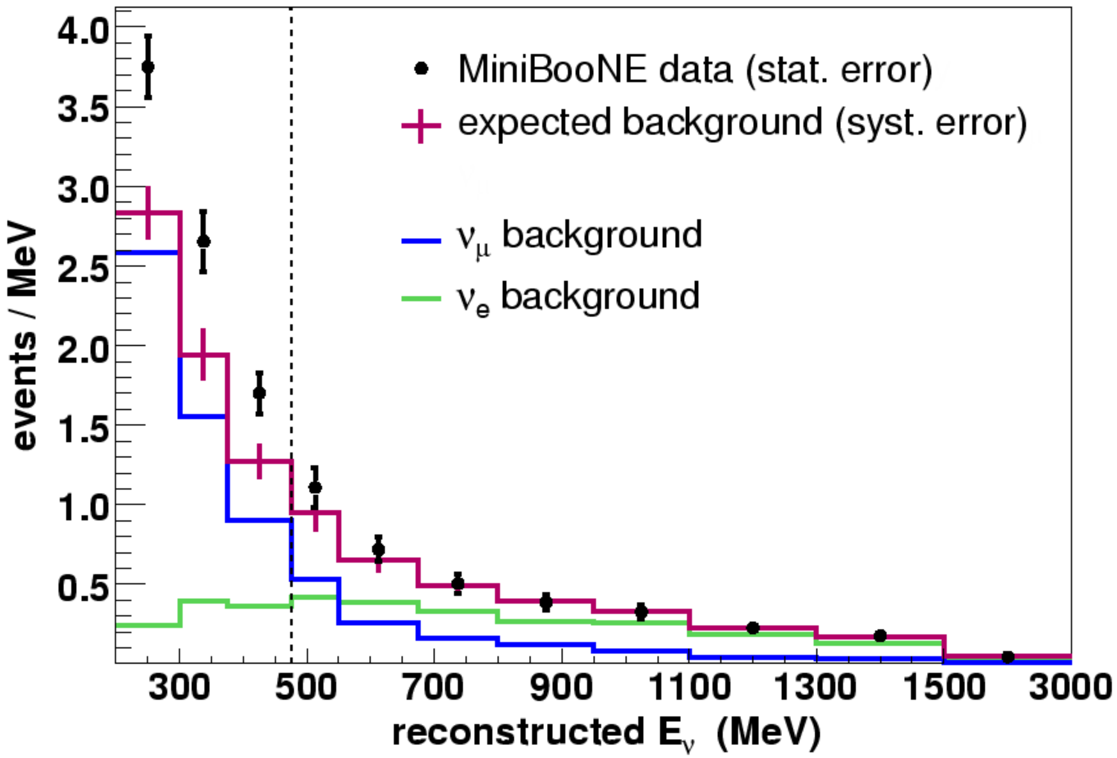
Low Energy Discrepancy

- direct oscillations governed by

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

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



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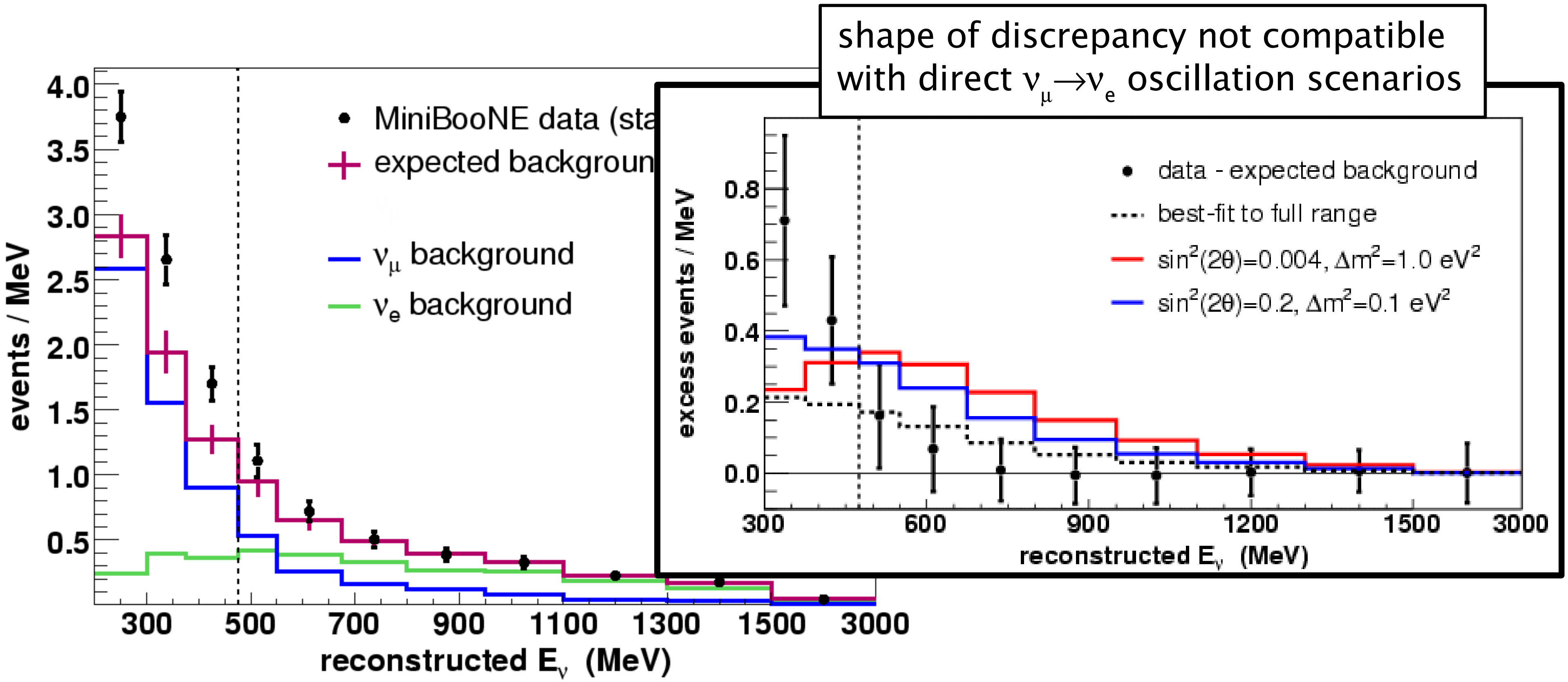


F u t u r e O u t l o o k

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 $\Delta \to N\gamma$	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 $\Delta \to N\gamma$ falling off
- Intrinsic ν_e negligible

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

- Intrinsic ν_e largest background

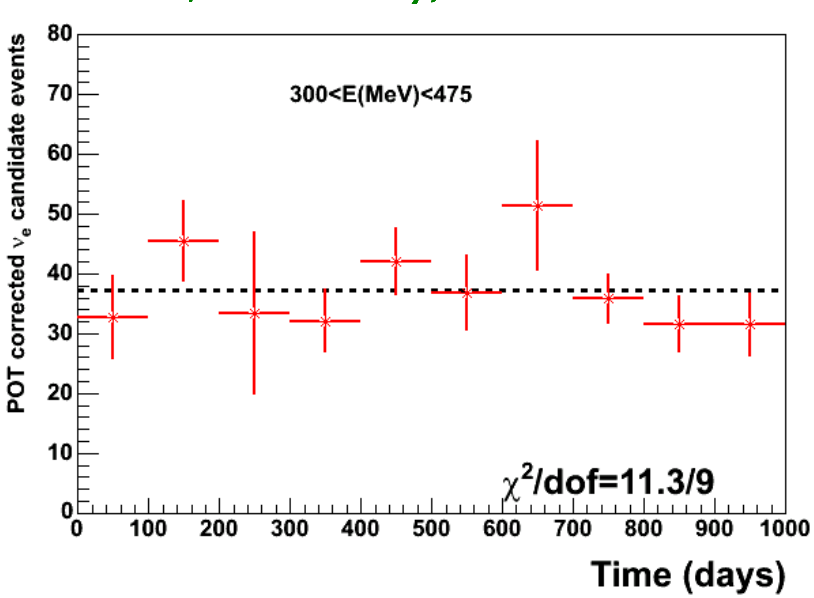
lower energy bins **oscillation analysis region**

Low Energy Discrepancy

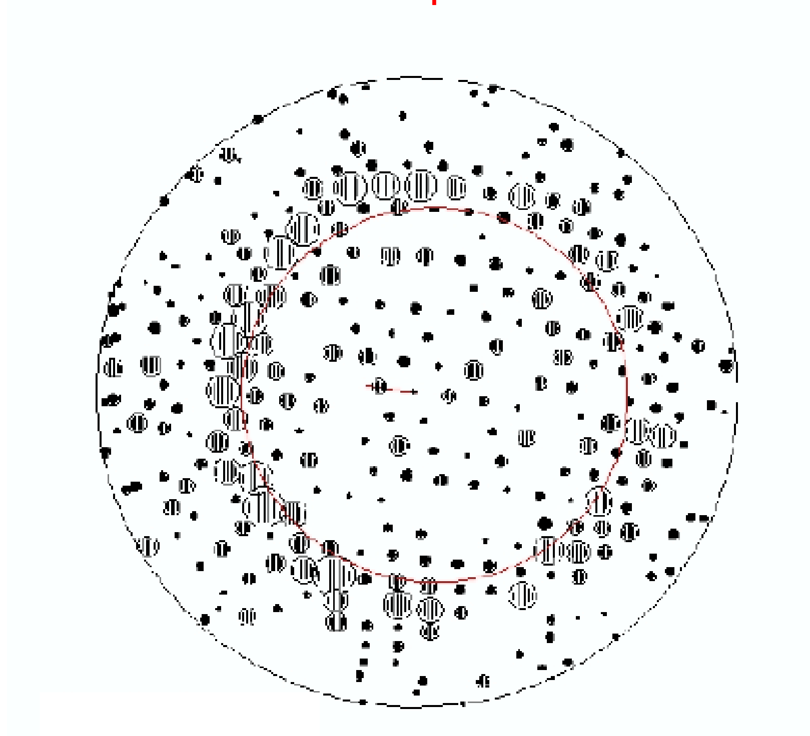
- ***investigating possible explanations:***
  - detector anomalies or reconstruction problems?
  - incorrect estimation of a background?
  - missing background?
  - new physics including exotic oscillation scenarios, neutrino decay, Lorentz violation?
  - is it related to excess seen by LSND?

No Detector anomalies found :

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



No Reconstruction problems found :



F u t u r e O u t l o o k

Future Run/Analysis Plans

- Working on several ***publications*** in support of and extensions to 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. . .

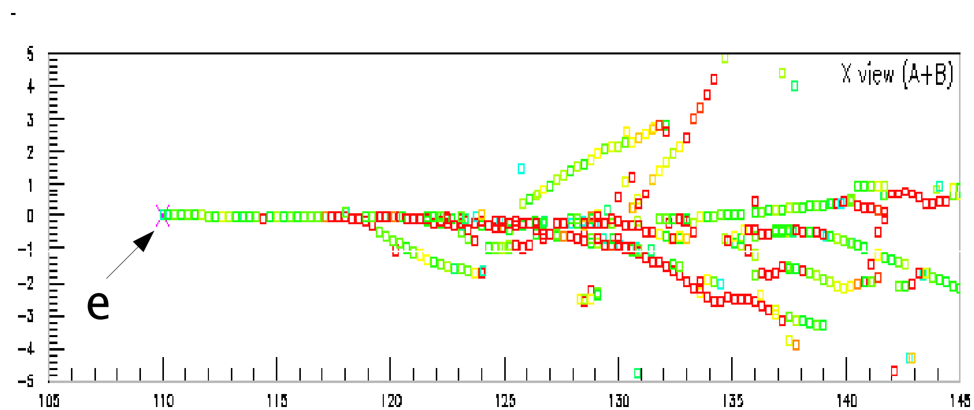
- Continue to re-examine low E backgrounds and significance of ***low E excess***

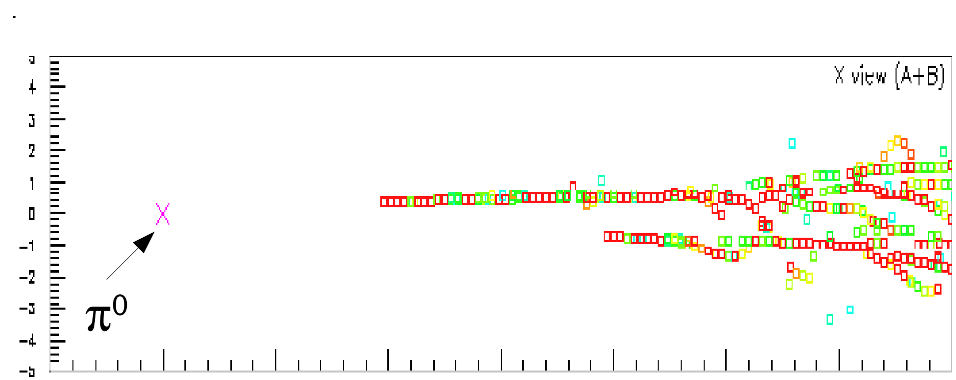
- MiniBooNE currently running in ***antineutrino mode*** and is proposing to run in this mode for several more years
  - important antineutrino low energy cross-sections not measured before
  - another low energy data set
  - direct test of LSND if enough statistics (sensitivities in upcoming PAC report)

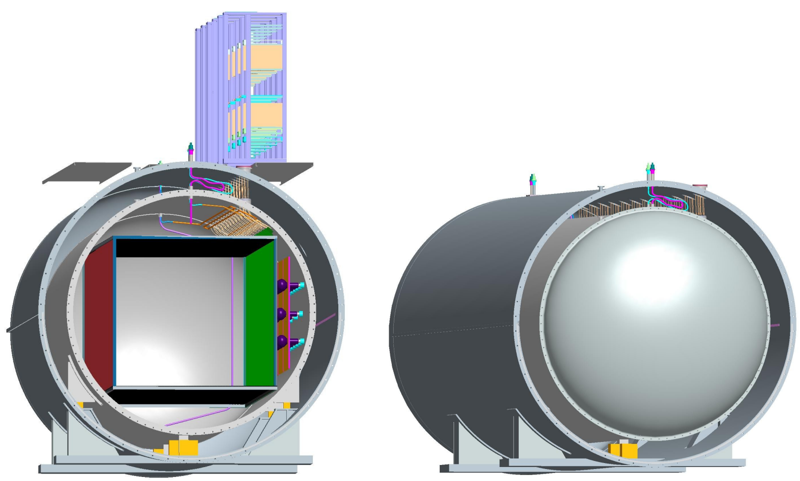
Future Outlook

Future Run/Analysis Plans

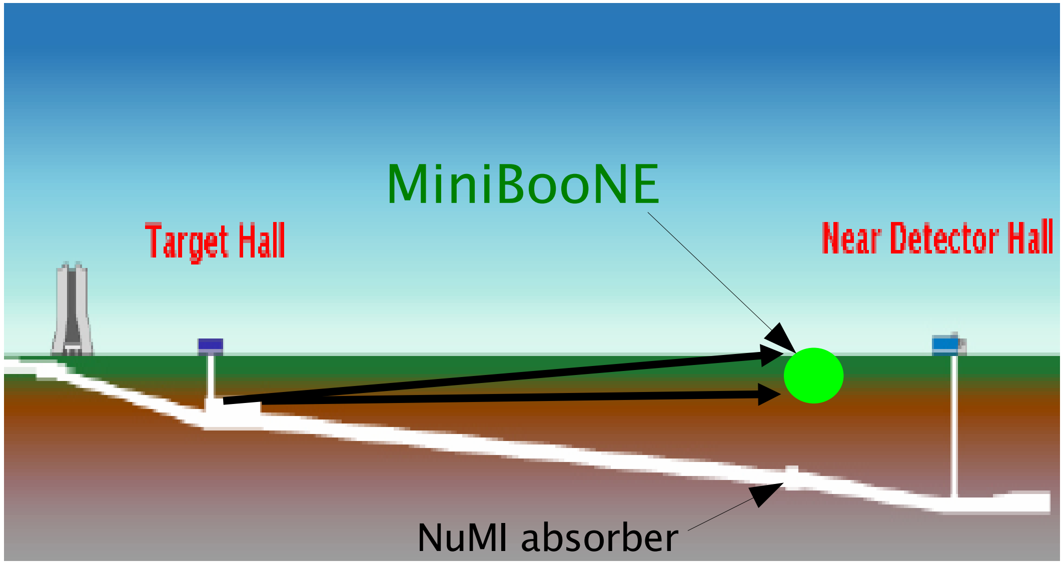
- Neutrino events in MiniBooNE from ***NuMI beam***
- ***SciBooNE*** currently taking data in Booster Neutrino Beam
- ***MicroBooNE, a 70 ton LArTPC detector***, has been proposed for BNB to study low energy region
  - sensitive at low energies
  - e/γ separation
  - ~80% efficiency
  - low backgrounds
  - liquid argon detector development





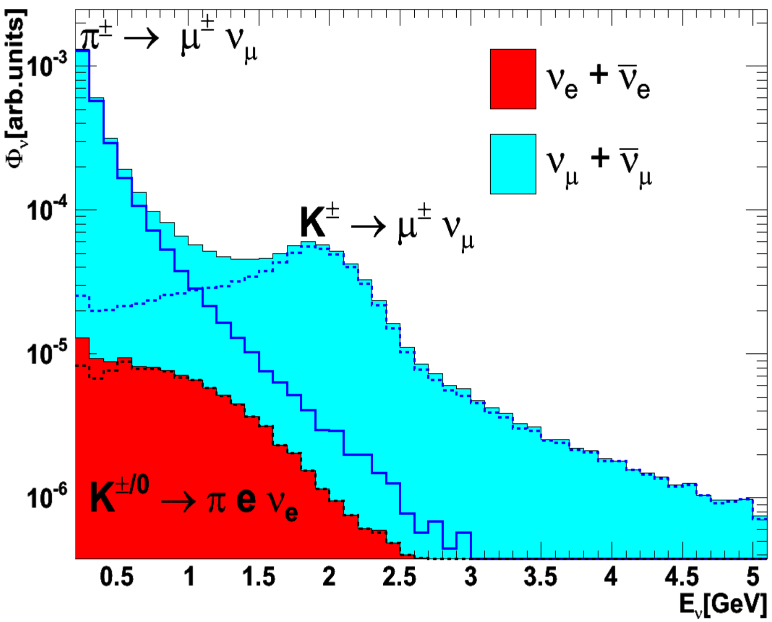


NuMI → MiniBooNE



- 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/0.75 GeV)

NuMI → MB flux prediction



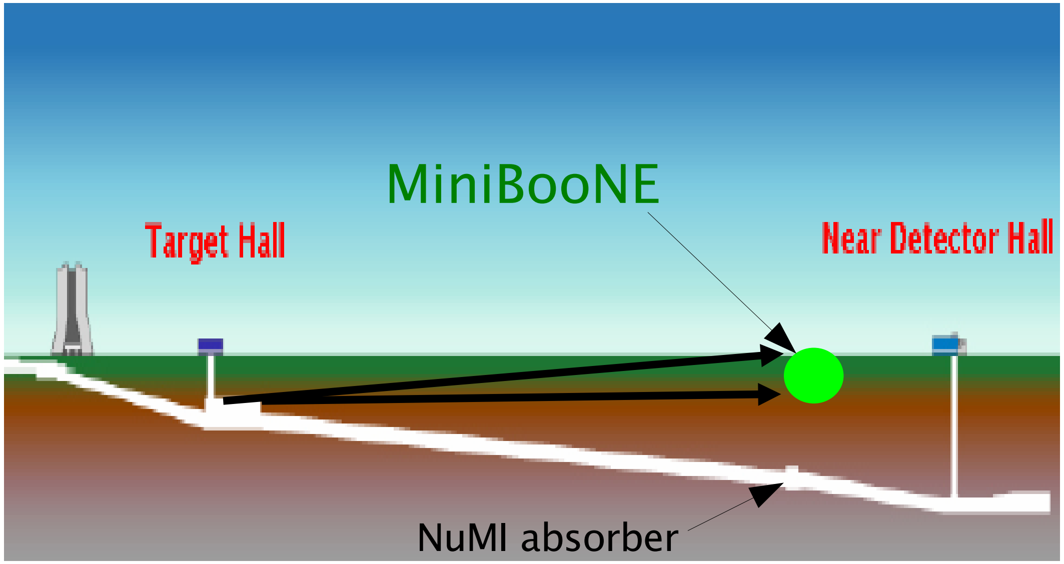
BNB → MB

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

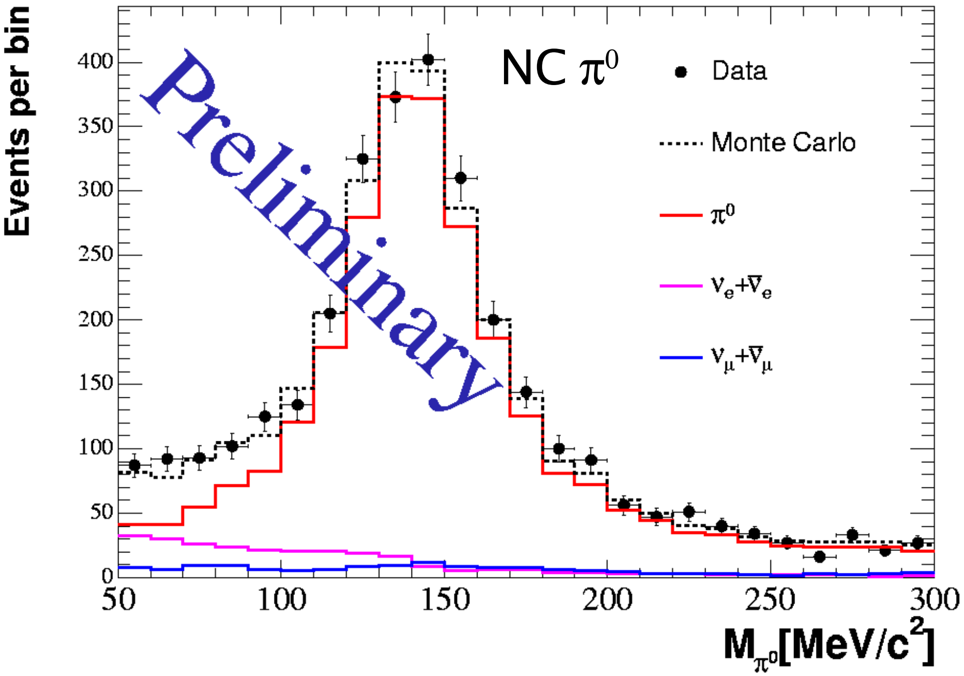
NuMI → MB

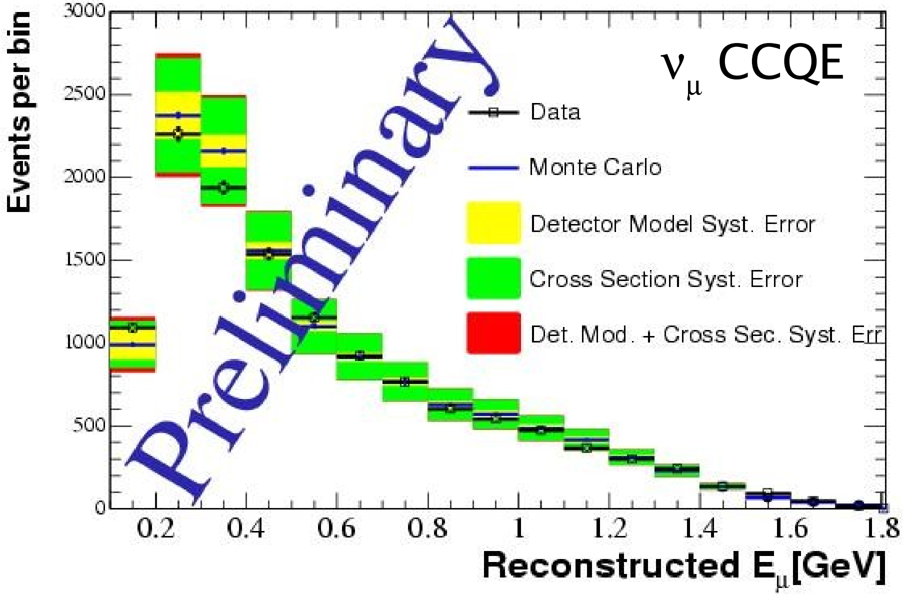
ν_μ	81%
$\bar{\nu}_\mu$	13%
ν_e	5%
$\bar{\nu}_e$	1%

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/0.75 GeV)
- nice agreement seen in ν_μ–CCQE and π^0 events
- ***ν_e analysis coming soon***





S u m m a r y

Summary

- **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

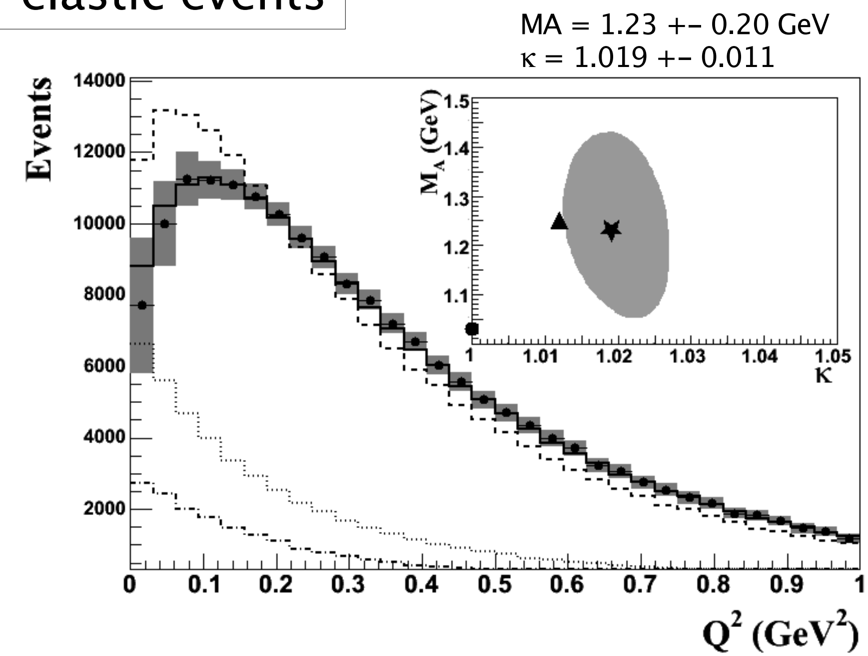
Domo arigato!

Backup Slides

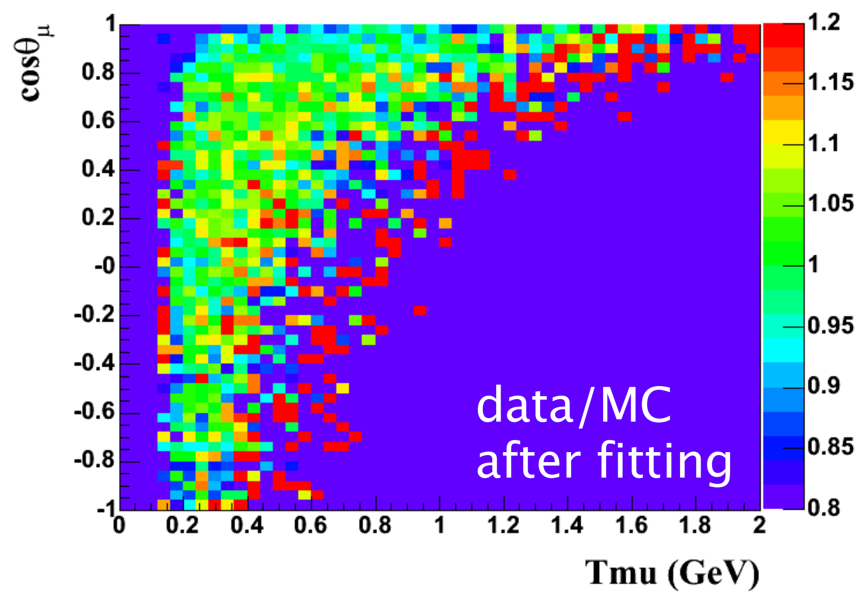
Neutrino Cross-section Model

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

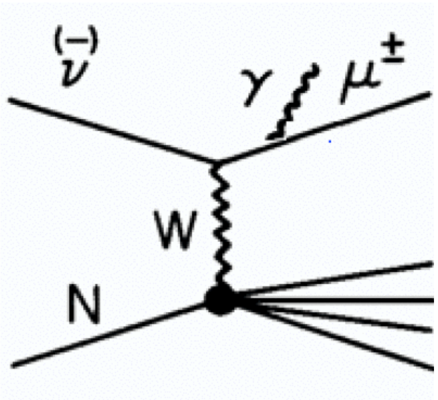


- From Q^2 fits to MiniBooNE ν_μ CCQE data:
  - M_A^{eff} -- effective axial mass
  - E_{lo}^{SF} -- Pauli Blocking parameter
- From electron scattering data:
  - E_b -- binding energy
  - p_f -- Fermi momentum

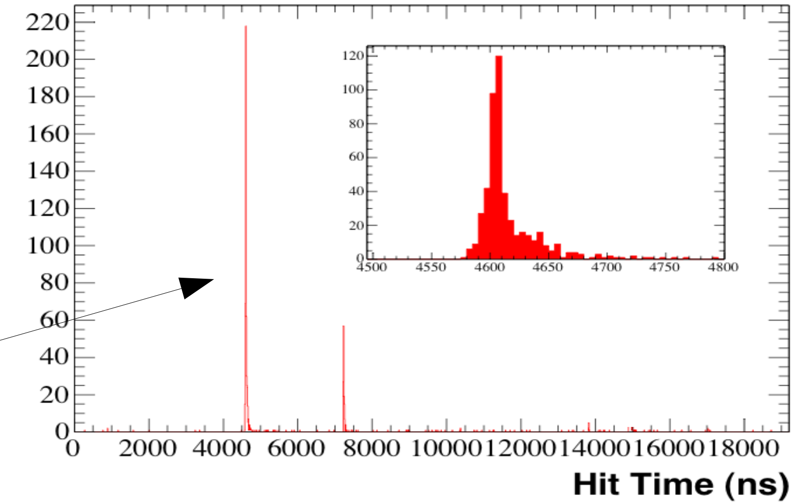


A.A. Aguilar-Arevalo et al., "Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon", arXiv:0706.0926 [hep-ex], submitted to Phys. Rev. Lett.

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 2nd sub-event and run PID on first sub-event only
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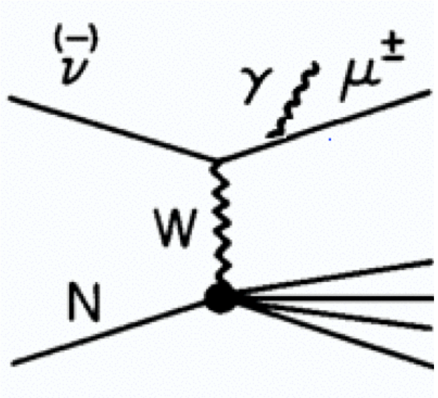
Muon bremsstrahlung



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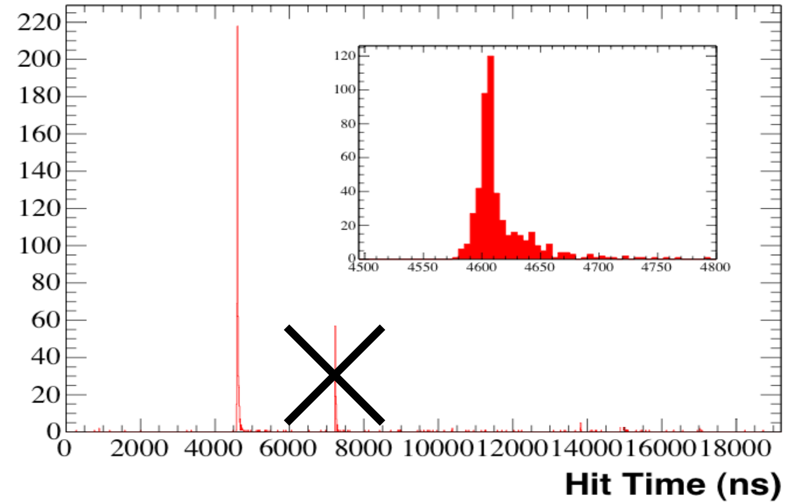

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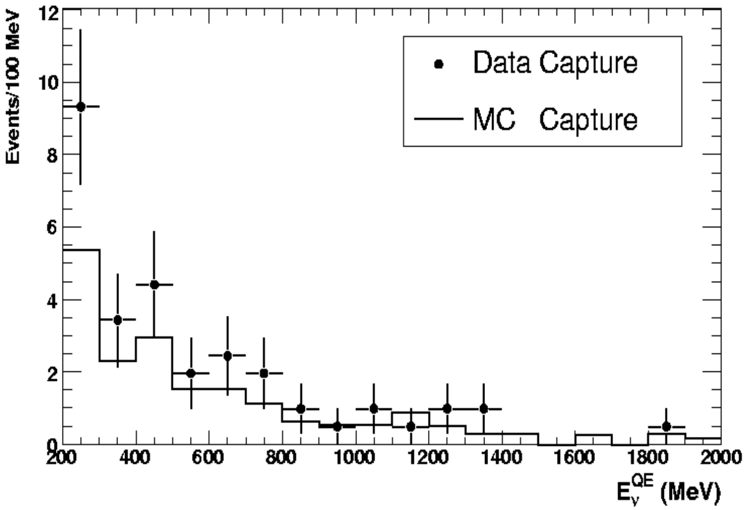
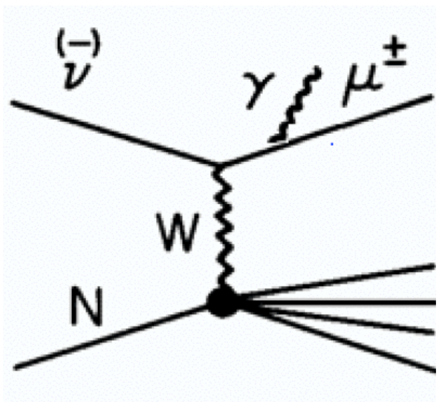


Muon bremsstrahlung



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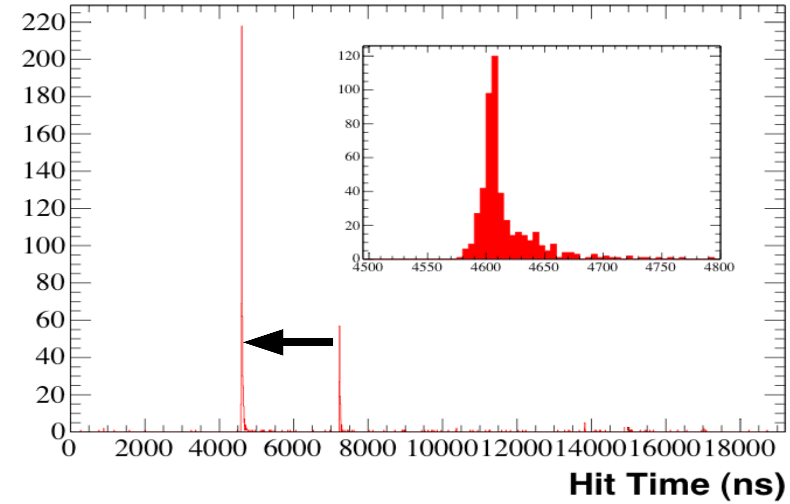

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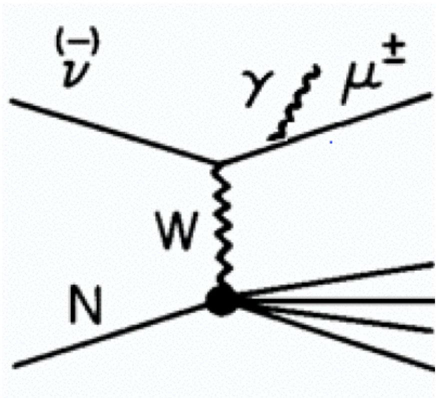
out of 10,000 events, the numbers passing ν_e cuts are:

28 Data
32 Monte Carlo

Muon bremsstrahlung



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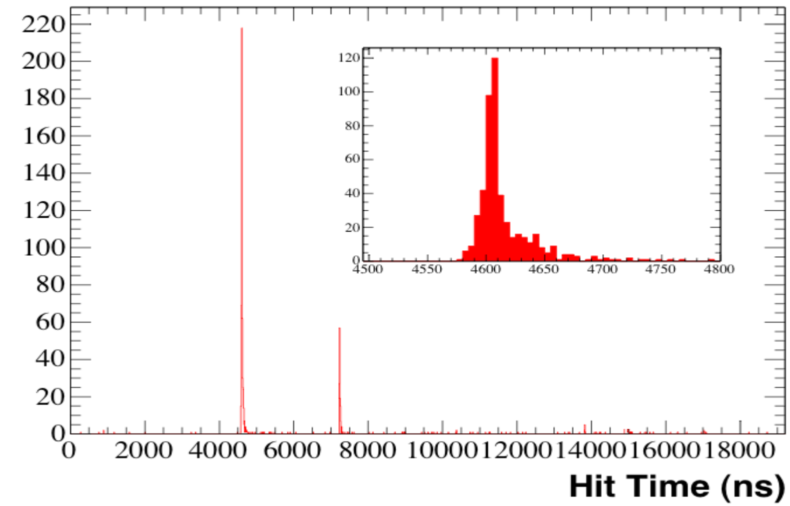

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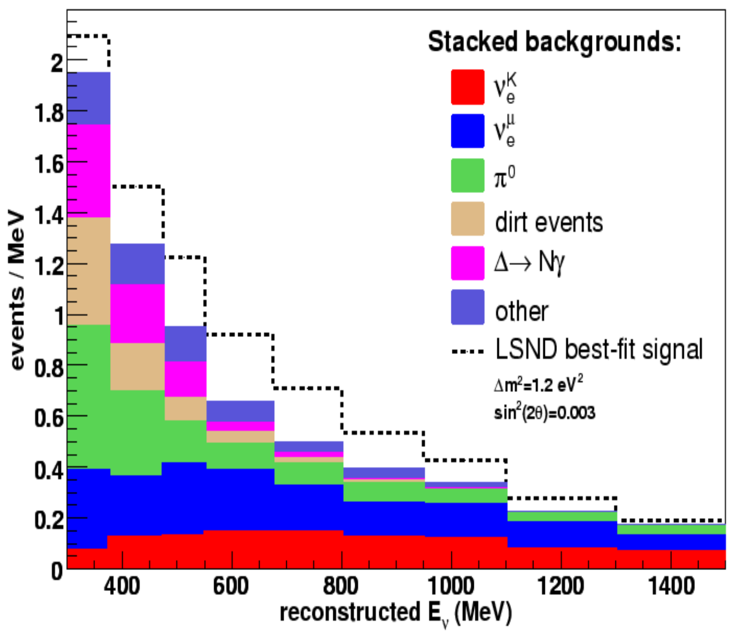
- can use the two sub-event sample to answer:
  - start with 2 sub-event CCQE sample, erase 2nd sub-event and run PID on first sub-event only
  - start with 2 sub-event CCQE sample, move 2nd sub-event in time to overlap the first sub-event (e/γ directly on top of μ)
- conclusion: ***these events still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

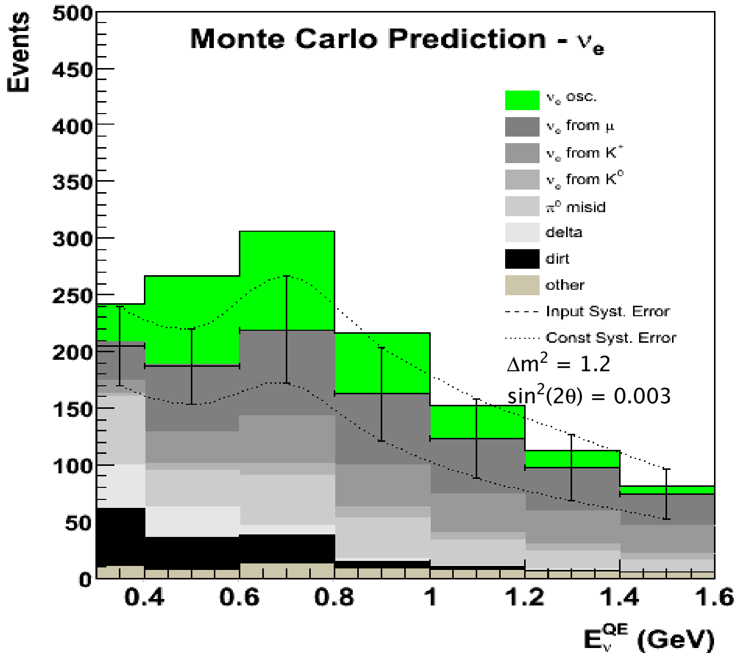
Background Predictions in Signal Region

TBL		BDT	
475 MeV – 1250 MeV		**300 MeV – 1600 MeV**	
ν_e^K	94	ν_e^K	253
ν_e^μ	132	ν_e^μ	343
π^0	62	π^0	224
dirt	17	dirt	117
$\Delta \to N\gamma$	20	$\Delta \to N\gamma$	78
other	33	other	54
	358		1069
LSND $\nu_\mu \to \nu_e$	126	LSND $\nu_\mu \to \nu_e$	273

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

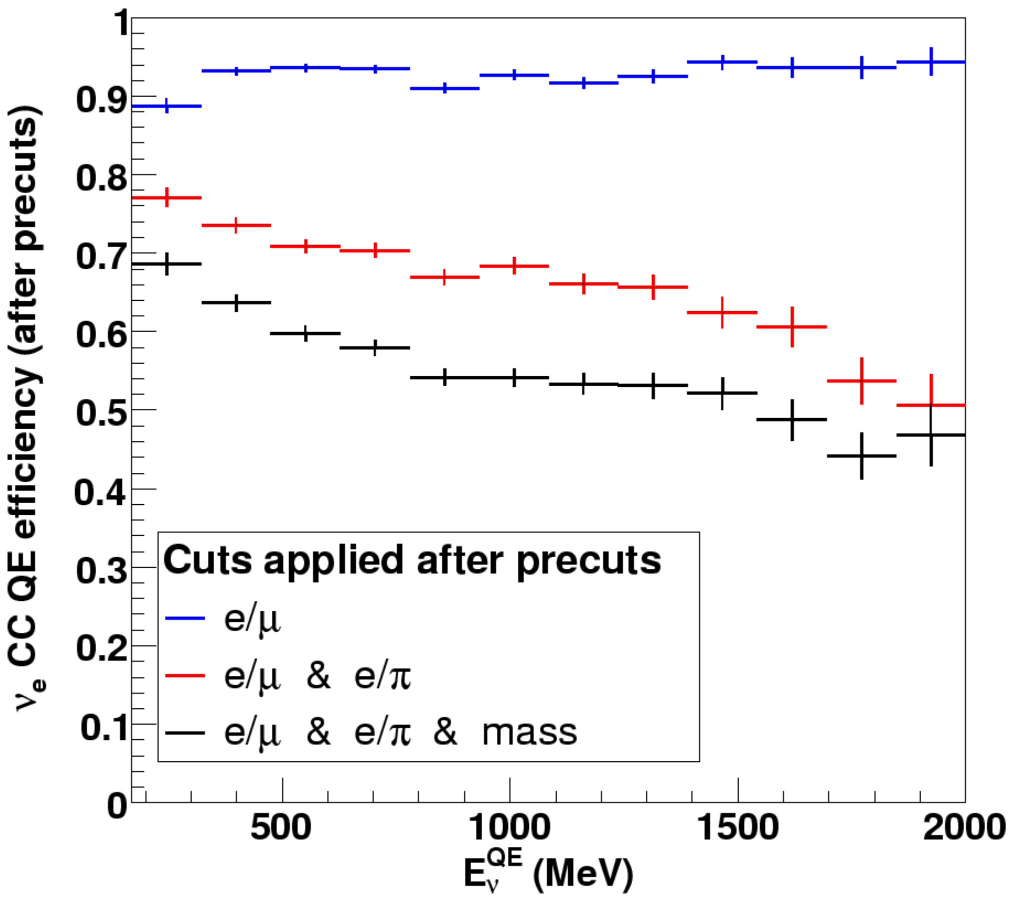
BDT: $\frac{S}{\sqrt{B}}=8.3$



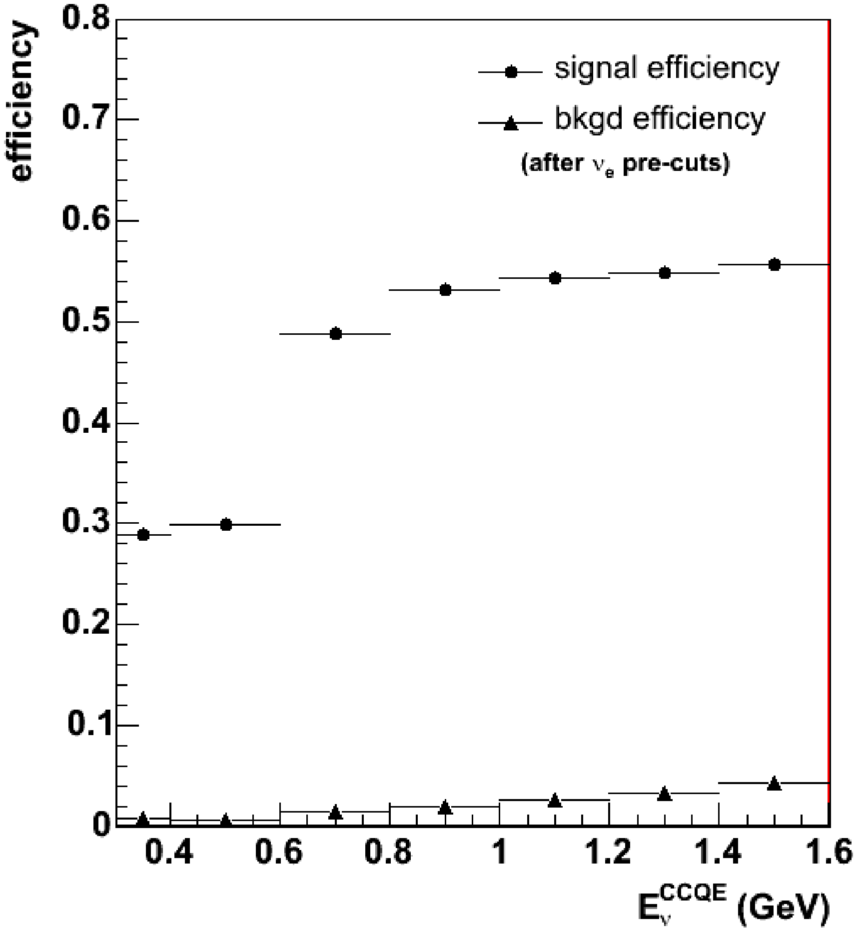


Signal Efficiency

TBL



BDT



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.

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

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

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

. . . and a χ^2 surface can be mapped