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

- Introduction and motivation for this oscillation search
- MiniBooNE design and analysis strategy
  - Brief aside on the prediction of neutrino fluxes
  - Description of neutrino events in the MiniBooNE detector
  - Overview of the oscillation analysis
- Constraining backgrounds for the oscillation analysis
- Maximizing ν_e appearance sensitivity
- MiniBooNE results & outlook

Dave Schmitz
Columbia University

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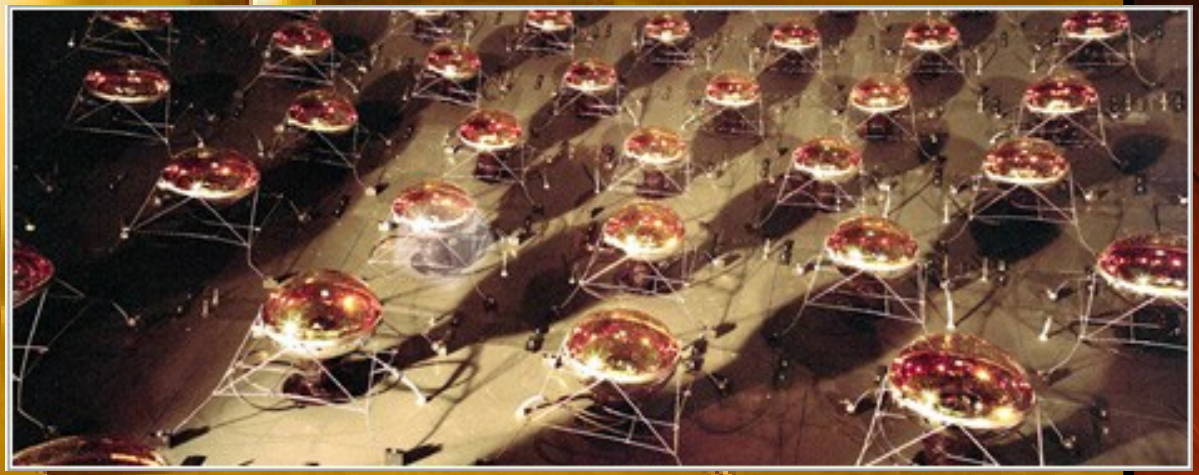

Neutrino Oscillations

- 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

mixing matrix describing mass state content of flavor states

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

mass states

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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
- $\Delta m_{ij}^2 = m_i^2 - m_j^2$: mass squared splitting between states
- **L** : the travel path-length of the neutrino
- **E** : the energy of the neutrino

Neutrino Oscillations

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- Non-zero mass means mass eigenstates ≠ flavor eigenstates:

Simplified case of direct 2 neutrino oscillations

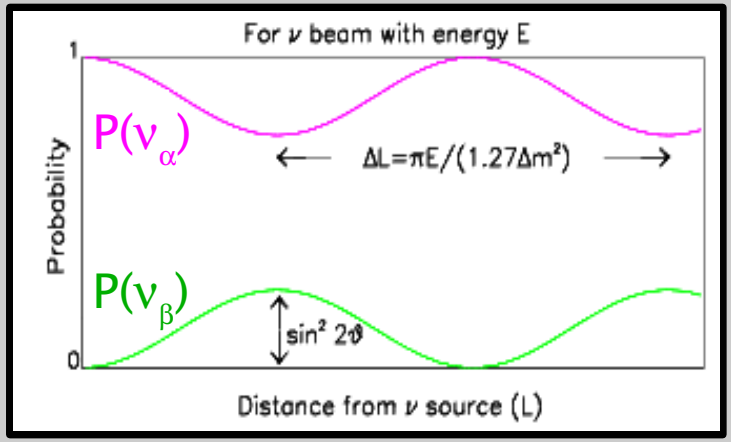
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos(\theta_{ij}) & \sin(\theta_{ij}) \\ -\sin(\theta_{ij}) & \cos(\theta_{ij}) \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

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

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

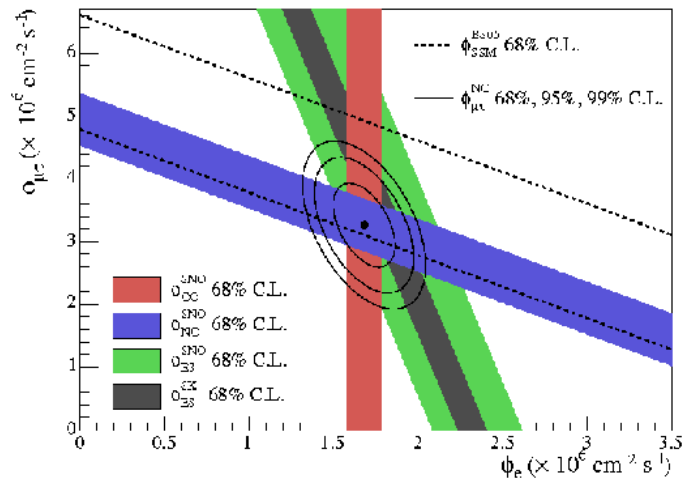


Neutrino Oscillations

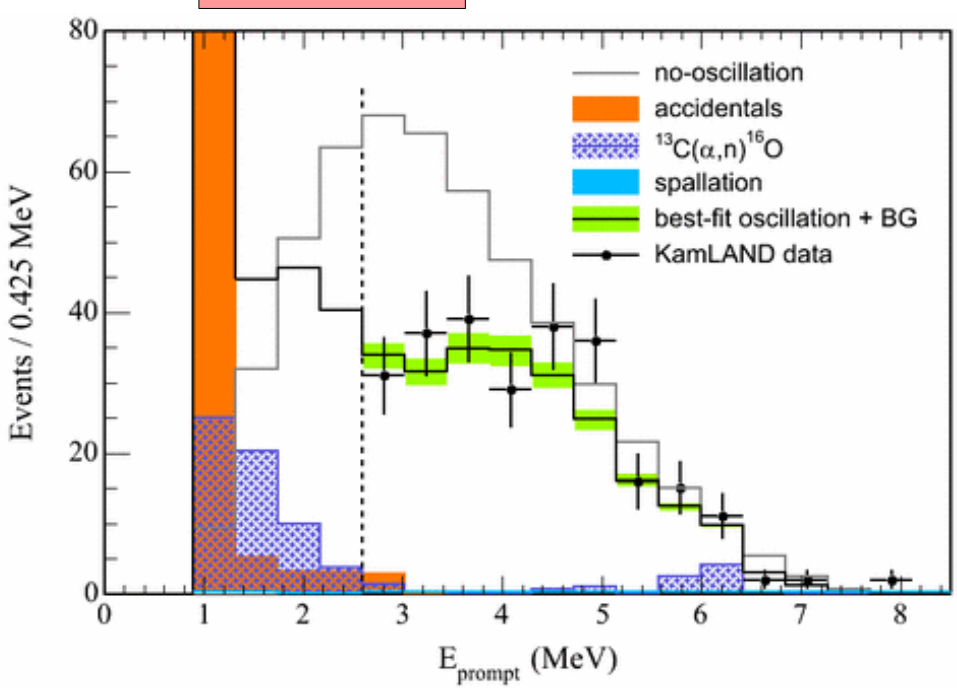
- ***First*** experimental evidence was seen in 1968 by R. Davis in the detection of solar neutrinos
  - observed ~1/3 as many ν_e from the sun as expected
  - disappearance $\nu_e \rightarrow \nu_x$
  - **$\Delta m^2 \sim 8 \times 10^{-5}$ eV^2**
  - later confirmed by SNO (solar), Super-K (solar) and KamLAND (reactor)

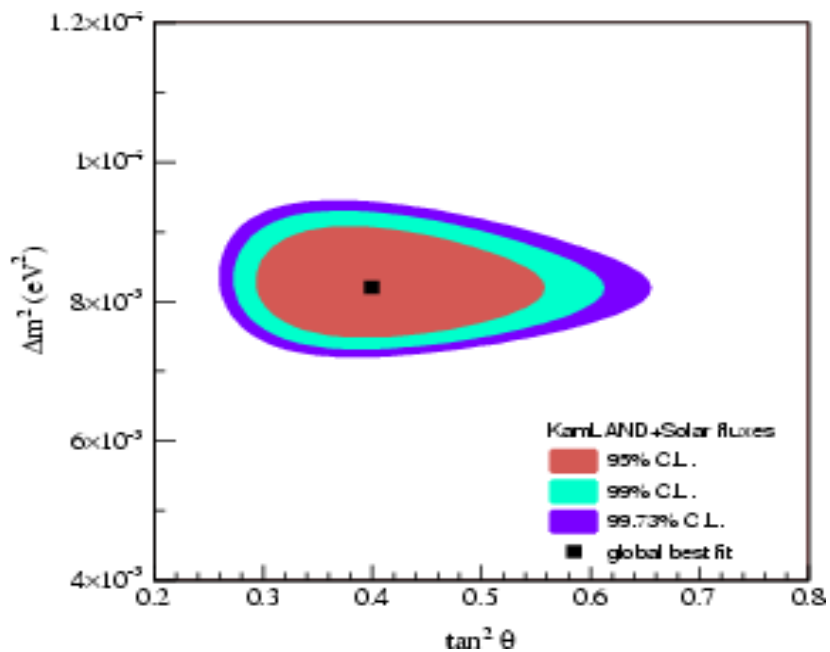
$$\Delta m^2_{12}$$

SNO



KamLAND hep-ex/0406035

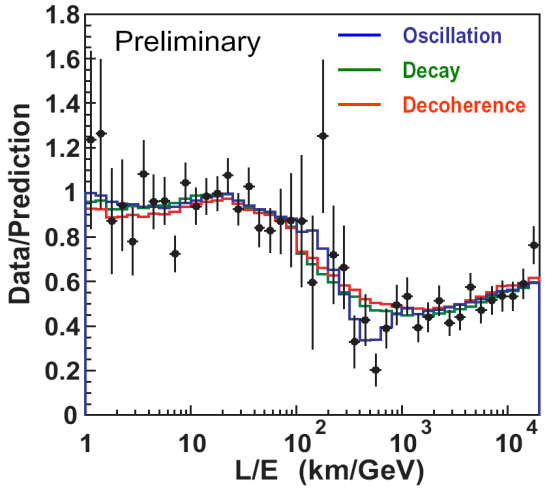




Neutrino Oscillations

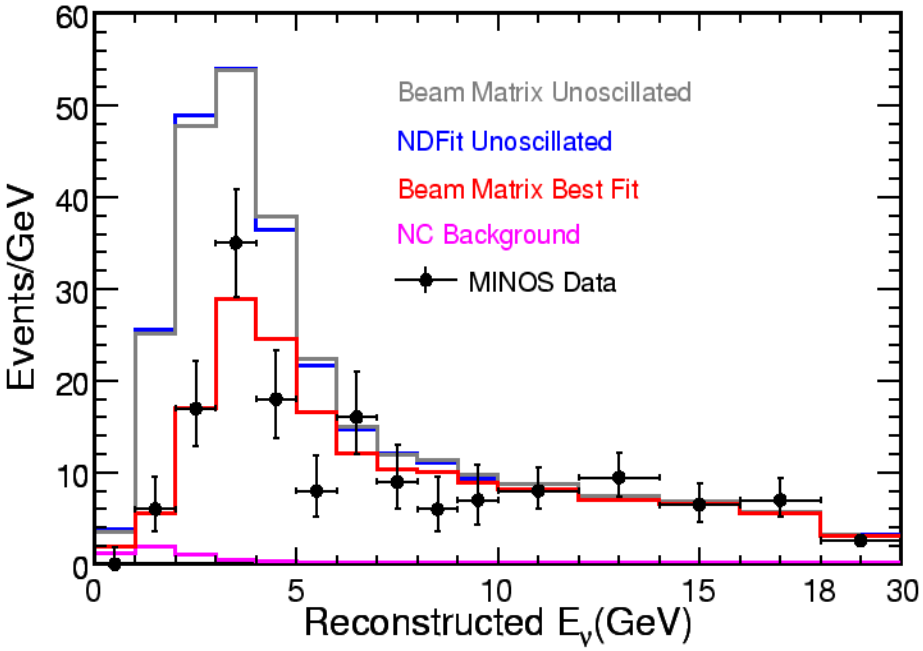
- Then a ***different*** mixing was seen by Super-K in neutrinos from the atmosphere
  - observed ~1/2 as many upward going ν_μ as downward going
  - disappearance $\nu_\mu \rightarrow \nu_x$
  - **$\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2**
  - later confirmed by K2K (accelerator) and MINOS (accelerator)

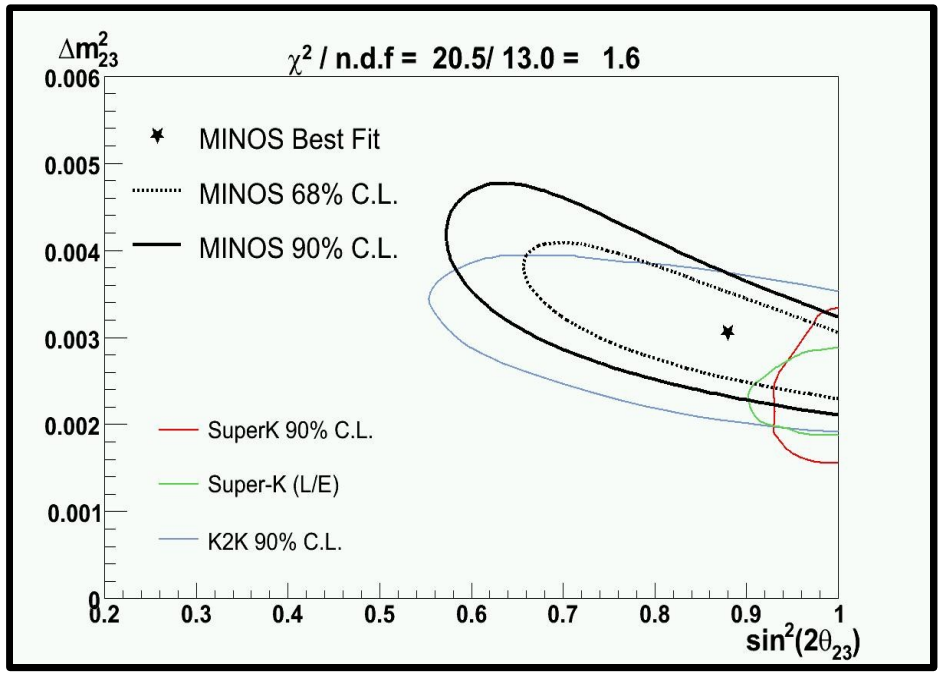
Super-K hep-ex/0404034



$$\Delta m^2_{23}$$

MINOS arXiv:0711.0769

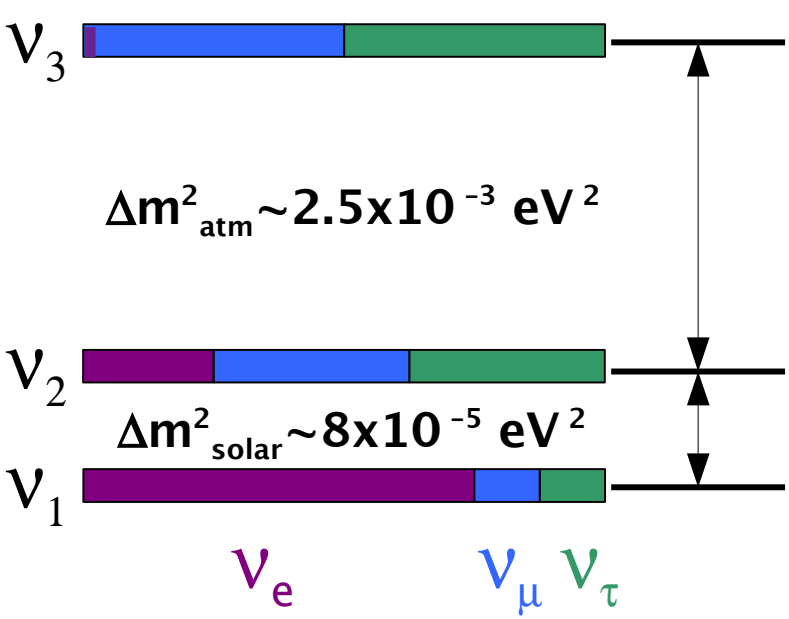


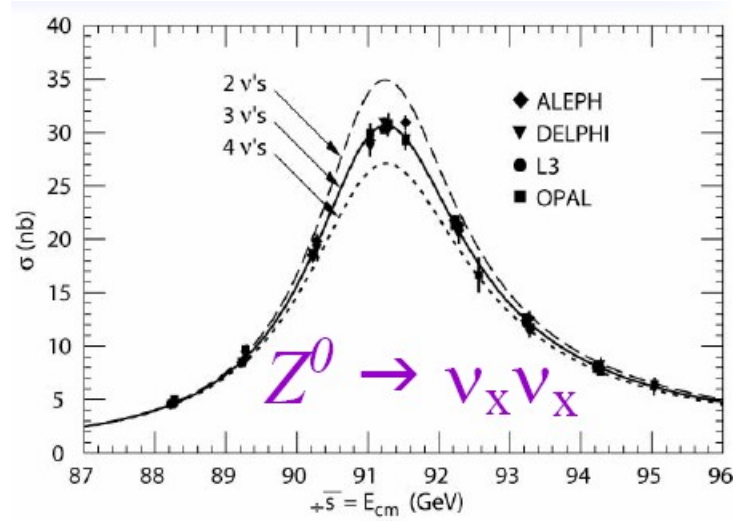


Neutrino Oscillations

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

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





- As nice and neat as this seems to us today, neutrino oscillations are relatively new to mainstream particle physics.

"This is about the simplest nontrivial quantum system conceivable. It is a crude model for **neutrino oscillations**. . . . . At present this is highly speculative – there is no experimental evidence for neutrino oscillations; however, a very similar phenomenon does occur in the case of neutral K-mesons."

David J. Griffiths – ***Introduction to Quantum Mechanics*** (Problem 3.58) **1995**

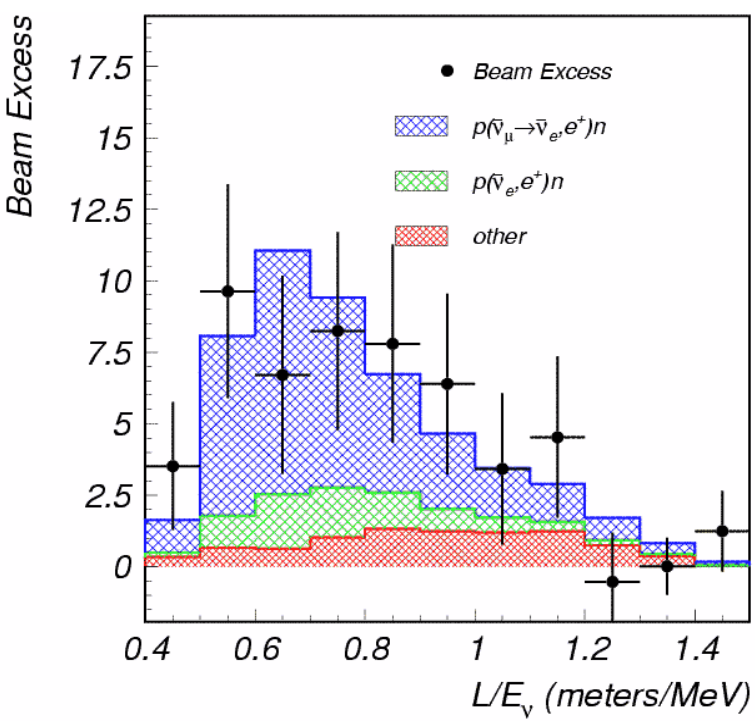
Experimental evidence for physics beyond the Standard Model !!!

Neutrino Oscillations

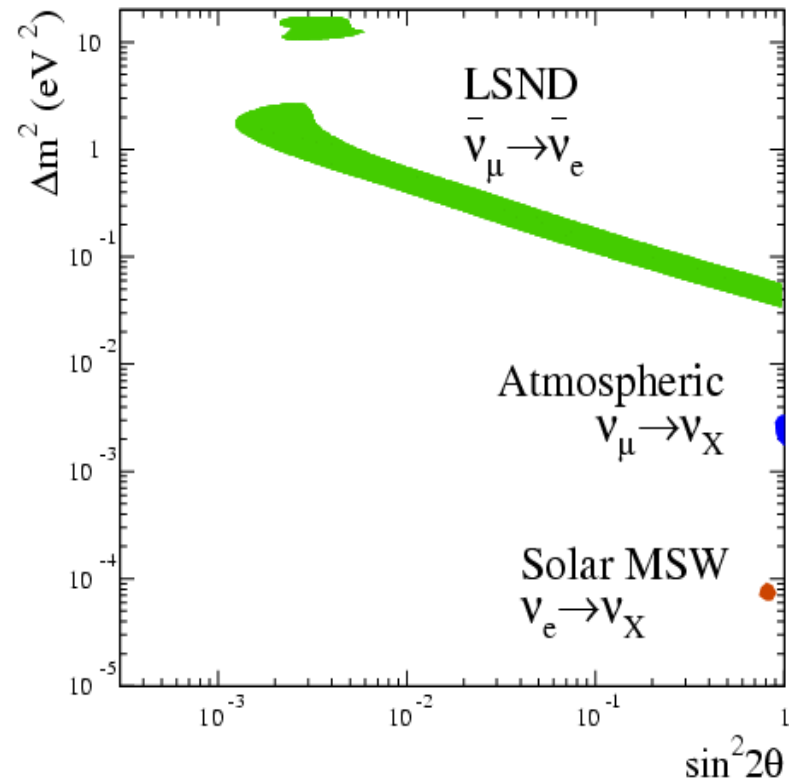
BUT . . .

- evidence for a ***third*** mixing was reported by the LSND experiment at Los Alamos
  - observed an excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam. 87.9 ± 22.4 ± 6.0 (3.8σ)
  - appearance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - **$\Delta m^2 \sim 10^0$ eV^2**
  - later experiments reduced allowed regions, but never confirmed

LSND hep-ex/0104049



Δm^2 ??

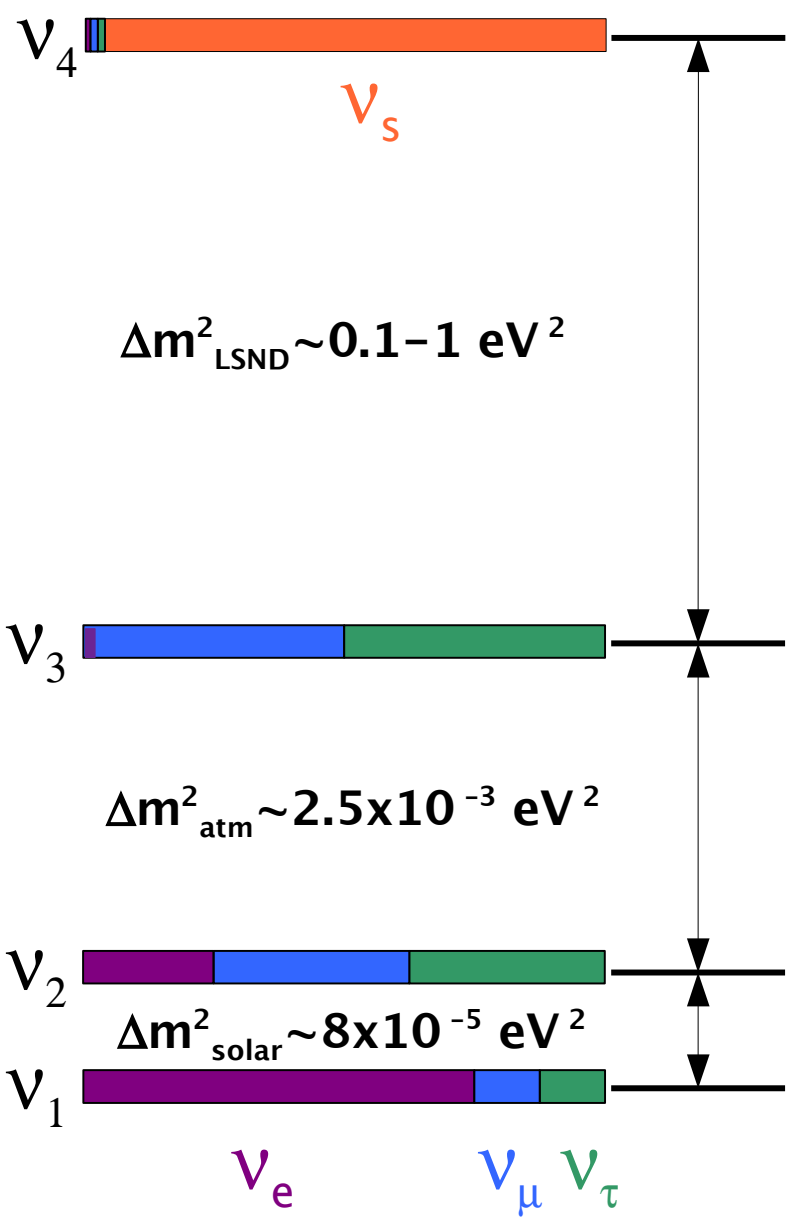


- If interpreted as 2 flavor oscillations, implies a $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probability of
  (**0.264** +– 0.067 +– 0.045)%

$$\sim 1 \neq 0.002508 = 0.00008 + 0.0025$$

$$\Delta m^2_{LSND} \neq \Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$

Neutrino Oscillations



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

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

- 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. . .**

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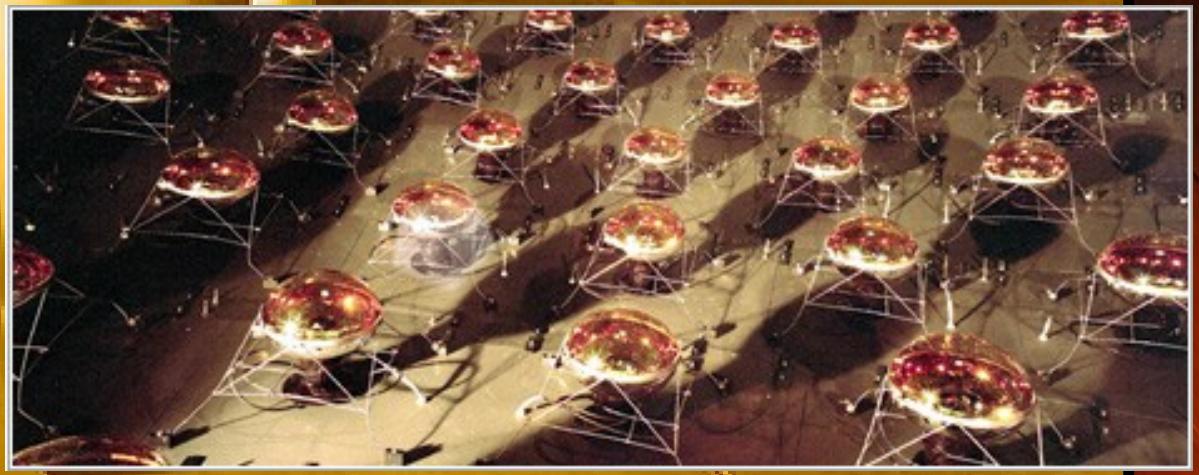


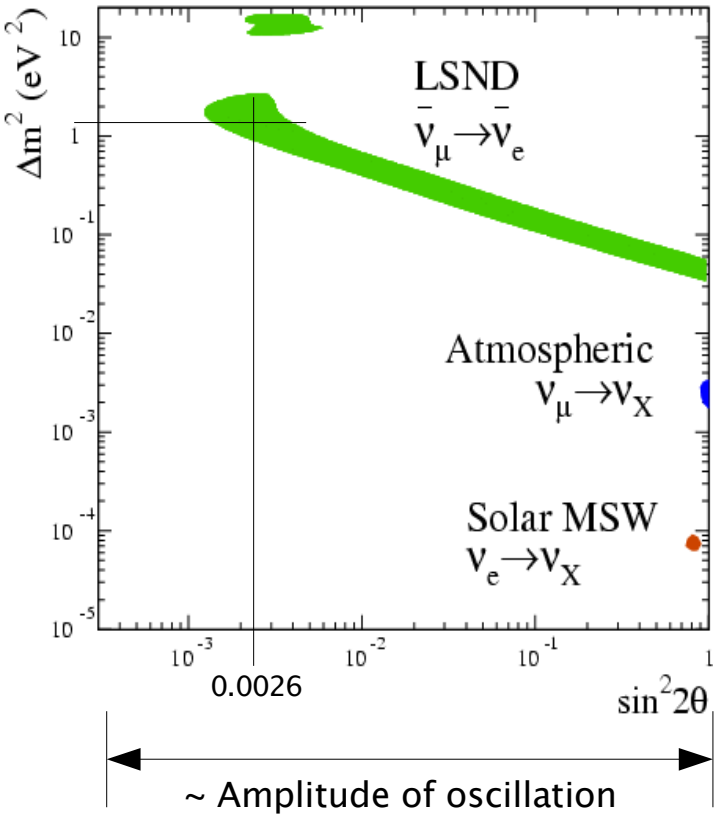
The MiniBooNE Collaboration

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

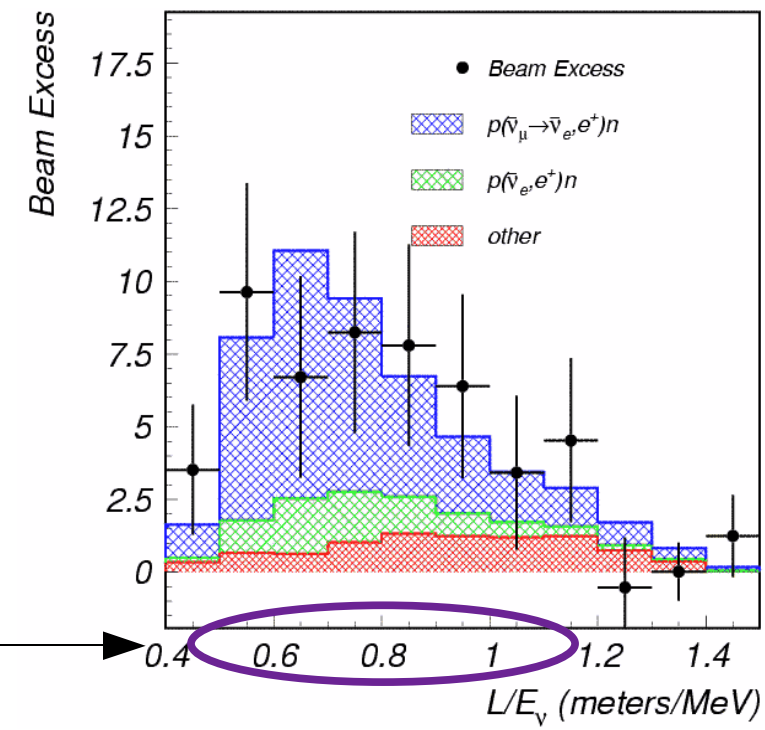
MiniBooNE Design and Analysis Strategy

- ***Two key factors*** in designing an experiment to look for these oscillations?



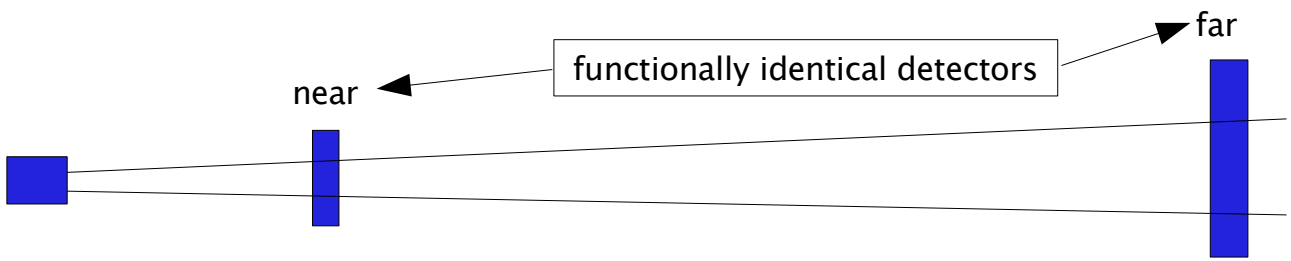
- **LSND best fit probability is tiny** **(~0.26%)**
- **Atm & solar effects are large** **(>60%)**

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



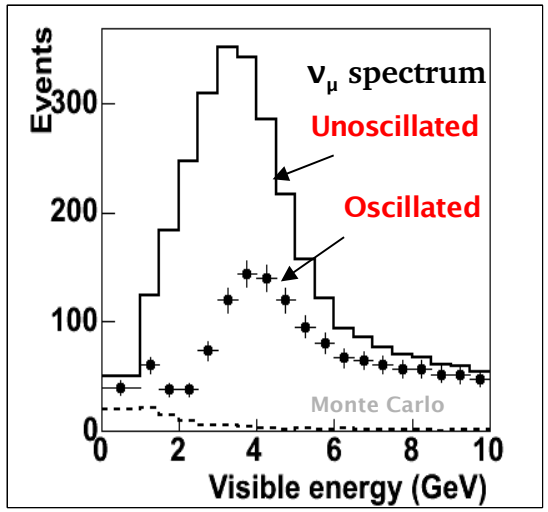
MiniBooNE Design and Analysis Strategy

long baseline, two detector disappearance experiment



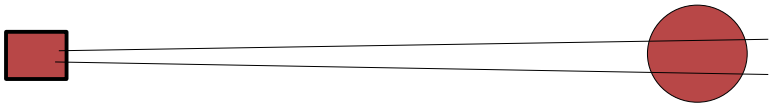
here you see the
unoscillated ν_μ flux

here you see the
oscillated ν_μ flux



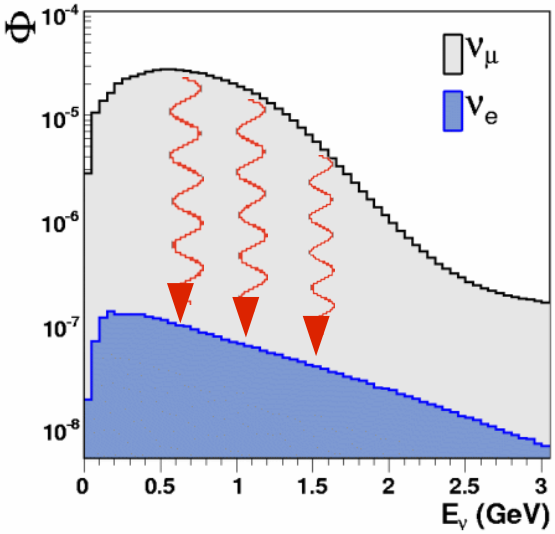
plot shamelessly stolen from MINOS collaboration

short baseline, one detector appearance experiment



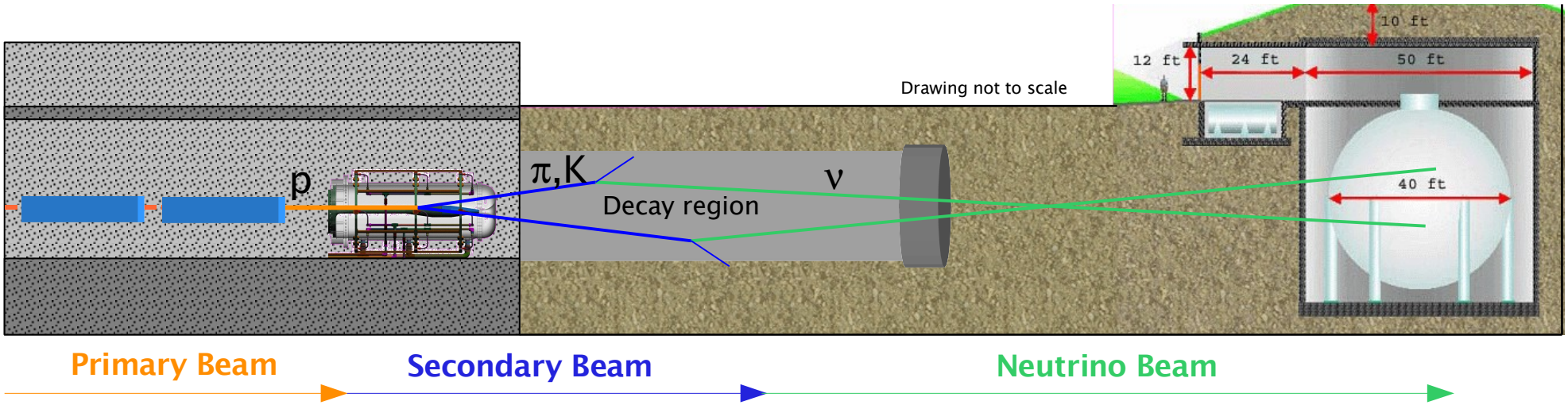
here you also see the
oscillated ν_μ flux
appearing as ν_e

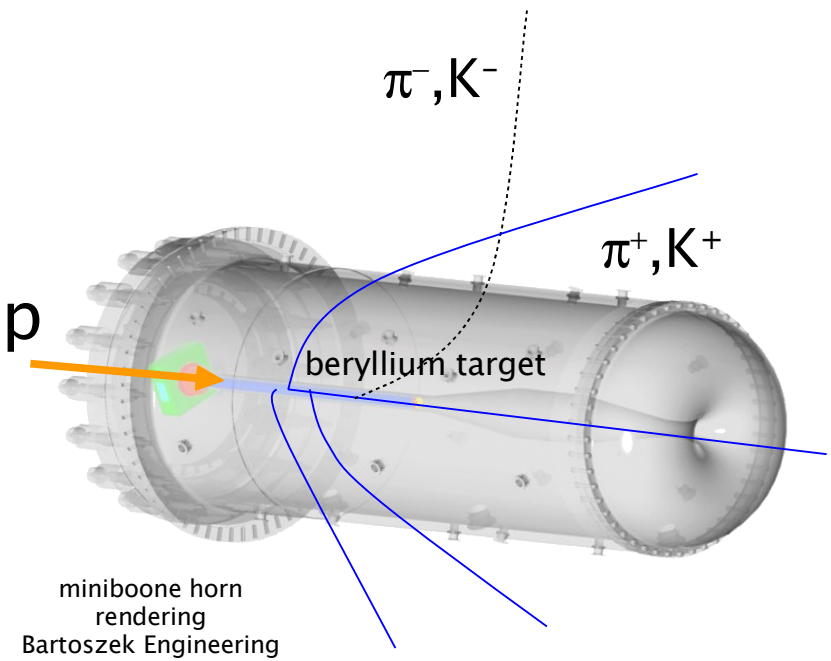
here you see a ν_μ flux
that is only 0.25% oscillated
effectively unoscillated ν_μ



MiniBooNE will look for an excess of ν_e events (~0.26% of ν_μ) above the predicted ν_e background (~0.6% of ν_μ) and ν_μ mis-identifications

MiniBooNE Design and Analysis Strategy





miniboone horn rendering
Bartoszek Engineering

- 8 GeV protons from Fermilab Booster focused on to a 1.7λ beryllium target inside a 174 kA focusing horn
- π and K decay to produce neutrinos with mean energy ~0.7 GeV
- 800T pure mineral oil detector approx ½ km away
  - 12 m diameter sphere
  - 1280 photomultiplier tubes
  - 240 optically isolated tubes in a veto region

$$\frac{<L>}{<E>} \approx \frac{0.540\,\mathrm{km}}{0.7\,\mathrm{GeV}} \approx 0.5-1.0$$

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

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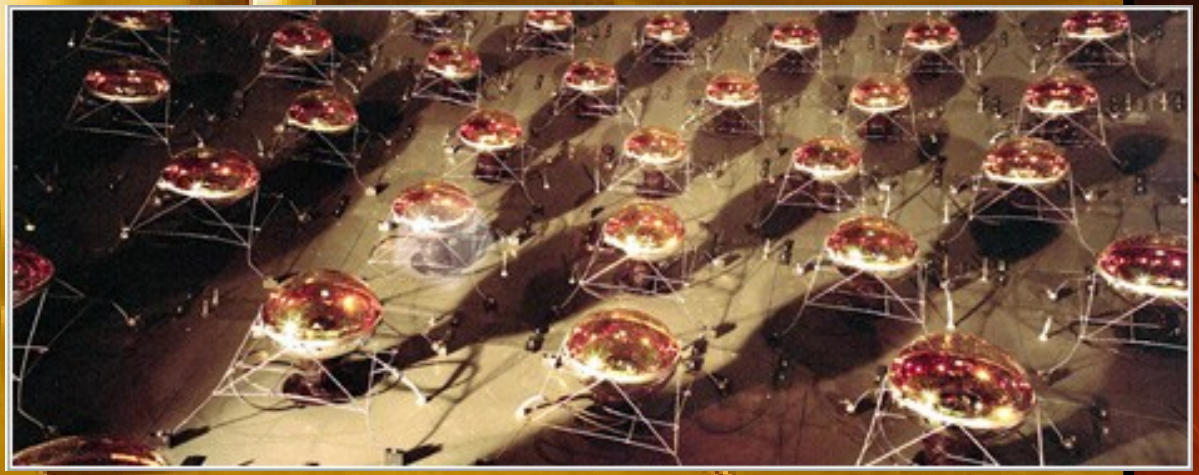
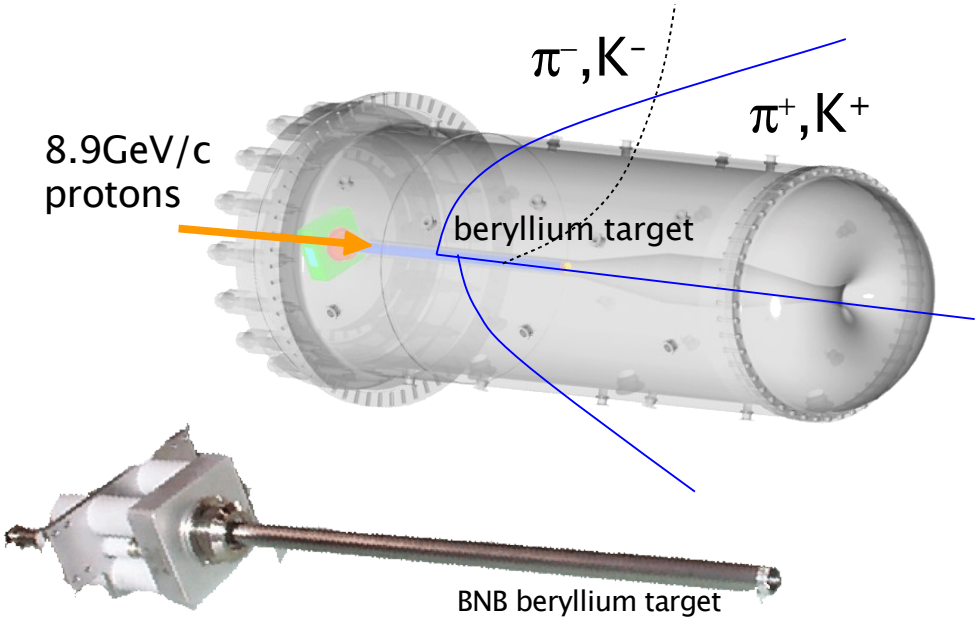
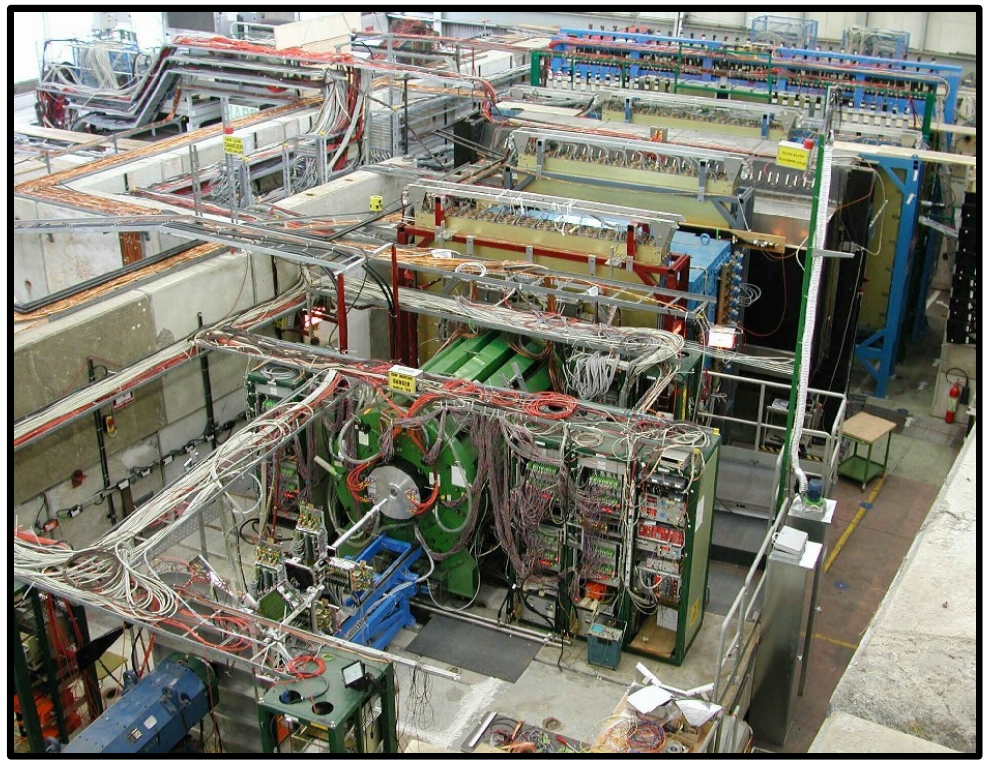


Neutrino Flux Prediction

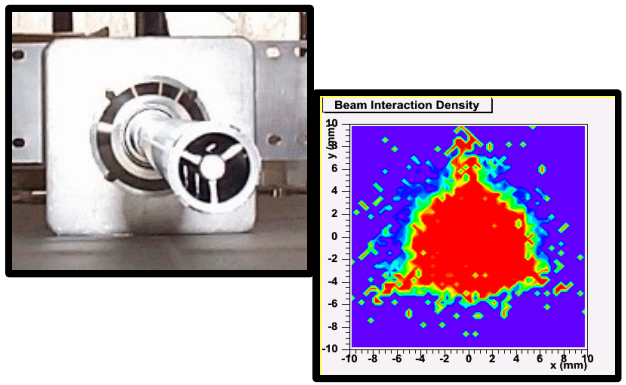
An aside on Hadron Production measurements at HARP – PS214 at CERN

- Hadron production measurements from the **HARP** and **E910** experiments constrain secondary production in the target





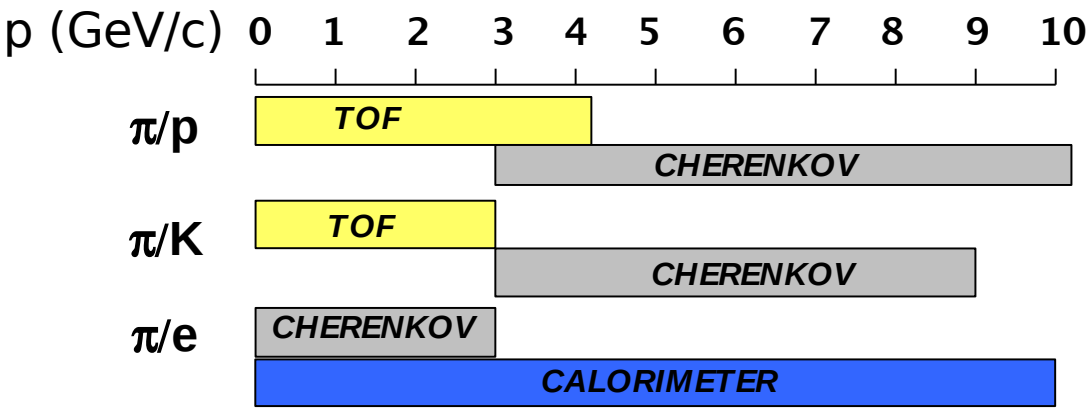
HARP spectrometer – PS214 at CERN

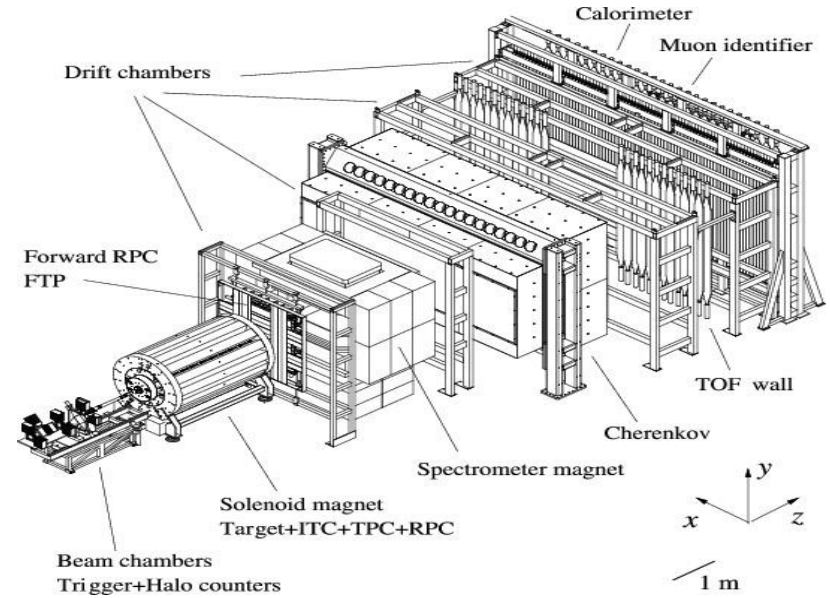


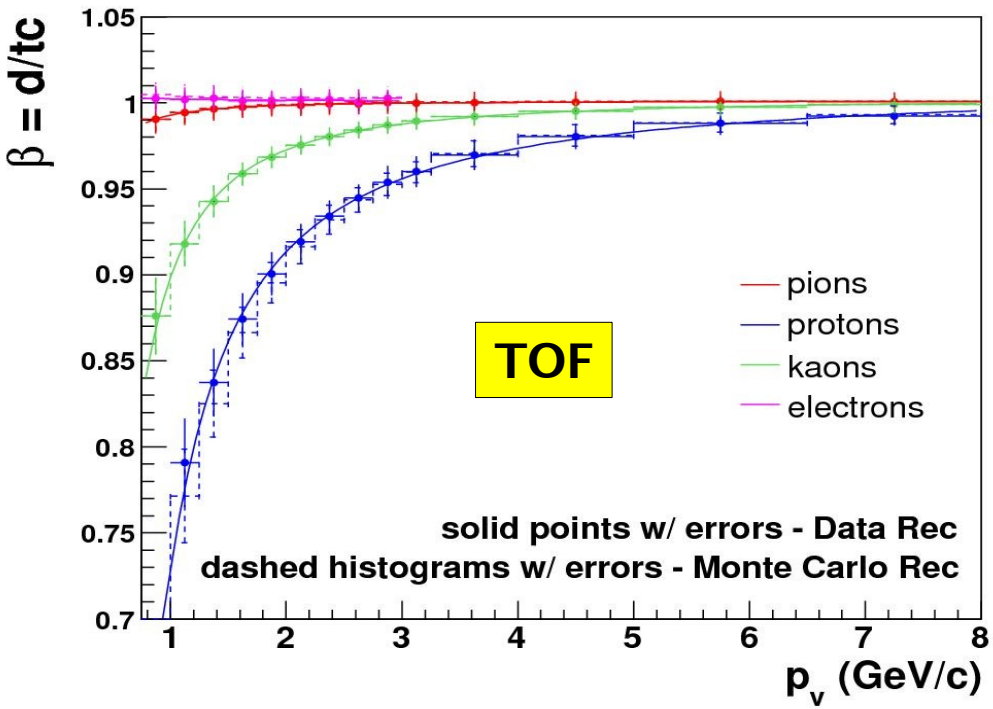
No target	5.7 M events	Subtraction
5% Be Disc	7.3 M events	p+Be x-section
50% λ MB replica	5.2 M events	Effects specific to MB target reinteraction absorption scattering
100% λ MB replica	6.4 M events	

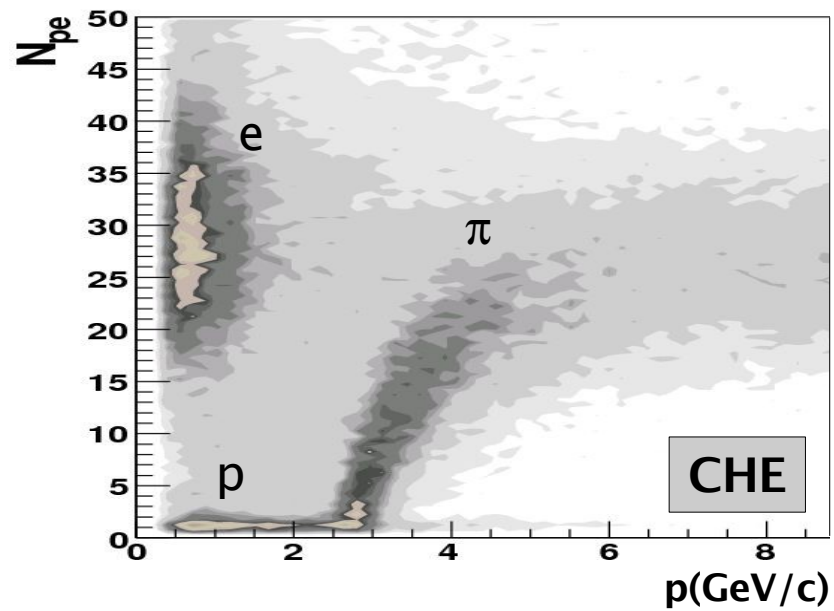
Neutrino Flux Prediction

An aside on Hadron Production measurements at HARP – PS214 at CERN







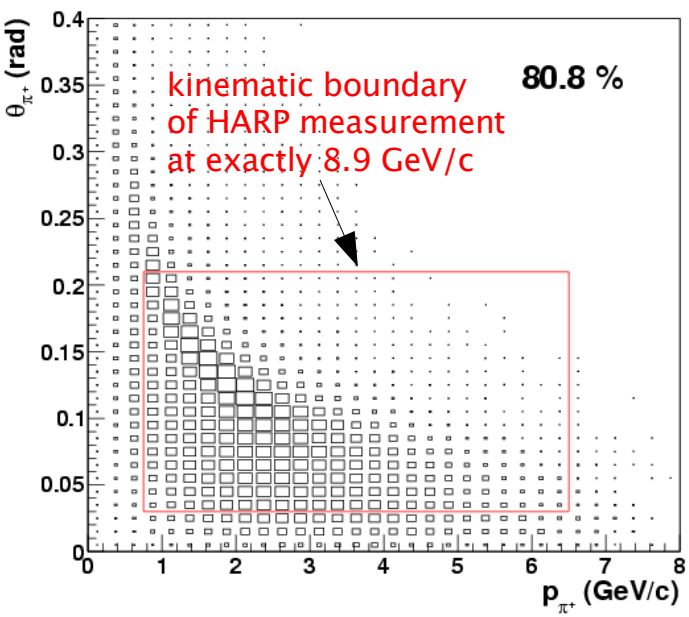


Neutrino Flux Prediction

An aside on Hadron Production measurements at HARP – PS214 at CERN

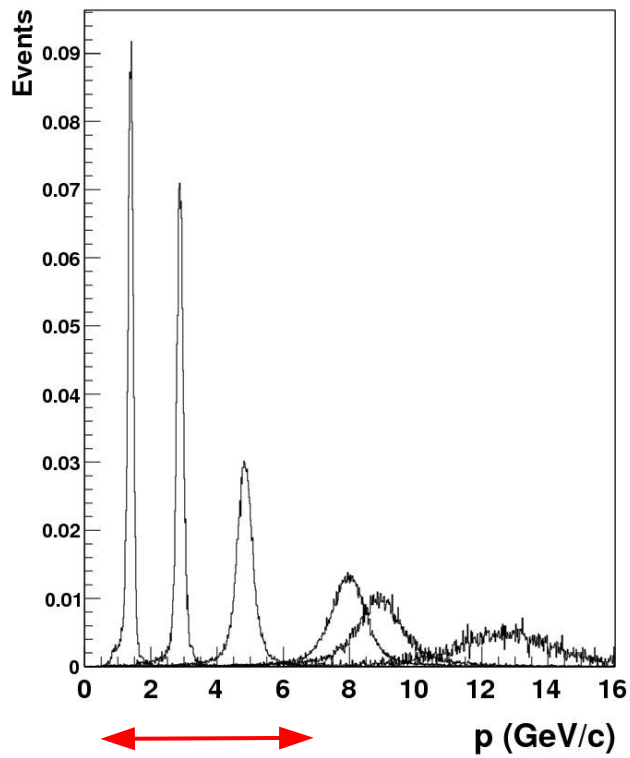
- HARP forward spectrometer well suited to measure relevant pions for Booster Neutrino Beamline

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



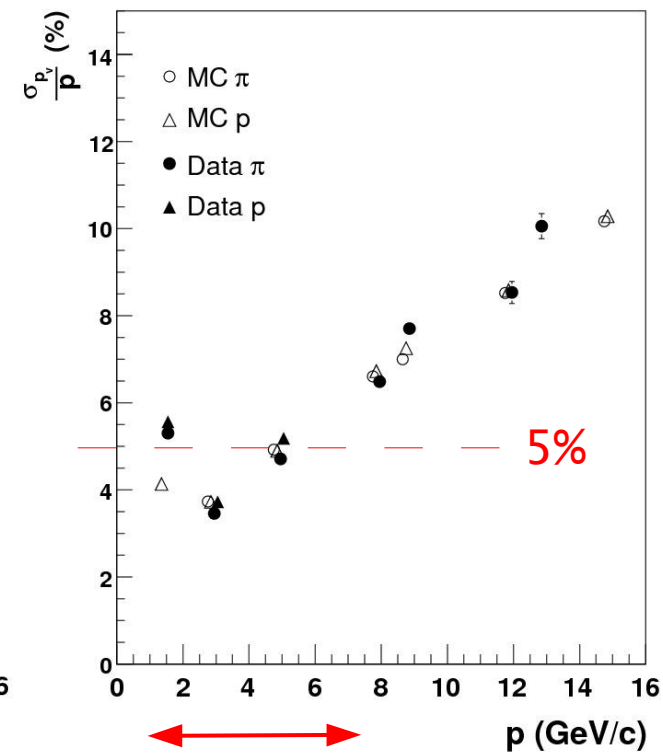
MiniBooNE beam MC

- reconstruction of empty target data sets at HARP



HARP data

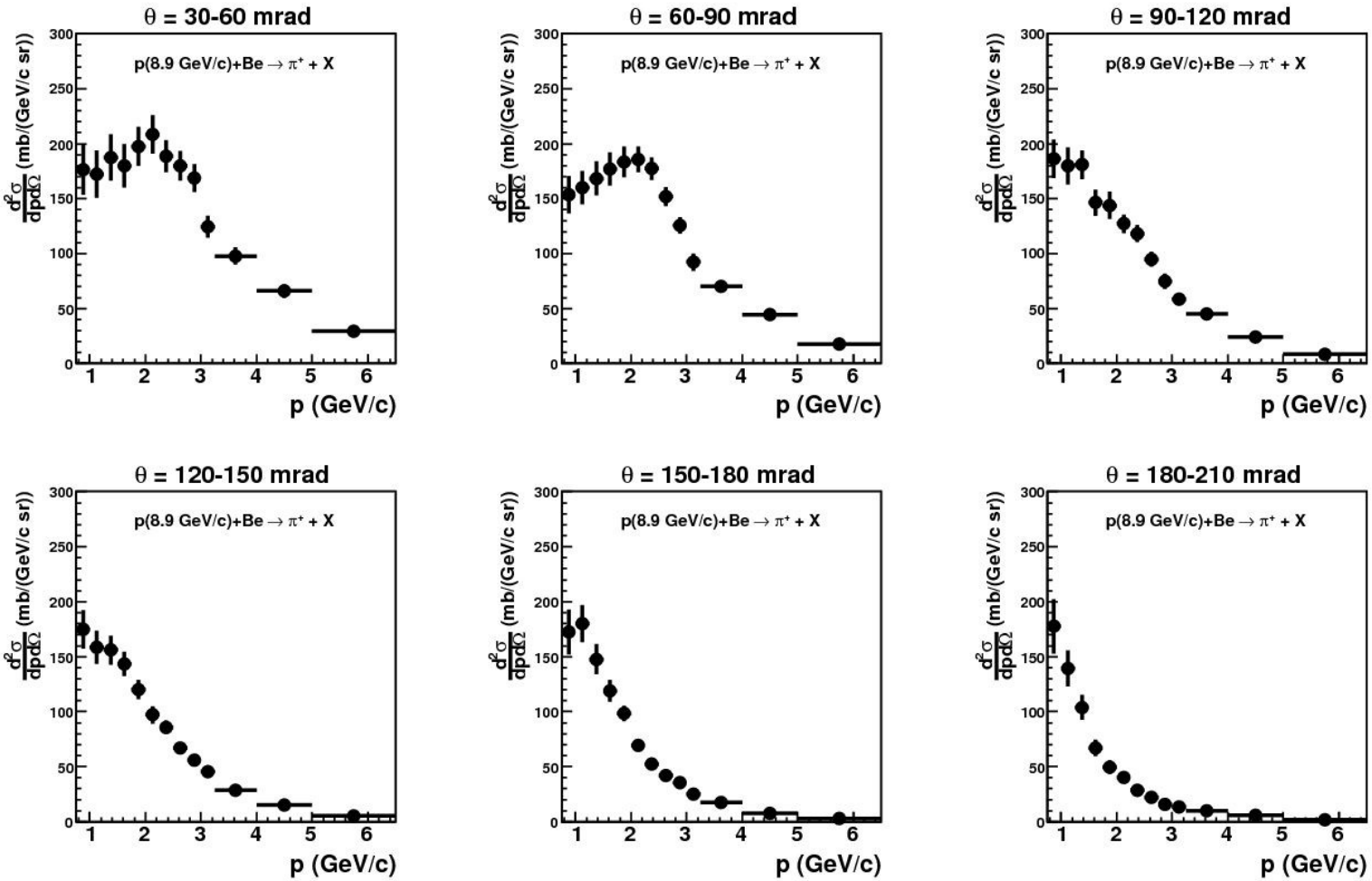
- momentum resolution of HARP forward spectrometer



HARP data/MC

Neutrino Flux Prediction

An aside on Hadron Production measurements at HARP – PS214 at CERN



- measure absolute double-differential production cross-sections:

$$p(8.9\,\mathrm{GeV/c})+\mathrm{Be}\rightarrow\pi^{+}+X$$

$$p(8.9\,\mathrm{GeV/c})+\mathrm{Be}\rightarrow\pi^{-}+X$$

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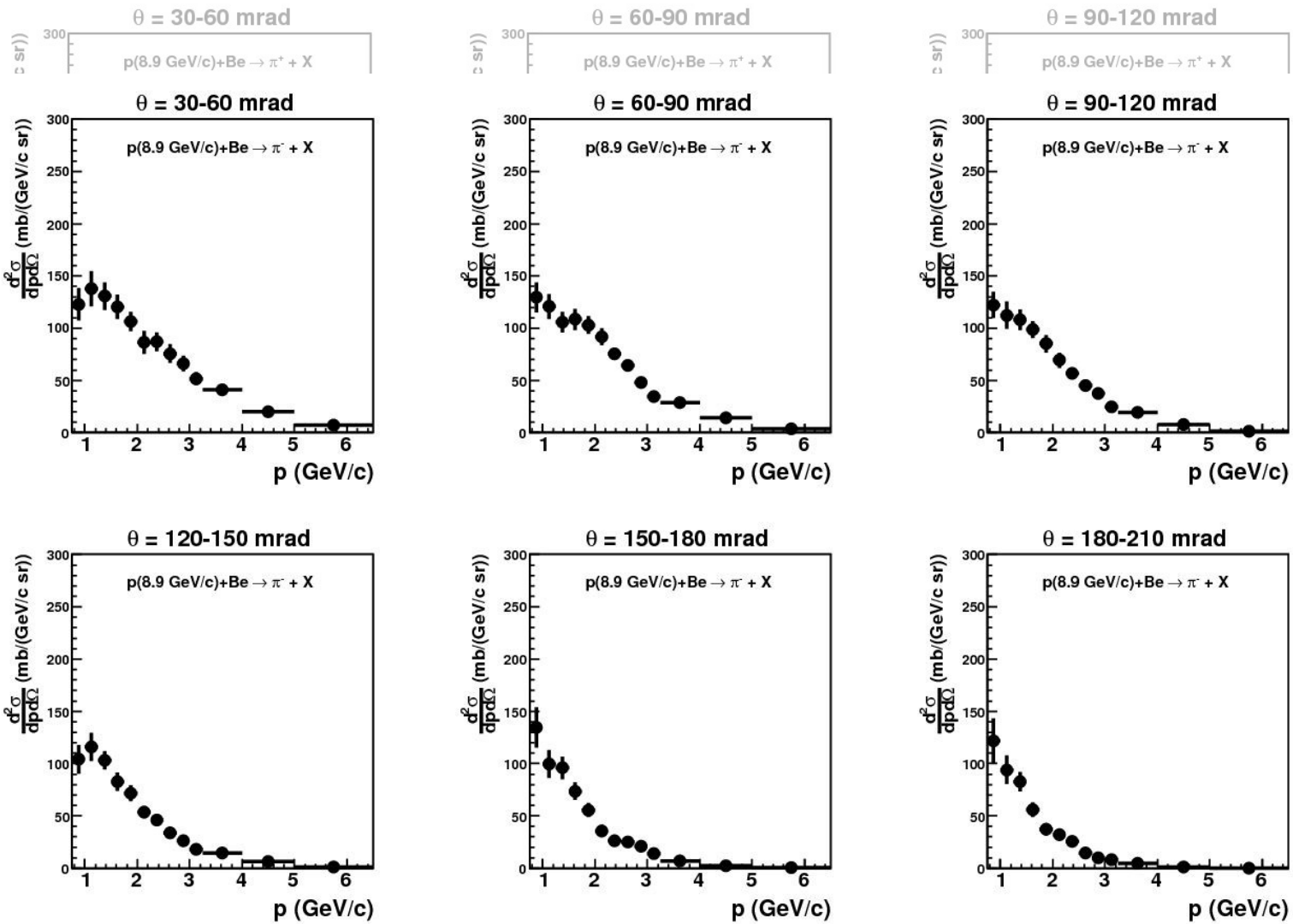

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Neutrino Flux Prediction

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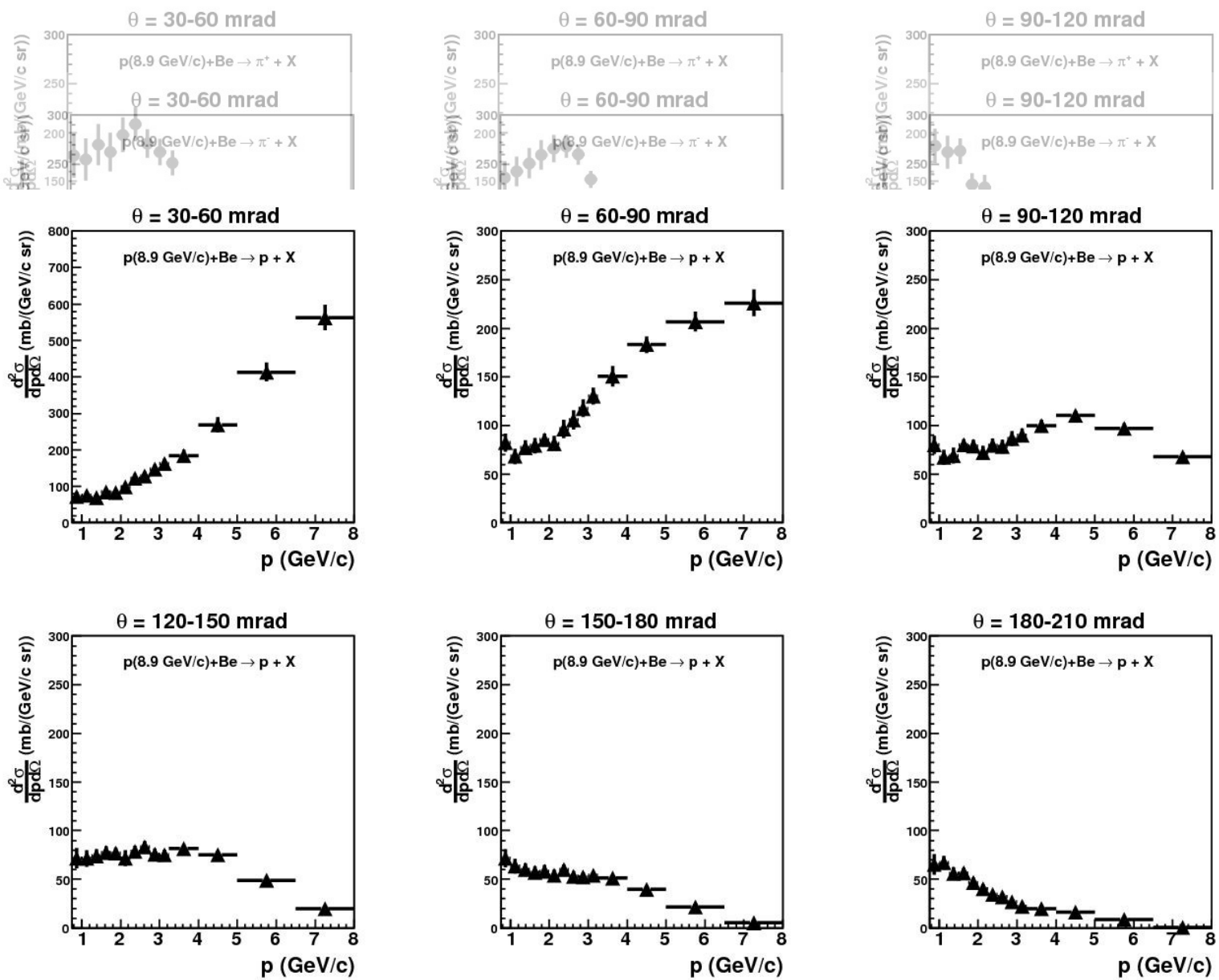

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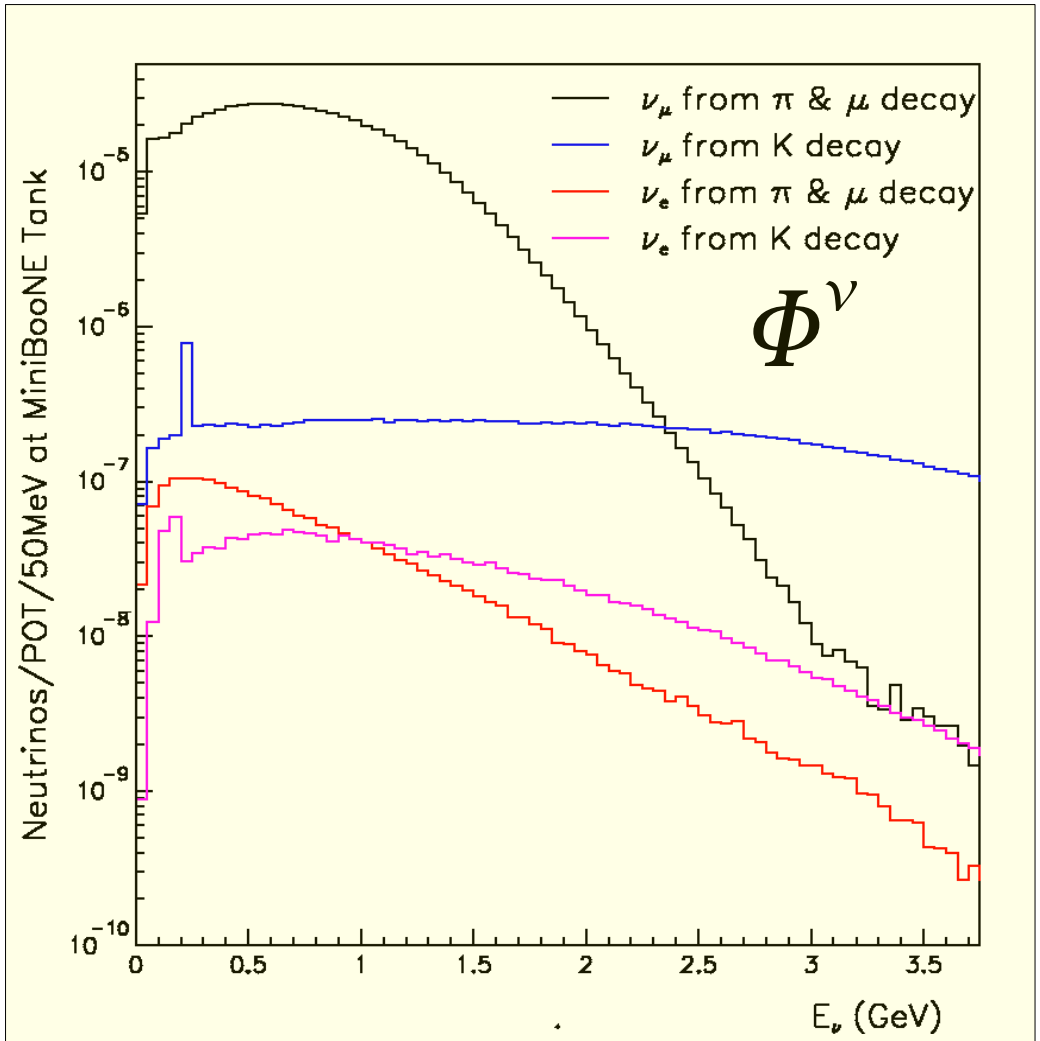
$$\boxed{p(8.9\,\mathrm{GeV/c})+\mathrm{Be}\rightarrow p^{+}+X}$$

Neutrino Flux Prediction

- systematic error analysis results in ~10% average uncertainty on production cross-sections
- statistical errors ≃ systematic errors
  - track yield corrections
  - momentum reconstruction
  - particle identification
  - normalization
- π^+/π^- data is parameterized and used in MiniBooNE beam Monte Carlo
- systematic error on production measurements directly effect absolute neutrino flux uncertainties
- HARP has a rich data set:
  - kaon production measurements
  - thick nuclear target data

Data Set	p(8.9GeV/c) + beryllium					
secondary particle	π^+		π^-		proton	
mometum range (GeV/c)	0.75 – 6.5		0.75 – 6.5		0.75 – 8.0	
angular range (rad)	0.03 – 0.21		0.03 – 0.21		0.03 – 0.21	
Error Category	$\delta^{\pi^+}_{\rm diff}$ (%)	$\delta^{\pi^+}_{\rm int}$ (%)	$\delta^{\pi^-}_{\rm diff}$ (%)	$\delta^{\pi^-}_{\rm int}$ (%)	$\delta^{\rm p}_{\rm diff}$ (%)	$\delta^{\rm p}_{\rm int}$ (%)
Statistical Errors:						
i. Target statistics	4.8	0.6	7.4	0.8	4.7	0.4
ii. Empty target statistics	4.9	0.6	6.3	0.8	5.1	0.4
Sub-total	**6.9**	**0.8**	**9.7**	**1.1**	**6.9**	**0.6**
Track yield corrections:						
iii. Empty target subtraction	1.5	0.1	2.1	0.2	1.4	0.1
iv. Reconstruction efficiency	1.1	0.5	4.4	1.0	1.2	0.2
v. Pion, proton absorption syst.	3.6	4.2	4.7	5.8	2.6	2.4
vi. Pion, proton absorption stat.	0.4	<0.1	0.4	<0.1	0.4	<0.1
vii. Tertiary subtraction syst.	1.5	1.7	1.1	1.2	2.2	1.6
viii. Tertiary subtraction syst.	0.5	0.1	0.6	0.2	0.7	0.1
Sub-total	**4.4**	**4.6**	**6.9**	**6.0**	**3.9**	**2.9**
Momentum recon:						
ix. Momentum scale	4.0	0.1	2.0	0.1	4.2	1.7
x. Momentum resolution syst.	2.2	0.8	4.6	0.5	2.6	0.7
xi. Momentum resolution stat.	1.4	<0.1	1.9	0.1	1.5	<0.1
Sub-total	**4.8**	**0.8**	**5.4**	**0.5**	**5.2**	**1.8**
Particle identification:						
xii. Electron veto	0.1	<0.1	0.1	<0.1	0.1	<0.1
xiii. Pion, proton ID correction	0.4	0.4	0.3	0.3	0.3	0.1
Sub-total	**0.4**	**0.4**	**0.3**	**0.3**	**0.3**	**0.1**
Overall normalization:	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**	**2.0**
Total	**9.7**	**5.2**	**13.2**	**6.4**	**9.7**	**4.0**

Neutrino Flux Prediction

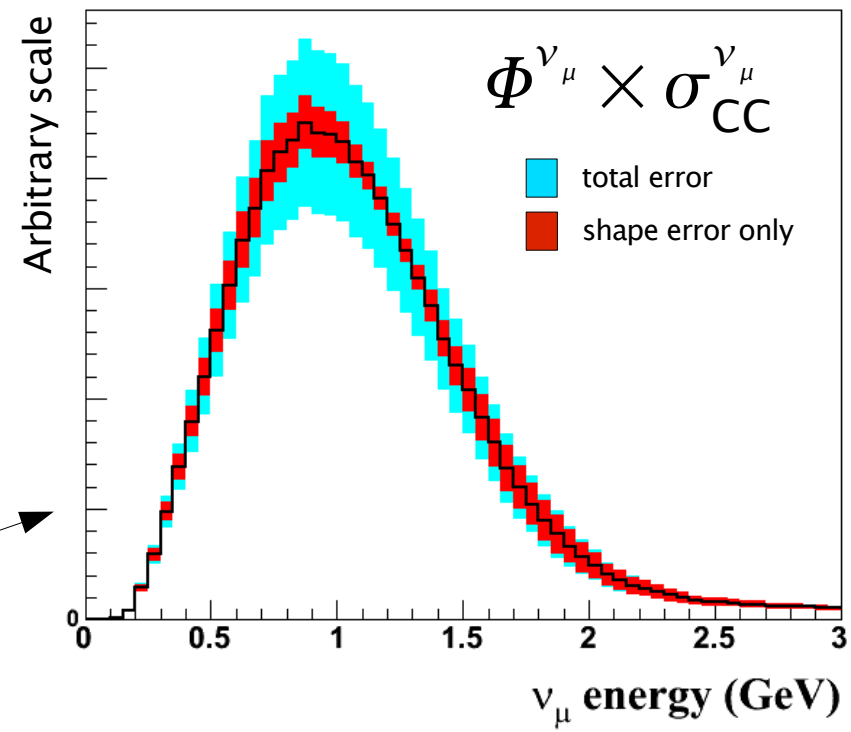


flux prediction at MiniBooNE detector

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%)



systematic uncertainties on ν_μ event rate from beam related sources including hadron production are **~15%**

- Introduction and motivation for this oscillation search
- MiniBooNE design and analysis strategy
  - Brief aside on the prediction of neutrino fluxes
  - Description of neutrino events in the MiniBooNE detector
  - Overview of the oscillation analysis
- Constraining backgrounds for the oscillation analysis
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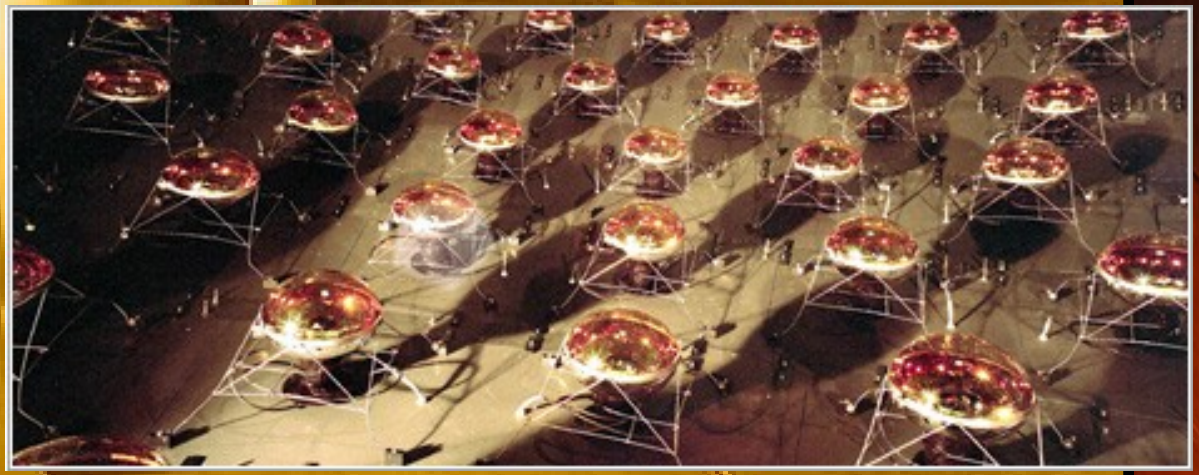
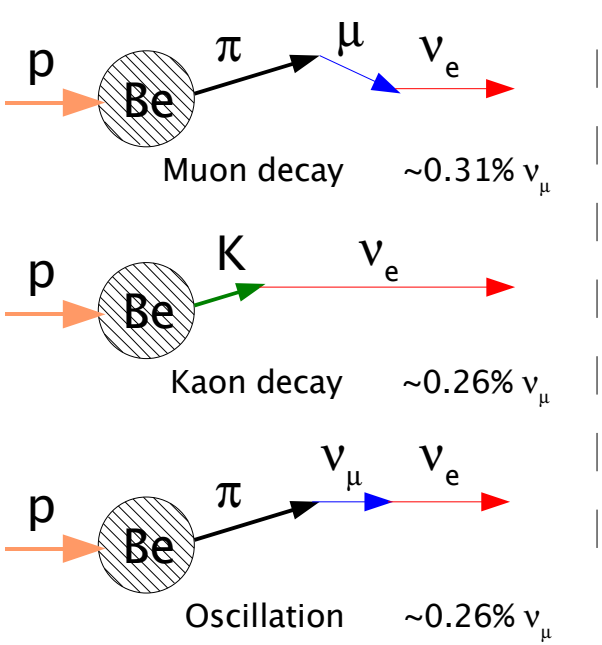


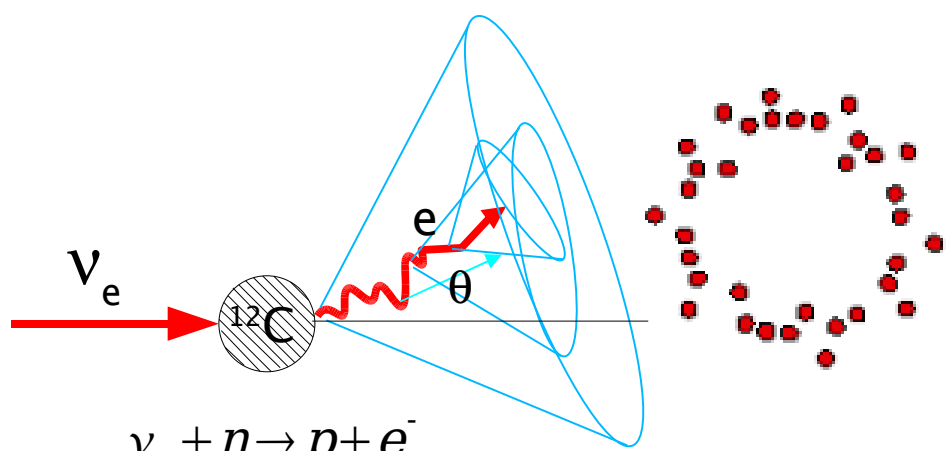
MiniBooNE Tank Events

- 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

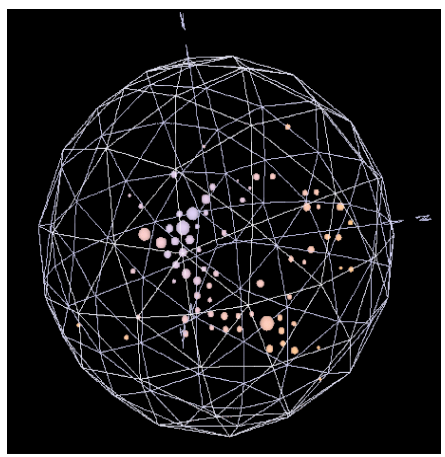
MiniBooNE Tank Events

- 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 irreducible** at the event level
    - **energy spectrum** of intrinsics differs from oscillation signal





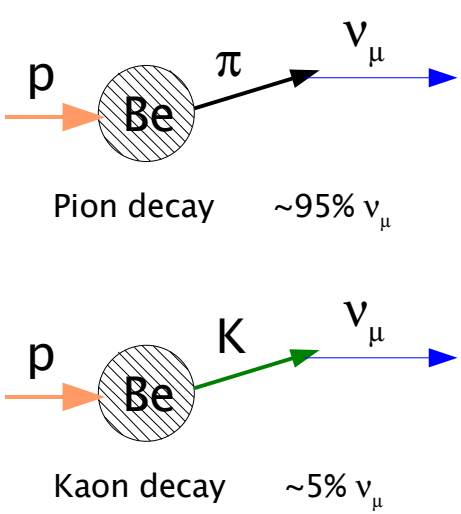
$$\nu_e + n \rightarrow p + e^-$$

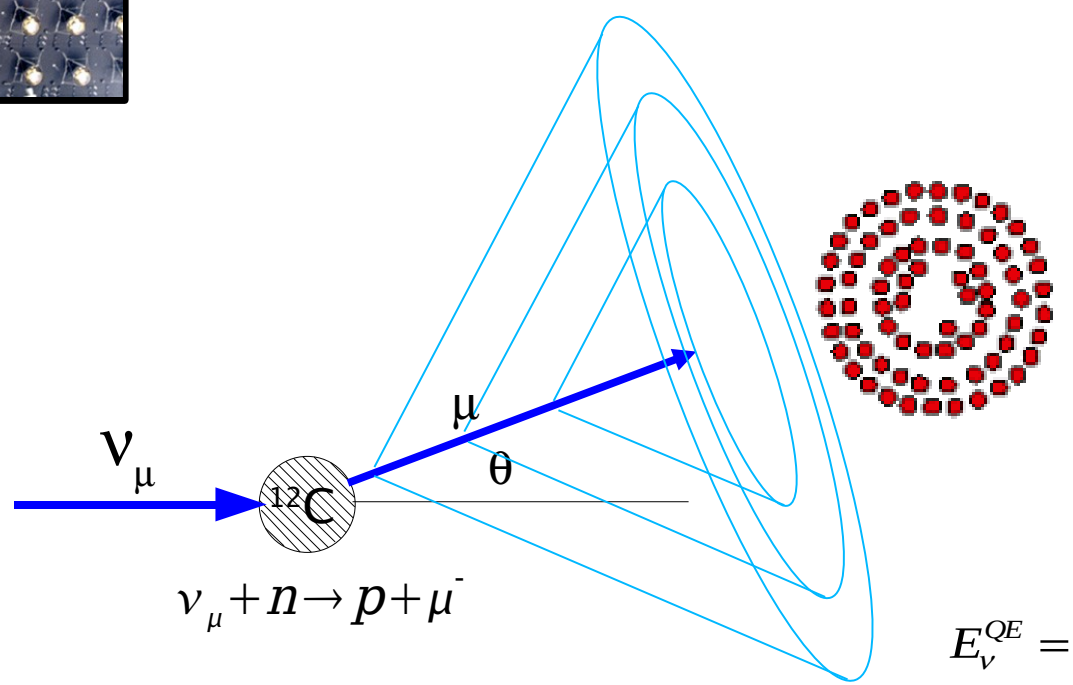


$$E_\nu^{QE} = \frac{1}{2}\frac{2ME_l - m_l^2}{M - E_l + P_l \cos\theta_e}$$

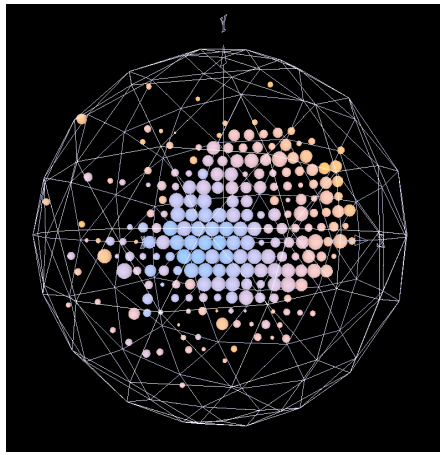
MiniBooNE Tank Events

- 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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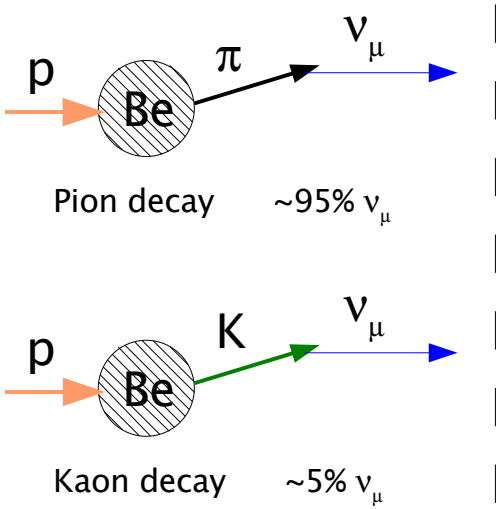
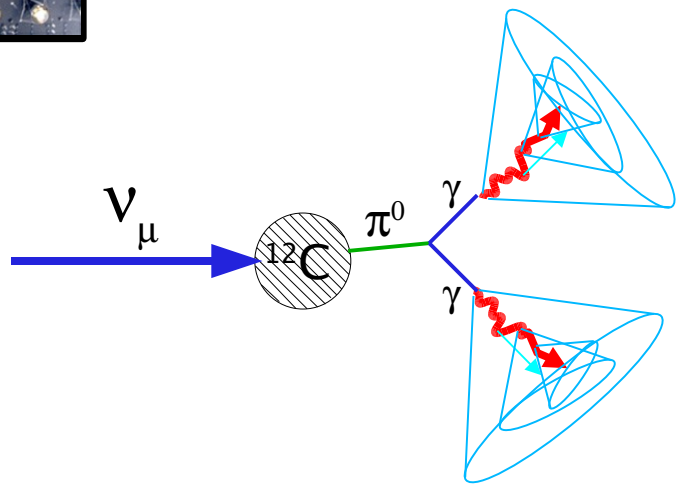
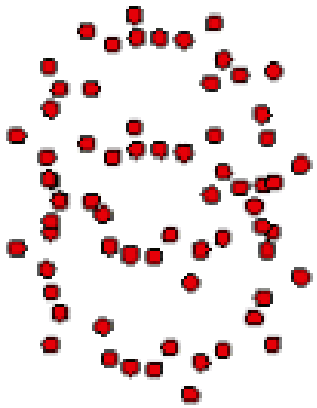
MiniBooNE Tank Events

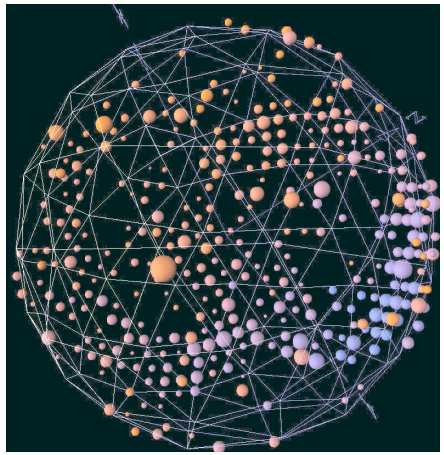
- After cuts, MiniBooNE must be able to find O(100s) ν_e CCQE interactions in a sea of O(100Ks) ν_μ interactions
  - ***neutral pions:***
    - π^0s create **two fuzzy, electron-like rings**
    - most π^0 can be removed by **two ring fit**





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





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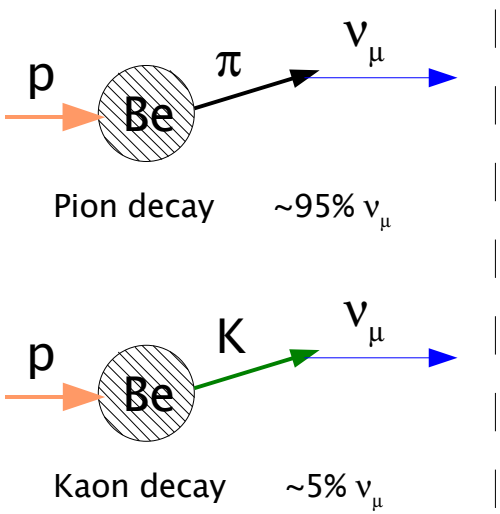
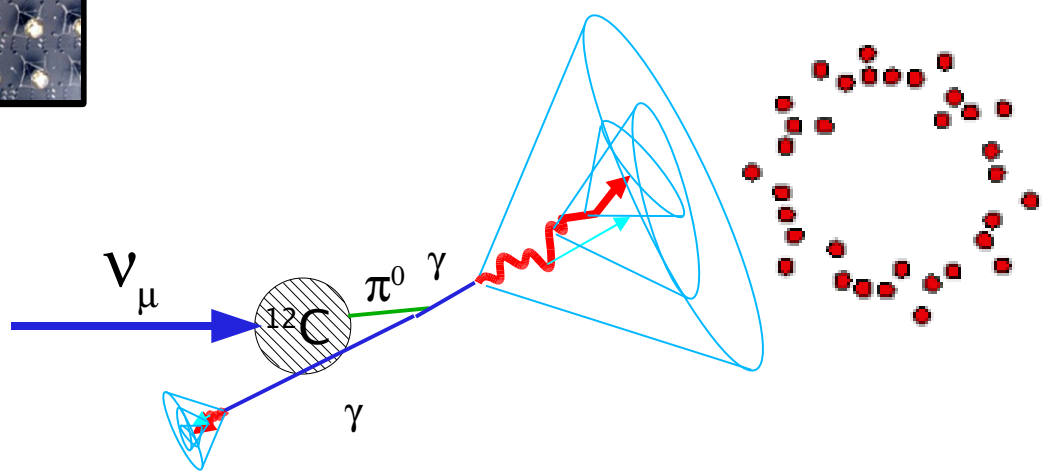
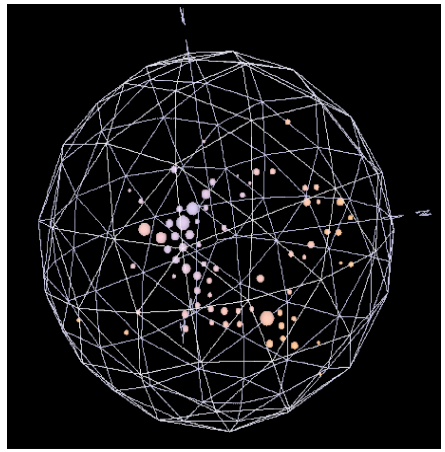
    - background comes from **asymmetric decays** where reconstruction cannot resolve both rings (kinematics)





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



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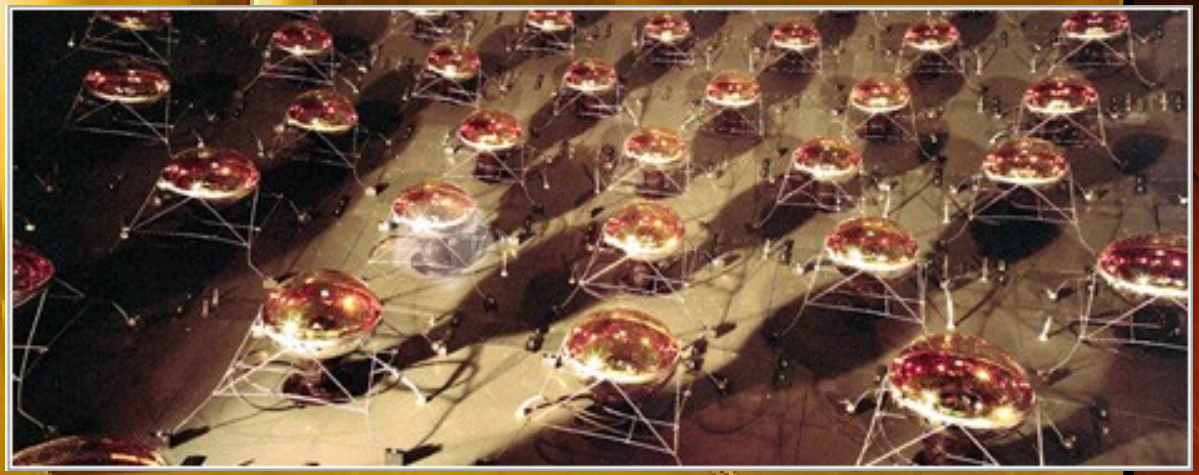
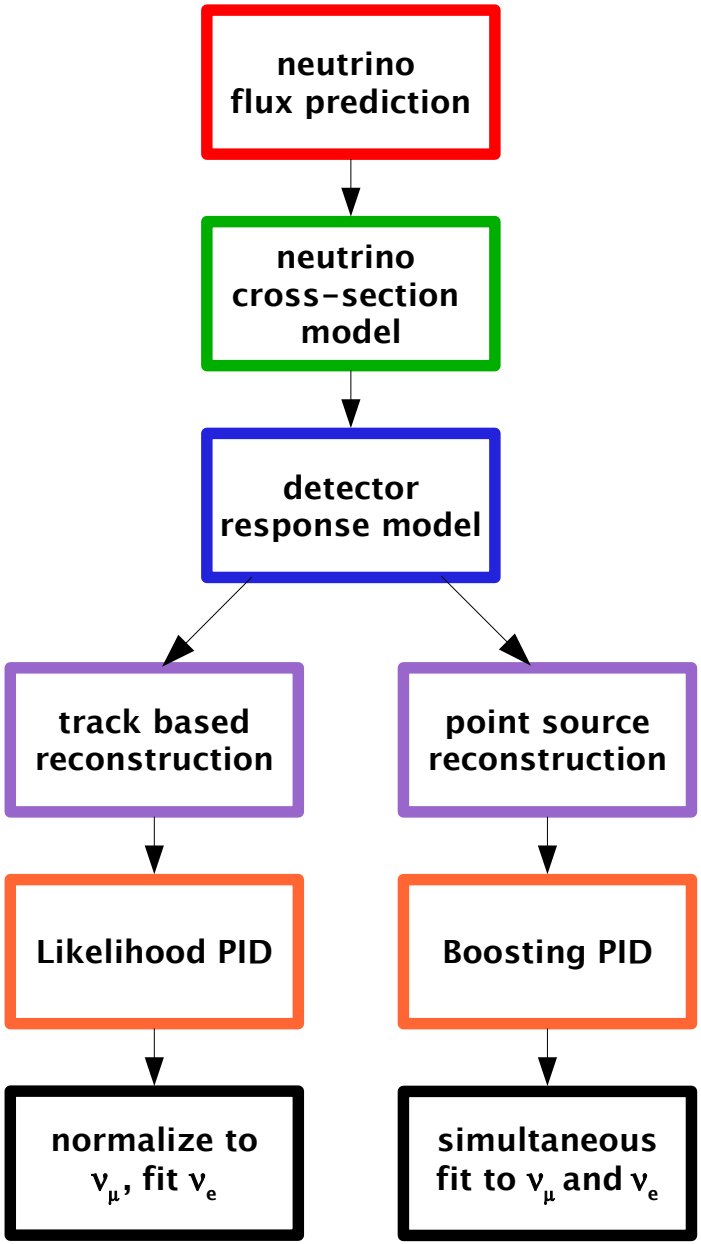


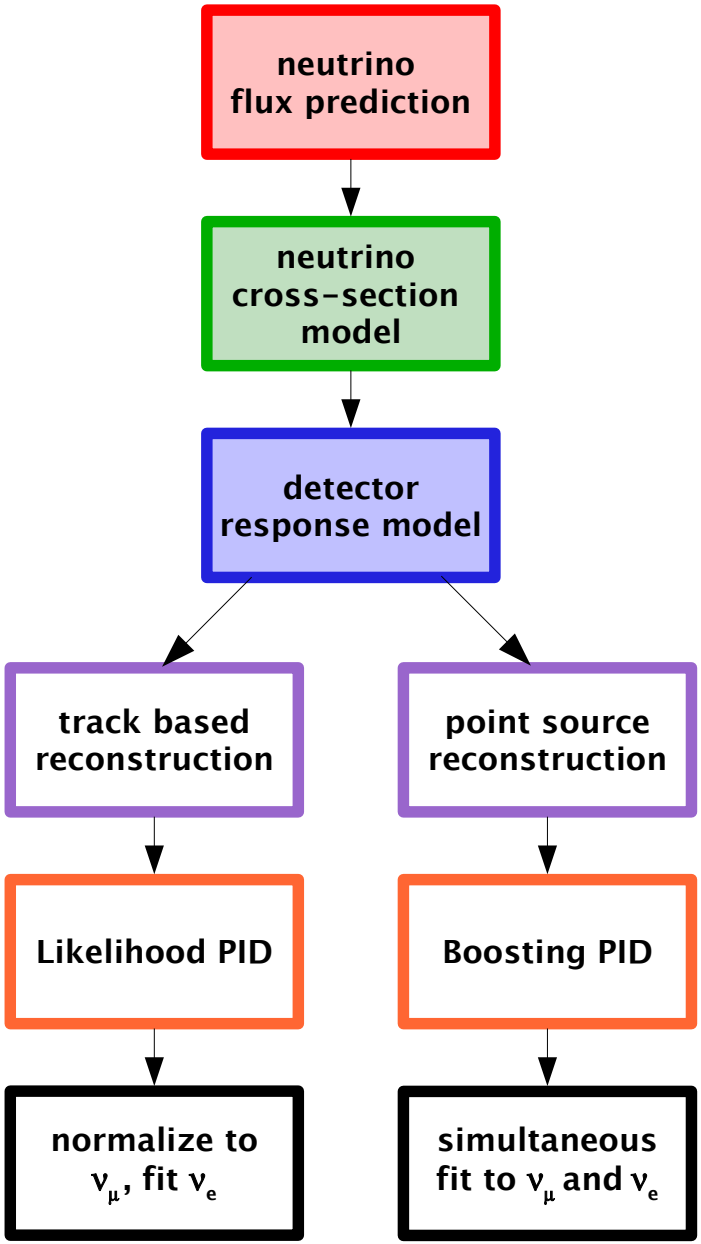
MiniBooNE Oscillation Analysis



- Sophisticated Monte Carlo simulation tuned using external data and/or MiniBooNE data

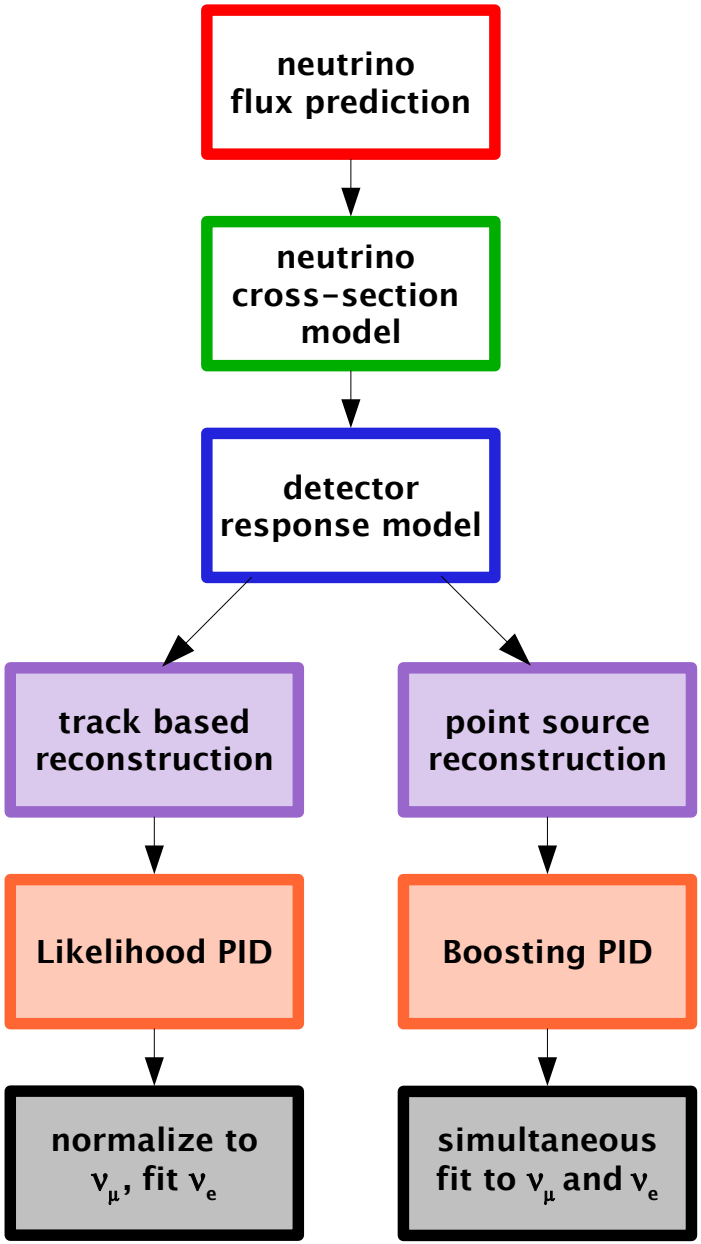
- Two event reconstruction packages, event classification techniques and ν_μ/ν_e constraint methods

MiniBooNE Oscillation Analysis



- we briefly looked at elements of the flux prediction in some detail
  - Booster neutrino beamline simulated with **GEANT4** simulation tuned to hadron data
- we looked only generally at the basic properties of the most important event types in the detector
  - cross-section model based on **NUANCE** neutrino interaction code tuned to MiniBooNE data
  - detector modeled by a GEANT3 simulation with an added **"optical model"** to describe the production, absorption and propagation of light within the tank
- 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)**

MiniBooNE Oscillation Analysis



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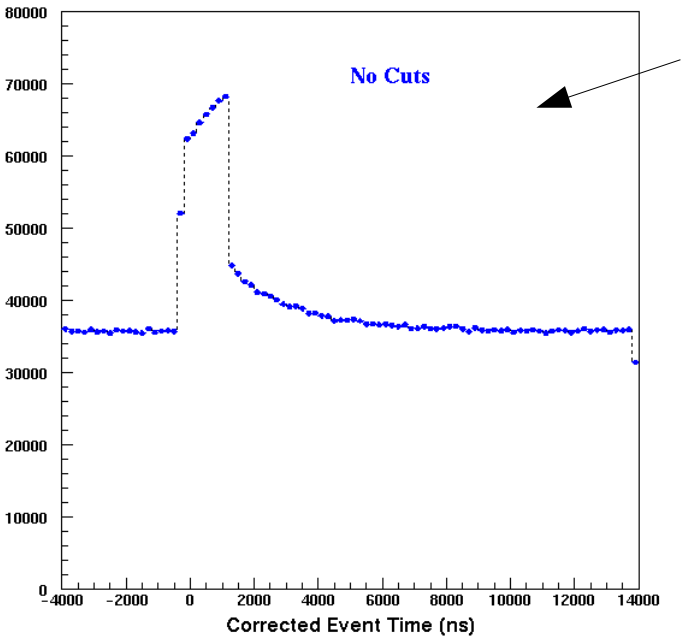
ν_e Event Selection Pre-cuts



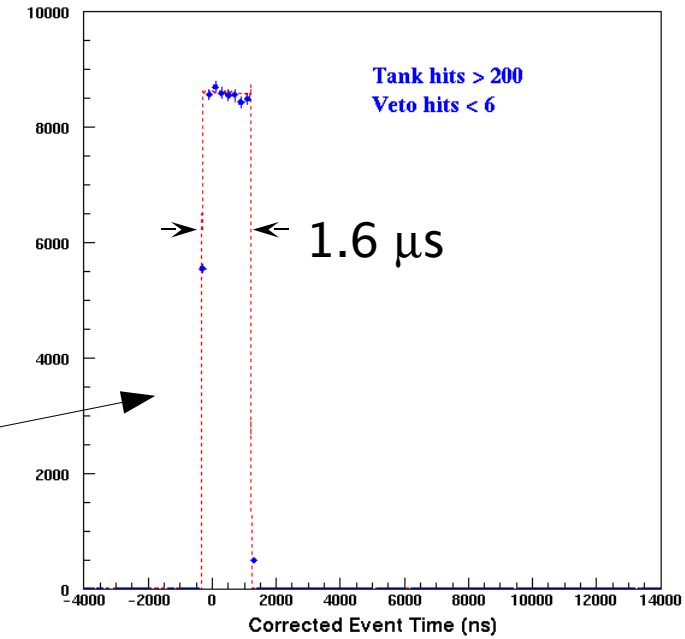
trigger window, no cuts

Beam Window

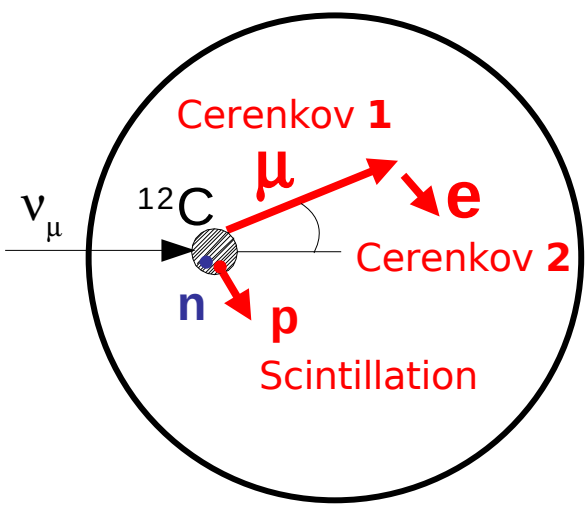
remove cosmic μ and decay e

PMT hits in veto < 6

PMT hits in tank > 200



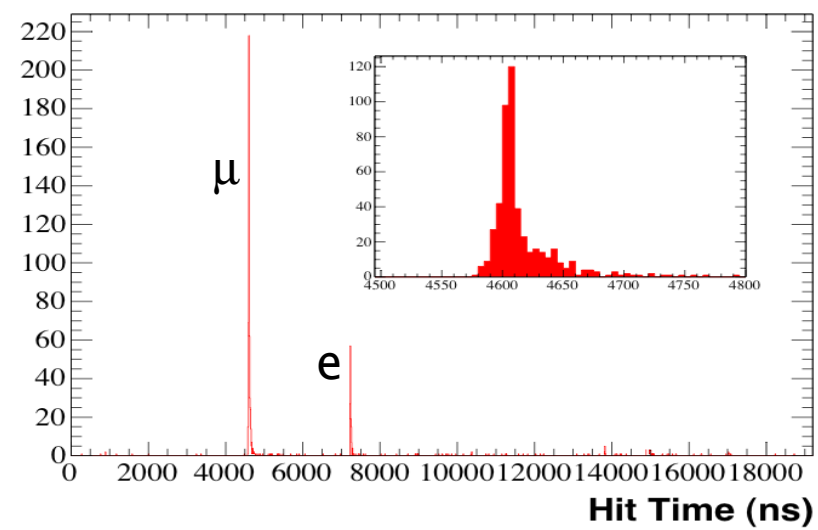
ν_μ CCQE: $\nu_\mu + n \rightarrow p + \mu^-$



Sub-events

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

Sub-events == 1



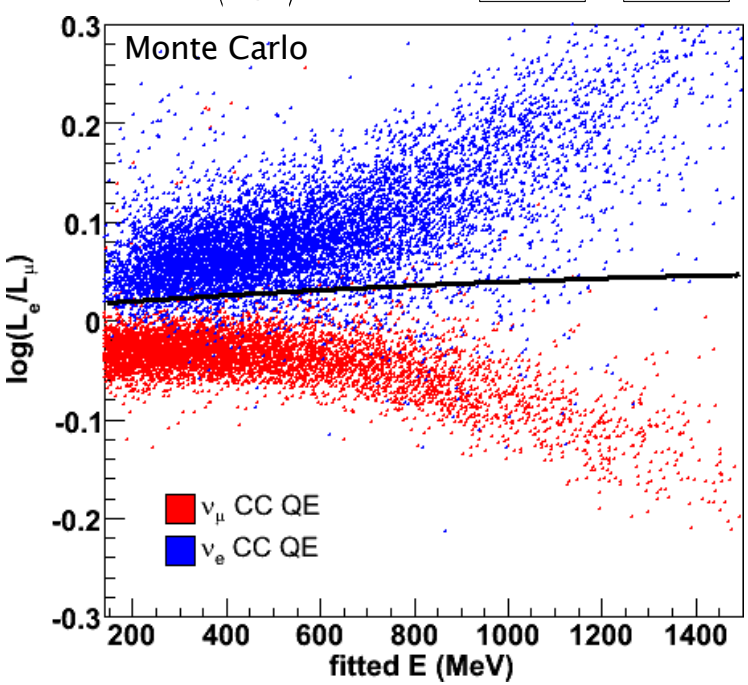
Event Reconstruction & ν_e Event Selection

- Track-based fitter uses a more robust and tenacious approach with the expected improvement in performance over the point-source approximation fitter
- Point source fitter runs ~ 10x faster

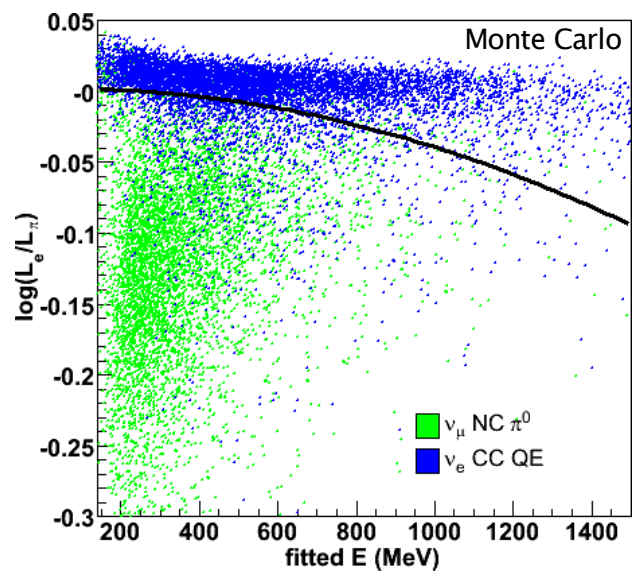
resolutions	TB	PS
vertex	22 cm	24 cm
direction	2.8 deg	3.8 deg
energy	11%	14%

- Track-based fitter used to construct likelihood ratios for identifying ν_e CCQE events
- Point source fitter employs a machine learning algorithm (Boosted Decision Tree) to identify ν_e CCQE events to make up for reduced fitter performance

$\log\left(\frac{L_e}{L_\mu}\right)$ e μ

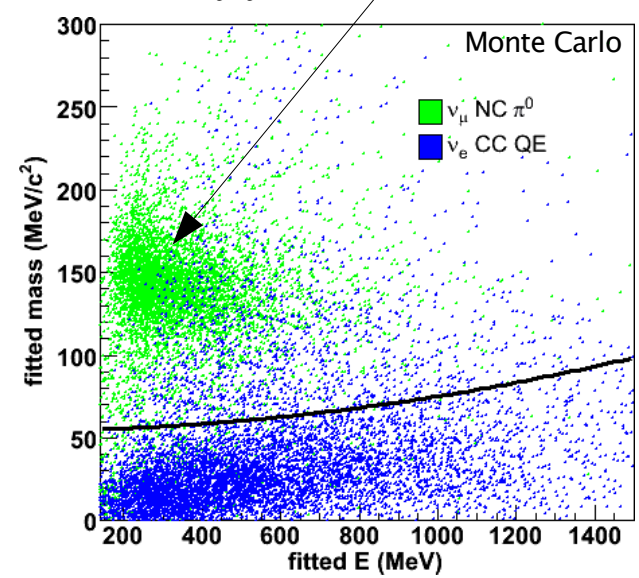


$\log\left(\frac{L_e}{L_{\pi^0}}\right)$ e π^0



$M_{\gamma\gamma}$

note π^0 peak at 140 MeV



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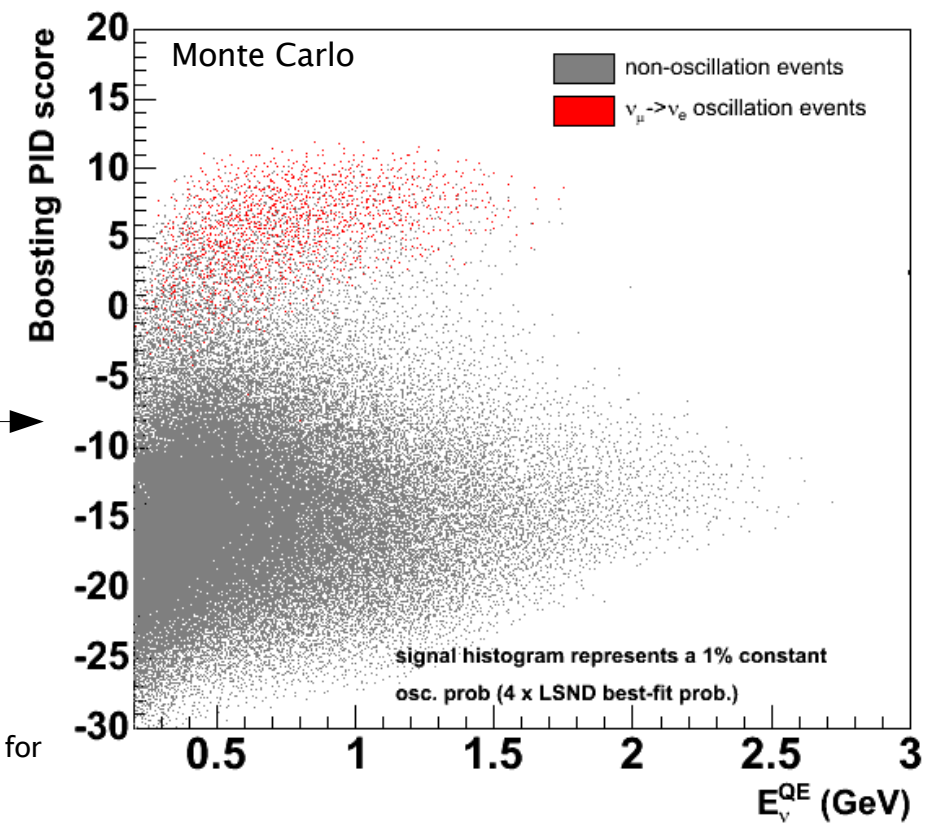
osc

non-osc

- 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)

ν_e Background Predictions in Signal Region

TBL = track-based + likelihood

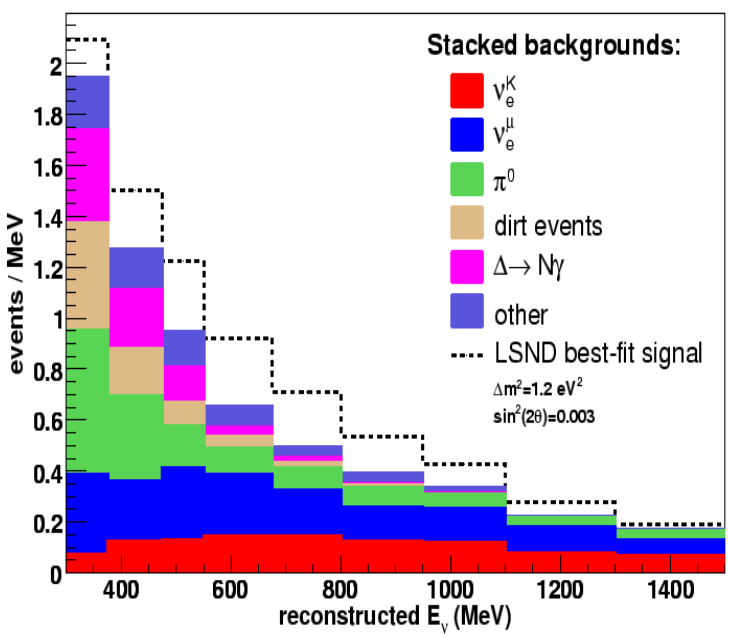
475 MeV – 1250 MeV

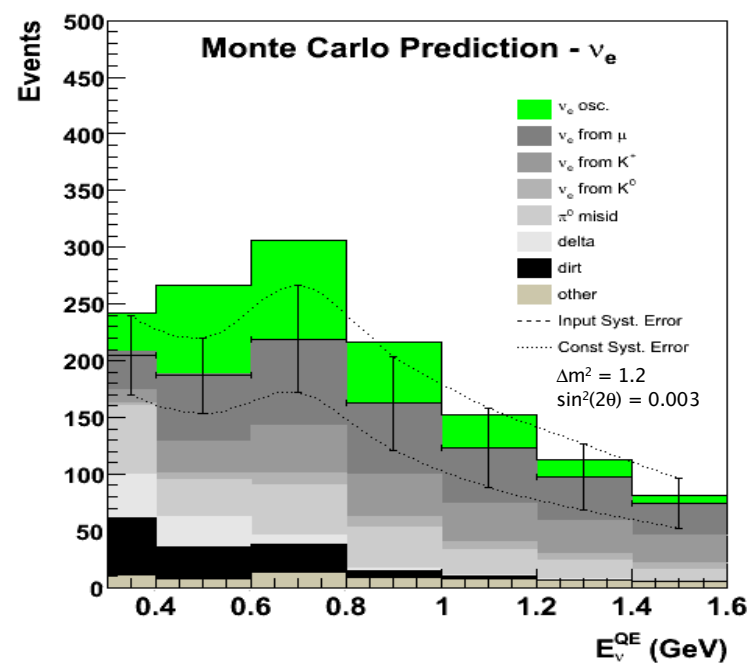
ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
	358
LSND $\nu_\mu \rightarrow \nu_e$	126

BDT = boosted decision tree

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





- Introduction and motivation for this oscillation search
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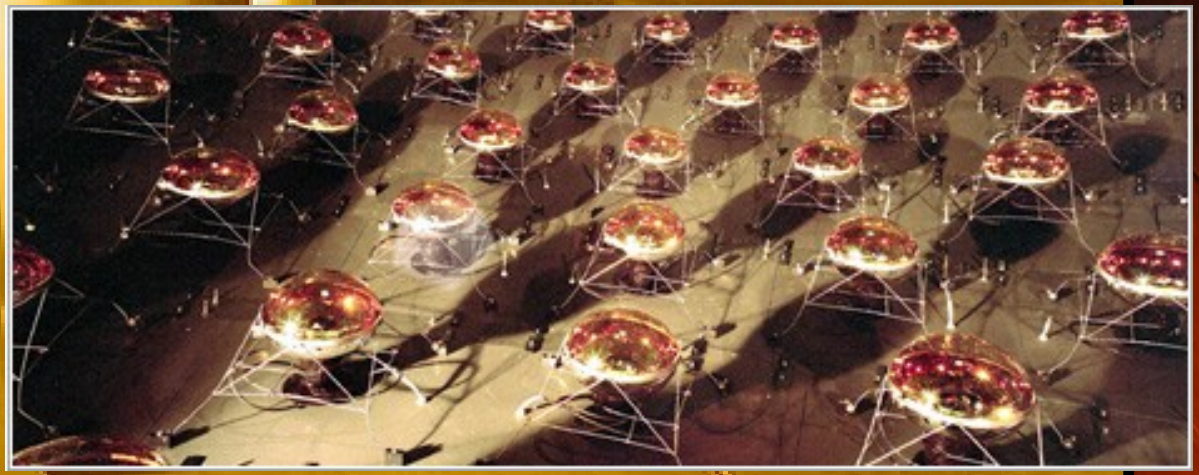
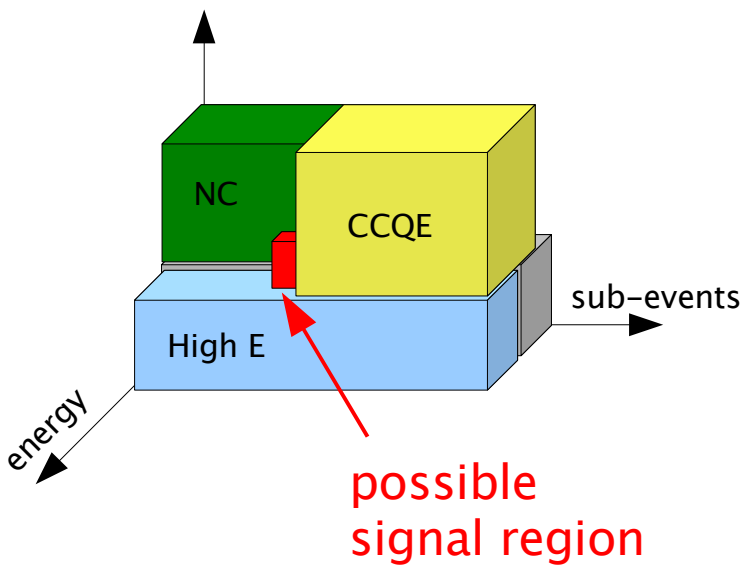


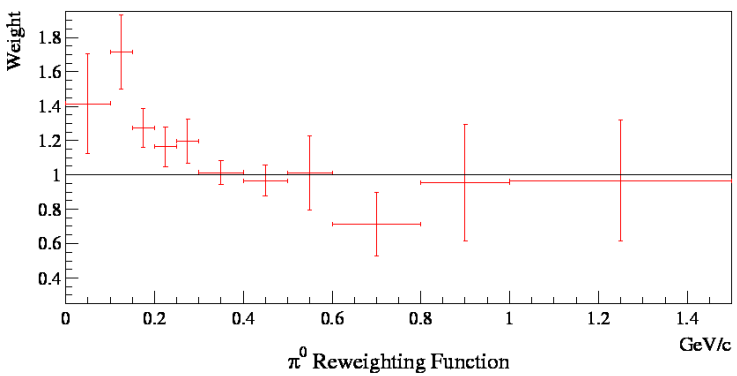
A Note on Blindness

- 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 the box
- Important ν_μ mis-IDs had to be constrained by data before opening the signal box

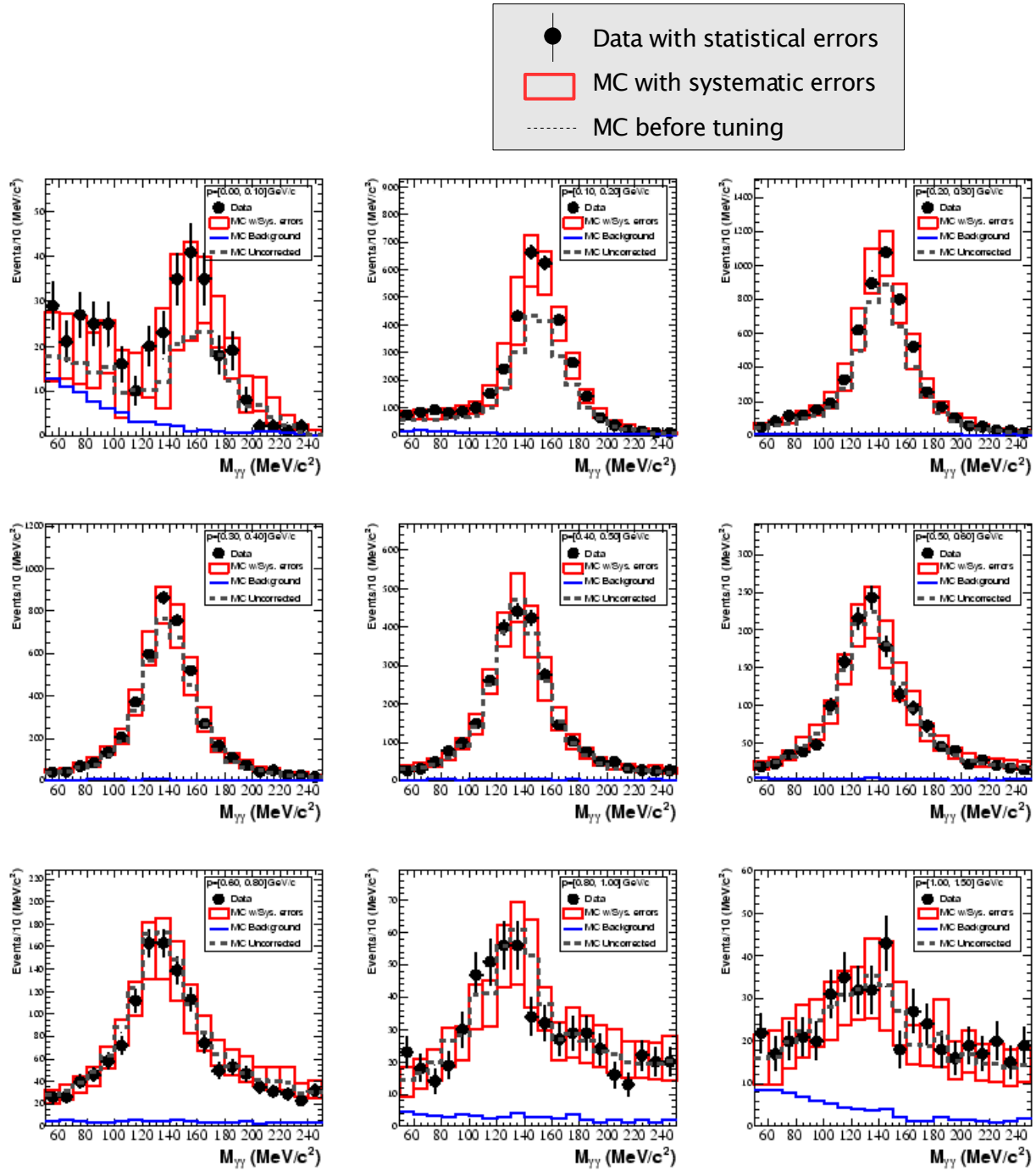


Constraining the NC π^0 Background with Data

- π^0 events are largest ν_μ mis-ID background
- selection cuts give 90%+ pure π^0 sample (mainly $\Delta \rightarrow N\pi^0$)
- Measure rate as function of pion momentum
- reweight MC in π^0 momentum bins to match data

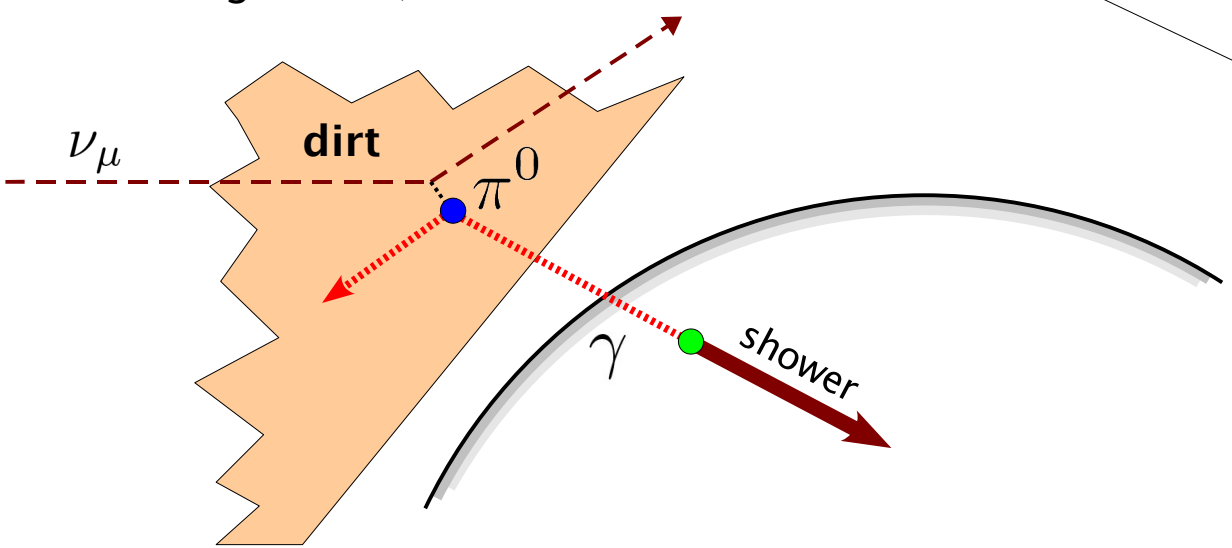


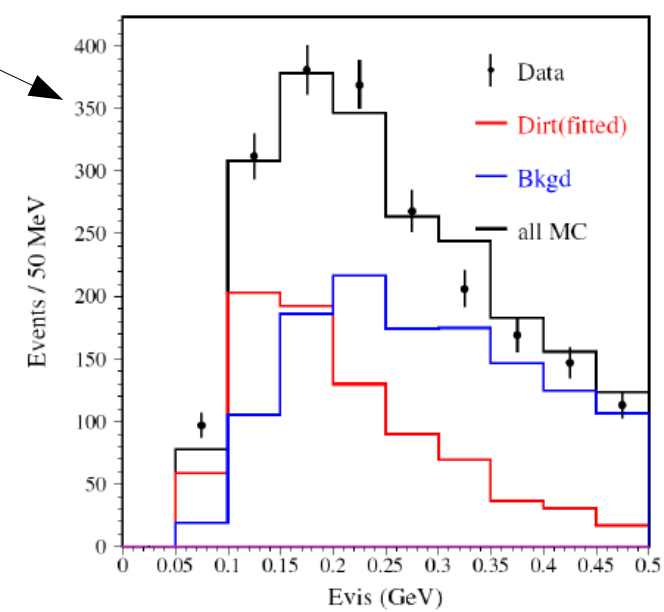
Invariant mass distributions in momentum bins



Constraining the Δ Decay and Dirt Backgrounds with Data

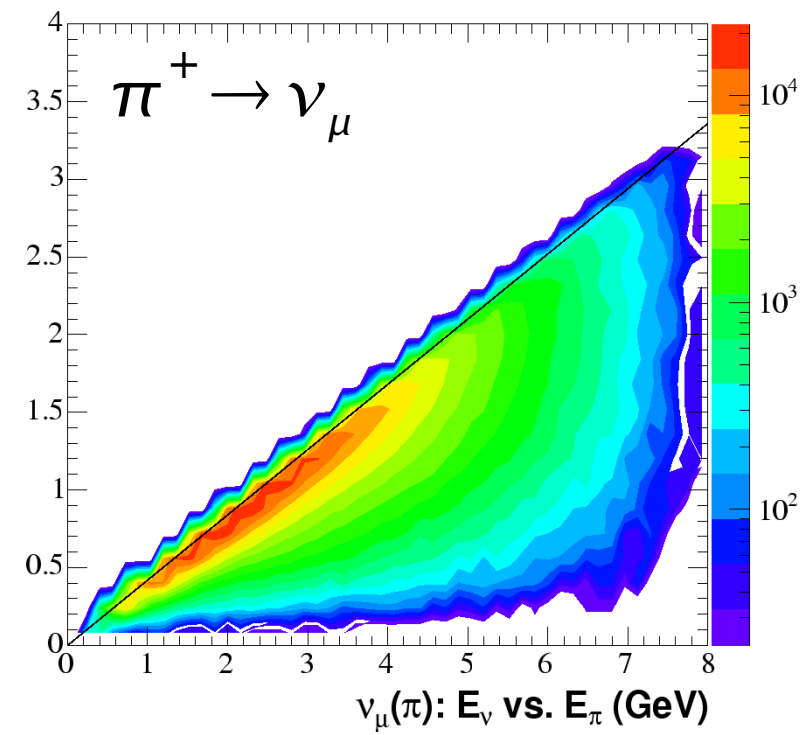
- Δ radiative decay, ***Δ→Nγ***, rate can be constrained by π^0 rate measurement
  - most of the NC–π^0 production is resonant production (through the Δ)
  - the branching ratio for the radiative decay is known
- ***"dirt"*** events are beam induced (so come in the beam time window), but the neutrino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

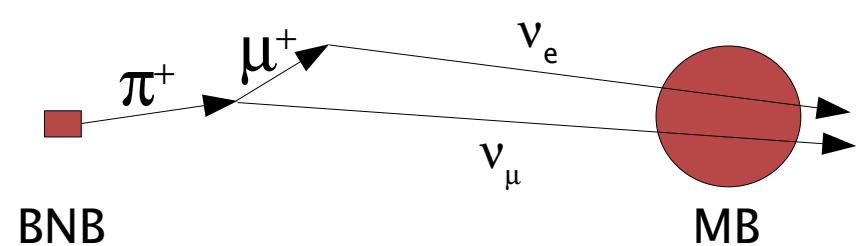




Using the Correlations between the ν_μ and ν_e Samples

- ν_μ flux constrains the potential signal shape from $\nu_\mu \rightarrow \nu_e$ oscillations
- ν_μ and ν_e share the same CCQE cross-section
- ν_μ flux is tied to the intrinsic ν_e flux from $\pi \rightarrow \mu \rightarrow \nu_e$ decay
- highest energy ν_μ flux provides small constraint on ν_e from kaon decay
- ν_μ and ν_e event reconstructions sensitive to the same detector model with some correlations (e.g. energy scale)

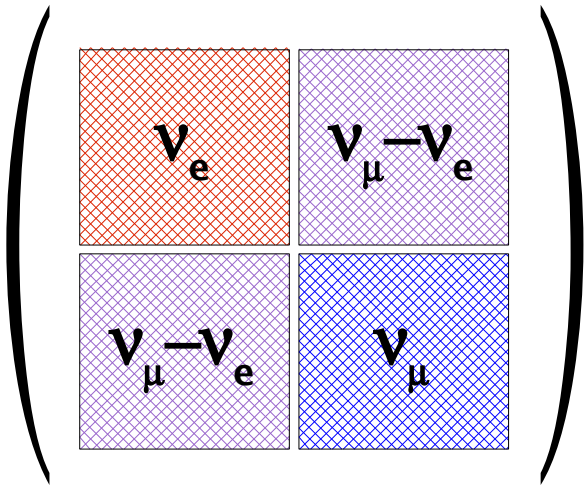




The Simultaneous $\nu_\mu - \nu_e$ Fit Method

- construct a single, large covariance matrix $(N_{\nu e}+N_{\nu\mu})$ x $(N_{\nu e}+N_{\nu\mu})$ in bins of E_ν^{QE}
- 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

$$\chi^2 = \left(\left[N^{\nu_e}_{\text{data}} - N^{\nu_e}_{\text{MC}}\right]_i \; \left[N^{\nu_\mu}_{\text{data}} - N^{\nu_\mu}_{\text{MC}}\right]_i \right)$$



$$\begin{pmatrix} \left[N^{\nu_e}_{\text{data}} - N^{\nu_e}_{\text{MC}}\right]_j \\ \left[N^{\nu_\mu}_{\text{data}} - N^{\nu_\mu}_{\text{MC}}\right]_j \end{pmatrix}$$

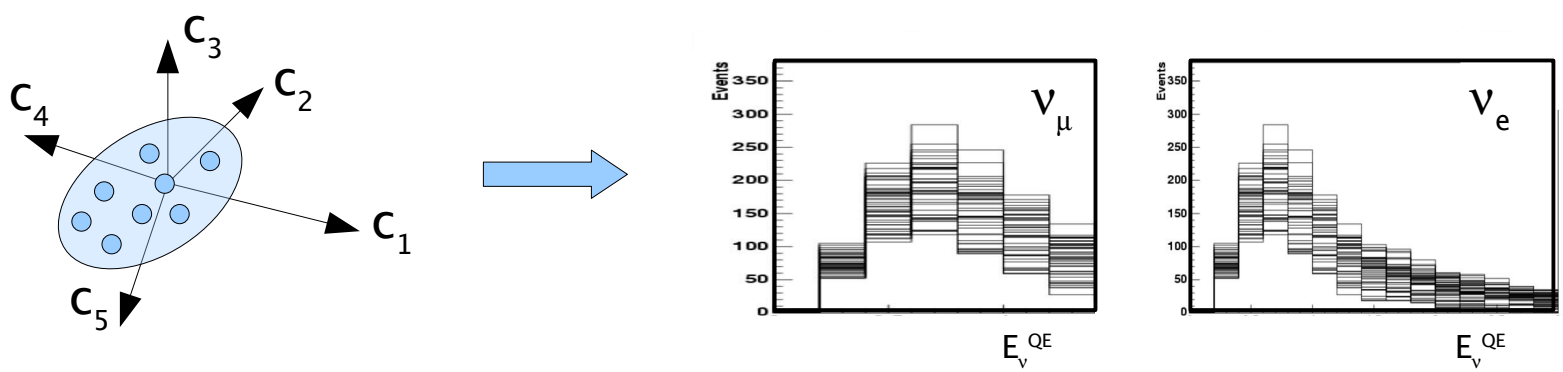
- ν_μ data set constrains ν_e background prediction through off-diagonal blocks
- error matrix contains all the $\nu_\mu - \nu_e$ correlations included in the simulation

Constructing the Error Matrix

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

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

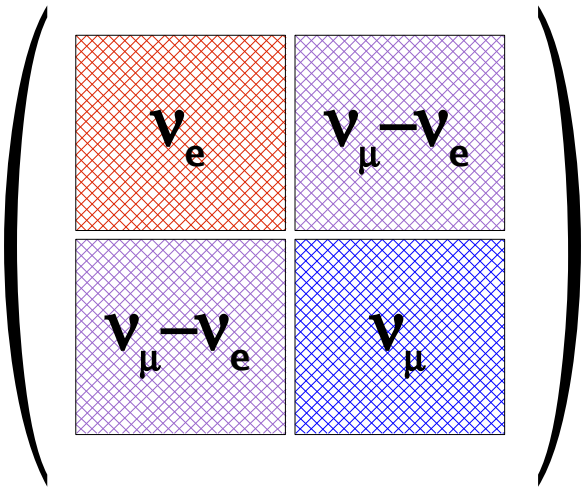
- using MC, map uncertainty in ***source parameters*** to uncertainty in neutrino energy, E_ν^{QE}
  - e.g. uncertainty in pion production in the target, cross-section params., optical model params.



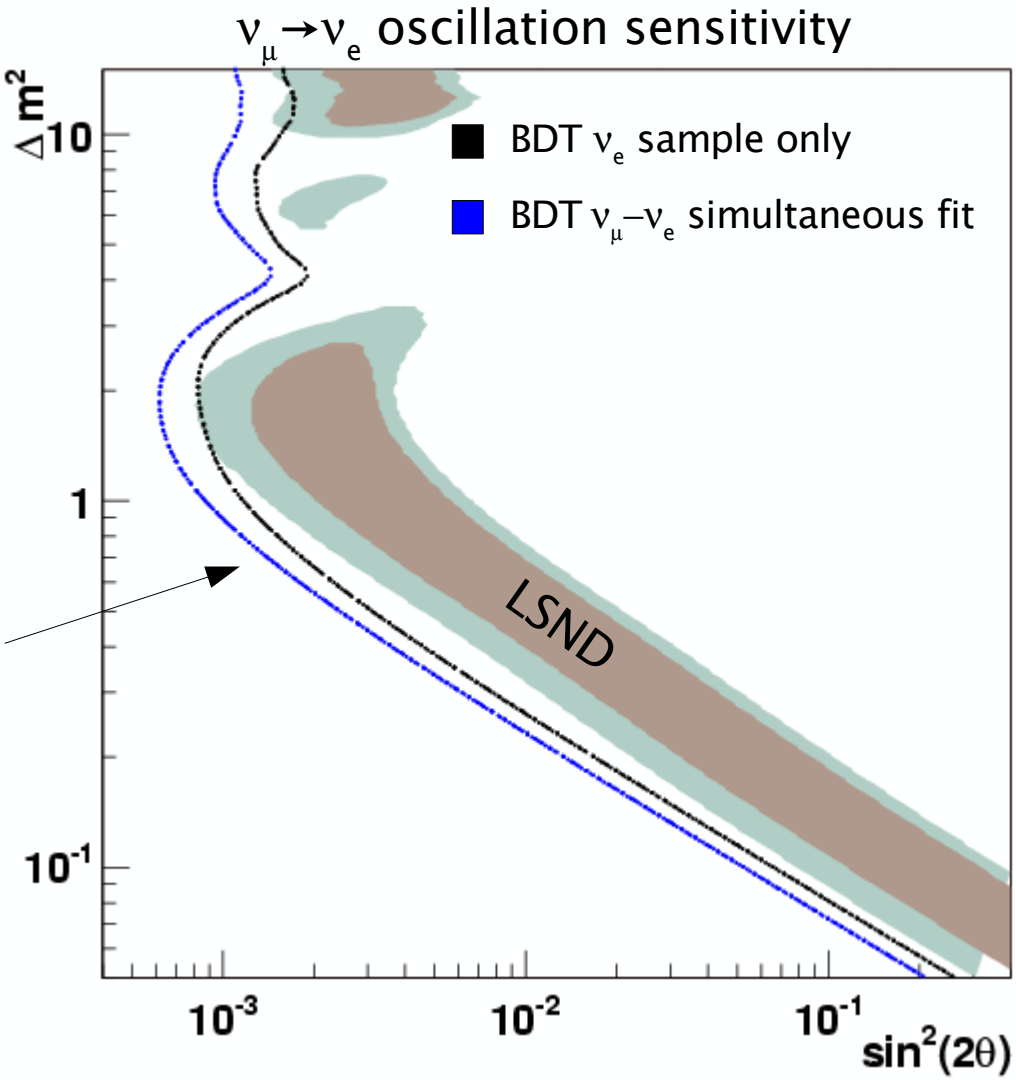
- Individual error matrices constructed using ***multisim approach :***
  - A multisim is a random draw from underlying parameters
  - correlations among input parameters are considered
  - flux and cross-sections are produced from re-weighting. Optical model multisims require generation of full hit-level Monte Carlo

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

The Simultaneous $\nu_\mu - \nu_e$ Fit Method

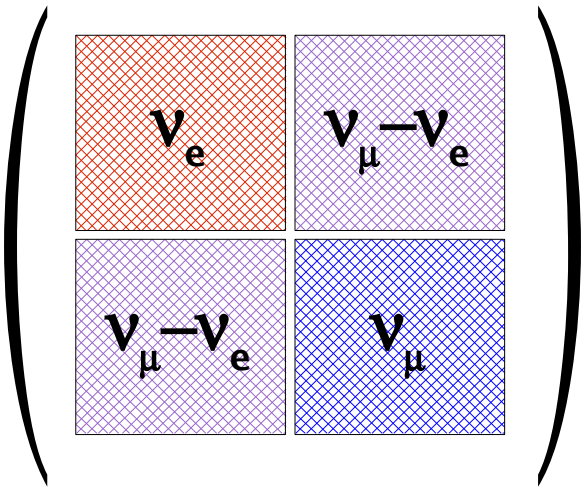


- all flux and cross-section errors considered
- turns out, however, detector model uncertainties dominate and are not sufficiently correlated with ν_μ (boosting variable)



- BDT ν_e selection
- flux and cross-section errors only
- no detector model uncertainties

The Simultaneous $\nu_\mu - \nu_e$ Fit Method



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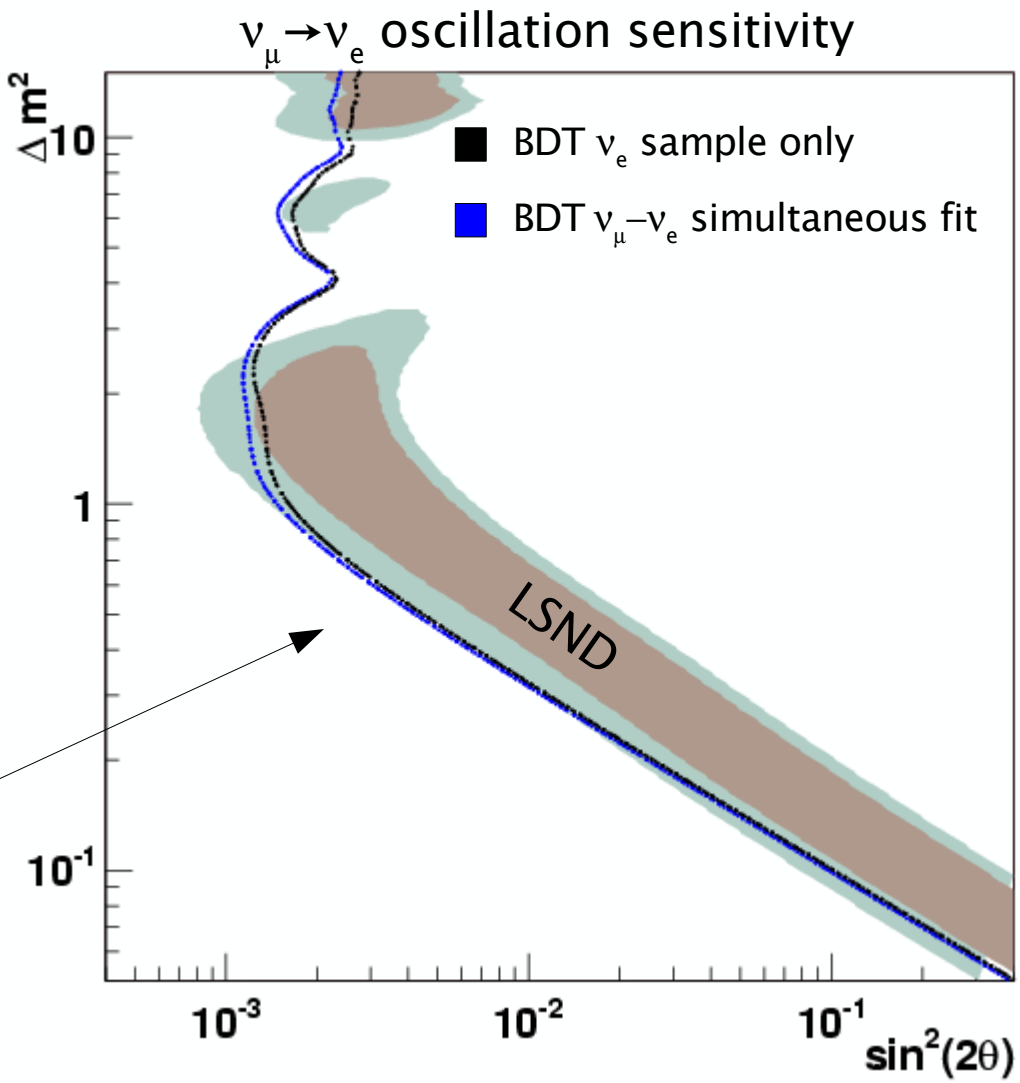
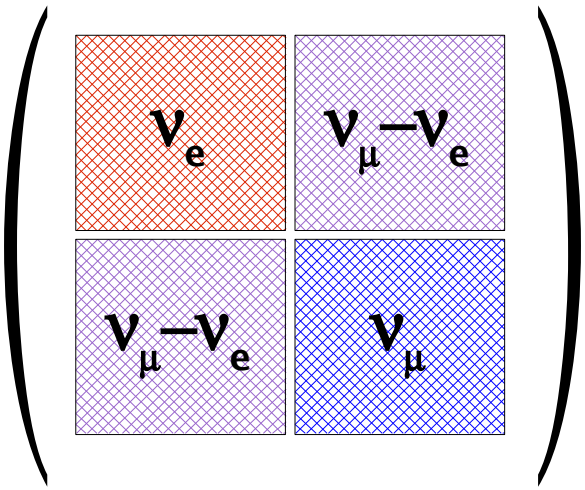


- BDT ν_e selection
- flux, cross-section & detector errors

The Simultaneous $\nu_\mu - \nu_e$ Fit Method



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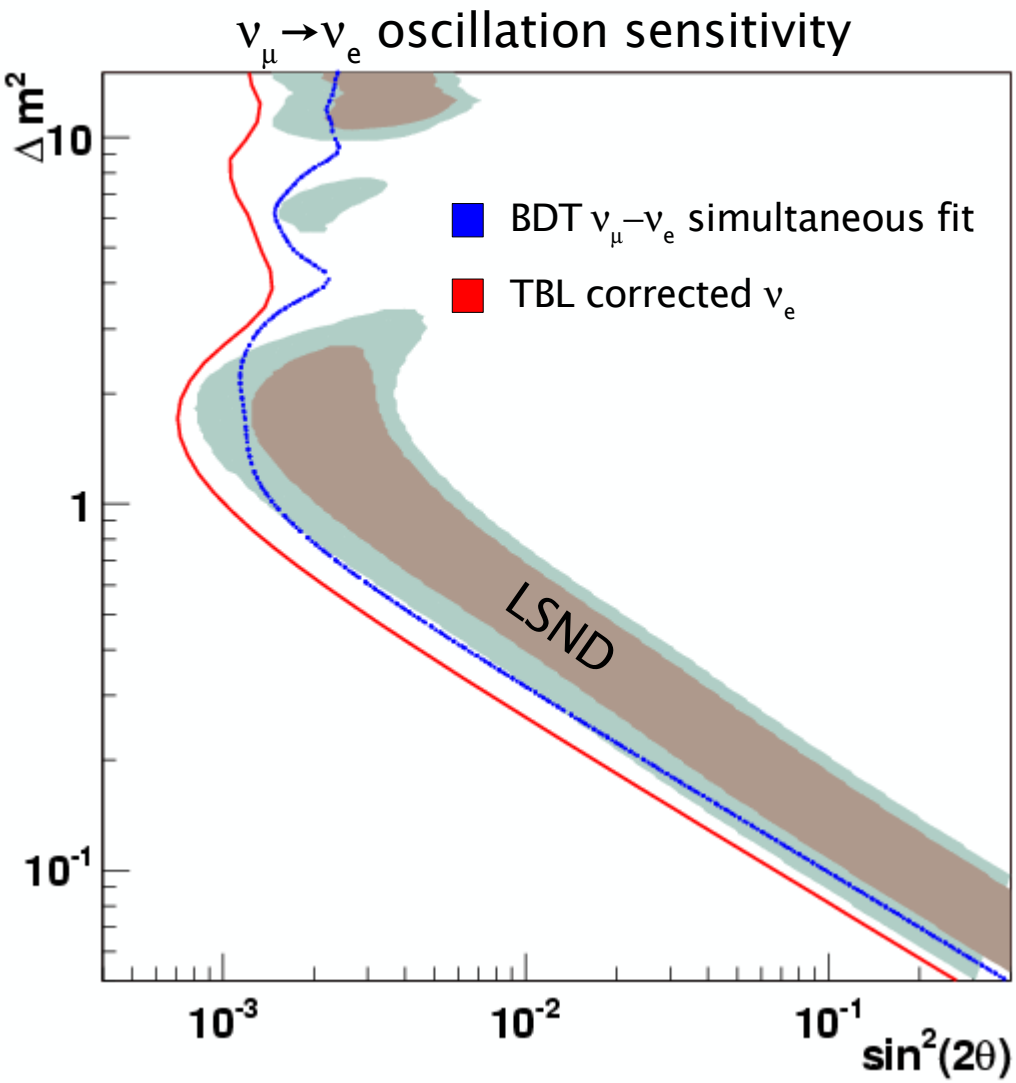

- BDT compared to TBL ν_e selection
- all errors

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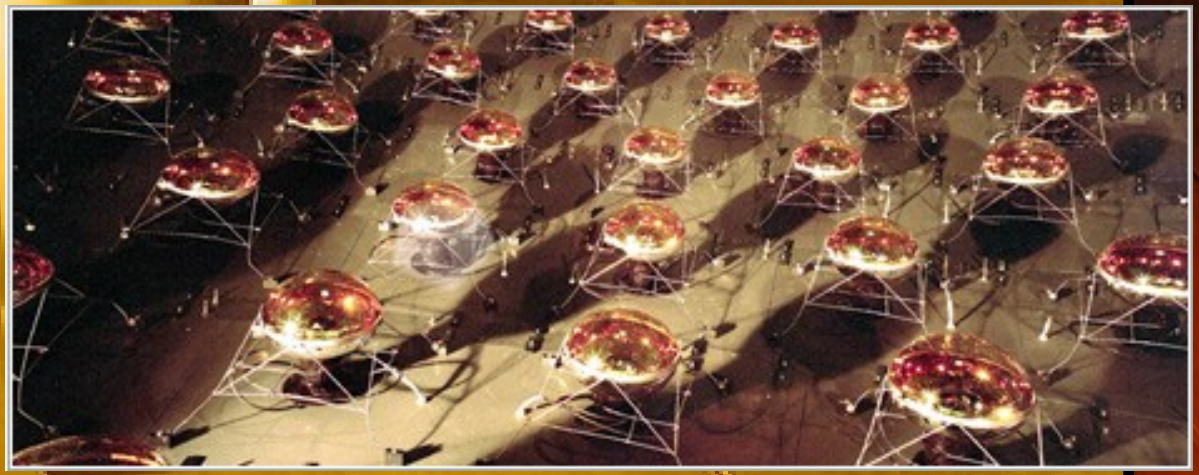
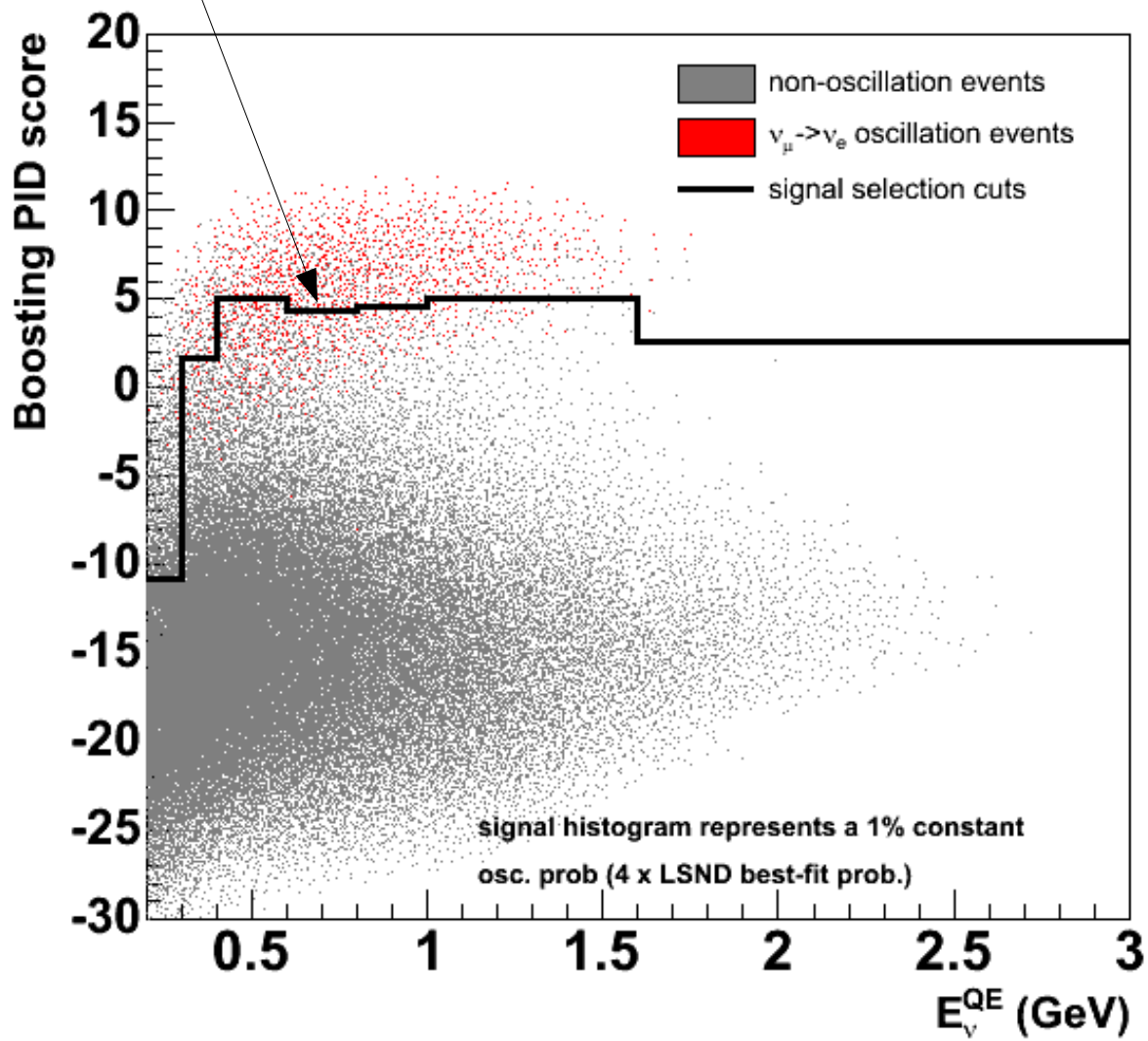


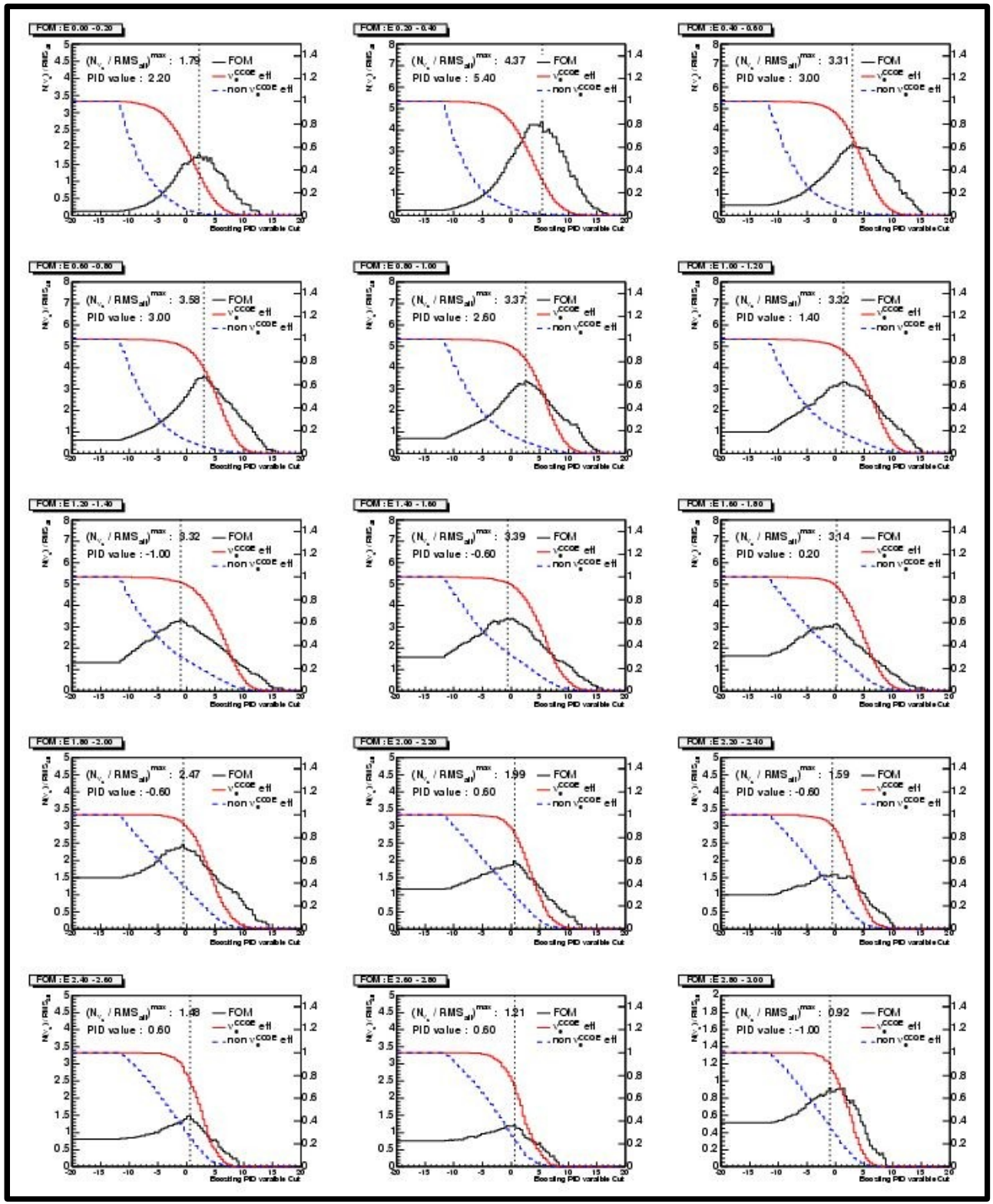
BDT ν_e Event Selection Optimization

- Is is possible to reduce the sensitivity to detector model uncertainties by altering the BDT ν_e selection cuts?



- original BDT ν_e selection cuts
  - "counting experiment optimization"
  - energy bins treated independently

bins of reconstructed neutrino energy



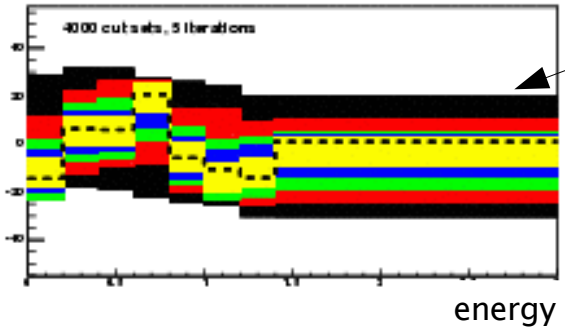
- F.o.M. $= \frac{N_{\nu_e}}{RMS_{all}}$
- ν_e^{CCQE} eff.
- non-ν_e^{CCQE} eff.

plotted vs. BDT PID cut position

$$\text{F.o.M.} = \frac{N_{\nu_e}}{RMS_{all}}$$

BDT ν_e Event Selection Optimization

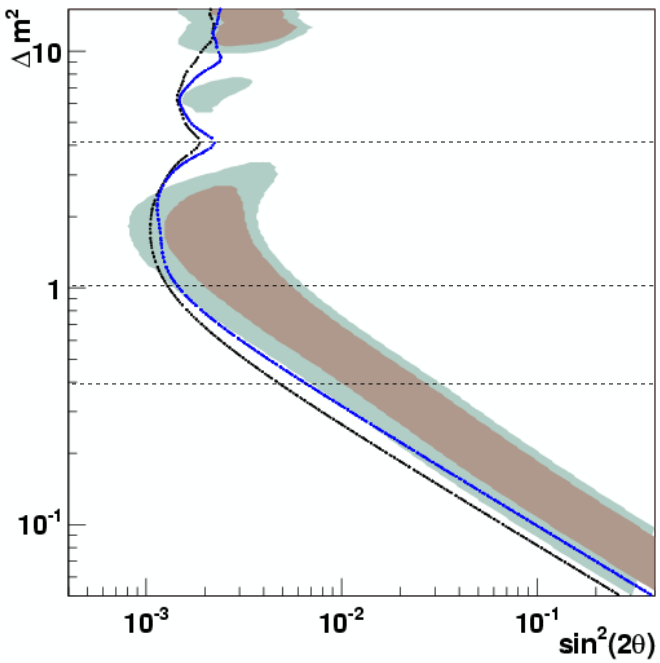
- lots of information exists in the energy spectrum of bkgd and signal which "counting experiment optimization" ignores
- explore optimization of ***sets of cuts*** instead of each energy bin independently

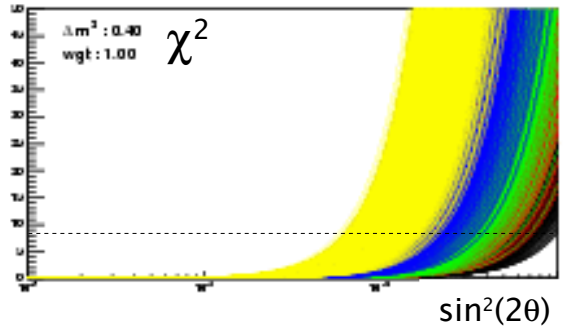


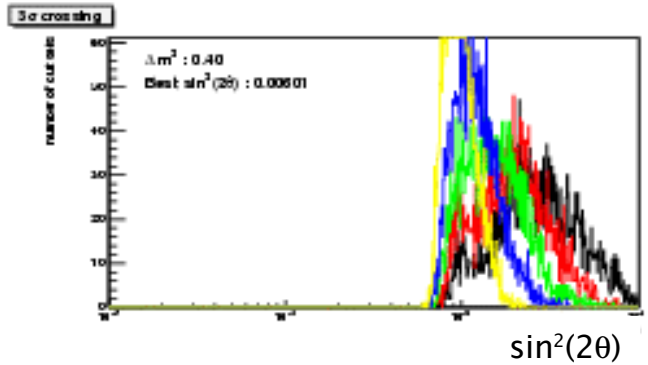
1) select BDT ν_e selection cut positions vs. neutrino energy

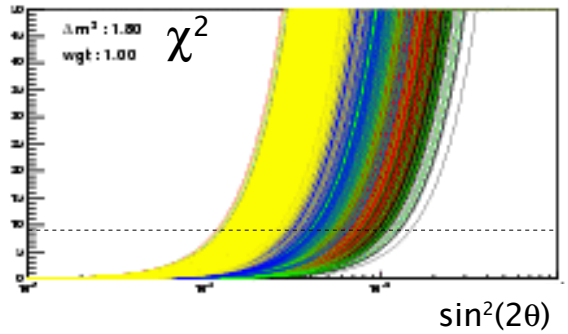
2) build detector model error matrix

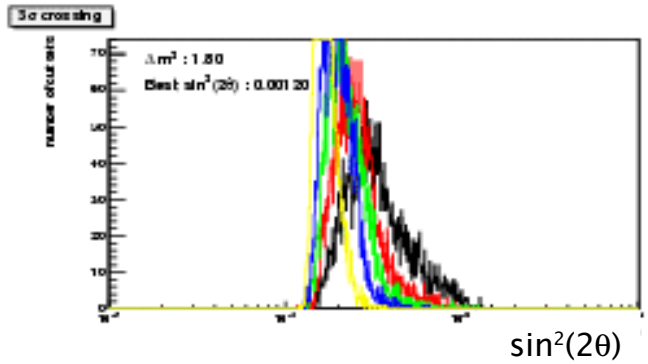
3) calculate sensitivity curve at Δm_i^2

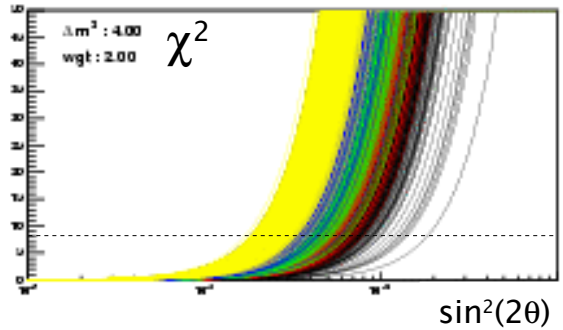


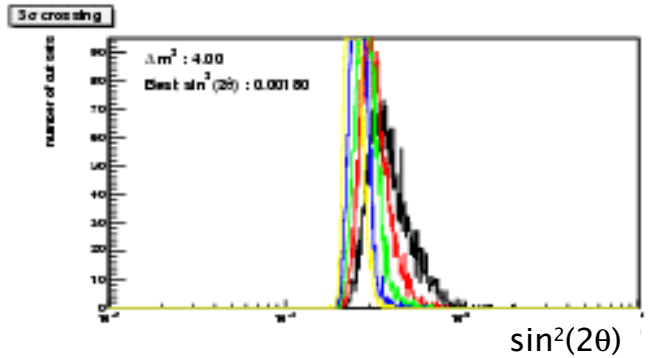








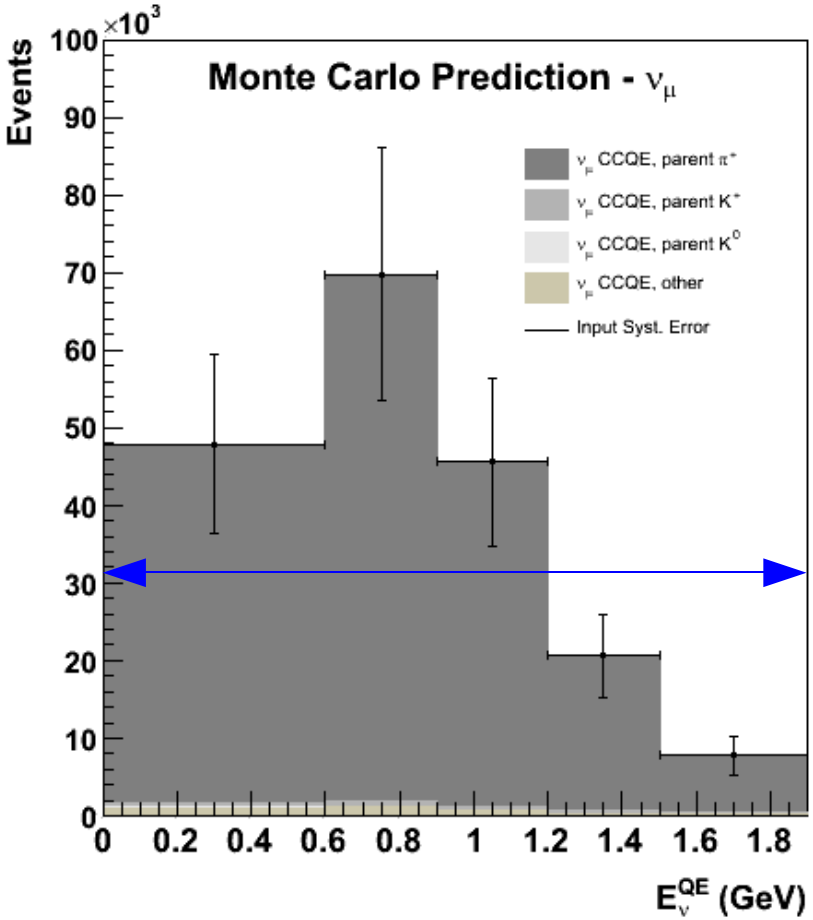


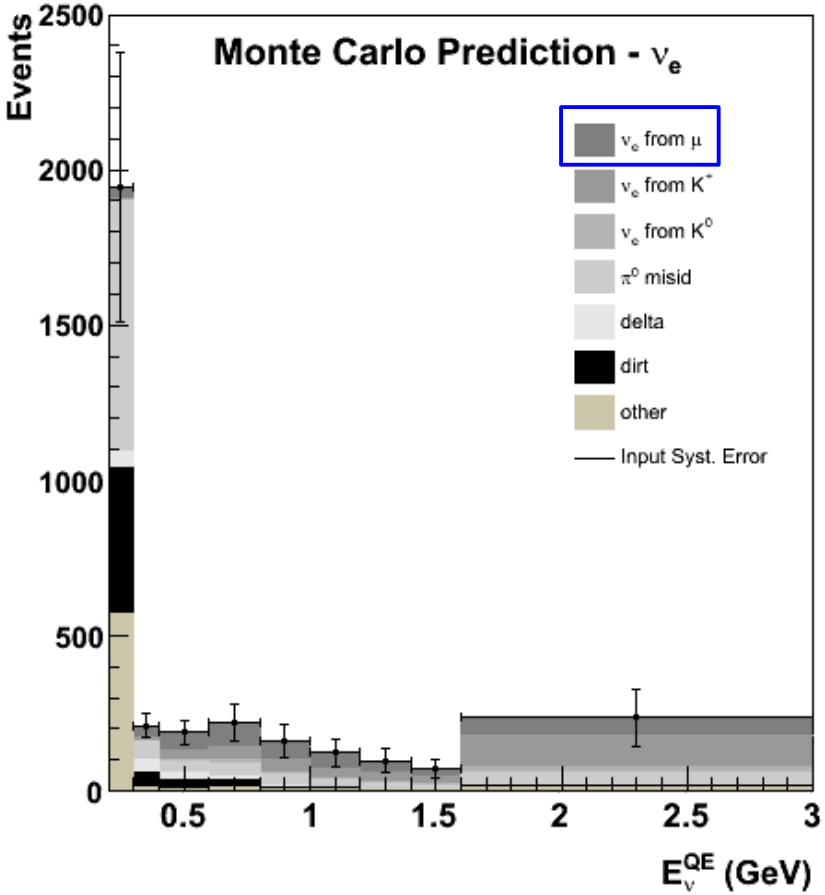


$$\text{F.o.M.} = \sum_{\Delta m^2} \frac{\sin^2(2\theta)_{3\sigma}}{w_{\Delta m^2}}$$

BDT ν_e Event Selection Optimization

- The signal region ν_e background distribution is constrained by two sources :
  - correlations with the observed ν_μ event rate
  - correlations with a low energy and high energy region containing no signal events





high statistics observed ν_μ rate provides a strong constraint on (flux x cross-section), energy scale and ν_e from μ decay intrinsic backgrounds

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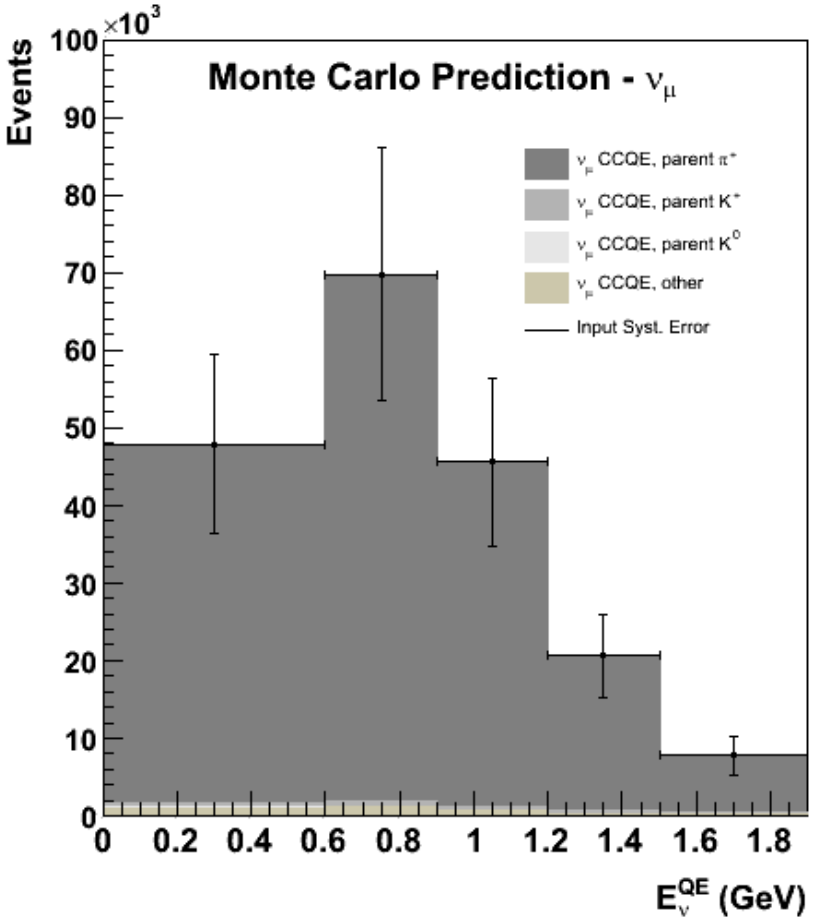
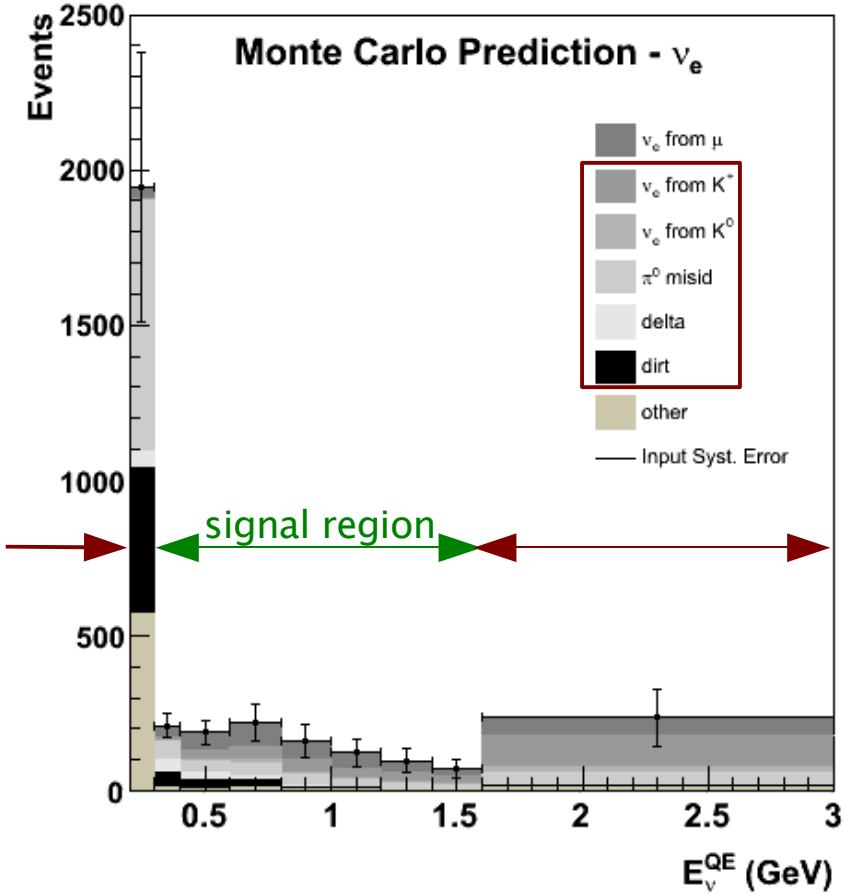
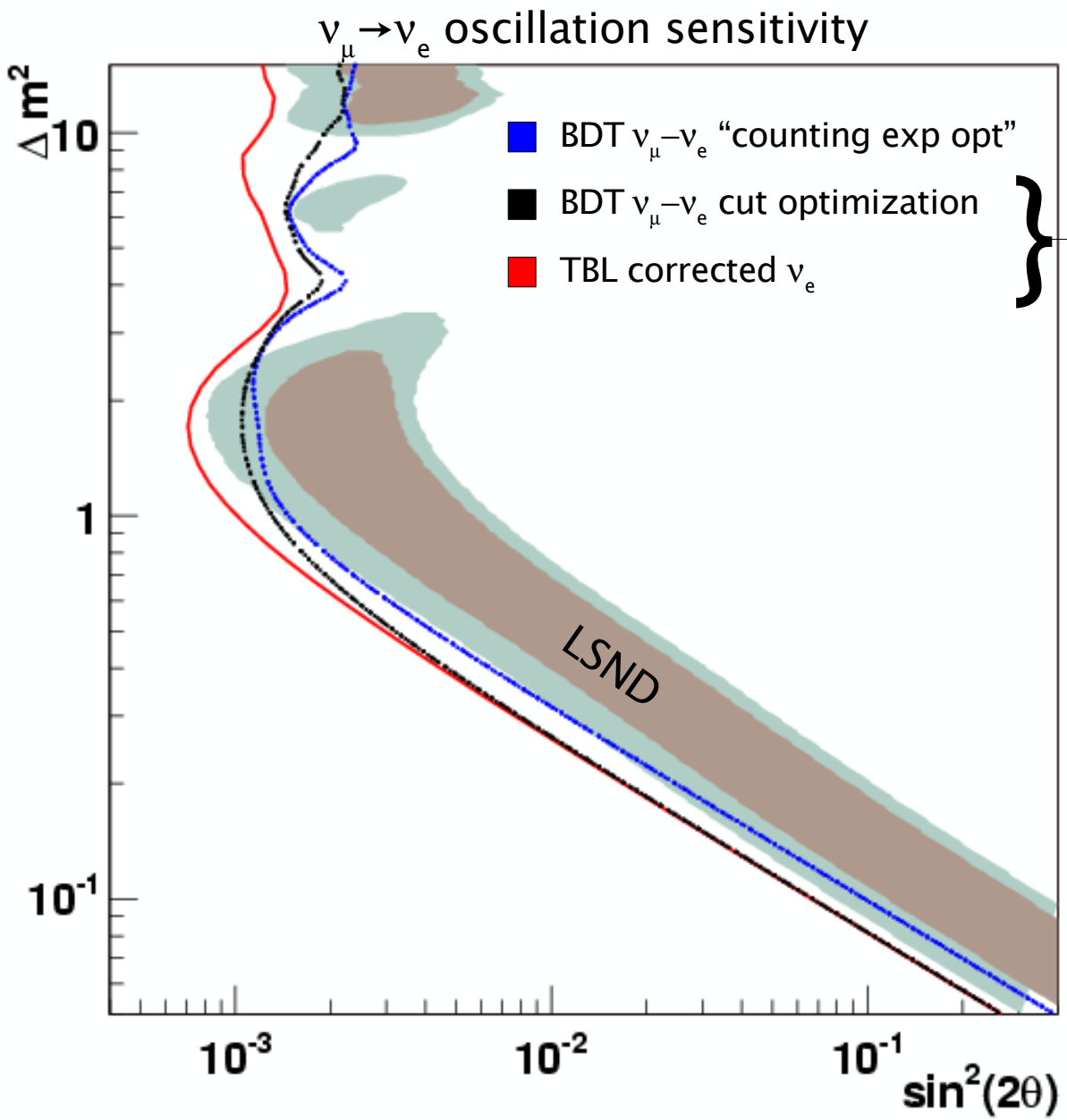




high statistics low and high energy ν_e events act as "sidebands" to the signal region and constrain largest backgrounds

LE background constraint	: 200 – 300 MeV
2-ν appearance signal region	: 300 – 1600 MeV
HE background constraint	: 1600 – 3000 MeV

BDT ν_e Event Selection Optimization



final published sensitivities
Phys. Rev. Lett. 98, 231801, 2007

- new BDT cuts gain back sensitivity at low Δm^2
- could move forward with two similarly sensitive analyses. . .

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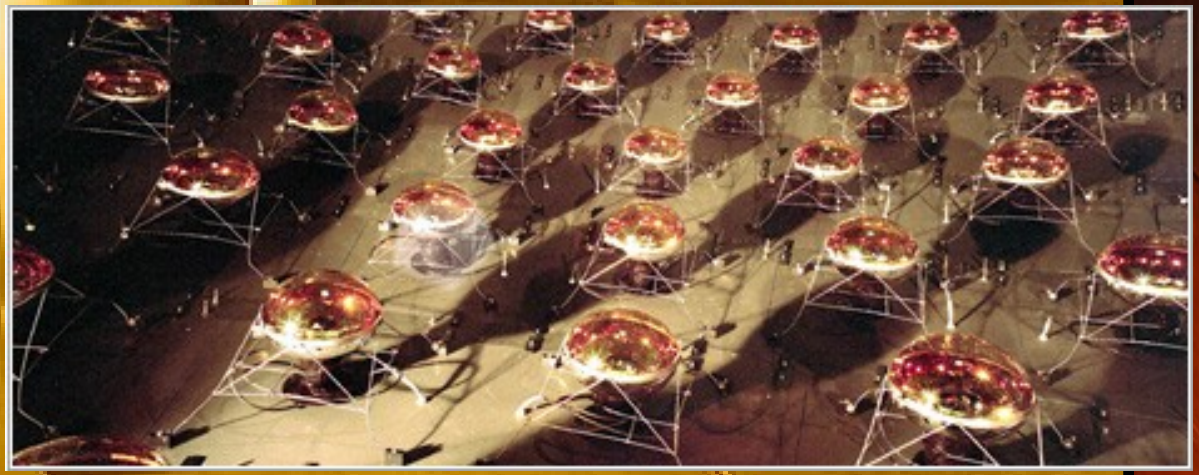


$\nu_\mu \rightarrow \nu_e$ Oscillation Results

- 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

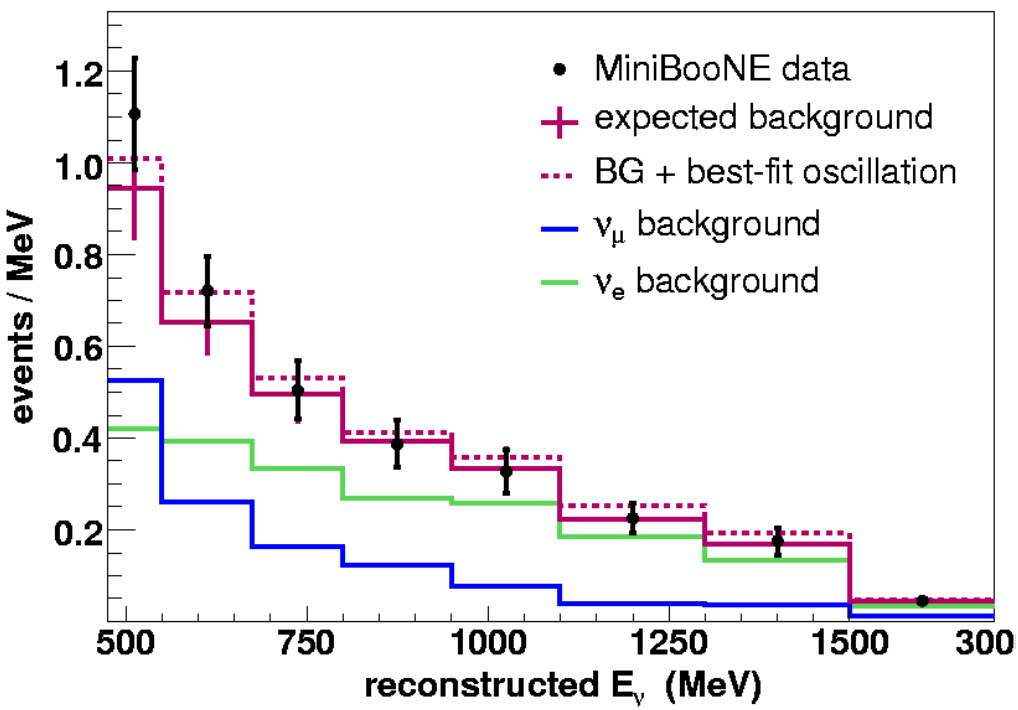
300 MeV < E_ν < 1600 MeV

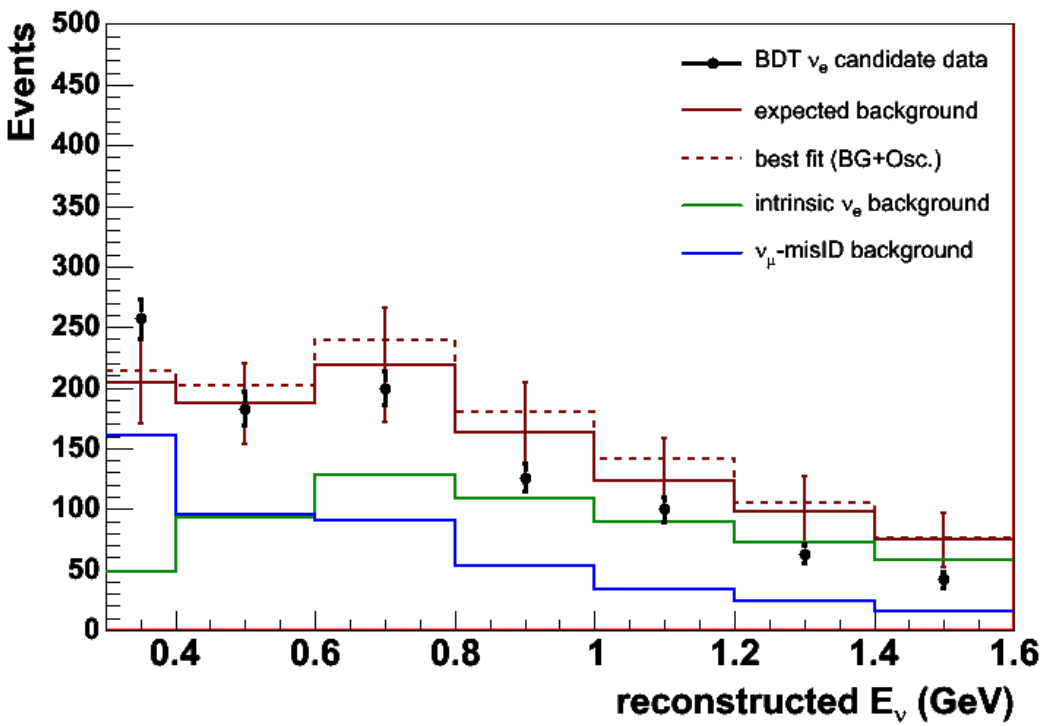
prediction : $1069 \pm 225(\text{syst})$

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

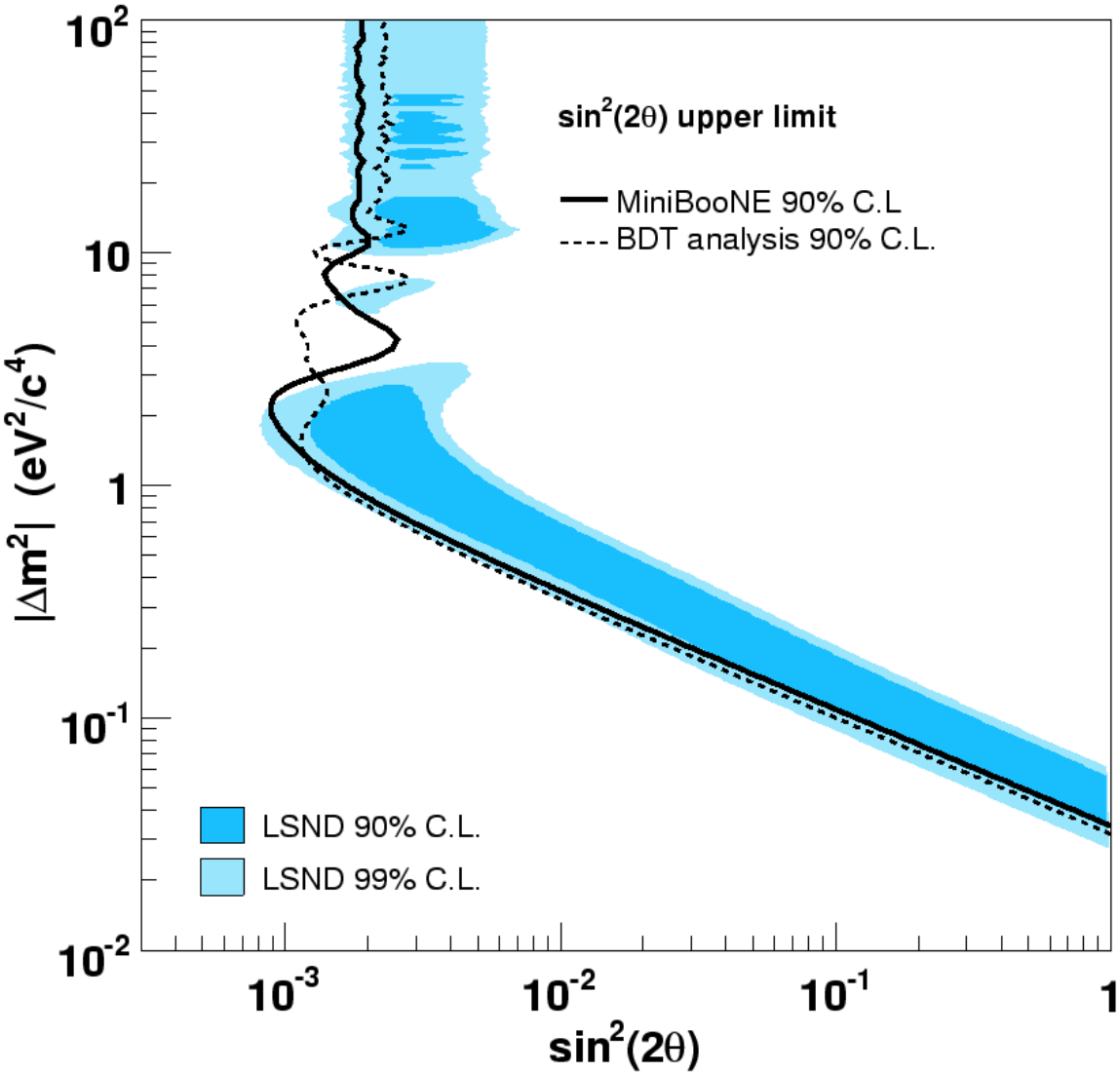
significance : -0.38σ

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

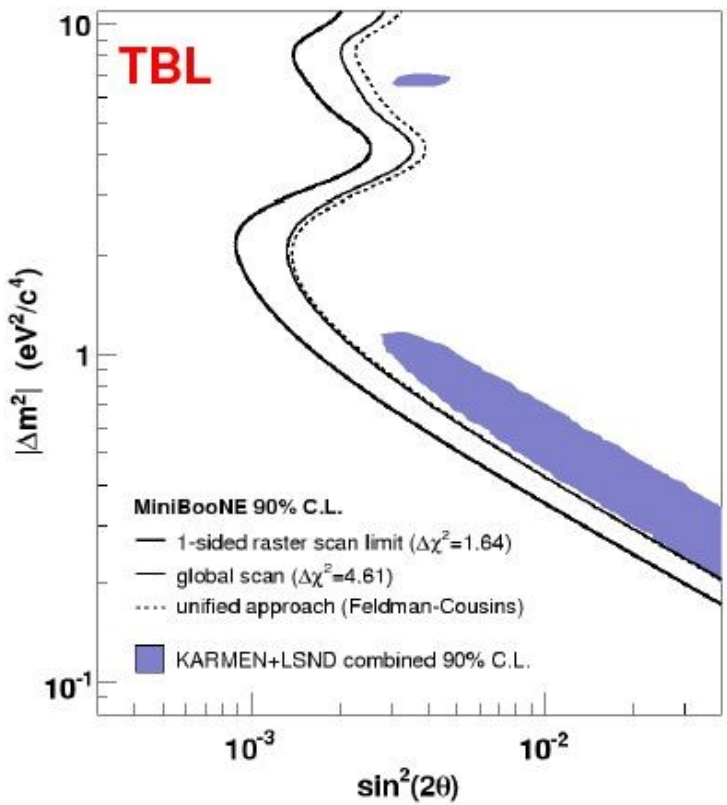




$\nu_\mu \rightarrow \nu_e$ Oscillation Results



- 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

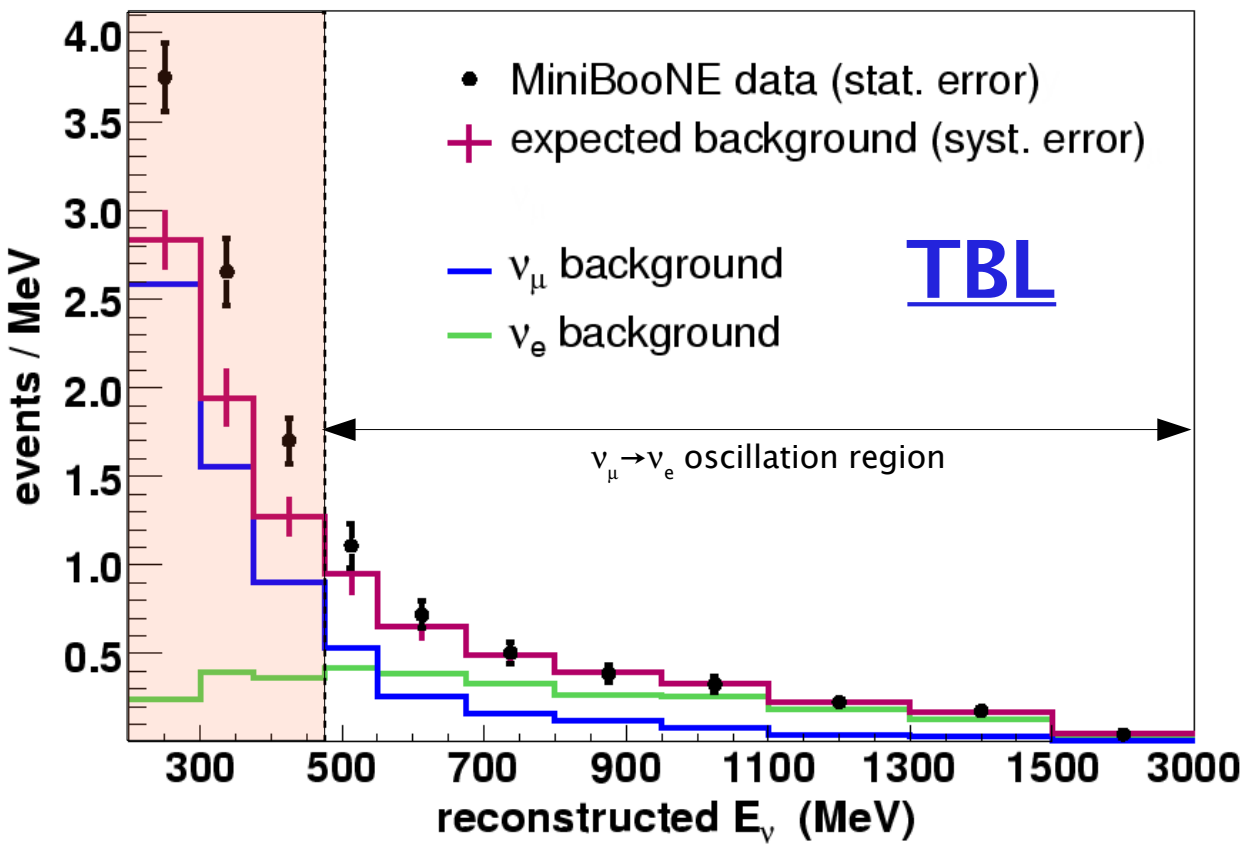


Low Energy Discrepancy

- 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



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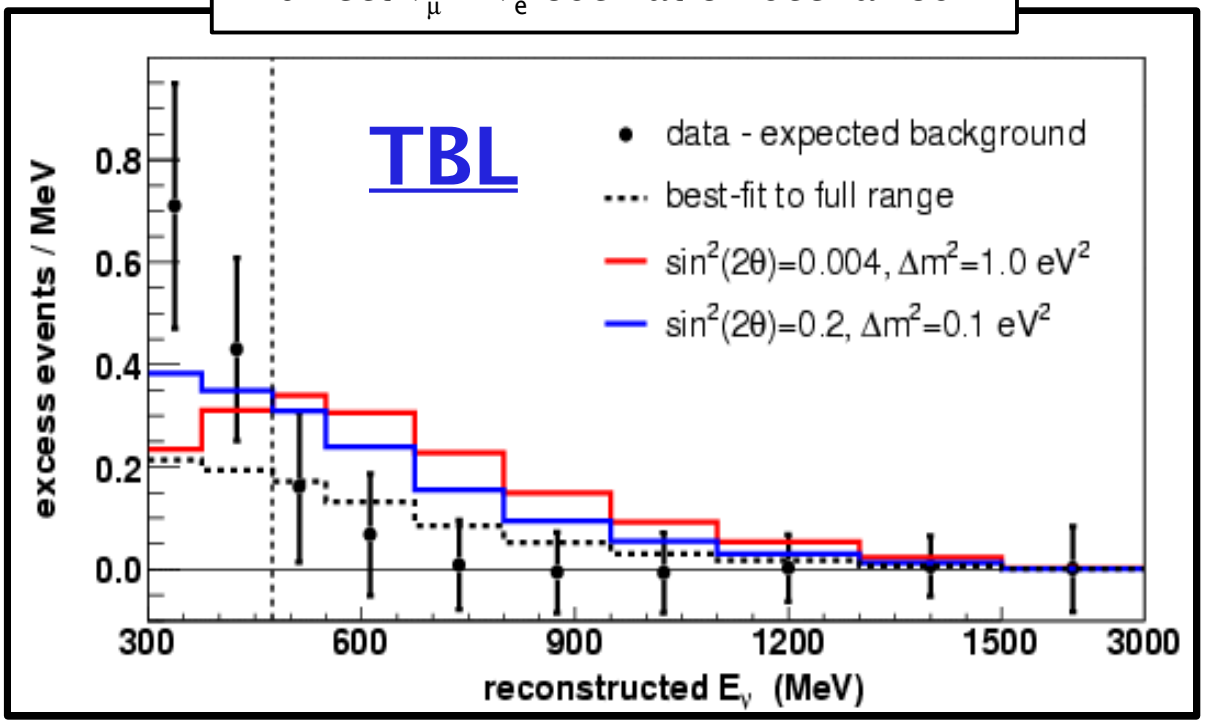
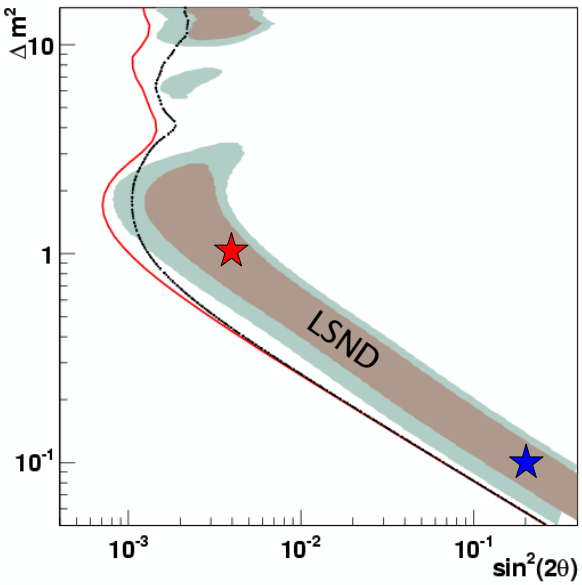
  would have peaked in the 500–1000 MeV region. Our data agrees well with the expectation in this region.

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

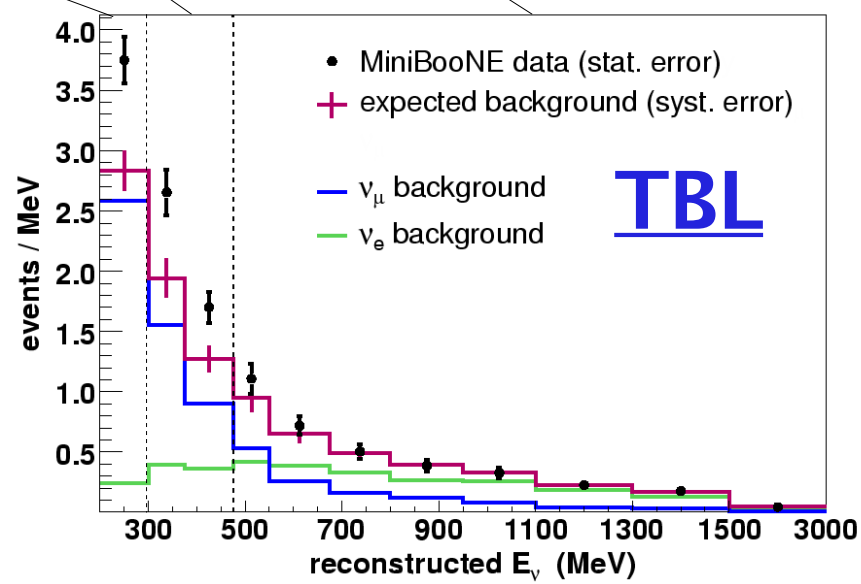
shape of excess not compatible with direct $\nu_\mu \rightarrow \nu_e$ oscillation scenarios





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)

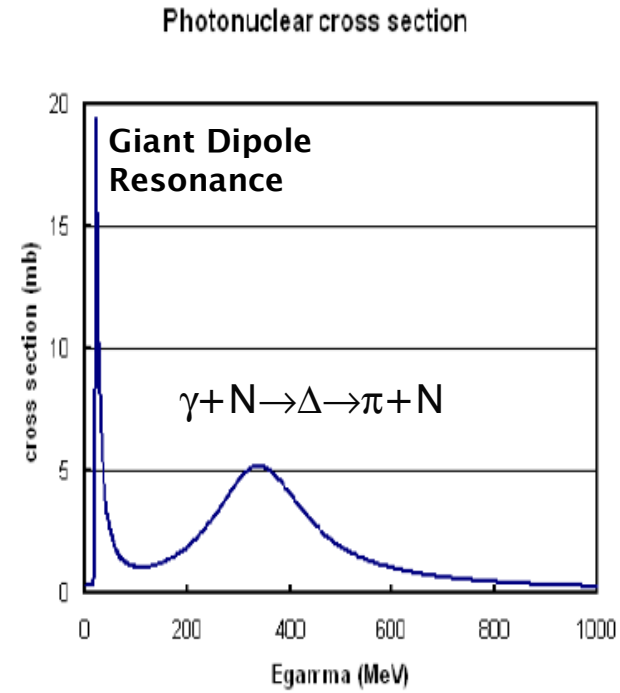
- ν_μ backgrounds are rising rapidly at low energy, but events continue to pass all tests for **electron/photon characteristics**
- no simple rescaling of π^0 or radiative-Δ backgrounds can explain excess
- dirt event enhanced samples before and after box-opening agree well with simulation



Low Energy Discrepancy

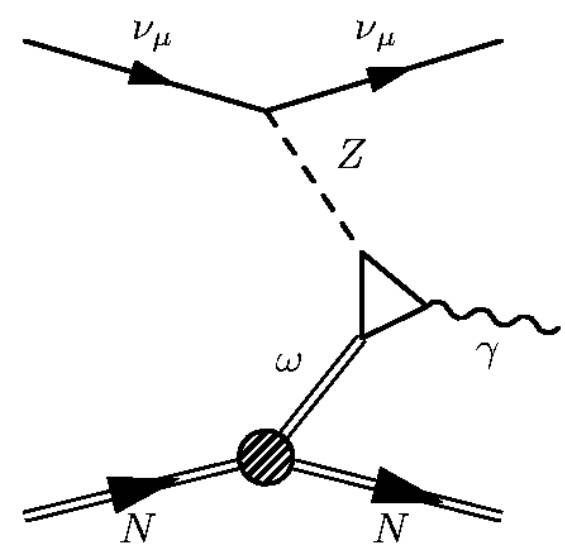
Standard Model possibilities?

- ***Is there some SM background missing from the prediction?***
- ***Any process with a <u>single gamma final state</u> is a background***



1) Processes that remove/absorb one gamma from a ν_μ induced NC $\pi^0 \rightarrow \gamma\gamma$

- these should all be included in GEANT detector simulation but there could be missing or inaccurate processes
- Example: **photonuclear absorption** (but tends to give extra final state particles in place of photon)
- under active investigation



2) All neutrino processes that produce a final state single gamma

- Example: "Anomaly mediated neutrino-photon interactions at finite baryon density" **Harvey, Hill and Hill, hep-ph0708.1281**
- under active investigation

Low Energy Discrepancy

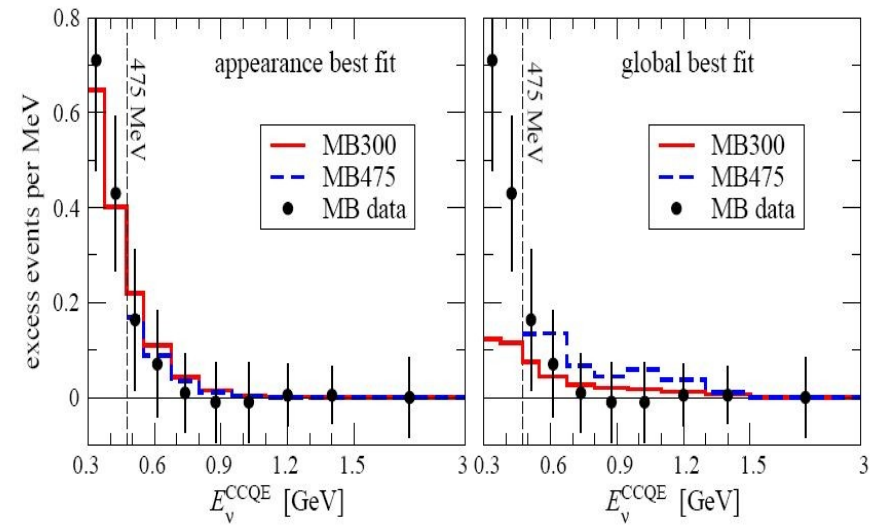
Beyond the Standard Model possibilities?

- ***Is this evidence for some beyond the SM process?***

1) Is it due to some kind of sterile-active neutrino oscillation?

- models with 3 active and 1 sterile neutrino (3+1) are excluded at >4σ
- 3+2 models can fit appearance data but fit is incompatible with disappearance data at >3σ
- **Maltoni and Schwetz hep-ph0705.0107**

3+2 fits hep-ph0705.0107



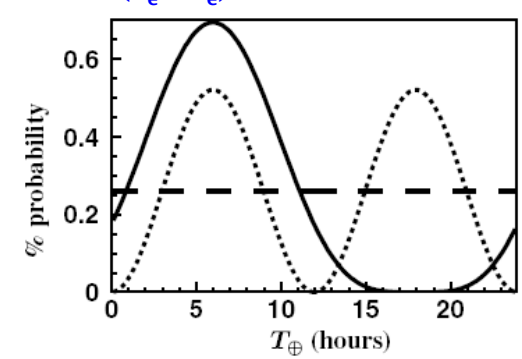
MiniBooNE, LSND, KARMEN, NOMAD

MiniBooNE, LSND, KARMEN, NOMAD, Bugey, Chooz, Palo Verde, CDHS

2) Other theoretical hypotheses published both before and after MiniBooNE's first results

- sterile neutrinos take shortcuts in extra dimensions
  Pas, Pakvasa and Weiler. Phys.Rev.D72 095017, 2005
- electron neutrino disappearance
  Giunti and Laveder, hep-ph0707.4593
- Lorentz invariance violation
  Katori, Kostelecky and Tayloe Phys.Rev.D74 105009, 2006

Prob ($\nu_e \rightarrow \nu_e$) over one sidereal day



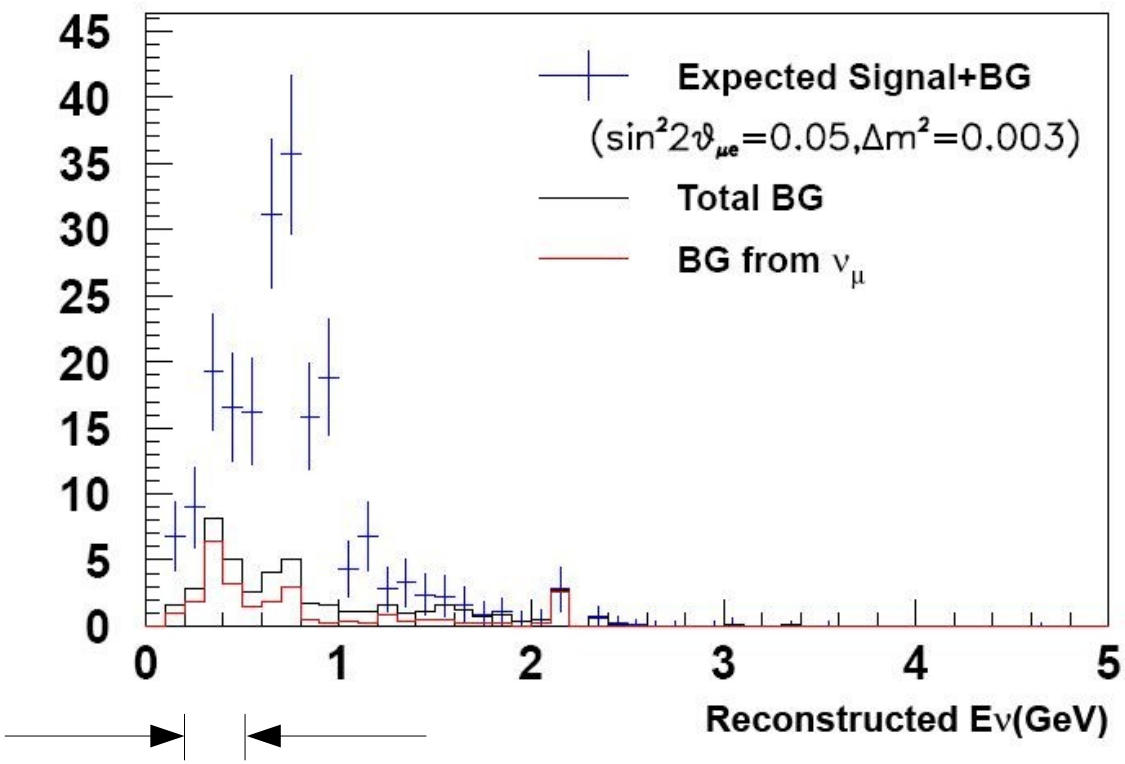
Low Energy Discrepancy

Implications?

- Depending on source of low energy events in MiniBooNE, ***could it have implications for other oscillation experiments?***
- Several next generation experiments will attempt similar measurements:
  - different baseline = different Δm^2 (Δm^2_{13})
  - near detectors help, but are not always identical so detector effects may remain important
  - potential ν_μ constraint effected by large disappearance rates
  - Example: could low energy excess seen by MiniBooNE be important to T2K?

T2K

hep-ex/0106019v1



Conclusions

- The MiniBooNE experiment and analysis techniques were carefully designed to search for very small oscillation probabilities through a measurement of ***electron neutrino appearance***
  - MiniBooNE demonstrated the ***constraining of key backgrounds*** (π^0, Δ, out-of-tank events) using data outside of the signal region
  - MiniBooNE demonstrated the ***constraining of the intrinsic ν_e*** event rate using the observed ν_μ event rate

- ***MiniBooNE saw no evidence*** of the two neutrino direct $\nu_\mu \rightarrow \nu_e$ oscillation interpretation of the LSND result **Phys. Rev. Lett. 98, 231801, 2007.**
  - An excess of events is seen between 200-475 MeV in the ν_e distribution and is still being investigated/interpreted. What is ***low energy excess*** of events telling us?
  - Look for electron result from ***NuMI → MB*** neutrino beam soon
  - Look for ***antineutrino*** results from BNB → MB

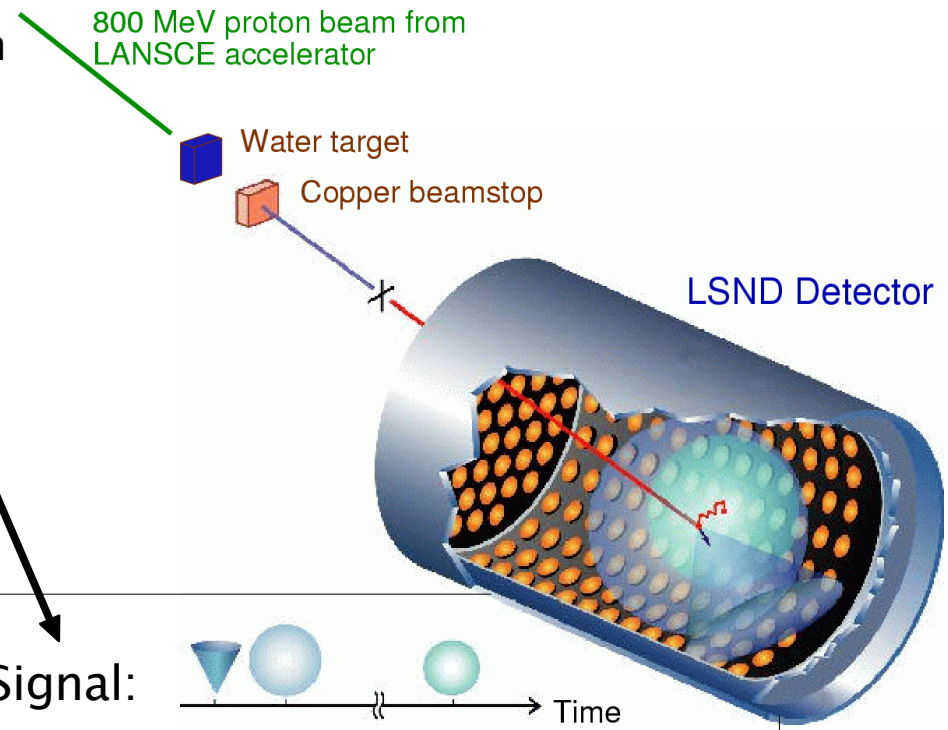
Backup Slides

The LSND Signal as Oscillations

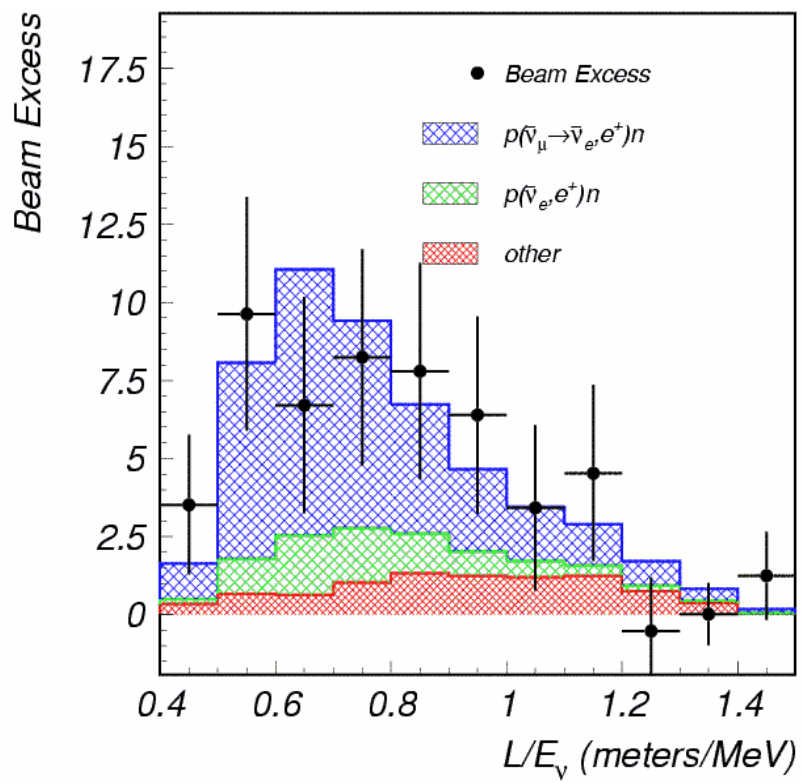
- LSND looked for an excess of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam

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

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



- 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

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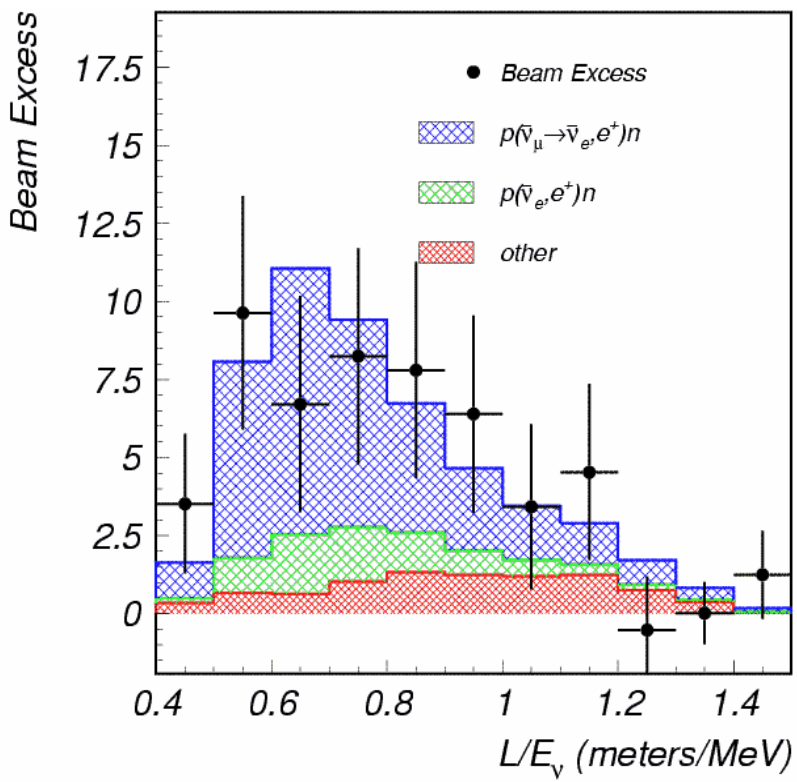

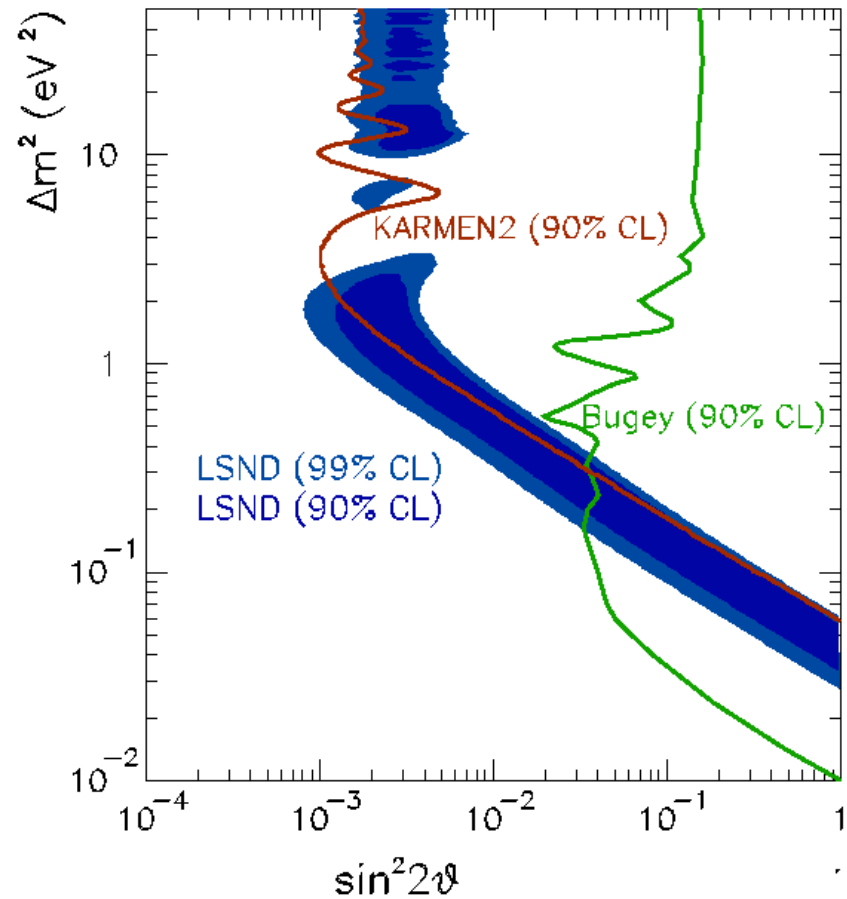

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Parameterizing Pion Data

$$\frac{d^2\sigma(p+A\rightarrow\pi^+ + X)}{dp\,d\Omega}(p,\theta)=c_1 p^{c_2}\left(1-\frac{p}{p_{beam}}\right)\exp\left[-c_3\frac{p^{c_4}}{p_{beam}^{c_5}}-c_6\theta\left(p-c_7 p_{beam}\cos^{c_8}\theta\right)\right]$$

- X : any other final state particle
- p_{beam} : proton beam momentum (GeV/c)
- p, θ : pion lab-frame momentum (GeV/c) and angle (rad)
- $c_1,\ldots, c_8$: empirical fit parameters

The Sanford-Wang parametrization is useful to:

- combine information from data sets at different beam energies
- input hadron cross-sections into neutrino beam Monte Carlos
- translate pion production uncertainties into neutrino flux uncertainties
- compare results of different experiments in similar energy regions for compatibility

J. R. Sanford and C. L. Wang "Empirical formulas for particle production in p-Be collisions between 10 and 35 BeV/c", Brookhaven National Laboratory, AGS internal report, (1967) (***unpublished)***

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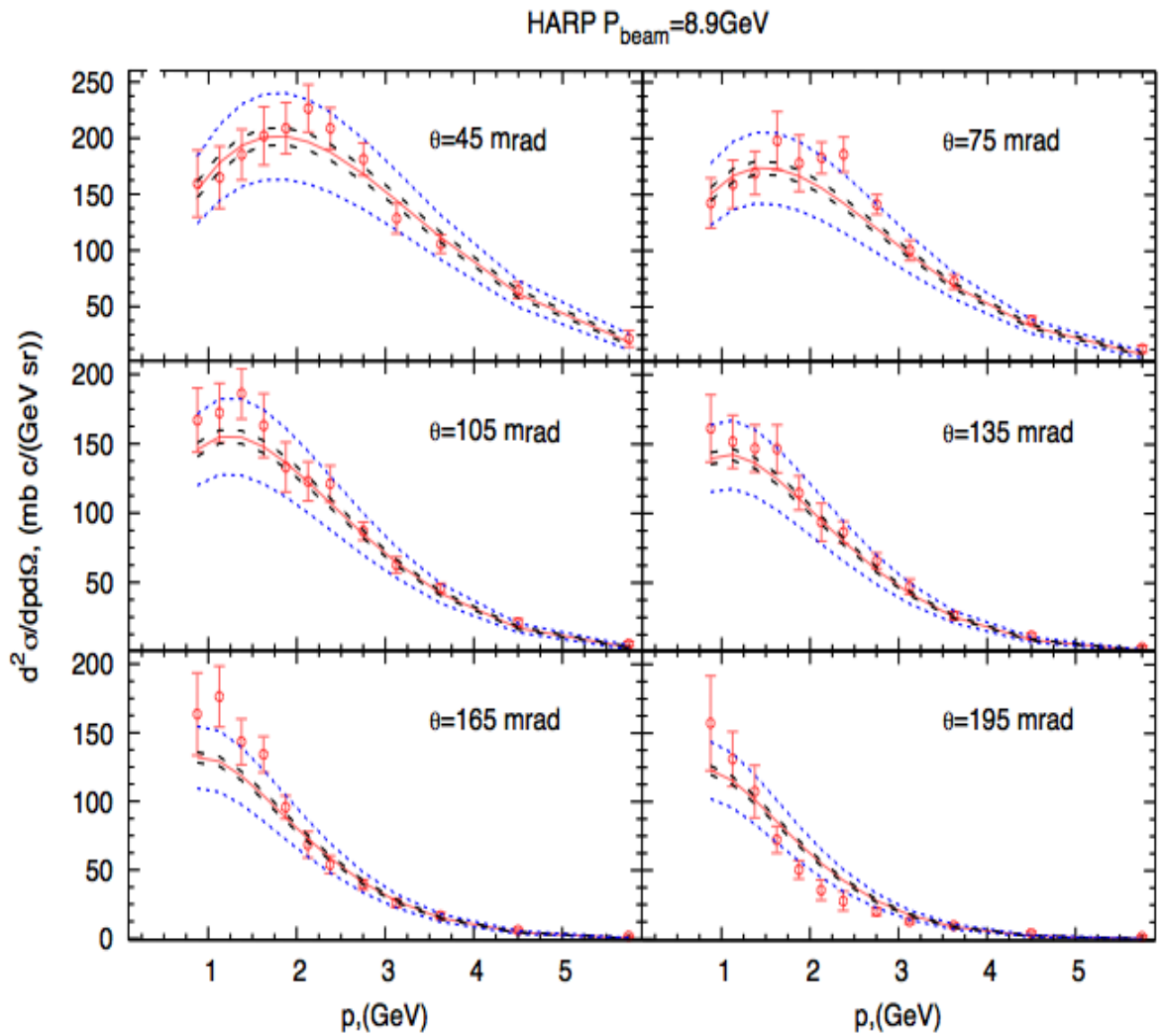
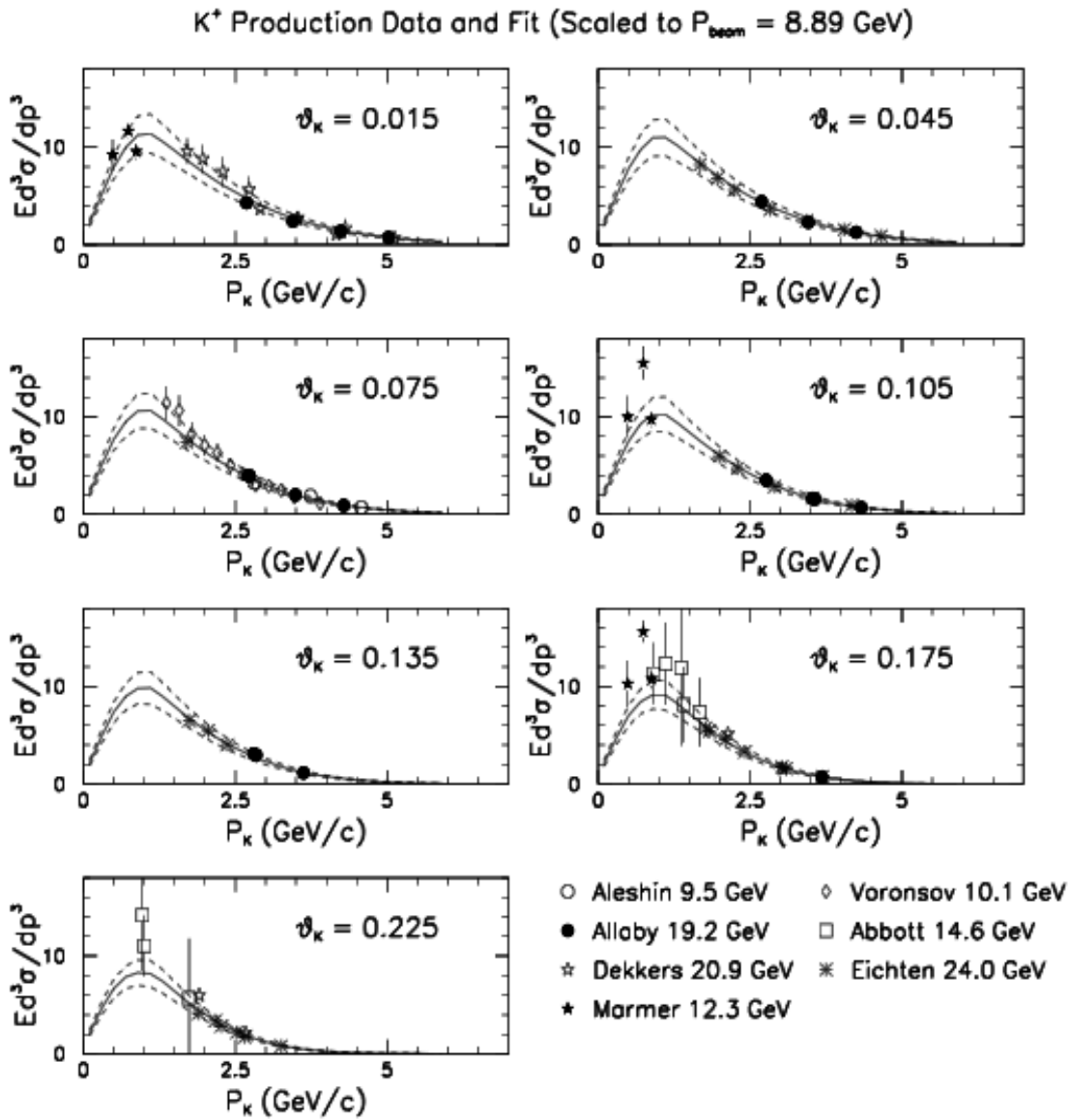


Kaon Production

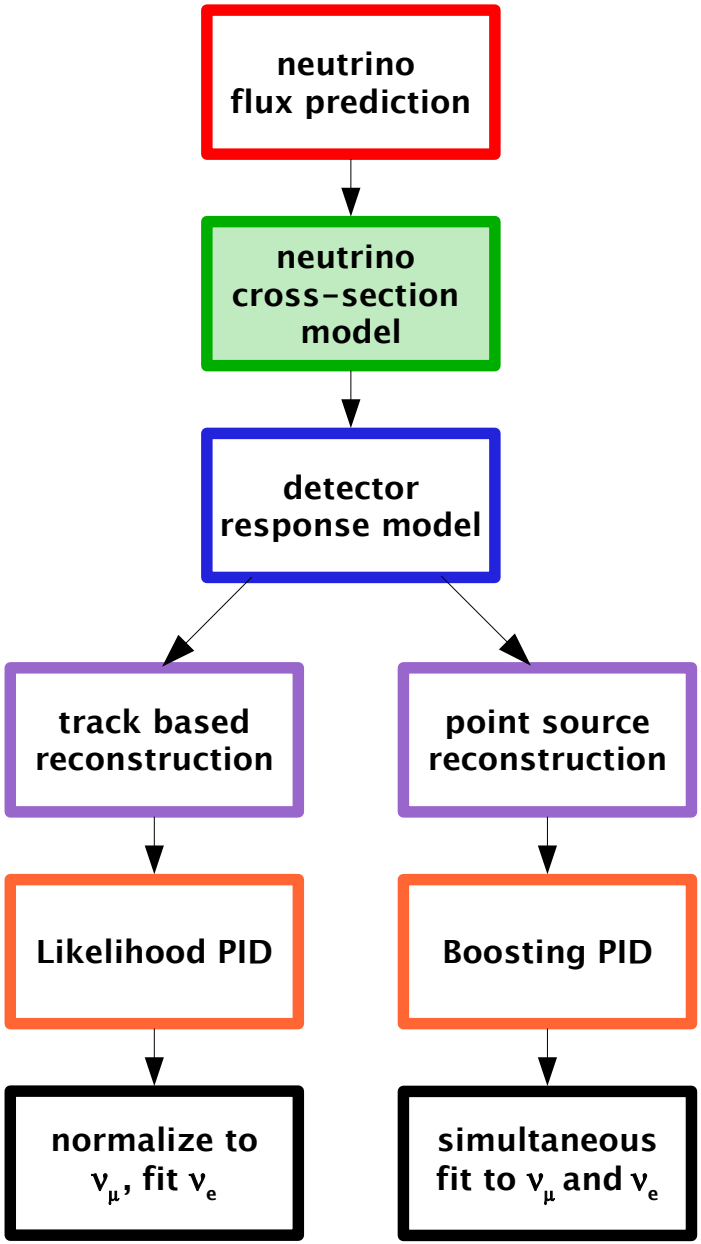
- intrinsic electron neutrinos come from **kaon decays** or the decay of muons coming from pions

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

- 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 Cross-section Model

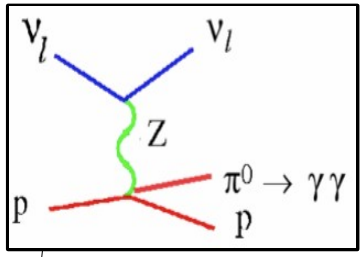


- armed with an input flux, neutrino interactions are simulated using the **NUANCE** neutrino event generator software
- exclusive channels are handled separately and use differing, appropriate models
- the most important exclusive channel for the MiniBooNE oscillation search is the **charged-current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

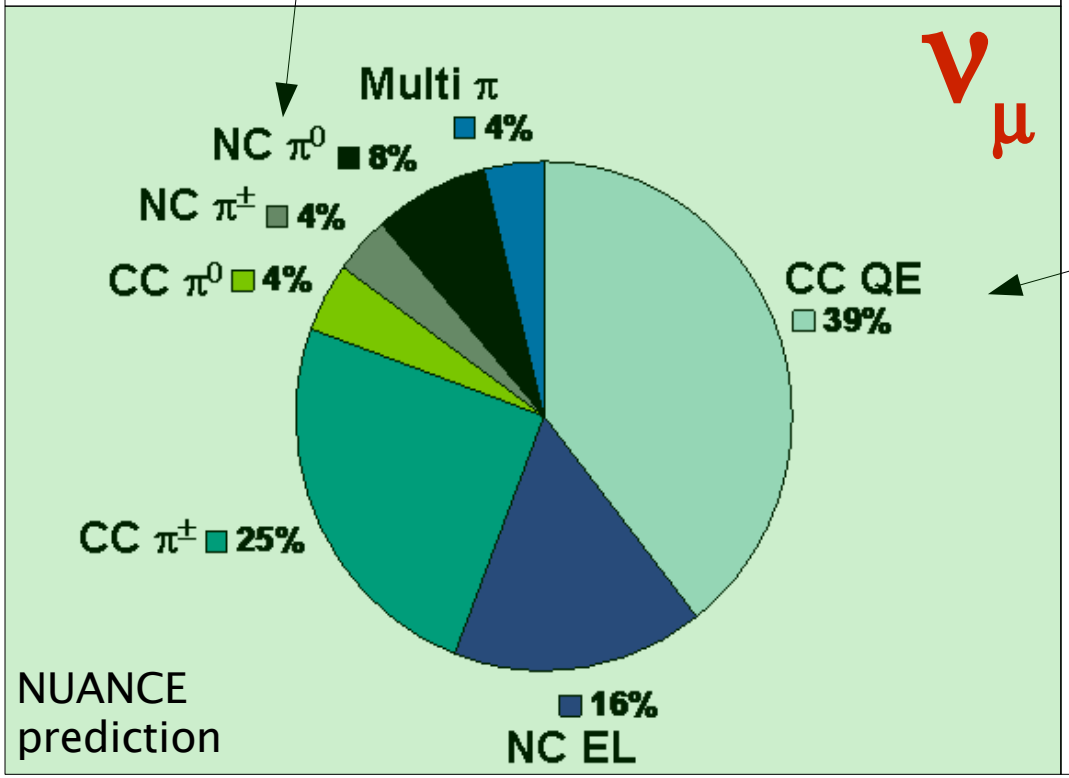
→ D. Casper, "The nuance Neutrino Physics Simulation, and the Future", Proceedings of NUINT01 workshop (2001)
→ R.A. Smith, E.J Moniz, "Neutrino Reactions on Nuclear Targets" Nucl.Phys.B43:605 (1972) Erratum-ibid.B101:547 (1975)
→ D. Rein, L.M. Sehgal, "Coherent pi0 production in neutrino reactions"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

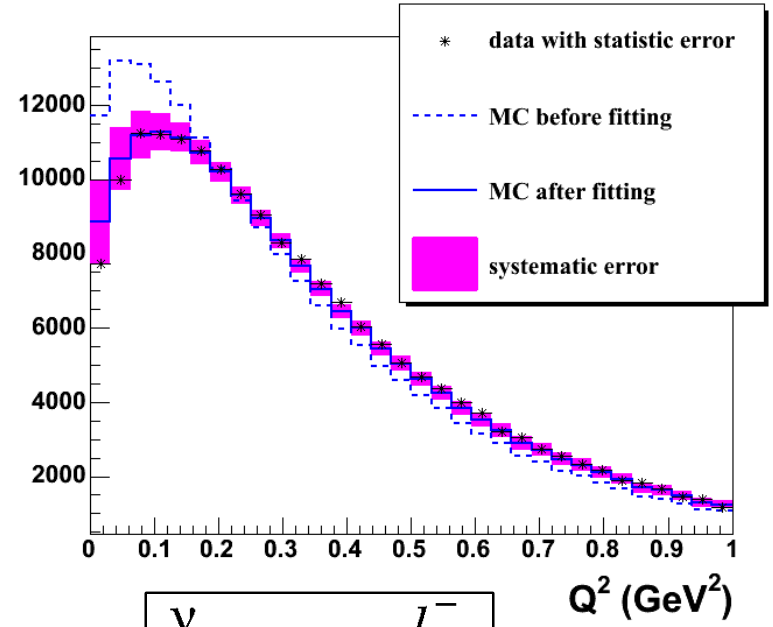
Neutrino Cross-section Model

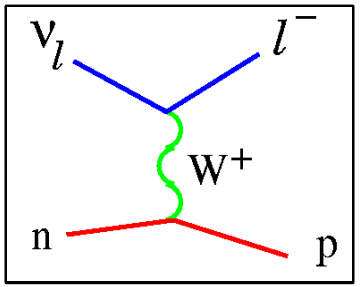
- largest mis-ID background in ν_e event sample
- NUANCE cross-section model ***tuned to observed π^0 rate***



NC π^0







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

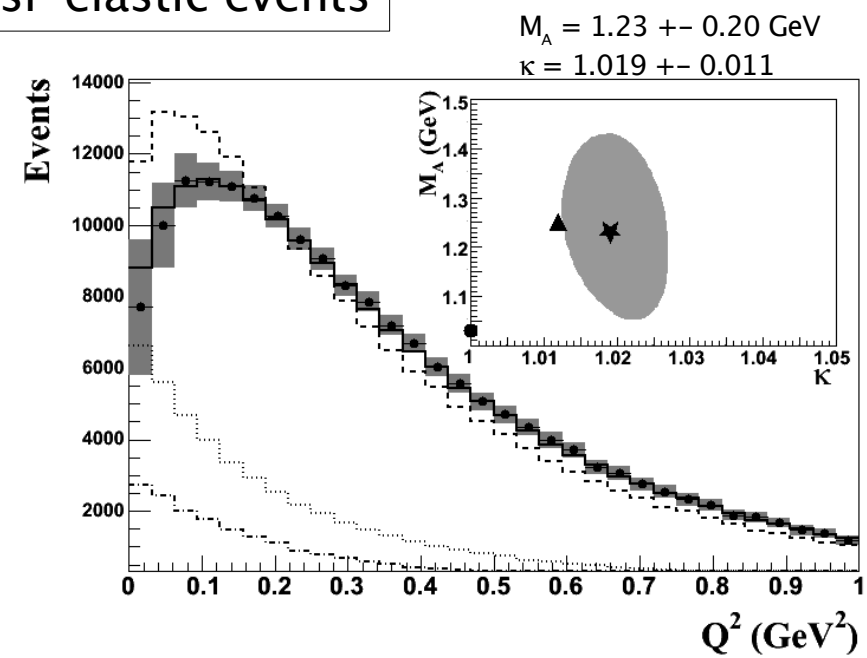
Neutrino Cross-section Model

charged-current quasi-elastic events

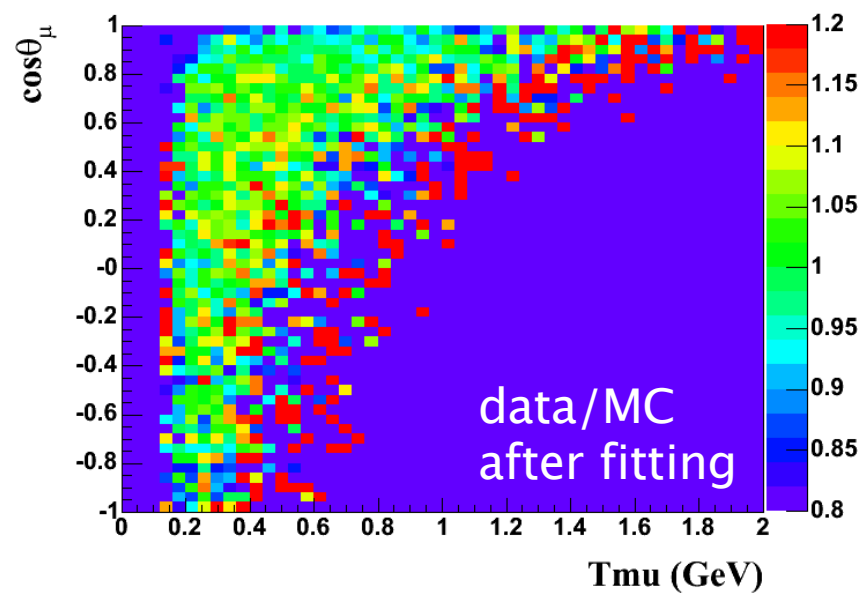
- A deficit is seen in the data for low values of the momentum transfer, Q^2

- **Solution:** use ν_μ data sample to adjust available parameters in present model to reproduce data. only $\nu_\mu - \nu_e$ 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



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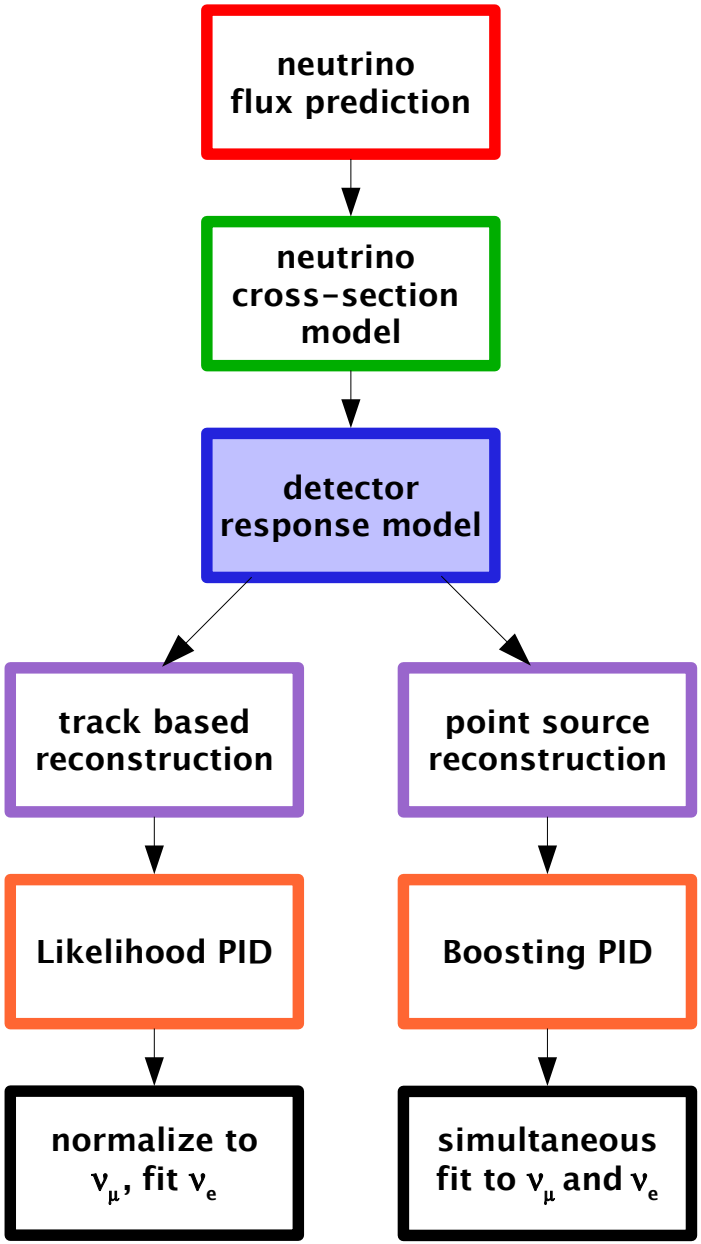
Detector Response Model



MiniBooNE detector :

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

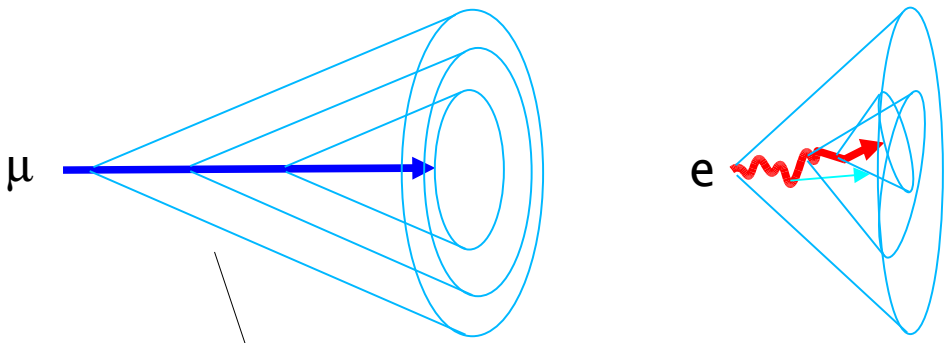
- detector modeled by a GEANT3 simulation with an added ***"optical model"*** to describe the production, absorption and propagation of light within the tank

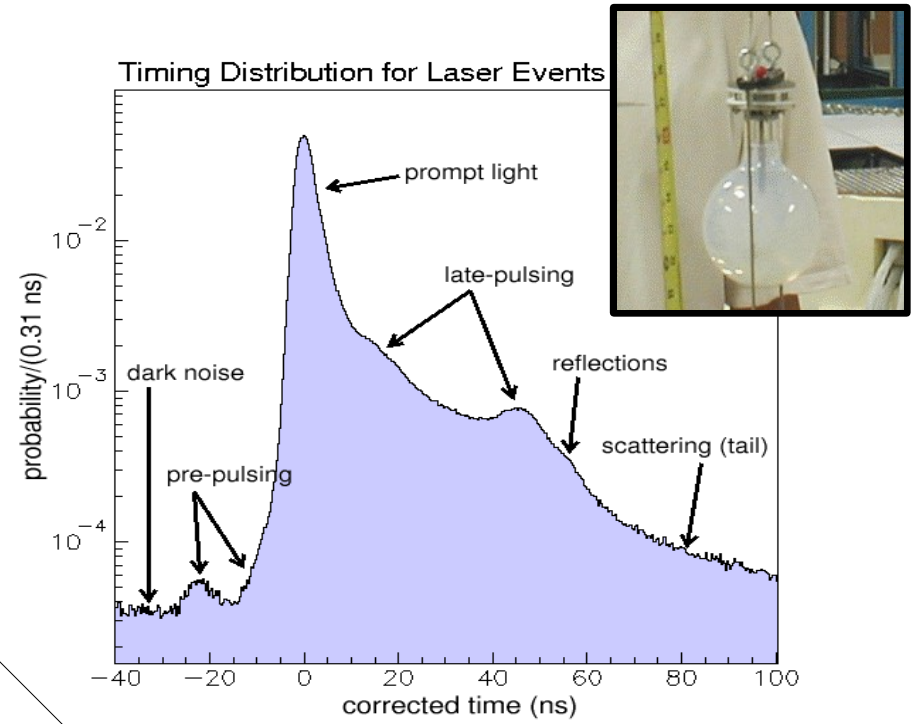
- OM parameters can be tuned by studying :
  - **external measurements**
  - **Michel electrons in the tank**
  - **cosmic rays in the tank**
  - **NC events in the tank**
  - **calibration lasers inside the tank**

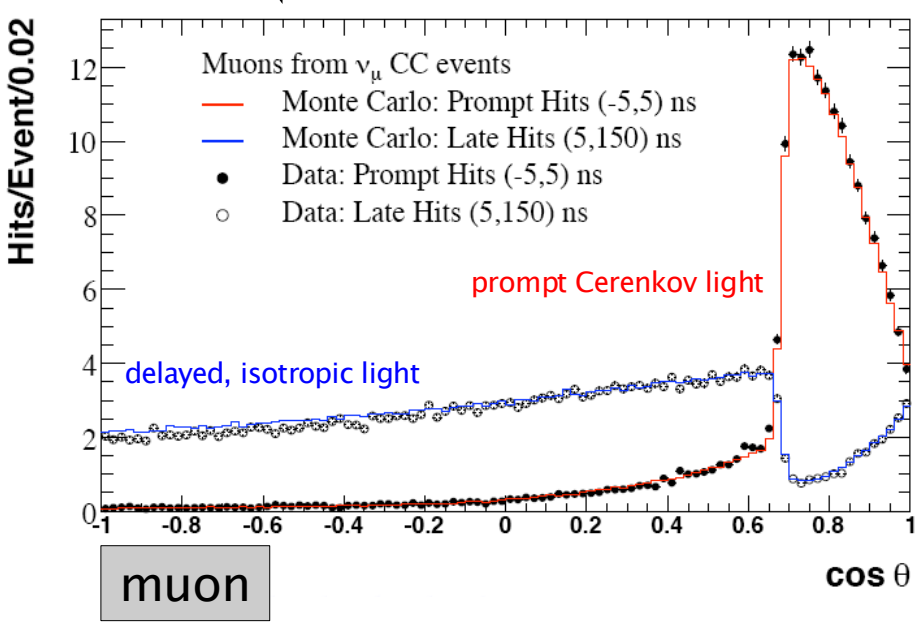
- lacking the ultimate energy calibration source (i.e. 1 GeV electron gun), we must calibrate the model very carefully with sources we do have to gain confidence we model the detector properly
  - **Michel decay endpoint at 53 MeV**
  - **reconstructed π^0 mass**
  - **scintillator cubes and muon hodoscope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

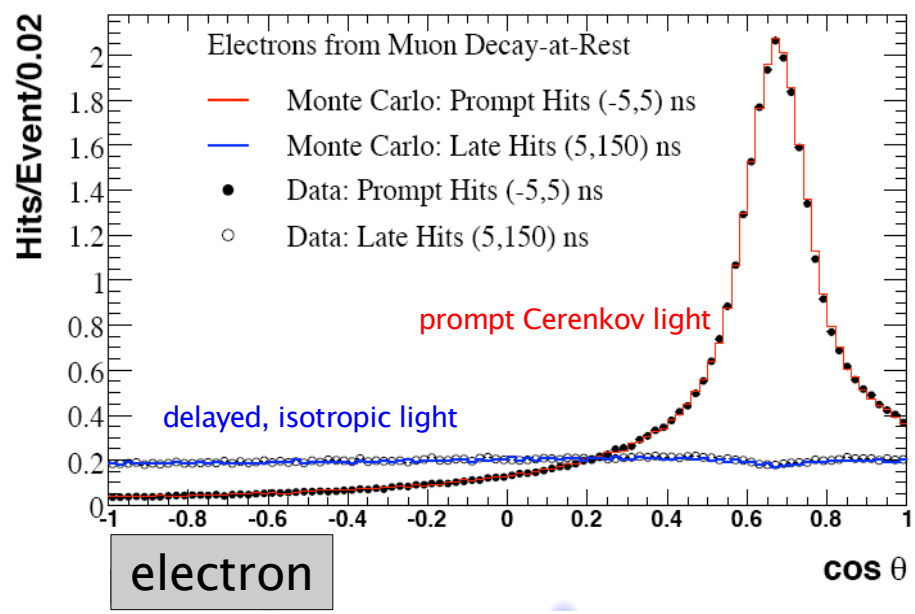
Detector Response Model

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

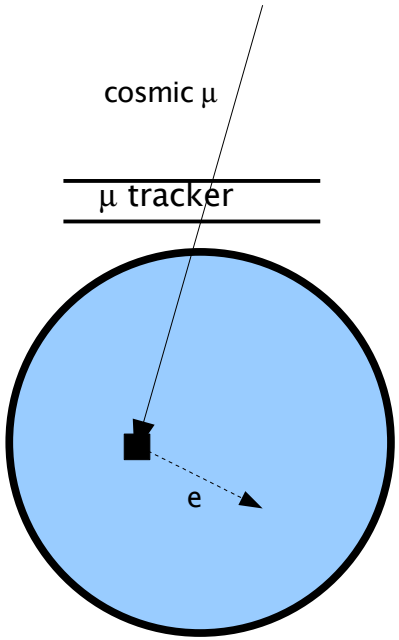






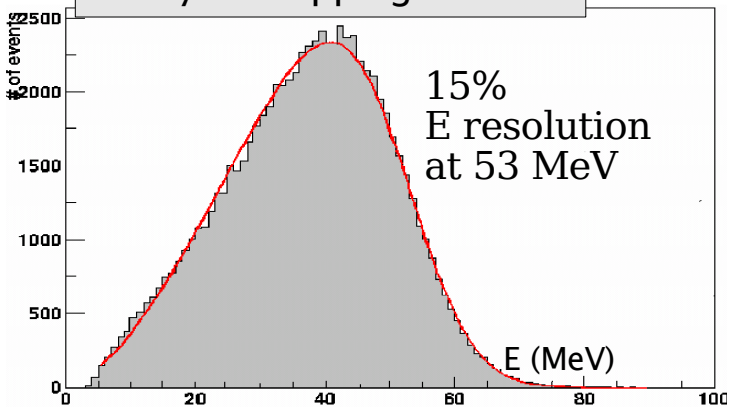


Detector Response Model

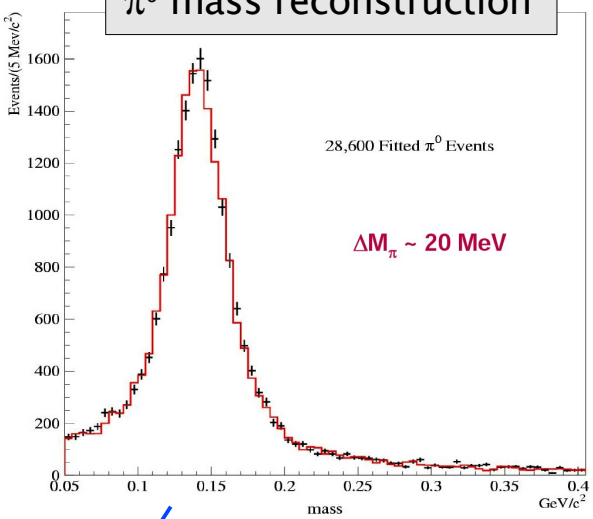


energy calibration

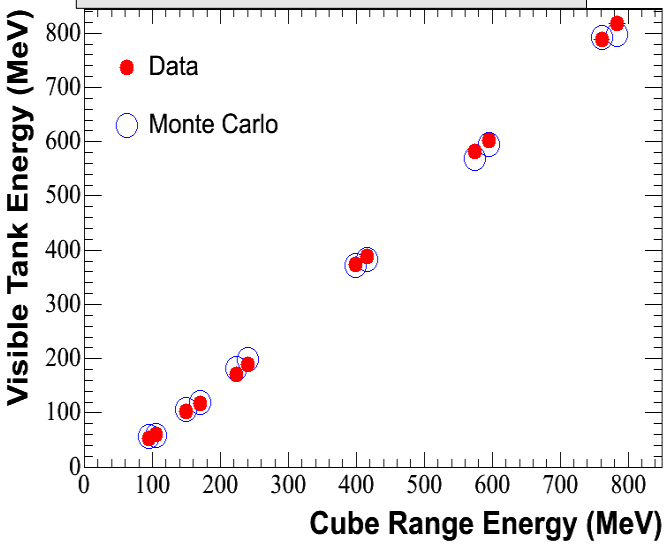
Michel electrons from the decay of stopping muons

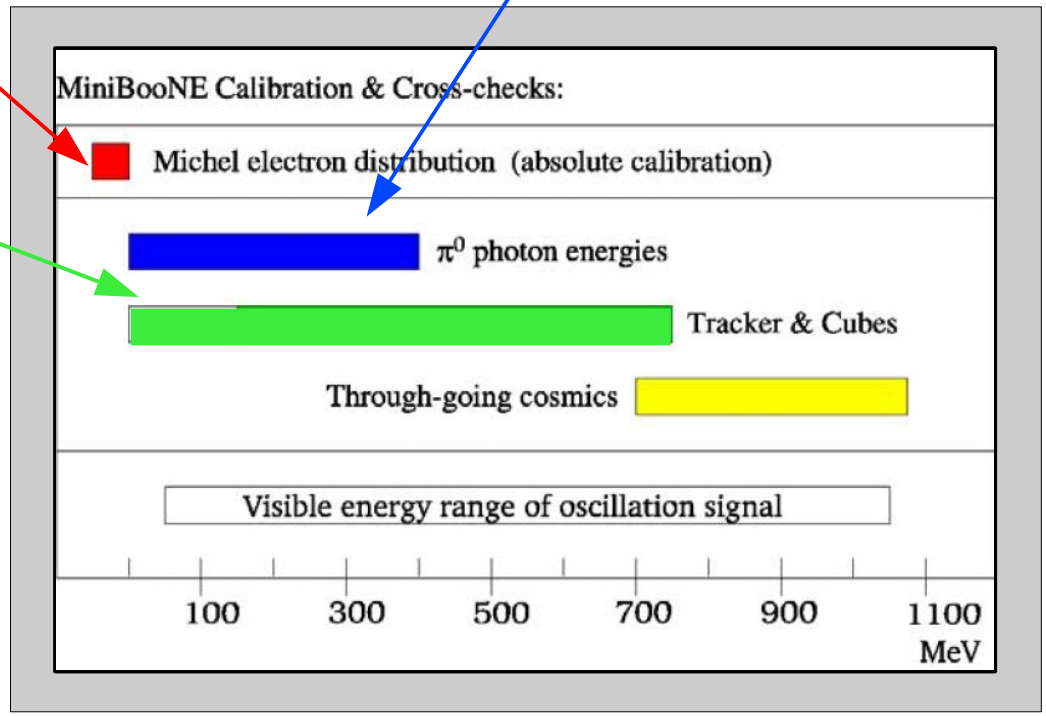


π^0 mass reconstruction

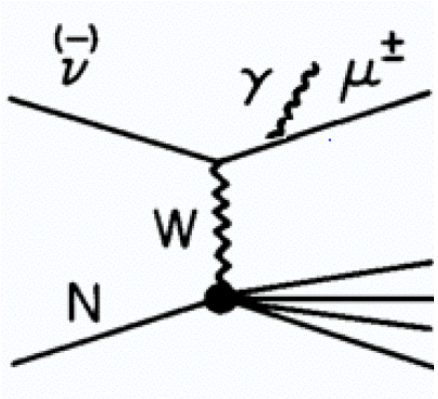


Cosmic muons stopping in scintillator cubes





Muon bremsstrahlung



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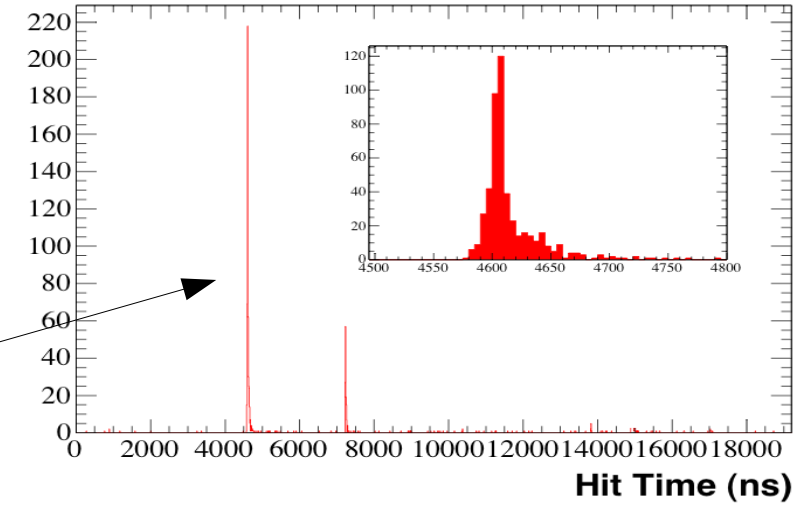

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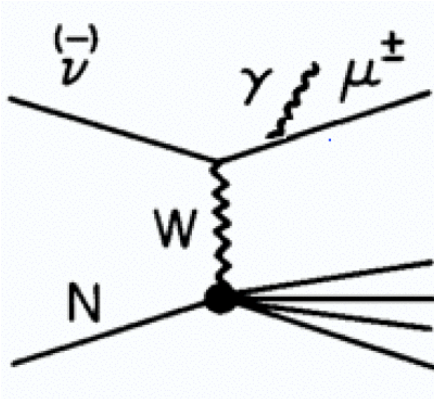

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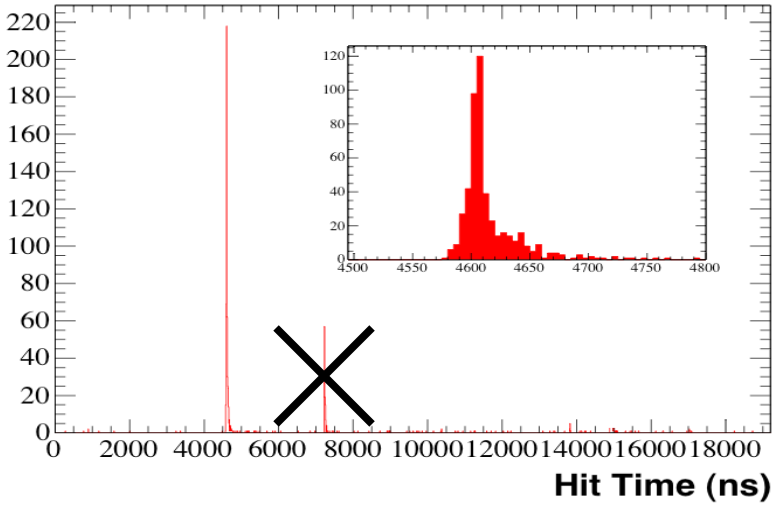

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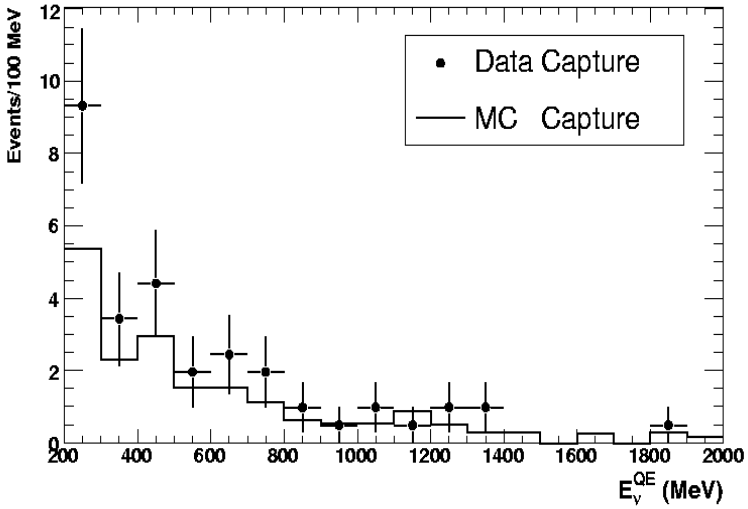

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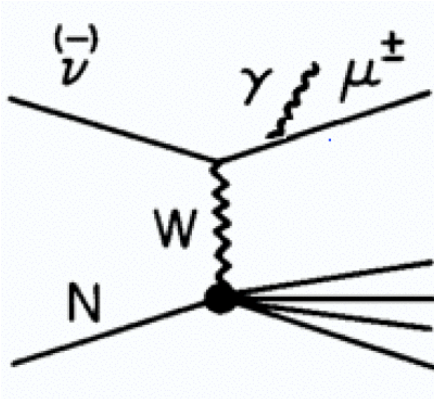

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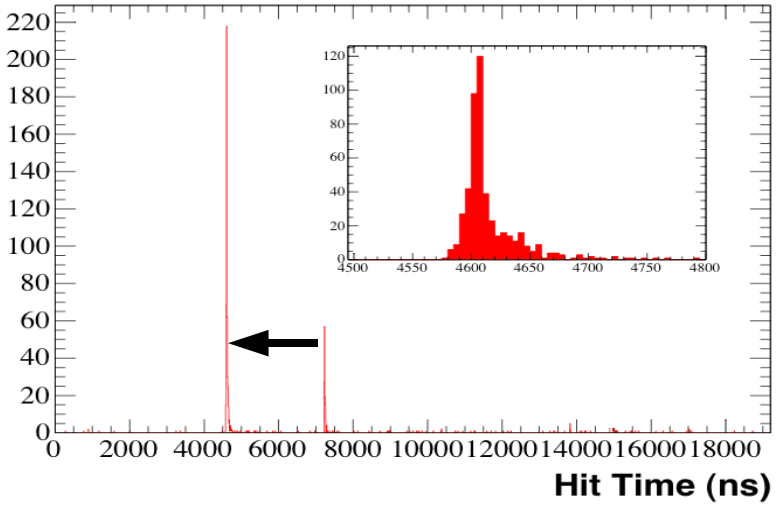

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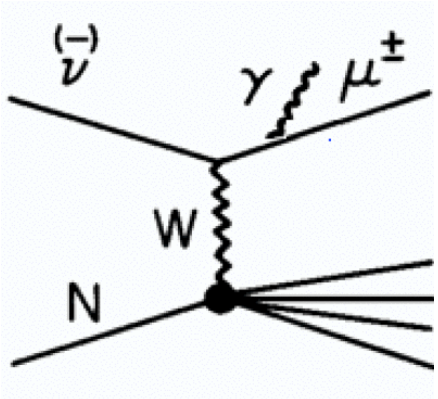
out of 10,000 events, the numbers passing ν_e cuts are:

28 Data
32 Monte Carlo

Muon bremsstrahlung



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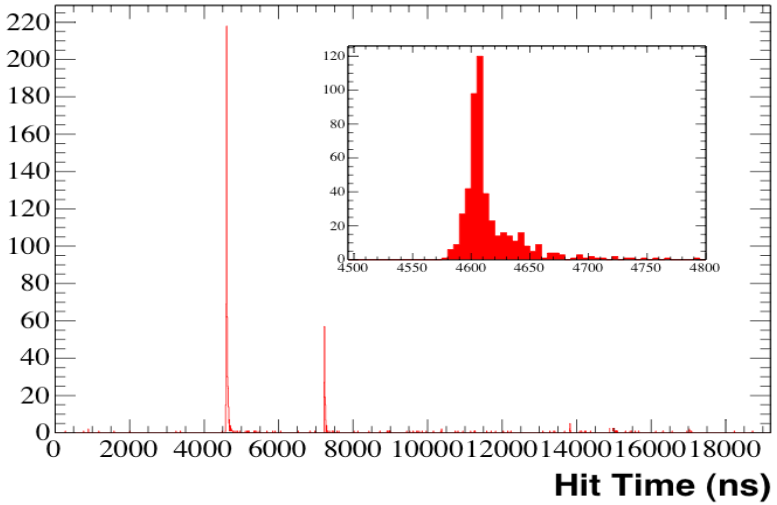

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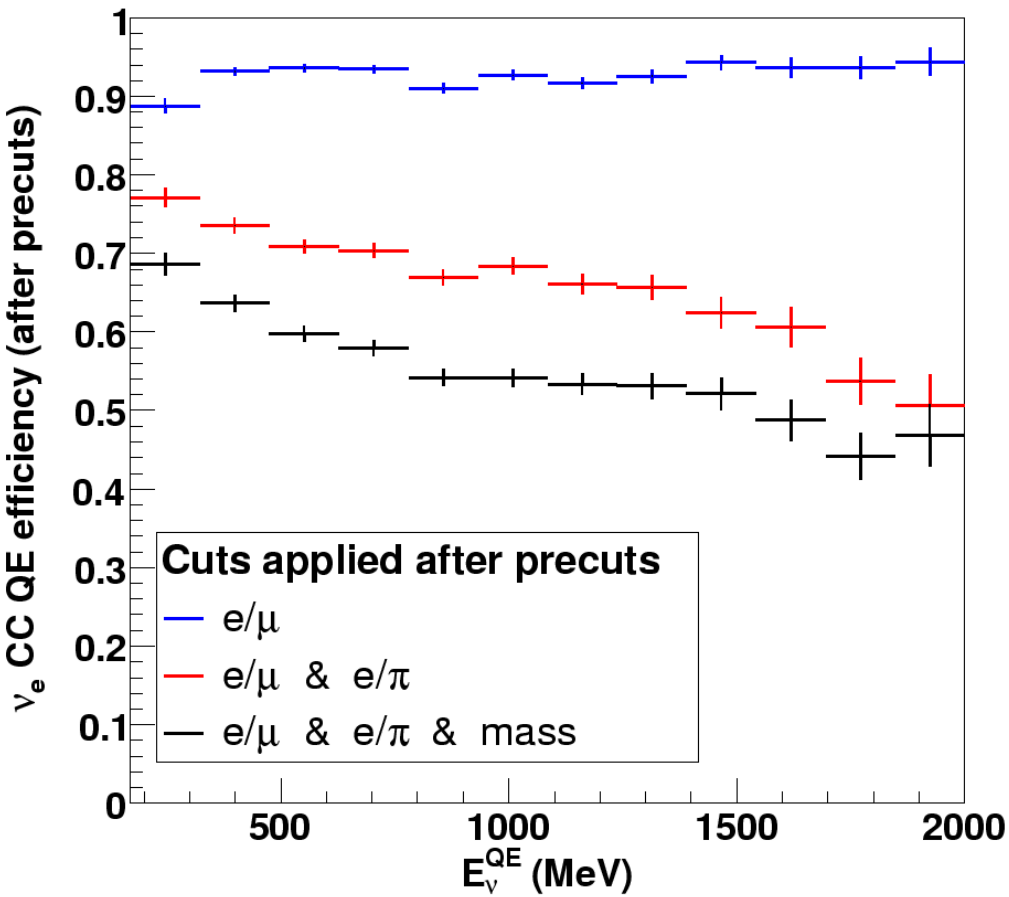
- conclusion: ***these events still look very muon-like and the small rate for mis-ID is well predicted by the Monte Carlo***

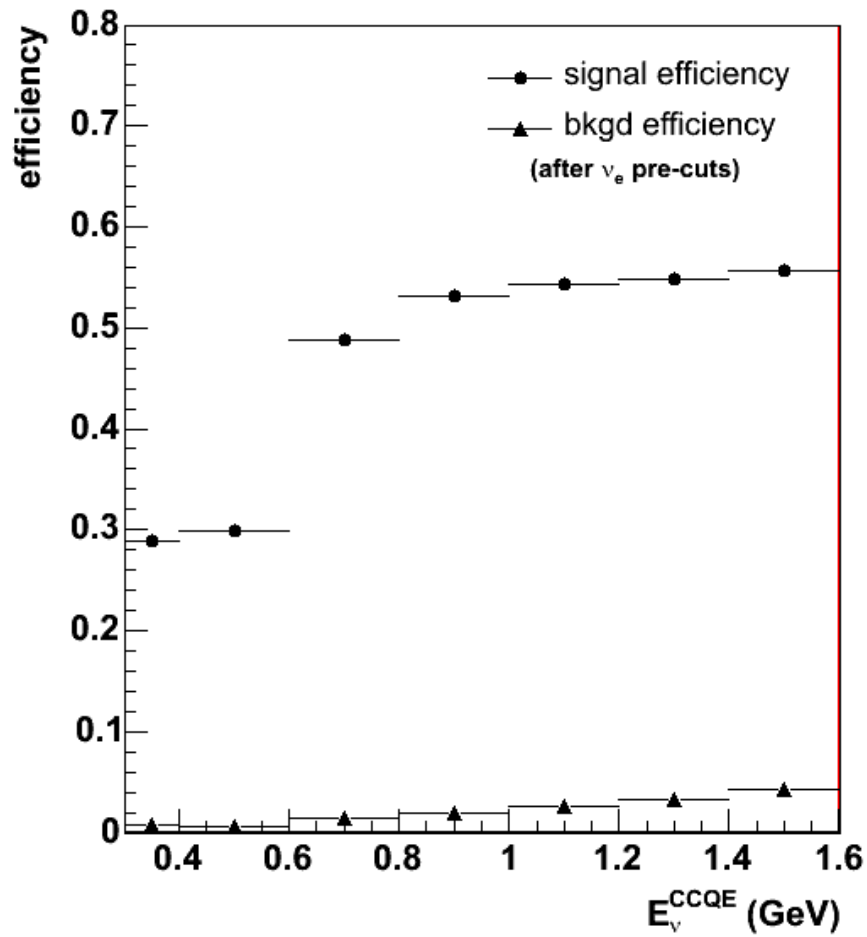
A.A. Aguilar-Arevalo et al., "Constraining Muon Internal Bremsstrahlung As A Contribution to the MiniBooNE Low Energy Excess", arXiv:0706.3897 [hep-ex], submitted to Phys. Rev. D (Brief Reports)

Signal Efficiency

TBL



BDT



Event Reconstruction & ν_e Event Selection

- 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 :

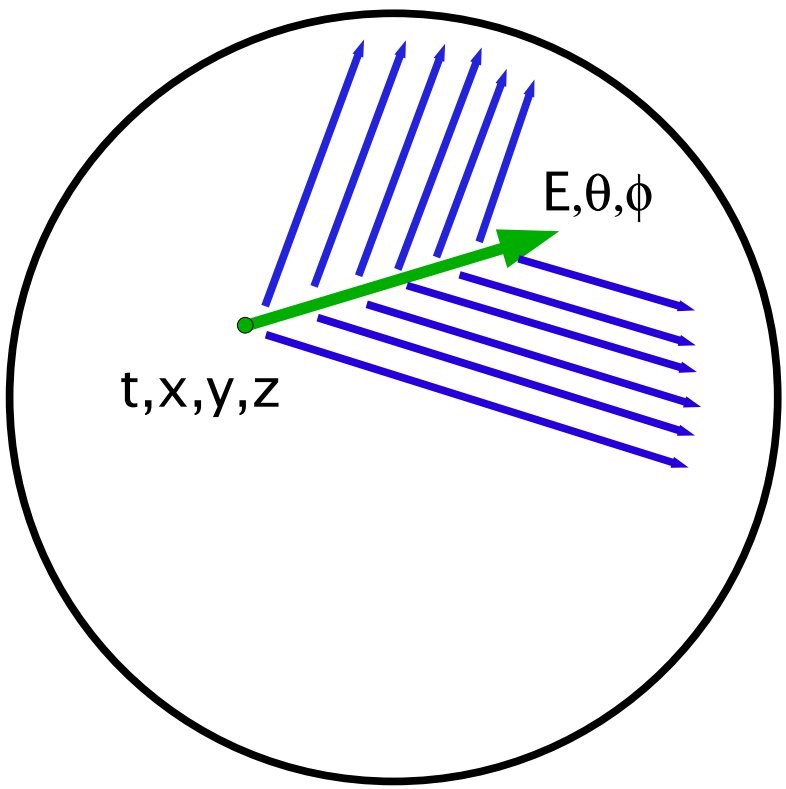
1. **Track Based** reconstruction + **Likelihood PID**
   - treats particles in the tank as extended tracks and carefully considers dE/dx effects
   - extremely tenacious fit. . . π^0 (2 ring) fitter takes ~8 minutes per event!
   - PID algorithm based on Likelihood ratios of different particle hypotheses

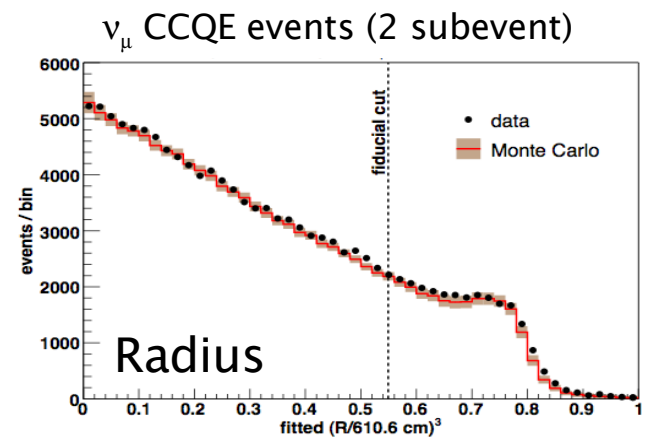
2. **Point Source** reconstruction + **Boosted Decision Tree PID**
   - treats particles more like point-sources and is less careful about dE/dx
   - fit not nearly as tenacious about getting out of local minima, particularly with π^0 fit
   - reconstruction runs nearly 10 times faster
   - to compensate 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%

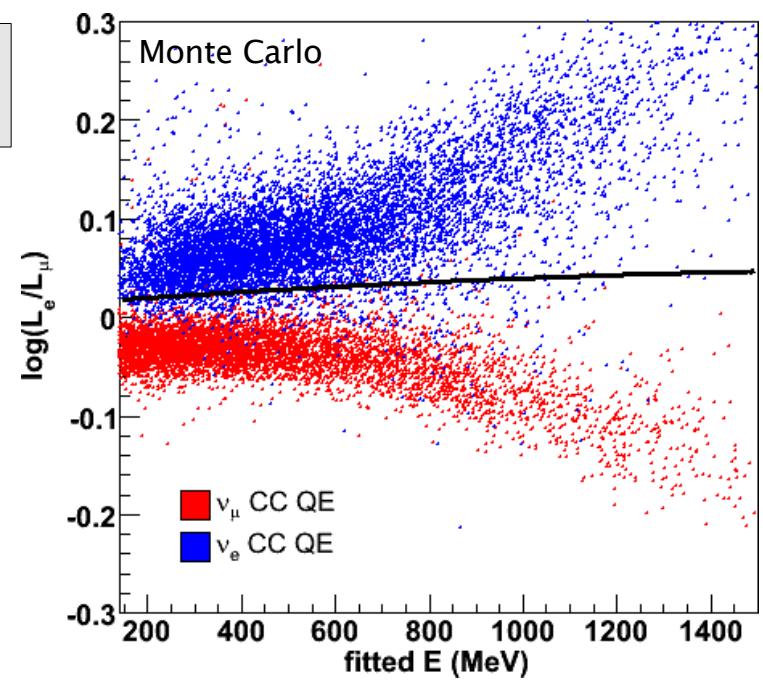
Track Based Rec + Likelihood PID

- 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



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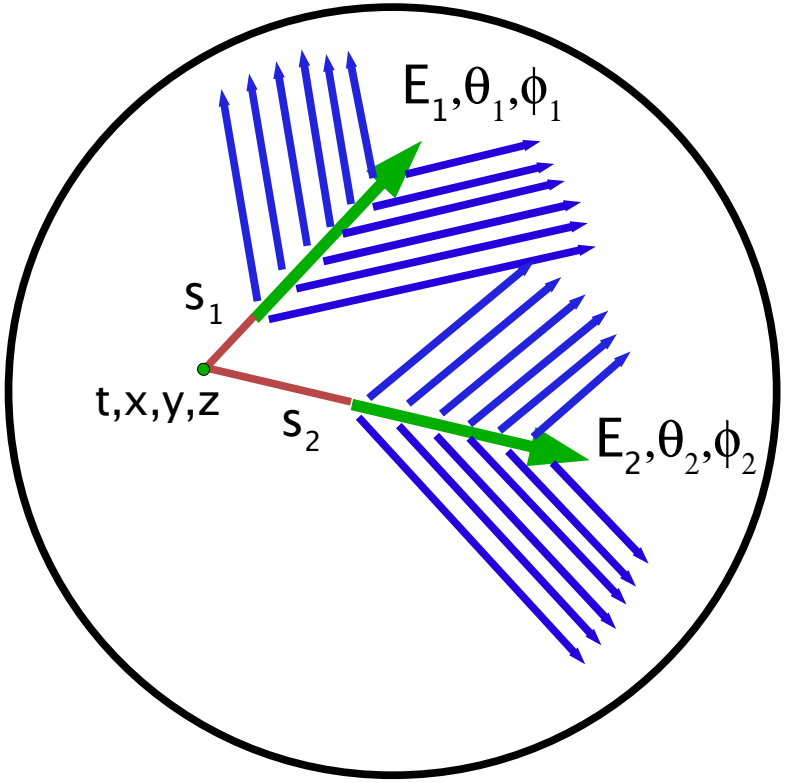
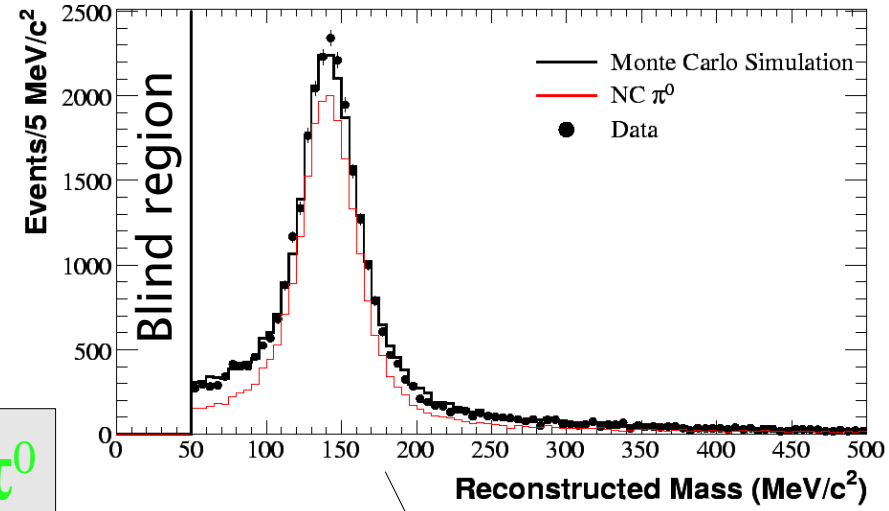
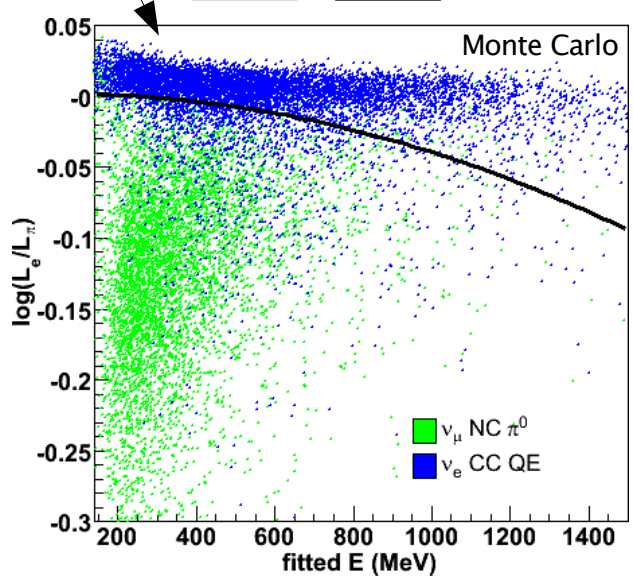
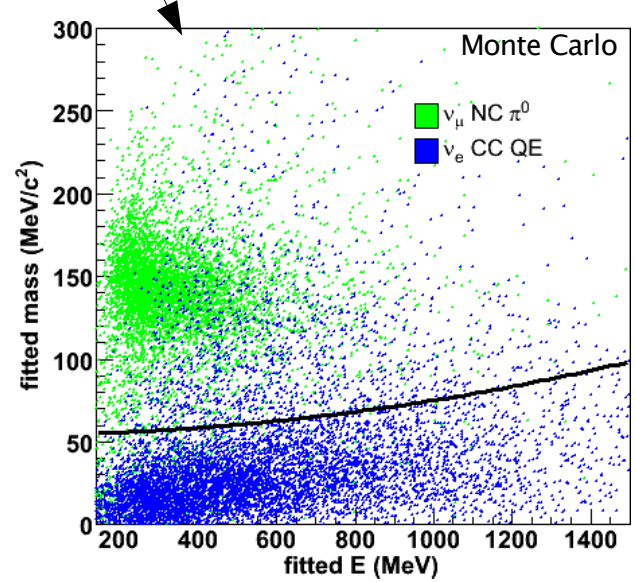




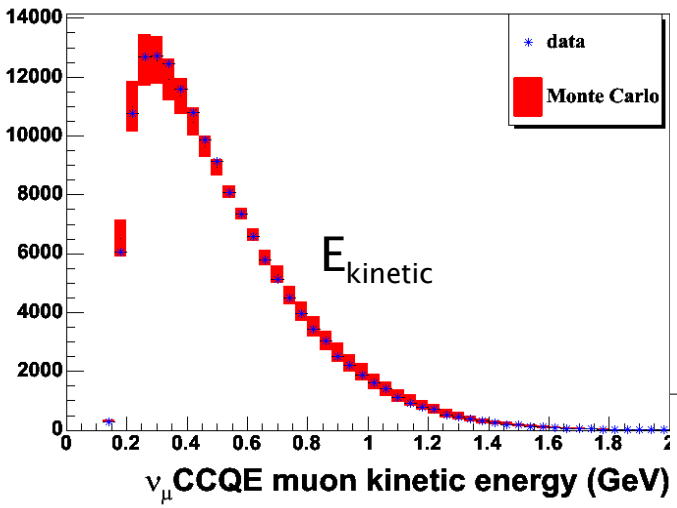
e π^0

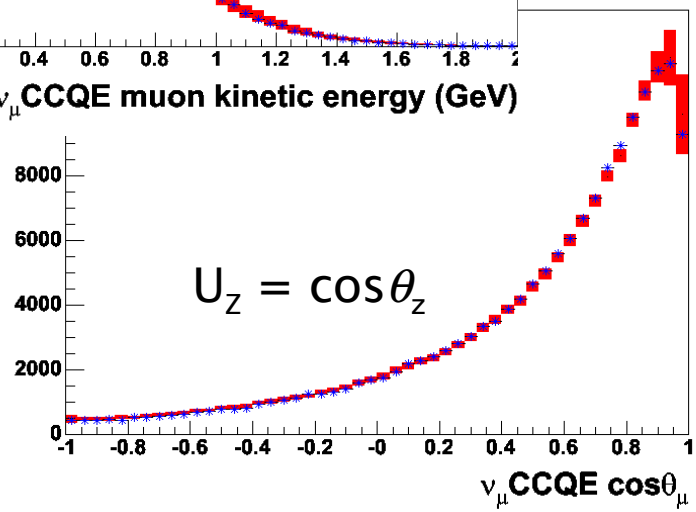


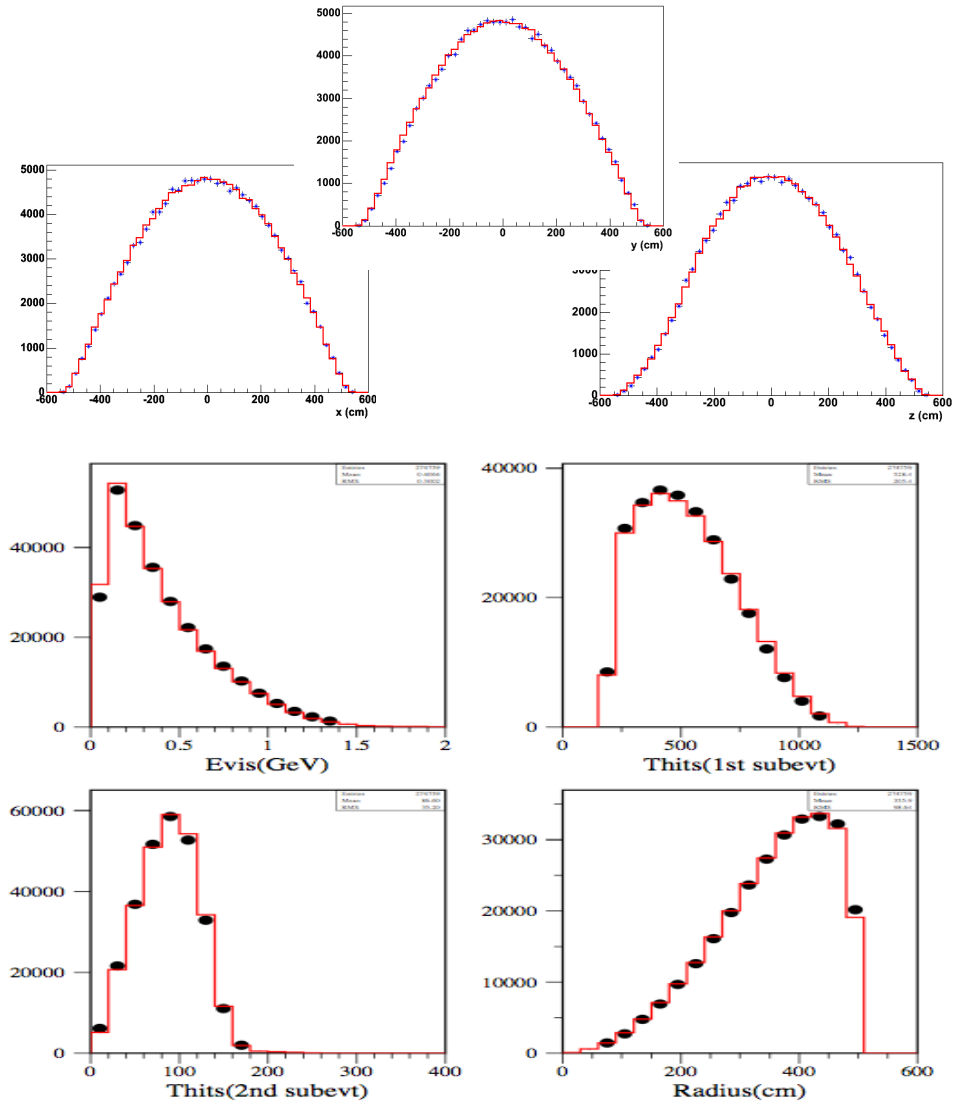


Point Source Rec + Boosting PID

- 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, . . .)







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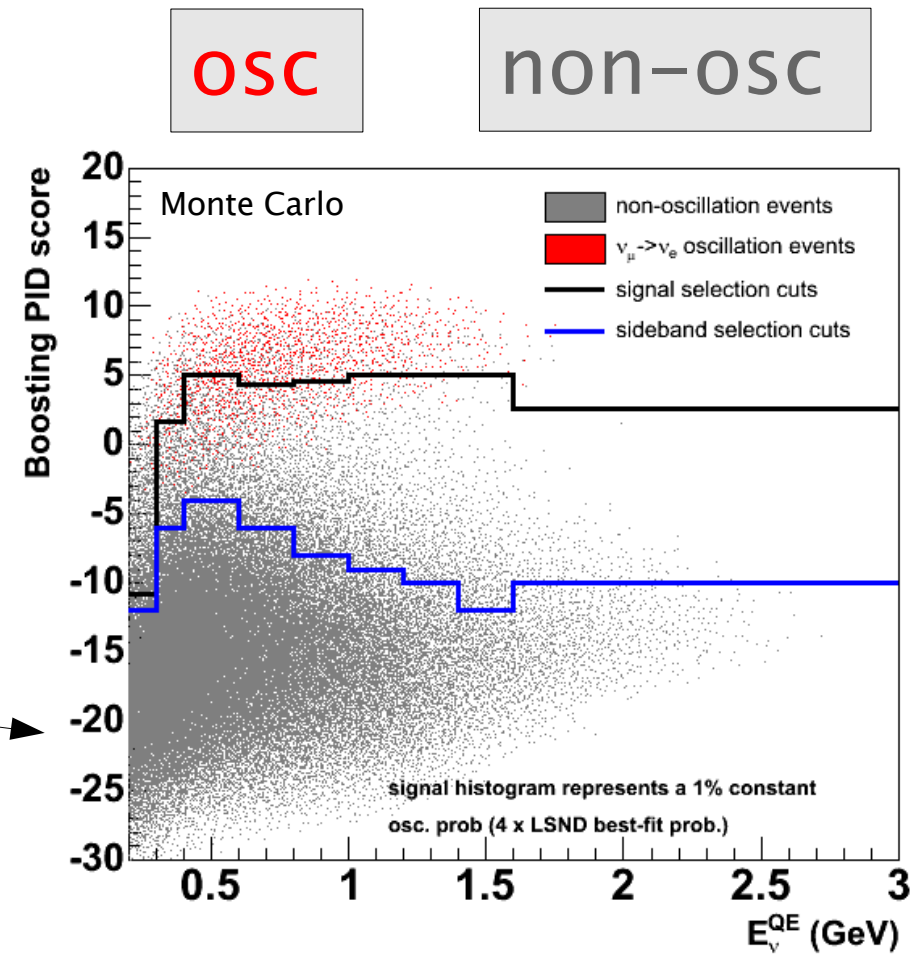
  - ***topology*** (charge in annuli, isotropic light, . . .)

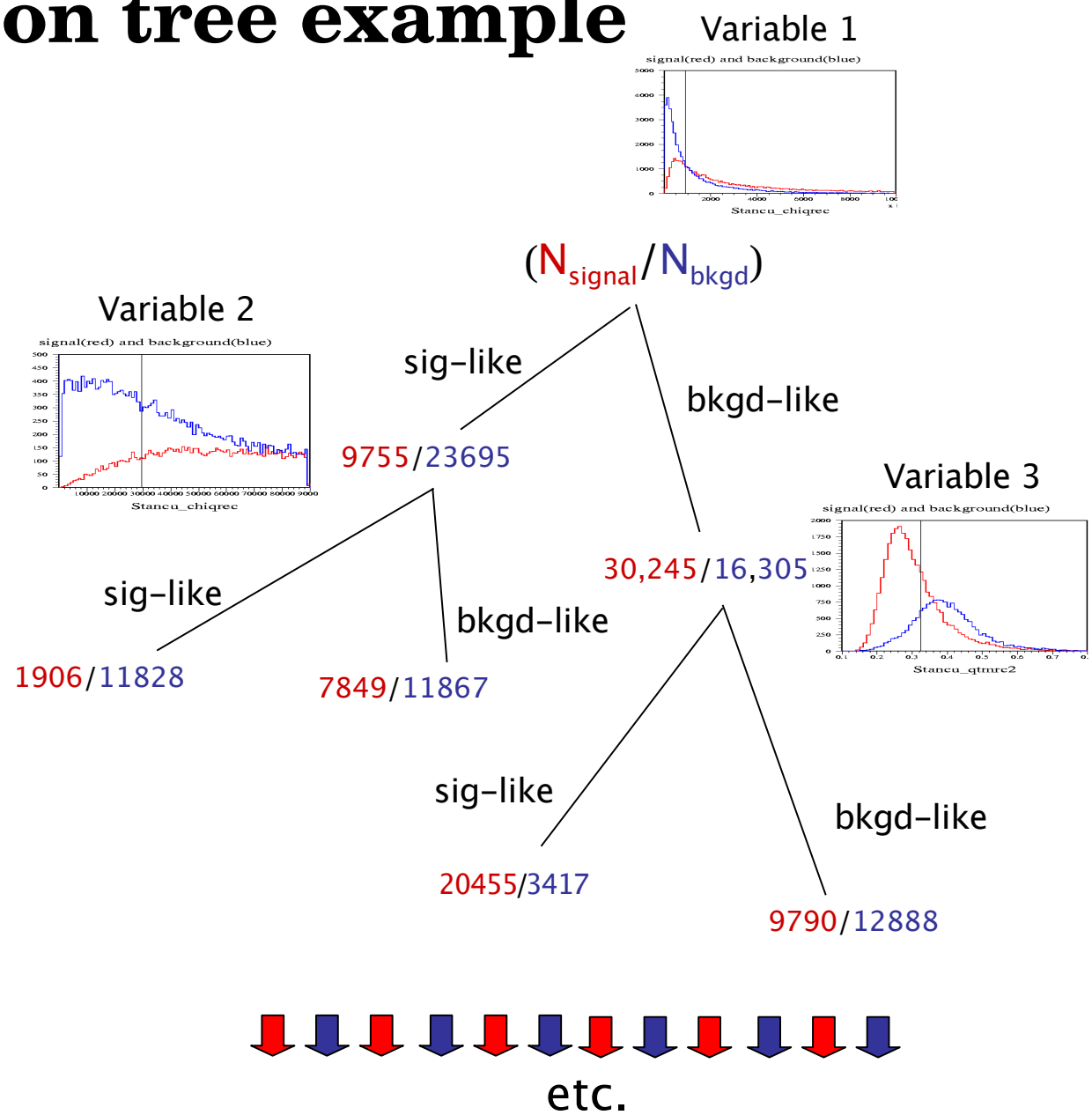
- A total of 172 such variables were used as input for the Boosted Decision Tree algorithm
- All 172 were checked for agreement within errors in 5 important 'boxes' (ν_μ CCQE, NC π^0, NC-elastic, Michel decay e, 10% closed)
- BDT is a technique involving the weighting and combining of many decision trees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

Decision tree example

- Optimal cuts on each variable are determined
- An event gets a weight of 1 if signal -1 if background
- Hard to identify backgrounds are iteratively given more weight
- Many trees built
- PID 'score' established from ensemble

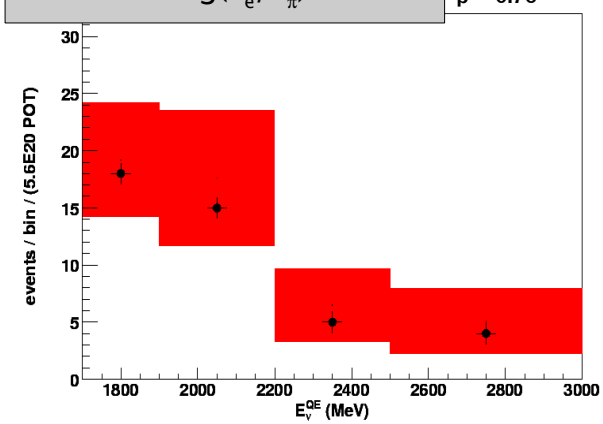


This tree is one of many possibilities...

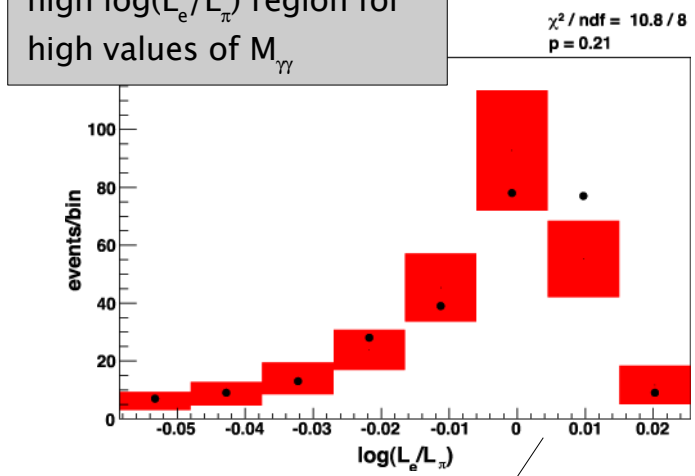
Verifying Sidebands (Likelihood PID)

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

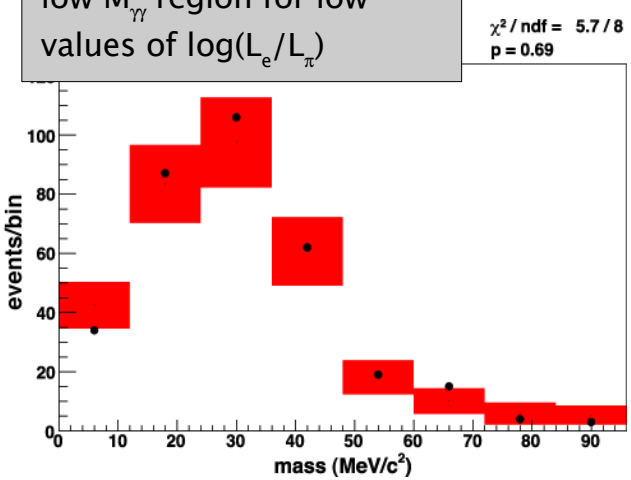
high energy region for low mass values and high values of $\log(L_e/L_\pi)$



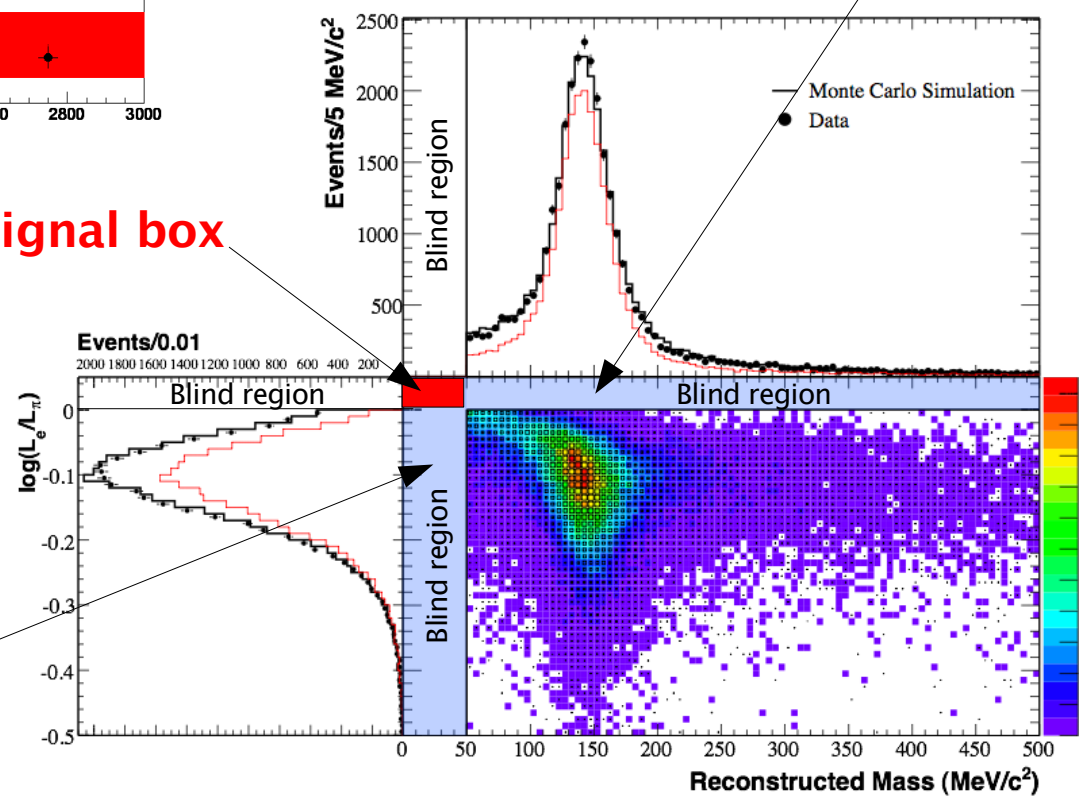
high $\log(L_e/L_\pi)$ region for high values of $M_{\gamma\gamma}$



low $M_{\gamma\gamma}$ region for low values of $\log(L_e/L_\pi)$

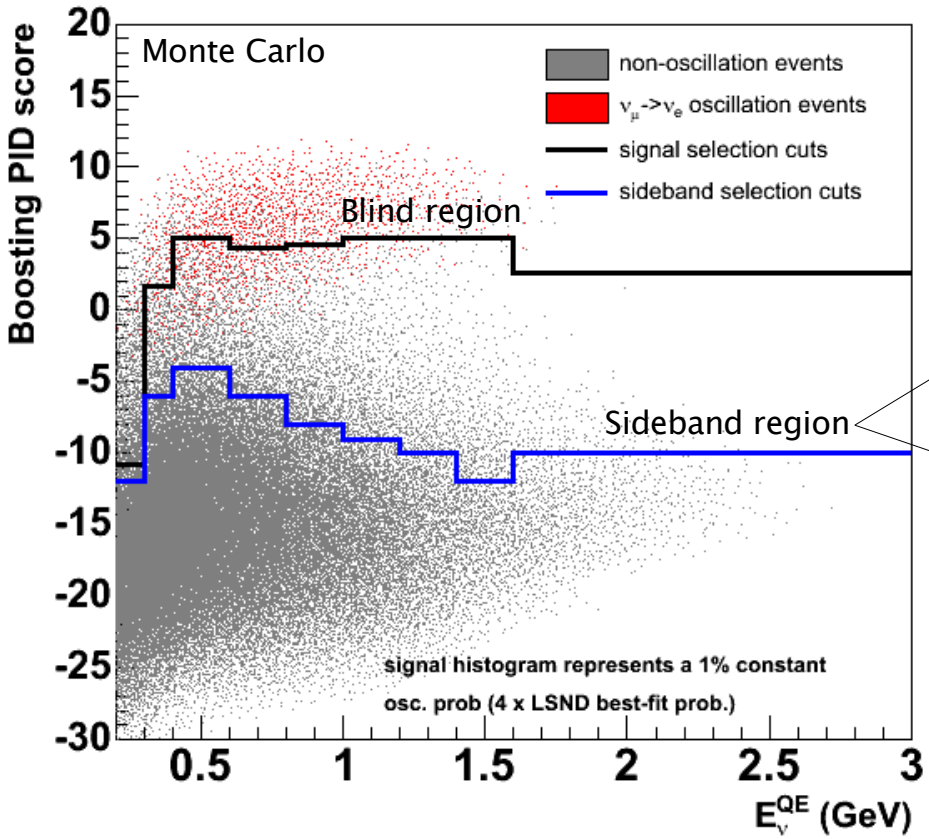


signal box

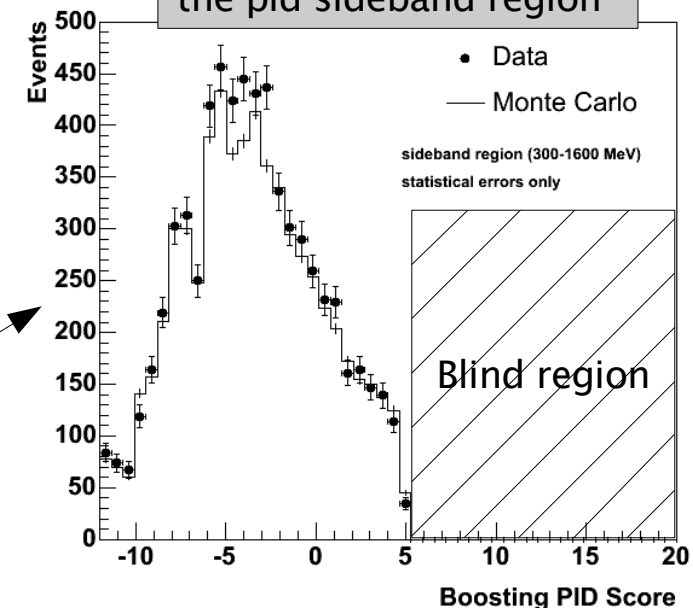


Verifying Sidebands (Boosting PID)

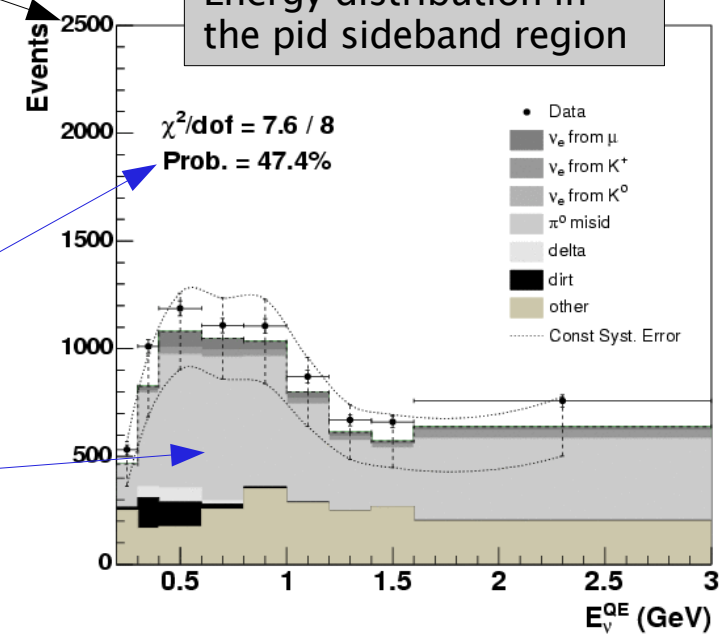
- use ***"side-bands"*** to verify the simulation



Boosting PID score in the pid sideband region



Energy distribution in the pid sideband region



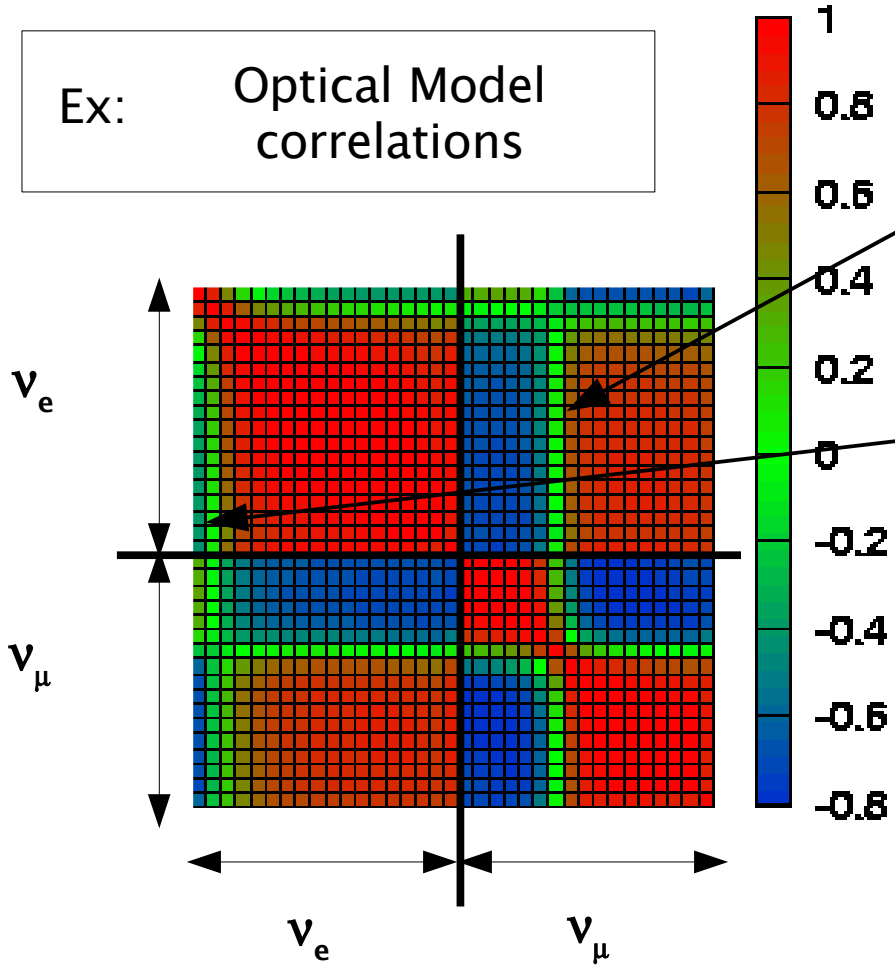
- good agreement within systematic errors
- sideband dominated by π^0 events

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)

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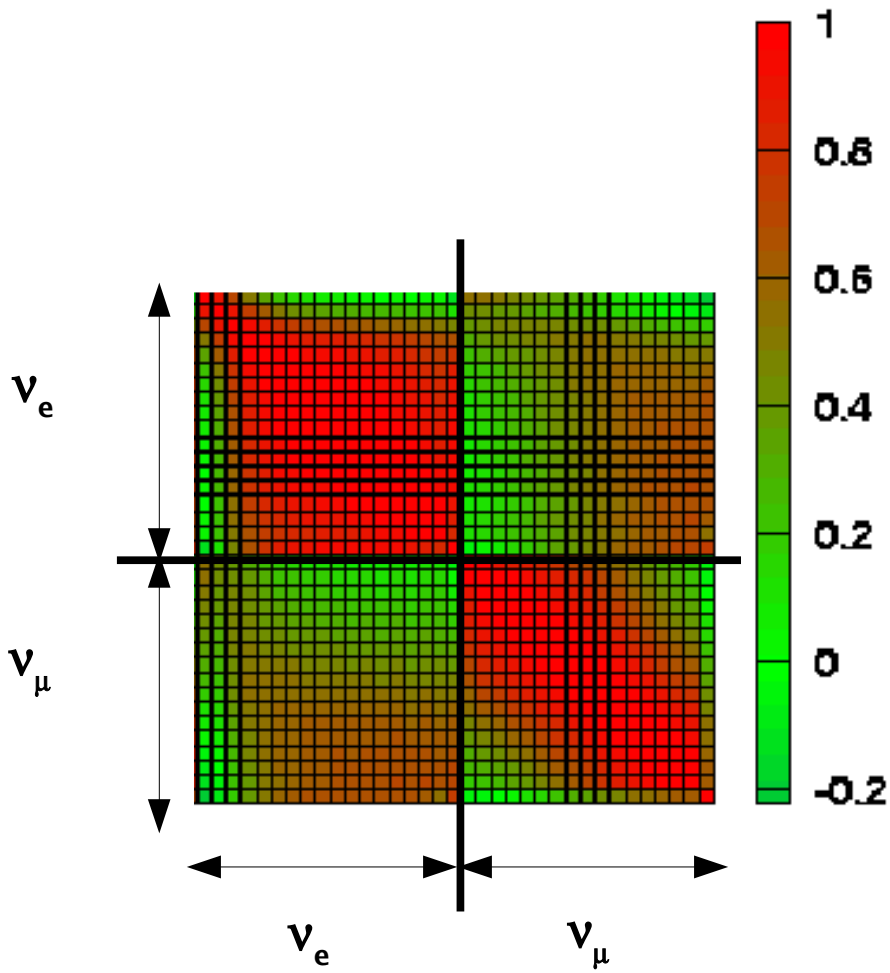
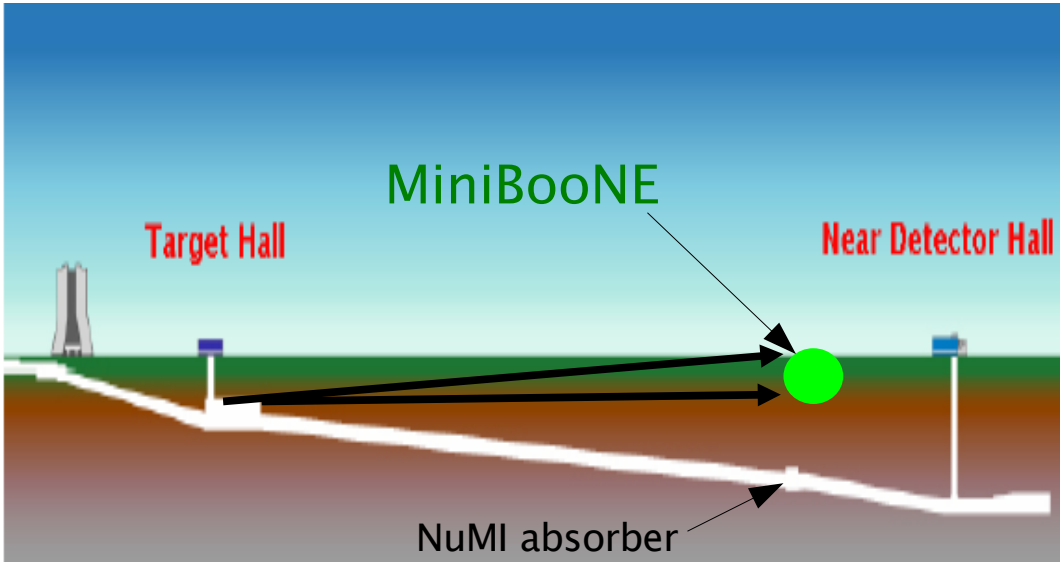
$$E_{ij}^{\text{total}} = E_{ij}^{\pi^+} + E_{ij}^{K^+} + E_{ij}^{K^0} + E_{ij}^{\text{beam}} + E_{ij}^{\text{xsec}} + E_{ij}^{\pi^0\text{-rate}} + E_{ij}^{\text{dirt-rate}} + E_{ij}^{\text{daq model}} + E_{ij}^{\text{optical model}}$$



- total systematic error matrix

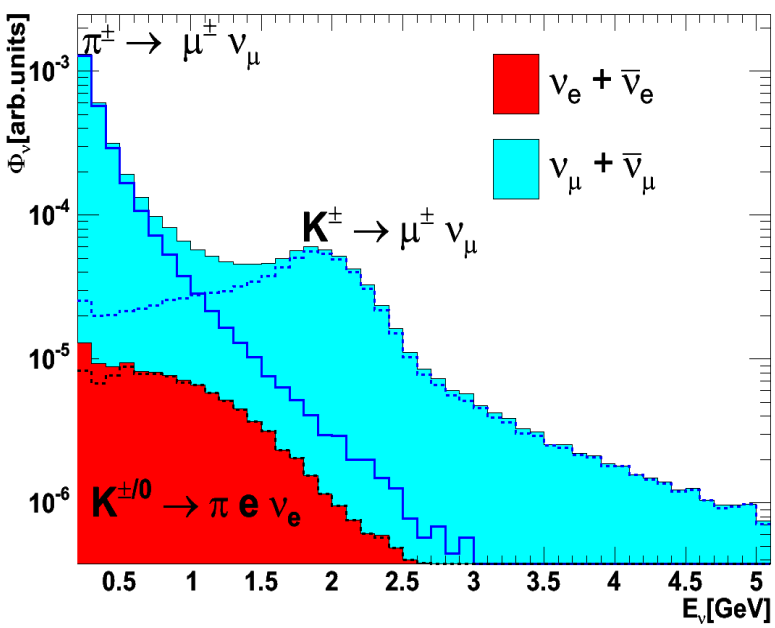
$$E_{ij}^{\text{total}}$$

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



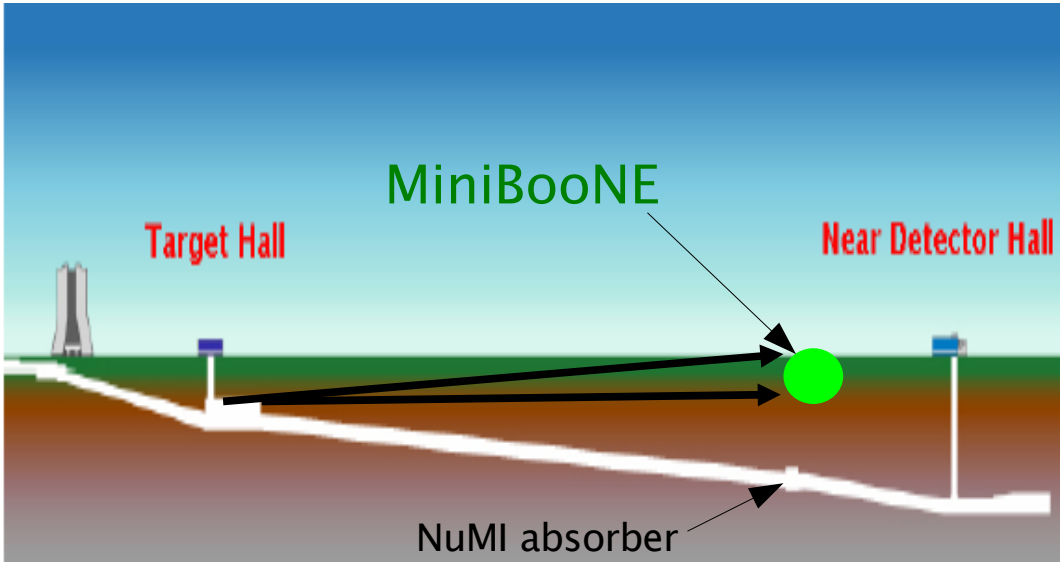
BNB → MB

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



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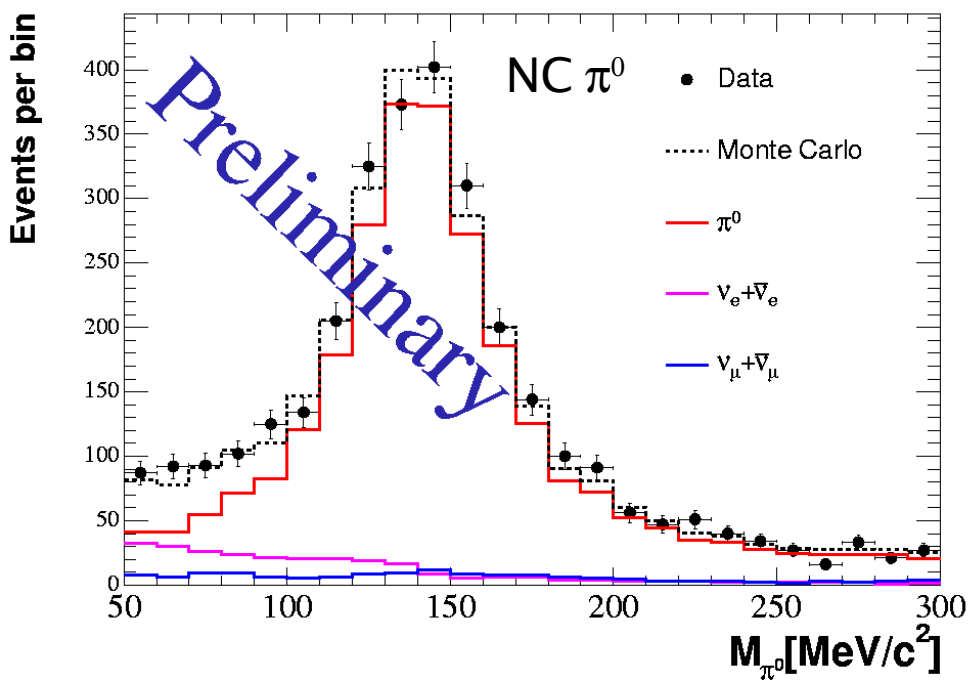
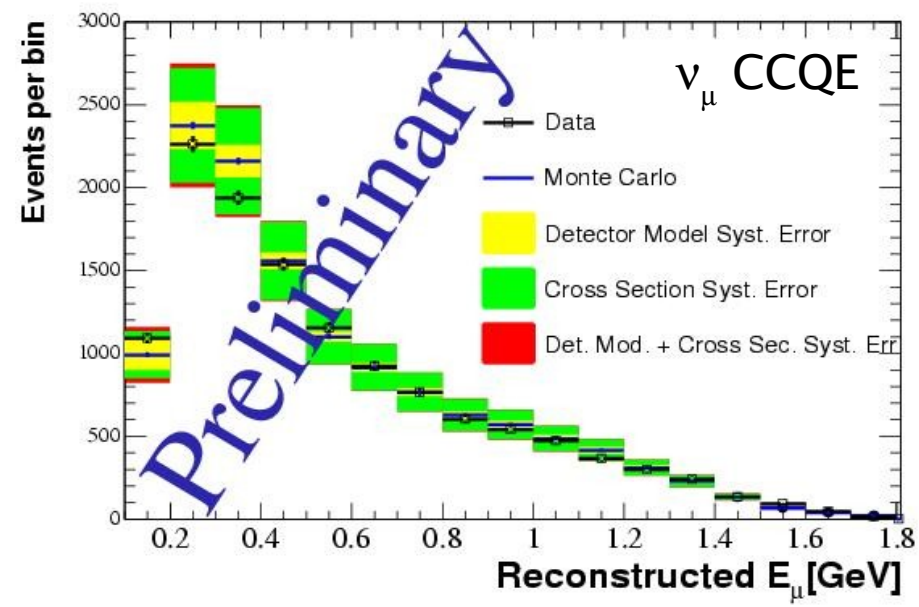
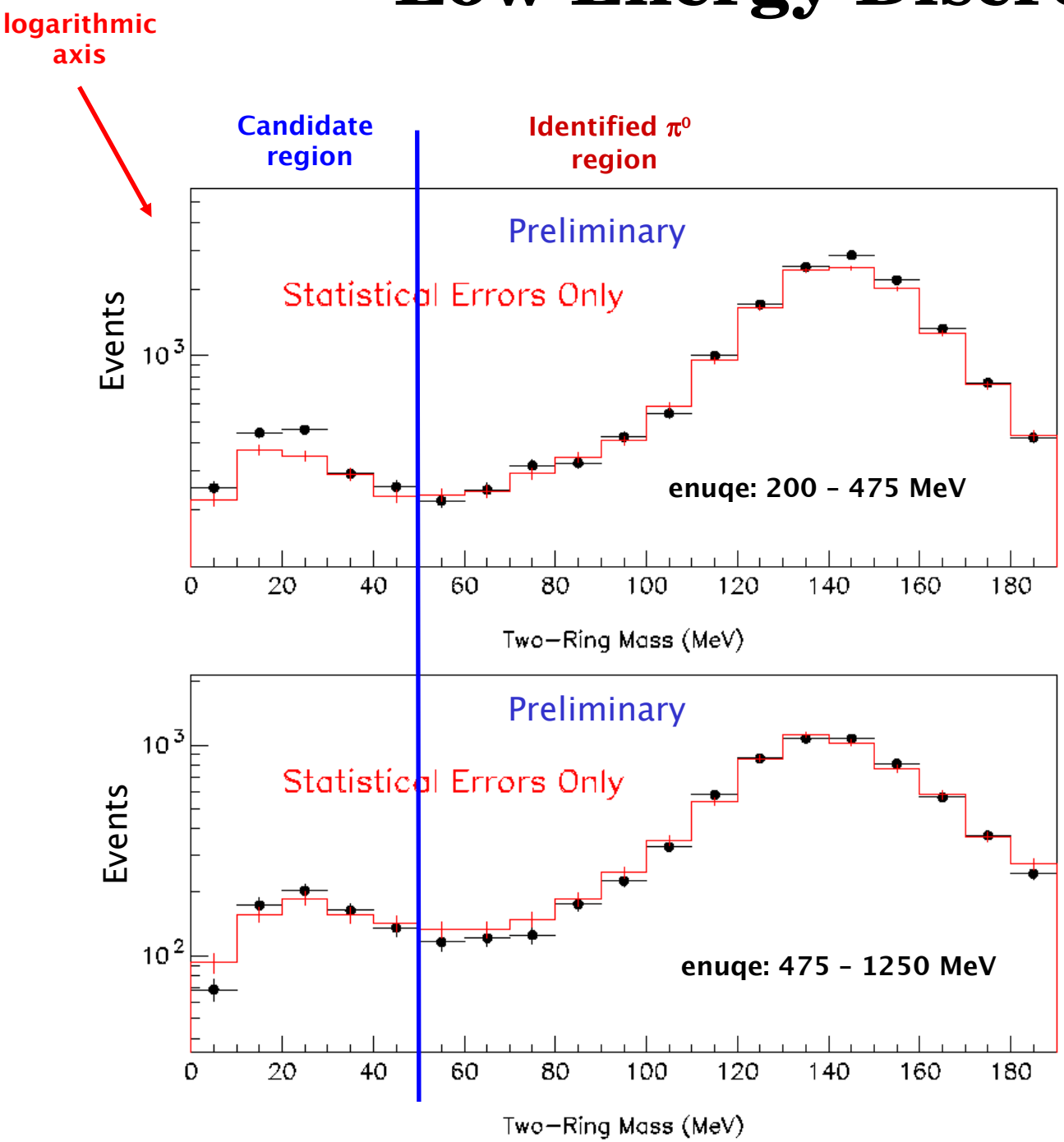
- beam contains enhanced (~x10) ν_e component from kaon decays
- L/E is similar to standard MB (750m/0.75 GeV)
- nice agreement seen in ν_μ-CCQE and π^0 events
- ***ν_e analysis coming soon***





Low Energy Discrepancy



Results after removing the mass and $L_{e\pi}$ cut

- Good agreement in "Identified π^0 region"
- Excess for low energy sample clearly observed below 50 MeV
- Excess cannot be explained by simply scaling up the π^0 and Rad-Δ background

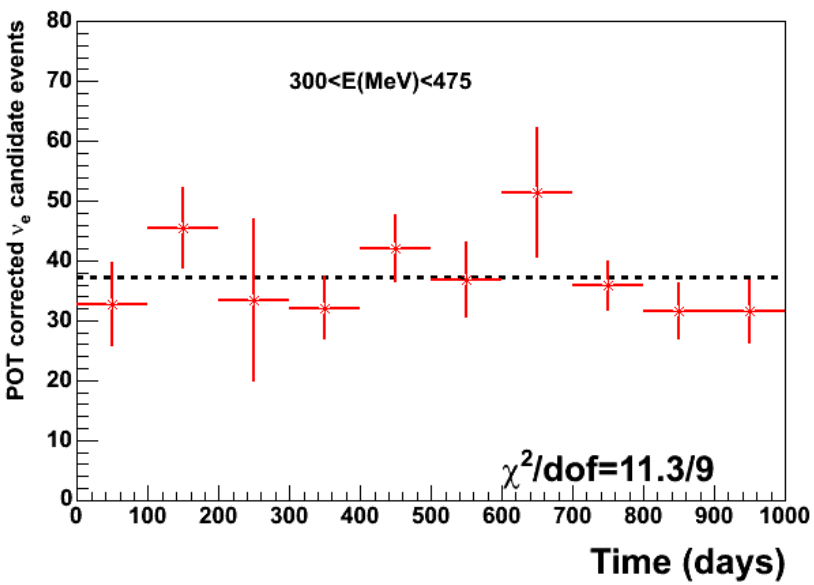
Black points: Data
Red histogram: Prediction

Low Energy Discrepancy

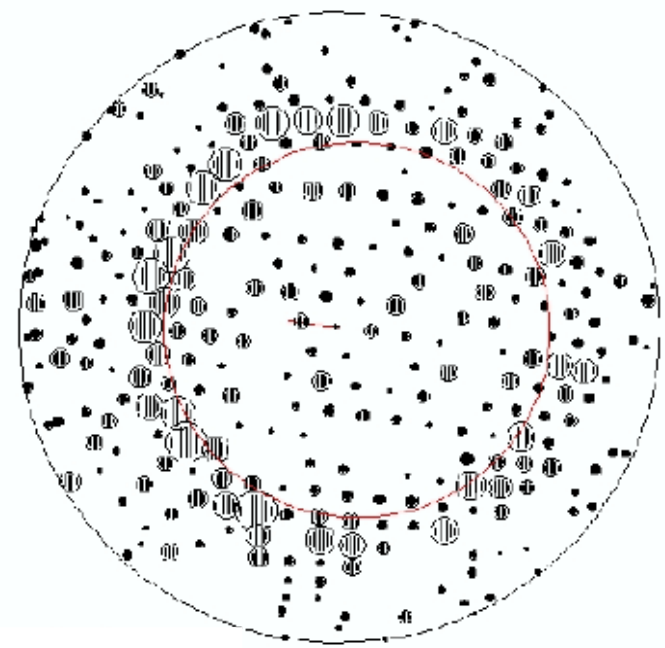
- ***investigating possible explanations:***
  - detector anomalies or reconstruction problems?
  - incorrect estimation of a background?
  - missing background?
  - new physics including exotic oscillation scenarios, neutrino decay, Lorentz violation?
  - is it related to excess seen by LSND?

No Detector anomalies found :

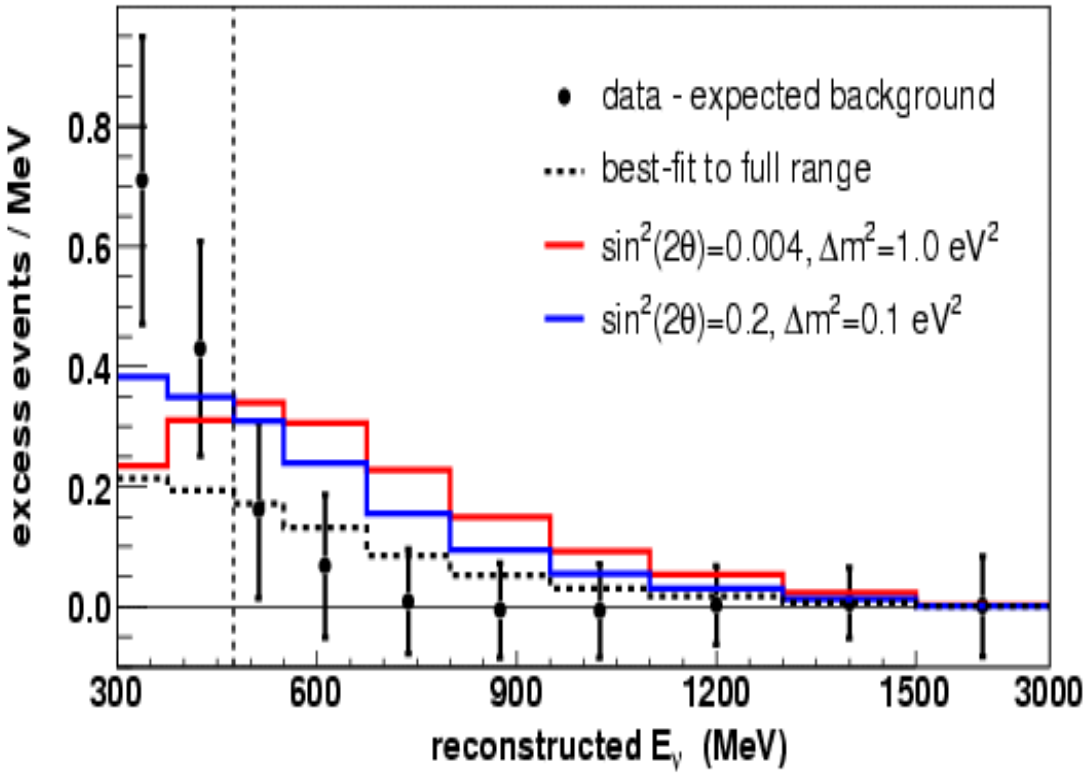
event/POT vis day, 300<Enu<475 MeV

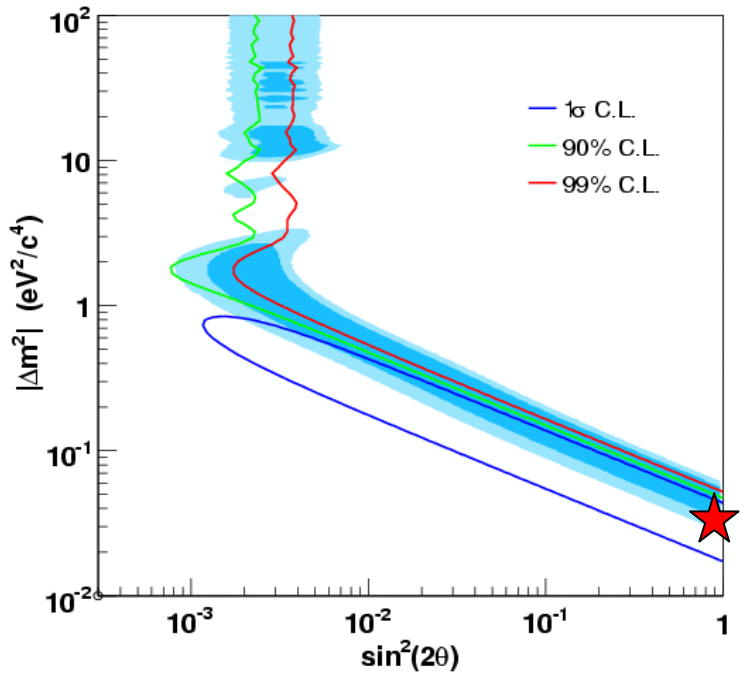


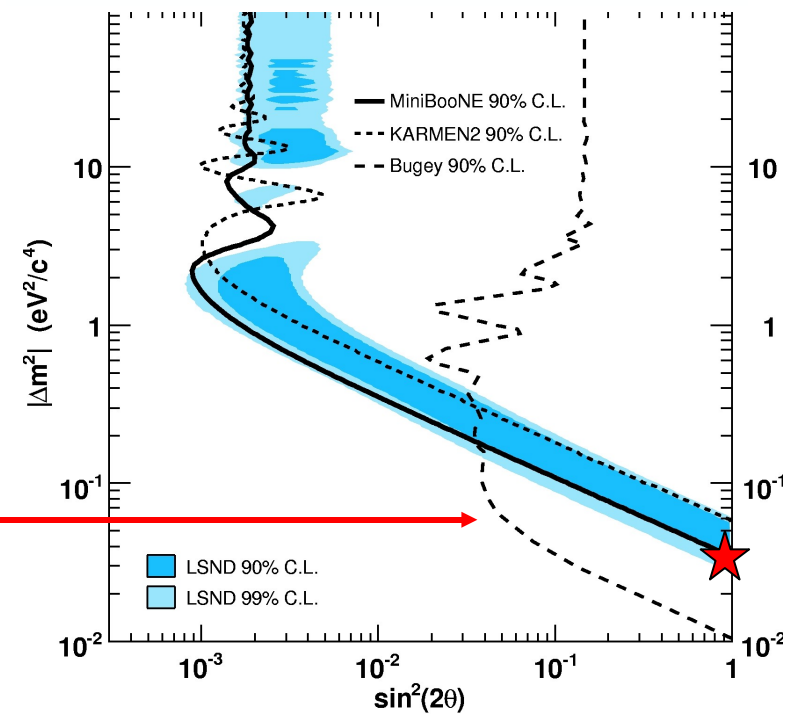
No Reconstruction problems found :



Low Energy Discrepancy







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

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

Future Run/Analysis Plans

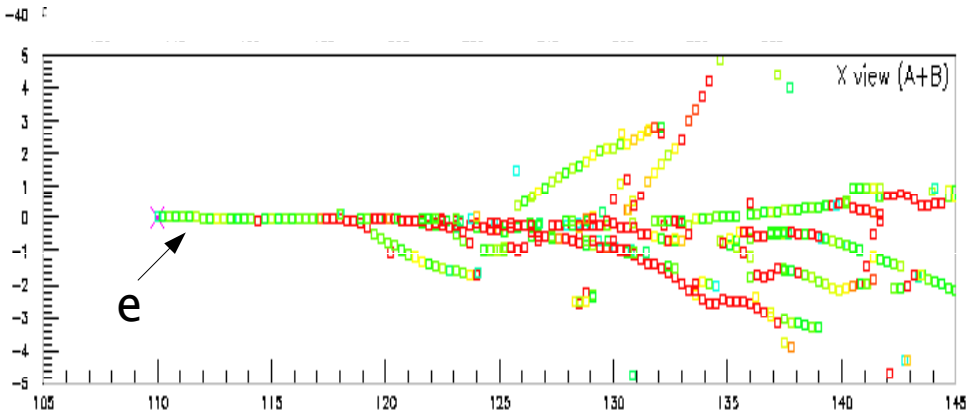
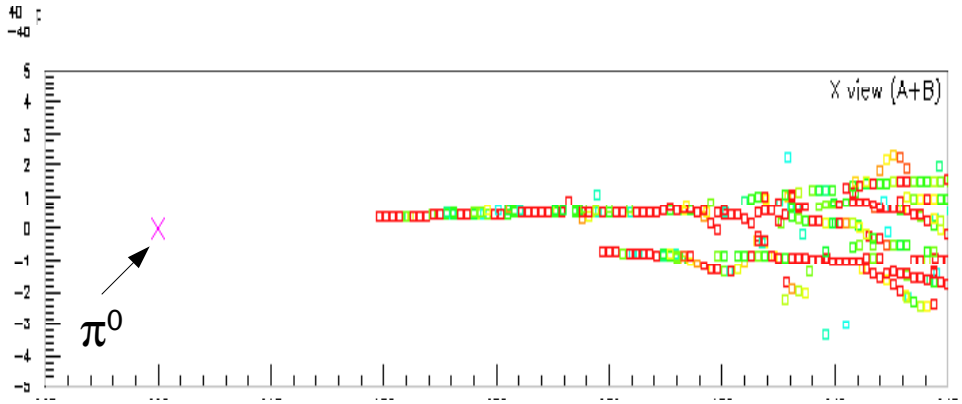
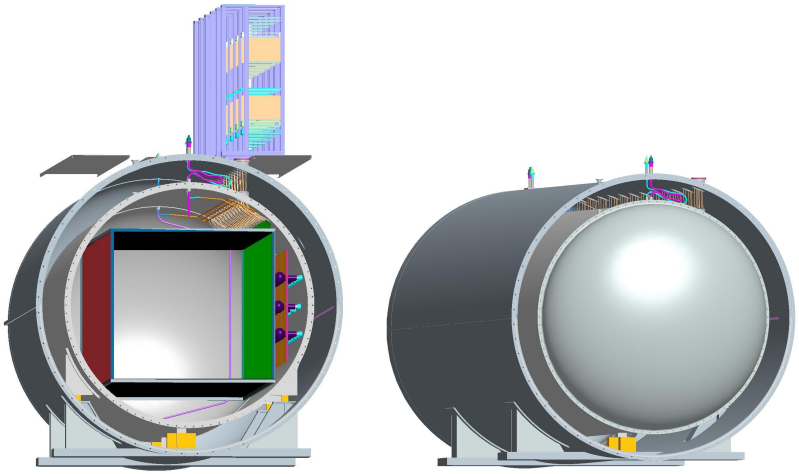
- Working on several ***publications*** in support of and extensions to this analysis
  - ν_μ CCQE paper submitted to PRL
  - NC π^0 background measurement
  - combined TBL/BDT analysis
  - combined LSND–MiniBooNE–KARMEN oscillation analysis
  - others. . .

- 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

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