First $\nu_\mu \rightarrow \nu_e$ Oscillation Results from MiniBooNE

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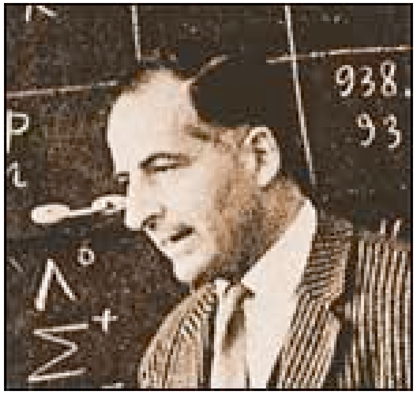
Outline

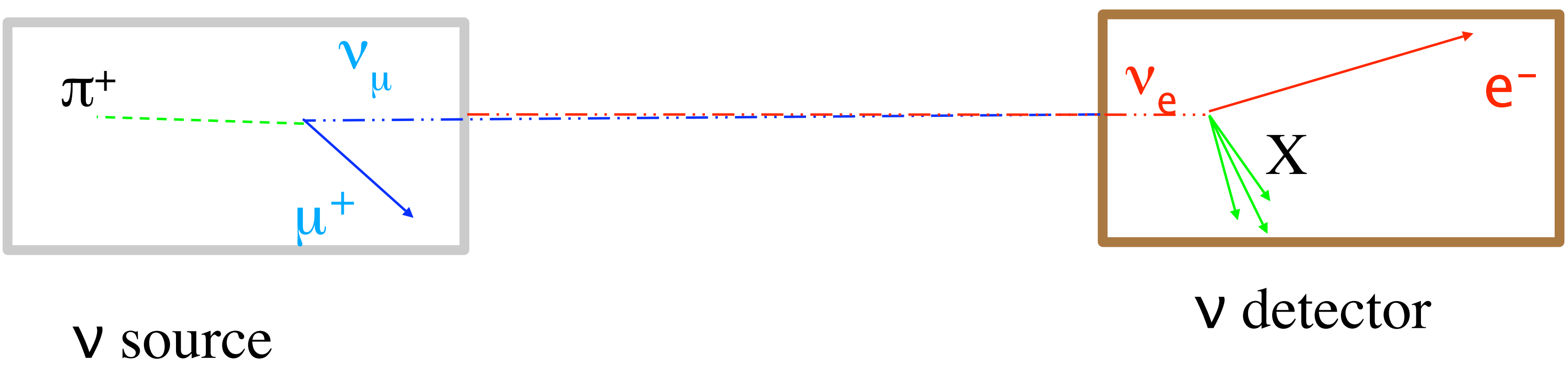
1. Motivation & Introduction
2. Description of the Experiment
3. Analysis Overview
4. Two Independent Oscillation Searches
5. First Results

Motivation: **Neutrino Oscillations**

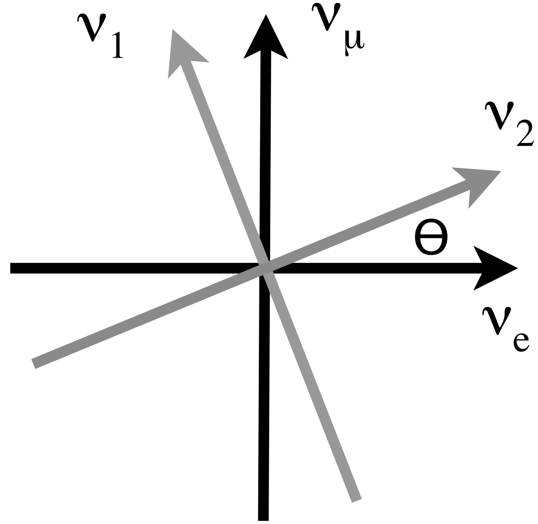


Pontecorvo, 1957

if neutrinos have mass, a neutrino that is produced as a ν_μ (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$) has a non-zero probability to oscillate and some time later be detected as a ν_e (e.g. $\nu_e\, n \rightarrow e^- p$)



Motivation: Neutrino Oscillations



In a world with 2 neutrinos,
if the weak eigenstates (ν_e, ν_μ)
are different from the mass eigenstates (ν_1, ν_2):

$$\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

The weak states are mixtures of the mass states:

$$|\nu_\mu> = \ -sin\theta|\nu_1> + cos\theta|\nu_2>$$
$$|\nu_\mu(t)> = \ -sin\theta\ (|\nu_1> e^{-iE_1 t}) + cos\theta\ (|\nu_2> e^{-iE_2 t})$$

The probability to find a ν_e when you started with a ν_μ is:

$$P_{oscillation}(\nu_\mu \rightarrow \nu_e) \ = \ | < \nu_e|\nu_\mu(t) > |^2$$

Motivation: Neutrino Oscillations

In units that experimentalists like:

$$P_{oscillation}(\nu_\mu \rightarrow \nu_e) \;=\; sin^2 2\theta sin^2\left(\frac{1.27\ \Delta m^2(eV^2)\ L(km)}{E_\nu(GeV)}\right)$$

Oscillation probability between 2 flavour states depends on:

1. fundamental parameters

   $\Delta m^2 = m_1^2 - m_2^2$ = mass squared difference between states

   $\sin^2 2\theta$ = mixing between ν flavours

2. experimental parameters

   L = distance from ν source to detector

   E = ν energy

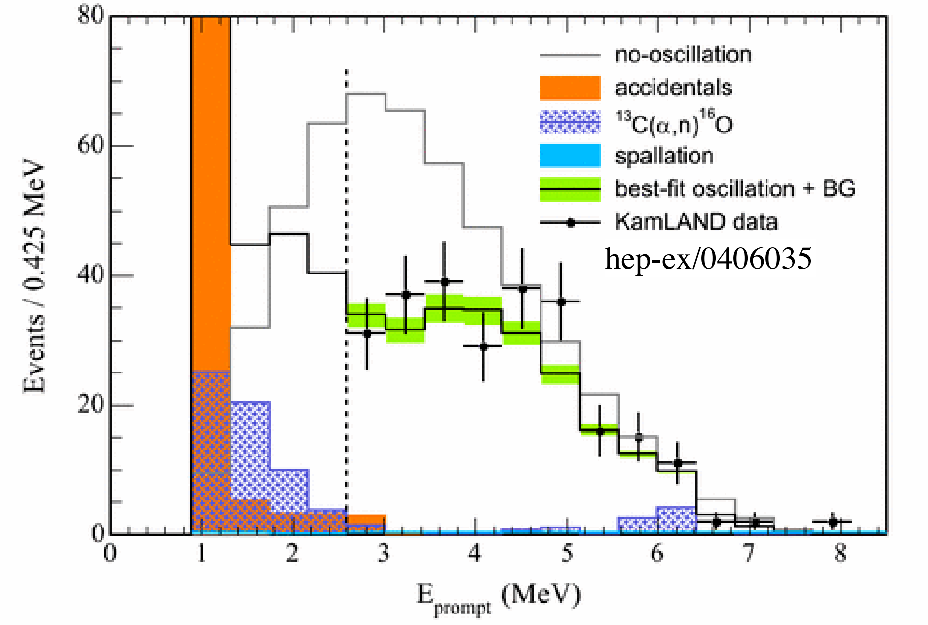
ν ν ν ν ν ν ν ν

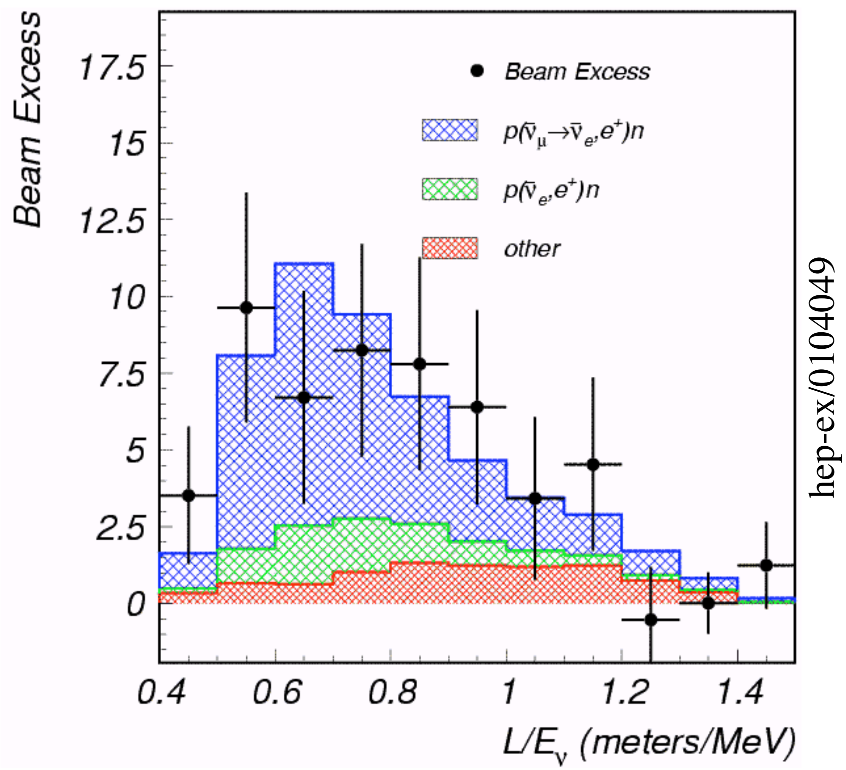
Motivation: Oscillation Signals

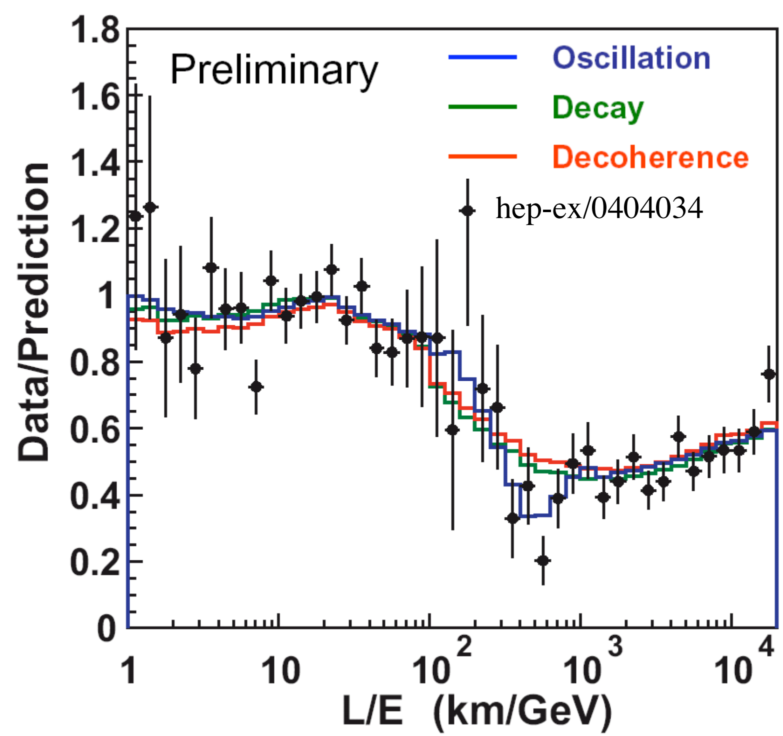
Solar ν: measured by Homestake, ..., SNO
confirmed by KamLAND

Atmospheric ν: measured by K-II, ..., Super-K
confirmed by K2K, MINOS

Accelerator ν: measured by LSND
unconfirmed



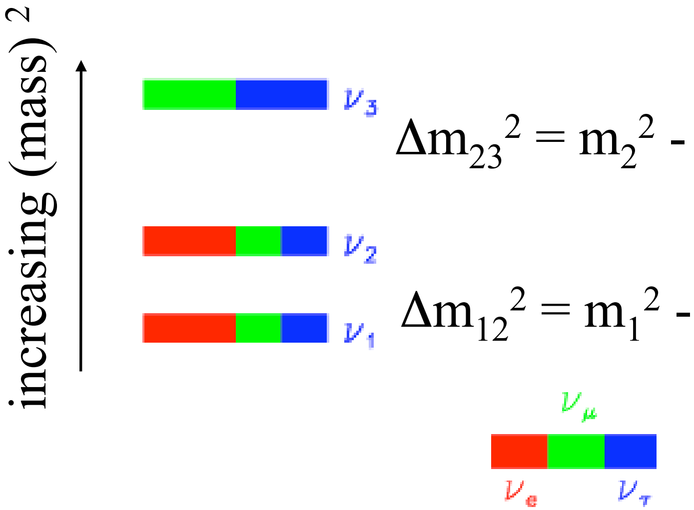




Motivation: The Problem

$$P_{oscillation}(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2\left(\frac{1.27\ \Delta m^2(eV^2)\ L(km)}{E_\nu(GeV)}\right)$$

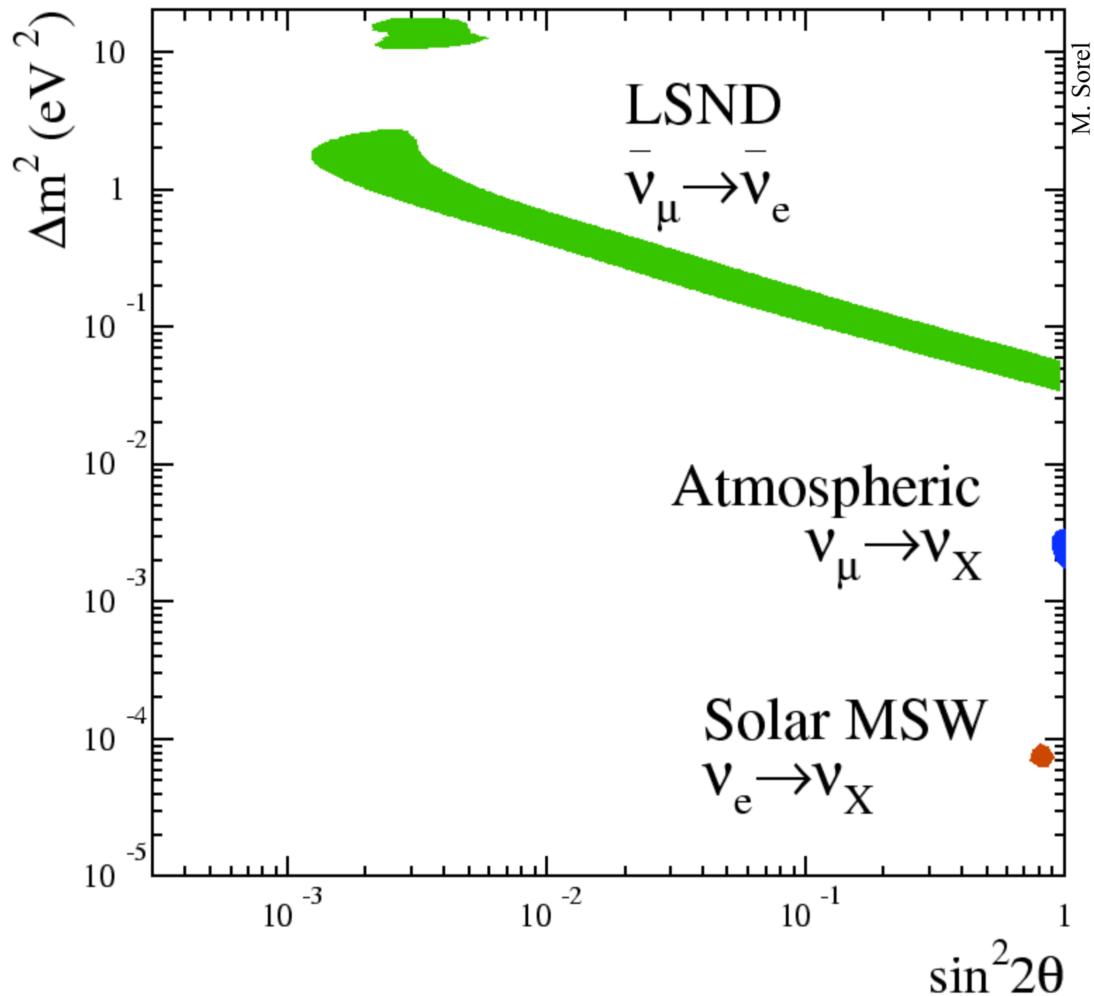
A standard 3 neutrino picture:



$\Delta m_{23}{}^2 = m_2{}^2 - m_3{}^2$

$\Delta m_{12}{}^2 = m_1{}^2 - m_2{}^2$

$$\Delta m_{13}{}^2 = \Delta m_{12}{}^2 + \Delta m_{23}{}^2$$



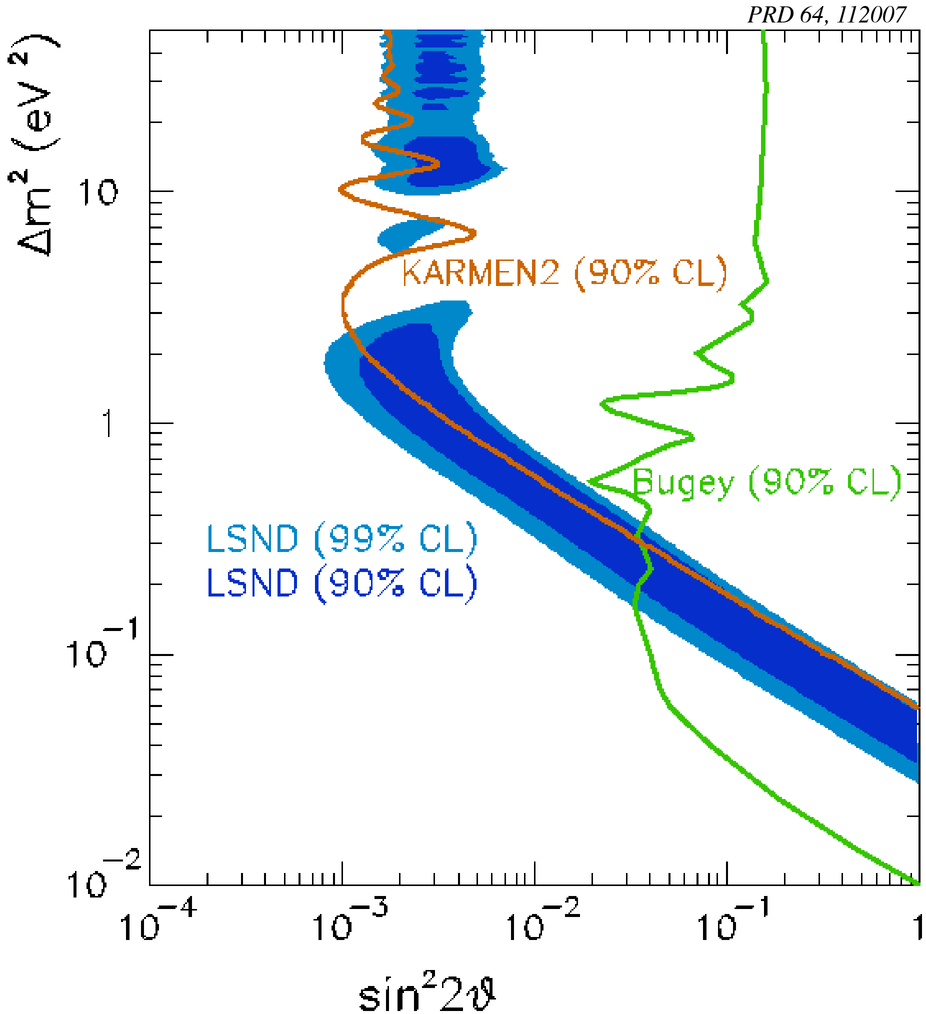
The oscillation signals cannot be reconciled without introducing physics beyond the Standard Model.

Motivation: LSND

MiniBooNE was proposed in 1997 to address the LSND result.

LSND observed a **4σ** excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam: **87.9 ± 22.4 ± 6.0**

interpreted as 2-neutrino oscillations, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 0.26\%$



$$P = sin^2 2\theta sin^2\left(\frac{1.27\ \Delta m^2(eV^2)\ L(km)}{E_\nu(GeV)}\right)$$

<u>MiniBooNE strategy:</u>

Keep (L/E_ν) same as LSND but change systematics, including event signature:

- Order of magnitude higher E_ν than LSND

- Order of magnitude longer baseline L than LSND

- Search for excess of ν_e events above background

The MiniBooNE Collaboration

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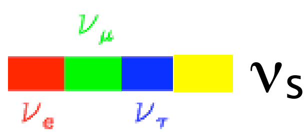
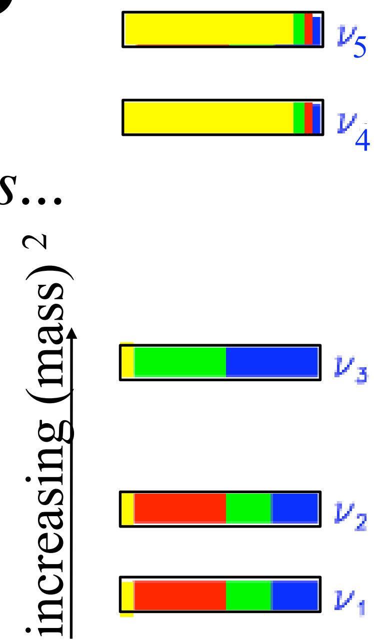
Motivation: MiniBooNE and LSND

If MiniBooNE observes LSND-type ν oscillations...

The simplest explanation is to add more νs, to allow more independent Δm^2 values.

The new νs would have to be **sterile,** otherwise they would have been seen already.





$\Delta m_{45}{}^2 = m_4{}^2 - m_5{}^2$

$\Delta m_{34}{}^2 = m_3{}^2 - m_4{}^2$

$\Delta m_{23}{}^2 = m_2{}^2 - m_3{}^2$

$\Delta m_{12}{}^2 = m_1{}^2 - m_2{}^2$

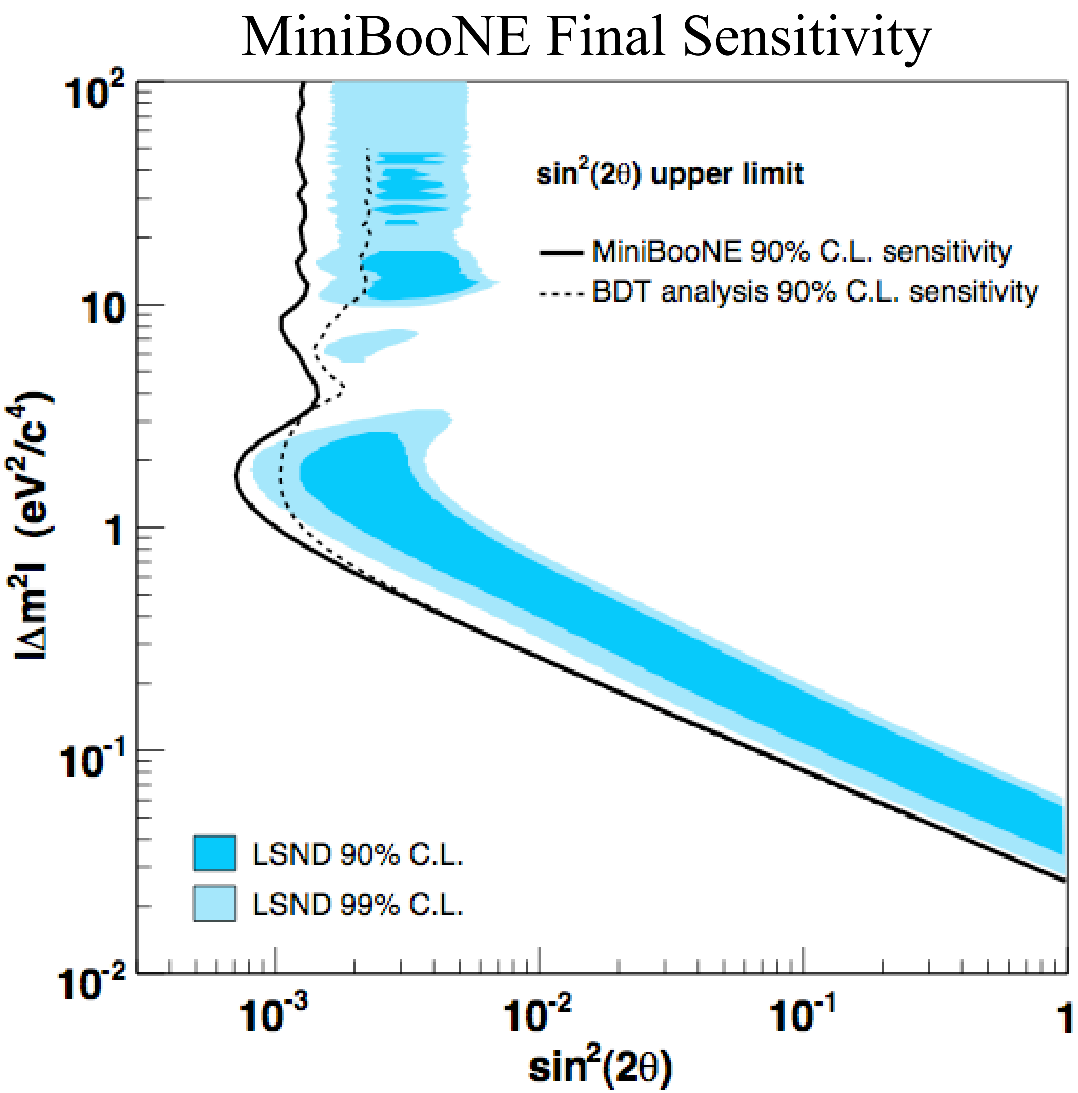
If MiniBooNE does not observe LSND-type oscillations...

The Standard Model wins again!

Today: MiniBooNE's initial results on testing the LSND anomaly

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

MiniBooNE Summary



MiniBooNE performed a *blind analysis* for the $\nu_\mu \rightarrow \nu_e$ appearance search

- Did not look at ν_e events while developing reconstruction, particle identification algorithms

- Final cuts made with no knowledge of the number of ν_e events in the box

Final sensitivity to ν_e appearance shown for two independent analyses

- "Primary" analysis chosen based on slightly better sensitivity

MOW
(blinded)
c.2002

We opened the box on March 26, 2007

And the answer is...

Primary Analysis

Counting Experiment:

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

expectation: **358 ±19 (stat) ± 35 (sys)**

data:

significance:

Cross-check Analysis

Counting Experiment:

$300 < E_\nu^{QE} < 1500$ MeV

expectation: **1070 ±33 (stat) ± 225(sys)**

data:

significance:

And the answer is...

Primary Analysis

Counting Experiment:

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

expectation: **358 ±19 (stat) ± 35 (sys)**

data: **380**

significance: **0.55 σ**

Cross-check Analysis

Counting Experiment:

$300 < E_\nu^{QE} < 1500$ MeV

expectation: **1070 ±33 (stat) ± 225(sys)**

data:

significance:

And the answer is...

Primary Analysis

Counting Experiment:

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

expectation: **358 ±19 (stat) ± 35 (sys)**

data: **380**

significance: **0.55 σ**

Cross-check Analysis

Counting Experiment:

$300 < E_\nu^{QE} < 1500$ MeV

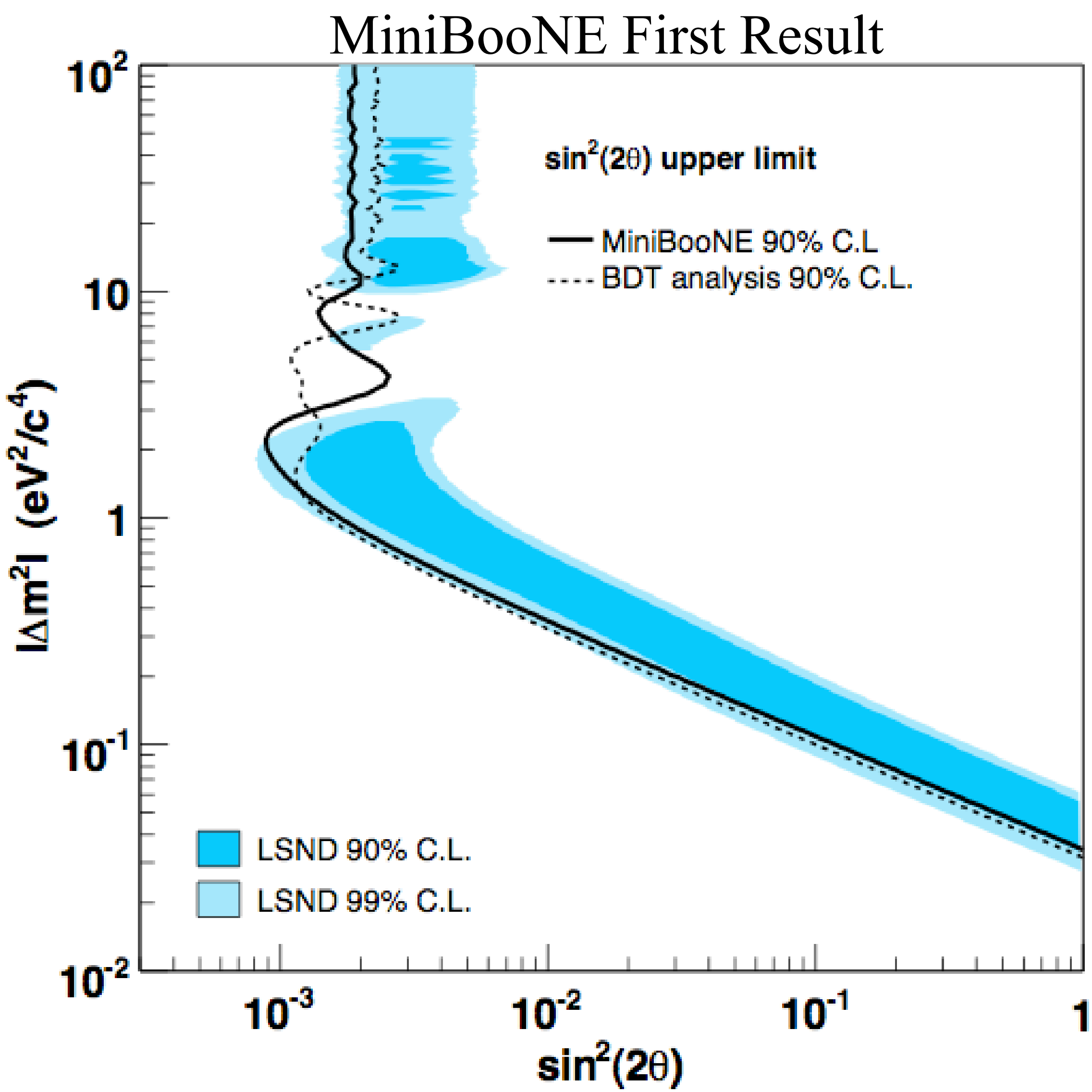
expectation: **1070 ±33 (stat) ± 225(sys)**

data: **971**

significance: **-0.38 σ**

And the answer is...

MiniBooNE observes no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations.



The two independent oscillation analyses are in agreement!

The rest of this talk is a presentation of the experimental methods used to get here.

Outline

1. Motivation & Introduction
2. Description of the Experiment
   - -Beam
   - -Detector
3. Analysis Overview
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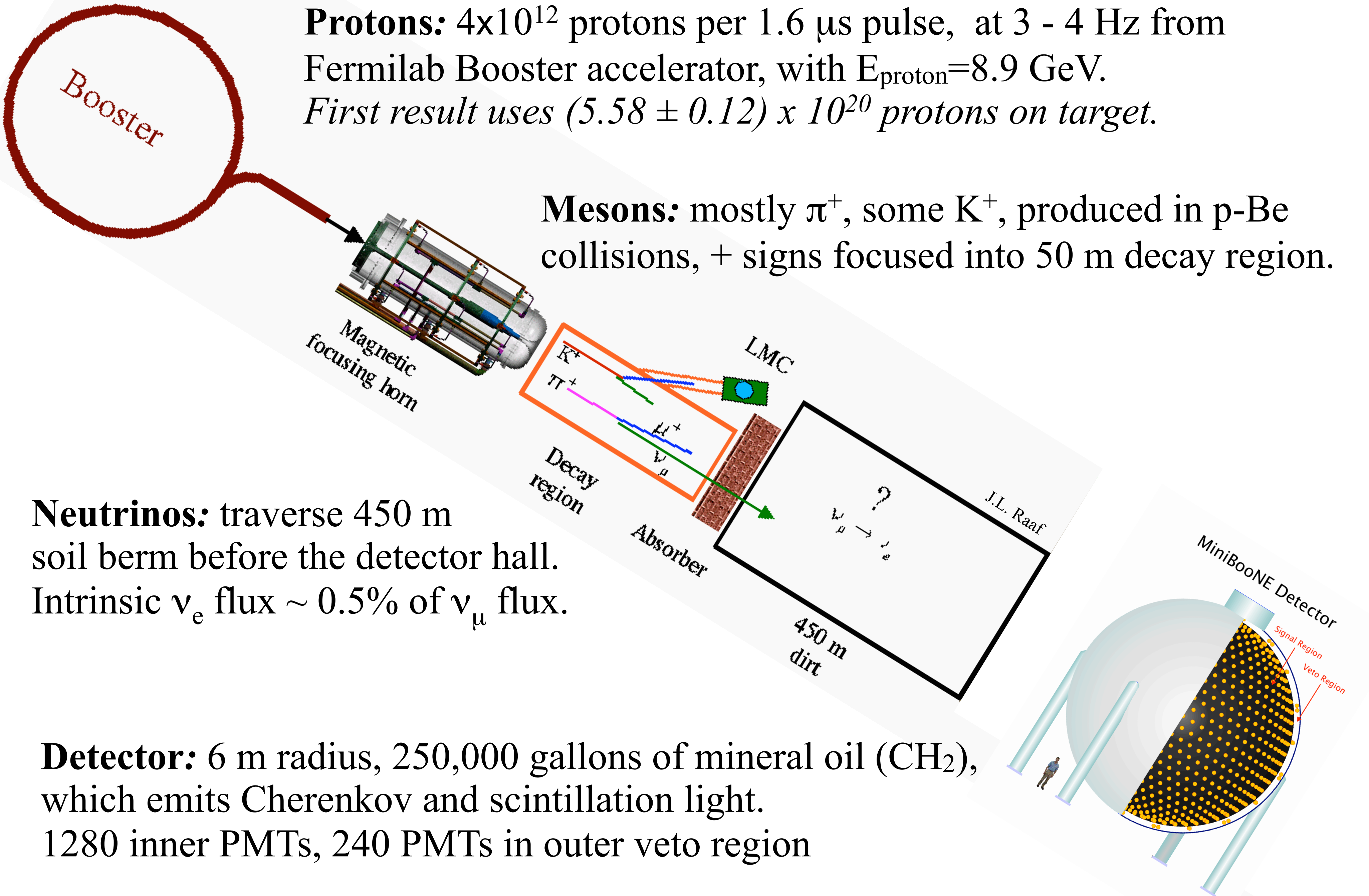
MiniBooNE Overview: **Beam and Detector**

Protons*:* 4×10^{12} protons per 1.6 μs pulse, at 3 - 4 Hz from Fermilab Booster accelerator, with E_{proton}=8.9 GeV.
First result uses (5.58 ± 0.12) x 10^{20} protons on target.

Mesons*:* mostly π^+, some K^+, produced in p-Be collisions, + signs focused into 50 m decay region.



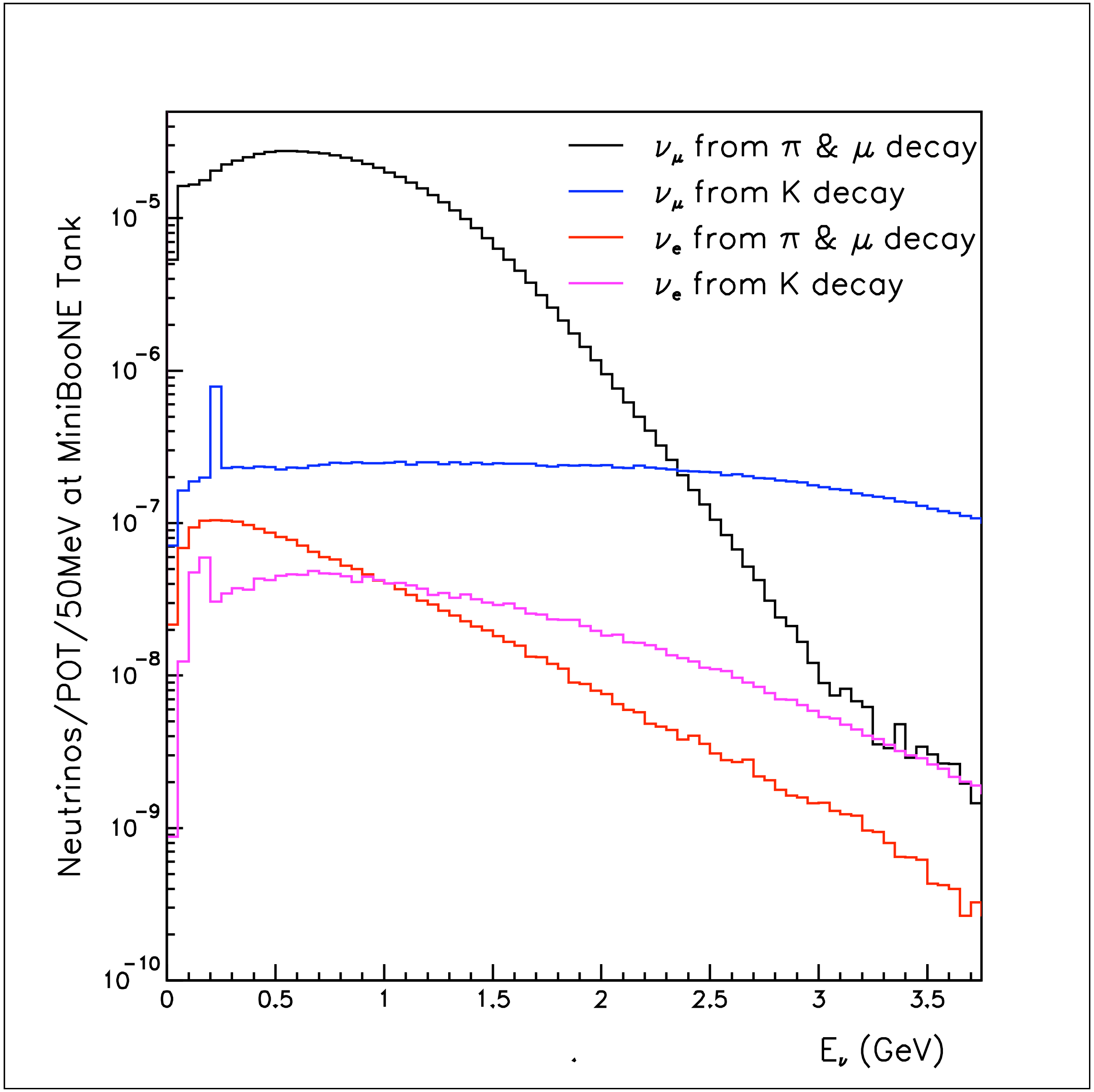
Neutrinos*:* traverse 450 m soil berm before the detector hall.
Intrinsic ν_e flux ~ 0.5% of ν_μ flux.

Detector*:* 6 m radius, 250,000 gallons of mineral oil (CH_2), which emits Cherenkov and scintillation light.
1280 inner PMTs, 240 PMTs in outer veto region

Booster Neutrino Beam: **Neutrino Flux**

MiniBooNE is searching for an excess of ν_e in a ν_μ beam

Modeled with a Geant4 Monte Carlo



"Intrinsic" $\nu_e + \bar{\nu}_e$ content: 0.5%

ν_e Sources:

$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ (42%)

$K^+ \to \pi^0 e^+ \nu_e$ (28%)

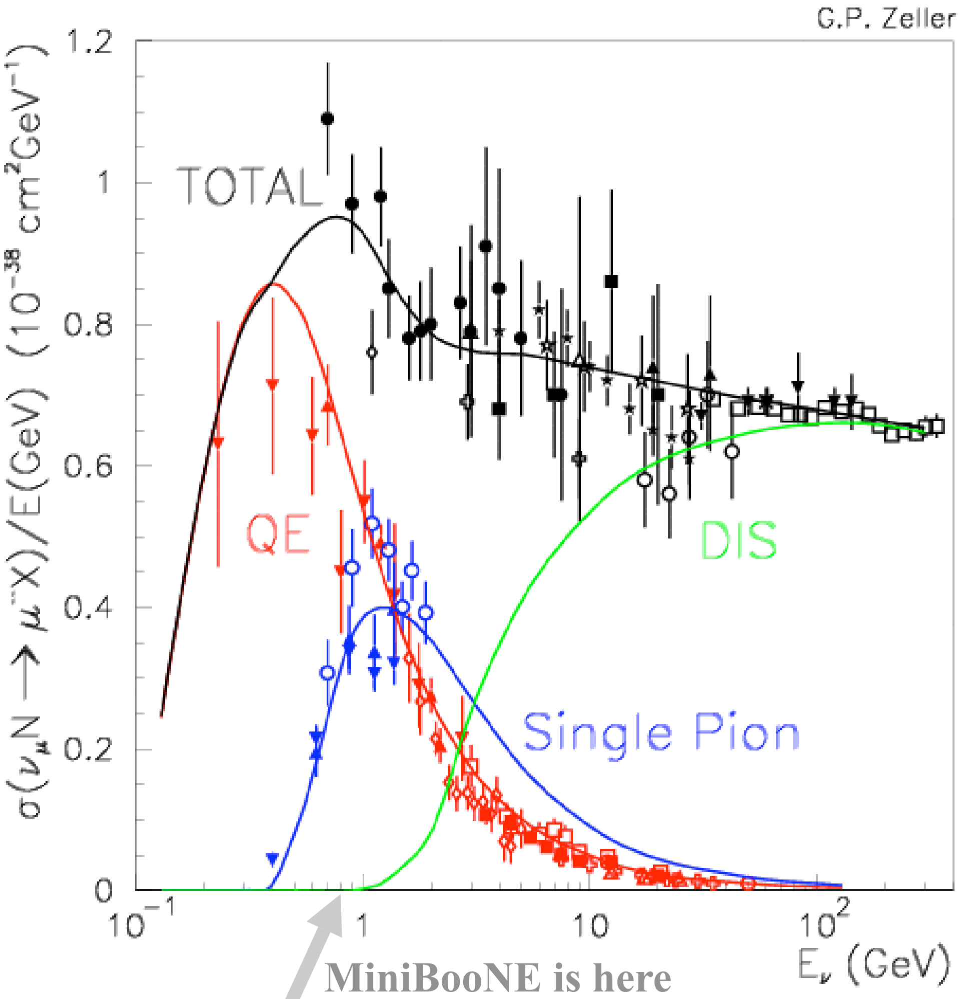
$K^0 \to \pi^+ e^- \nu_e$ (16%)

$\pi^+ \to e^+ \nu_e$ (4%)

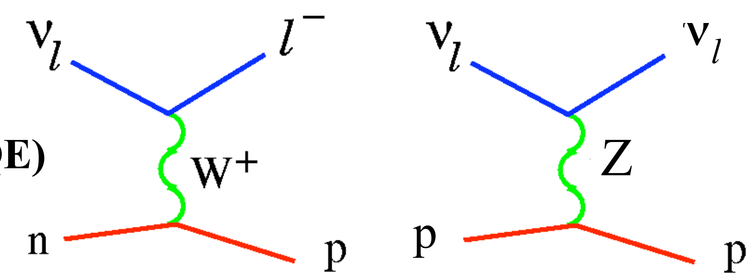
Antineutrino content: 6%

MiniBooNE Detector: Neutrino Cross Sections

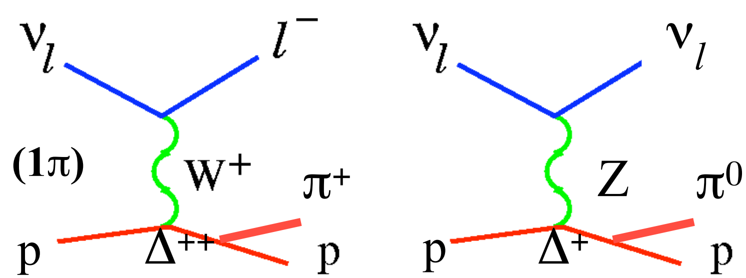
Modeling what the neutrinos do in the detector



CC / NC quasi-elastic scattering (QE)
42% / 16%



CC / NC resonance production (1π)
25% / 7%



Cross section predictions from NUANCE Monte Carlo

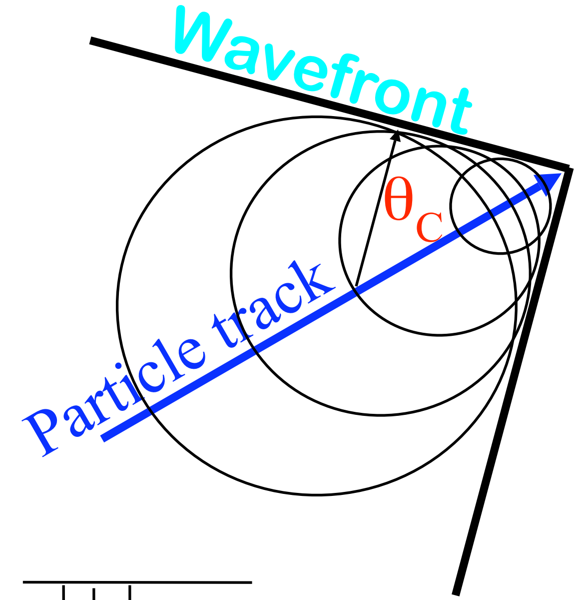
Use CCQE events for oscillation analysis signal channel:

$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\ell - m_\ell^2}{M_p - E_\ell + \sqrt{(E_\ell^2 - m_\ell^2)}\cos\theta_\ell}$$

Only need lepton direction and angle to find ν energy!

MiniBooNE Detector: **Optics**

charged final state particles produce **γ**s

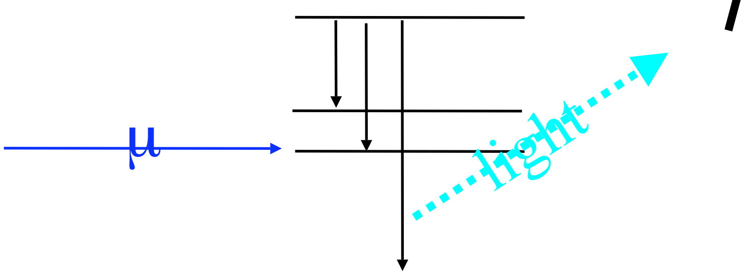


<u>Cherenkov radiation</u>

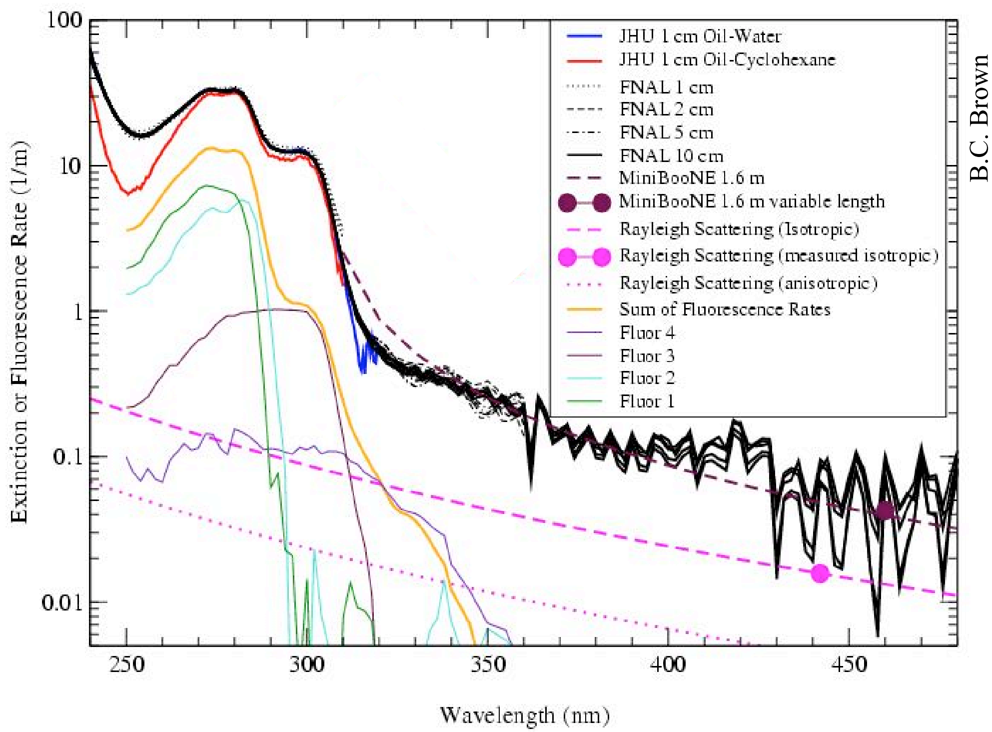
- Light emitted by oil if particle v > c/n
- forward and prompt in time

<u>Scintillation</u>

- Excited molecules emit de-excitation **γ**s
- isotropic and late in time



Extinction Rate for MiniBooNE Marcol 7 Mineral Oil



γs *are (possibly) detected by PMTs after undergoing absorption, reemission, scattering, fluorescence*

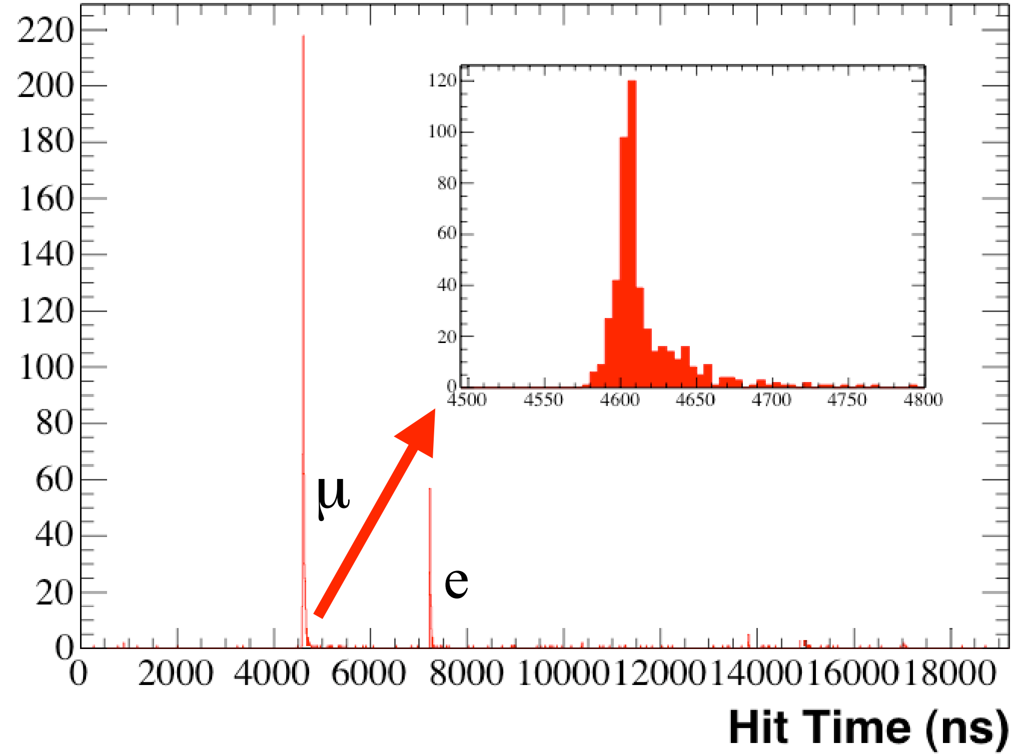
"the optical model"

MiniBooNE Detector: **Hits**

First set of cuts based on simple hit clusters in time: “sub-events.”

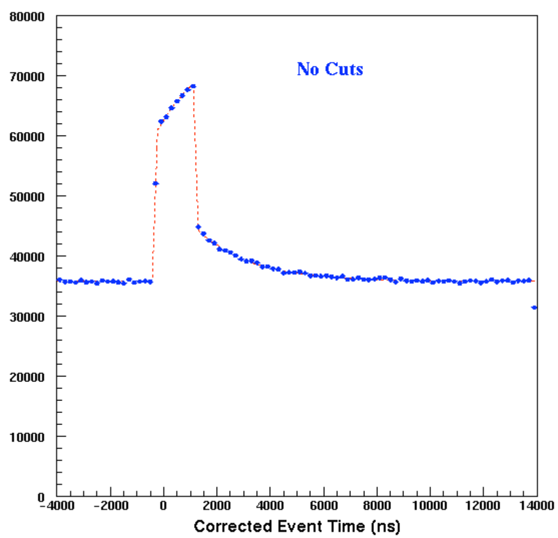
Most events are from ν_μ CC interactions, with characteristic two “sub-event” structure from stopped μ decay.

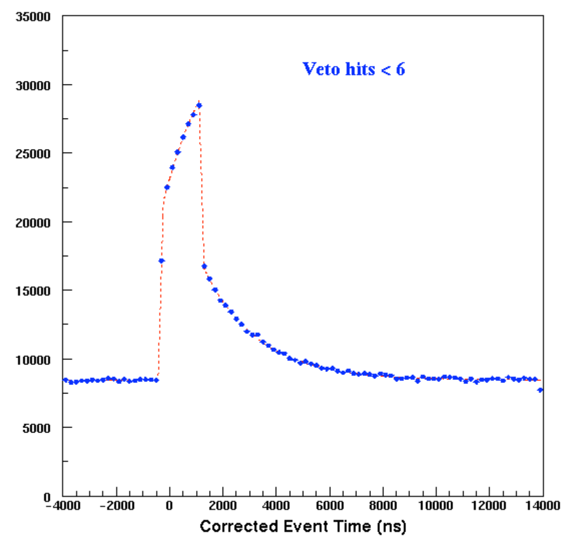
ν_e CC interactions have 1 “sub-event”.



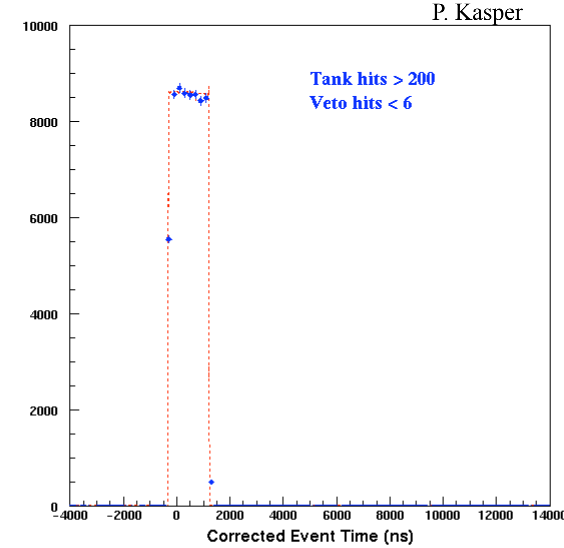
Simple cuts eliminate cosmic ray events:

1. Require < 6 veto PMT hits,
2. Require > 200 tank PMT hits.

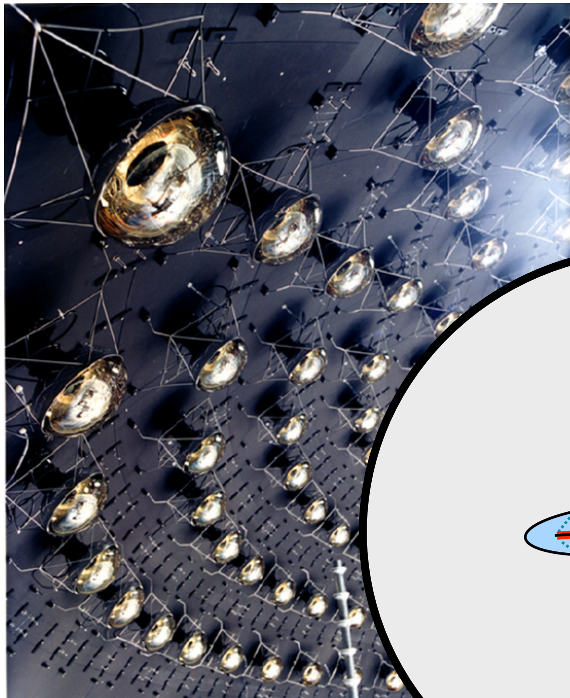


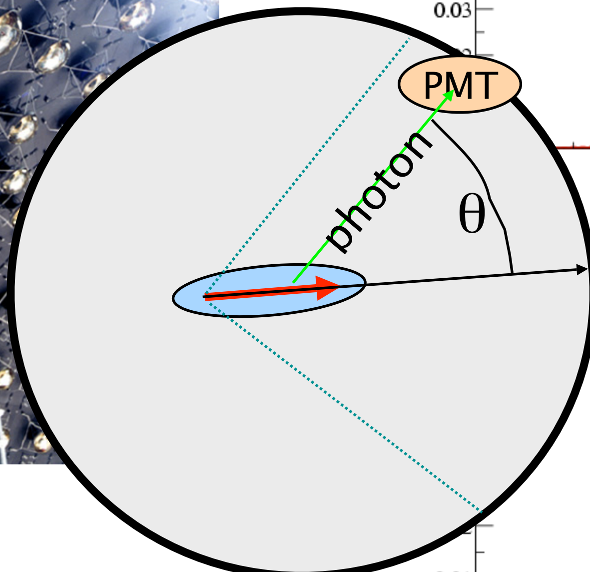


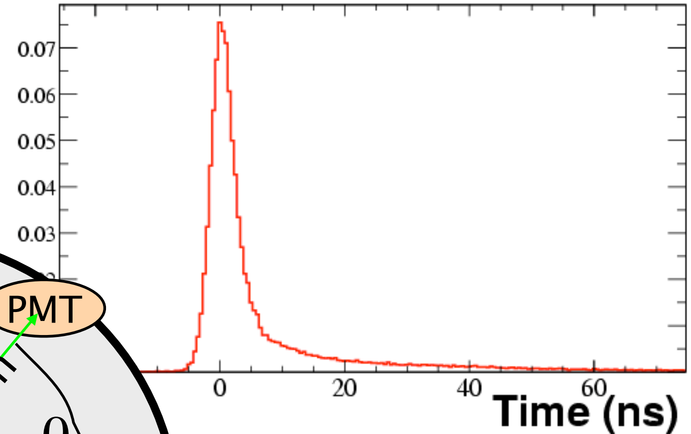
P. Kasper

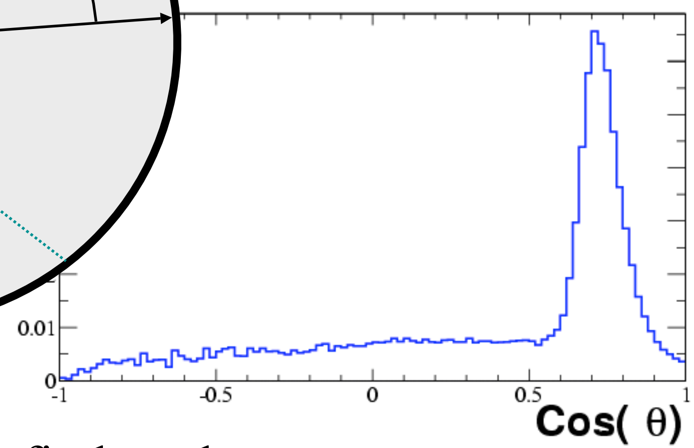


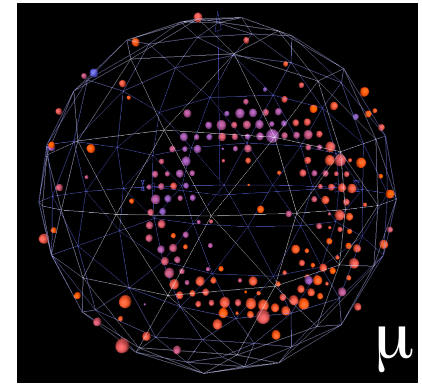
MiniBooNE Detector: Reconstruction and Particle ID

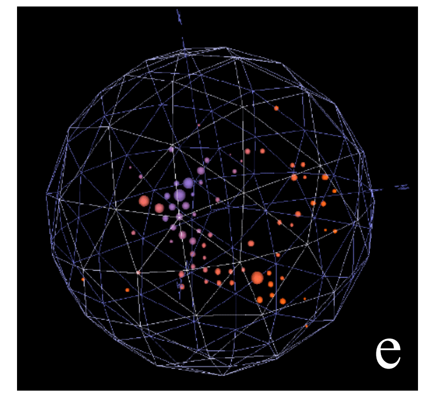


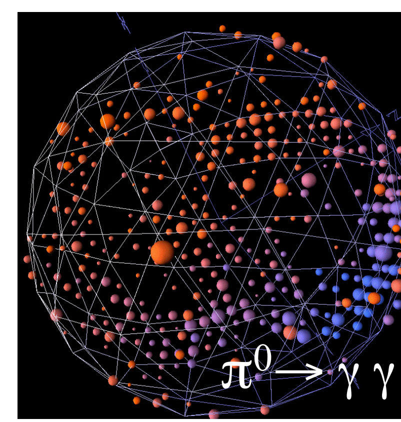












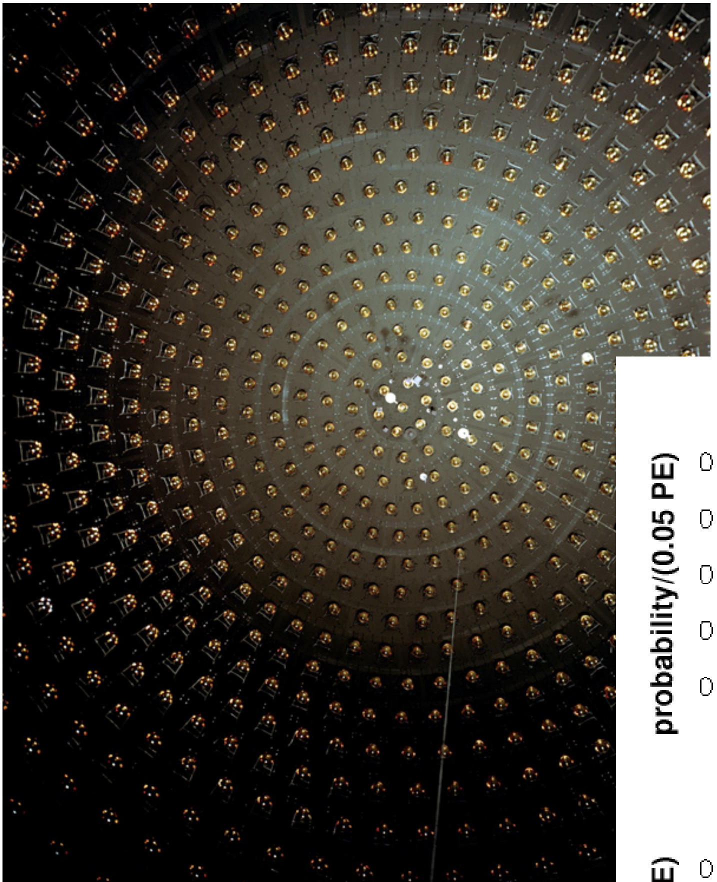
<u>Reconstruction:</u>

PMTs collect γs, record t and q,
fit time and angular distributions to find tracks

<u>Final State Particle Identification:</u>

muons have sharp Cherenkov rings and long tracks
electrons have fuzzy rings, from multiple scattering, and short tracks
neutral pions decay to 2 γs, which convert and produce 2 fuzzy rings,
easily misidentified as electrons if one ring gets lost!

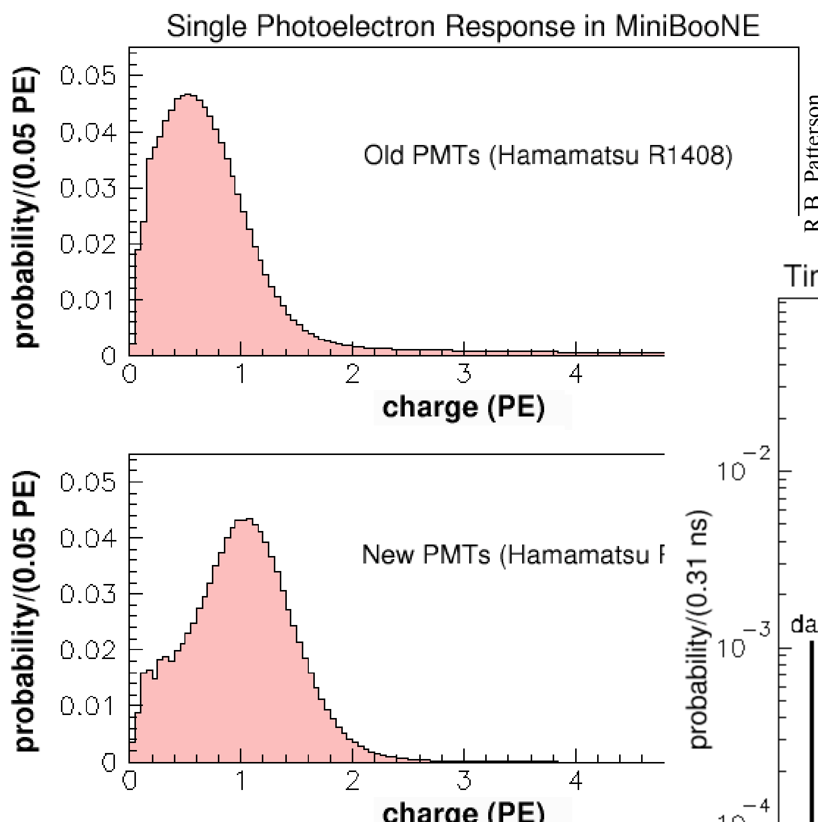
MiniBooNE Detector: **PMT Calibration**

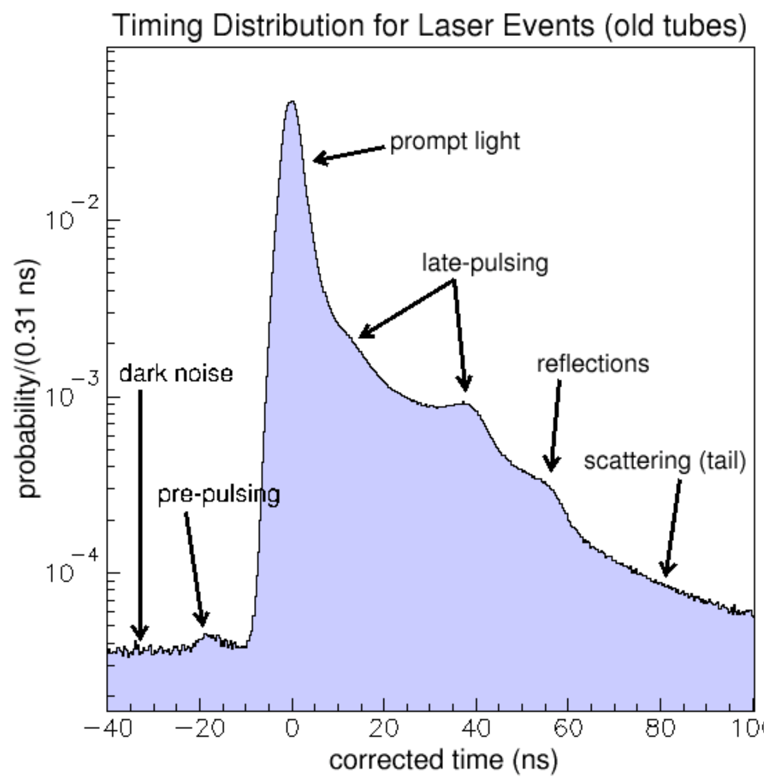


10% photo-cathode coverage

PMTs are calibrated with a laser + 4 flask system

PMT Charge Resolution: 1.4 PE, 0.5 PE
PMT Time Resolution: 1.7 ns, 1.1 ns





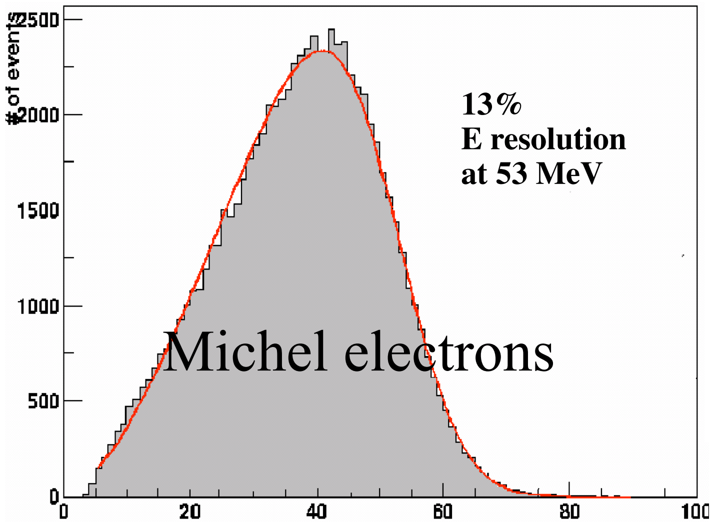
Two types of 8" Hamamatsu Tubes: R1408, R5912

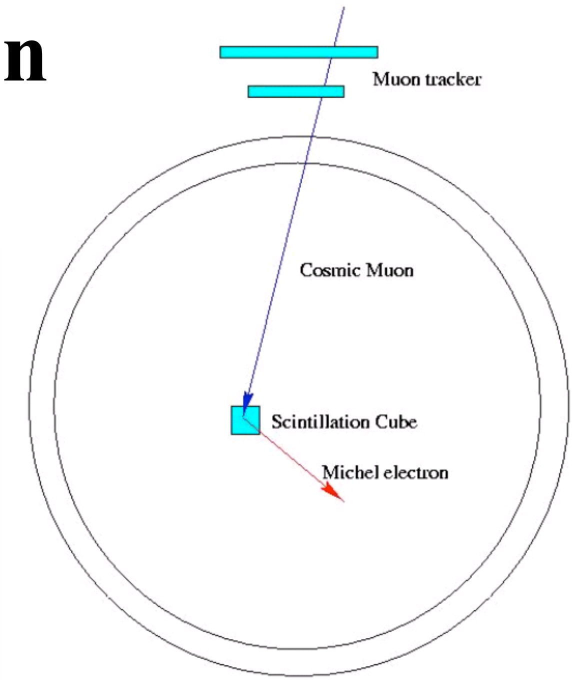
Laser data are acquired at 3.3 Hz to continuously calibrate PMT gain and timing constants

MiniBooNE Detector: Cosmic Calibration

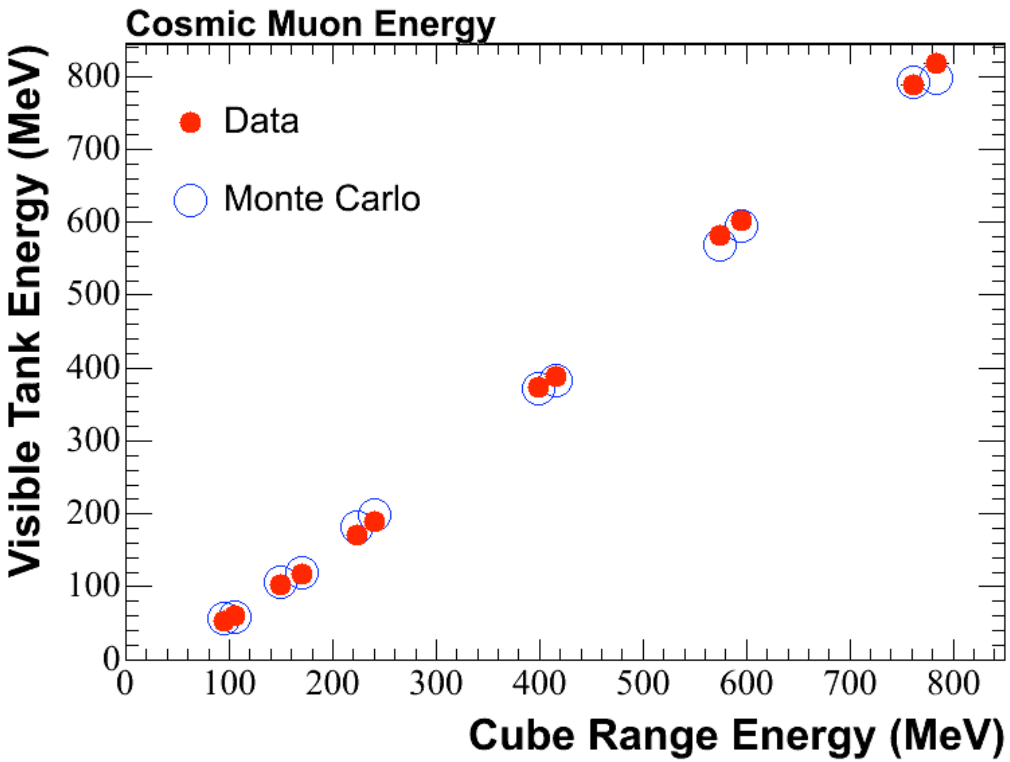
use cosmic muons and their decay electrons (Michels)

<u>Michel electrons:</u>
-set absolute energy scale and
 resolution at 53 MeV endpoint
-optical model tuning





Muon tracker
7 scintillator cubes

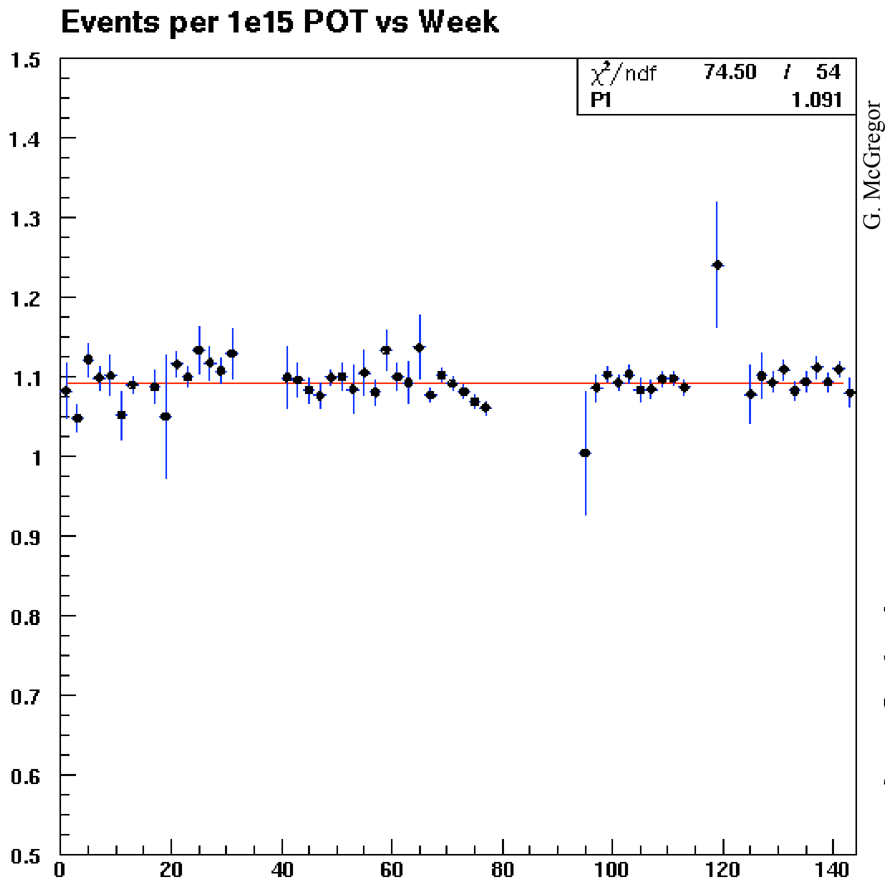


<u>Cosmic muons which stop in cubes:</u>
-test energy scale extrapolation up to
 800 MeV
- measure energy, angle resolution
- compare data and MC

Muon tracker + cube calibration
data continuously acquired at 1 Hz

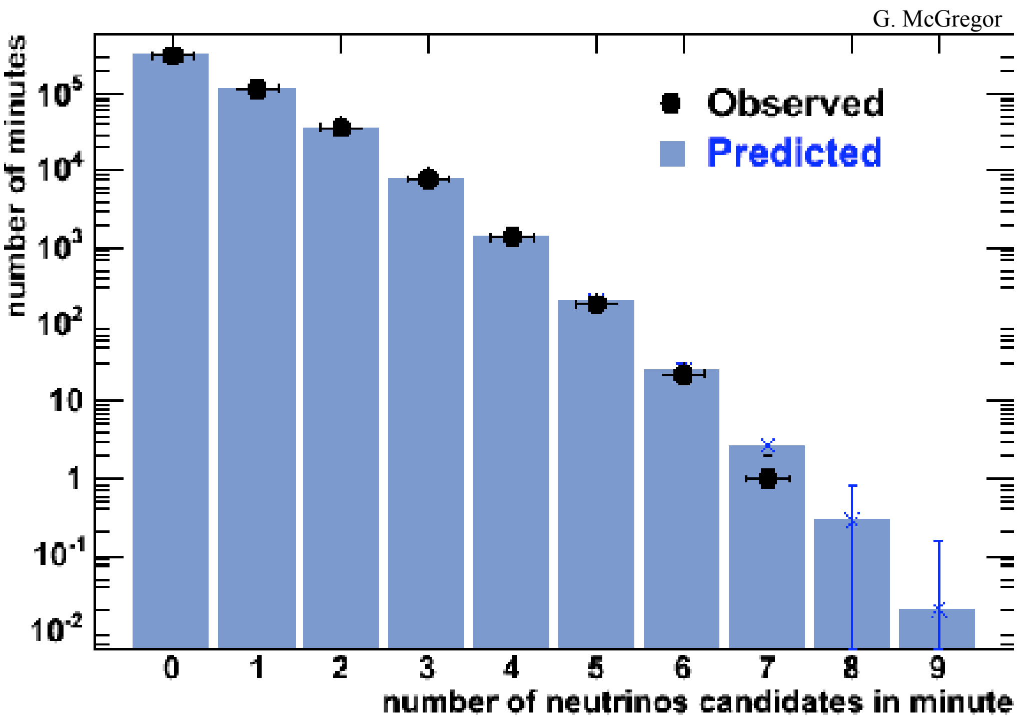
MiniBooNE Beam & Detector: **Stability**

Neutrinos per proton on target throughout the neutrino run:



MiniBooNE observes
~1 neutrino interaction
per 1E15 protons.

Observed and expected
events per minute



Outline

1. Motivation & Introduction
2. Description of the Experiment
3. Analysis Overview
   -Signal and Backgrounds
   -Strategy
4. Two Independent Oscillation Searches
5. First Results

Analysis Overview: **Blind Analysis**

To avoid bias, MiniBooNE has done a blind analysis.

"Closed Box" Analysis

To study the data, we defined specific event sets with $< 1\sigma$ ν_e signal for analysis.

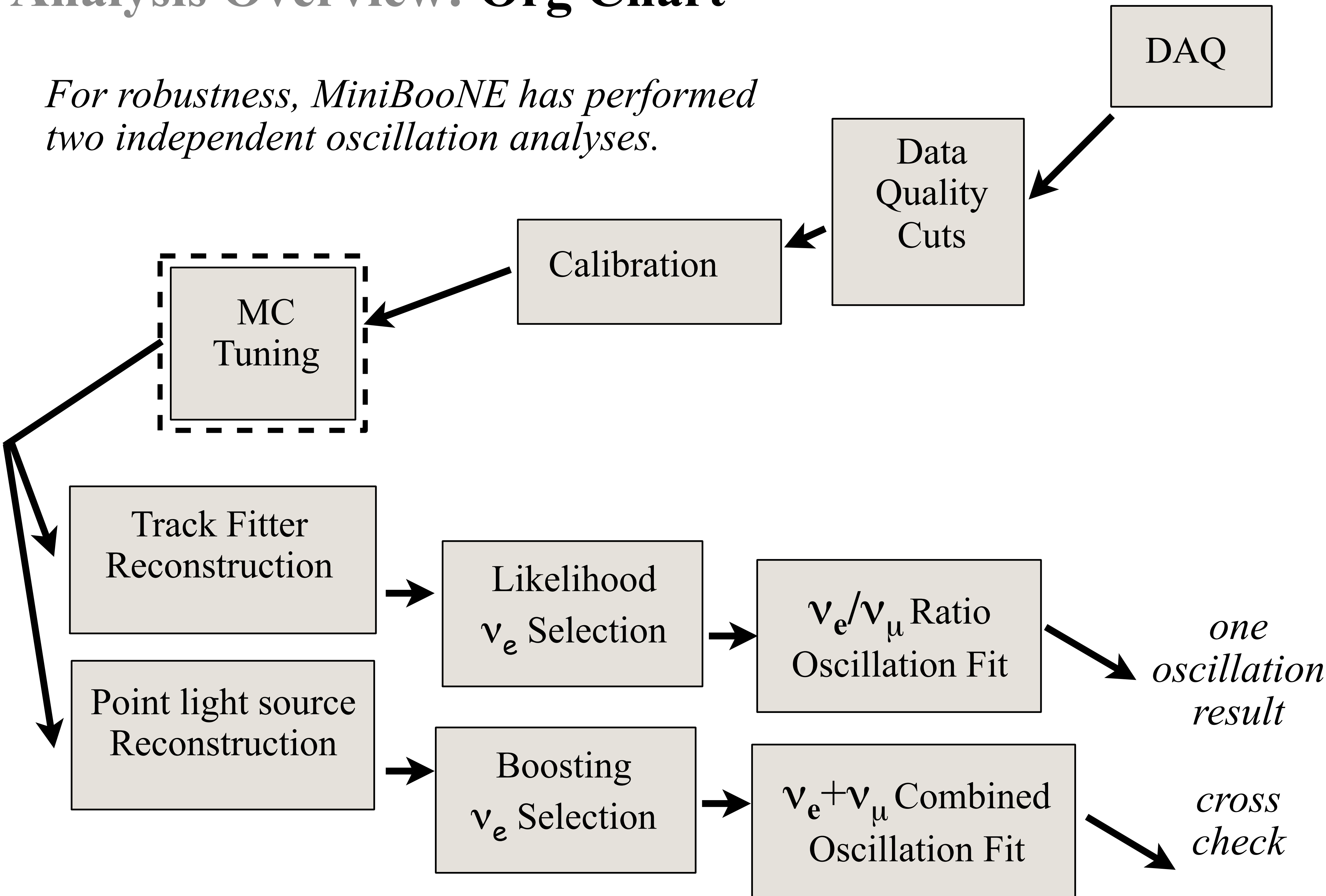
<u>Initial Open Boxes</u>	<u>Use</u>
all non-beam-trigger data	calibration and MC tuning
0.25% random sample	an unbiased data set
ν_μ CCQE	measure flux, E_ν^{QE}, oscillation fit
ν_μ NC1π^0	measure rate for MC
"dirt"	measure rate for MC
all events with E_ν>1.4 GeV	check MC rate
ν_μ CC1π^+	check MC rate
ν_μ-e elastic	check MC rate

<u>Second Step:</u>

One closed signal box — explicitly sequester the signal, 99% of data open

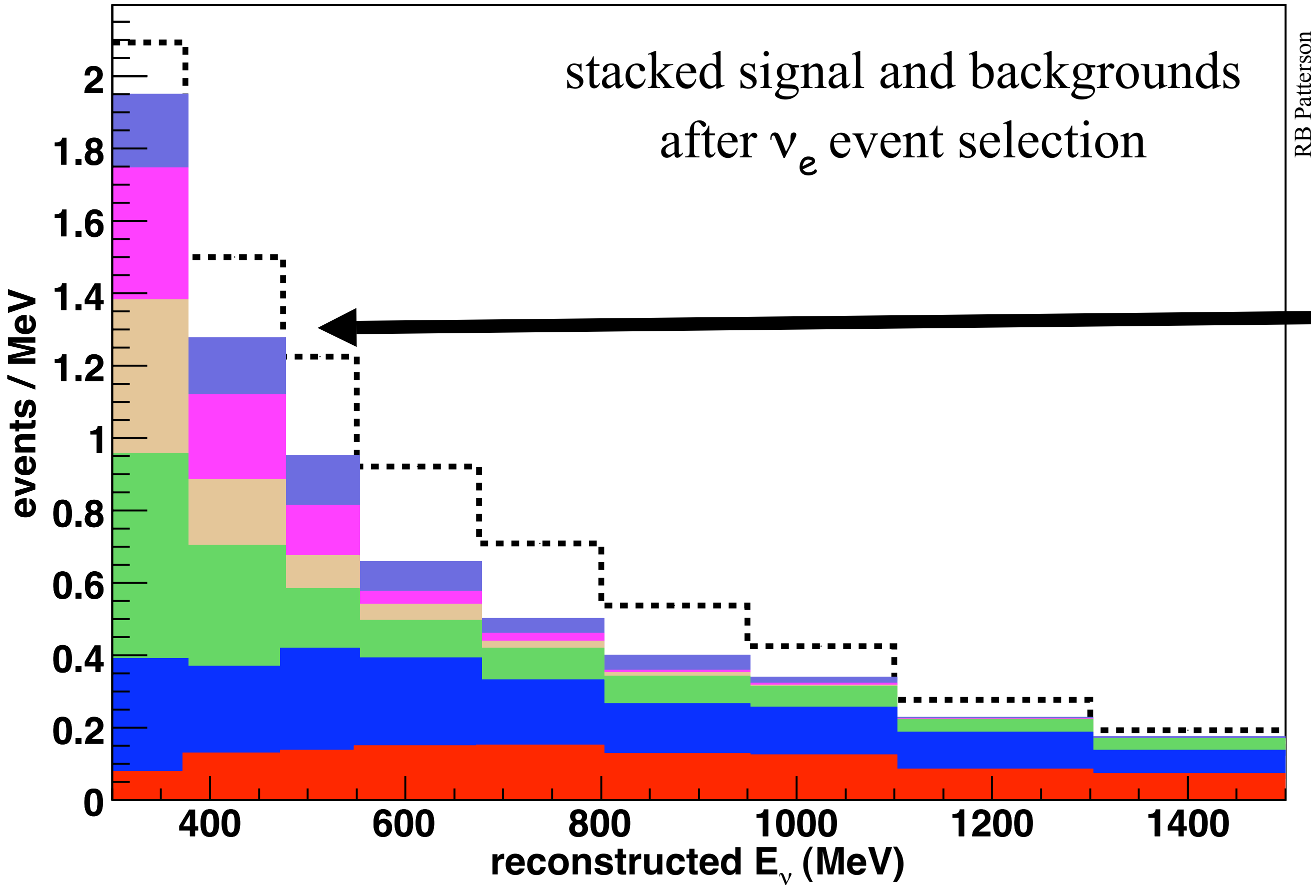
Analysis Overview: **Org Chart**

For robustness, MiniBooNE has performed two independent oscillation analyses.



Analysis Overview: Signal and Backgrounds

what we predict for the full ν data set (5.6E20 protons on target):



Oscillation ν_e

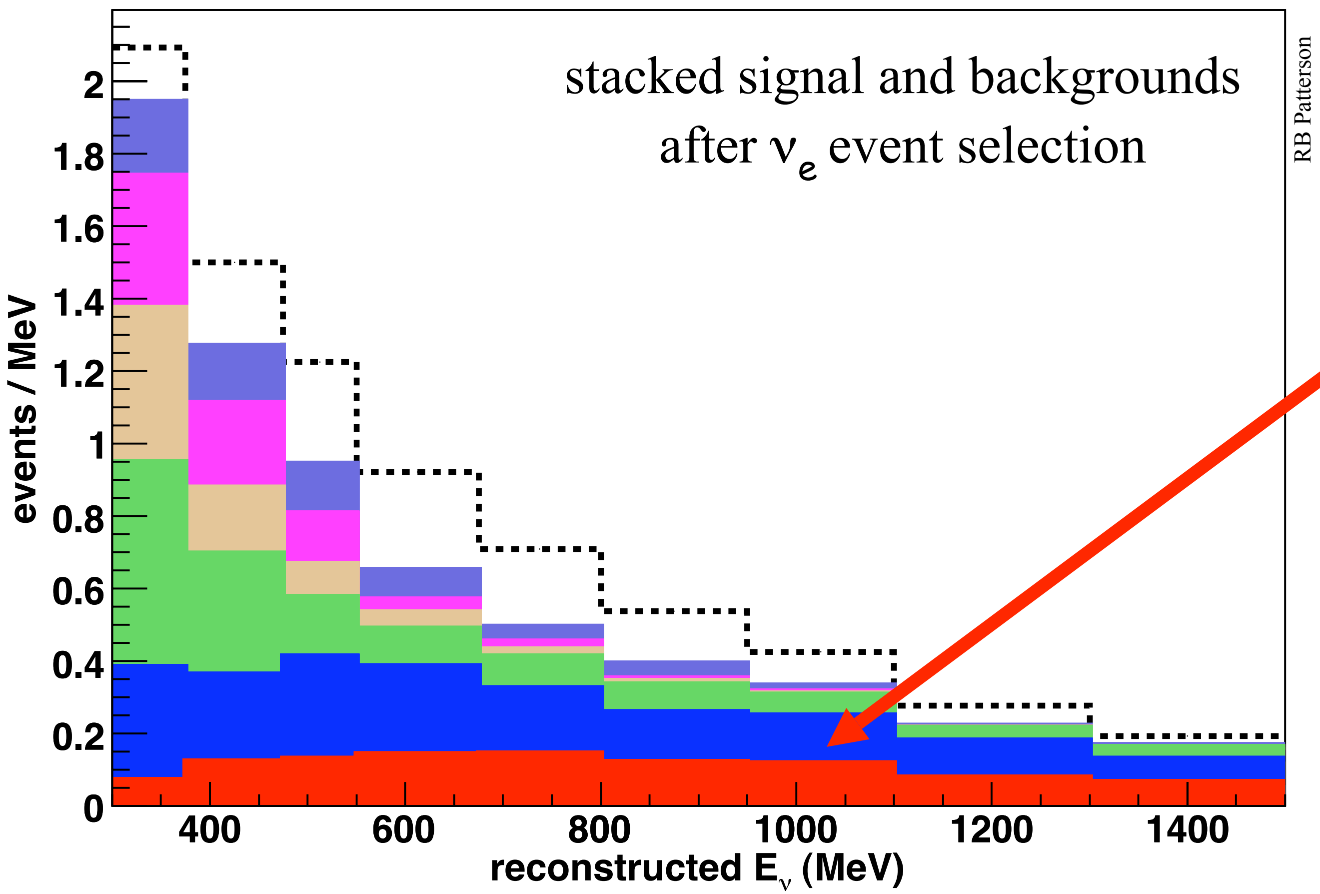
Example oscillation signal

- $\Delta m^2 = 1.2\ eV^2$
- $SIN^2 2\theta = 0.003$

Fit for excess as a function of reconstructed ν_e energy

Analysis Overview: **Signal and Backgrounds**

what we predict for the full ν data set (5.6E20 protons on target):



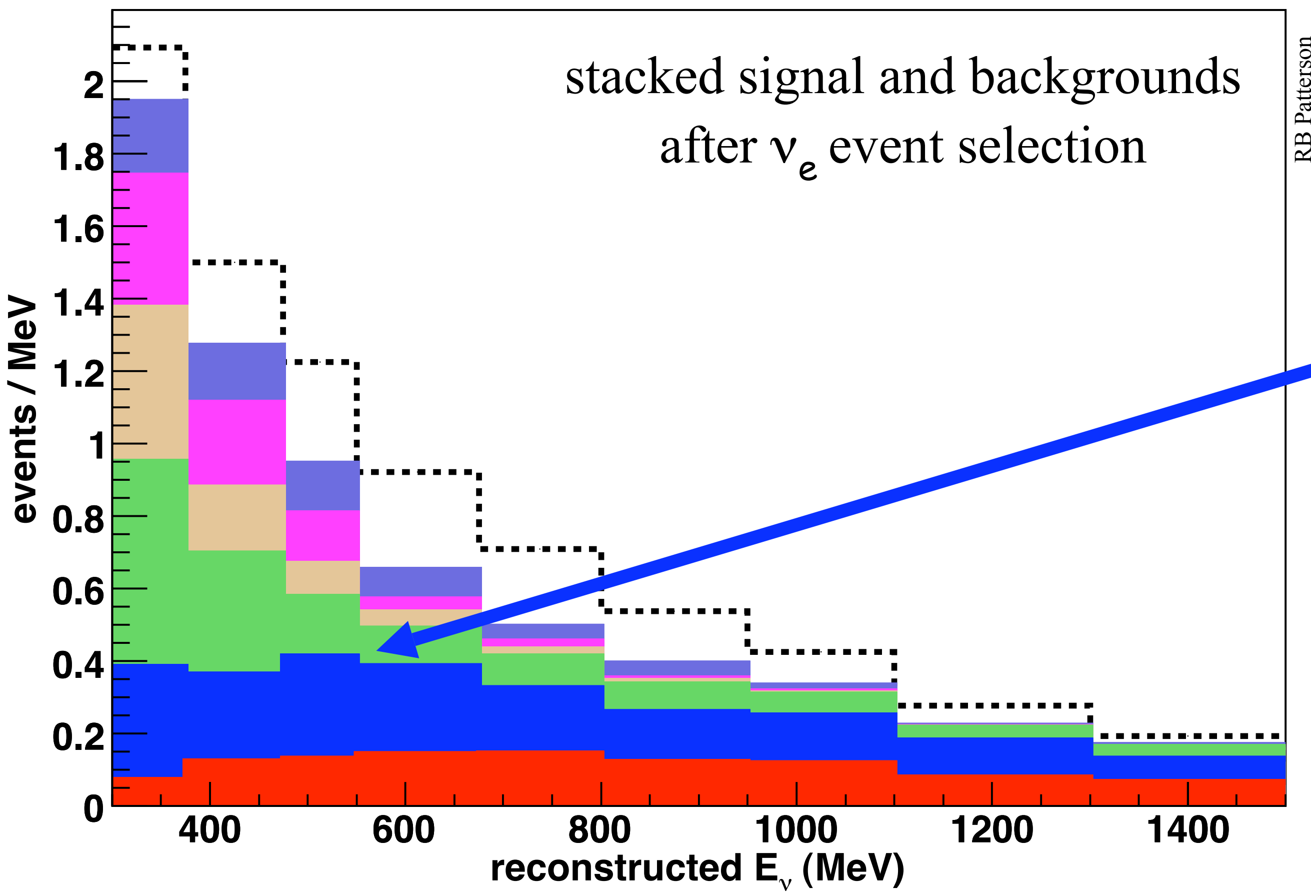
ν_e from K^+ and K^0

Use high energy ν_e and ν_μ in-situ data for normalization cross-check

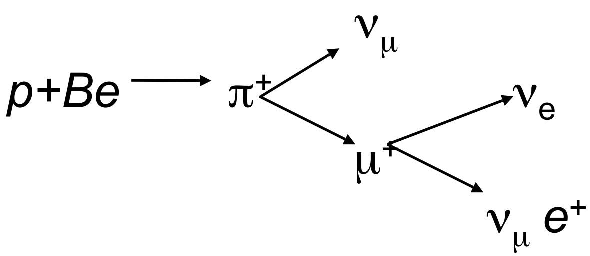
Use fit to kaon production data for shape

Analysis Overview: **Signal and Backgrounds**

what we predict for the full ν data set (5.6E20 protons on target):



ν_e from μ^+



Measured with in-situ ν_μ CCQE sample

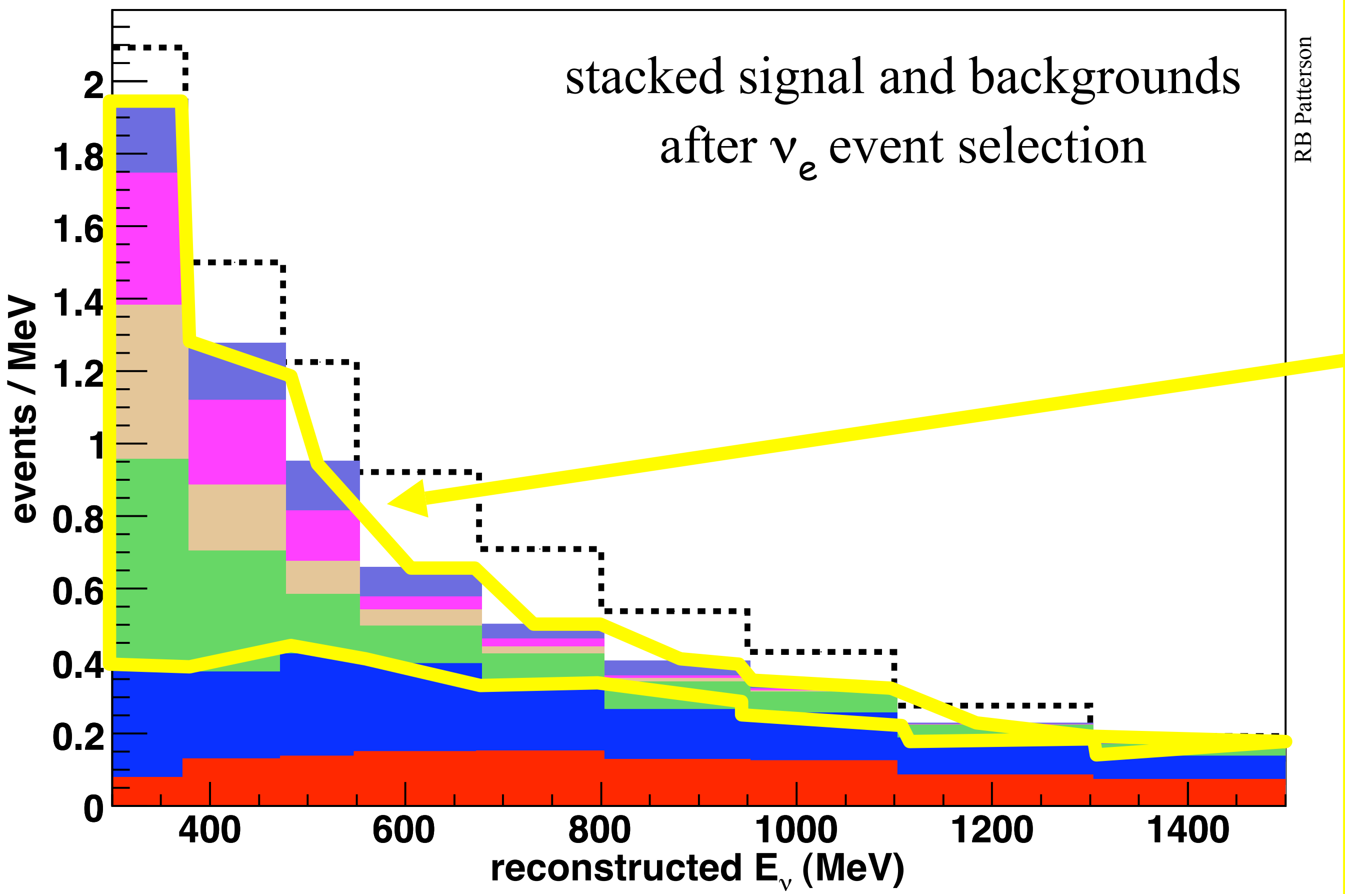
- Same ancestor π^+ kinematics

Most important background

- Constrained to a few %

Analysis Overview: **Signal and Backgrounds**

what we predict for the full ν data set (5.6E20 protons on target):



MisID ν_μ

~46% π^0

- Determined by clean π^0 measurement

~14% "dirt"

- Measure rate to normalize and use MC for shape

~16% Δ γ decay

- π^0 measurement constrains

~24% other

- Use ν_μ CCQE rate to normalize and MC for shape

Analysis Overview: **Strategy**

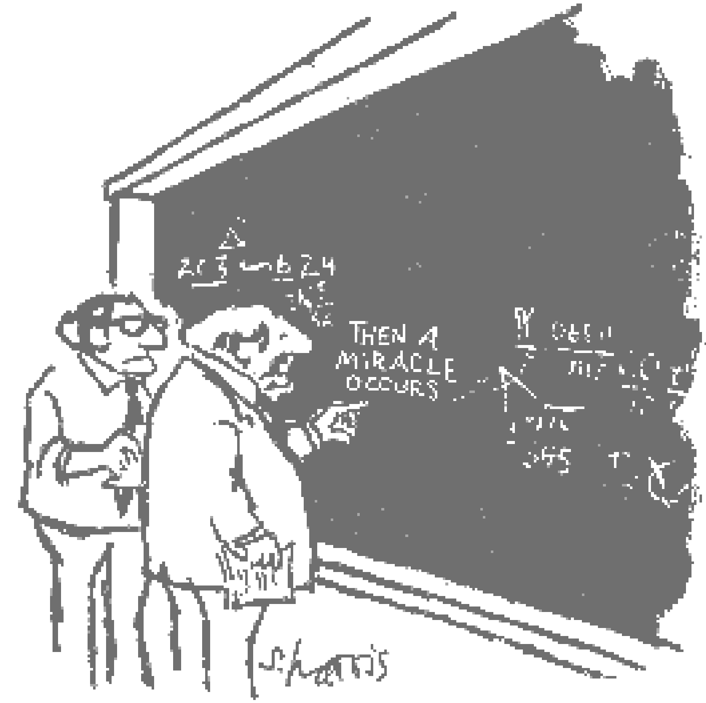
recurring theme: good data/MC agreement

in-situ data are incorporated wherever possible...

(i) MC tuning with calibration data
- energy scale
- PMT response
- optical model of light in the detector

(ii) MC fine-tuning with neutrino data
- cross section nuclear model parameters
- π^o rate constraint

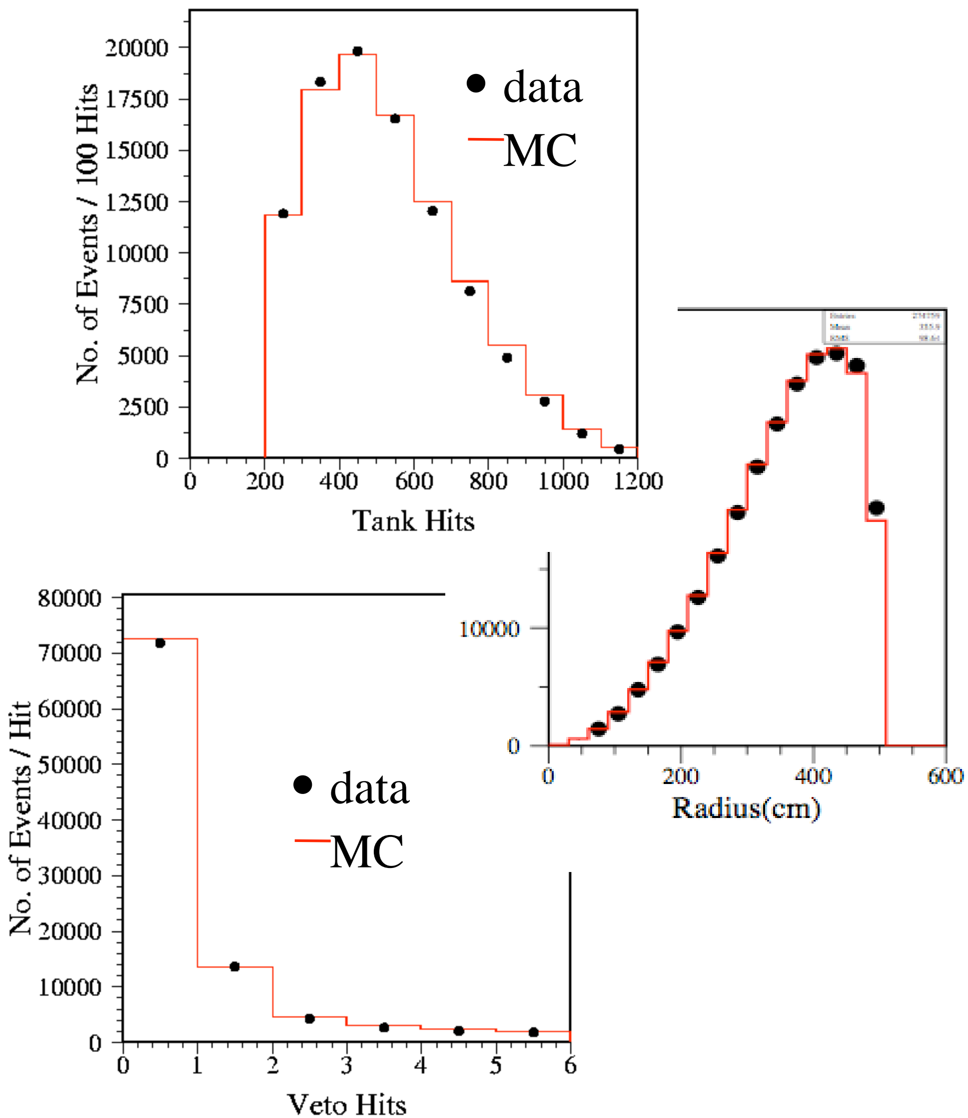
(iii) constraining systematic errors with neutrino data
- ratio method example: ν_e from μ decay background
- combined oscillation fit to ν_μ and ν_e data

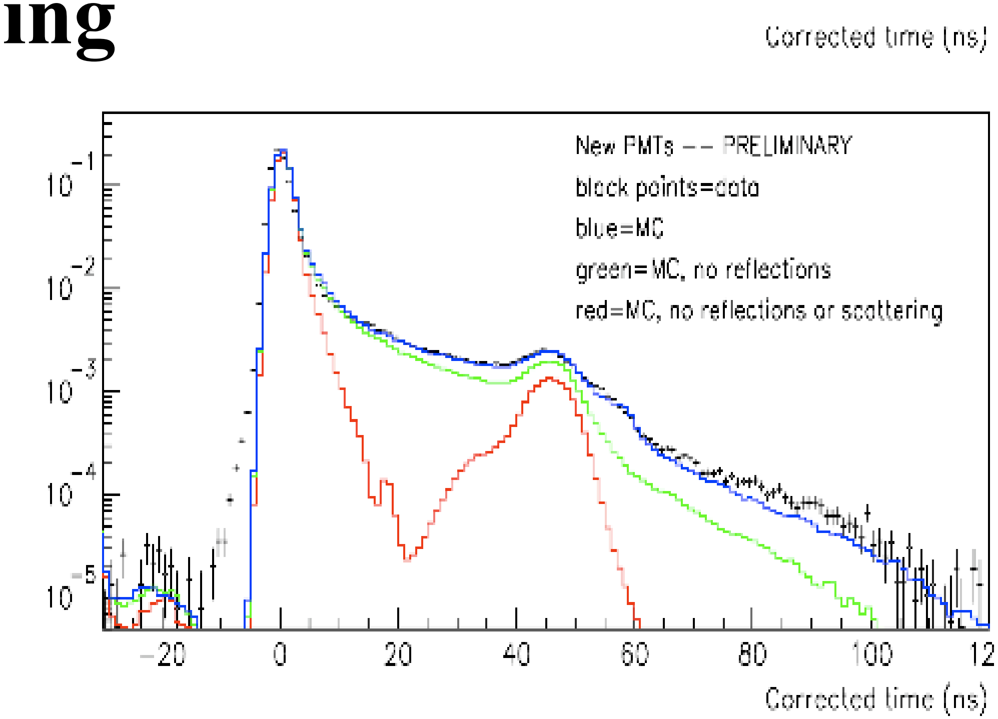


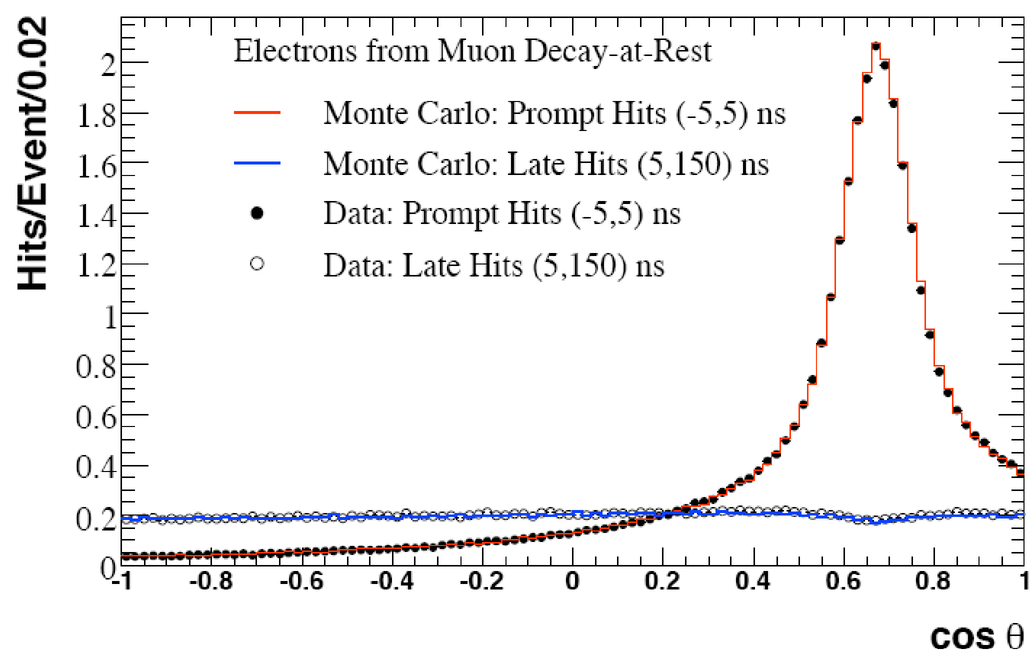
"I think you should be more explicit here in step two."

Analysis Overview: **MC Tuning**

MC tuning with calibration data







Analysis Overview: **Strategy**

in-situ data are incorporated wherever possible...

(i) MC tuning with calibration data
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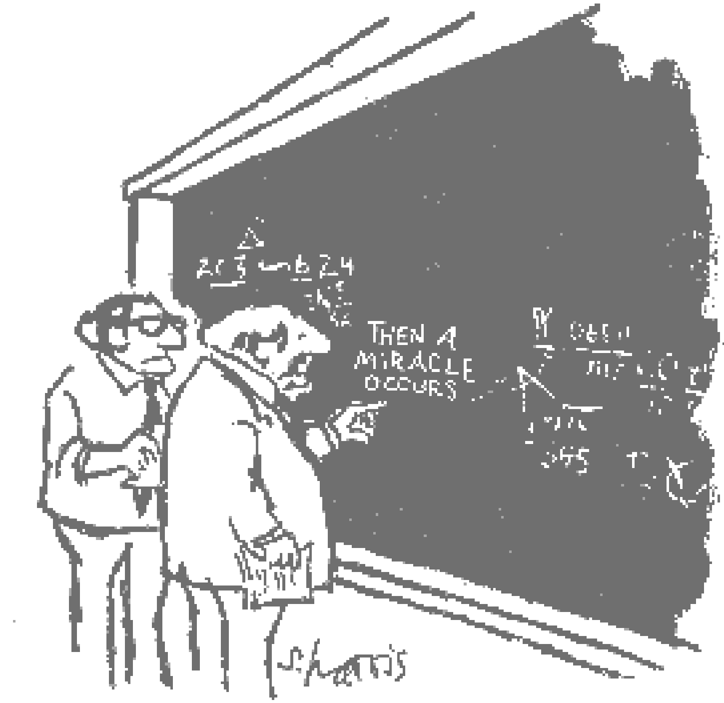


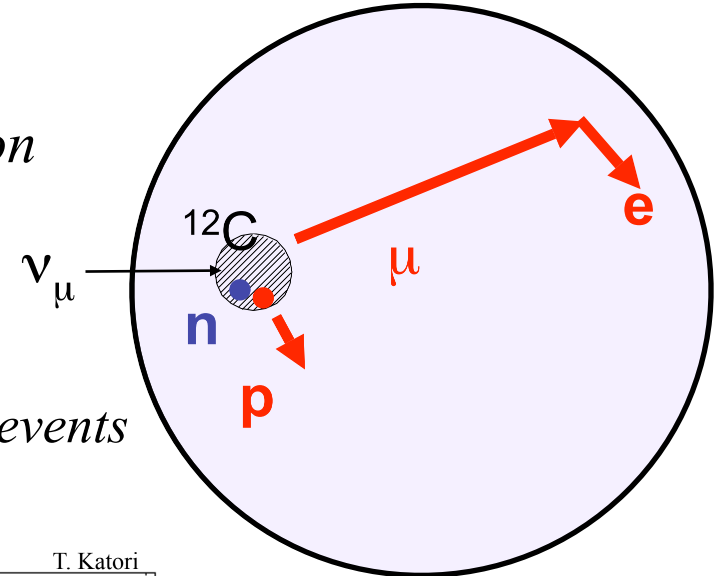
"I think you should be more explicit here in step two."

(iii) constraining systematic errors with neutrino data
- ratio method example: ν_e from μ decay background
- combined oscillation fit to ν_μ and ν_e data

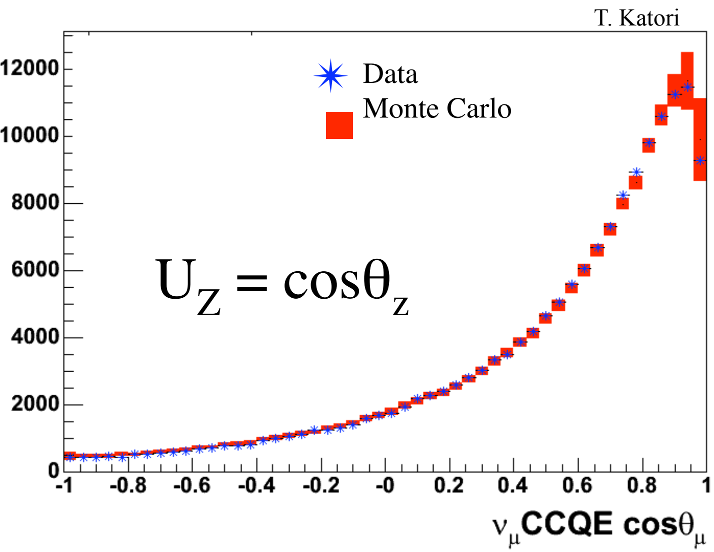
Analysis Strategy: ν_μ CCQE Events

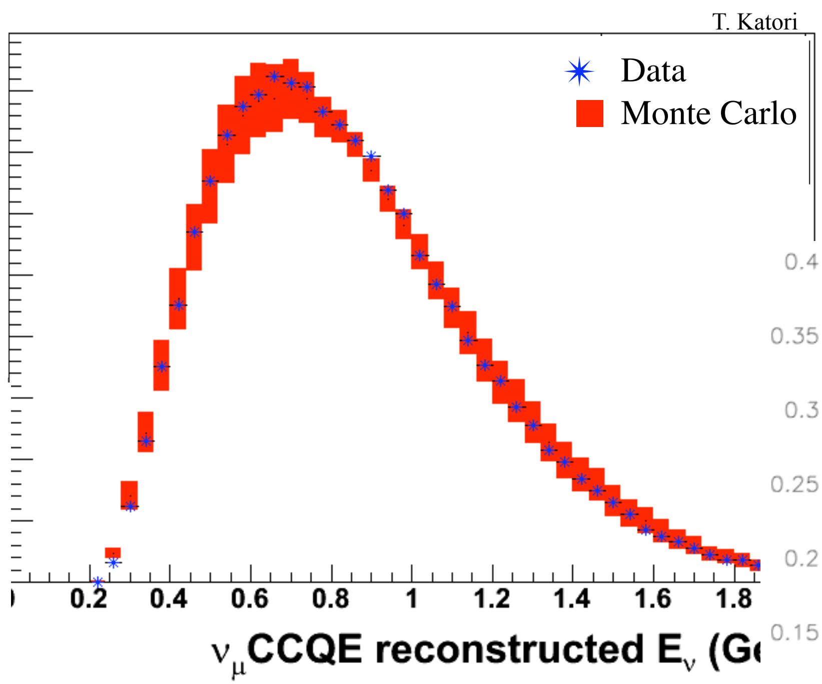
used to measure the ν_μ flux and check E_ν^{QE} reconstruction

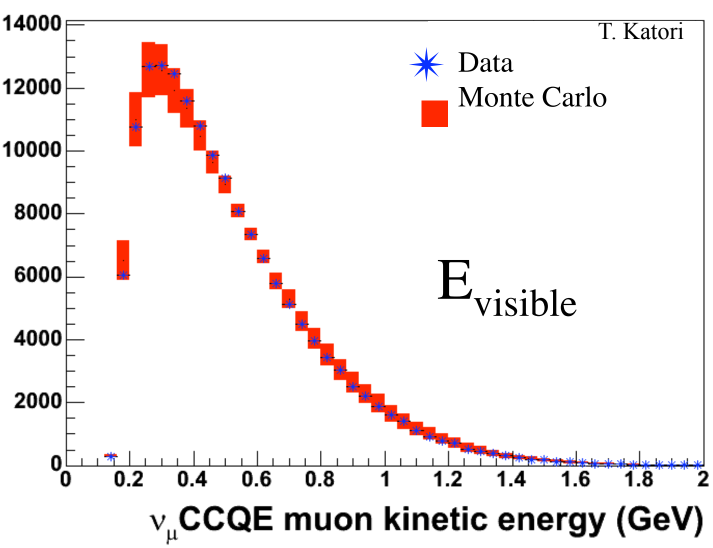
1. tag muons by requiring 2 sub-events in time
2. require reconstructed distance between sub-events < 1*m*



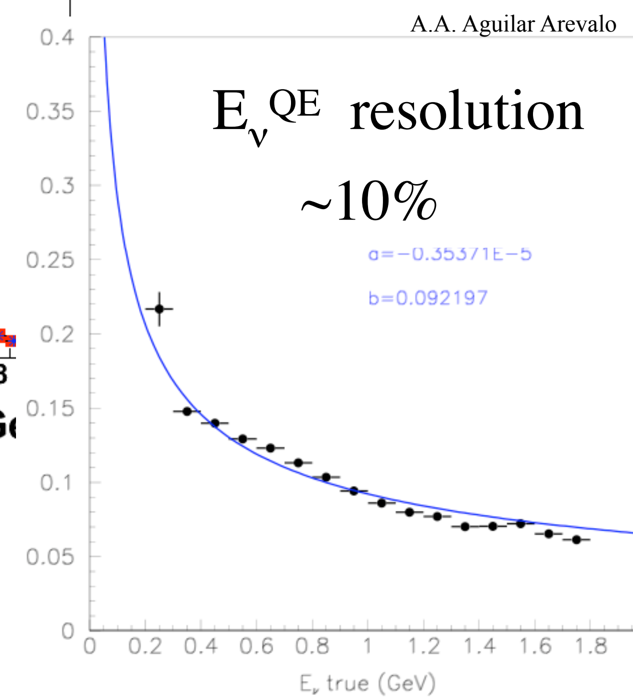
~74% CCQE purity, ~190k events





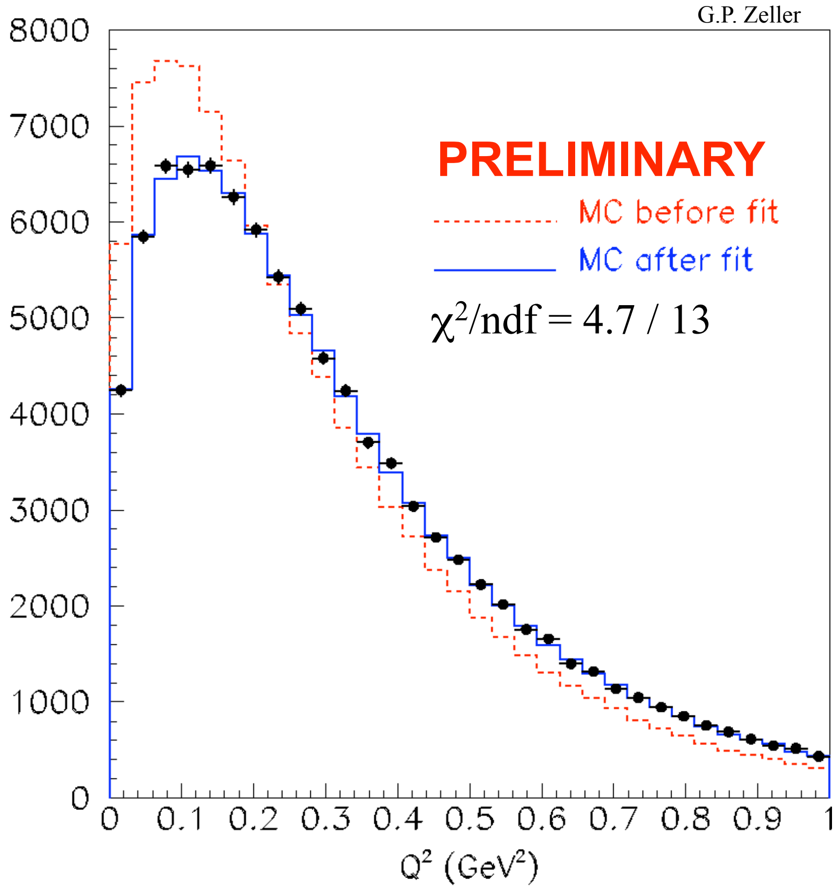


$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

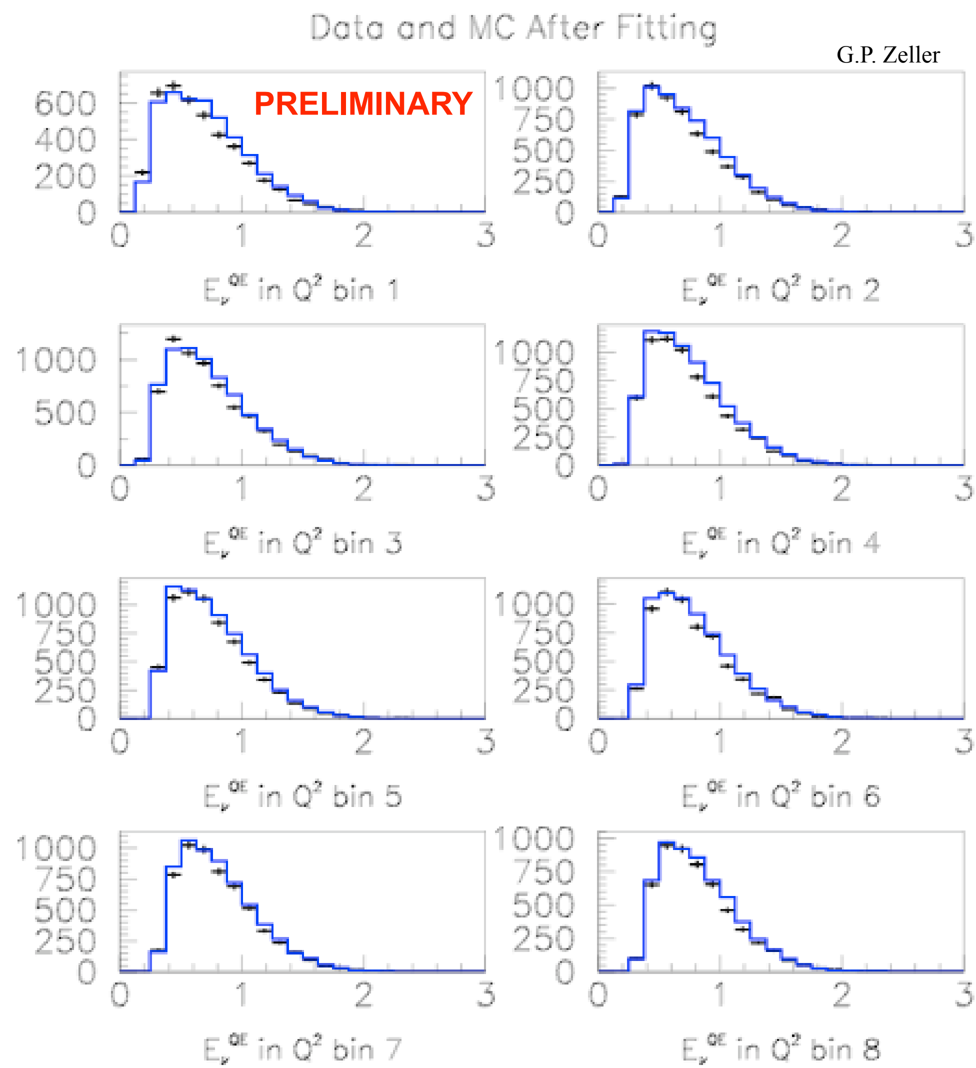


Incorporating ν_μ Data: **CCQE Cross Section**

The ν_μ CCQE data Q^2 distribution is fit to tune empirical parameters of the nuclear model (^{12}C target)



this results in good data-MC agreement for variables **not** used in tuning

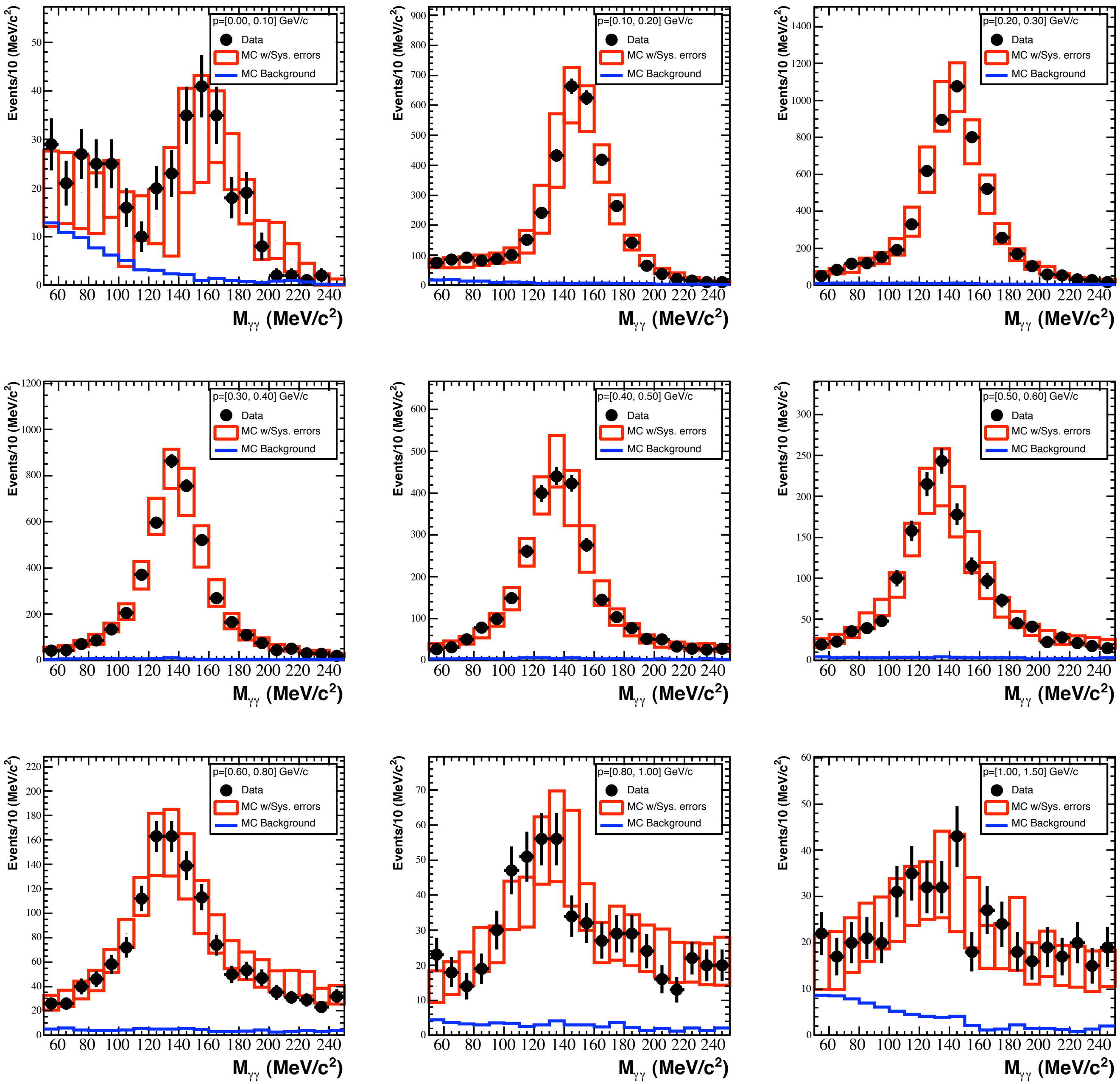


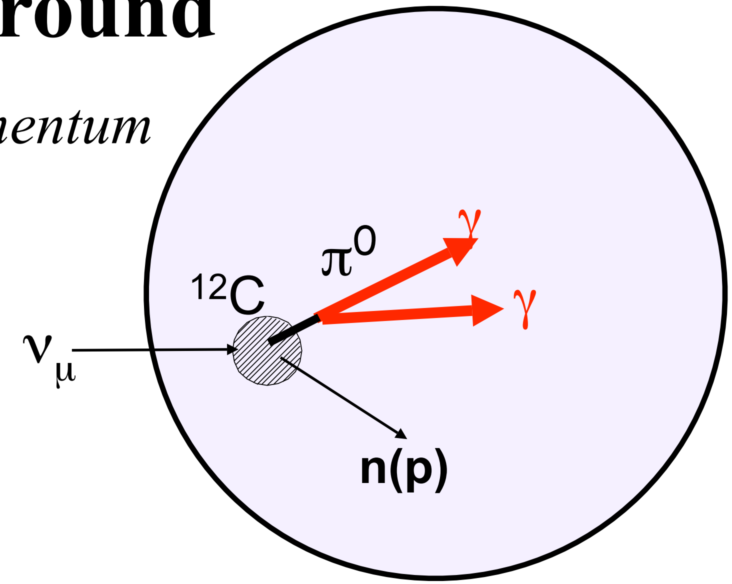
the tuned model is used for both ν_μ and ν_e CCQE

Analysis Strategy: π^0 Mis-ID Background

clean π^0 events are used to tune the MC rate vs. π^0 momentum

H. Tanaka



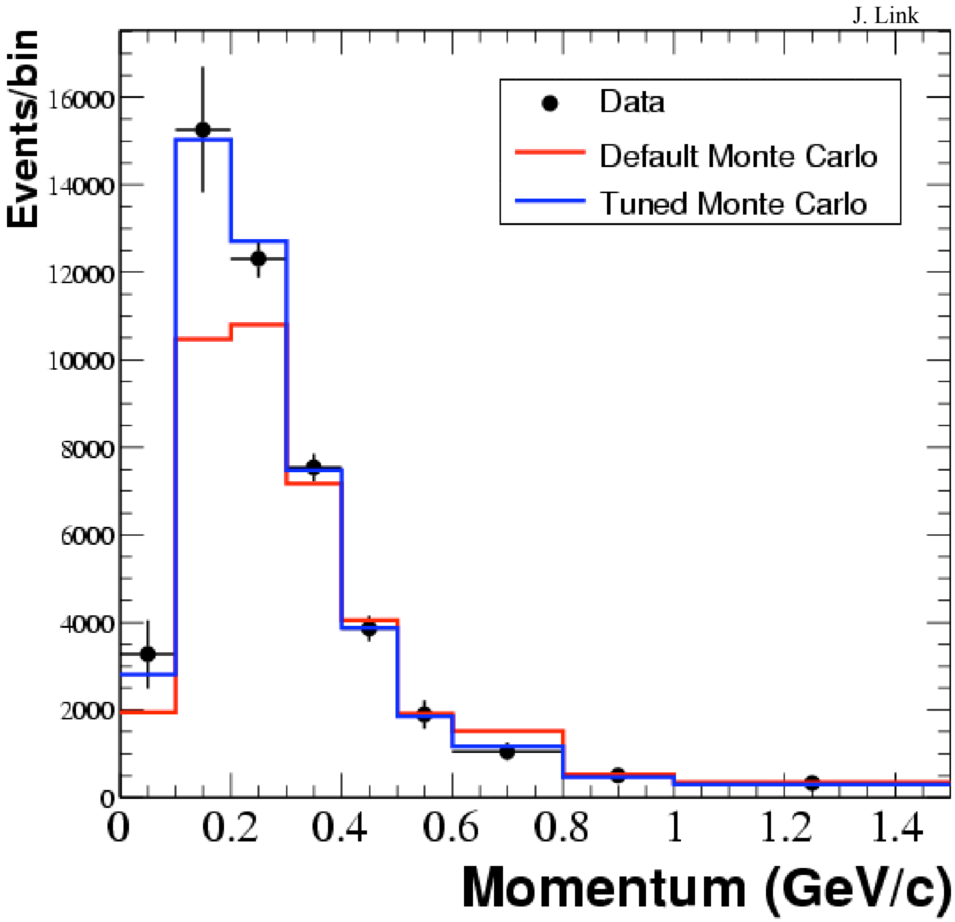


π^0 events can reconstruct outside of the mass peak when:

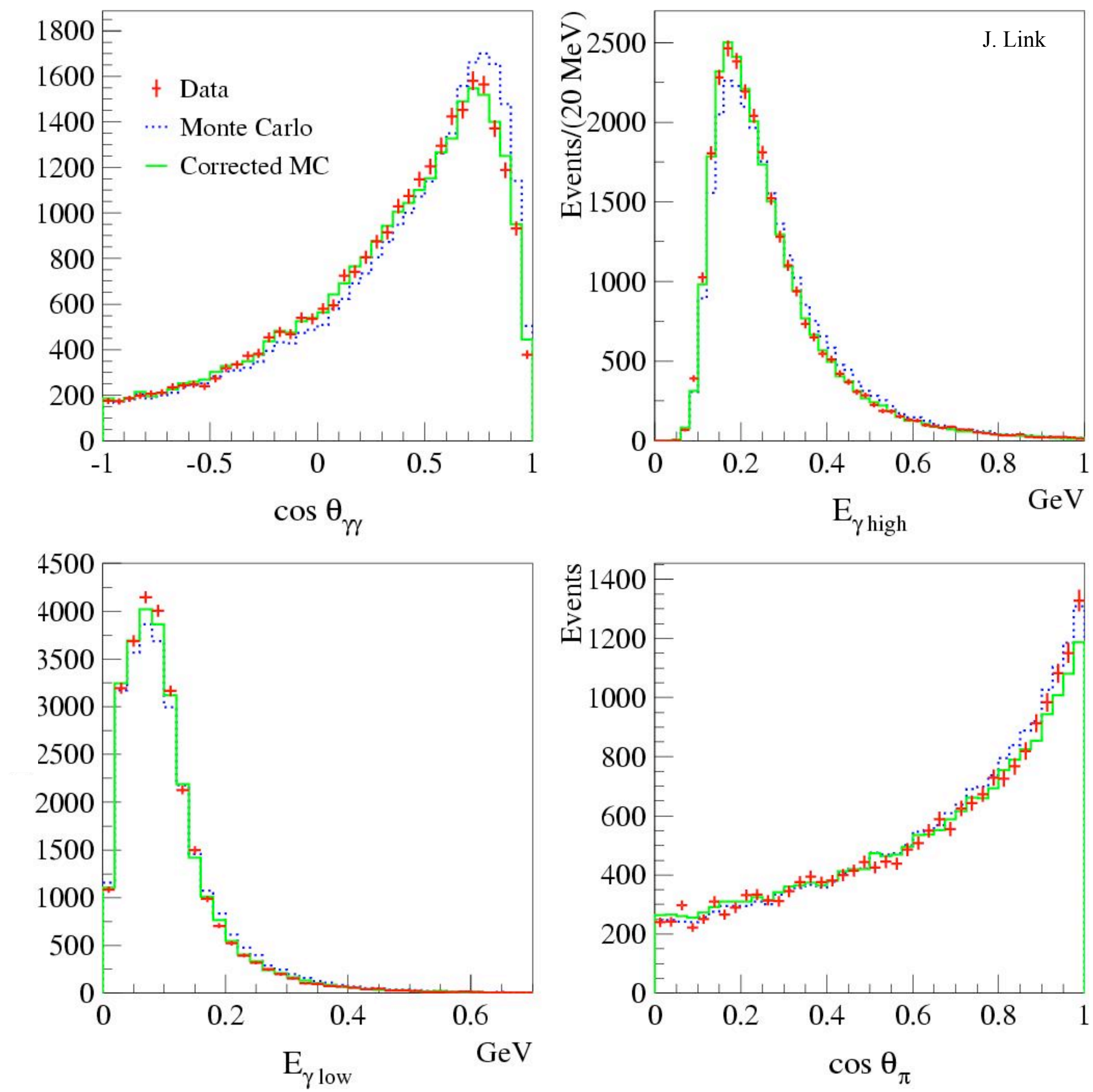
1. asymmetric decays fake 1 ring
2. 1 of the 2 photons exits the detector
3. high momentum π^0 decays produce overlapping rings

Analysis Strategy: π^0 Mis-ID Background

The MC π^0 rate (flux × xsec) is reweighted to match the measurement in p_π bins.



this procedure results in good data-MC agreement for variables **not** used in tuning



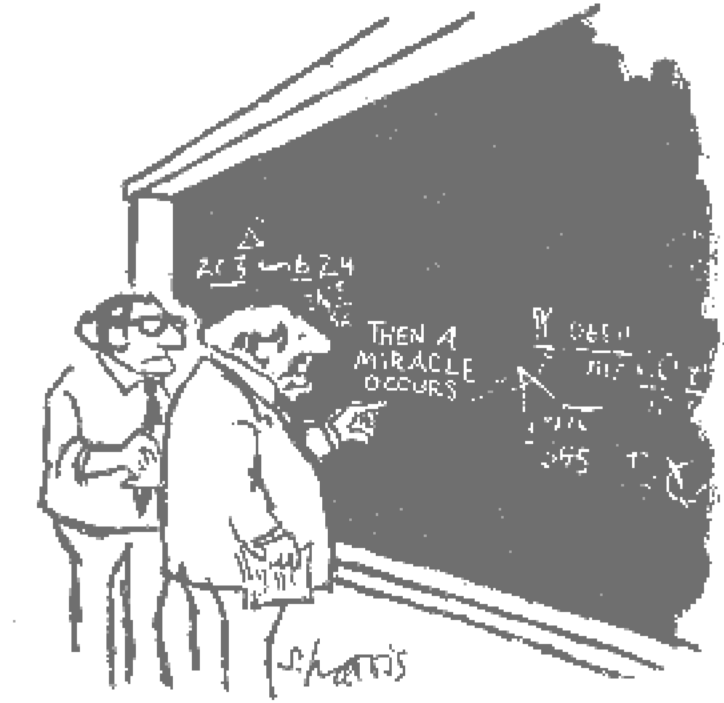
Because this constrains the Δ resonance rate, it also constrains the rate of Δ→Nγ in MiniBooNE

Analysis Overview: **Strategy**

in-situ data is incorporated wherever possible...

(i) MC tuning with calibration data
- energy scale
- PMT response
- optical model of light in the detector

(ii) MC fine-tuning with neutrino data
- cross section nuclear model parameters
- π^o rate constraint



"I think you should be more explicit here in step two."

(iii) constraining systematic errors with neutrino data
- ratio method example: ν_e from μ decay background
- combined oscillation fit to ν_μ and ν_e data

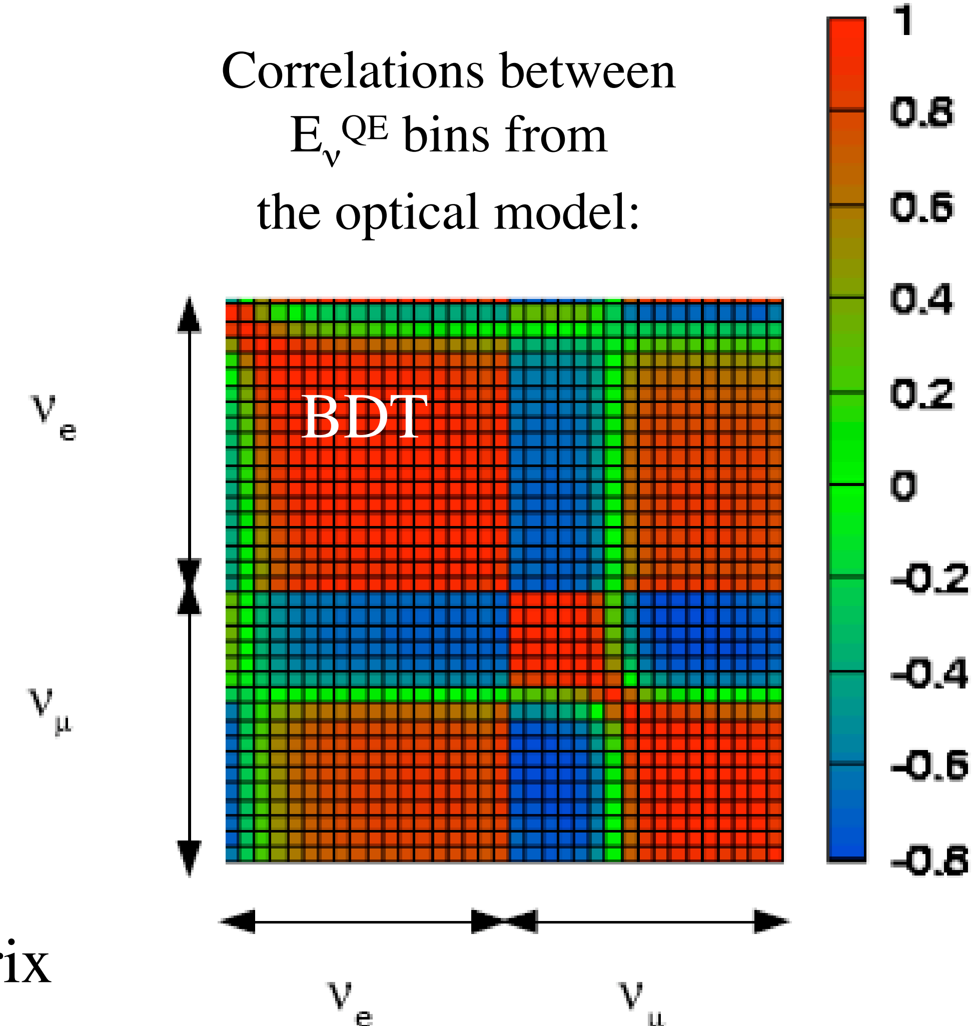
Analysis Strategy: Error Matrix

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

- N is number of events passing cuts
- MC is standard Monte Carlo
- α represents a different MC draw (*called a "multisim"*)
- M is the total number of MC draws
- i,j are E_ν^{QE} bins

Total error matrix is sum from each source.

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

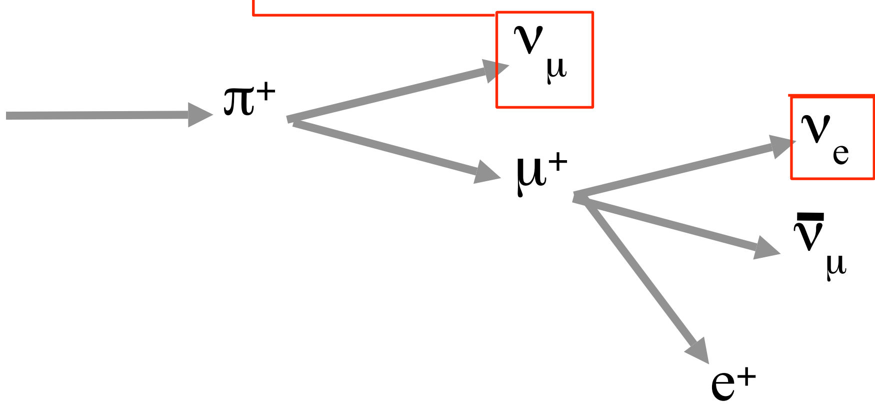


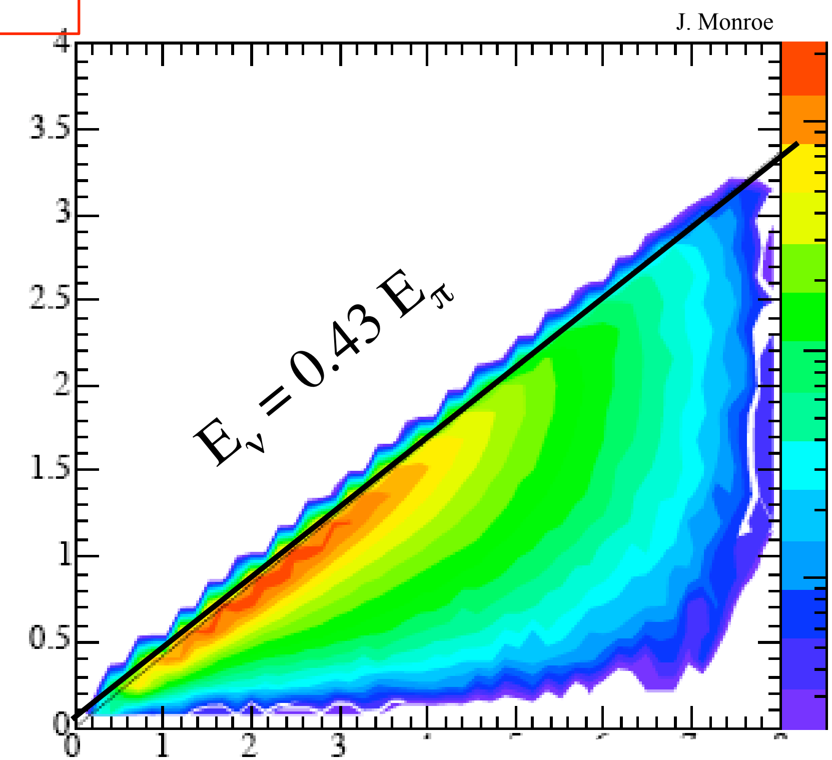
Primary (TB): ν_e-only total error matrix

Cross-check (BDT): ν_μ-ν_e total error matrix

Incorporating ν_μ Data: μ^+-Decay ν_e Background

ν_μ CCQE events measure the π^+ spectrum, this constrains the μ^+-decay ν_e flux





this works well because the ν_μ energy is highly correlated with the π^+ energy

Ratio Method Constraint:

1. MC based on external data predicts a central value and a range of possible $\nu_\mu(\pi)$ fluxes

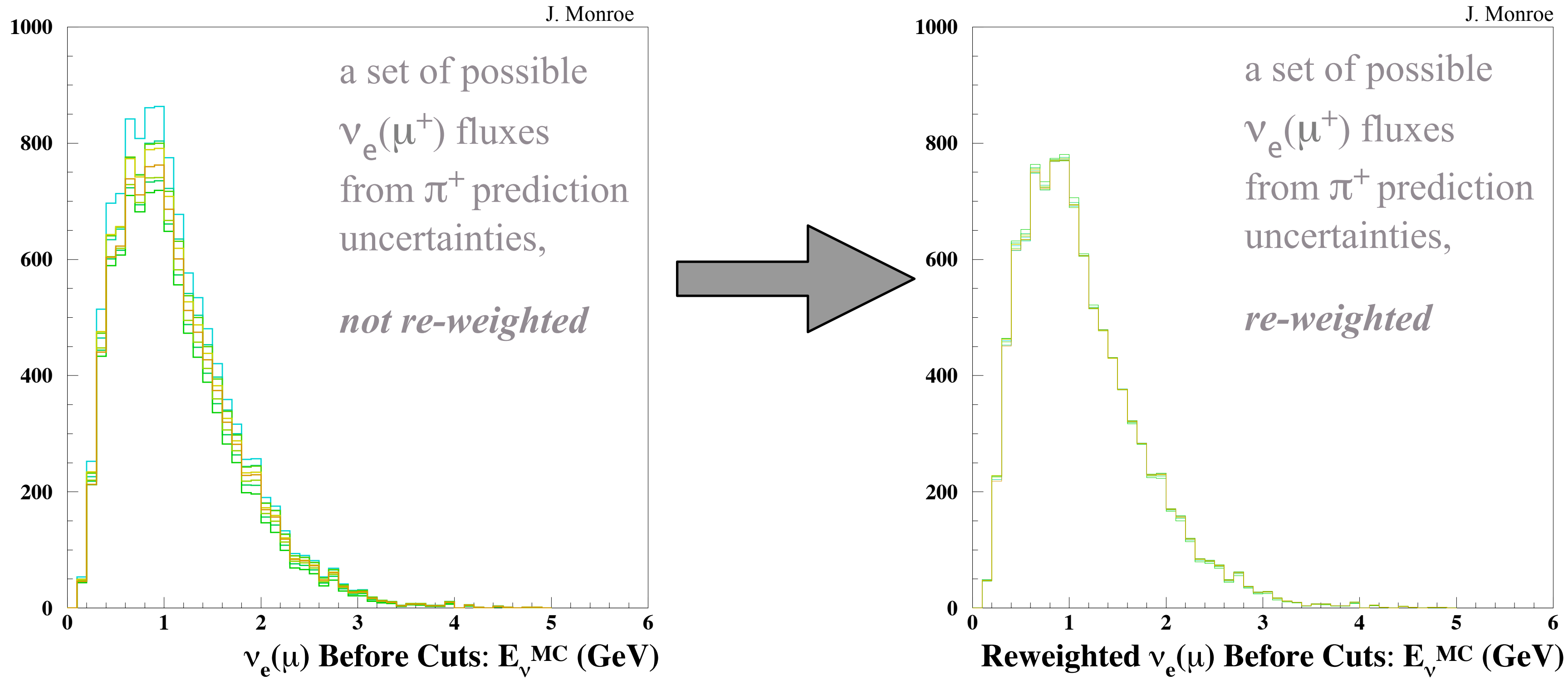
2. make Data/MC ratio vs. E_ν^{QE} for ν_μCCQE data

3. re-weight each possible MC flux by the ratio (2) including the ν_μ, its parent π^+, sister μ^+, and niece ν_e

Analysis Strategy 1: **Ratio Method**

Impact of re-weighting the simulation using "fake data" (MC):

$\nu_e(\mu^+)$:



this reduction in the spread of possible fluxes translates directly into a reduction in the μ^+-decay ν_e background uncertainty

Can use ratio method to constrain most BG sources

Analysis Strategy 2: **Combined Fit**

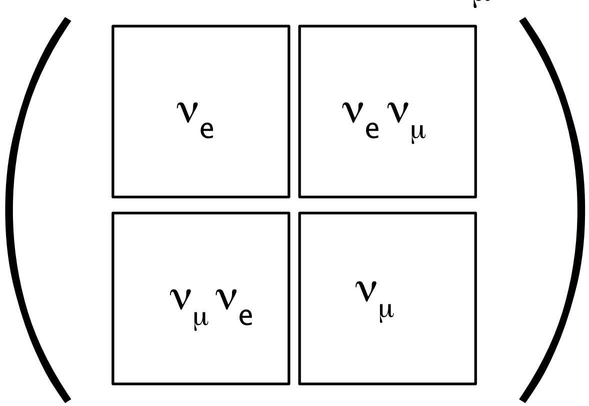
Fit the E_ν^{QE} distributions of ν_e and ν_μ events for oscillations, together

Raster scan in Δm^2 , and $sin^2 2\theta_{\mu e}$ ($sin^2 2\theta_{\mu x} == 0$),
calculate χ^2 value over ν_e **and** ν_μ bins

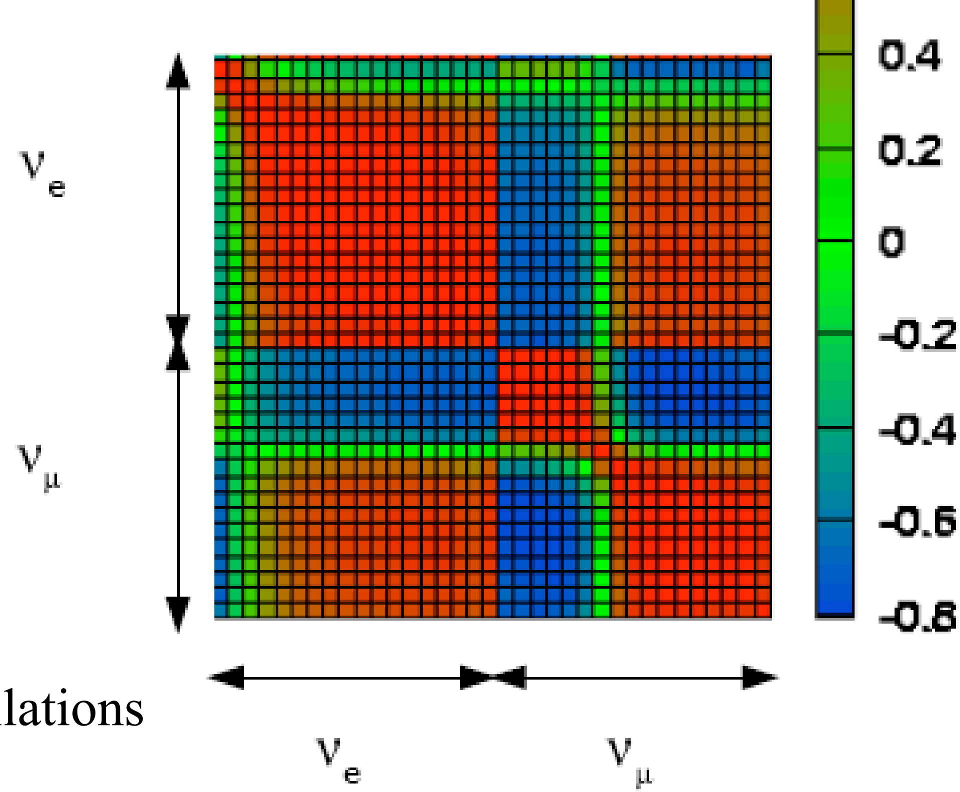
$$\chi^2 = \sum_{i=1}^{N_{bins}} \sum_{j=1}^{N_{bins}} (m_i - t_i)\, \mathcal{M}_{ij}^{-1}\, (m_j - t_j)$$

In this case, systematic error matrix M_{ij} includes predicted uncertainties for ν_e **and** ν_μ bins

M_{ij} =



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



Left: example, m_i = "fake data" = MC with no oscillations

a combined fit constrains uncertainties in common

Analysis Overview: **Systematic Errors**

A long list of systematic uncertainties are estimated using Monte Carlo:

<u>neutrino flux predictions</u>

- π^+, π^-, K^+, K^-, K^0, n, and p total and differential cross sections ☑
- secondary interactions of mesons ☑
- focusing horn current ☐
- target + horn system alignment ☐

<u>neutrino interaction cross section predictions</u>

- nuclear model ☑
- rates and kinematics for relevant exclusive processes ☑
- resonance width and branching fractions ☑

<u>detector modelling</u>

- optical model of light propagation in oil (39 parameters!) ☑
- PMT charge and time response ☑
- electronics response ☑
- neutrino interactions in dirt surrounding detector hall ☑

✓ ***Most** are constrained or checked using in-situ MiniBooNE data.*

Outline

1. Motivation & Introduction
2. Description of the Experiment
3. Analysis Overview
4. Two Independent Oscillation Searches
   - Reconstruction and Event Selection
   - Systematic Uncertainties
5. First Results

Two Independent Oscillation Searches: **Methods**

Method 1: Track-Based Analysis

Primary analysis

- *Use careful reconstruction of particle tracks*
- *Identify particle type by likelihood ratio*
- *Use ratio method to constrain backgrounds*

Strengths:

Relatively insensitive to optical model

Simple cut-based approach with likelihoods

Method 2: Boosted Decision Trees

Independent cross-check

- *Classify events using "boosted decision trees"*
- *Apply cuts on output variables to improve separation of event types*
- *Use combined fit to constrain backgrounds*

Strengths:

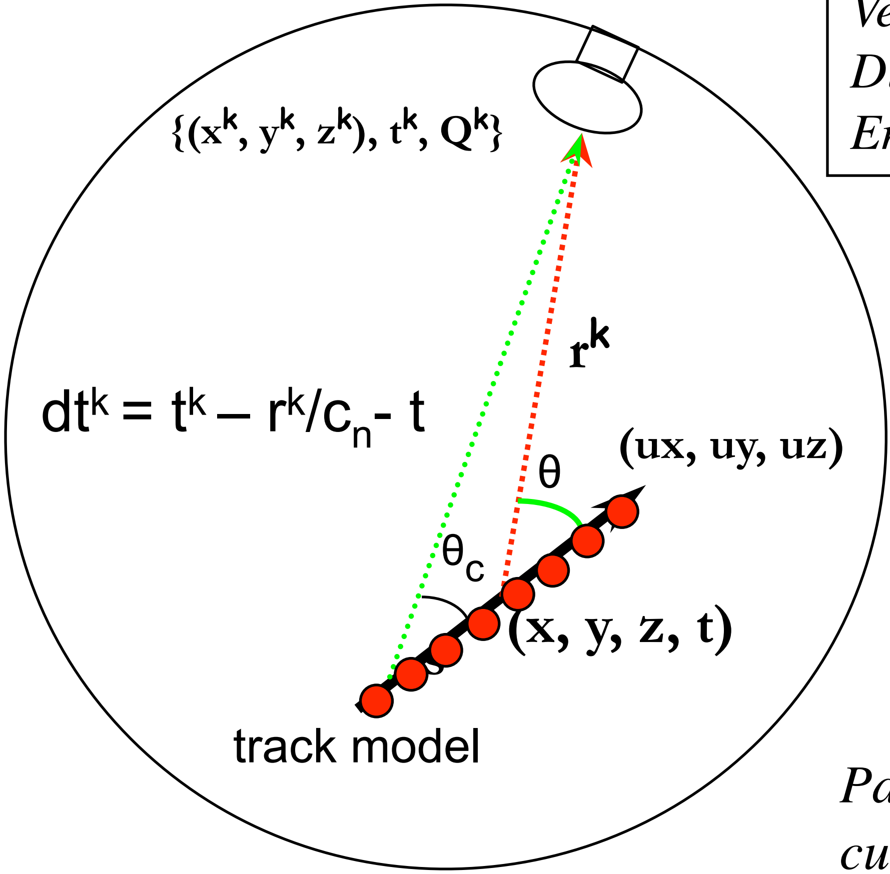
Combination of many weak variables form strong classifier

Better constraints on background events

Method 1: Track-Based Analysis

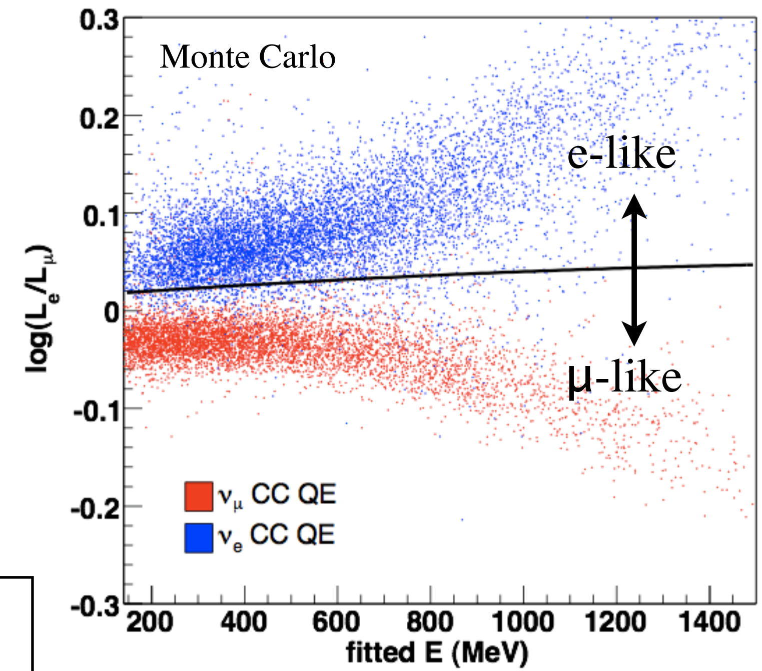
Reconstruction fits an extended light source with 7 parameters: vertex, direction (θ, ϕ), time, energy

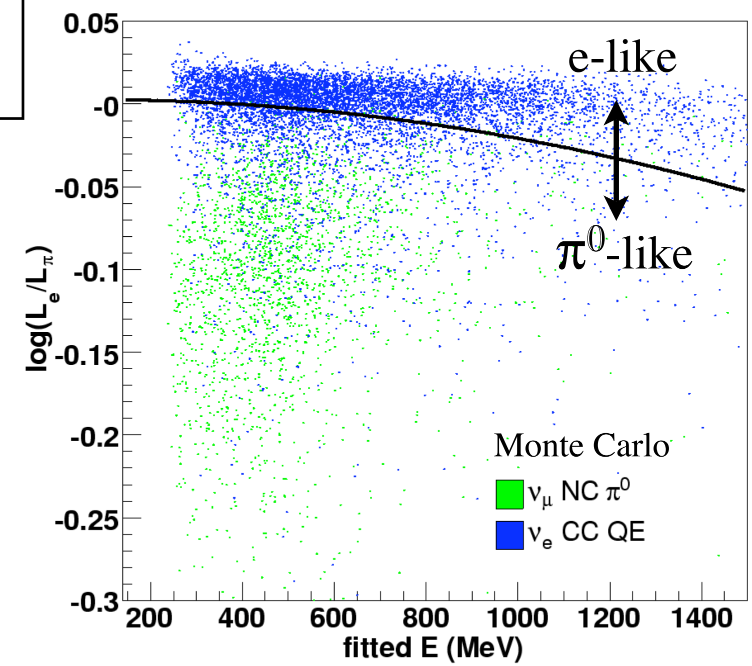
Fit events under 3 possible hypotheses:
μ-like, e-like, two track (π^0-like)



Fitter resolution

Vertex:	22 cm
Direction:	2.8°
Energy:	11%

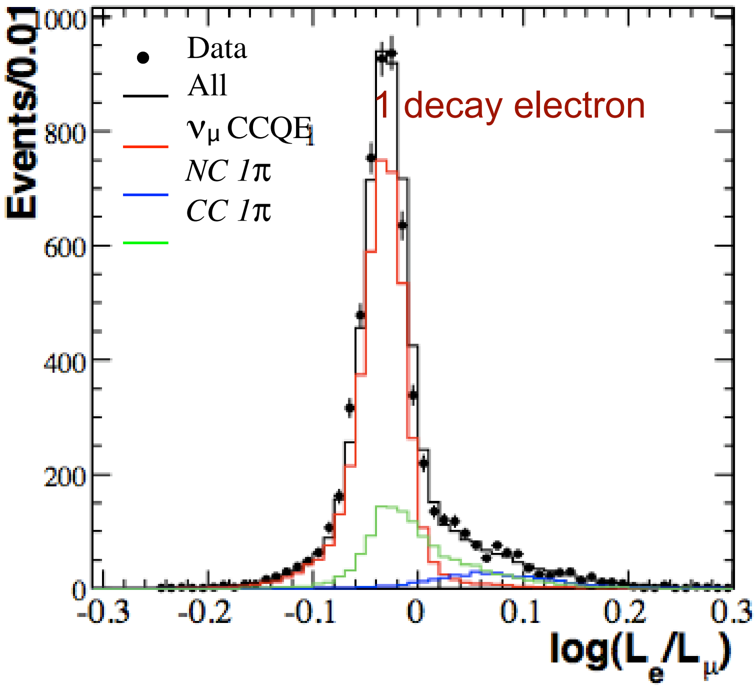




Particle ID relies on likelihood ratio cuts to select ν_e, cuts chosen to maximise sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillation

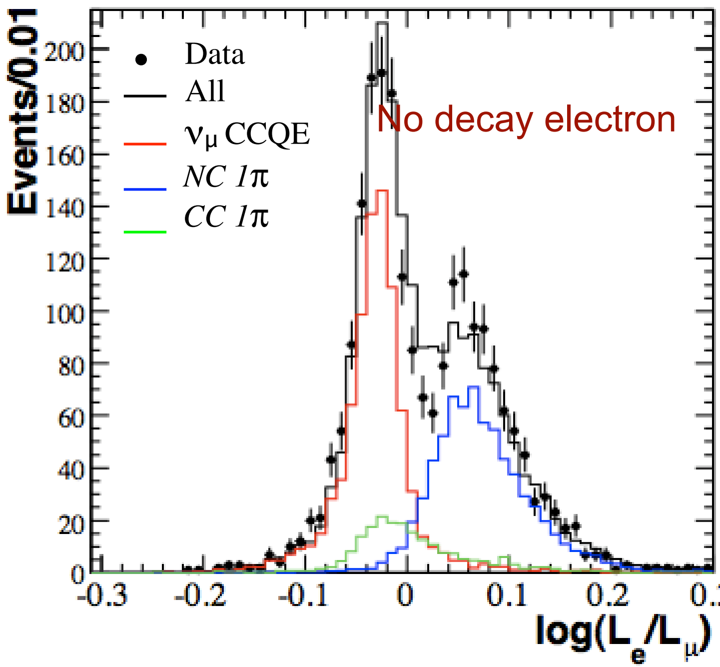
Track-Based Analysis: e/μ Likelihood

Test μ-e separation on data:



ν_μ CCQE data sample

Pre-selection cuts
Fiducial volume: (R < 500 cm)
2 subevents: muon + decay electron



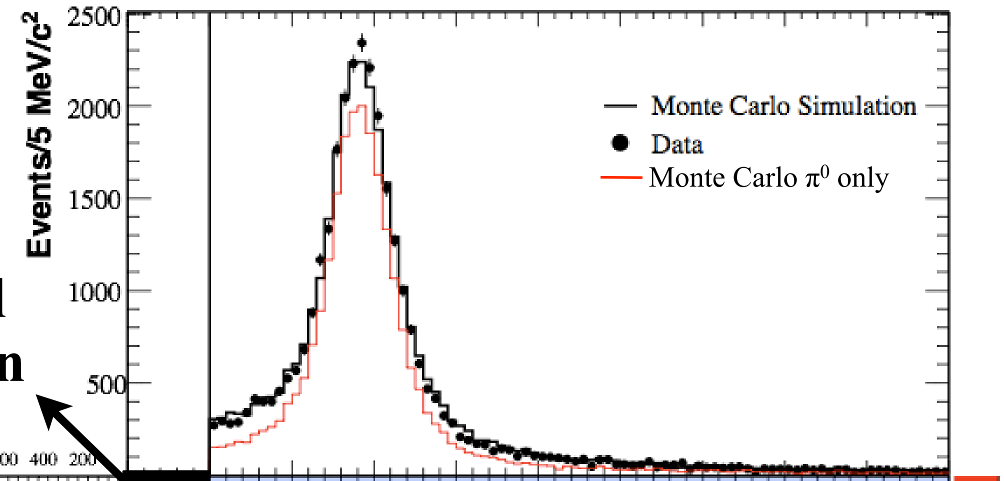
"All-but-signal" data sample

Pre-selection cuts
Fiducial volume: (R < 500 cm)
1 subevent: 8% of muons capture on ^{12}C

Events with $\log(L_e/L_\mu) > 0$ *(e-like) undergo additional fit with two-track hypothesis.*

Track-Based Analysis: e/π^0 Likelihood

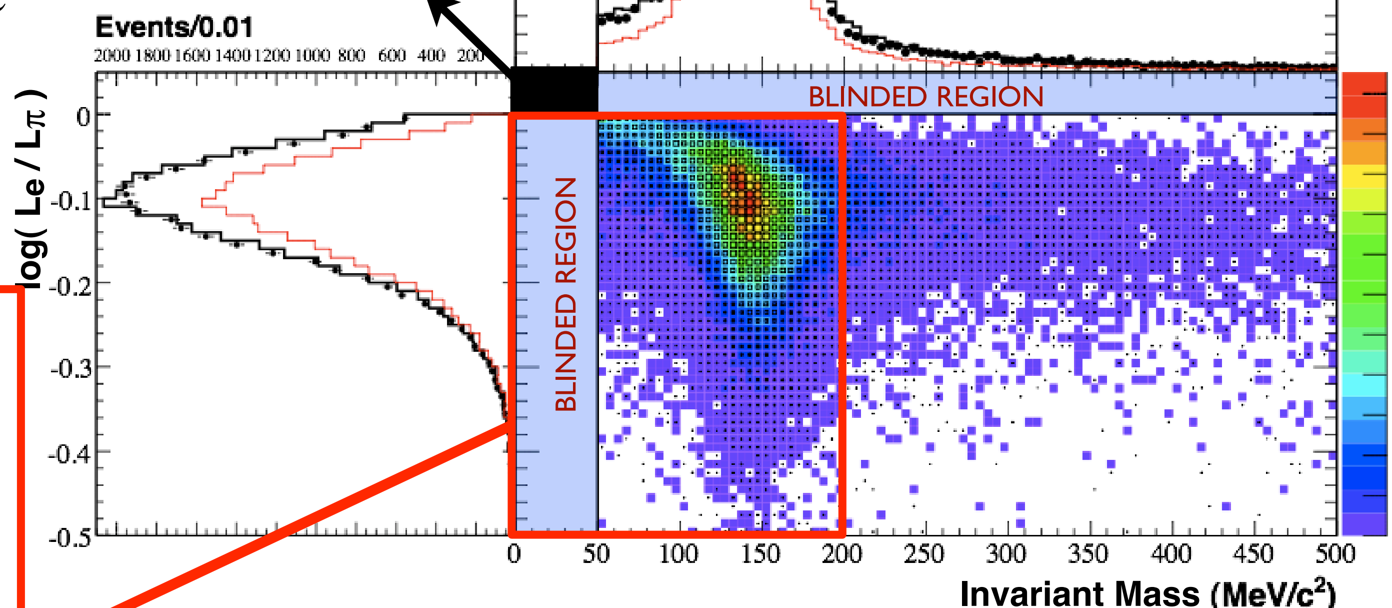
Test e-π^0 separation on data:

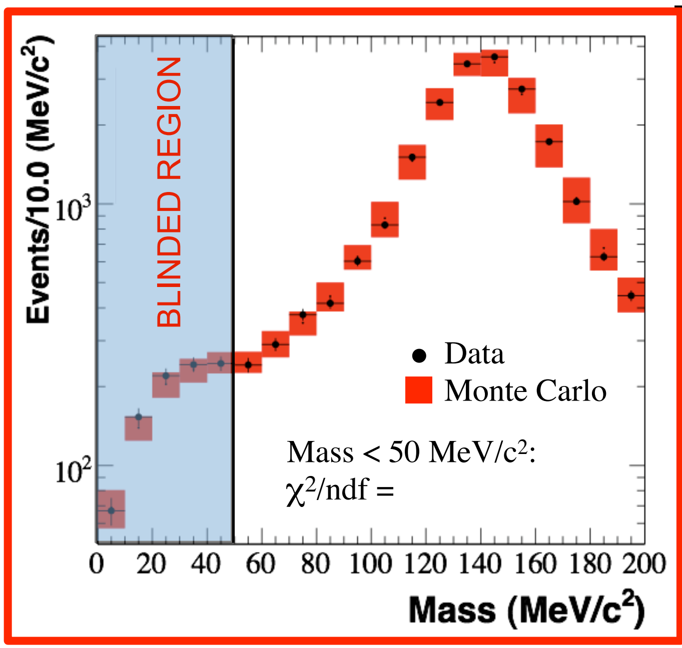


<u>"All-but-signal" data sample</u>

- Pre-selection cuts
- Fiducial volume cut (R < 500 cm)
- 1 subevent
- Invariant mass > 50 MeV/c^2
- $\log(L_e / L_\pi) < 0$ (π-like)

Signal Region





<u>Tighter selection cuts:</u>

- Invariant mass < 200 MeV/c^2
- $\log(L_e / L_\mu) > 0$ (e-like)
- $\log(L_e / L_\pi) < 0$ (π-like)

Method 2: Boosted Decision Trees

Decision Trees: A machine-learning technique which tries to recover signal events that would be eliminated in cut-based analyses.

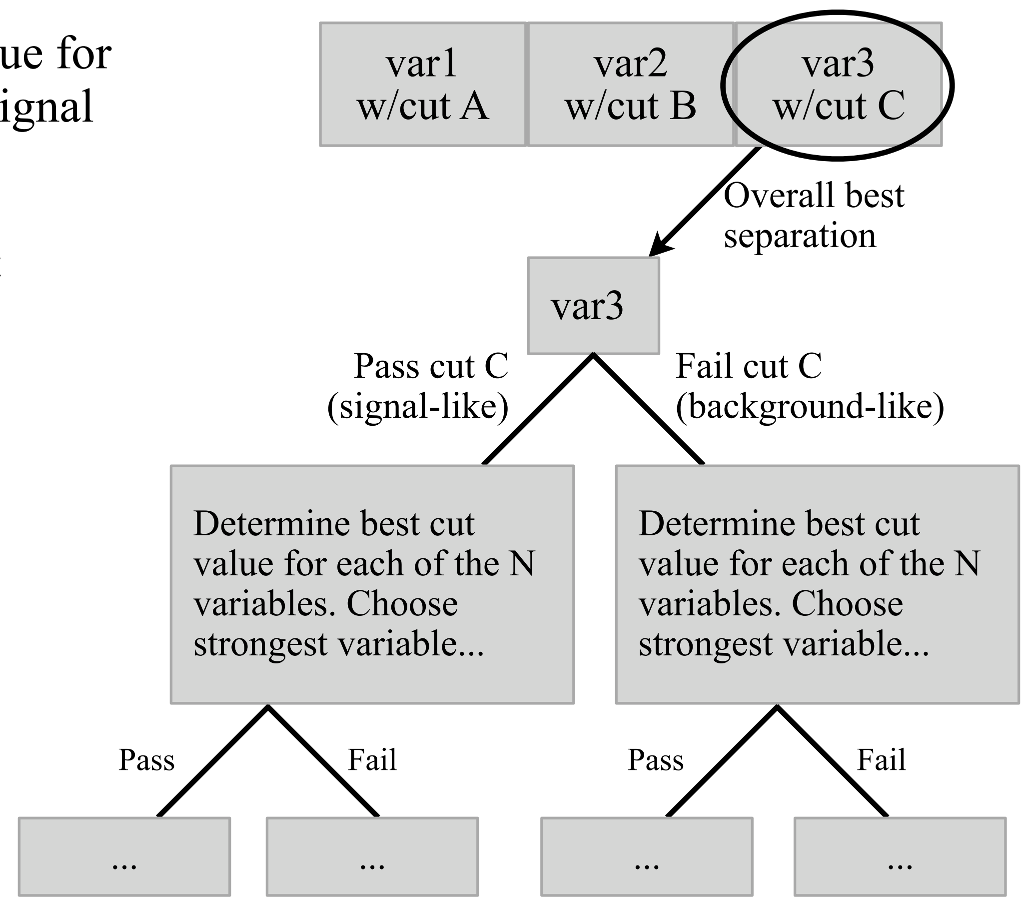
Training a decision tree:

Step 1: For a set of N variables, determine the cut value for each variable that gives the best separation between signal and background.

Step 2: Choose the variable with the overall strongest separation; divide the events between two branches:
  Events which passed the cut (classified as “signal”)
  Events which failed the cut (classified as “background”)

Steps 3-n: Repeat recursively for each node...
  Stop when reach min. purity or max. iterations
  (Stopping points called “leaves” or “terminal nodes”)

Final score: For each leaf,
  - 1 for events on a “background-like” leaf
  +1 for events on a “signal-like” leaf

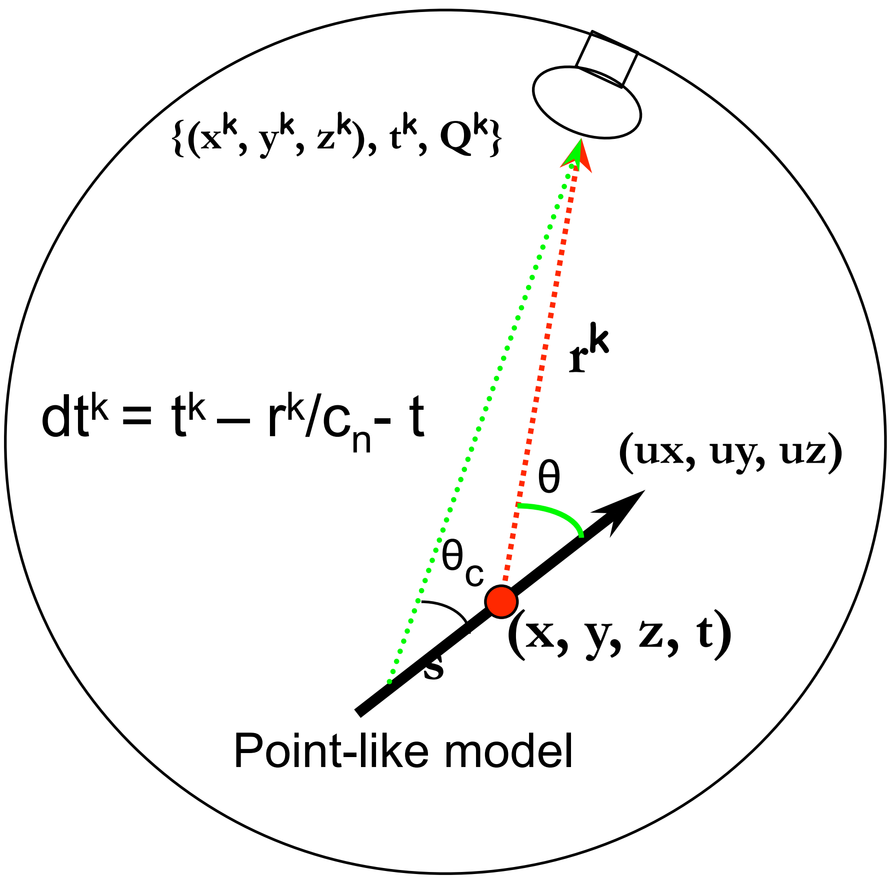


Boosting: Give a new weight to all events in leaves of decision tree; misclassified events receive a stronger weight. Re-training the decision tree with newly weighted events improves performance.

B.P. Roe, et al., NIM A543 (2005) 577.
H. Yang, B.P. Roe, J. Zhu, NIM A555 (2005) 370

Boosted Decision Trees: **Reconstruction and Particle ID**

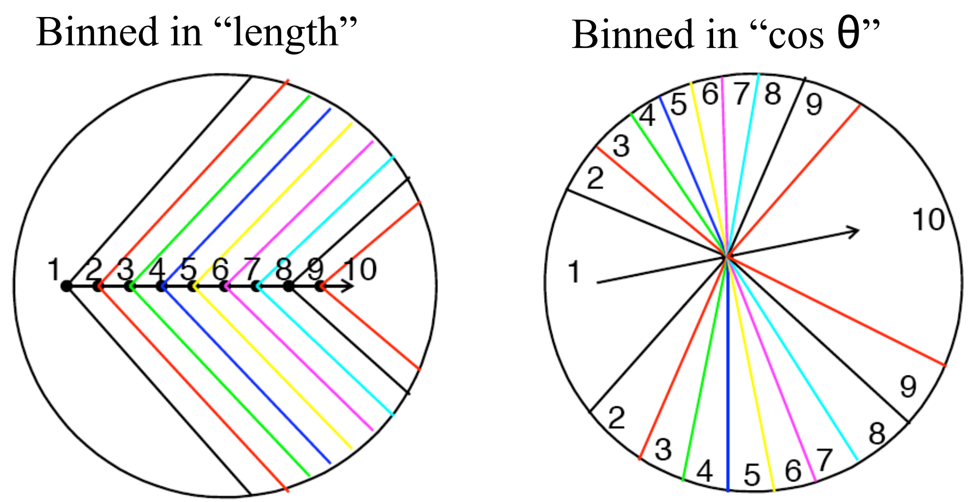
Reconstruction fits a point-like light source:
vertex, direction (θ, ϕ), time, energy



Fitter resolution

Vertex:	24 cm
Direction:	3.8°
Energy:	14%

Characterize topology of each event by dividing detector into "bins" relative to track:



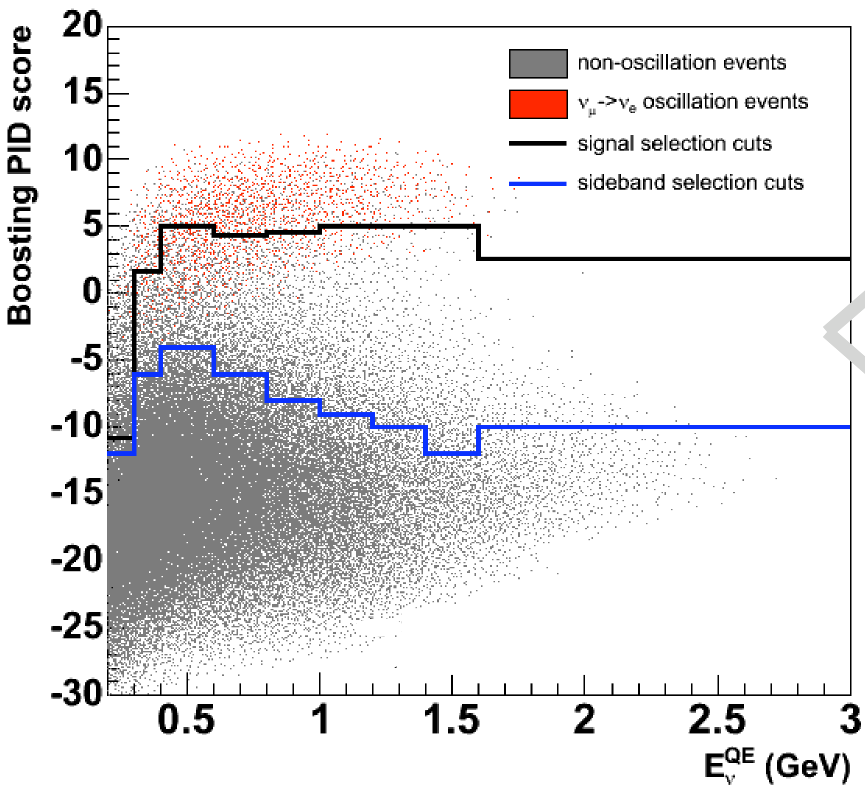
Particle ID "input variables" for the boosted decision trees are created from basic quantities in each bin: *e.g.*, charge, number of hits...

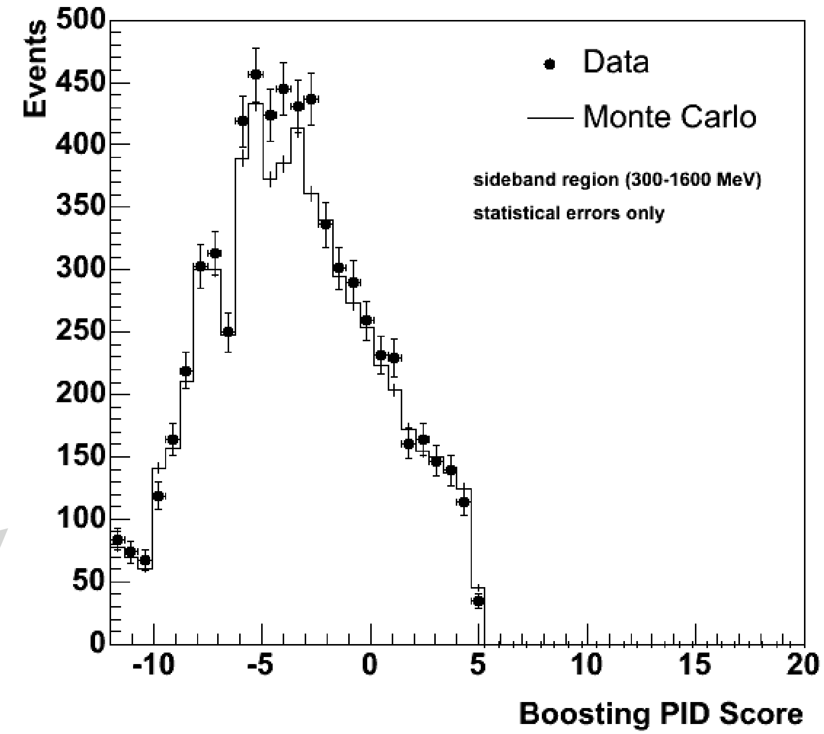
To select events, a particle ID cut is made on the Boosting output score.

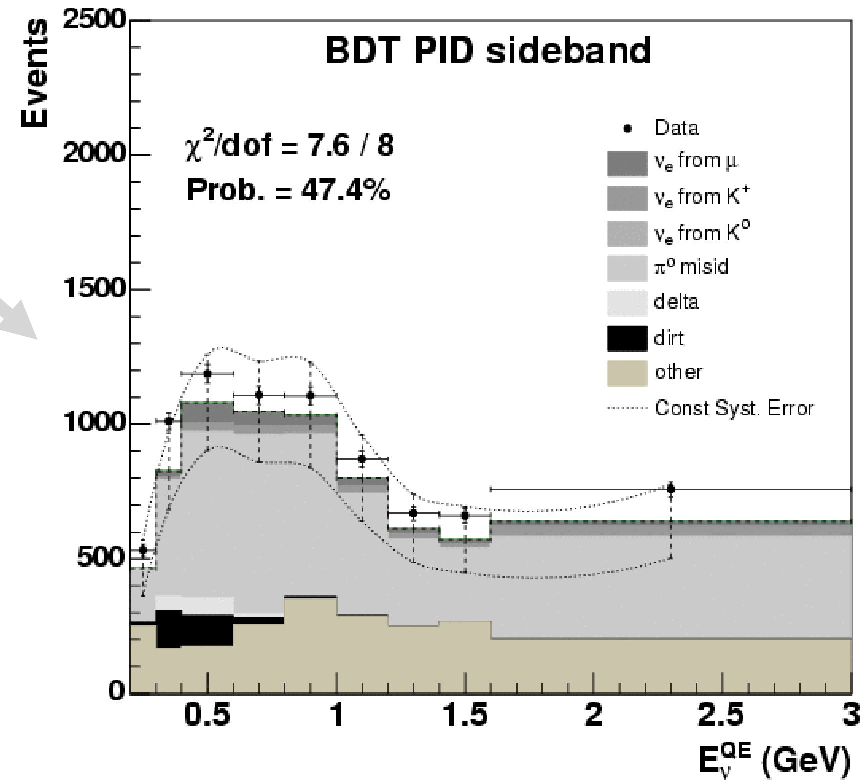
Boosted Decision Trees: **Particle ID**

A sideband region is selected to validate MC in region near signal.

Sideband contains mostly mis-identified π^0 background events.





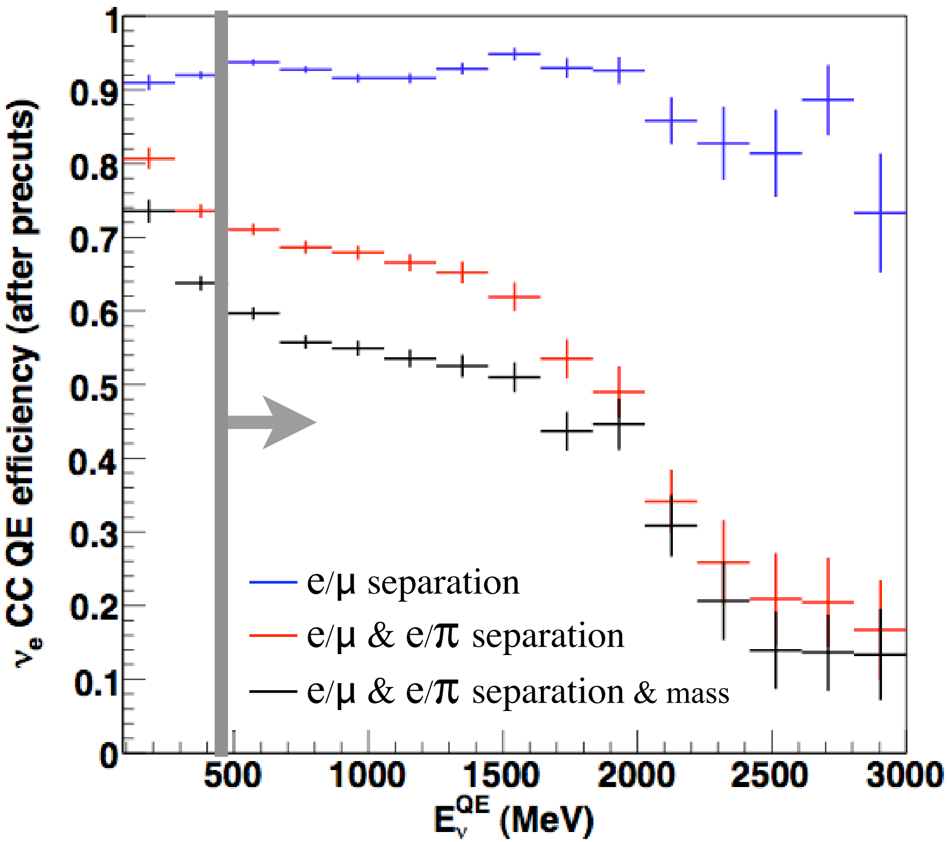


A χ^2 is calculated using the full systematic error matrix, data and MC are consistent.

Comparison: Efficiencies

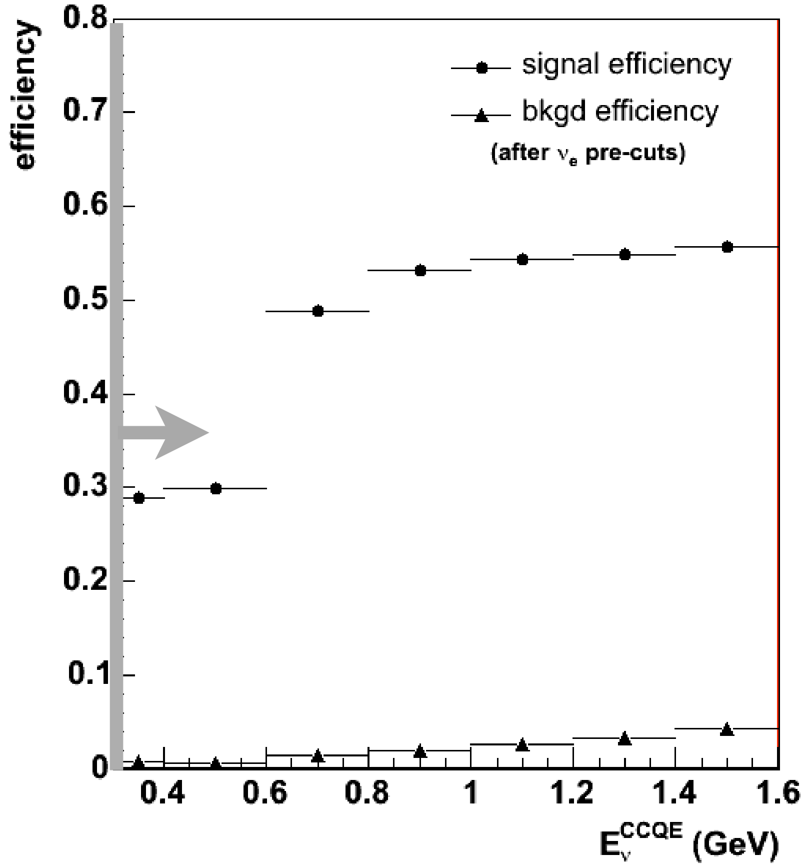
The two analyses have different event selection efficiency vs. energy trends,

<u>Track-Based Analysis</u>



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

<u>Boosting Analysis</u>



$E_\nu^{QE} > 300$ MeV

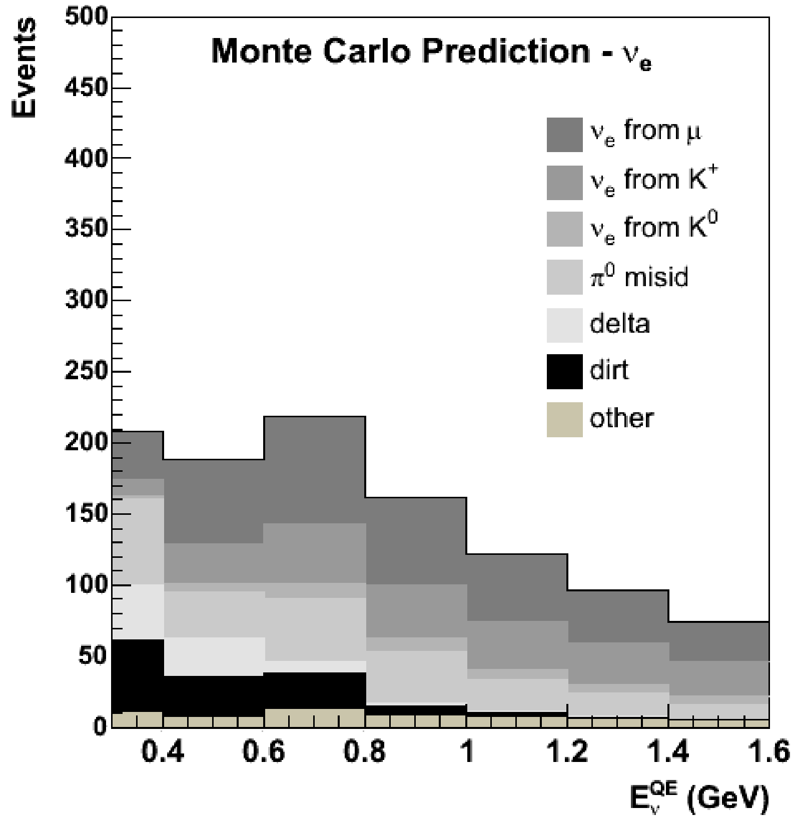
and different reconstructed E_ν regions for the oscillation analyses.

Comparison: Backgrounds

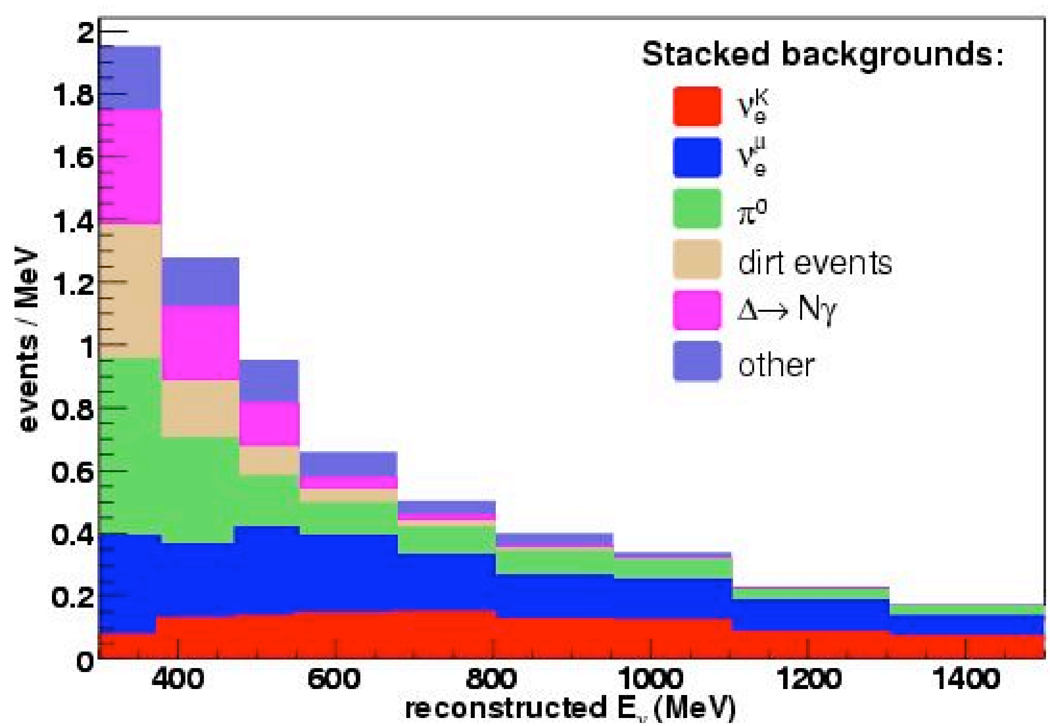
Source	T-B	B
ν_e *from* μ *decay*	0.37	0.32
ν_e *from K decay*	0.26	0.24
π^0 *mis – ID*	0.17	0.21
$\Delta \rightarrow N\gamma$	0.06	0.07
Dirt	0.05	0.11
Other	0.09	0.05

The two analyses have somewhat different background compositions.

Boosting Analysis



Track-Based Analysis



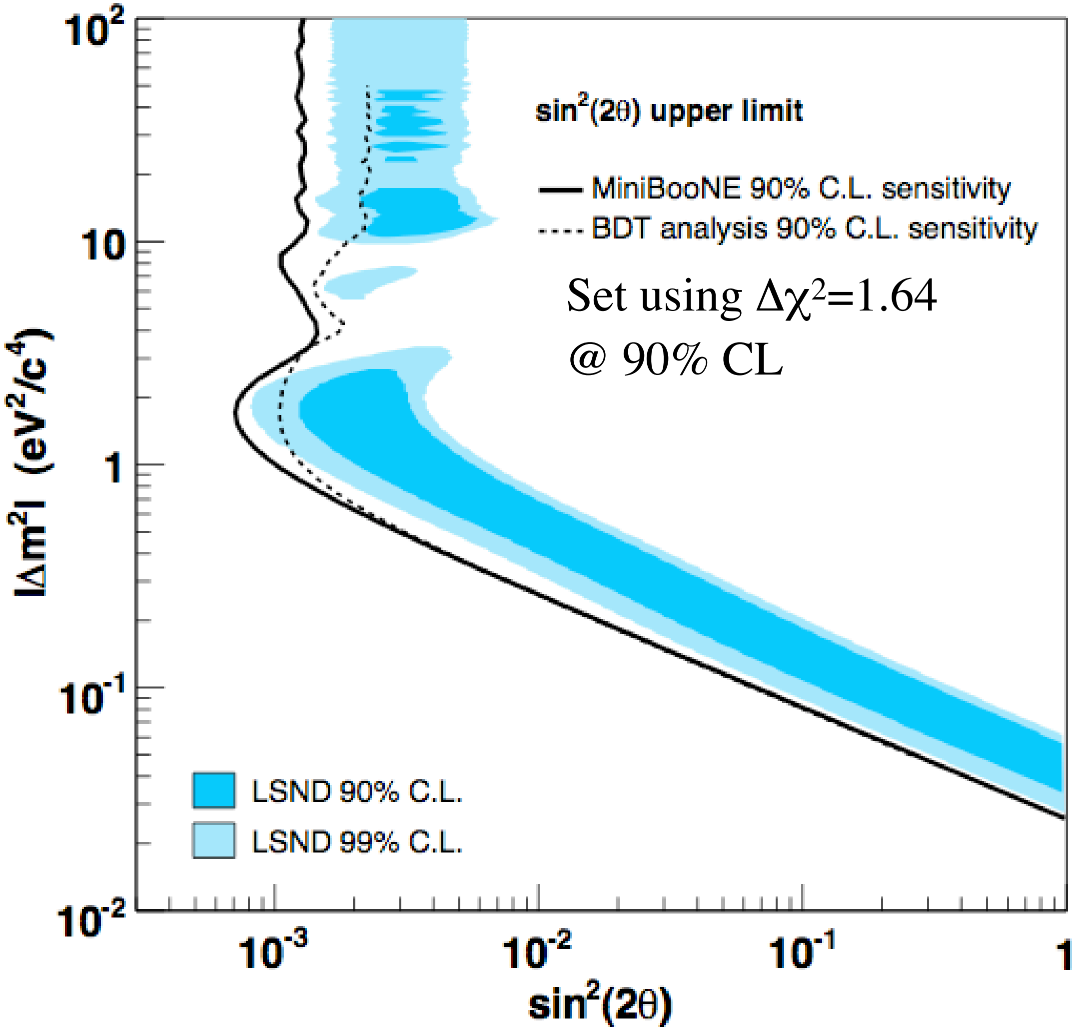
Comparison: Systematic Errors

Both analyses construct error matrices for the oscillation fit, binned in E_ν, to estimate the uncertainty on the expected number of ν_e background events.

	source	*track-based (%)*	*boosting (%)*
√	Flux from π^+/μ^+ decay	6.2	4.3
√	Flux from K^+ decay	3.3	1.0
√	Flux from K^0 decay	1.5	0.4
	Target and beam models	2.8	1.3
√	ν-cross section	12.3	10.5
	NC π^0 yield	1.8	1.5
	External interactions	0.8	3.4
√	Optical model	6.1	10.5
	DAQ electronics model	7.5	10.8
	constrained total	9.6	14.5

Note:
"total" is **not** the quadrature sum-- errors are further reduced by fitting with ν_μ data √

Comparison: **Sensitivity**



Fit the Monte Carlo E_ν^{QE} event distributions for oscillations

Raster scan in Δm^2, and $sin^2 2\theta_{\mu e}$ (*assume* $sin^2 2\theta_{\mu x} == 0$), calculate χ^2 value over E_ν bins

$$\chi^2 = \sum_{i=1}^{N_{bins}} \sum_{j=1}^{N_{bins}} (m_i - t_i)\, \mathcal{M}_{ij}^{-1}\, (m_j - t_j)$$

m_i = Number of measured data events in bin i

t_i = Number of predicted events in bin i

(t_i events are a function of Δm^2, $\sin^2 2\theta$,

M_{ij}^{-1} = Inverse of the covariance matrix

Since the track-based analysis achieved better sensitivity than the boosted decision tree analysis, we decided (before opening the box) that it would be used for the primary result.

Outline

1. Motivation & Introduction
2. Description of the Experiment
3. Analysis Overview
4. Two Independent Oscillation Searches
5. First Results

Results: Opening the Box

After applying all analysis cuts:

Step 1: Fit sequestered data to an oscillation hypothesis

Fit does not return fit parameters

Unreported fit parameters applied to MC; diagnostic variables compared to data

Return only the χ^2 of the data/MC comparisons (for diagnostic variables only)

Step 2: Open plots from Step 1 (Monte Carlo has unreported signal)

Plots chosen to be useful diagnostics, without indicating if signal was added (reconstructed position, direction, visible energy...)

Step 3: Report only the χ^2 for the fit to E_ν^{QE}

No fit parameters returned

Track-Based
χ^2 Probability: 99%
Boosting
χ^2 Probability: 62%

Step 4: Compare E_ν^{QE} for data and Monte Carlo,

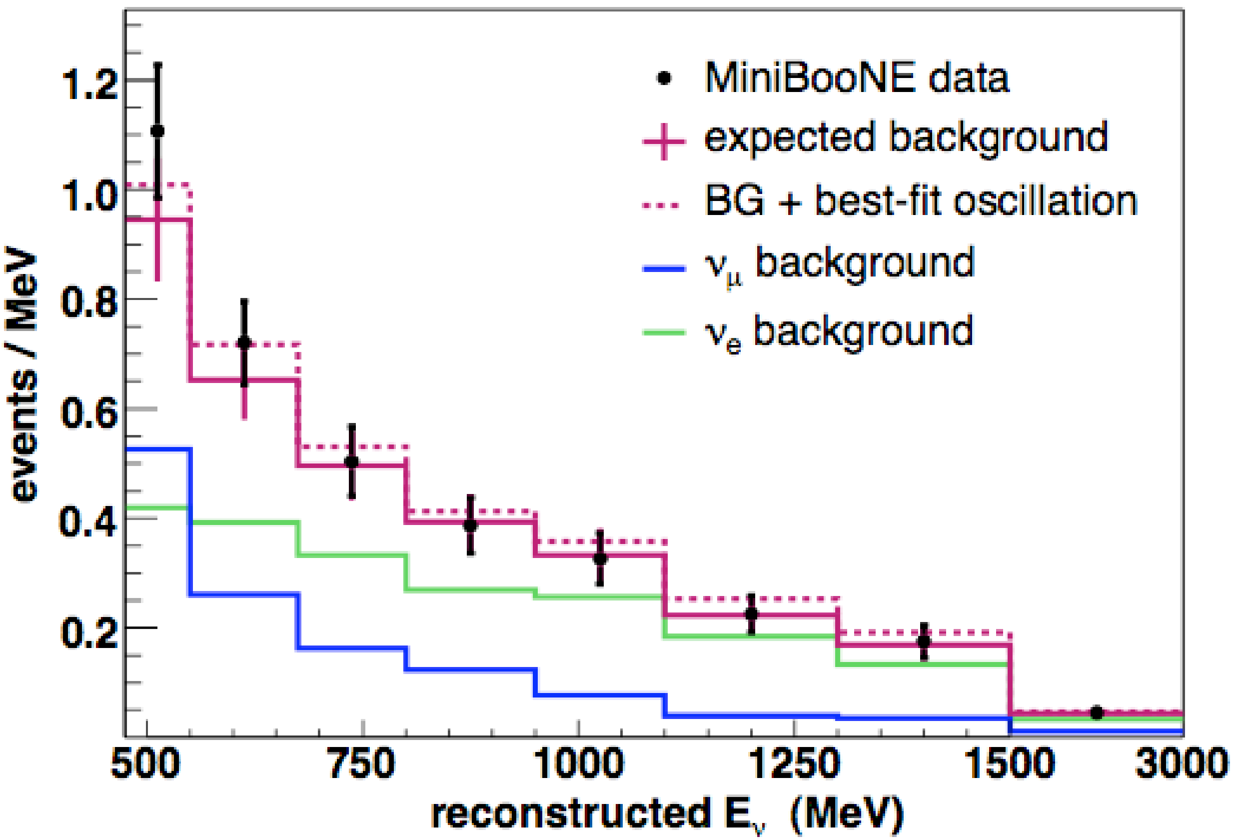
Fit parameters **are** returned

At this point, the box is open (March 26, 2007)

Step 5: Present results two weeks later (today!)

The Box Opening

Results: Track Based Analysis



We observe no significant evidence for an excess of ν_e events in the energy range of the analysis.

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

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

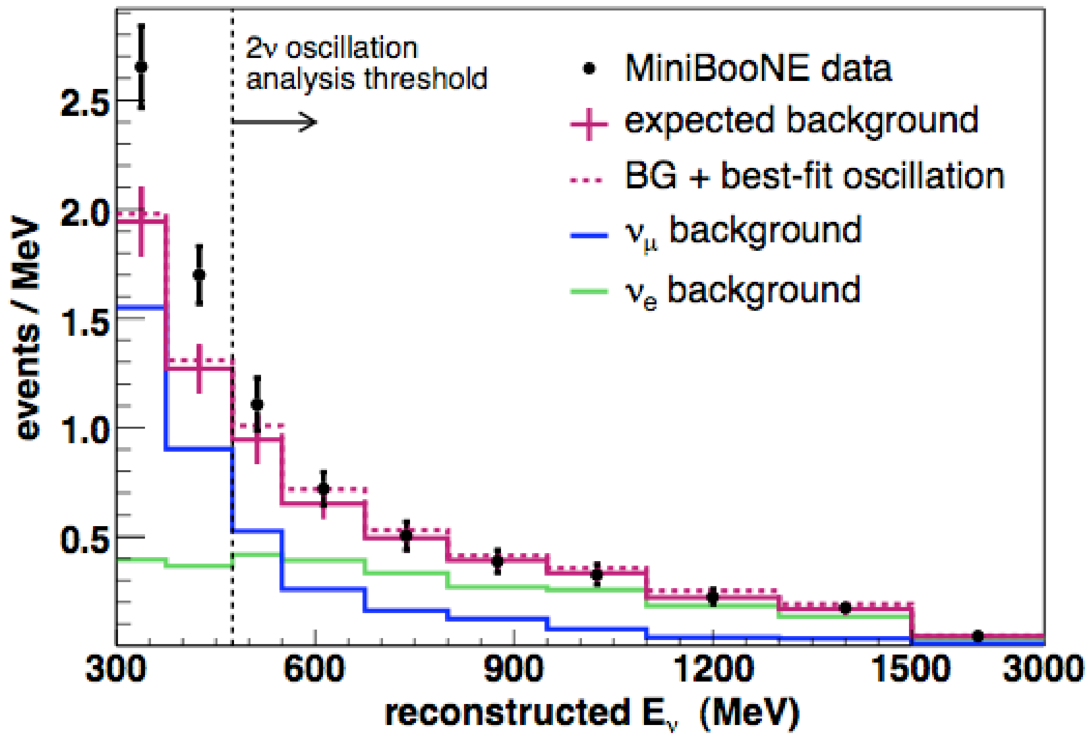
data:	380
expectation:	358 ±19 (stat) ± 35 (sys)

significance:
0.55 σ

χ^2 probability of best-fit point: 99%

χ^2 probability of null hypothesis: 93%

Results: Track Based Analysis, Lower Energy Threshold



Extending down to energies below the analysis range: E_ν^{QE}> 300 MeV

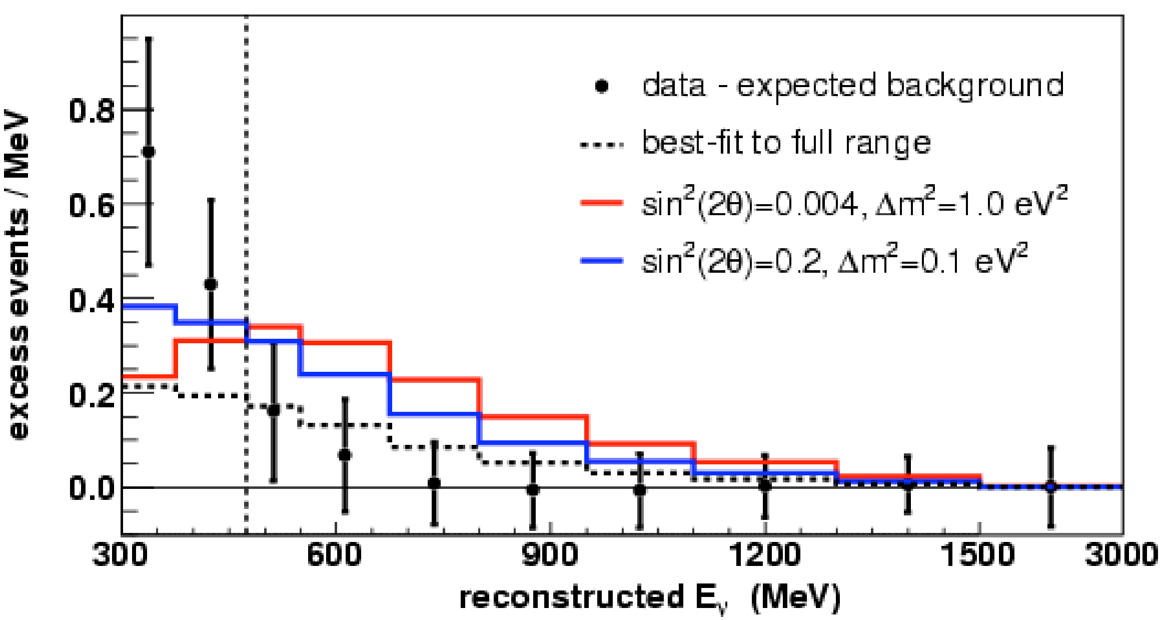
(we agreed to report this before box opening)

Data deviation for

$300<E_\nu^{QE}<475$ MeV: 3.7σ

Oscillation fit to E_ν^{QE}> 300 MeV:

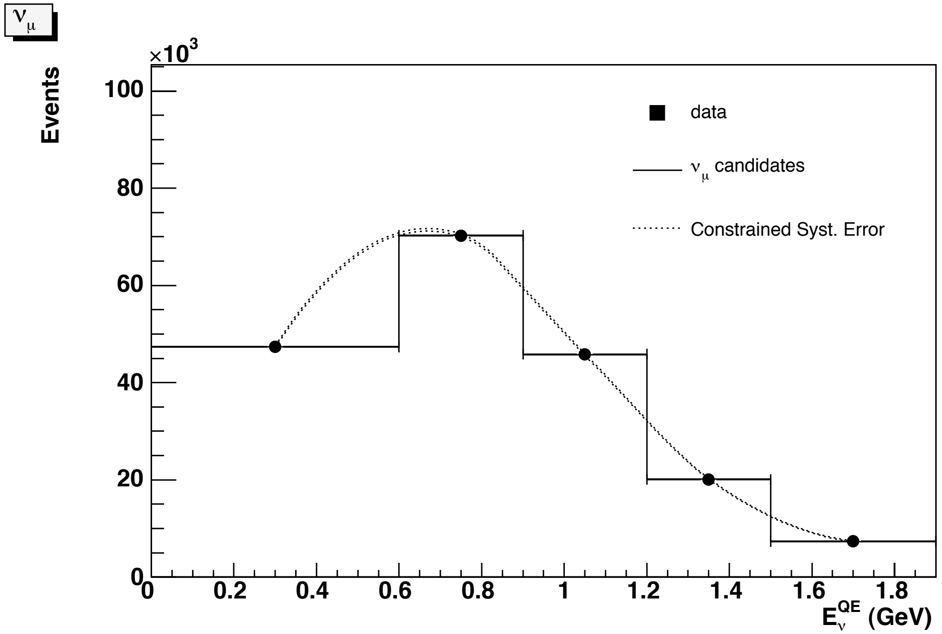
Best Fit ($\sin^2 2\theta$, Δm^2) = (1.0, 0.03 eV^2)



χ^2 probability at best-fit point: 18%

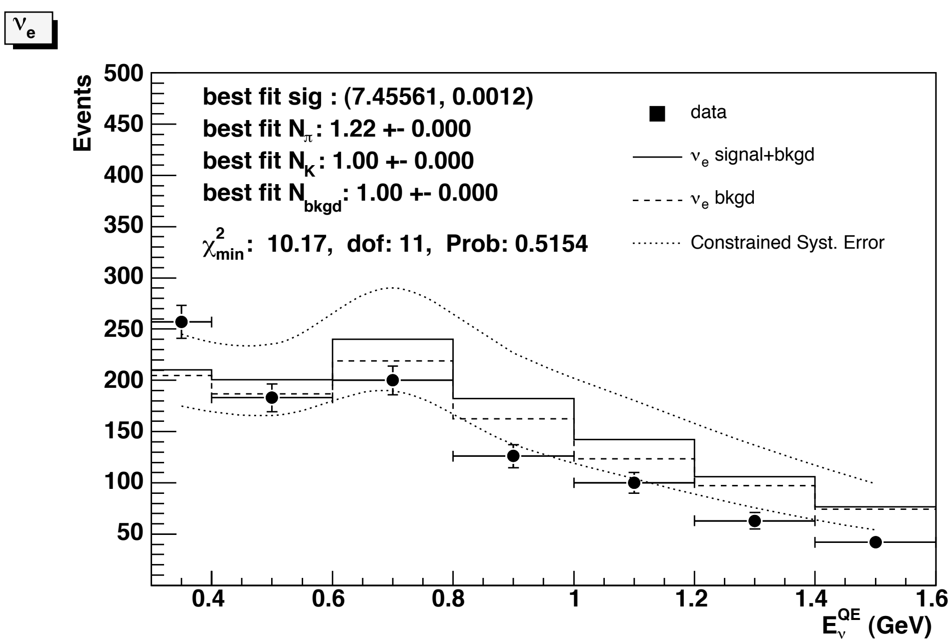
Fit is inconsistent with $\nu_\mu \rightarrow \nu_e$ oscillations.

Results: Boosted Decision Tree Analysis



We observe no significant evidence for an excess of ν_e events in the energy range of the analysis.

<u>Counting Experiment</u>:
$300 < E_\nu^{QE} < 1500$ MeV
data: **971**
expectation: **1070 ±33 (stat) ± 225(sys)**



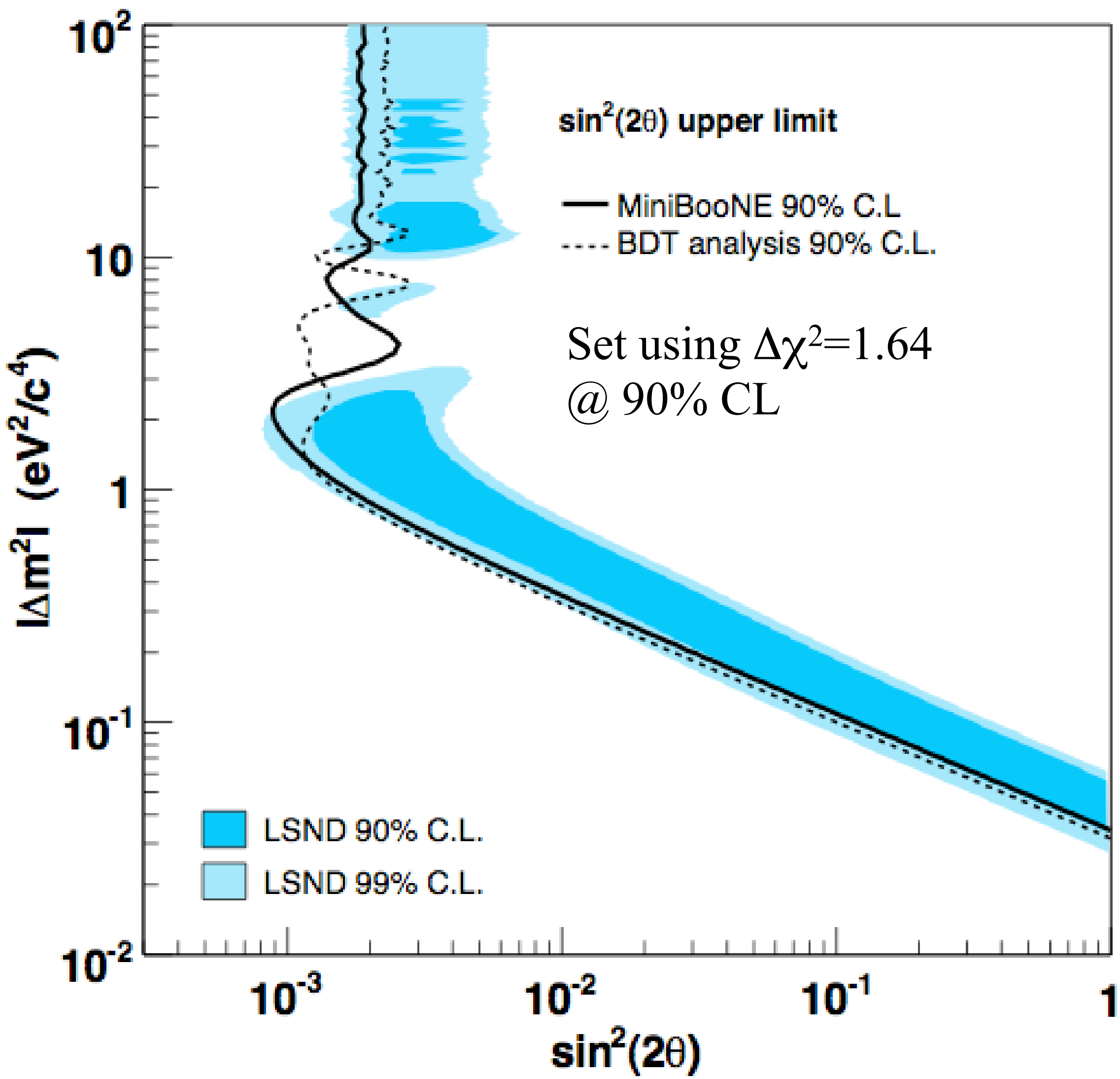
Best Fit Point (dashed):
$(\sin^2 2\theta, \Delta m^2) = (0.001, 7\ eV^2)$

χ^2 probability of best-fit point: 62%
χ^2 probability of null hypothesis: 52%

significance:
$-0.38\ \sigma$

Results: **Comparison**

MiniBooNE observes no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations.



The two independent oscillation analyses are in agreement.

solid: track-based

$$\Delta\chi^2 = \chi^2_{best\ fit} - \chi^2_{null} = 0.94$$

dashed: boosting

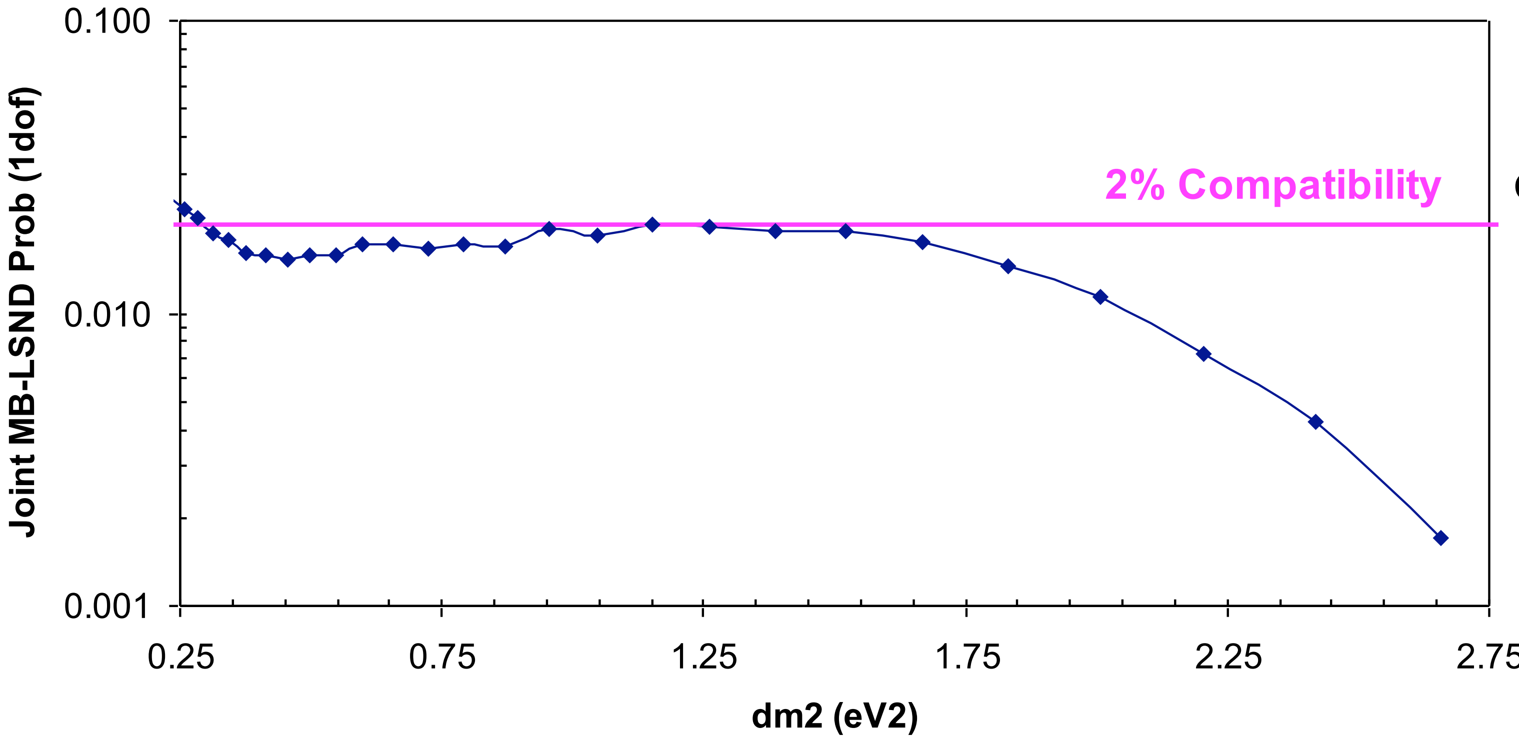
$$\Delta\chi^2 = \chi^2_{best\ fit} - \chi^2_{null} = 0.71$$

Therefore, we set a limit.

Results: Compatibility with LSND

A MiniBooNE-LSND Compatibility Test: $$\chi_0^2 = \frac{(z_{MB} - z_0)^2}{\sigma_{MB}^2} + \frac{(z_{LSND} - z_0)^2}{\sigma_{LSND}^2}$$

- For each Δm^2, form χ^2 between MB and LSND measurement
- Find z_0 *($sin^2 2\theta$)* that minimises χ^2 (weighted average of 2 measurements), this gives χ^2_{min}
- Find probability of χ^2_{min} for 1 dof = joint compatibility probability for this Δm^2



cf. LSND-KARMEN:
64% compatibility

MiniBooNE is incompatible with a $\nu_\mu \rightarrow \nu_e$
appearance-only interpretation of LSND at ***98% CL***

Results: Plans

A paper on this analysis is posted to the archive.

Many more papers supporting this analysis will follow, in the very near future:

- ν_μ CCQE production
- π^0 production

We are pursuing further analyses of the neutrino data, including:

- an analysis which combines TB and BDT,
- less simplistic models for the LSND effect.

MiniBooNE is presently taking data in antineutrino mode.

SciBooNE will start taking data in June!

- Will improve constraints on ν_e backgrounds
  - (intrinsic ν_es, improved π^0 kinematics)
- Will provide important constraints on “wrong-sign” BGs for antineutrino oscillation analysis

Conclusions

1. Within the energy range of the analysis, MiniBooNE observes no statistically significant excess of ν_e events above background.

2. In two independent oscillation analyses, the observed E_ν distribution is inconsistent with a $\nu_\mu \rightarrow \nu_e$ appearance-only model.

3. Therefore, we set a limit on $\nu_\mu \rightarrow \nu_e$ oscillations at $\Delta m^2 \sim 1$ eV^2. The MiniBooNE - LSND joint probability is 2%.

Results: Interpreting Our Limit

There are various ways to present limits:

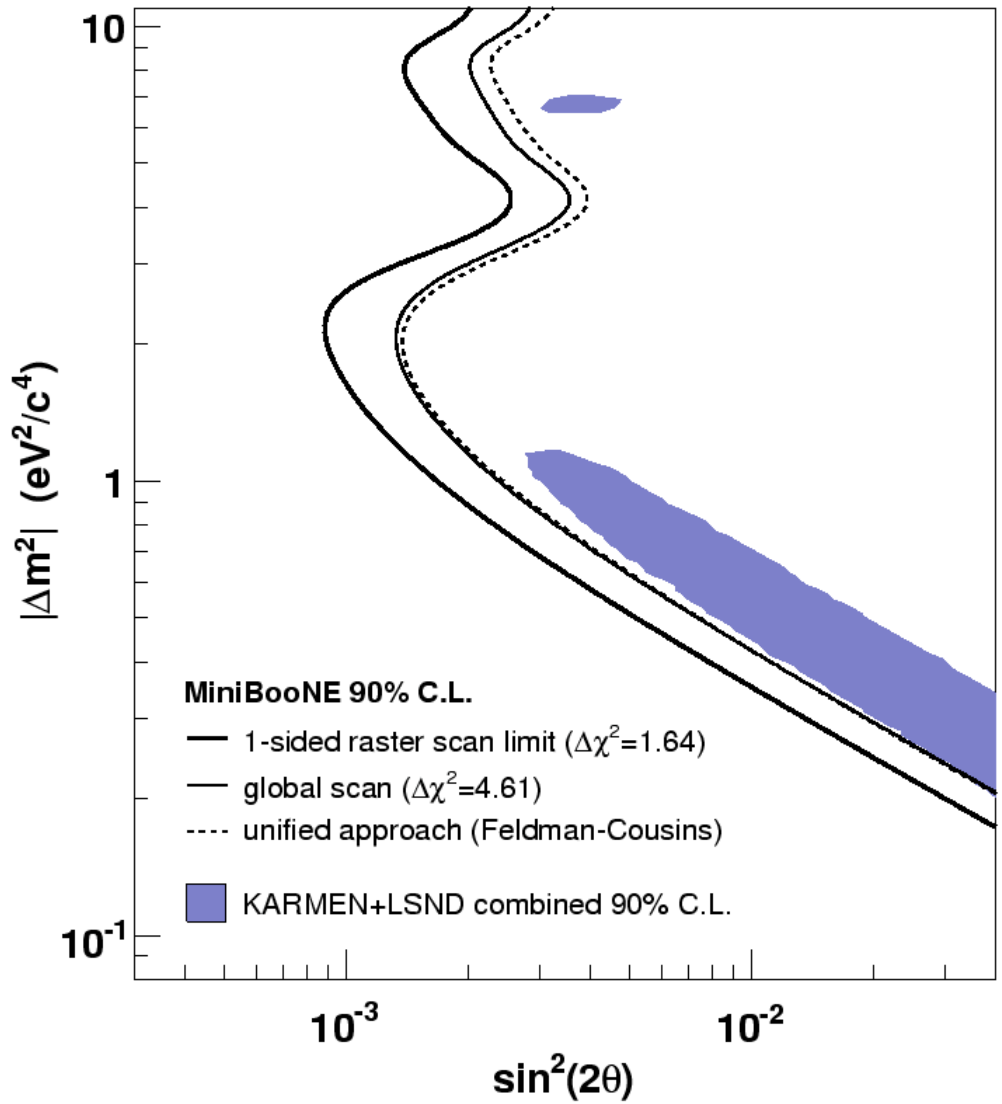
- Single sided raster scan
  (historically used, presented here)

- Global scan

- Unified approach
  (most recent method)

This result must be folded into an LSND-Karmen joint analysis.

Church, et al., PRD 66, 013001

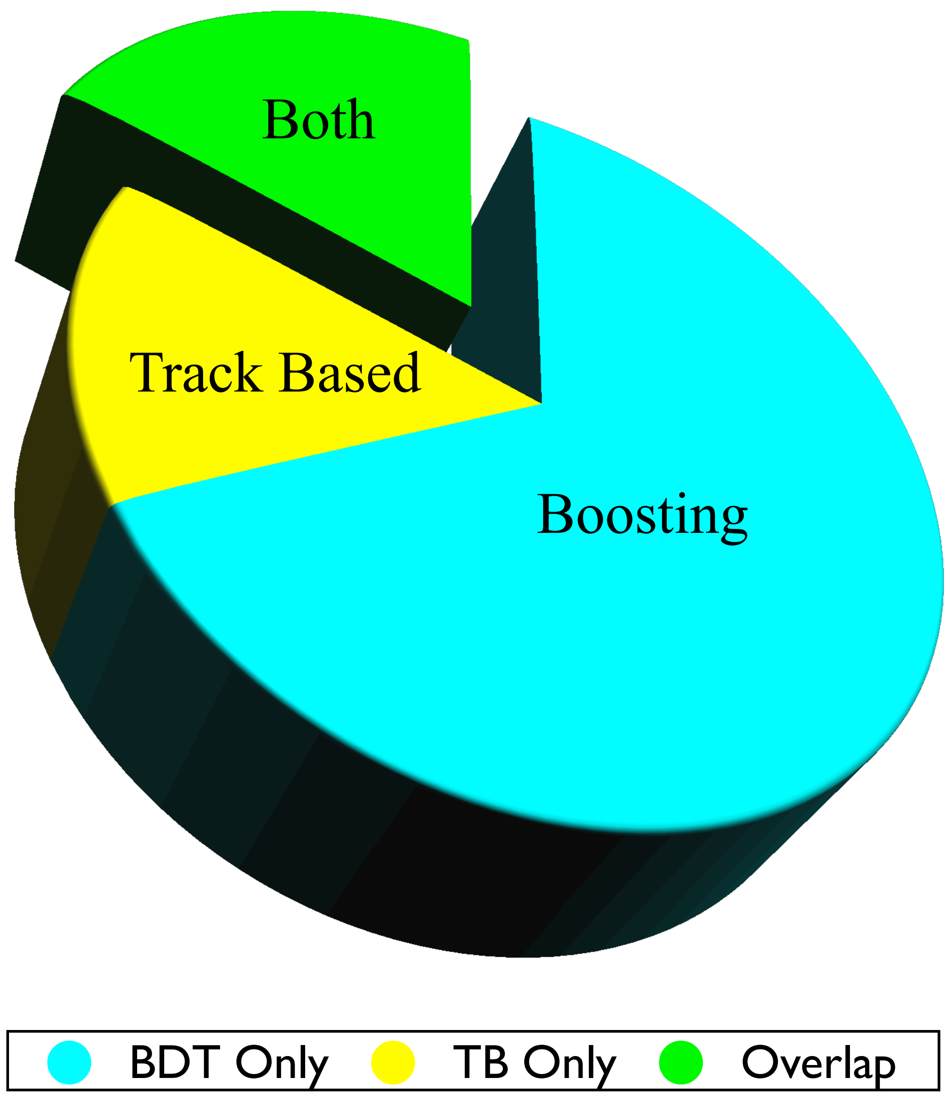


We will present a full joint analysis soon.

Results: Event Overlap

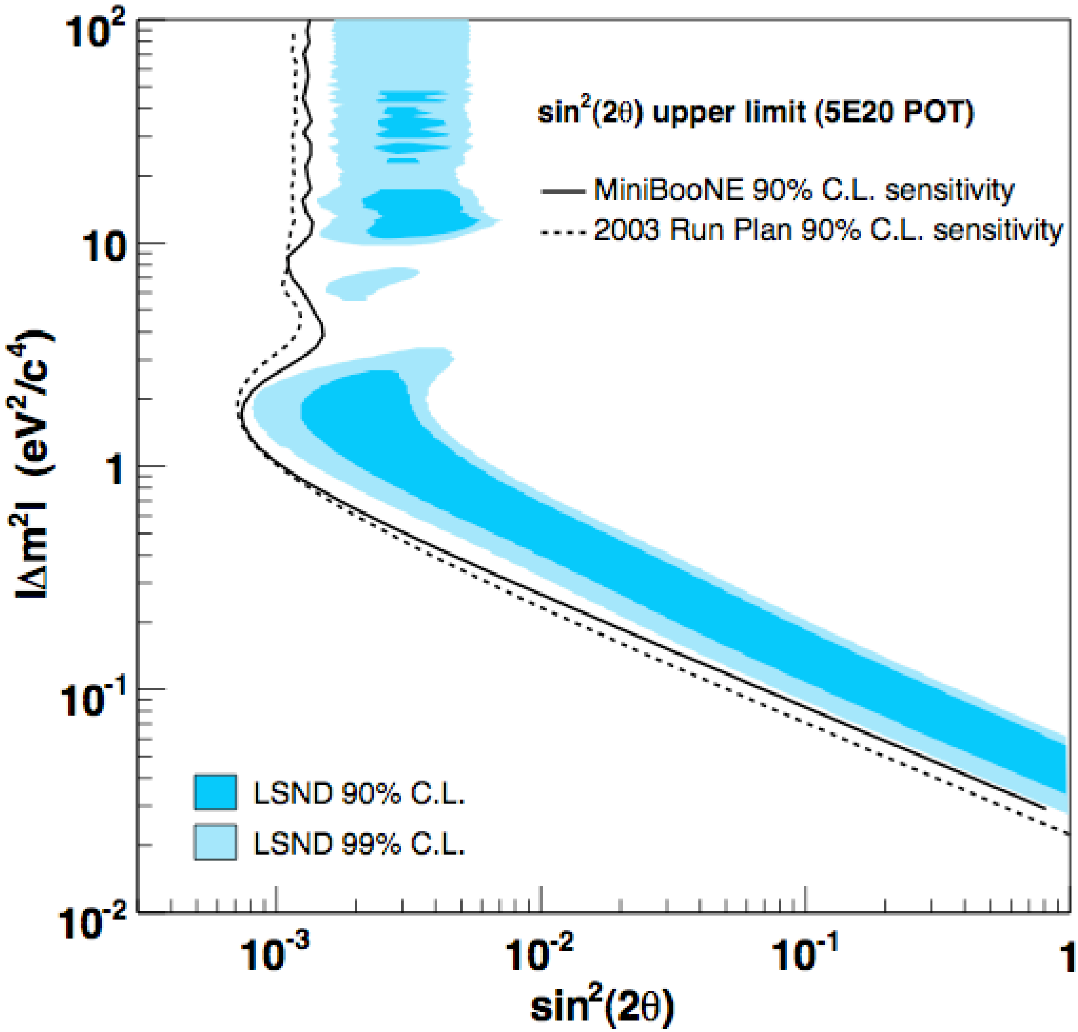
Counting experiment numbers:
Track Based Algorithm finds 380 events
Boosting Algorithm finds 971 events

However, only 1131 events total,
because 220 overlap
- chosen by both algorithms!



Results: Sensitivity Goal

Compared to our sensitivity goal for 5E20 protons on target from 2003 Run Plan



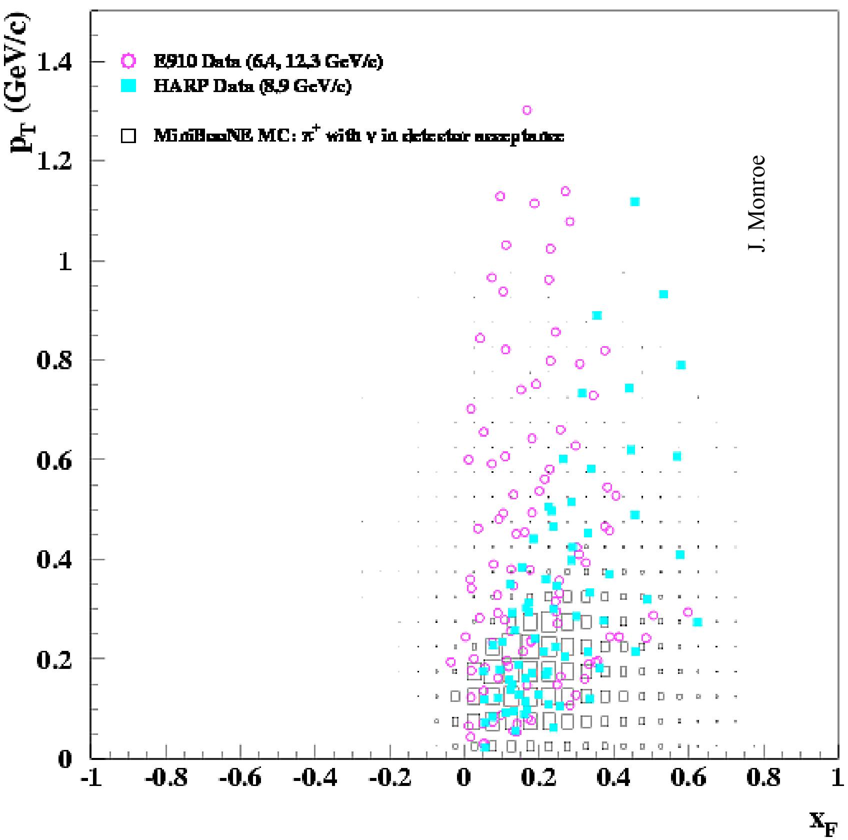
Set using $\Delta\chi^2$=1.64 @ 90% CL

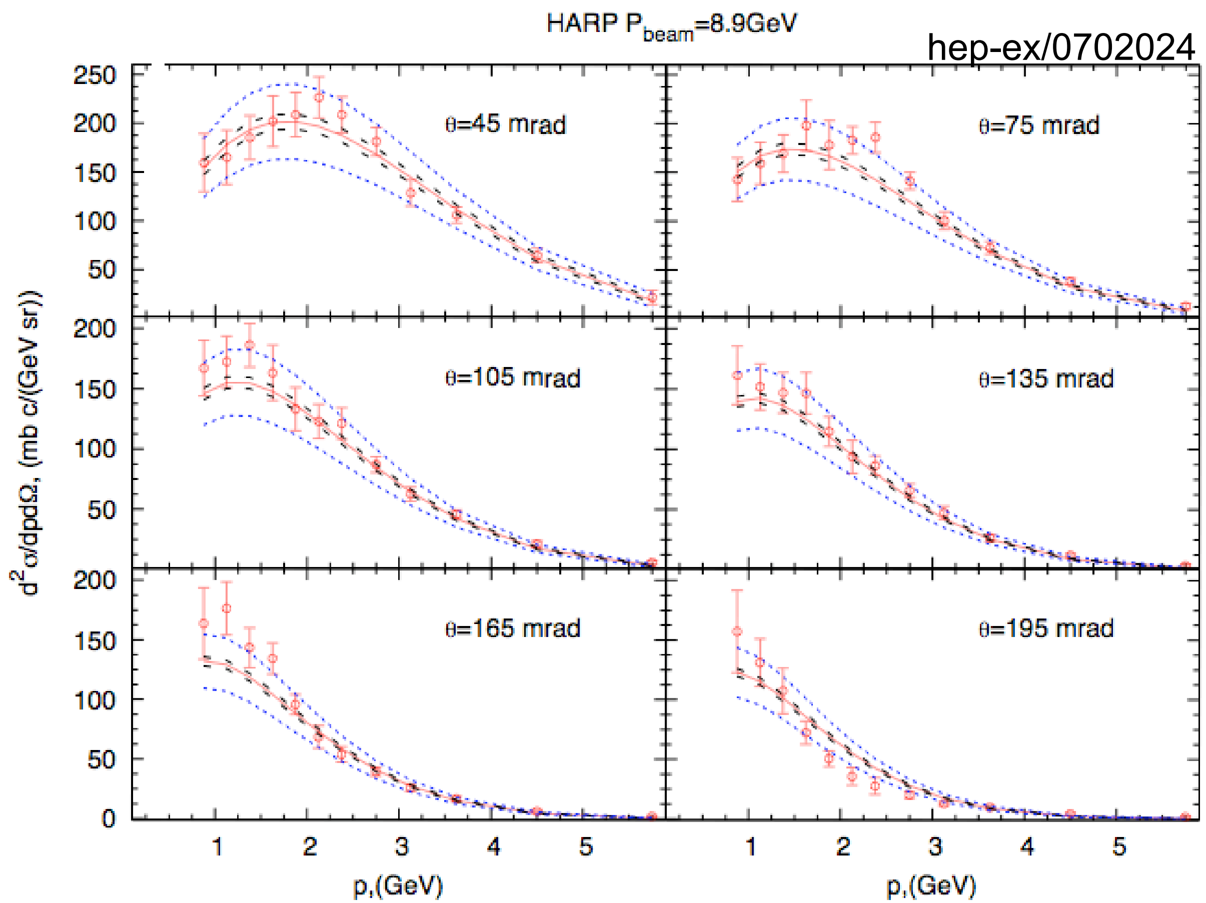
Booster Neutrino Beam: Modeling Meson Production

***Prediction** from a fit to p Be ➔ π^+ X production data from E910 and HARP experiments (p_p = 6-12 GeV/c, Θ_p = 0 - 330 mrad.)*

Fit (shown at right) uses Sanford-Wang parametrisation

HARP has excellent phase space coverage for MiniBooNE



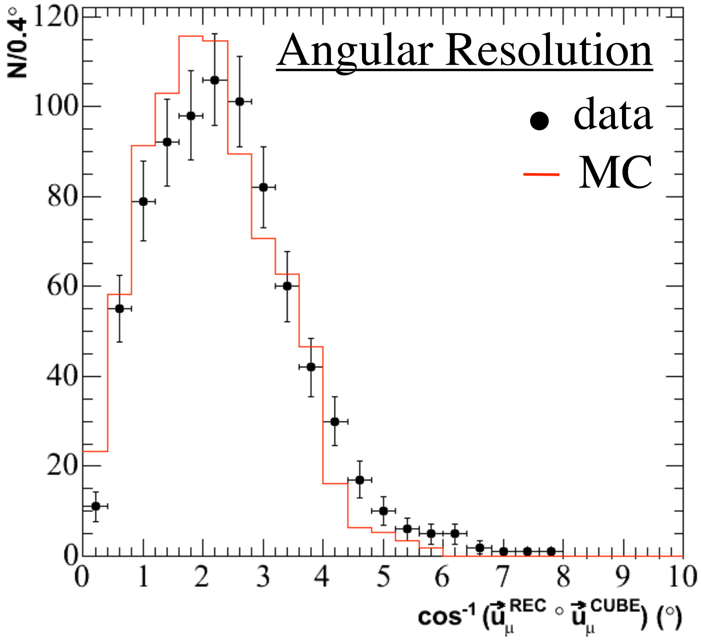


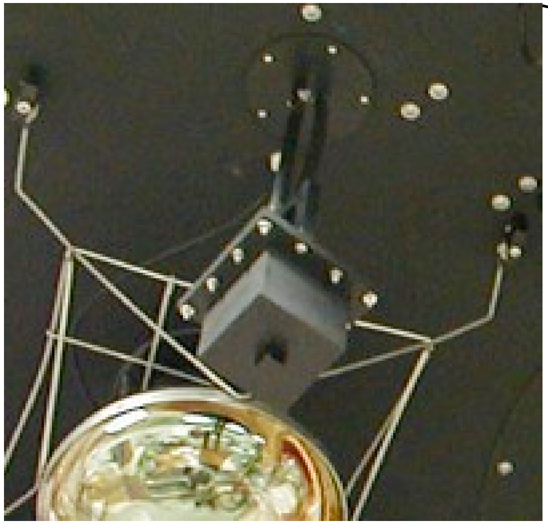
π^- similarly parametrised

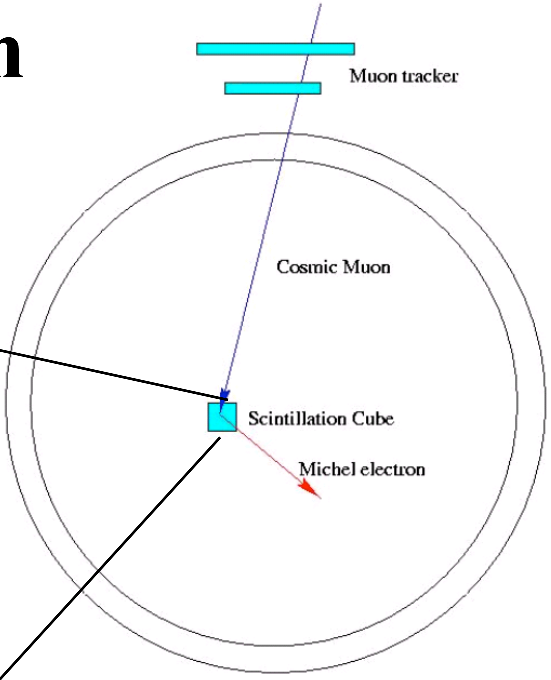
Kaons flux predictions use a Feynman Scaling parametrisation (no HARP data)

MiniBooNE Detector: **Cosmic Calibration**

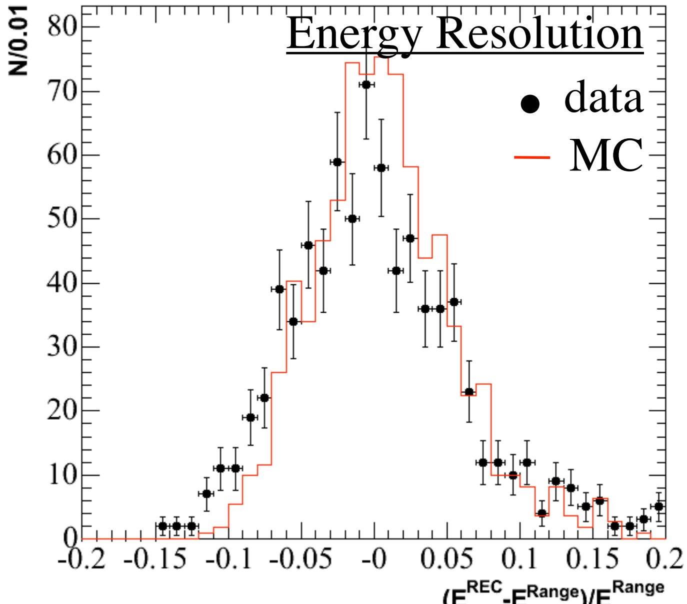
use cosmic muons and their decay electrons (Michels)







Muon tracker
7 scintillator cubes



Cosmic muons which stop in cubes:

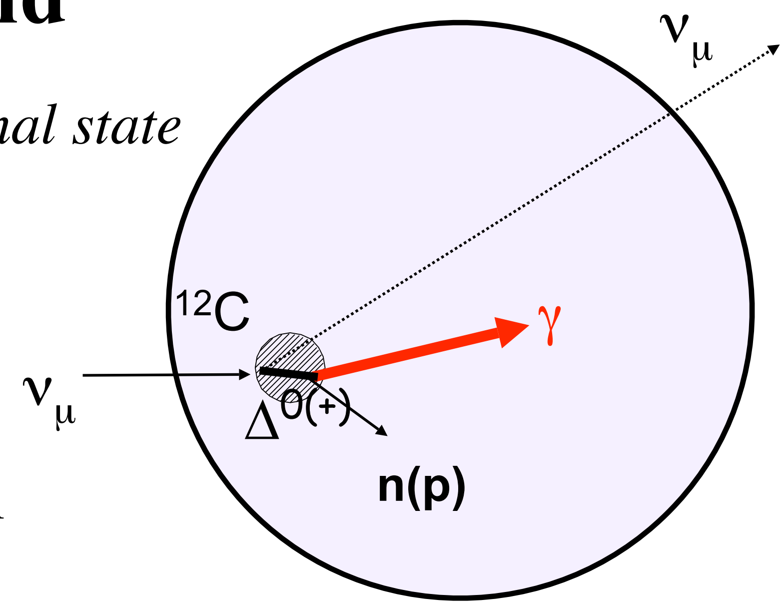
-test energy scale extrapolation up to 800 MeV

- measure energy, angle resolution
- compare data and MC

Muon tracker + cube calibration data continuously acquired at 1 Hz

Analysis Strategy: **Delta Background**

ν induced interactions that produce single γs in the final state



Radiative Delta Decay (NC)

(i) Use π^0 events to measure rate of NC Δ production

(ii) Use PDG branching ratio for radiative decay
- 15% uncertainty on branching ratio

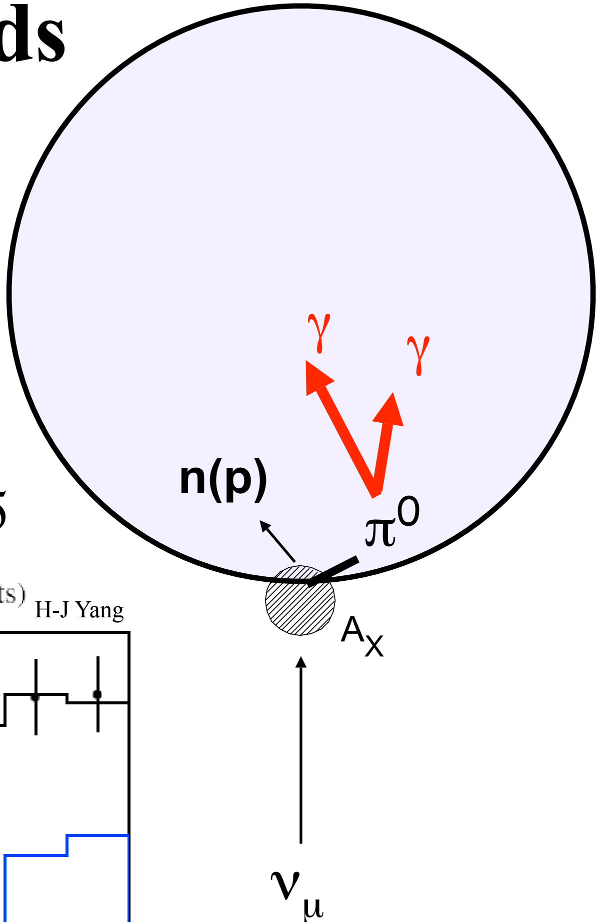
Inner Bremsstrahlung (CC)

(i) Hard photon released from neutrino interaction vertex

(ii) Use events where the μ is tagged by the decay e^-
- study misidentification using BDT algorithm.

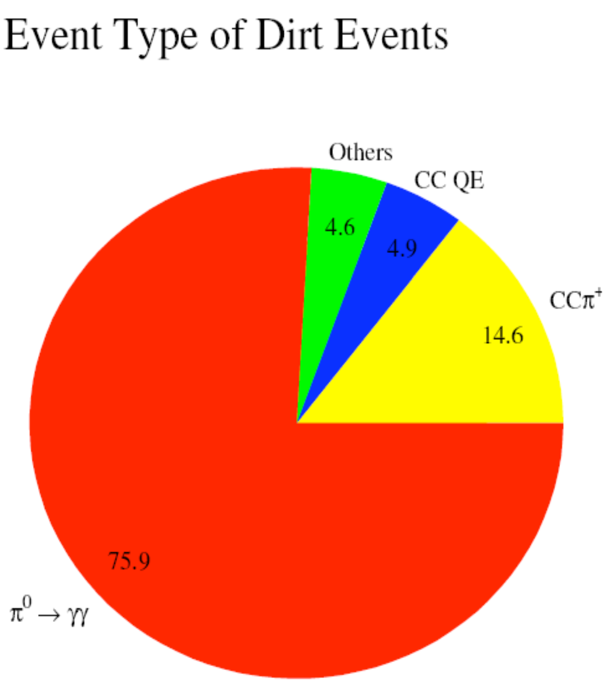
Analysis Strategy: External Backgrounds

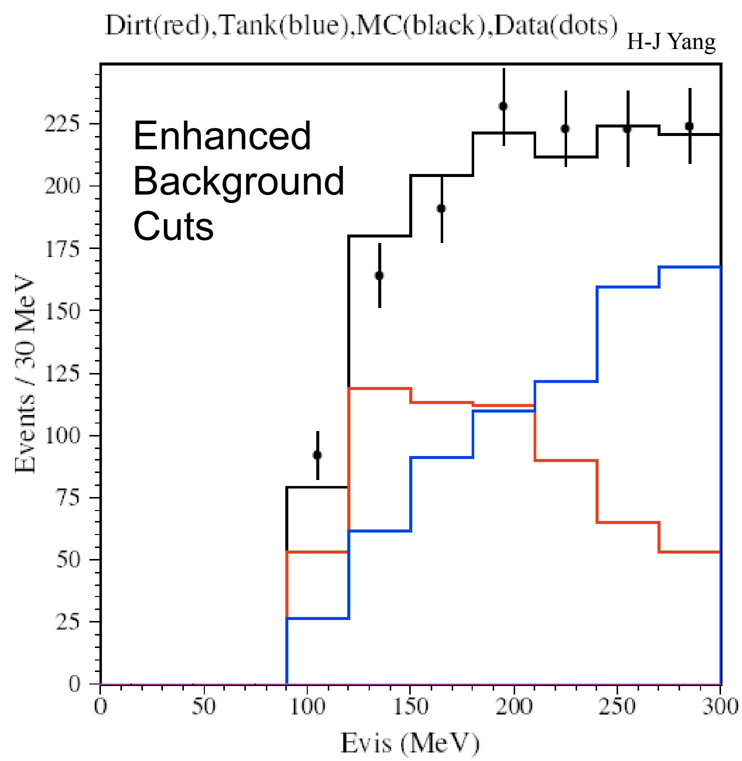
interactions outside the detector that deposit energy in the fiducial volume and pass the veto PMT hits cut



1. "Dirt" Events

ν interactions outside of the detector are measured in the "dirt box:" $N_{data}/N_{MC} = 0.99 \pm 0.15$





2. Cosmic Ray Background Events

Measured from 126E6 strobe data triggers: 2.1 ± 0.5 events.

Analysis Overview: **Background Summary**

Summary of predicted backgrounds for the primary MiniBooNE result
(Track-Based Analysis):

Process	Number of Events
ν_μ CCQE	10
$\nu_\mu e \rightarrow \nu_\mu e$	7
Miscellaneous ν_μ Events	13
NC π^0	62
NC $\Delta \rightarrow N\gamma$	20
NC Coherent & Radiative γ	< 1
Dirt Events	17
ν_e from μ Decay	132
ν_e from K^+ Decay	71
ν_e from K^0_L Decay	23
ν_e from π Decay	3
Total Background	358
0.26% $\nu_\mu \rightarrow \nu_e$	(example signal) 163