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

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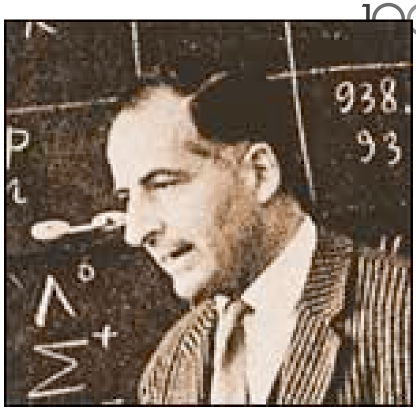
Outline

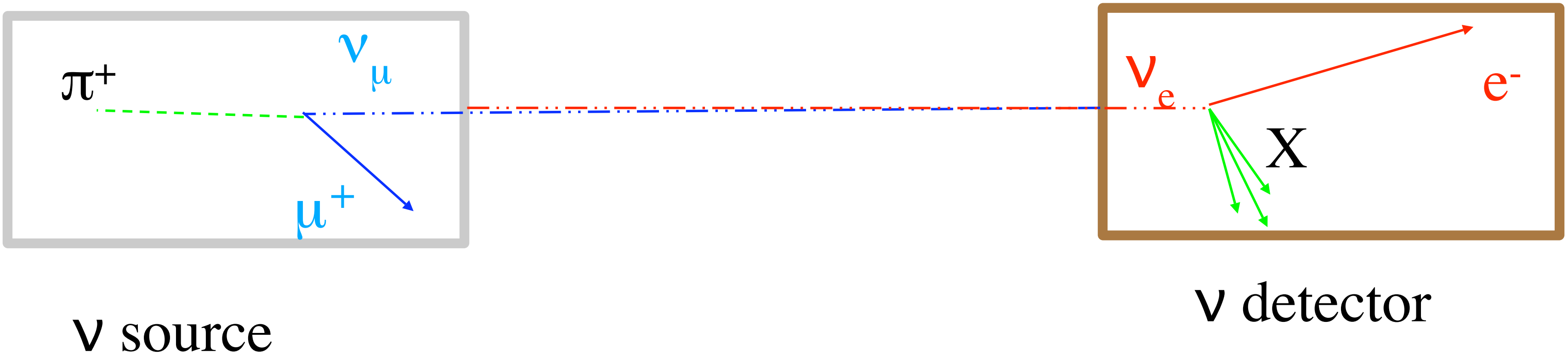
1. Motivation & Introduction
2. Description of the Experiment
3. Analysis Overview
4. Two Independent Oscillation Searches
5. First Results

Motivation: **Neutrino Oscillations**

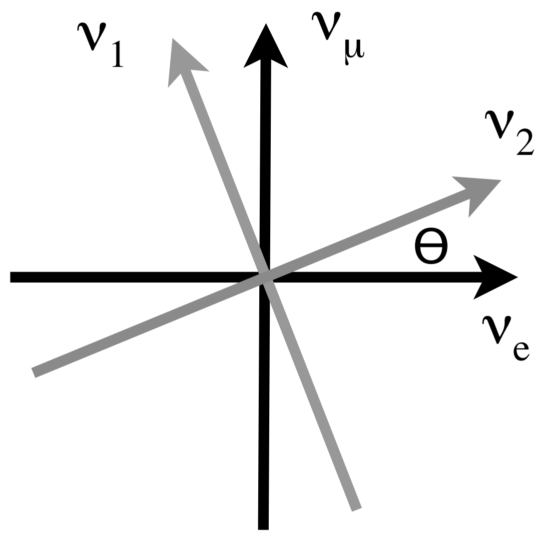


Pontecorvo, 1957

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:

$$|\nu_\mu> = -sin\theta|\nu_1> + cos\theta|\nu_2>$$

$$|\nu_\mu(t)> = -sin\theta\left(|\nu_1> e^{-iE_1t}\right) + cos\theta\left(|\nu_2> e^{-iE_2t}\right)$$

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:

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

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

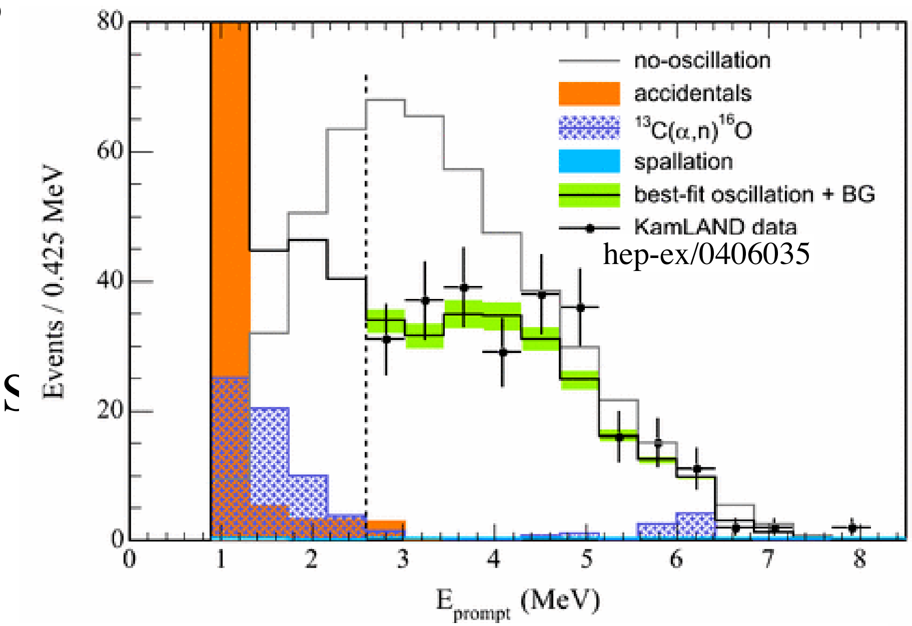
ν ν ν ν ν ν ν ν

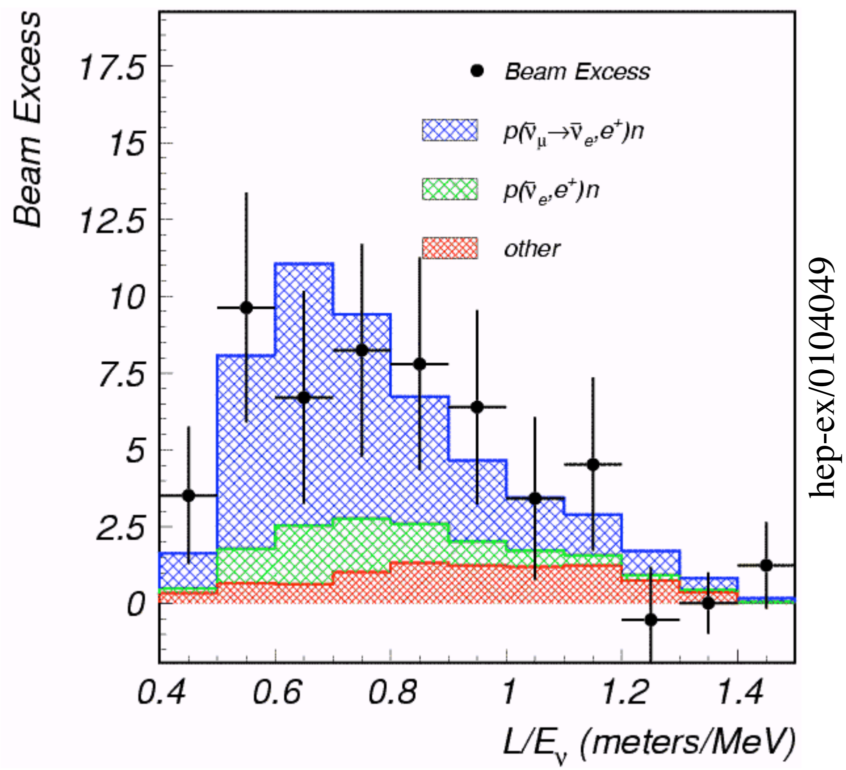
Motivation: **Oscillation Signals**

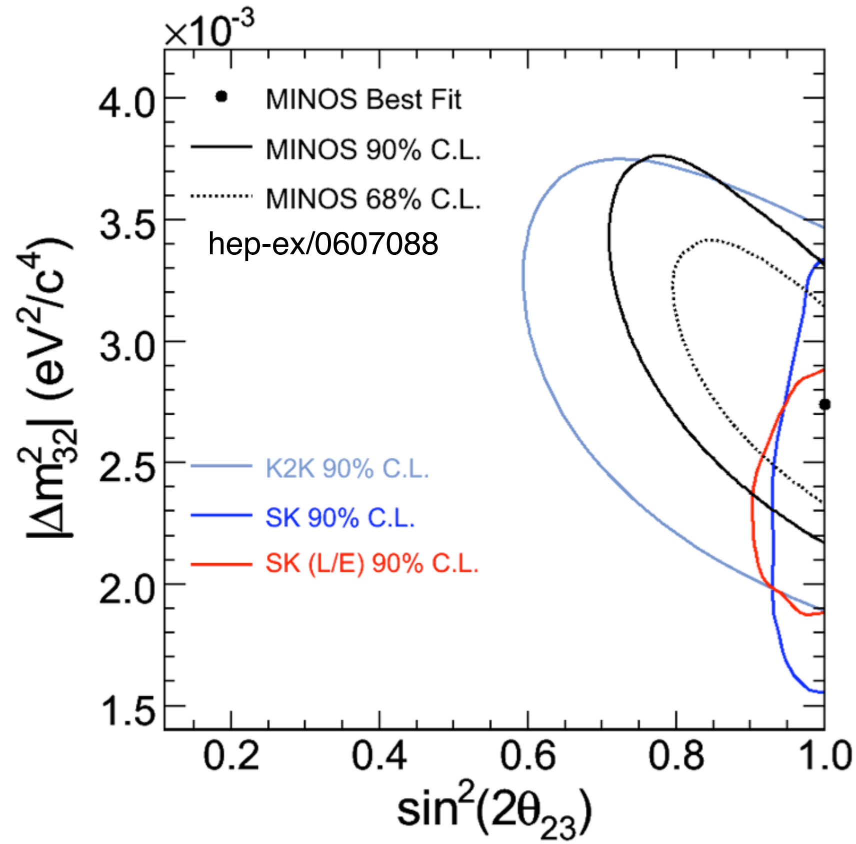
Solar ν: measured by Homestake, ..., SNO
confirmed by KamLAND

Atmospheric ν: measured by K-II, ..., Super-K
confirmed by Soudan2, MACRO, K2K, MINOS

Accelerator ν: measured by LSND
unconfirmed



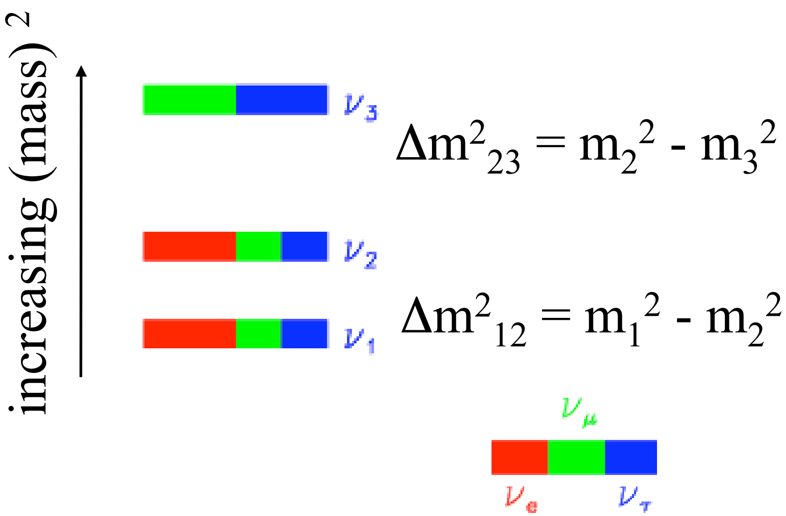




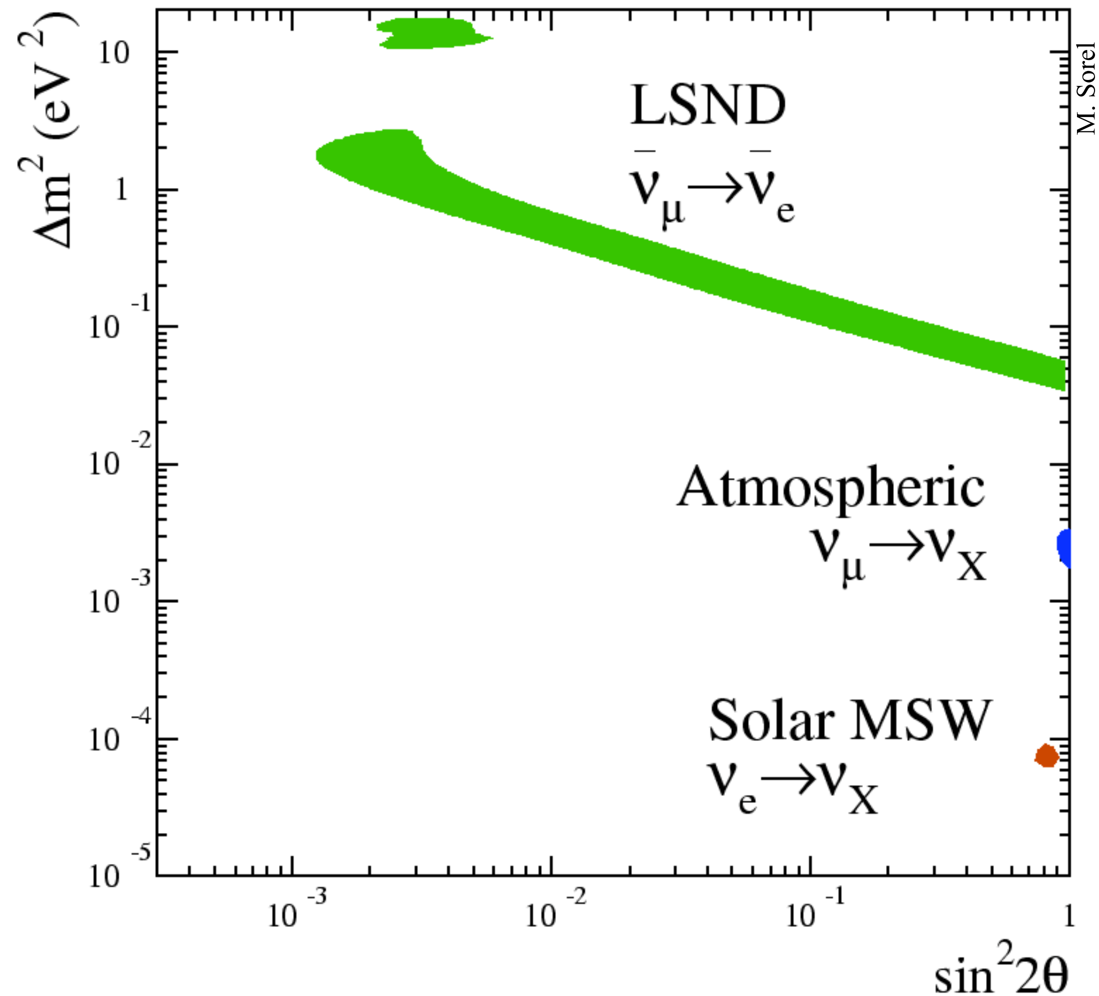
Motivation: The Problem

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

A standard 3 neutrino picture:



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



The oscillation signals cannot be reconciled without introducing physics (even farther) beyond the Standard Model.

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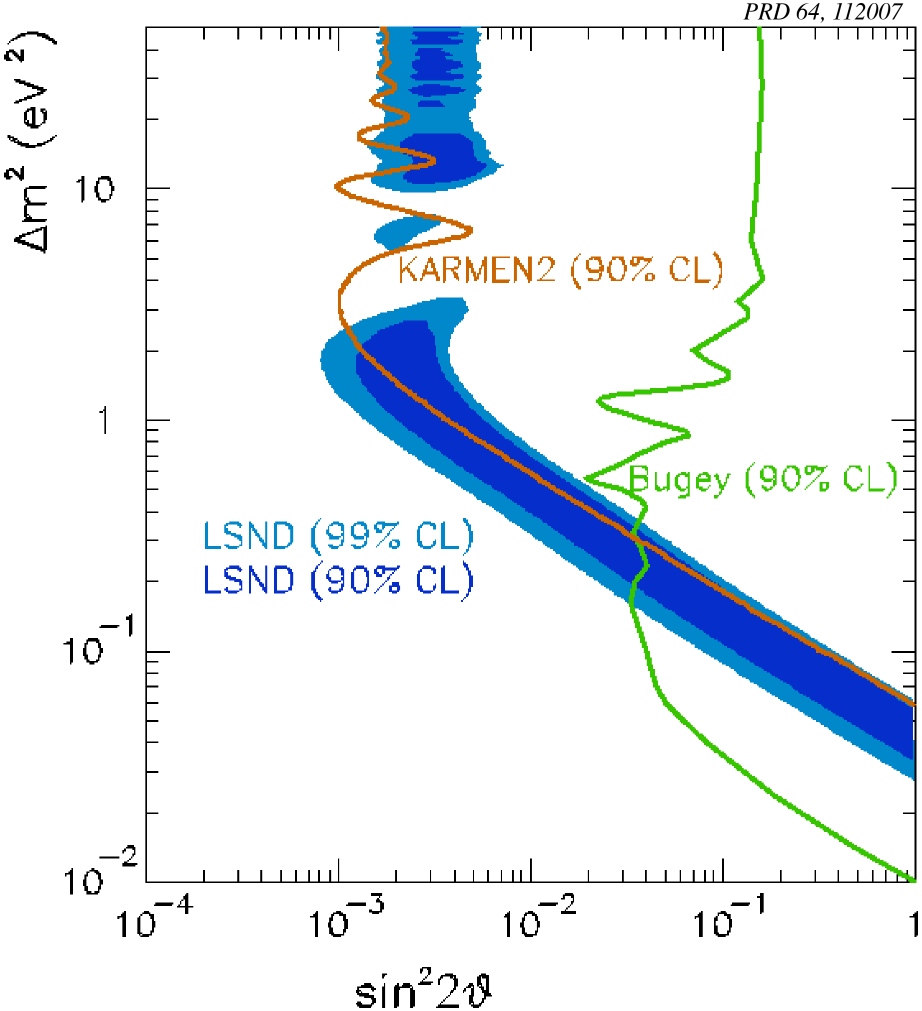
Motivation: LSND

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, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 0.26\%$

PRD 64, 112007



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

MiniBooNE strategy:

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

Simple $\nu_\mu \rightarrow \nu_e$ oscillation

The MiniBooNE Collaboration

A. A. Aguilar-Arevalo[5], A. O. Bazarko[12], S. J. Brice[7], B. C. Brown[7], L. Bugel[5], J. Cao[11], L. Coney[5], J. M. Conrad[5], D. C. Cox[8], A. Curioni[16], Z. Djurcic[5], D. A. Finley[7], B. T. Fleming[16], R. Ford[7], F. G. Garcia[7], G. T. Garvey[9], J. A. Green[8,9], C. Green[7,9], T. L. Hart[4], E. Hawker[15], R. Imlay[10], R. A. Johnson[3], P. Kasper[7], T. Katori[8], T. Kobilarcik[7], I. Kourbanis[7], S. Koutsoliotas[2], E. M. Laird[12], J. M. Link[14], Y. Liu[11], Y. Liu[1], W. C. Louis[9], K. B. M. Mahn[5], W. Marsh[7], P. S. Martin[7], G. McGregor[9], W. Metcalf[10], P. D. Meyers[12], F. Mills[7], G. B. Mills[9], J. Monroe[5], C. D. Moore[7], R. H. Nelson[4], P. Nienaber[13], S. Ouedraogo[10], R. B. Patterson[12], D. Perevalov[1], C. C. Polly[8], E. Prebys[7], J. L. Raaf[3], H. Ray[9], B. P. Roe[11], A. D. Russell[7], V. Sandberg[9], R. Schirato[9], D. Schmitz[5], M. H. Shaevitz[5], F. C. Shoemaker[12], D. Smith[6], M. Sorel[5], P. Spentzouris[7], I. Stancu[1], R. J. Stefanski[7], M. Sung[10], H. A. Tanaka[12], R. Tayloe[8], M. Tzanov[4], M. O. Wascko[10], R. Van de Water[9], D. H. White[9], M. J. Wilking[4], H. J. Yang[11], G. P. Zeller[5], E. D. Zimmerman[4]

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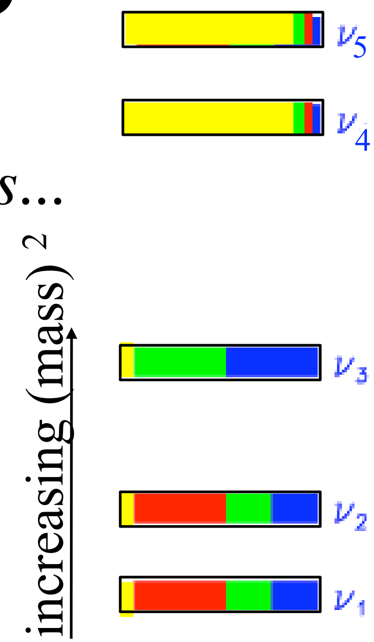
Motivation: MiniBooNE and LSND



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

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

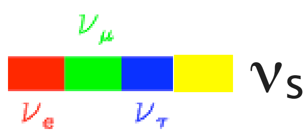
$\Delta m^2_{23} = m_2^2 - m_3^2$

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

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.



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

The Standard Model wins again!

<u>Today</u>: 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

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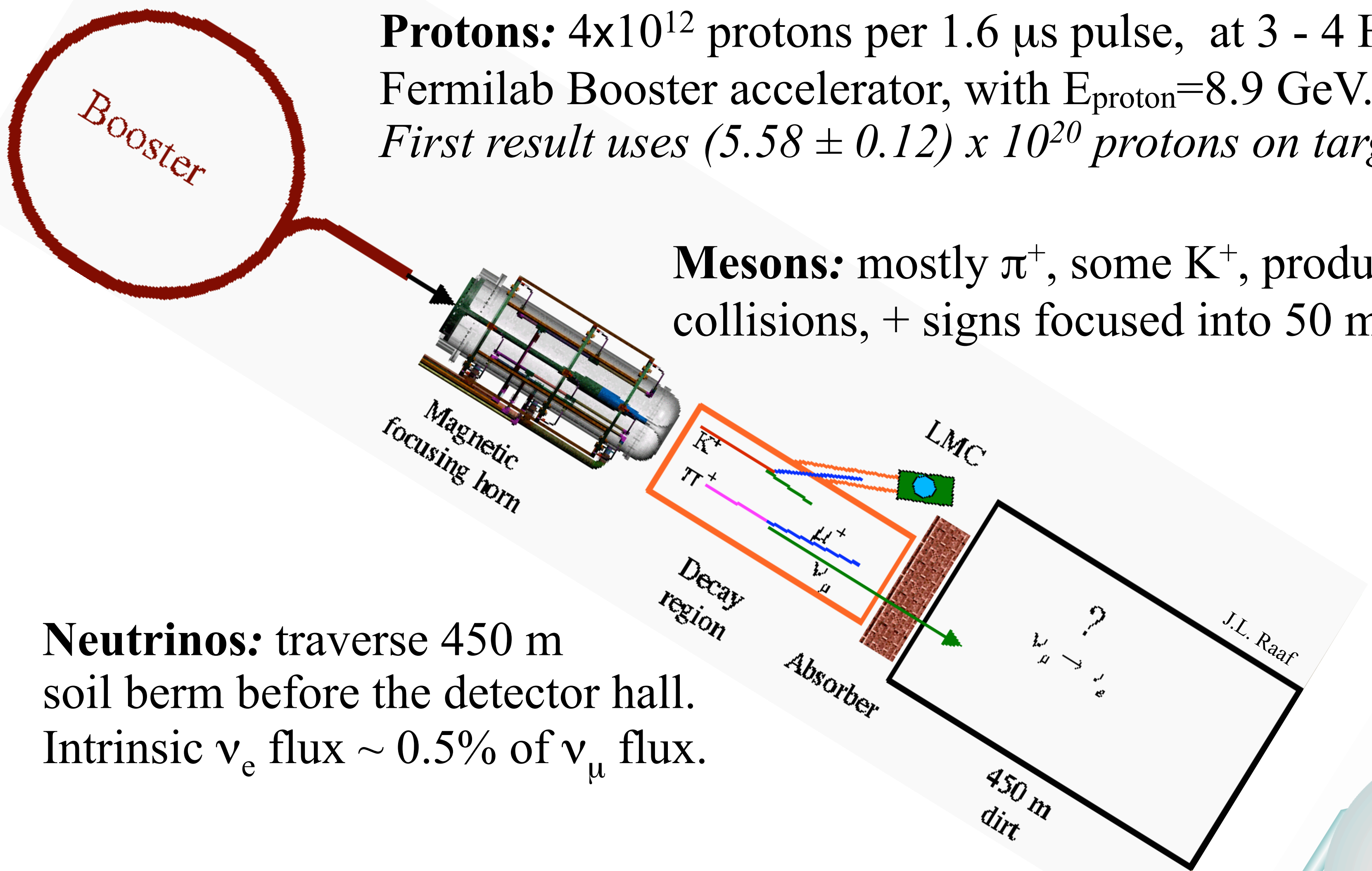
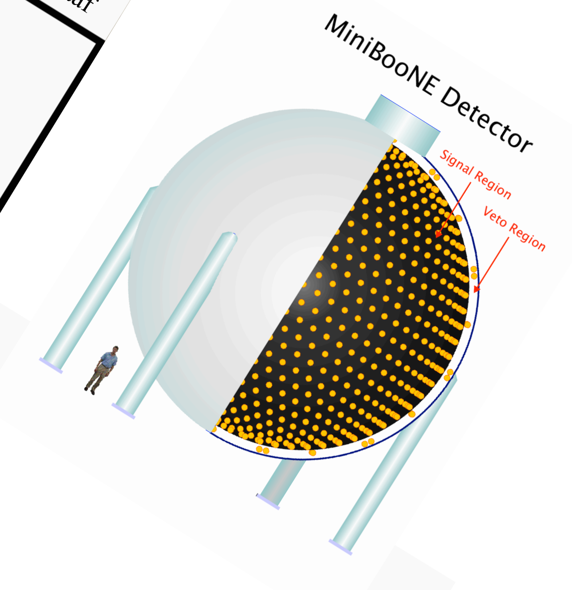
MiniBooNE Overview: **Beam and Detector**

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.



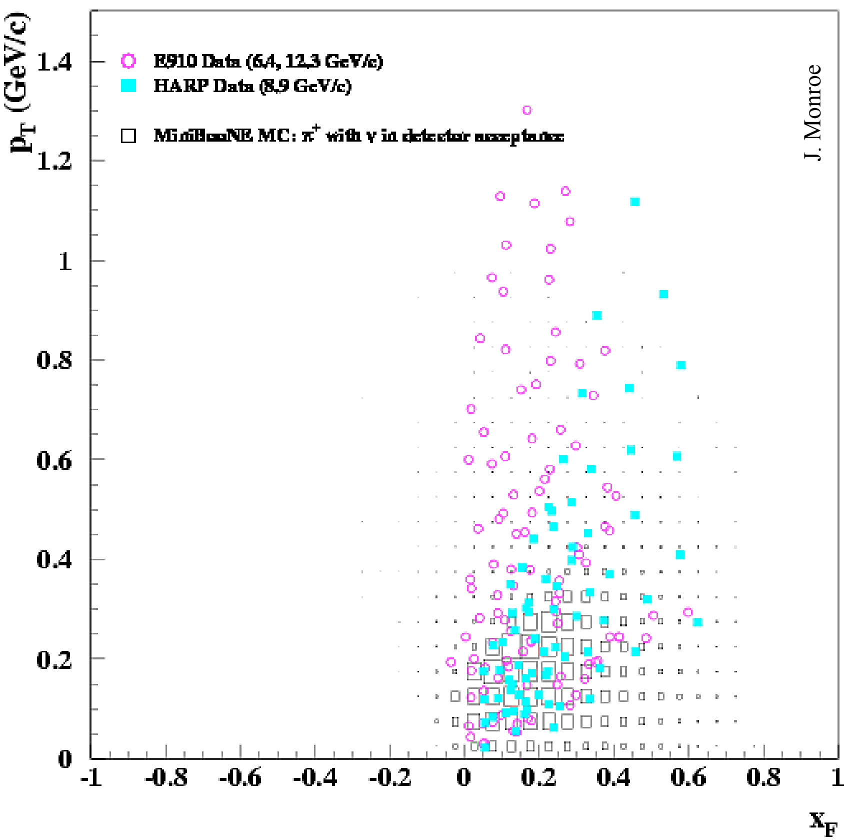
Detector: 6 m radius, 250,000 gallons of mineral oil (CH_2), which emits Cherenkov and scintillation light.
1280 inner PMTs, 240 PMTs in outer veto region

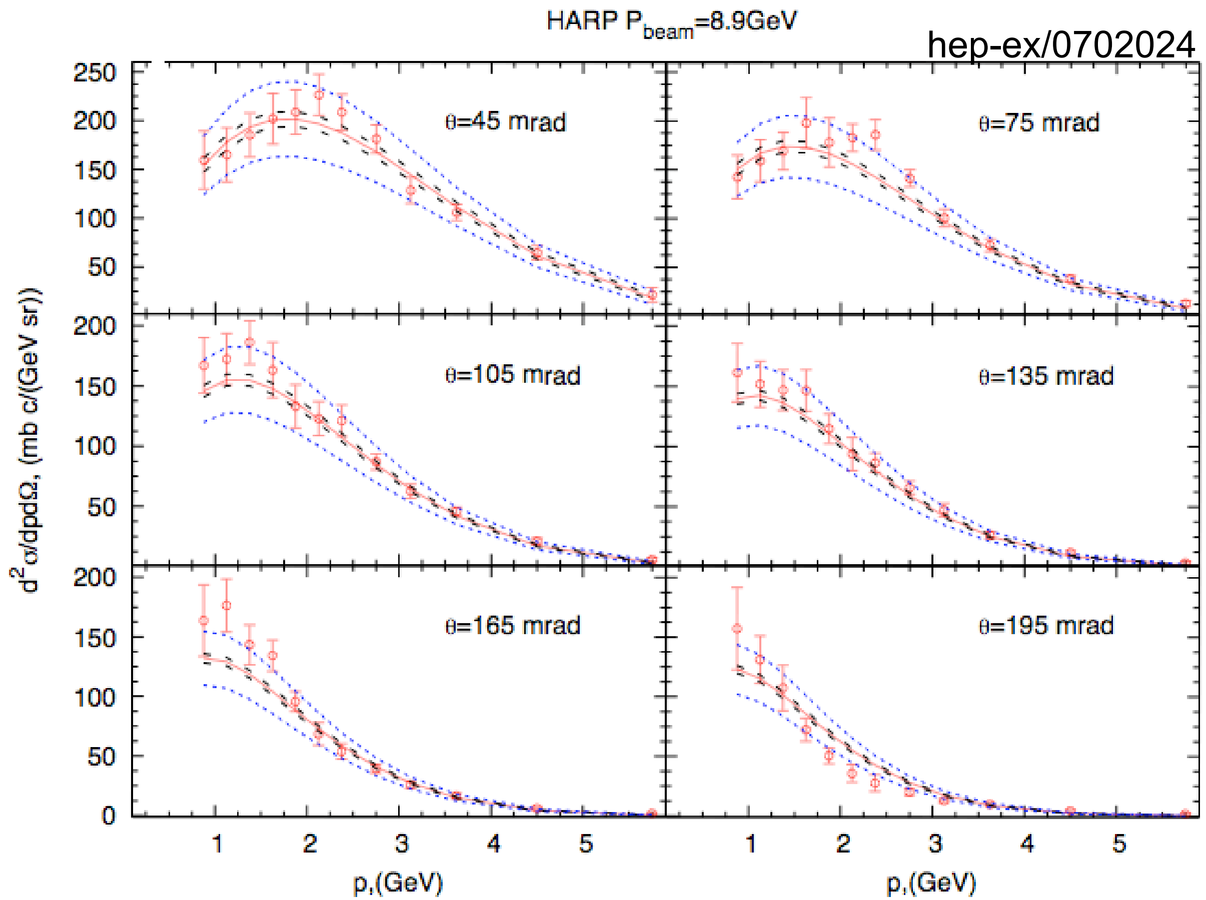
Booster Neutrino Beam: Modelling Meson Production

***Prediction** from a fit to p Be → π^+ X production data from E910 and HARP experiments (p_p = 6-12 GeV/c, Θ_π = 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 yet)

Booster Neutrino Beam: **Neutrino Flux**

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

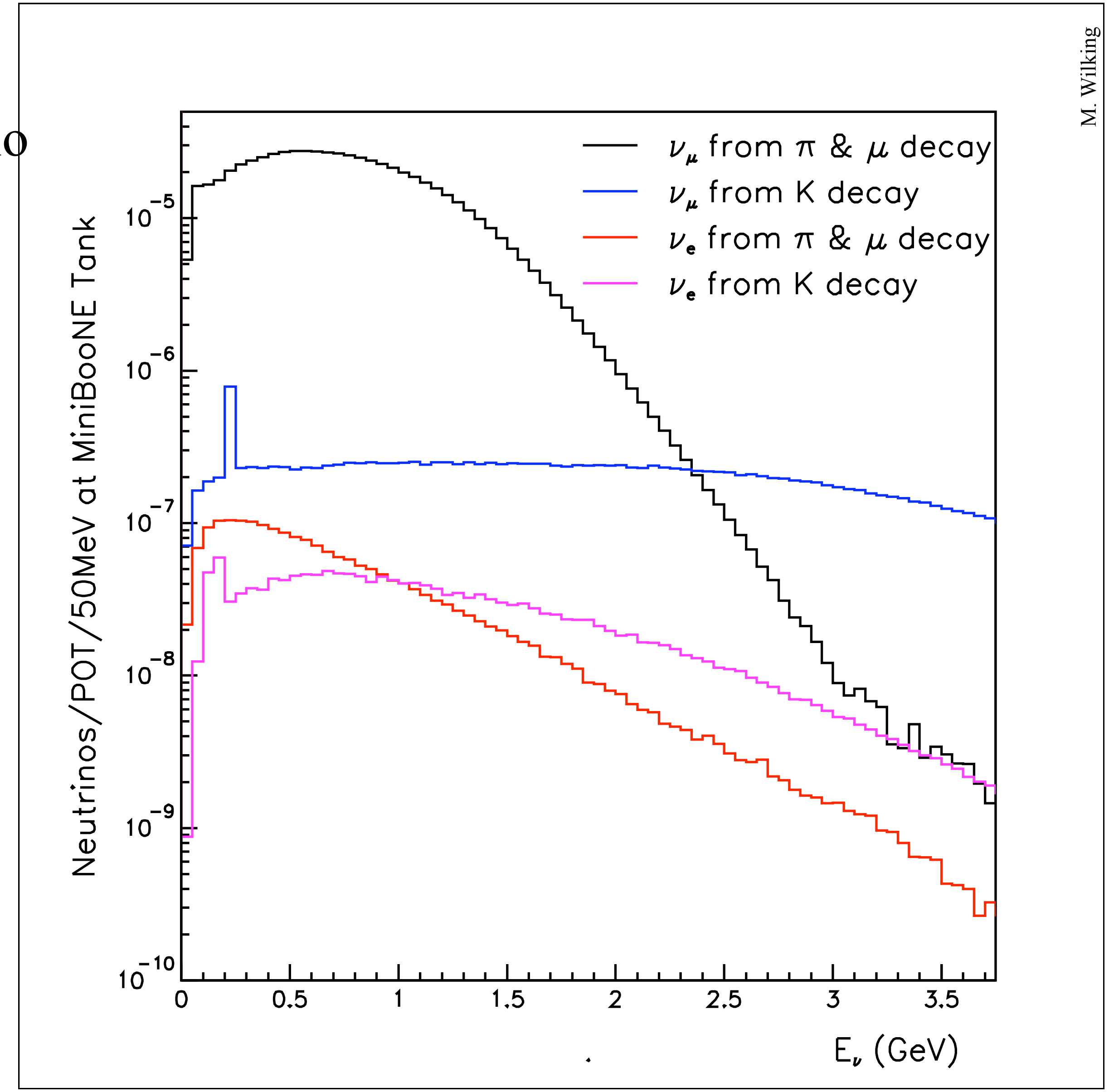
Modelled with a Geant4 Monte Carlo

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

ν_e Sources:

- $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$ (42%)
- $K^+ \rightarrow \pi^0 e^+ \nu_e$ (28%)
- $K^0 \rightarrow \pi^+ e^- \nu_e$ (16%)
- $\pi^+ \rightarrow e^+ \nu_e$ (4%)

Antineutrino content: 6%



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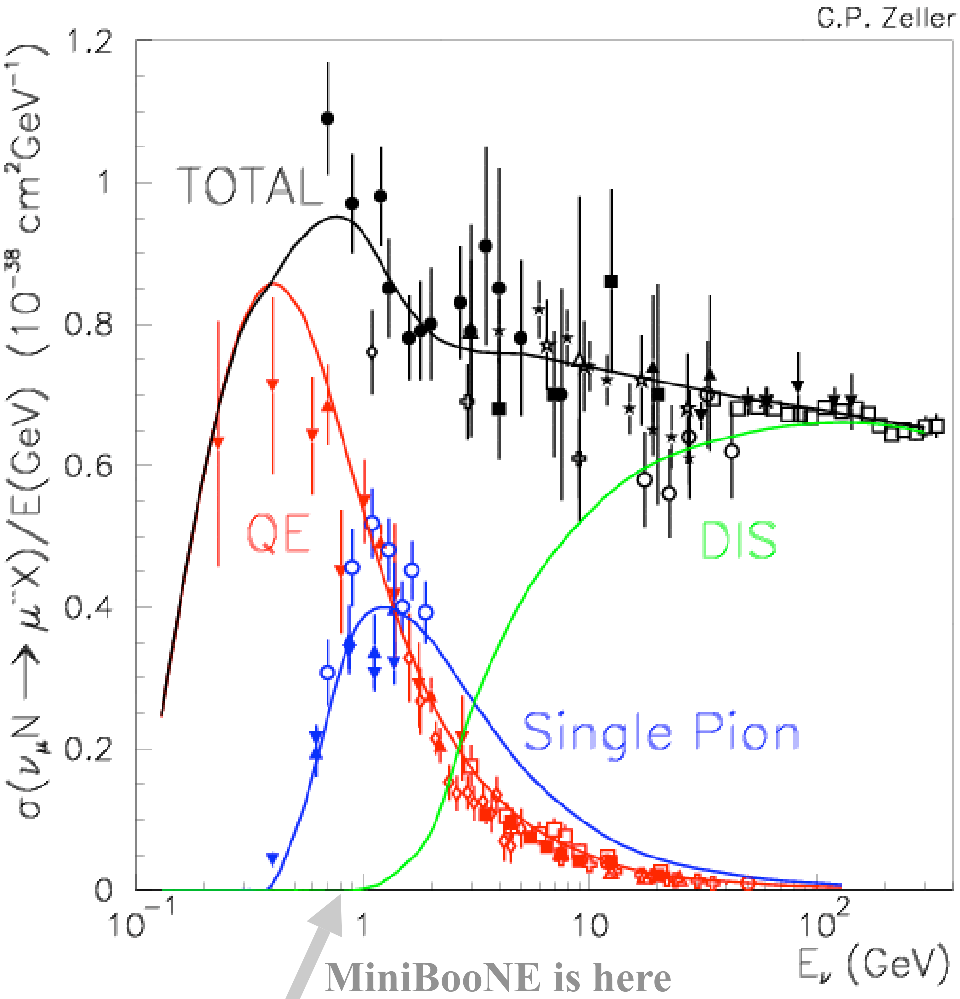
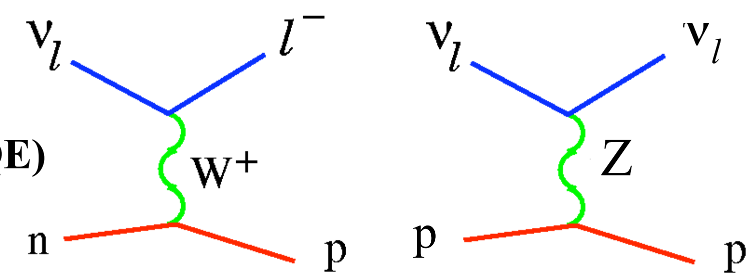
MiniBooNE Detector: **Neutrino Cross Sections**

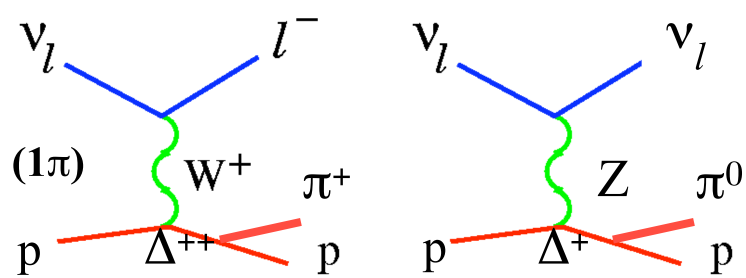
Modelling what the neutrinos do in the detector



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



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



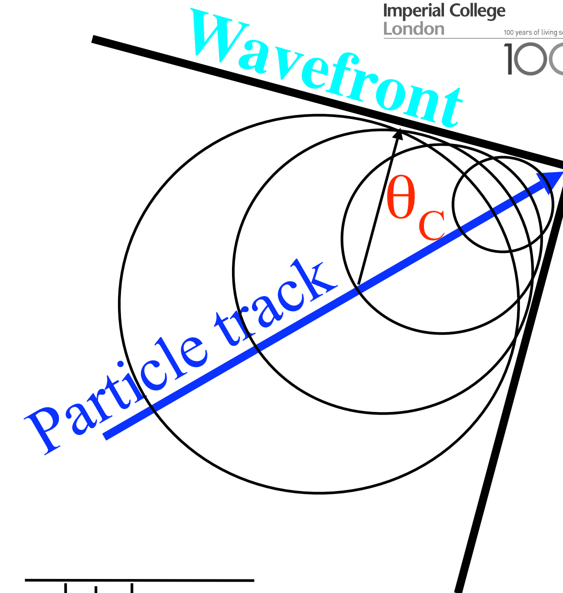
Cross section predictions from NUANCE Monte Carlo

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**



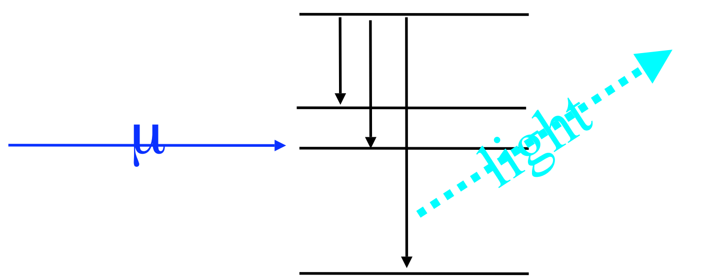
charged final state particles produce **γ**s

Cherenkov radiation

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

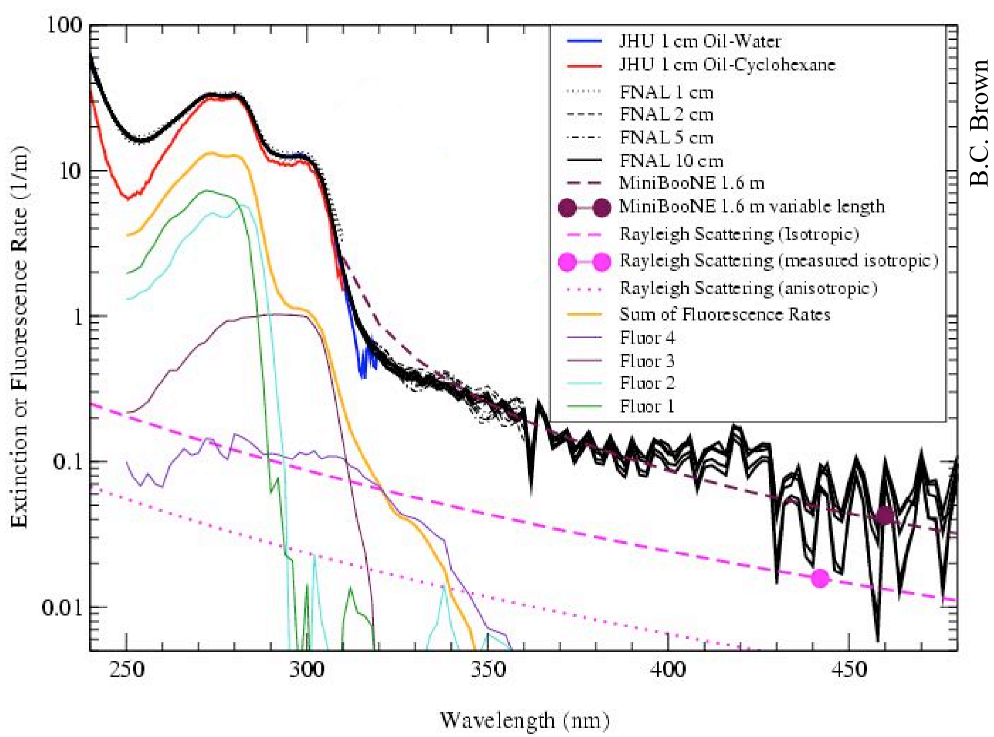
Scintillation

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



Molecular energy levels of oil

Extinction Rate for MiniBooNE Marcol 7 Mineral Oil



***γ**s detected by PMTs after undergoing absorption reemission, scattering, fluorescence*

"the optical model"

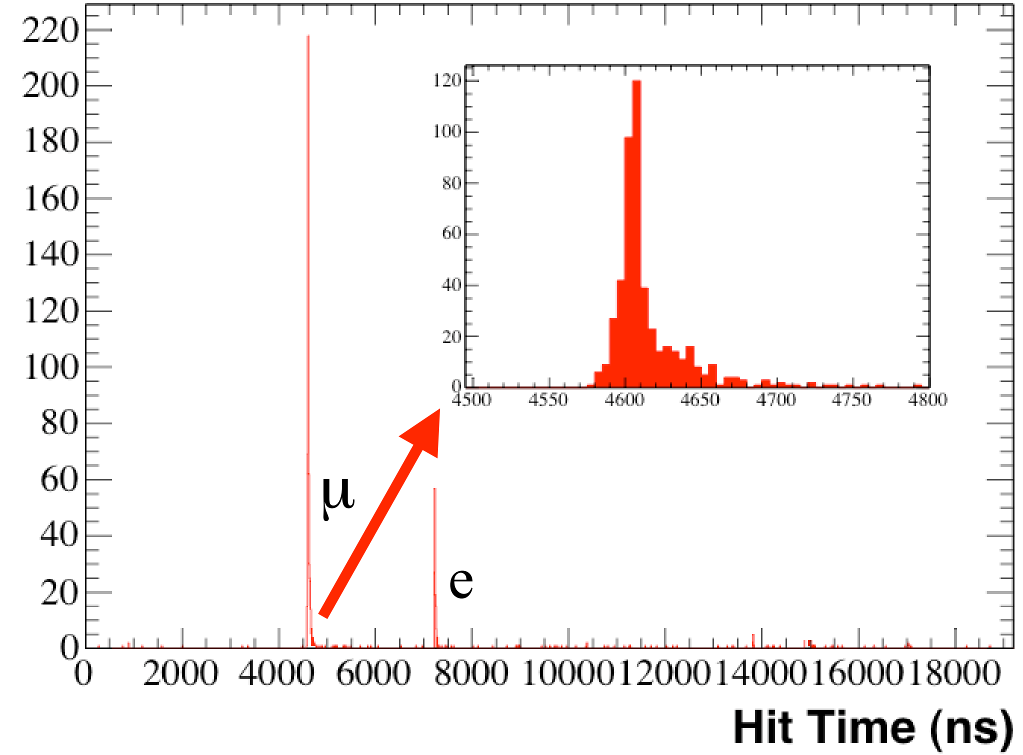
→ *PMT Hits*

MiniBooNE Detector: **Hits**

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

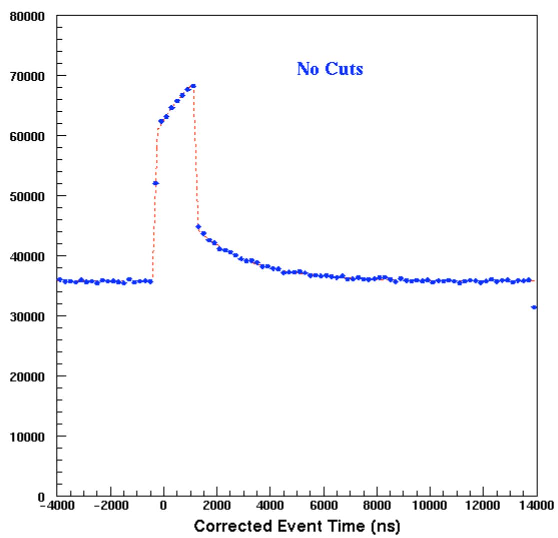
Most events are from ν_μ CC interactions, with characteristic two "sub-event" structure from stopped μ decay.

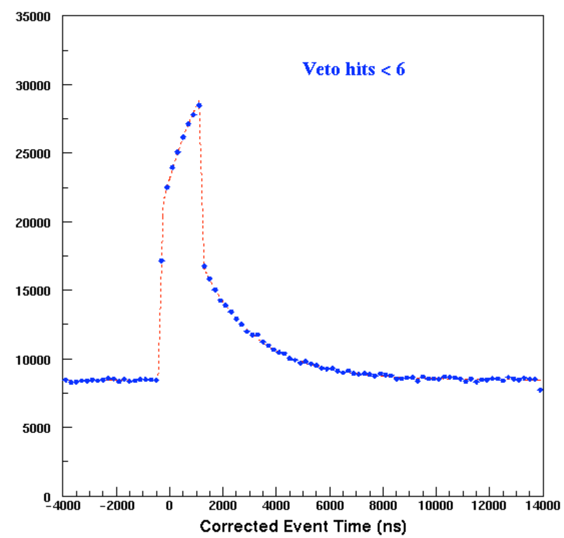
ν_e CC interactions have 1 "sub-event".



Simple cuts eliminate cosmic ray events:

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





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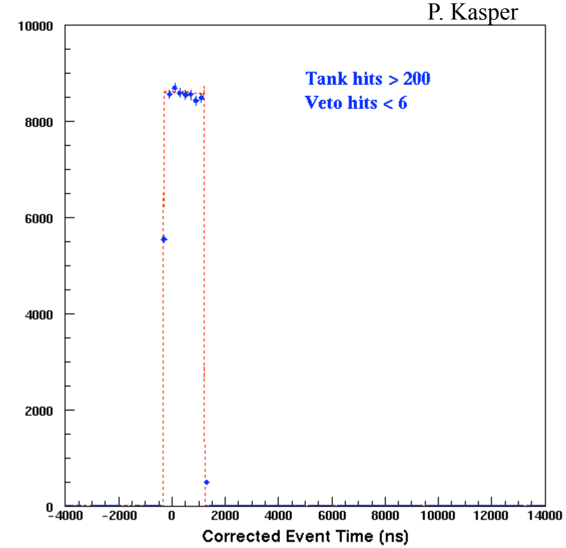
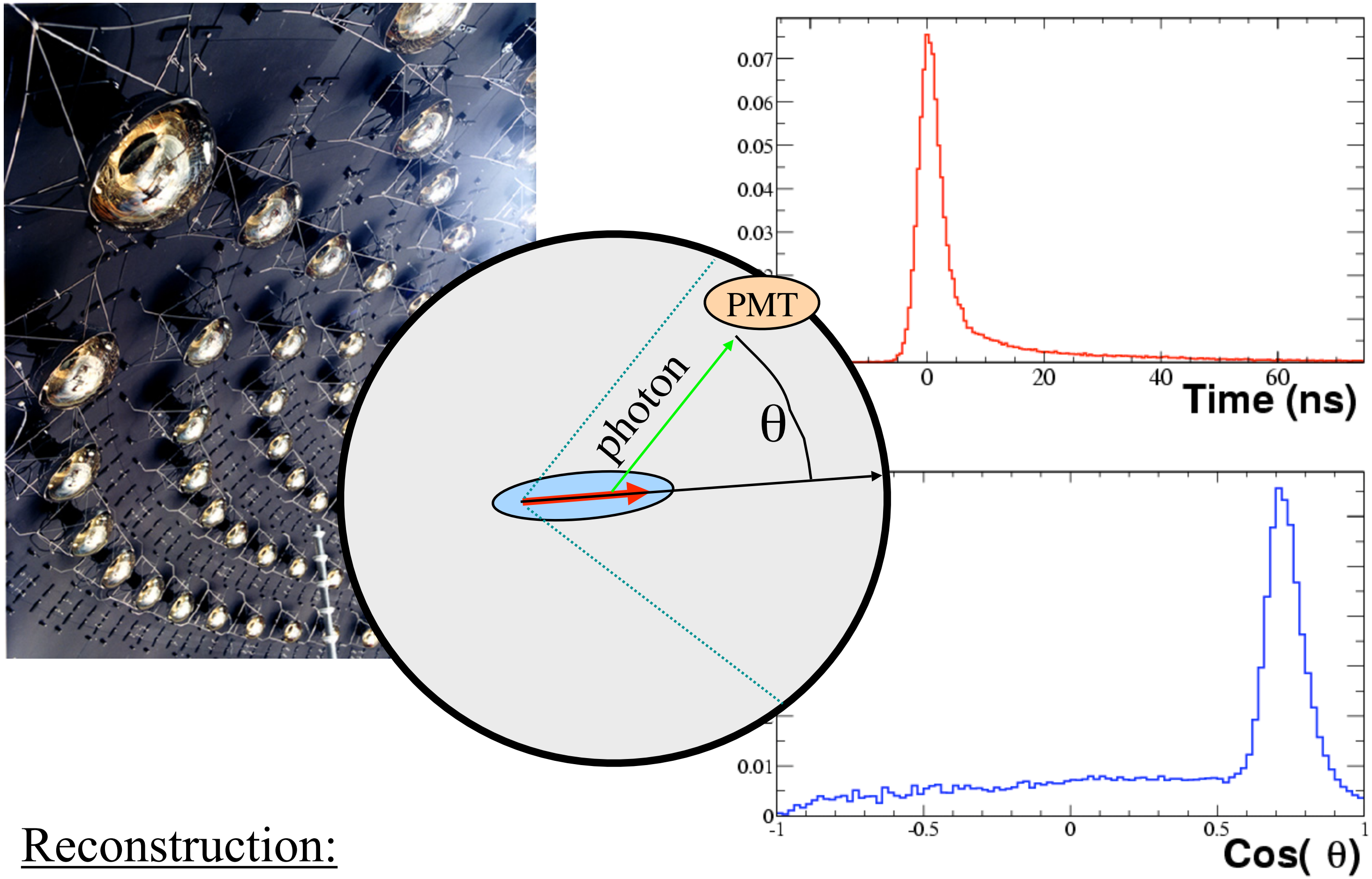
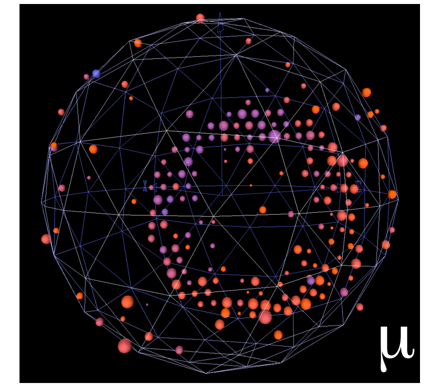
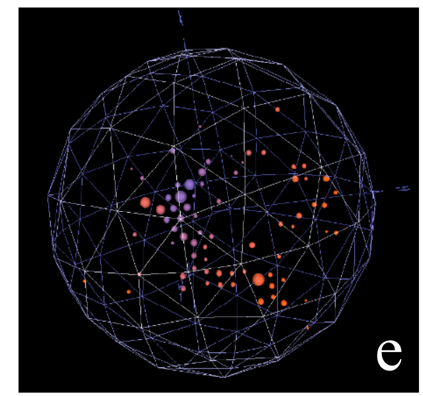
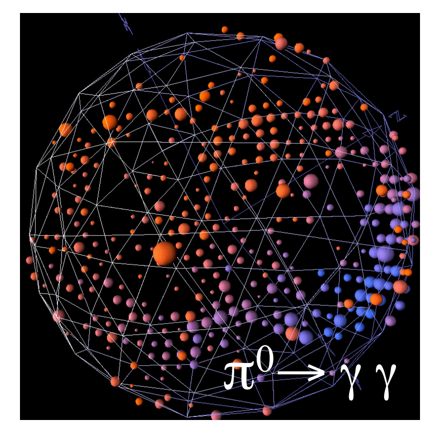


MiniBooNE Detector: Reconstruction and Particle ID







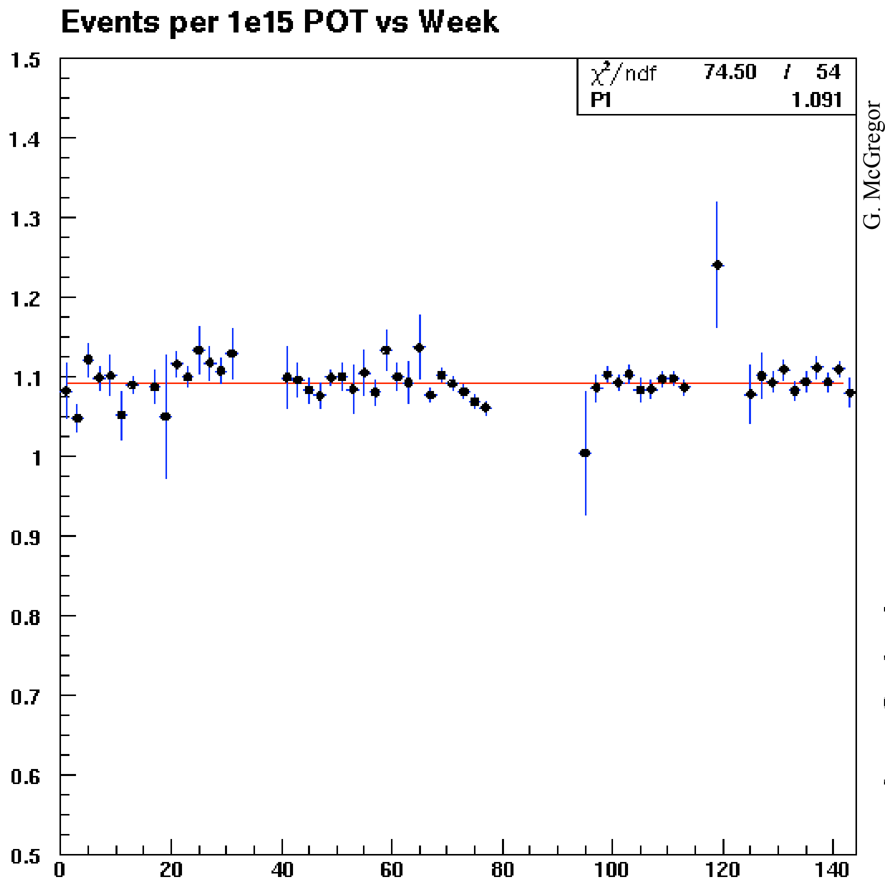


<u>Reconstruction:</u>
Fit time and angular distributions to find tracks

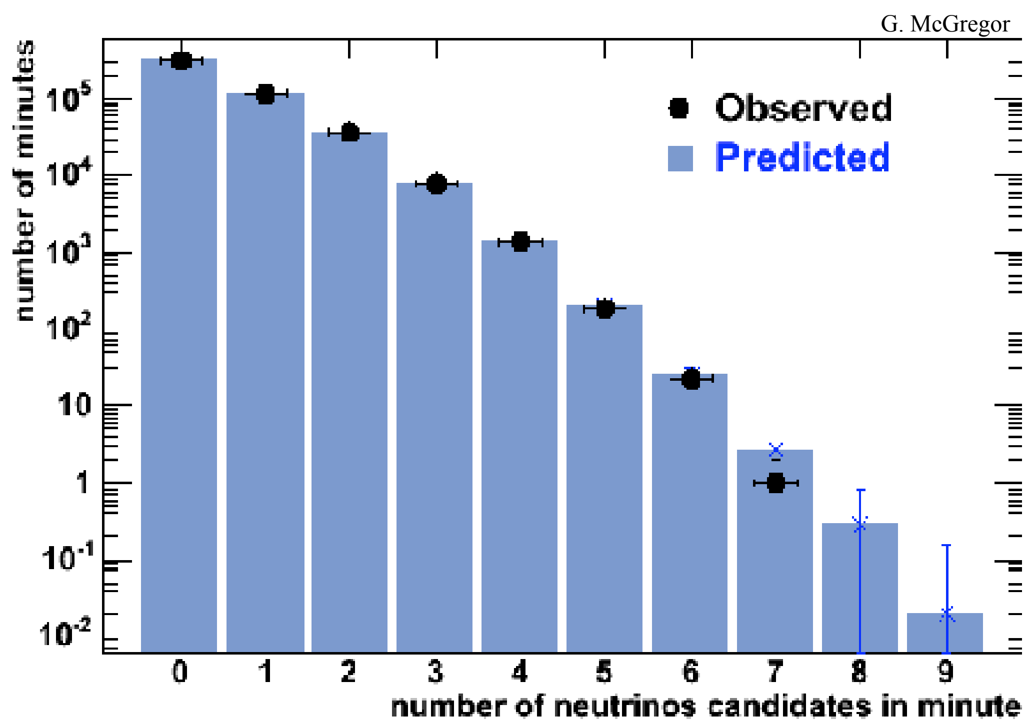
<u>Final State Particle Identification:</u>
muons have sharp Cherenkov rings and long tracks
electrons have fuzzy rings, from multiple scattering, and short tracks
neutral pions decay to 2 γs, which convert and produce 2 fuzzy rings,
easily misidentified as electrons if one ring gets lost!

MiniBooNE 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

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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.

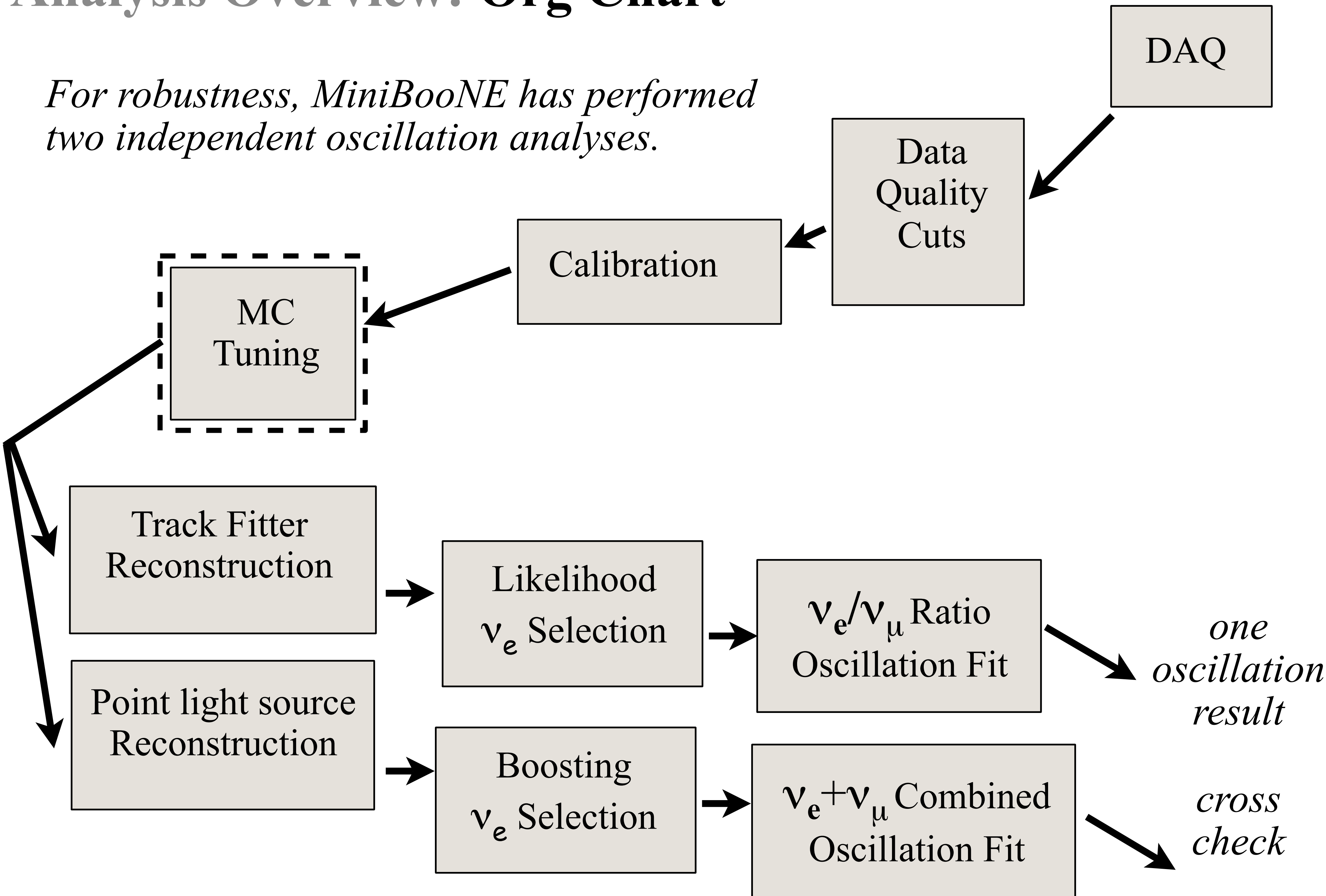
<u>Initial Open Boxes</u>	<u>Use</u>
all non-beam-trigger data	calibration and MC tuning
0.25% random sample	an unbiased data set
ν_μ CCQE	measure flux, E_ν^{QE}, oscillation fit
ν_μ NC1π^0	measure rate for MC
"dirt"	measure rate for MC
all events with E_ν>1.4 GeV	check MC rate
ν_μ CC1π^+	check MC rate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

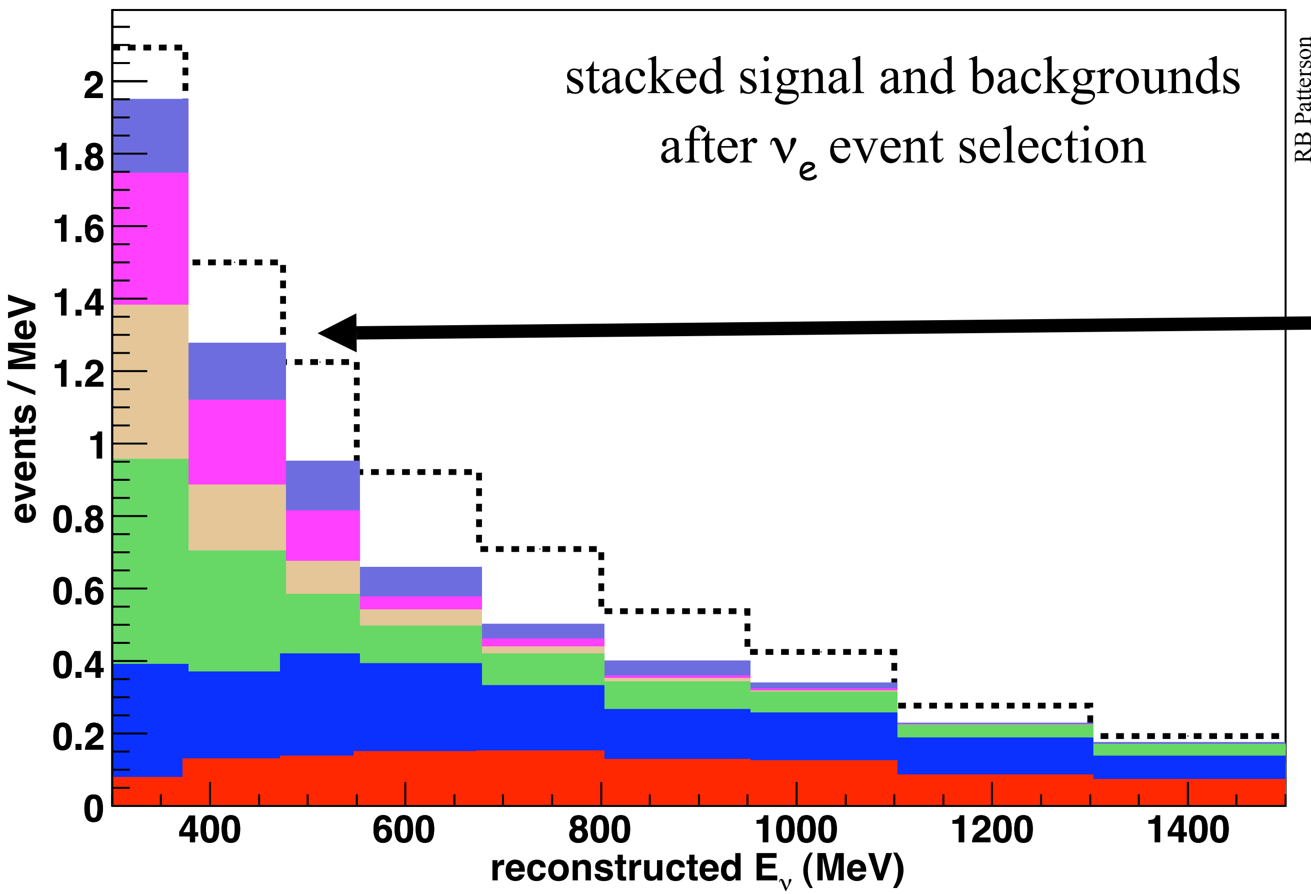
For robustness, MiniBooNE has performed two independent oscillation analyses.



Imperial College London 100 years of living science

Analysis Overview: **Signal and Backgrounds**

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



Oscillation ν_e

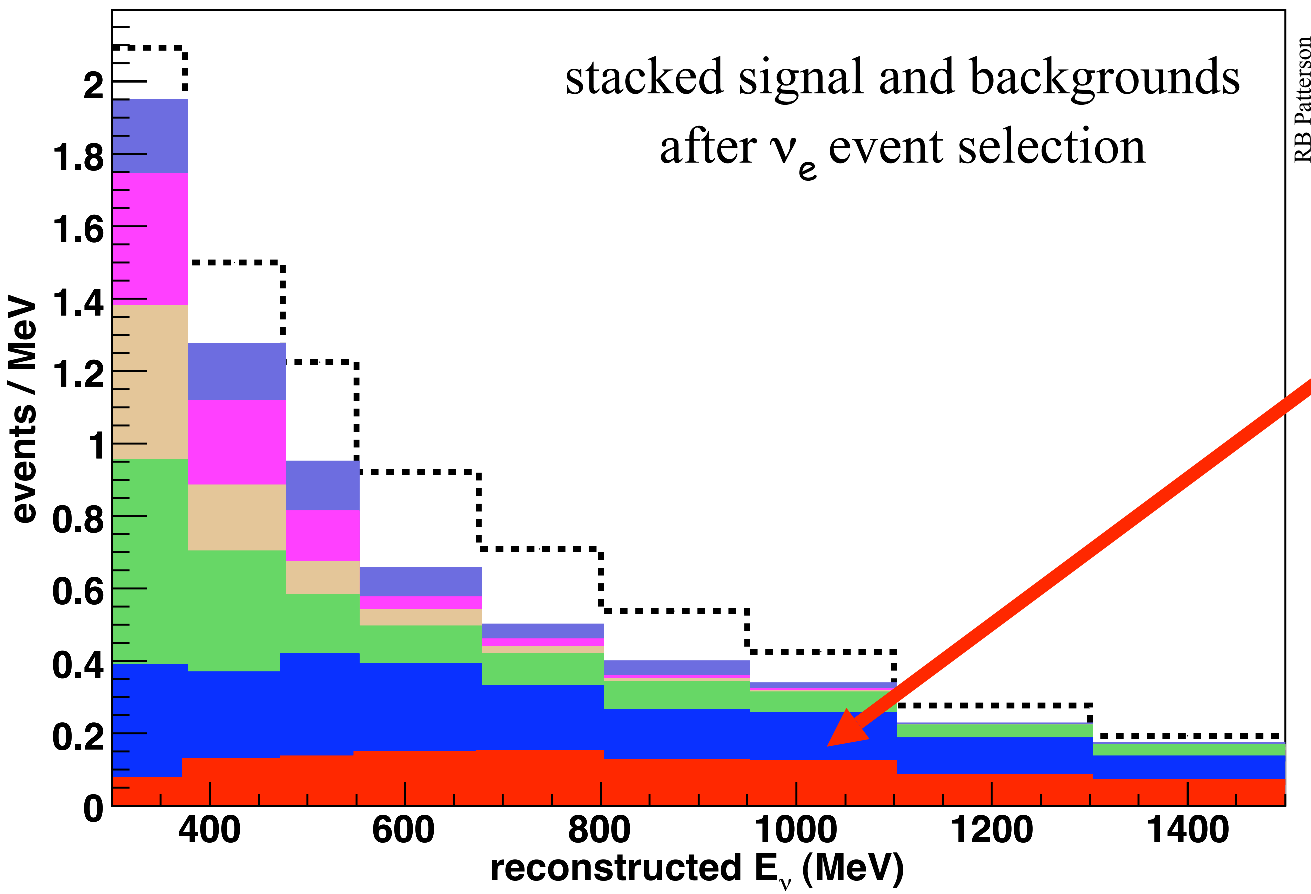
Example oscillation signal

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

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):



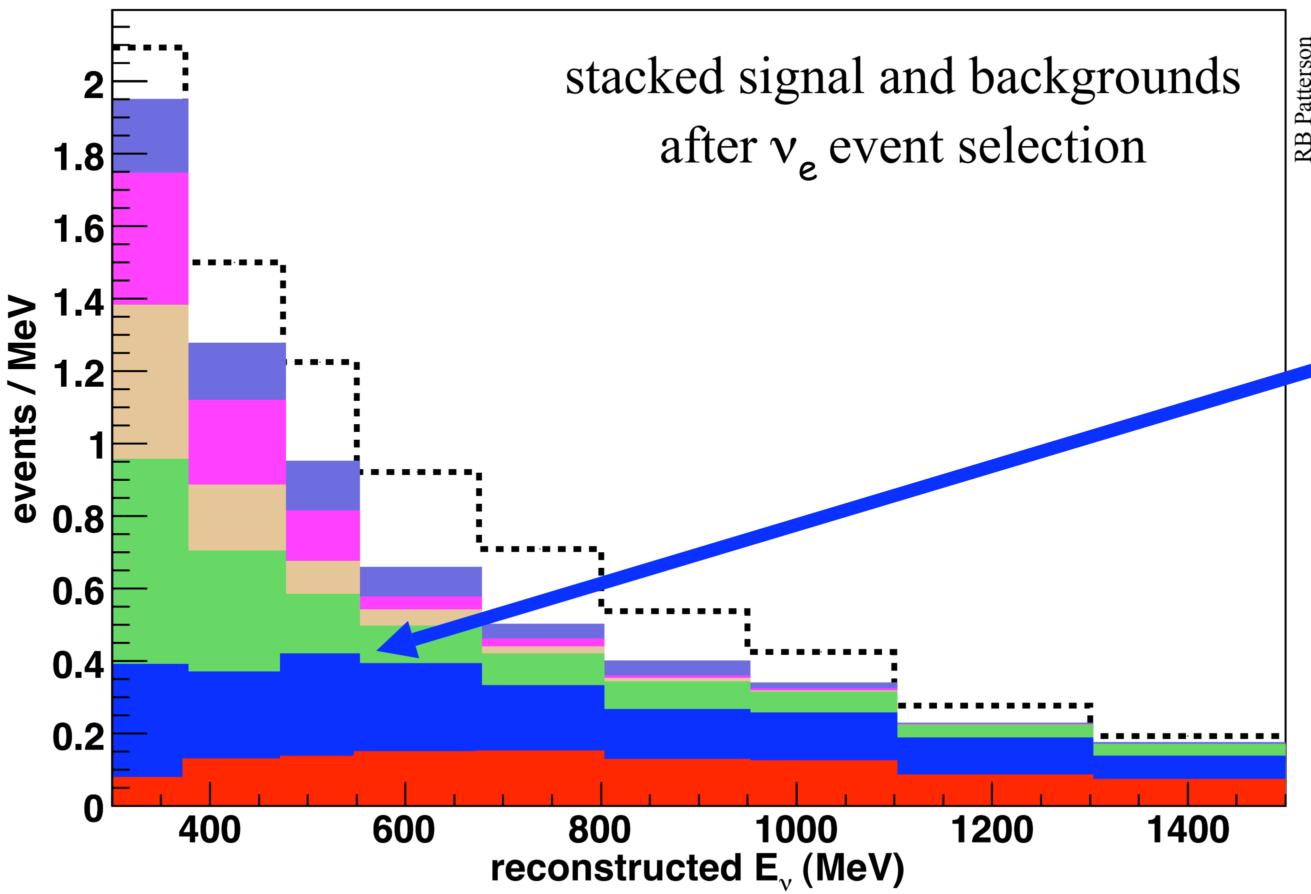
ν_e from K^+ and K^0

Use fit to kaon production data for shape

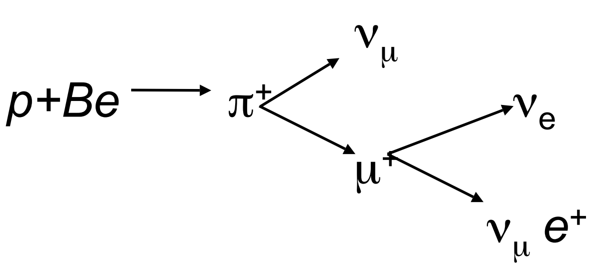
Use high energy ν_e and ν_μ in-situ data for normalisation cross-check

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

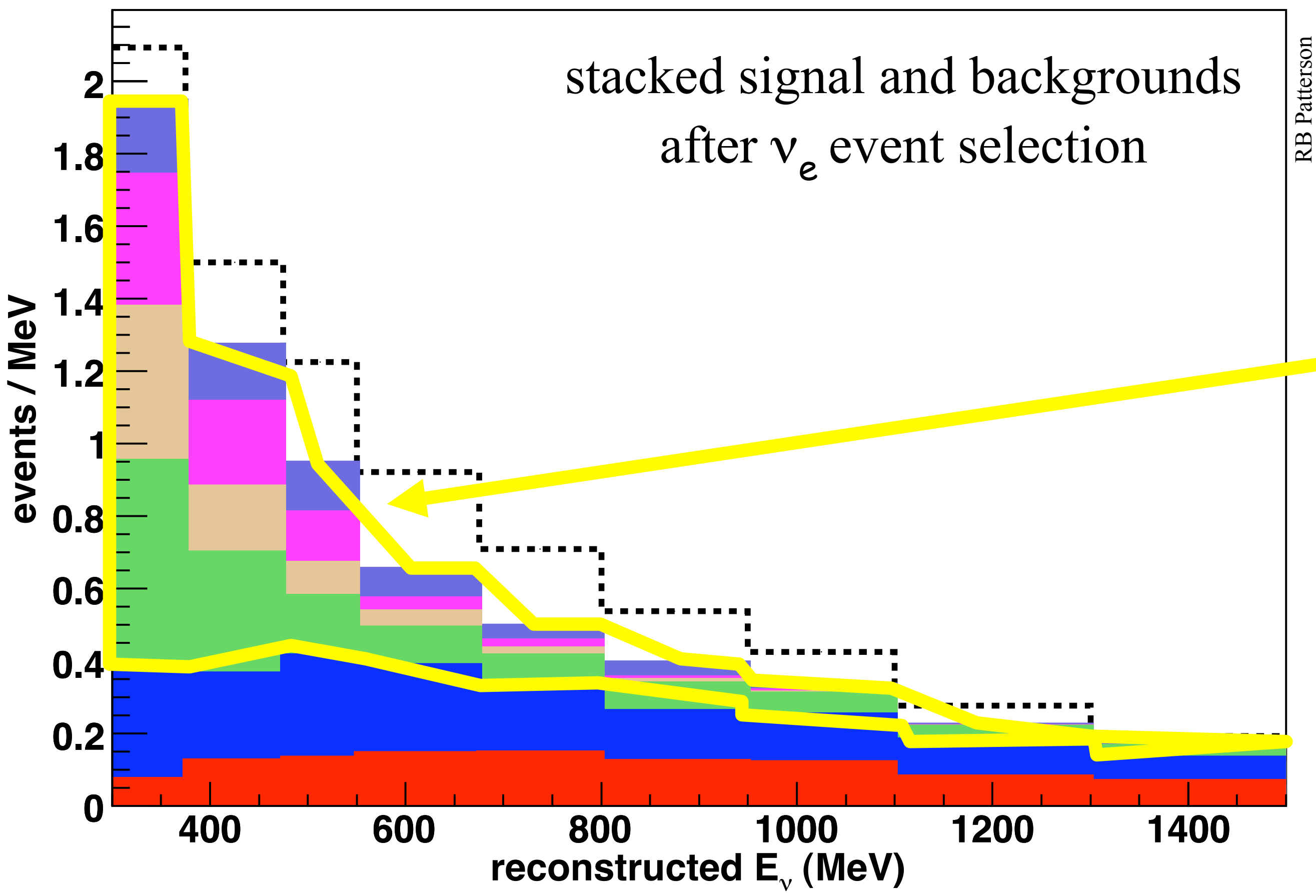
- Same ancestor π^+ kinematics

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 normalise and use MC for shape

~16% Δ γ decay

- π^0 measurement constrains

~24% other

- Use ν_μ CCQE rate to normalise and MC for shape

Analysis Overview: **Strategy**

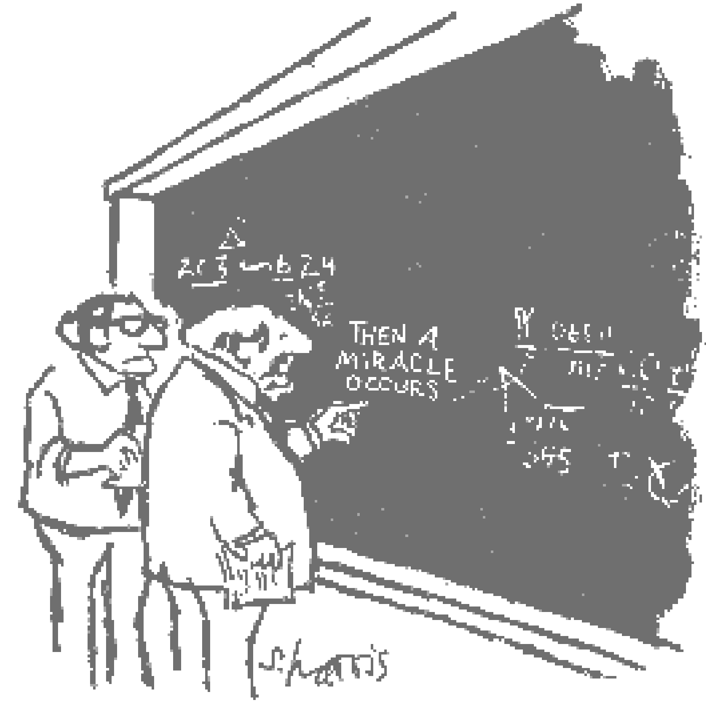
recurring theme: good data/MC agreement

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."

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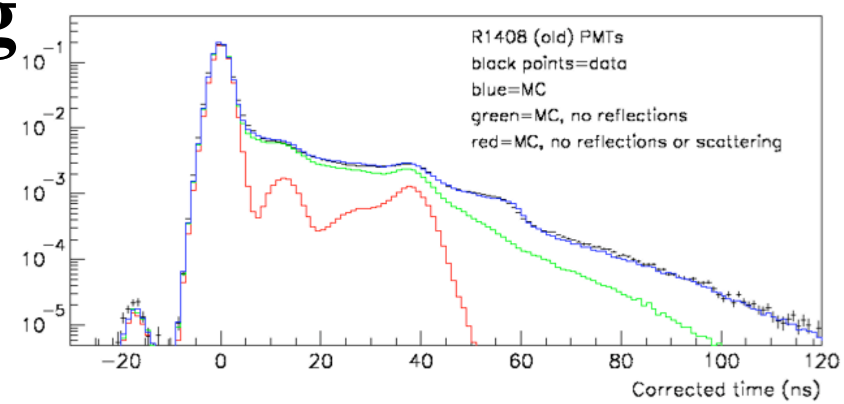
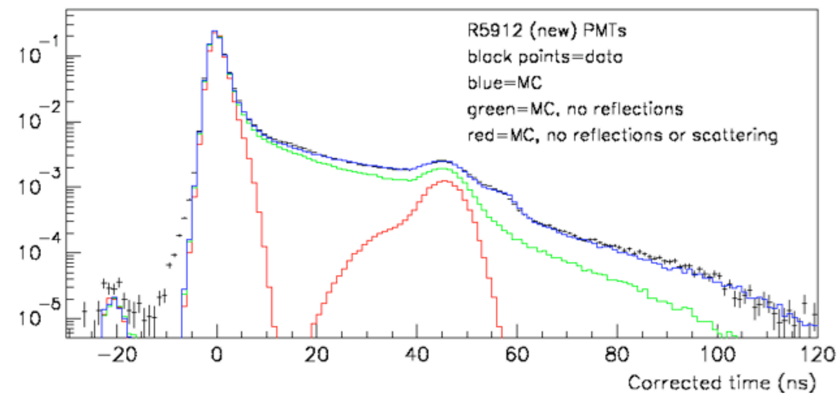
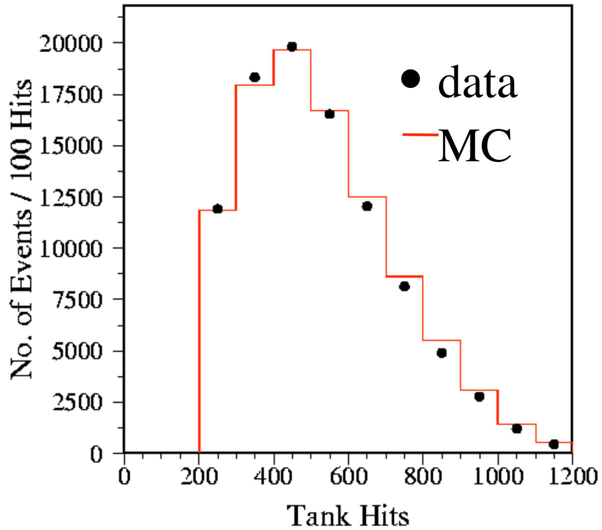
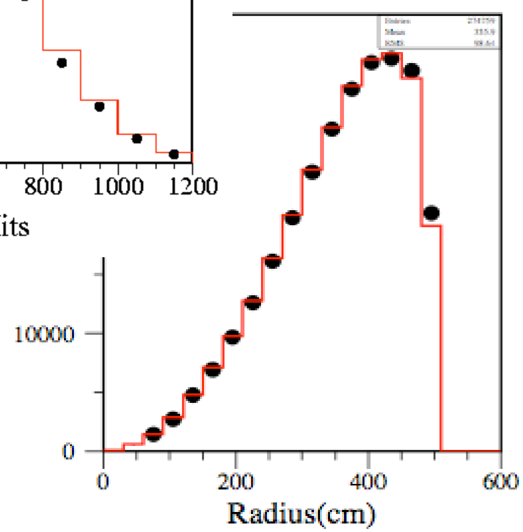
Analysis Overview: MC Tuning

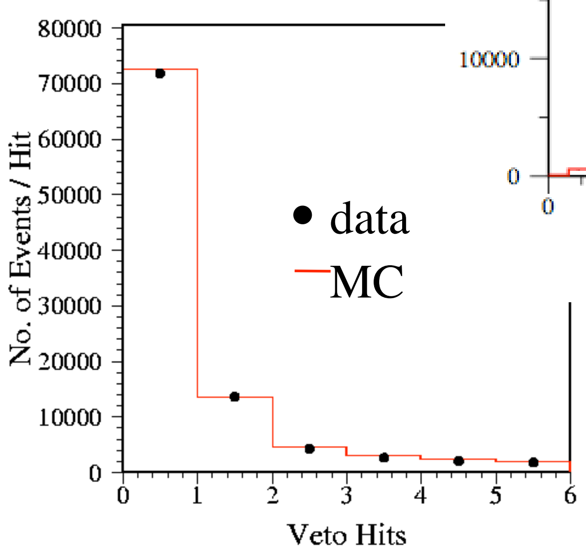
MC tuning with calibration data

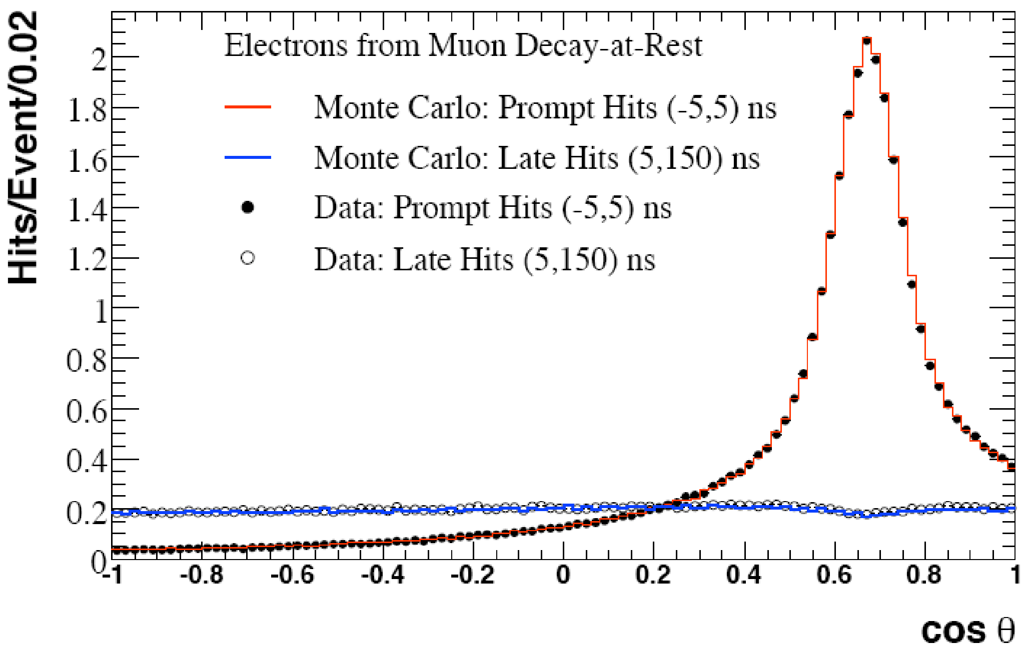












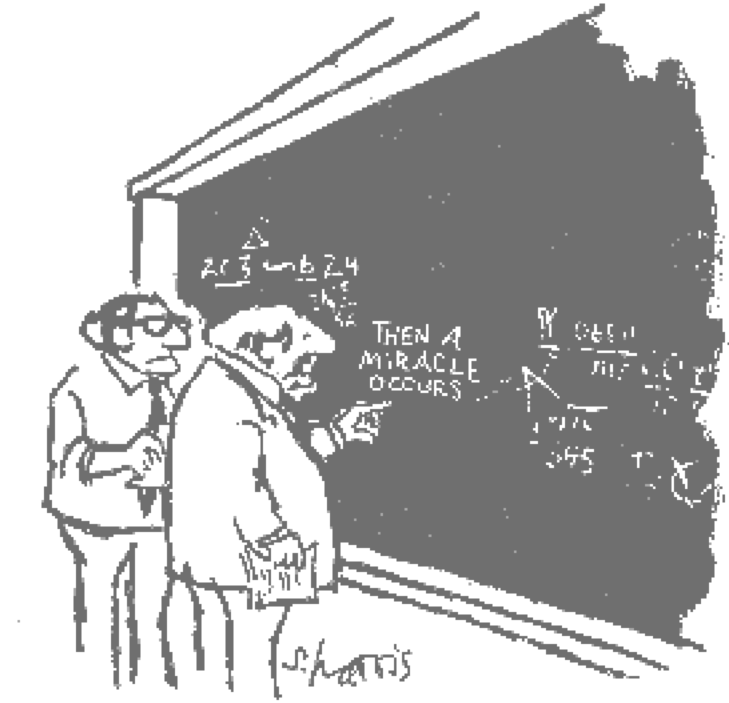
Analysis Overview: **Strategy**

in-situ data are incorporated wherever possible...

(i) MC tuning with calibration data
- 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."

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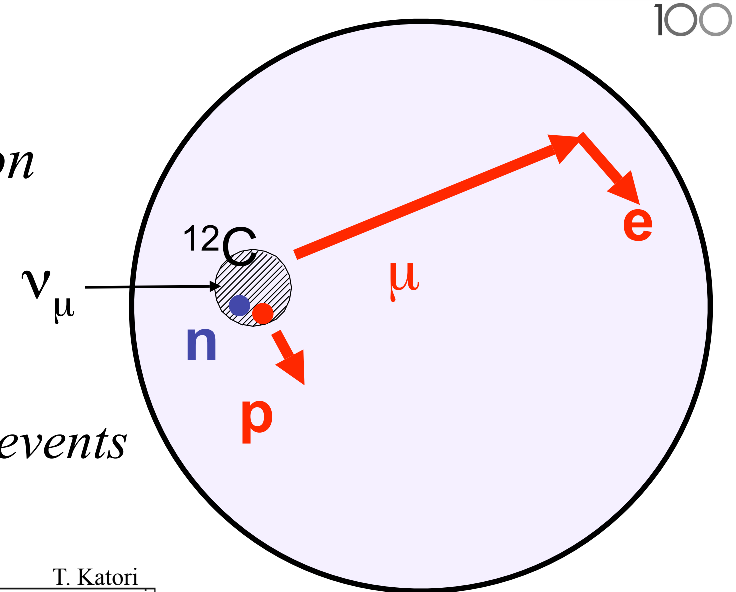
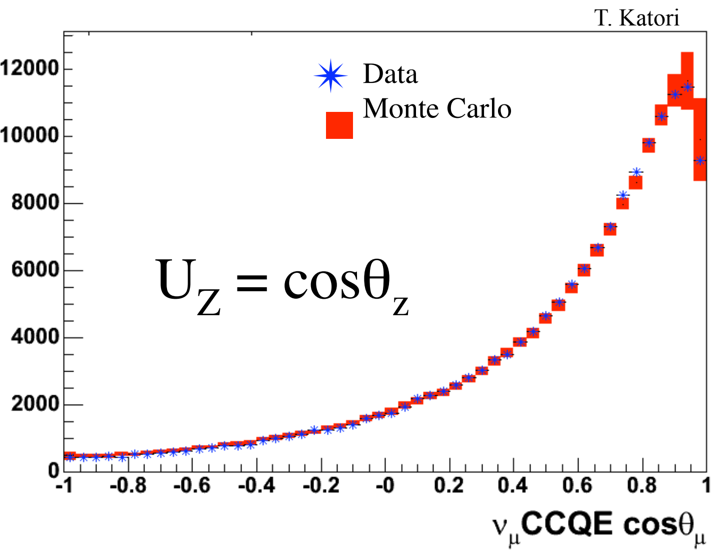
Analysis Strategy: ν_μ CCQE Events

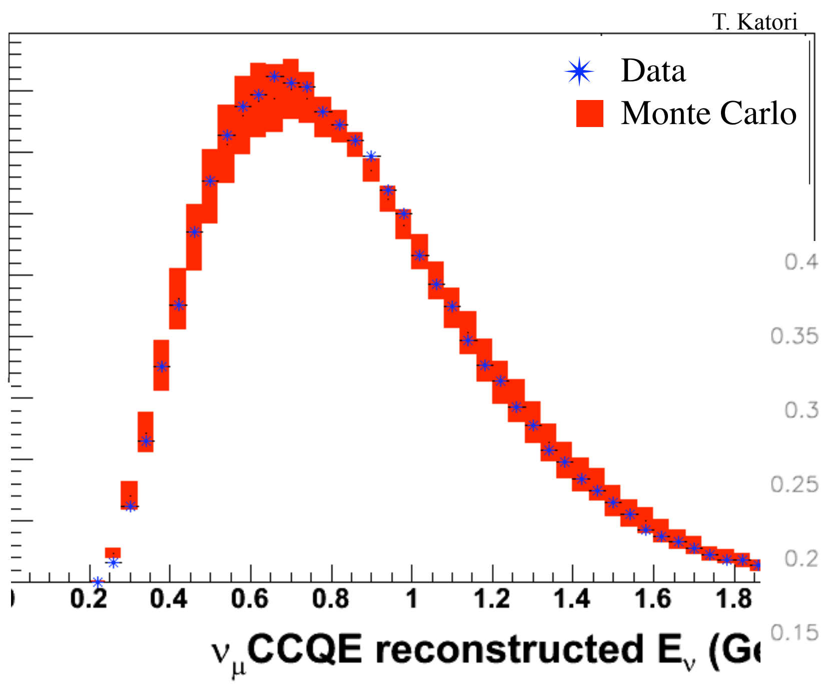
used to measure the ν_μ flux and check E_ν^{QE} reconstruction

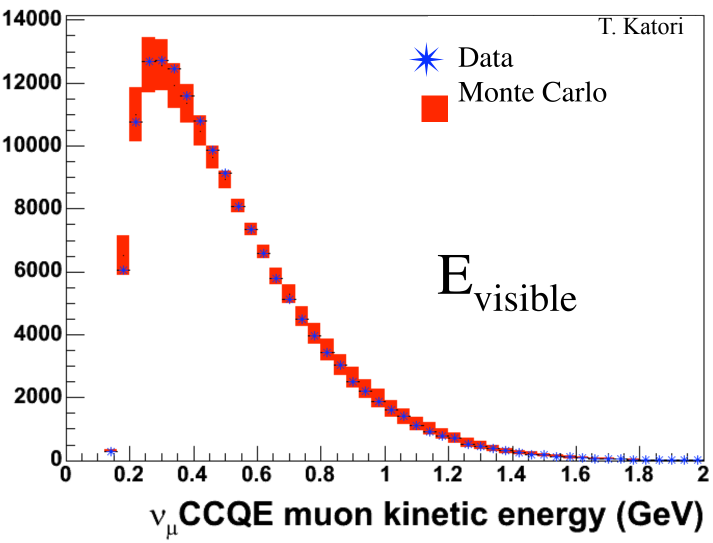
1. tag muons by requiring 2 sub-events in time
2. require reconstructed distance between sub-events < 1*m*



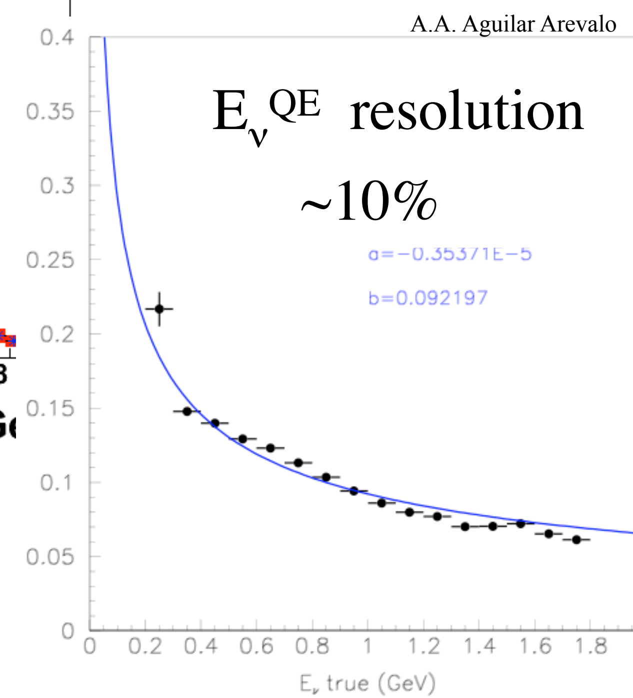
~74% CCQE purity, ~190k events





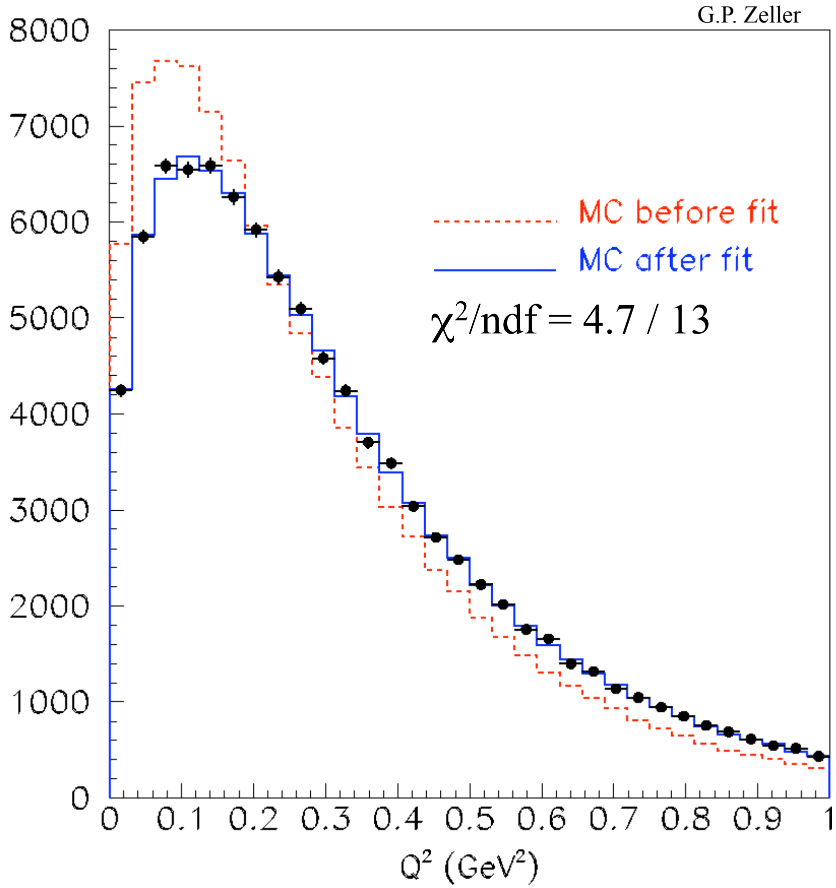


$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\ cos\theta_\mu}$$

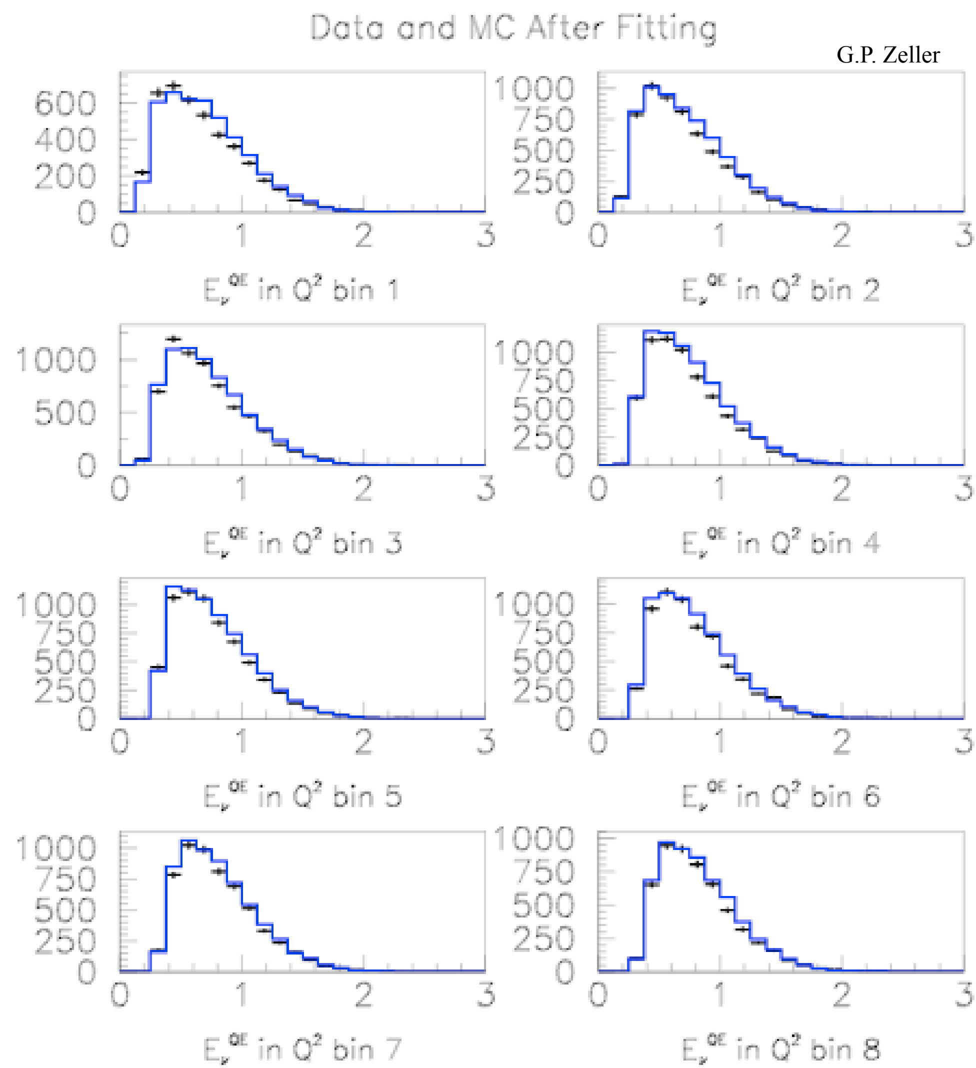


Incorporating ν_μ Data: CCQE Cross Section

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

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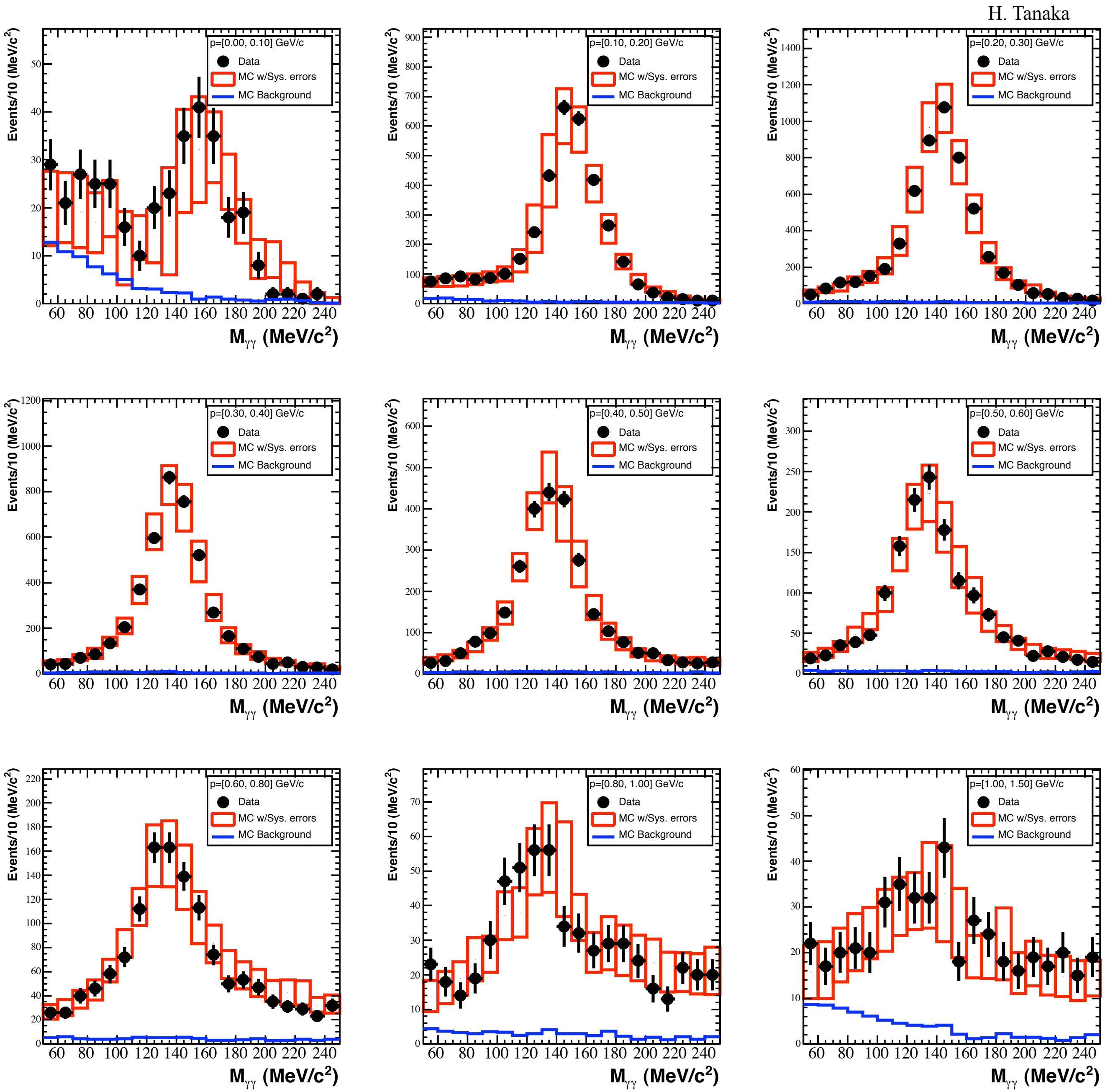
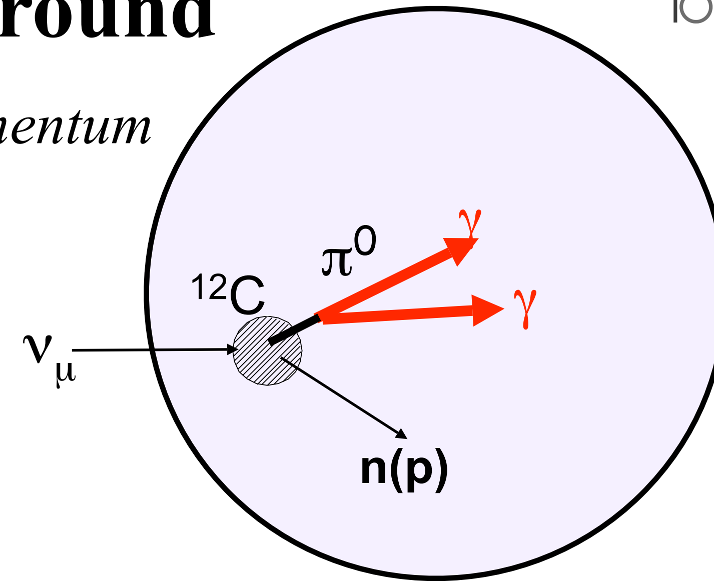
Analysis Strategy: π^0 Mis-ID Background

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



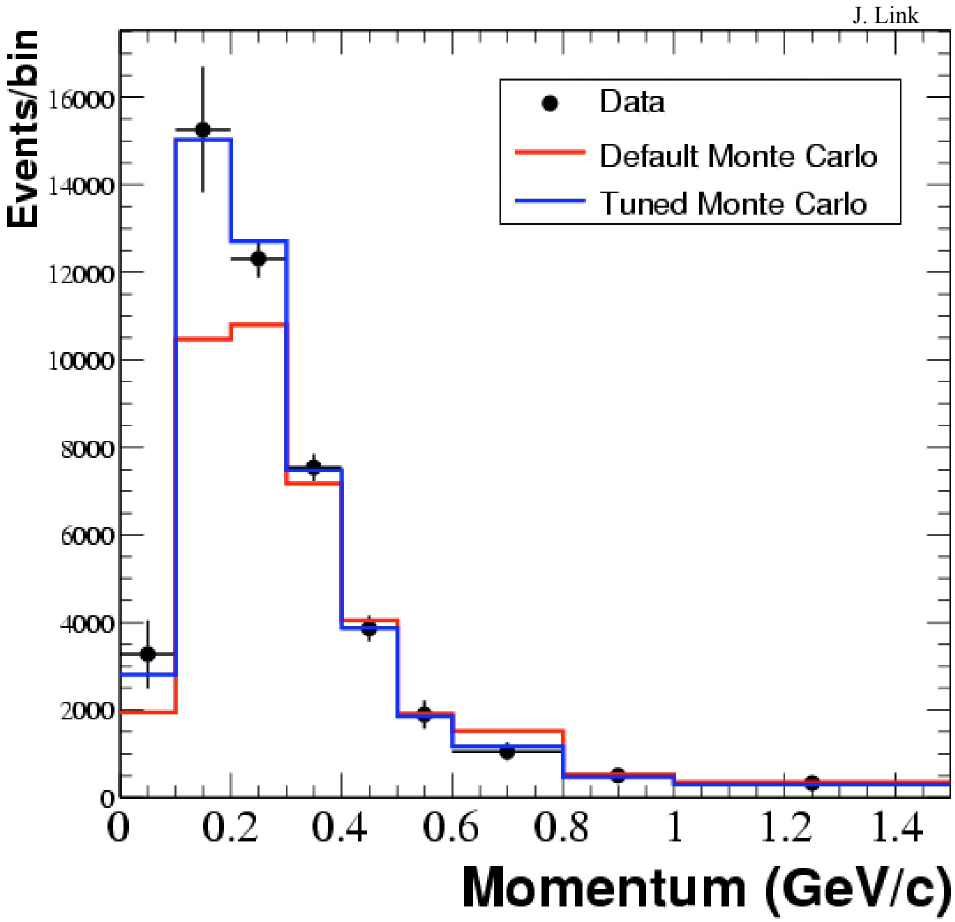


π^0 events can reconstruct outside of the mass peak when:

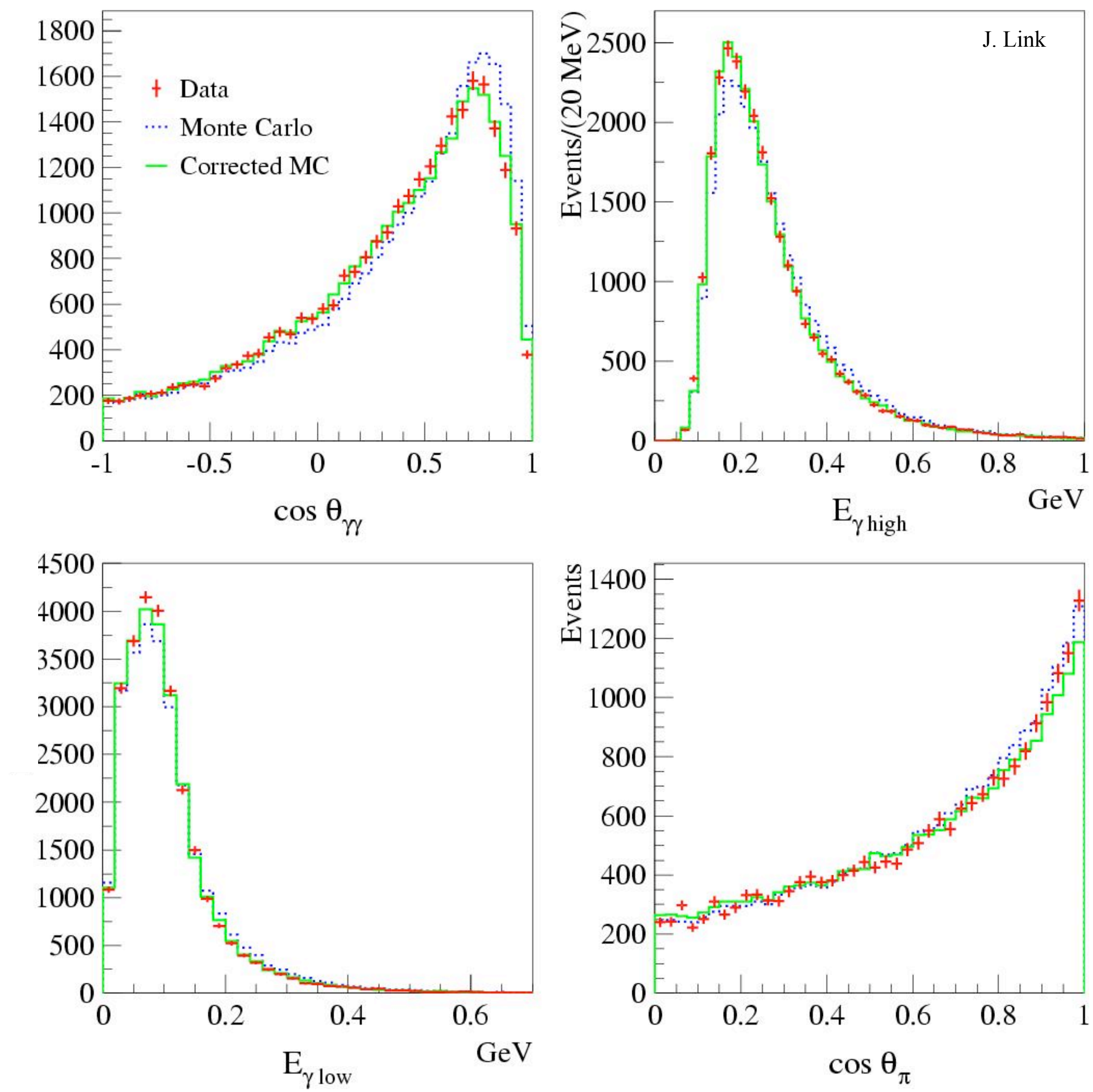
1. asymmetric decays fake 1 ring
2. 1 of the 2 photons exits the detector
3. high momentum π^o decays produce overlapping rings

Analysis Strategy: π^0 Mis-ID Background

The MC π^0 rate (flux × xsec) is re-weighted 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 $\Delta \rightarrow N\gamma$ in MiniBooNE

Analysis Overview: **Strategy**

in-situ data is incorporated wherever possible...

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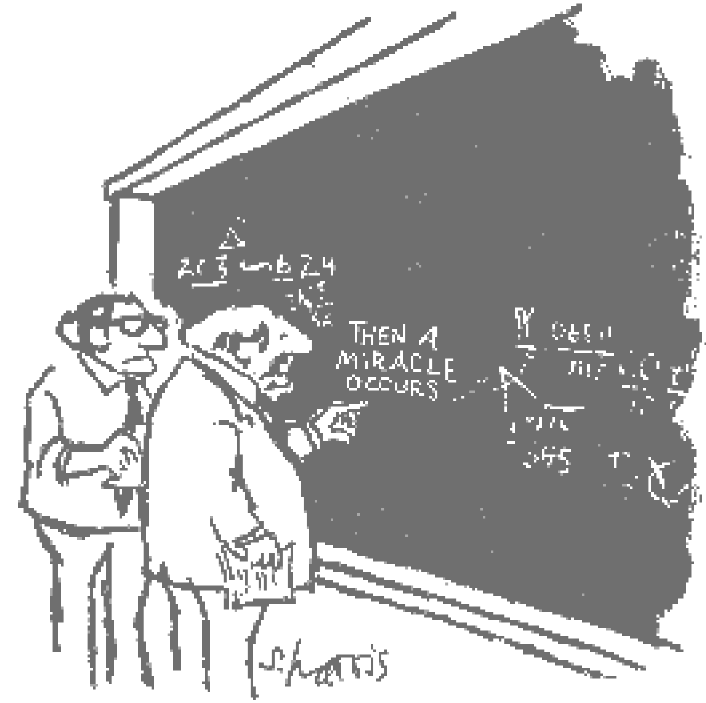
- combined oscillation fit to ν_μ and ν_e data

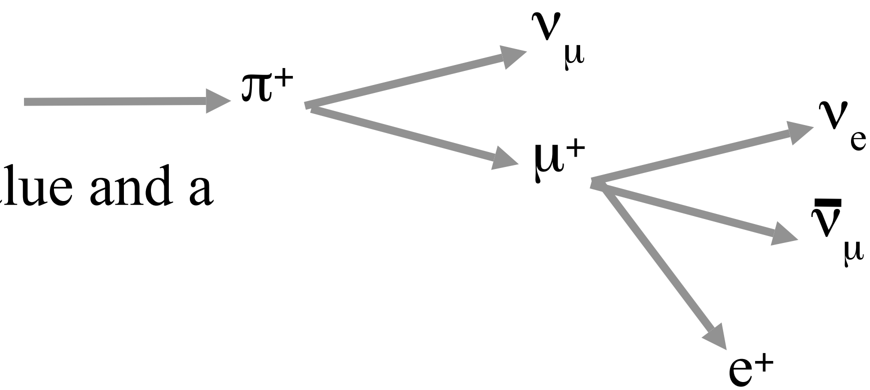


"I think you should be more explicit here in step two."

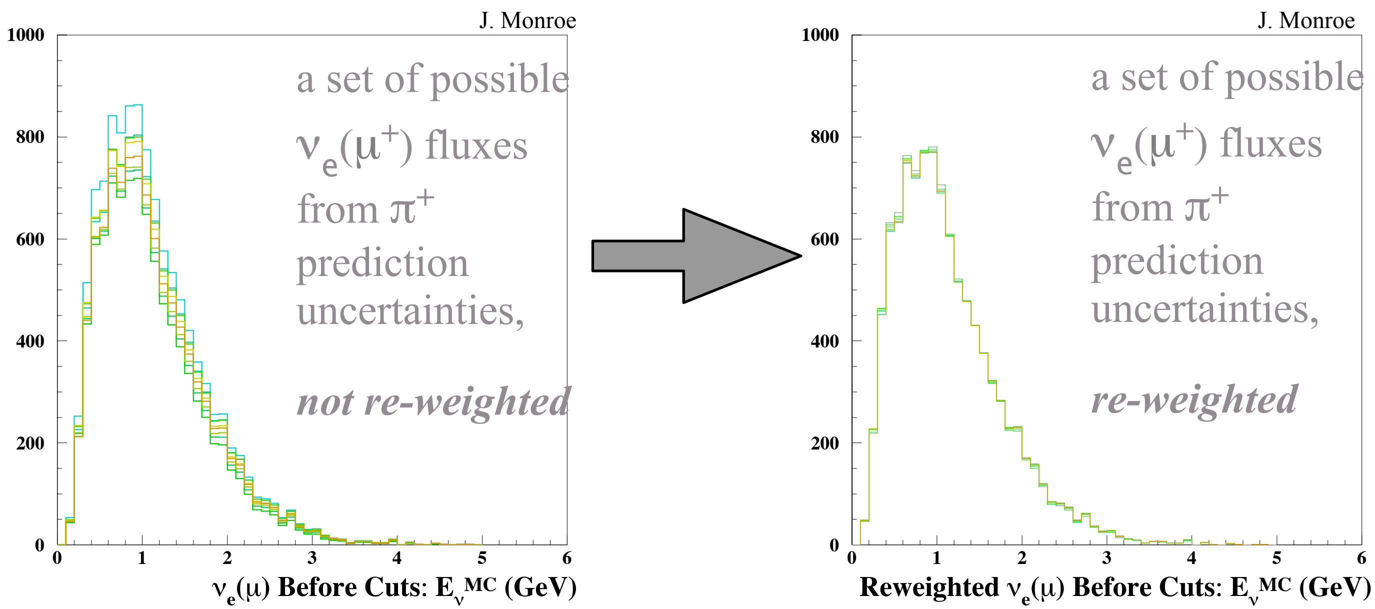
Analysis Strategy 1: **Ratio Method**

Example: ν_μ CCQE events measure π^+ spectrum, constrain μ^+-decay ν_e flux

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 parent-π^+ flux by the ratio (2), including sister μ^+ & niece ν_e



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

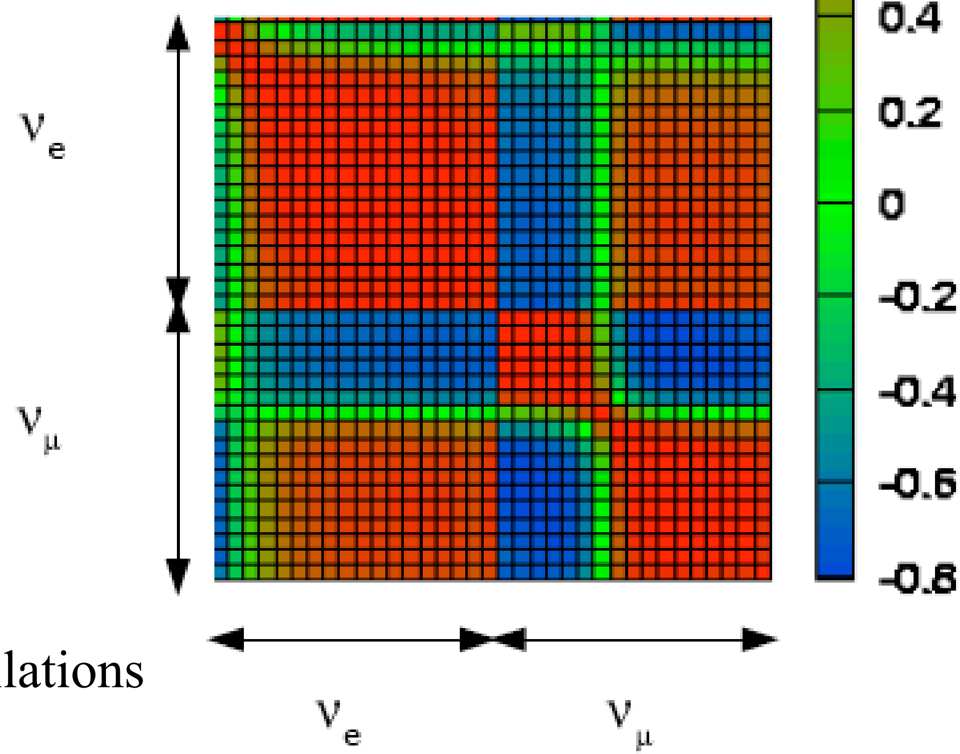
Raster scan in Δm^2 , and $sin^2 2\theta_{\mu e}$ ($sin^2 2\theta_{\mu x} == 0$),
calculate χ^2 value over ν_e **and** ν_μ bins

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

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

$$M_{ij} = \begin{pmatrix} \nu_e & \nu_e \nu_\mu \\ \nu_\mu \nu_e & \nu_\mu \end{pmatrix}$$

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

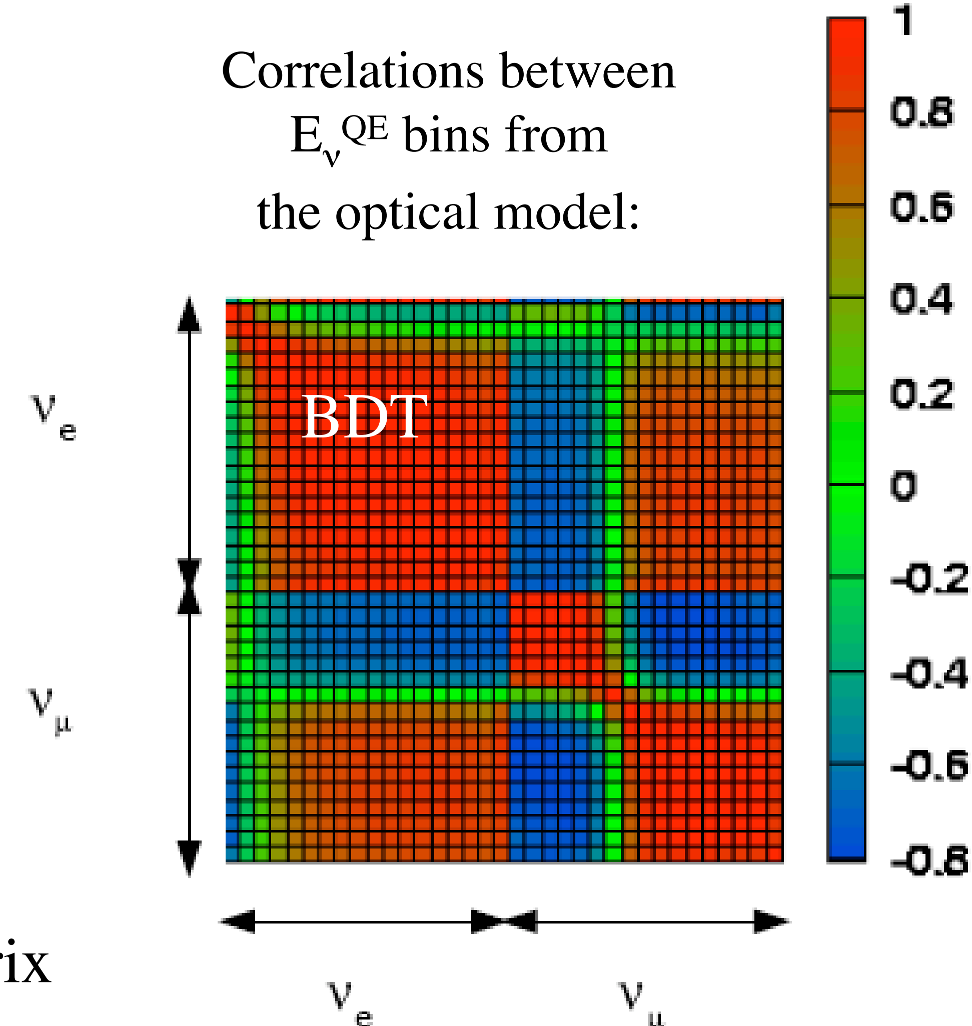
Analysis Strategy: Error Matrix

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

- 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

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*

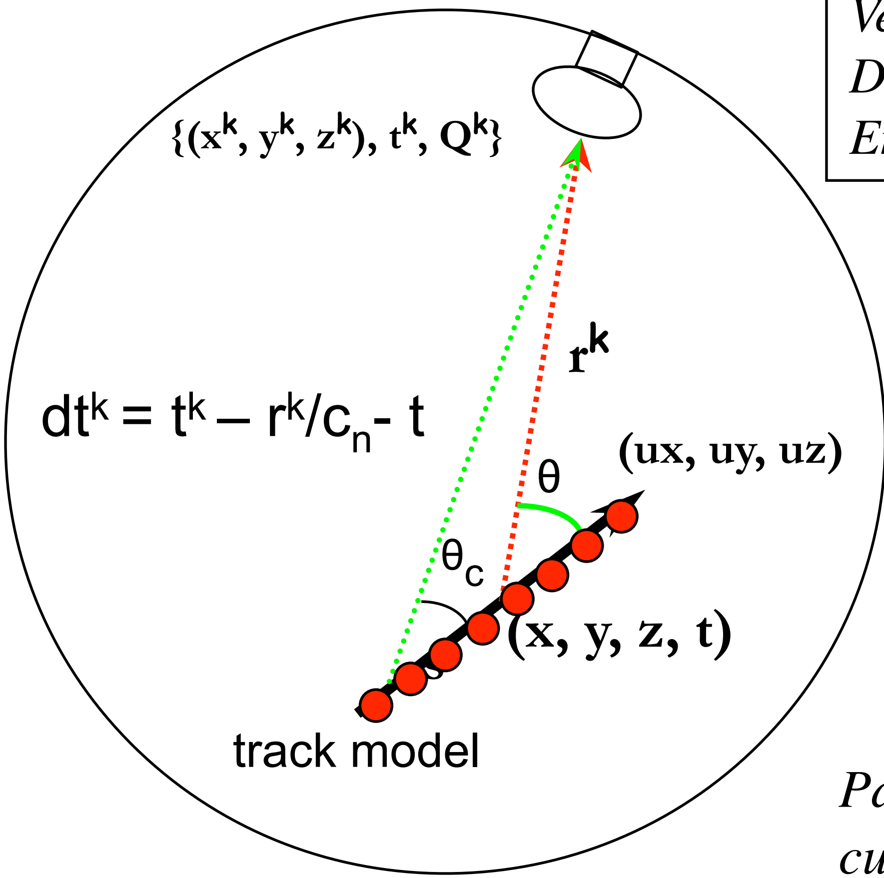
Strengths:

Combination of many weak variables form strong classifier
Better constraints on background events

Method 1: Track-Based Analysis

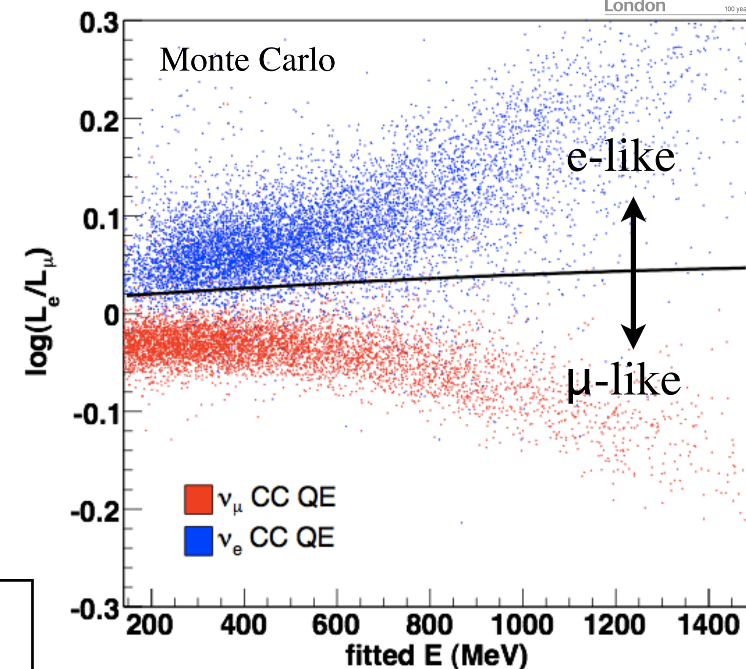
Reconstruction fits an extended light source with 7 parameters: vertex, direction (θ, ϕ), time, energy

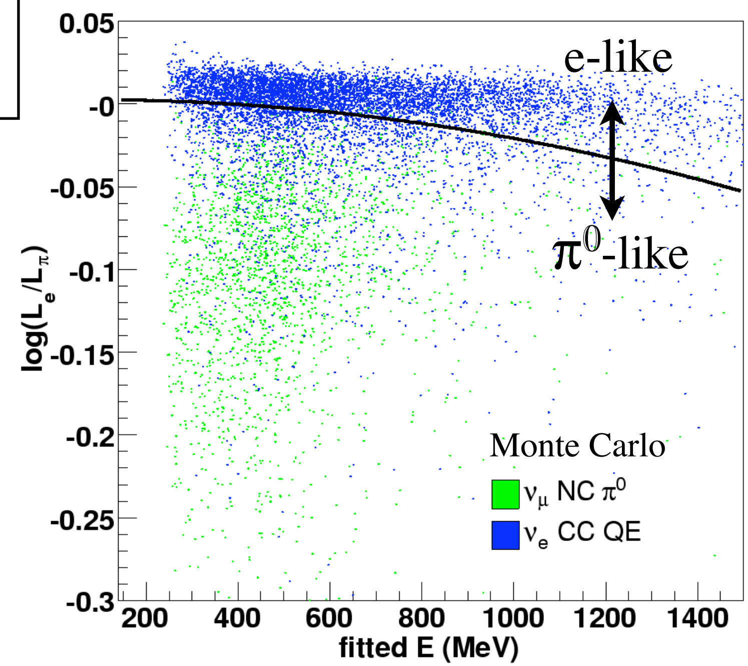
Fit events under 3 possible hypotheses:
μ-like, e-like, two track (π^0-like)



Fitter resolution

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

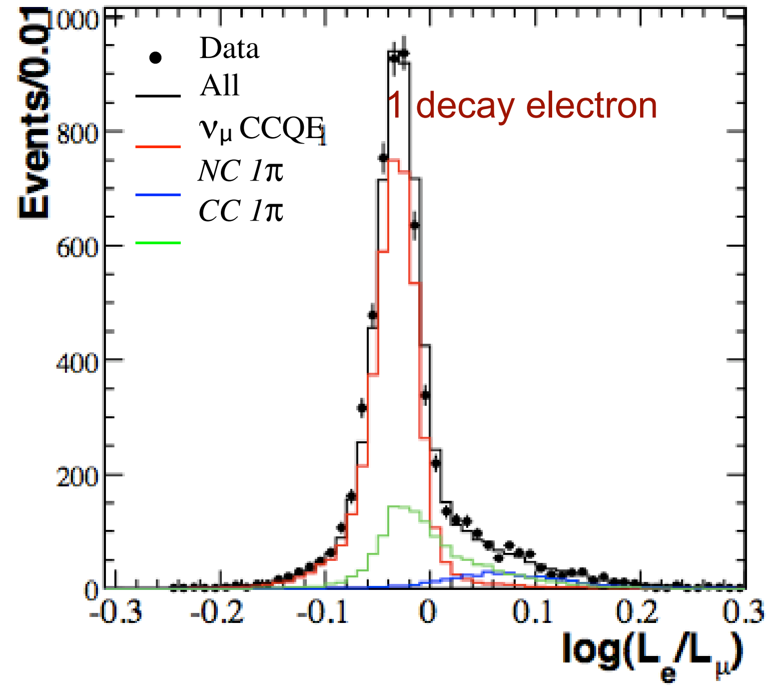




Particle ID relies on likelihood ratio cuts to select ν_e, cuts chosen to maximise sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillation

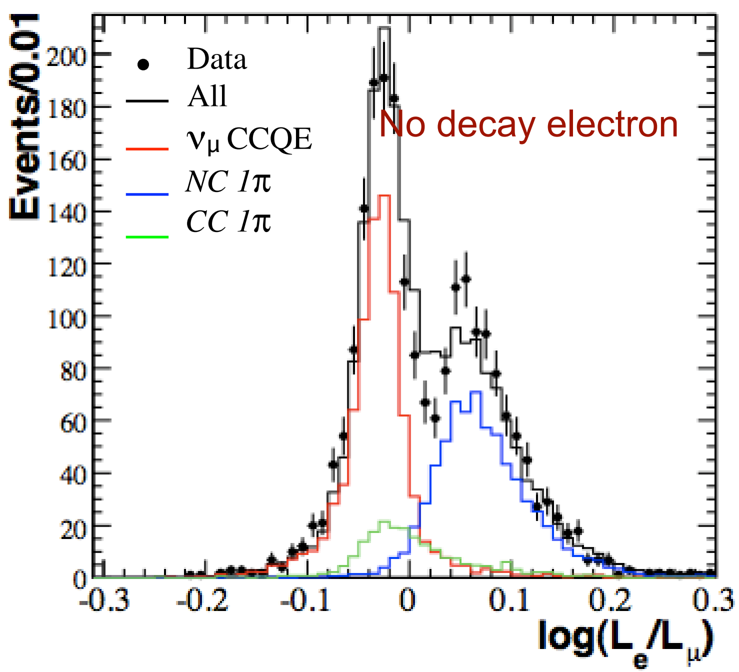
Track-Based Analysis: e/μ Likelihood

Test μ-e separation on data:



<u>ν_μ CCQE data sample</u>

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



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

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.*

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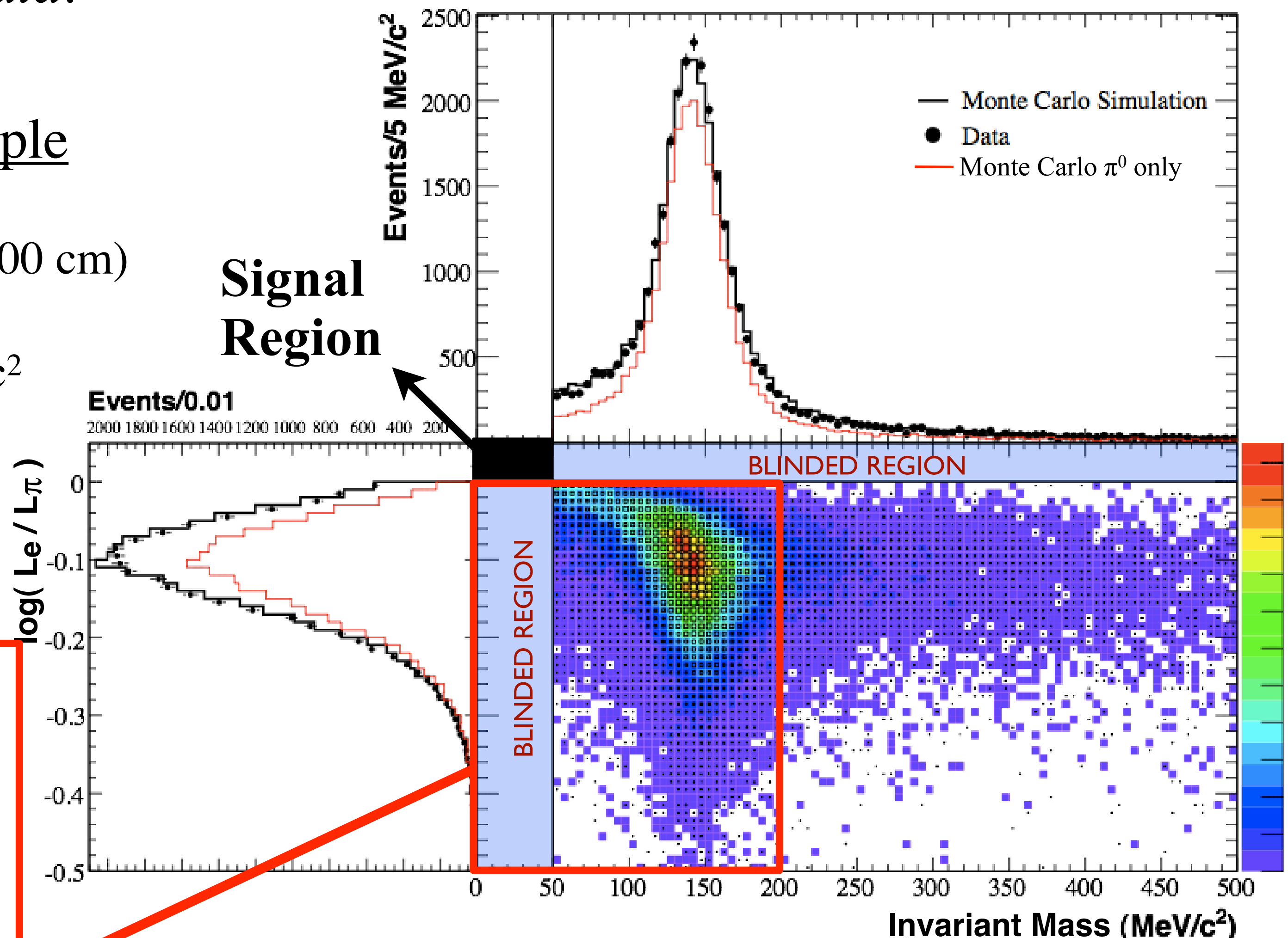
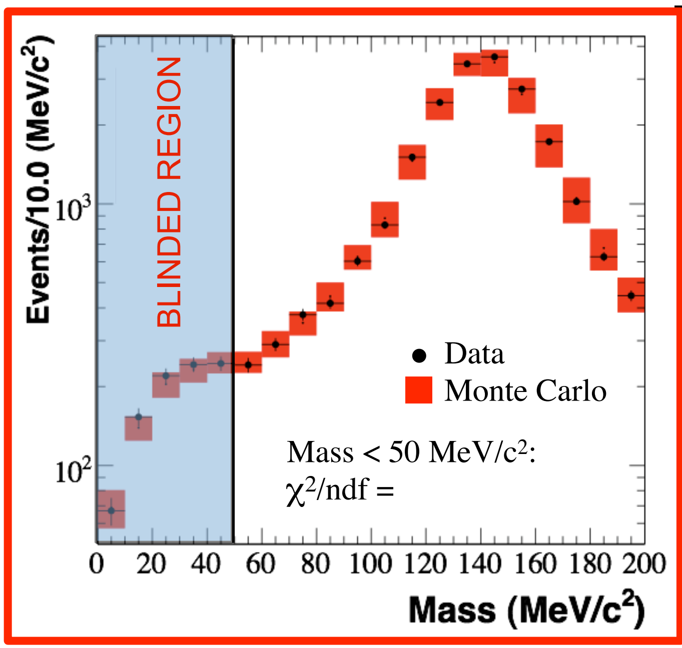
Track-Based Analysis: e/π^0 Likelihood

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)





<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

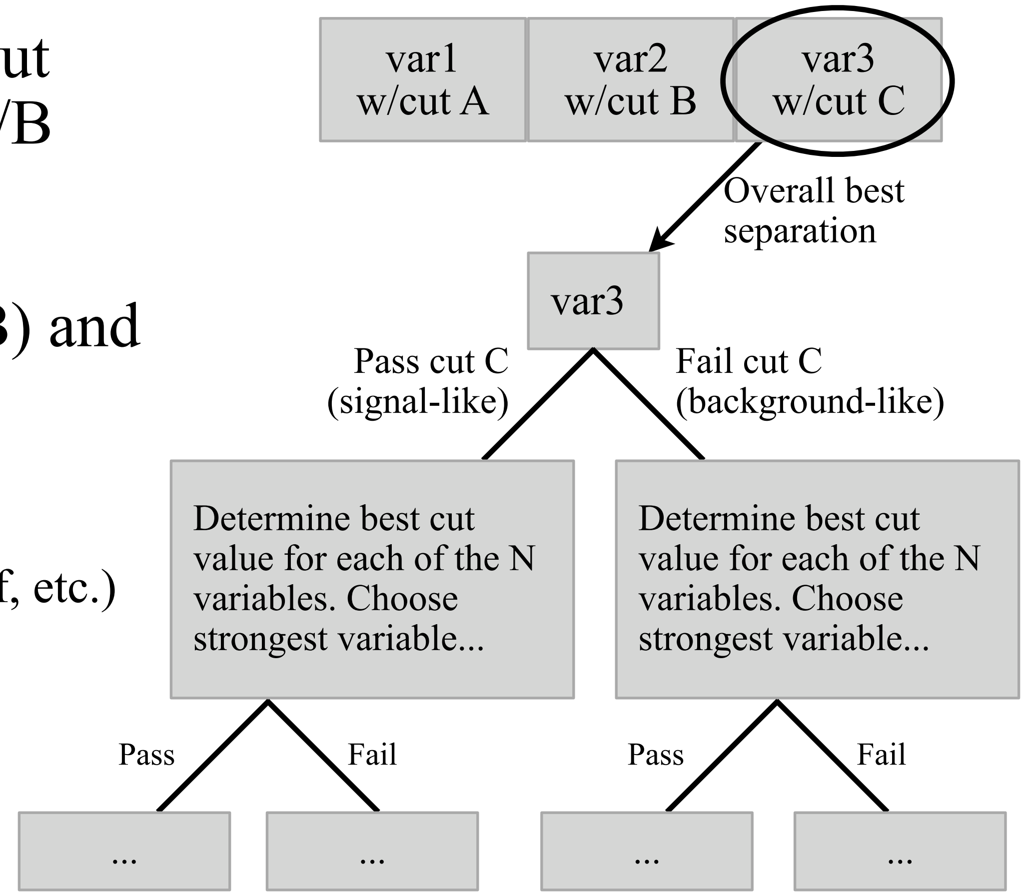
Decision Trees: A machine-learning technique which tries to recover signal events that would be eliminated in cut-based analyses.

Training a decision tree:

For a set of N variables, determine the cut value for each variable that gives best S/B separation.

Cut on the best variable (i.e. highest S/B) and repeat.

Final score: For each leaf,
- 1 for correct events (signal event on a signal leaf, etc.)
+1 for incorrect events

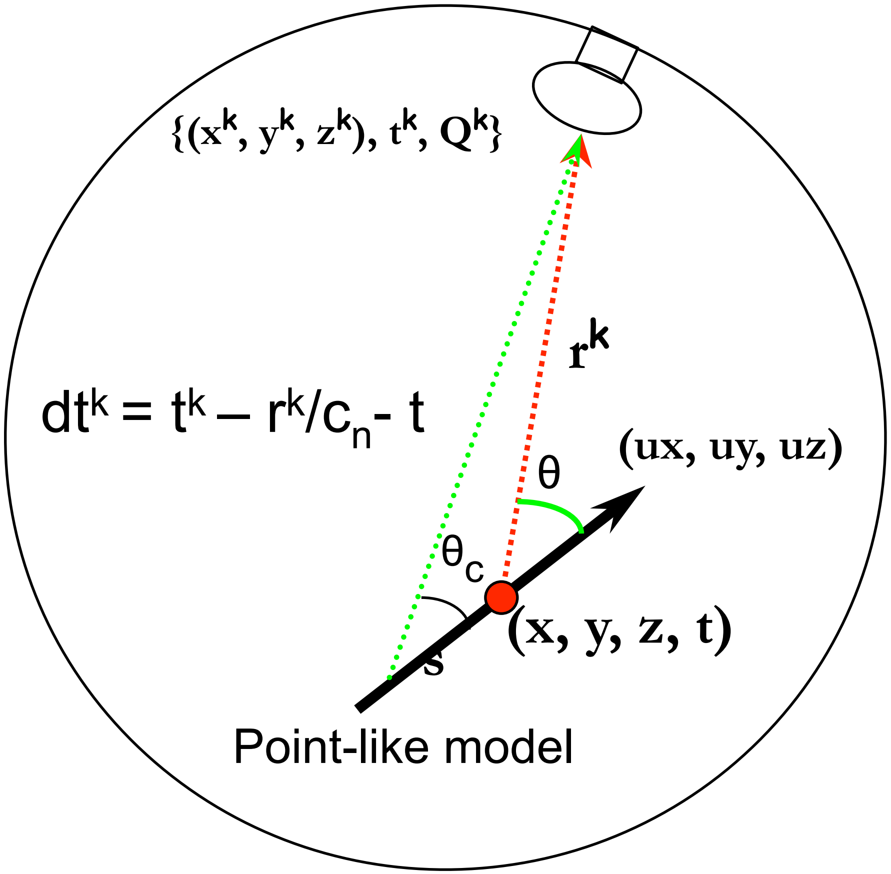


Boosting: Increase weight of misclassified events.
Re-training with newly weighted events improves performance.

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

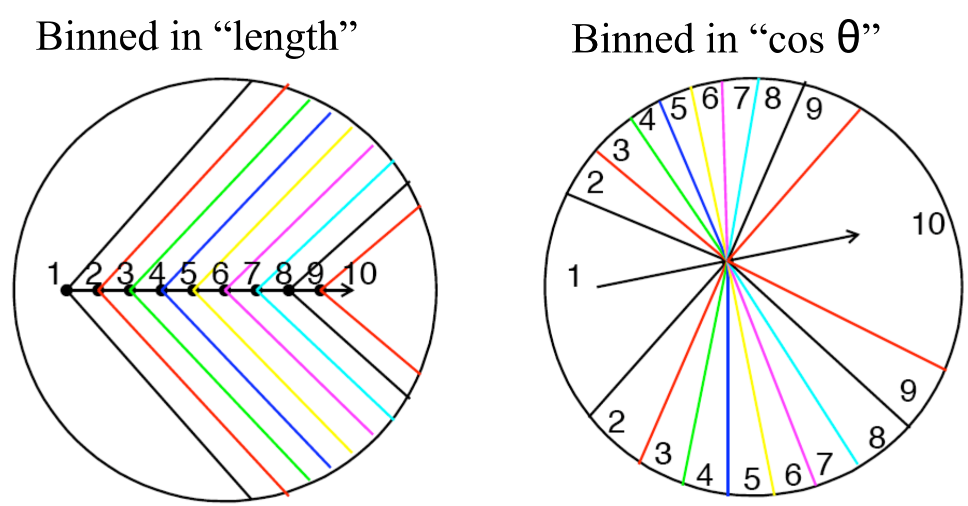
Reconstruction fits a point-like light source:
vertex, direction (θ, ϕ), time, energy



Fitter resolution

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

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

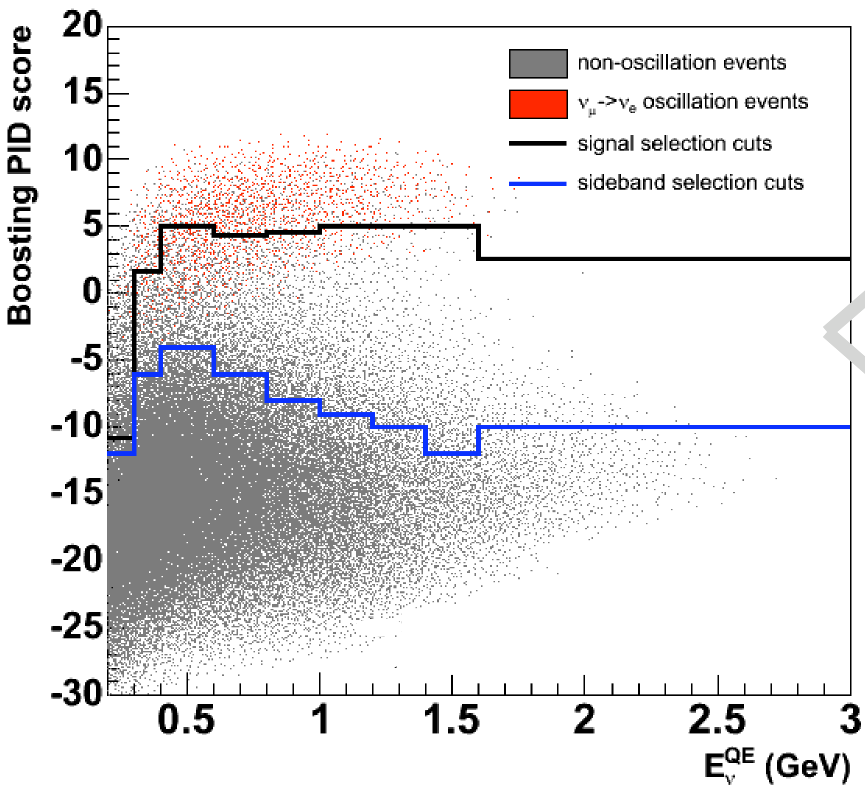


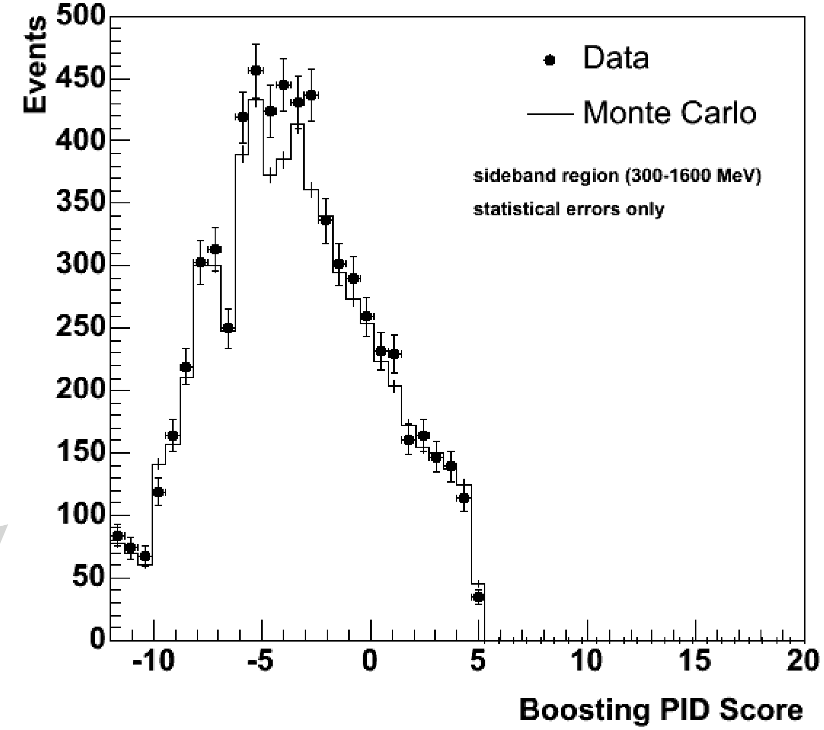
Particle ID "input variables" for the boosted decision trees are created from basic quantities in each bin: *e.g.*, charge, number of hits...
To select events, a particle ID cut is made on the Boosting output score.

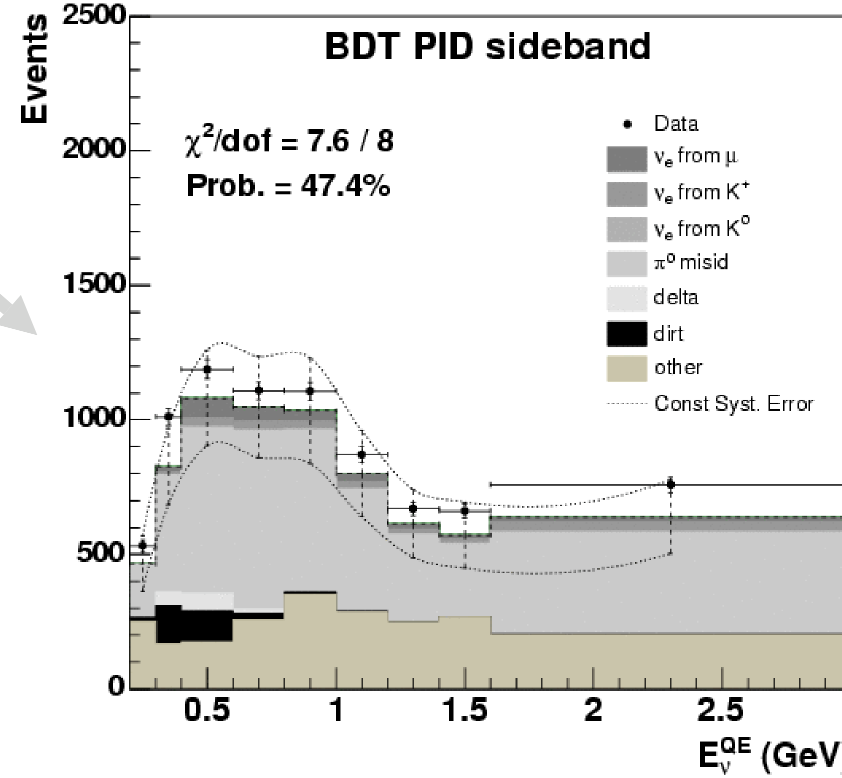
Boosted Decision Trees: **Particle ID**

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

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





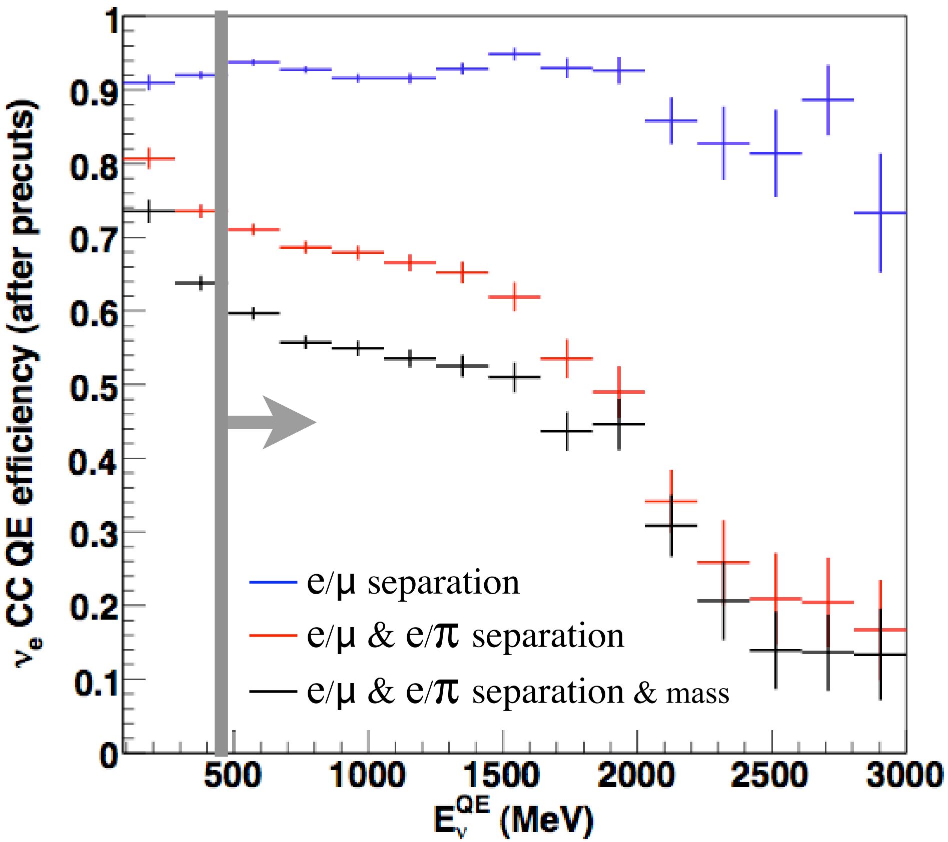


A χ^2 is calculated using the full systematic error matrix, data and MC are consistent.

Comparison: Efficiencies

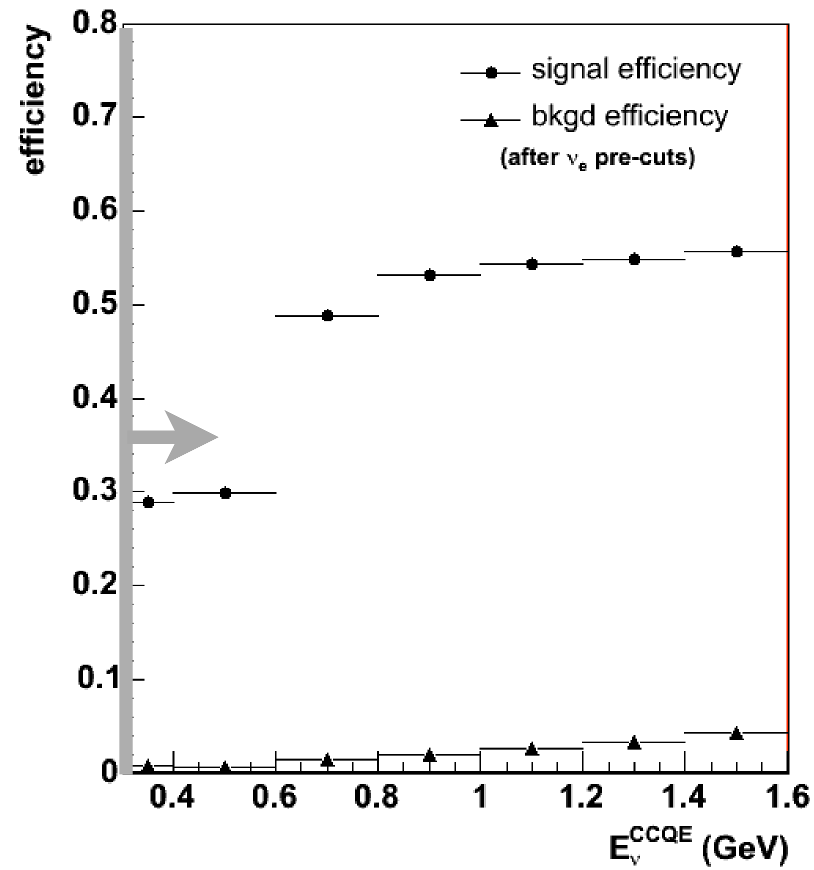
The two analyses have different event selection efficiency vs. energy trends,

Track-Based Analysis



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

Boosting Analysis



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

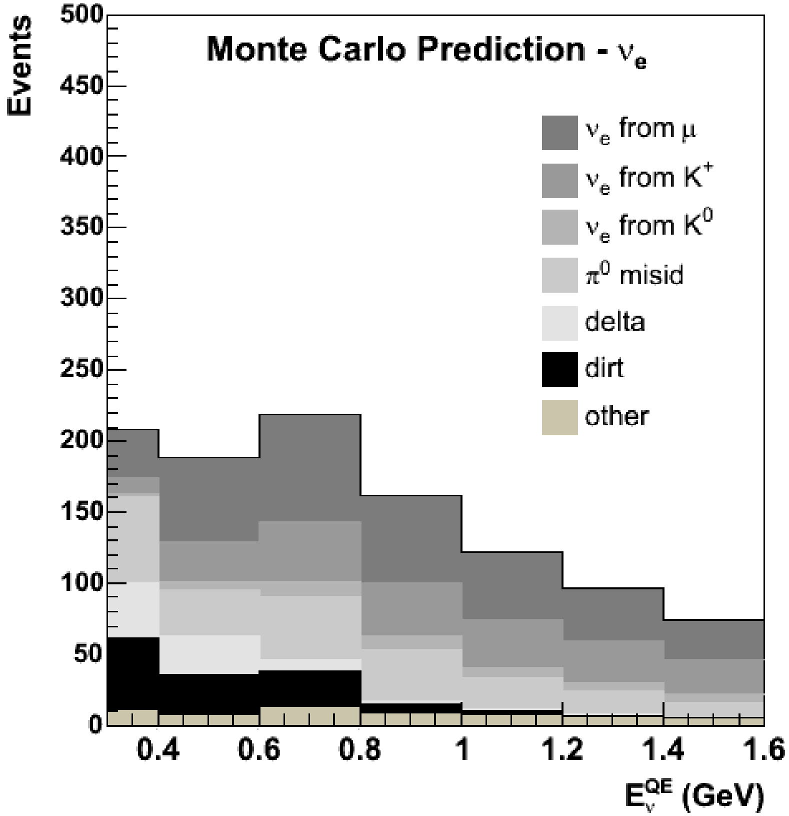
and different reconstructed E_ν regions for the oscillation analyses.

Comparison: **Backgrounds**

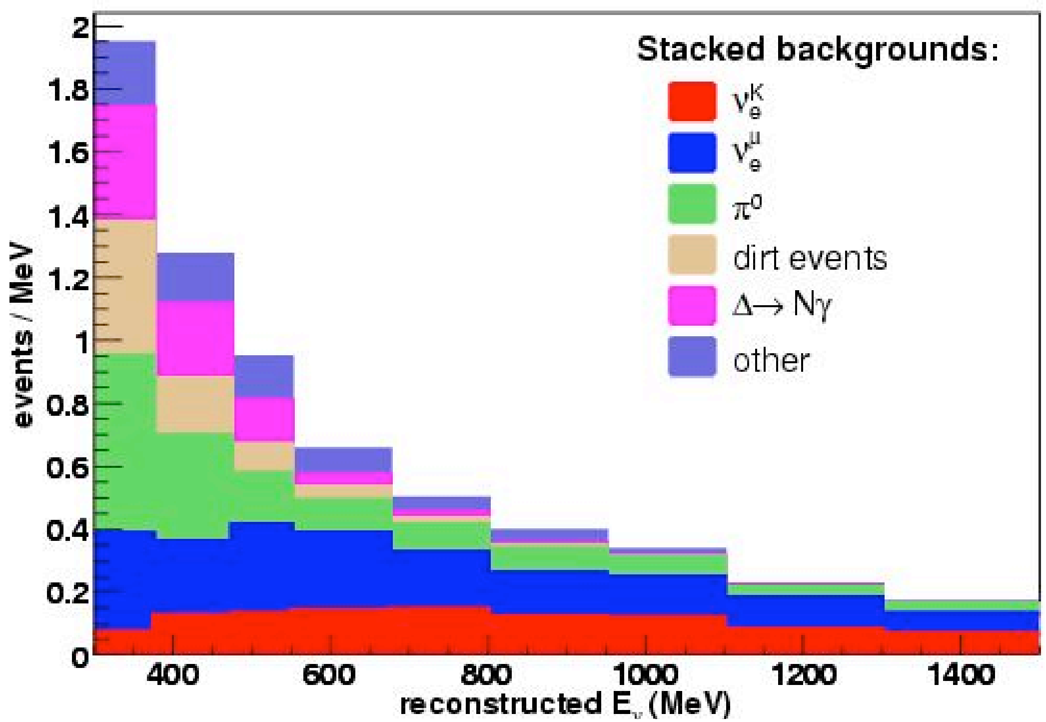
The two analyses have somewhat different background compositions.

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

Boosting Analysis



Track-Based Analysis



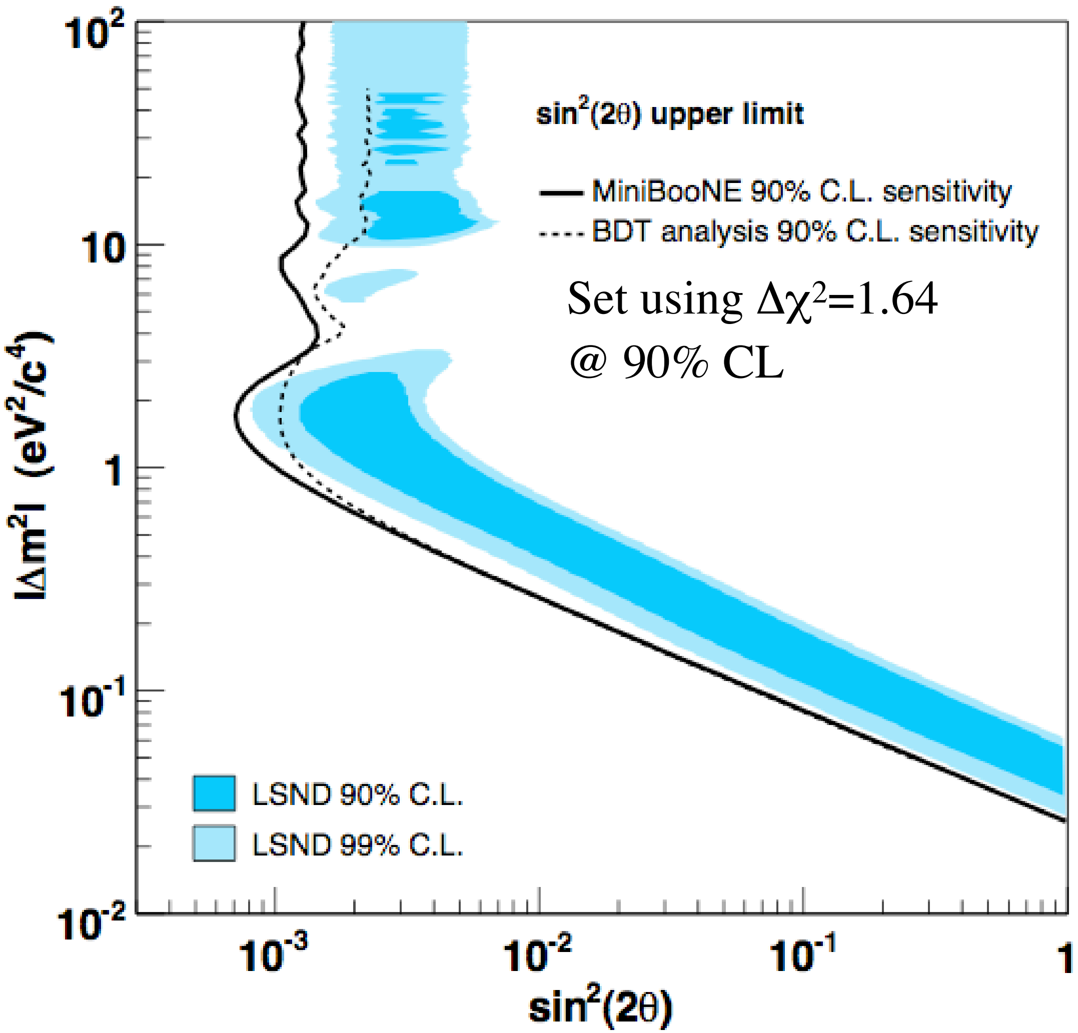
Comparison: Systematic Errors

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

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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}

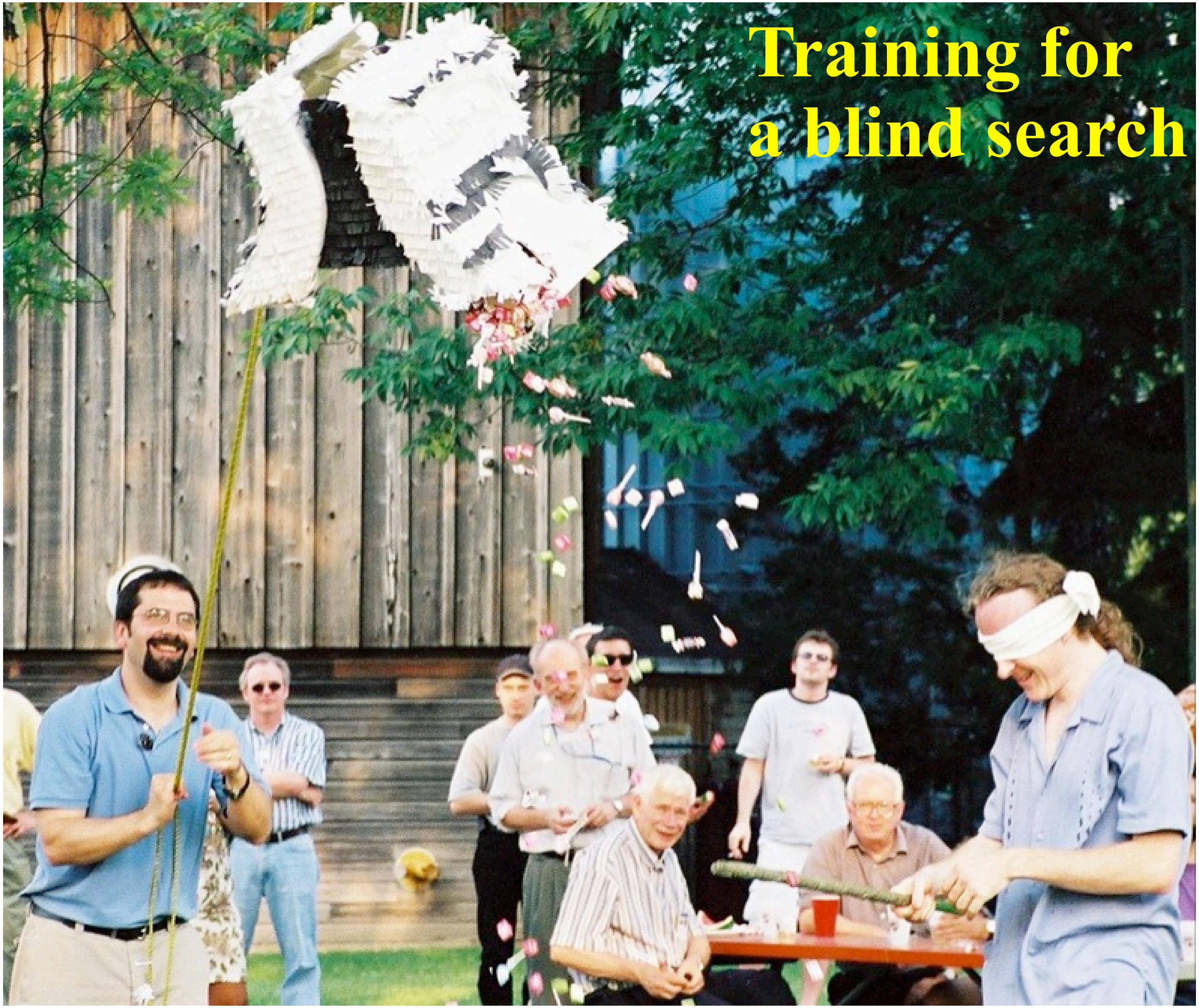
No fit parameters returned

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

Fit parameters **are** returned

This step breaks blindness

Step 5: Present results within two weeks



MOW
(blinded)
c.2002

We opened the box on March 26, 2007

The Box Opening

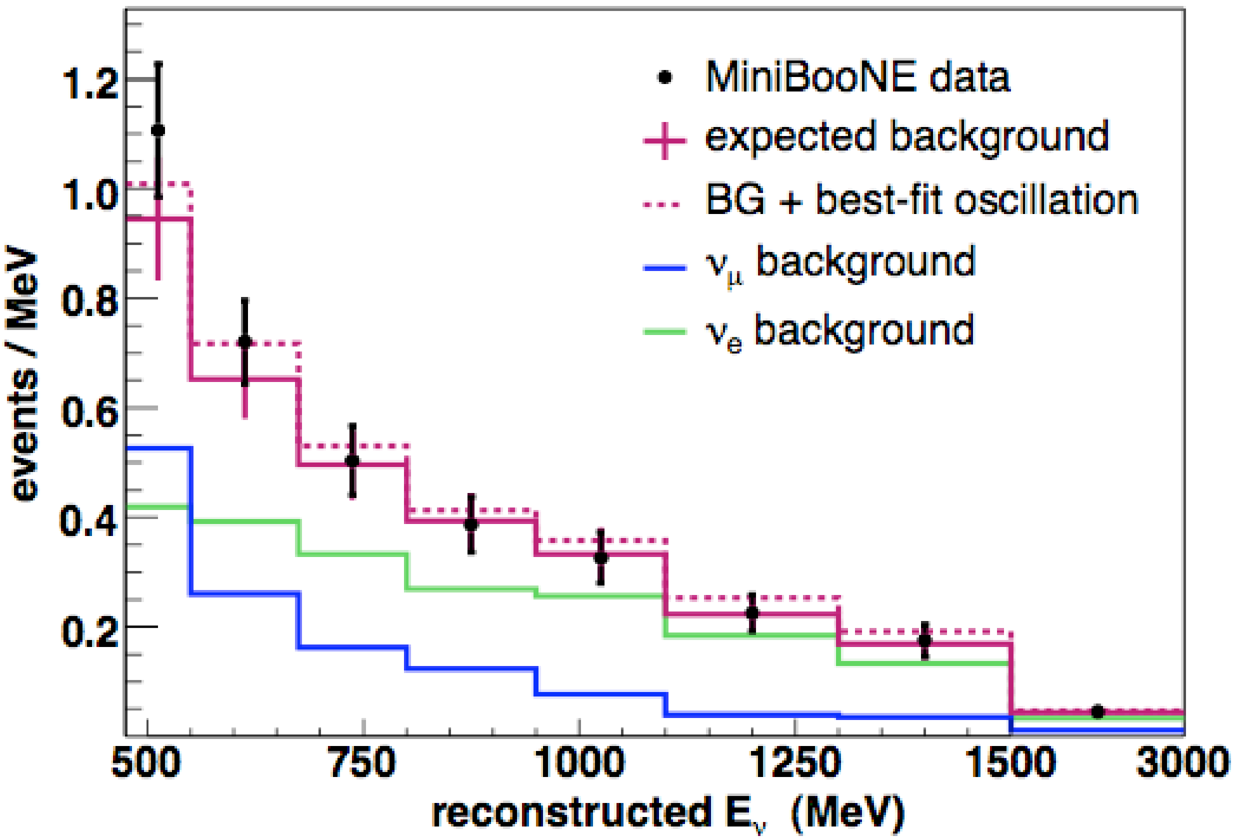
Results: Track Based Analysis

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

data: **380**

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

significance: 0.55 σ



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

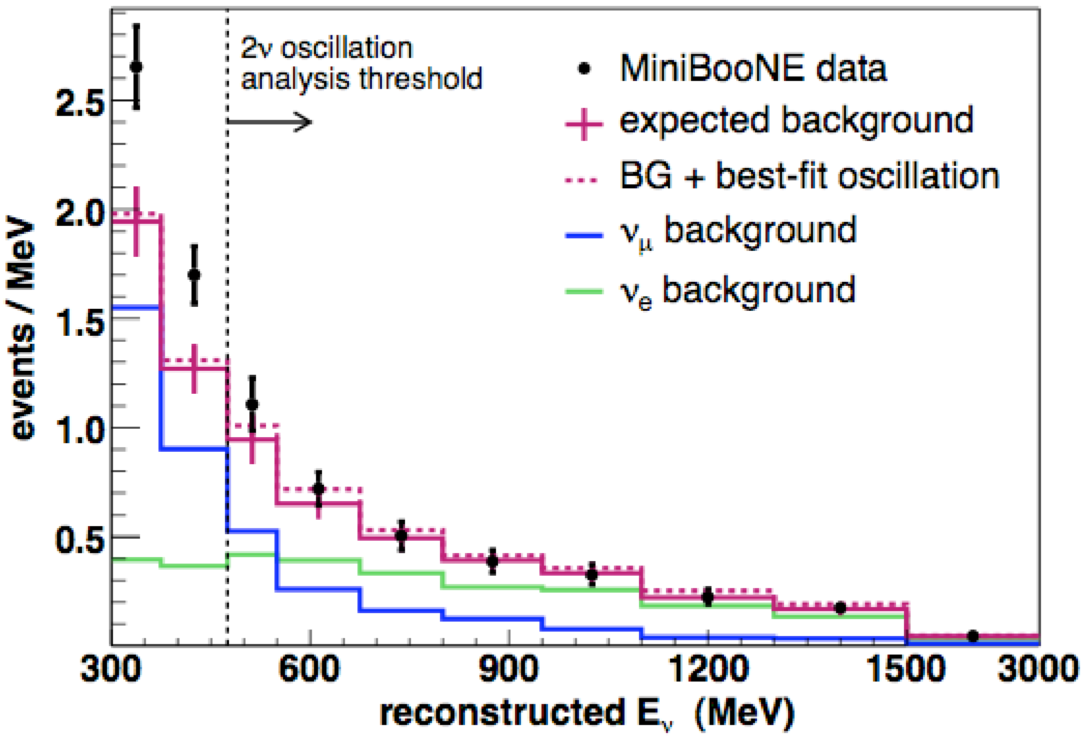
χ^2 prob. of best-fit point: 99%

χ^2 prob. of null hypothesis: 93%

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

NB: Errors bars = diagonals of error matrix

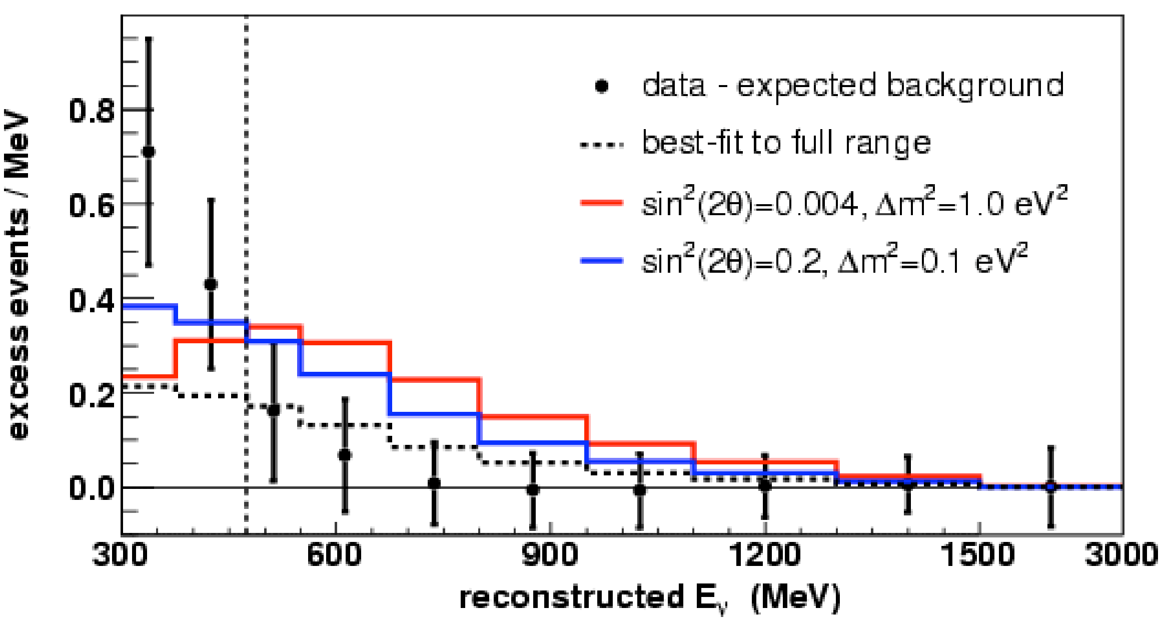
Results: Track Based Analysis, Lower Energy Threshold



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

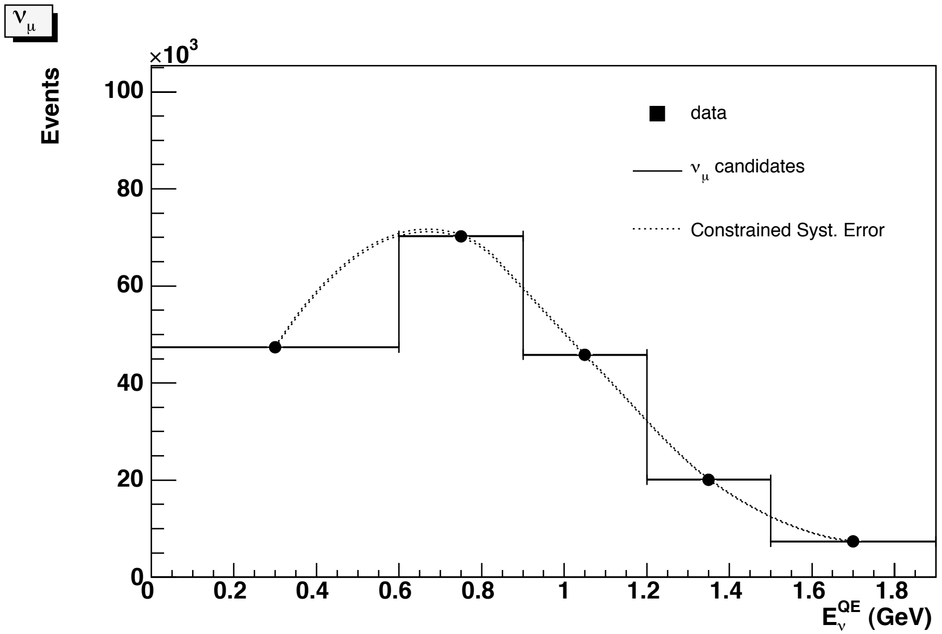
Oscillation fit to E_ν^{QE}> 300 MeV:
Best Fit ($\sin^2 2\theta$, Δm^2) = (1.0, 0.03 eV^2)
Ruled out by Bugey

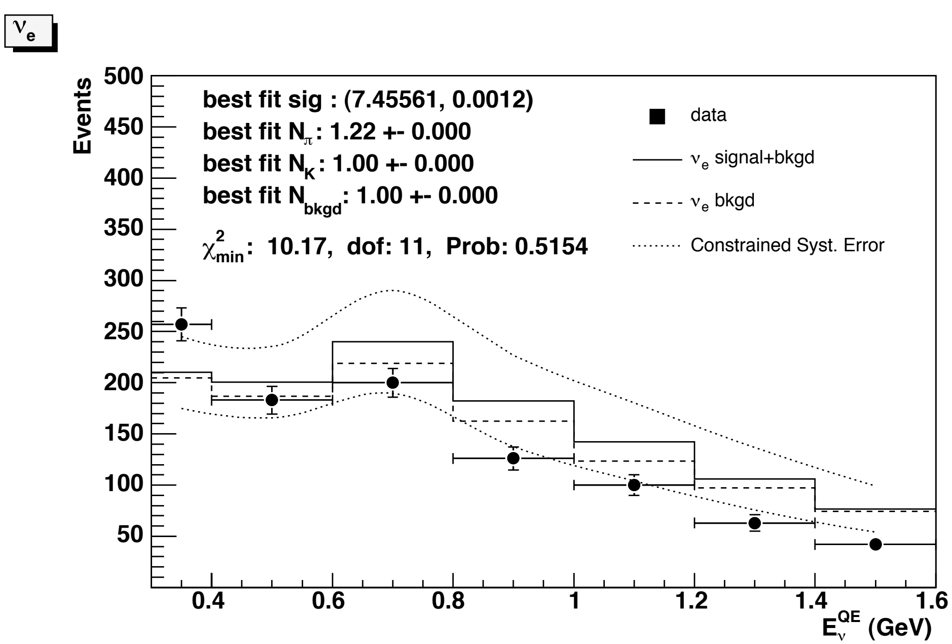


χ^2 prob. at best-fit point: 18%
No closed contour for 90%CL

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

Results: Boosted Decision Tree Analysis





<u>Counting Experiment</u>:

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

data: **971**

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

significance: -0.38 σ

Best Fit Point (dashed):

$(\sin^2 2\theta, \Delta m^2) = (0.001, 7\ eV^2)$

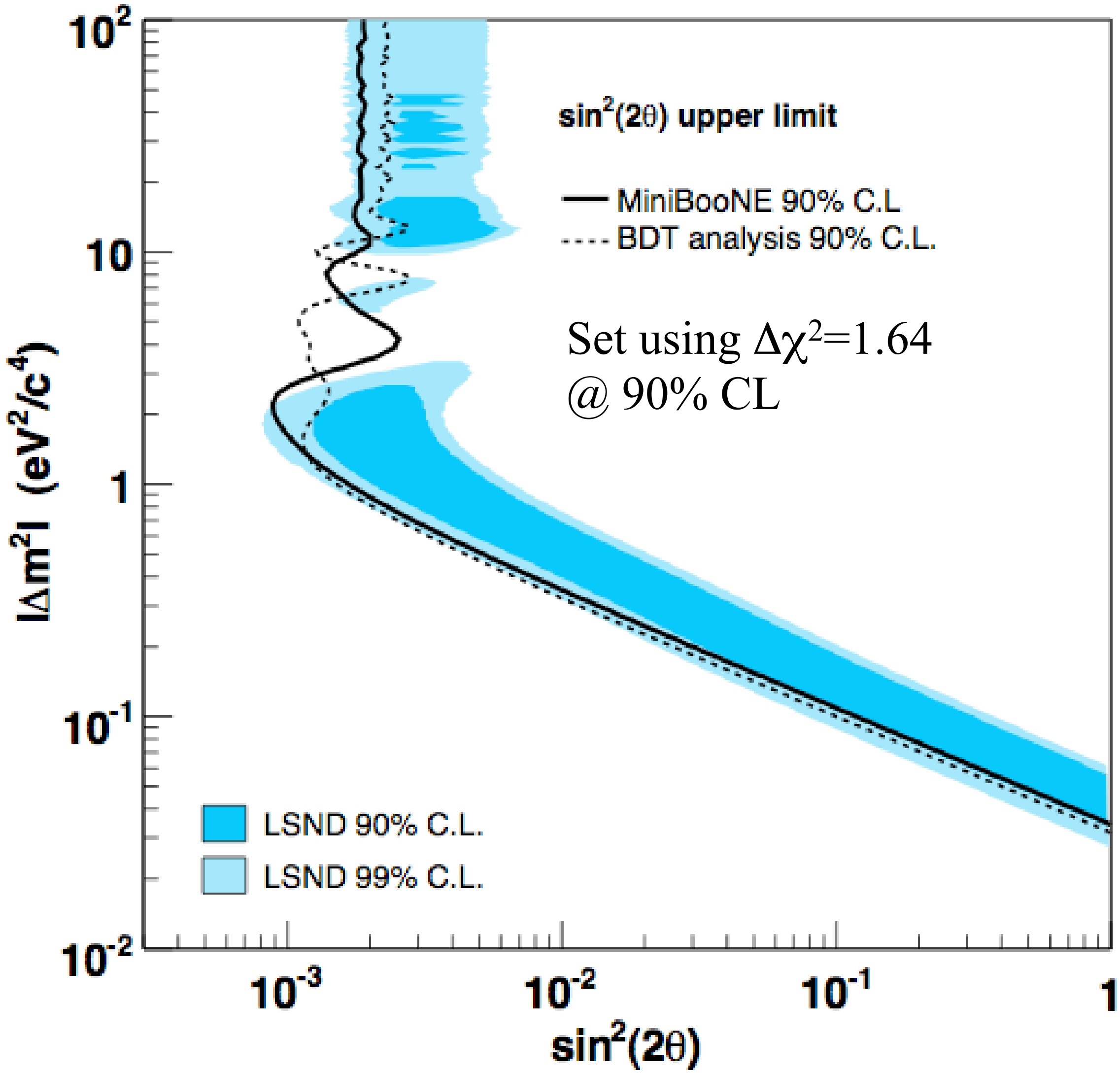
χ^2 probability of best-fit point: 52%

χ^2 probability of null hypothesis: 62%

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

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

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

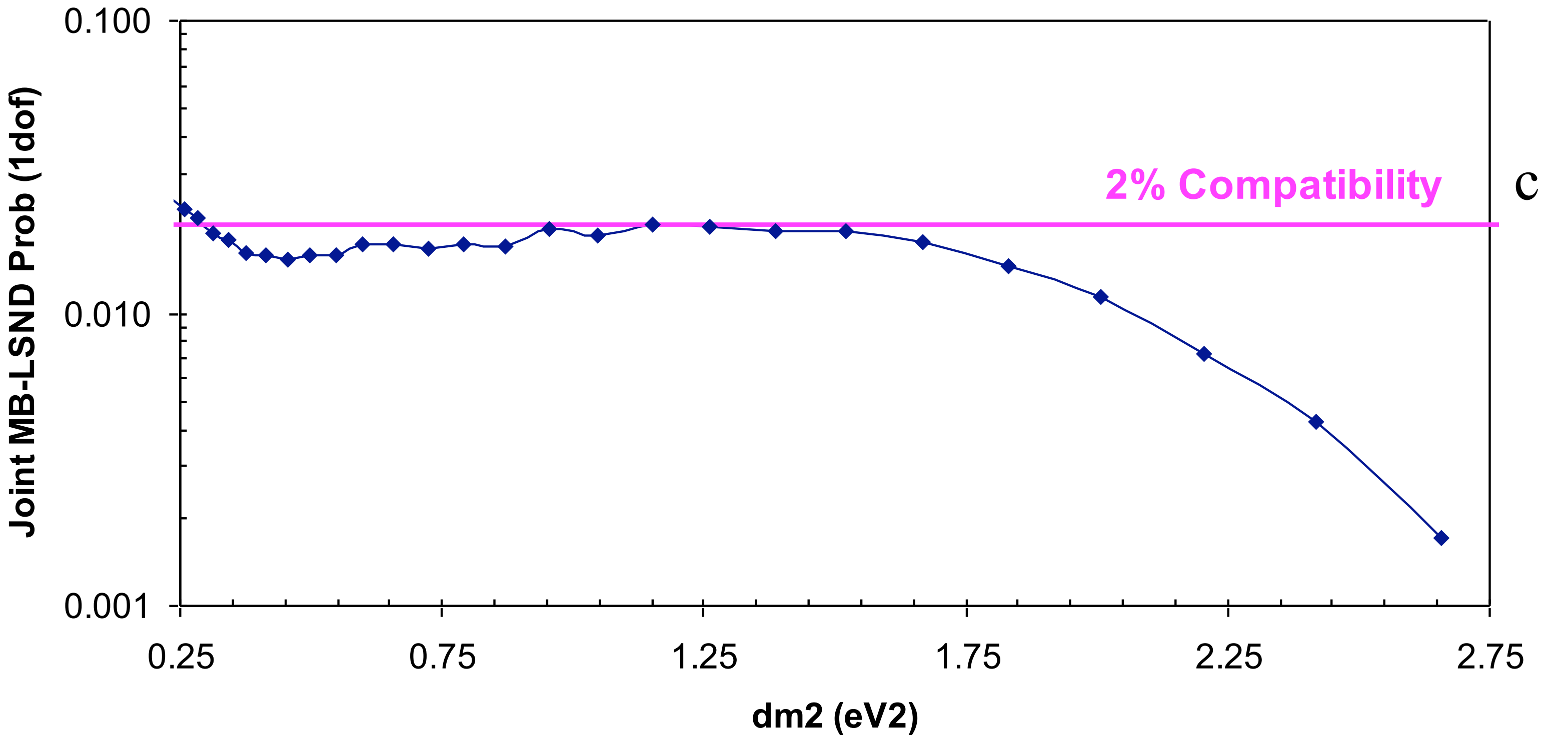
Therefore, we set a limit.

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:

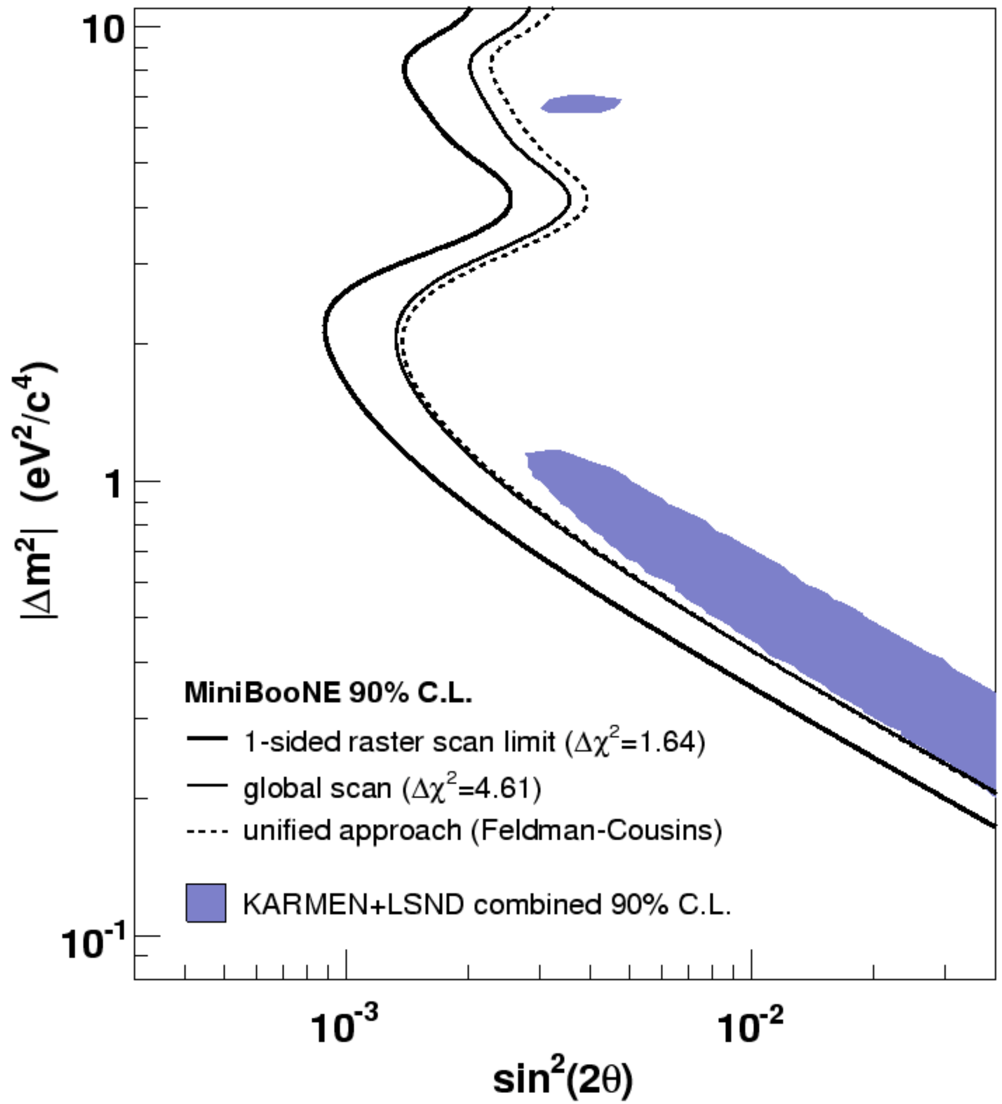
- Single sided raster scan
  (historically used, presented here)

- Global scan

- Unified approach
  (most recent method)

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

Church, et al., PRD 66, 013001

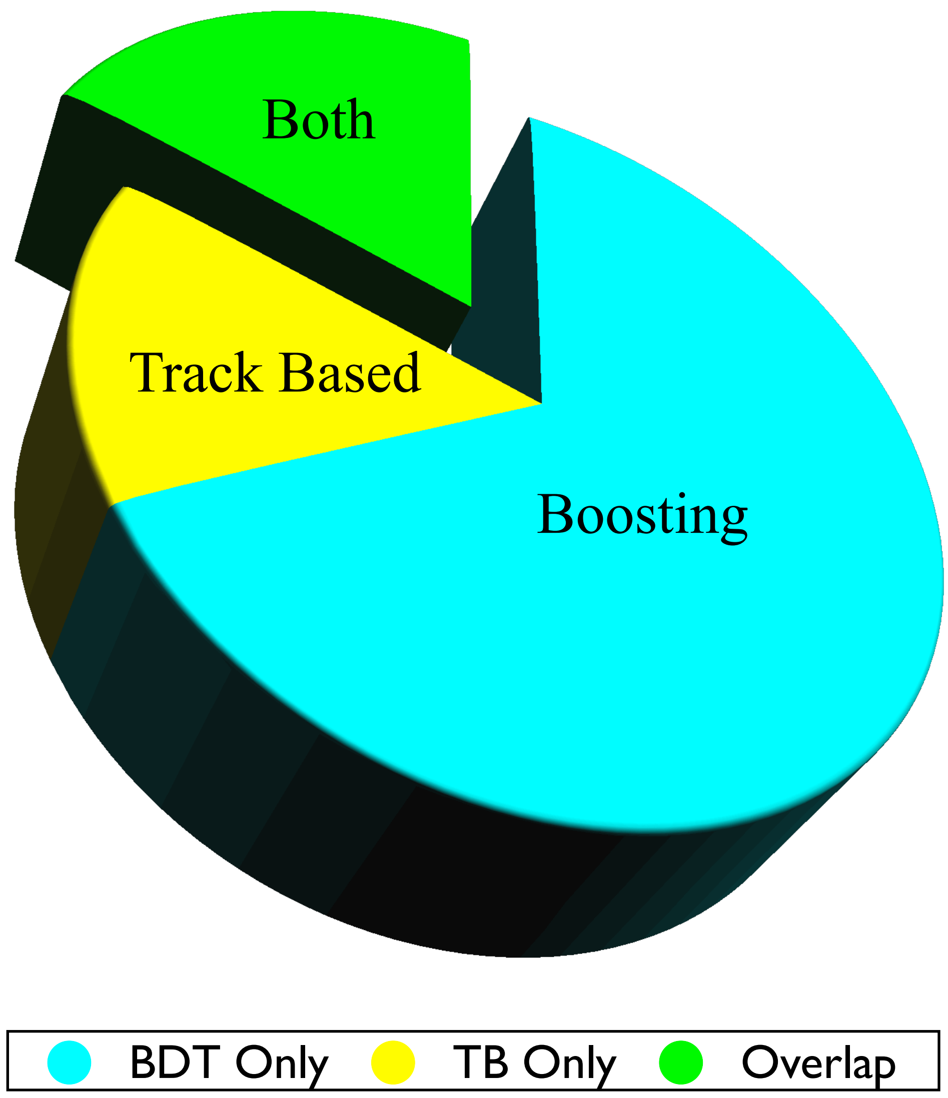


We will present a full joint analysis soon.

Results: Event Overlap

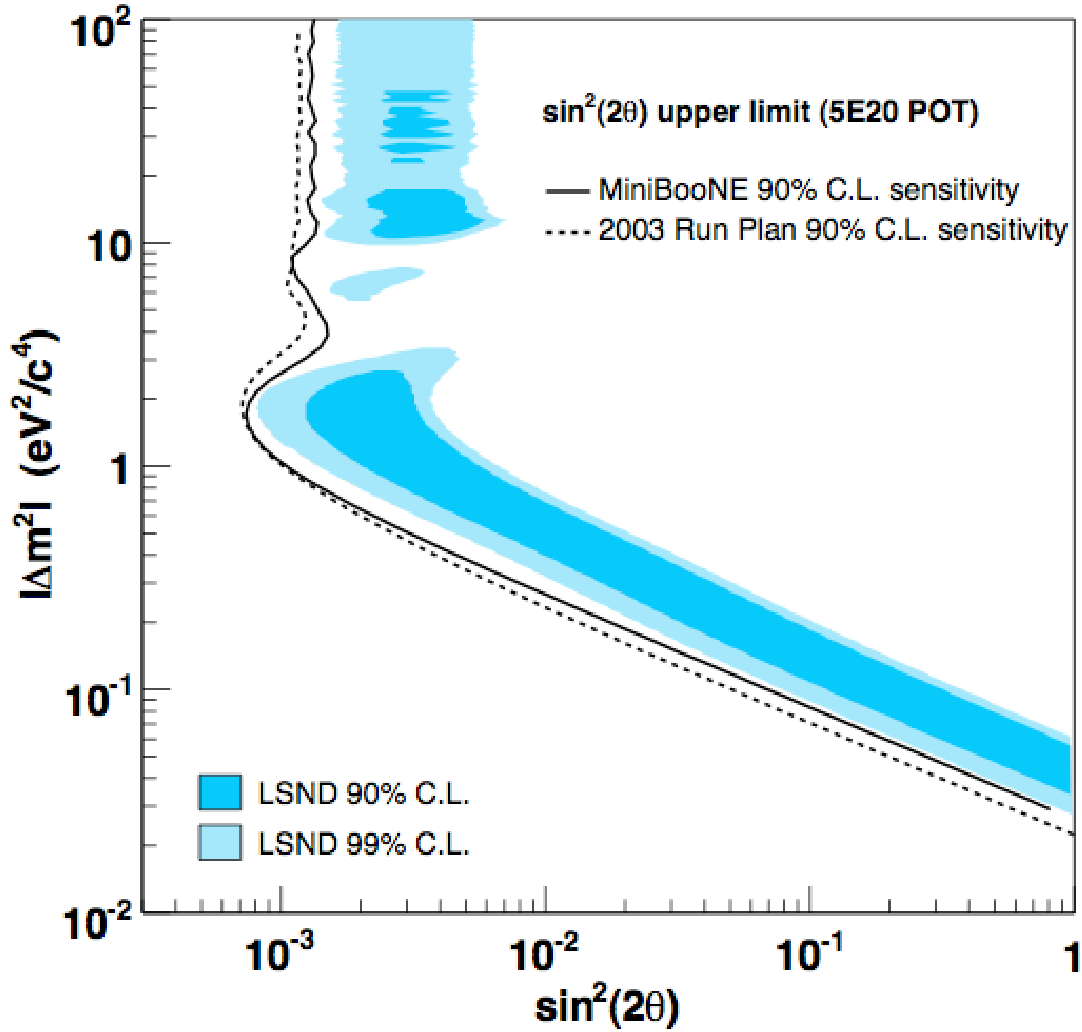
Counting experiment numbers:
Track Based Algorithm finds 380 events
Boosting Algorithm finds 971 events

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



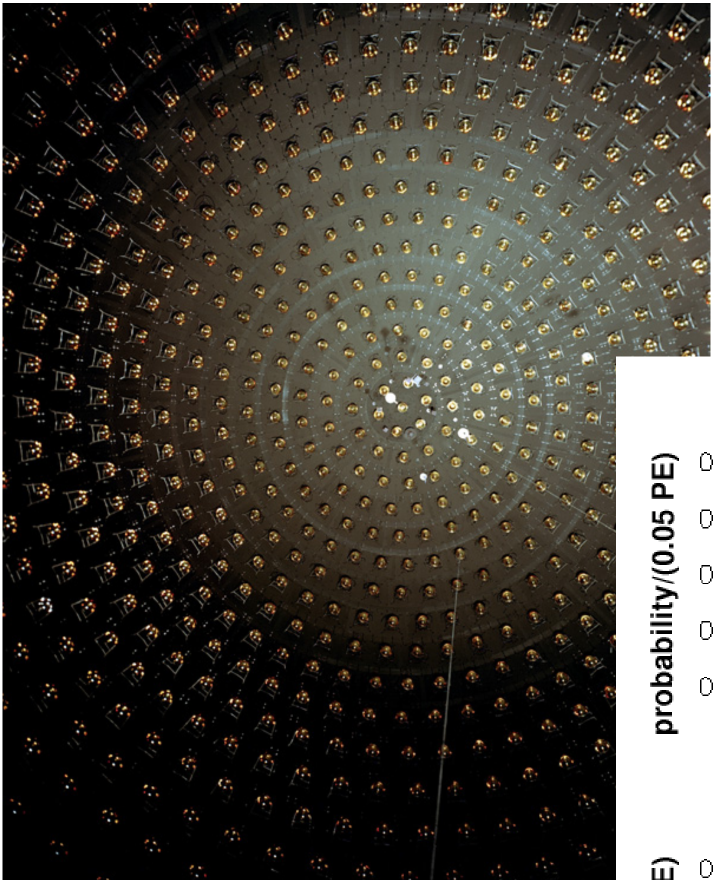
Results: Sensitivity Goal

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



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

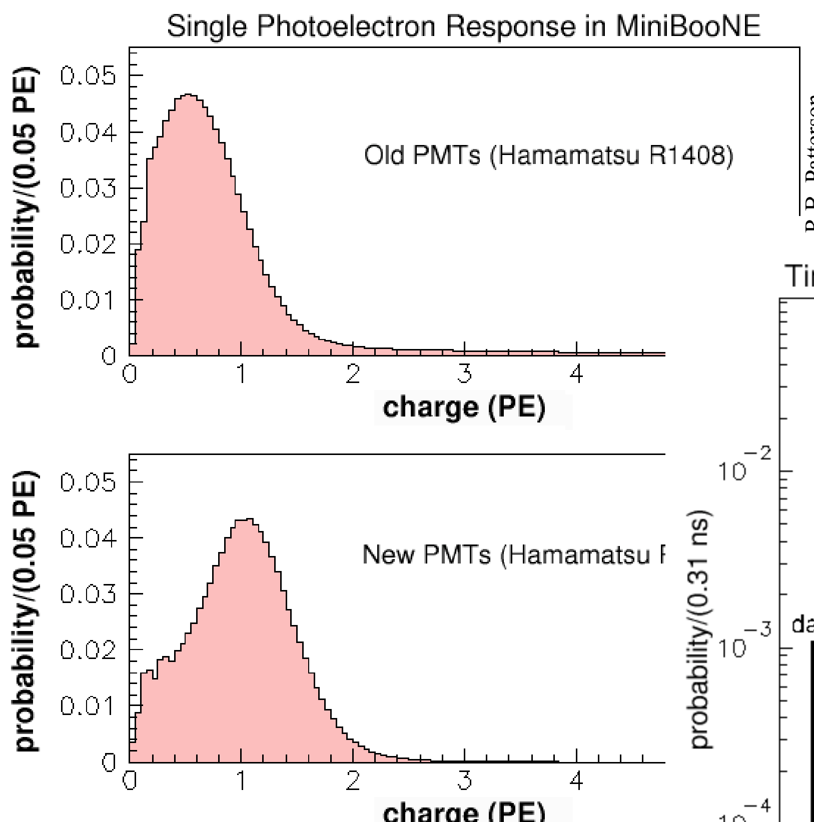
MiniBooNE Detector: **PMT Calibration**

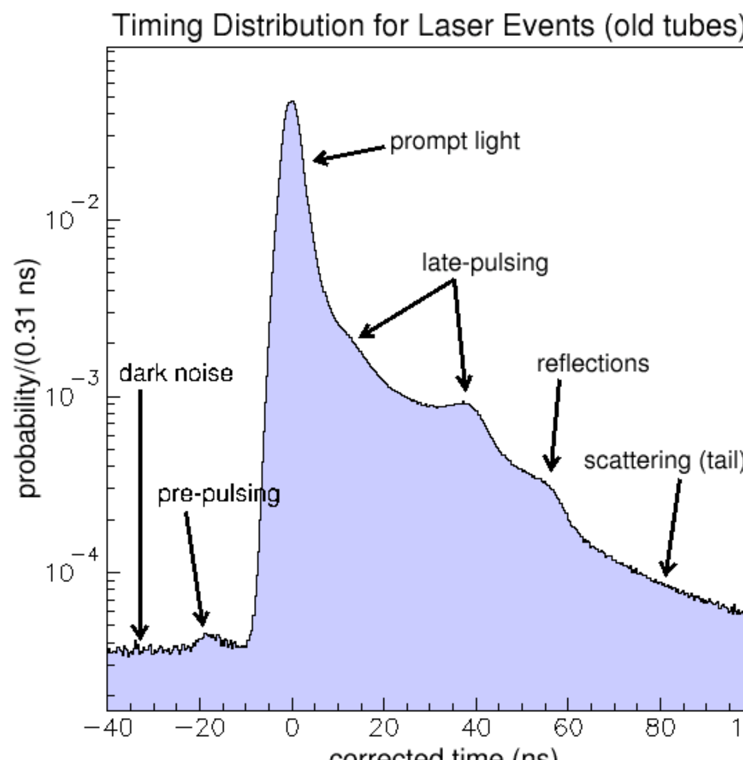


10% photo-cathode coverage

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



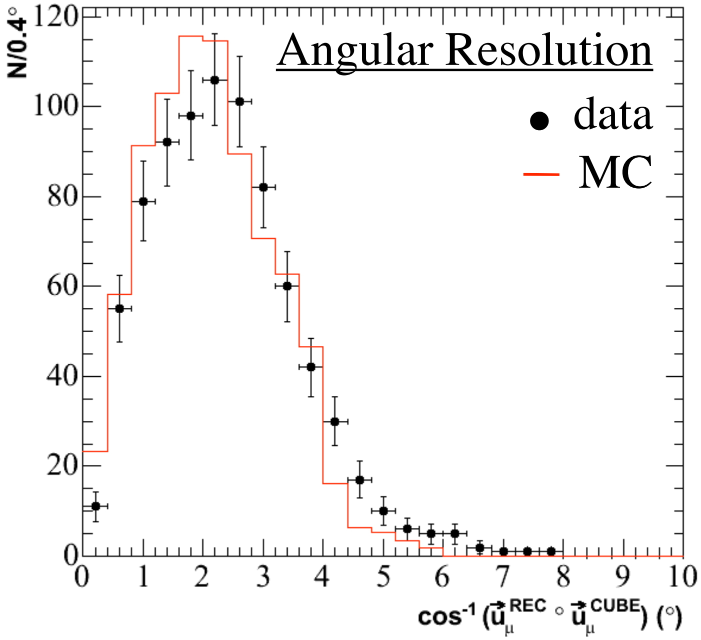


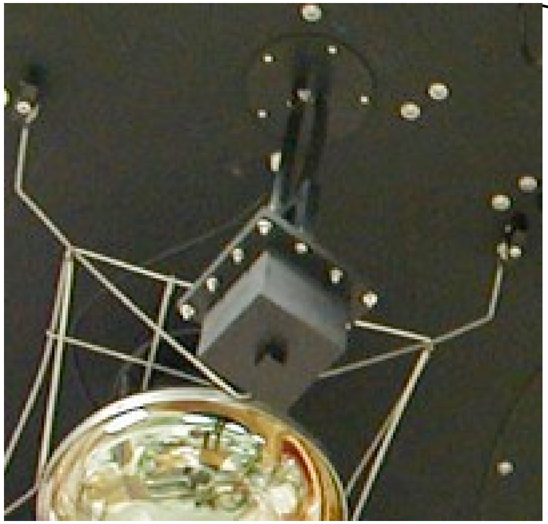
Two types of 8" Hamamatsu Tubes: R1408, R5912

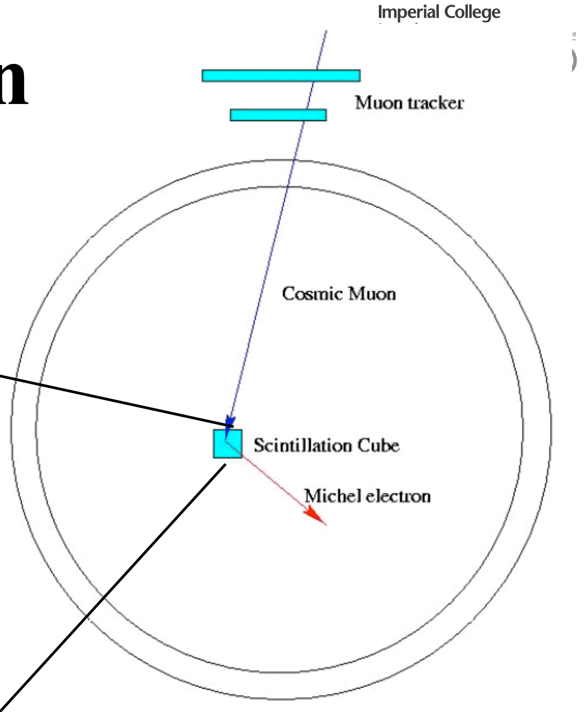
Laser data are acquired at 3.3 Hz to continuously calibrate PMT gain and timing constants

MiniBooNE Detector: Cosmic Calibration

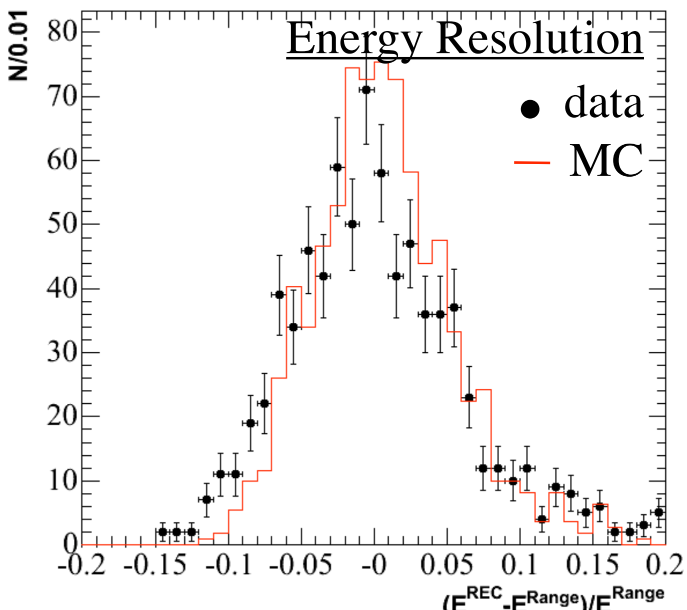
use cosmic muons and their decay electrons (Michels)







Muon tracker
7 scintillator cubes



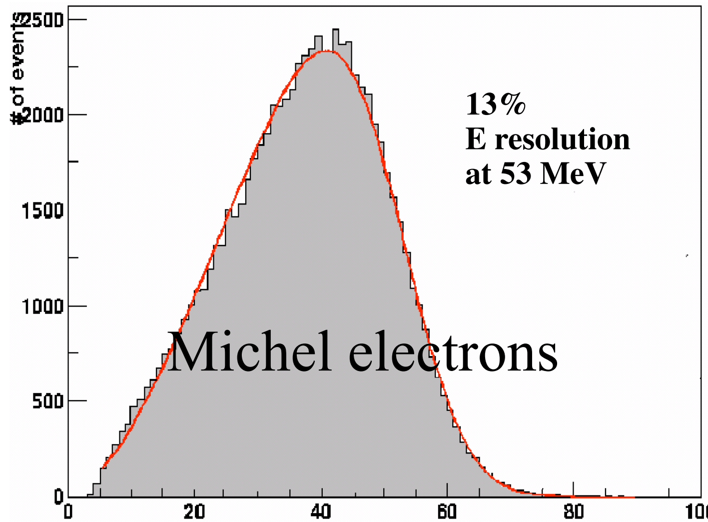
Cosmic muons which stop in cubes:

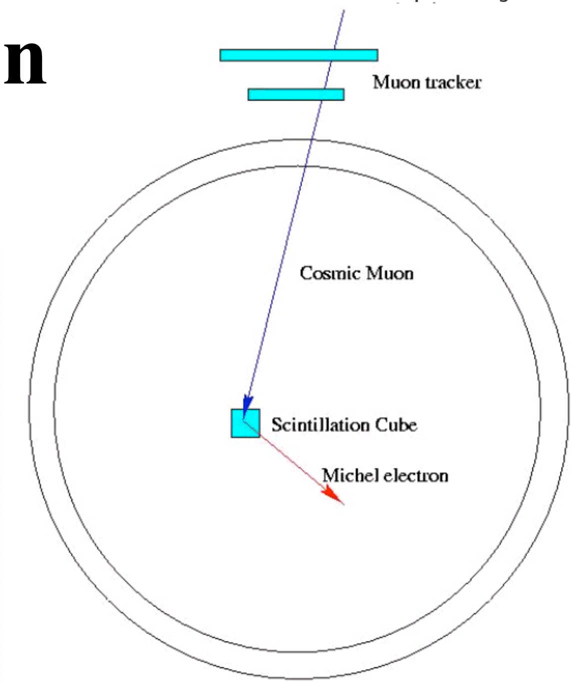
- test energy scale extrapolation up to 800 MeV
- measure energy, angle resolution
- compare data and MC

Muon tracker + cube calibration data continuously acquired at 1 Hz

MiniBooNE Detector: Cosmic Calibration

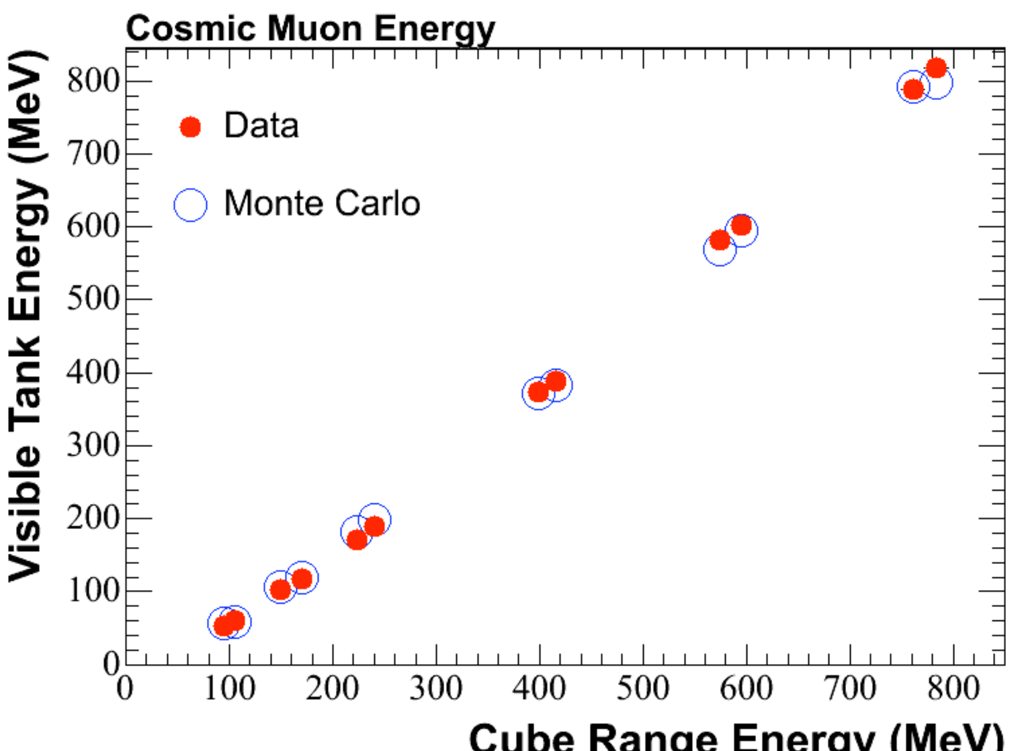
use cosmic muons and their decay electrons (Michels)





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

Muon tracker
7 scintillator cubes

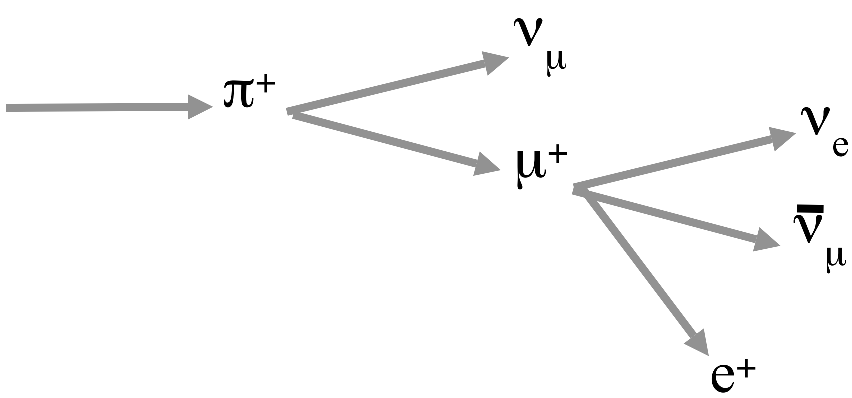


<u>Cosmic muons which stop in cubes:</u>
-test energy scale extrapolation up to 800 MeV
- measure energy, angle resolution
- compare data and MC

Muon tracker + cube calibration
data continuously acquired at 1 Hz

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

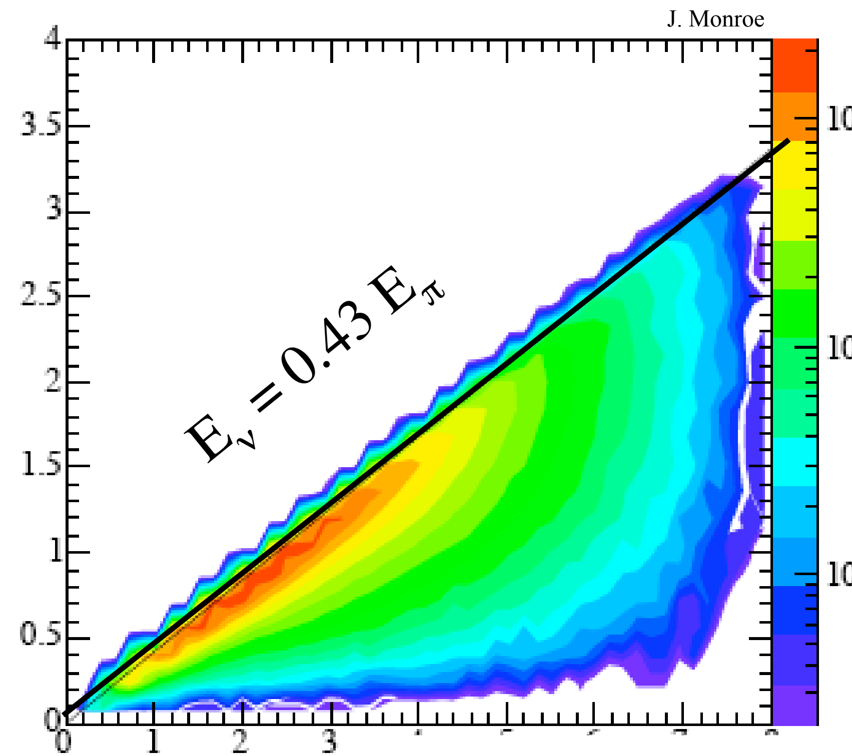


Ratio Method Constraint:

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

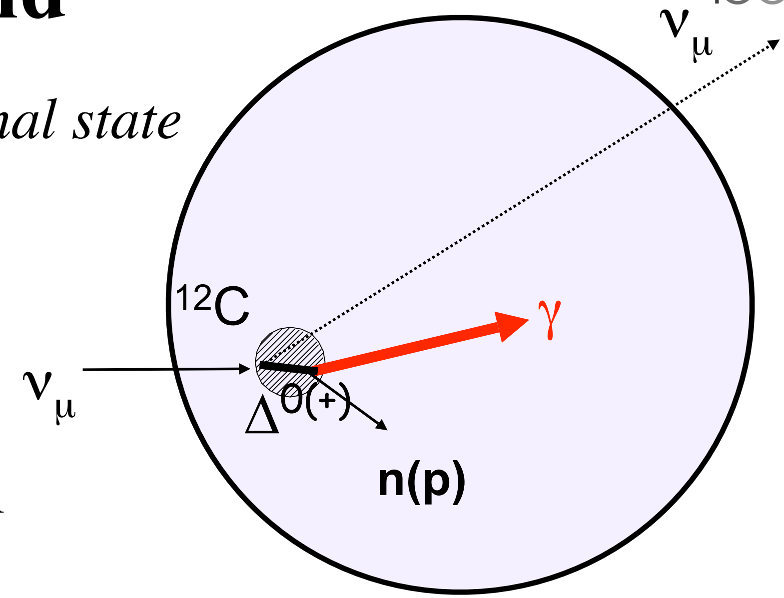
3. re-weight each possible MC flux by the ratio (2) including the ν_μ, its parent π^+, sister μ^+, and niece ν_e



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

Analysis Strategy: **Delta Background**

ν induced interactions that produce single γs in the final state



<u>Radiative Delta Decay (NC)</u>

(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

<u>Inner Bremsstrahlung (CC)</u>

(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.

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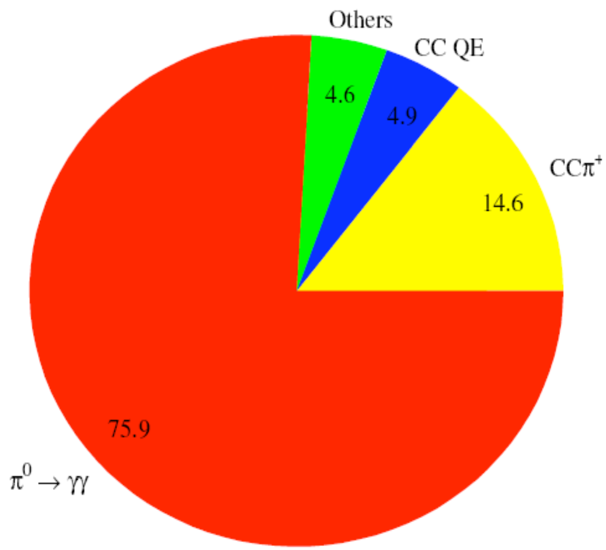
Analysis Strategy: External Backgrounds

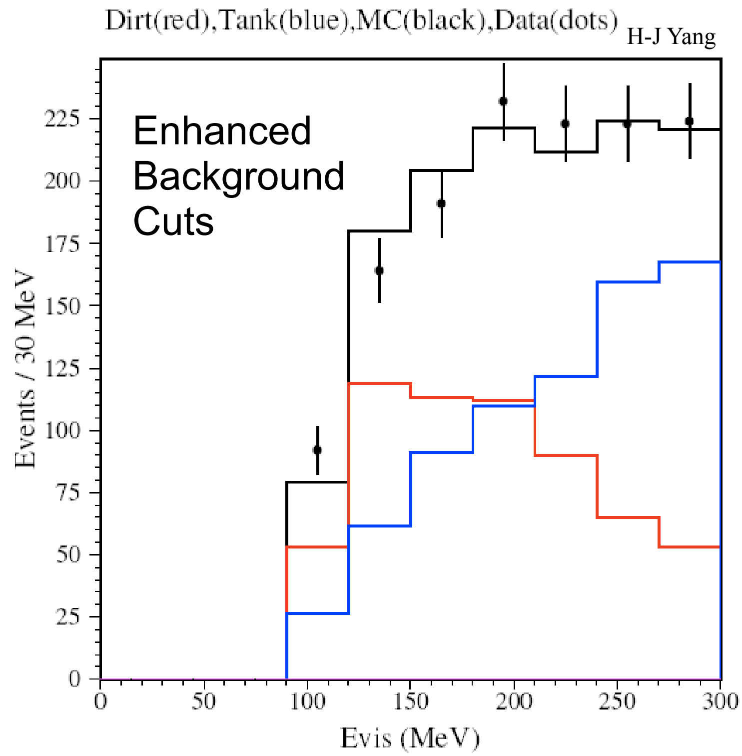
interactions outside the detector that deposit energy in the fiducial volume and pass the veto PMT hits cut

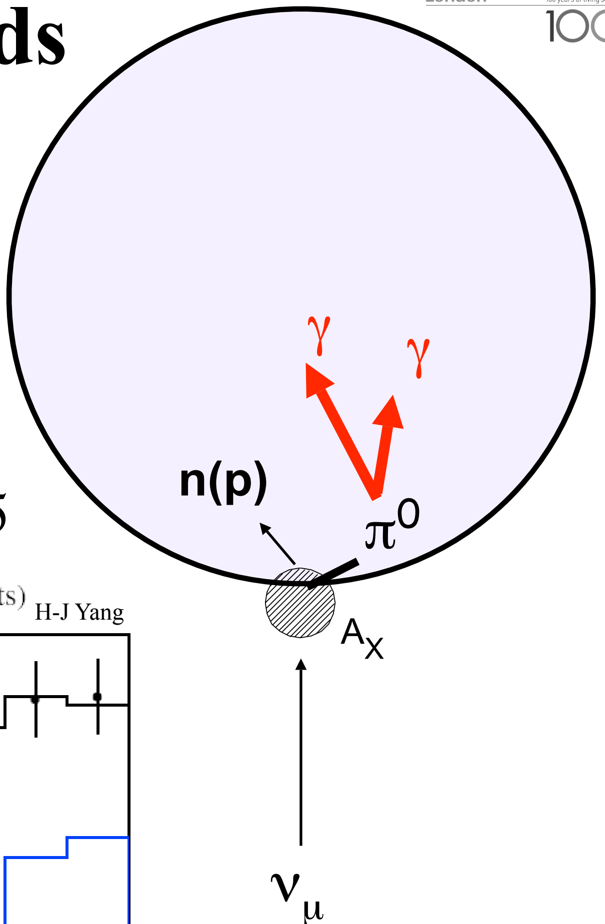
1. "Dirt" Events

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

Event Type of Dirt Events







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

Step 1

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

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

All analysis variables were returned with good probability except...

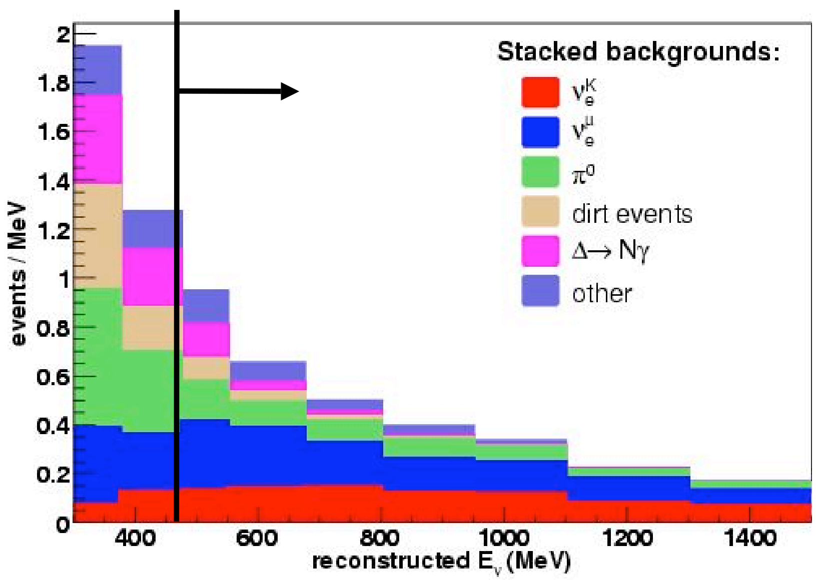
TB analysis χ^2 Probability of $E_{visible}$ fit: 1%

This probability was sufficiently low to merit further consideration

In the TB analysis

- We re-examined our background estimates using sideband studies.
  $\Rightarrow$ *We found no evidence of a problem*

- However, knowing that backgrounds rise at low energy,
  We tightened the cuts for the oscillation fit:



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

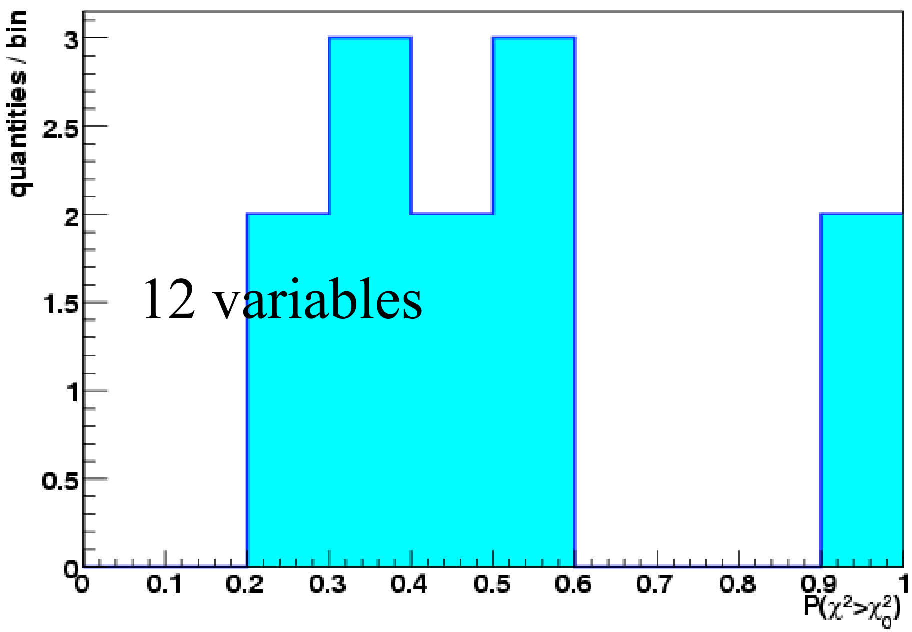
We agreed to report events over the original full range: $E_\nu^{QE} > 300$ MeV,

Step 1: again!

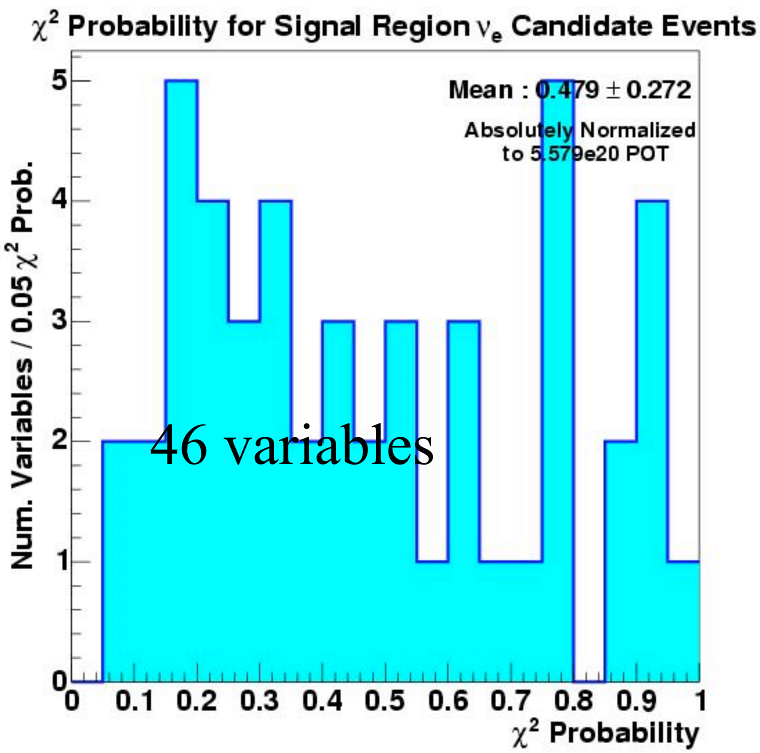
Return the χ^2 of the data/MC comparison for a set of diagnostic variables

χ^2 probabilities returned:

TB (E_ν^{QE}>475 MeV)



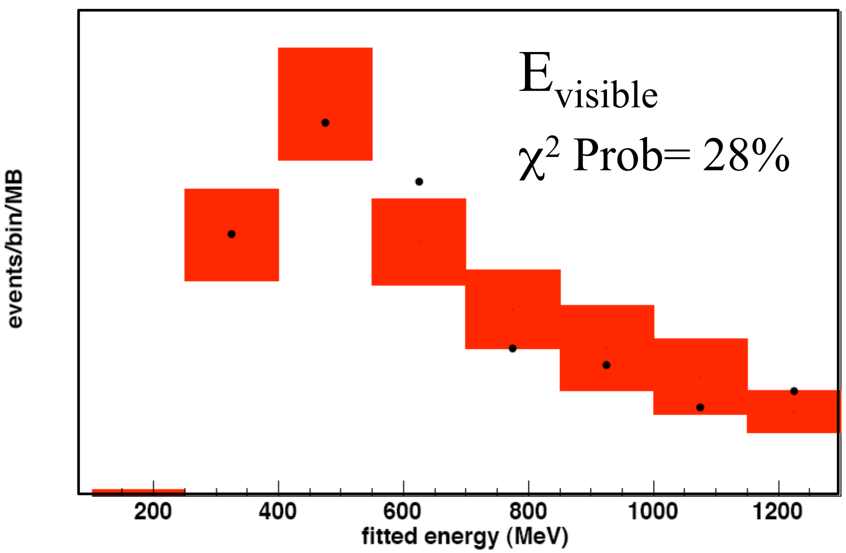
BDT



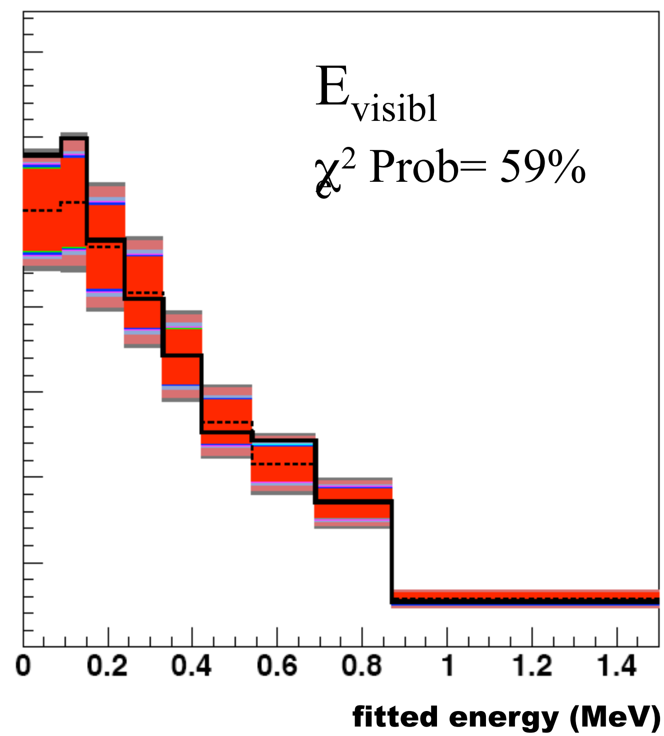
Parameters of the oscillation fit were not returned.

Step 2
Open up the plots from step 1 for approval.

Examples of what we saw:



TB (E_ν^{QE}>475 MeV)



BDT

MC contains fitted signal at unknown level

Step 3

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

TB (E_ν^{QE}>475 MeV) χ^2 Probability of fit: 99%

BDT analysis χ^2 Probability of fit: 52%

Leading to...

Step 4

Open the box...