MiniBooNE Neutrino Oscillation Analyses

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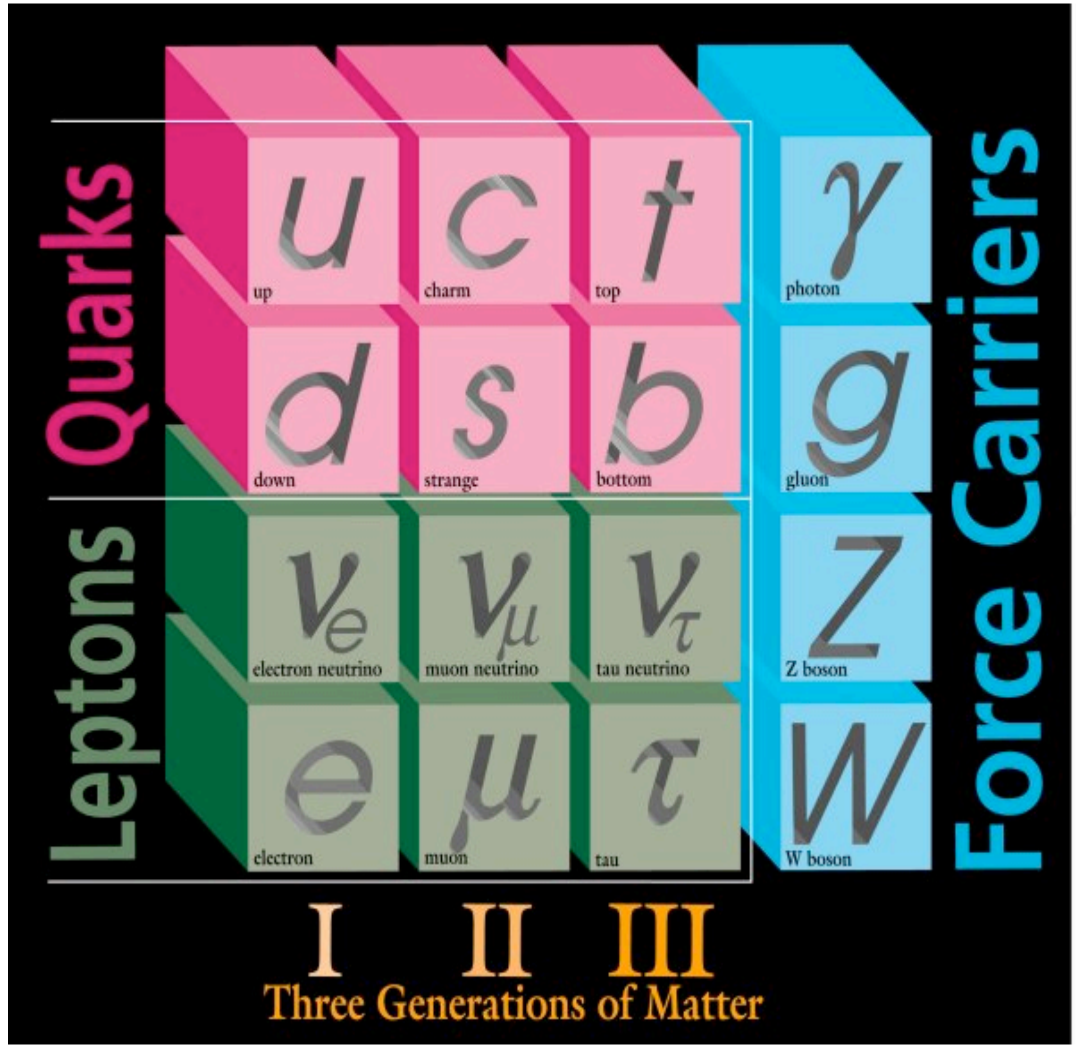
Outline

- Introduction to neutrinos
- LSND and the great oscillation mystery
- MiniBooNE
  - Neutrino oscillation review
  - **Combined oscillation analysis**
  - **World's data joint analysis**

Standard Model of Physics

- Three flavors of neutrinos associated with weak interactions
- Massless
- Only LH neutrinos (no RH partners)



Neutrino Oscillations

Δm^2 is the difference of the squared masses of the two neutrino states

Distance from point of creation of neutrino beam to detection point

$$P_{osc} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\, \Delta m^2 \, L}{E}\right)$$

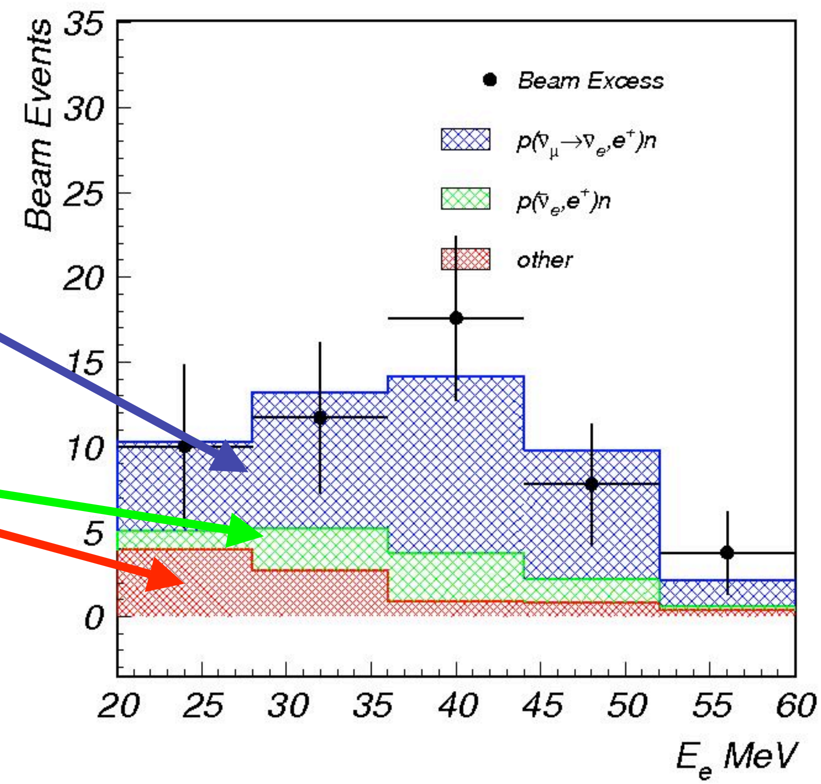
θ Is the mixing angle

E is the energy of the neutrino beam

LSND

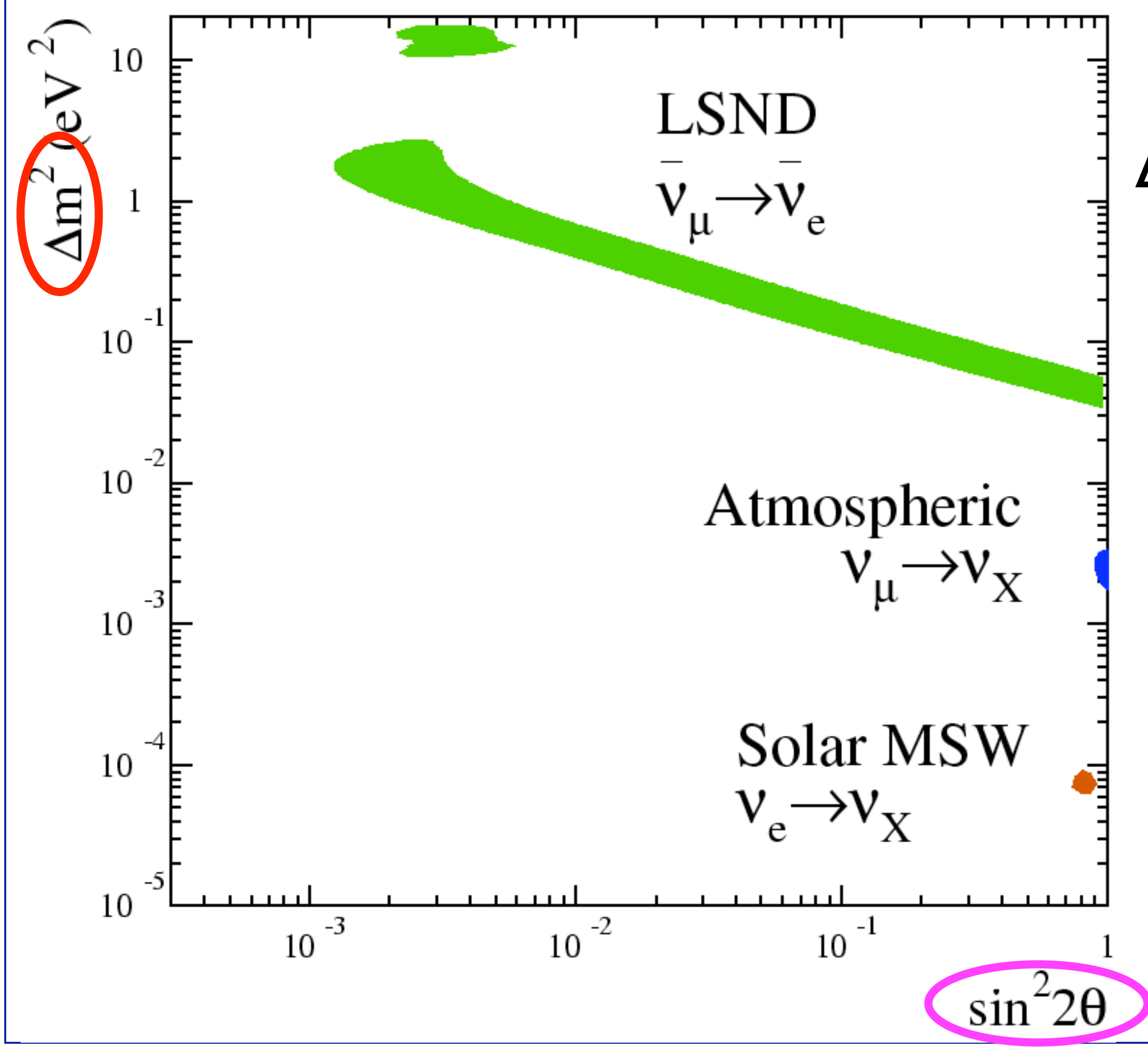
Fit to oscillation hypothesis

Backgrounds



- Significant excess of events best fit by a 2-neutrino oscillation hypothesis
- Different from other oscillation signals
  - Higher Δm^2, smaller mixing angle, much smaller probability (~0.3%)

Current Oscillation Status



$\Delta m_{ab}^2 = m_a^2 - m_b^2$

If there are only 3 :

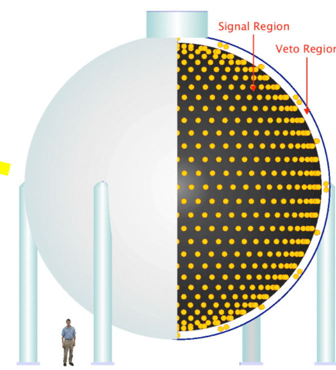
$\Delta m_{ac}^2 =$

$\Delta m_{ab}^2 +$

Δm_{bc}^2

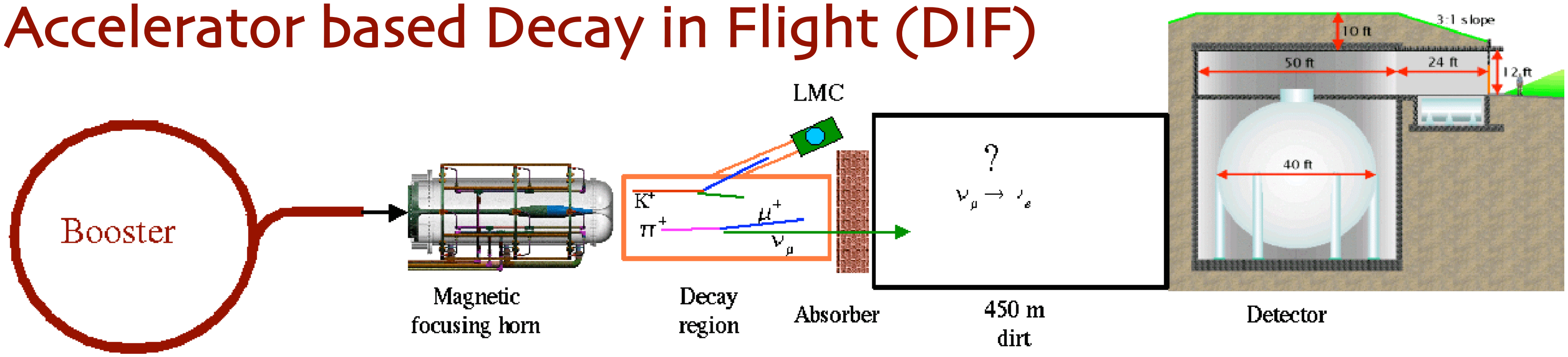
MiniBooNE

MiniBooNE Detector



MiniBooNE Beam

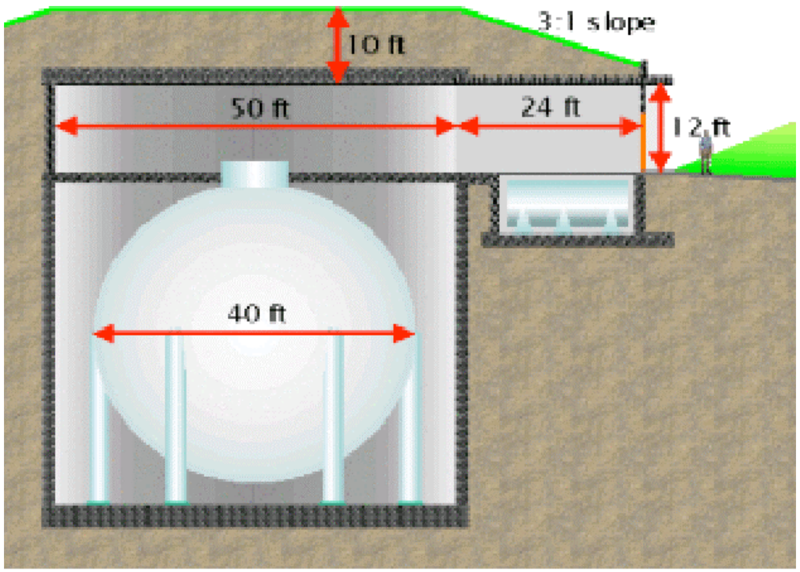
Accelerator based Decay in Flight (DIF)



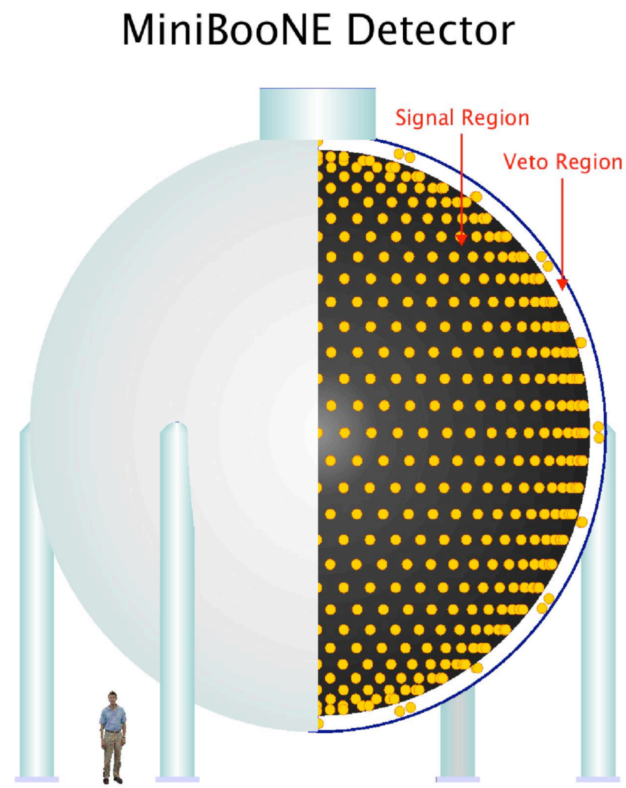
- Beam of protons + a target material (Be)
  - mesons (π, K)
- Looking for $\nu_\mu \to \nu_e$: appearance analysis
- Mesons decay into the neutrino beam sampled by a detector
  - $K^+ / \pi^+ \to \mu^+ + \nu_\mu$
    - $\mu^+ \to e^+ + \text{anti-}\nu_\mu + \nu_e$

Flux paper arXiv:0806.1449

MiniBooNE Detector



Detector



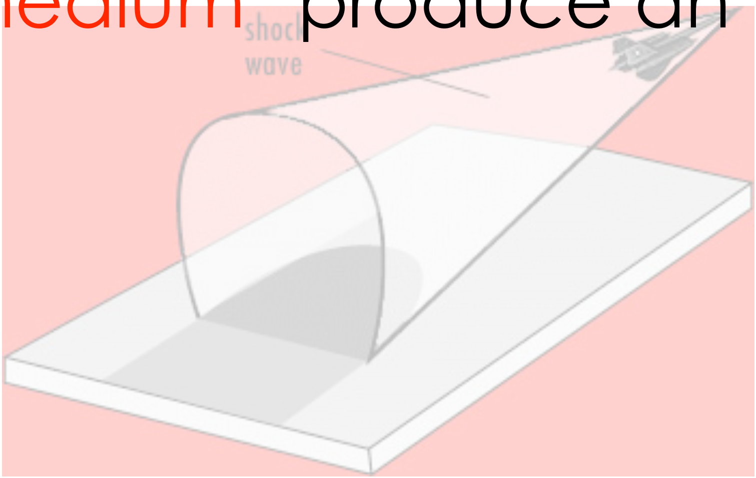
- 12.2 meter diameter sphere
- **Pure** mineral oil
- 2 regions
  - Inner light-tight region, 1280 PMTs (10% coverage)
  - Optically isolated outer veto-region, 240 PMTs

Observing ν Interactions

- Passage of particles through matter leaves a distinct mark
  - **Cerenkov radiation / light**
  - **Scintillation light**

Cerenkov and Scintillation Light

- Particles with a velocity greater than the speed of light * in the medium* produce an E-M shock wave
  - $v > c/n$
  - Similar to a sonic boom
- Prompt light signature



- Particles deposit energy in the medium
- Isotropic, delayed

Neutrino Interactions

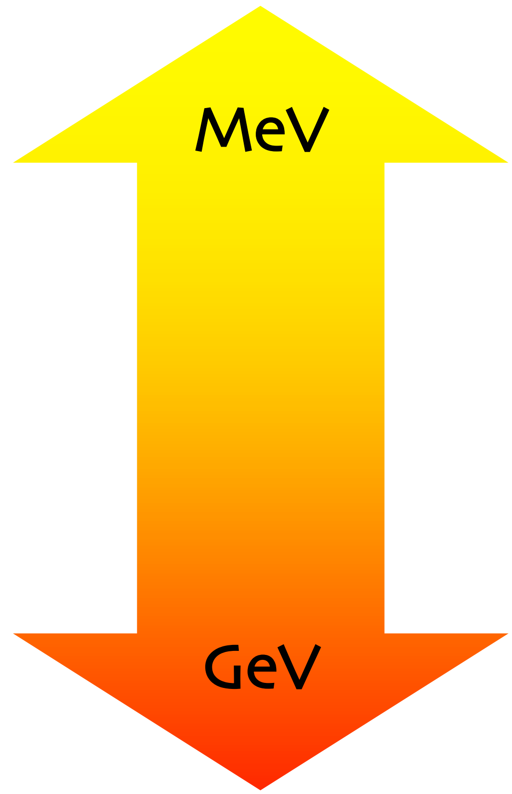
$$\nu_e\, n \rightarrow p\, e^-$$

Elastic Scattering

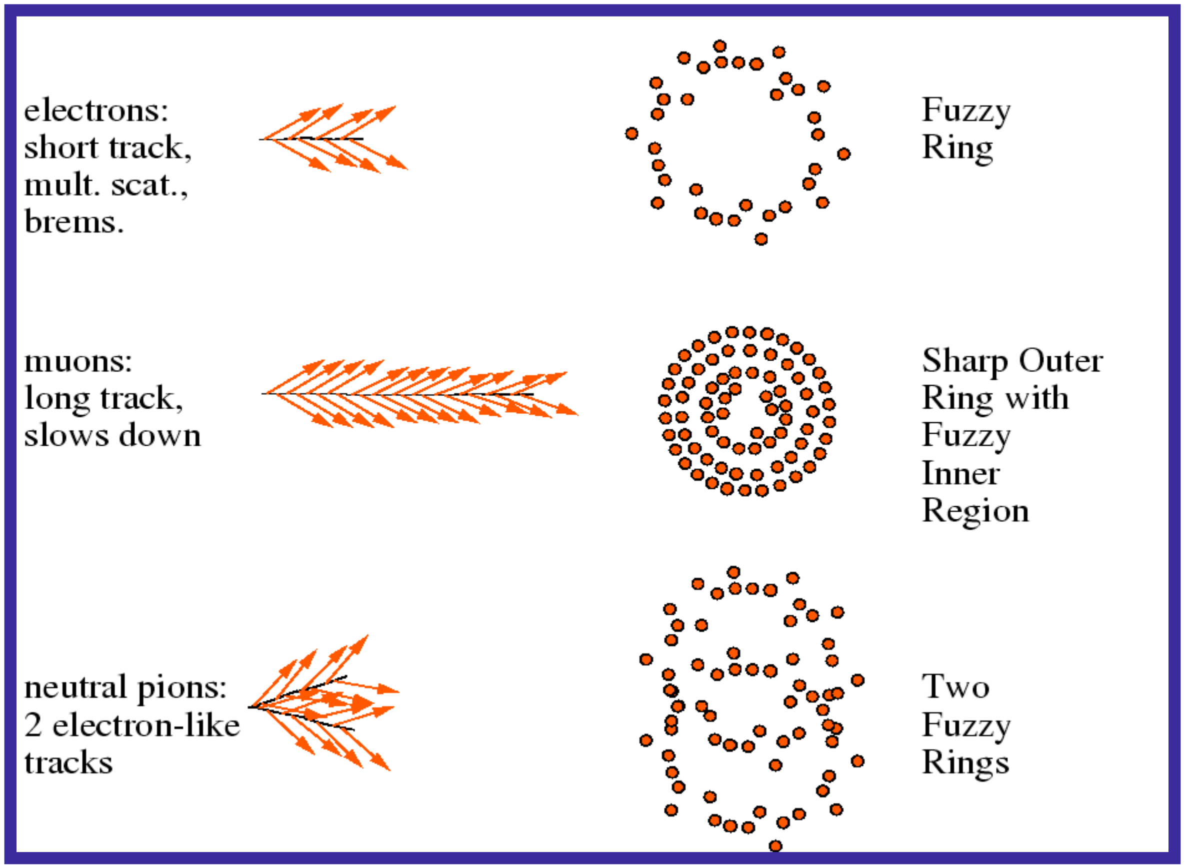
Quasi-Elastic Scattering

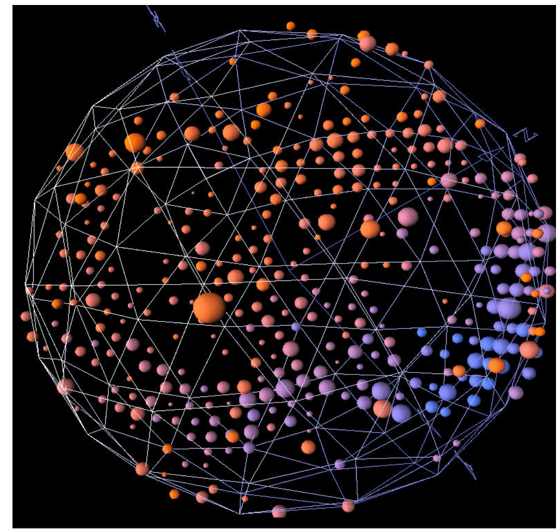
Single Pion Production

Deep Inelastic Scattering



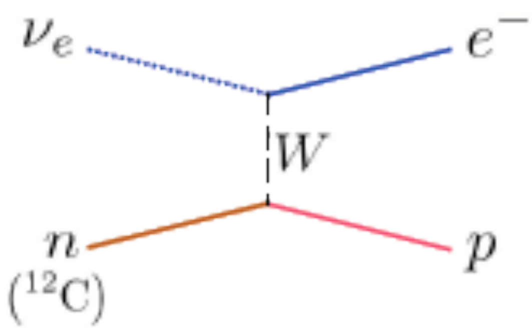
Event Signature





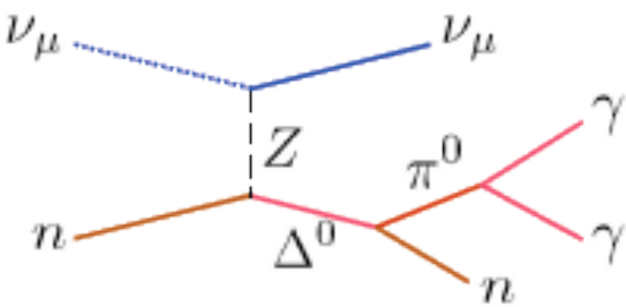
ν_e Event Selection

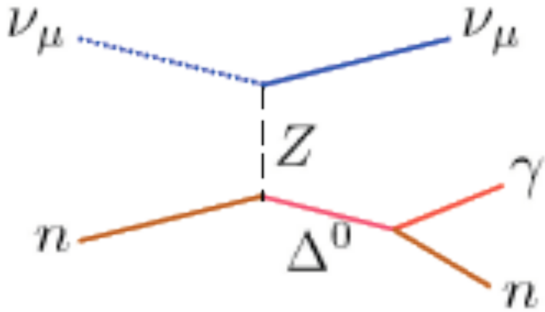
- Looking for $\nu_\mu \rightarrow \nu_e$ oscillations
- Use charged current interaction to identify ν_e events



Two backgrounds to the Oscillation search

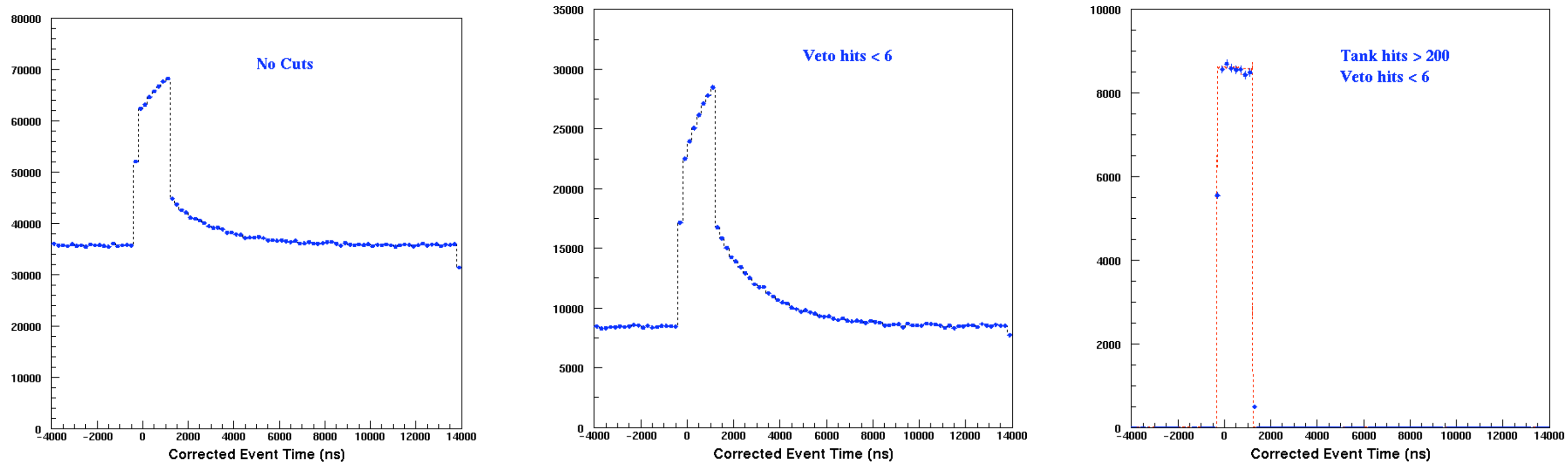
- Real ν_e inherent in beam
- Mis-identified "electron-like" events
  - NC π^0, Radiative Delta decays, etc.





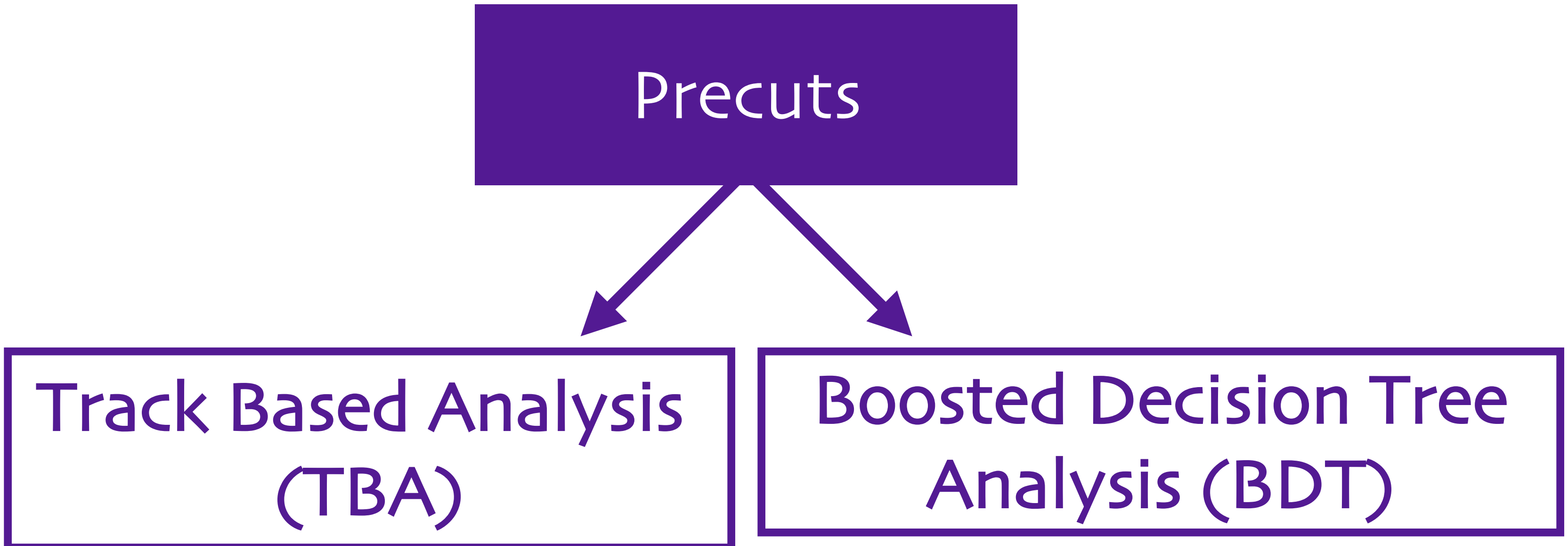
ν_e Event Selection

Precuts



- 1 contained cluster of tank hits in beam time window
  - Reconstructed interaction vertex within fiducial volume of detector
- # Veto Hits < 6, # Tank Hits > 200
  - Removes cosmic rays, removes low E electrons from muon decays

ν_e Event Selection



Track Based Analysis (TBA)

fit events under different track hypotheses

ratios of resulting maximum likelihoods provide particle ID information

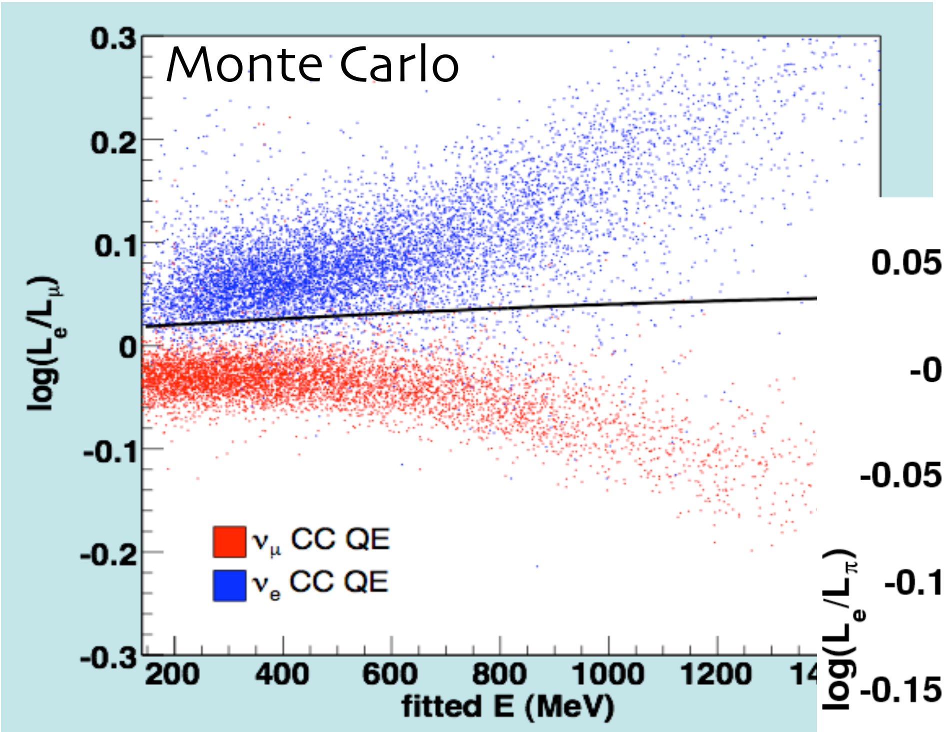
Boosted Decision Tree Analysis (BDT)

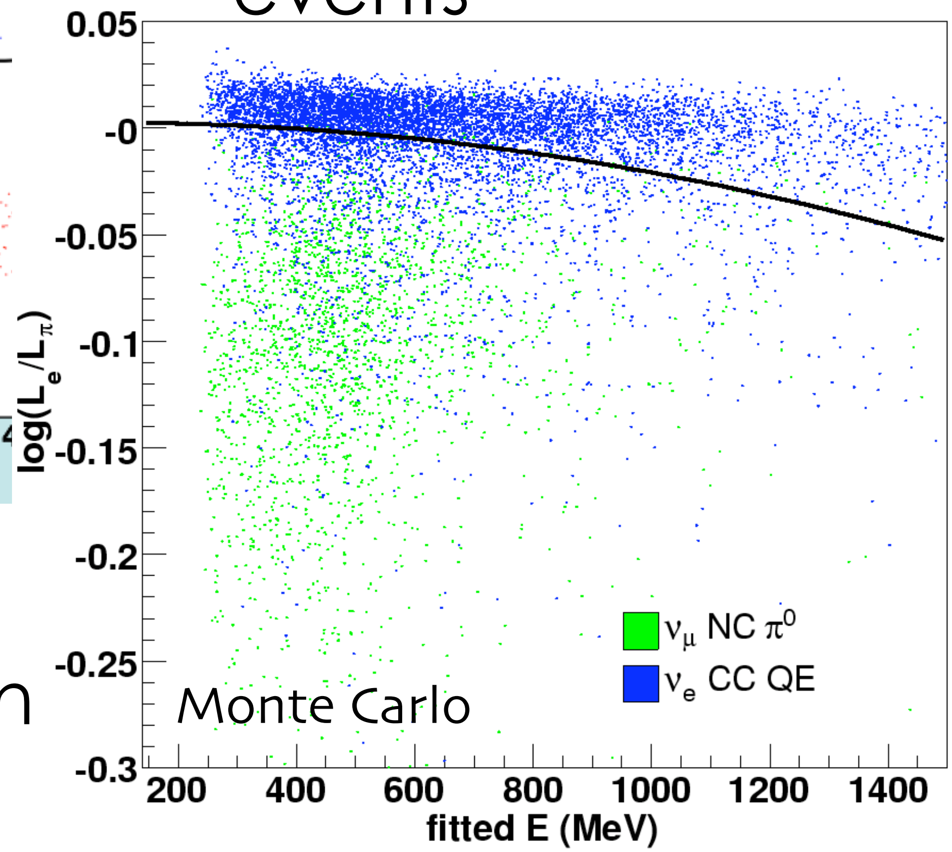
calculate O(100) topological variables

use boosted decision trees to assemble/optimize information

Track Based Analysis

- Separate pion events from electron events

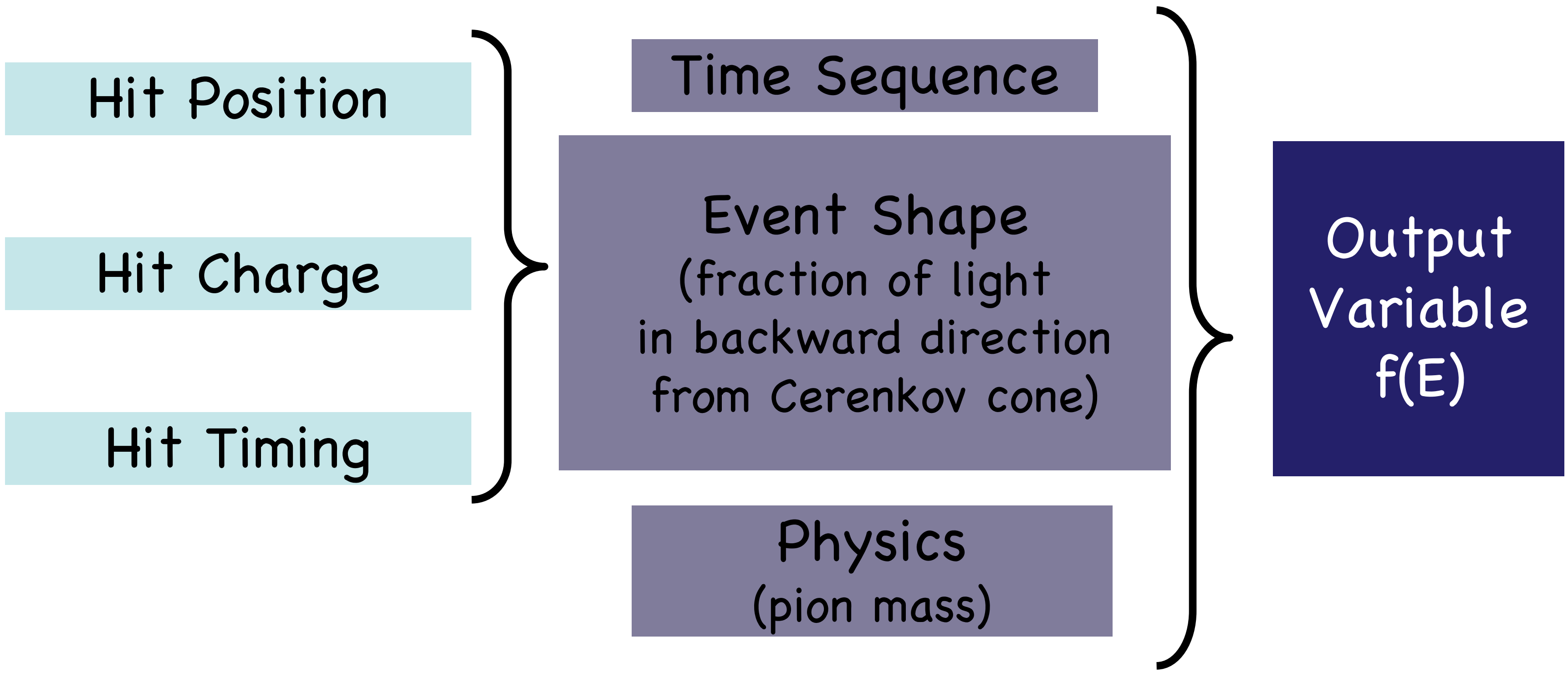




- Separate muon events from electron events

Boosted Decision Trees

- Use low level variables (hit timing, charge information, Cerenkov cone) to create analysis variables
- Combine analysis variables into a single value which is then cut on



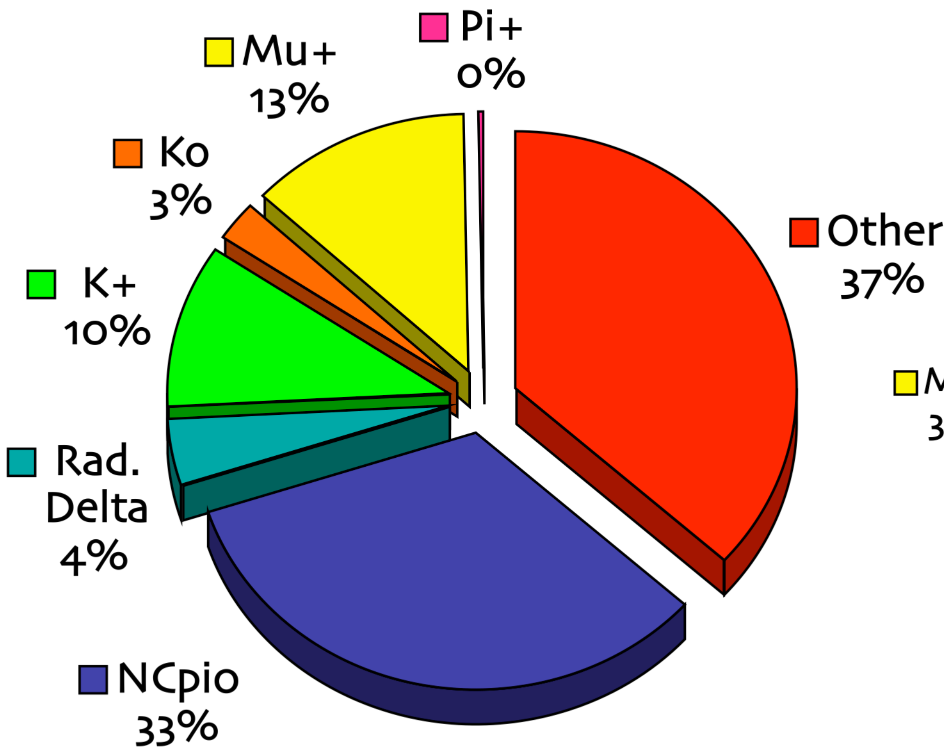
B.P. Roe, et. al : physics/0408124, NIM A543 (2005) 577-584

Final Event Composition

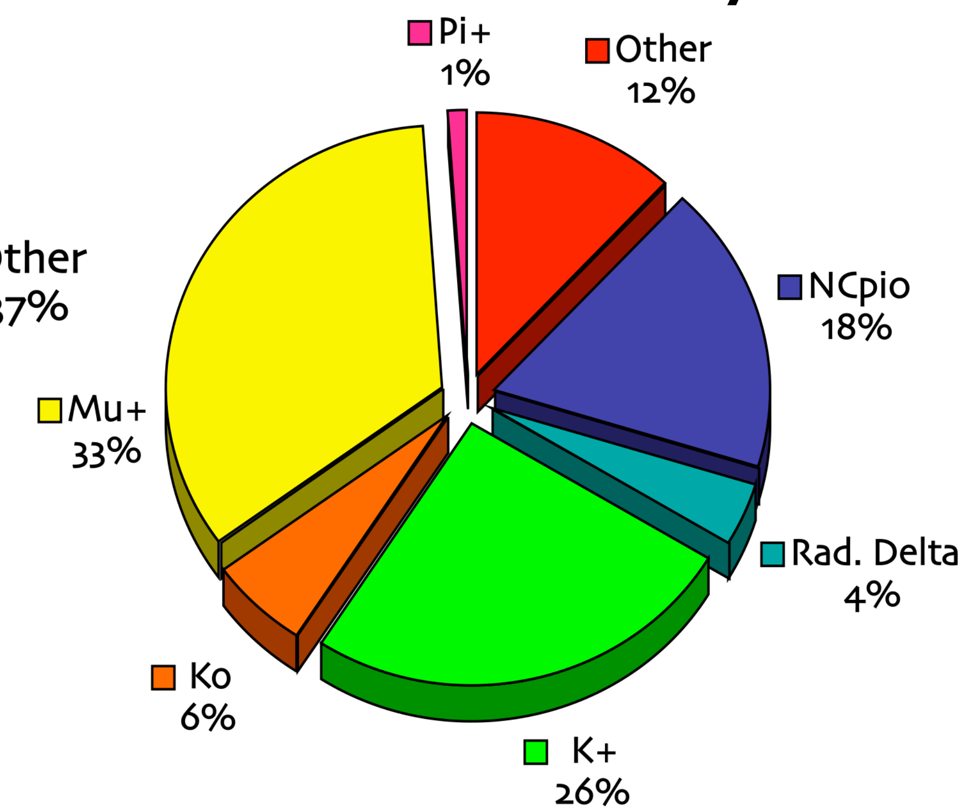
intrinsic ν_e

ν_μ mis-id

Boosting Analysis



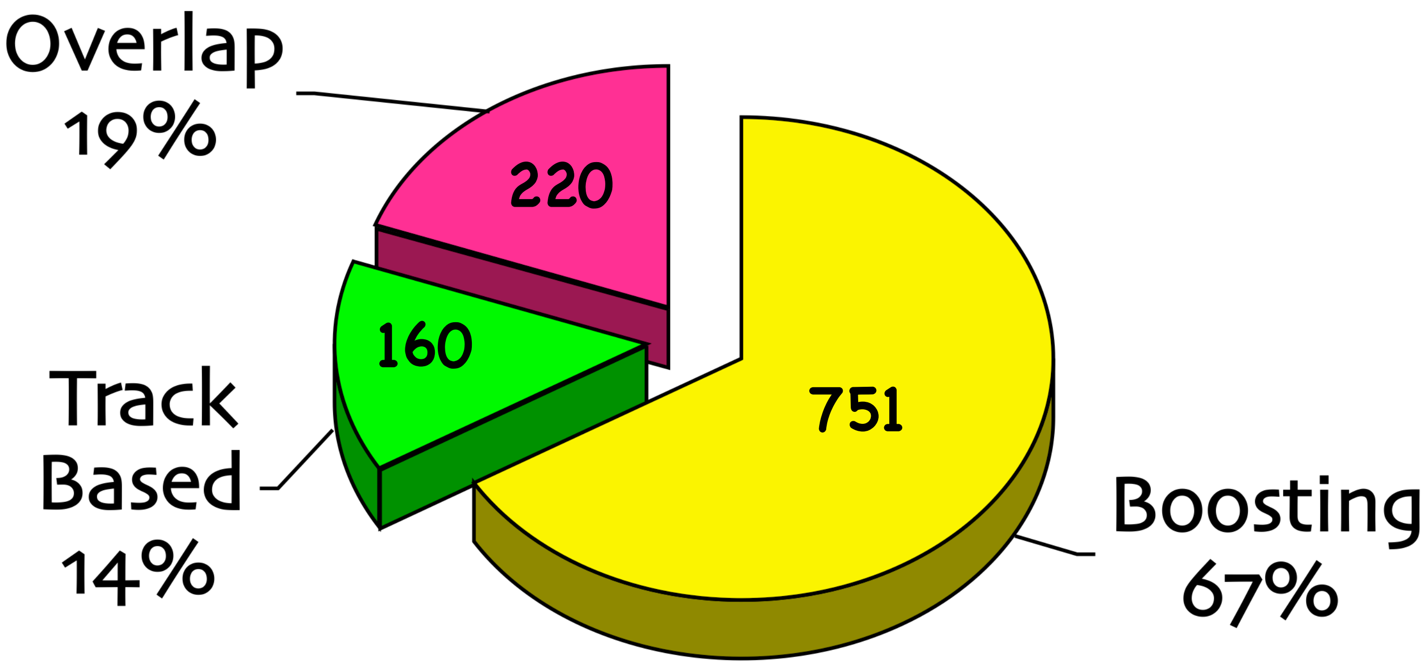
Track Based Analysis



Overlap of Events

Track Based : 475 MeV < E_ν^{QE} < 1.250 GeV

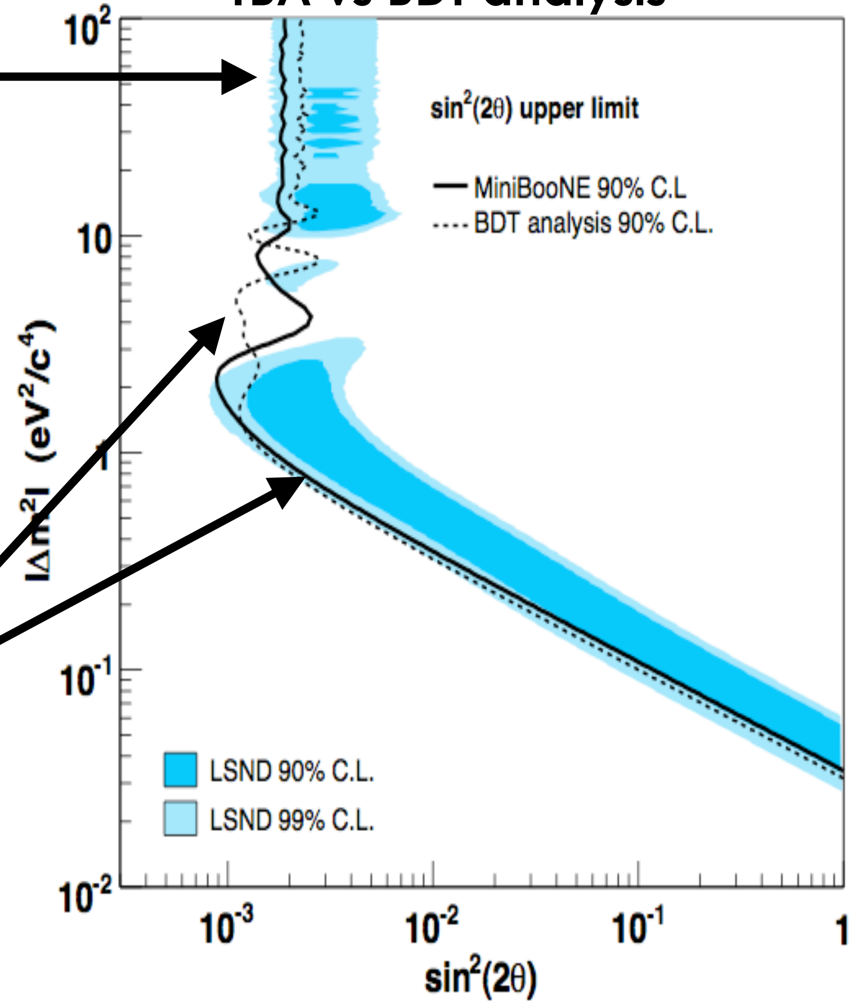
Boosting : 300 MeV < E_ν^{QE} < 1.60 GeV



Final Exclusion Curves

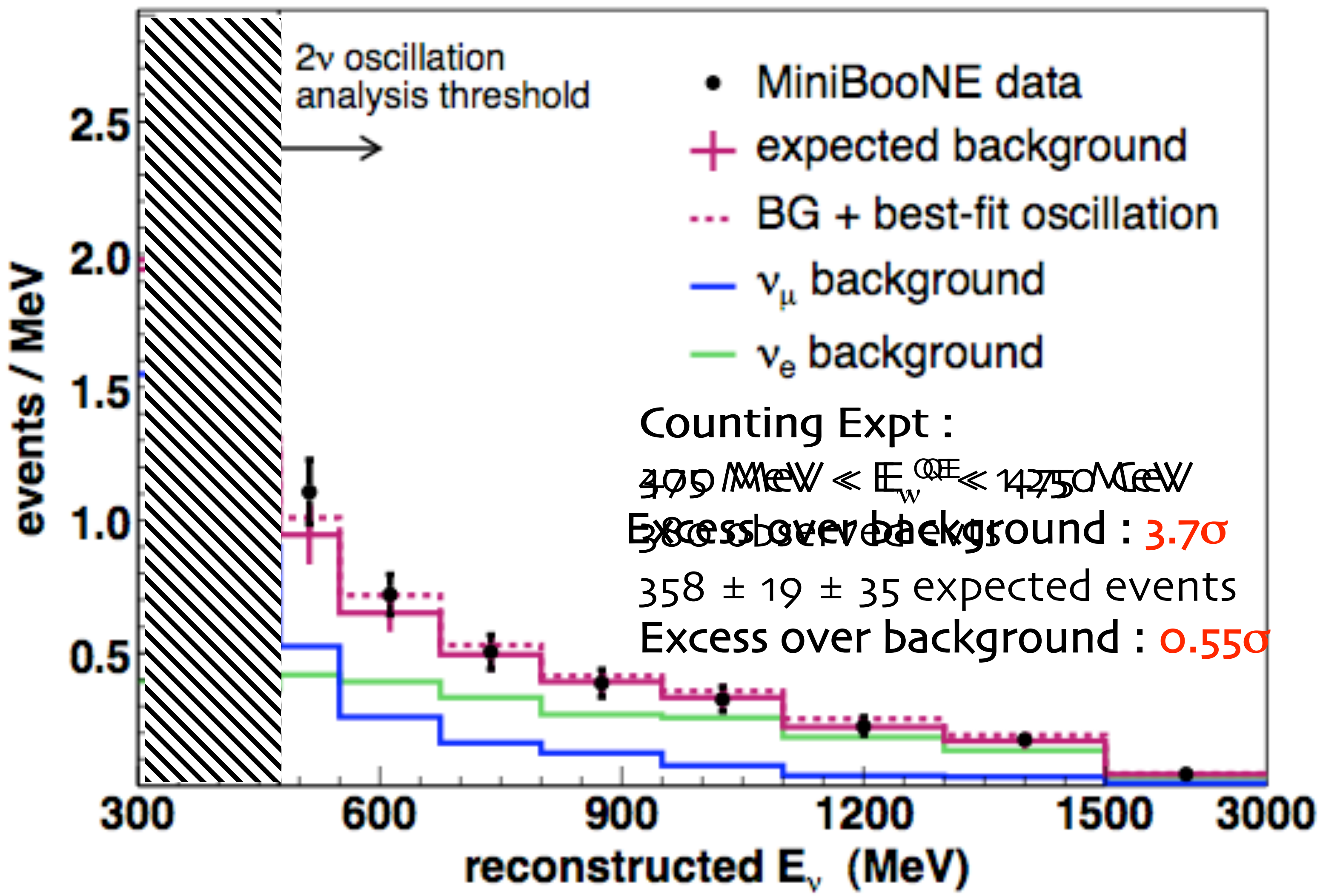
- Track Based Analysis more sensitive at high Δm^2
- Boosted Decision Tree slightly more sensitive at low Δm^2

TBA vs BDT analysis



Phys. Rev. Lett. 98, 231801 (2007)

Observed Event Distribution



Counting Expt :

475 MeV < E_ν^{QE} < 1250 MeV

Excess over background : 3.7σ

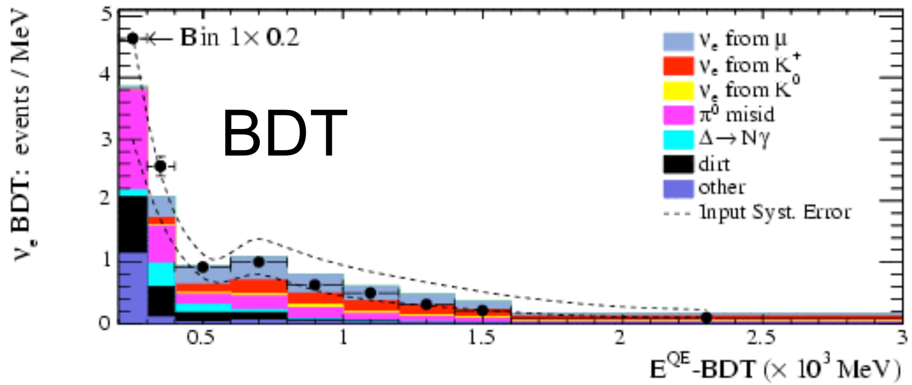
380 observed evts

358 ± 19 ± 35 expected events

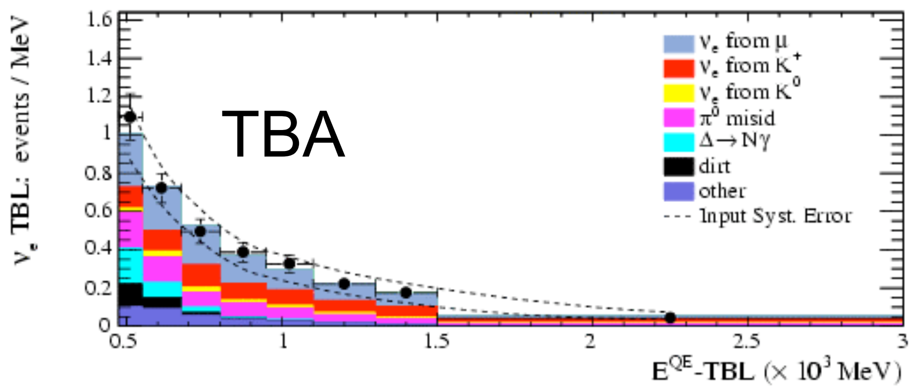
Excess over background : 0.55σ

Joint Analysis

- Combine data from 2 oscillation analyses to produce a more sensitive result in the region below ~2 eV^2 in Δm^2
  - Does not include low E excess



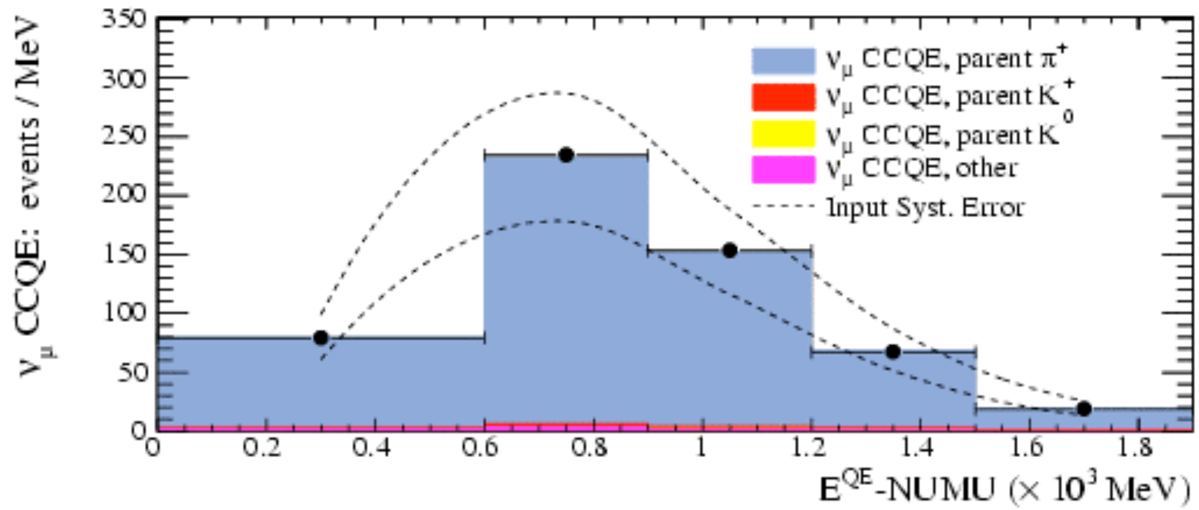
- Two different event reconstruction algorithms
  - Different reconstructed neutrino energy, even for events common to both samples



Joint Analysis

- Each analysis used ν_μ CCQE to constraint intrinsic ν_e backgrounds
  - Different reconstruction = different samples!
- Use same ν_μ CCQE sample for both analyses

Use CCQE sample from xsec pub.
PRL 100, 032301 (2008)



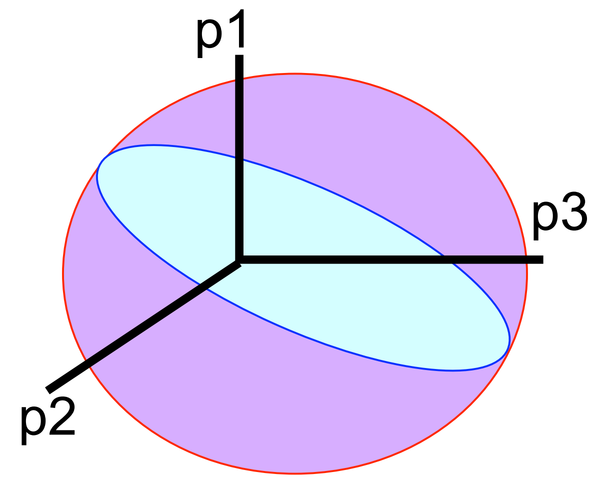
Joint Analysis

- In general, can reweight central MC to calculate systematic errors
  - Don't need to generate multiple million evt samples!

- Can't do that for the optical response of detector!

Joint Analysis

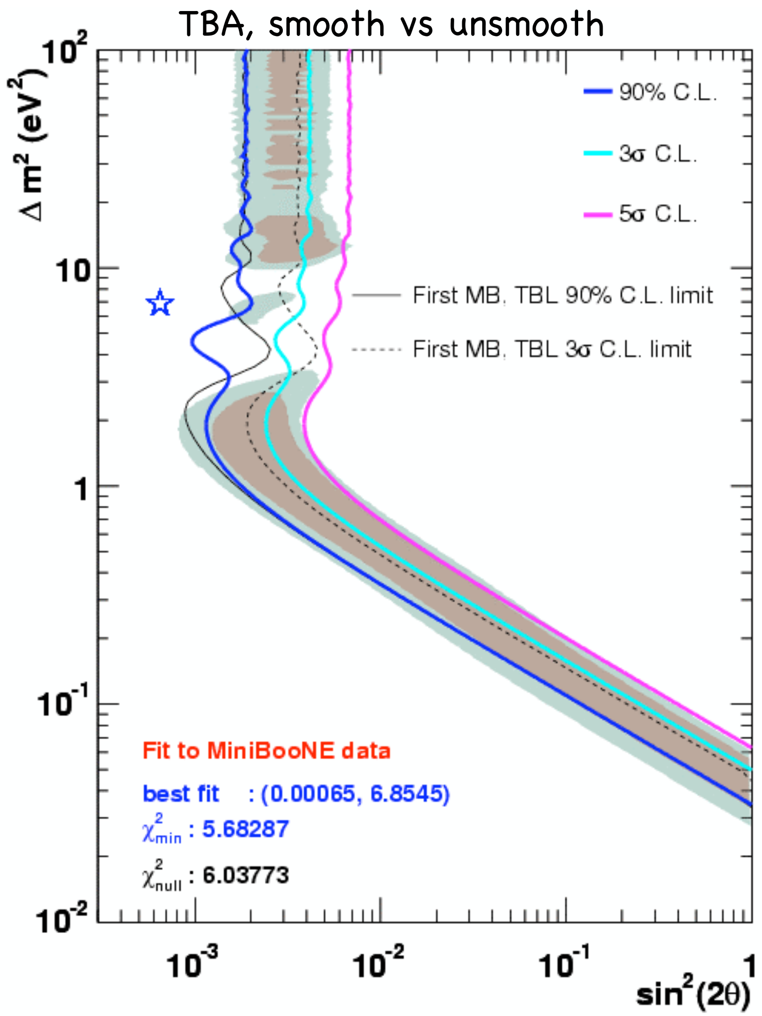
- Simultaneously vary all parameters within errors = 1 multisim
- Create 66 multisims
- Computing power = only produce data sized samples (vs central MC/other syst)



Joint Analysis

- Data sized stat error built in to OM systematic
- Can use that as the stat error, or remove & explicitly add in data stat error
- TBA does the former
- BDT : former causes pathologies in output variable
  - Fit 5^{th} order poly to (multi/mc) before calculating error matrix
  - *Smoothing*, removes jitter associated with statistical fluctuations
  - Causes *slight* overestimate of systematic

Joint Analysis



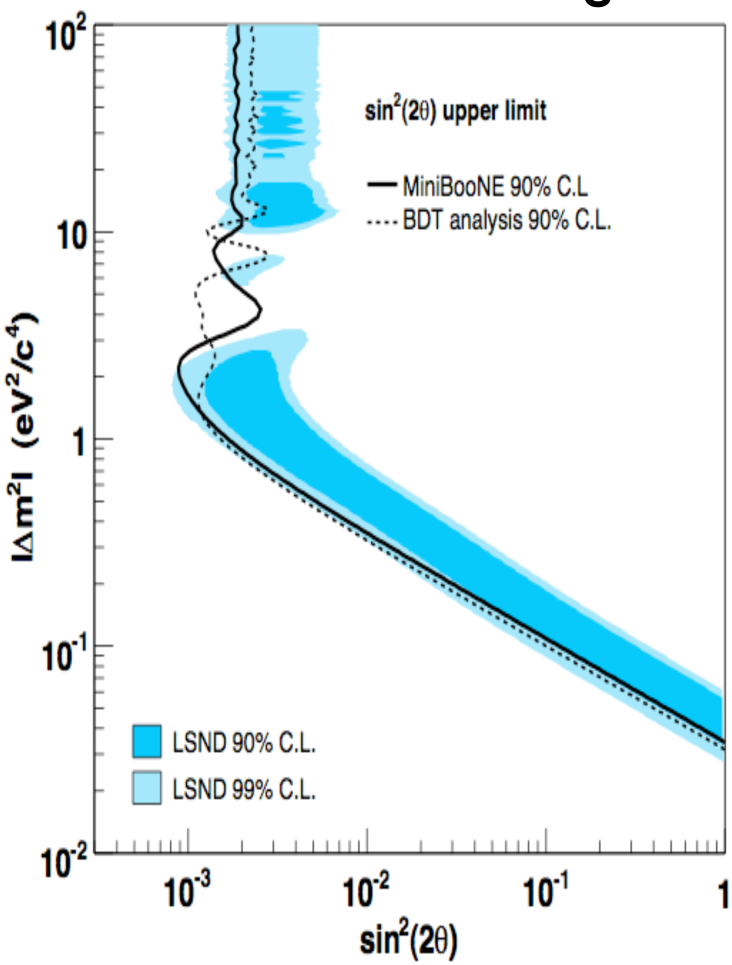
- Smoothing degrades limit slightly in track based analysis
- Smoothing is more conservative, non-smoothing produces pathologies we can't control
- Apply smoothing to both analyses

Joint Analysis

- Some events common to both analyses
- Need to consider correlations in statistical error matrix!

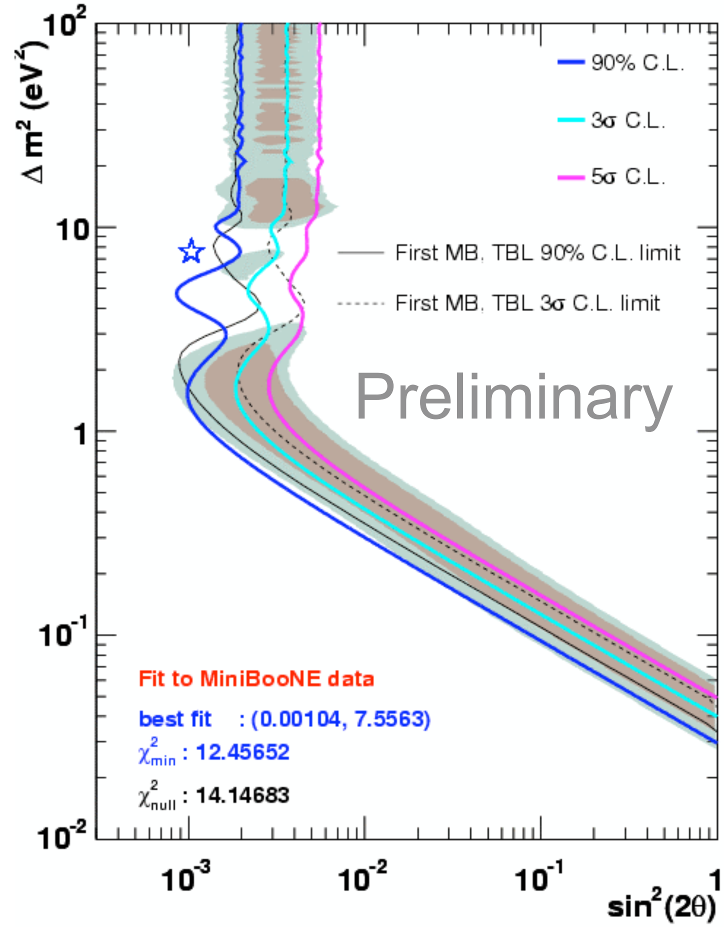
Joint Analysis

Track-based vs Boosting analysis



Phys. Rev. Lett. 98, 231801 (2007)

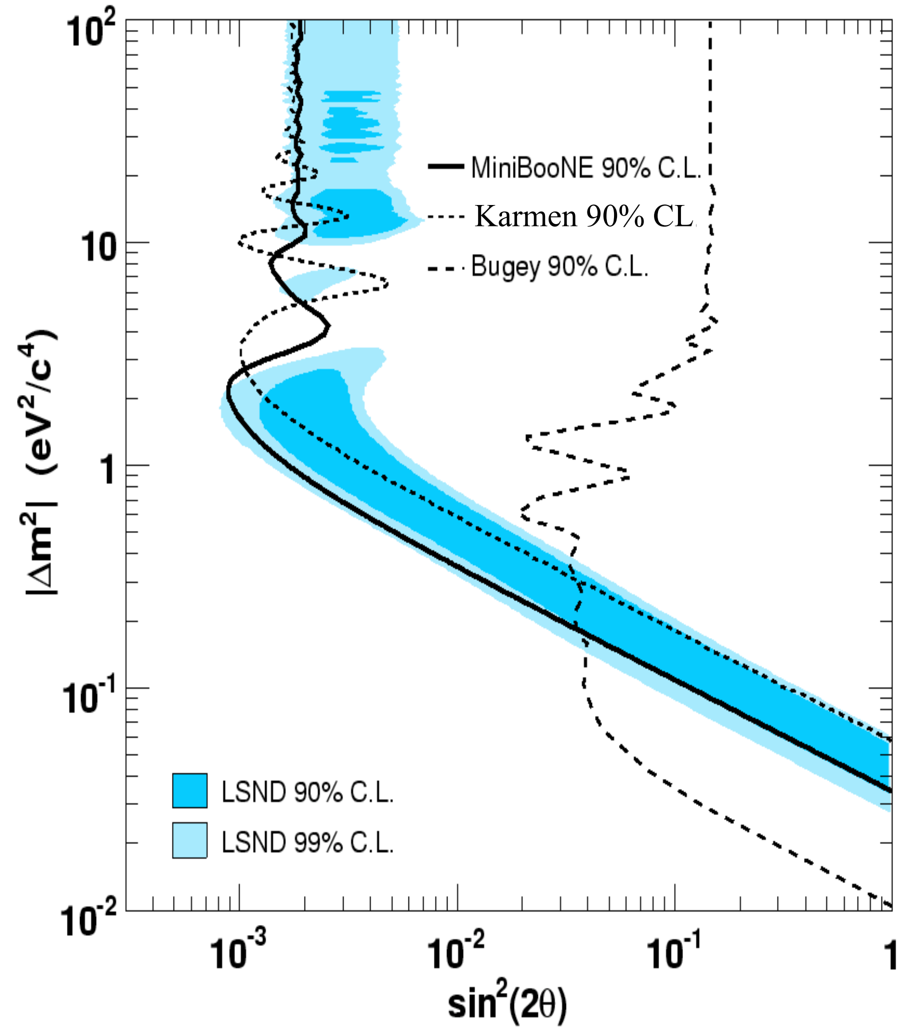
Combining both analyses



Publication in progress

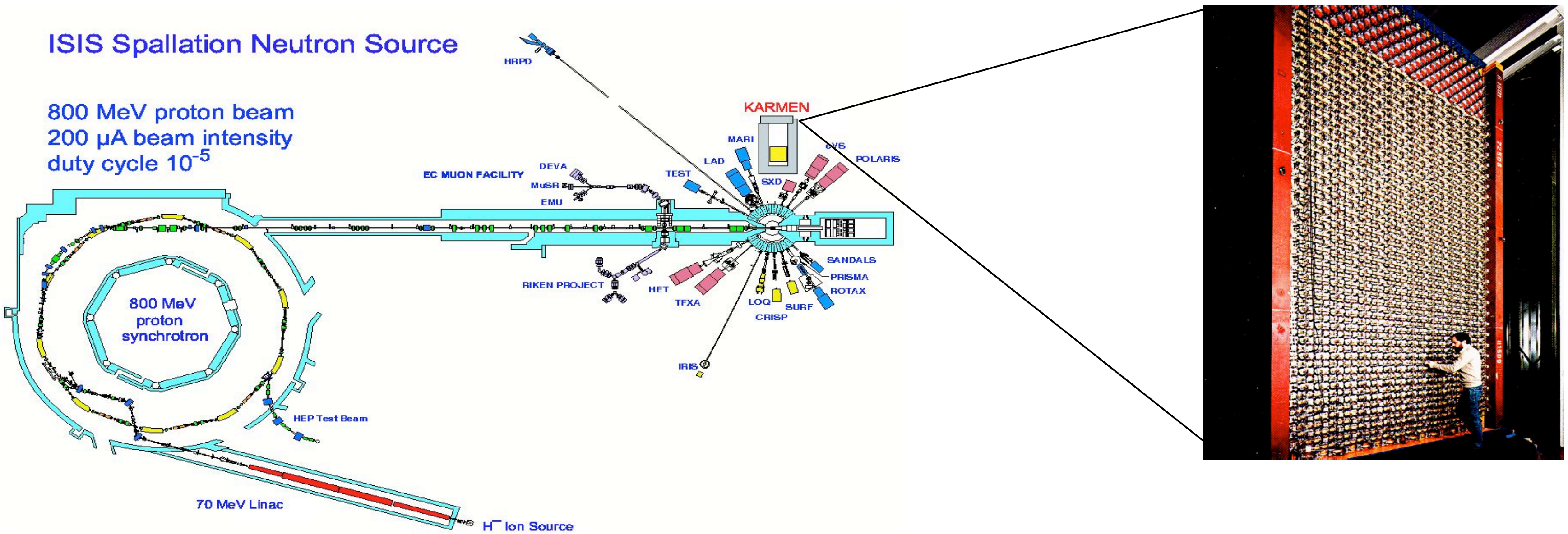
Global Data Analysis

- Determine if LSND excess is result of 2-ν osc, considering 3 null expts
- Combine data from Bugey, KARMEN2, LSND, MiniBooNE
  - *MB track-based analysis > 475 MeV only!*



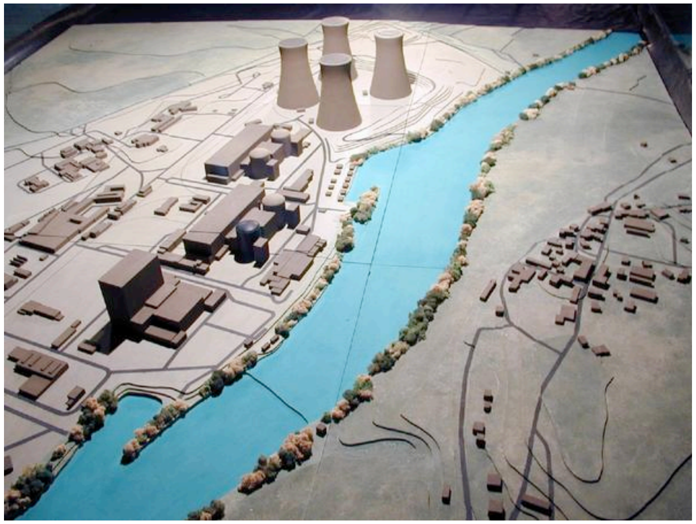
arXiv:0805.1764, accepted by PRD

KARMEN(2)

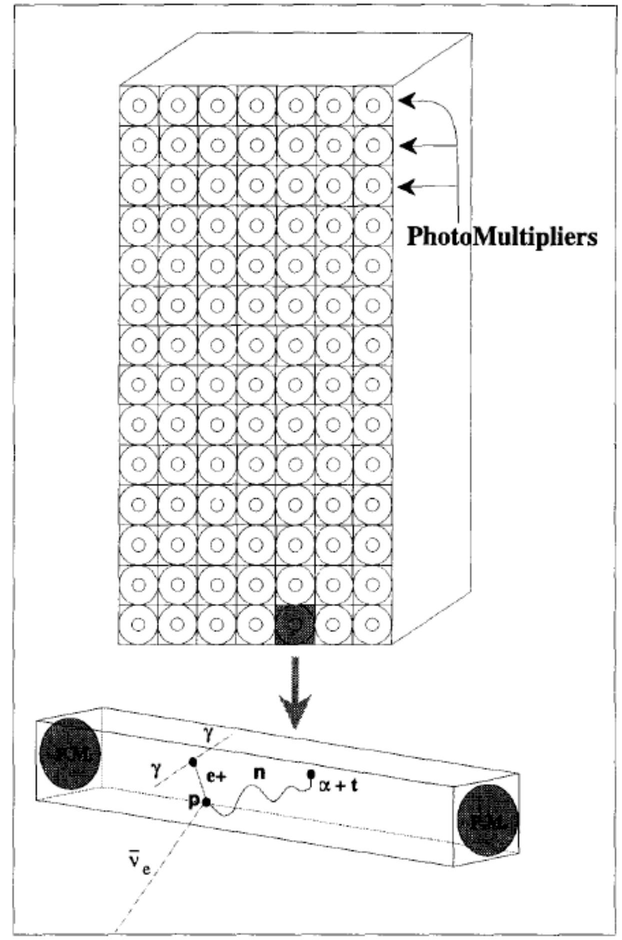


- Located at ISIS neutron spallation source, Oxford
  - 800 MeV p + tantalum/heavy H_20
- July, 1990 to March, 2001
- Large volume segmented liquid scintillator detector, lined with PMTs
- Surrounded by shielding interspersed with scintillating veto counters

Bugey



- Located at Bugey nuclear power plant
- Ran through mid 1990's
- Modules of scintillating liquid, read out by PMTs
- Performed oscillation searches at 15m, 40m, 95m from reactor



Global Data Analysis

- Compatibility
  - How probable is it that all experimental results come from the same underlying 2-ν oscillation hypothesis?
- Allowed regions
  - Indicate where oscillation parameters would lie, at a given CL, assuming all expt. results can arise in a framework of 2-ν osc.
  - The compatibility is the metric for the validity of this assumption.

Global Data Analysis

- Data provided as points on Δm^2 - $\sin^2 2\theta$ grid
- Each pt = agreement between data & 2-ν hypothesis at that point
- Data in ln(L), Δln(L), χ^2 grids

- *Not able to obtain absolute χ^2 (goodness of fit) from all experiments!*

- Must use $\Delta\chi^2$ grids in this analysis

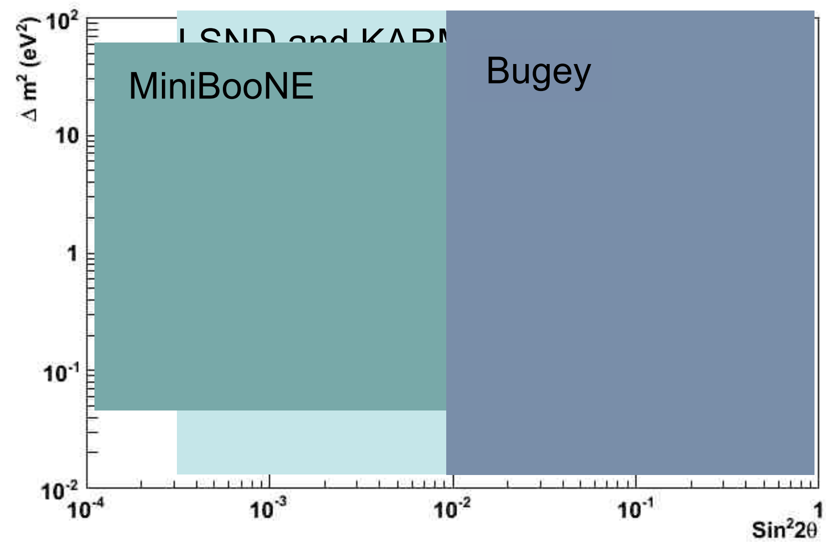
Two $\Delta\chi^2$ Analyses

- 2-D grid uses global best fit point to calculate the $\Delta\chi^2$ at each point
  – Prob to observe all expt results if nature has 2-ν osc in this entire Δm^2 region

- 1-D (Raster Scan) uses local best fit point at each Δm^2 to produce $\Delta\chi^2$
  – Compatibility at each Δm^2, if nature truly had 2-ν osc at that specific Δm^2

Input Data

- LSND
  - DIF and DAR data
- MiniBooNE
  - Most restrictive Δm^2 range upper $\sin^2 2\theta$ limit most coarse binning
    - Used to set default grid
- KARMEN2
- Bugey
  - Acero, Giunti, Laveder, hep-ph/0711.4222
  - Data spans large region not covered by MB
    - Convert into delta grid before put into MiniBooNE grid format to avoid bias



Same binning, range of Δm^2 - $\sin^2 2\theta$ common to all expts used

Compatibility Calculation

- Construct a $\Delta\chi^2$ grid for each expt.
  - each pt = local value - best fit value
- Sum individual $\Delta\chi^2$ grids
- Compatibility = χ^2 prob. of minimum of summed grid, using a reduced NDF
  - Σ(indep. α) - (# indep α estimated from data)
  - ex : 2-D MB + LSND = 4 - 2 = 2 NDF

Maltoni and Schwetz, Phys. Rev. D. 68, 033020 (2003)

Allowed Region

- Each expt's $\Delta\chi^2$ grid converted into $\Delta\chi^2$ prob grid using standard NDF (2, 1)
- Multiply prob grids together, produce pdf x

$$P(x) = x \sum_{J=0}^{n-1} \frac{1}{J!} |\ln^{j}(x)|$$

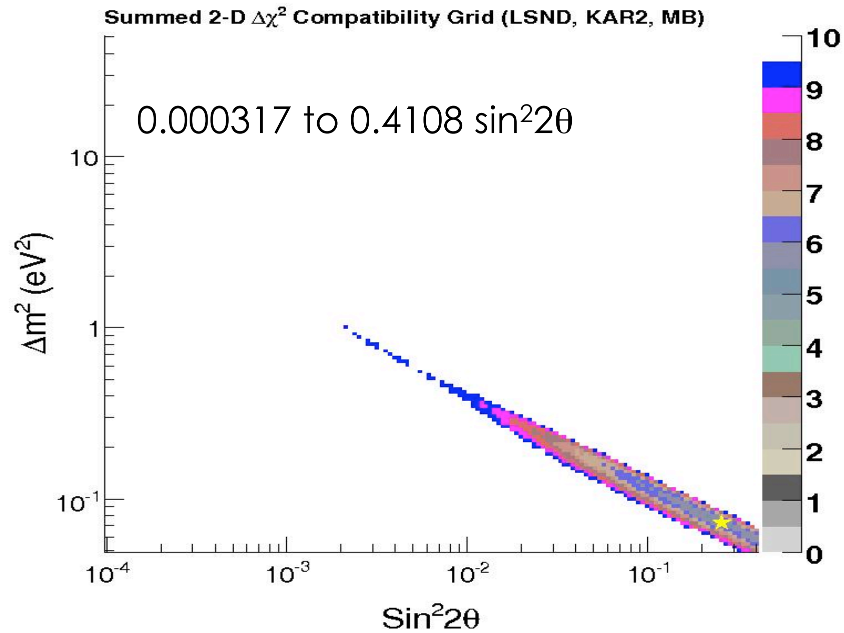
- Allowed regions = closed contours in space
- Exclusion bands = non-closed contours
  - Values to R are excluded at a given CL

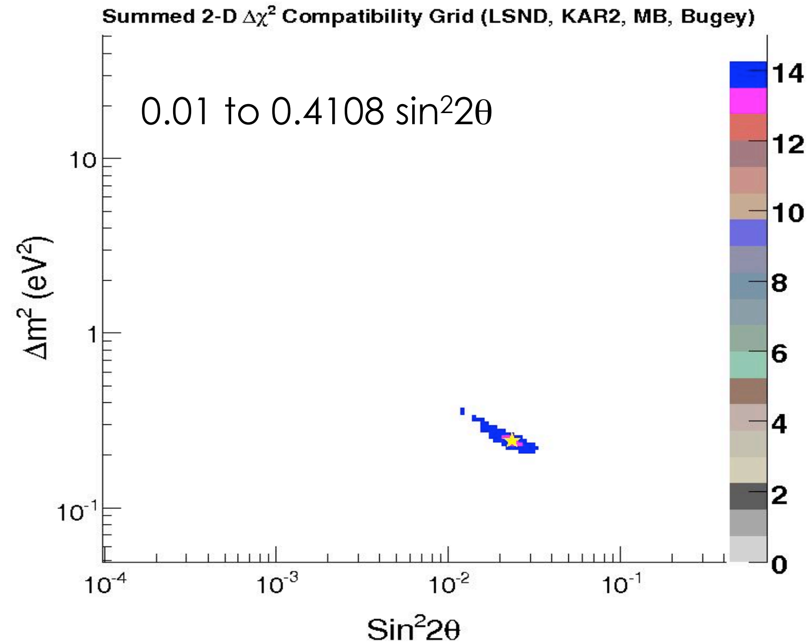
Roe, Probability and Statistics in Experimental Physics, (2001)

2-D Results

LSND	KARMEN2	MB	Bugey	Max Compat (%)	Δm^2	$\sin^2 2\theta$
X	X	X		25.36	0.072	0.256
X	X	X	X	3.94	0.242	0.023
	X	X		73.44	0.052	0.147
	X	X	X	27.37	0.221	0.012
X		X		16.00	0.072	0.256
X		X	X	2.14	0.253	0.023
X	X			32.21	0.066	0.4

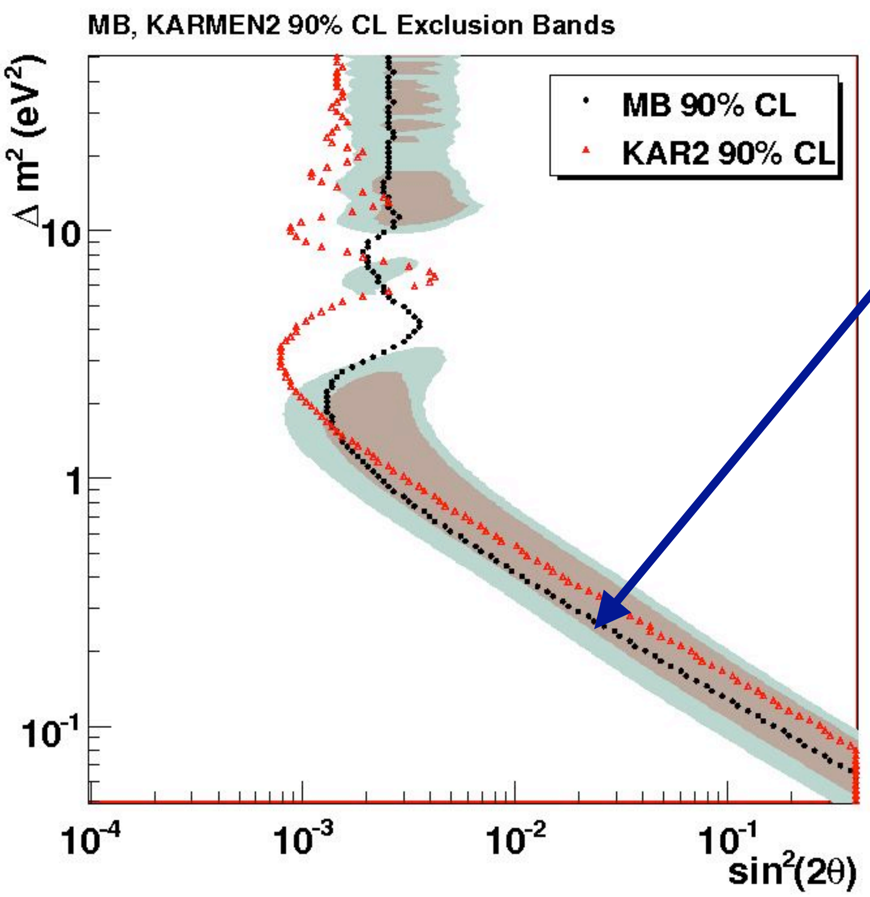
LSND, MB, KAR2, ± Bugey





- 25.36% compat at $\Delta m^2 = 0.072$ eV^2, $\sin^2 2\theta = 0.256$
- Area covered by Bugey!
- 3.94% compat at $\Delta m^2 = 0.242$ eV^2, $\sin^2 2\theta = 0.023$

LSND, MB, Bugey, ± KAR2



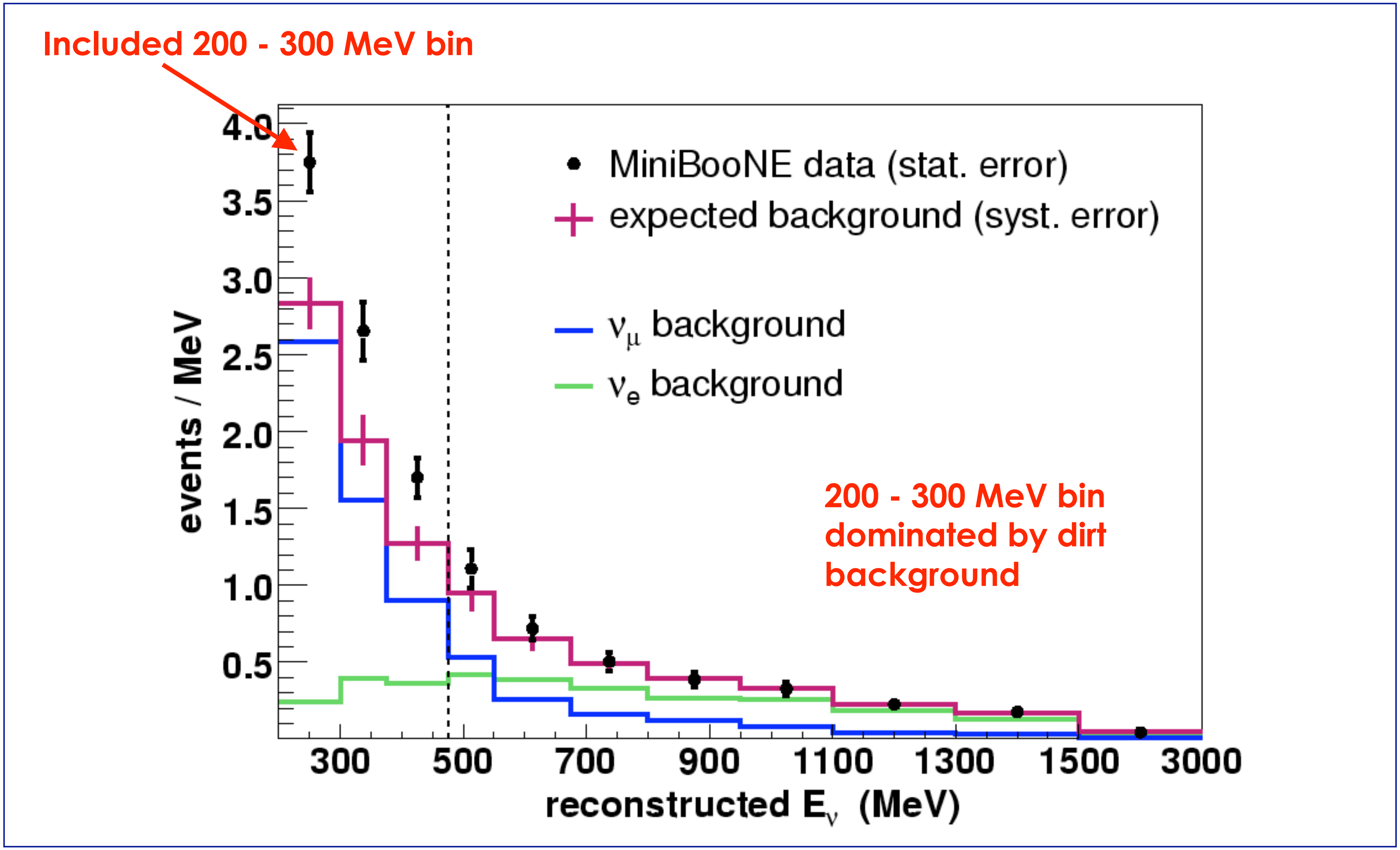
- 2.14% vs 3.94%!
- Best fit point = 0.242 eV^2, 0.023 $\sin^2 2\theta$
- Including KARMEN2 increases the NDF used to calculate prob, but provides no increase in sensitivity!

THE FOLLOWING **PREVIEW** HAS BEEN APPROVED FOR

ALL AUDIENCES

BY THE **MINIBOONE COLLABORATION**

Low-Energy Excess



Understanding the Excess

- Excess is electron-like, seen by both analyses
- Backgrounds to the osc. analysis are mainly ν_μ induced at low E : NCπ^0, radiative Δ, dirt

- Double/triple checked various backgrounds
  - Dirt or radiative Δ decays NO
  - Pion or muon mis-id (including muon bremstrahluung) NO
    - arXiv:0710.3897

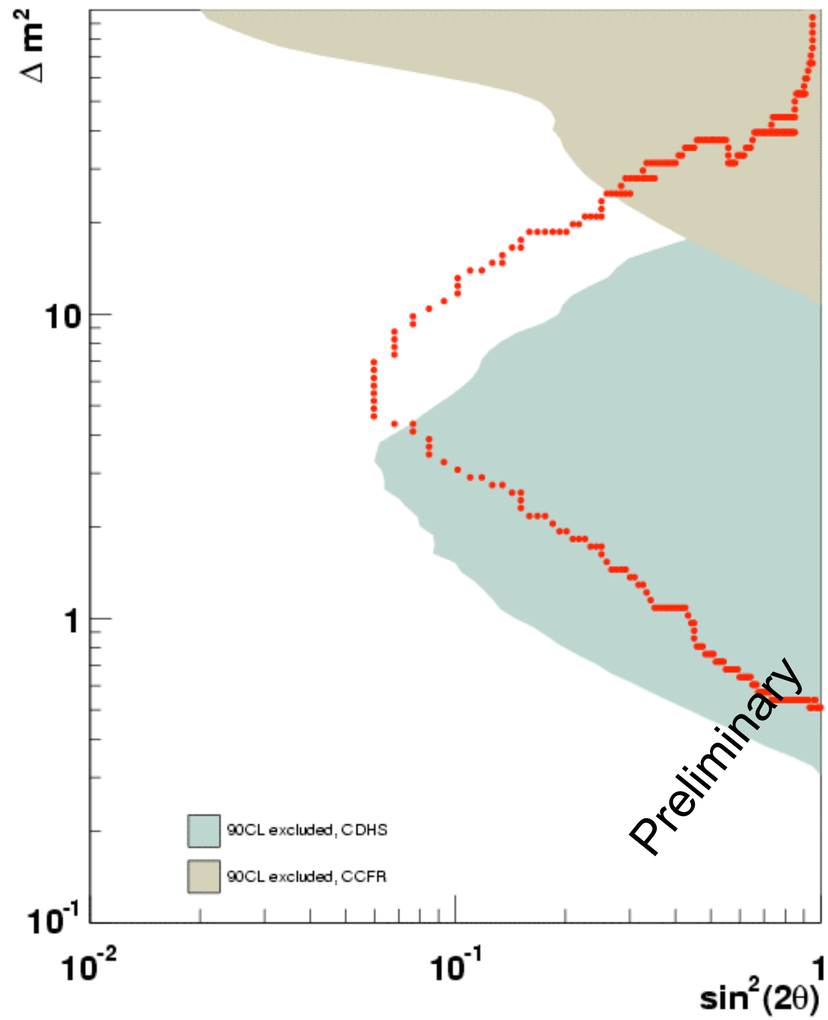
- Refine hadronic model
  - Added π^- radiative capture, photonuclear absorption

The Low-E Excess

- Work in progress, expect W&C this summer
- Great interest in the community!
  - Lorentz Violation
    - Katori, Kostelecky, Tayloe, Phys. Rev. D74 (2006) 105009
  - Anomaly-mediated photon production
    - Harvey, Hill, and Hill, hep-ph0708.1281
  - 3+2 + CP violation : MB excess + LSND, Karmen2, Nomad, appearance only data
    - Maltoni and Schwetz, Phys. Rev. D76 (2007) 093005
  - Sterile neutrino short-cuts in extra dimensions
    - Päs, Pakvasa, Weiler, Phys.Rev. D72 095017, 2005
  - ν_e disappearance, deficit in Ga expts
    - Giunti and Laveder, hep-ph 0707.4593
  - New light gauge boson
    - A. Nelson and J. Walsh, hep-ph/0711.1363

ν_μ Disappearance Sensitivity

- Work in progress, expect W&C this summer
- **MiniBooNE data 90% CL sensitivity (NOT limit from data)**
- CDHS CCFR 90% CL
- Combined analysis with SciBooNE data will significantly improve this sensitivity



Summary

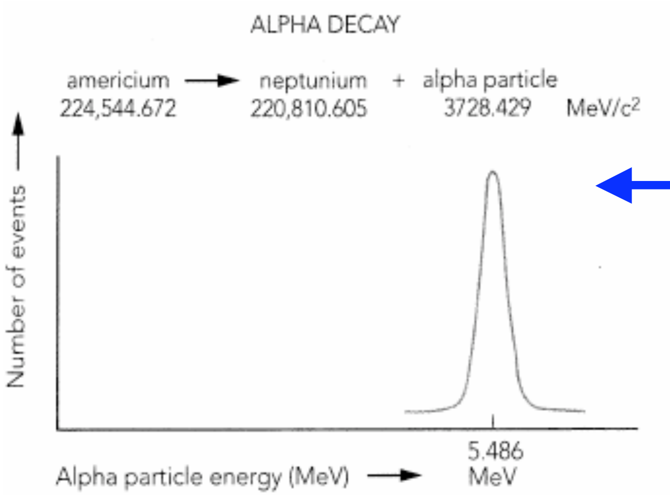
- Combination of TBA, BDT results in a more restrictive exclusion band at low Δm^2
  - TBA 475 MeV and up data set
- Joint analysis finds 3 null result experiments (KARMEN2, Bugey, MB) and LSND only 4% compatible with having come from 2 neutrino oscillations
  - TBA 475 MeV and up data set only

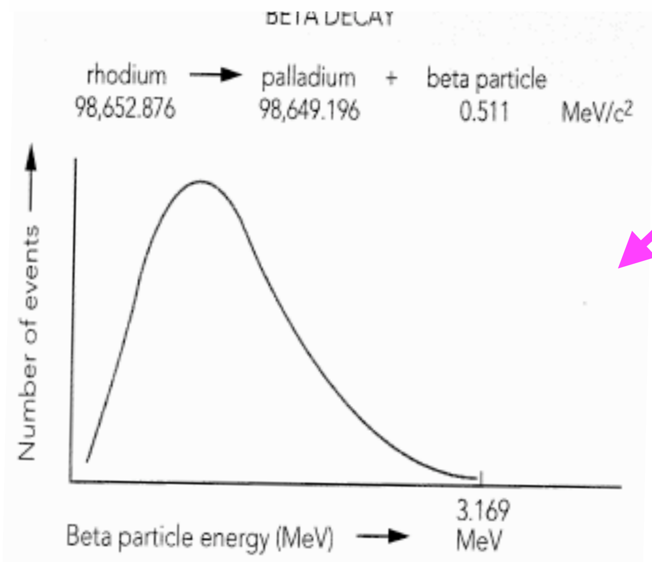
MiniBooNE Future

- Focus today on ν mode oscillation analyses
- Many more papers/analyses just released & in the pipeline!
  - ν_μ disappearance in ν mode
  - ν mode xsec measurements : NCE, $CC\pi^+$, CCQE (PRL 100, 032301 (2008)), $NC\pi^0$ (arXiv:0803.3423, Phys. Lett. B. 664, 41 (2008))
  - Anti-ν mode xsec measurements : $CC\pi^+$, CCQE, $NC\pi^0$
- Complete low-energy check in next few months
- Anti-ν oscillation analysis coming soon!

Backup Slides

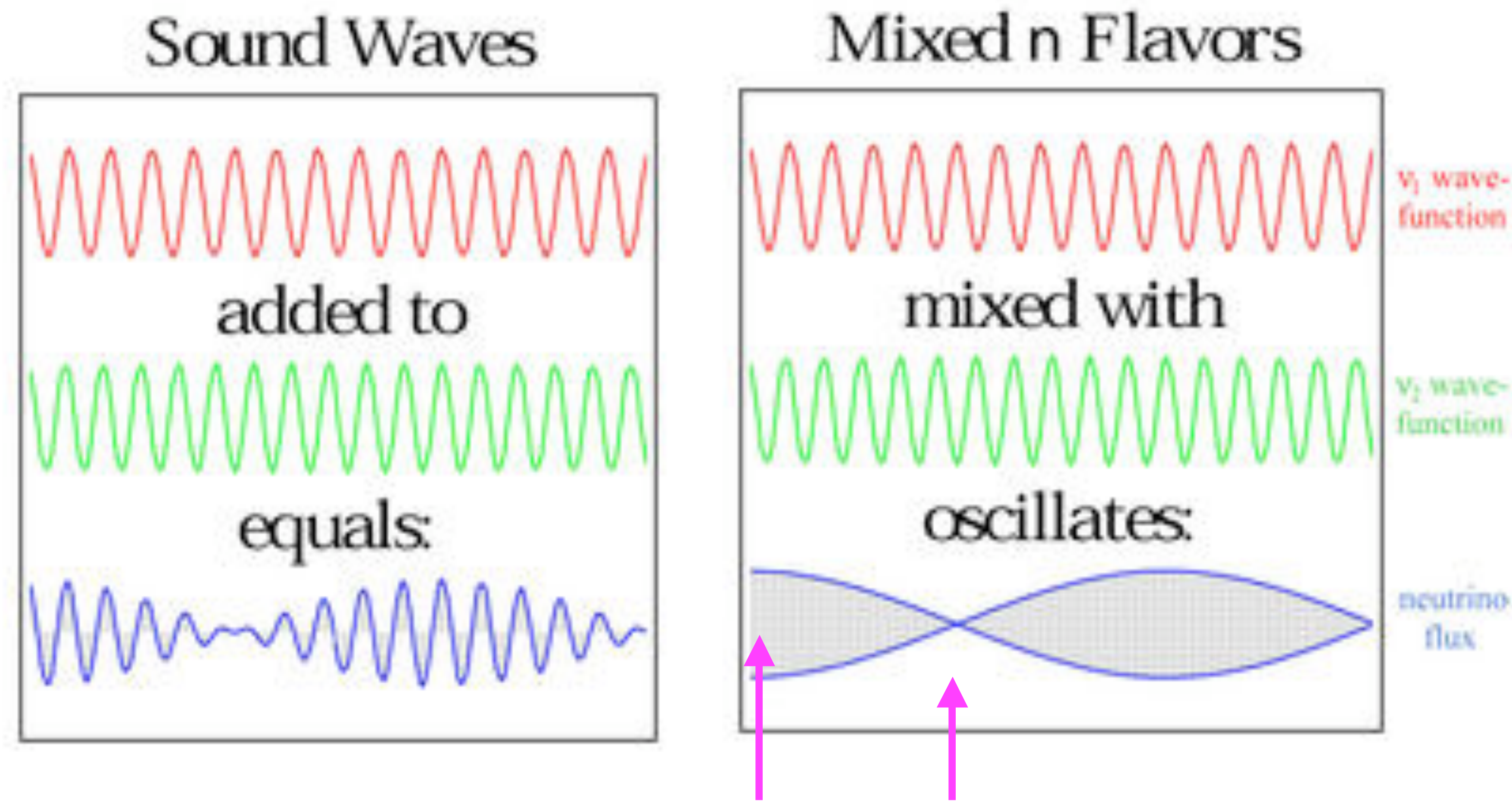
Proposing the Neutrino





- 2 body alpha decay, E of decay products always the same
- 1913 - 1930 : beta decay = continuous spectrum of E
  - E not conserved?
  - P not conserved?
- "I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do." (Pauli, 1930)

Superposition of Masses



$\nu_\mu \rightarrow \nu_e$

Neutrino Oscillations

Weak state Mass state

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

$$|\nu_\mu(o)\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

Neutrino Oscillations

Weak state Mass state

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

$$|\nu_\mu(t)> \;=\; -\sin\theta\,|\nu_1> \;+\; \cos\theta\,|\nu_2>$$

e^{-iE_1t} (↑ $|\nu_1>$) e^{-iE_2t} (↑ $|\nu_2>$)

Neutrino Oscillations

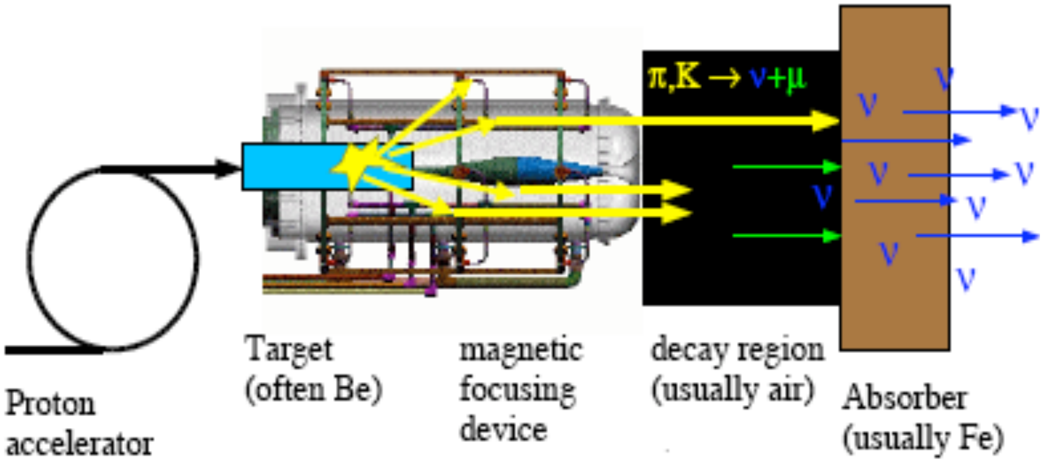
$$P_{osc} = |\langle \nu_e | \nu_\mu(t) \rangle|^2$$

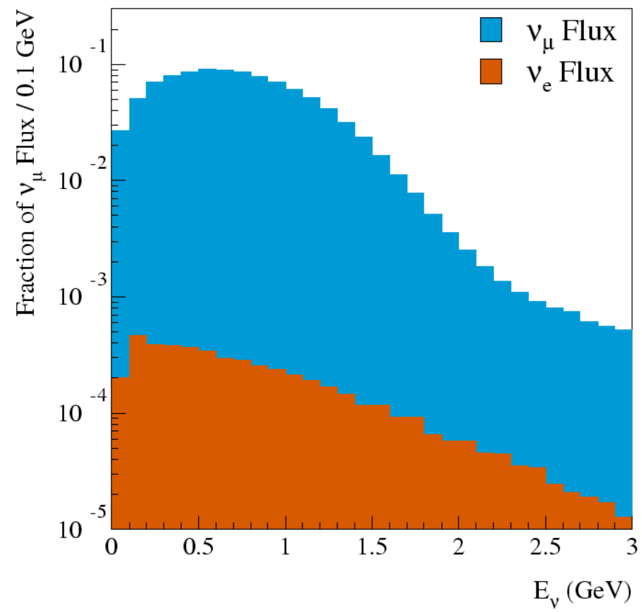
$$P_{osc} = \sin^2 2\theta \, \sin^2 \left[\frac{1.27 \, \Delta m^2 L}{E} \right]$$

Neutrino Masses

- Electron neutrino < ~2 eV
  - Tritium beta decay experiments
- Muon neutrino < few MeV
- Tau neutrino < few MeV

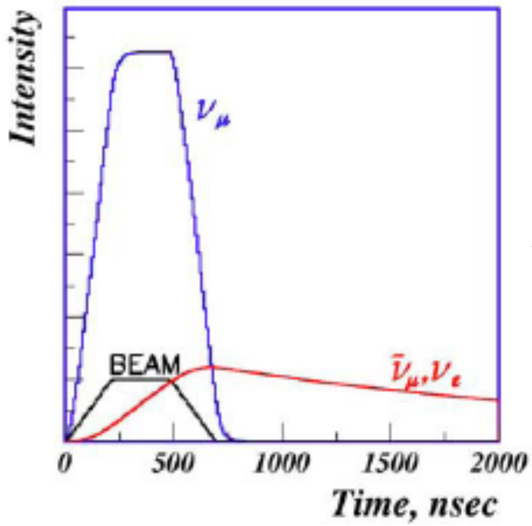
Decay In Flight

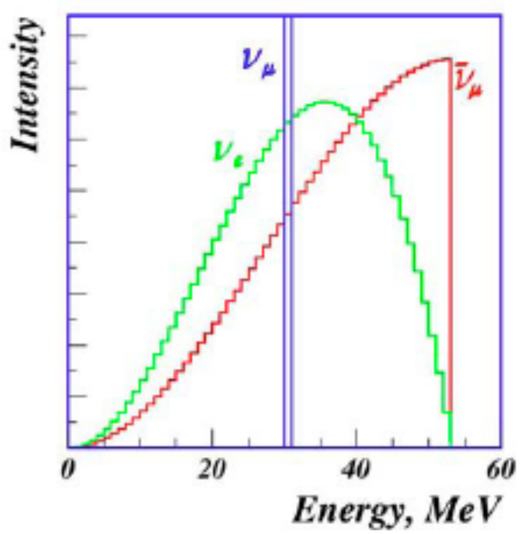




- Advantage : more intense beam because mesons are focused (not isotropic)
- Advantage : can select neutrino, anti-nu beam
- Disadvantage : difficult to understand the flux (in content and in E)!

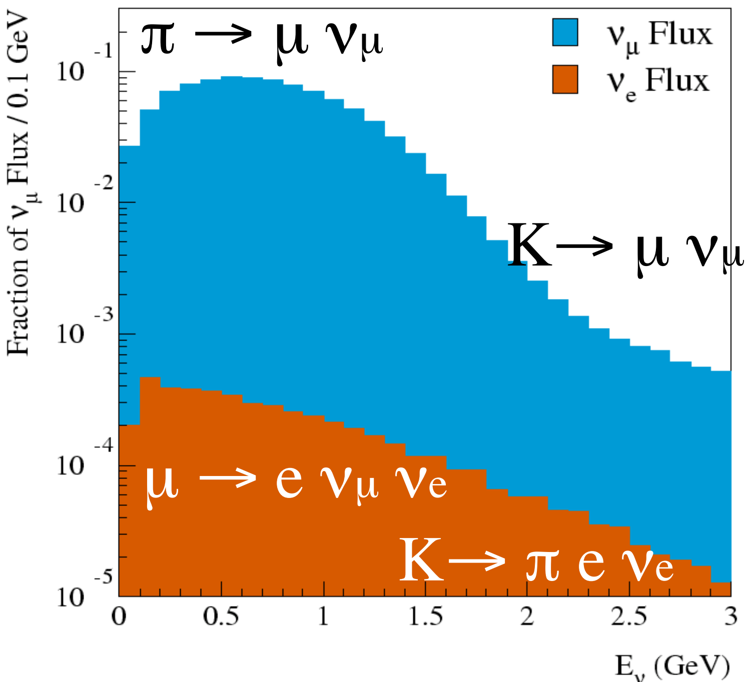
Decay At Rest

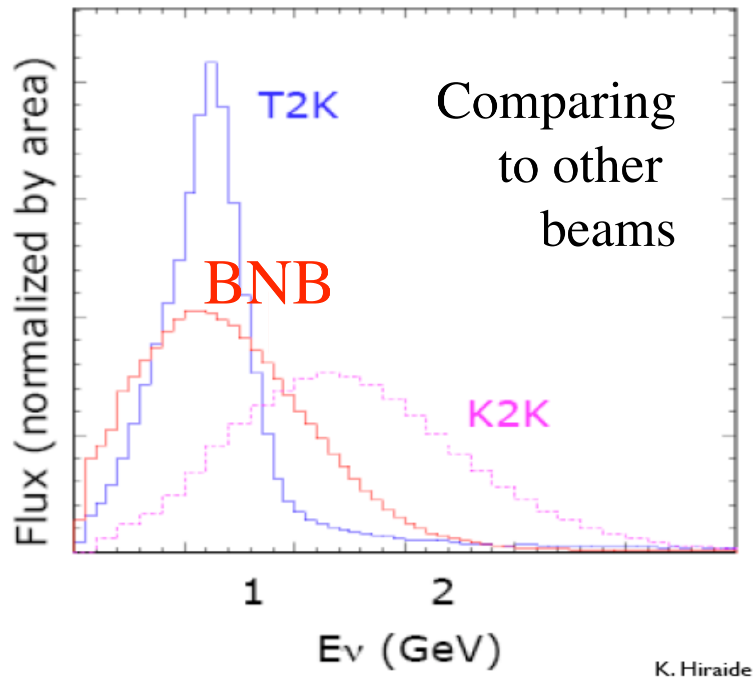




- Advantage = Know timing of beam, lifetime of particles, use to greatly suppress cosmic ray background
- Advantage = extremely well defined flux
- Disadvantage = Low E limits choices of neutrino interaction signal
- Disadvantage = Beam is isotropic - no directionality
  - Hard to make an intense isotropic beam

The resulting ν flux

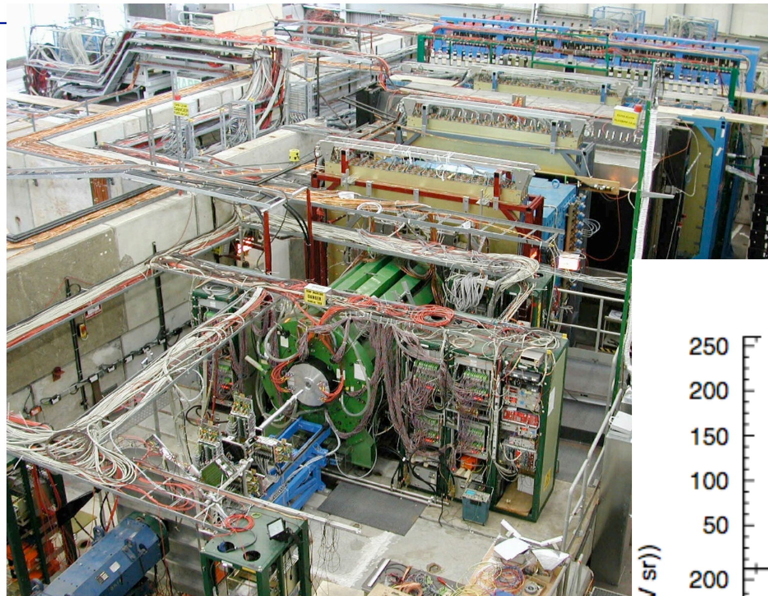




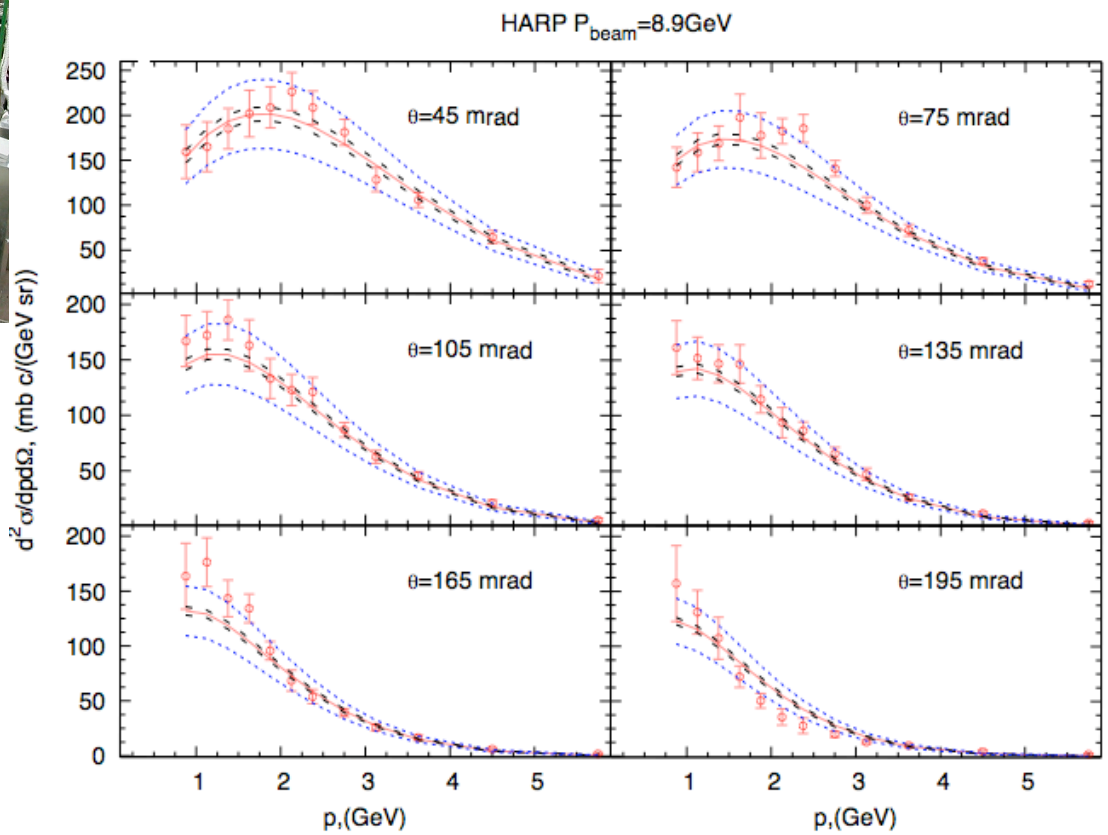
Different from LSND, which was a beam dump flux (neutrinos from stopped muon decay, ~30 MeV)

MiniBooNE is a precision experiment,
We need to understand this flux well!

How to know your flux: Part I



Incorporate fits to external data for production cross sections in the Monte Carlo



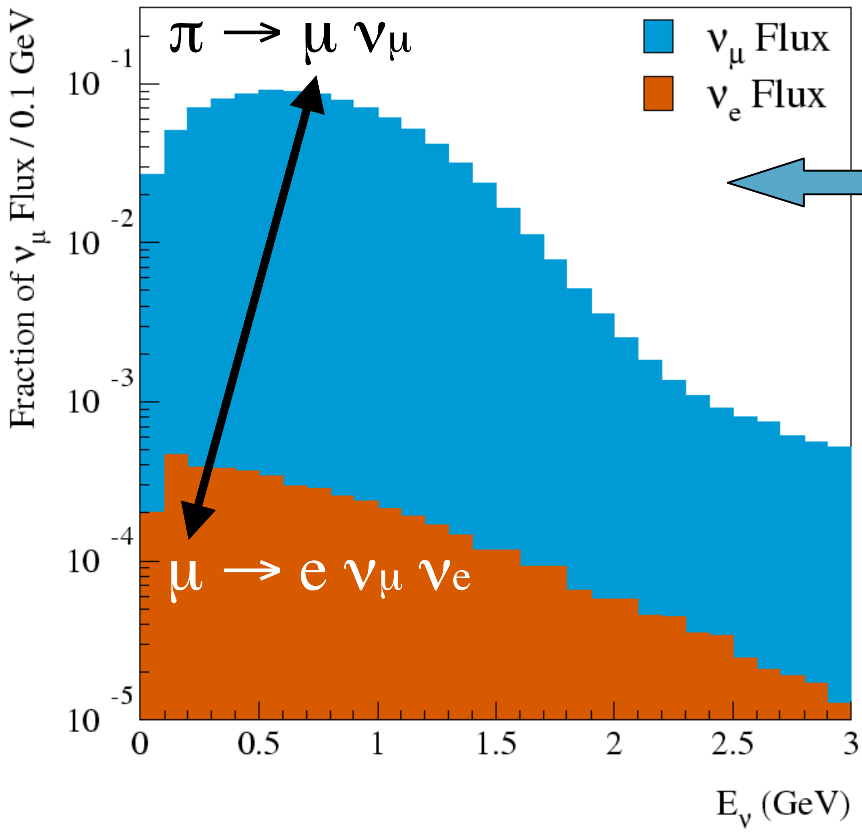
e.g. HARP (CERN)

- Data taken with MiniBooNE target slugs
- 8 GeV beam

Nucl.Phys.B732:1-45,2006,
Eur.Phys.J.C52:29-53,2007

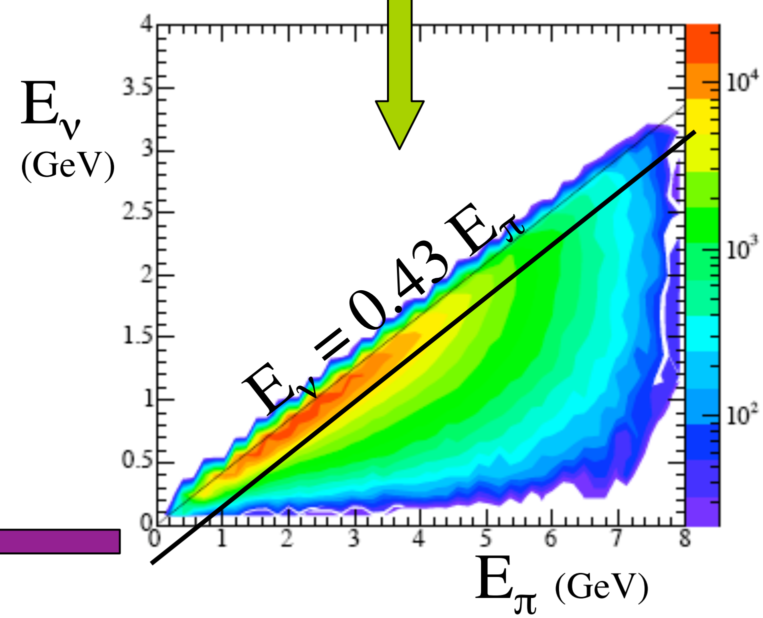
K^+ and K_L fits are also performed to world data

How to know your flux: Part II



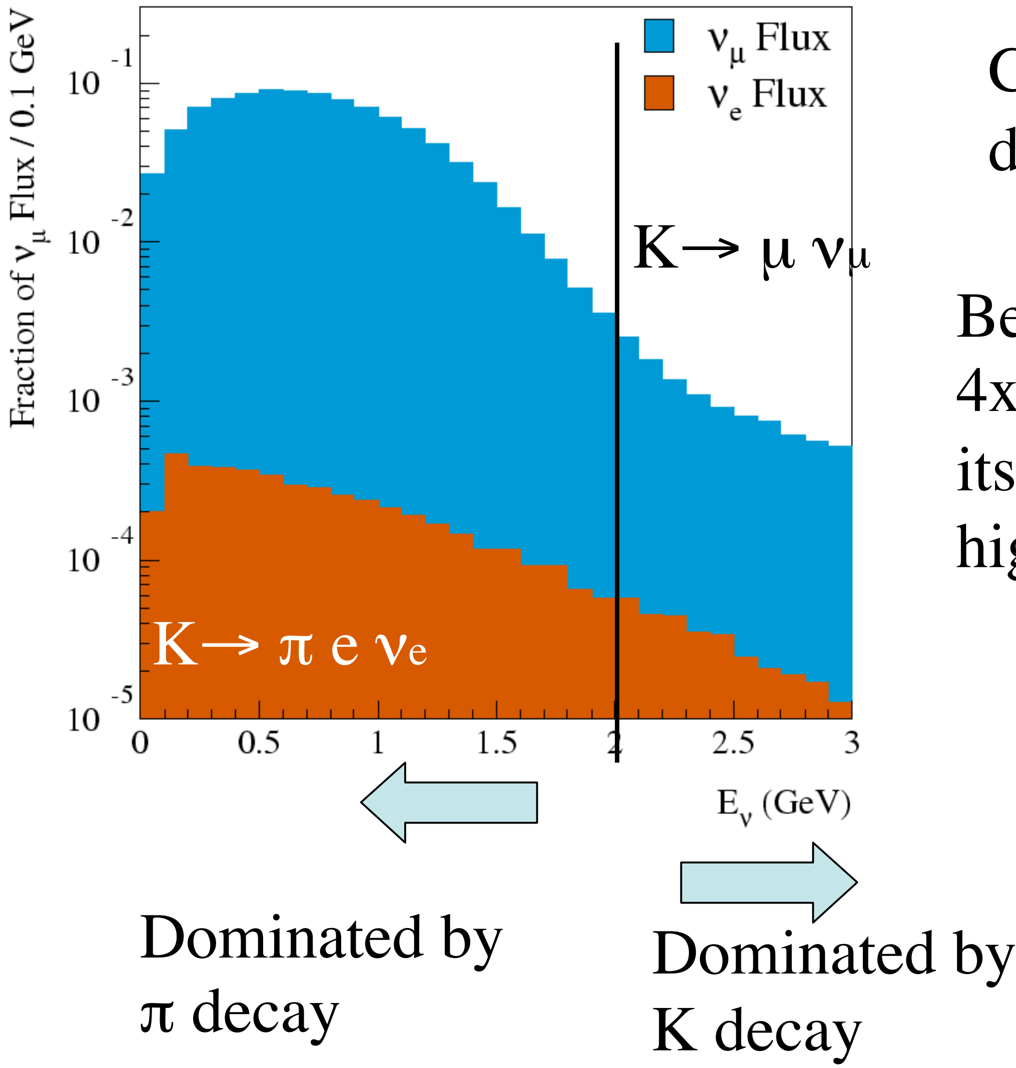
To constrain the ν_e from μ decay :

- Measure the ν_μ flux
- Kinematics allows connection to the π flux



- Once the π flux is known, the μ flux is determined = constrains the ν_e!

How to know your flux: Part III

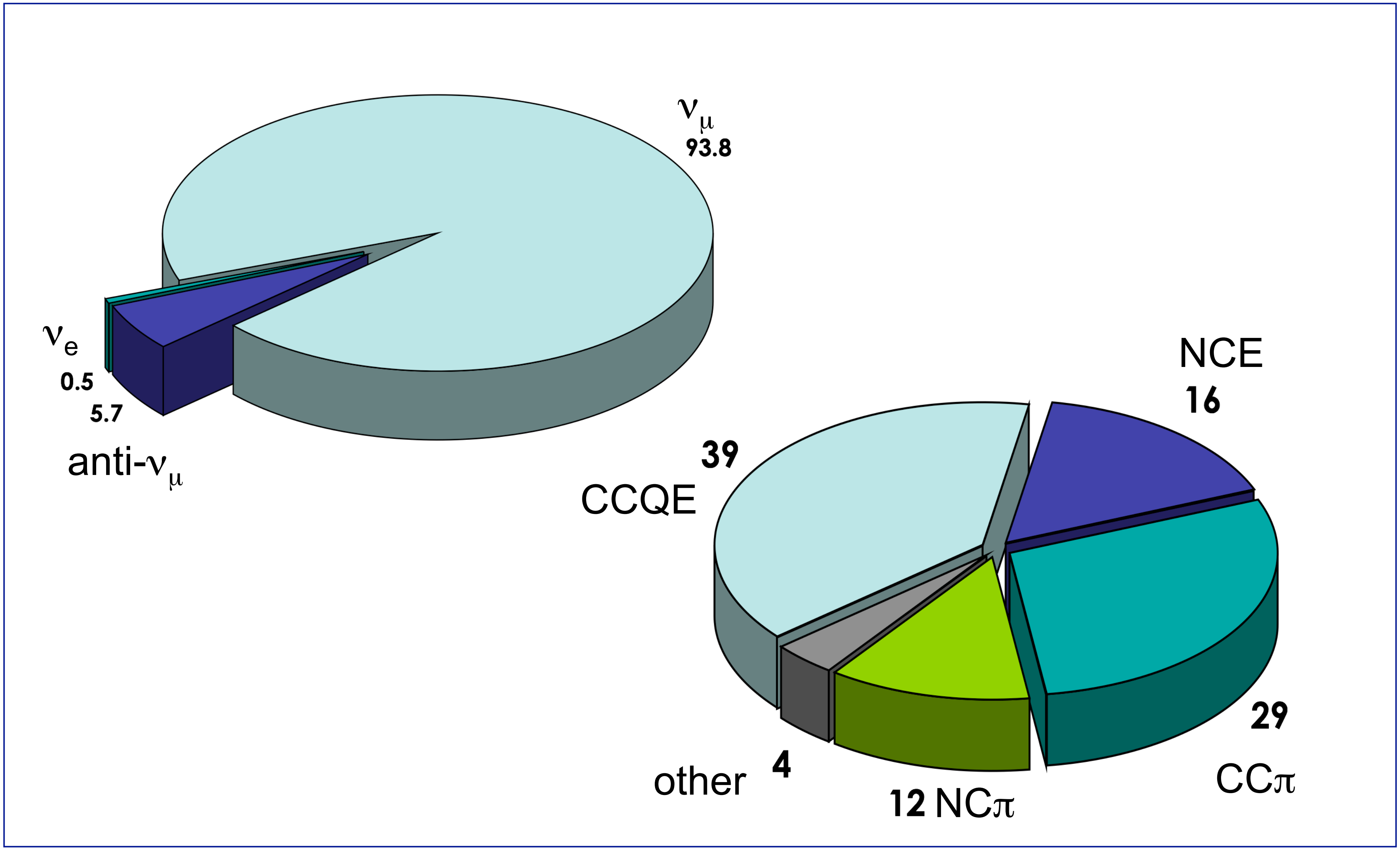


Constrain the ν_e from Kaon decay

Because the K is about 4x more massive than the π, its decay can produce higher energy neutrinos

Use the high energy events to constrain the neutrinos from Ks!

Predicted Flux

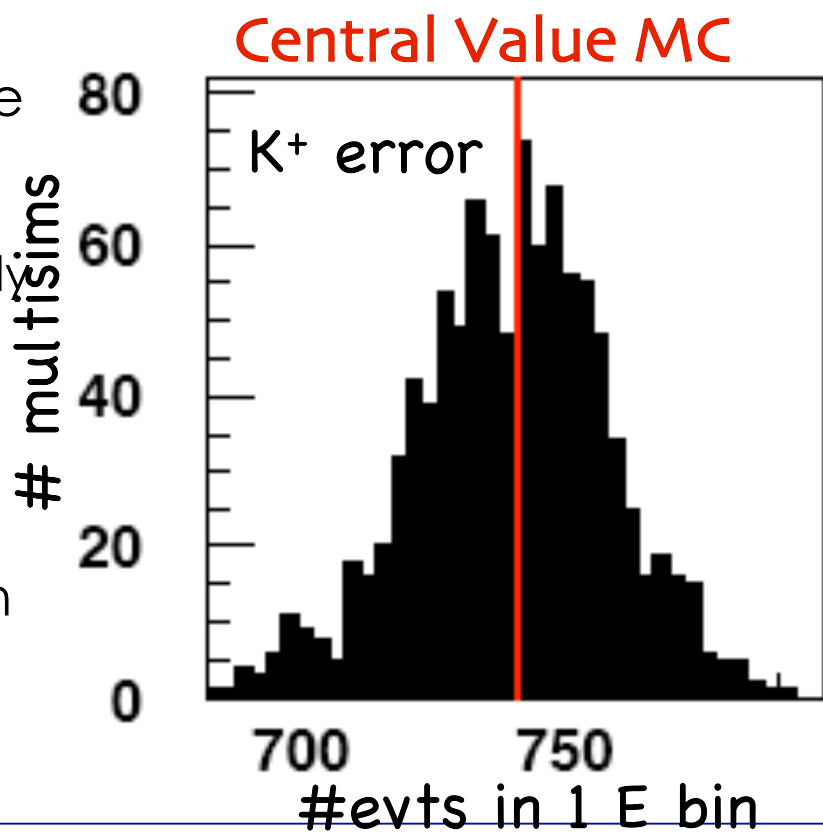


Sources of Errors

- Data collection
- Proton beam + Be target models
- Pion and kaon production
  - π^{+}, π^{-}, K^{+}, K^{0}
- Neutrino cross sections / interaction rates
  - Dirt, $NC\pi^{0}$, neutrino cross sections
- Detector response to these interactions
  - OM

Systematic Errors

- Use Multisims to calculate systematic errors
- In each MC event vary all parameters at once, according to a full covariance matrix
  - Ex : Feynman scaling of K^+ varies 8 params simultaneously
- Vary full set of parameters many times per event
- OM = 70 multisims. All other errors = 1000
- Use this information to form an error matrix



Systematic Errors

Error	Track vs Boosting (%)	Checked or Constrained by data
DAQ	7.5 / 10.8	☺
Target/Horn	2.8 / 1.3	☺
π^+ Flux	6.2 / 4.3	☺
K^+ Flux	3.3 / 1.0	☺
K^0 Flux	1.5 / 0.4	☺
Dirt	0.8 / 3.4	☺
NC π^0 yield	1.8 / 1.5	☺
Neutrino Xsec	12.3 / 10.5	☺
OM	6.1 / 10.5	☺

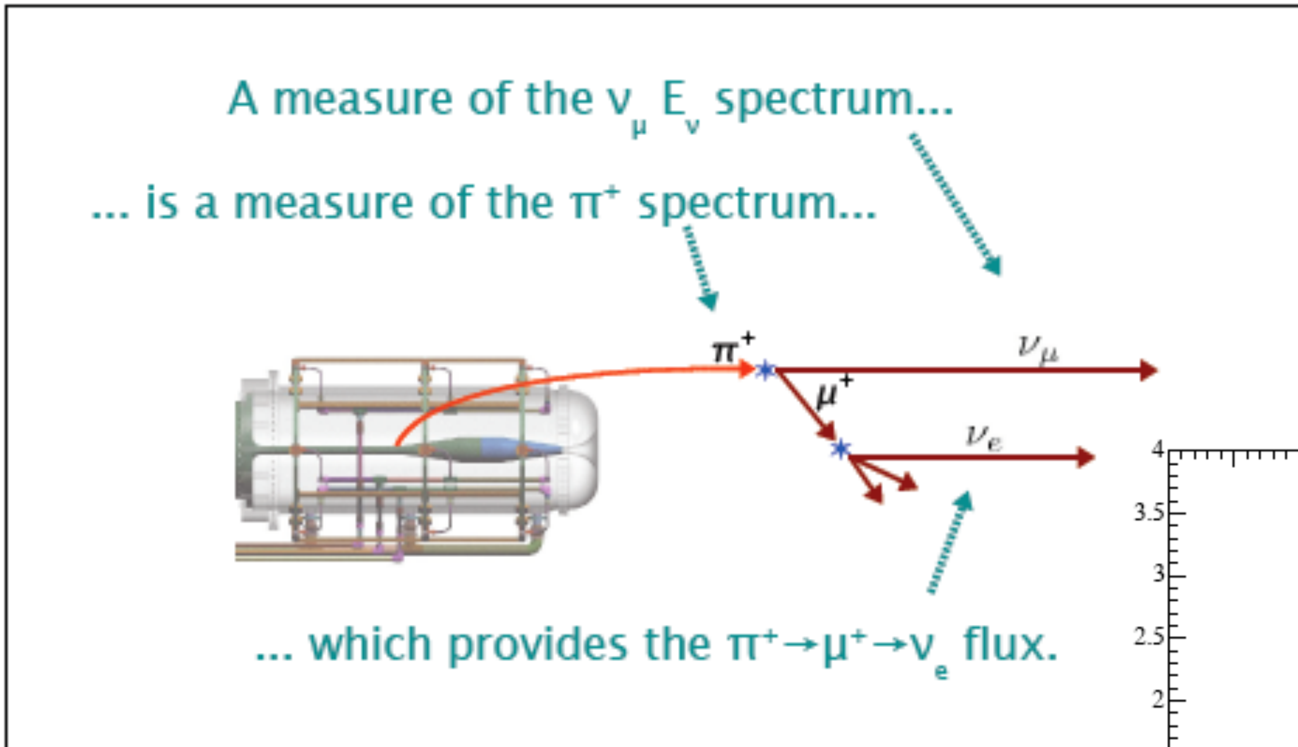
Systematic Errors

source of uncertainty on ν_e background	TBL syst. error (%)	constrained by MB data?	Further reduced by relating ν_e to ν_μ
Flux from π^+/μ^+ decay	6.2	Y	Y
Flux from K^+ decay	3.3	Y	
Flux from K^0 decay	1.5	Y	
Target/Beam model	2.8	Y	Y
ν cross section	12.3	Y	Y
NC π^0 yield	1.8	Y	
Out of tank events	0.8	Y	
Optical Model	6.1	Y	Y
DAQ electronics model	7.5	Y	

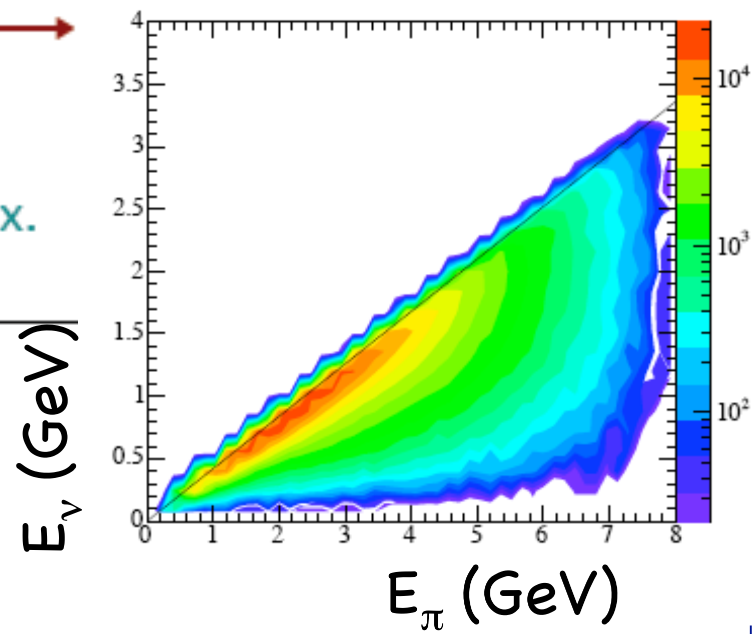
Internal Constraints

- NCπ^0 data
  - Constrains NCπ^0 and Radiative Delta xsections
- ν_μ CCQE
  - Constrains flux of ν_e flux from $\pi \rightarrow \mu\ \nu_\mu$
  - Constrains CC mis-id backgrounds
  - Constrains xsec errors
- High E events
  - Constrains ν_e flux from Kaons
- High R events
  - Constrains dirt backgrounds / xsections

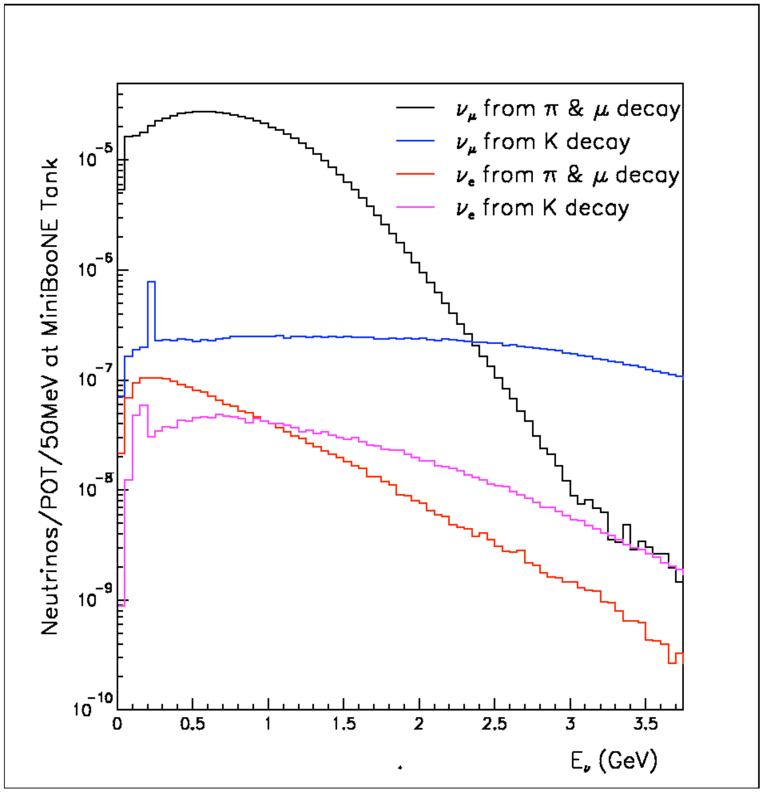
ν_μ CCQE Constraint on ν_e

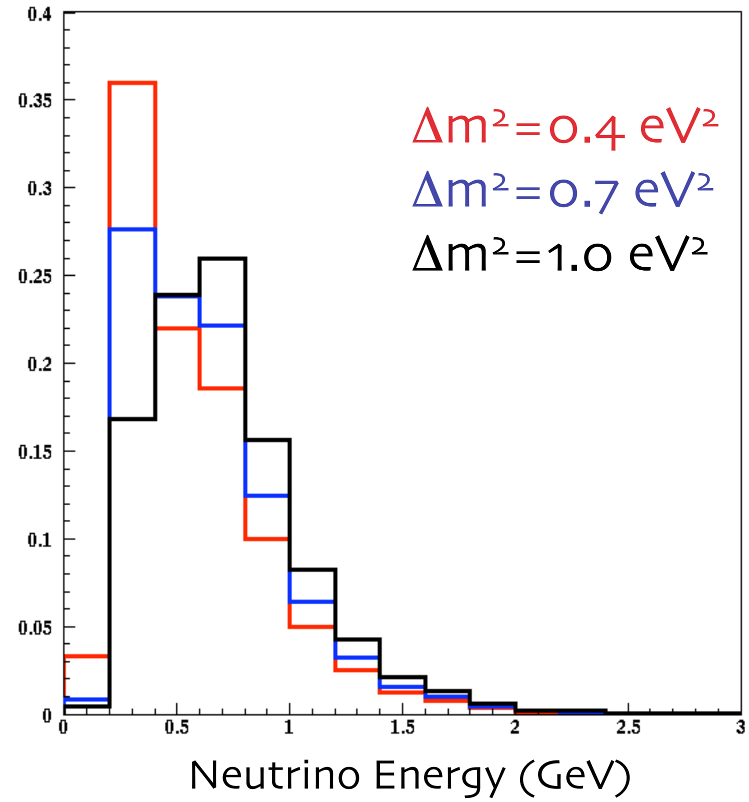


Kinematic correlation allows tight constraint on $\pi \to \mu \to \nu_e$



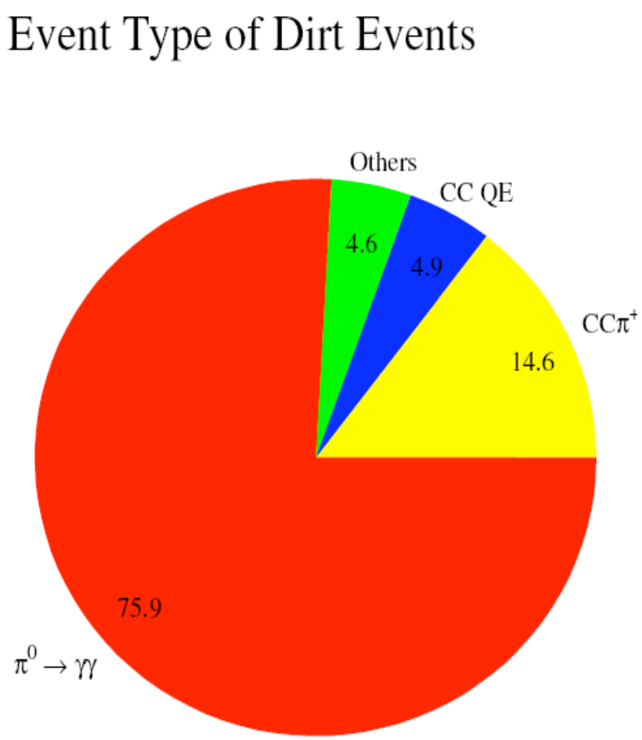
High Energy Constraint



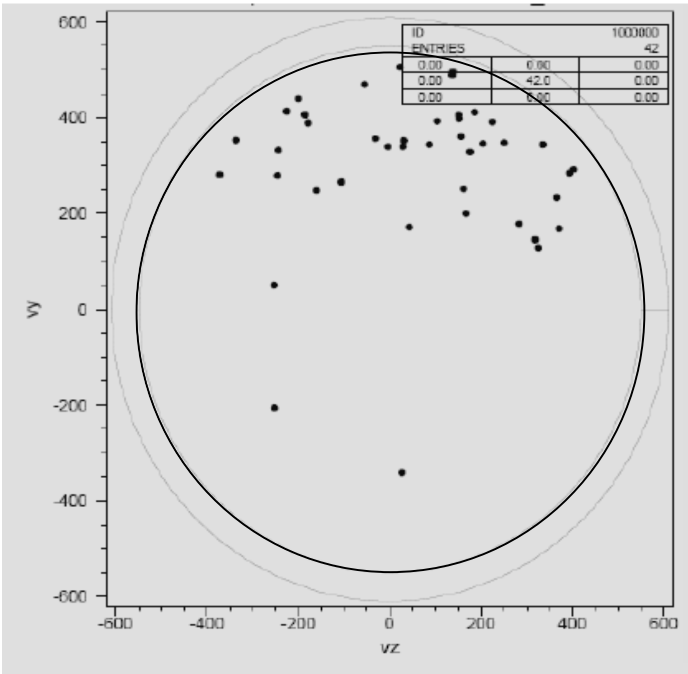


- Predicted range for signal = 300 MeV to 1.5 GeV
- At high E, ν_μ and ν_e - like events due to K decay
- Both analyses use high-E evts to constrain ν_e bgd

External Events

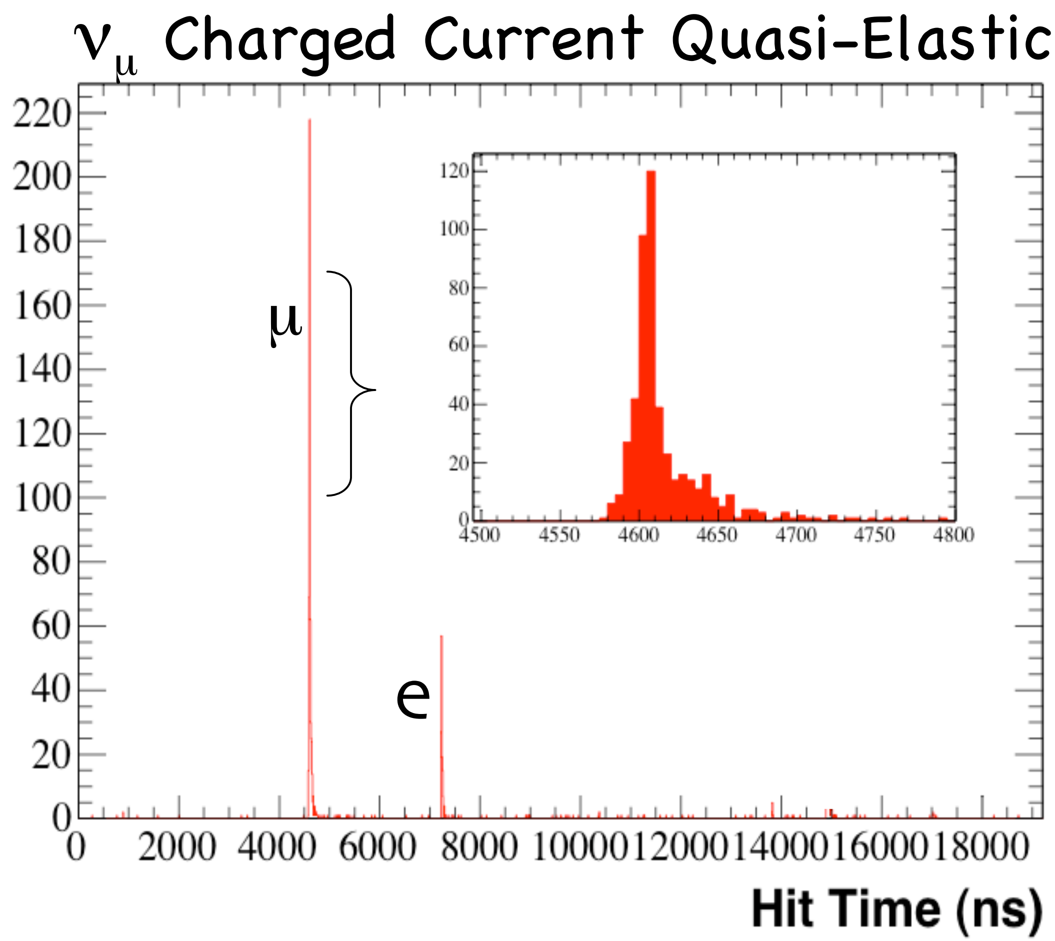


- Cosmic ray events measured with beam-off data
- 2 events expected in oscillation analysis



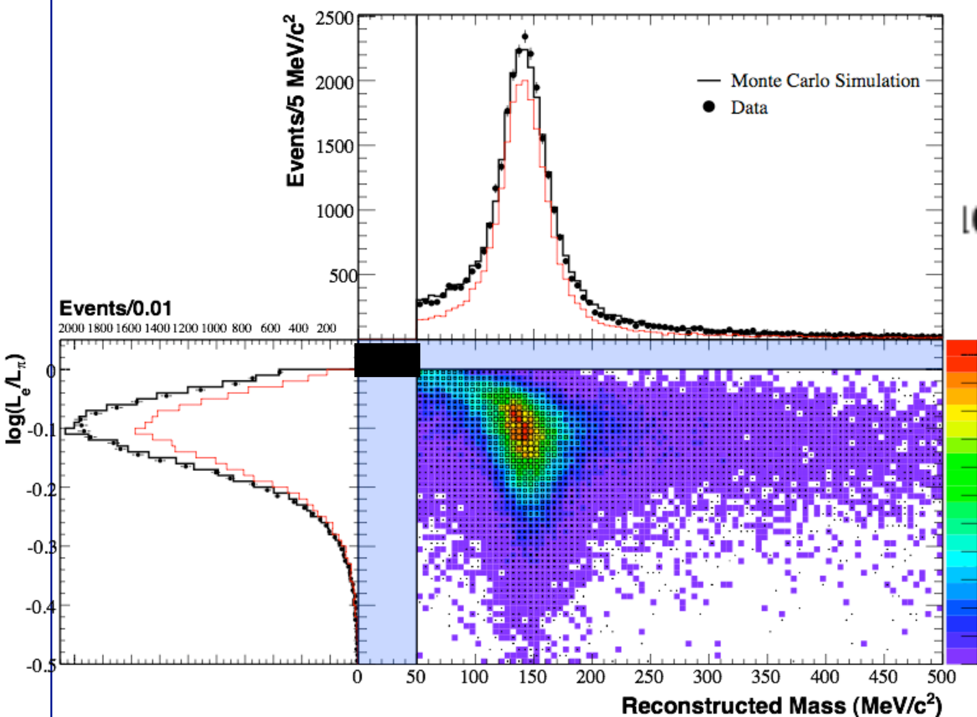
- ν interactions outside of the detector
- Measured using high R events

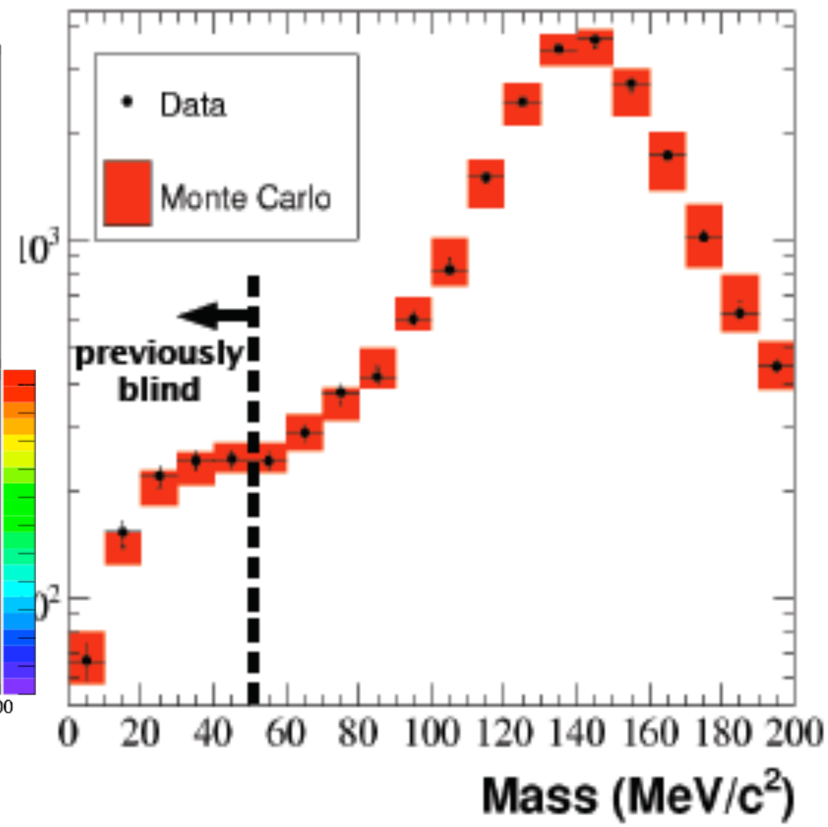
ν_e Event Selection



- A 19.2 μs beam trigger window encompasses the 1.6 μs spill
- Multiple hits within a ~100 ns window form "subevents"

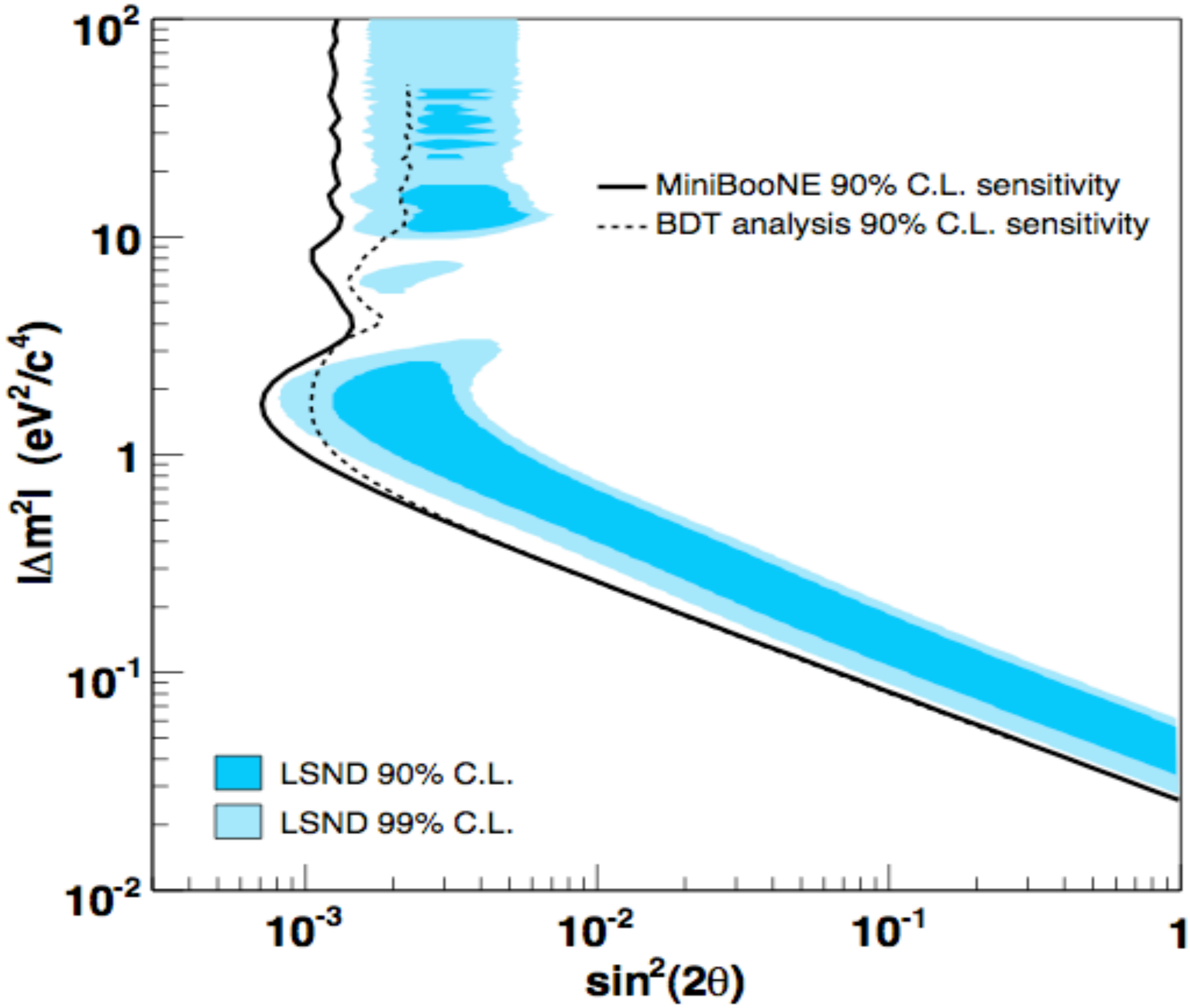
Sideband Regions



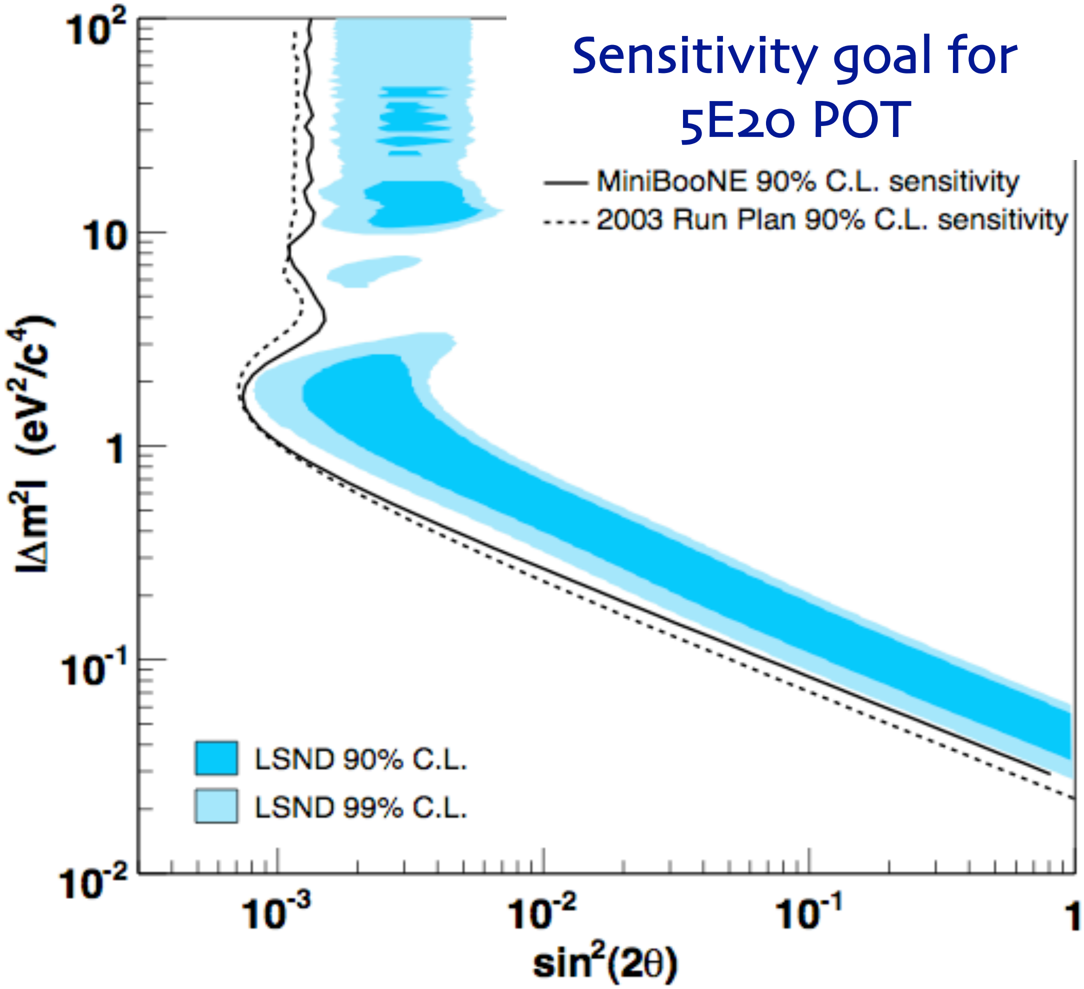


- Look at full mass range for electron-like events
  - Signal-like in mass, background like in L ratio

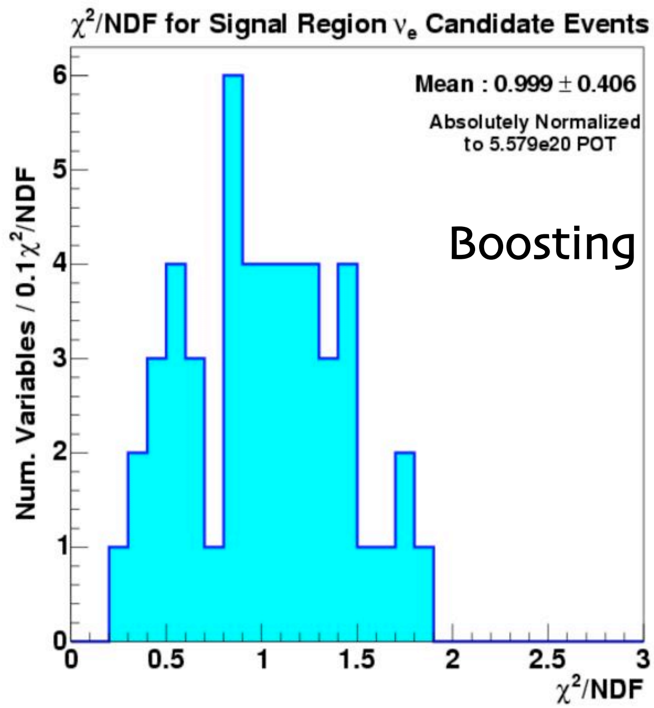
Choosing the Default Analysis

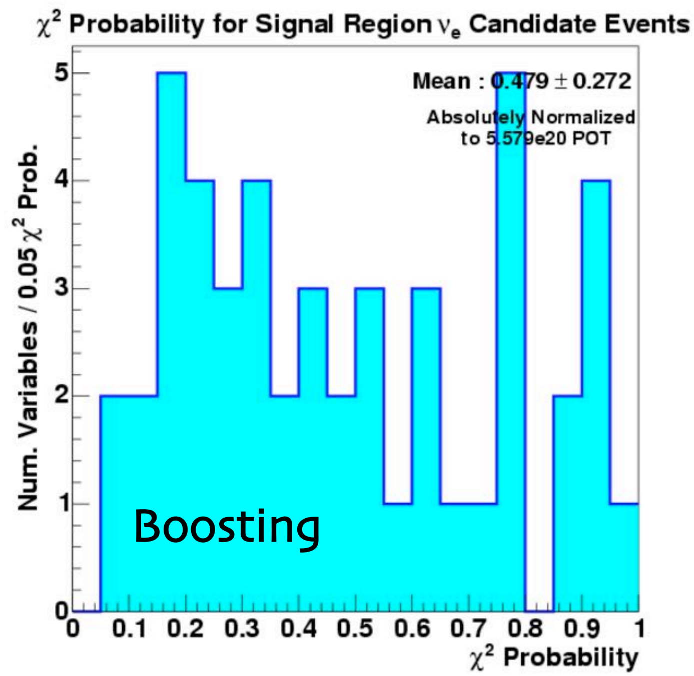


Final Results vs Design Goal



Step 1





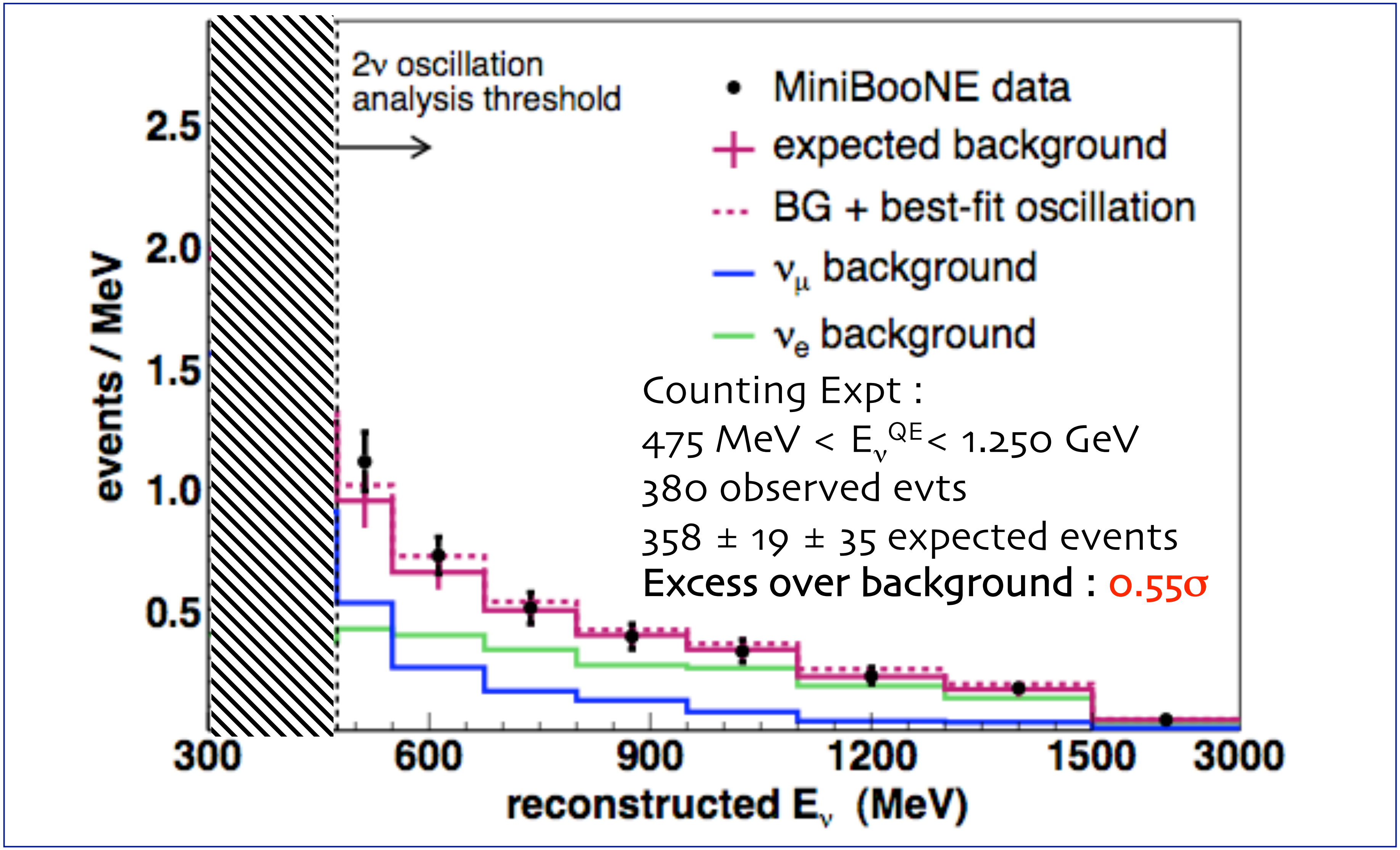
- Perform fit from 300 MeV to 3 GeV, for both analyses
- Found Track Based visible E had a χ^2 Probability= 1%
- Stopped the unblinding process
- ** still fully blind **

Step 1

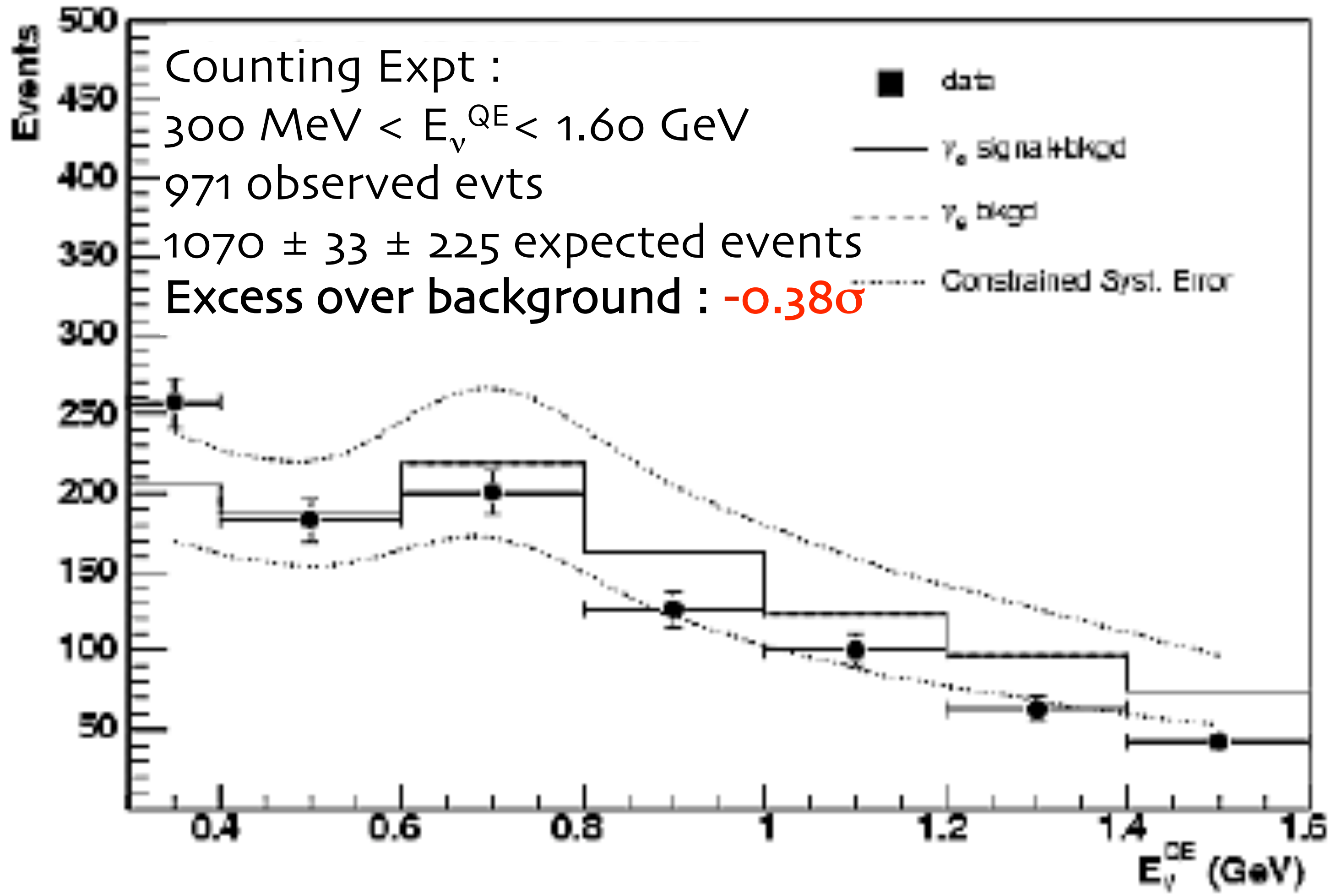
- We felt that we had checked everything to our full ability, and to our best knowledge could not further constrain processes
- MC studies of potential LSND oscillation signals indicated we could tighten the E requirement with a negligible loss in sensitivity

- Prior to unblinding, we agreed to also examine events with $E_\nu^{QE} > 300$ MeV in the Track Based analysis

Observed Event Distribution



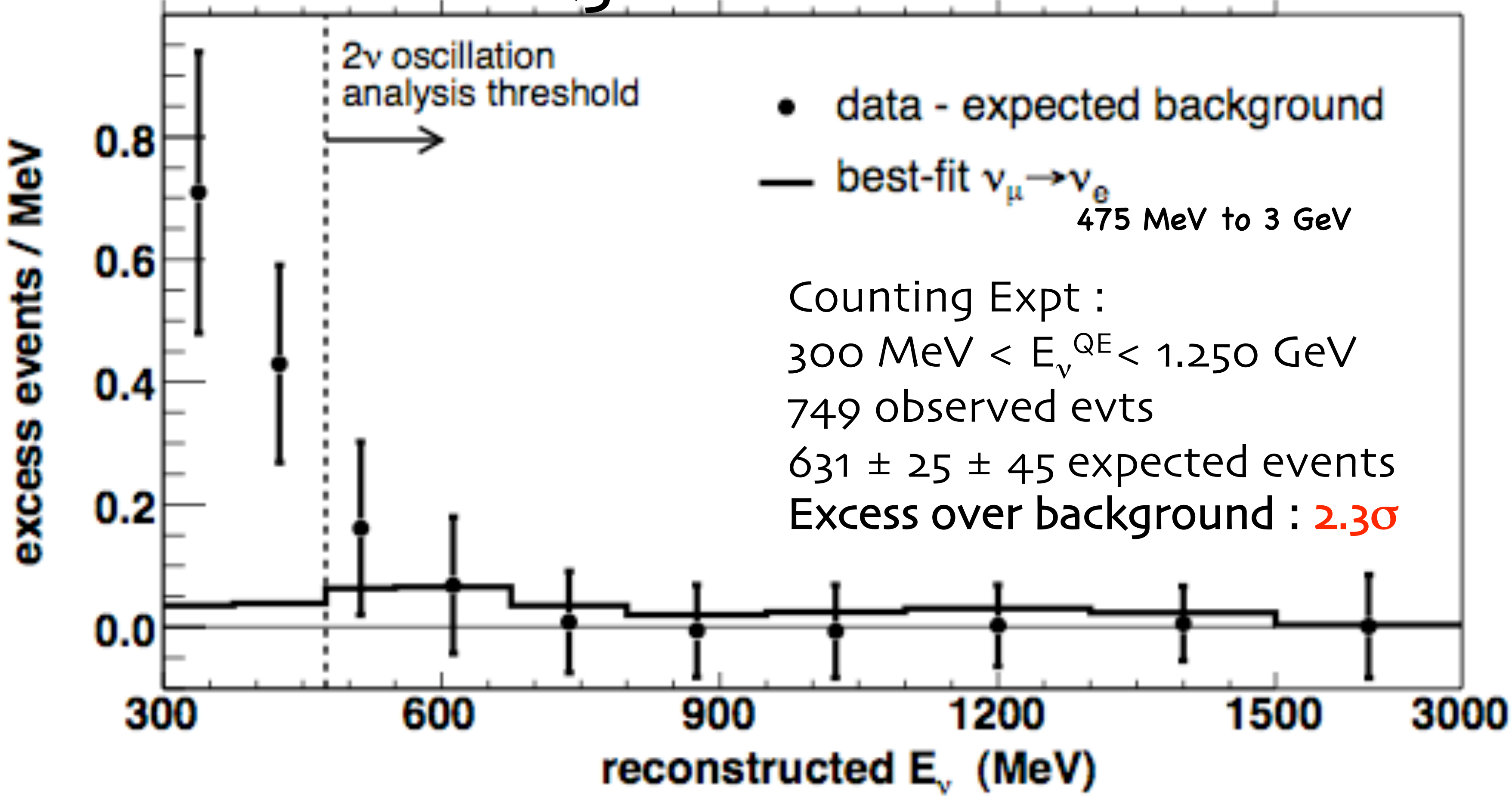
Observed Event Distribution



Counting Expt :
300 MeV < E_ν^{QE} < 1.60 GeV
971 observed evts
1070 ± 33 ± 225 expected events
Excess over background : -0.38σ

Observed Event Distribution

Background-subtracted



Counting Expt :

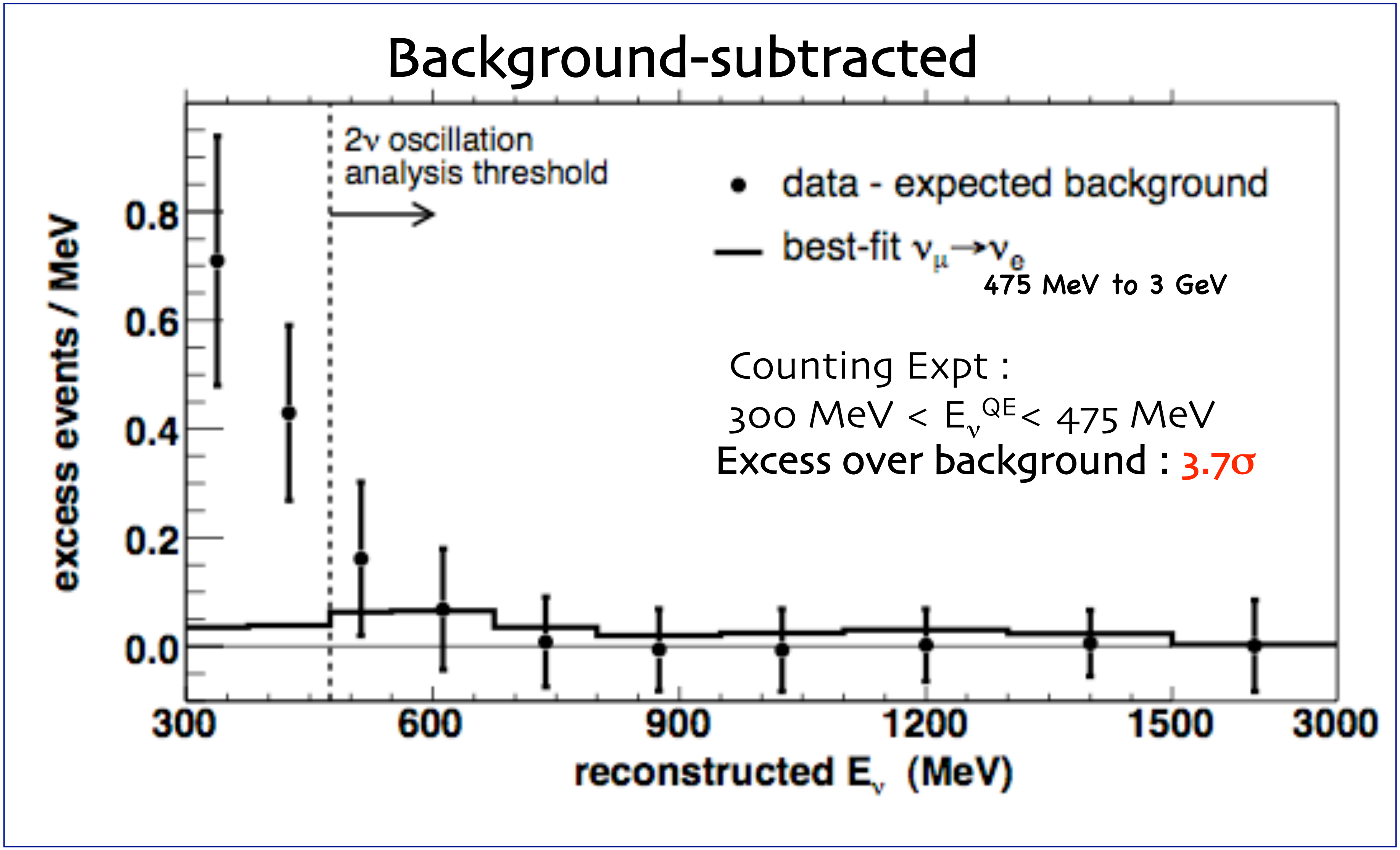
300 MeV < E_ν^{QE} < 1.250 GeV

749 observed evts

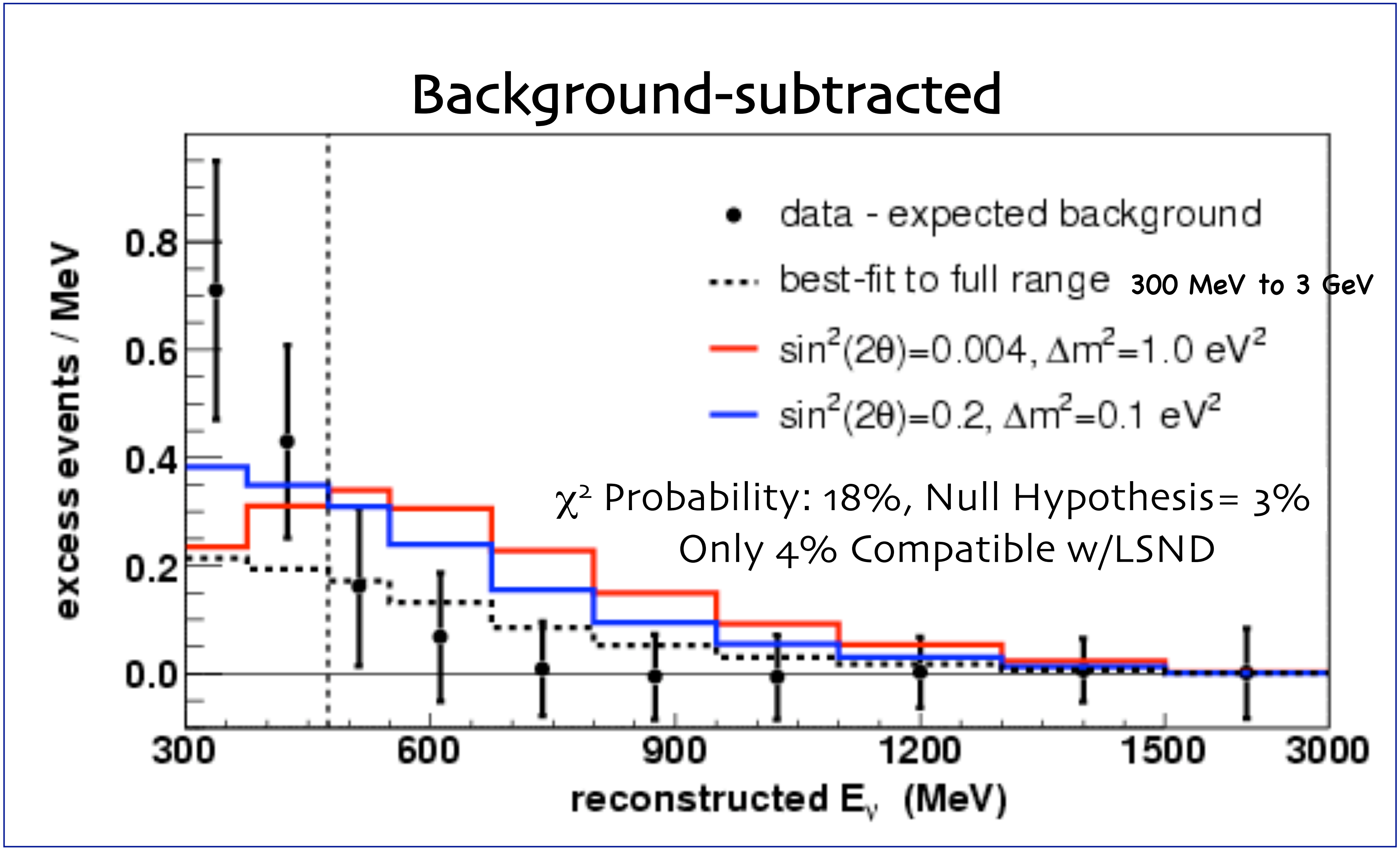
631 ± 25 ± 45 expected events

Excess over background : 2.3σ

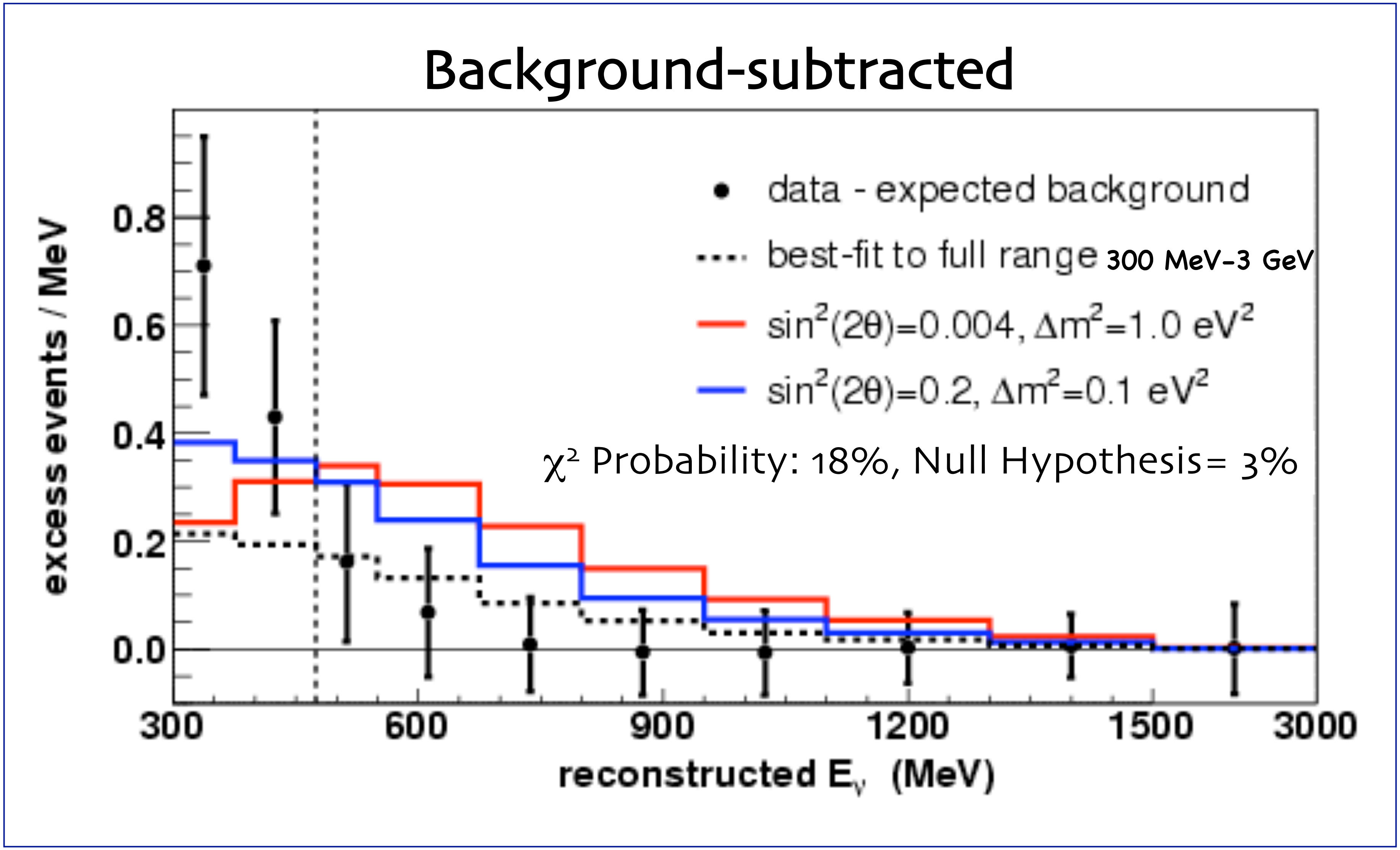
Observed Event Distribution



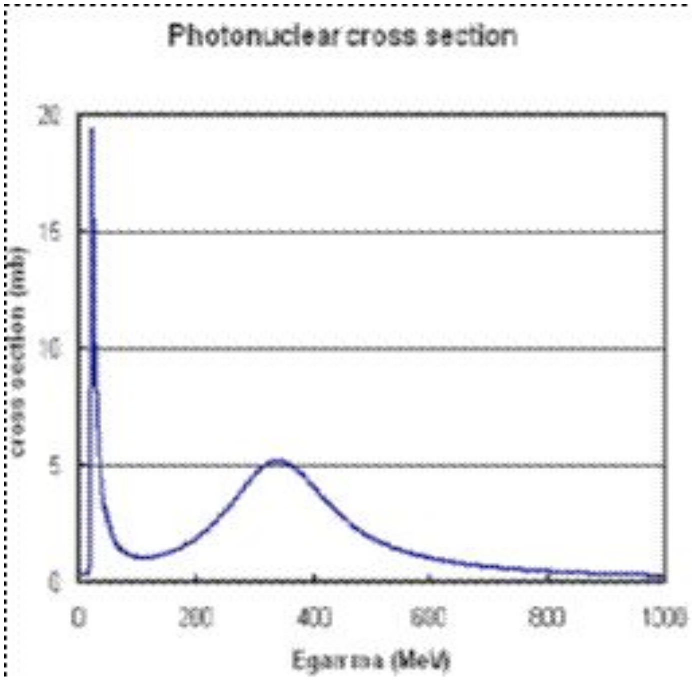
Observed Event Distribution

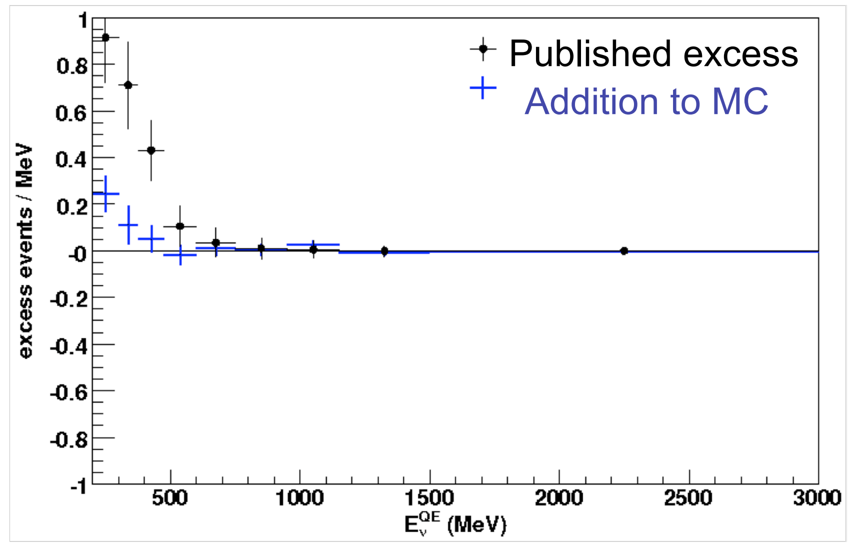


Observed Event Distribution



Photonuclear Background





- SM effect = absorption of γs through photonuclear interaction
- Not included in Geant3, has small effect on low E excess

Global Data Analysis

- All analyses use Δm^2 0.0488 to 51.13 eV^2

- No Bugey : 0.000317 to 0.4108 $\sin^2 2\theta$
- With Bugey : 0.01 to 0.4108 $\sin^2 2\theta$

LSND Input Data

- DIF and DAR data
- 0.0098 to 101.16 eV^2, 0.000313 to 1.01 $\sin^2 2\theta$
- Best fit point : 0.0025 $\sin^2 2\theta$, 1.226 eV^2
- Arbitrary offset to all points to force maximum value to 25 units
- Published 2-D global scan

KARMEN2 Input Data

- 0.01 to 100 eV^2, 0.000316 to 1 $\sin^2 2\theta$
- Published 2-D global scan
- Provided as $\Delta \ln(L)$, not given absolute value of global best fit point

Bugey Input Data

- Collaborators refused multiple requests for data
- Carlo Giunti provided us with the grid
  - Hep-ph/0711.4222
- 0.01 to 100 eV^2, 0.01 to 1 $\sin^2 2\theta$
- Convert into delta grid before put into MiniBooNE grid format to avoid bias
  - Data spans large region not covered by MB
- Published 1-D Raster scan

MiniBooNE Input Data

- 0.0488 to 51.13 eV^2, 0.0001 to 0.4108 $\sin^2 2\theta$
- Most restrictive Δm^2 range, upper $\sin^2 2\theta$ limit, most coarse binning
  - Used to set the default grid/binning
- Published 1-D Raster scan

Global Data Analysis

- All analyses use Δm^2 0.0488 to 51.13 eV^2
- No Bugey : 0.000317 to 0.4108 $\sin^2 2\theta$
- With Bugey : 0.01 to 0.4108 $\sin^2 2\theta$

Track Based Analysis

- Advanced track reconstruction fitting algorithm
- Each event is characterized by 7 track parameters
  - vertex (x,y,z), time, energy, and direction $(\theta,\varphi) \Leftrightarrow (U_x, U_y, U_z)$
- Use ratio of likelihood variables to identify particles/event type