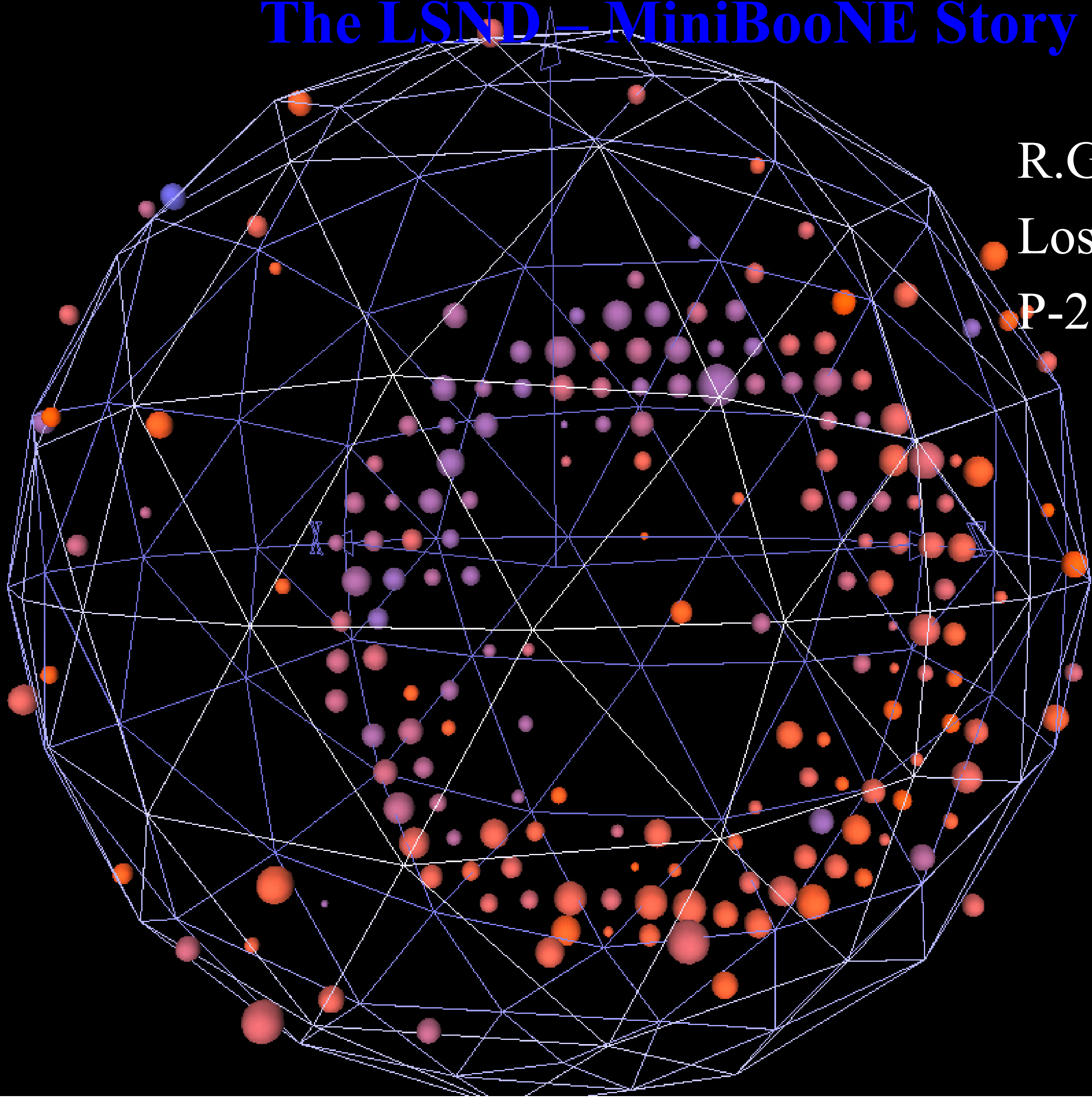
Searching for Physics Beyond the Standard Model with Neutrinos
The LSND – MiniBooNE Story

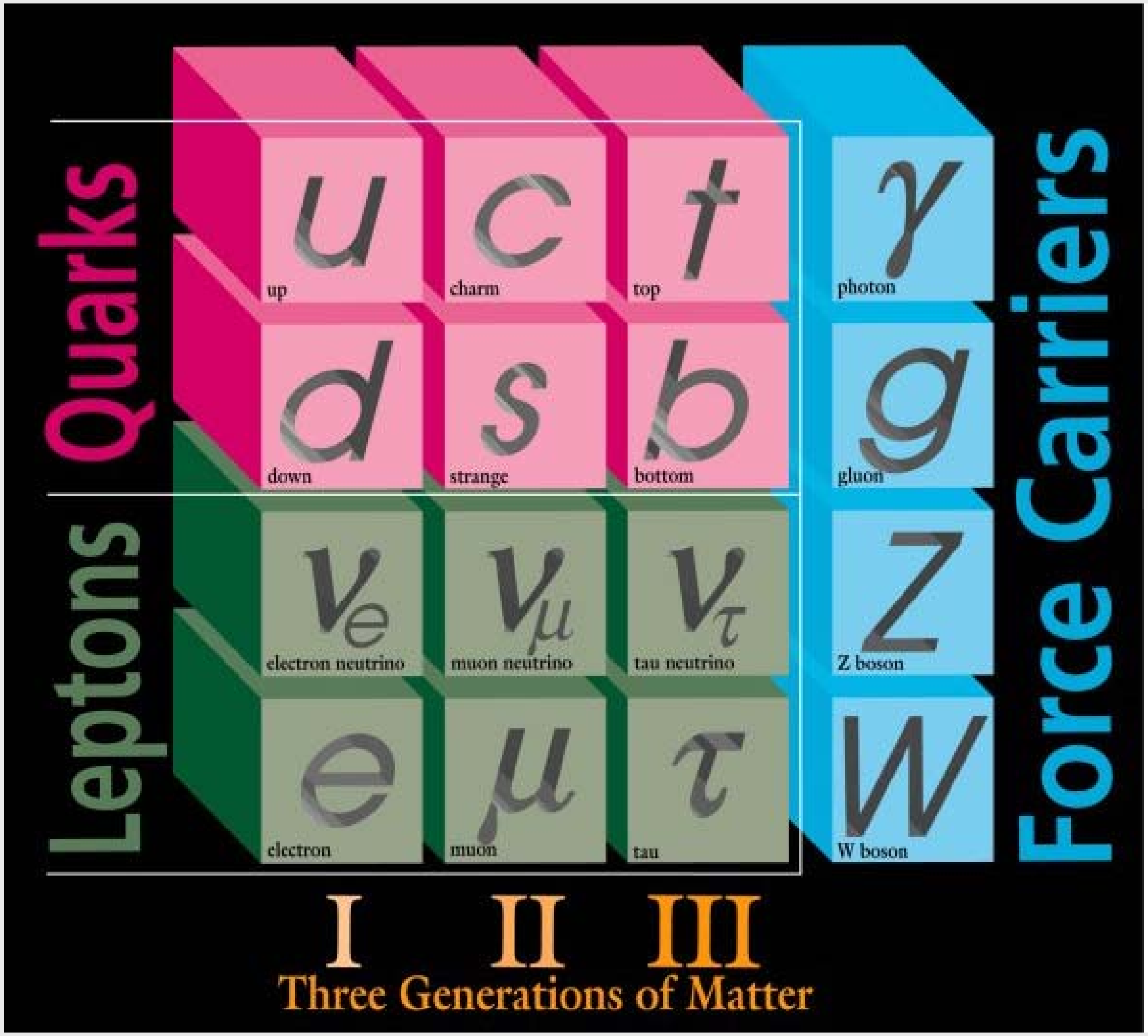


R.G. Van de Water
Los Alamos National Laboratory
P-25

Outline

1. Neutrino oscillations, mass, other neutrino properties.
2. The LSND oscillation signal.
3. The MiniBooNE experiment: Testing LSND.
4. Original oscillation results.
5. New results on low energy anomaly.

The Standard Model building blocks...



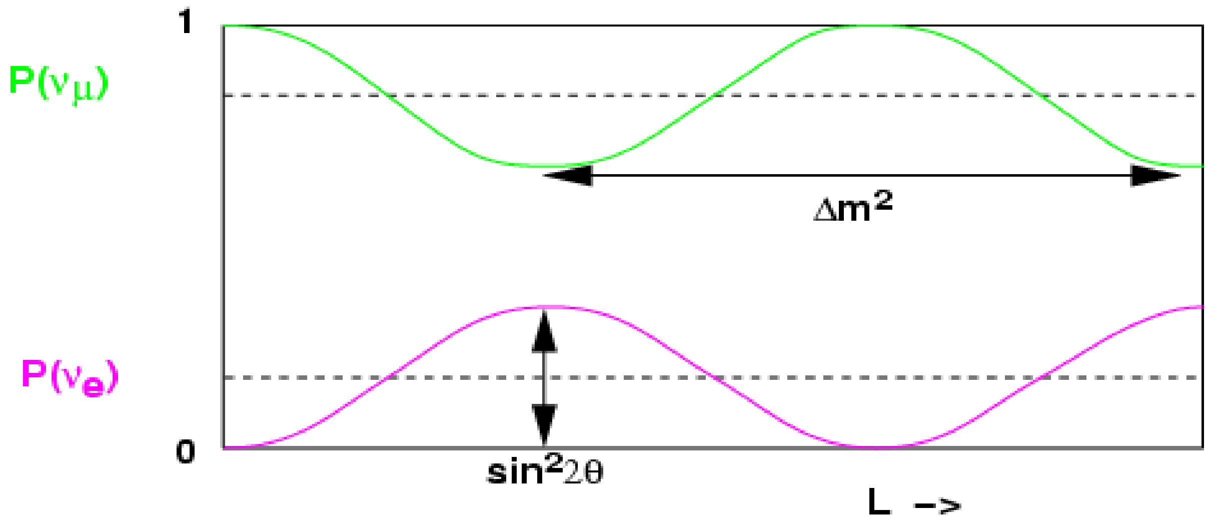
- Force carriers
  - photons ⇔ electromagnetic
  - gluons (g) ⇔ strong force
  - W, Z bosons ⇔ weak force
  - no inclusion of gravity...yet
- Quarks
  - Feel all the forces
  - Other than gluons, only particles that experience the strong force
- Leptons
  - Charged leptons
    - Feel EM and weak
  - Neutrinos
    - Interact ONLY via weak force W and Z exchange.

Three Salient Features of Neutrinos

- **Neutrinos interact very weakly with matter**
- **Neutrinos (& photons) dominate the universe in terms of number of particles**
- **Neutrinos undergo oscillations**

Neutrino Oscillations

Weak Eigenstates		Eigenstates of Propagation
ν_μ	=	$\cos\Theta\, \nu_1 + \sin\Theta\, \nu_2$
ν_e	=	$-\sin\Theta\, \nu_1 + \cos\Theta\, \nu_2$

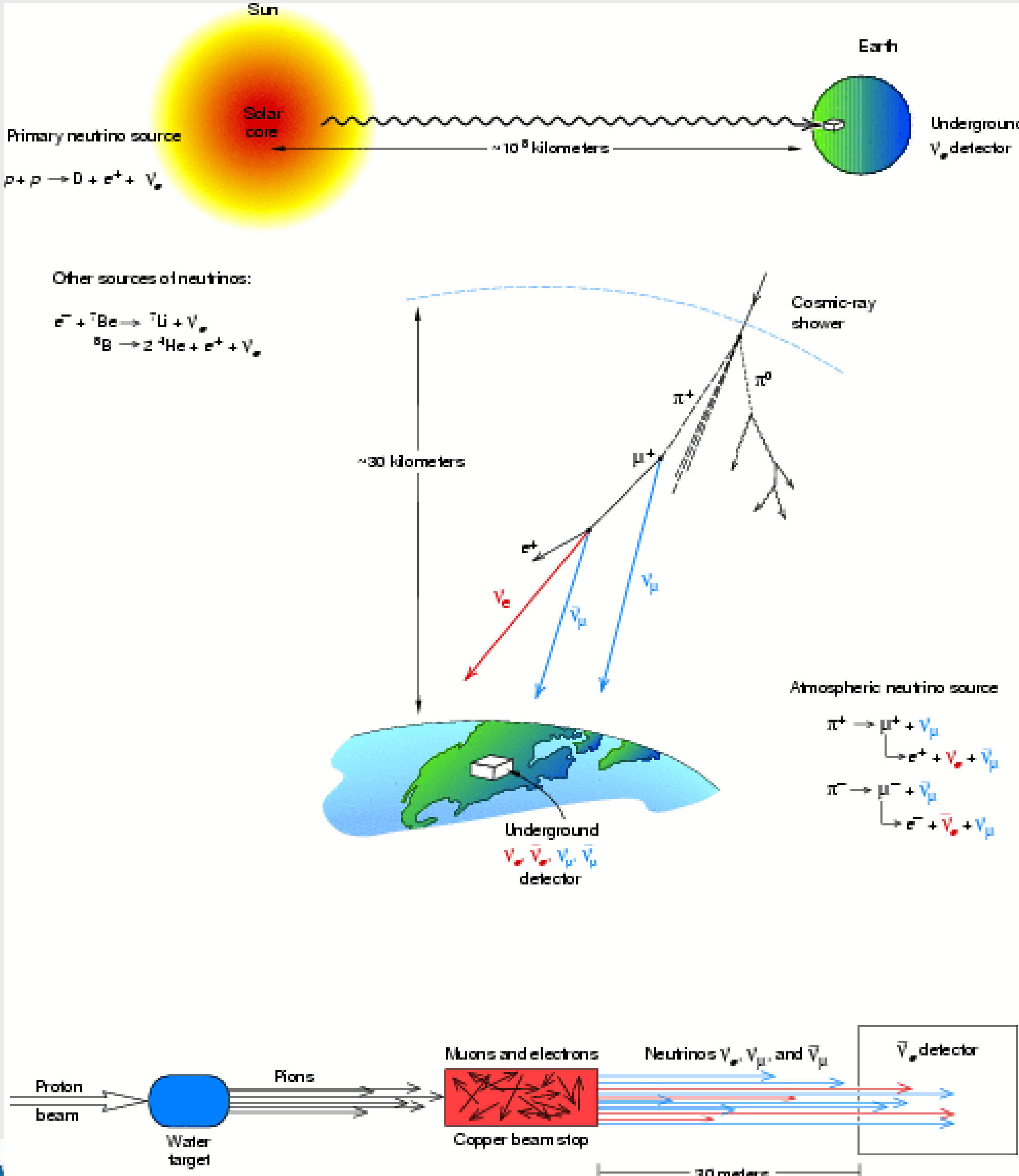


$$P_{\nu_\mu \to \nu_e} = \sin^2(2\Theta)\ \sin^2(1.27\ \Delta m^2\ L/E_\nu)$$

$\Delta m^2 = m_2^2 - m_1^2$ in eV^2, L in meters, E_ν in MeV

For oscillations to occur, neutrinos must have mass!

Neutrino Oscillations Have Been Observed!



SuperK, SNO, KamLAND (Very long baseline)

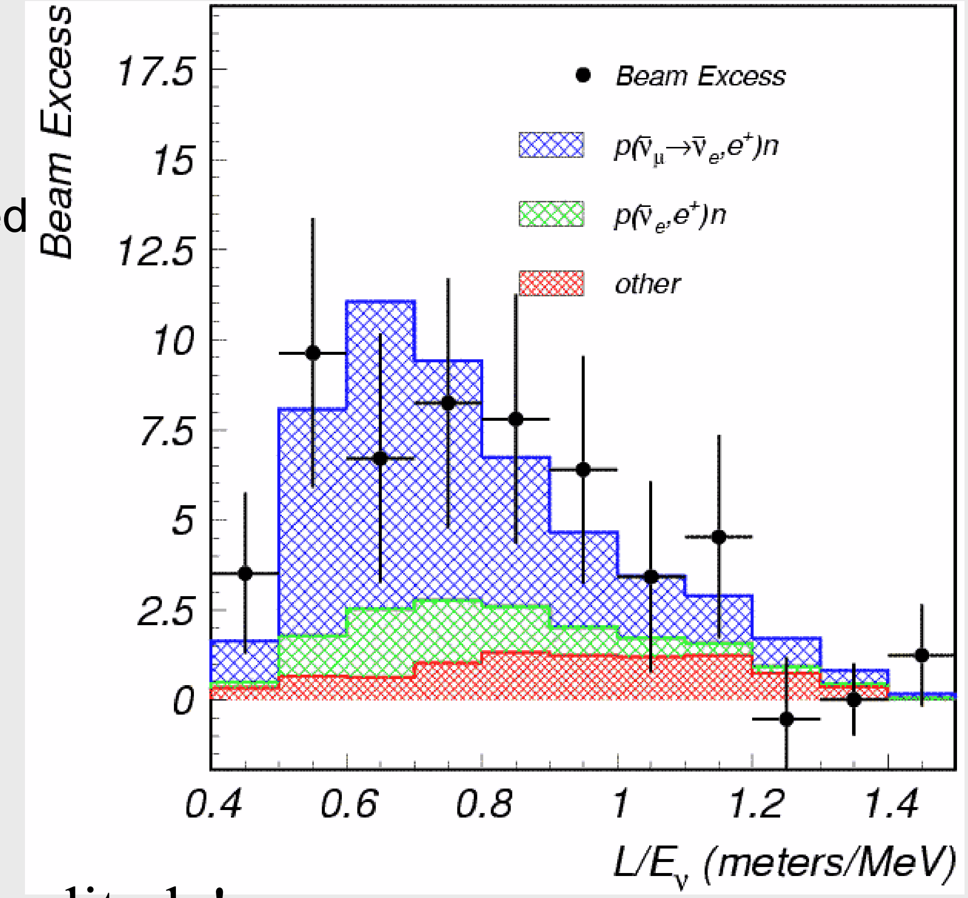
SuperK, K2K, MINOS (intermediate baseline)

LSND? (short baseline)

Evidence for Oscillations from LSND

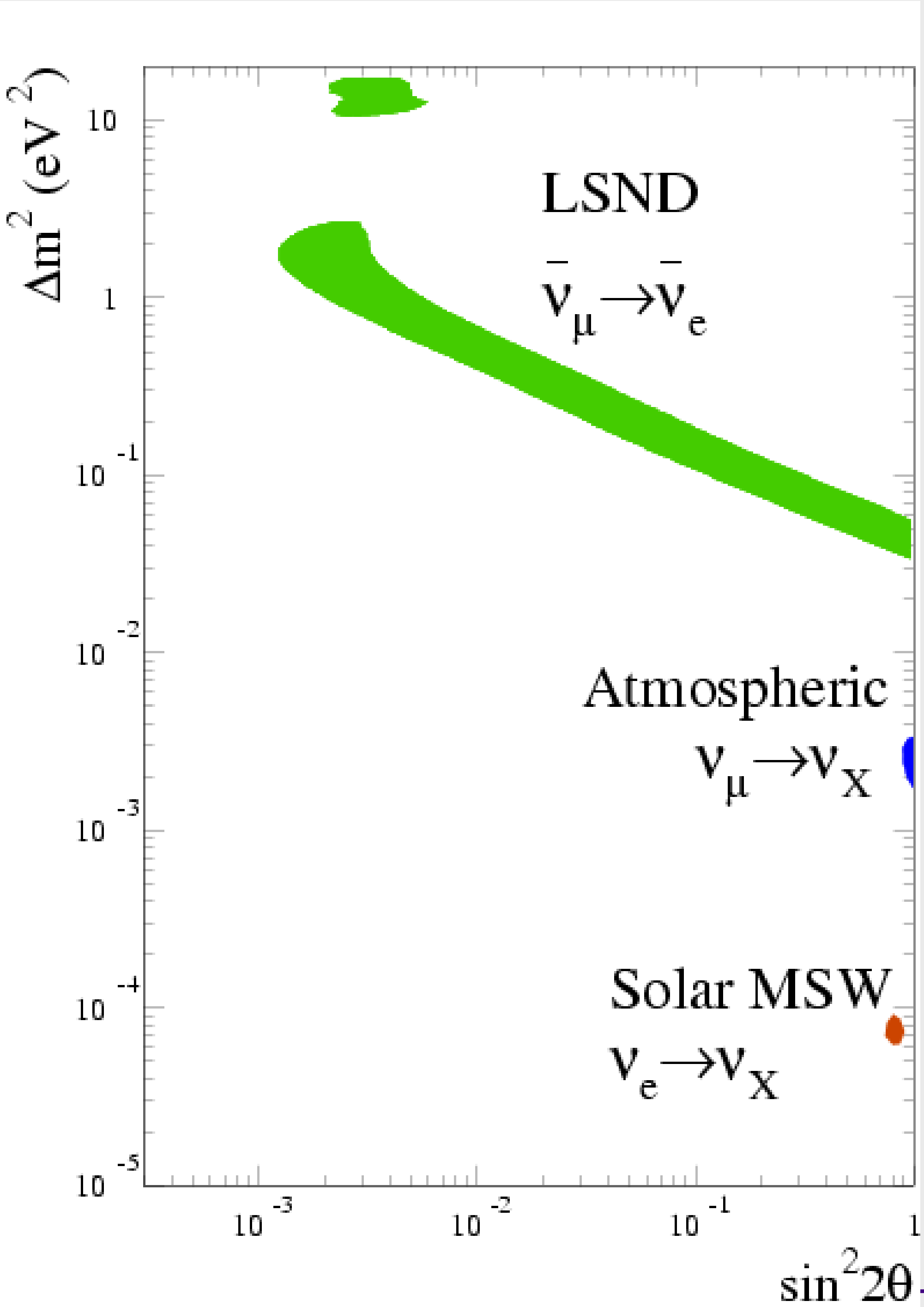
- LSND found an excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a two neutrino mixing hypothesis:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\ \Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$



Extremely small mixing amplitude!

Current State of Neutrino Oscillation Evidence



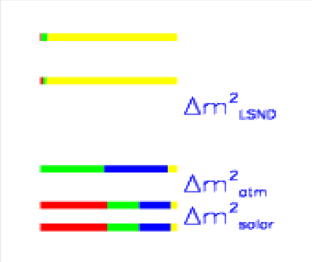
3-ν oscillations require
$\Delta m_{12}^2 + \Delta m_{23}^2 = \Delta m_{13}^2$
and cannot explain the data!

Expt.	Type	Δm^2 (eV^2)	$\sin^2 2\theta$
LSND	$\bar{\nu}_\mu \to \bar{\nu}_e$	~1	~3x10^{-3}
Atm.	$\nu_\mu \to \nu_x$	~2x10^{-3}	~1
Solar	$\nu_e \to \nu_x$	~8x10^{-5}	~0.8

Los Alamos

If LSND Excess Confirmed: Physics Beyond the Standard Model!

3+2 Sterile Neutrinos Sorel, Conrad, & Shaevitz (PRD70(2004)073004)



Explain Pulsar Kicks?
Explain R-Process in Supernovae?
Explain Dark Matter?

Sterile Neutrino Kaplan, Nelson, & Weiner (PRL93(2004)091801)

Explain Dark Energy?

New Scalar Bosons Nelson, Walsh (arXiv:0711-1363)

CPT Violation Barger, Marfatia, & Whisnant (PLB576(2003)303)

Explain Baryon Asymmetry in the Universe?

Quantum Decoherence Barenboim & Mavromatos (PRD70(2004)093015)

Lorentz Violation Kostelecky & Mewes (PRD70(2004)076002)
Katori, Kostelecky, Tayloe (hep-ph/0606154)

Extra Dimensions Pas, Pakvasa, & Weiler (PRD72(2005)095017)

Sterile Neutrino Decay Palomares-Ruiz, Pascoli, & Schwetz (JHEP509(2005)48)

Current Urgent Questions in ν Physics

1. What is the absolute neutrino mass scale?
2. What are all of the neutrino mixing angles?
3. Are neutrinos Majorana or Dirac type?
4. Do light, sterile neutrinos exist?
5. Do sterile neutrinos explain the dark matter of the universe?
6. Is CP violated in the neutrino sector?
7. Is CPT or Lorentz Invariance violated in the neutrino sector?
8. Do neutrinos decay or have large magnetic moments?

LANL experimentalist and theorists are working on many of these questions!

Review of the MiniBooNE Experiment

MiniBooNE: A Test of the LSND Evidence for Oscillations: Search for $\nu_\mu \rightarrow \nu_e$

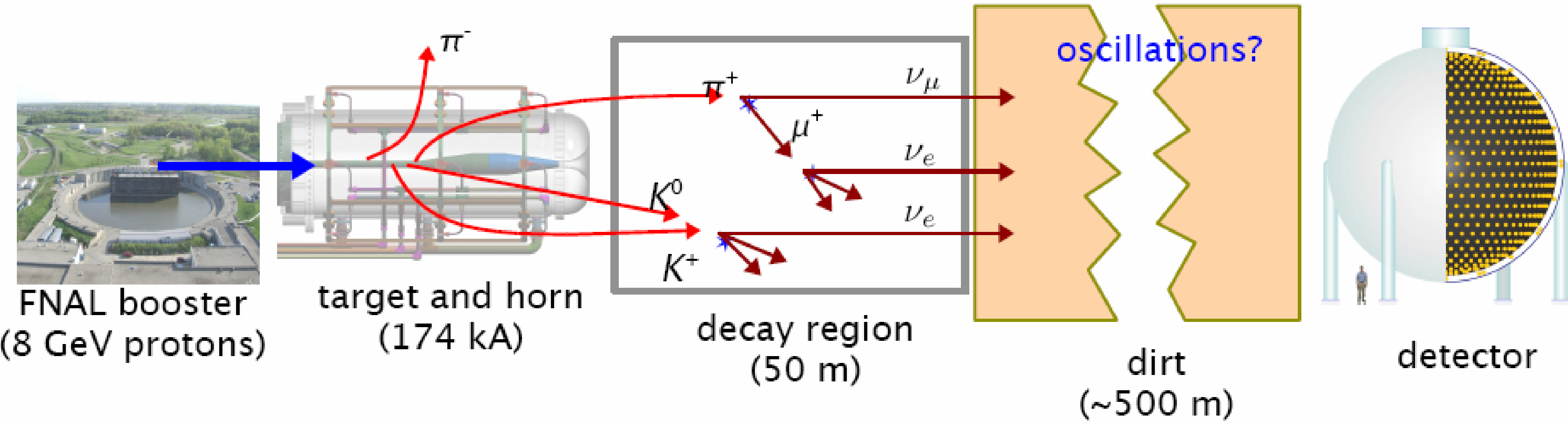
Completely different systematic errors than LSND

Much higher energy than LSND

Blind Analysis

Alabama, Bucknell, Cincinnati, Colorado, Columbia, Embry-Riddle, Fermilab, Florida, Indiana, Los Alamos, LSU, Michigan, Princeton, St. Mary's, Virginia Tech, Yale

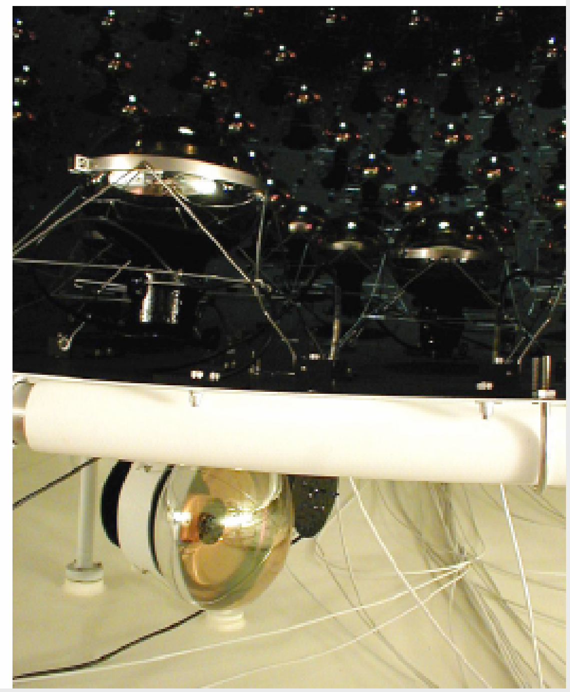
The MiniBooNE design strategy...must make ν_μ



- Start with 8 GeV proton beam from FNAL Booster
- Add a 174 kA pulsed horn to gain a needed x 6
- Requires running ν (not anti-ν) to get flux
- Pions decay to ν with E_ν in the 0.8 GeV range
- Place detector to preserve LSND L/E:

MiniBooNE:	(0.5 km) / (0.8 GeV)
LSND:	(0.03 km) / (0.05 GeV)

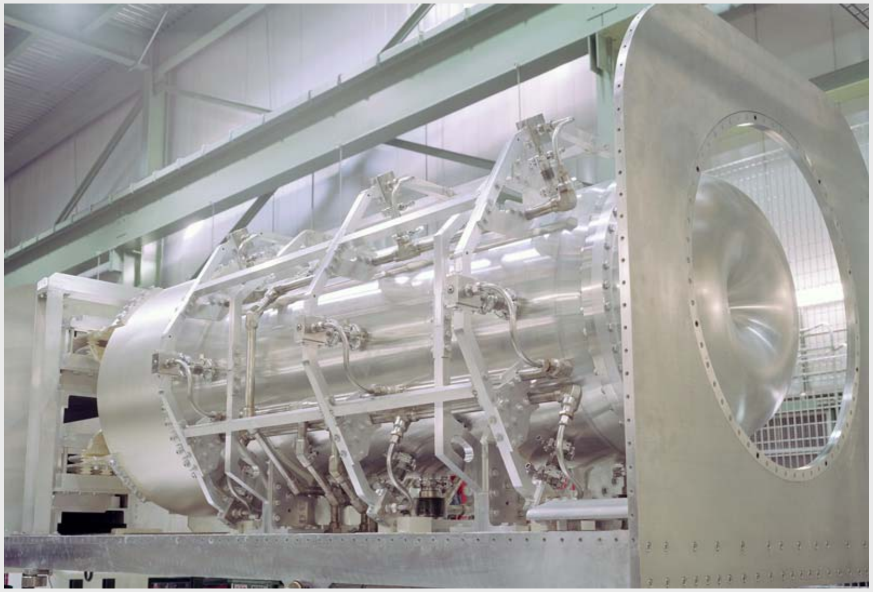
- 5.58×10^{20} P.O.T. total; up to 5×10^{12} p/pulse at up to 4 Hz



$$\nu_\mu = 93.5\%, \ \nu_e = 0.5\%, \ \overline{\nu}_\mu = 6\%$$

MiniBooNE extracts beam from the 8 GeV Booster

Delivered to a 1.7 λ Be target



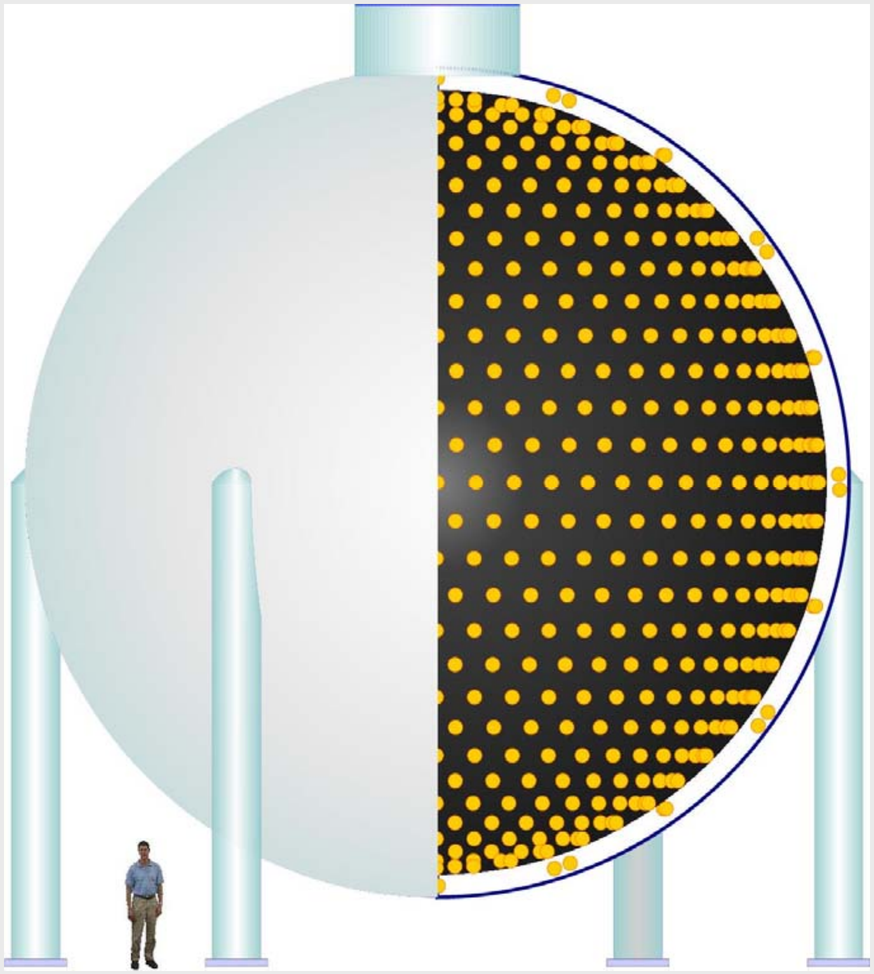
within a magnetic horn (2.5 kV, 174 kA) that (increases the flux by ×6)

4×10^{12} protons per 1.6 μs pulse delivered at up to 5 Hz.

6.3×10^{20} POT delivered 2002 thru end of 2005

Collected another 1 x 10^{20} POT during 2007 SciBooNE Run

The MiniBooNE Detector (arXiv: 0806.4201)



- 541 meters downstream of target
- 3 meter overburden
- 12.2 meter diameter sphere

  (10 meter “fiducial” volume)

  - Filled with 800 t

    of pure mineral oil (CH_2)

    (Fiducial volume: 450 t)
  - 1280 inner phototubes

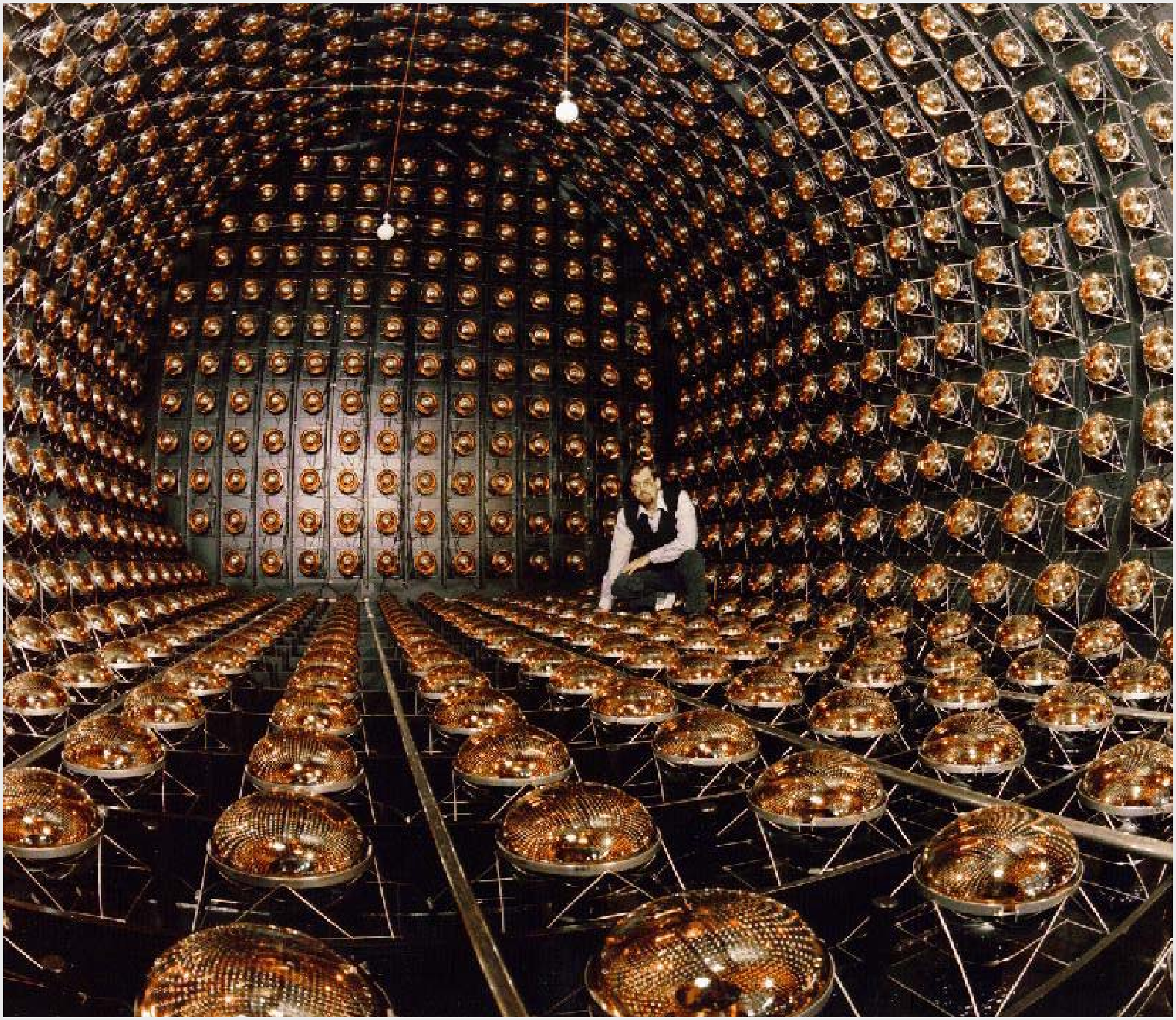
    (10% photocathode coverage),

    240 veto phototubes
  - Simulated with a GEANT3 Monte Carlo

MiniBooNE Detector Tank, Lots of Valuable Oil!

Picture of LSND photomultipliers (used later in MB)

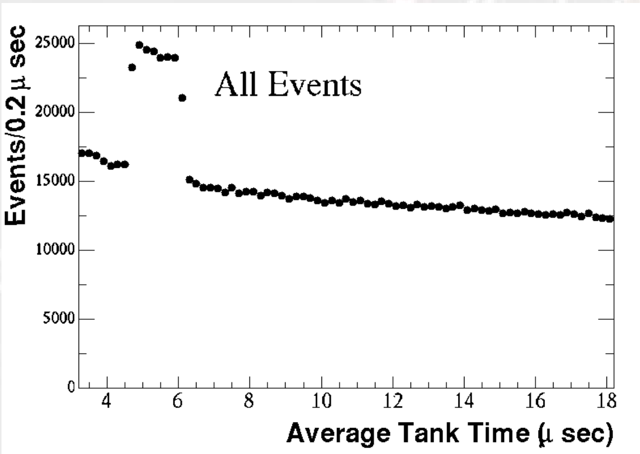
hep-ex/0404



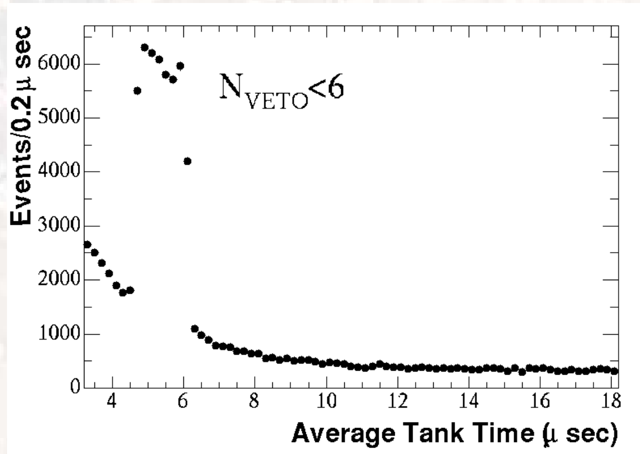
Electronics reused as well.

A 19.2 μs beam trigger window encompasses the 1.6 μs spill

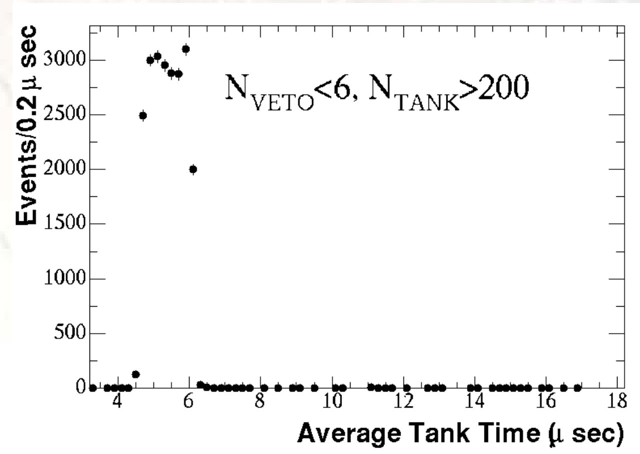
Tank time for first subevent



Raw data

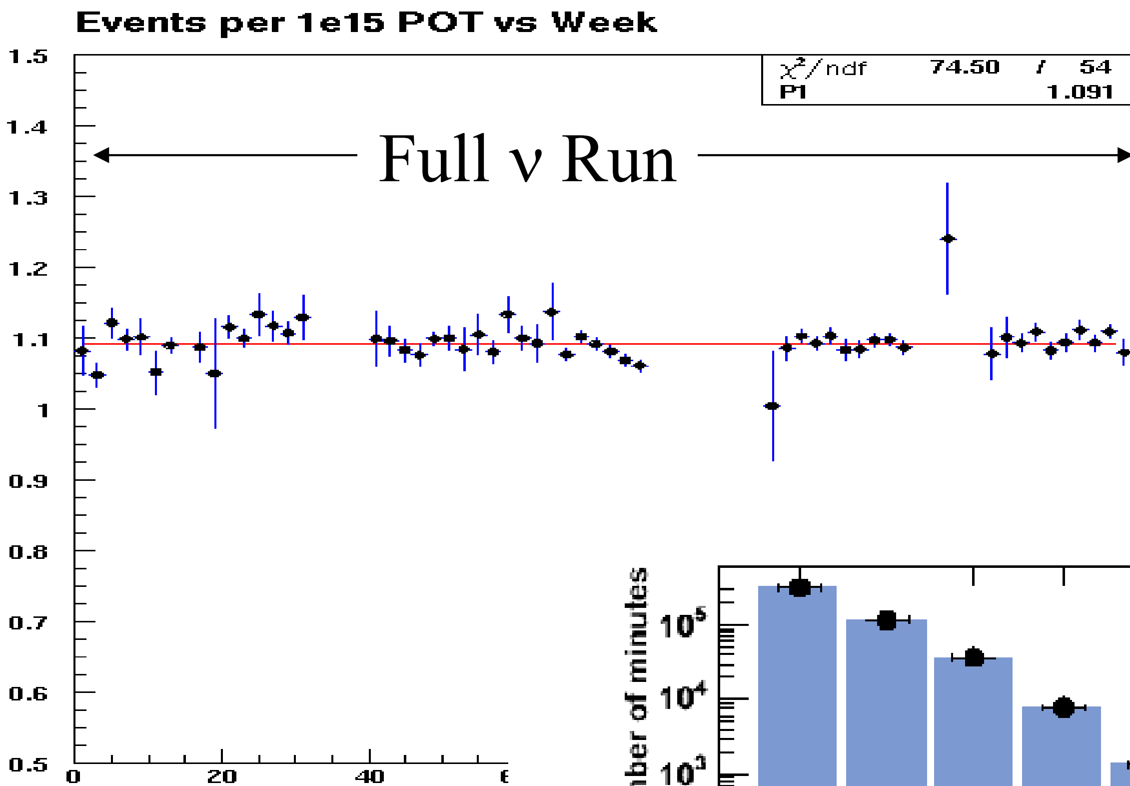


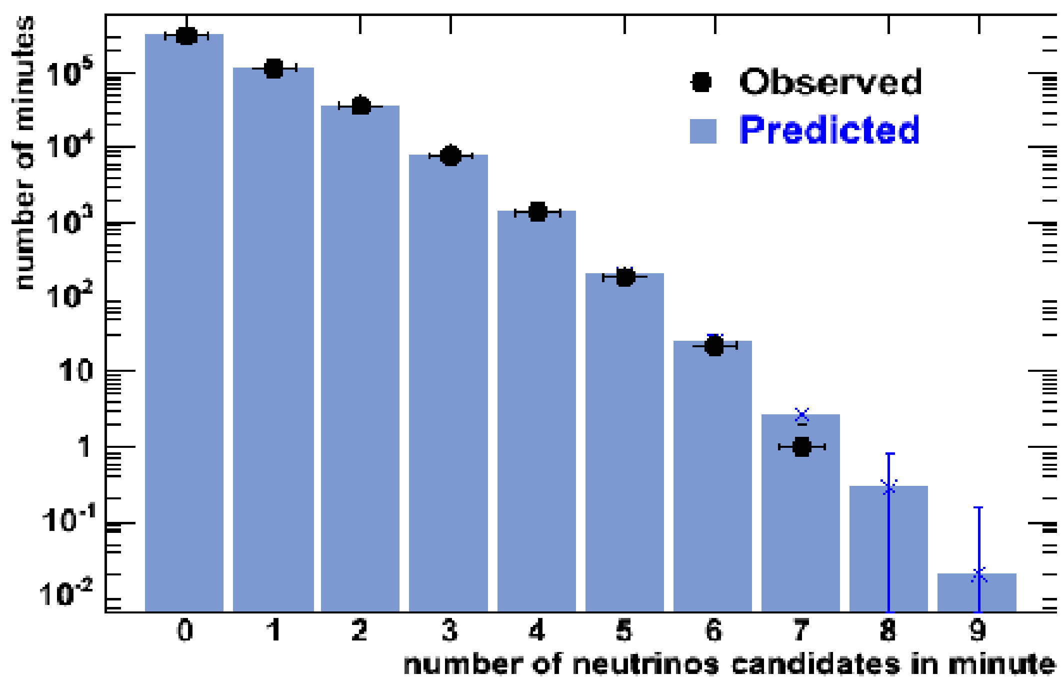
Veto<6 removes
Cosmic ray muons
leaving
" Michel electrons"
$(\mu \rightarrow \nu_\mu \nu_e e)$



Tank Hits > 200
(equivalent to energy)
removes Michel electrons,
which have
52 MeV endpoint

Stability of running:



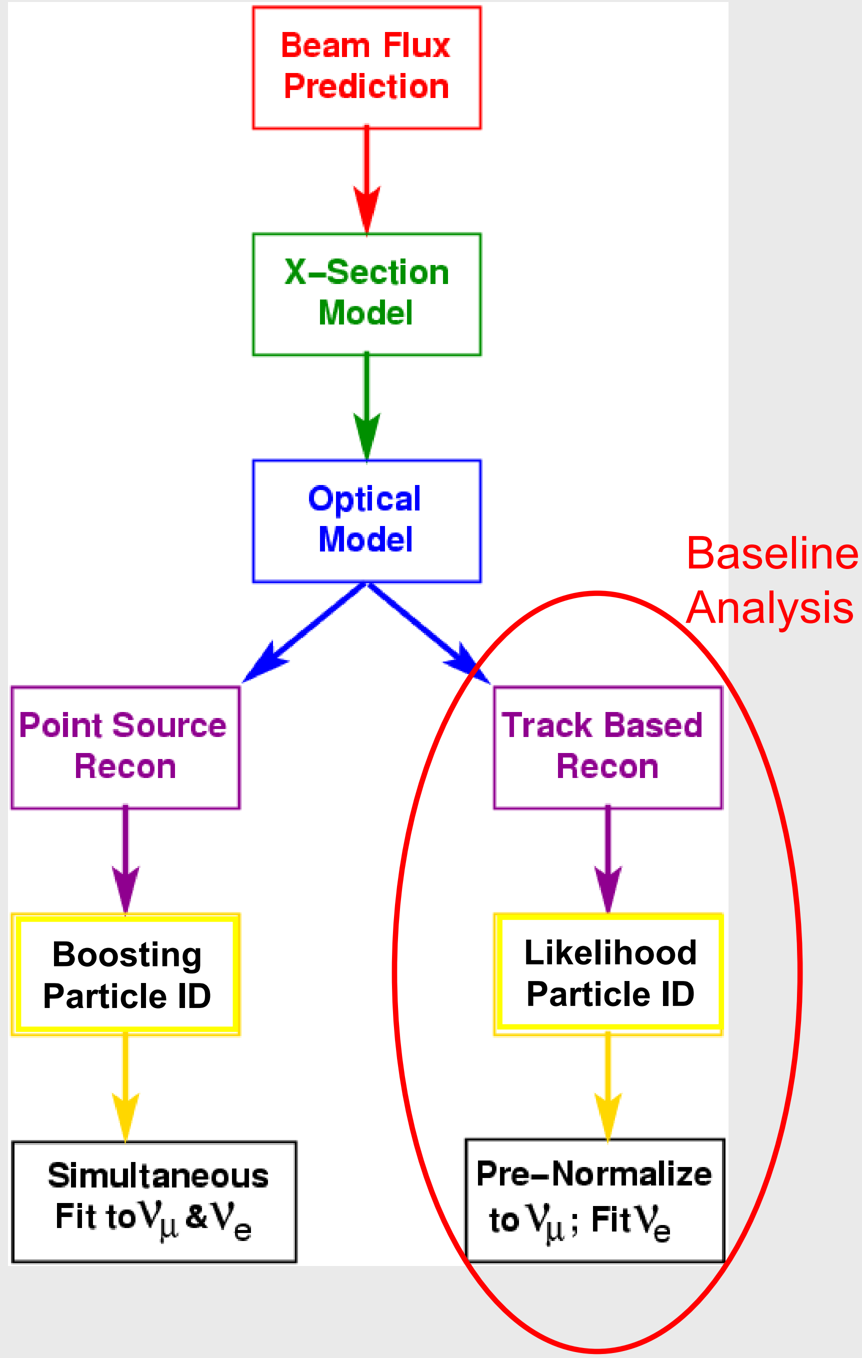


Observed and expected events per minute

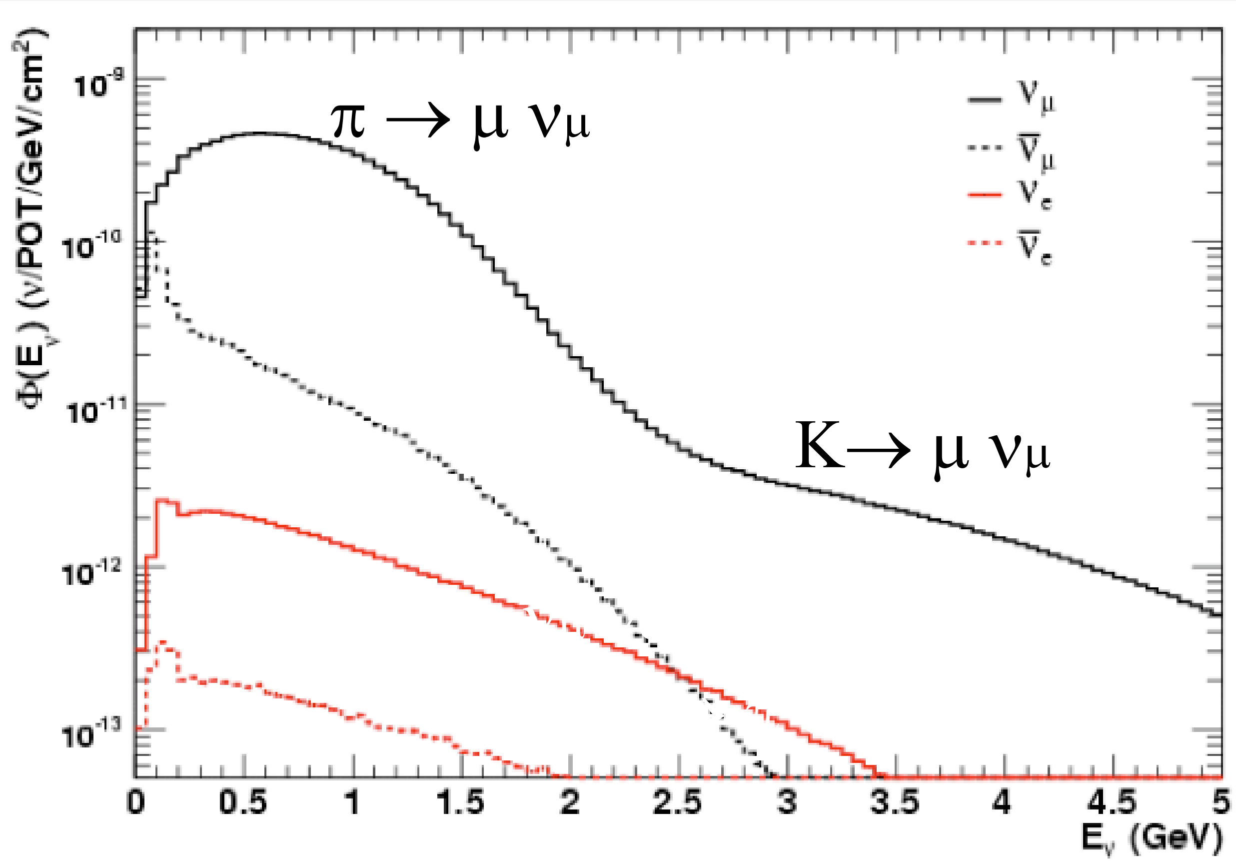
Oscillation Analysis

MiniBooNE oscillation analysis structure

- Start with a Geant 4 flux prediction for the ν spectrum from π and K produced at the target
- Predict ν interactions using the Nuance cross section parameterization
- Pass final state particles to Geant 3 to model particle and light propagation in the tank
- Starting with event reconstruction, independent analyses:
  - Boosted Decision Tree (BDT)
  - Track Based Likelihood (TBL)
- Develop particle ID/cuts to separate signal from background
- Fit reconstructed E_ν spectrum for oscillations, apply muon constraint and systematic errors (full error matrix with correlations).



Neutrino Flux from GEANT4 Simulation



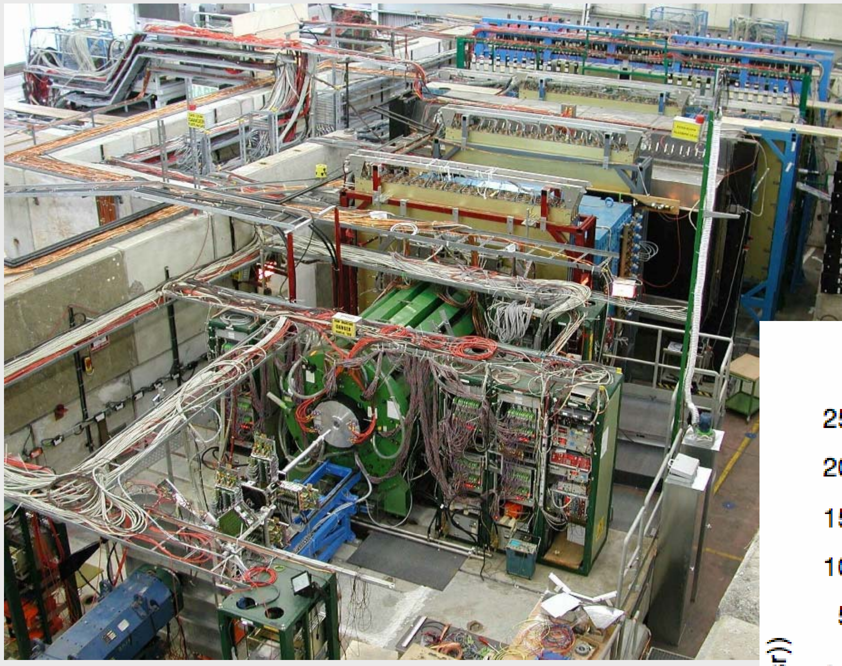
See Flux paper for details
arXiv: 0806.1449

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

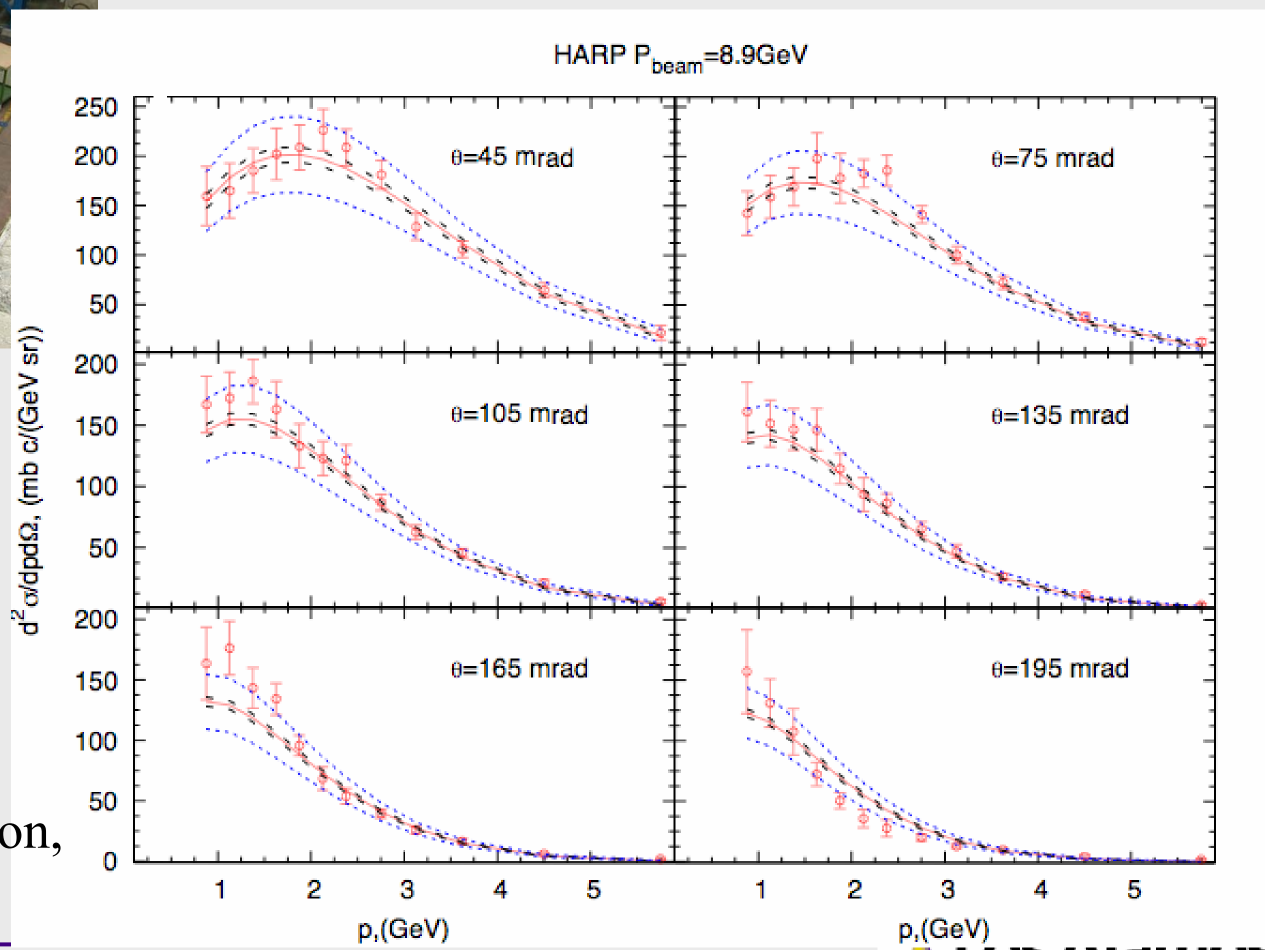
$\mu^+ \rightarrow e^+\ \bar{\nu}_\mu\, \nu_e$	(52%)
$K^+ \rightarrow \pi^0\, e^+\, \nu_e$	(29%)
$K^0 \rightarrow \pi\, e\, \nu_e$	(14%)
Other	(5%)

$\nu_e/\nu_\mu = 0.5\%$
Antineutrino content: 6%

Modeling Production of Secondary Pions



- HARP (CERN)
  - 5% λ Beryllium target
  - 8.9 GeV proton beam momentum

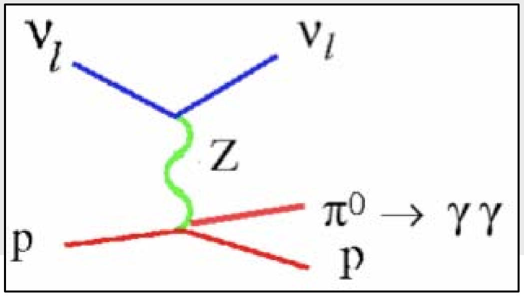


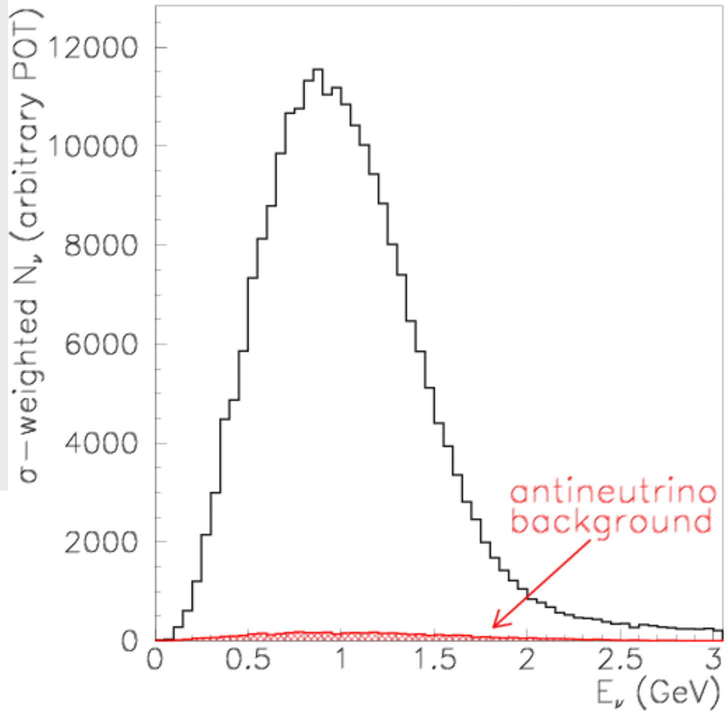
Data are fit to
a Sanford-Wang
parameterization.

HARP collaboration,
hep-ex/0702024

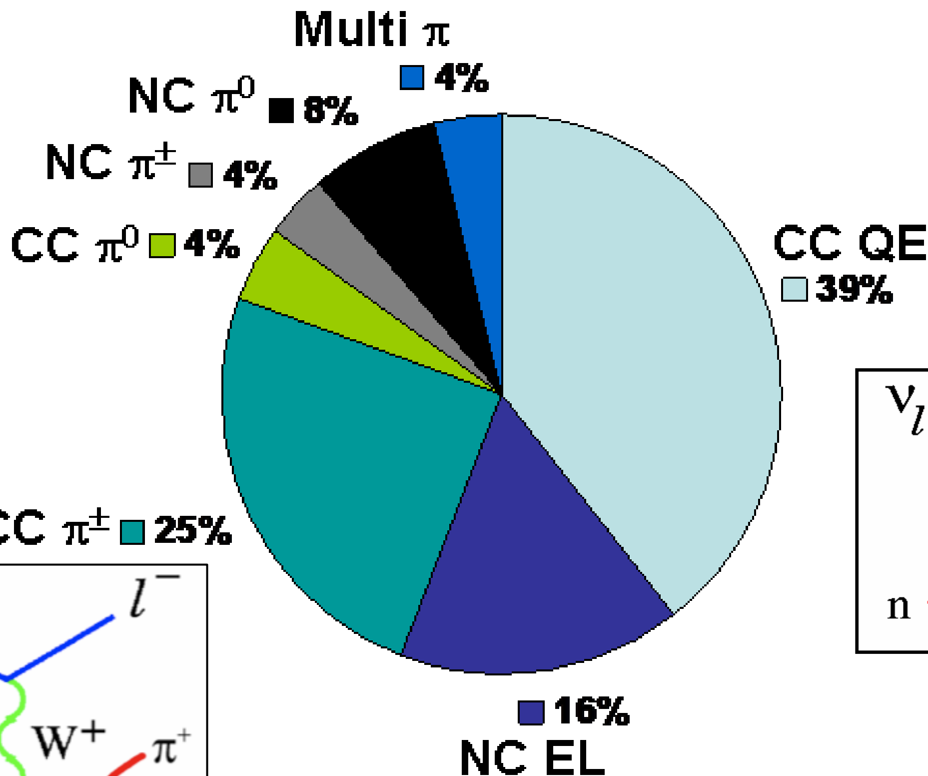
Predicted event rates before cuts (NUANCE Monte Carlo)

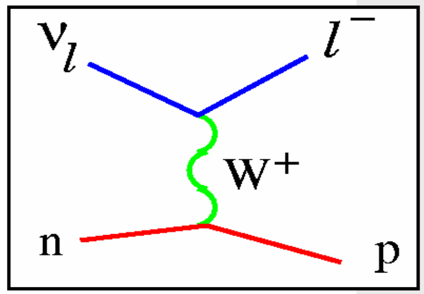
D. Casper, NPS, 112 (2002) 161

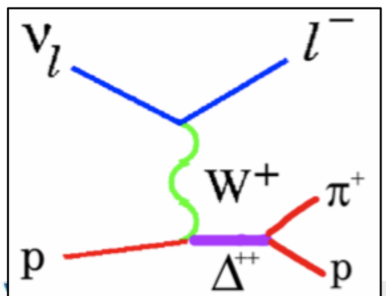




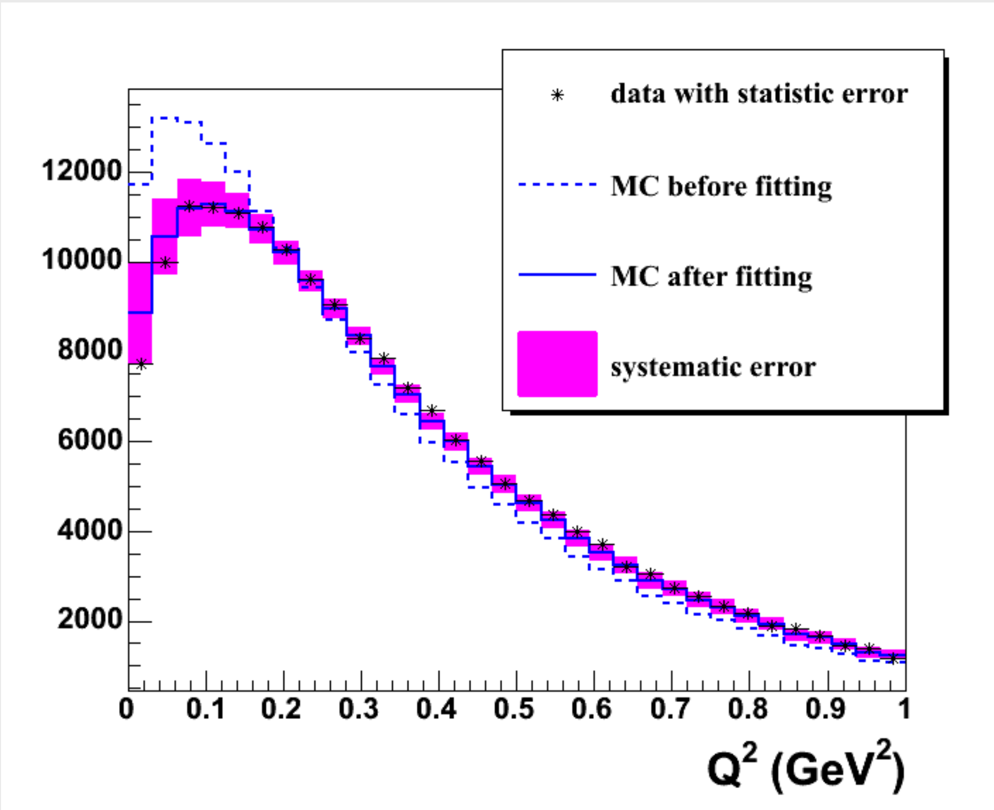
Event neutrino energy (GeV)







CCQE Scattering (Phys. Rev. Lett 100, 032301 (2008))



From Q^2 fits to MB ν_μ CCQE data:

M_A^{eff} -- effective axial mass

κ -- Pauli Blocking parameter

From electron scattering data:

E_b -- binding energy

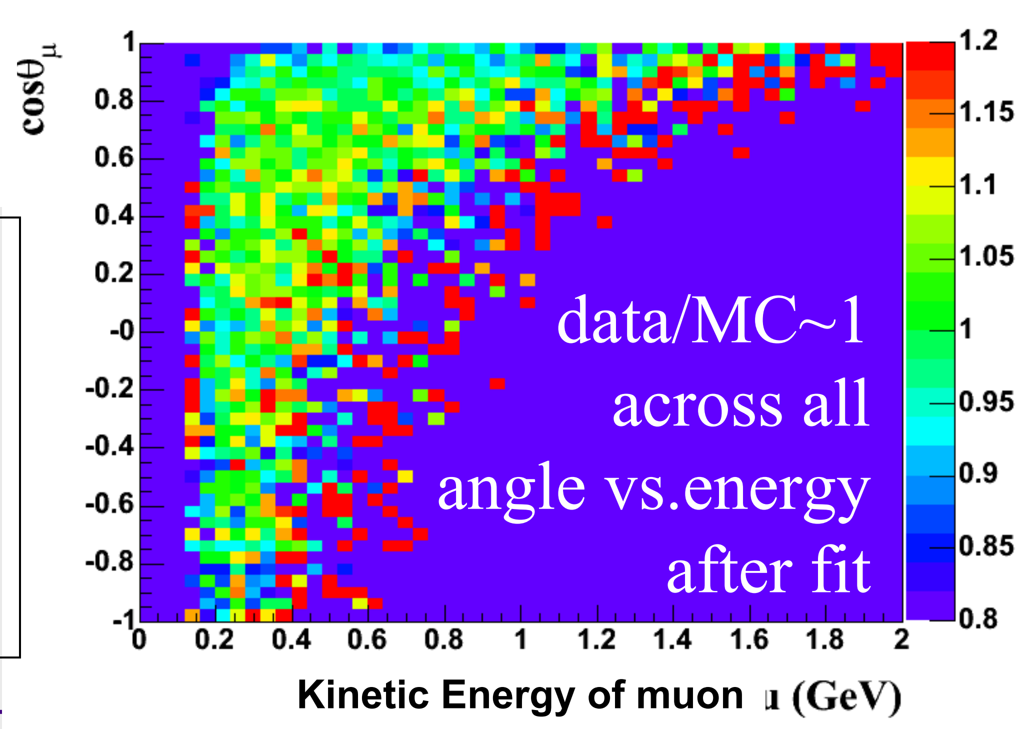
p_f -- Fermi momentum

Fermi Gas Model describes CCQE ν_μ data well

M_A = 1.23+-0.20 GeV

κ = 1.019+-0.011

Also used to model ν_e interactions



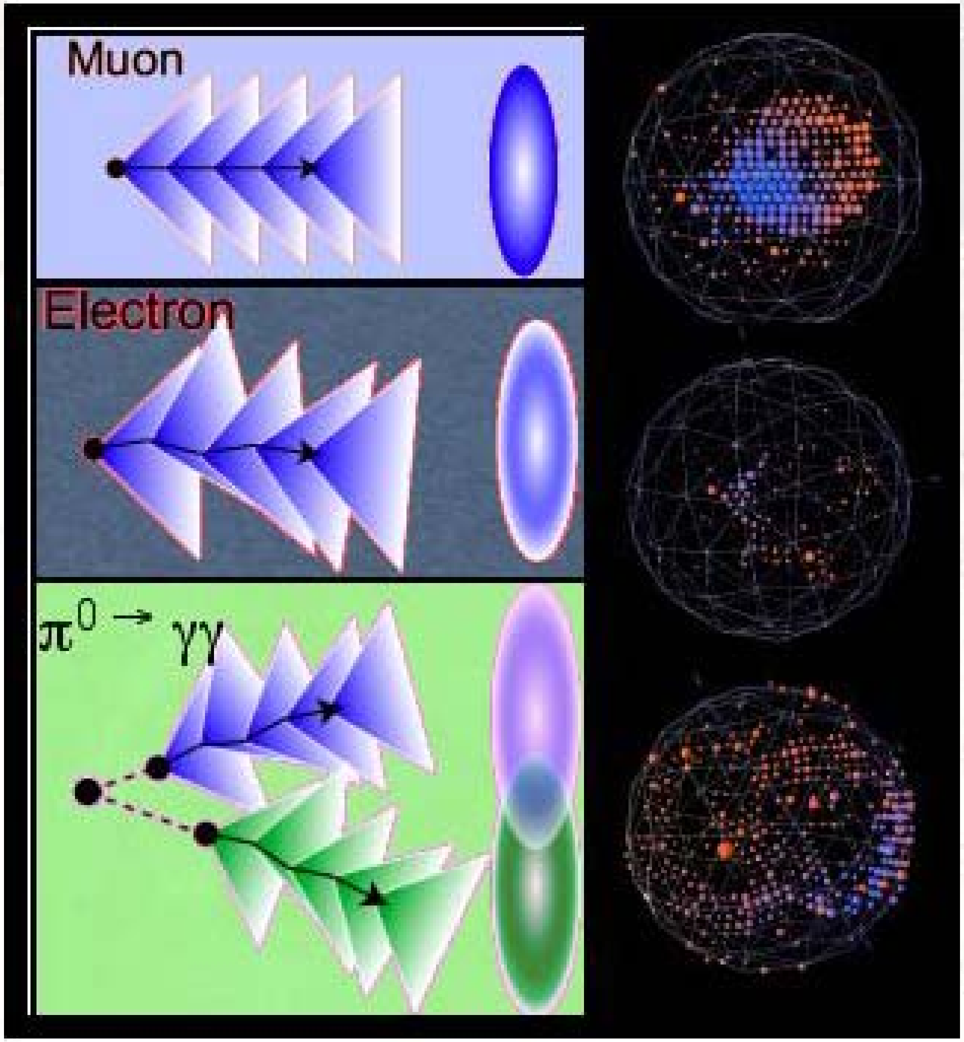
MiniBooNE is a Cerenkov Light Detector:

The main types of particles our neutrino events produce:

Muons (or charged pions):
Produced in most CC events.
Usually 2 or more subevents
or exiting through veto.

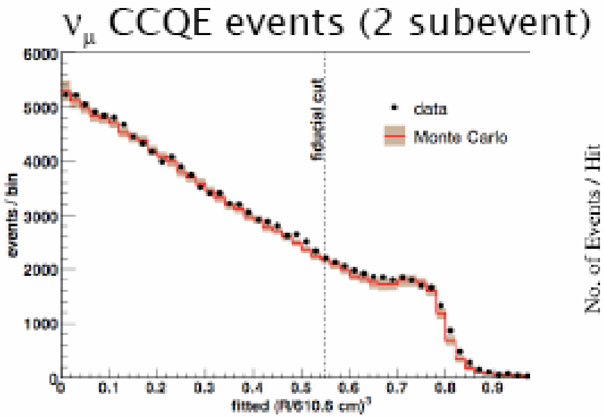
Electrons:
Tag for $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent

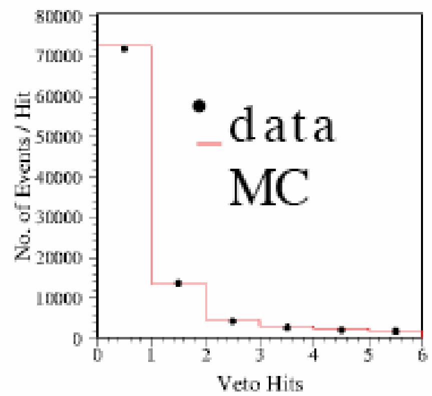
π^0s:
Can form a background if one photon is weak or exits tank.
In NC case, 1 subevent.

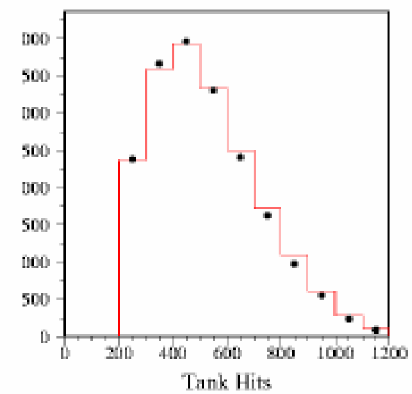


TBL Analysis: Separating e from μ

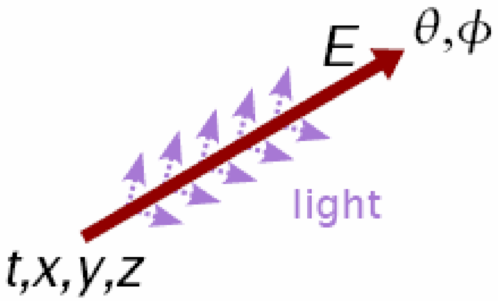
- Analysis pre-cuts
  - Only 1 subevent
  - Veto hits < 6
  - Tank hits > 200
  - Radius < 500 cm

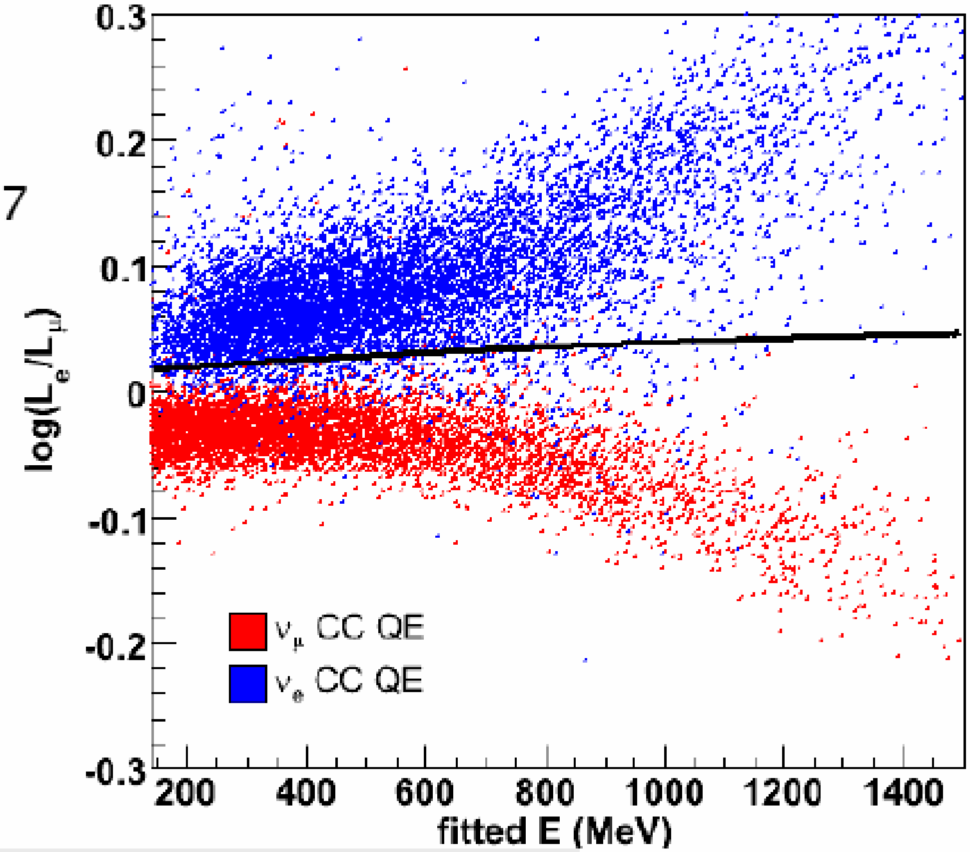






- Event is a collection of PMT-level info (q,t,x)
- Form sophisticated Q and T pdfs, and fit for 7 track parameters under 2 hypotheses
  - The track is due to an electron
  - The track is coming from a muon



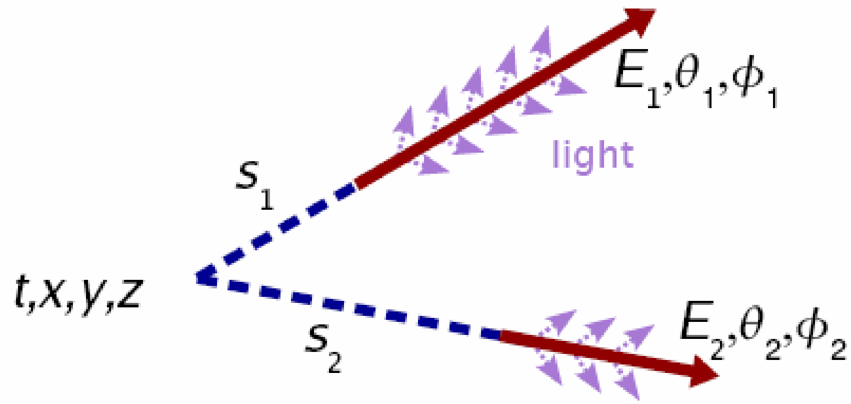


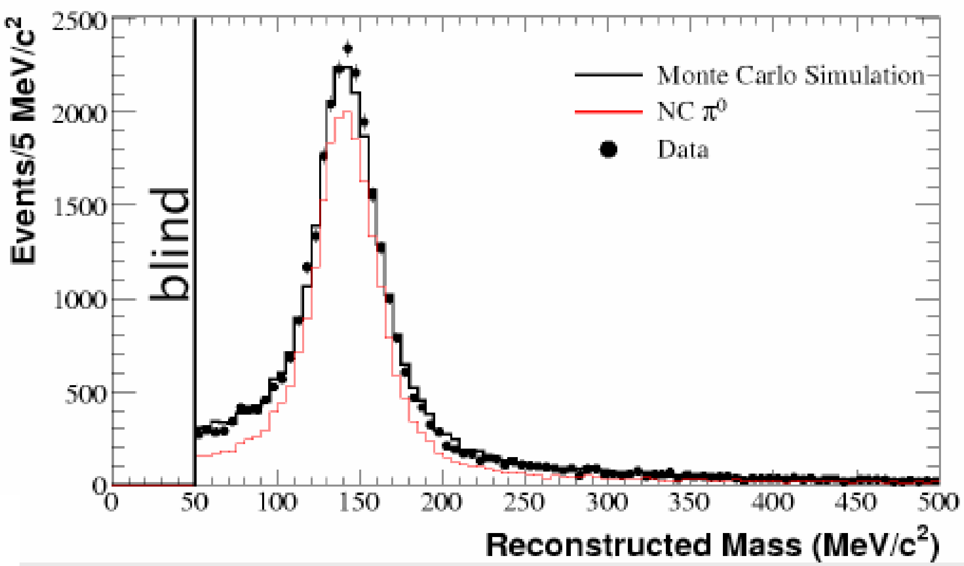
NNSA

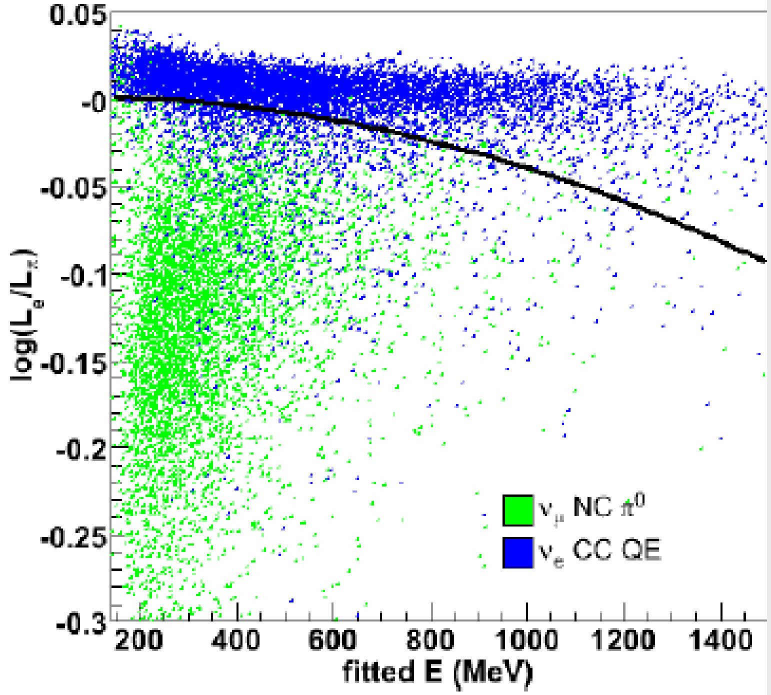
Los Alamos

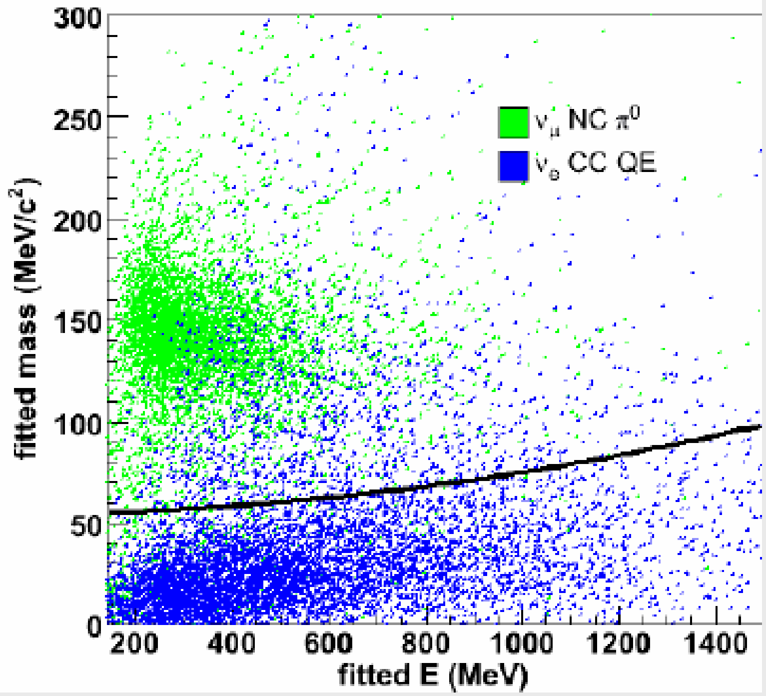
Separating e from π^0

- Extend fit to include two e–like tracks
- Very tenacious fit…8 minutes per event
- Nearly 1M CPU hours used (thanks OSG!)









Summary of Track Based cuts

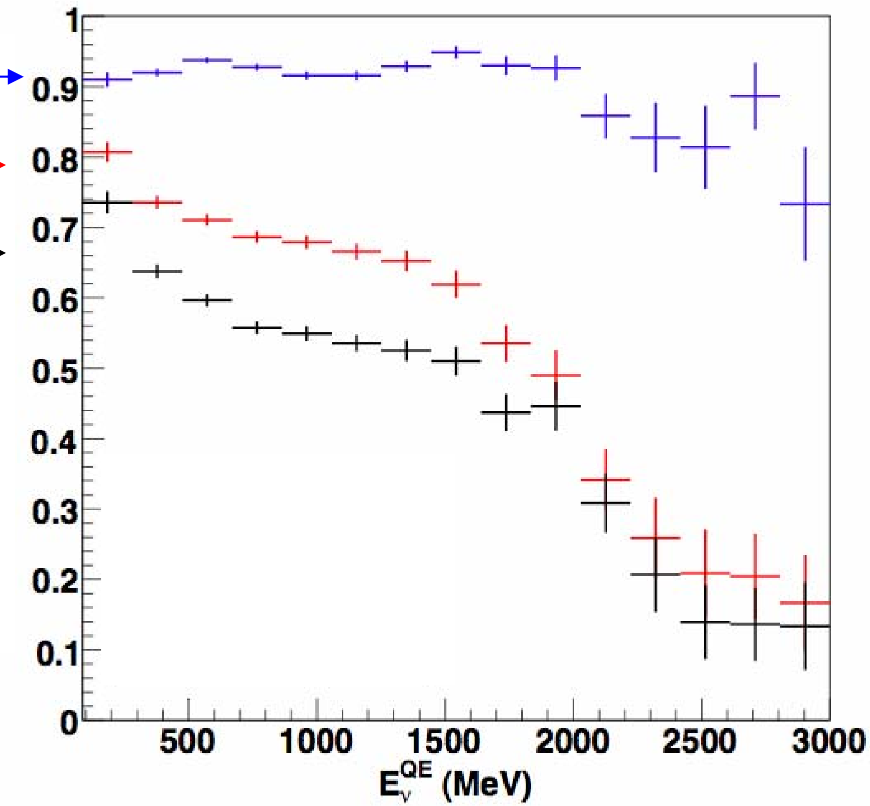
"Precuts" +

$\mathrm{Log}(L_e/L_\mu)$

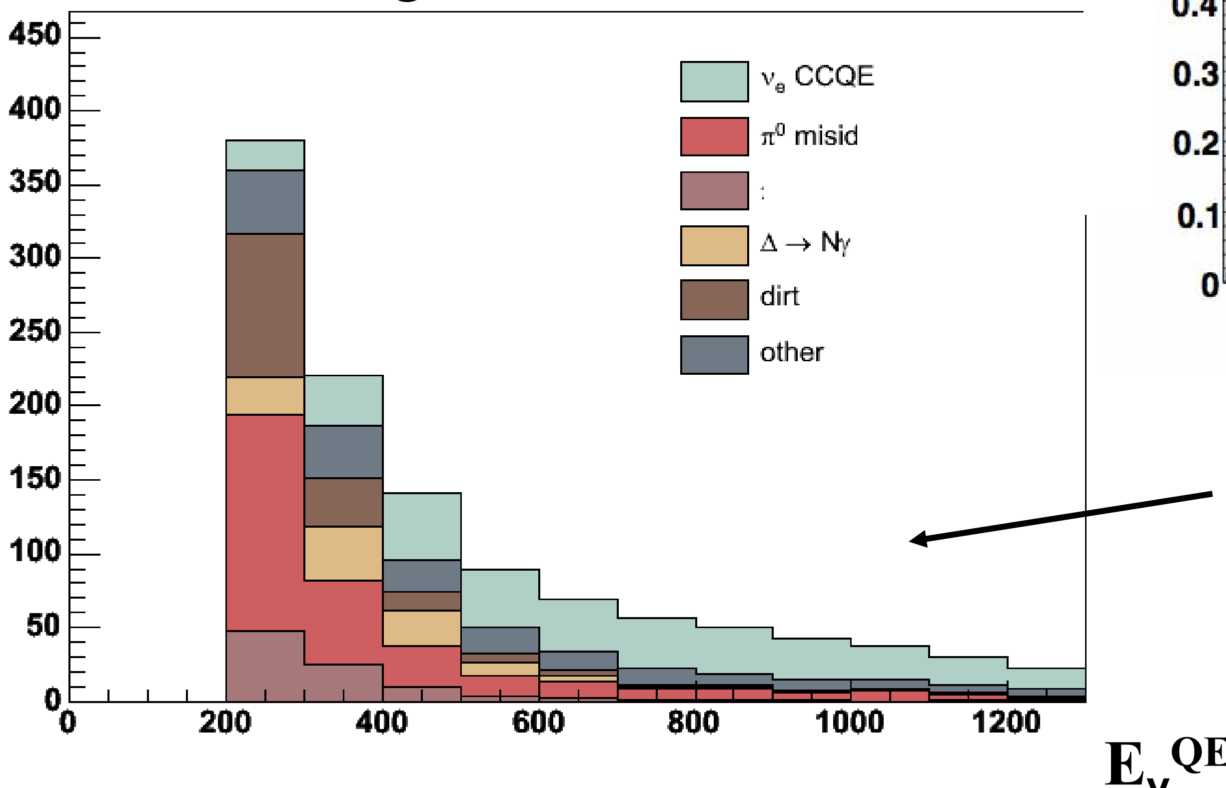
$+ \mathrm{Log}(L_e/L_\pi)$

+ invariant mass

Efficiency:



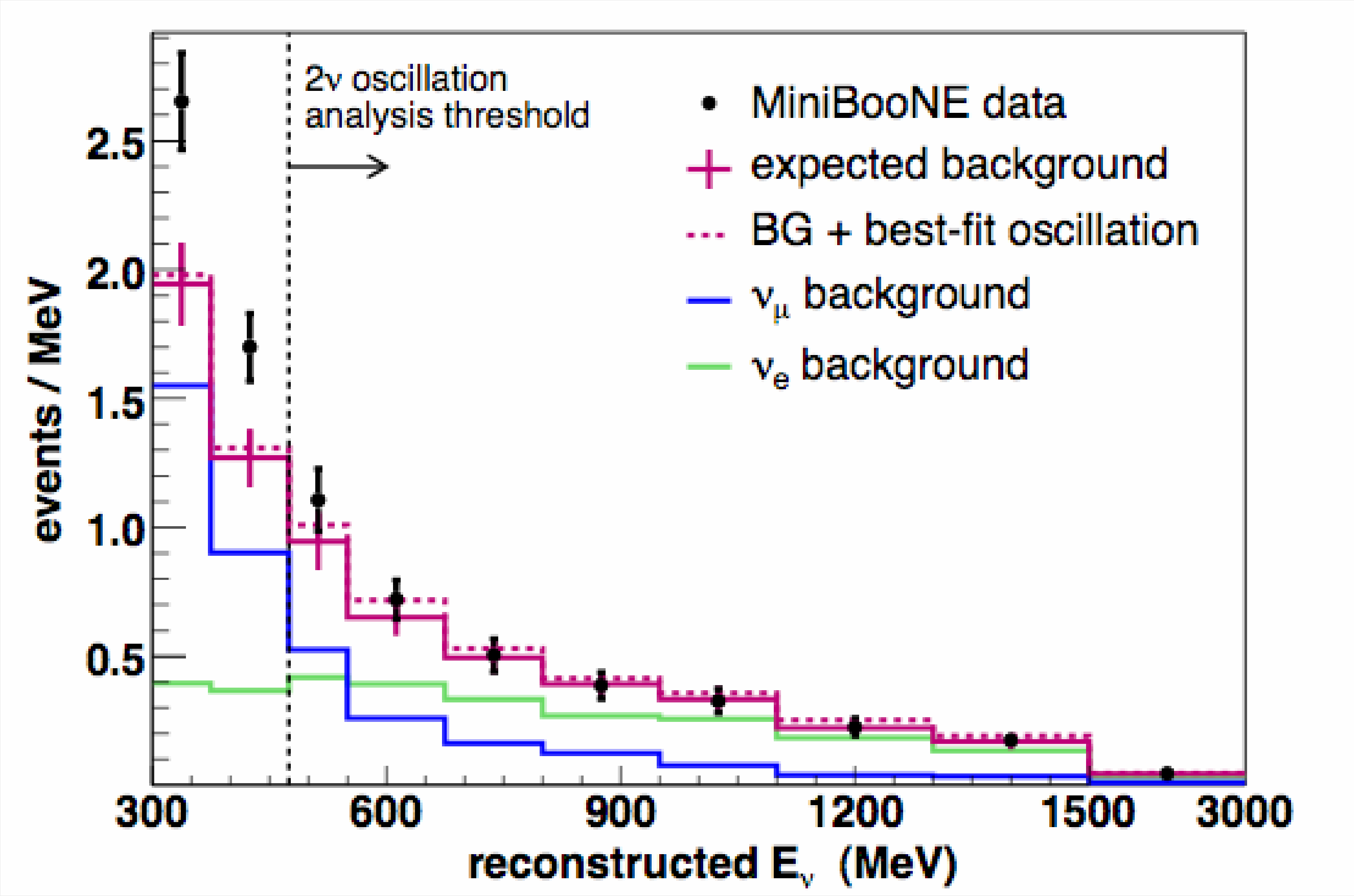
Backgrounds after cuts



LSND oscillations adds 100 to 150 events

First $\nu_\mu \rightarrow \nu_e$ Oscillation Result from One year ago.

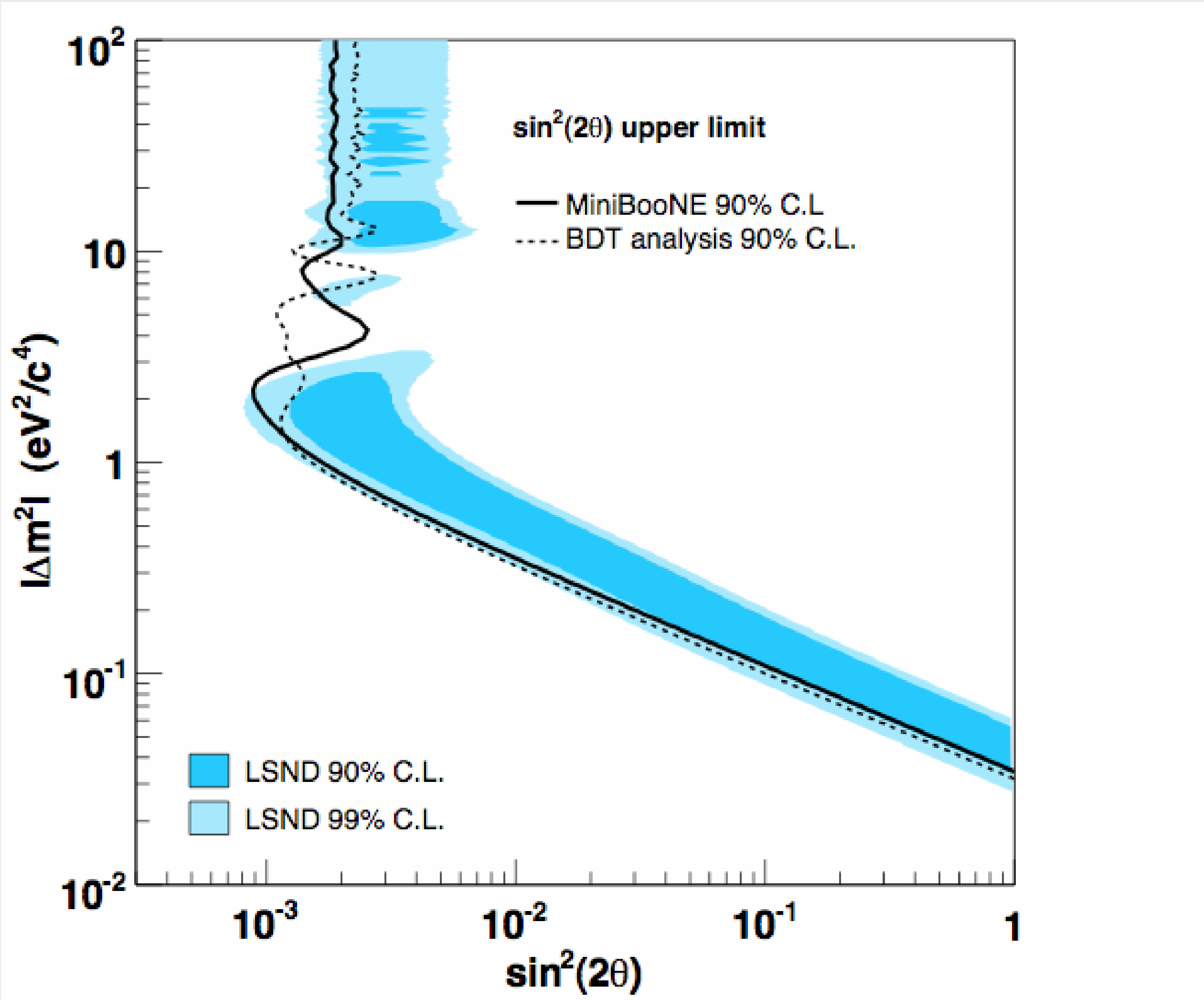
The Track-based $\nu_\mu \rightarrow \nu_e$ Appearance-only Result:



$475 < E_\nu^{QE} < 1250$ MeV : data: 380 events, MC: 358 ±19 ±35 events, 0.55 σ

The result of
the $\nu_\mu \rightarrow \nu_e$ appearance-only analysis
is a <u>limit</u> on oscillations:

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



Simple 2-neutrino oscillations excluded at 98% C.L.

Energy fit: $475<E_\nu^{QE}<3000$ MeV

Ten Top Physics Stories for 2007

Number 850 #1, December 13 , 2007 by Phil Schewe

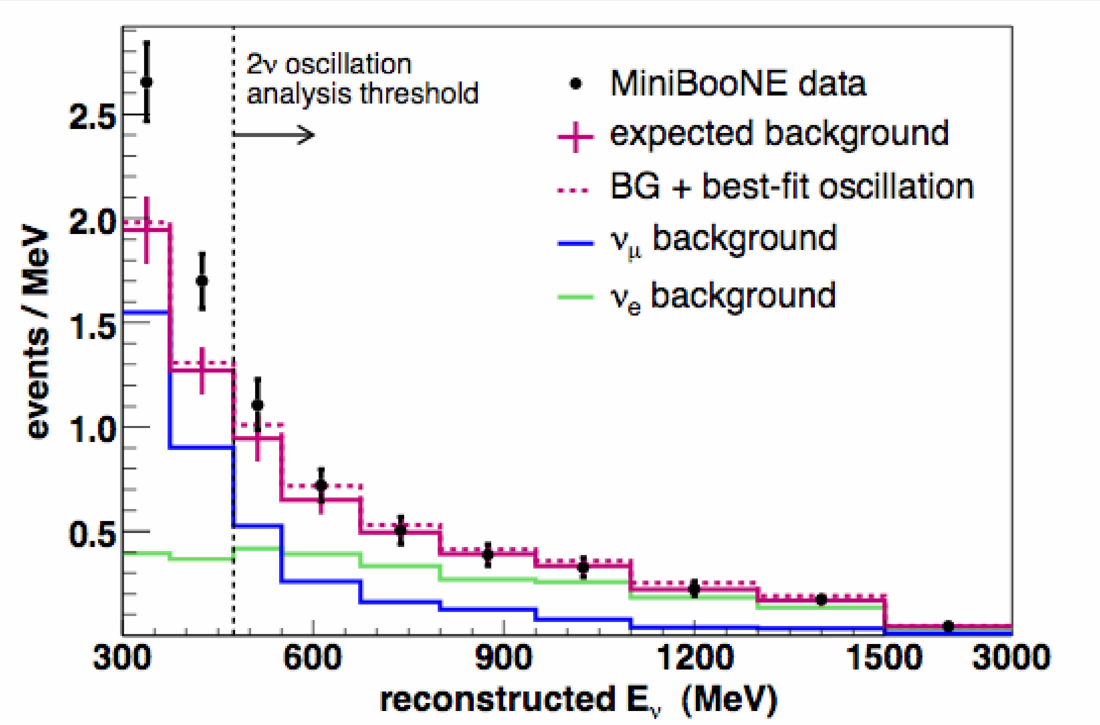
Ten Top Physics Stories for 2007

In chronological order during the year:

1. Light, slowed in one Bose Einstein condensate (BEC), is passed on to another BEC (http://www.aip.org/pnu/2007/split/812-1.html);
2. Electron tunneling in real time can be observed with the use of attosecond pulses (http://www.aip.org/pnu/2007/split/818-2.html);
3. Laser cooling of coin-sized object, at least in one dimension (http://www.aip.org/pnu/2007/split/818-1.html);
4. The best test ever of Newton's second law, using a tabletop torsion pendulum (http://www.aip.org/pnu/2007/split/819-1.html);
5. First Gravity Probe B first results, the measurement of the geodetic effect---the warping of spacetime in the vicinity of and caused by Earth-to a precision of 1%, with better precision yet to come (http://www.aip.org/pnu/2007/split/820-2.html).
6. The MiniBooNE experiment at Fermilab solves a neutrino mystery, apparently dismissing the possibility of a fourth species of neutrino (http://www.aip.org/pnu/2007/split/820-1.html);
7. The Tevatron, in its quest to observe the Higgs boson, updated the top quark mass and observed several new types of collision events, such as those in which only a single top quark is made, and those in which a W and Z boson or two Z bosons are made simultaneously (http://www.aip.org/pnu/2007/split/821-1.html);
8. The shortest light pulse, a 130-attosecond burst of extreme ultraviolet light (http://www.aip.org/pnu/2007/split/823-1.html);
9. Based on data recorded at the Auger Observatory, astronomers conclude that the highest energy cosmic rays come from active galactic nuclei (http://www.aip.org/pnu/2007/split/846-1.html);

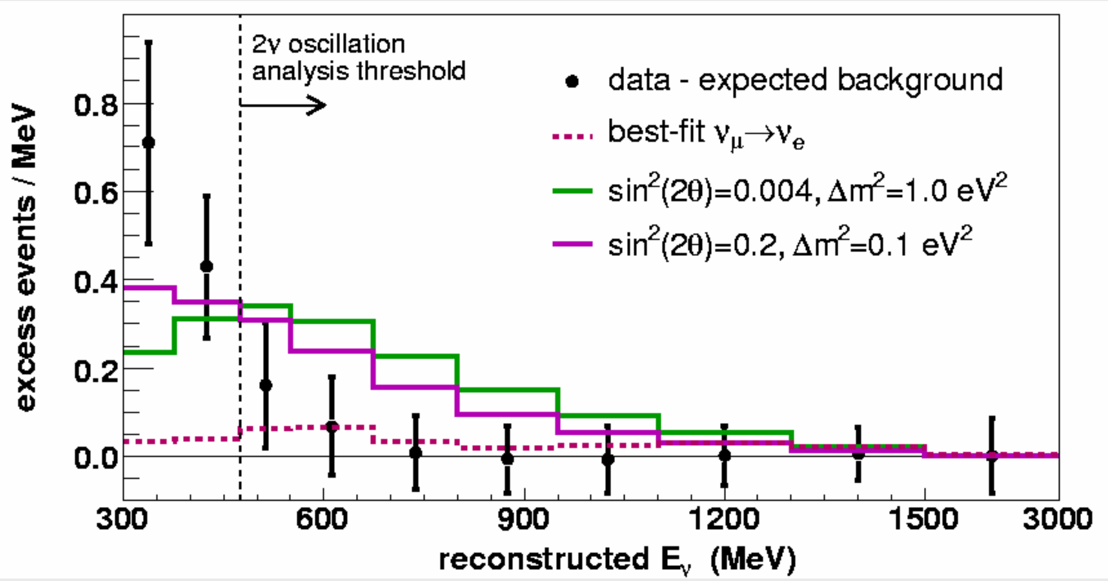
The MiniBooNE experiment at Fermilab solves a neutrino mystery.

But an Excess of Events Observed Below 475 MeV



$96 \pm 17 \pm 20$ events above background, for $300 < E_\nu^{QE} < 475$MeV

Deviation: $3.7\ \sigma$



Excess Distribution inconsistent with a 2-neutrino oscillation model

Going Beyond the First Result

Investigations of the Low Energy Excess

- Possible detector anomalies or reconstruction problems
- Incorrect estimation of the background
- New sources of background
- New physics including exotic oscillation scenarios, neutrino decay, Lorentz violation, …….

Any of these backgrounds or signals could have an important impact on other future oscillation experiments.

Re-analysis of the Low Energy Anomaly

Improvements in the Analysis

- Check many low level quantities (PID stability, etc)
- Rechecked various background cross-section and rates (π^0, $\Delta \rightarrow N\gamma$, etc.)
- Photo-nuclear interactions included.
- Improved π^0 (coherent) production incorporated.
- Improved estimate of the background from external events ("dirt") performed.
- Developed cut to efficiently reject "dirt" events.
- Analysis threshold lowered to 200 MeV, with reliable errors.
- Systematic errors rechecked, and some improvements made (i.e. flux, $\Delta \rightarrow N\gamma$, etc).
- Additional data set included in new results:

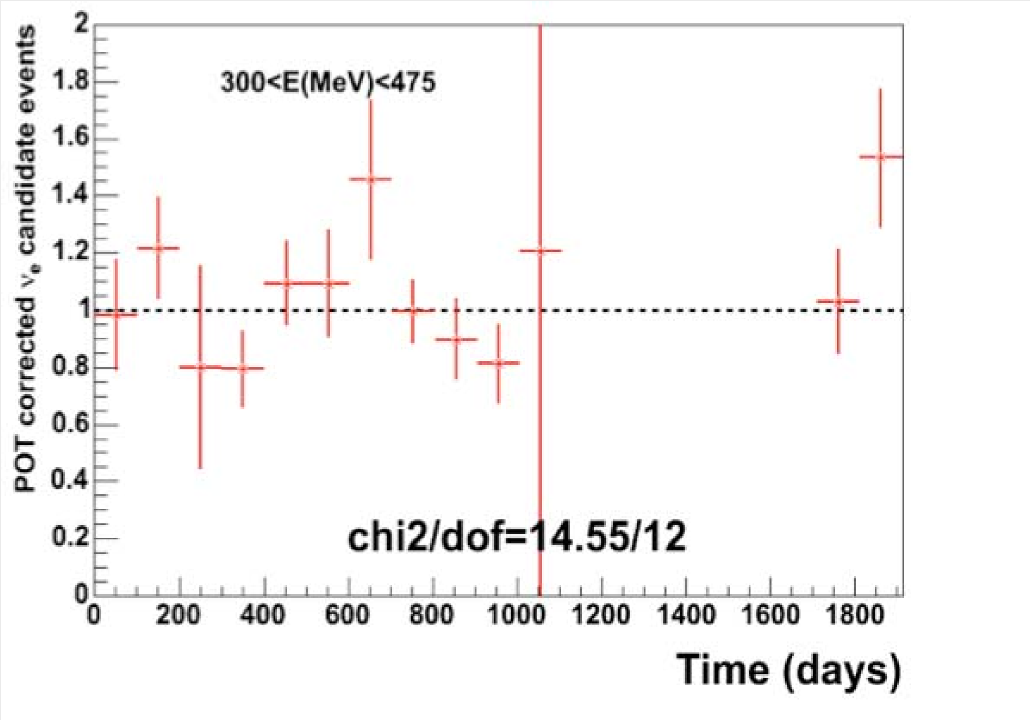
  Old analysis: 5.58×10^{20} protons on target.

  New analysis: 6.46×10^{20} protons on target.

Detector Anomalies or Reconstruction Problems

No Detector anomalies found

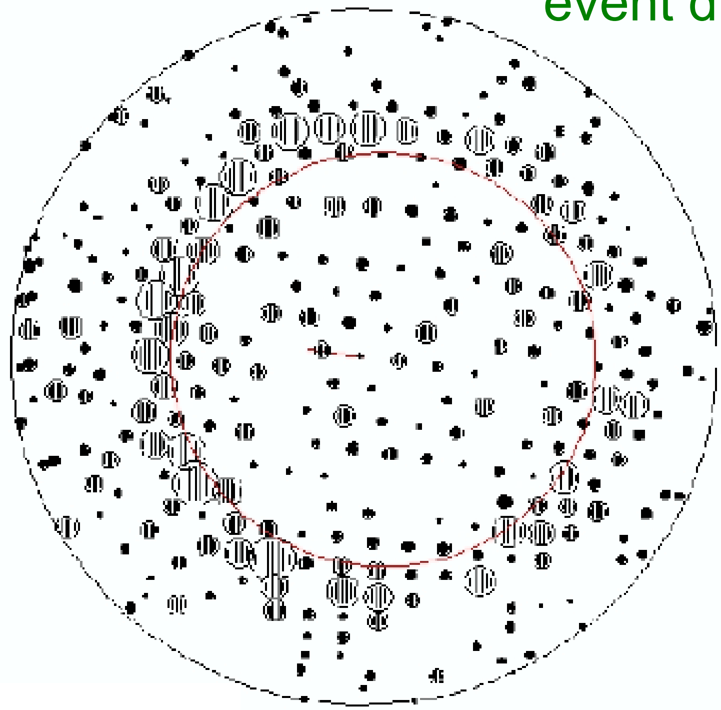
- Example: rate of electron candidate events is constant (within errors) over course of run



No Reconstruction problems found

- All low-E electron candidate events have been examined via event displays, consistent with 1-ring events

example signal-candidate event display



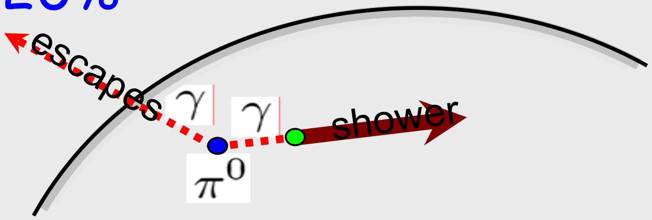
Signal candidate events are consistent with single-ring neutrino interactions

$\Rightarrow$ But could be either electrons or photons

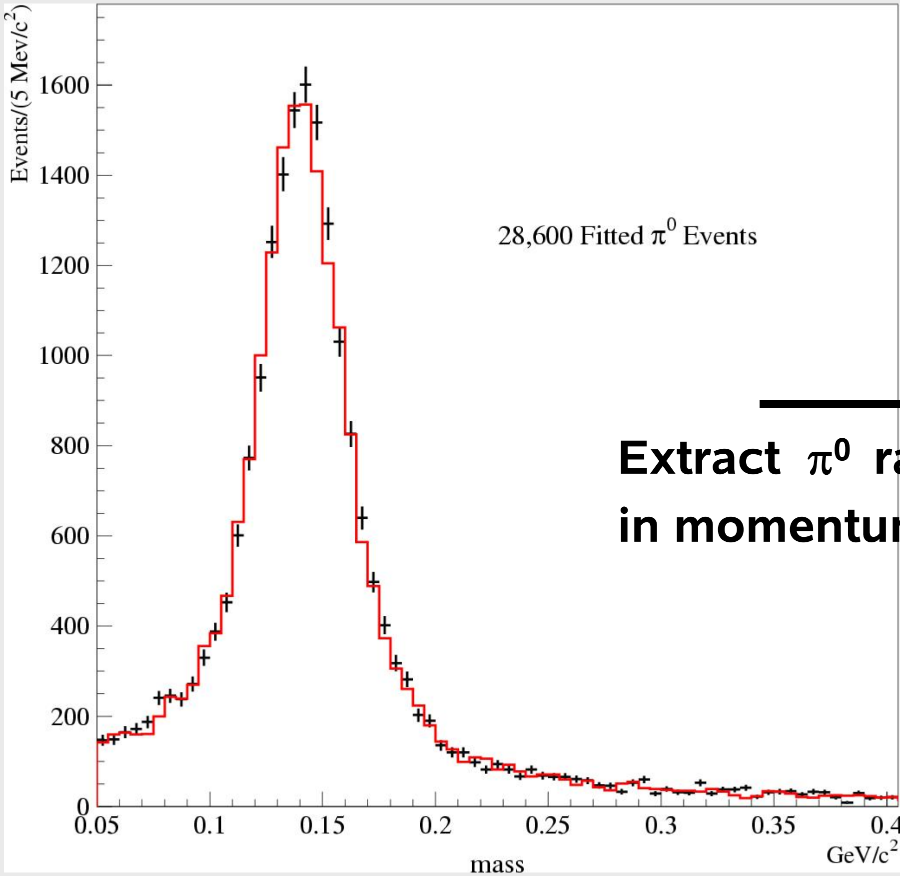
Measuring π^0 and constraining misIDs from π^0

Phys.Lett.B664, 41(2008)

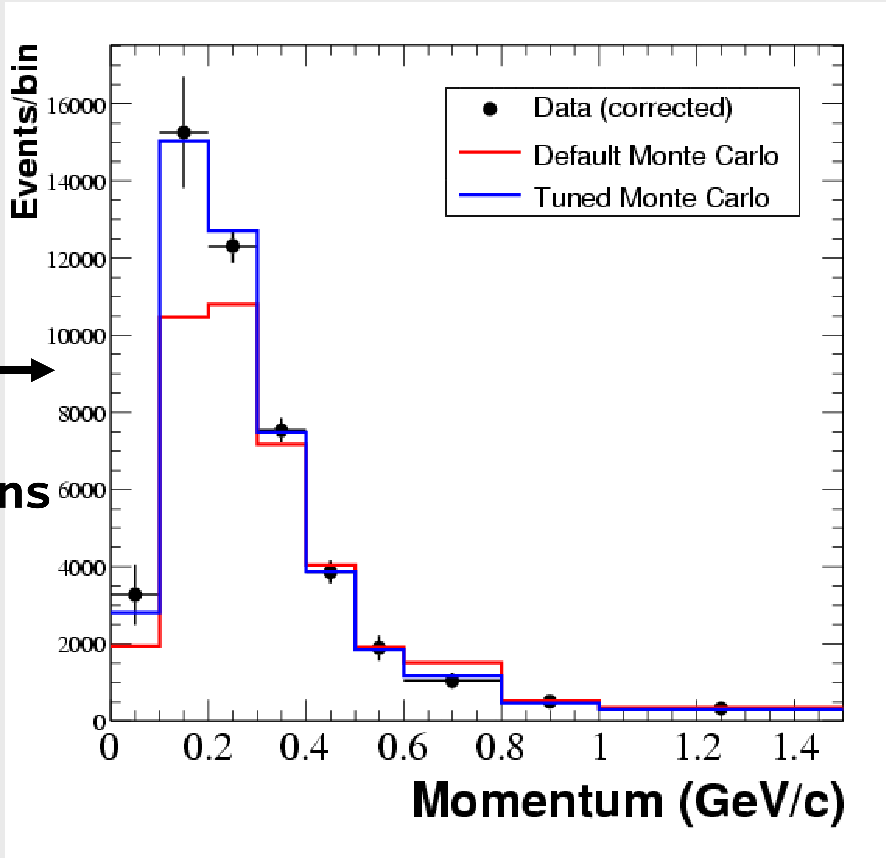
π^0 rate measured to a few percent. Critical input to oscillation analysis: without constraint π^0 errors would be ~ 20%



The π^0's constrains the Δ resonance rate, which determines the rate of $\Delta \rightarrow N\gamma$. Rechecked Δ re-interaction rate. Increased errors 9 -> 12%



Extract π^0 rate in momentum bins



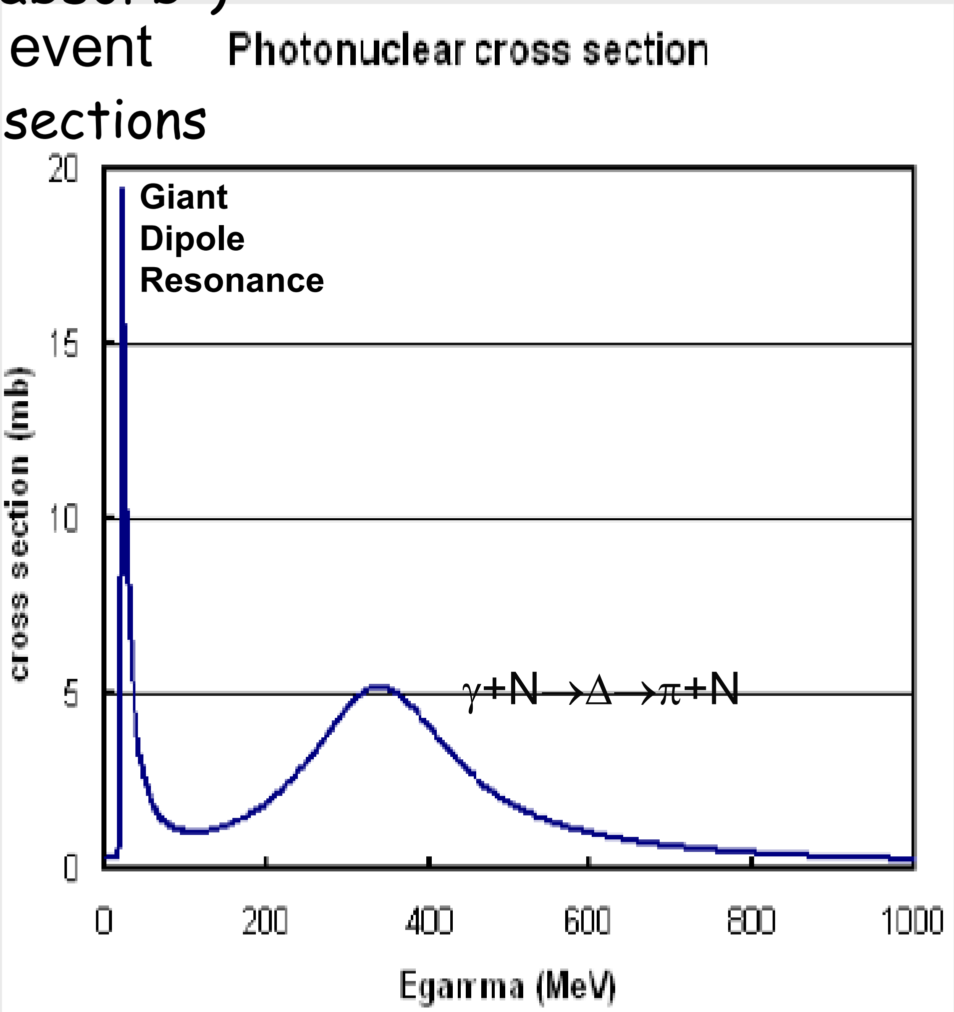
Pion analysis rechecked, only small changes made

Photonuclear absorption of π^0 photon

Since MiniBooNE cannot tell an electron from a single gamma, any process that leads to a single gamma in the final state will be a background

Photonuclear processes can remove ("absorb") one of the gammas from NC $\pi^0 \rightarrow \gamma\gamma$ event

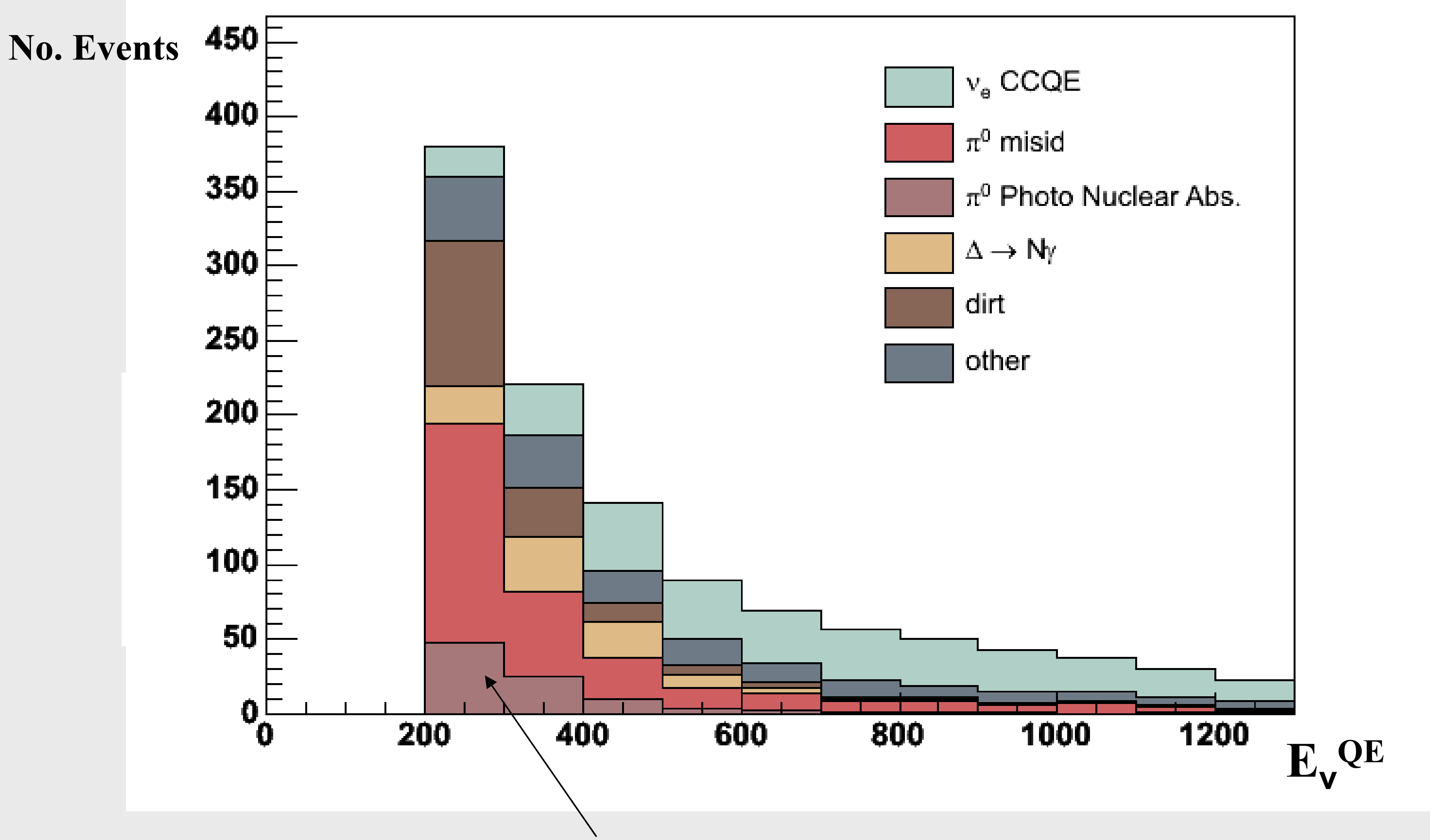
- Total photonuclear absorption cross sections on Carbon well measured.



Photonuclear absorption was missing from our GEANT3 detector Monte Carlo.

- Extra final state particles carefully modelled
- Reduces size of excess
- Systematic errors are small.
- No effect above 475 MeV

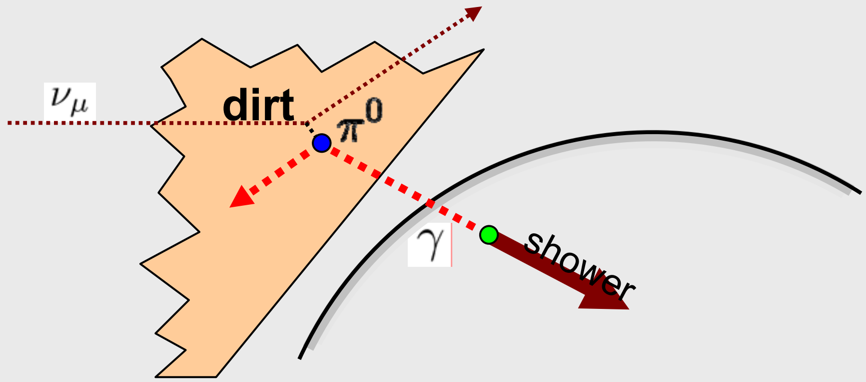
Estimated Effects of Photonuclear Absorption

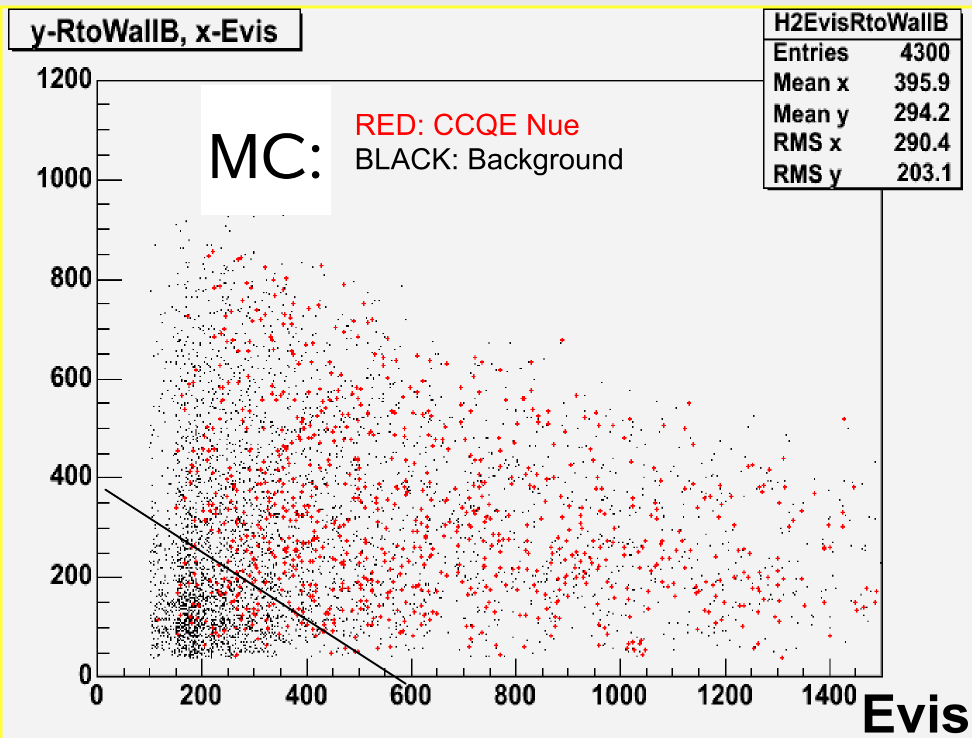


Photonuke adds ~25% to pion background in the 200 <E < 475 MeV region

Reducing Dirt Backgrounds with an Energy Dependent Geometrical Cut

In low energy region there is a significant background from neutrino interactions in the dirt





Dirt events tend to be at large radius, heading inward

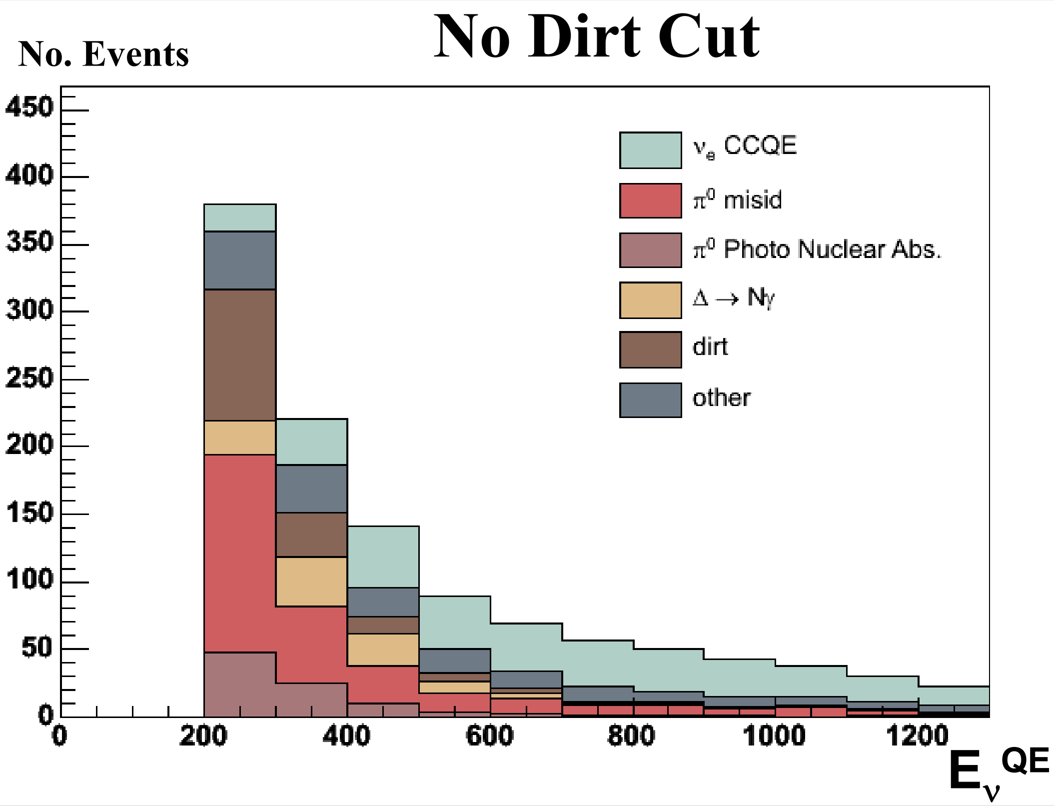
Add a new cut on distance to wall in the track backwards direction, optimized in bins of visible energy.

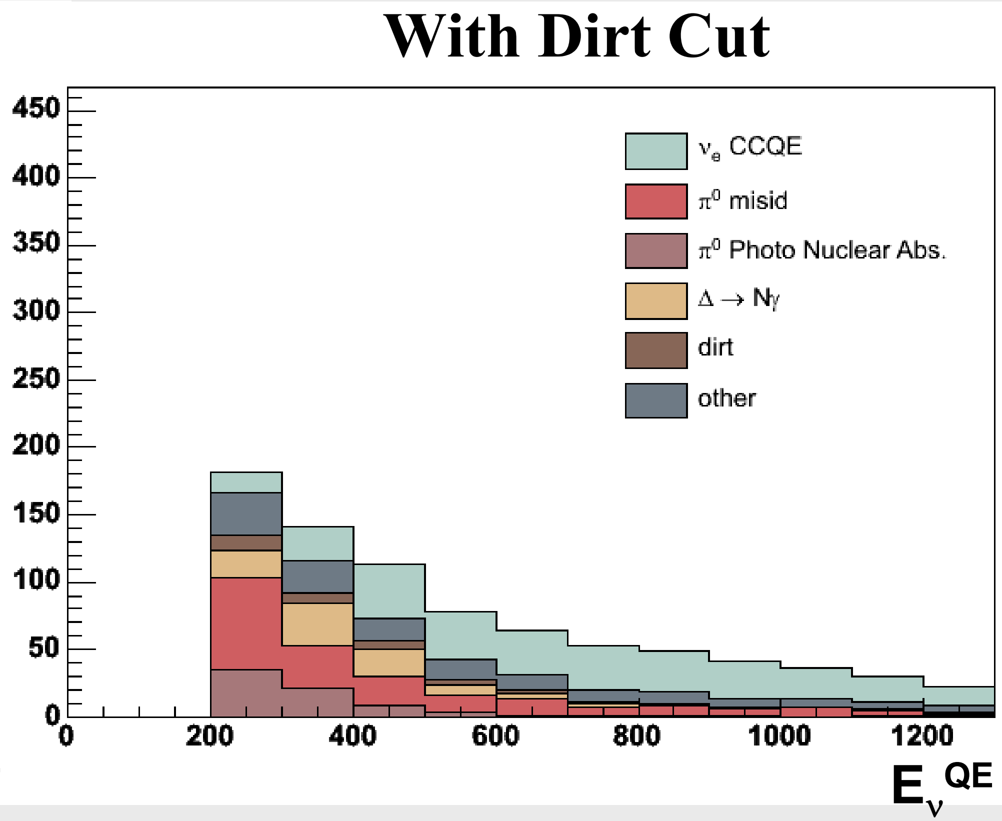
Has significant effect below 475 MeV

- Big reduction in dirt
- Some reduction of π^0
- Small effect on ν_e

Has almost no effect above 475 MeV

Effects of the Dirt Cut





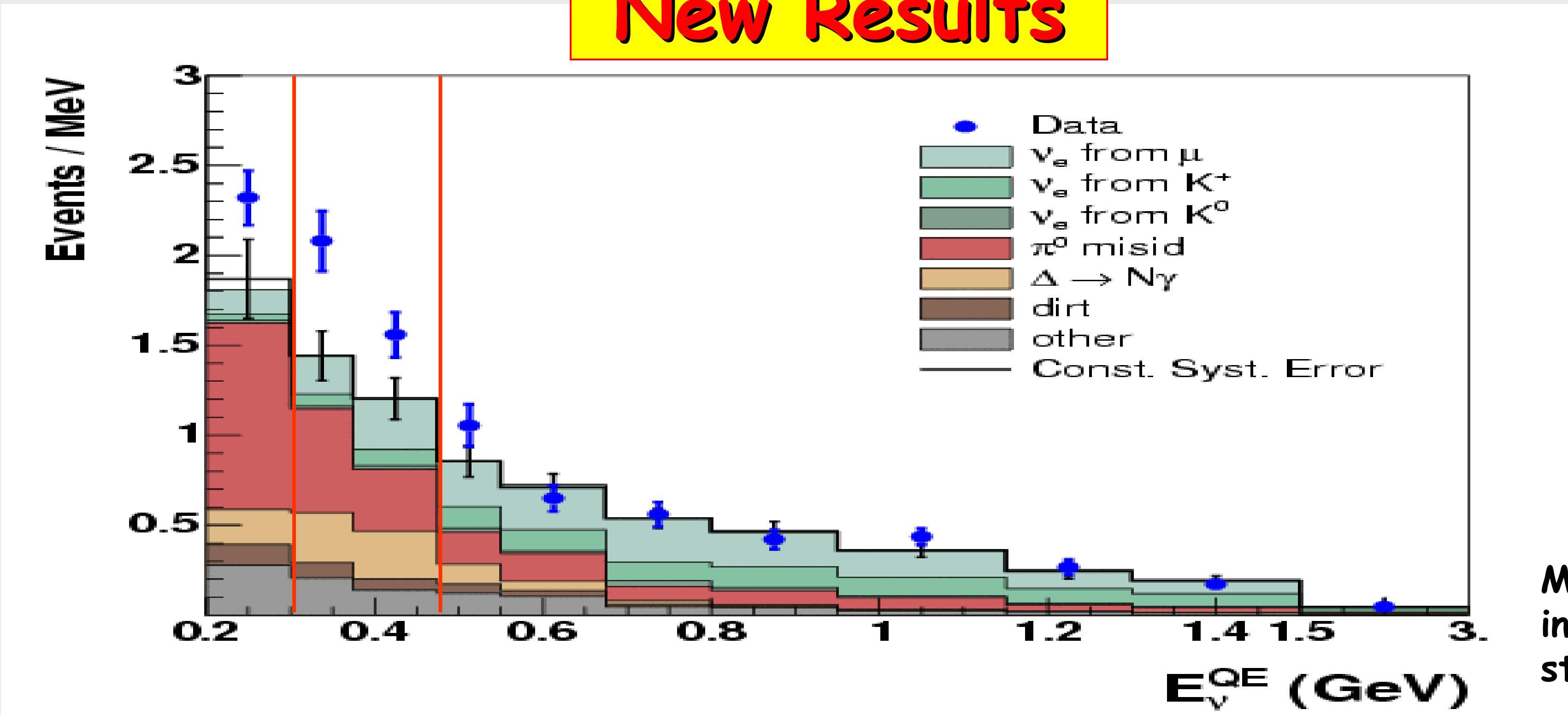
- The dirt cut:
  - significantly reduce dirt background by ~80%,
  - reduce pion background by ~40%
  - reduce electron/gamma-rays by ~20%.

Sources of Systematic Errors

Source of Uncertainty On ν_e background	Track Based error in % 200-475 MeV	Track Based error in % 475-1250 MeV	Checked or Constrained by MB data
Flux from π^+/μ^+ decay	1.8	2.2 **	√
Flux from K^+ decay	1.4	5.7	√
Flux from K^0 decay	0.5	1.5	√
Target and beam models	1.3	2.5	
ν-cross section	5.9	11.8	√
NC π^0 yield	1.4	1.8	√
External interactions ("Dirt")	0.8	0.4	√
Optical model	9.8	5.7	√
DAQ electronics model	5.0	1.7 **	
Hadronic	0.8	0.3 (new error)	
Total Unconstrained Error	13.0	15.1	

All Errors carefully rechecked; ** = significant decrease

New Results



MC systematics includes data statistics.

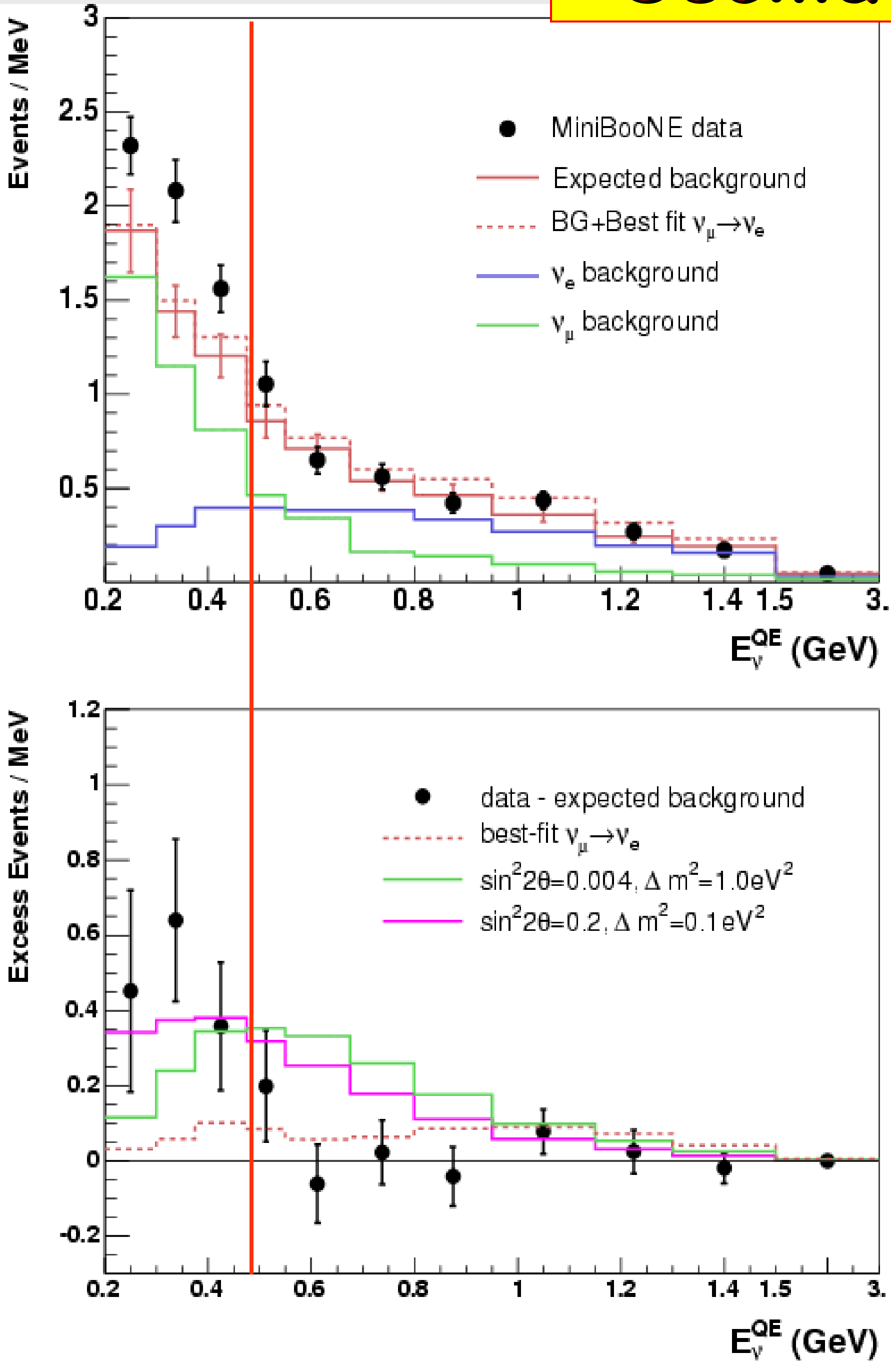
E_ν [MeV]	200-300	300-475	475-1250
total background	186.8±26	228.3±24.5	385.9±35.7
ν_e intrinsic	18.8	61.7	248.9
ν_μ induced	168	166.6	137
NC π^0	103.5	77.8	71.2
NC $\Delta \to N\gamma$	19.5	47.5	19.4
Dirt	11.5	12.3	11.5
other	33.5	29	34.9
Data	232	312	408
Data-MC	45.2±26	83.7±24.5	22.1±35.7
Significance	1.7σ	3.4σ	0.6σ

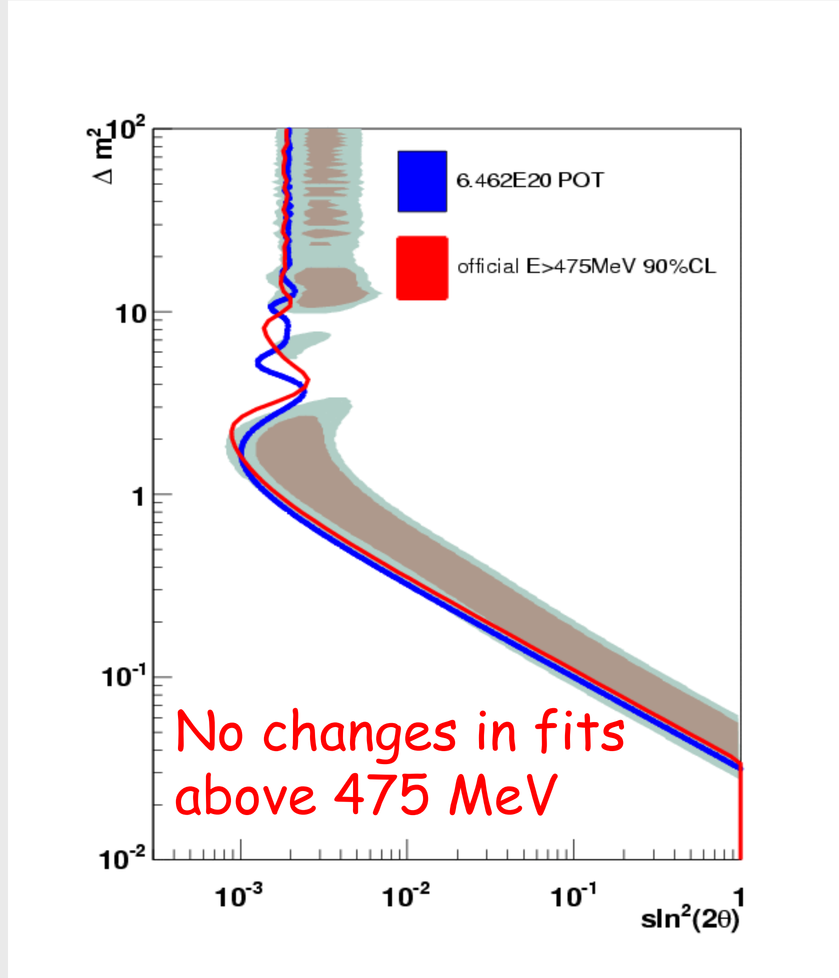
The excess at low energy remains significant!

This will be Published soon.

Oscillation Fit Check

475 MeV



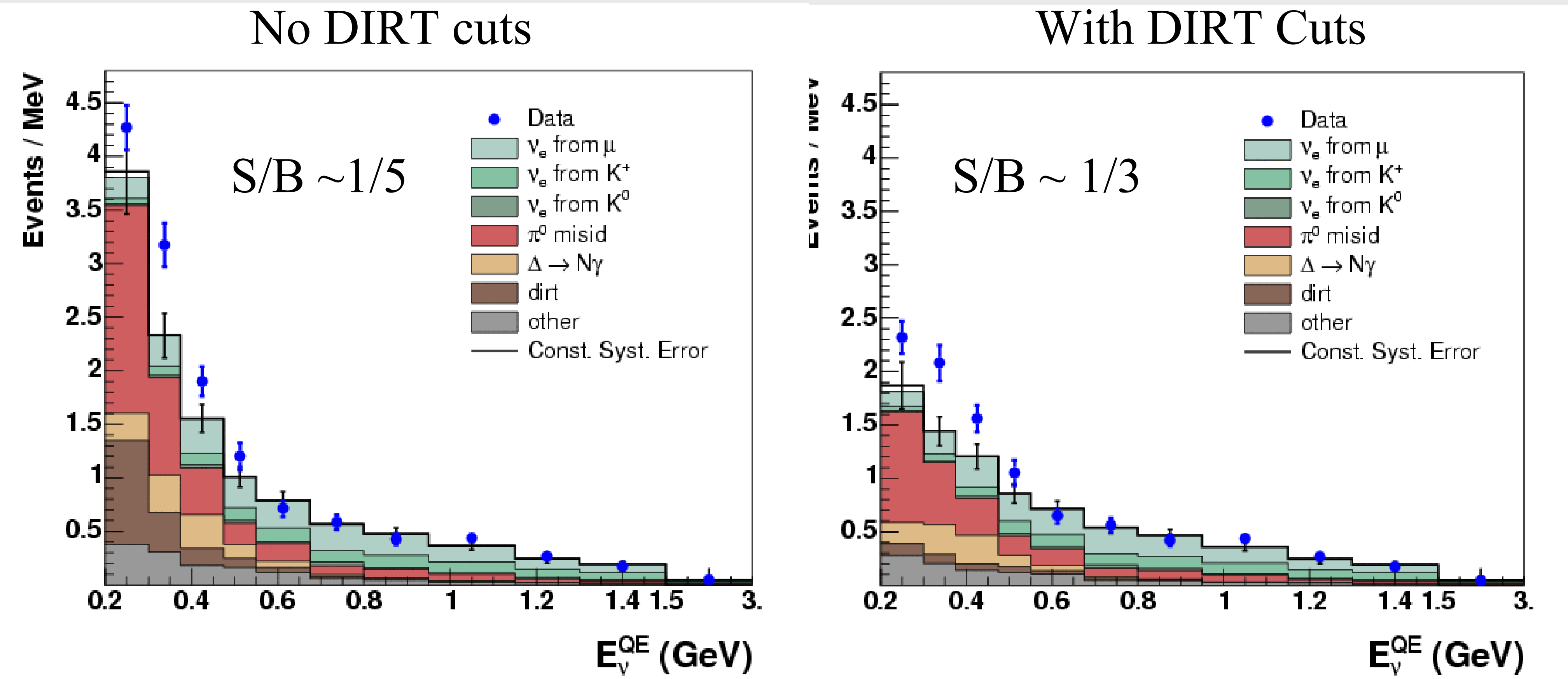


	E_ν>475 MeV	E_ν>200 MeV
Null fit χ^2 (prob.):	9.1(91%)	22(28%)
Best fit χ^2 (prob.):	7.2(93%)	18.3(37%)

Inclusion of low energy excess does not improve oscillation fits

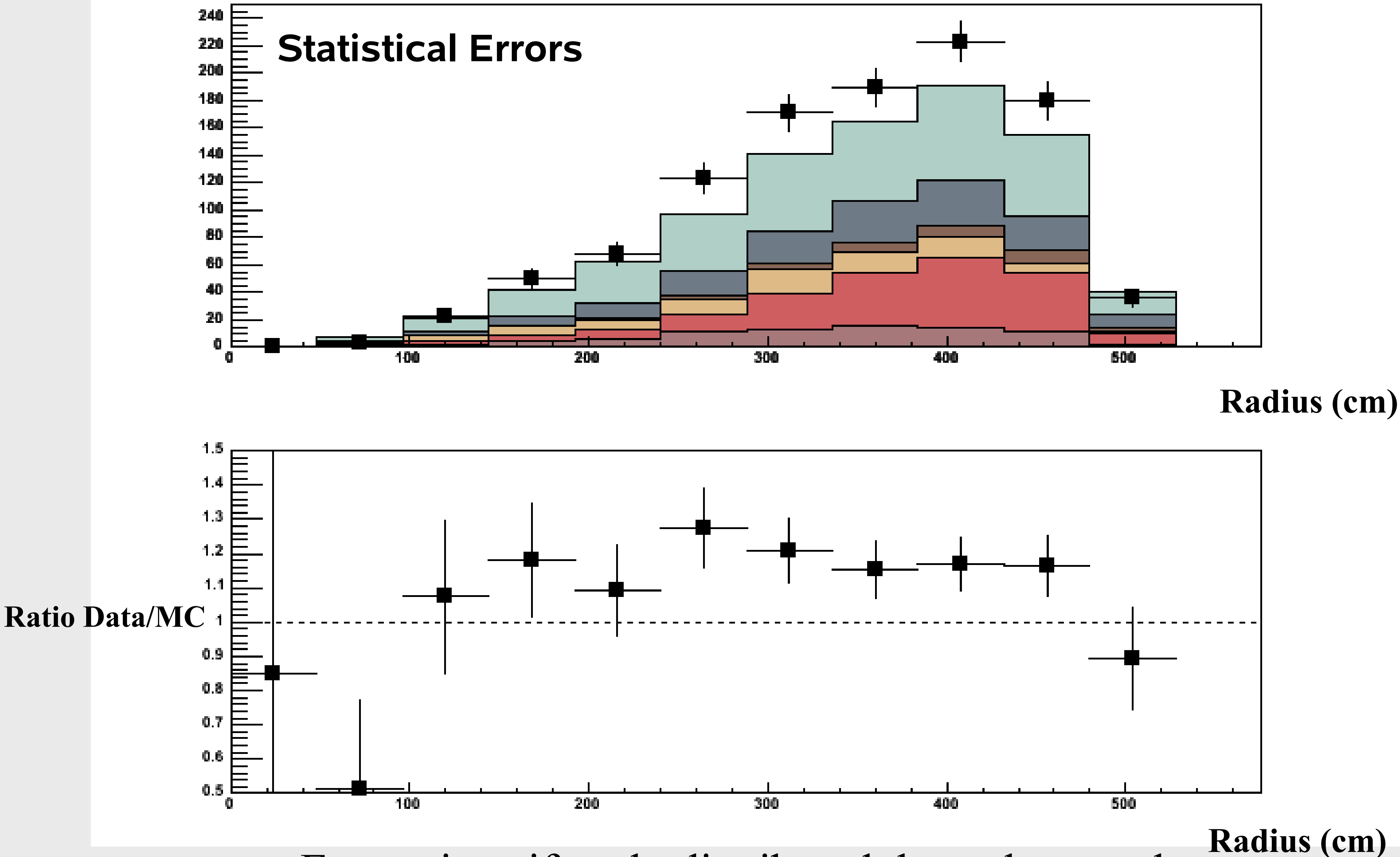
Properties of the Excess
Is it Signal like?

Dirt Cuts Improves Signal/Background



Excess decreases by ~7%, consistent with electron/gamma-ray signal

Reconstructed Radius

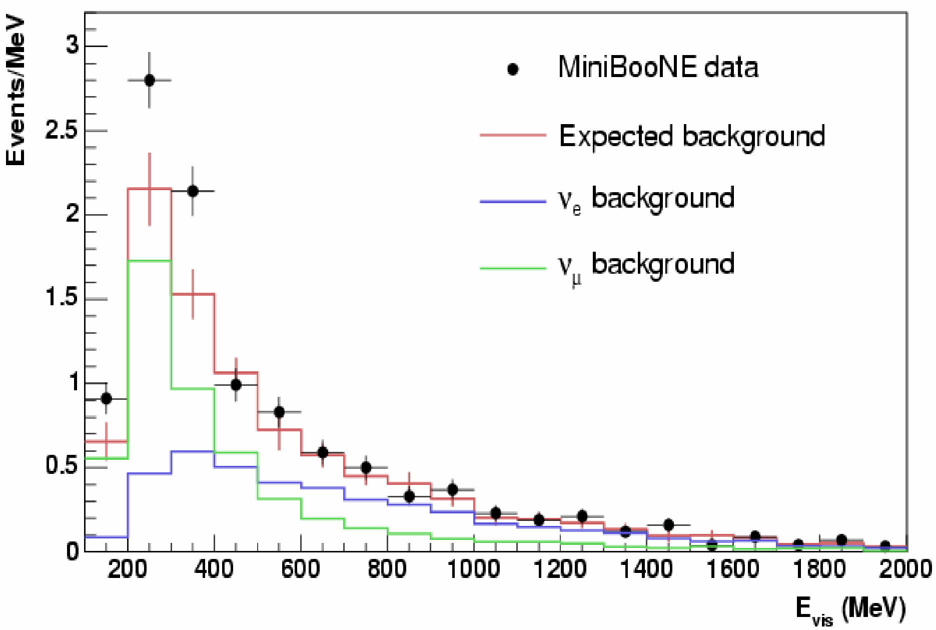


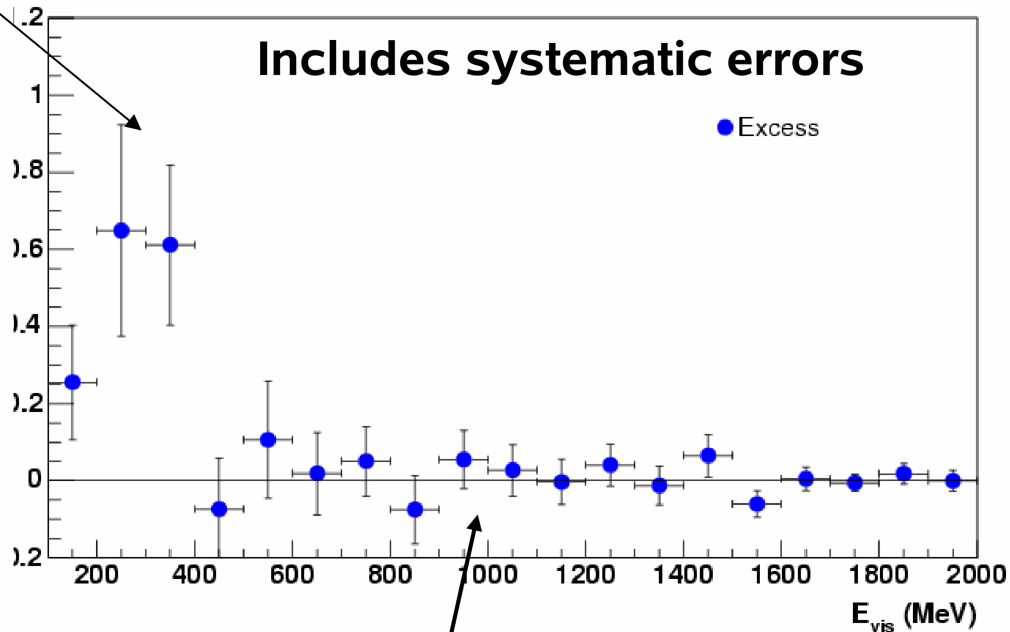
Excess is uniformly distributed throughout tank.

-consistent with neutrino induced interactions

Reconstructed Visible Energy (E_{vis})

Pronounced excess/peak
From 140 - 400 MeV





Excellent agreement
for Evis > 400 MeV

Excess does not track ν_μ backgrounds or ν_e intrinsics!

Low Energy Excess Remains Significant!

- It is consistent with low energy production of neutrino induced electrons or gamma-rays.
- Actively performing fits to event kinematics (visible energy, beam angle, Q**2) to help identify source, e.g. gamma-ray or pion background, mis-identified muons, ν_e, $\bar{\nu}_e$, etc.

What is the Source of the Excess?

- Theoretical ideas
- Other data sources

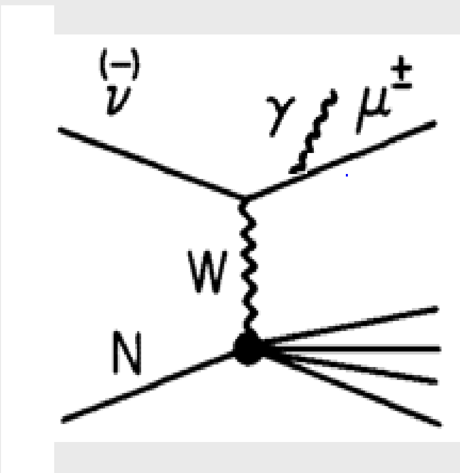
Is MiniBooNE Low Energy Excess consistent with LSND??

- LSND assumed excess was two neutrino oscillations,
  - Prob($\bar{\mathbf{v}}_\mu \rightarrow \bar{\mathbf{v}}_e$) = $\sin^2(2\theta)\ \sin^2(1.27\ \ \Delta m^2\ \ L/E)$
- Both LSND and MiniBooNE are at the same L/E and look for an excess of (anti)electron neutrinos in a (anti)muon neutrino beam
  - Yes, consistent! ~~Though~~ looking at different charge species.
- LSND measures Prob($\mathbf{v}_\mu \rightarrow \mathbf{v}_e$)= (0.25 +/- 0.08) %, MiniBooNE measures Prob($\mathbf{v}_\mu \rightarrow \mathbf{v}_e$)= (0.30 +/- 0.10)% at low E.
  - Yes, consistent!
- MiniBooNE fails two neutrino oscillation fits to reconstructed neutrino energy.
  - No, not consistent!! Requires more complicated oscillations, e.g. 3+2

The low E excess has fueled much speculation...

Commonplace

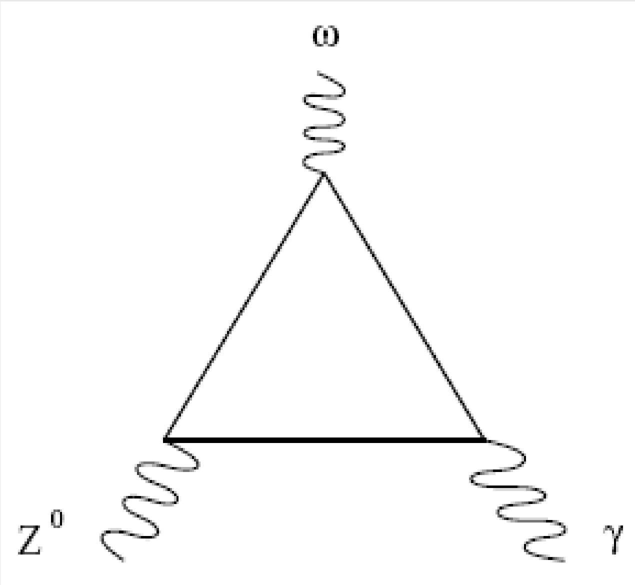
- Muon bremstrahlung
  (Bodek, 0709.4004)



- Easy to study in MB with much larger stats from events with a Michel tag
- Proved negligible in 0710.3897

SM, but odd

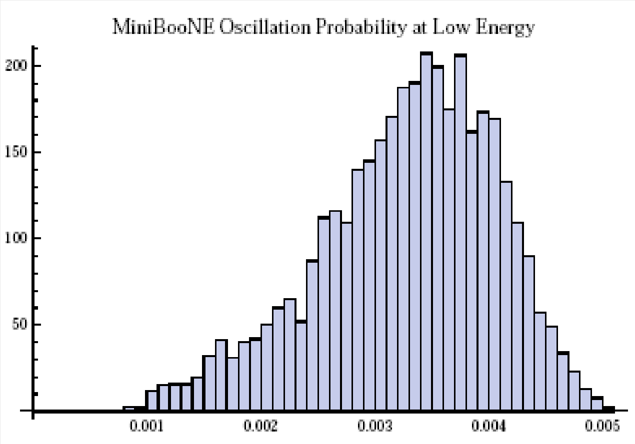
- Anomaly-mediated γ
  (Harvey, Hill, Hill, 0708.1281)



- Still under study, large rate uncertainties
- NC process; anti-neutrino data will determine if it is source of the excess

Beyond the SM

- New gauge boson
  (Nelson, Walsh,0711.1363)

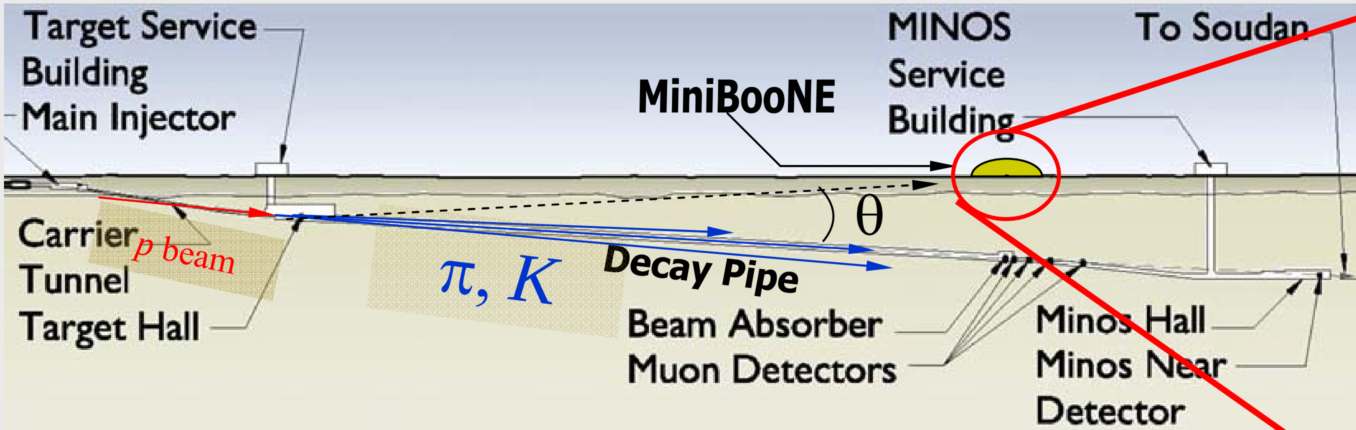


- Firm prediction for anti-neutrinos
- Many other beyond the Standard Model ideas.

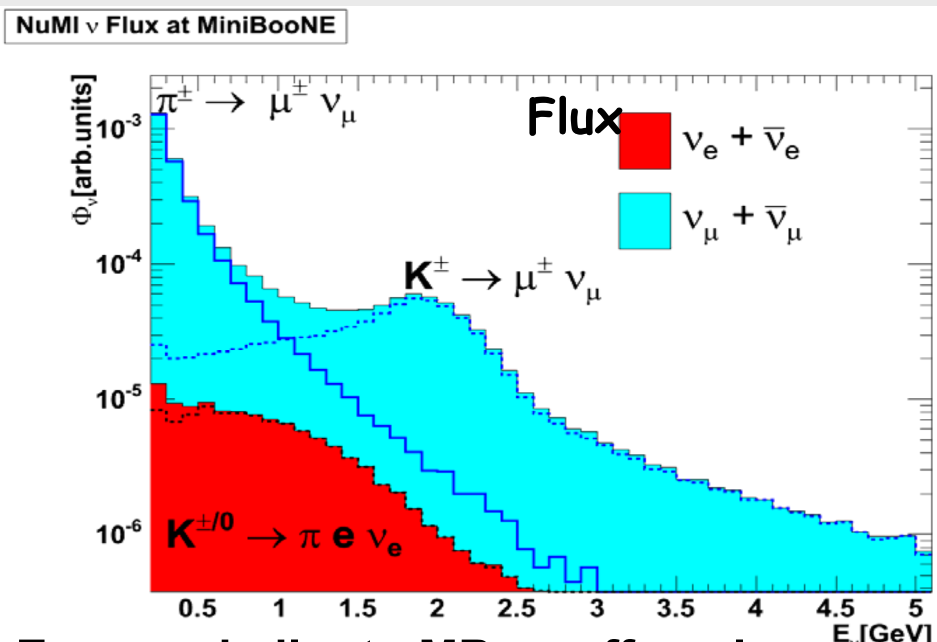
Other Data Sources

- Limitations of MiniBooNE:
  - We do not have two detectors or complete set of source and background calibration sources.
- We do have different detectors and sources of neutrinos that provide more information on background estimates, signal cross sections, PID, etc
  - SciBooNE detector at 100m -- measure neutrino flux and cross sections.
  - Off axis neutrinos (NuMI) -- ν_e rich source.
  - Anti-neutrino running -- similar backgrounds to neutrino mode

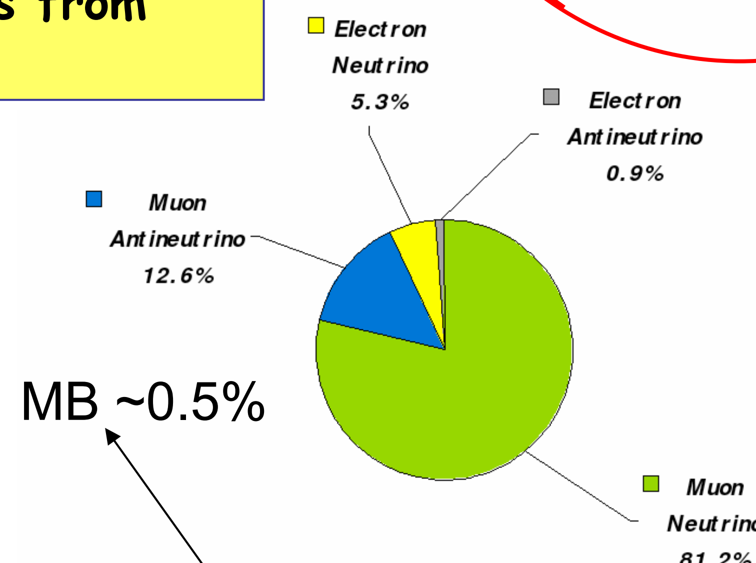
Events from NuMI detected at MiniBooNE



MiniBooNE detector is 745 meters downstream of NuMI target.
MiniBooNE detector is 110 mrad off-axis from the target along NuMI decay pipe.



Energy similar to MB as off angle



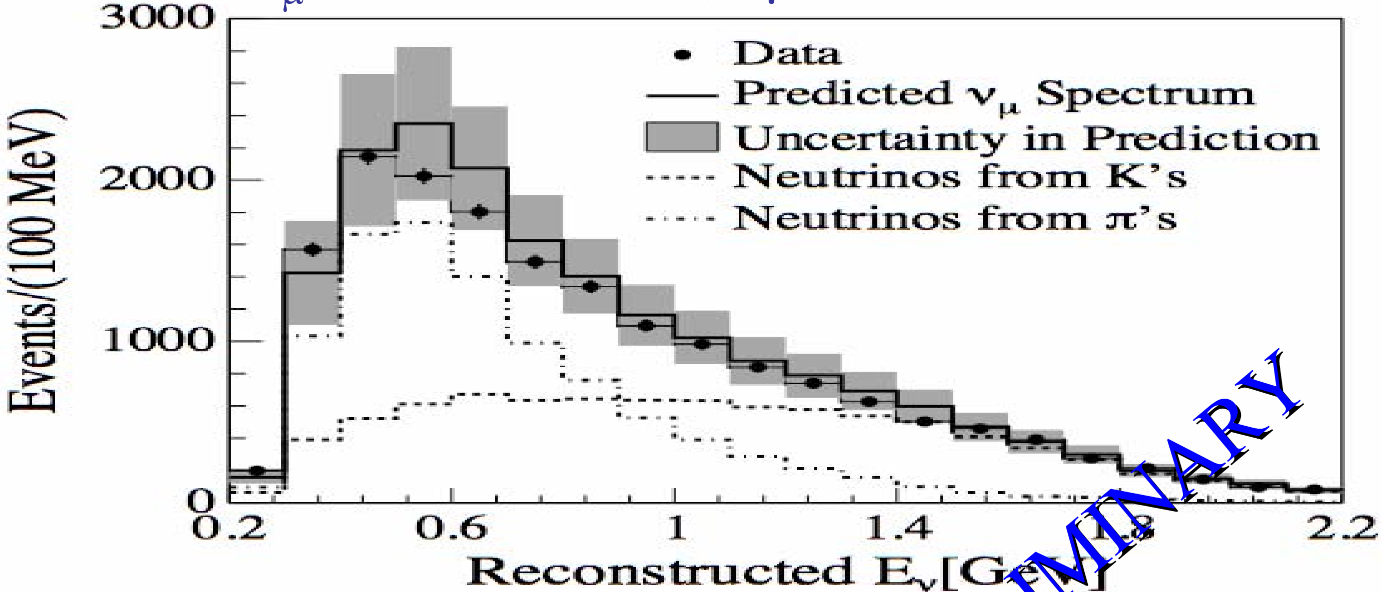
Event rates

NuMI event composition at MB
ν_μ-81%, ν_e-5%, $\bar{\nu}_\mu$-13%, $\bar{\nu}_e$-1%

Los Alamos

ν_μ CCQE and ν_e CCQE samples from NuMI

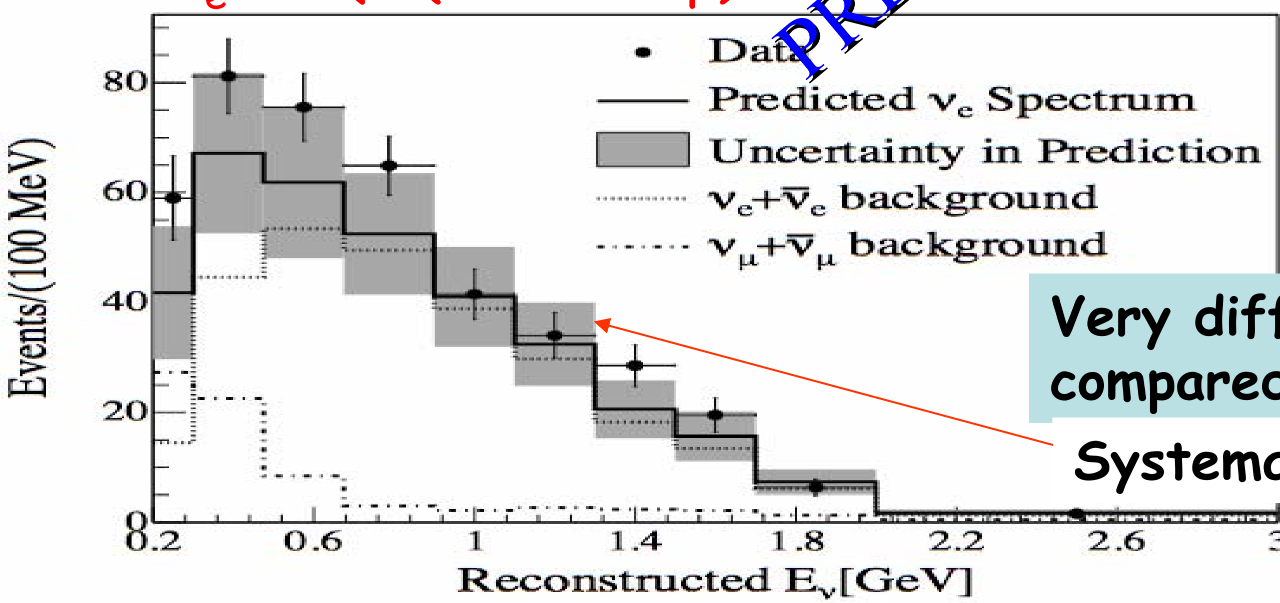
ν_μ CCQE (ν+n $\rightarrow$ μ+p)



Because of the good data/MC agreement in ν_μ flux and because the ν_μ and ν_e share same parents the beam MC can now be used to predict:

ν_e rate and mis-id backgrounds for a ν_e analysis.

ν_e CCQE (ν+n $\rightarrow$ e+p)



Very different backgrounds compared to MB (Kaons vs Pions)!

Systematics not yet constrained!

NuMI ν_e data provide limits on cross sections and PID

MiniBooNE Anti-neutrino Run

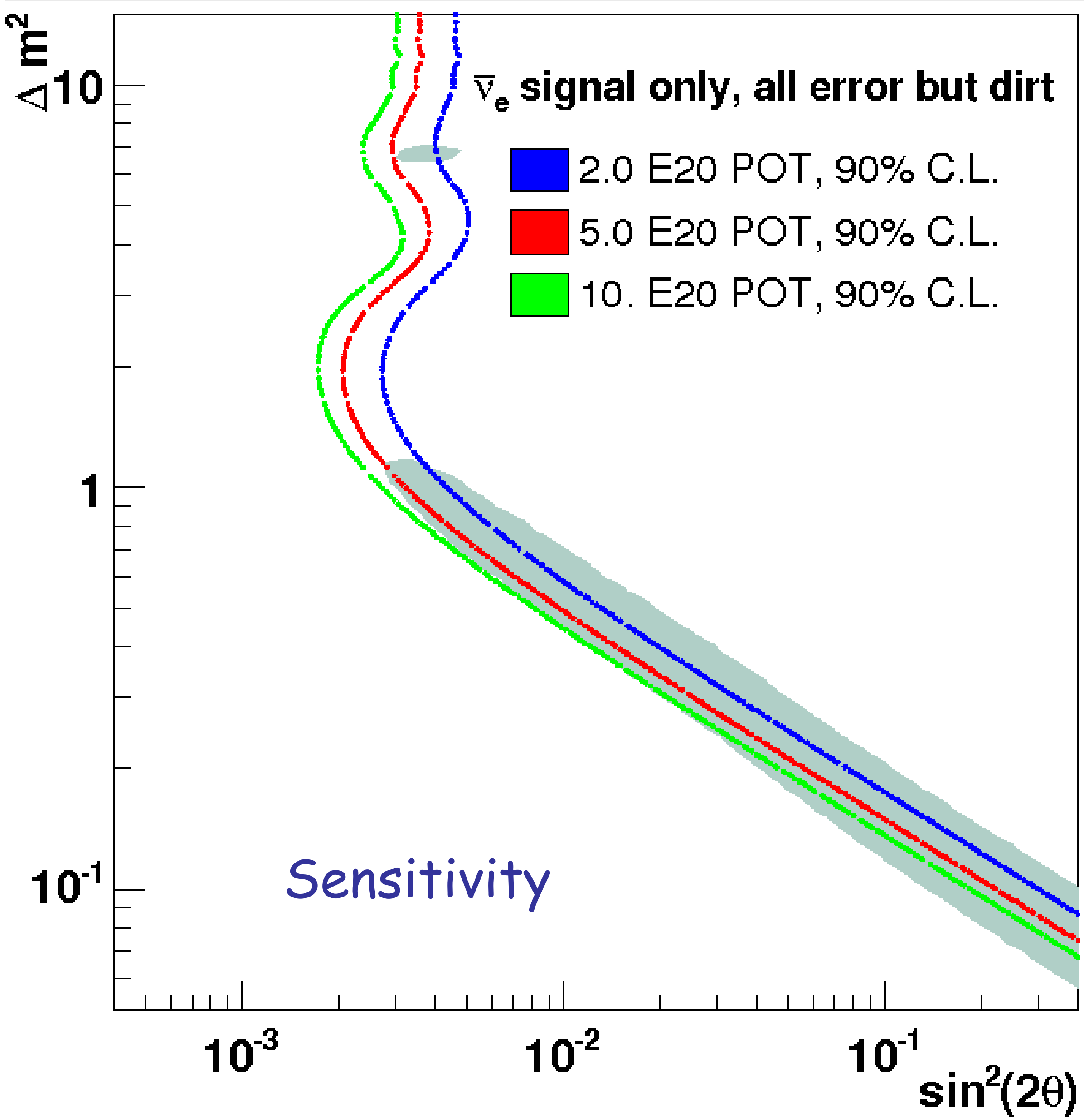
MiniBooNE is currently taking data in anti-neutrino mode.

In November 07 Physics Advisory Committee (Fermilab) recommended MiniBooNE run to get to a total of 5×10^{20} POT in anti neutrino mode.

Provides direct check of LSND result.

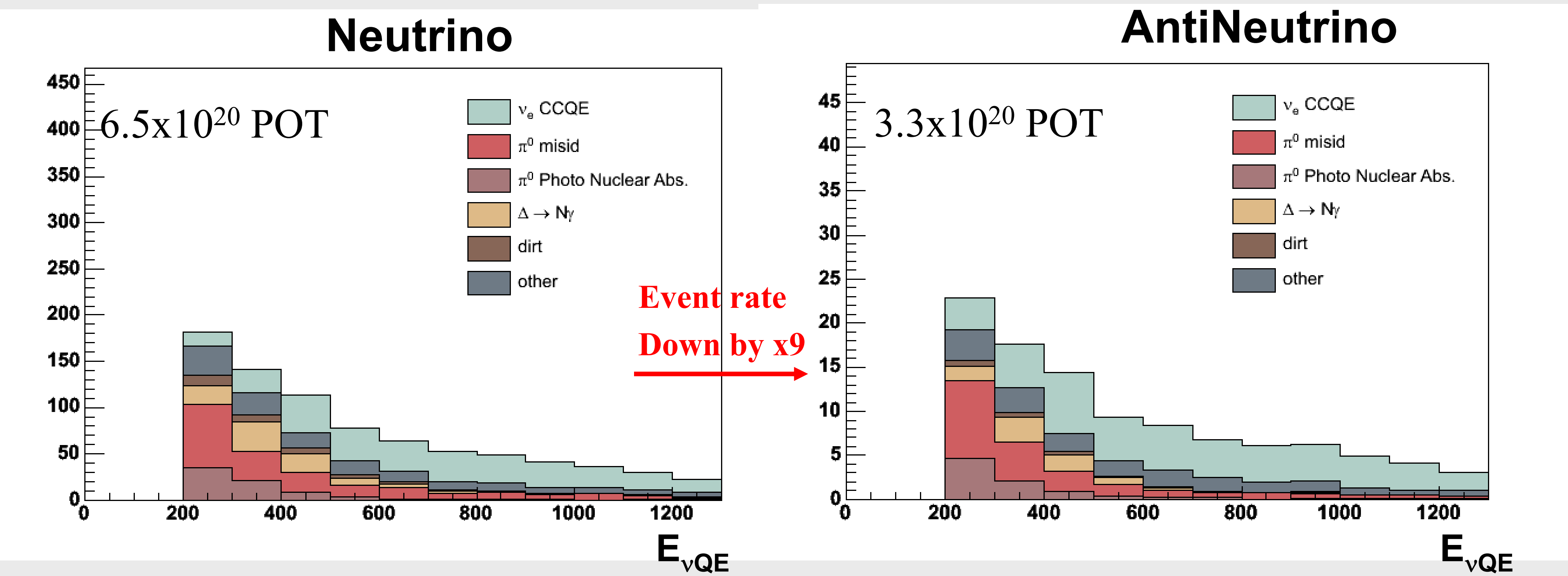
Provides additional data set for low energy excess study.

Collected ~3.3×10^{20} POT so far.
Oscillation data set "blinded".
Box planned to be opened soon!



Comparing Neutrino/Antineutrino Low Energy ν_e Candidates

Background breakdown is very similar between neutrino and antineutrino mode running



- Various background/signal hypotheses for the excess can have measurably different effects in the two modes:
  - Backgrounds at low energy, expect an excess of 15 to 25 events
  - Two neutrino oscillations produce ~20 events at higher energy
- Can compare the two modes to test some of the hypotheses

NNSA Los Alamos

Conclusions

- Despite recent progress, many basic properties of neutrinos are still unknown and the possibility of future surprises remains strong!
- MiniBooNE rules out a simple two neutrino $\nu_\mu \rightarrow \nu_e$ appearance-only model as an explanation of the LSND excess at 98% CL. (Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500v2 [hep-ex])
  - This is still true!
- However, a 128.8+/-43.4 event (3.0σ) excess of electron or gamma-ray events are observed in the lower energy range from $200 < E_\nu < 475$MeV.
  - This could be important to next generation long baseline neutrino experiments (T2K, Nova).
- This unexplained deviation is under intense investigation.
  - Event kinematics, Antineutrino data, and NuMI data will provide more information, stay tuned!
- New Experiments might be required to fully understand the low energy excess.

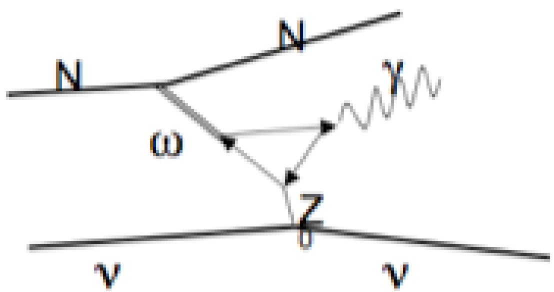
BACKUP SLIDES

Excess Significance For Different Analysis

	Original analysis 5.58E20 POT	**Revised analysis 5.58E20 POT**	**Revised Analysis 6.46E20 POT**	**Revised Analysis 6.46E20 POT With DIRT cuts**
Event Sample	Analysis 1	Analysis 2	Analysis 3	Analysis 4
200 – 300 MeV				
Data	375	368	427	232
Background	283 ± 37	332.4 ± 38.9	386.0 ± 44.3	186.8 ± 26.0
Excess	92 ± 37	35.6 ± 38.9	41.0 ± 44.3	45.2 ± 26.0
Significance	2.5σ	0.9σ	0.9σ	1.7σ
300 – 475 MeV				
Data	369	364	428	312
Background	273 ± 26	282.9 ± 28.3	330.0 ± 31.8	228.3 ± 24.5
Excess	96 ± 26	81.1 ± 28.3	98.0 ± 31.8	83.7 ± 24.5
Significance	3.7σ	2.9σ	3.1σ	3.4σ
200 – 475 MeV				
Data	744	732	855	544
Background	556 ± 54	615.3 ± 58.0	716.1 ± 66.2	415.2 ± 43.4
Excess	188 ± 54	116.7 ± 58.0	138.9 ± 66.2	128.8 ± 43.4
Significance	3.5σ	2.0σ	2.1σ	3.0σ
475 – 1250 MeV				
Data	380	369	431	408
Background	358 ± 40	356.0 ± 33.3	412.7 ± 37.6	385.9 ± 35.7
Excess	22 ± 40	13.0 ± 33.3	18.3 ± 37.6	22.1 ± 35.7
Significance	0.6σ	0.4σ	0.5σ	0.6σ

Axial Anomaly- an explanation within the standard model

- Recent paper by Harvey &Hill[2], hep-ph 0708.1281 ,0712.1230 has put forth an explanation of the MiniBooNE low energy electron excess by employing the axial anomaly.
- The anomaly is employed to create a (ν_μ,γ) process that mimics (ν_e,e)



- The low energy limit cross section with no proton recoil is

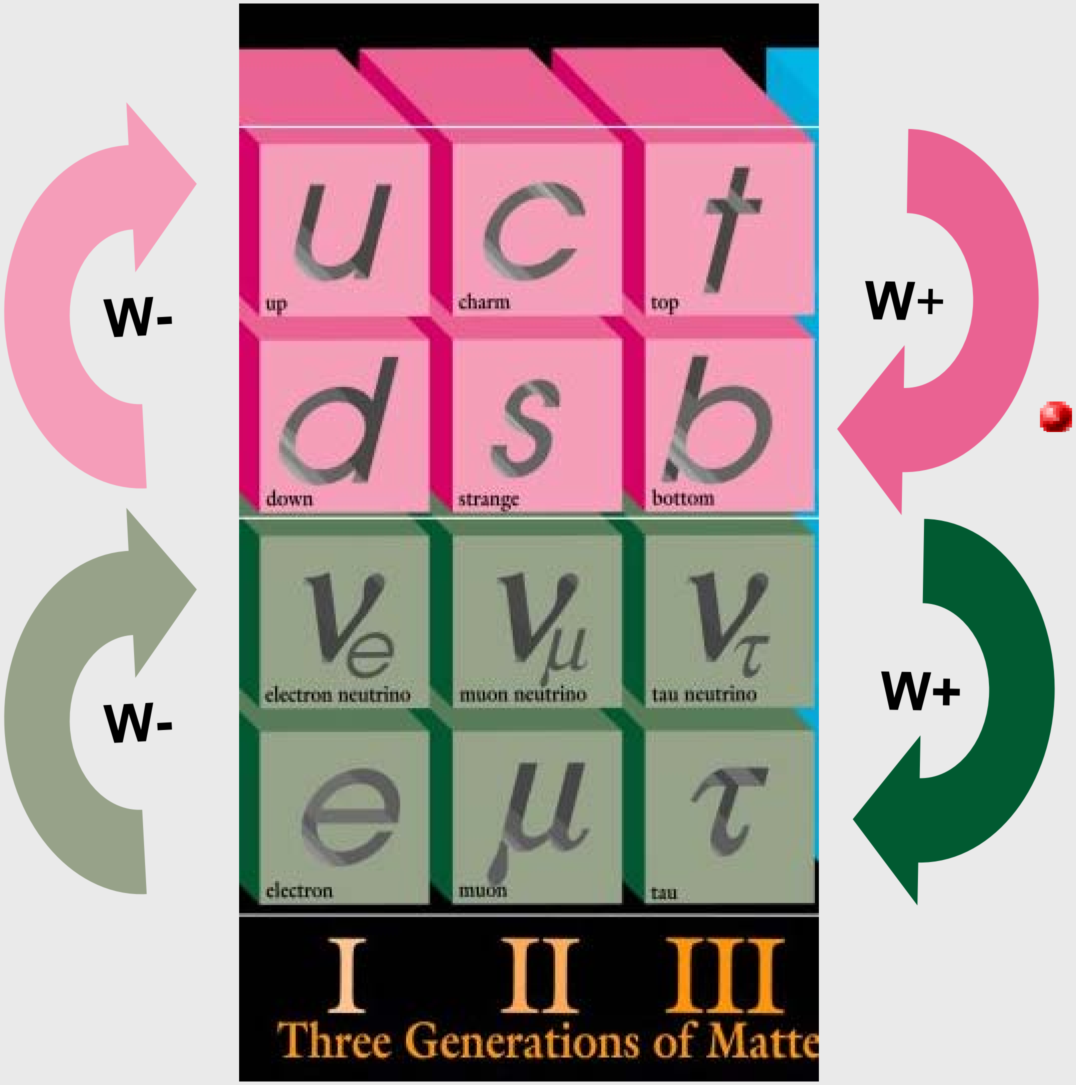
$$\sigma = \frac{\alpha g_\omega^4 G_F^2}{480\pi^6 m_\omega^4} E_\nu^6 = 2.2(10)^{-41}\left(\frac{E_\nu}{GeV}\right)^6\left(\frac{g_\omega}{10}\right)^4$$

g_ω can vary from 10 - 30.

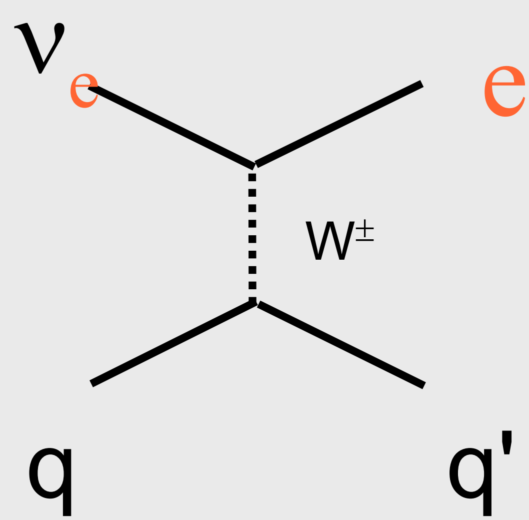
$\sim 140(g_\omega/10)^4$ events

Use photon energy and angle to examine this

The weak force...force of transmutation



- Makes the weak interaction truly a force of transmutation
  - The CC channel converts neutrinos into their charged alter egos
  - Converts -1/3 charge quarks into +2/3 counterparts
- Incidentally, CC also proves that we have three distinct neutrino flavors



Charged Current

Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\Sigma_i\Sigma_j\, |U_{\alpha i}\, U^*_{\beta i}\, U^*_{\alpha j}\, U_{\beta j}|\, \sin^2(1.27\Delta m_{ij}{}^2 L/E_\nu)$$

As N increases, the formalism gets rapidly more complicated!

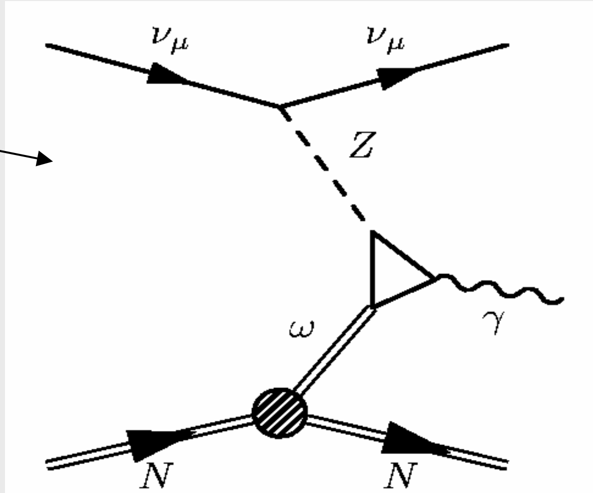
N	$\#\Delta m_{ij}{}^2$	$\#\theta_{ij}$	#CP Phases
2	1	1	0
3	2	3	1
6	5	15	10

Checks and Changes in the low Energy Region

- Instrumental background? NO
- Track and Boosting analyses consistent? YES
- Is excess electron/gamma ray like? YES
- Dirt or Delta(1232) radiative decays? NO
- Pion or muon mis-id (including brem.)? NO
- Photonuclear process. Excess down ~30%
- More comprehensive hadronic errors and better handling of pi+/- interactions. Excess down slightly
- Modification of pi0 background calculation. Excess down slightly
- Improved measurement of pi0 backgrounds. Excess up slightly
- Better handling of beam pi+ production uncertainties. Smaller error
- **None of these are expected to have any appreciable effect above 475 MeV**

The MiniBoonE Low energy Excess remains, the question now is whether the Low-Energy Excess is due to a Signal?

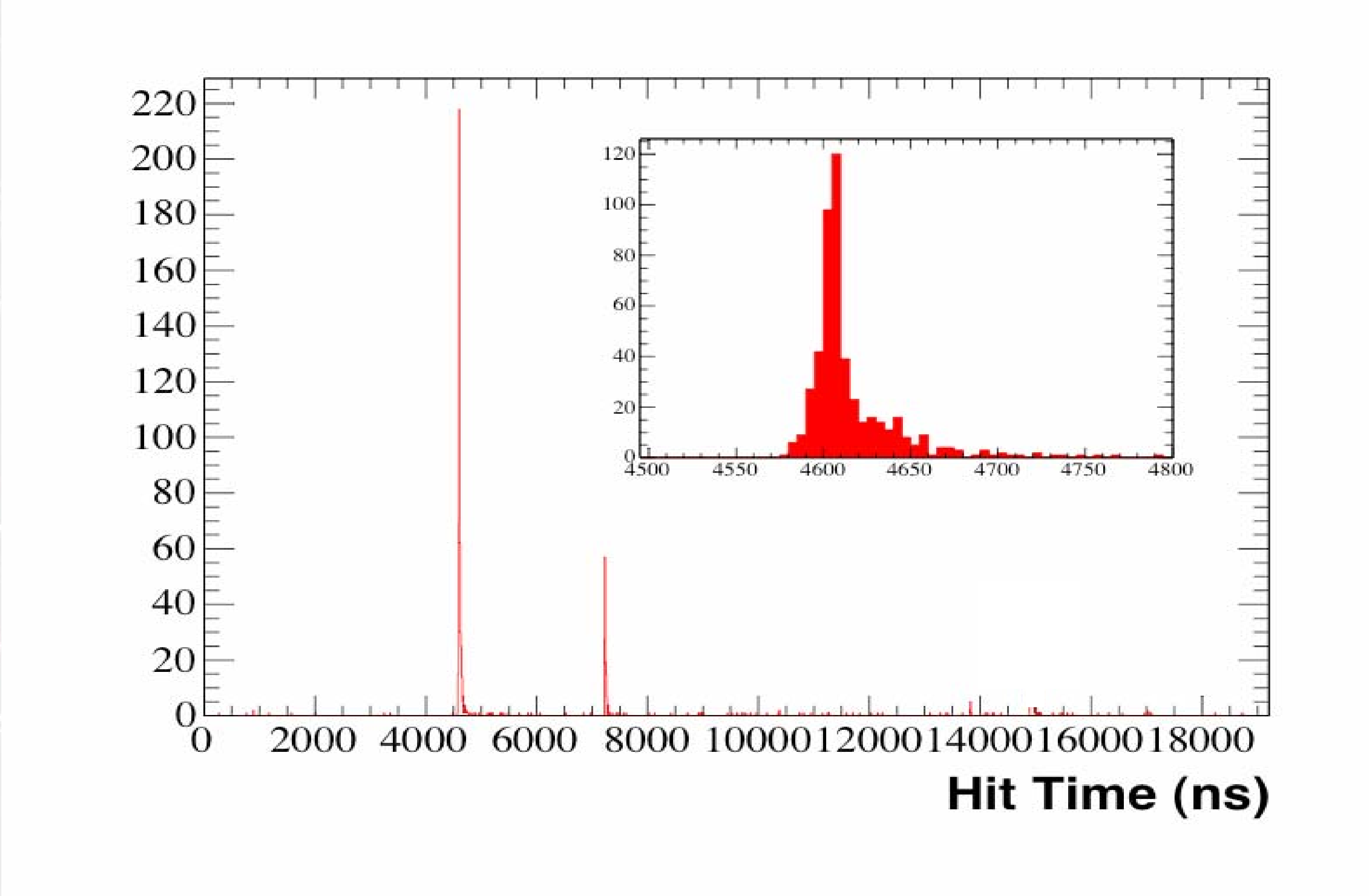
- Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density (arXiv:0708.1281: Jeffrey A. Harvey, Christopher T. Hill, Richard J. Hill)
- New Scalar Boson: Nelson & Walsh, arXiv:0711-1363
- CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107
- Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017
- Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009
- CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303



Event structure: "subevents"

Multiple hits within a ~100 ns window form "subevents"

Most events are from ν_μ CC interactions,
with characteristic two "subevent" structure from stopped $\mu \rightarrow \nu_\mu \nu_e e$



Updates to Low Energy ν_e Prediction

Nearing the end of a comprehensive review of the ν_e appearance backgrounds and their uncertainties
→ Not Quite Ready for Release Yet

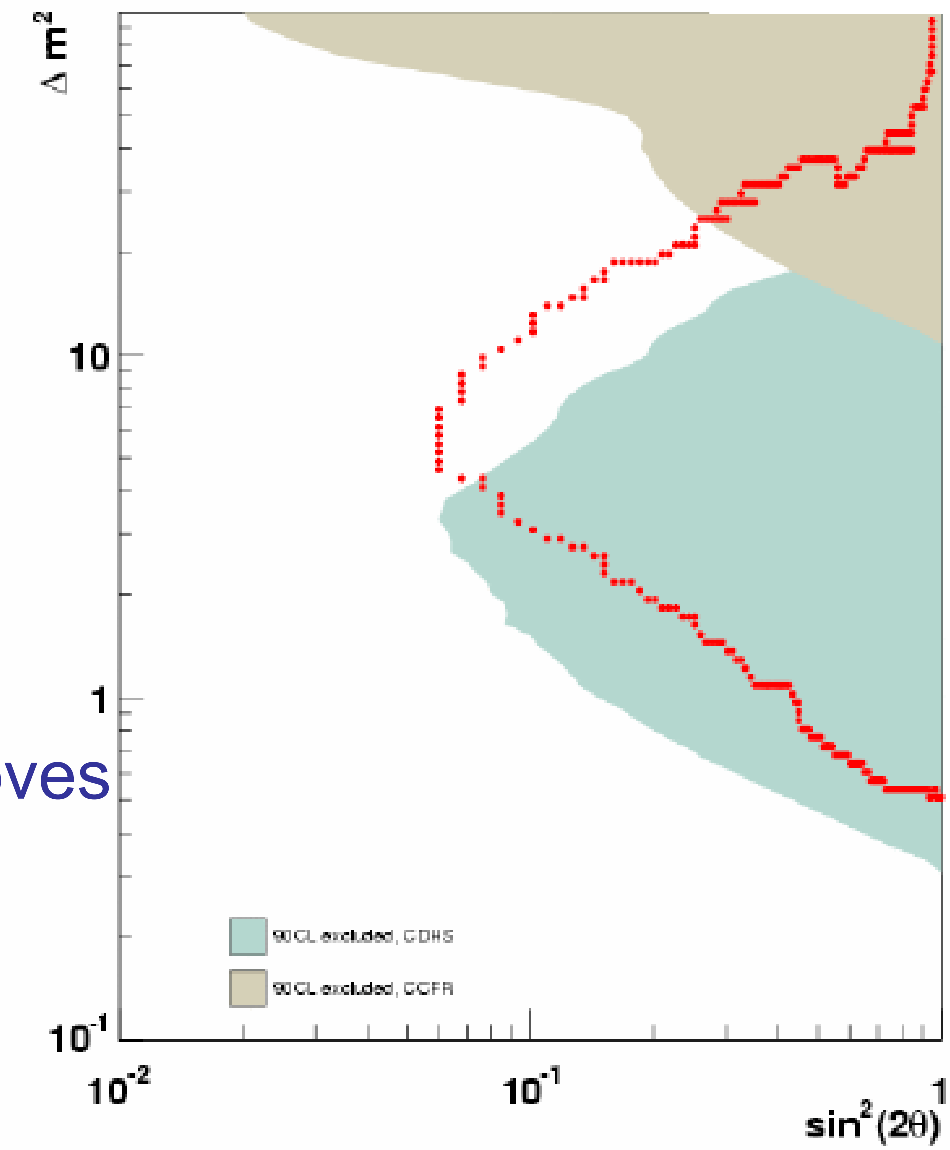
Arrows indicate whether effect is to increase or decrease the low energy data excess
The effects have different magnitudes despite the arrows all being the same size

- ↓ Included photonuclear effect
  - Absent from GEANT3 – creates background from π^0s
- ← More comprehensive hadronic errors
  - e.g. uncertainties in final state following photonuclear interaction
- ↓ Better handling of beam π^+ production uncertainties
  - Errors propagated in model-independent way
- ↑ Improved measurement of ν induced π^0s
  - e.g. finer momentum binning
- ↑ Incorporation of MiniBooNE π^0 coherent/resonant measurement
  - No longer need to rely on more uncertain past results
- ↓ Better handling of the radiative decay of the Δ resonance
  - Comprehensive review of how the $\Delta^{0,+}$ radiative decay rate is inferred from the measured π^0 rate

Complete MiniBooNE ν_μ Disappearance Sensitivity

- MiniBooNE only 90% CL sensitivity

- CDHS CCFR 90% CL



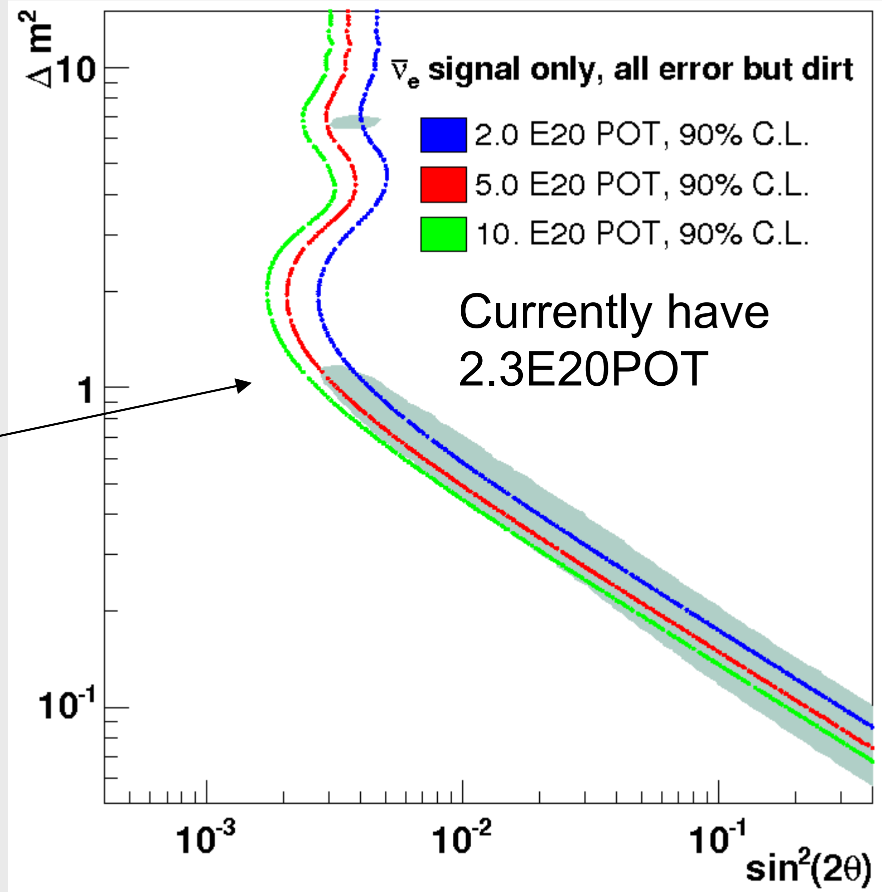
Inclusion of SciBooNE as a near detector, dramatically improves the sensitivity by reducing flux and cross section uncertainties

Many oscillations models predict large muon disappearance.

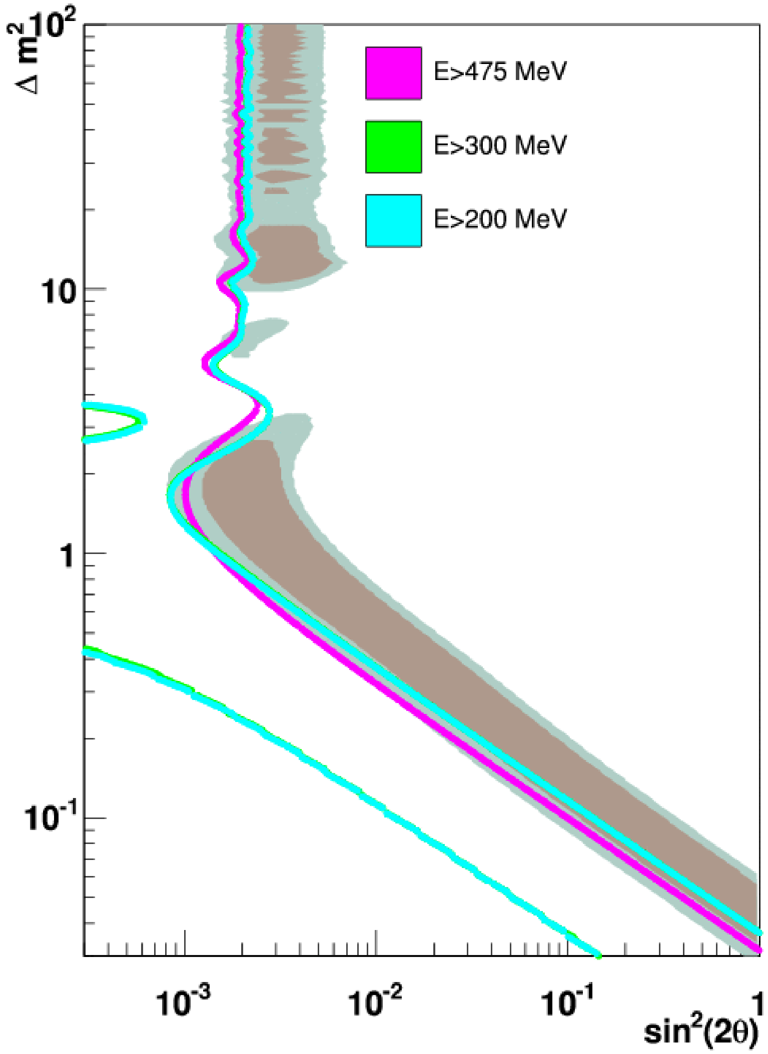
Future Work

- **Continue to investigate low energy excess**
  - **Consider other backgrounds and/or signals**
- **Analyze antineutrino data, NuMI ν in MiniBooNE data, & SciBooNE data.**
- **Approved to run one more year to collect enough antineutrino data to test LSND with antineutrinos.**
- **If low-energy excess is consistent with a signal, new experiments at FNAL (BooNE) and/or SNS (OscSNS) will be proposed to continue exploring interesting physics at this L/E region.**

Anti-nue Appearance Sensitivity



numu->nue Oscillation Fits



Energy	χ2_null(prob)	χ2_bf(prob)	(dm2, sin2theta)
>200	22.0(28%)	18.3(37%)	(3.1, 0.0017)
>300	21.8(24%)	18.3(31%)	(3.1, 0.0017)
>475	9.1(91%)	7.2(93%)	(3.5, 0.0012)

-Low energy best fits only marginally better than null!

-Above 475, fit consistent with original results, i.e. inconsistent with two neutrino oscillations.

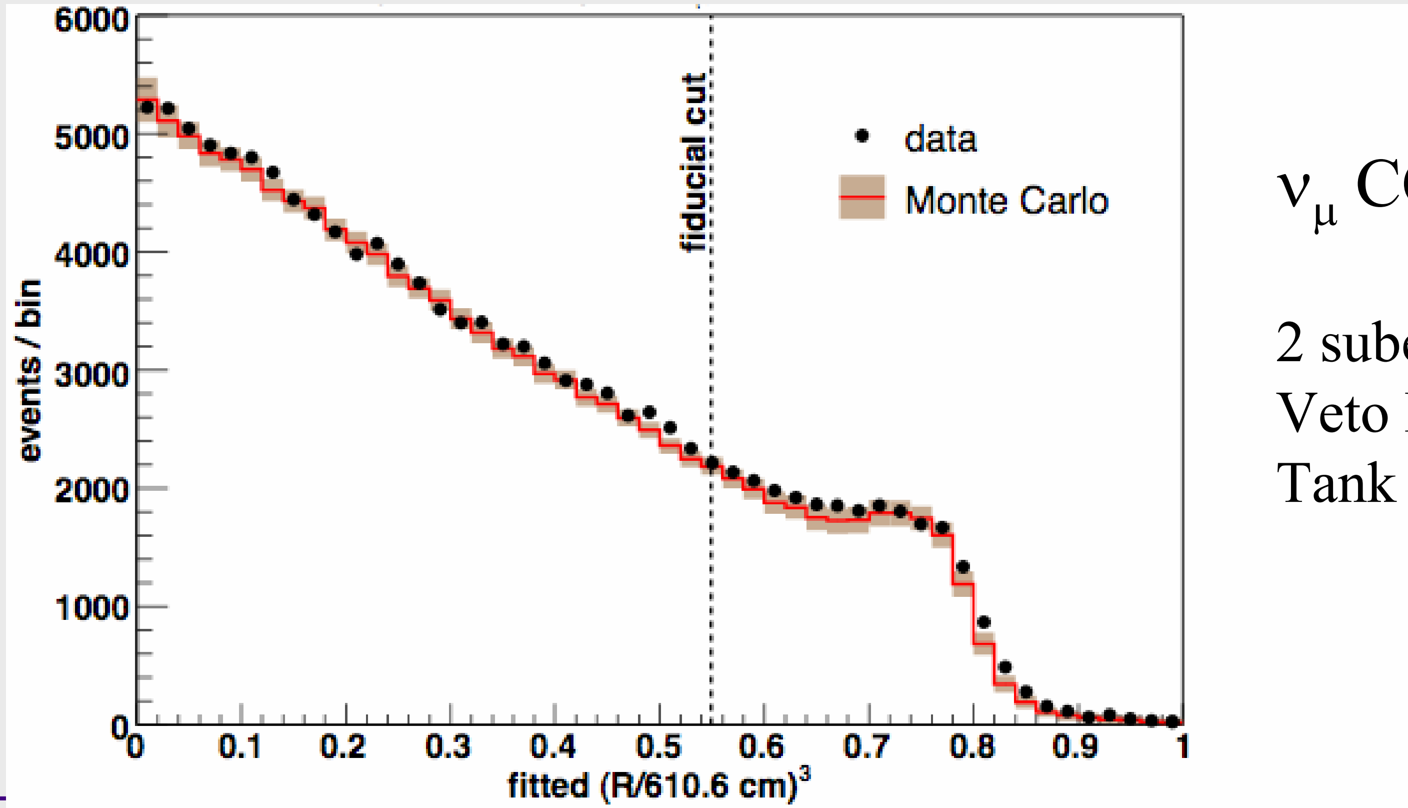
Each event is characterized by 7 reconstructed variables:

vertex *(x,y,z)*, time, energy, and direction $(\theta,\phi) \Leftrightarrow (U_x, U_y, U_z)$.

Resolutions: vertex: 22 cm

direction: 2.8°

energy: 11%



ν_μ CCQE events

2 subevents

Veto Hits<6

Tank Hits>200

Event “pre-cuts”:

Only 1 subevent

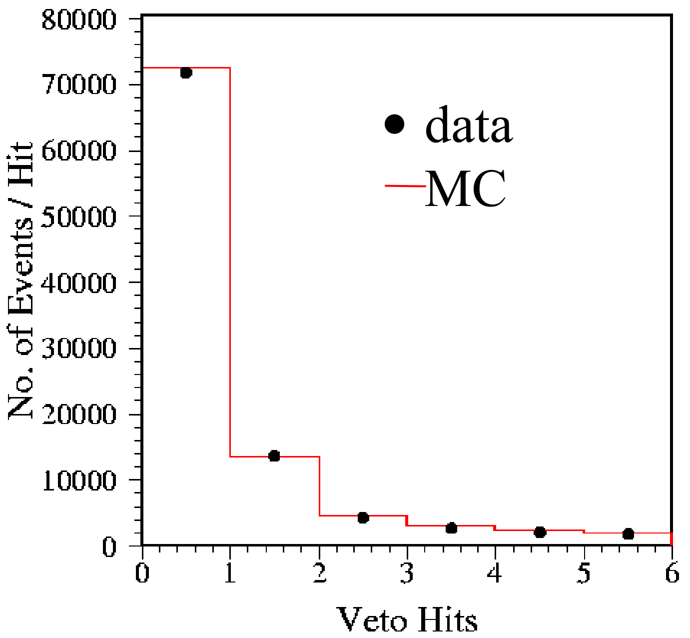
Veto hits < 6

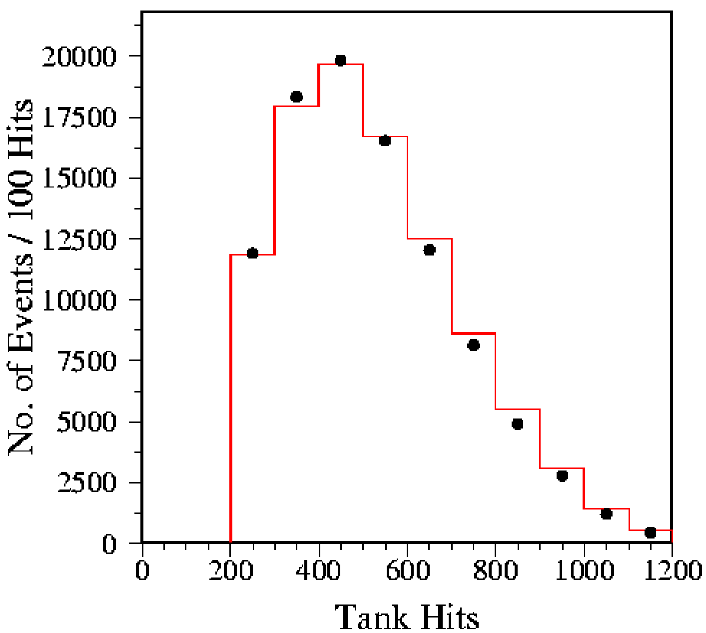
Tank hits > 200

And a radius precut:

R<500 cm

(where reconstructed R is algorithm-dependent)





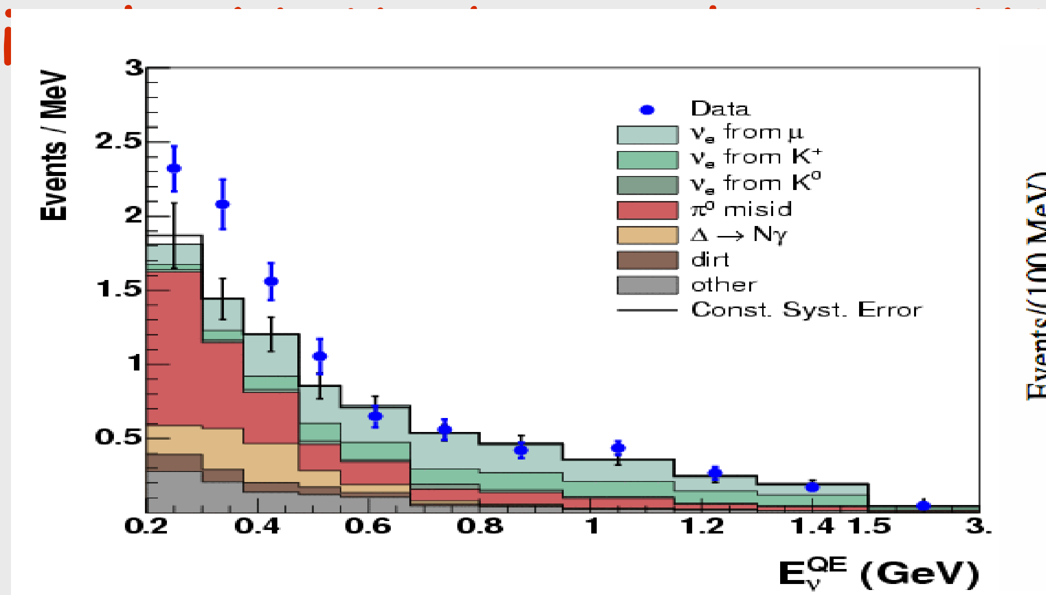
NuMI vs Booster Beam at MiniBooNE

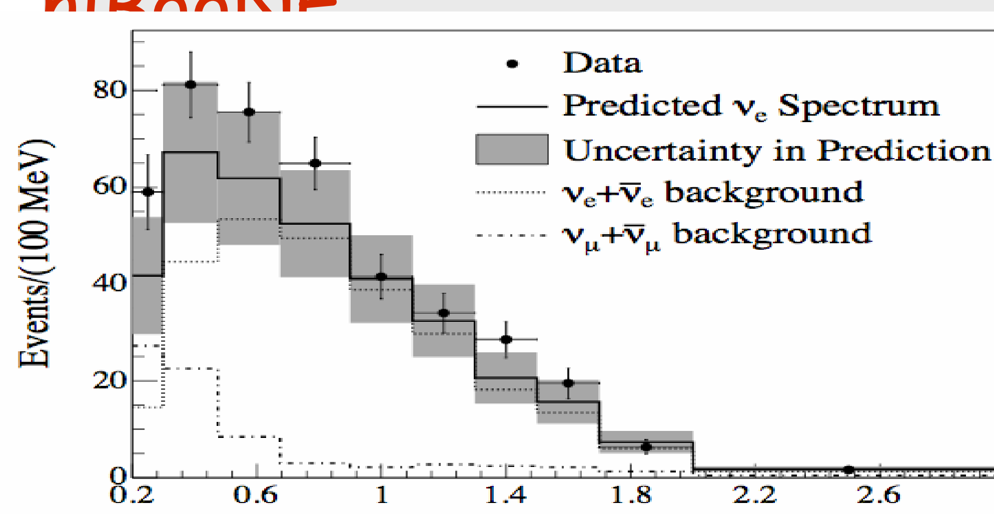
Recall:

1) Distance to MiniBooNE:
L (from NuMI source) ≈ 1.4 L (from Booster beam source).

2) Neutrino Oscillation depends on L and E through L/E ratio.

Therefore, if an anomaly seen at some E in Booster beam data is due to oscillation it should appear at 1.4E i… …niBooNE

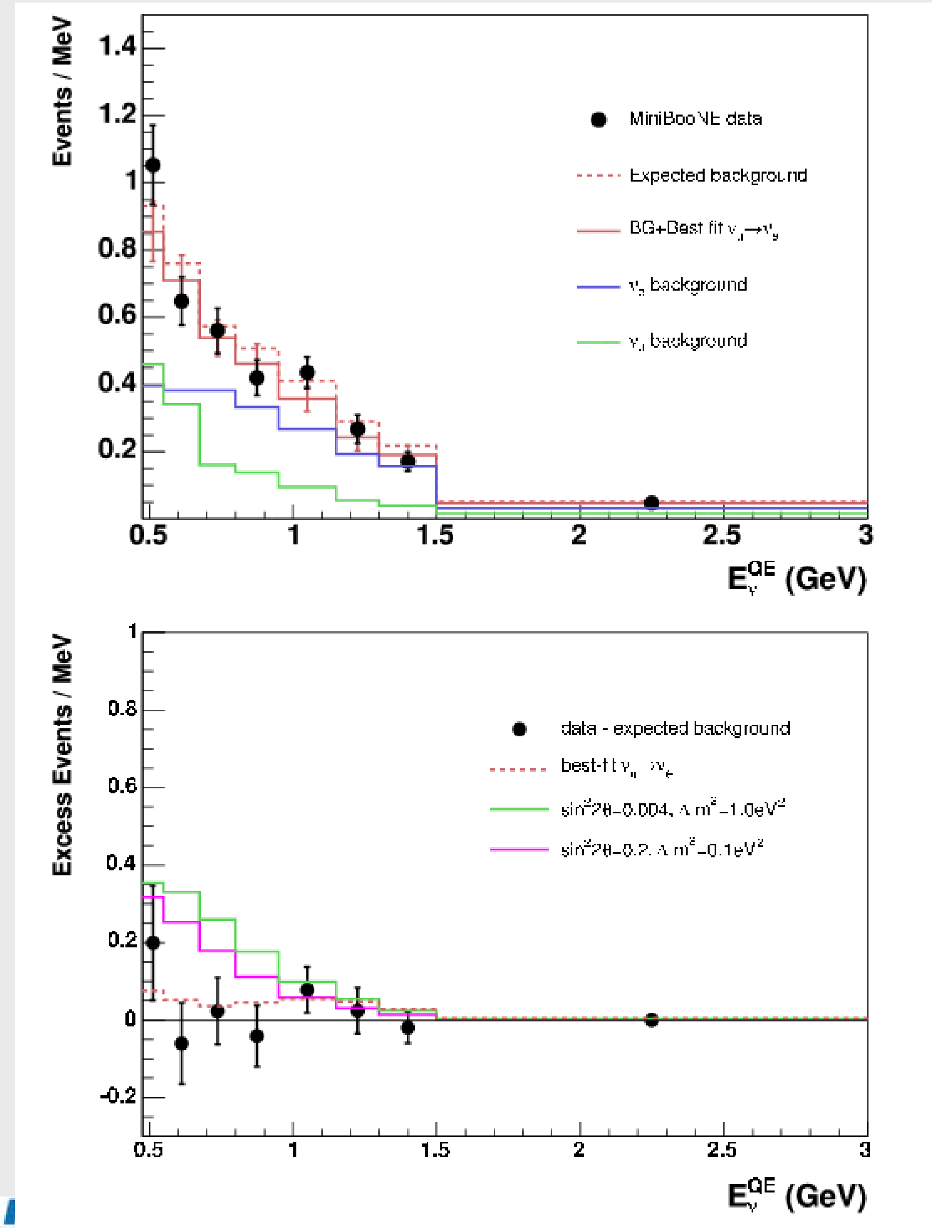




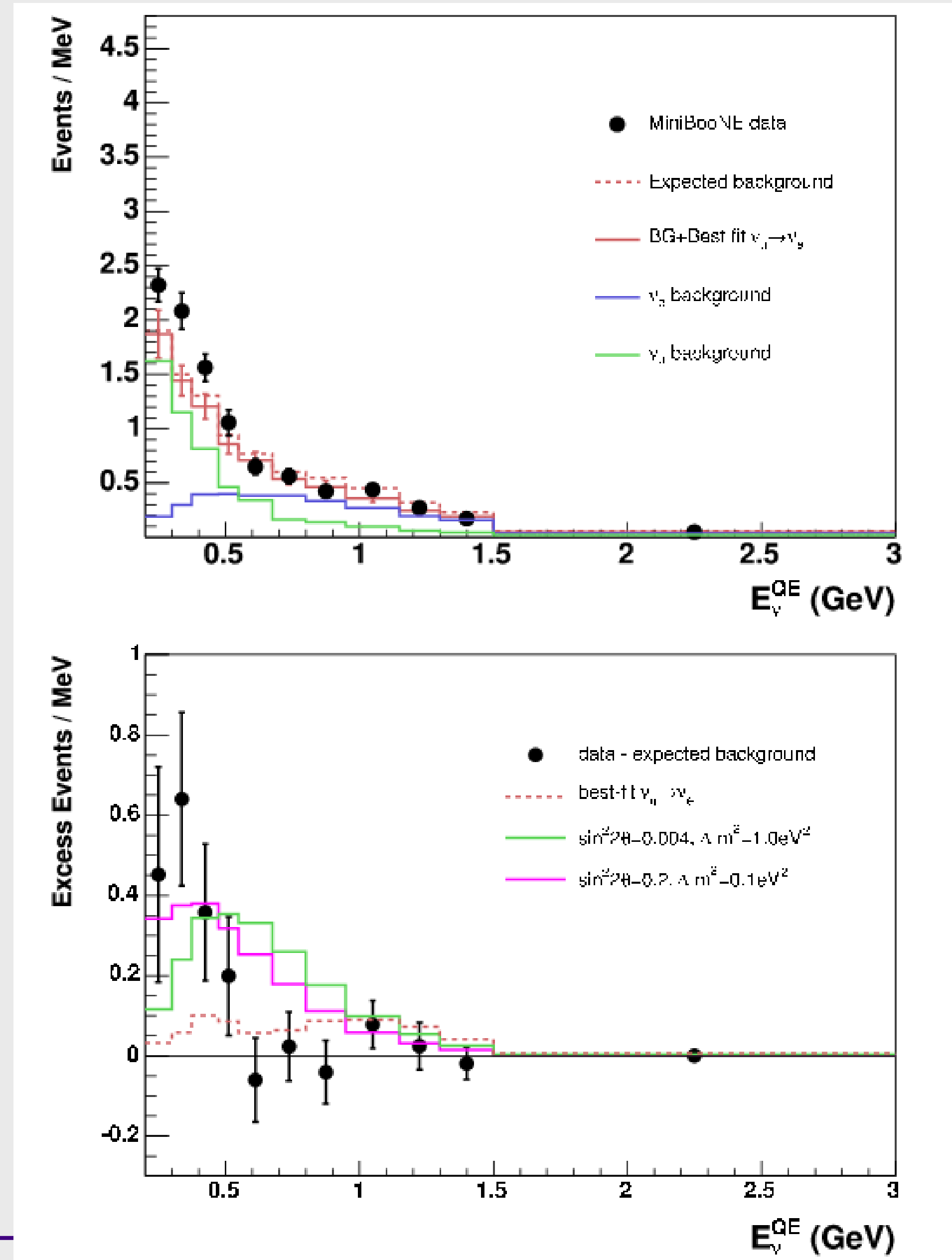
Currently collecting and analyzing more data from NuMI beamline!

Oscillations Fits

Fit above 475 MeV



Fit above 200 MeV



Background Rates (with DIRT cuts)

Process	$200-300$	$300-475$	$475-1250$
ν_μ CCQE	9.0	17.4	11.7
$\nu_\mu e \to \nu_\mu e$	6.1	4.3	6.4
NC π^0	103.5	77.8	71.2
NC $\Delta \to N\gamma$	19.5	47.5	19.4
Dirt Events	11.5	12.3	11.5
Other Events	18.4	7.3	16.8
ν_e from μ Decay	13.6	44.5	153.5
ν_e from K^+ Decay	3.6	13.8	81.9
ν_e from K^0_L Decay	1.6	3.4	13.5
Total Background	186.8 ± 26.0	228.3 ± 24.5	385.9 ± 35.7

Publications: Lots or results coming out, more to come!

A.A. Aguilar-Arevalo et. Al.:

0707.0926, PRL 98, 231801 (2007) Oscillation search

0706.0926, PRL 100, 032301 (2008) numu CCQE

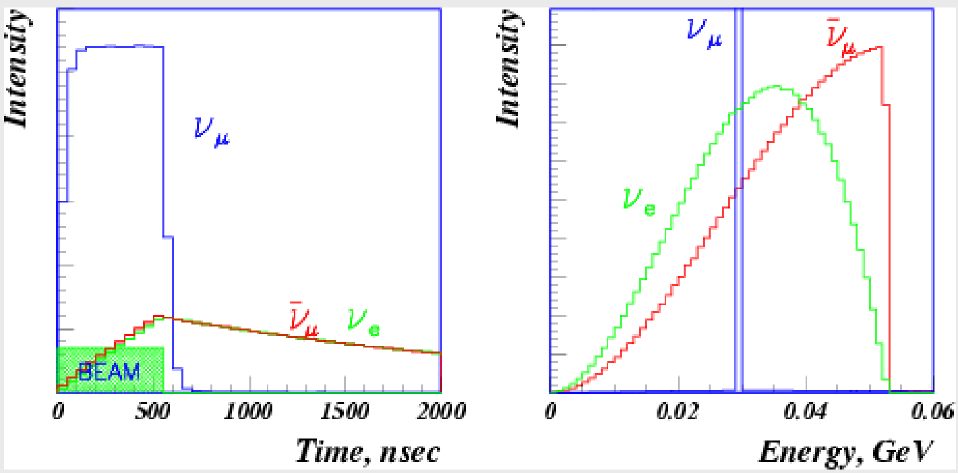
0706.3897, showing mu internal bremsstrahlung small

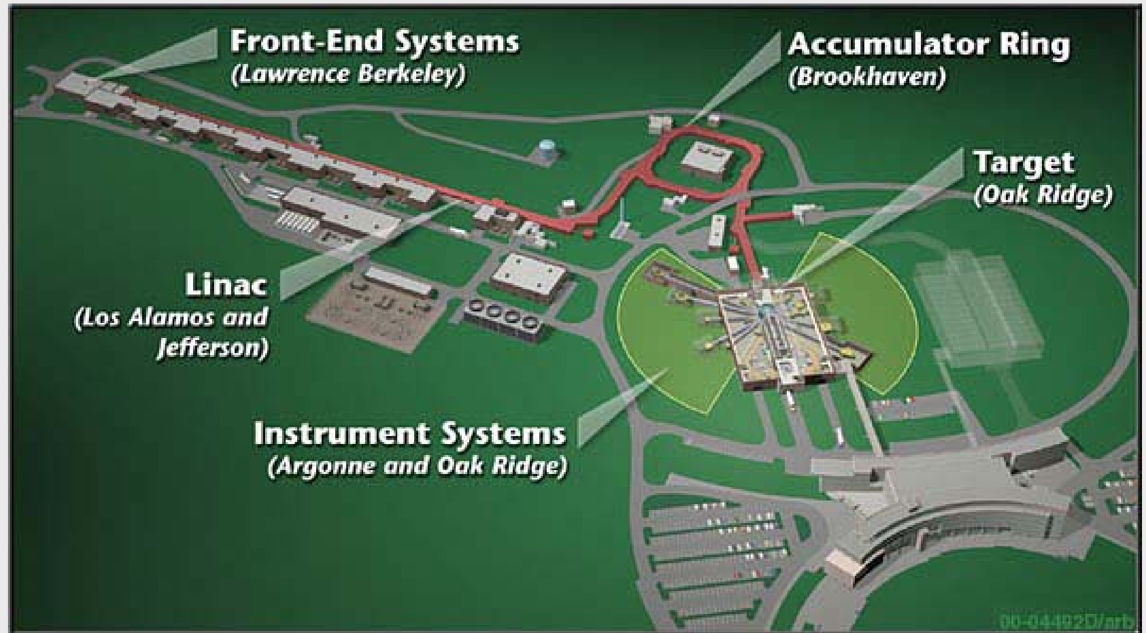
0803.3423, submitted to PL, neutral current pi0 prod.

In draft form within the collaboration:
3 NIM papers--Flux, Detector, and Reconstruction
3 others--combined limits, NUMI/MB, improved osc fit

9 further physics papers in various stages of progress
At least 8 more contemplated

OscSNS at ORNL: A Smoking Gun Measurement of Active-Sterile Neutrino Oscillations





SNS: ~1 GeV, ~1.4 MW

$\nu_\mu \to \nu_e$; $\nu_e\, p \to e^+ n$ => re-measure LSND an order of magnitude better.

$\nu_\mu \to \nu_s$; **Monoenergetic** ν_μ ; $\nu_\mu\, C \to \nu_\mu\, C^*(15.11)$ => search for sterile ν

OscSNS would be capable of making precision measurements of ν_e appearance & ν_μ disappearance and proving, for example, the existence of sterile neutrinos! (see Phys. Rev. D72, 092001 (2005)). Flux shapes are known perfectly and cross sections are known very well.

Sterile Neutrinos in the Standard Model Gauge Group

- With spontaneous symmetry breaking, Dirac neutrino mass terms of type,

$$m_D \bar{\nu}_L \nu_R$$

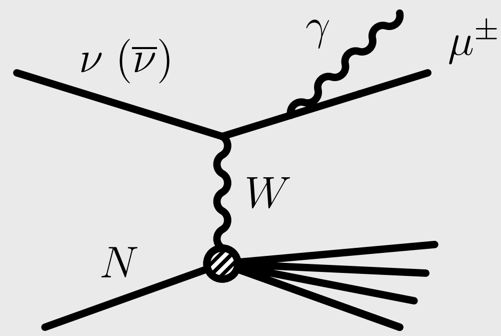
- Neutrino mass implies ν_R exits!
- ν_R has the quantum numbers of the vacuum, thus sterile with respect to the standard model gauge interactions!
- SM with neutrino mass now looks like,

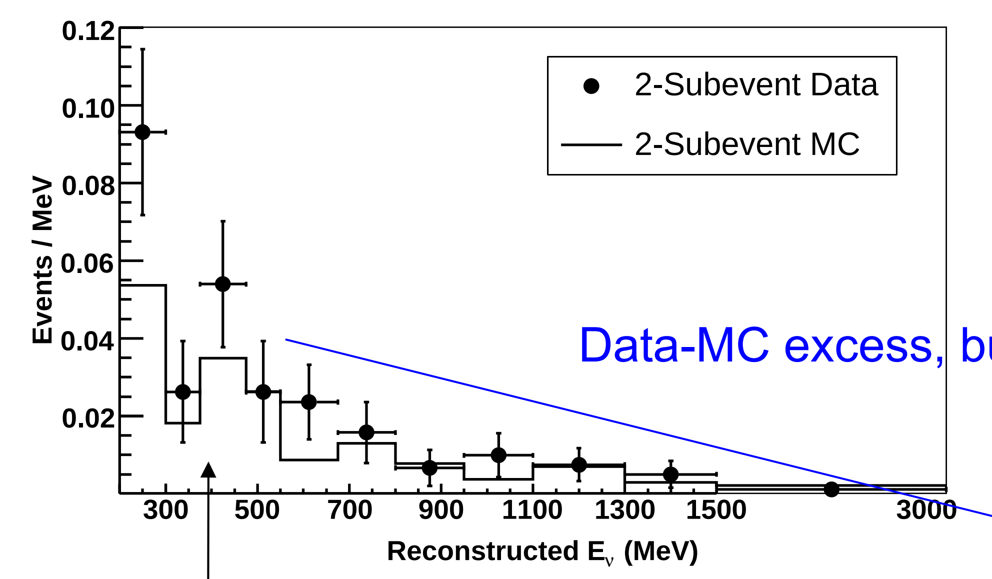
$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (3,2)(1/3), \qquad d_R \sim (3,1)(-2/3), \qquad u_R \sim (3,1)(4/3);$$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1,2)(-1), \qquad e_R \sim (1,1)(-2), \qquad \nu_R \sim (1,1)(0)$$

- Open question as to mass of sterile states. Look for Active-Sterile neutrino oscillations.

Muon Misidentification (including muon internal bremsstrahlung)





-Misidentified Muons not a problem.

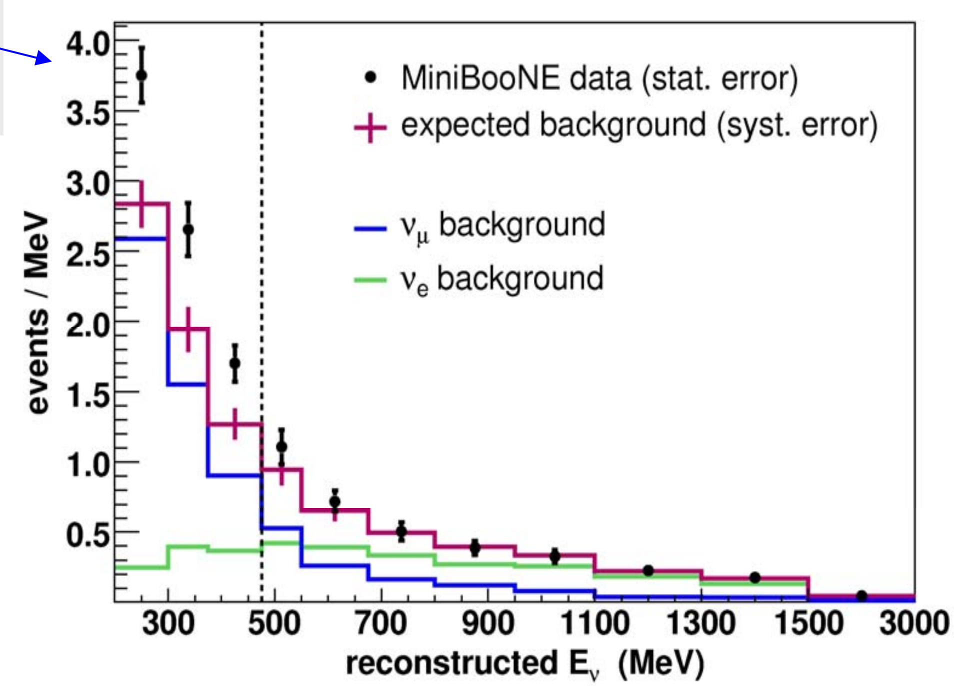
Paper on this work:
arXiv:0710.3897 [hep-ex]

Data-MC excess, but note the scale!

Apply reconstruction and particle identification to clean sample muon CCQE events (muon decay visible).

Then scale normalization to account for how often the second subevent is missing

What results is a direct measurement and MC prediction for almost all the rate at which events with a final state muon enter the ν_e background



M. Sorel, et. al. hep-ph/0305255

3+2 Analysis

Idea: If light sterile neutrinos (ν_s) exist, then:

Includes CP phase; $\varphi = -\varphi$ for antineutrinos

$\nu_\mu \to \nu_s \to \nu_e$

$$P(\nu_\alpha \to \nu_\beta) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2 x_{41} + 4|U_{\alpha 5}|^2|U_{\beta 5}|^2 \sin^2 x_{51} + 8|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \sin x_{41} \sin x_{51} \cos(x_{54} - \phi_{54})$$

$\nu_\mu \to \nu_s$

$\nu_e \to \nu_s$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4[(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2 x_{41} + |U_{\alpha 5}|^2 \sin^2 x_{51}) + |U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2 x_{54}]$$

With SBL approximation $\Delta m_{solar}=0$, $\Delta m_{ATM}=0$, and $x_{ij}= \Delta m_{ij}L/4E$

Experimental constraints from:

LSND, KARMEN, NOMAD, MB, CCFR, CDHS, CHOOZ, BUGEY (+ atm constraint)

appearance experiments ($\nu_\mu \to \nu_e$)

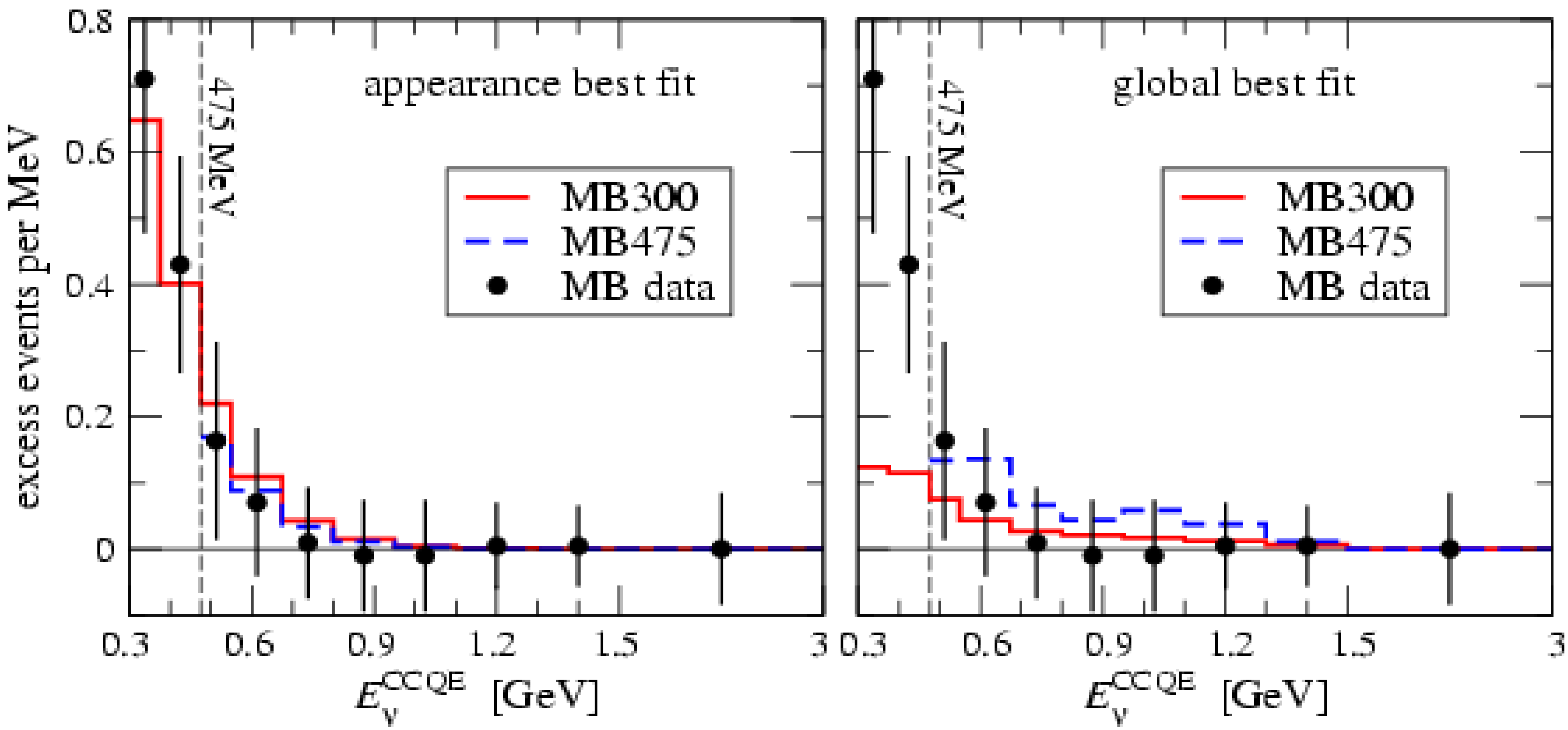
disappearance experiments ($\nu_\mu \not\to \nu_\mu$ or $\nu_e \not\to \nu_e$)

(ν_μ disappearance Constraint)

3+2 models can produce differences between neutrino and antineutrino appearance rates!

Analysis by Maltoni & Schwetz [hep-ph/0705.0107]

3+2 Global Fit Results



3+2 neutrino models:

- provide a **good fit** to LSND and the original MB oscillation data
- can **account for the low energy** event **excess in MB**

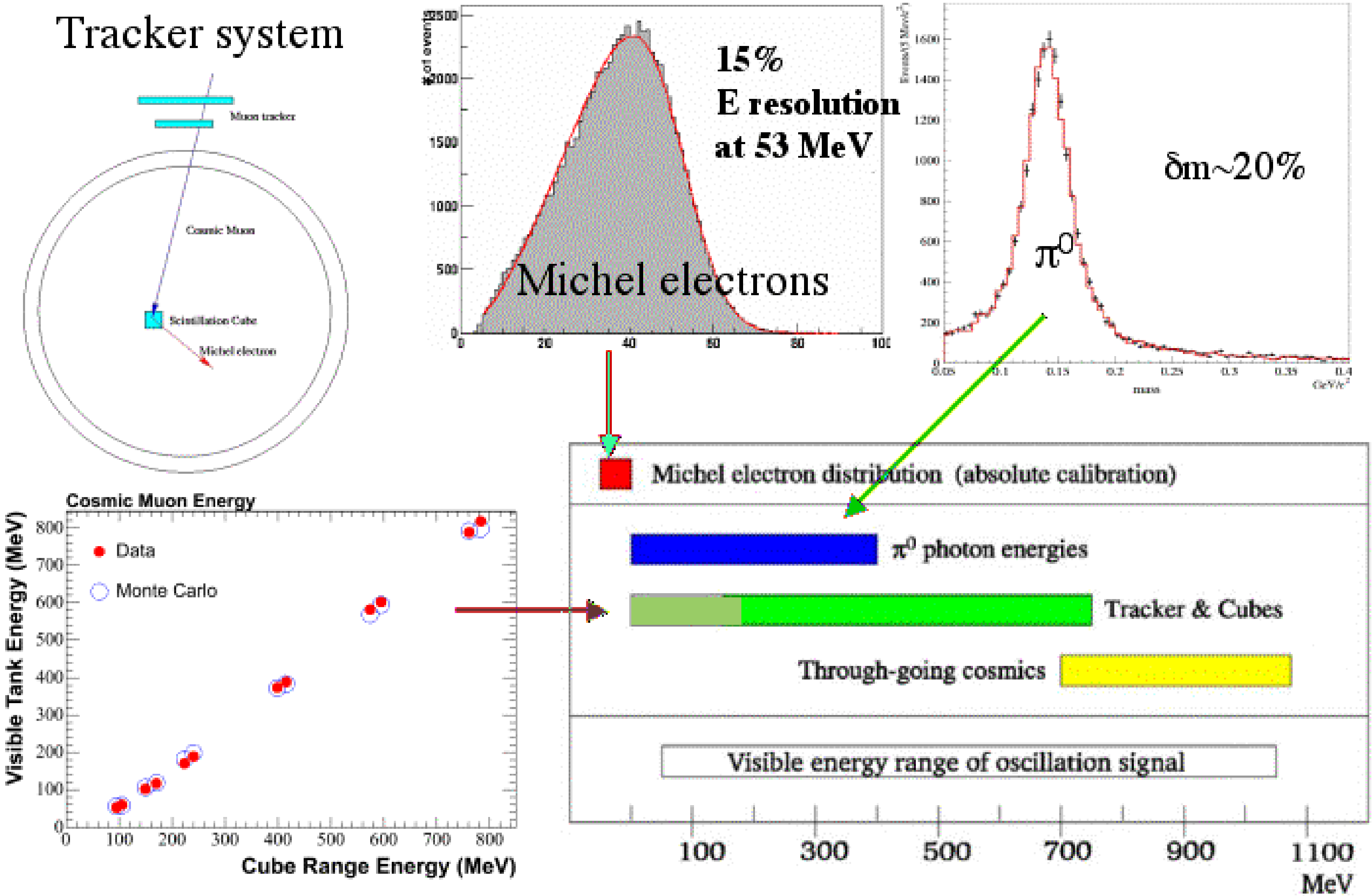
However:

- there is significant **tension between appearance and disappearance data**

Note: analysis done without full MiniBooNE error matrix

MB will perform full analysis, G. Karagiorgi.

Calibration Sources



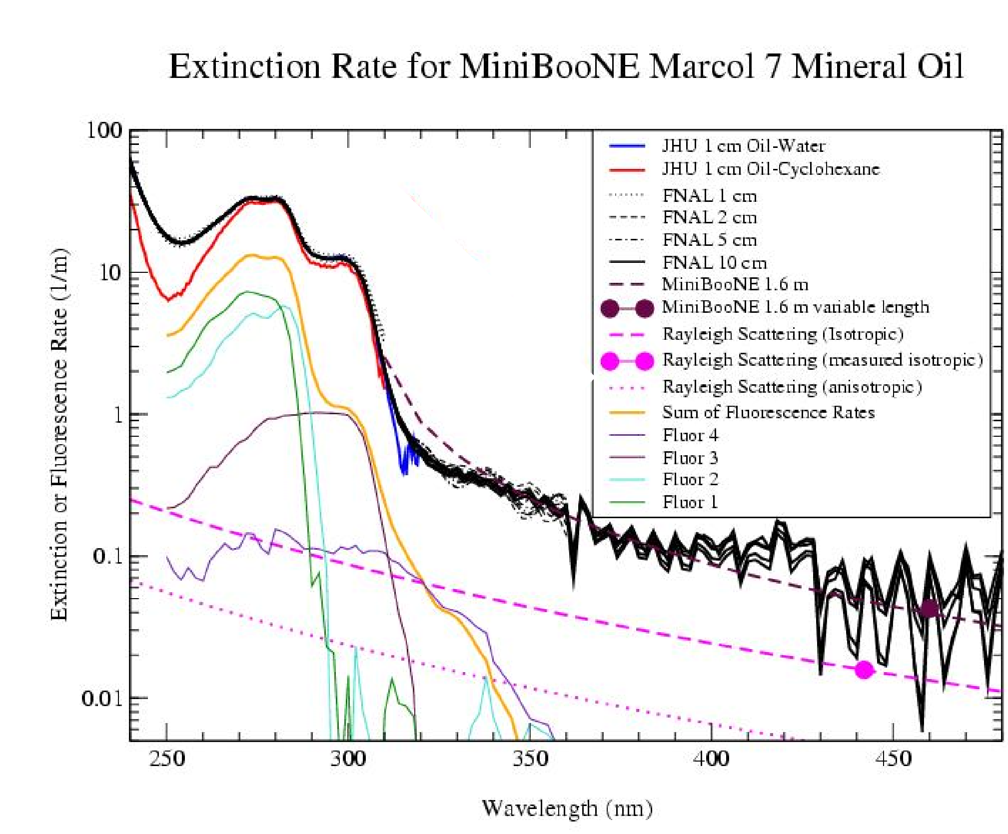
Optical Model

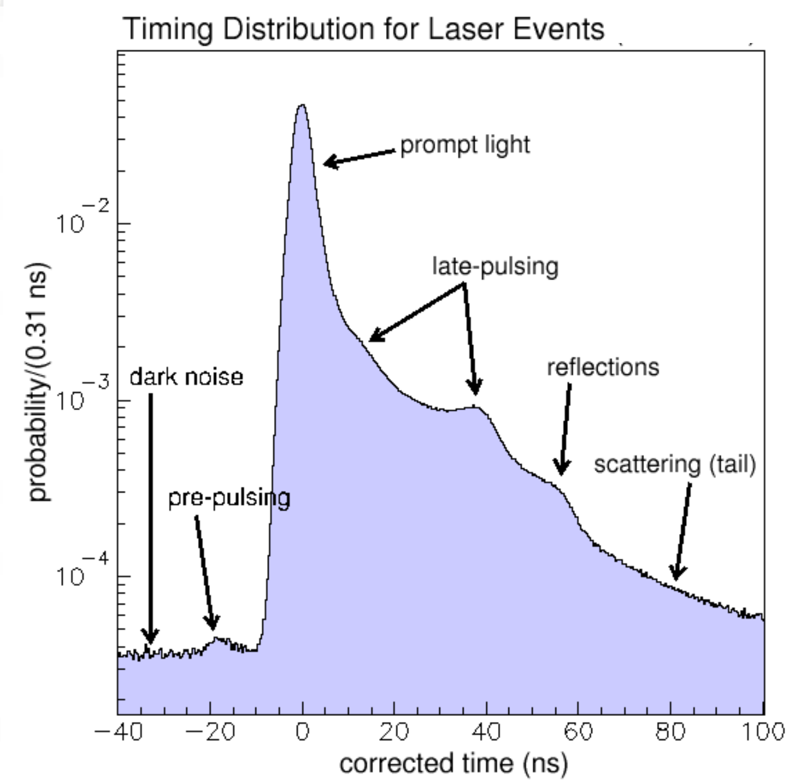
Attenuation length: >20 m @ 400 nm

Detected photons from

- Prompt light (Cherenkov)
- Late light (scintillation, fluorescence)
  in a 3:1 ratio for $\beta\sim1$

We have developed 39-parameter "Optical Model" based on internal calibration and external measurement





Cuts Used to Separate ν_μ events from ν_e events

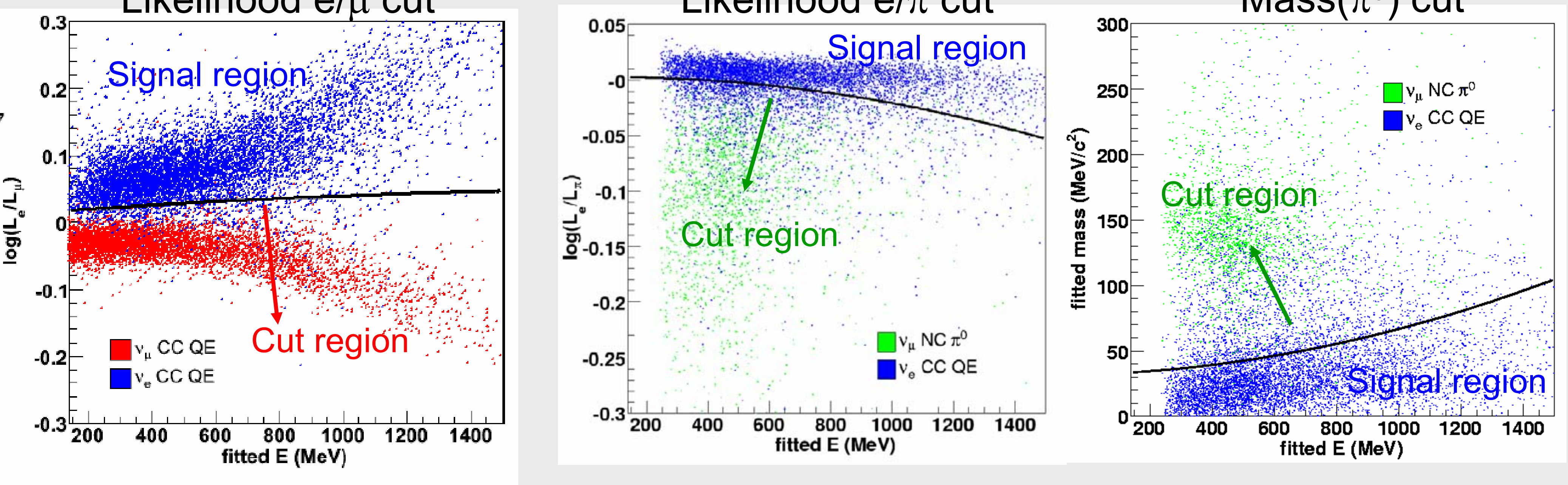
Compare observed light distributions to fit prediction:

Apply these likelihood fits to three hypotheses:
- **single electron track L_e**
- **single muon track L_μ**
- **two electron-like rings (π^0 event hypothesis) L_π**

TBL Analysis

Combine three cuts to accomplish the separation: $L_{e\mu}$, $L_{e\pi}$, and 2-track mass

Likelihood e/μ cut | Likelihood e/π cut | Mass(π^0) cut



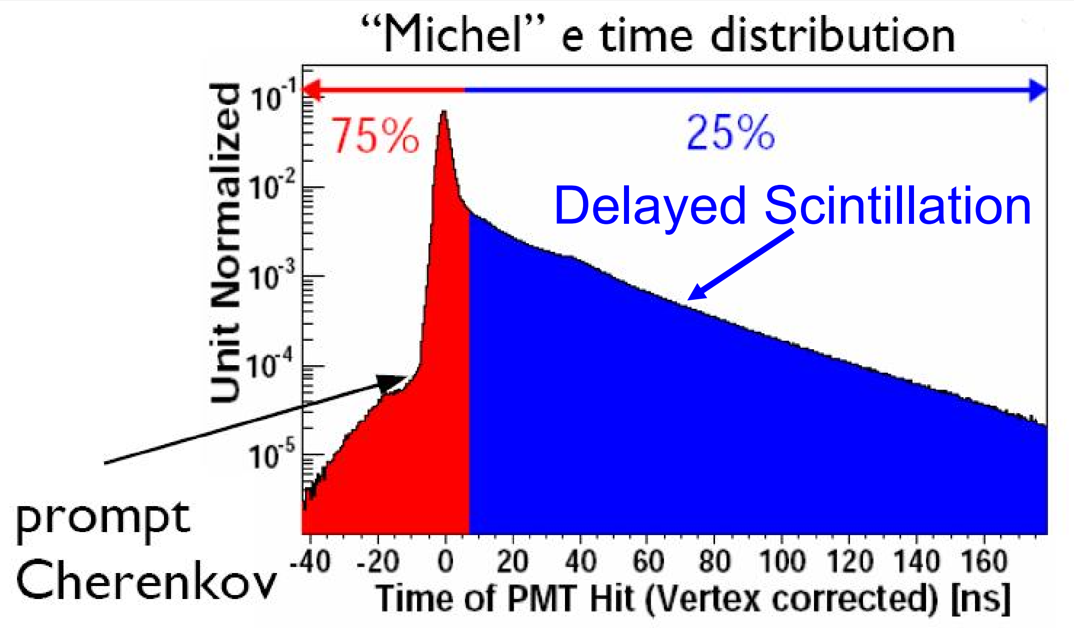
Blue points are signal ν_e events

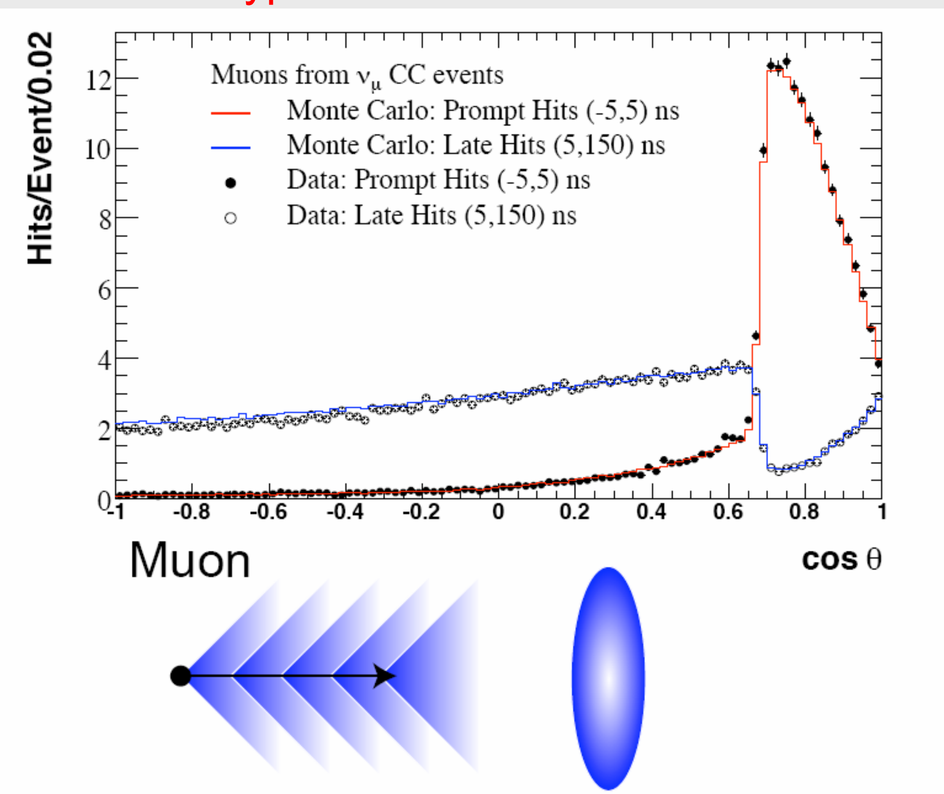
Red points are background ν_μCC QE events

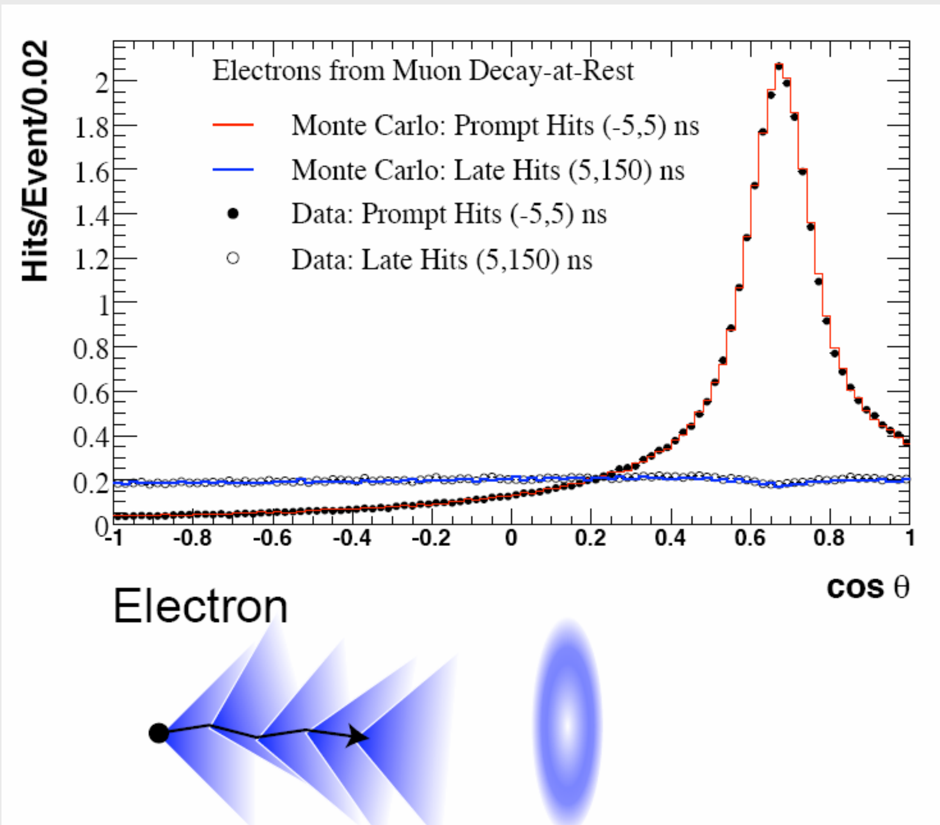
Green points are background ν_μ NC π^0 events

Event Reconstruction

- Use energy deposition and timing of hits in the phototubes
  - Prompt Cherenkov light
    - Highly directional with respect to particle direction
    - Used to give particle track direction and length
  - Delayed scintillation light
    - Amount depends on particle type





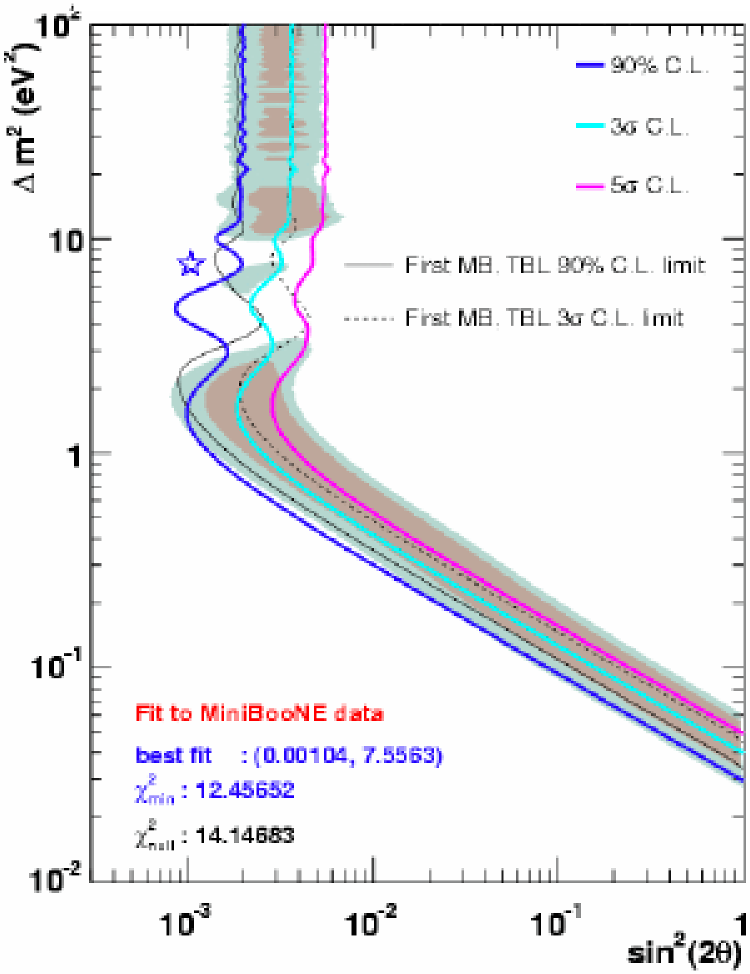


The ν_eBDT + ν_eTBL + ν_μCCQE results:

The combination of the three samples gives a increase in coverage in the region $\Delta m^2 < 1$ eV^2.

Differences in the details are due to the specific fluctuations in the three data samples and the interplay with correlations among them.

The combination yields a consistent result.



(A.A. Aguilar-Arevalo)

10%-30% improvement in 90% C.L. limit below ~1eV^2.

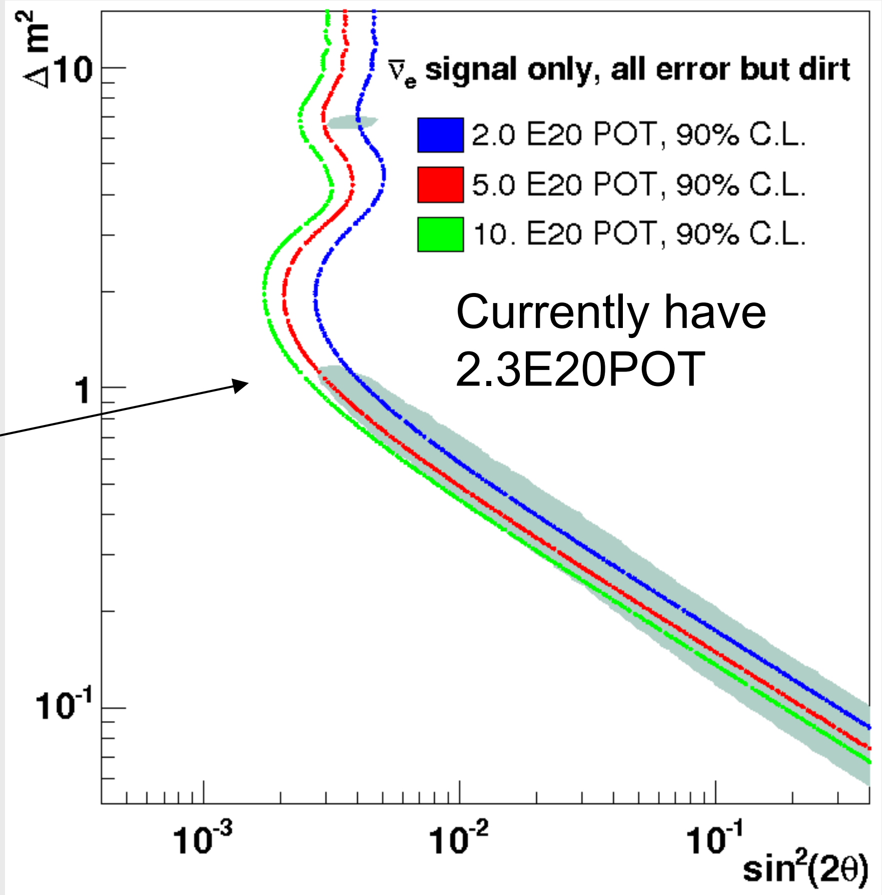
Global Fits to Experiments

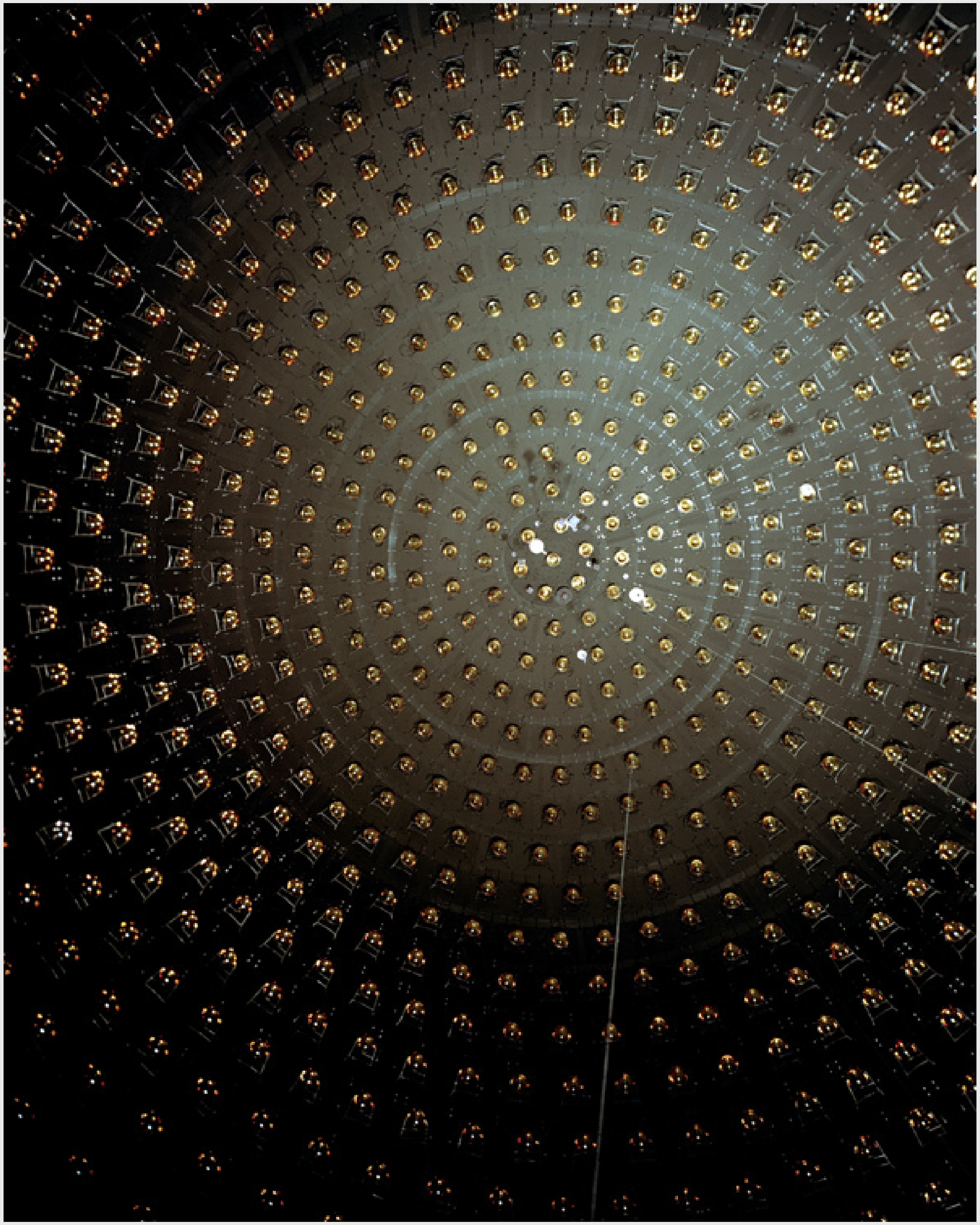
LSND	KARMEN2	MB	Bugey	Max Compat %	Δm^2	$\sin^2\theta$
X	X	X		25.36	0.072	0.256
X	X	X	X	3.94	0.242	0.023
X		X		16.00	0.072	0.256
X		X	X	2.14	0.253	0.023
	X	X		73.44	0.052	0.147
	X	X	X	27.37	0.221	0.012

Antineutirno Oscillation Fits

- **Approved to run one more year to collect enough antineutrino data to test LSND with antineutrinos.**
  - **Have already taken 0.9E20 POT**
- **Working to open the antineutrino box soon.**

Anti-nue Appearance Sensitivity





10% Photocathode coverage

Two types of Hamamatsu Tubes: R1408, R5912

Charge Resolution: 1.4 PE, 0.5 PE

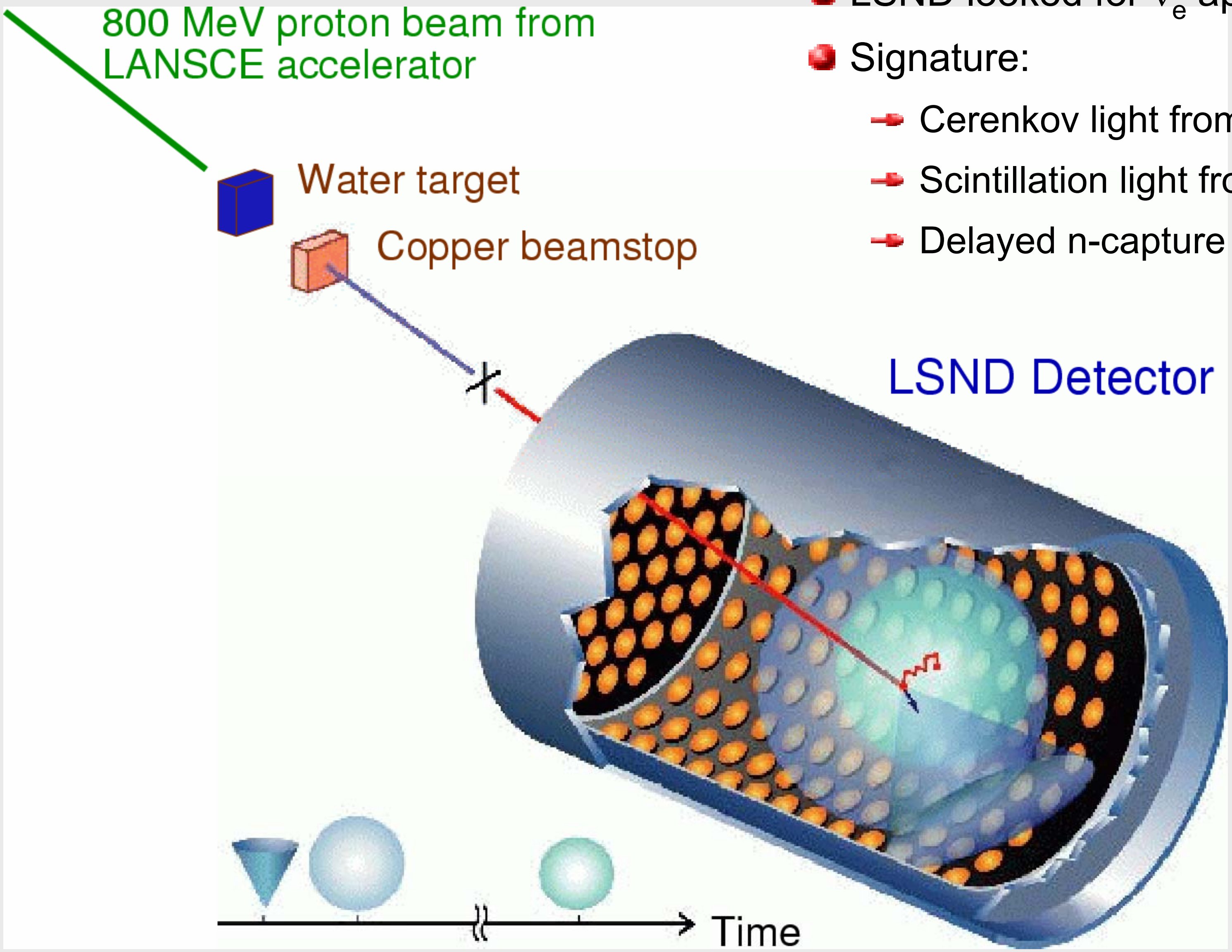
Time Resolution 1.7 ns, 1.1ns

Los Alamos

Identifying Neutrinos

The Liquid Scintillator Neutrino Detector at LANL

- LSND looked for $\bar{\nu}_e$ appearing in a $\bar{\nu}_\mu$ beam
- Signature:
  - Cerenkov light from e^+ (CC)
  - Scintillation light from nuclear recoil
  - Delayed n-capture (2.2 MeV)

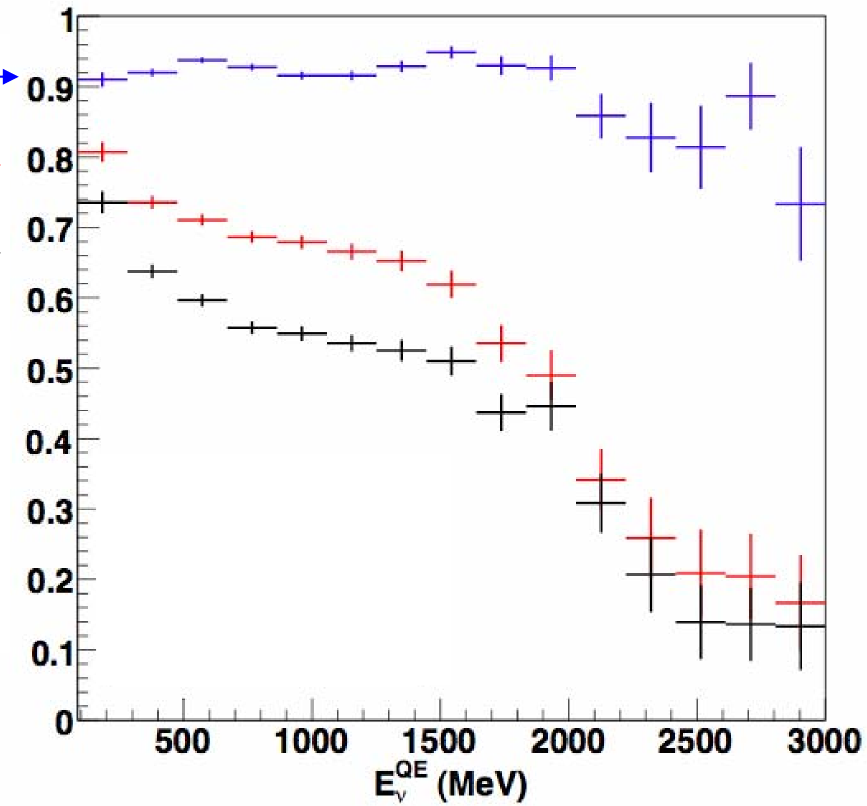


Summary of Track Based cuts

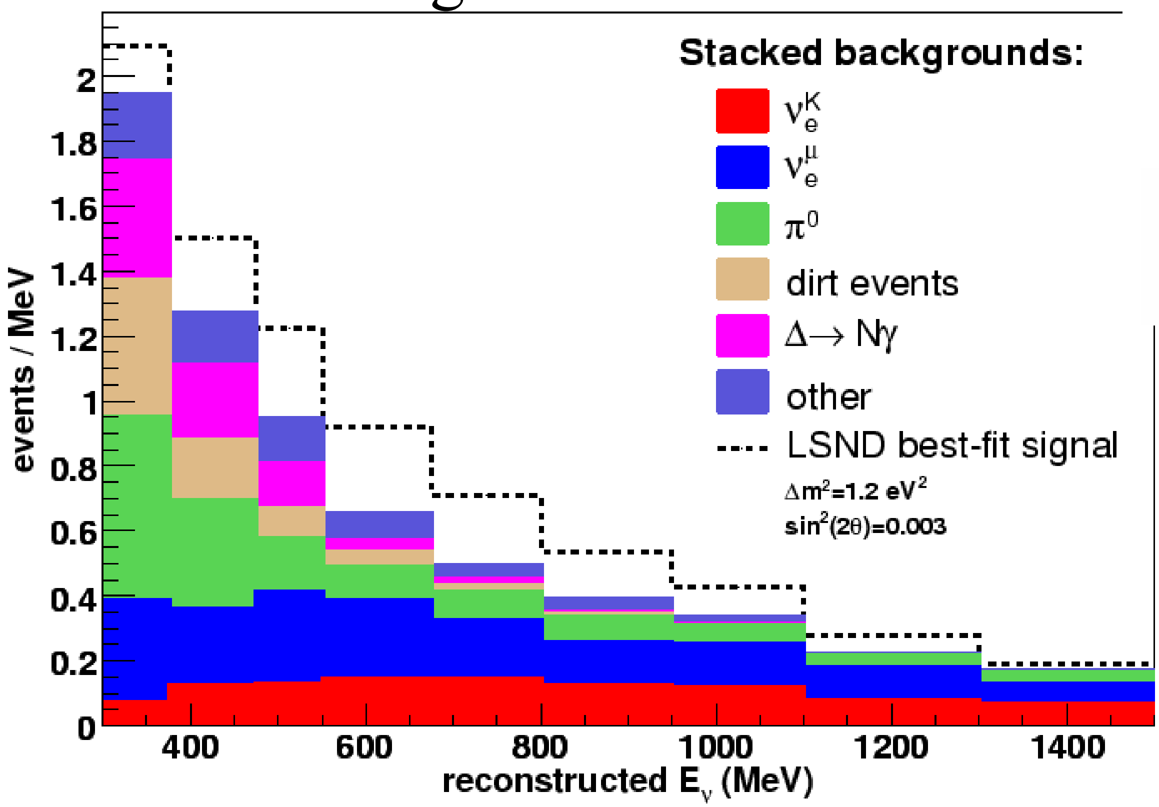
"Precuts" +

Log(L_e/L_μ)
+ Log(L_e/L_π)
+ invariant mass

Efficiency:



Backgrounds after cuts



Los Alamos