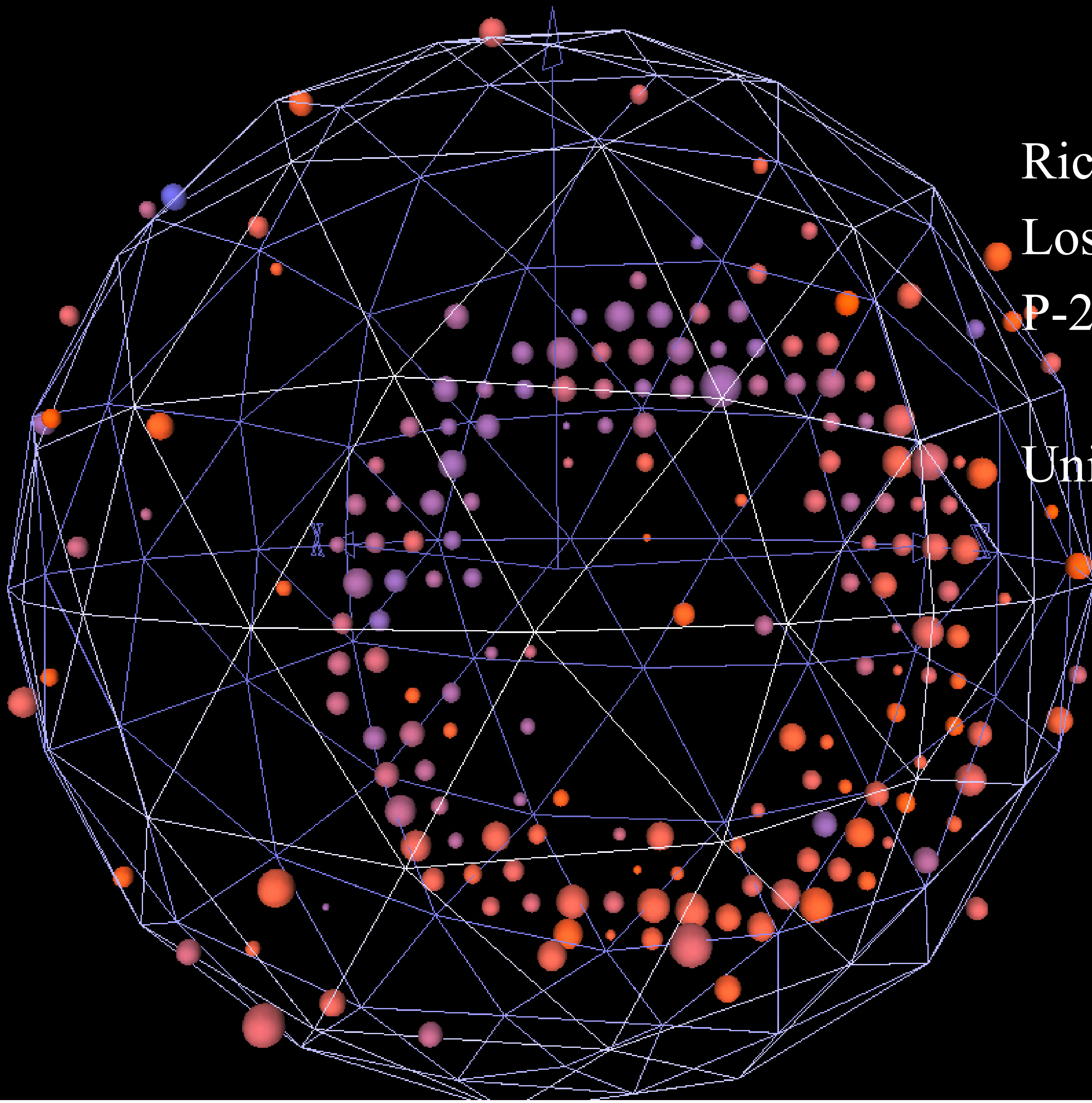
Updated Oscillation Results from MiniBooNE



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P-25 Subatomic Physics Group

University of Pennsylvania 2009

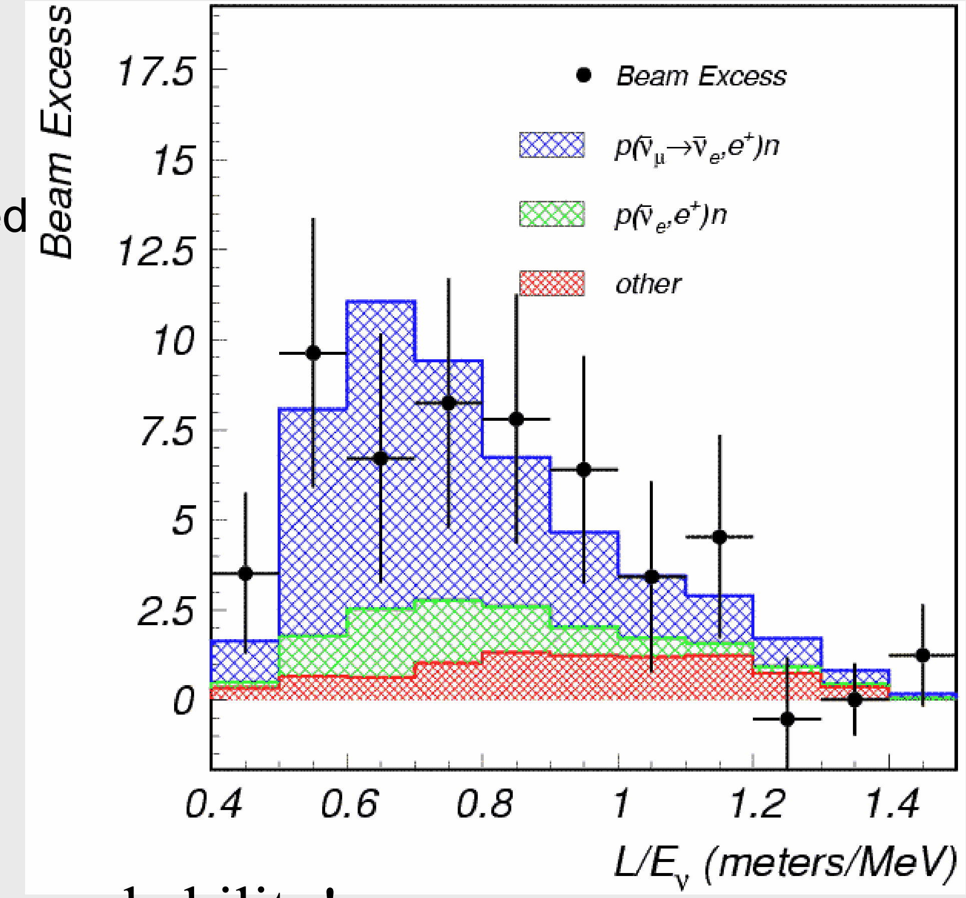
Outline

1. The LSND oscillation signal.
2. The MiniBooNE experiment: Testing LSND.
3. Original oscillation results.
4. New results on low energy anomaly.
5. First Antineutrino oscillation results.
6. Conclusions and Future work.

Evidence for Oscillations from LSND

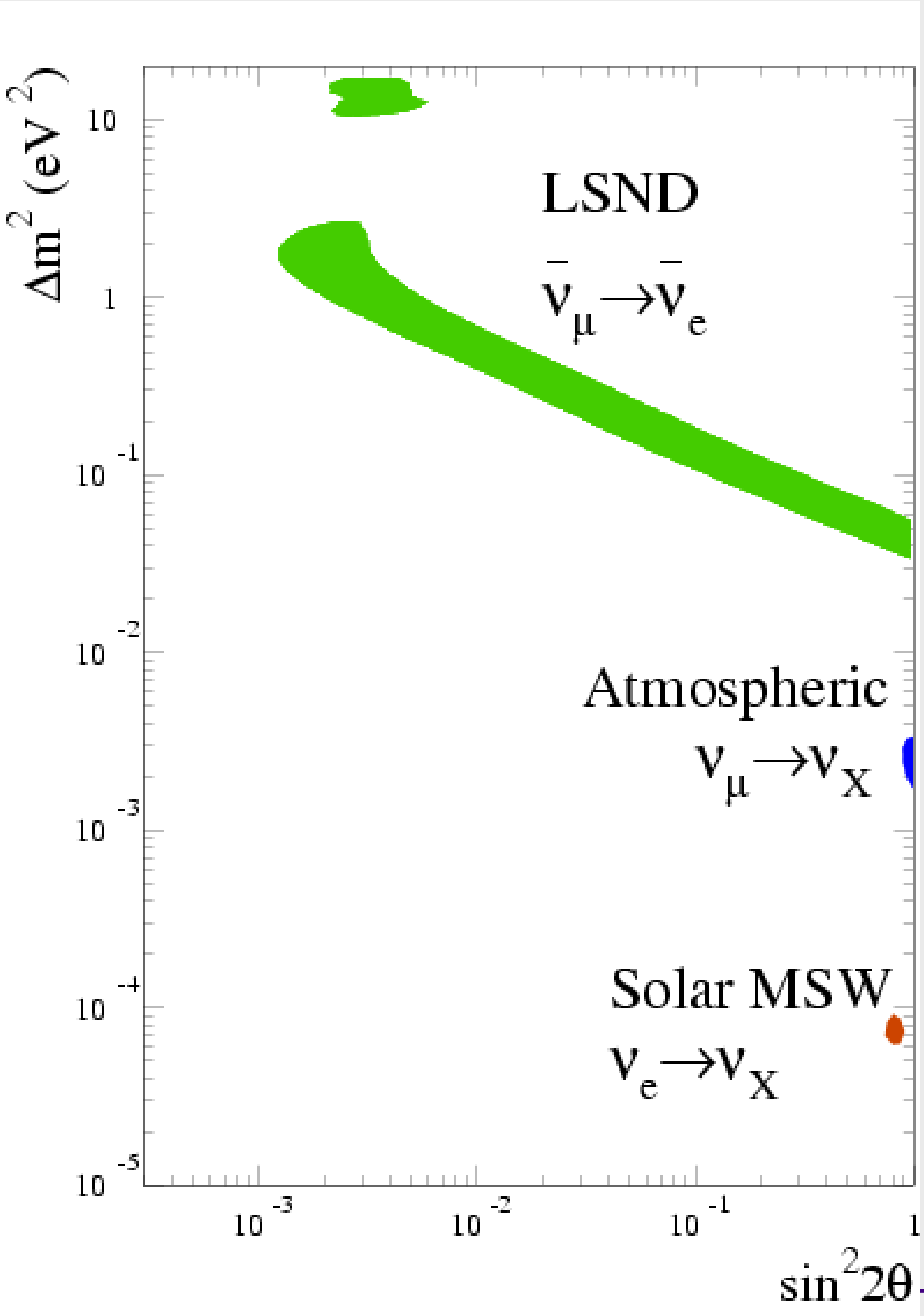
- LSND found an excess of $\overline{\nu}_e$ in $\overline{\nu}_\mu$ beam
- Signature: Cerenkov light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a two neutrino mixing hypothesis:

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



Extremely small oscillation probability!

Current State of Neutrino Oscillation Evidence



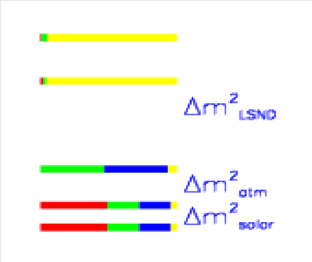
3-ν oscillations require
$\Delta m_{12}^2 + \Delta m_{23}^2 = \Delta m_{13}^2$
and cannot explain the data!

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

Sterile Neutrino Decay — Palomares-Ruiz, Pascoli, Schwetz (hep-ph/0505216v2)

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

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

Explain Baryon Asymmetry in the Universe?

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

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

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

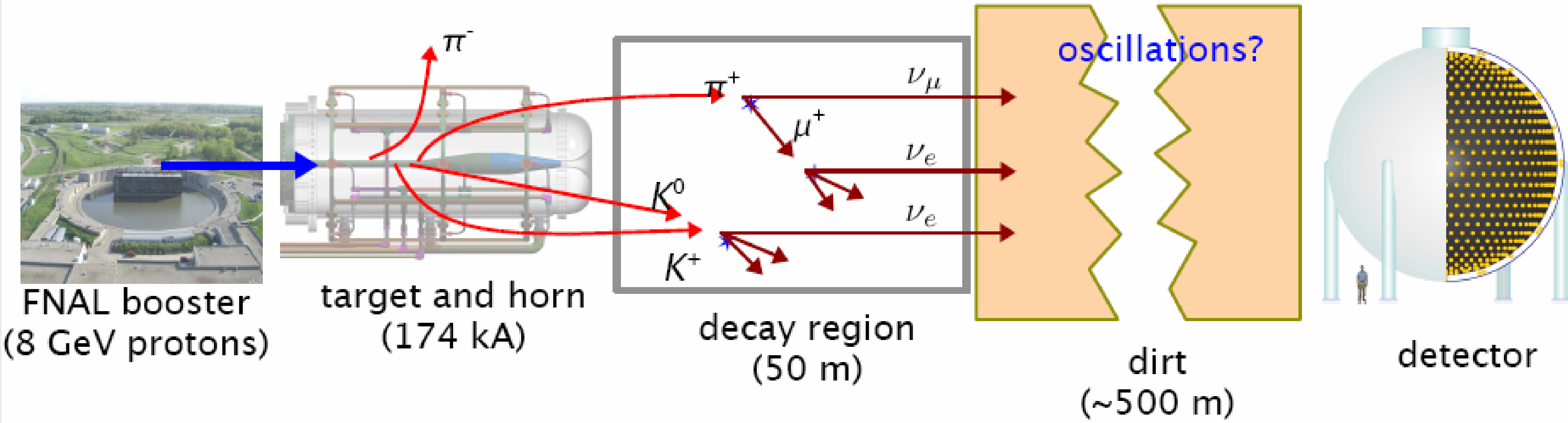
Completely different systematic errors than LSND

Much higher energy than LSND

Blind Analysis

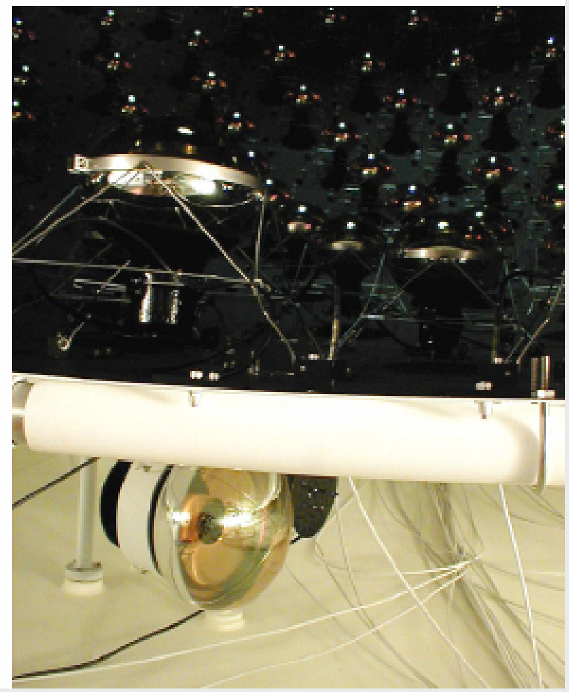
Alabama, Bucknell, Cincinnati, Colorado, Columbia, Embry-Riddle, Fermilab, Florida, Indiana, Los Alamos, LSU, Michigan, Princeton, St. Mary's, Virginia Tech, Yale

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)
- Detect ν interations in 800T pure mineral oil detector

  1280 inner PMT's and 240 Veto PMT's
  ~10% reconstruction energy resolution

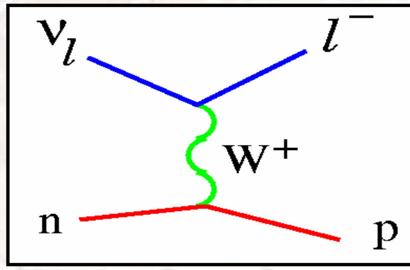


Data collected: 6.5E20 POT in neutrino and 3.4E20 POT in antineutrino mode

MiniBooNE is a Cerenkov Light Detector:

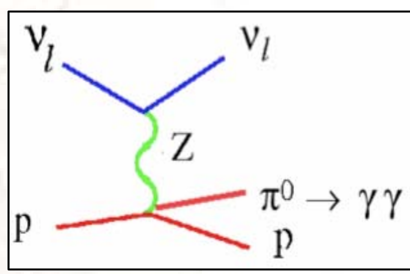
The main types of particles neutrino events produce:

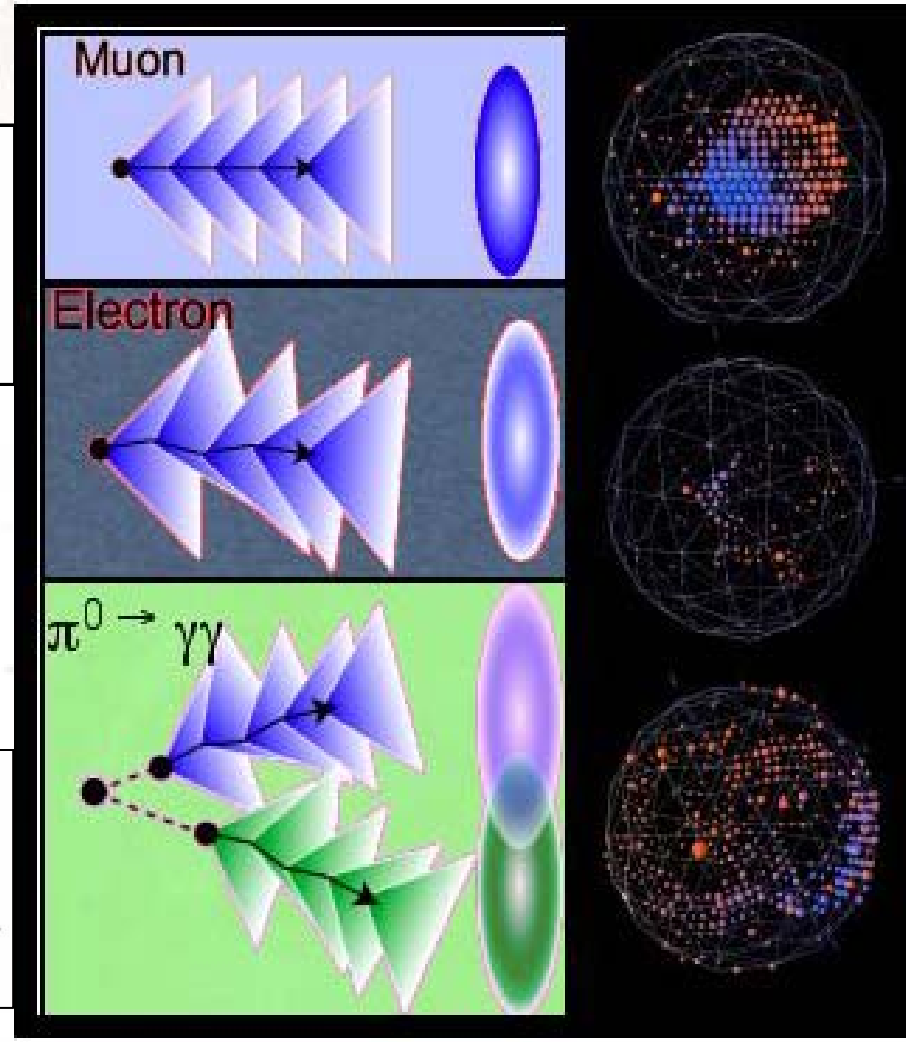
Muons (or charged pions):
Produced in most CC events.
Usually 2 or more subevents
or exiting through veto.



Electrons (or single photon):
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.





ν_e *Event Rate Predictions*

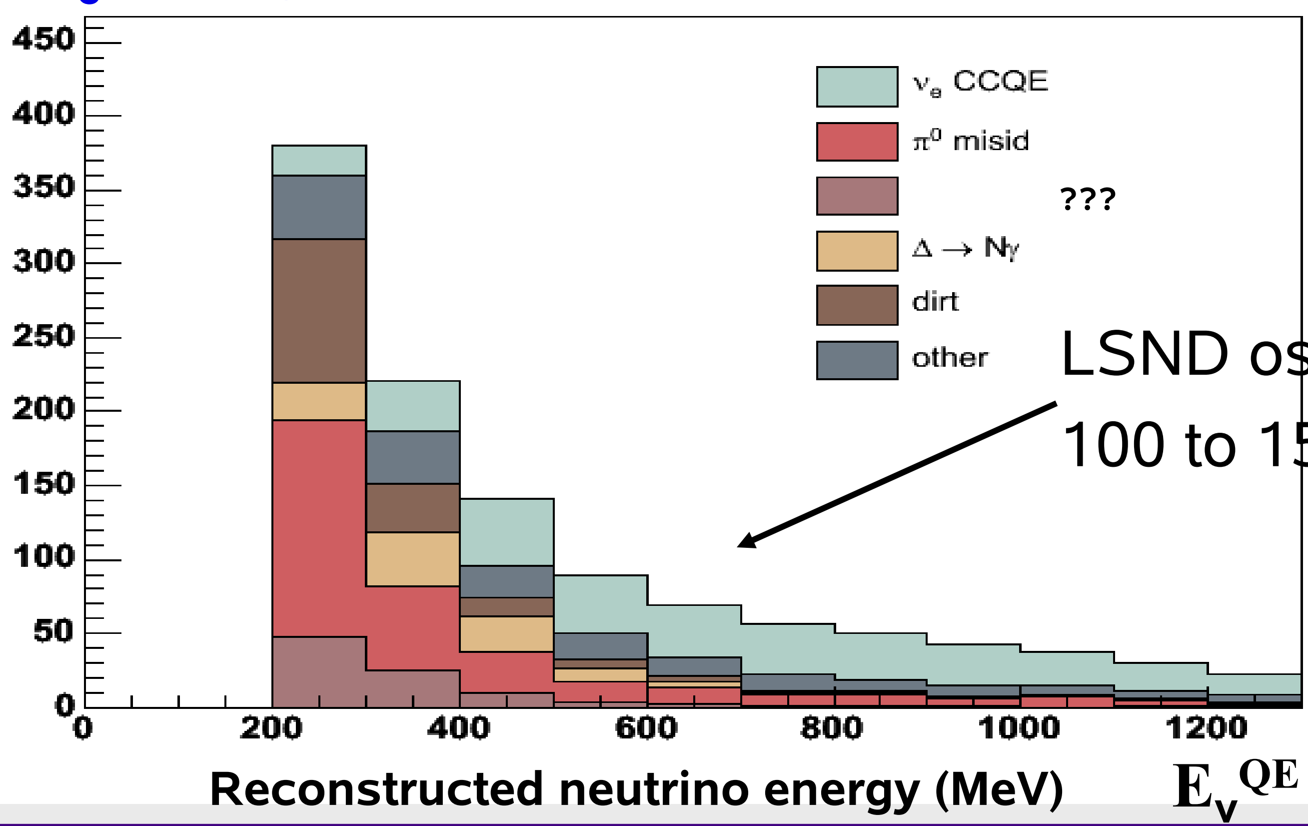
#Events = Flux x Cross-sections x Detector response

External measurements (HARP, etc)
ν_μ rate constrained by neutrino data

External and MiniBooNE measurements
-π^0, delta and dirt backgrounds constrained from data.

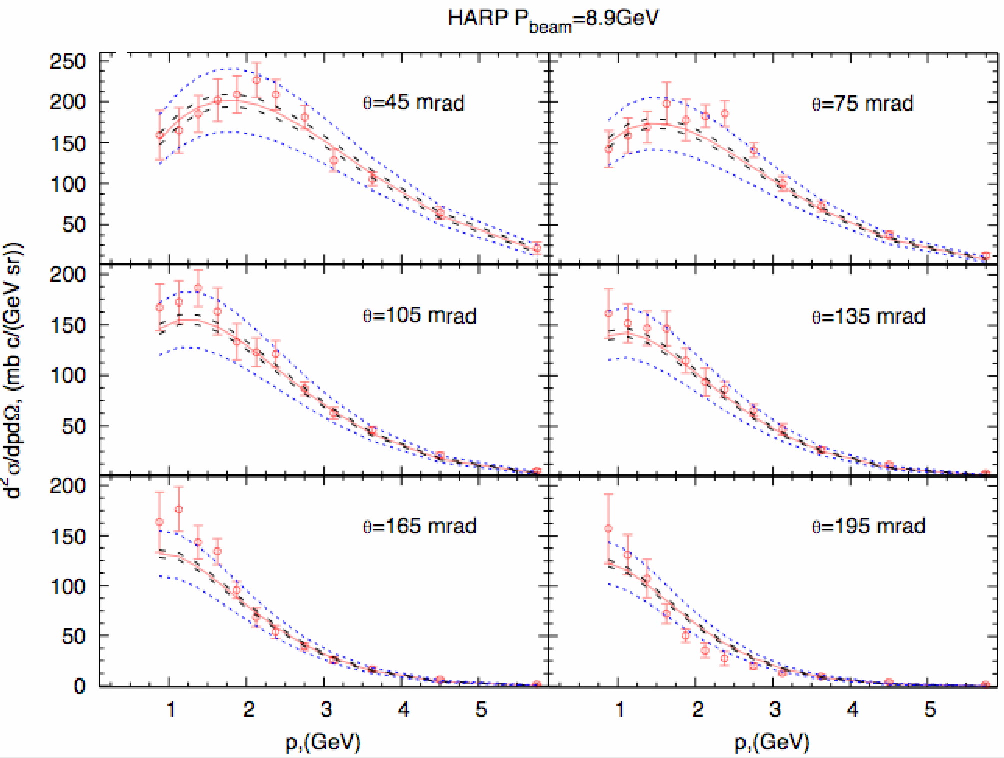
Detailed detector simulation checked with neutrino data and calibration sources.

ν_e Backgrounds after PID cuts (Monte Carlo)



Meson production at the target (Flux paper arXiv: 0806.1449)

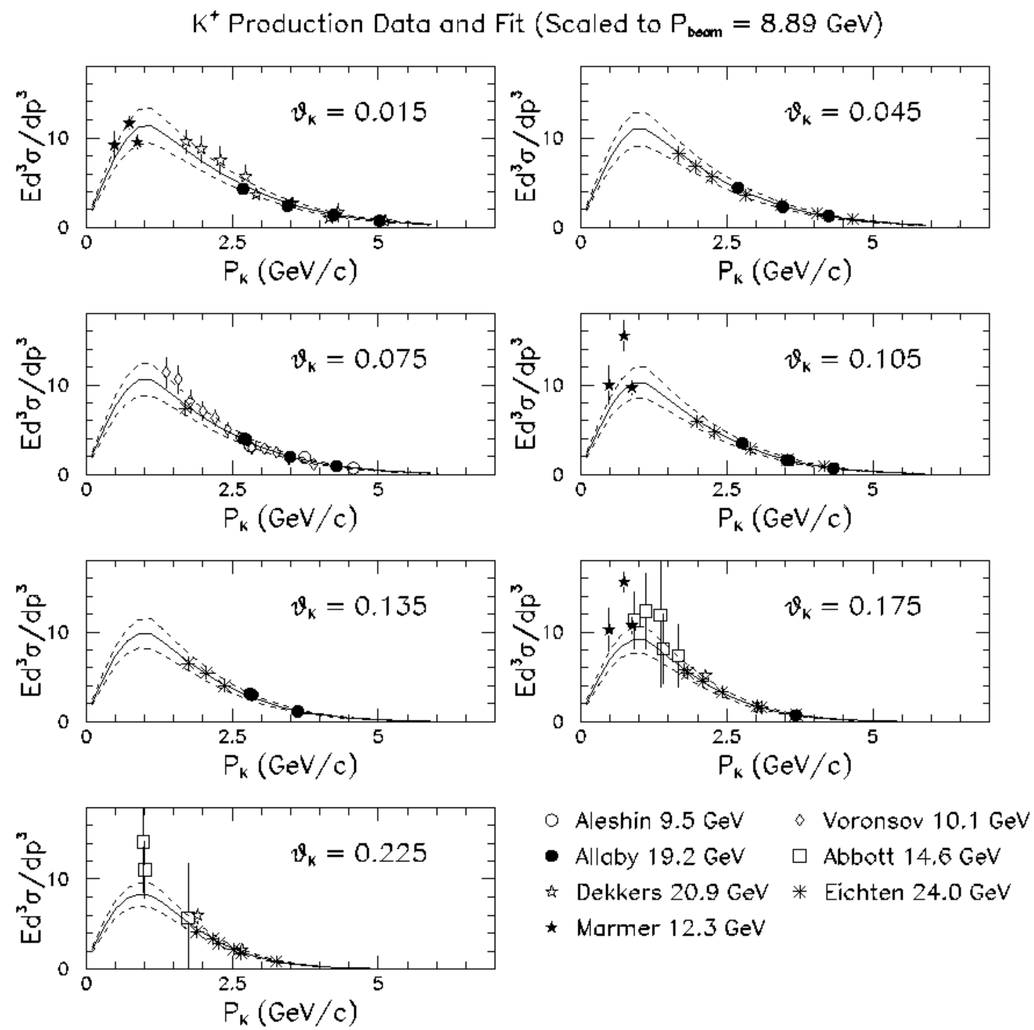
Pions(+/-):



HARP collaboration, hep-ex/0702024

- MiniBooNE members joined the HARP collaboration
  - 8 GeV proton beam
  - 5% Beryllium target
- Spline fits were used to parameterize the data.

Kaons:

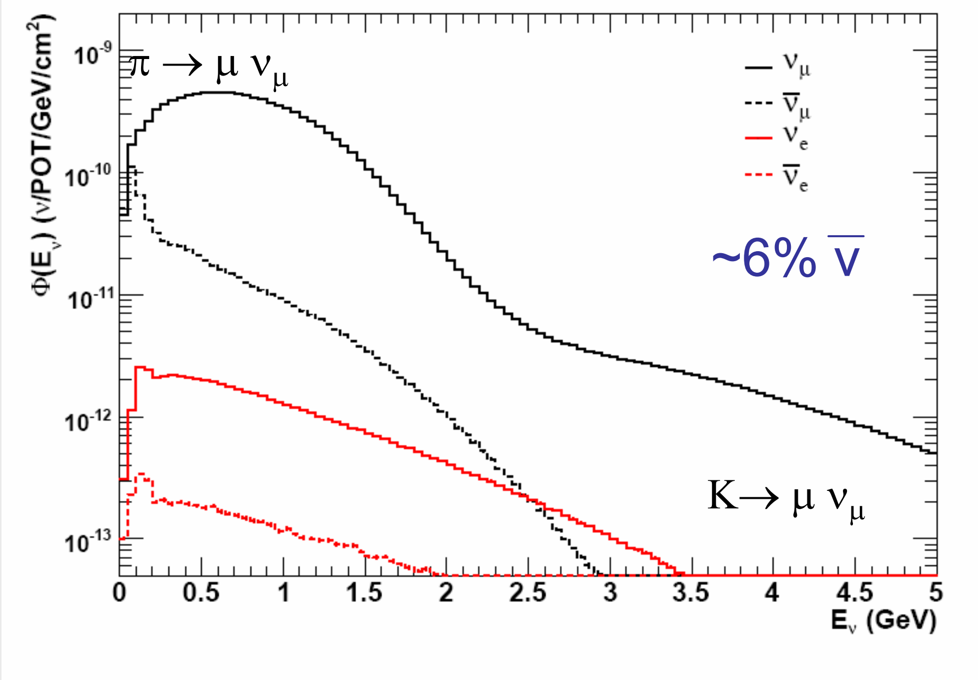


- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assessed

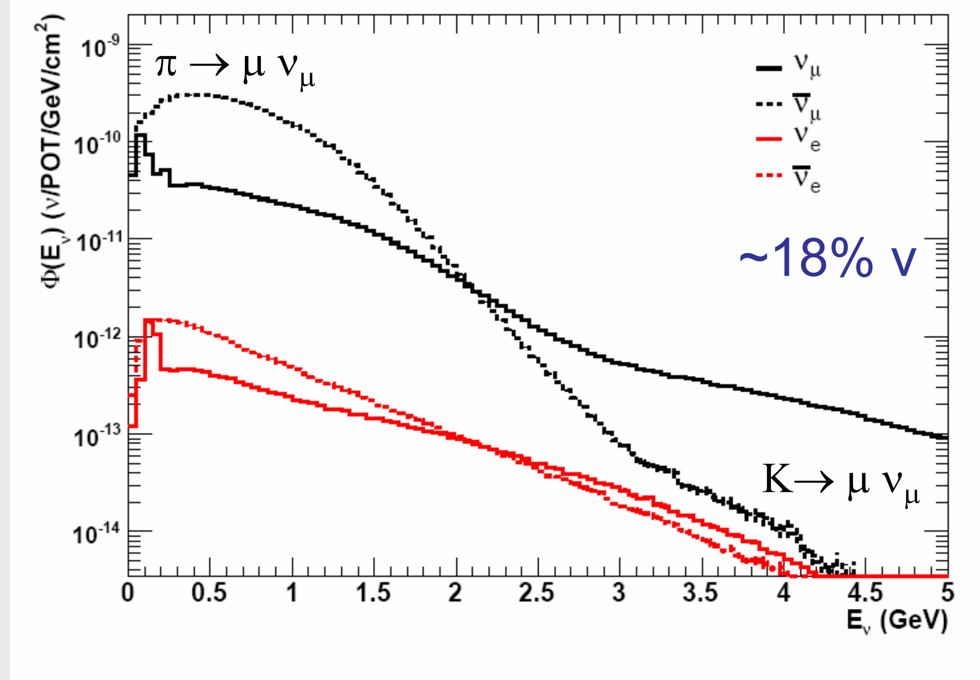
MiniBooNE experiment

Appearance experiment: it looks for an excess of electron neutrino events in a predominantly muon neutrino beam

ν mode flux



$\bar{\nu}$ mode flux

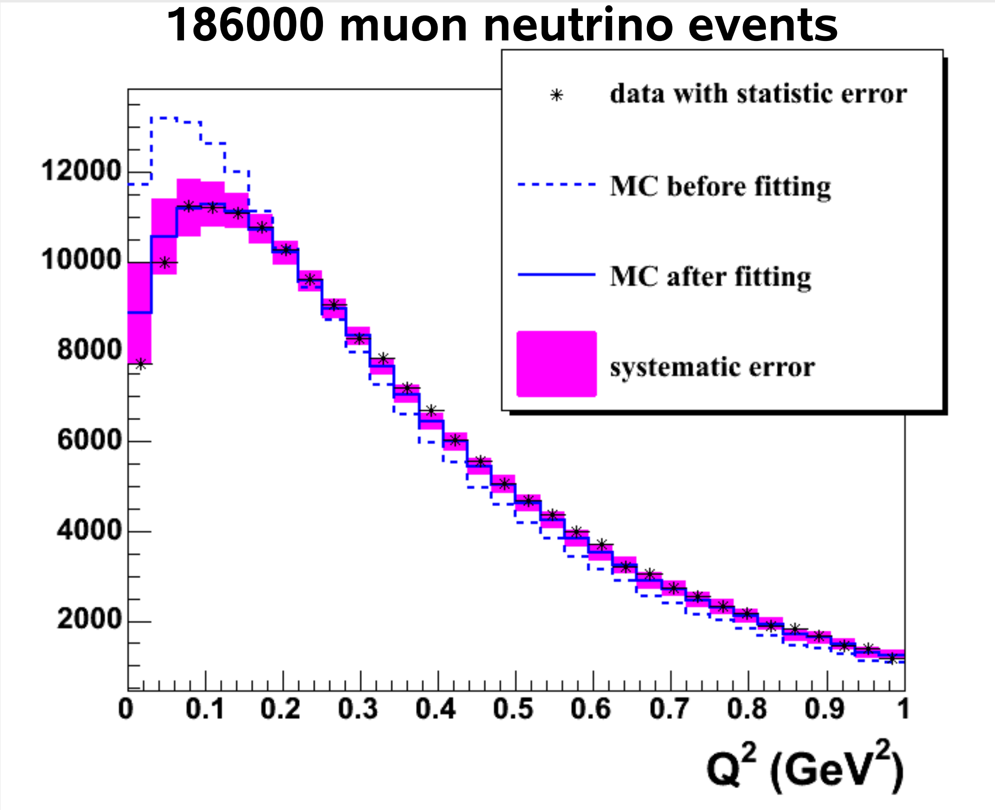


Subsequent decay of the **μ+ (μ-)** produces $\boldsymbol{\nu_e}$ $(\boldsymbol{\bar{\nu}_e})$ intrinsics ~0.5%

neutrino mode: $\nu_\mu \rightarrow \nu_e$ oscillation search

antineutrino mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation search

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

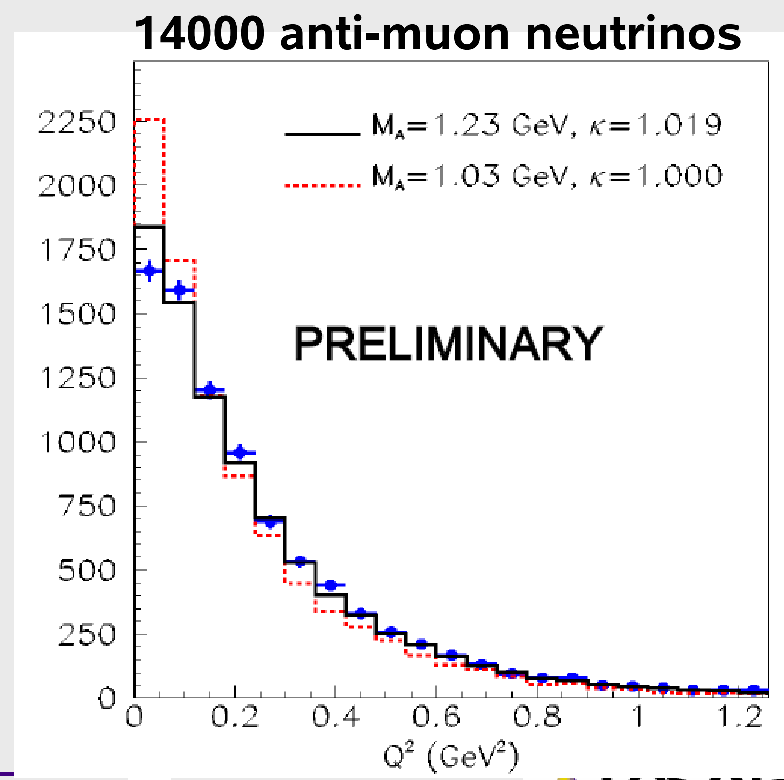
p_f -- Fermi momentum

Fermi Gas Model describes CCQE ν_μ data well

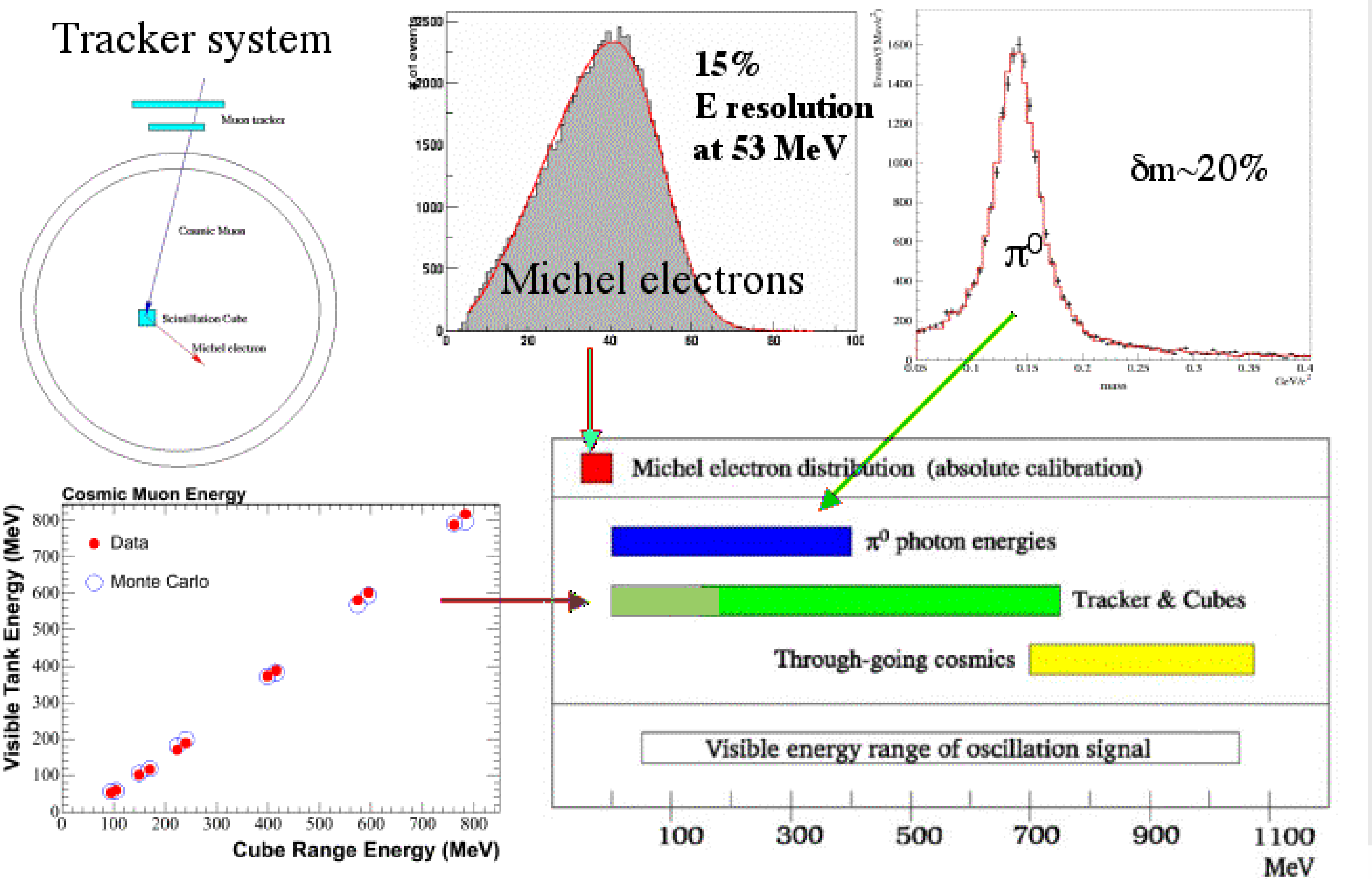
M_A = 1.23+-0.20 GeV

κ = 1.019+-0.011

Also used to model ν_e and $\bar{\nu}_e$ interactions

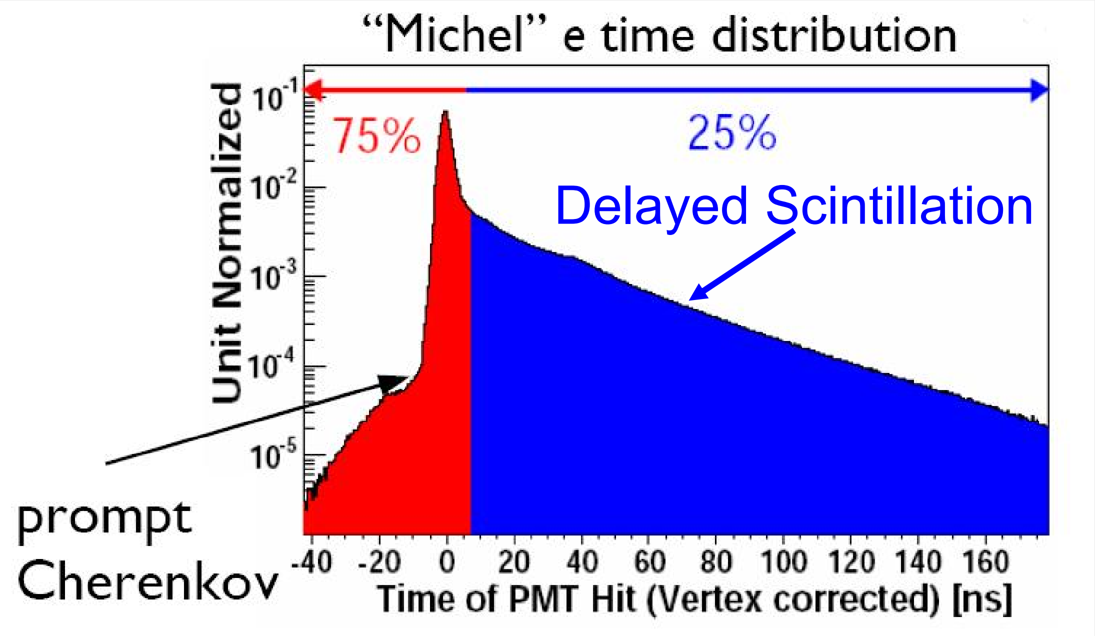


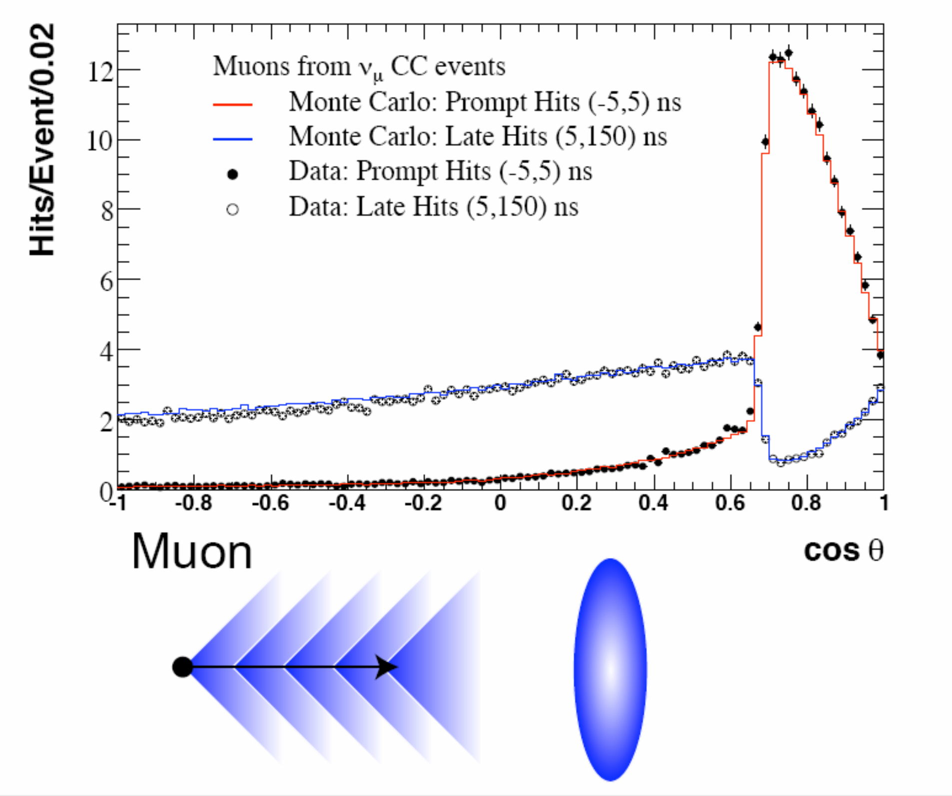
Calibration Sources

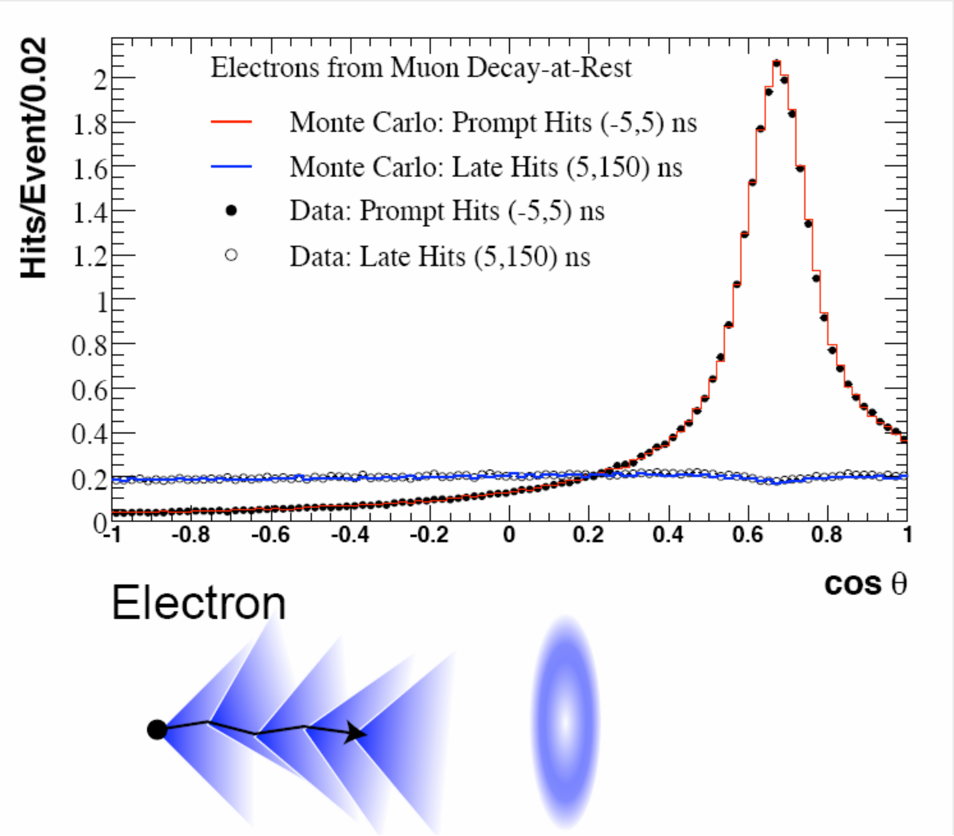


Event Reconstruction

- 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

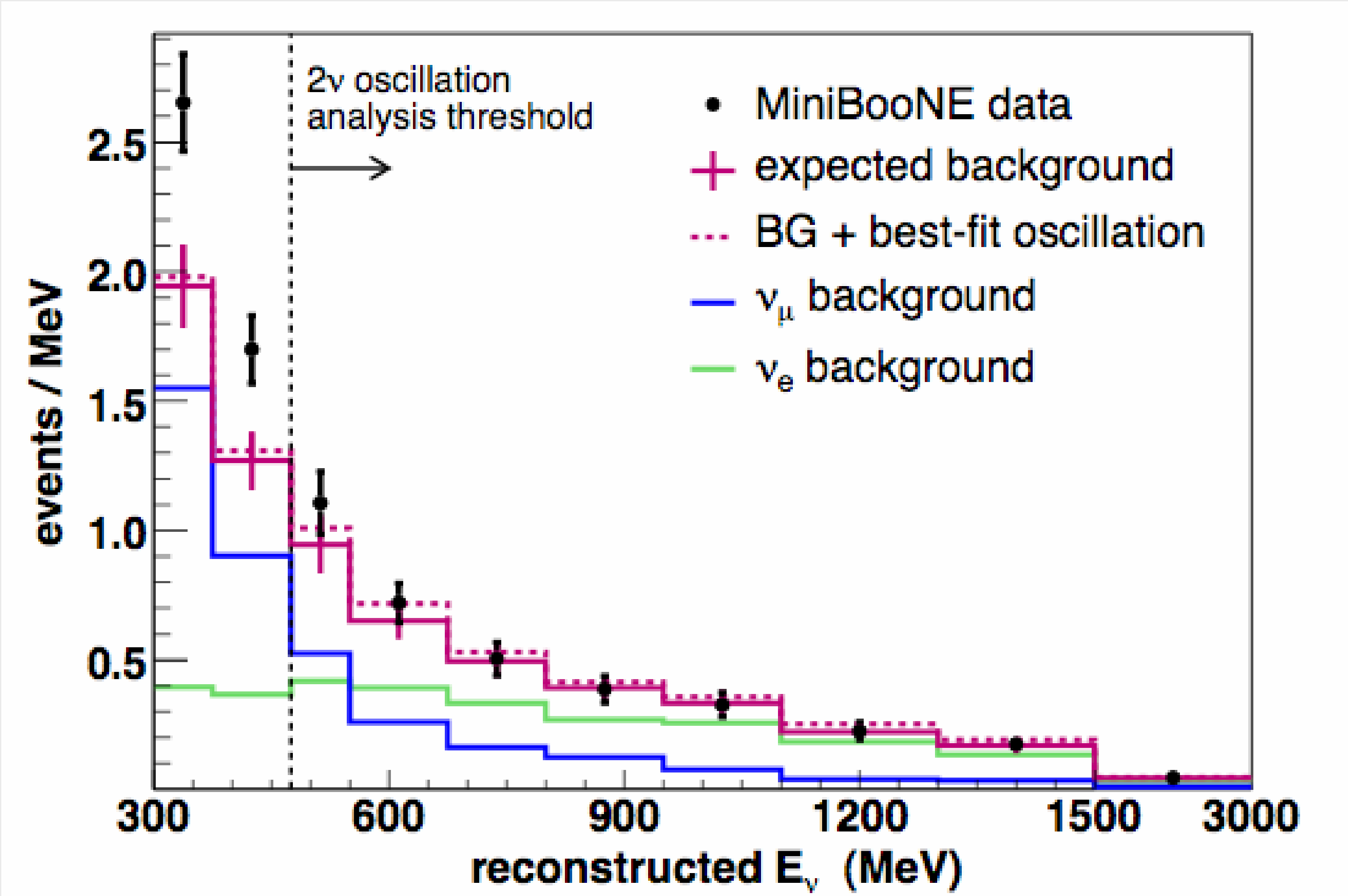






First $\nu_\mu \rightarrow \nu_e$ Oscillation Result from One year ago.

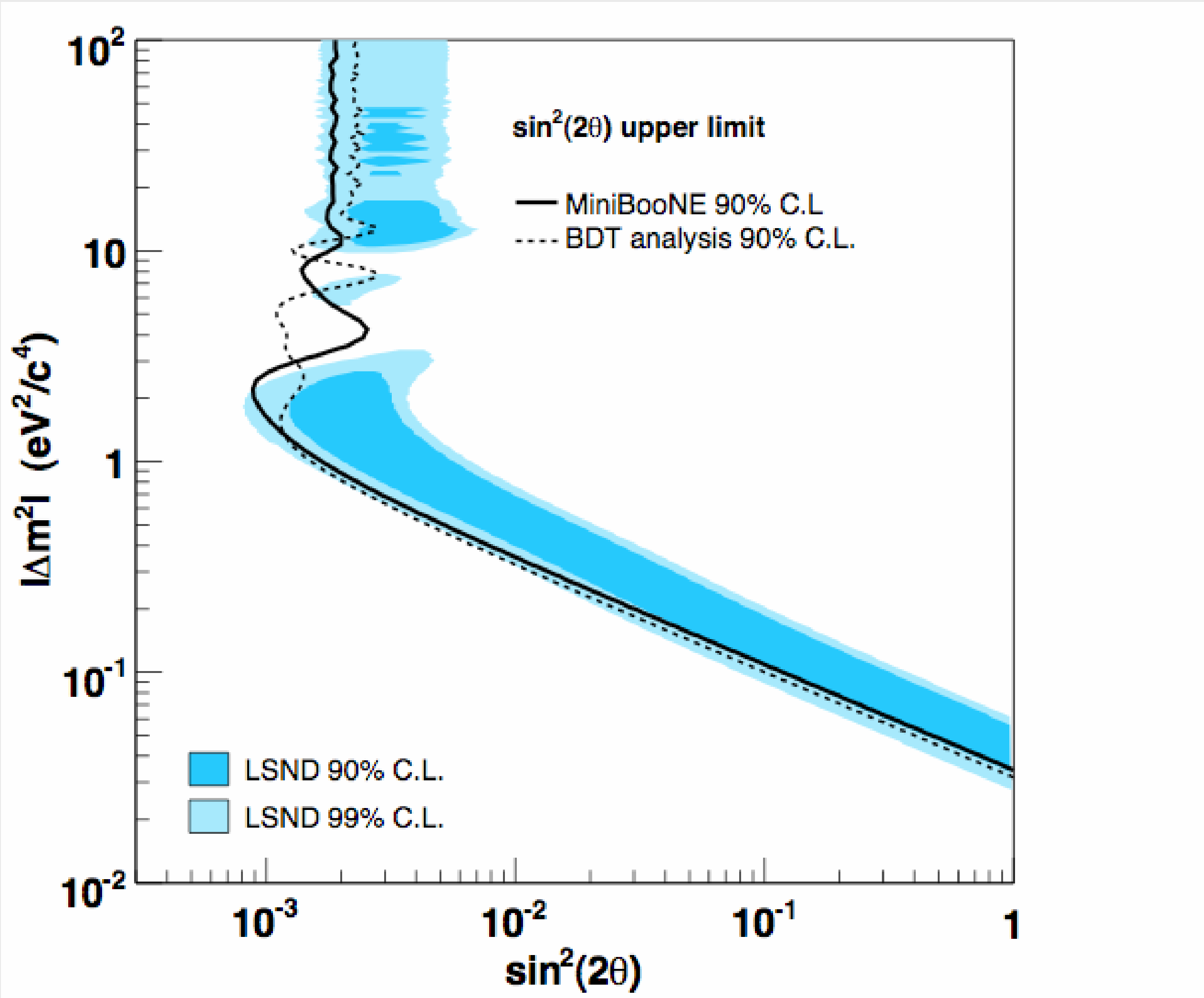
The Track-based $\nu_\mu \rightarrow \nu_e$ Appearance-only Result:



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

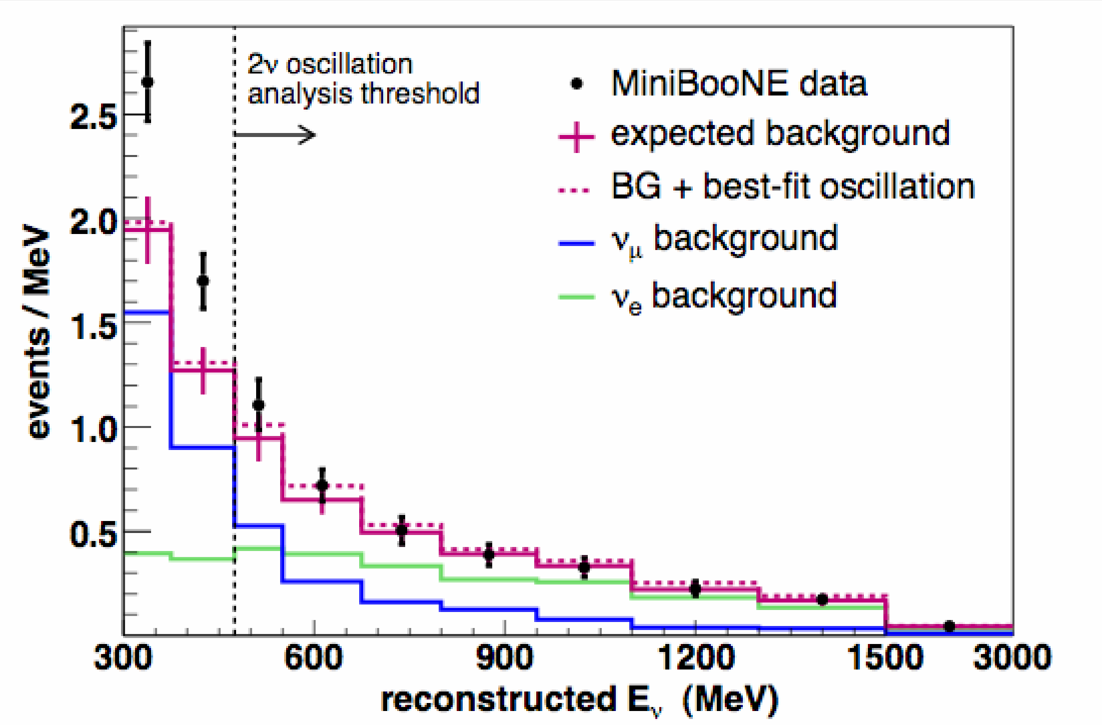
Phys. Rev. Lett. 98, 231801 (2007)



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

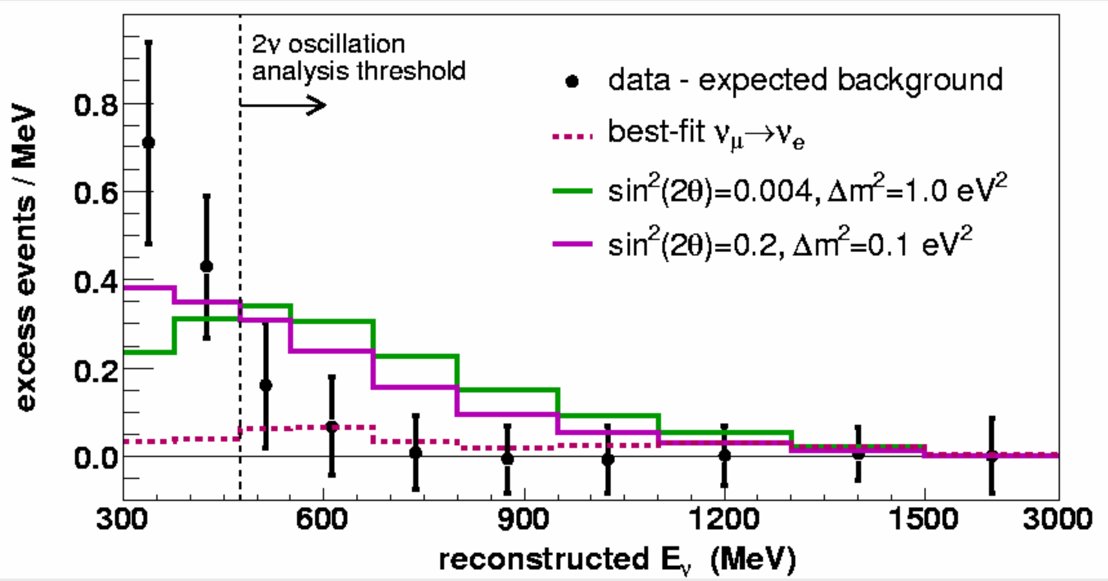
Energy fit: $475 < E_\nu^{QE} < 3000$ MeV

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.

Investigation 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, $\Delta \to N\gamma$, etc.)
- Improved π^0 (coherent) production incorporated.
- Better handling of the radiative decay of the Δ resonance
- Photo-nuclear interactions included.
- 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, $\Delta \to N\gamma$, etc).
- Additional data set included in new results:

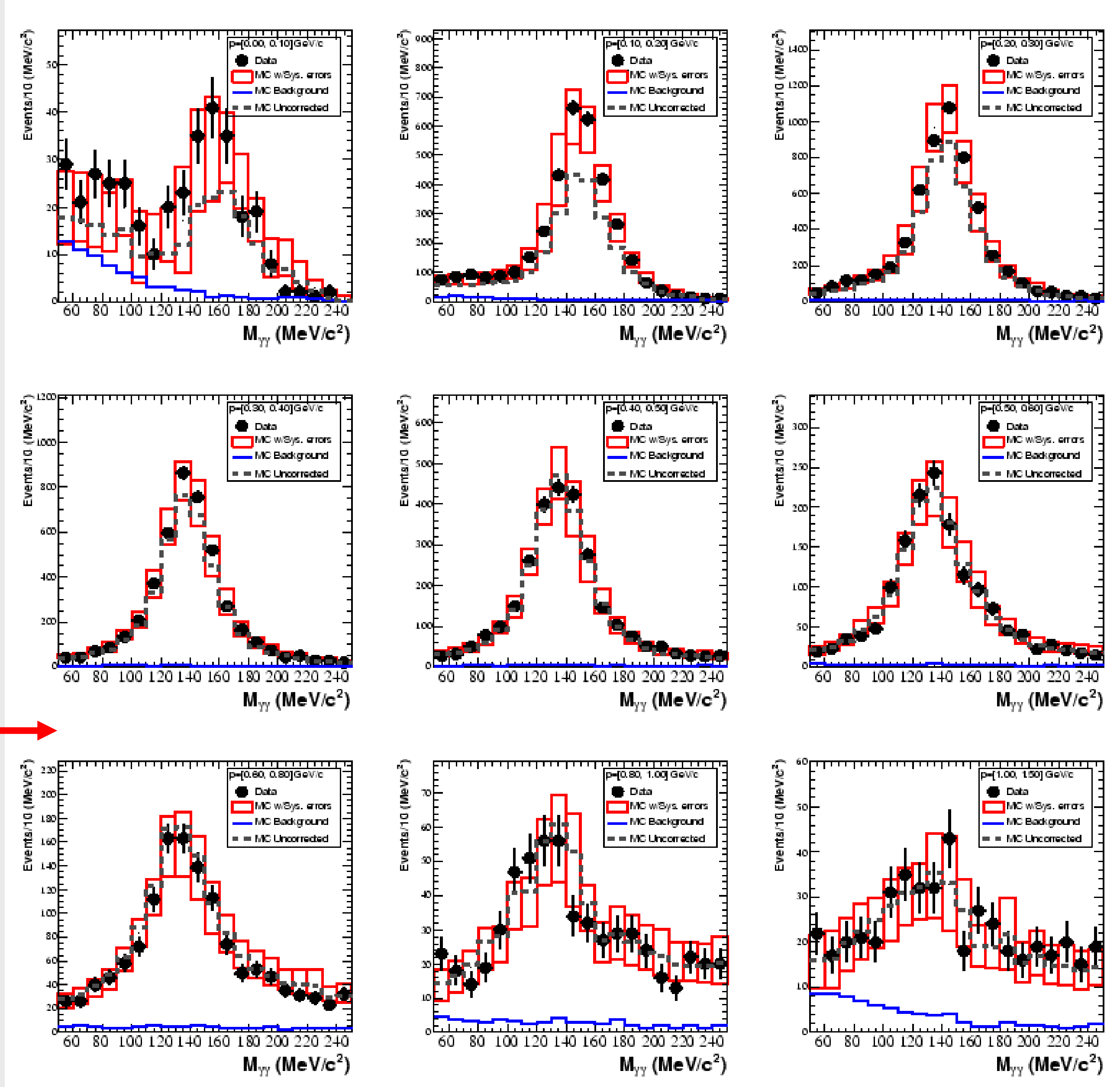
  Old analysis: 5.58×10^{20} protons on target.

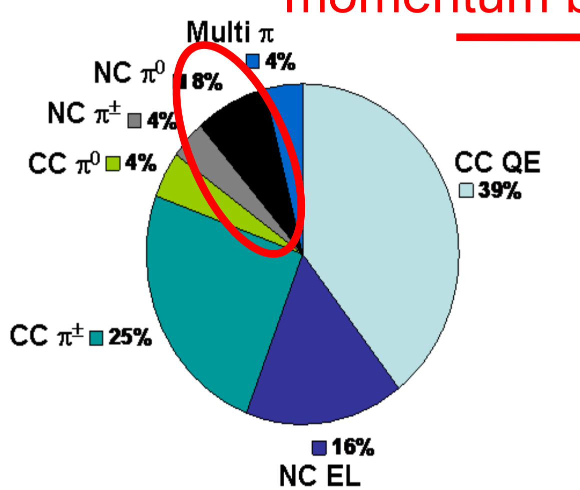
  New analysis: 6.46×10^{20} protons on target.

Tuning the MC on internal NC π^0 data

- NC π^0 important background
- 90%+ pure π^0 sample
- Measure rate as function of momentum
- Default MC underpredicts rate at low momentum
- $\Delta \rightarrow N\gamma$ also constrained

Invariant mass distributions in momentum bins

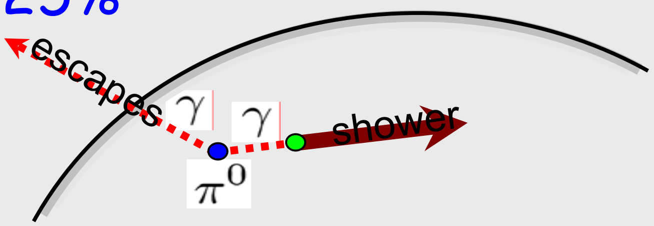




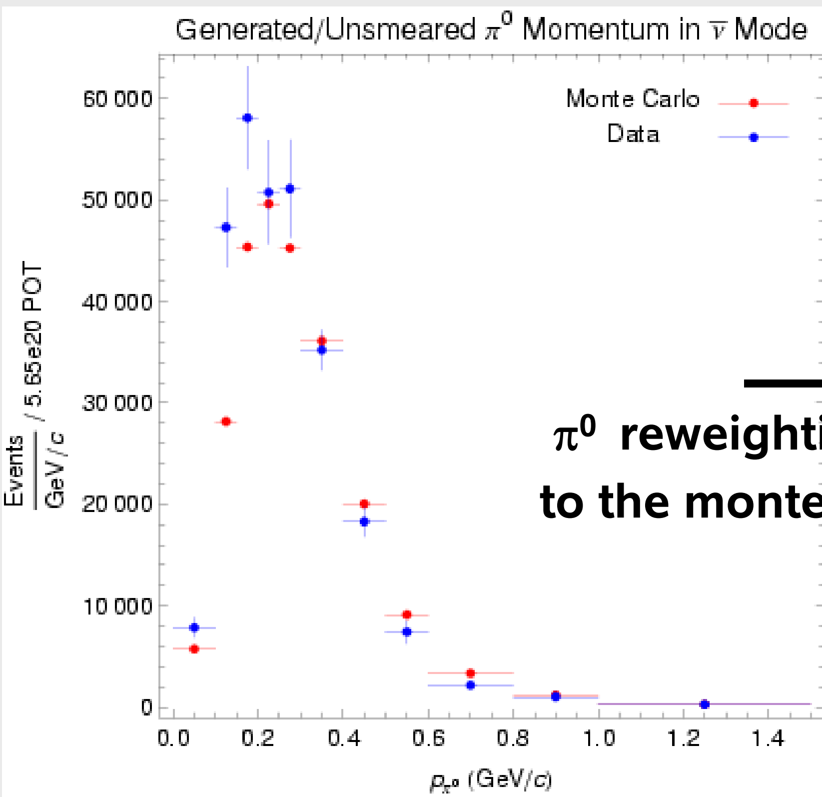
Measuring π^0 and constraining misIDs from π^0

π^0 rate measured to a few percent. Critical input to oscillation analysis: without constraint π^0 errors would be ~ 25%

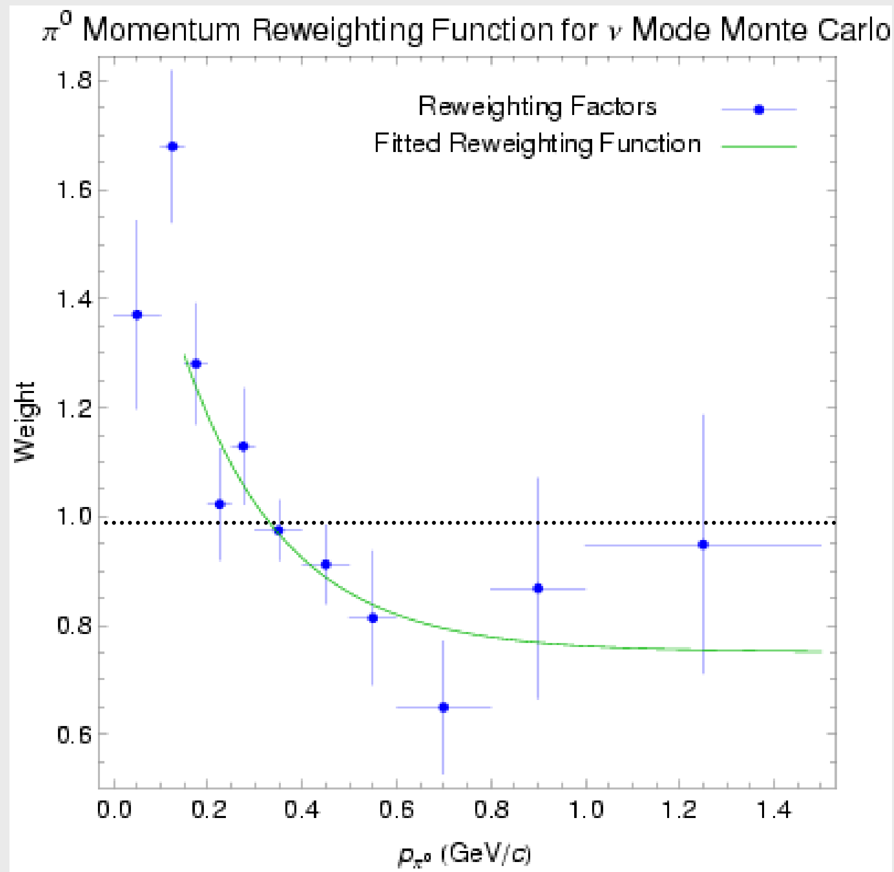
Phys.Lett.B664, 41(2008)



The π^0's constrains the Δ resonance rate, which determines the rate of $\Delta \to N\gamma$.



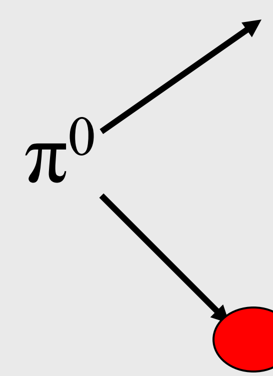
π^0 reweighting applied to the monte carlo



Pion analysis rechecked, only small changes made

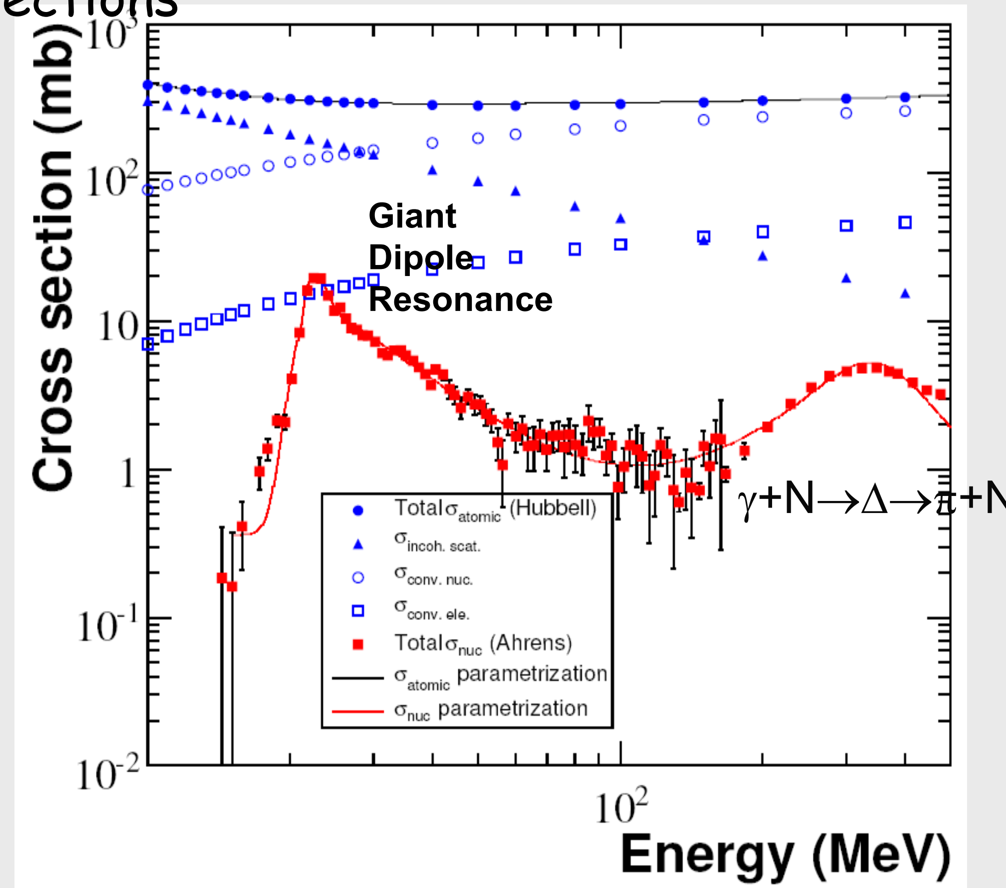
Photonuclear absorption of π^0 photon

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

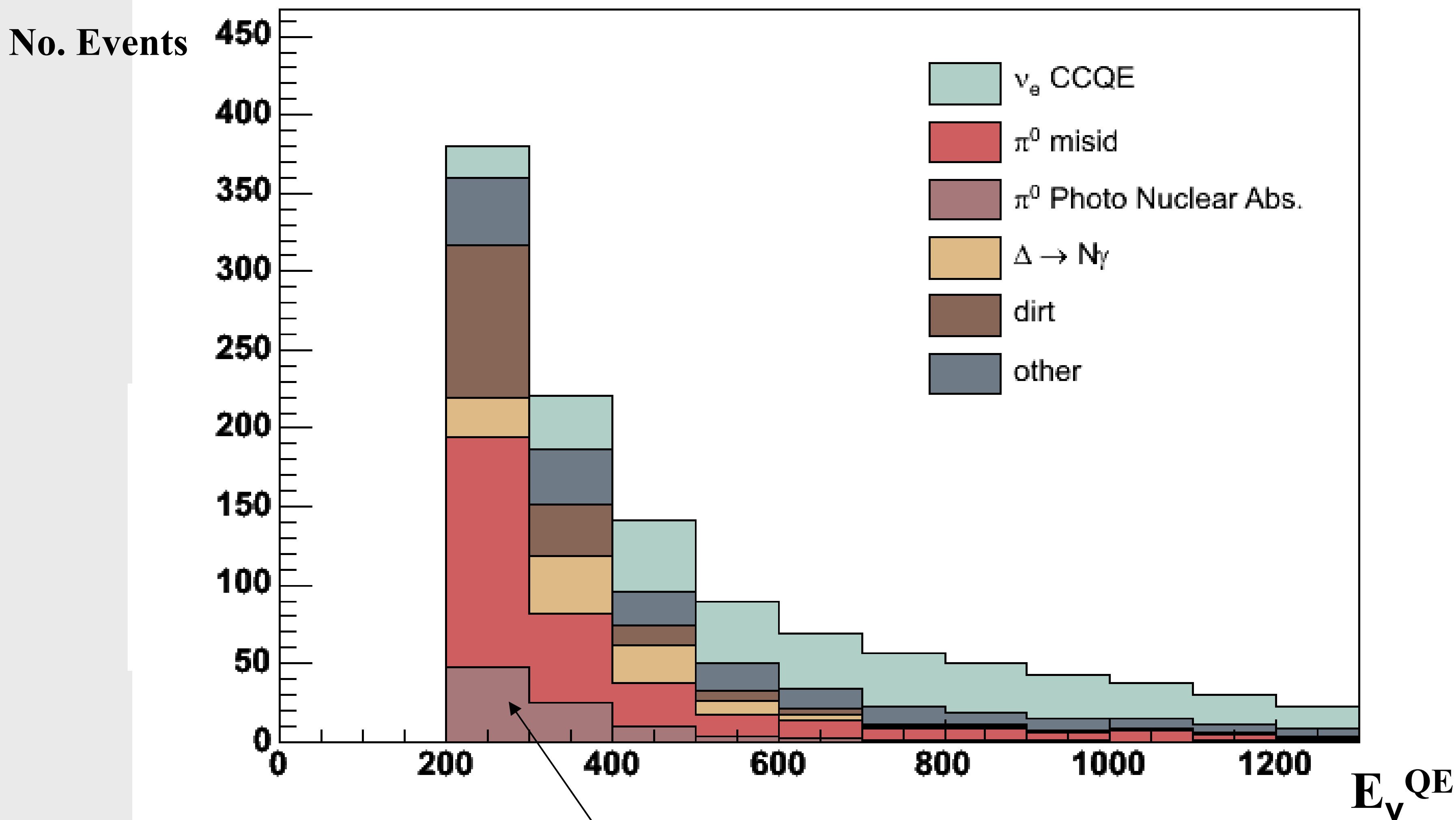
- Total photonuclear absorption cross sections on Carbon well measured.



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

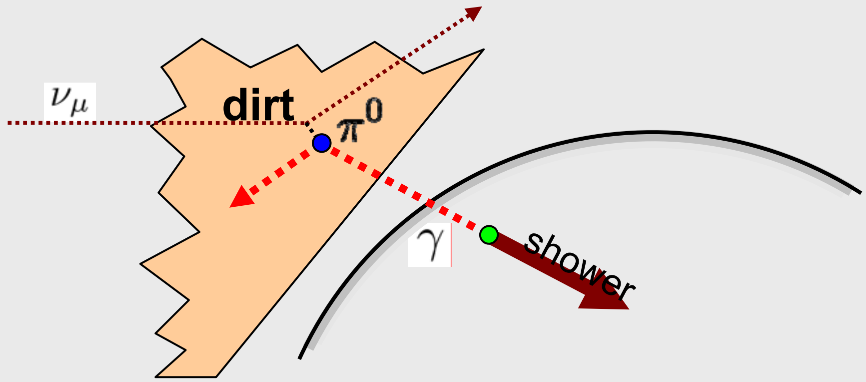
Estimated Effects of Photonuclear Absorption

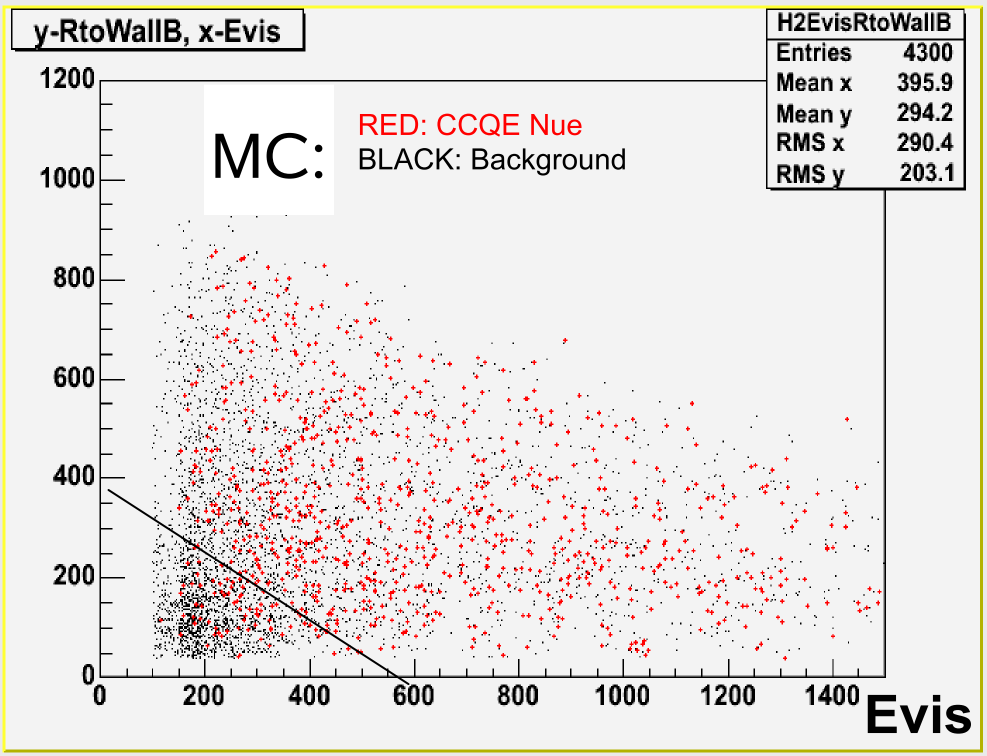


Photonuke adds ~25% to pion background in the 200 <E < 475 MeV region

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

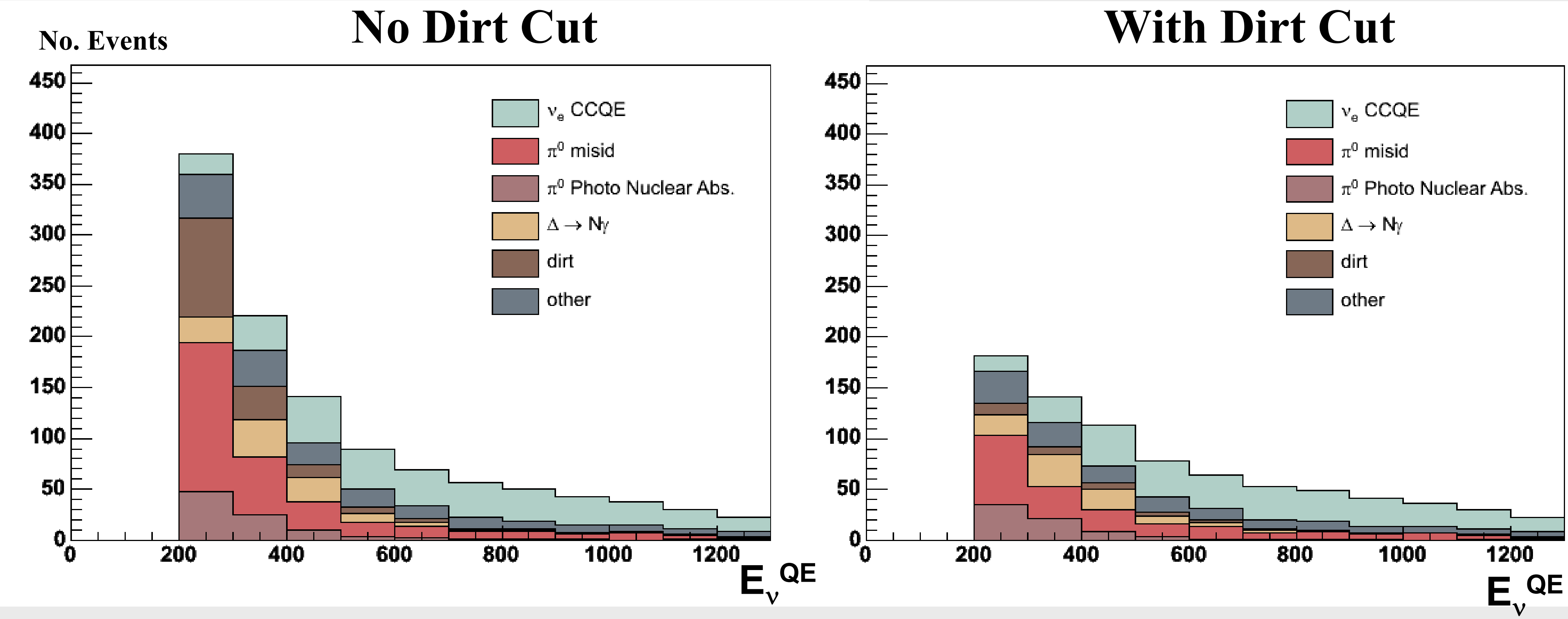
Add a new cut on distance to wall in the track backwards direction, optimized in bins of visible energy.

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

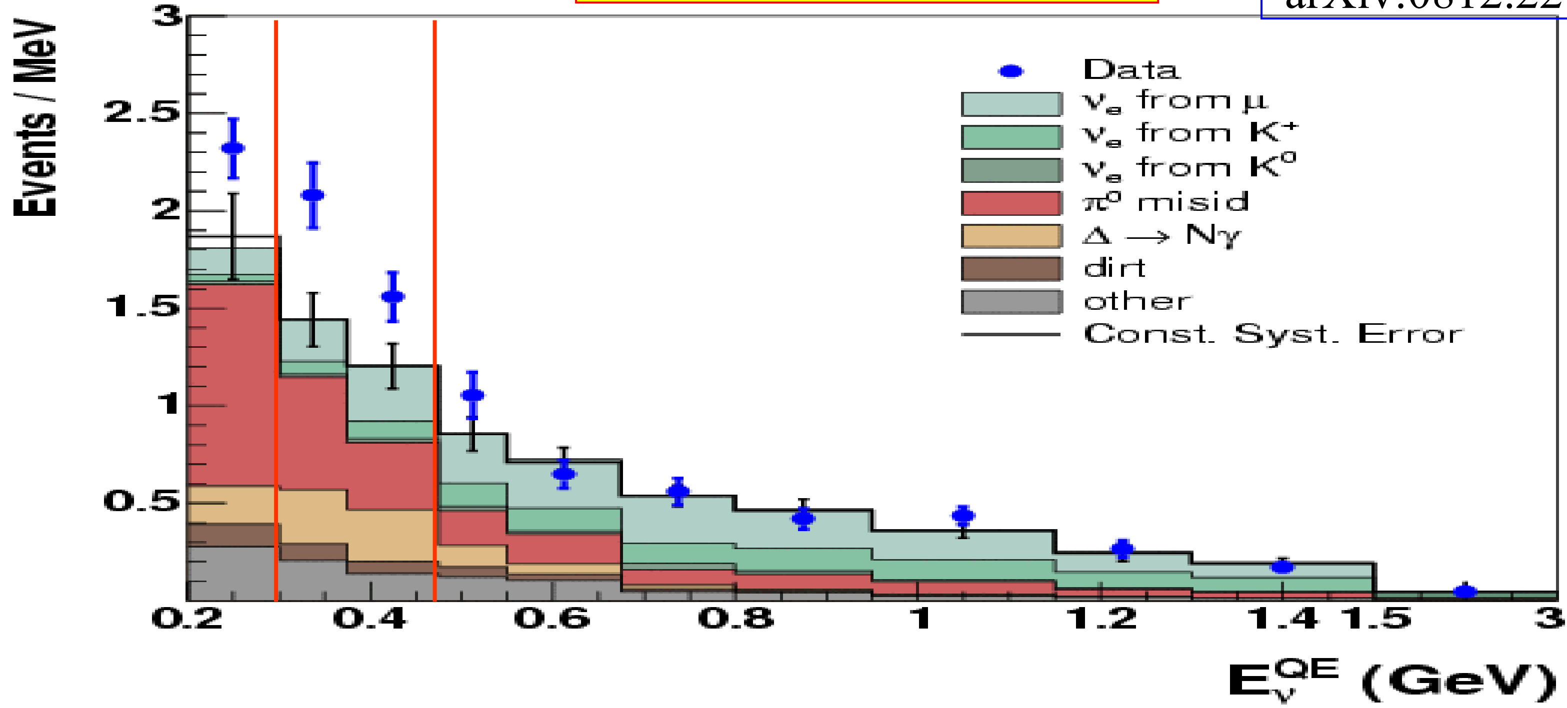
Source of Uncertainty On ν_e background	Track Based error in % 200-475 MeV	Track Based error in % 475-1250 MeV	Checked or Constrained by MB data
Flux from π^+/μ^+ decay	1.8	2.2 **	√
Flux from K^+ decay	1.4	5.7	√
Flux from K^0 decay	0.5	1.5	√
Target and beam models	1.3	2.5	
ν-cross section	5.9	11.8	√
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

Similar errors for antineutrino mode

New Results

submitted to PRL
arXiv:0812.2243 [hep-ex]



MC background prediction includes statistical and systematic error

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 $\Delta \rightarrow N\gamma$	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

"other" mostly muon mid-ID's

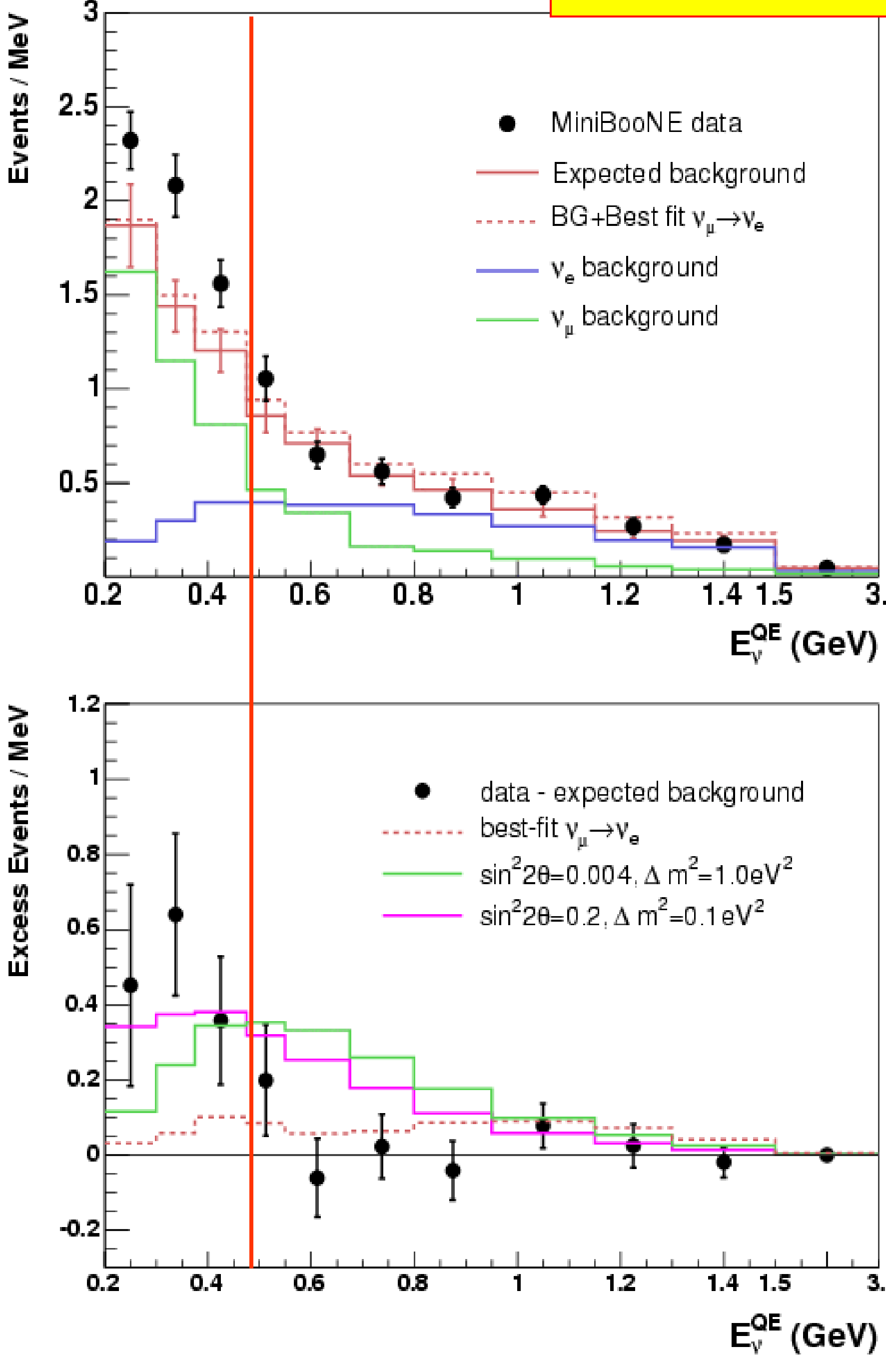
The excess at low energy remains significant!

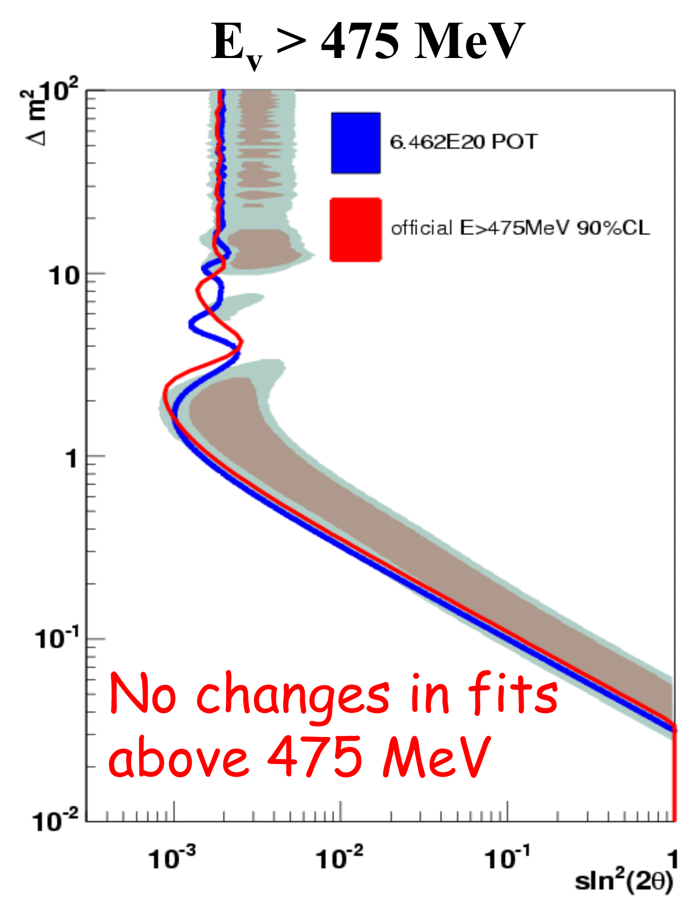
Excess Significance For Different Analysis

Event Sample	Analysis 1 Original analysis 5.58E20 POT	Analysis 2 Revised analysis 5.58E20 POT	Analysis 3 Revised Analysis 6.46E20 POT	Analysis 4 Revised Analysis 6.46E20 POT With DIRT cuts
$200 - 300$ 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

Oscillation Fit Check

475 MeV





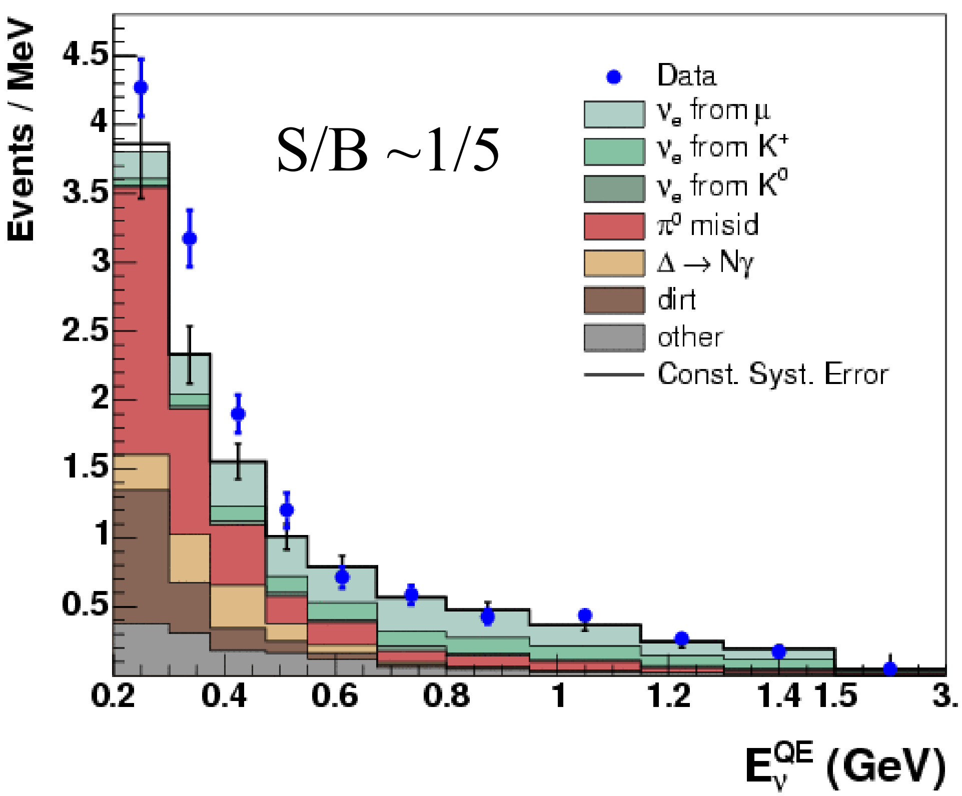
	E_ν>475 MeV	E_ν>200 MeV
Null fit χ^2 (prob.):	9.1(91%)	22(28%)
Best fit χ^2 (prob.):	7.2(93%)	18.3(37%)

Inclusion of low energy excess does not improve oscillation fits

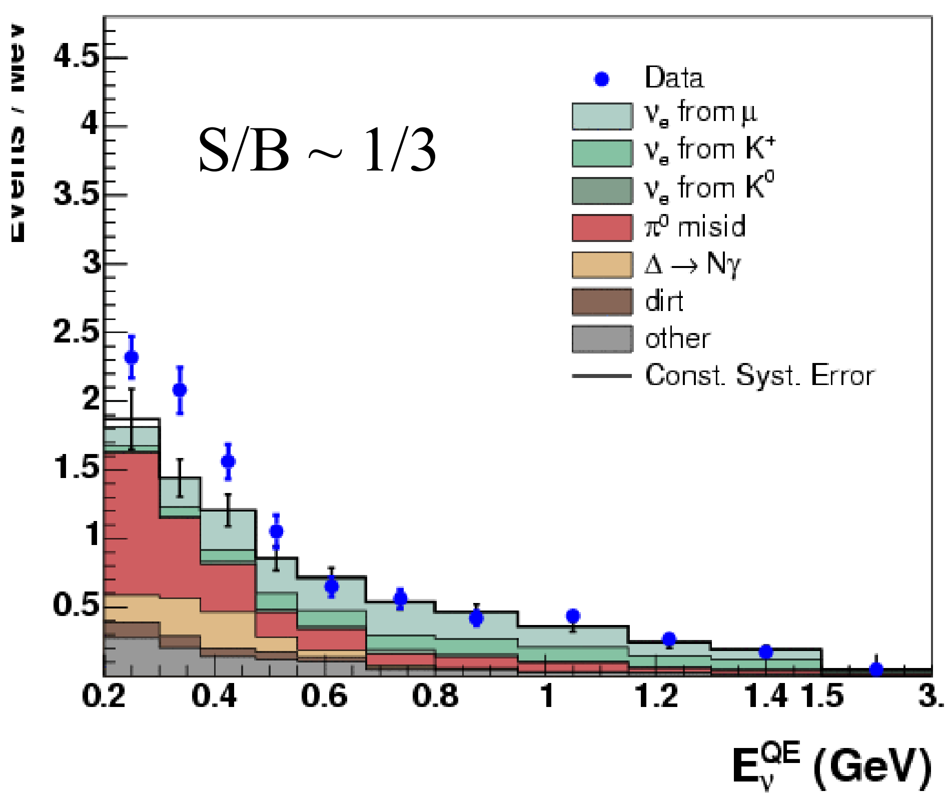
Properties of the Excess
Is it Signal like?

Dirt Cuts Improves Signal/Background

No DIRT cuts

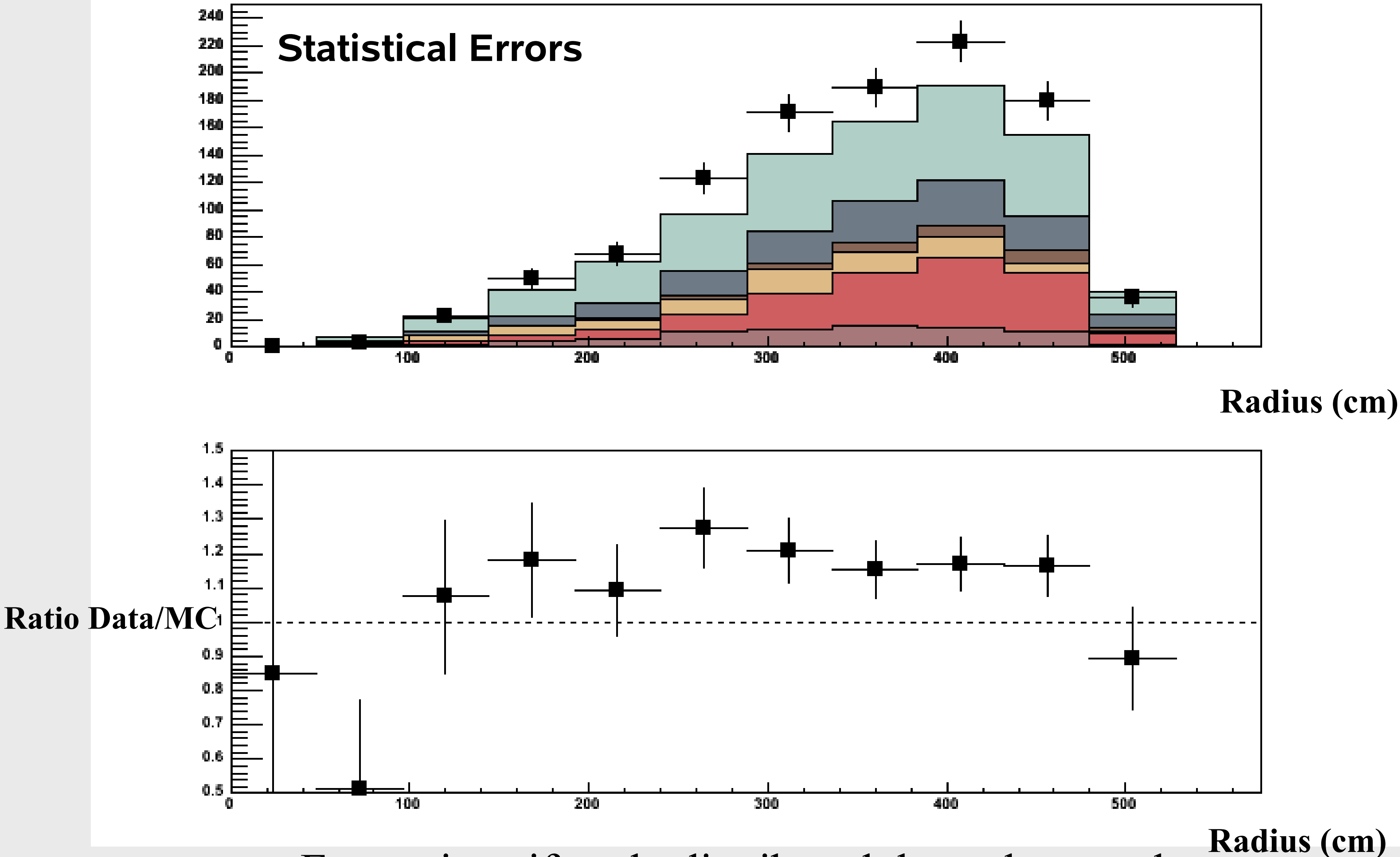


With DIRT Cuts



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

Reconstructed Radius



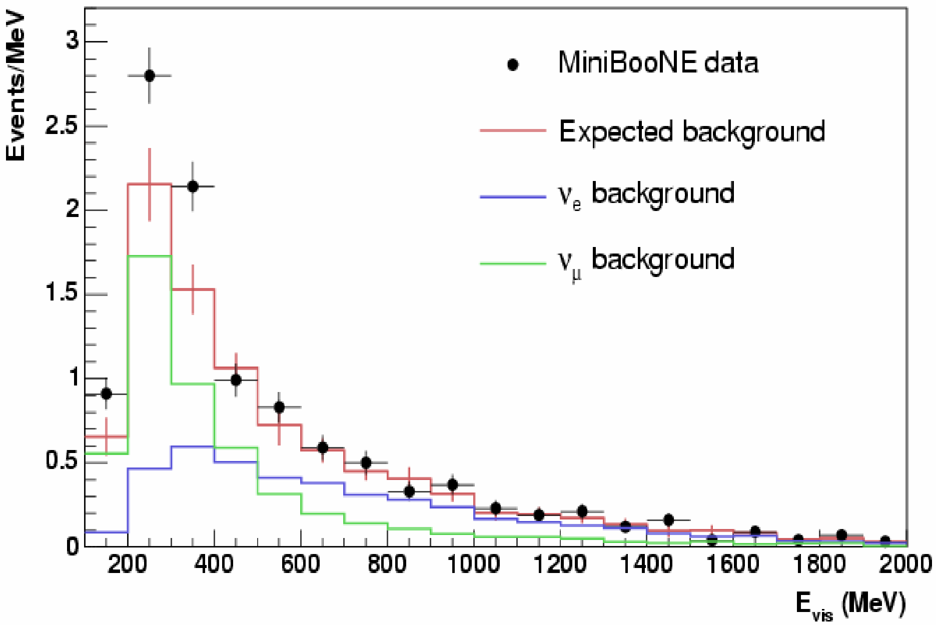
Excess is uniformly distributed throughout tank.

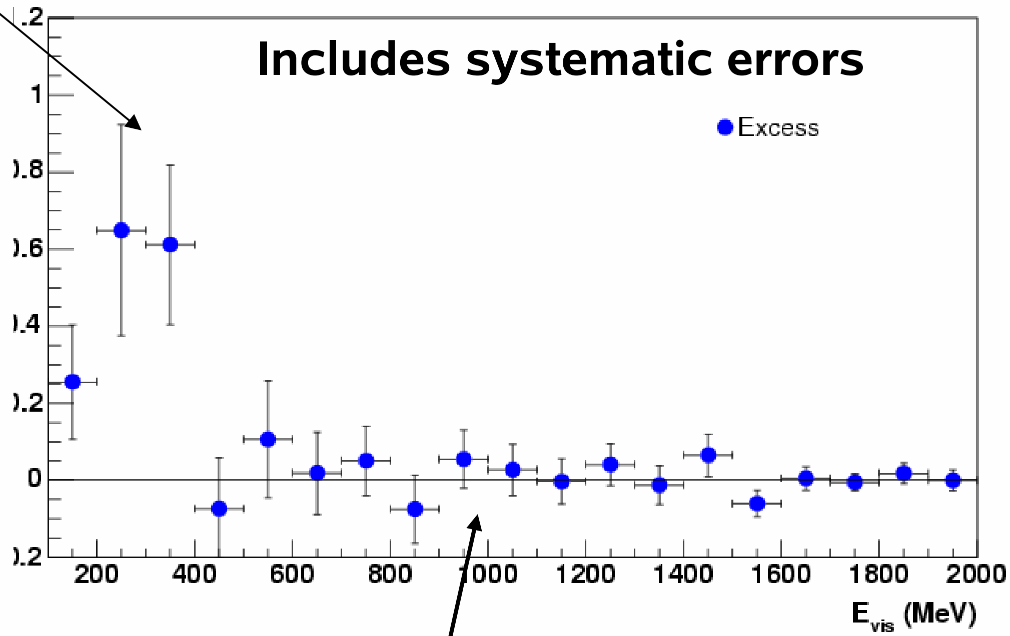
-consistent with neutrino induced interactions

Reconstructed Visible Energy (E_{vis})

Pronounced excess/peak

From 140 - 400 MeV



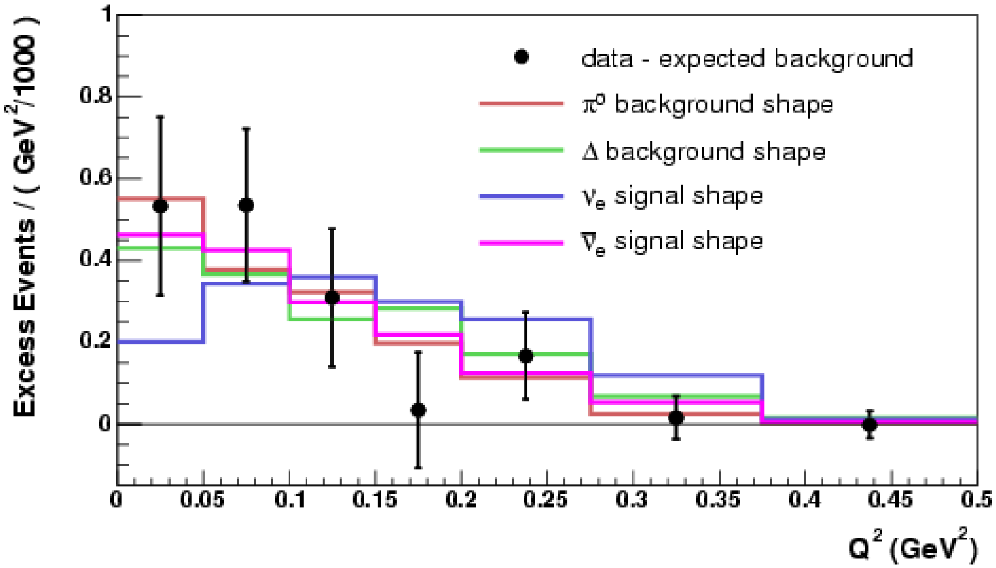


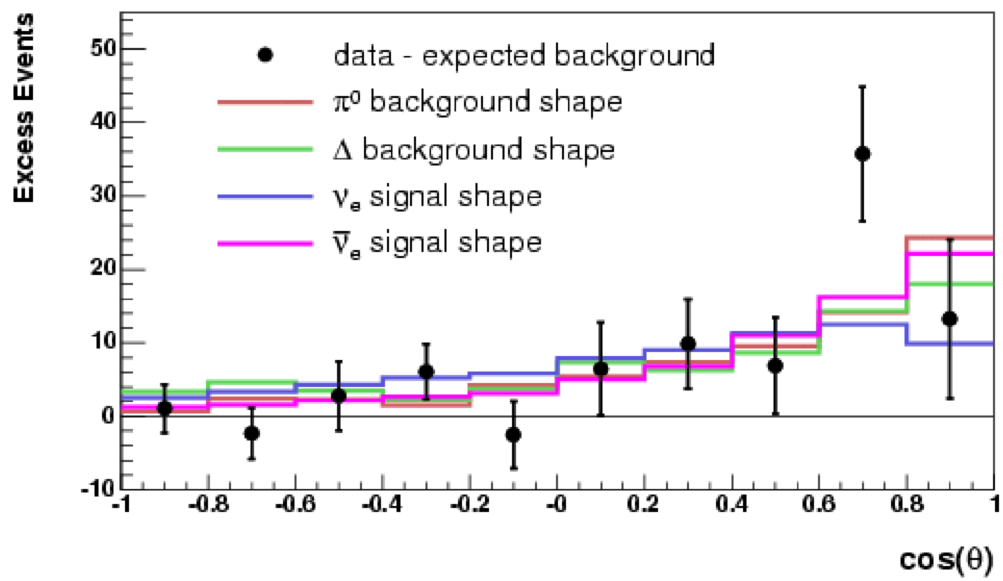
Excellent agreement

for Evis > 400 MeV

Also look at other kinematic distributions, e.g. Q^2, $\cos\theta_{beam}$

Reconstructed Q**2 and Cos(θ_{beam})





Process	$\chi^2(cos\theta)/9$ DF	$\chi^2(Q^2)/6$ DF	Factor Increase
NC π^0	13.46	2.18	2.0
$\Delta \to N\gamma$	16.85	4.46	2.7
$\nu_e C \to e^- X$	14.58	8.72	2.4
$\bar{\nu}_e C \to e^+ X$	10.11	2.44	65.4

Individual processes require >5σ increase to account for excess.

.

What is the Source of the Excess?

-consistent with neutrino induced electrons or gamma-rays.

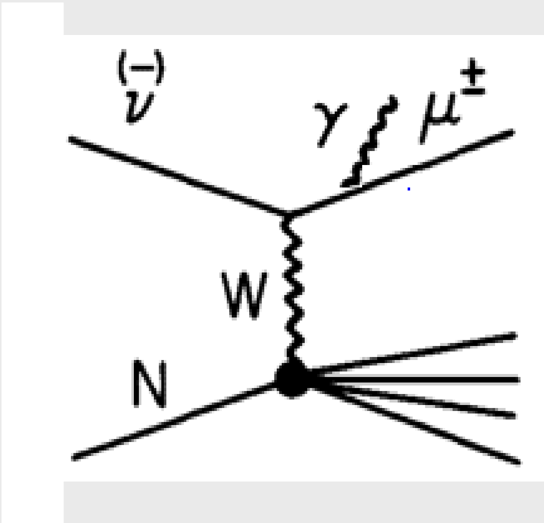
Is MiniBooNE Low Energy Excess consistent with LSND??

- LSND assumed excess was two neutrino oscillations,
  - $\text{Prob}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta)\,\sin^2(1.27\ \Delta m^2\ L/E)$
- 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.
- Rates: LSND measures $\text{Prob}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.25 \pm 0.08)\ \%$, MiniBooNE measures $\text{Prob}(\nu_\mu \rightarrow \nu_e) = (0.17 \pm 0.07)\%$
  - Yes, appearance rates consistent!
- Spectrum: MiniBooNE excess fails two neutrino oscillation fits to reconstructed neutrino energy.
  - No, energy fit not consistent!!

The low E excess has fueled much speculation...

Commonplace

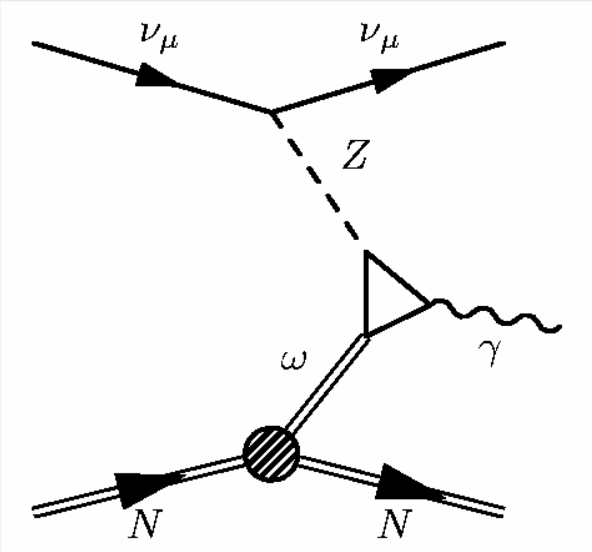
- Muon bremstrahlung
  (Bodek, 0709.4004)



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

SM, but odd

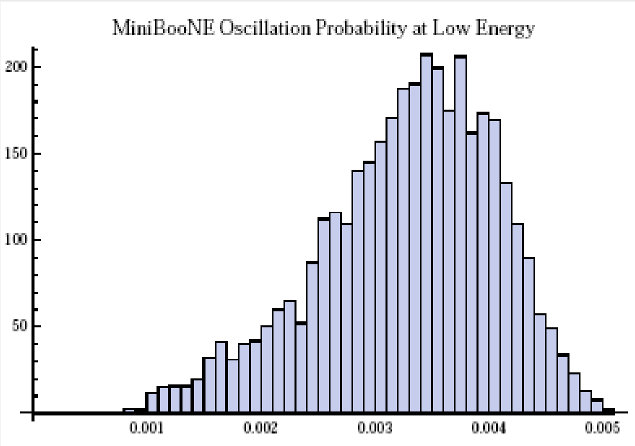
- Anomaly-mediated γ
  (Harvey, Hill, Hill, 0708.1281)



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

Beyond the SM

- New gauge boson
  (Nelson, Walsh,0711.1363)

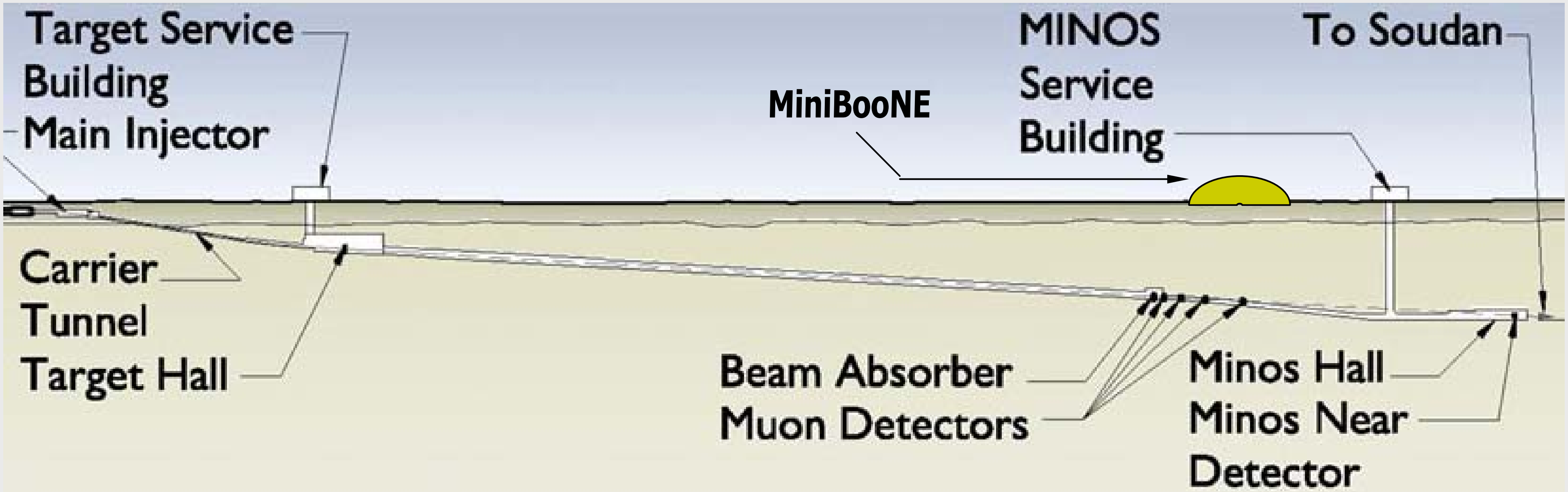


- Firm prediction for anti-neutrinos
- Many other beyond the Standard Model ideas.

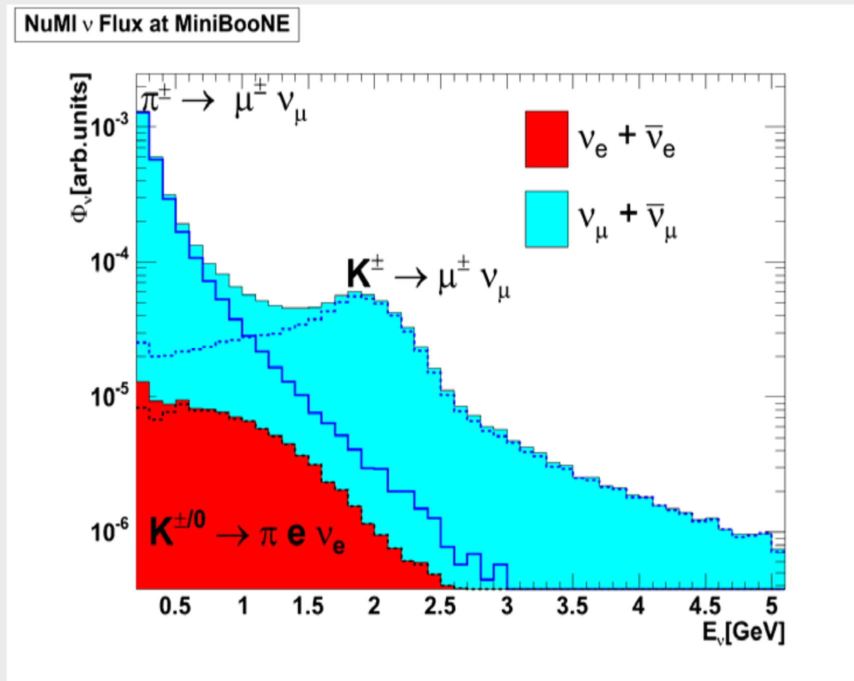
Other Data Sources

- Limitations of MiniBooNE:
  - We do not have two similar detectors at different distances 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, results soon.
  - Off axis neutrinos from NuMI -- ν_e rich source, test cross sections and PID.
  - Anti-neutrino running – test backgrounds which are similar to neutrino mode, can also test Axial Anomaly.

NuMI Events in MiniBooNE



The beam at MiniBooNE from NuMI is significantly enhanced in ν_e from K decay because of the 110 mrad off-axis position. MiniBooNE is 745m from NuMI target



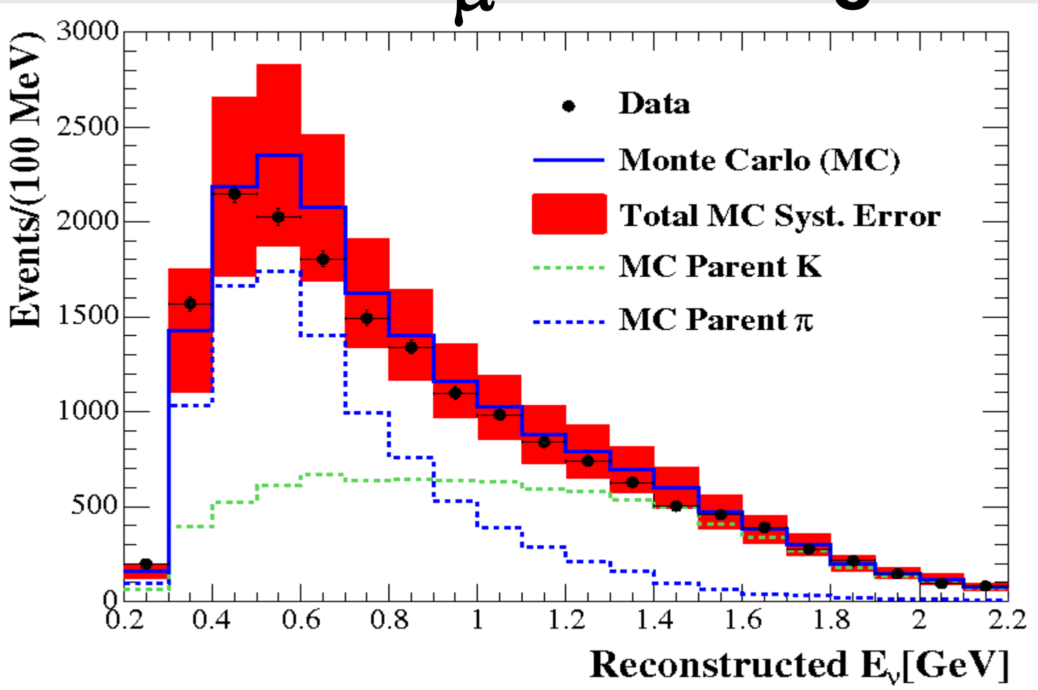
NuMI event rates:

ν_μ: 81% ν_e: 5% $\bar{\nu}_\mu$: 13% $\bar{\nu}_e$: 1%

NuMI ν_μ and ν_e Data

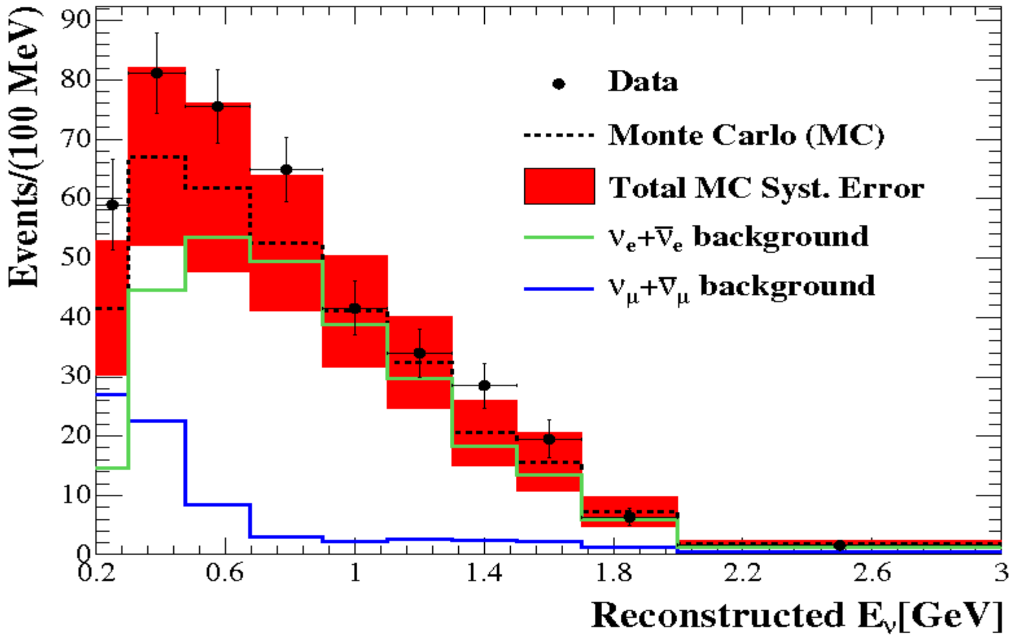
arXiv:0809.2447v1

ν_μ CCQE sample



Good agreement between data and Monte Carlo:the MC is tuned well.

ν_e CCQE sample



Very different backgrounds compared to MB (Kaons vs Pions)

Ongoing effort to reduce ν_e CCQE sample systematics

NuMI ν_e data provide limits on cross sections and PID

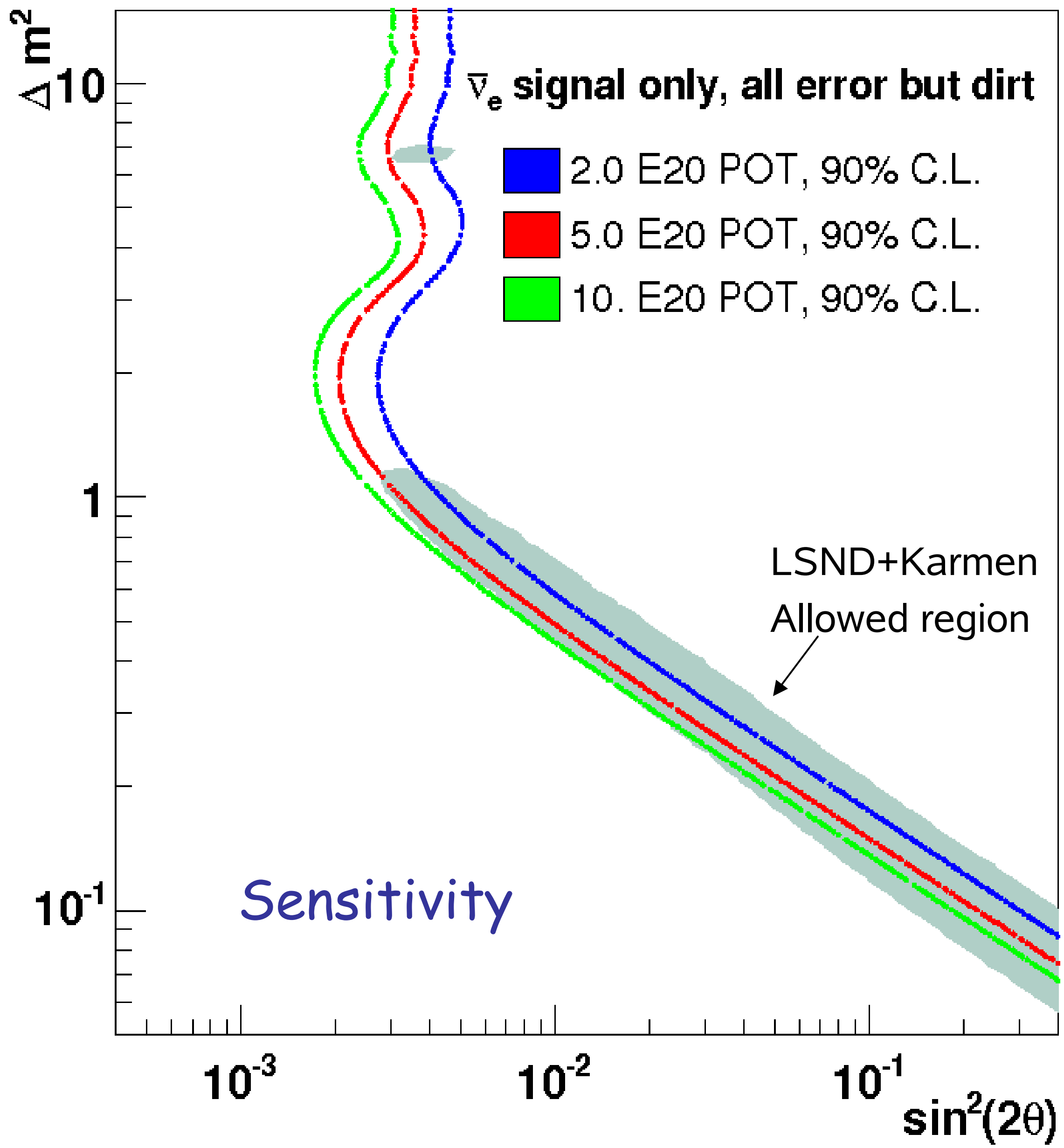
MiniBooNE Anti-neutrino Run

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.

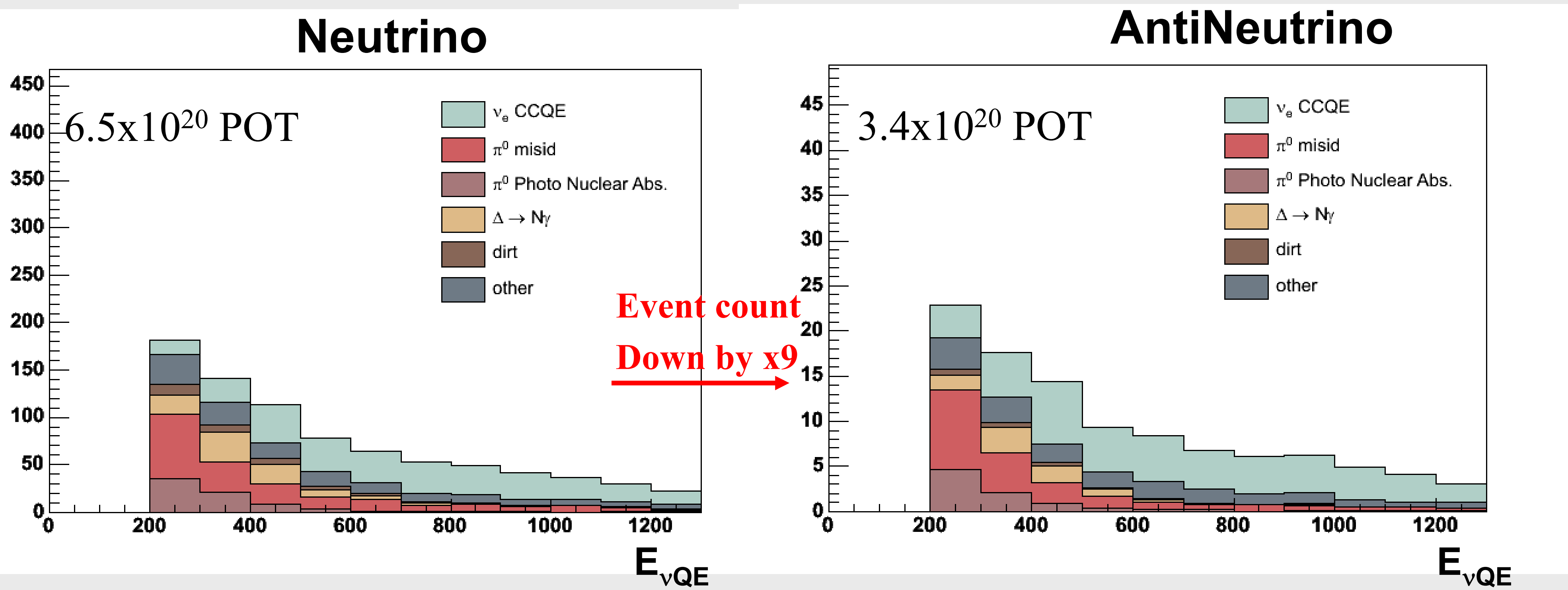
Provides additional data set for low energy excess study.

Collected ~3.4×10^{20} POT so far.
Oscillation data set "blinded".
Box opened Oct 22, 2008, results made public early December.



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 a few 10's of events.
  - Two neutrino oscillations produce ~13 events at higher energy.
- Can compare the two modes to test some of the hypotheses.

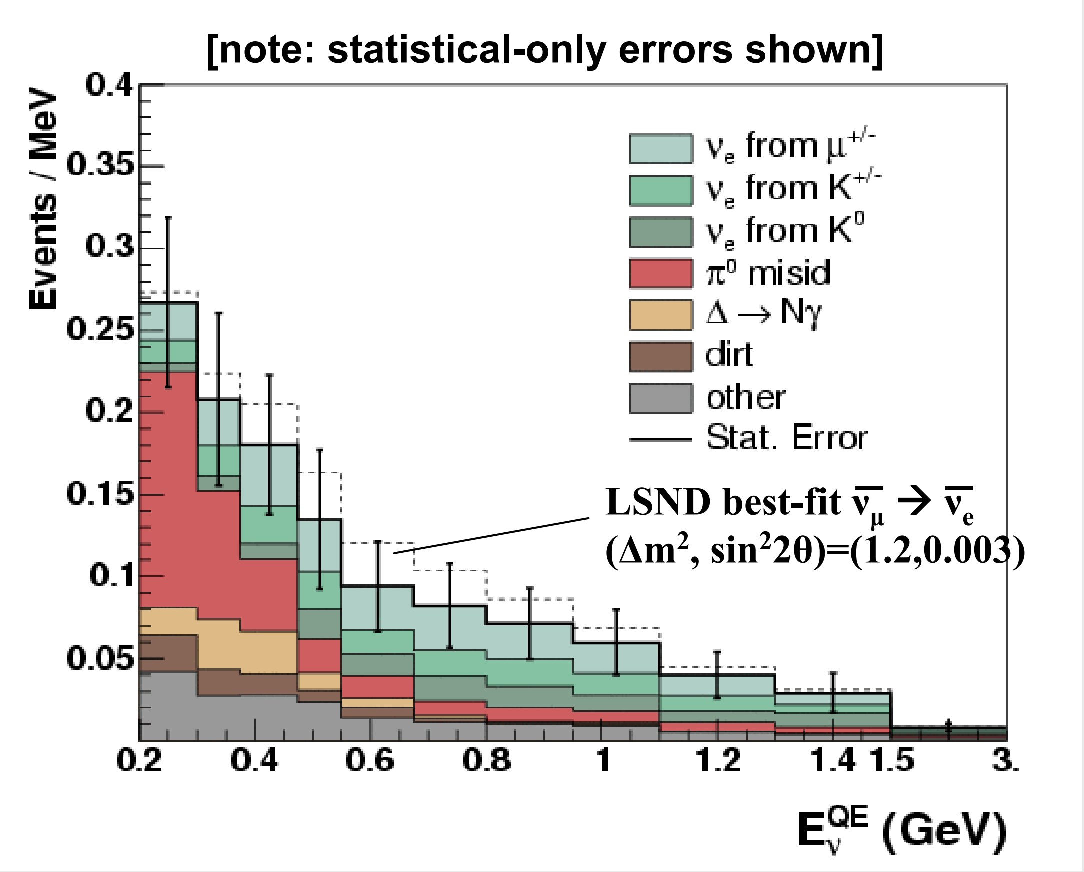
NNSA

Los Alamos

MiniBooNE $\bar{\nu}_e$ appearance analysis

Background composition for $\bar{\nu}_e$ appearance search (3.386e20 POT):

N_{events}	200-475 MeV	475-1250 MeV
intrinsic ν_e	17.74	43.23
from $\pi^{\pm}/\mu^{\pm}$	8.44	17.14
from $K^{\pm}$, K^0	8.20	24.88
other ν_e	1.11	1.21
mis-id ν_μ	42.54	14.55
CCQE	2.86	1.24
NC π^0	24.60	7.17
Δ radiative	6.58	2.02
Dirt	4.69	1.92
other ν_μ	3.82	2.20
Total bkgd	60.29	57.78
LSND best fit	4.33	12.63



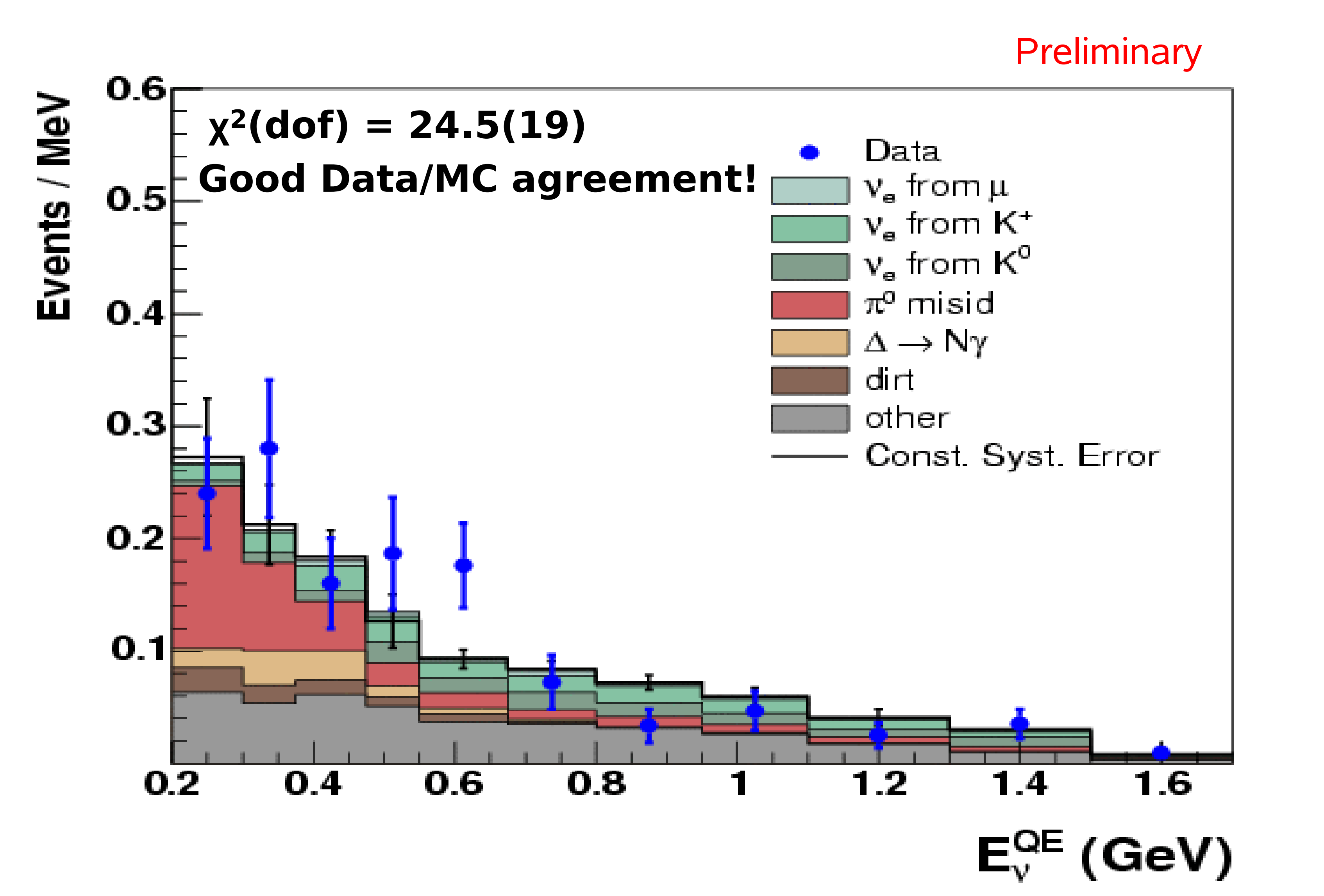
Systematic errors similar to neutrino mode. Statistical errors dominate

Assume neutrino Low E excess (129 events from 200-475 MeV), what do we expect for Antineutrinos at Low E: POT Ratio ~ 0.5, Flux Ratio ~ 0.5

- Neutral particle production in the target: scaled by POT, expect 68 events.
- Low energy Kaons: expect 40 events.
- π^0 background: xsections scale ~0.5, expect 20 events.
- CC background: xsections scale ~0.5, expect 20 events.
- Pure NC (e.g. Axial Anomaly): xsections equal, expect 37 events.
- Only neutrinos produce excess: 7 events.

Unblinding the Electron AntiNeutrino Data

Antineutrino Results (3.39e20POT)



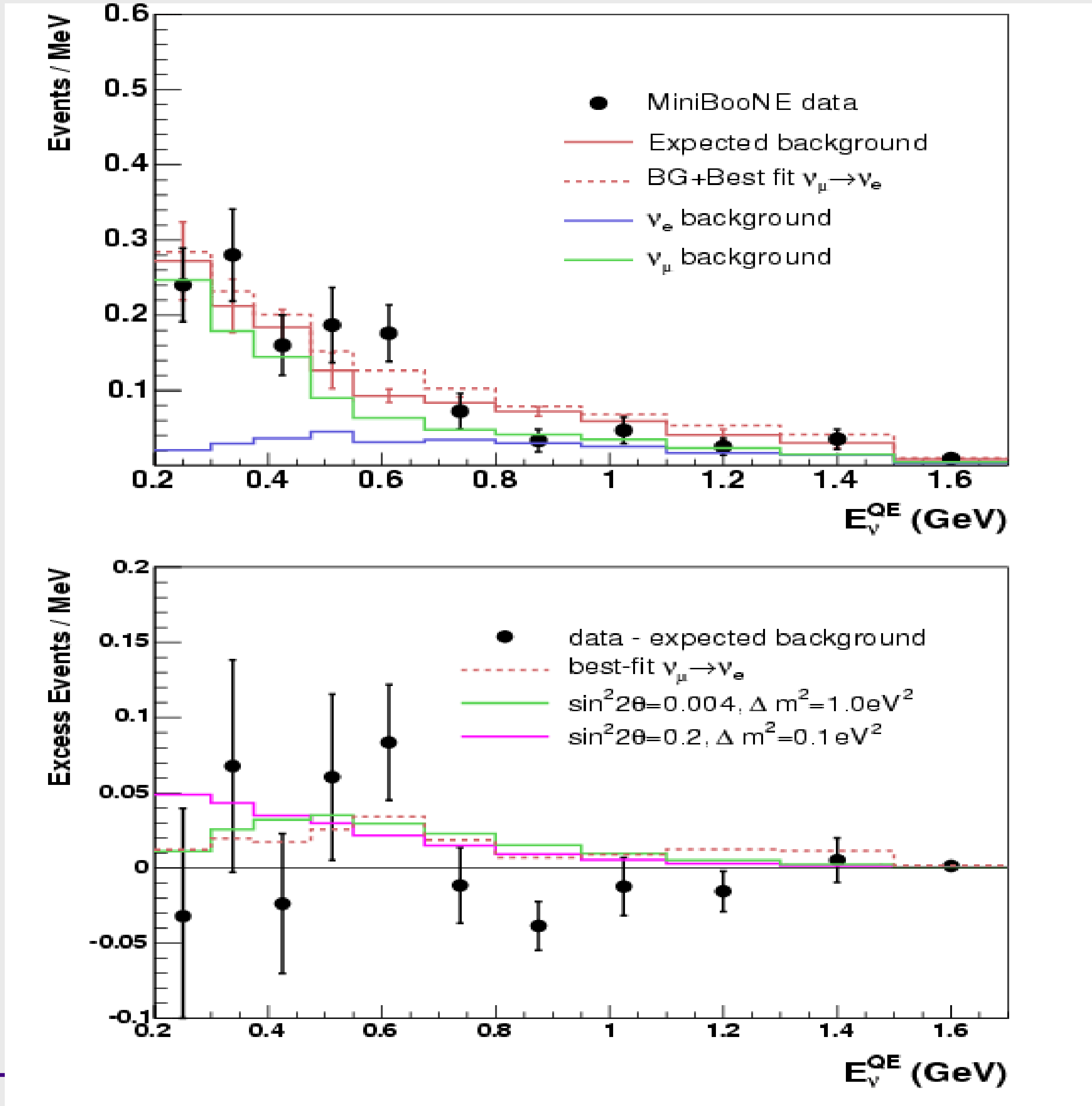
Data - MC → 200-475 MeV: -0.5 +/- 11.7 events

Data - MC → 475-1250 MeV: 3.2 +/- 10.0 events

Events summary (constrained syst + stat uncertainty)

E_ν^{QE} range (MeV)		$\bar{\nu}$ mode (3.386e20 POT)	ν mode (6.486e20 POT)
200-300	Data	24	232
	MC ± sys+stat (constr.)	27.2 ± 7.4	186.8 ± 26.0
	Excess (σ)	-3.2 ± 7.4 (-0.4σ)	45.2 ± 26.0 (1.7σ)
300-475	Data	37	312
	MC ± sys+stat (constr.)	34.3 ± 7.3	228.3 ± 24.5
	Excess (σ)	2.7 ± 7.3 (0.4σ)	83.7 ± 24.5 (3.4σ)
200-475	Data	61	544
	MC ± sys+stat (constr.)	61.5 ± 11.7	415.2 ± 43.4
	Excess (σ)	-0.5 ± 11.7 (-0.04σ)	128.8 ± 43.4 (3.0σ)
475-1250	Data	61	408
	MC ± sys+stat (constr.)	57.8 ± 10.0	385.9 ± 35.7
	Excess (σ)	3.2 ± 10.0 (0.3σ)	22.1 ± 35.7 (0.6σ)

Oscillation fit (>200 MeV) consistent with LSND and Null



Preliminary

Fit yields 18+/-13 events, consistent with expectation from LSND.
However, not conclusive due to large errors.

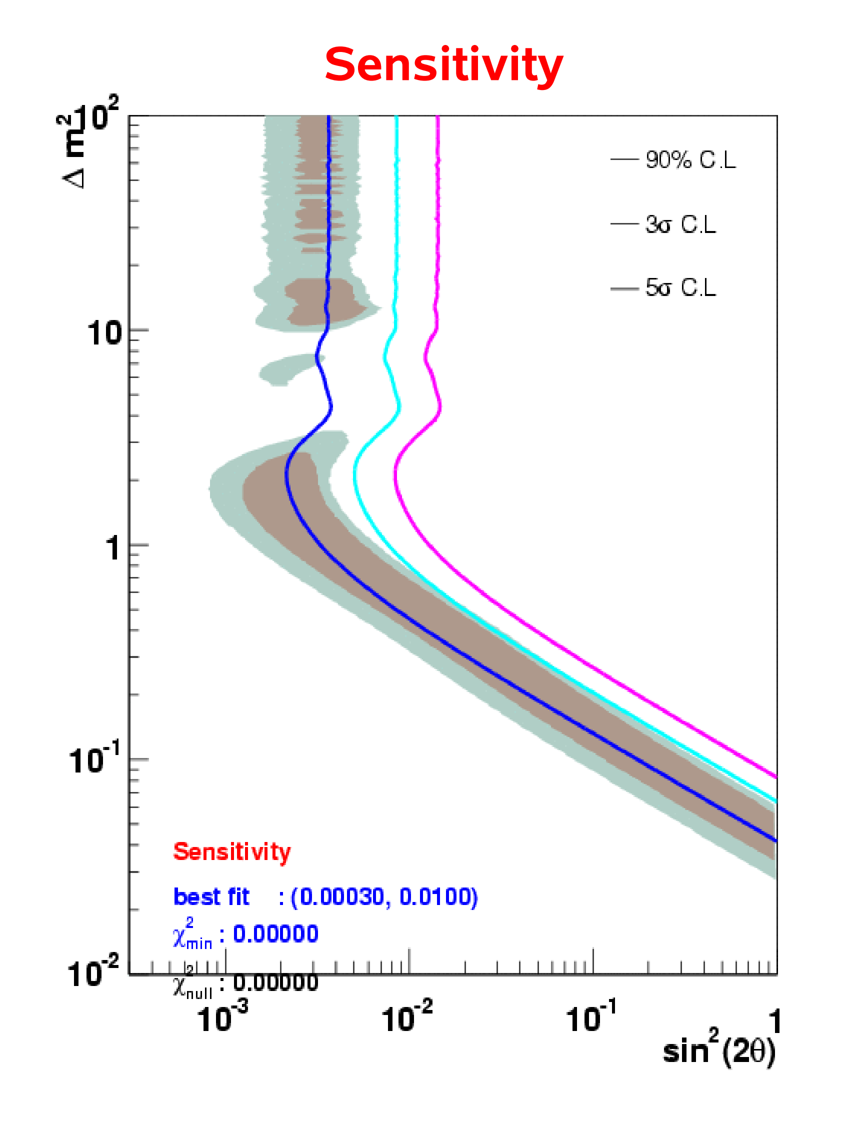
Fit summary

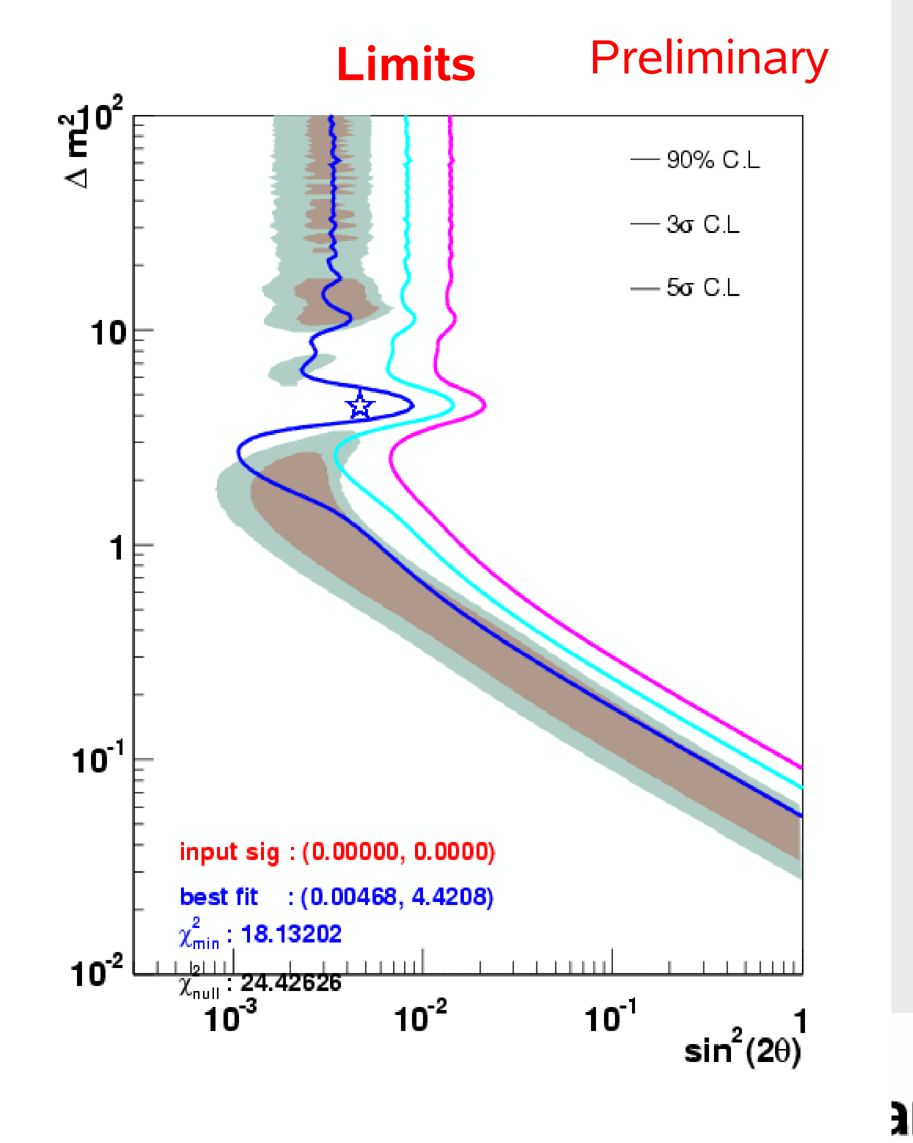
E_ν^{QE} fit	χ^2_{null}(dof) χ^2-prob	χ^2_{null}(dof)* χ^2-prob	$\chi^2_{best\text{-}fit}$(dof)* χ^2-prob	$\chi^2_{LSND\ best\text{-}fit}$(dof) χ^2-prob
> 200 MeV	24.51(19) 17.7%	20.18(17) 26.5%	18.18(17) 37.8%	20.14(19) 38.6%
> 475 MeV	22.19(16) 13.7%	17.88(14) 21.2%	15.91(14) 31.9%	17.63(16) 34.6%

(*Covariance matrix approximated to be the same everywhere by its value at best fit point)

E_ν^{QE} > 200 MeV and E_ν^{QE} > 475 MeV fits are consistent with each-other.
No strong evidence for oscillations in antineutrino mode.
(3.386e20 POT)

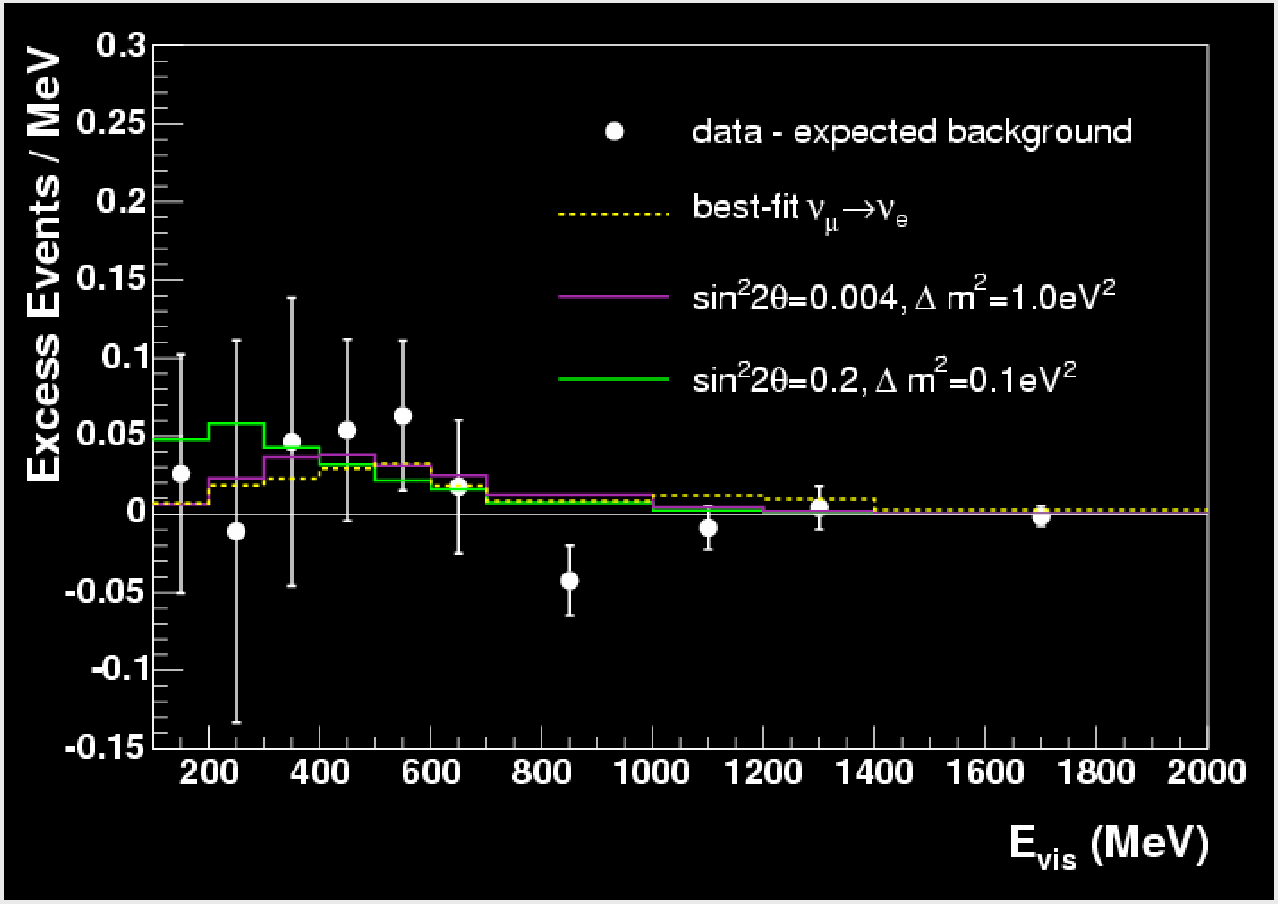
Oscillation fit (>200 MeV) consistent with LSND and Null at ~90% level





Complementary information: $E_{visible}$

Excess distribution as a function of $E_{visible}$ and comparison with possible signal predictions:



Preliminary

Error bars indicate
data statistical and constrained
bkgd systematic uncertainty

Comparison with Neutrino Low E Excess

Maximum χ^2 probability from fits to ν and $\bar{\nu}$ excesses in 200-475 MeV range

	Stat Only	Correlated Syst	Uncorrelated Syst	#Events
Same $\nu,\bar{\nu}$ NC	0.1%	0.1%	6.7%	37
NC π^0 scaled	3.6%	6.4%	21.5%	20
POT scaled	0.0%	0.0%	1.8%	68
Bkgd scaled	2.7%	4.7%	19.2%	21
CC scaled	2.9%	5.2%	19.9%	20
Low-E Kaons	0.1%	0.1%	5.9%	40
ν scaled	38.4%	51.4%	58.0%	7

Same ν and $\bar{\nu}$ NC cross-section (HHH axial anomaly), POT scaled, Low-E Kaon scaled: strongly disfavored as an explanation of the MiniBooNE low energy excess!

The most preferred model is that where the low-energy excess comes from neutrinos in the beam (no contribution from anti-neutrinos).

Currently in process of more careful consideration of correlation of systematics in neutrino and antineutrino mode… results coming soon!

Conclusions

- NEUTRINO MODE:
  - 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]).
  - However, a 128.8 +/- 43.4 event (3.0σ stat+sys, 6.4σ stat)) excess of electron or gamma-ray events are observed in the low energy range from $200 < E_\nu < 475$MeV (submitted to PRL, arXiv:0812.2243 [hep-ex]).
- ANTI-NEUTRINO MODE:
  - MiniBooNE is inconclusive on oscillations, need more data.
  - No low energy excess is observed similar to neutrino mode, which disfavors many types of backgrounds/signal processes (e.g. HHH Axial Anomaly).
- If the low energy excess is a background, these could be important to next generation long baseline neutrino experiments (T2K, Nova, DUSEL-FNAL).
- If new physics (complicated oscillations, sterile neutrinos, neutrino decay, etc), would be a major discovery.

Future Work

- Continue running antineutrino mode till summer 2009 shutdown, plan to collect a total of ~5.3E20 POT (50% more data).
  - Will perform combined neutrino/antineutrino analysis with extra data, most systematic errors will cancel.
- More data and new experiments will be required to fully understand the low energy excess.
  - Request antineutrino running for a total of 10E20 POT.
  - Propose moving the MiniBooNE detector to 200m, or build new detector. Can study L dependence of excess: backgrounds scale as 1/L**2, oscillation signal as $\sin^2(L/E)$, and decay as L/E.
  - MicroBooNE (approved) is a 70 ton liquid argon time projection chamber that can differentiate gamma-rays from electrons.

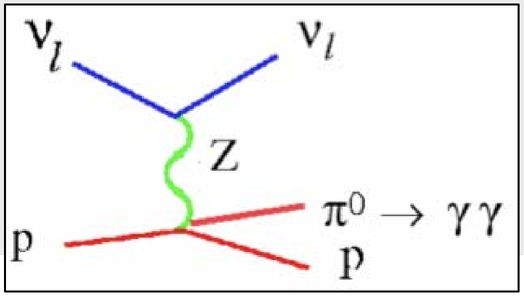
BACKUP SLIDES

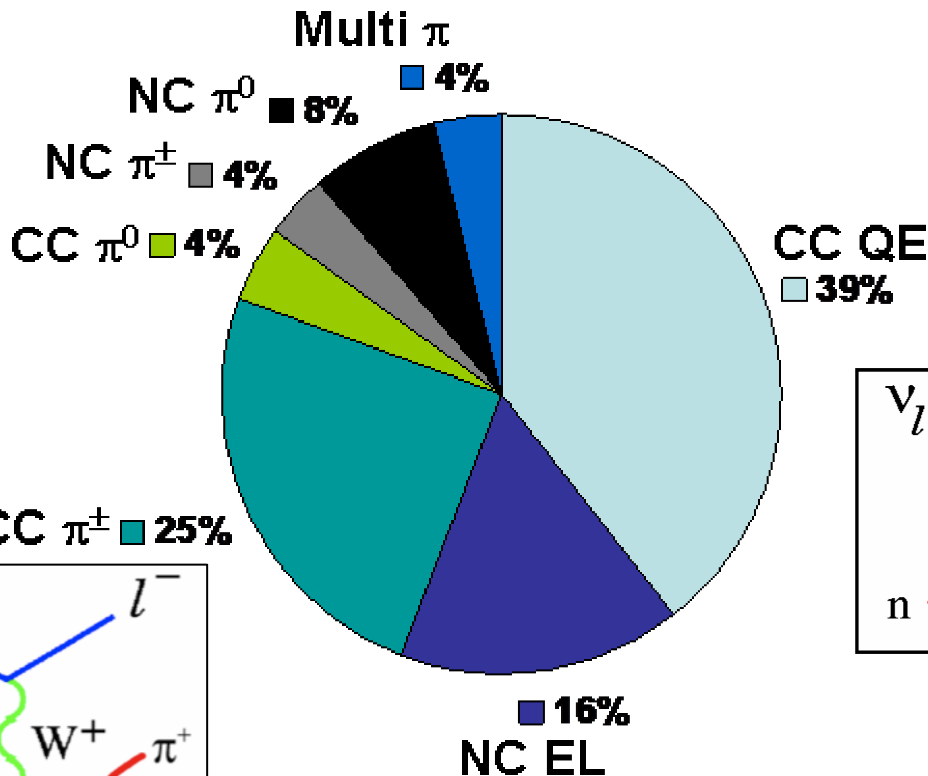
Current MiniBooNE Publication List

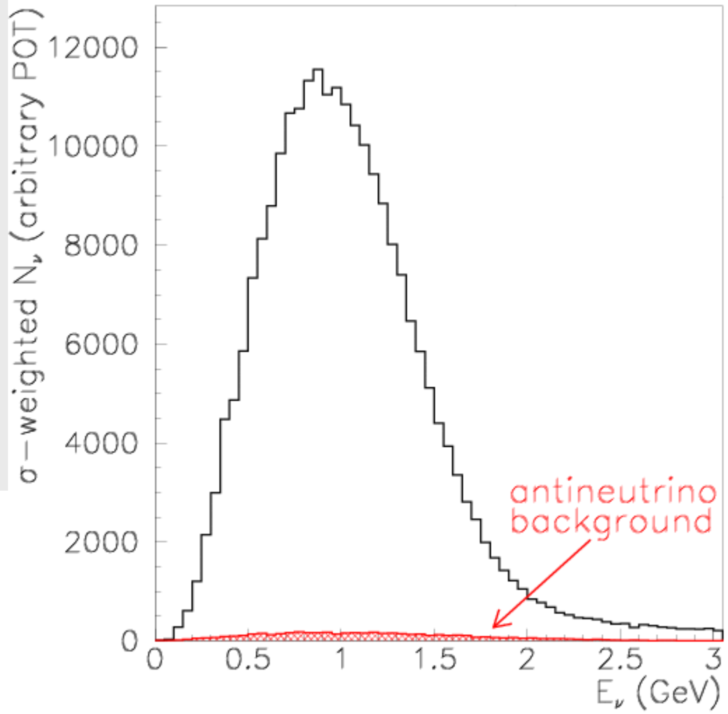
- P. Adamson et al., "First Measurement of νμ and νe Events in an Off-Axis Horn-Focused Neutrino Beam", arXiv:0809.2446 [hep-ex], submitted to Phys. Rev. Lett.
- A.A. Aguilar-Arevalo et al., "The MiniBooNE Detector", arXiv:0806.4201 [hep-ex], submitted to Nucl. Instr. Meth. A
- A.A. Aguilar-Arevalo et al., "The Neutrino Flux Prediction at MiniBooNE", arXiv:0806.1449 [hep-ex], submitted to Phys. Rev. D.
- A.A. Aguilar-Arevalo et al., "Compatibility of high Δm2 νe and νebar Neutrino Oscillation Searches", arXiv:0805.1764 [hep-ex], Phys. Rev. D. 78, 012007 (2008)
- A.A. Aguilar-Arevalo et al., "First Observation of Coherent π0 Production in Neutrino Nucleus Interactions with Eν<2 GeV", arXiv:0803.3423 [hep-ex], Phys. Lett. B. 664, 41 (2008)
- A.A. Aguilar-Arevalo et al., "Constraining Muon Internal Bremsstrahlung As A Contribution to the MiniBooNE Low Energy Excess", arXiv:0706.3897 [hep-ex]
- A.A. Aguilar-Arevalo et al., "Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon", arXiv:0706.0926 [hep-ex], Phys. Rev. Lett. 100, 032301 (2008)
- A.A. Aguilar-Arevalo et al., "A Search for Electron Neutrino Appearance at the Δm2 ~1 eV2 Scale", arXiv:0704.1500 [hep-ex], Phys. Rev. Lett. 98, 231801 (2007)

Predicted event rates before cuts (NUANCE Monte Carlo)

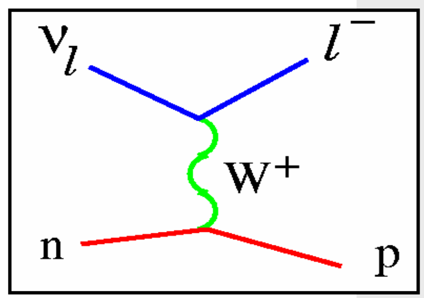
D. Casper, NPS, 112 (2002) 161

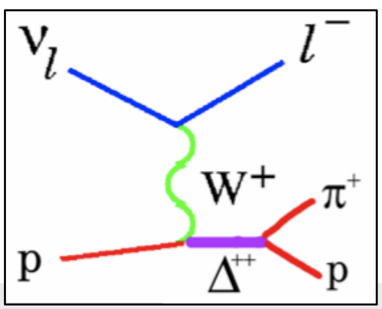






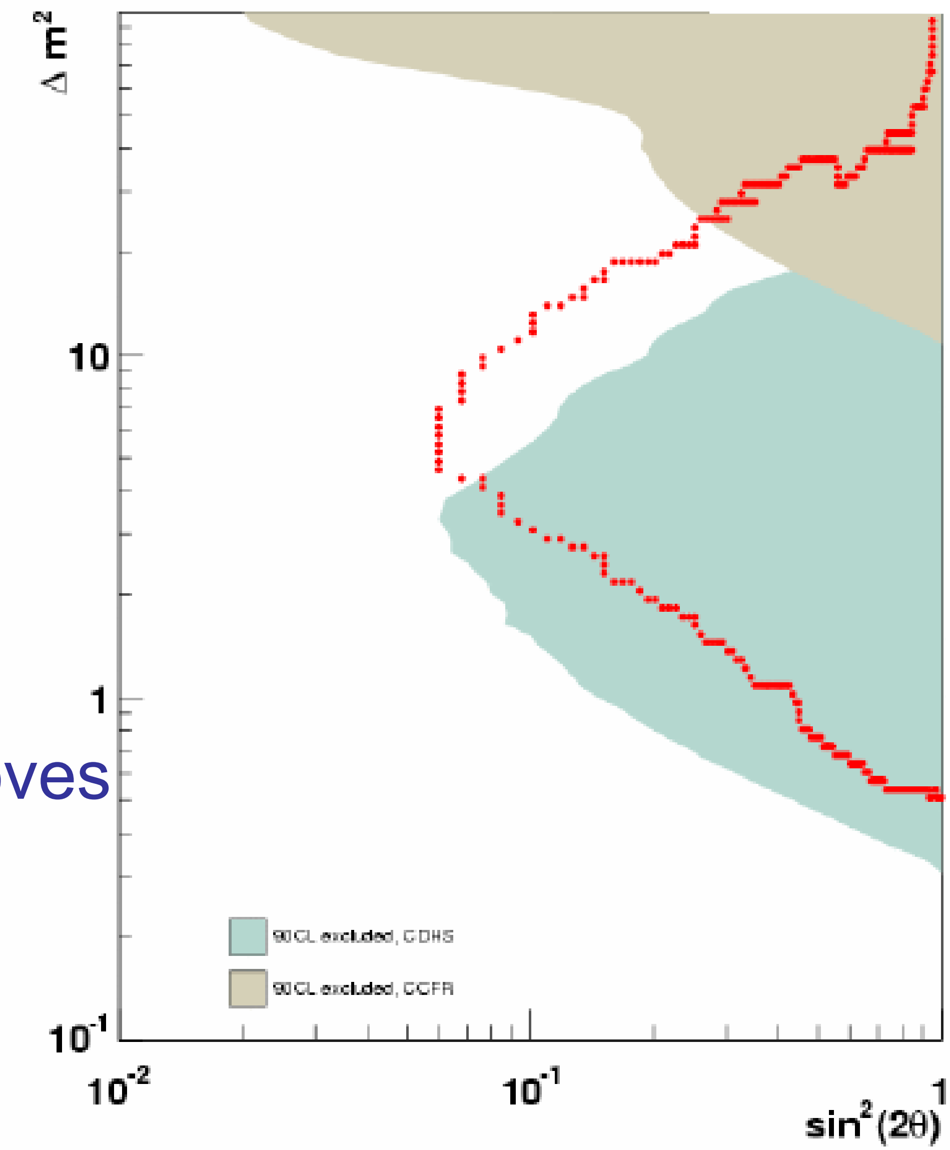
Event neutrino energy (GeV)





Complete MiniBooNE ν_μ Disappearance Sensitivity

- MiniBooNE only 90% CL sensitivity
- CDHS CCFR 90% CL



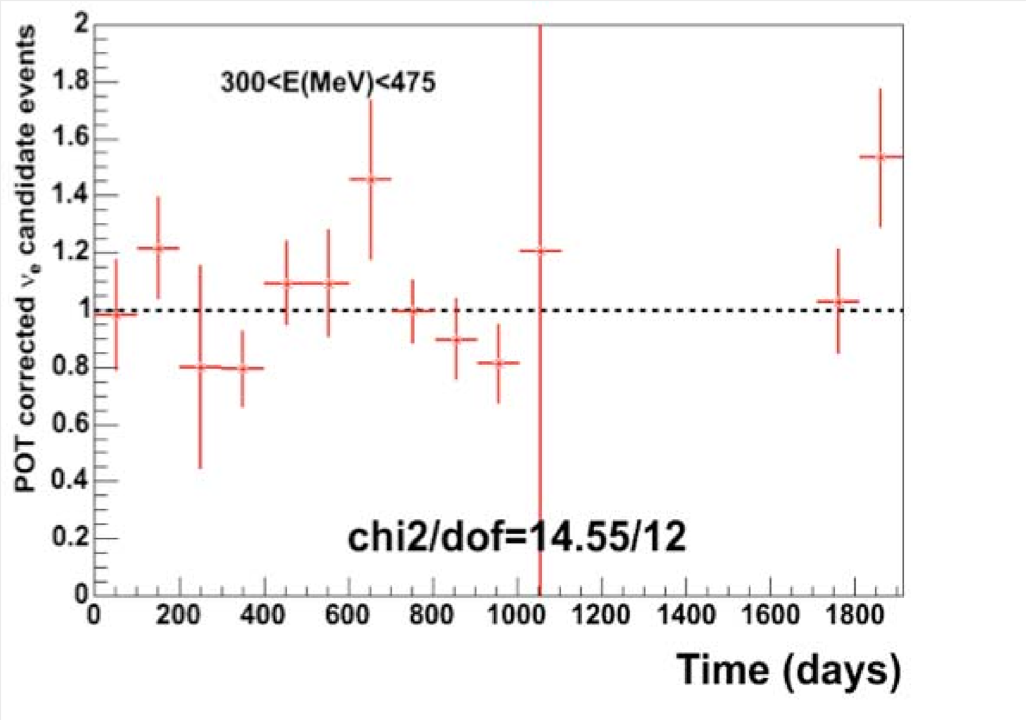
Inclusion of SciBooNE as a near detector, dramatically improves the sensitivity by reducing flux and cross section uncertainties

Many oscillations models predict large muon disappearance.

Detector Anomalies or Reconstruction Problems

No Detector anomalies found

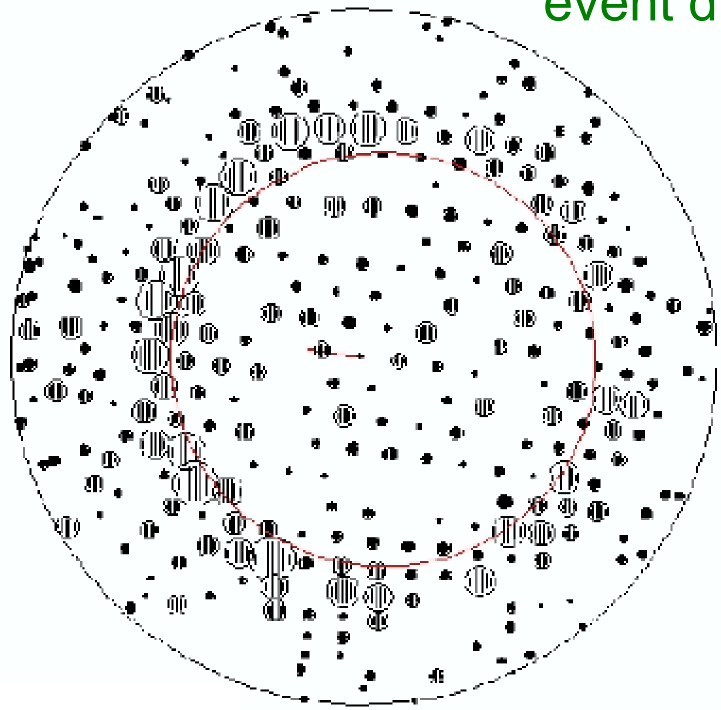
- Example: rate of electron candidate events is constant (within errors) over course of run



No Reconstruction problems found

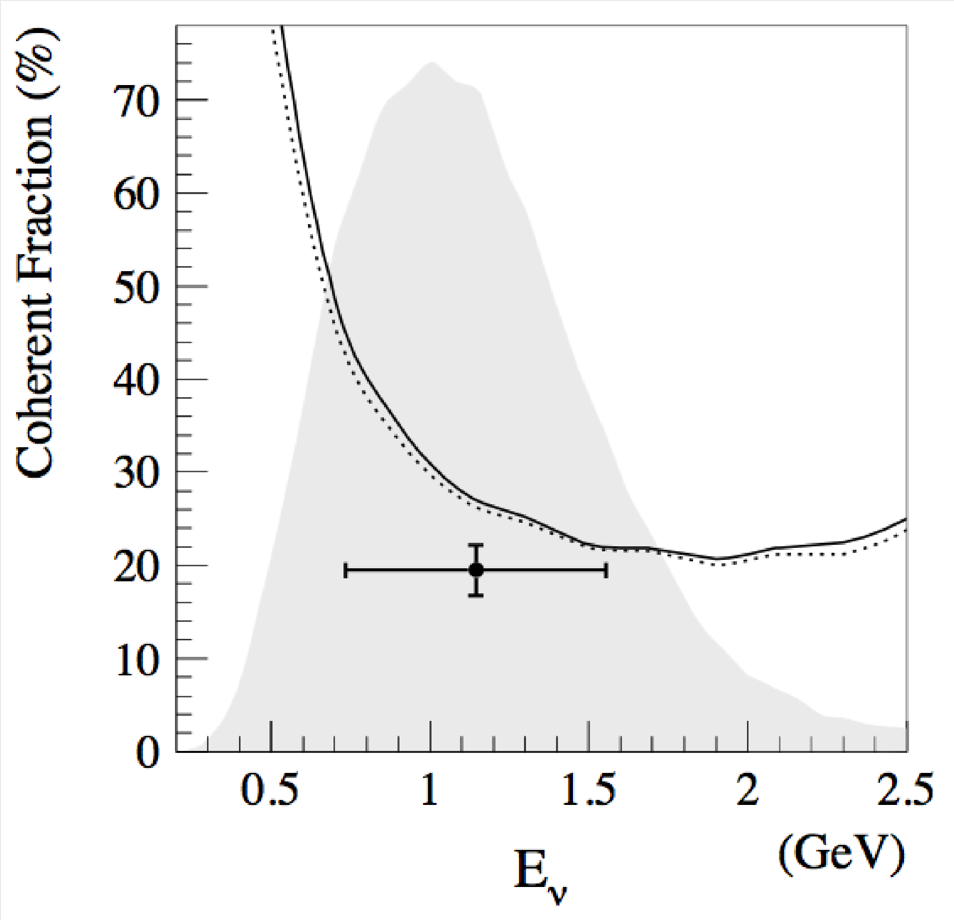
- All low-E electron candidate events have been examined via event displays, consistent with 1-ring events

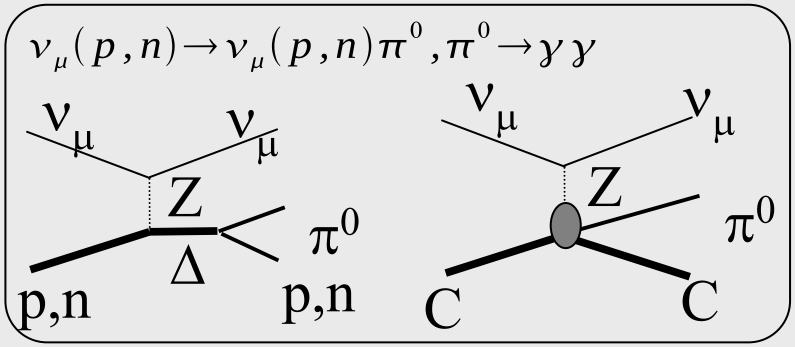
example signal-candidate event display



Signal candidate events are consistent with single-ring neutrino interactions
$\Rightarrow$ But could be either electrons or photons

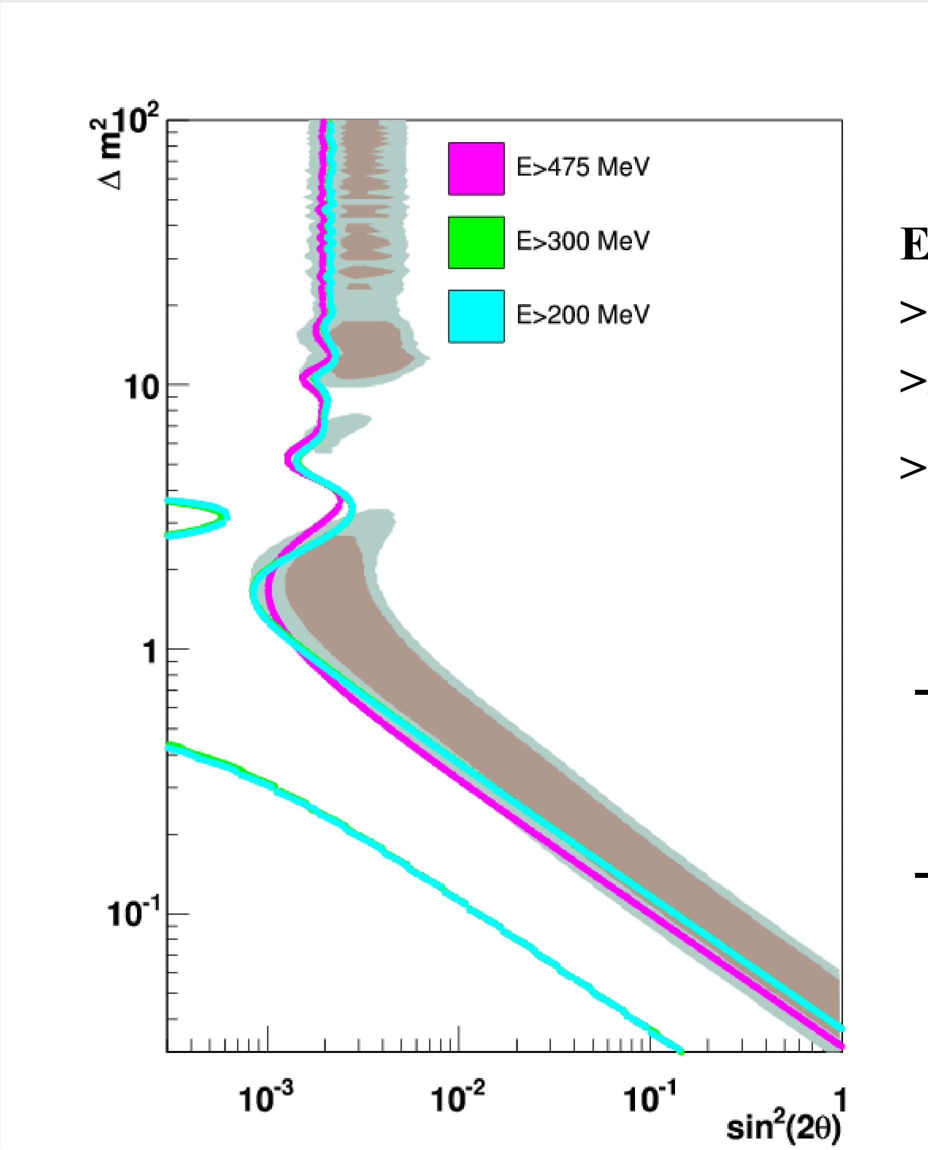
Improved π^0 and radiative Δ analysis





- Applied *in situ* measurement of the coherent/resonant production rate
  - Coherent event kinematics more forward
  - Resonant production increased by 5%
- Improvements to Δ -> Nγ bkg prediction
  - Resonant π^0 fraction measured more accurately
  - Old analysis, π created in struck nucleus not allowed to reinteract to make new Δ
  - Δ -> Nγ rate increased by 2%
  - Error on Δ -> Nγ increased from 9 to 12%
- bottom line: Overall, produces a small change in ν_e appearance bkgs

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.

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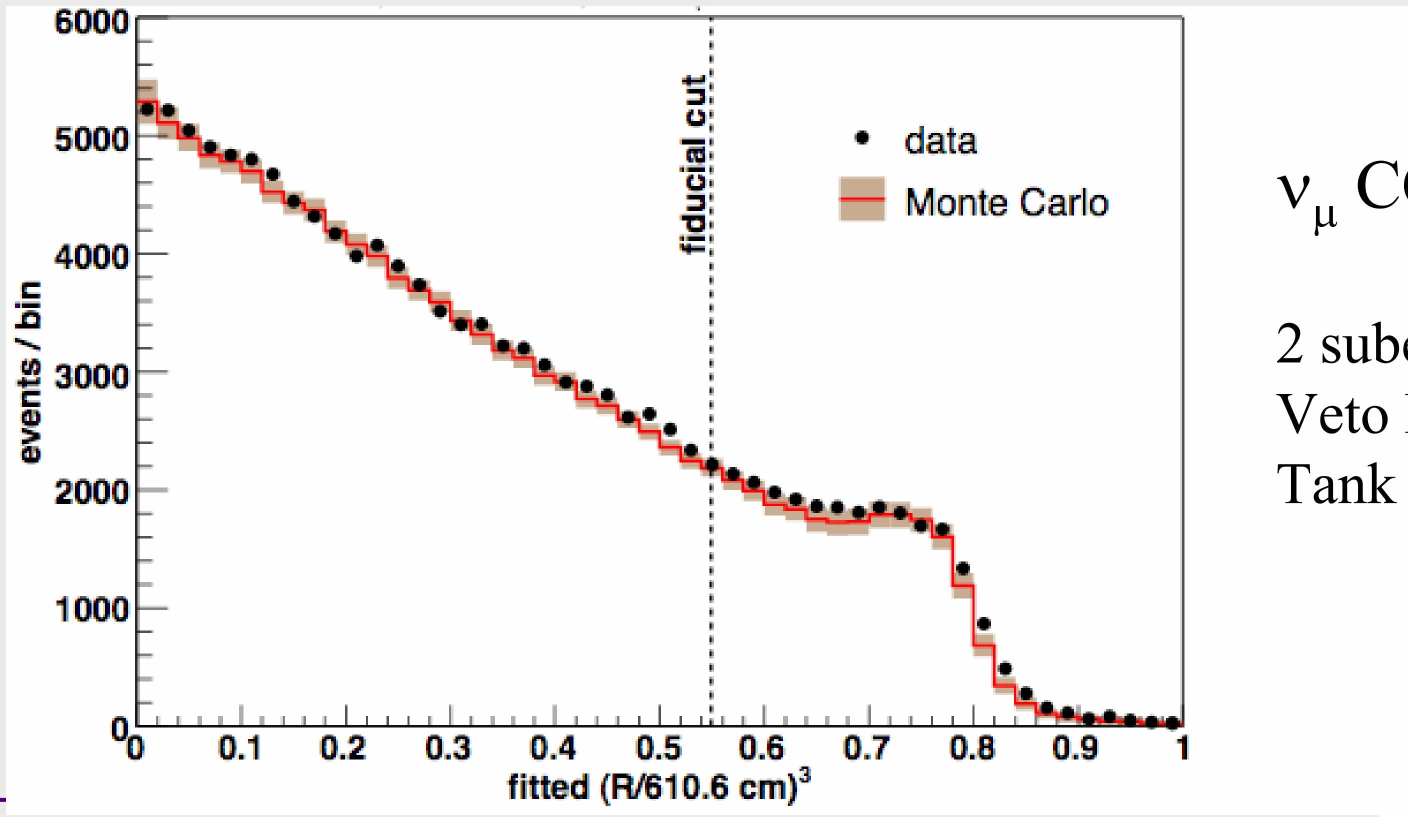
Each event is characterized by 7 reconstructed variables:

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

Summary of Track Based ν_e cuts

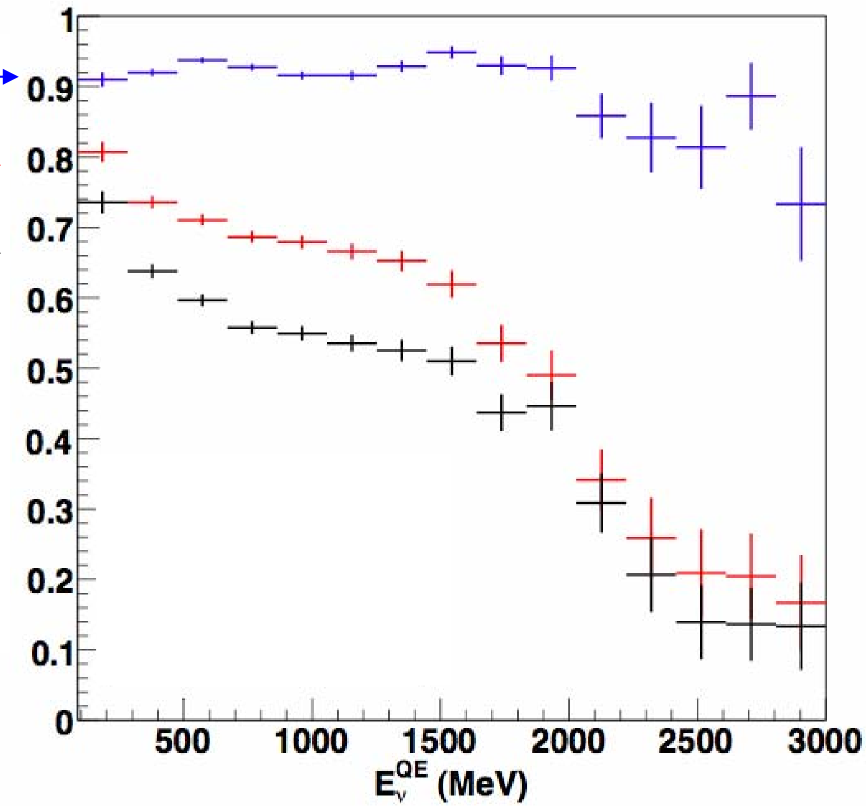
"Precuts" +

$Log(L_e/L_\mu)$

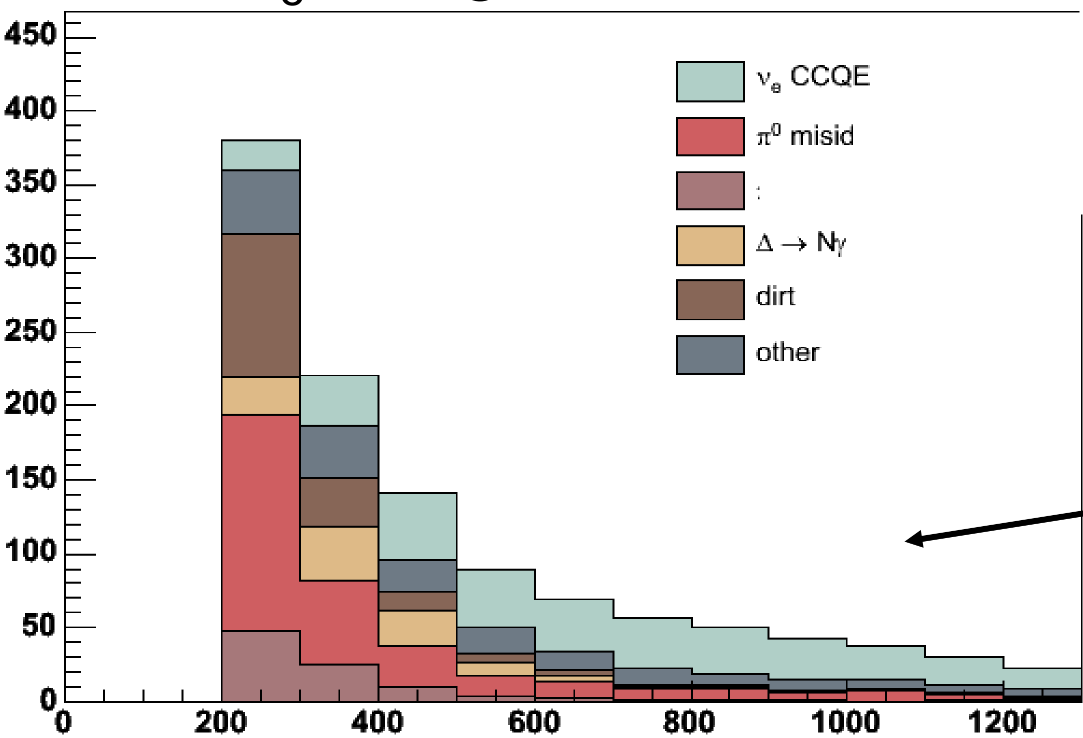
$+ Log(L_e/L_\pi)$

+ invariant mass

Efficiency:



ν_e Backgrounds after cuts



LSND oscillations adds 100 to 150 ν_e events

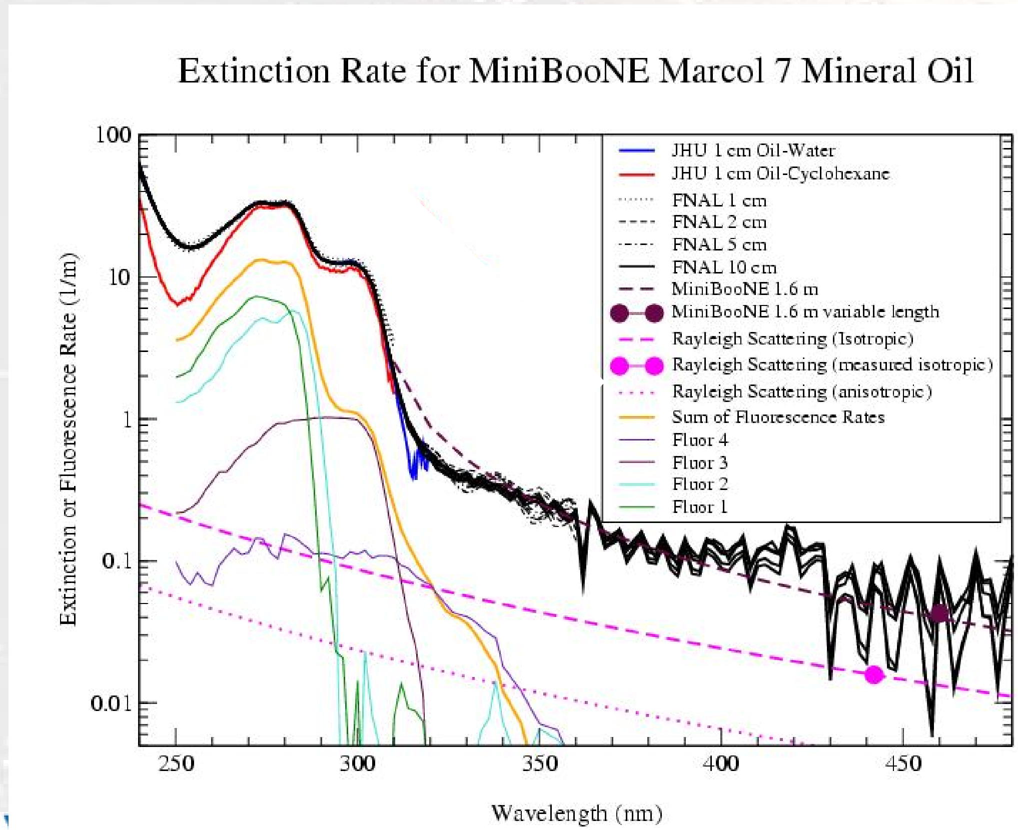
Optical Model

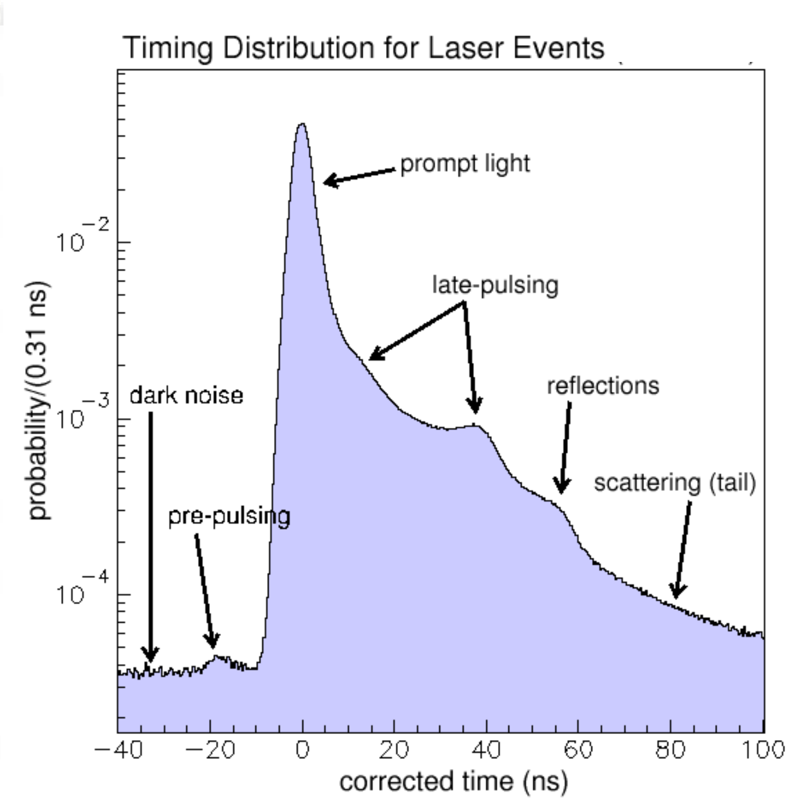
Attenuation length: >20 m @ 400 nm

Detected photons from

- Prompt light (Cherenkov)
- Late light (scintillation, fluorescence)
  in a 3:1 ratio for β~1

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

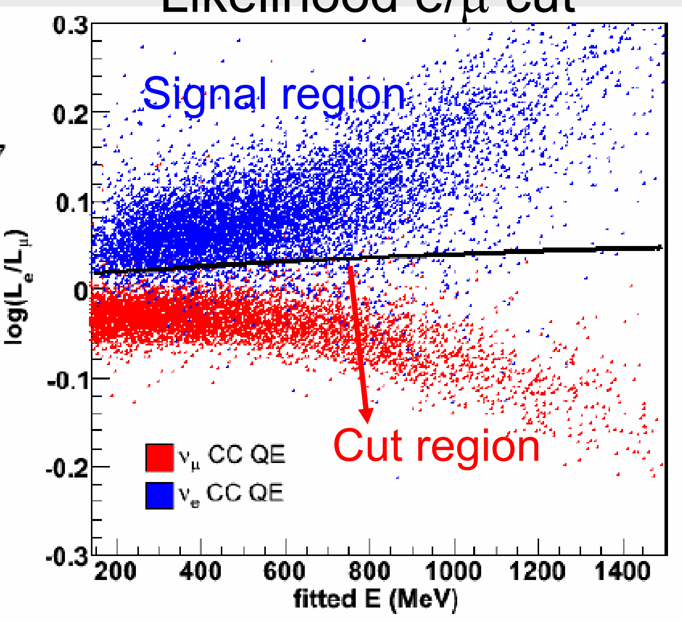
Compare observed light distributions to fit prediction:

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**

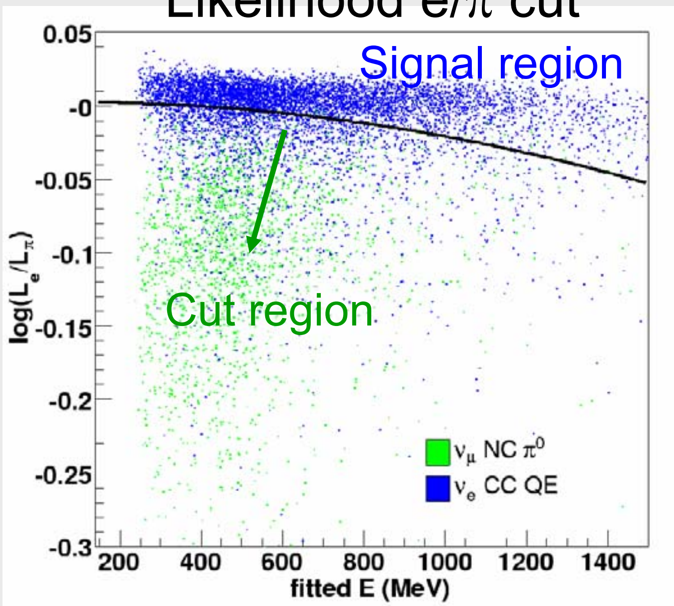
TBL Analysis

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

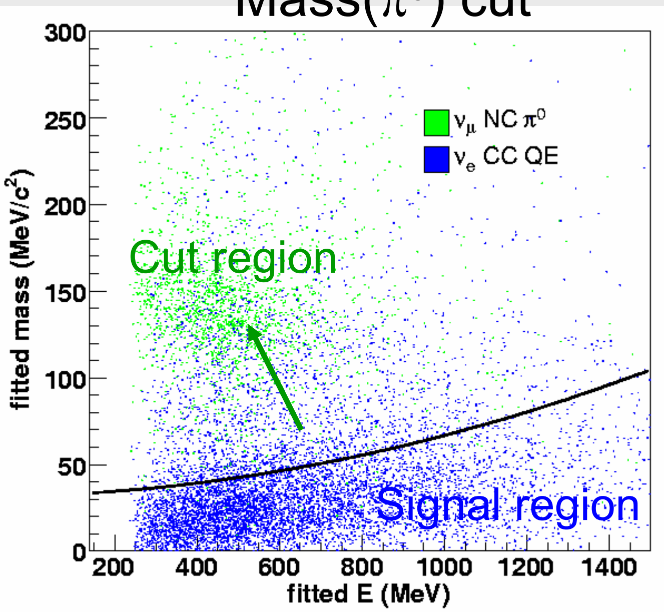
Likelihood e/μ cut



Likelihood e/π cut



Mass(π^0) cut



Blue points are signal ν_e events

Red points are background ν_μCC QE events

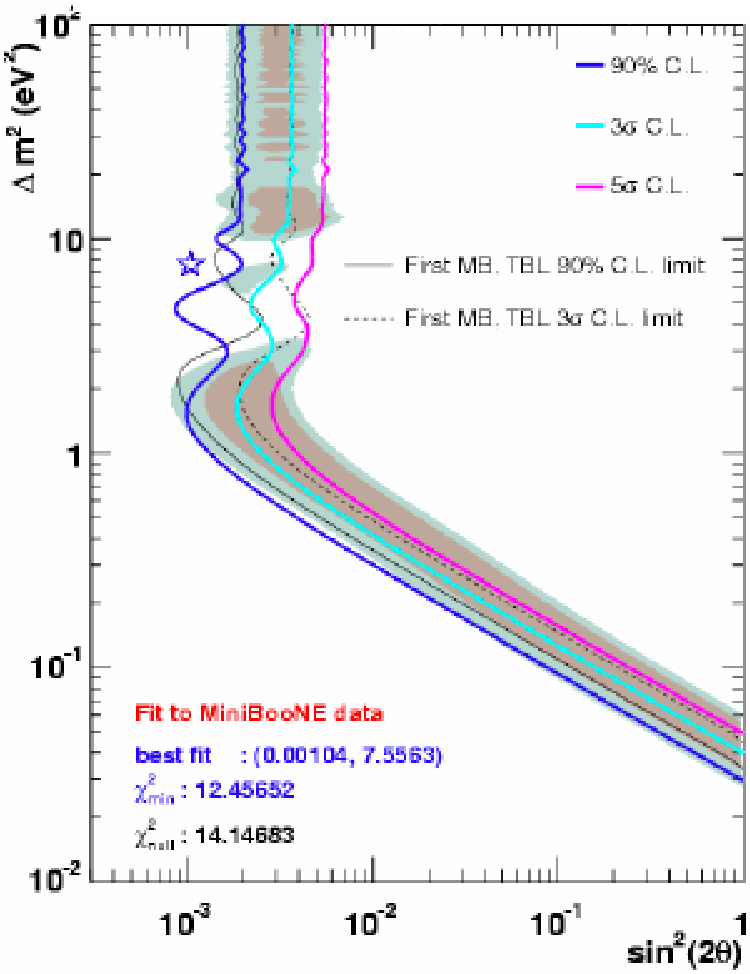
Green points are background ν_μ NC π^0 events

The ν_eBDT + ν_eTBL + ν_μCCQE results:

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

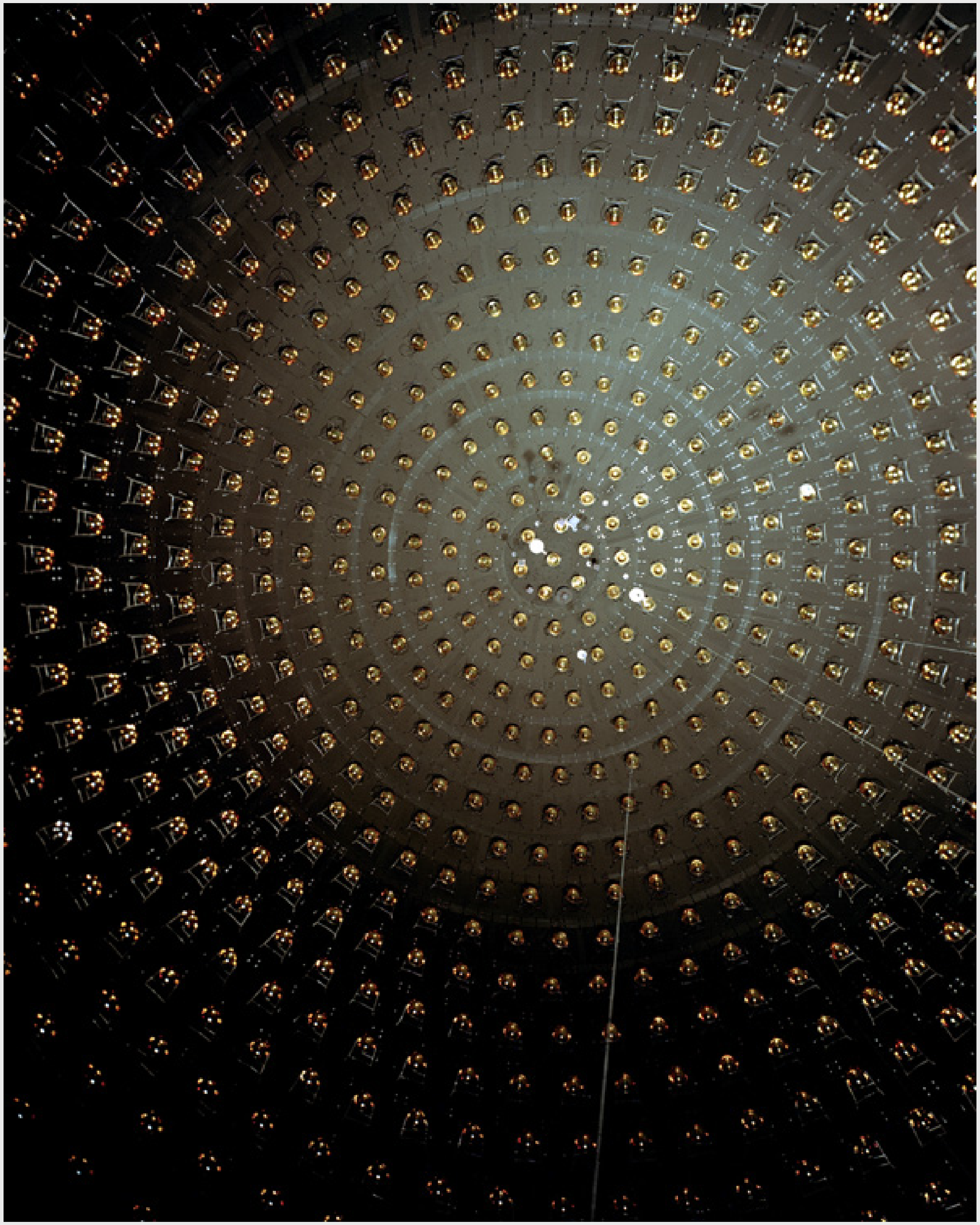
Differences in the details are due to the specific fluctuations in the three data samples and the interplay with correlations among them.

The combination yields a consistent result.



(A.A. Aguilar-Arevalo)

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



10% Photocathode coverage

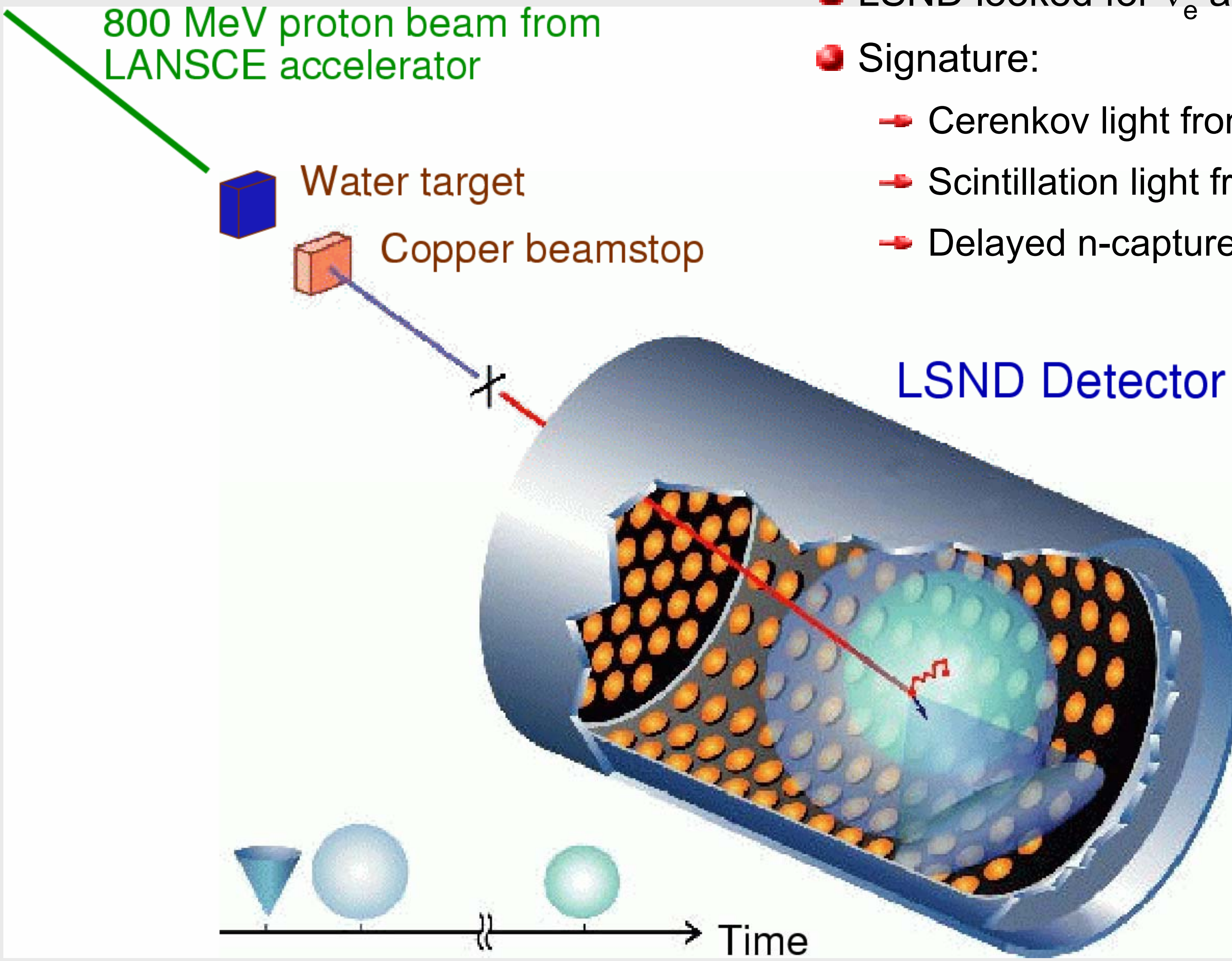
Two types of Hamamatsu Tubes: R1408, R5912

Charge Resolution: 1.4 PE, 0.5 PE

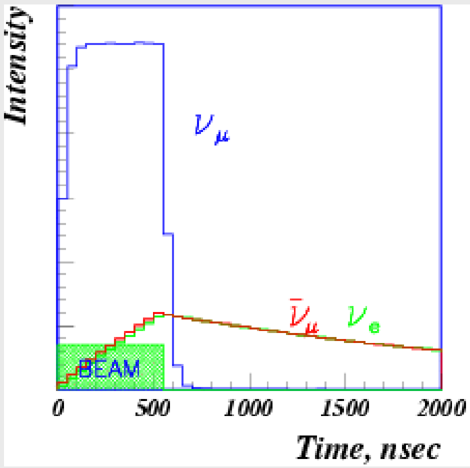
Time Resolution 1.7 ns, 1.1ns

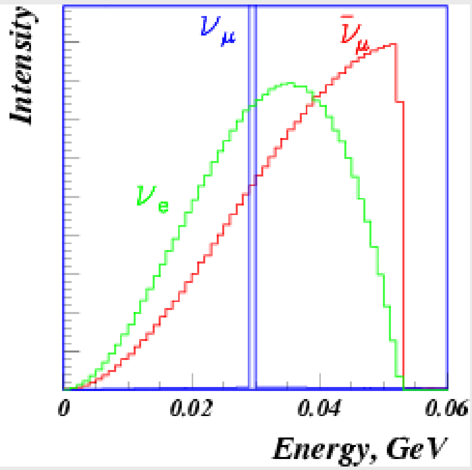
The Liquid Scintillator Neutrino Detector at LANL

- 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)



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





SNS: ~1 GeV, ~1.4 MW

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

$\nu_\mu \rightarrow \nu_s$; **Monoenergetic ν_μ** ; $\nu_\mu\, C \rightarrow \nu_\mu\, C^*(15.11)$ => 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.