MiniBooNE Oscillation Results

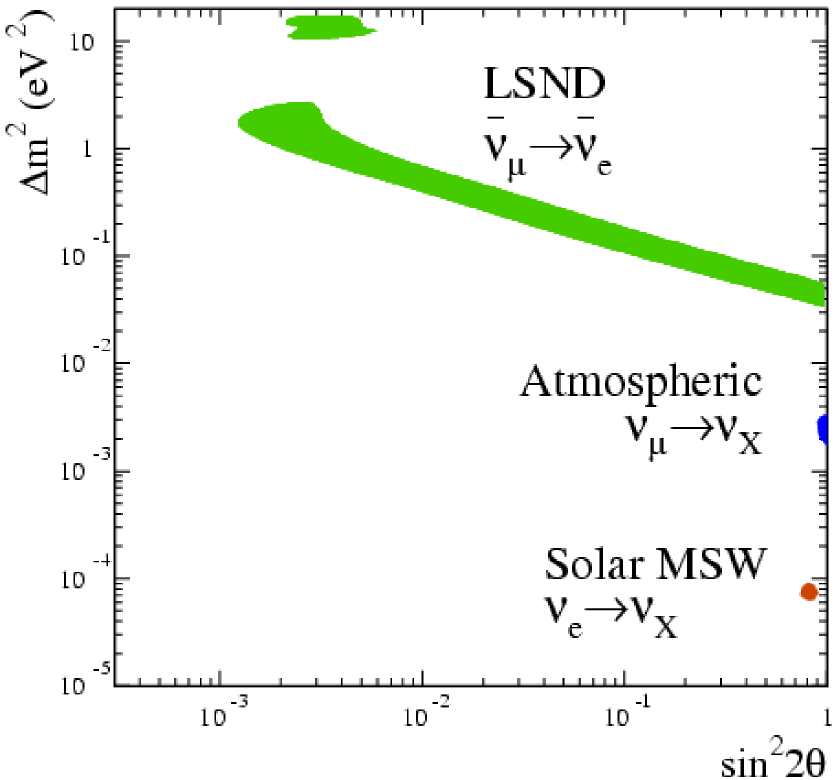
Zelimir Djurcic
Physics Department
Columbia University

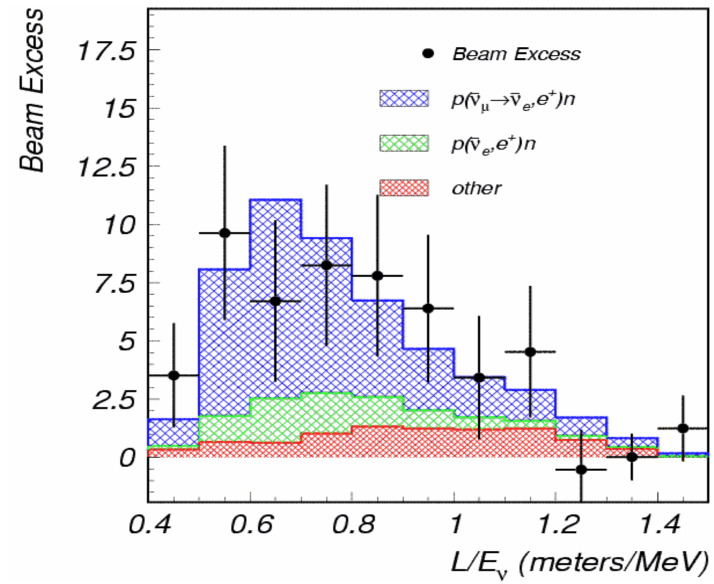
Rencontres de Moriond EW 2009
March 7-14, 2009

Outline

- MiniBooNE Experiment Description
- MiniBooNE's Neutrino Results
- MiniBooNE's Anti-neutrino Results
- MiniBooNE's NuMI Results
- Next Steps and Summary

Oscillation Status After LSND

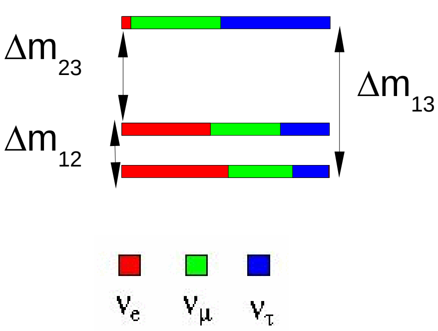




This signal looks very different from the others...

- Much higher $\Delta m^2 = 0.1 - 10$ eV^2
- Much smaller mixing angle
- Only one experiment!

In SM there are only 3 neutrinos



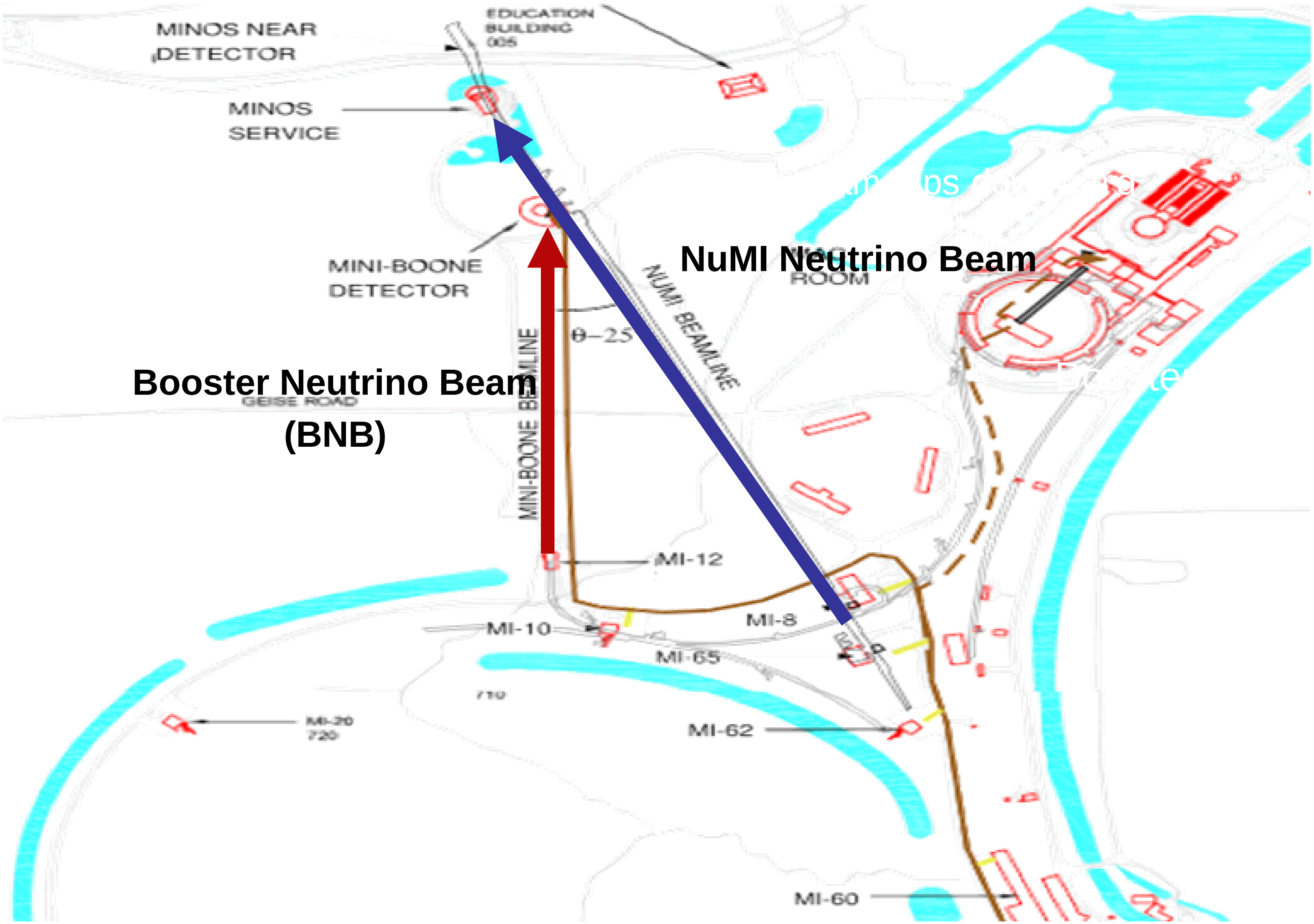
- Three distinct neutrino oscillation signals, with $\Delta m^2_{solar} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$
- For three neutrinos, expect $\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$

The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics

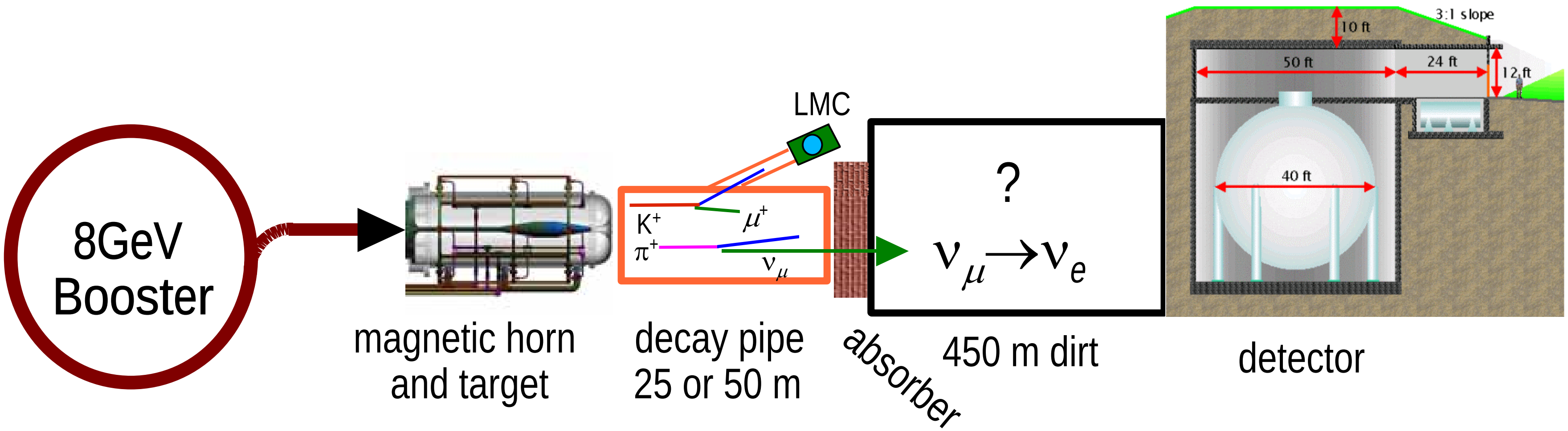
It was important to check LSND what was left to MiniBooNE

(Booster Neutrino Experiment)

Fermilab Neutrino Beams



MiniBooNE setup:



Similar L/E as LSND

Baseline: L = 540 meters, ~ x15 LSND

Neutrino Beam Energy: E ~ x(10-20) LSND

$$P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L/E\right)$$

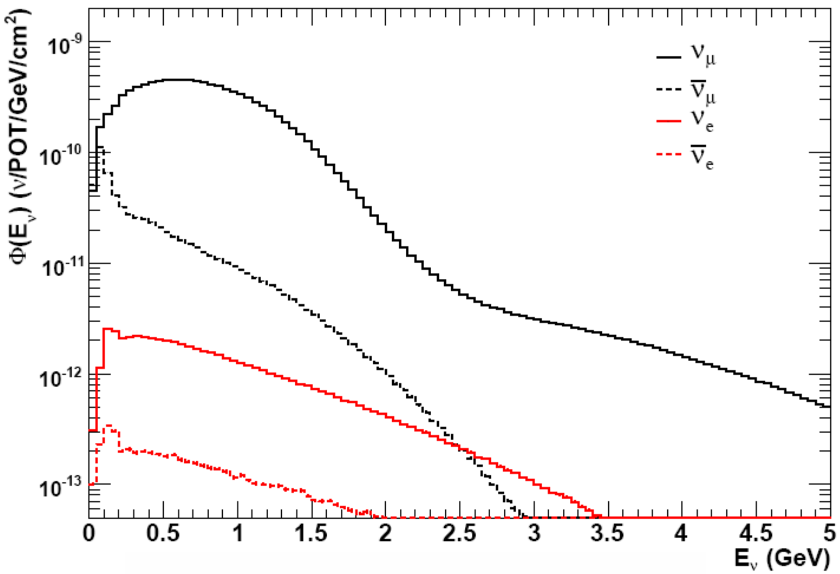
Different systematics: event signatures and backgrounds different from LSND

High statistics: ~ x6 LSND

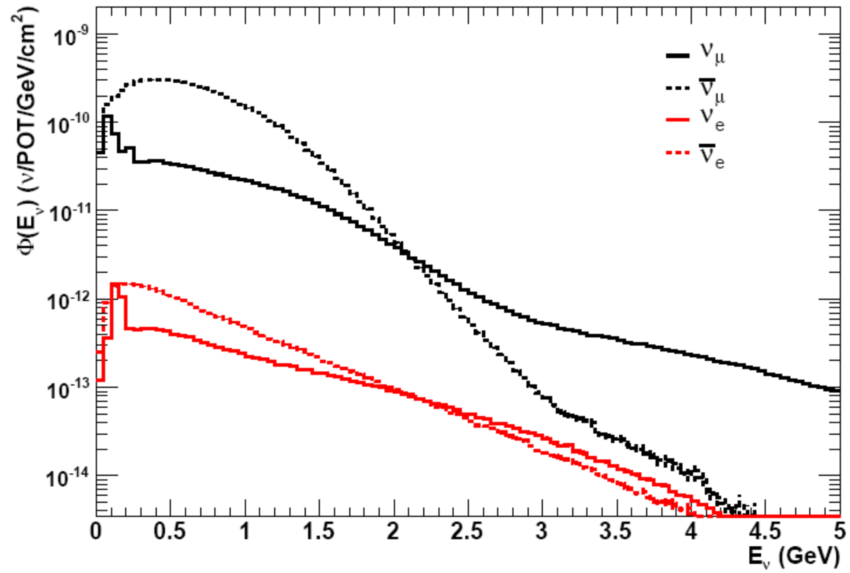
Perform experiment in both neutrino and anti-neutrino modes.

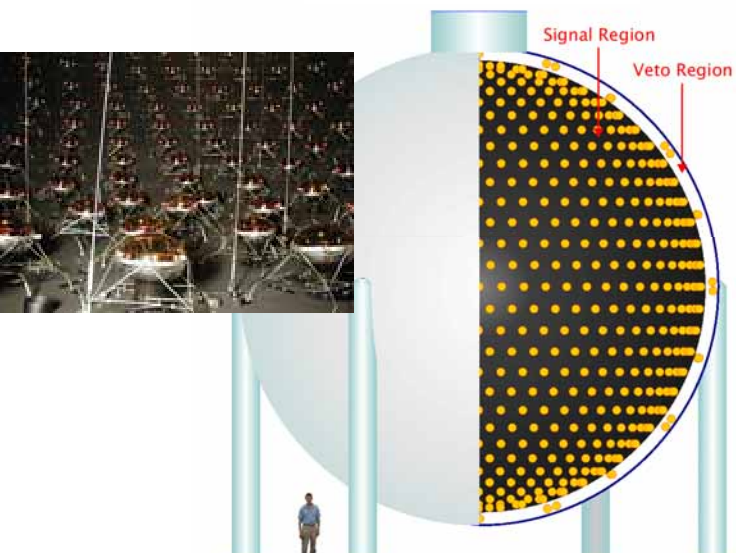
$\nu_\mu \rightarrow \nu_e$ and $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ Oscillation Searches

Neutrino-Mode Flux



Antineutrino-Mode Flux

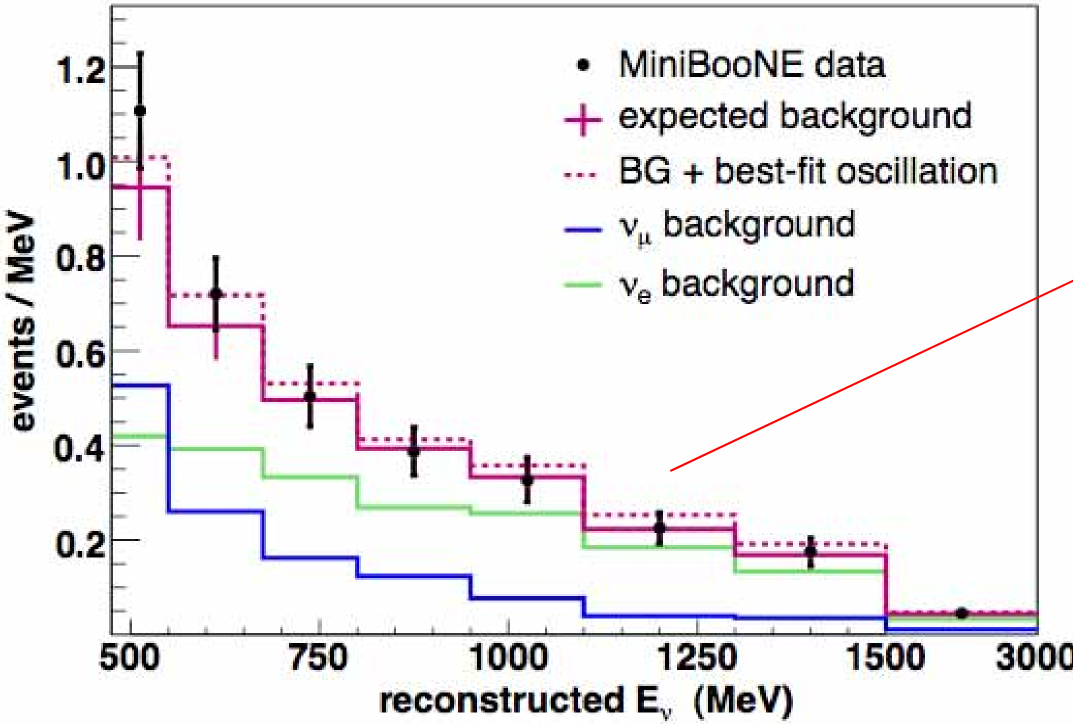


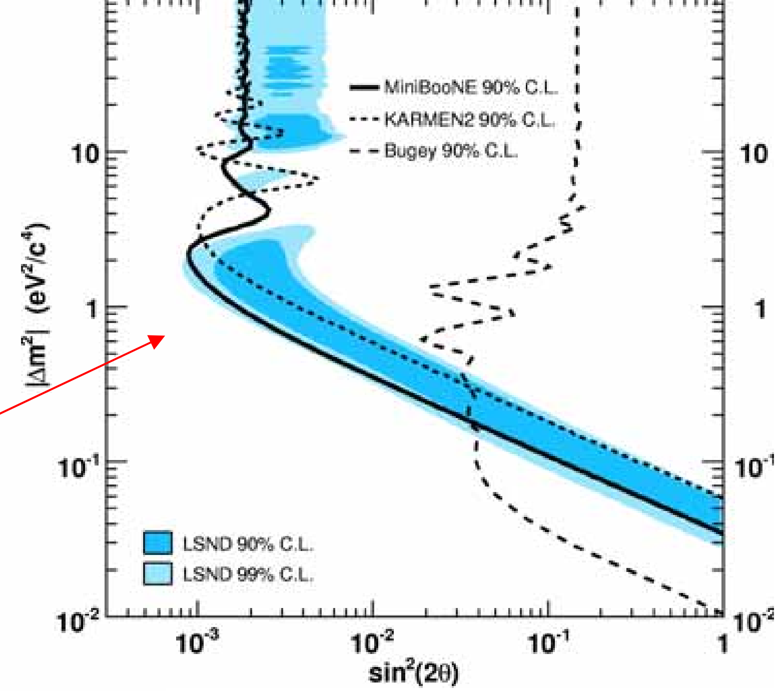


MiniBooNE Detector:
- 12m diameter sphere
- 950000 liters of oil(CH_2)
- 1280 inner PMTs
- 240 veto PMTs

Detector Requirements:
- Detect and Measure Events: Vertex, E_ν …
- Separate ν_μ events from ν_e events.

ν Oscillation Analysis: Results





Fit $475 < E_\nu < 3000$ MeV

Region $475 < E_\nu < 1250$ MeV
Data: 380 events
Expected: 358□19□35 events
Difference: 0.55 σ

MiniBooNE's first result show **no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations** in the analysis region: simple 2ν oscillation excluded at 98% CL.

Details:

Phys. Rev. Lett. 98, 231801 (2007), arXiv:0704.1500 [hep-ex]

Physics News Update

The AIP Bulletin of Physics News

Article Tools
Enlarge text
Shrink text
Print
E-mail

Subscribe
E-mail alert
RSS feed RSS

Save and Share
Digg this
Del.icio.us
Furl

· PNU Archives
· Physics News Graphics
· FYI: Science Policy News Bulletin

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

AIP Ten Top Physics Stories for 2007

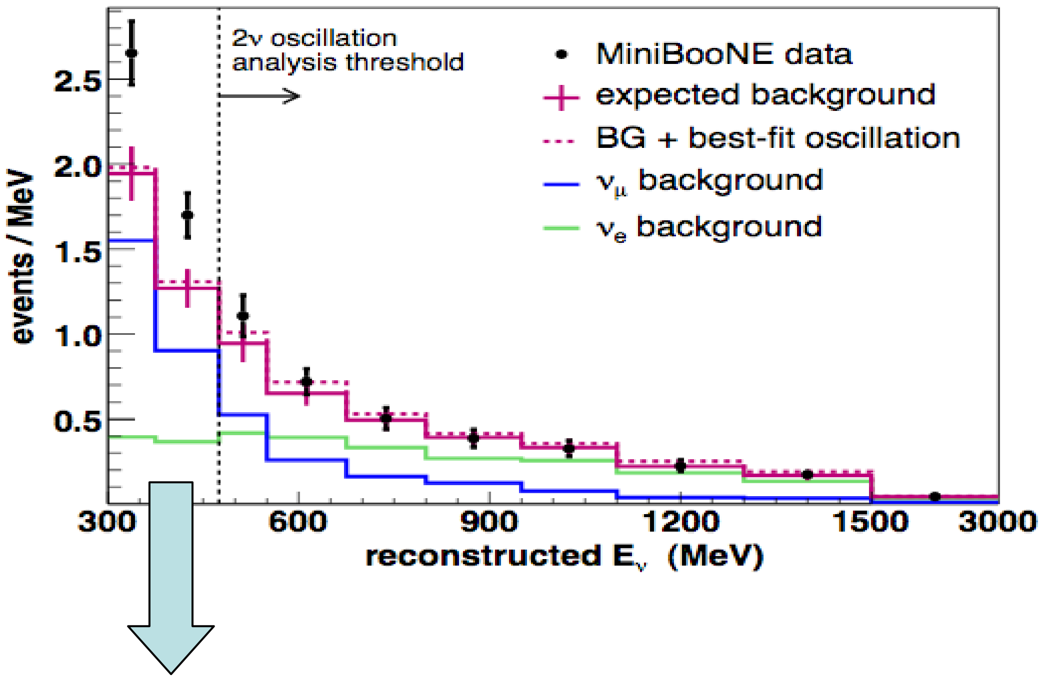
Ten Top Physics Stories for 2007

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.

Yes, we solved one neutrino mystery but found another one!



-Good description of data at high energy.

-Excess of data events at low energy.

Excess of data over prediction!

Investigation of observed low-energy excess

What is the nature of the excess?

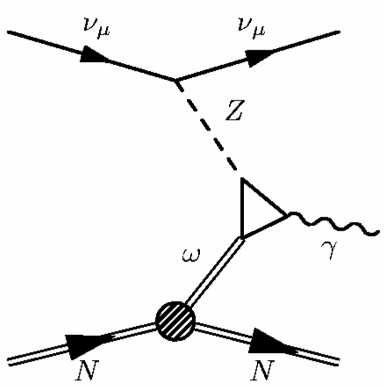
- Possible detector anomalies or reconstruction problems?
- Incorrect estimation of the background?
- New sources of background?
- New physics including exotic oscillation scenarios?

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

Range of possible explanations for observed excess

Several possible explanations have been put forth by the physics community, attempting to reconcile the MiniBooNE neutrino mode result with LSND and other appearance experiments…

- 3+2 with CP violation
  [Maltoni and Schwetz, hep-ph0705.0107 ; G. K., NuFACT 07 conference]
- Anomaly mediated photon production
  [Harvey, Hill, and Hill, hep-ph0708.1281]
- New light gauge boson
  [Nelson, Walsh, Phys. Rev. D 77, 033001 (2008)]
- Neutrino decay
  [hep-ph/0602083]
- Extra dimensions
  [hep-ph/0504096]
- CPT/Lorentz violation
  [PRD(2006)105009]
- …



Improvements in the Analysis

-Improved π^0 (coherent) production incorporated.

-Rechecked various background cross-section and rates ($\Delta \rightarrow \gamma N$,etc.)

-Photo-nuclear interactions included.

-Improved estimate of the background from external events ("dirt") performed.

-Analysis threshold lowered to 200 MeV.

-Improved estimates of systematic errors (i.e. flux).

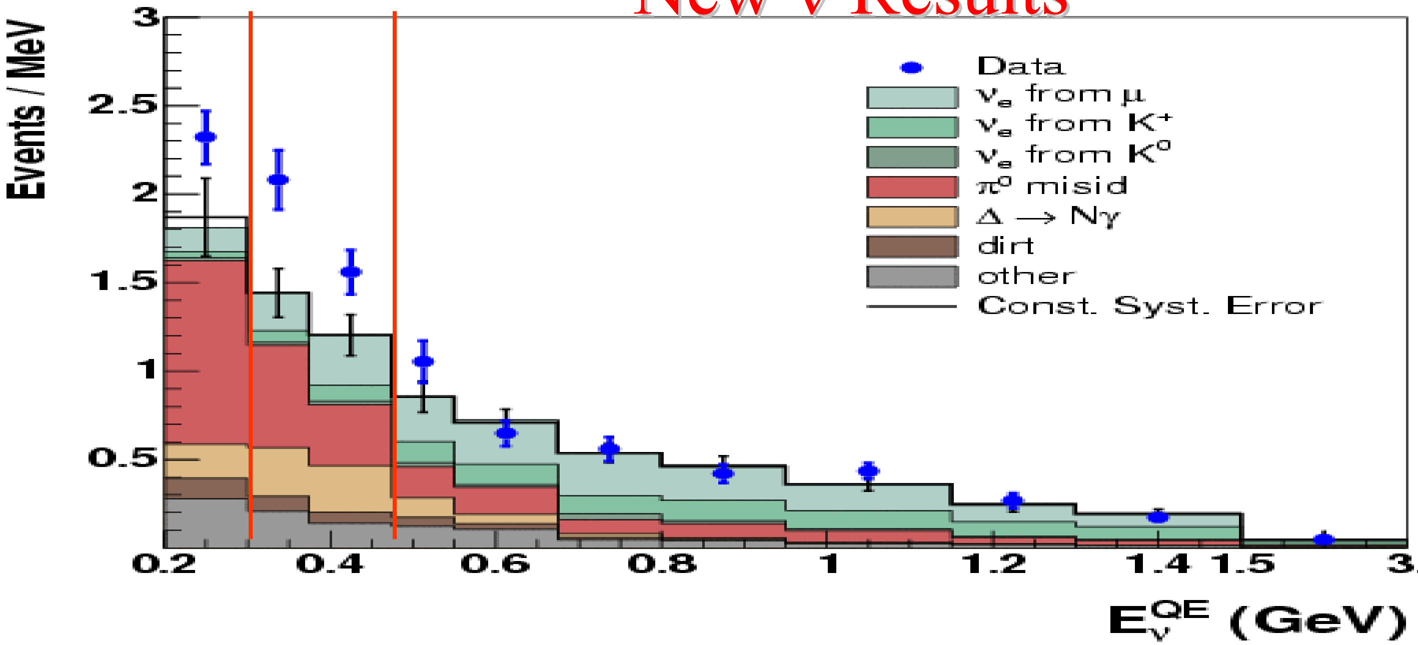
-Additional data set included in new results:

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

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

Putting all these improvements and checks in the analysis together gives …

New ν Results



Small change at low energy, no change at high energy!

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 Δ→Nγ	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!

Details Phys. Rev. Lett.102 (2009) 101802, arXiv:0812.2243 [hep-ex]

OK, those were neutrino results so far.

What about anti-neutrinos?

Provides direct check of LSND result.

Provides additional data set for low energy excess study.

Collected 3.386×10^{20} POT so far.

What can antineutrino running tell us?

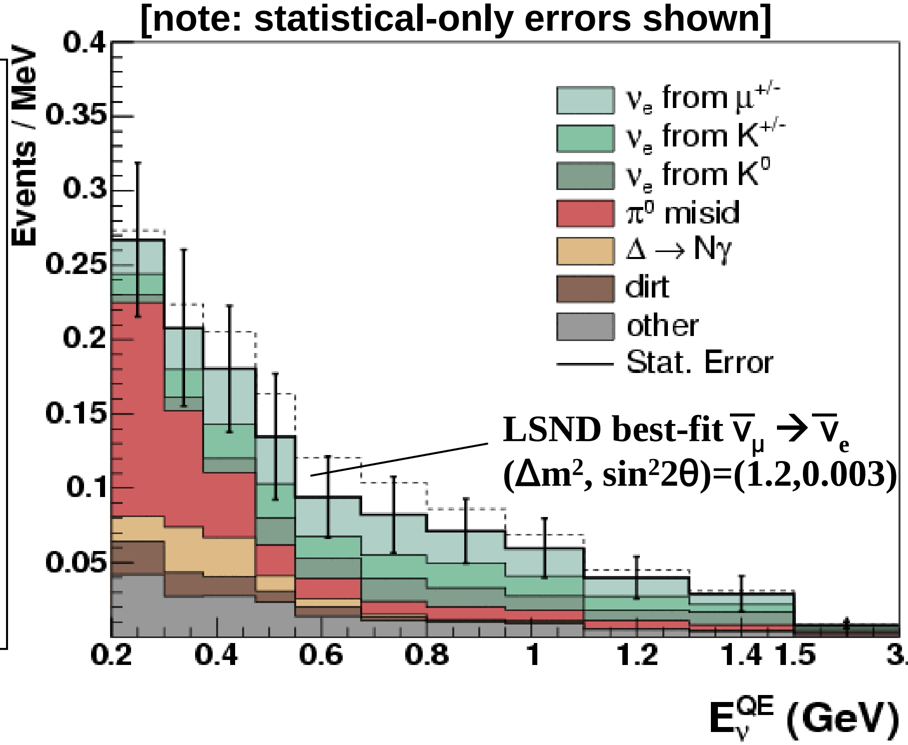
We have collected only about 1/9 the number of interactions as in neutrino mode

- Fewer protons on target so far (~x2, but more are coming!)
- The flux per proton on target is lower (~×1.5)
- The cross section is lower (~×3)

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

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

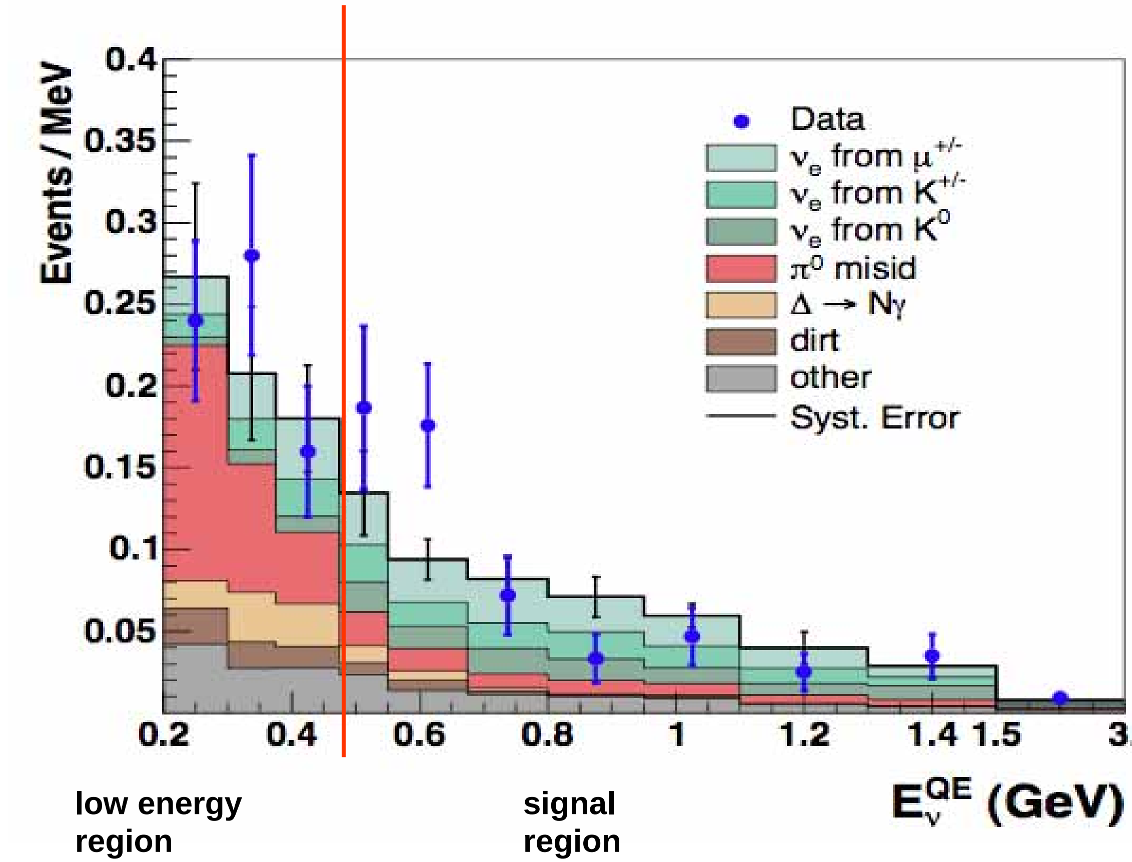
E_ν [MeV]	200-475	475-1250
total background	60.29	57.78
ν_e intrinsic	17.74	43.23
ν_μ induced	42.54	14.55
NC π^0	24.60	7.17
NC $\Delta \rightarrow N\gamma$	6.58	2.02
Dirt	4.69	1.92
CCQE	2.86	1.24
other	3.82	2.20
LSND best fit	4.33	12.63



Compare Data to MC Predicition

ν_e data vs. background distribution:

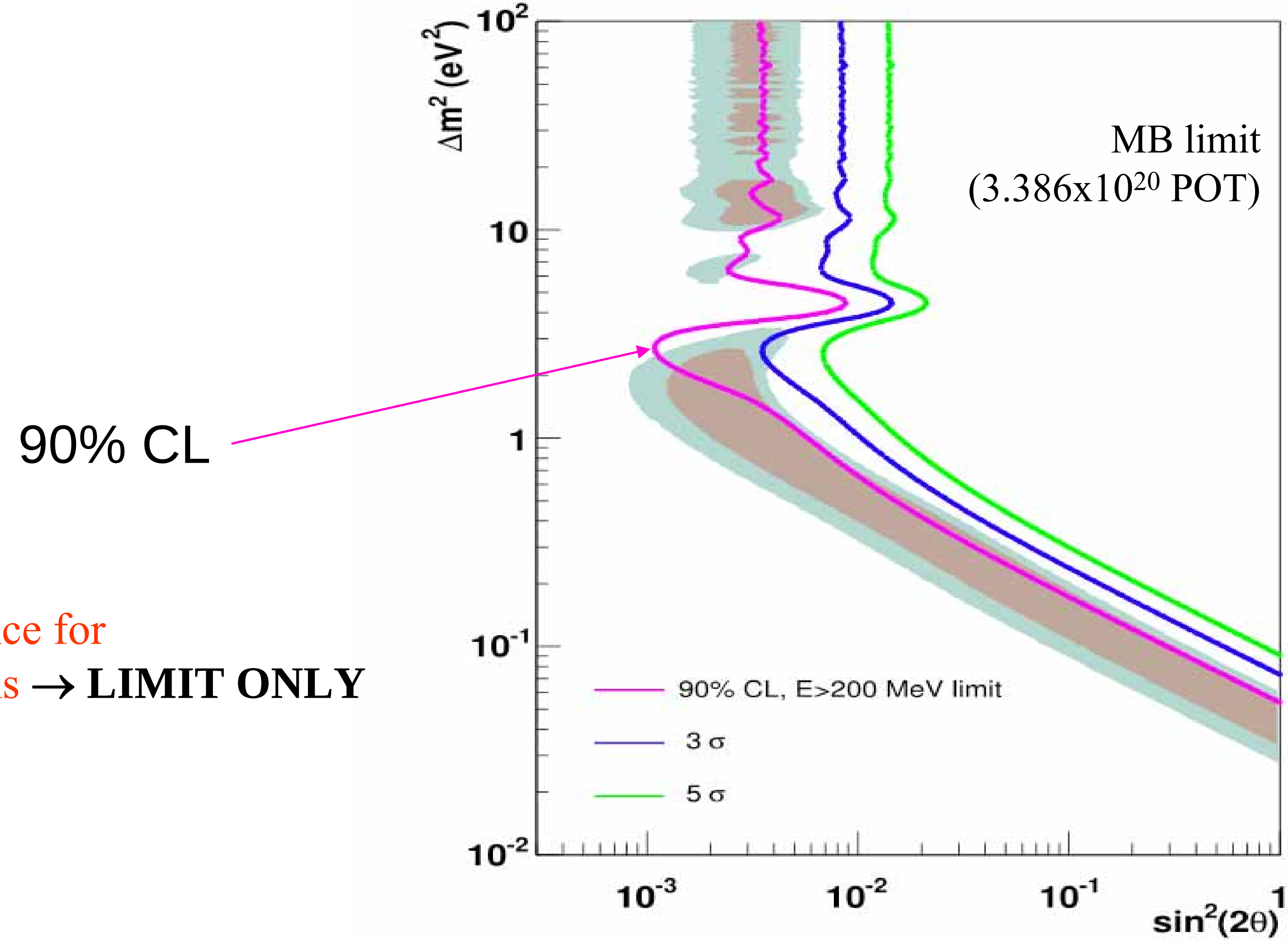
χ^2(dof) = 24.51 (19)
χ^2-probability = 17.7%
(calculated using error matrix at null)



Data → statistical uncertainty
MC → unconstrained systematic uncertainty

Note the size of statistical over systematic errors!

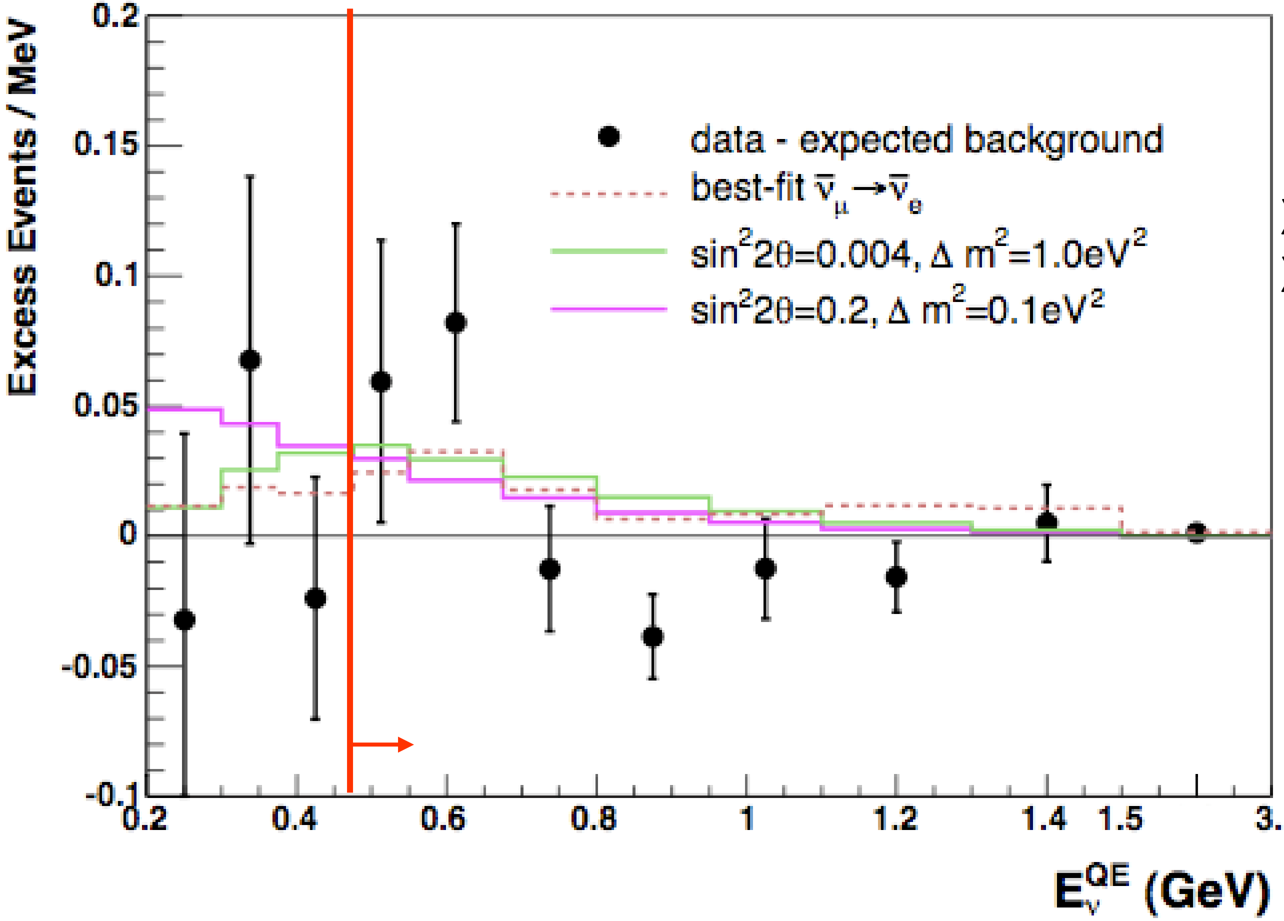
MiniBooNE Fit to to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation Hypothesis



No evidence for oscillations → **LIMIT ONLY**

MiniBooNE Fit to to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation Hypothesis

Excess distribution and comparison with possible signal predictions:



MiniBooNE best-fit:

(Δm^2, $\sin^2 2\theta$) = (4.4 eV^2, 0.004)

$\chi^2_{best\text{-}fit\text{-}MB}$(dof) = 15.91 (14)
χ^2-probability = 31.9%

$\chi^2_{null\text{-}fit}$(dof) = 22.19 (16)
χ^2-probability = 13.7%

$\chi^2_{best\text{-}fit\text{-}LSND}$(dof) = 17.63 (16)
χ^2-probability = 34.6%

LSND best-fit:

(Δm^2, $\sin^2 2\theta$) = (1.2 eV^2, 0.003)

Therefore anti-neutrinos show:

-No significant excess at low energies.
-Data consistent with both LSND-like oscillations and null signal.

First Comparison of $\bar{\nu}$ and ν Results 200-475 MeV

200-475 MeV		$\bar{\nu}$	ν
	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)

How consistent $\bar{\nu}$ and ν excess is under different assumptions (models)?

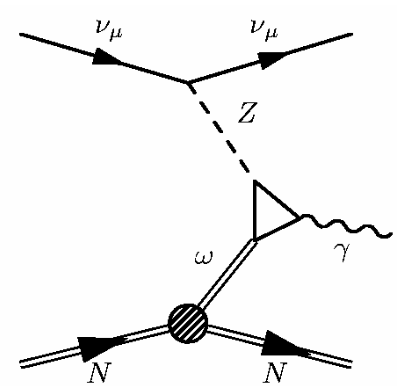
Example 1: Assume ν excess scales with number of protons (POT).
(e.g., "paraphoton" [Nelson, Walsh, Phys. Rev. D 77, 033001 (2008))

Antineutrino POT: 3.386e20
Neutrino POT: 6.486e20

$$\frac{\text{Antineutrino POT}}{\text{Neutrino POT}} = 0.52$$

One would expect a $\bar{\nu}$ excess of ~(128.8 events)*0.52 = ~67 events

Example 2: Assume all 128.8 ± 43.4 excess events in ν mode come from a NC process (e.g., HHH axial anomaly)
Then:
-cross-section is same for ν and $\bar{\nu}$ NC process
-excess scale with POT, and with flux (antineutrino/neutrino flux ~0.55)
One would expect a $\bar{\nu}$ excess of ~(128.8 events)*0.52*0.55 = ~37 events



Harvey, Hill, and Hill, hep-ph0708.1281

Some models strongly disfavored as an explanation of the MiniBooNE low energy excess!

First Comparison of $\bar{\nu}$ and ν Results 200-475 MeV

200-475 MeV		$\bar{\nu}$	ν
	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)

How consistent $\bar{\nu}$ and ν excess is under different assumptions (models)?

Hypothesis	Stat Only	Cor. Syst	Uncor. Syst	# $\bar{\nu}$ Expec.
POT scaled	0.0%	0.0%	1.8%	67.5
Same $\nu,\bar{\nu}$ NC	0.1%	0.1%	6.7%	37.2
NC π^0 scaled	3.6%	6.4%	21.5%	19.4
Bkgd scaled	2.7%	4.7%	19.2%	20.9
CC scaled	2.9%	5.2%	19.9%	20.4
Low-E Kaons	0.1%	0.1%	5.9%	39.7
* ν scaled	38.4%	51.4%	58.0%	6.7

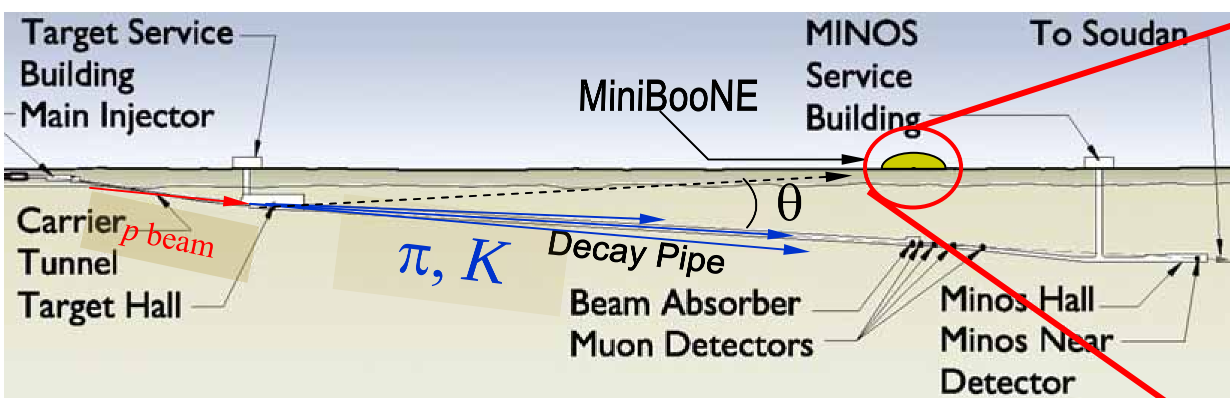
*** Best fit is where excess scales only with neutrino flux!**

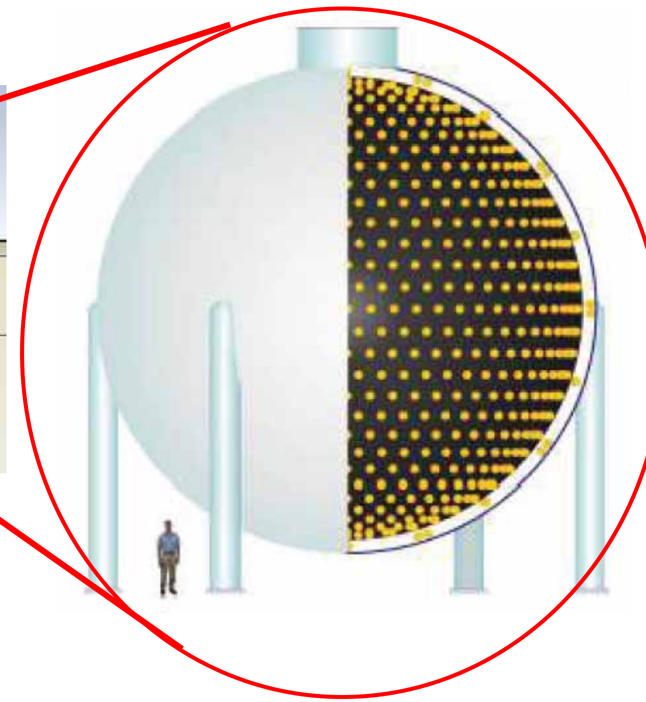
Proper systematic comparison of results in neutrino and anti-neutrino mode is underway!

We still have more results coming …

Events from NuMI detected at MiniBooNE

NuMI (Neutrinos from Main Injector) are used in MINOS experiment, measuring atmospheric Δm^2_{23}, $\sin^2 2\theta_{23}$ at Fermilab/Soudan Mine (735 km away).

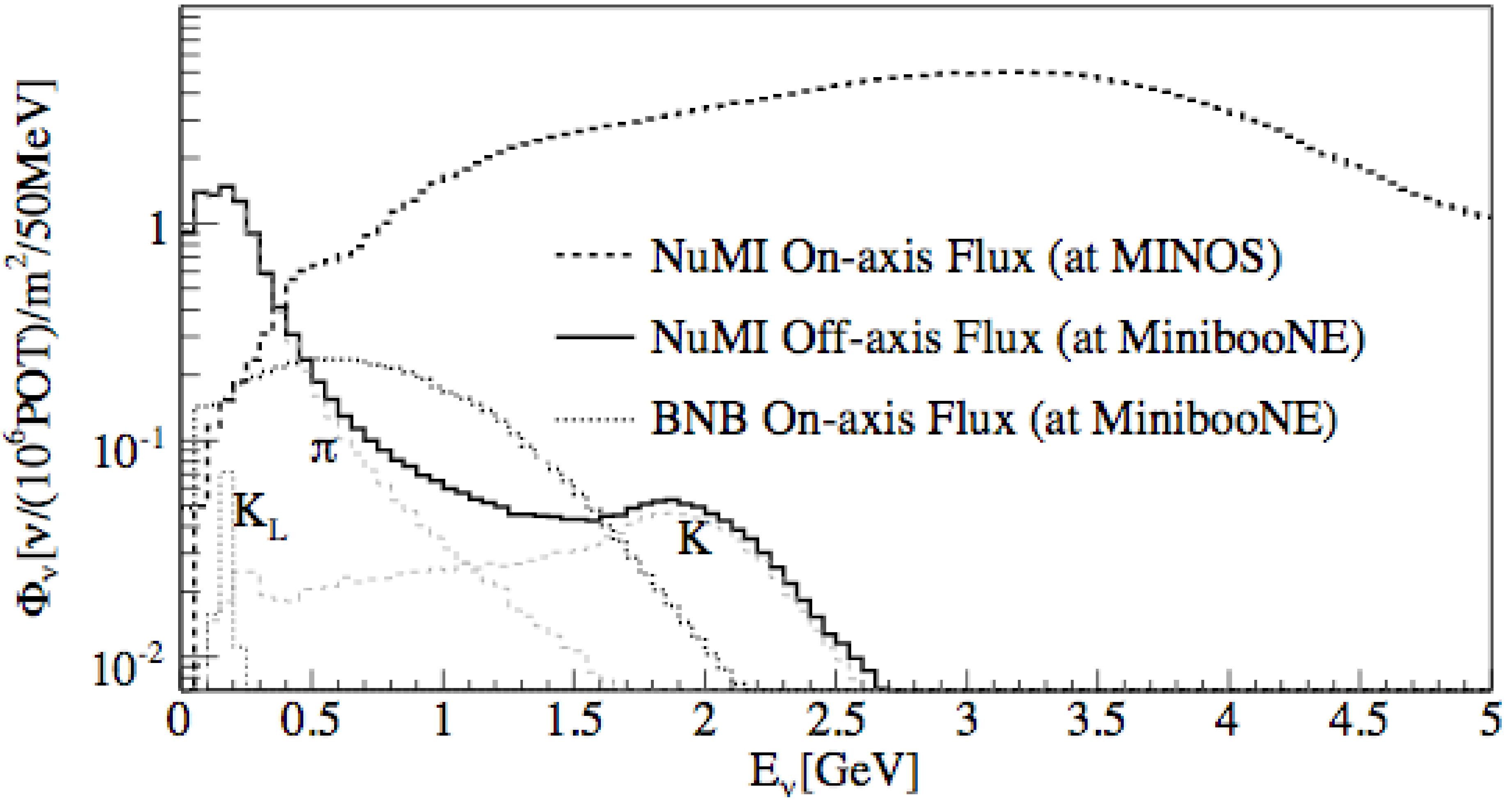




MiniBooNE detector is 745 meters downstream of NuMI target.

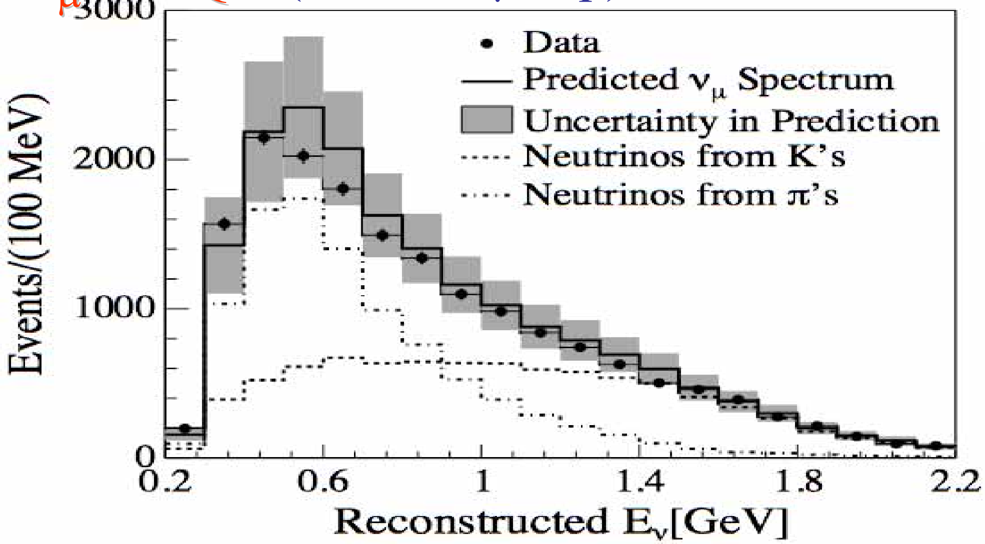
MiniBooNE detector is 110 mrad off-axis from the target along NuMI decay pipe.

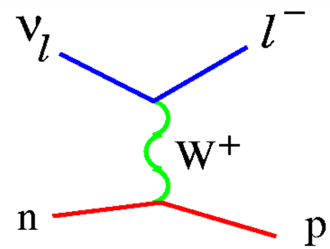
This is an off-axis beam!



ν_μ CCQE and ν_e CCQE samples from NuMI

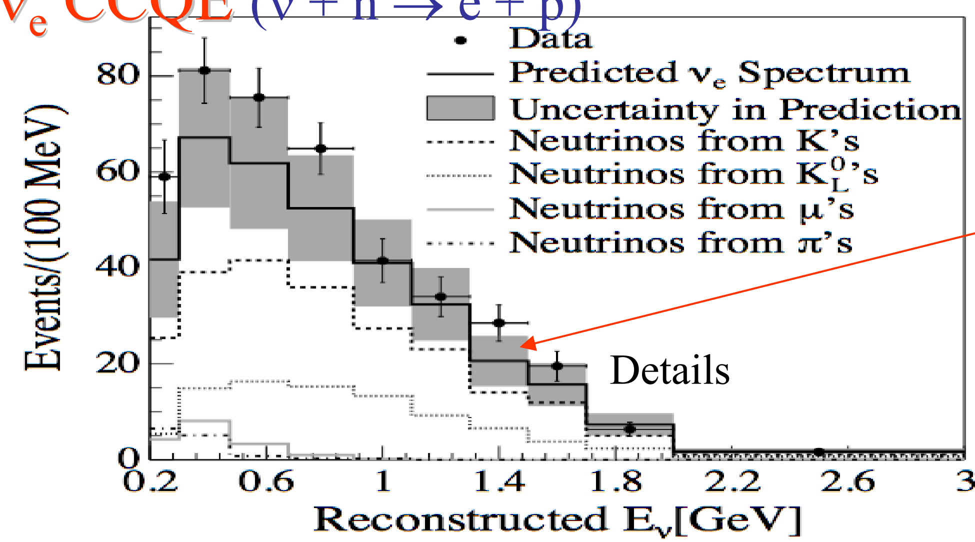
ν_μ CCQE ($\nu + n \rightarrow \mu + p$)





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

ν_e CCQE ($\nu + n \rightarrow e + p$)



arXiv:0809.2447 [hep-ex], submitted to Phys. Rev. Lett.

Systematics not yet constrained!

Meanwhile we collected more data from NuMI at MiniBooNE.

ν_e appearance analysis is underway!

Summary and Next Steps

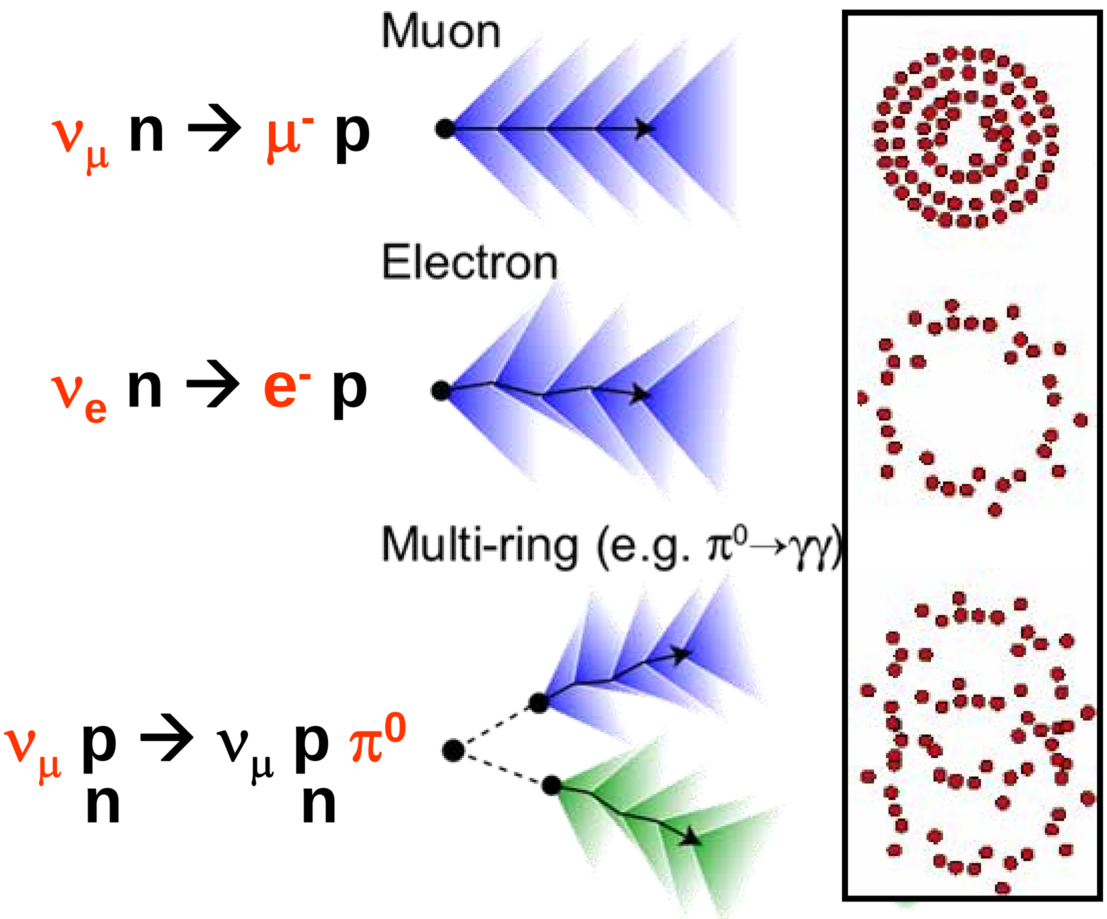
- MiniBooNE observes a low-energy excess of events in neutrino mode; the magnitude of the excess is what is expected from the LSND signal, although the energy shape is not very consistent with simple 2-ν oscillations.
- MiniBooNE so far observes no low-energy excess in antineutrino mode; this suggests that the excess may not be due to a Standard Model background. At present, the high-energy antineutrino data are consistent with both the LSND best-fit point & the null point.
- More antineutrino data & other data sets (NuMI & SciBooNE) will help improve our understanding of the low-energy excess.
- Proposal submitted to Fermilab PAC to collect more antineutrino data! (~5E20 POT by summer & ~1E21 POT by end of 2011) to study low-energy excess and LSND signal directly.

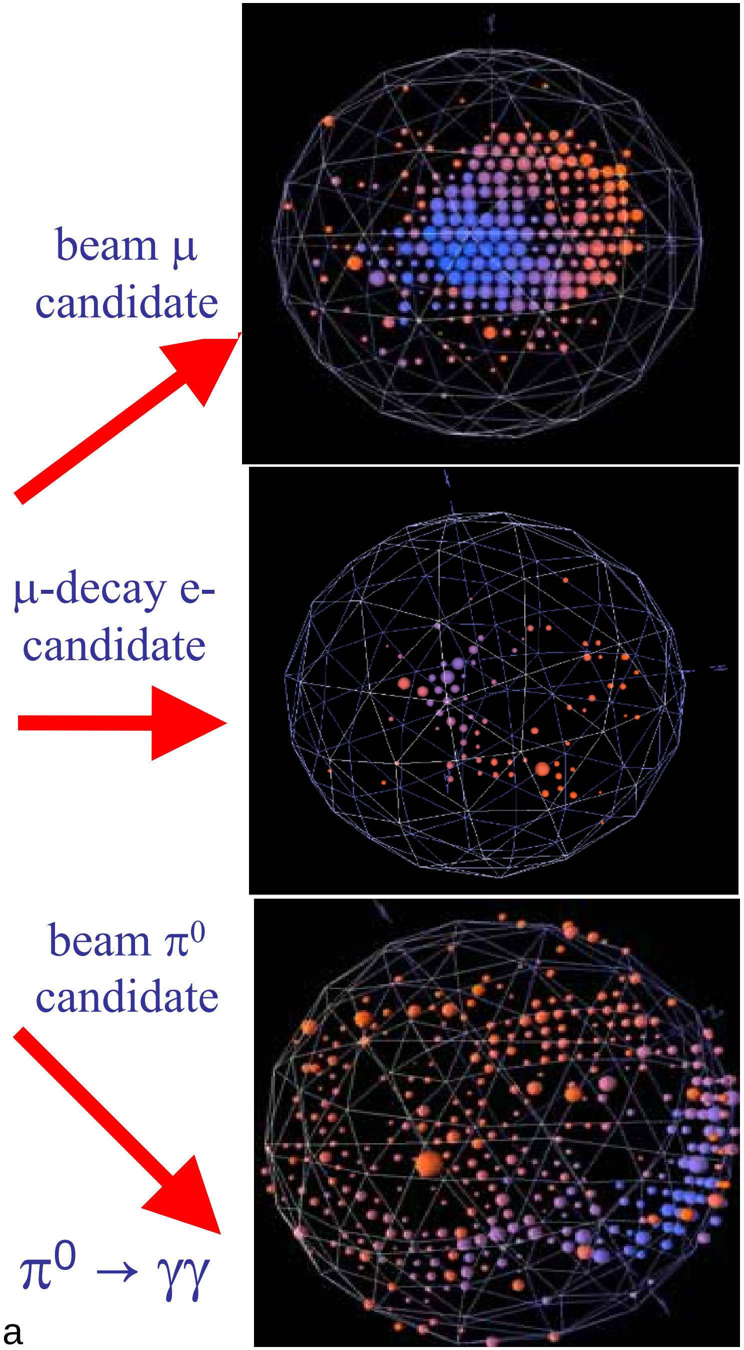
Thank you!

Backup Slides

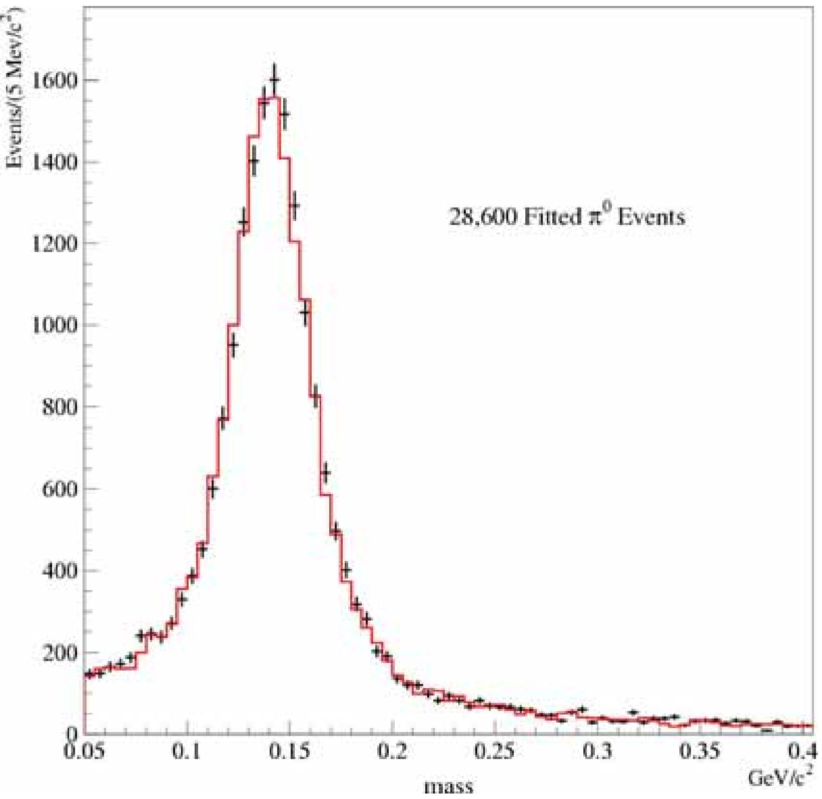
Particle Identification

Čerenkov rings provide primary means of identifying products of ν interactions in the detector





Measuring π^0 and constraining misIDs from π^0



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

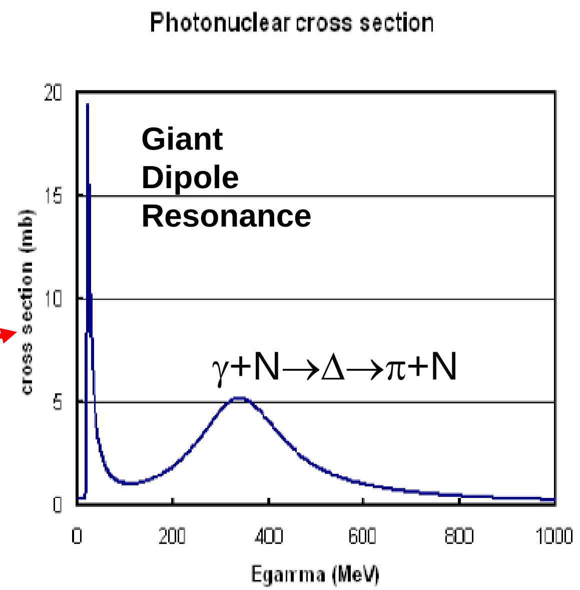
π^0 rate measured to a few % .
Critical input to oscillation analysis:
without constraint π^0 errors would be ~ 20%

Details Phys.Lett.B664, 41(2008)

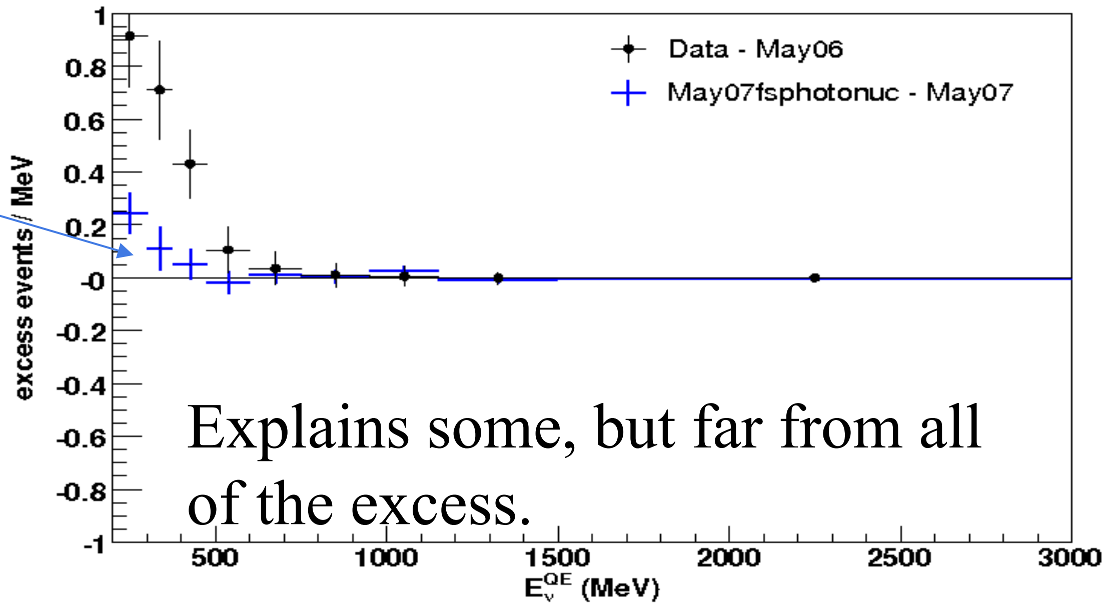
Photonuclear absorption of π^0 photon

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.

Processes that remove ("absorb") one of the gammas from a ν_μ-induced NC $\pi \rightarrow \gamma\gamma$ photonuclear absorption.

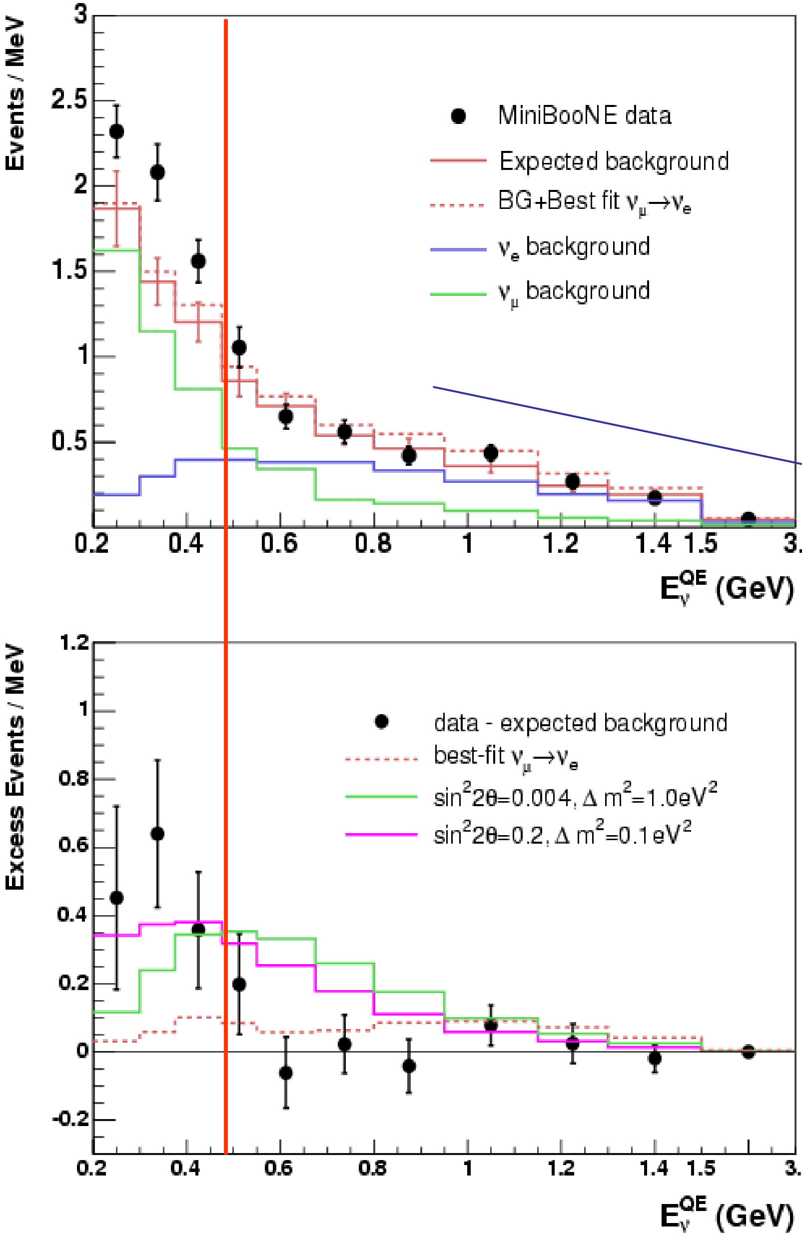


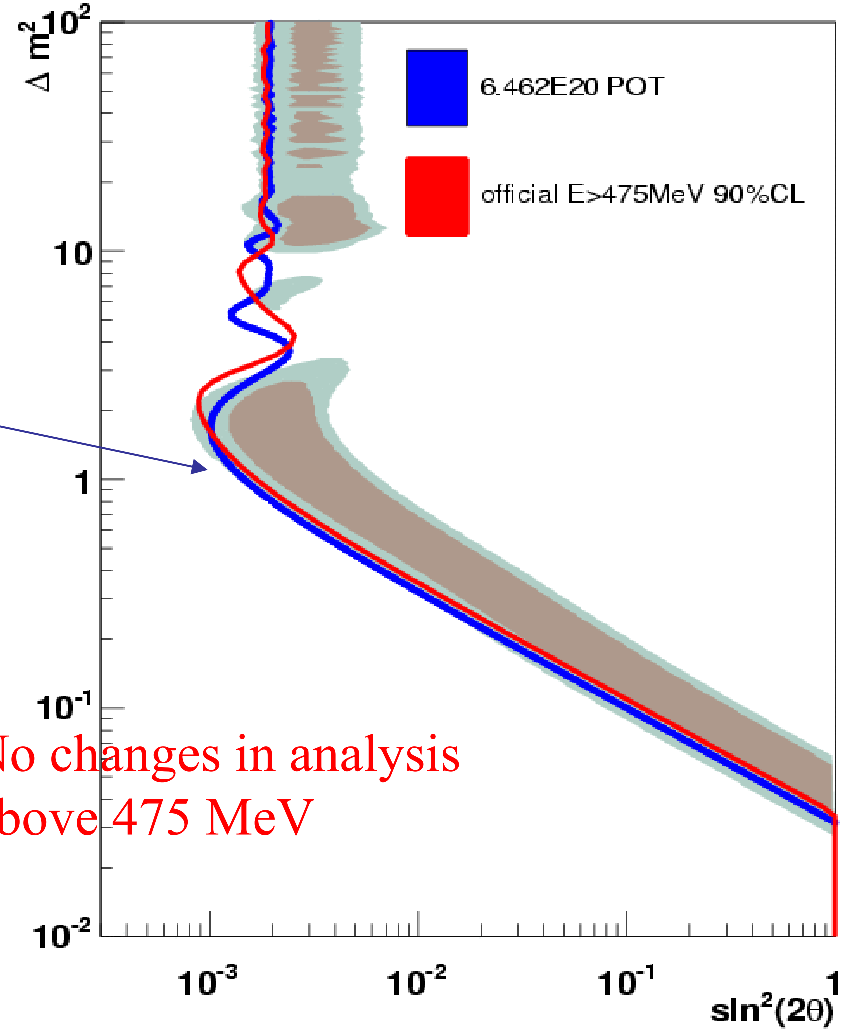
Adding this into the MC increases π^0 background by about 20%.



Explains some, but far from all of the excess.

Oscillation Fit Check





No changes in analysis above 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%)

MiniBooNE sensitivity to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Effect of E_ν threshold on sensitivity:

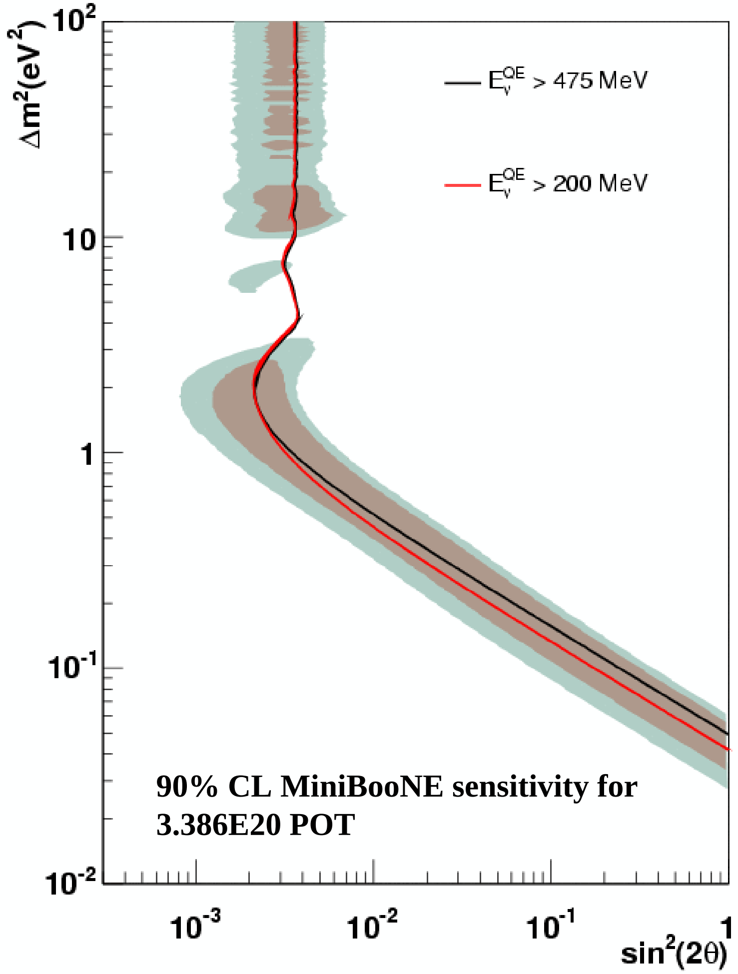
E_ν > 475 MeV

E_ν > 200 MeV

P ~ sin²(1.27 Δm²[eV²] L[m] / E[MeV])

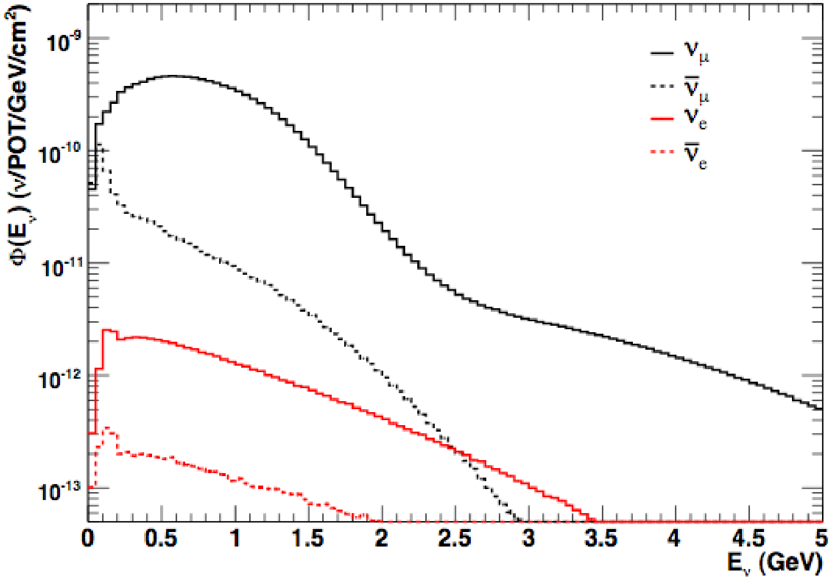
~ Δm²/E ~ 1 for maximum sensitivity

fitting to lower energy increases sensitivity for lower Δm²

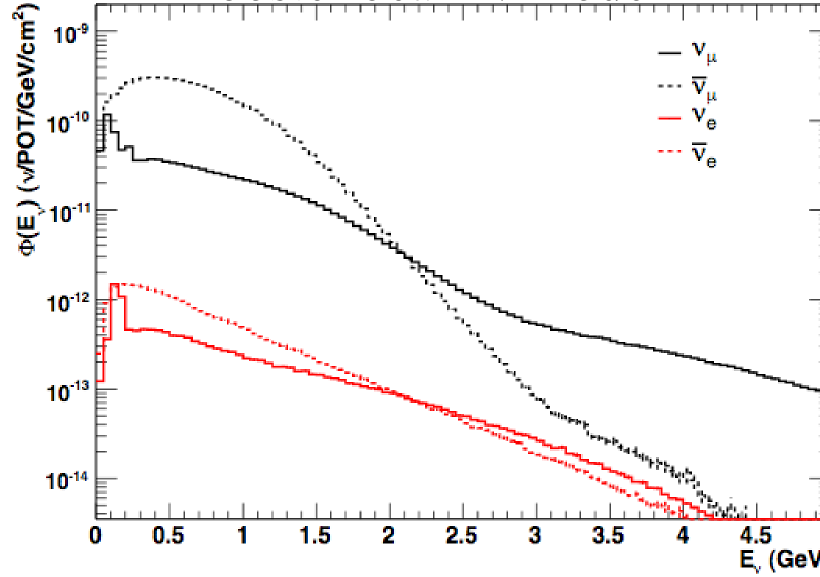


Comparison of BNB and NuMI fluxes at MiniBooNE

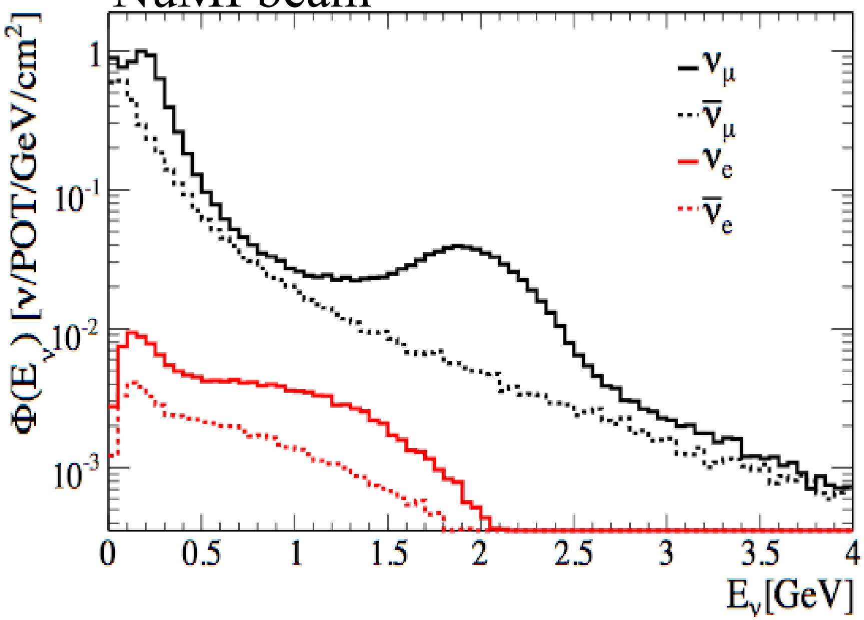
Booster beam ν mode



Booster beam $\bar{\nu}$ mode



NuMI beam



NuMI flux is a “connection” between MiniBooNE Booster Neutrino Beam (BNB) ν and $\bar{\nu}$ events.

Analysis of the ν_e CCQE events from NuMI beam

ν_e CCQE ($\nu + n \rightarrow e + p$)

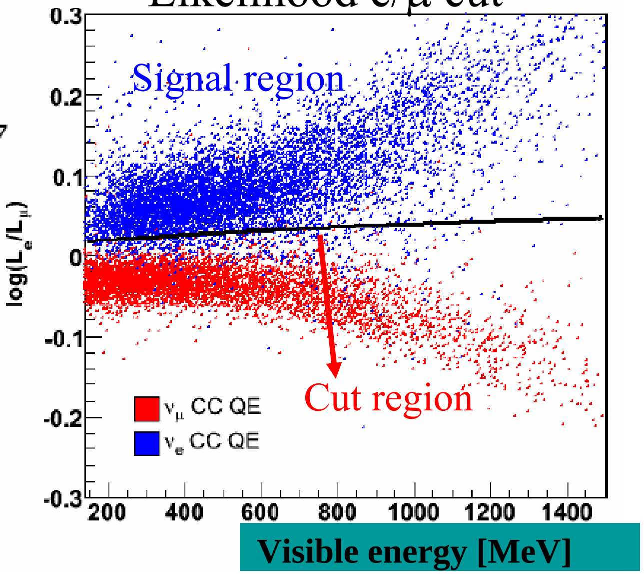
1 Subevent
Thits > 200, Vhits < 6
R < 500 cm, E_e > 200 MeV

\+

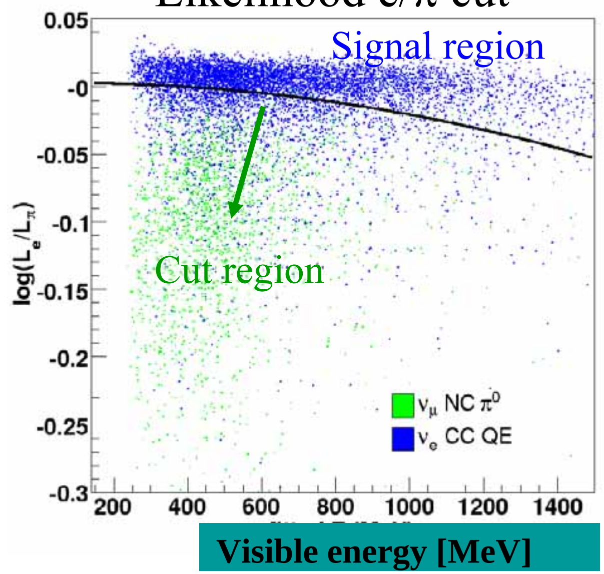
Likelihood cuts as the as shown below

E_e>200MeV cut is appropriate to remove ν_e contribution from the dump that is hard to model.

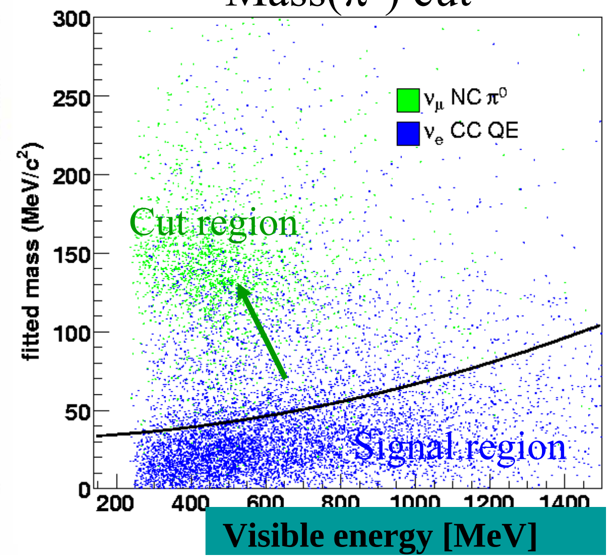
Likelihood e/μ cut



Likelihood e/π cut



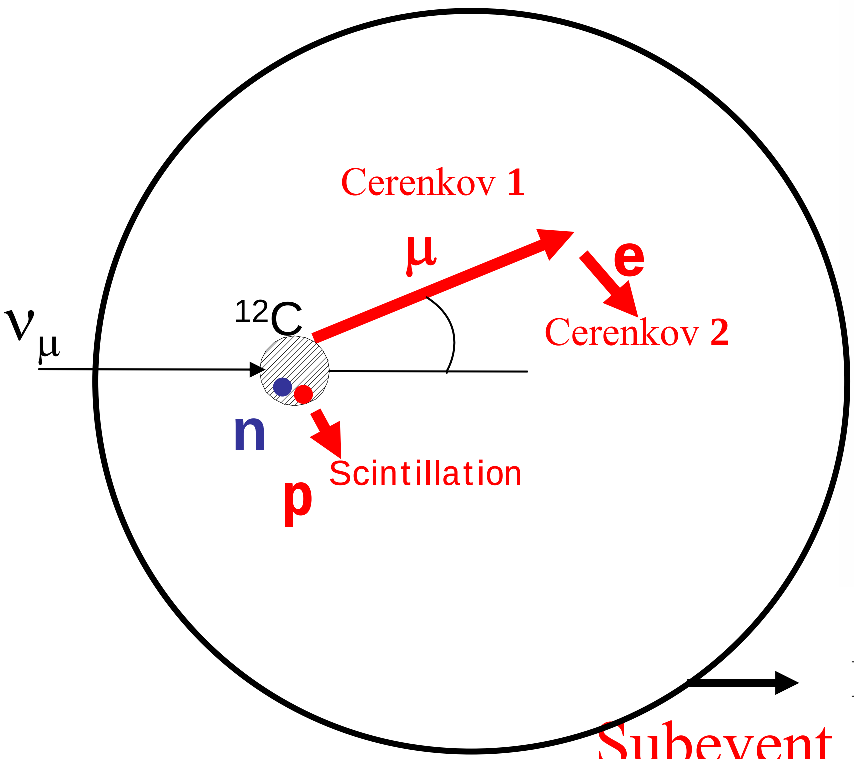
Mass(π^0) cut

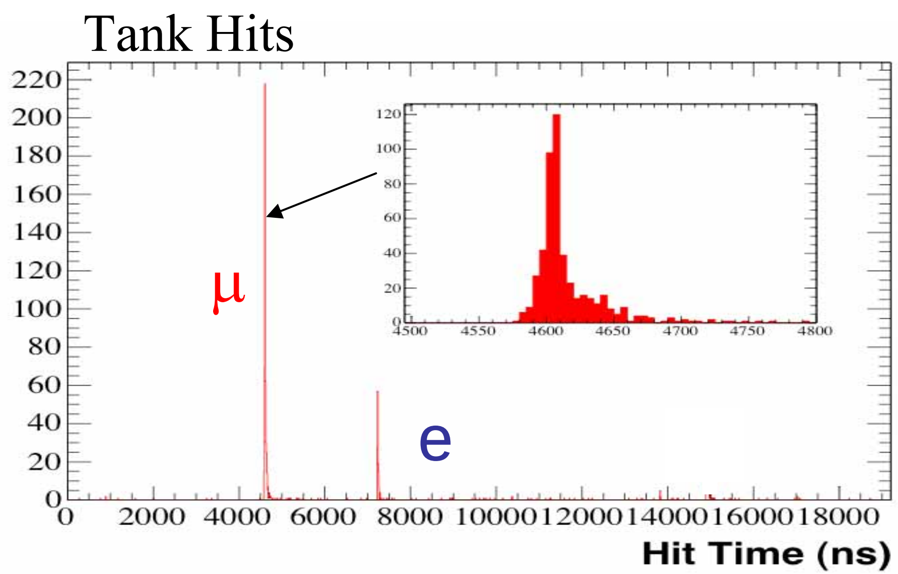


Analysis of the ν_μ CCQE events from NuMI beam

ν_μ CCQE ($\nu + n \rightarrow \mu + p$) has a two “subevent” structure

(with the second subevent from stopped $\mu \rightarrow \nu_\mu \nu_e e$)





Event Selection:

Subevent 1:

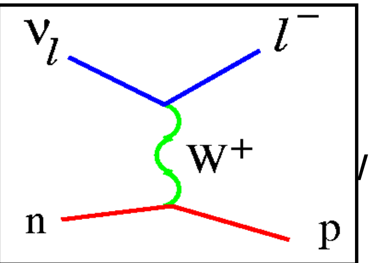
Thits>200, Vhits<6

R<500 cm

$L_e/L_\mu < 0.02$

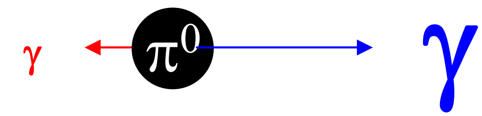
Subevent 2:

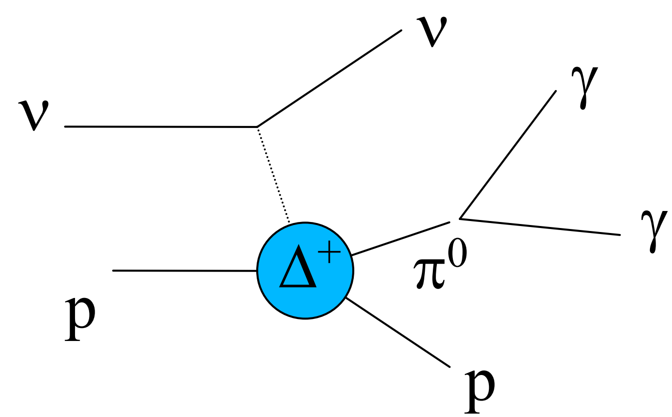
Thits < 200, Veto < 6



Analysis of π^0 events from NuMI beam

Among the e-like mis-ids, π^0 decays which are boosted, producing 1 weak ring and 1 strong ring is largest source.





Strategy: Don't try to predict the π^0 mis-id rate, **measure it!**
Measured rates of reconstructed π^0… tie down the rate of mis-ids

What is applied to select π^0s

Event pre-selection:

1 subevent

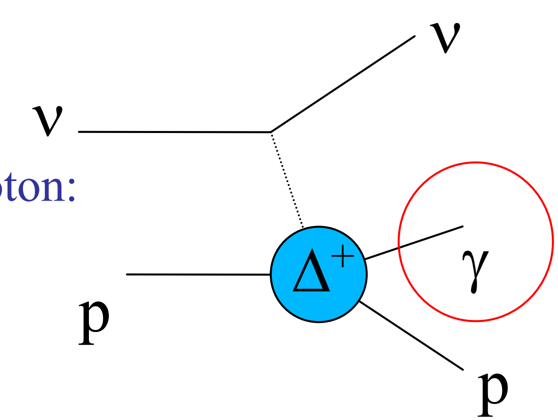
Thits>200, Vhits<600

R<500 cm

$\log(L_e/L_\mu)>0.05$ (e-like)

$\log(L_e/L_\pi)<0$ (π^0-like)

Δ decays to a single photon: with 0.56% probability:



Selecting the dirt events

Event pre-selection:
1 subevent
Thits>200, Vhits<600
R<500 cm

$\log(L_e/L_\mu)>0.05$ (e-like)

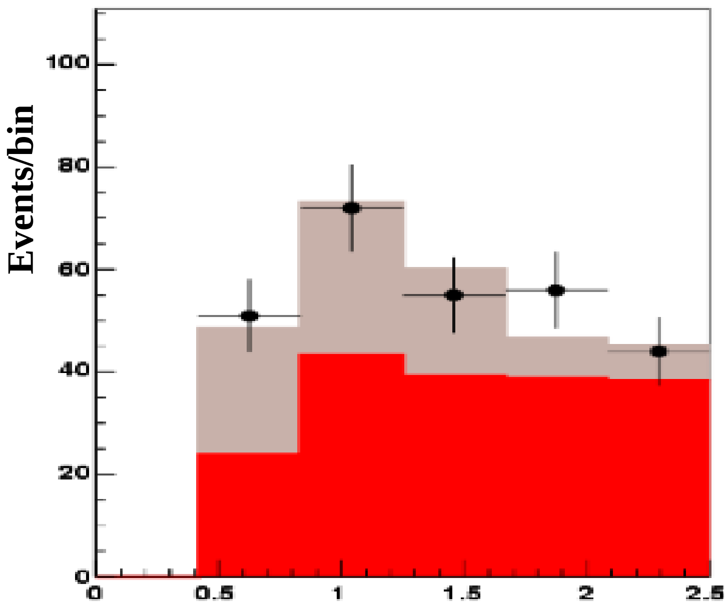
$E_e<550$ MeV

Distance-to-wall < 250 cm

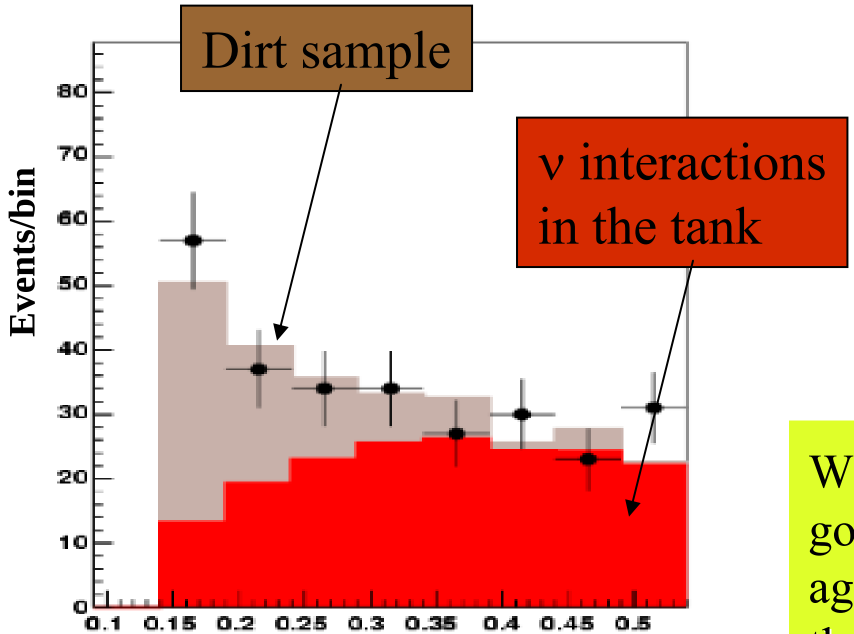
$m_\pi<70$ MeV/c^2 (not π^0-like)

Fits to dirt enhanced sample:

Uncertainty in the dirt rate is less than 20%.



Dist-to-wall of tank along track [m]

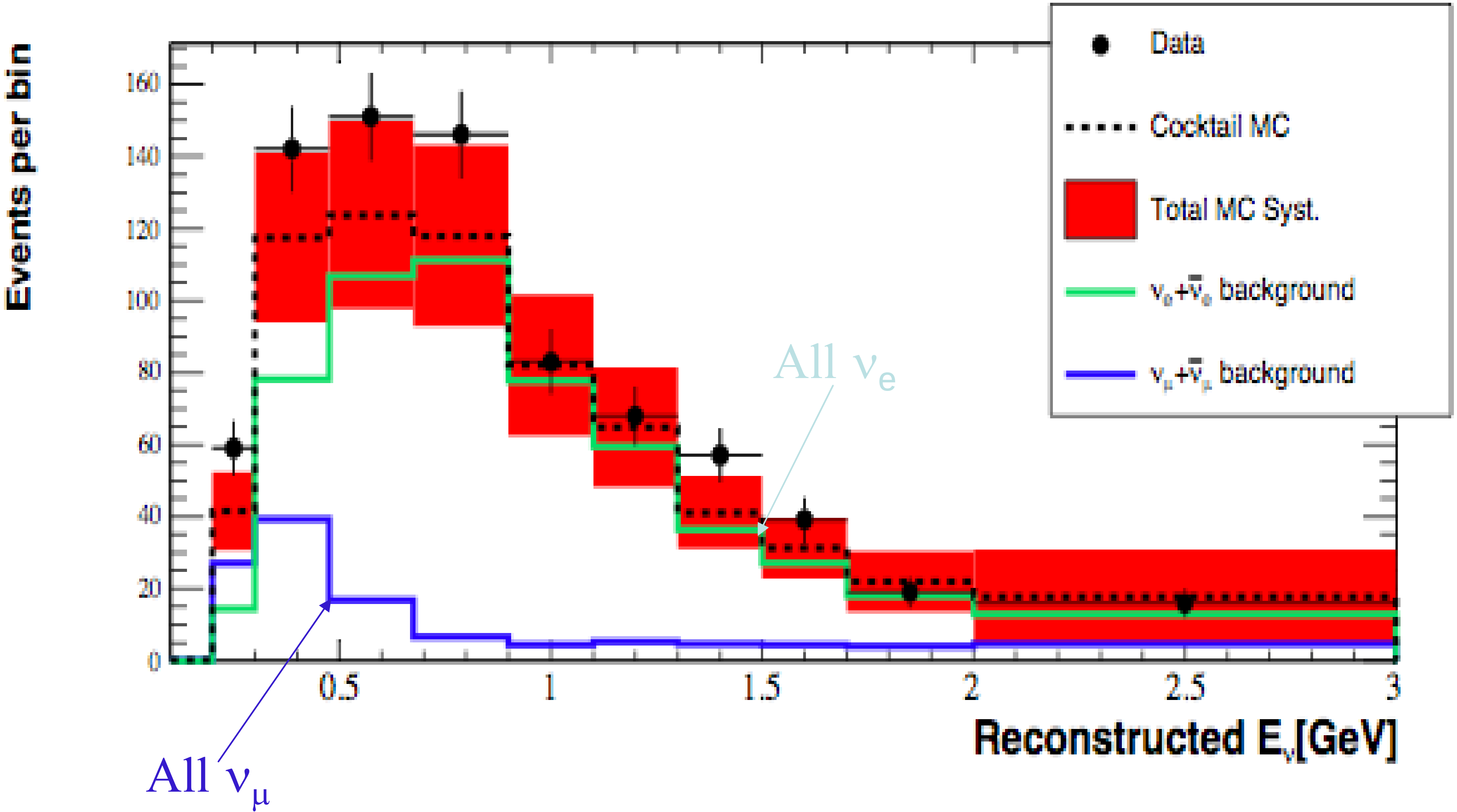


Visible energy [GeV]

We declare good MC/Data agreement for the dirt sample.

ν_e CCQE sample: Reconstructed energy E_ν of incoming ν

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

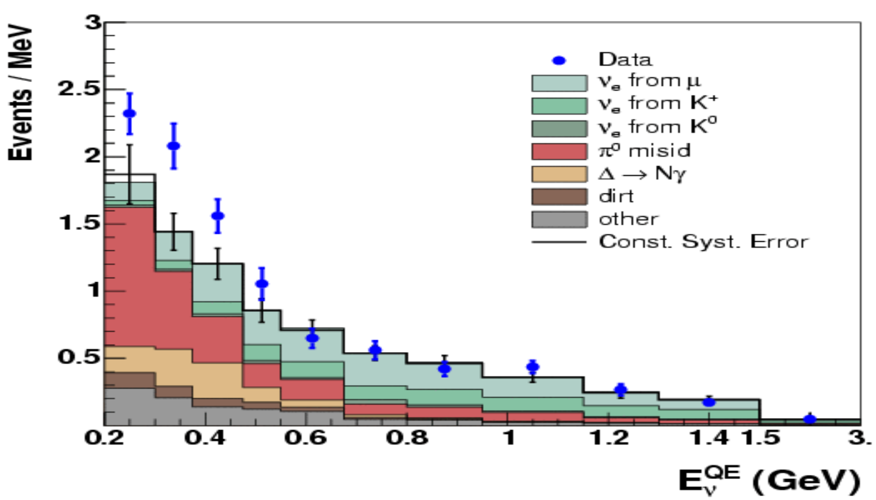


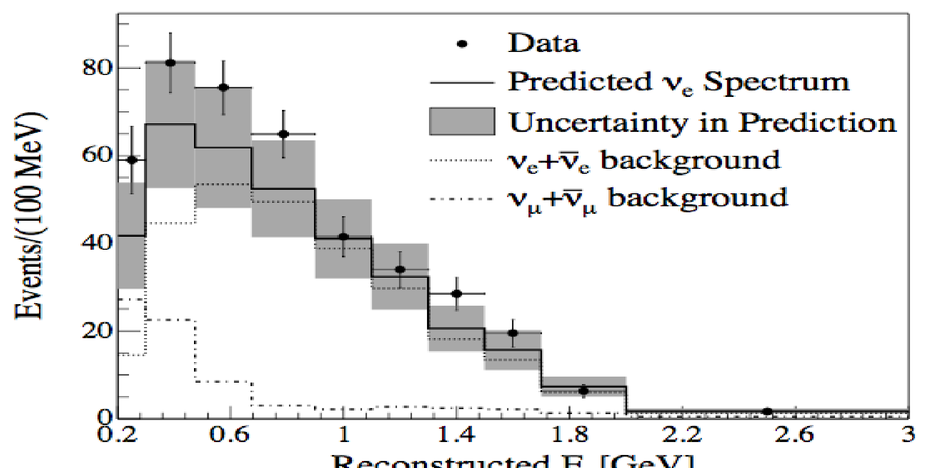
NuMI vs Booster Beam at MiniBooNE

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 in the NuMI beam data at MiniBooNE.





Currently collecting and analyzing more data from NuMI beamline!

- Performed 2-bin χ^2 test for each assumption
- Calculated χ^2 probability assuming 1 dof

$$\chi^2 = \sum_{i,j} \left(D_i - \left(B_i + S_i \right) \right) M_{ij}^{-1} \left(D_j - \left(B_j + S_j \right) \right)$$

$i, j = \nu, \bar{\nu}$ 200-475MeV bin

The underlying signal for each hypothesis, S, was allowed to vary (thus accounting for the possibility that the observed signal in neutrino mode was a fluctuation up, and the observed signal in antineutrino mode was a fluctuation down), and an absolute χ^2 minimum was found.

- Three extreme fit scenarios were considered
  - Statistical + fully-correlated systematics
  - Statistical + fully-uncorrelated systematics

MiniBooNE appearance analysis

Background systematic uncertainties

Source	$\bar{\nu}$ mode uncer. (%)		ν mode uncer. (%)	
E_{ν}^{QE} range (MeV)	200-475	475-1100	200-475	475-1100
Flux from π^+/μ^+ decay	0.4	0.7	1.8	2.2
Flux from π^-/μ^- decay	3.3	2.2	0.1	0.2
Flux from K^+ decay	2.3	4.9	1.4	5.7
Flux from K^- decay	0.5	1.1	-	-
Flux from K^0 decay	1.5	5.7	0.5	1.5
Target and beam models	1.9	3.0	1.3	2.5
ν-cross section	6.4	12.9	5.9	11.9
NC π^0 yield	1.7	1.6	1.4	1.9
Hadronic interactions	0.5	0.6	0.8	0.3
External interactions (dirt)	2.4	1.2	0.8	0.4
Optical model	9.8	2.8	8.9	2.3
Electronics & DAQ model	9.7	3.0	5.0	1.7
Total (unconstrained)	16.3	16.2	12.3	14.2