MiniBooNE Results

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Outline

Before MiniBooNE

MiniBooNE Experiment Description

MiniBooNE's First Oscillation Results

Low Energy Electron Candidate Excess

MiniBooNE's New Data

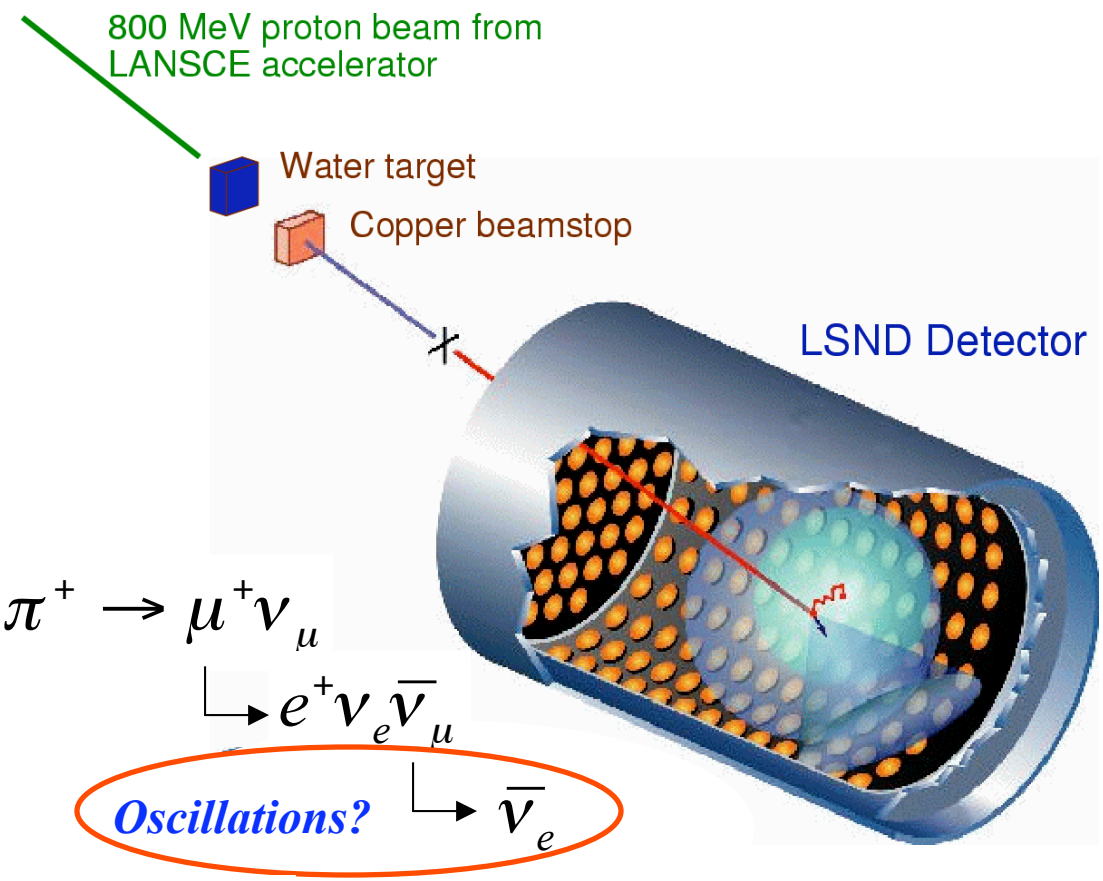
What has MiniBooNE told us?

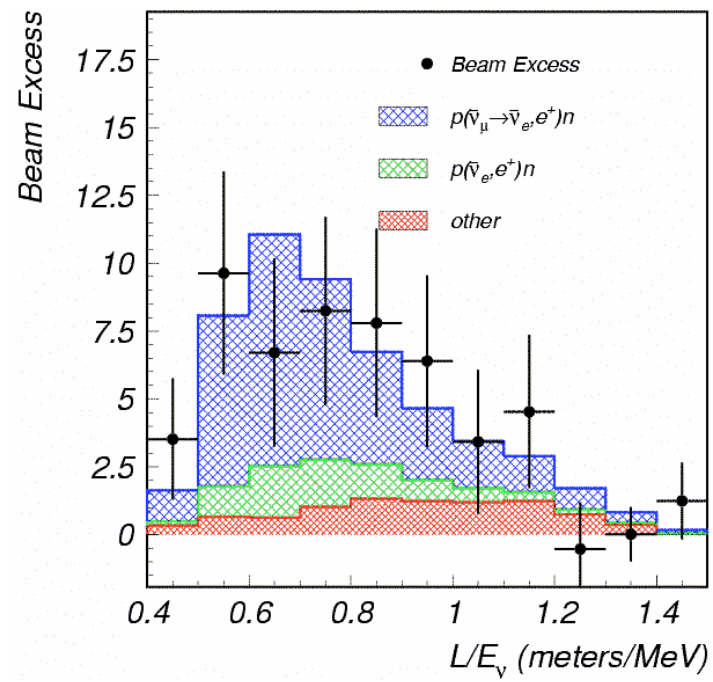
Anti-neutrinos at MiniBooNE

Summary

Before MiniboonE

The LSND Experiment





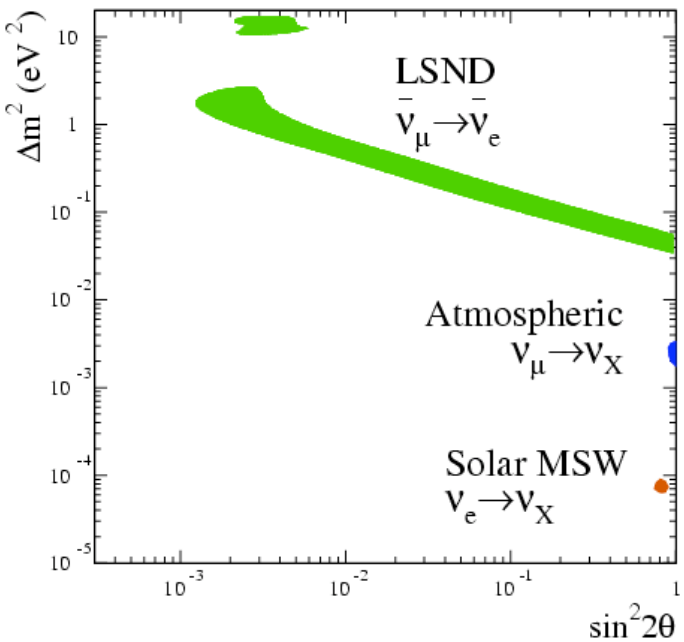
Signal: $\bar{\nu}_e$ p → e⁺ n

n p → d γ(2.2MeV)

With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ significance for excess.

Oscillation Status After LSND

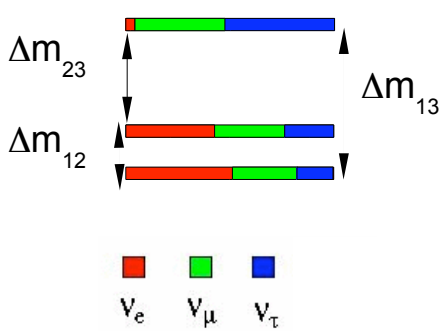


This signal looks very different from the others...

- Much higher Δm^2 = 0.1 – 10 eV^2
- Much smaller mixing angle
- Only one experiment!

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

In SM there are only 3 neutrinos

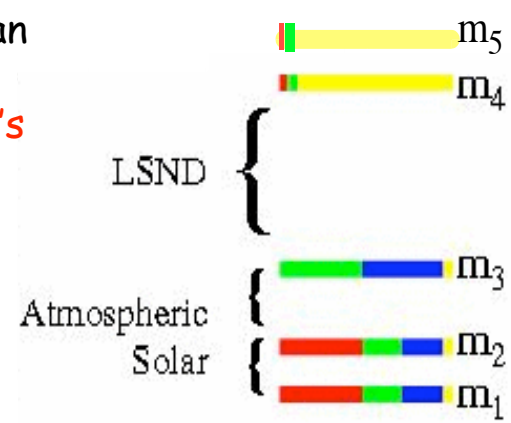


LSND in conjunction with the atmospheric and solar oscillation results needed more than 3 ν's

Models developed with 1 or more sterile ν's

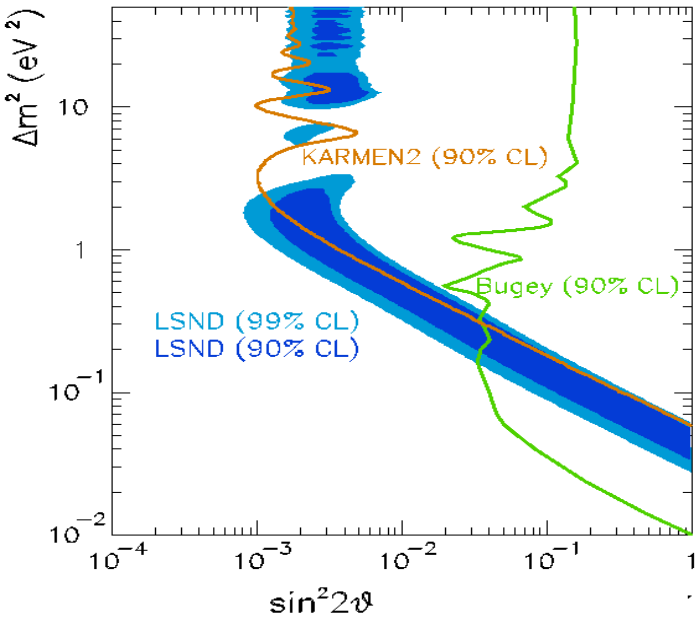
or other new physics models.

3+2 models



It was important to check LSND what was left to ...

Oscillation Status After LSND



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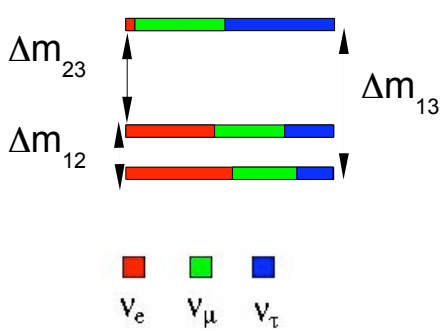

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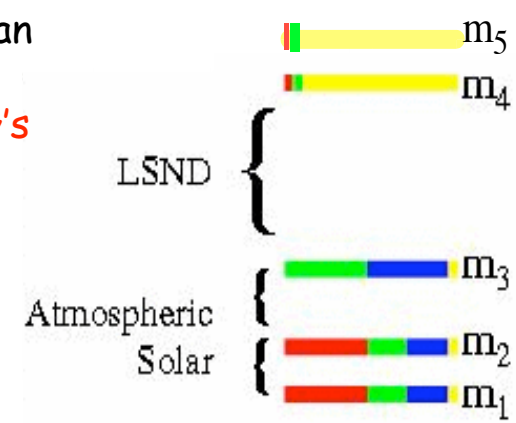


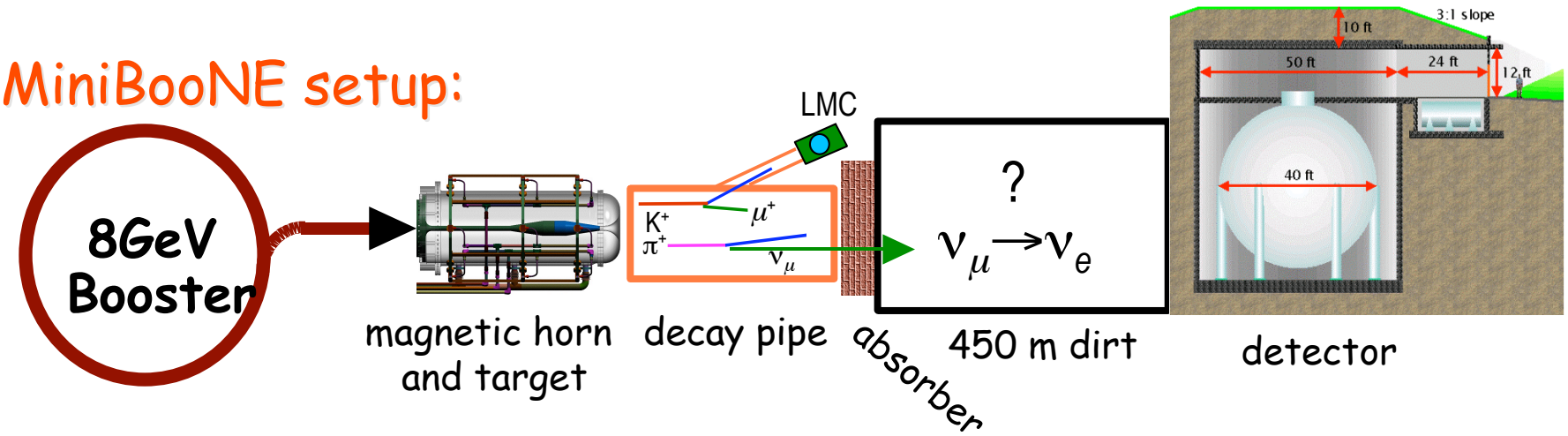
It was important to check LSND what was left to ...

MiniBooNE

(Booster Neutrino Experiment)

Search for ν_e appearance in ν_μ beam

MiniBooNE setup:



$\nu_\mu \rightarrow \nu_e$???

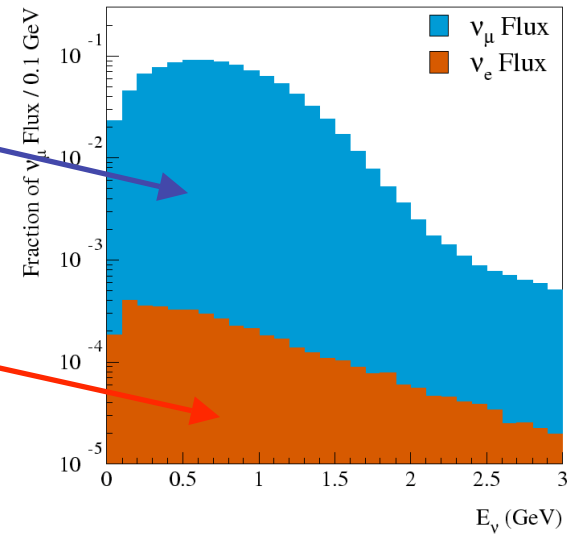
Similar L/E as LSND
Baseline: L = 540 meters, ~ x15 LSND
Neutrino Beam Energy: E ~ x(10-20) LSND

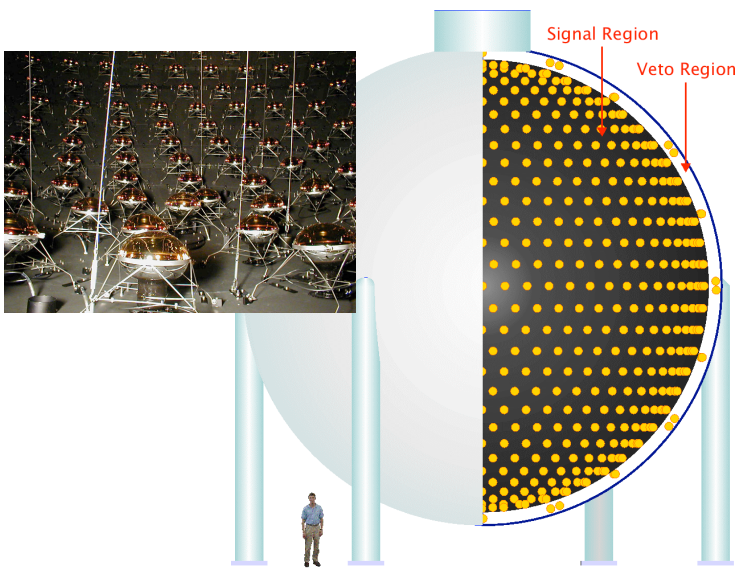
Different systematics: event signatures and backgrounds different from LSND
High statistics: ~ x5 LSND

$\nu_\mu \rightarrow \nu_e$ Oscillation Search

- Main ν_μ flux from $\pi^+ \rightarrow \mu^+ \ \nu_\mu$
- Intrinsic ν_e flux from
  - $\mu^+ \rightarrow \nu_\mu \ e^+ \ \nu_e$
  - $K^+ \rightarrow \pi^0 \ e^+ \ \nu_e$
  - $K^0_L \rightarrow \pi^- \ e^+ \ \nu_e$

$\Rightarrow \nu_e / \nu_\mu \approx 0.5\%$





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 ...

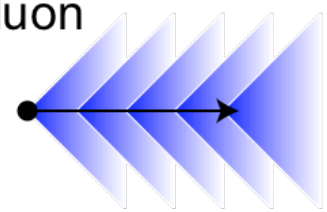
-Separate ν_μ events from ν_e events.

Particle Identification

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

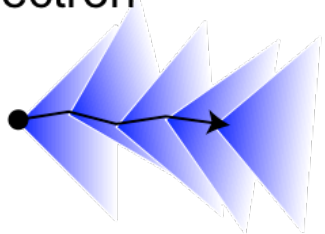
Muon

ν_μ n → μ^- p



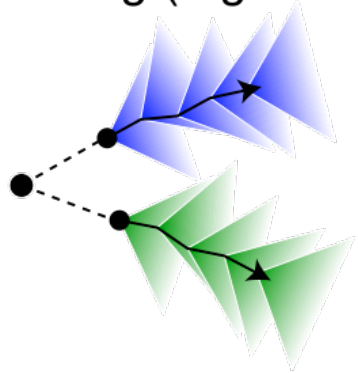
Electron

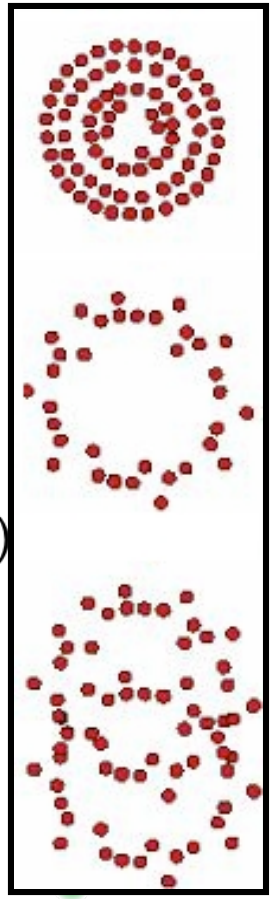
ν_e n → e^- p



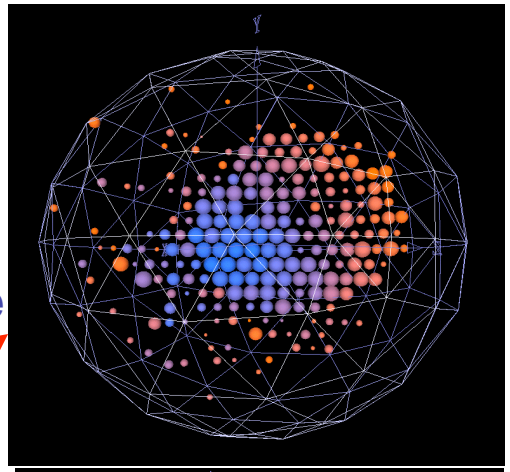
Multi-ring (e.g. $\pi^0 \rightarrow \gamma\gamma$)

ν_μ p → ν_μ p π^0
n n

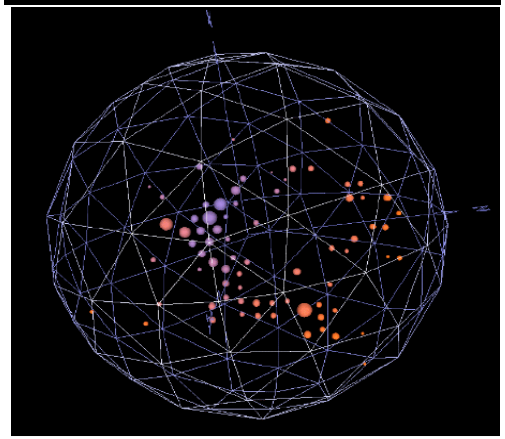




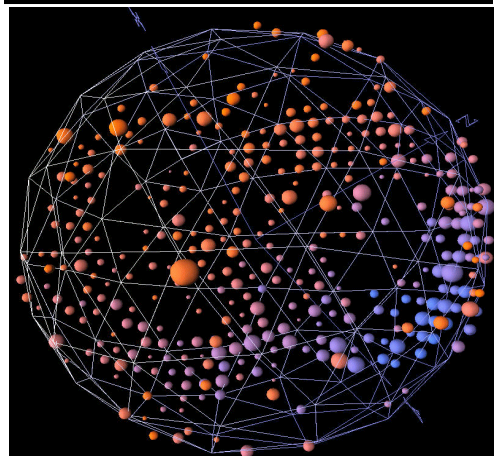
beam μ candidate



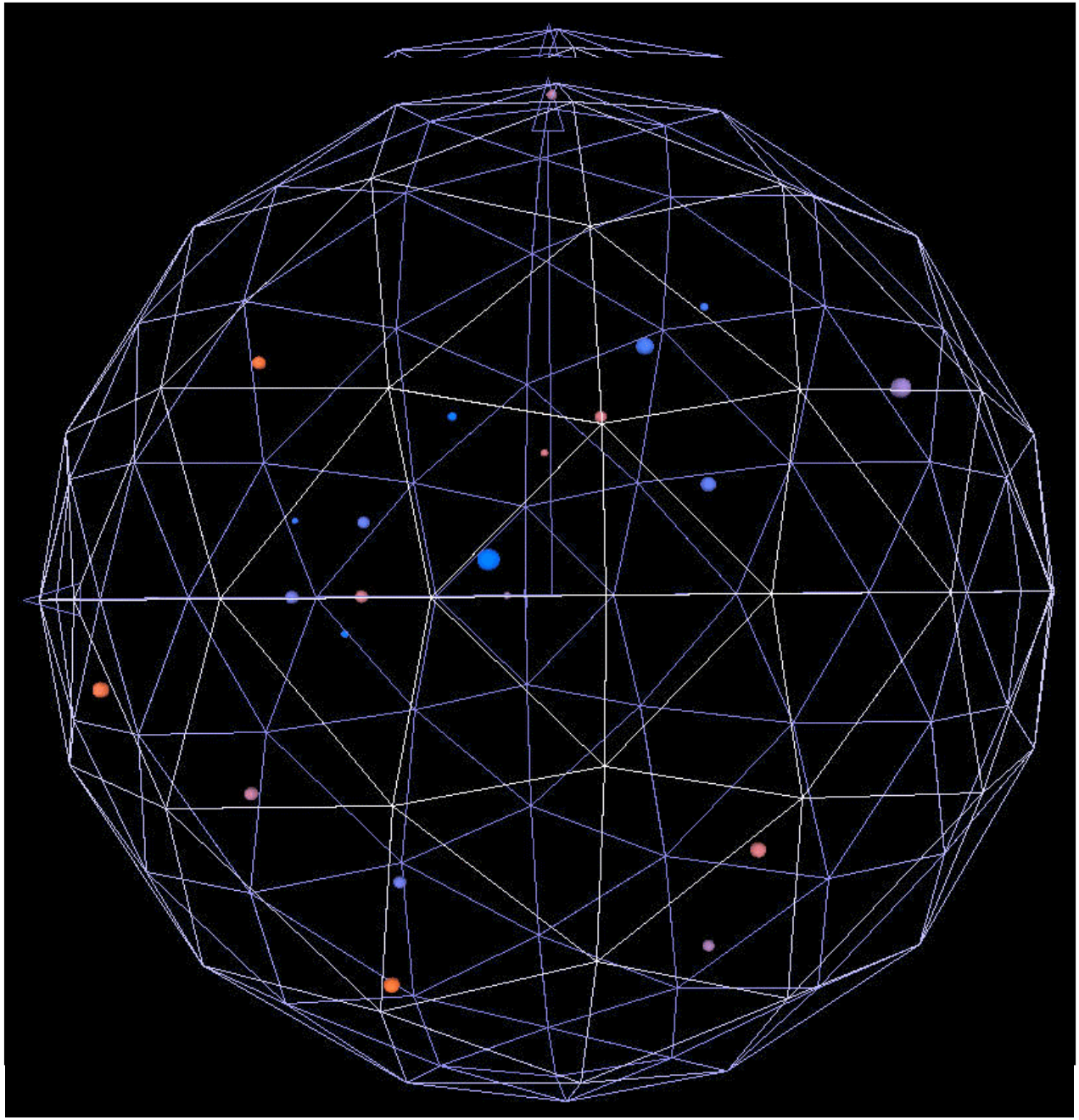
μ-decay e^- candidate



beam π^0 candidate



$\pi^0 \rightarrow \gamma\gamma$



Muon Identification Signature:

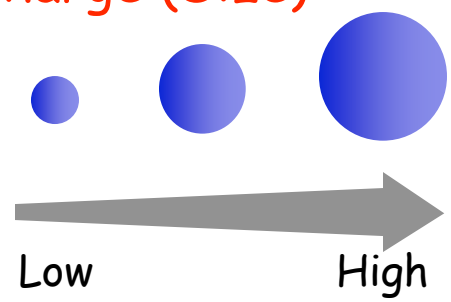
$\mu \rightarrow e\, \nu_\mu\, \nu_e$

after ~2μsec

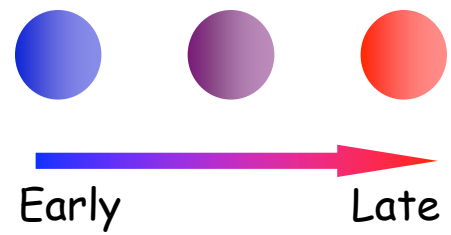
Animation

Each frame is 25 ns with 10 ns steps.

Charge (Size)



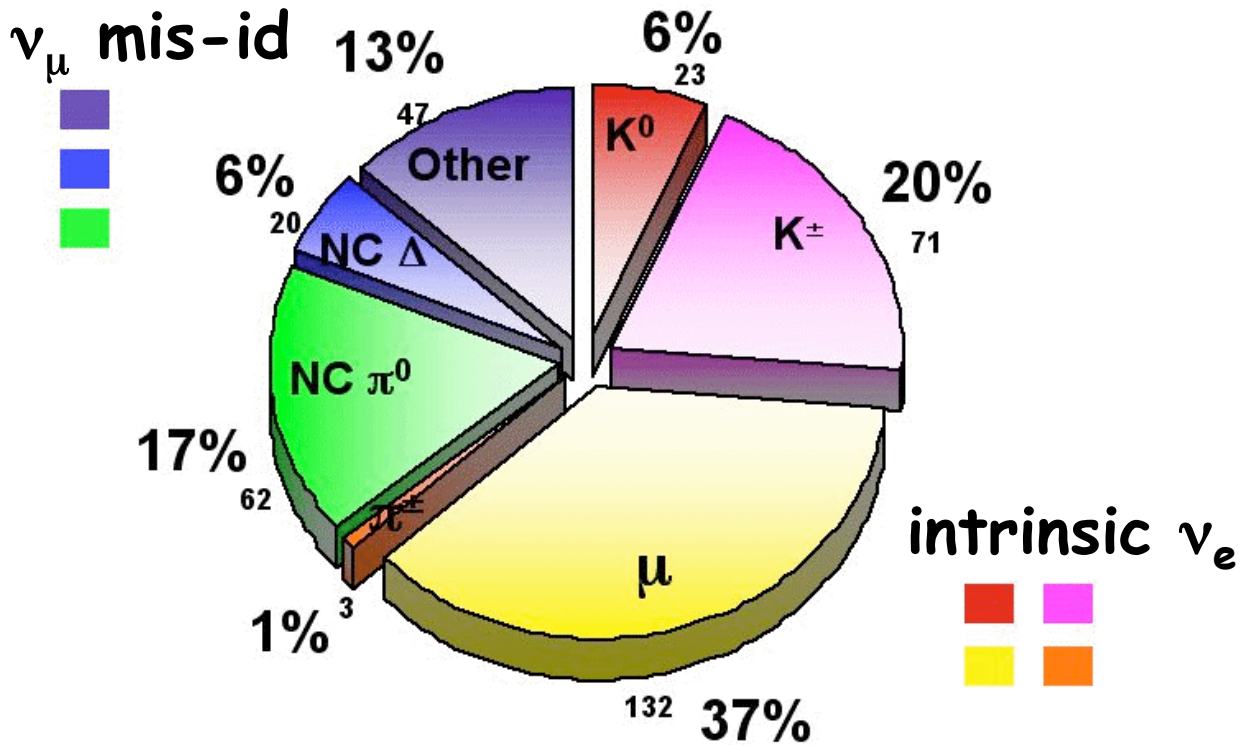
Time (Color)



Oscillation Analysis

Oscillation Analysis: Expected Background Events

Two main categories of backgrounds: ν_μ mis-ids and intrinsic ν_e



→ Events with ν_e Selection requirements

$475 < E_\nu < 1250$ MeV

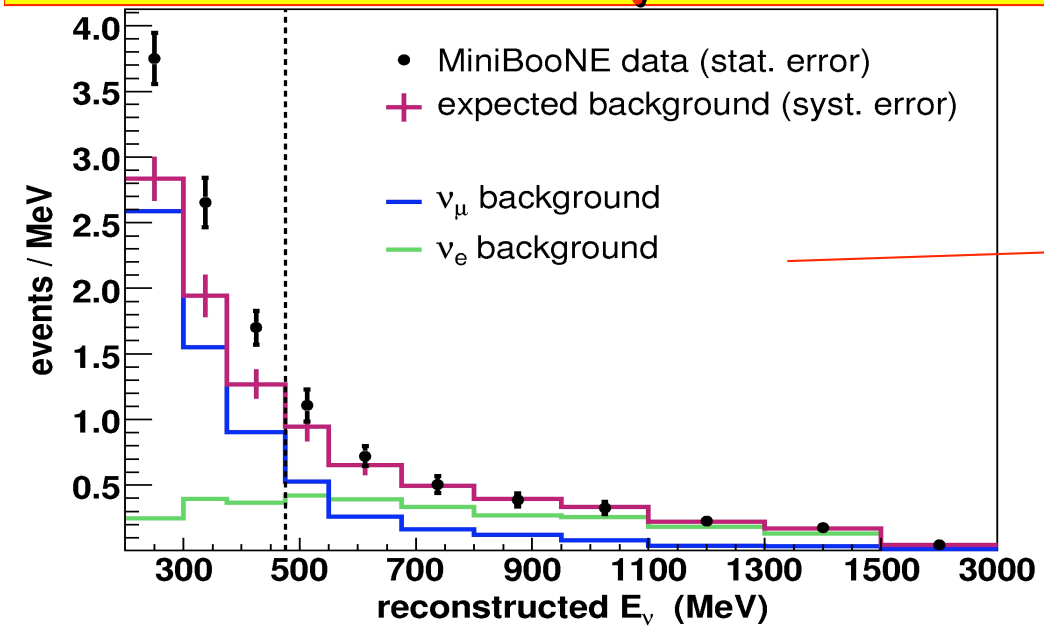
Predicted backgrounds:

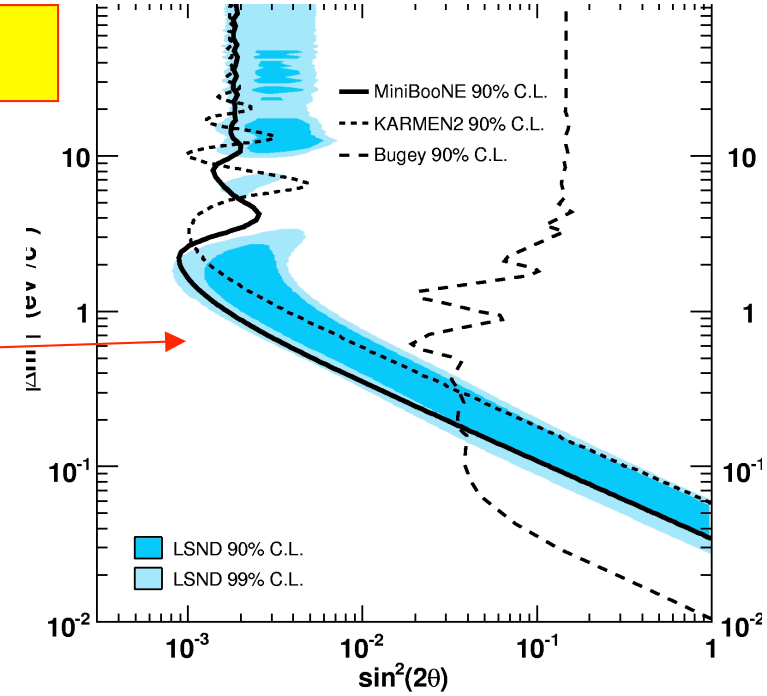
Total Expected Background = 358 events.

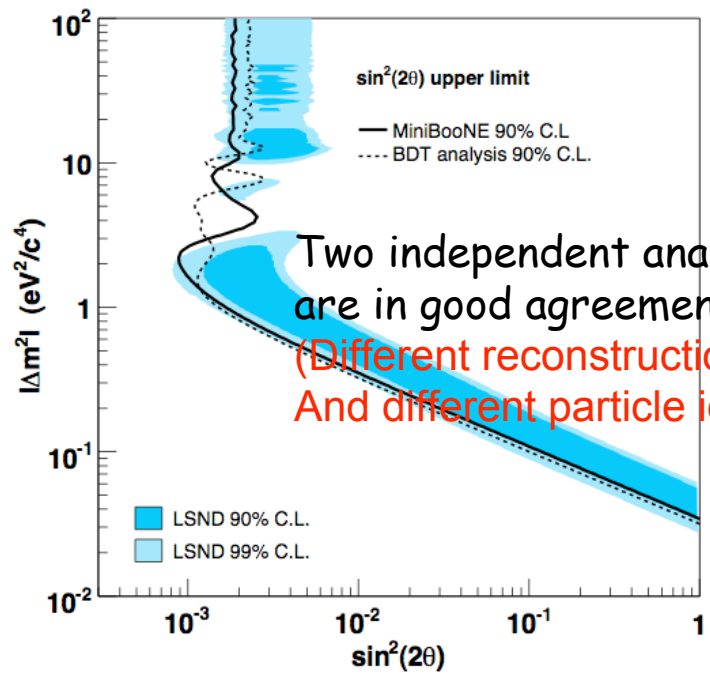
Example LSND Osc Signal = 163 events ($\Delta m^2 = 0.4\ eV^2$, $\sin^2 2\theta = 0.017$).

5.6×10^{20} POT in neutrino mode used for the analysis.

Oscillation Analysis: Results







Two independent analyses are in good agreement.
(Different reconstructions
And different particle id)

MiniBooNE's first result show no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations in the analysis region!

Details:

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

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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);

Ten Top Physics Stories for 2007

The MiniBooNE experiment at Fermilab solves a neutrino mystery.

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Mon Feb 18 2:15 PM

Beyond First Result

Combining Two Analyses

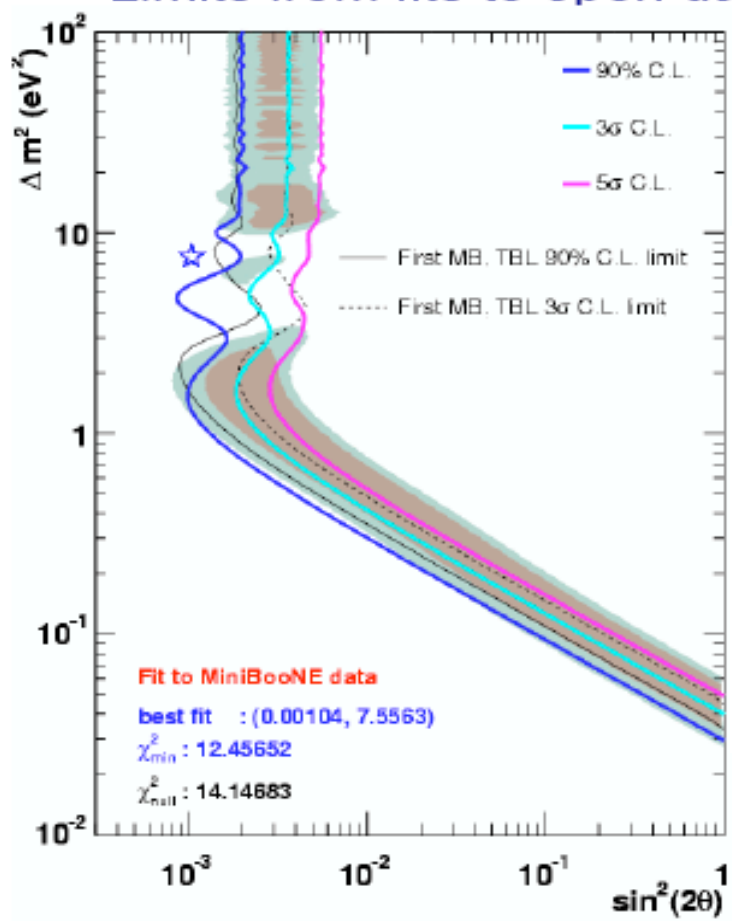
The ν_eBDT + ν_eTBL + ν_μCCQE results:

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.

Limits from fits to open data



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

Global Data Analysis

Combine results from several experiments: LSND, MiniBooNE, Karmen and Bugey.

Get compatibility

How probable is that all experimental results come from the same underlying $\nu_\mu \rightarrow \nu_e$ oscillation hypothesis?

Done by combining $\Delta\chi^2$ from each experiment.

Get allowed regions

Where would oscillation parameters Δm^2 , $\sin^2 2\theta$ lie assuming that all experimental results come from the same underlying $\nu_\mu \rightarrow \nu_e$ oscillation hypothesis?

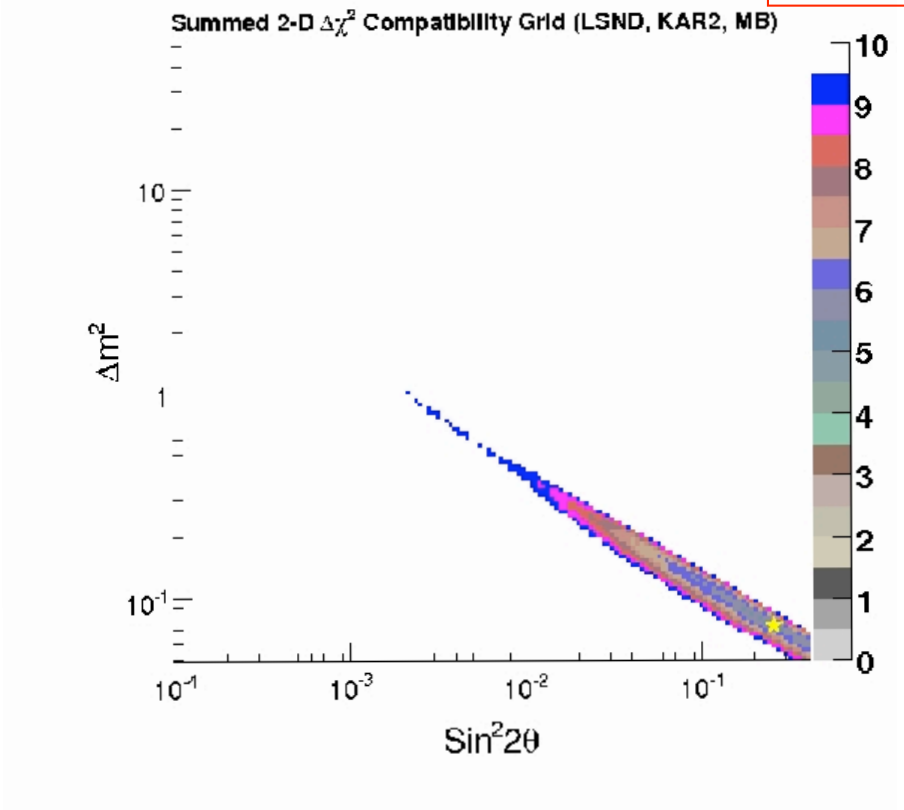
Details arXiv:0805.1764 [hep-ex]

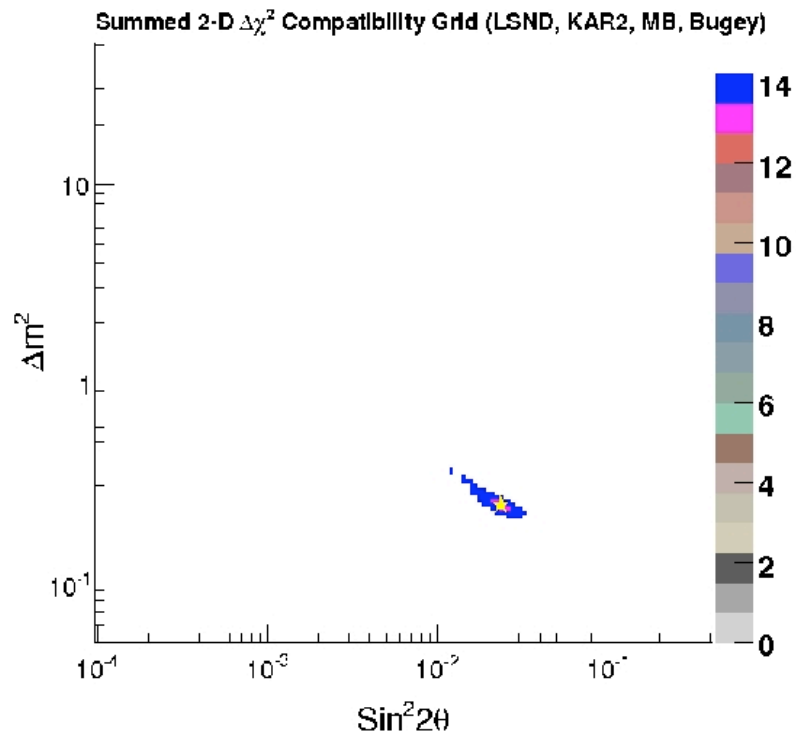
Global Fit to Experiments

LSND	KARMEN 2	MB	Bugey	Max Compat %	Delta M2	Sinsq 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

Global Fit Results

Colors represent $\Delta\chi^2$



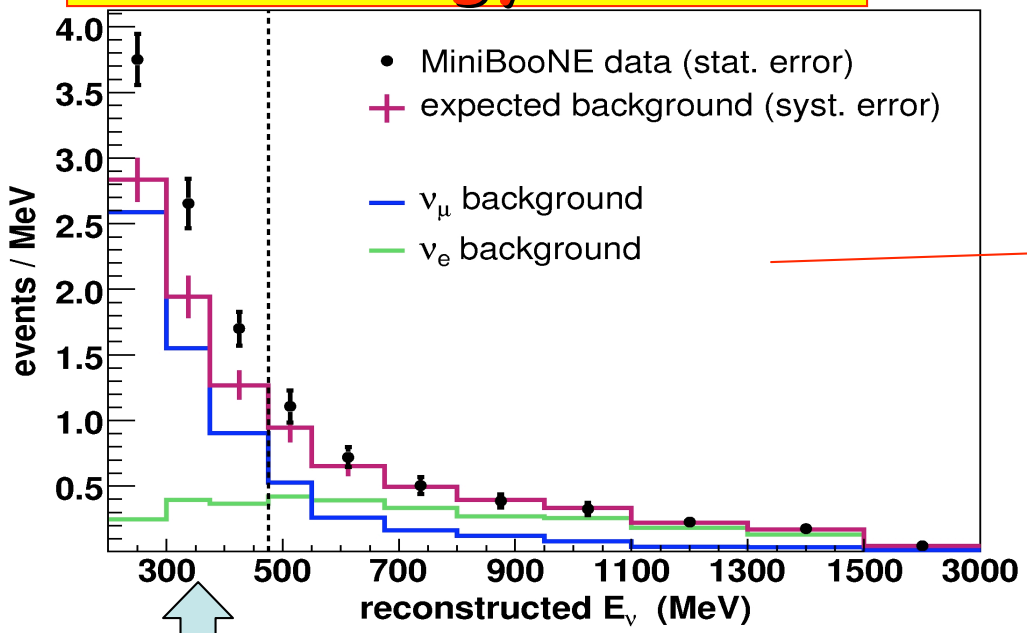


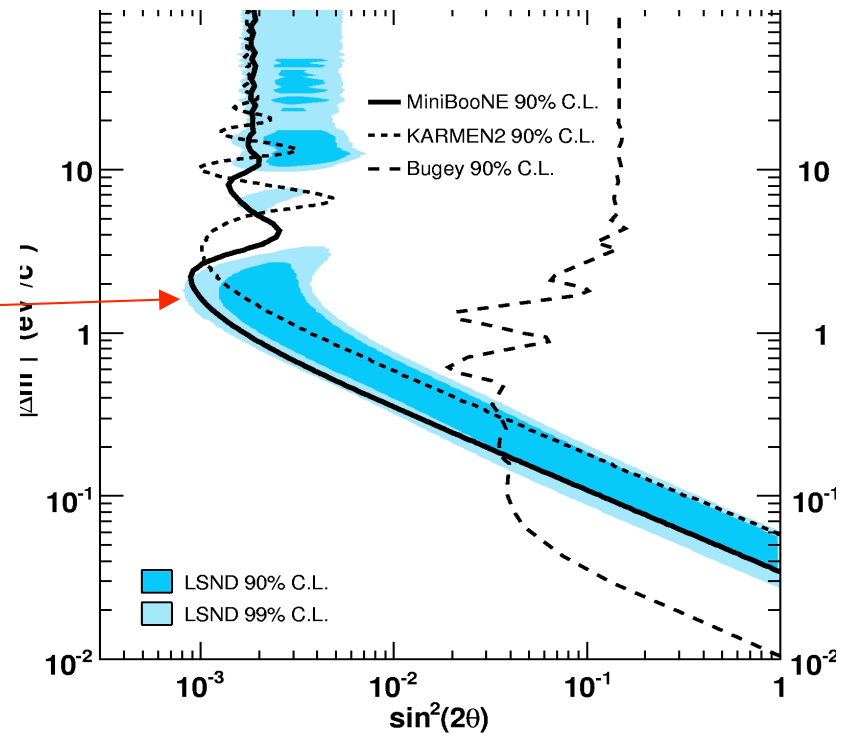
The star is the point of maximum compatibility

LSND, KARMEN2, MB + BUGEY

Low Energy Excess

Low Energy Excess





No evidence for $\nu_\mu \rightarrow \nu_e$ appearance in the analysis region!

However, at low energy observed excess

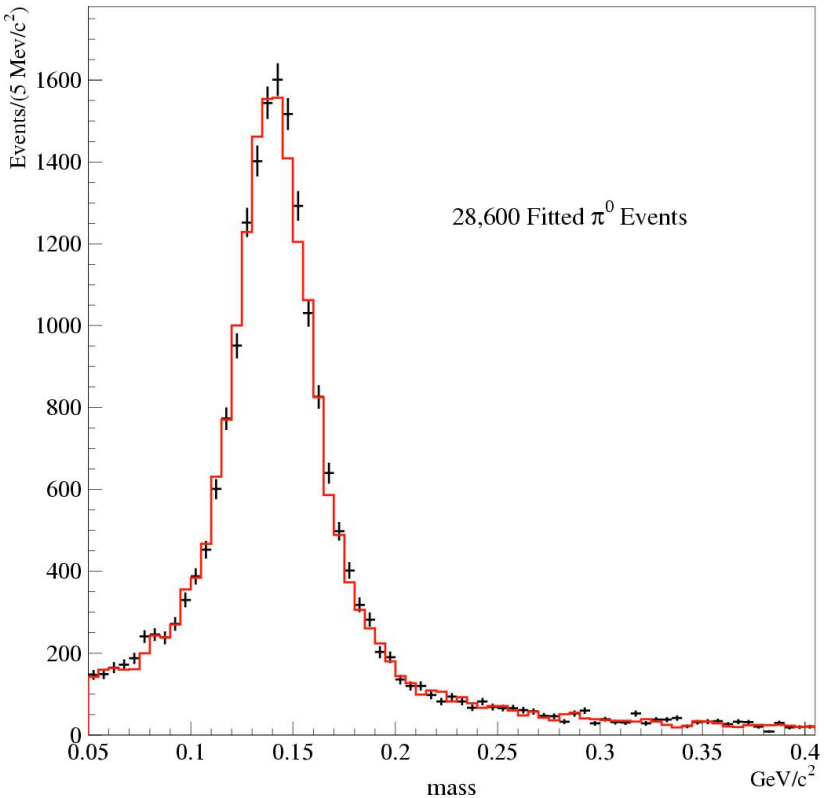
E_ν [MeV]	200-300	300-475	475-1250
total background	284±25	274±21	358±35
ν_e intrinsic	26	67	229
ν_μ induced	258	207	129
NC π^0	115	76	62
NC $\Delta \rightarrow N\gamma$	20	51	20
Dirt	99	50	17
other	24	30	30
Data	375±19	369±19	380±19
Data-MC	91±31	95±28	22±40

Investigation of observed low-energy excess

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

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

Measuring π^0 and constraining misIDs from π^0



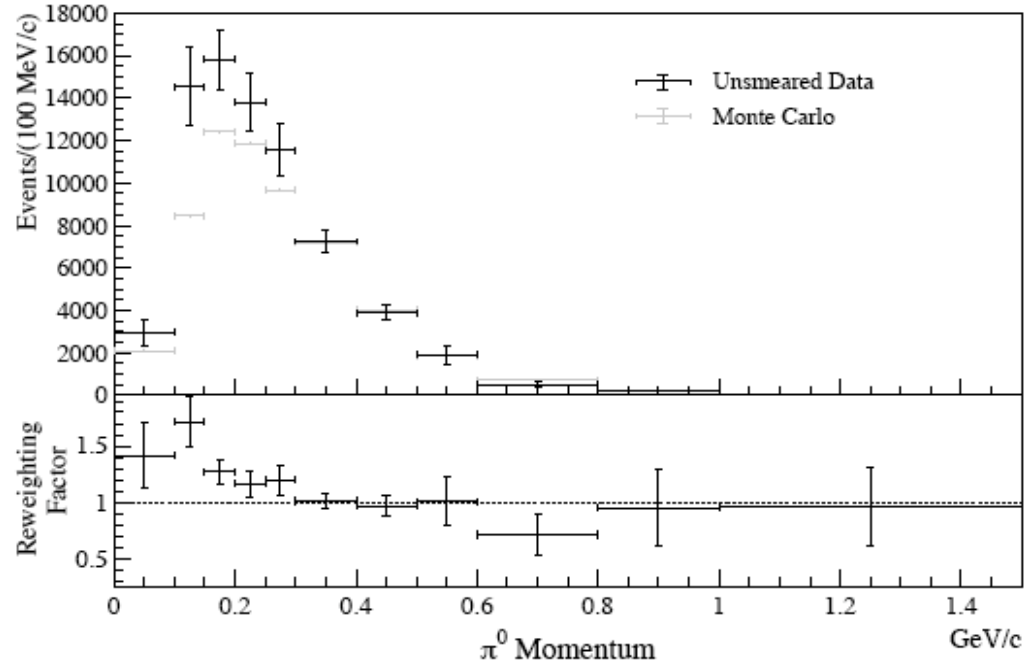


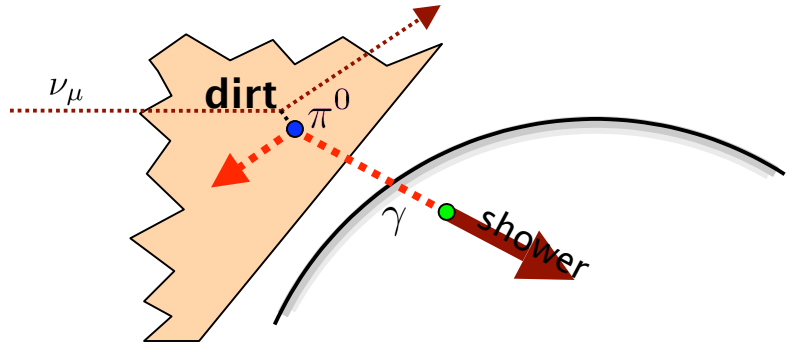
Fig. 1. Top: Results of the π^0 unsmearing in bins of momentum. The dark points show the unsmeared data π^0 momentum distribution and the light points show the uncorrected MC π^0 momentum distribution. The unsmeared data error bars contain all sources of error propagated through the unsmearing, while the MC error bars are from finite MC statistics. Bottom: The reweighing function, formed by taking ratio of the two points above (data/MC).

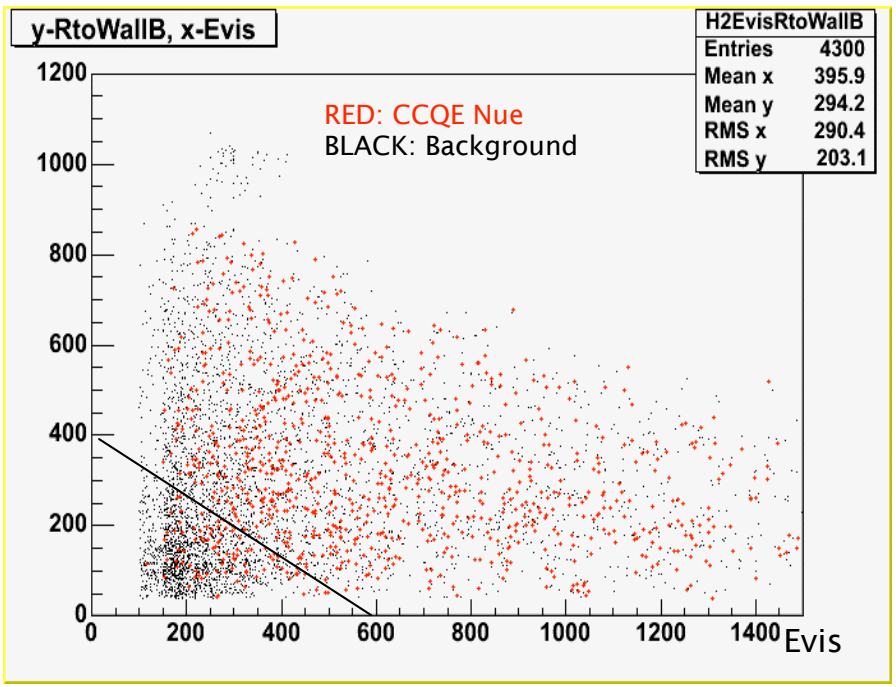
π^0 rate measured to a few % .
Critical input to oscillation analysis:
without constraint π^0 errors would
be ~ 20%

Details arXiv:0803.3424 [hep-ex]

Is the dirt responsible for the low-energy excess?

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 "DistancetoWall backward" to reduce these.

Has significant effect below 475 MeV

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

Low energy excess unchanged in magnitude!

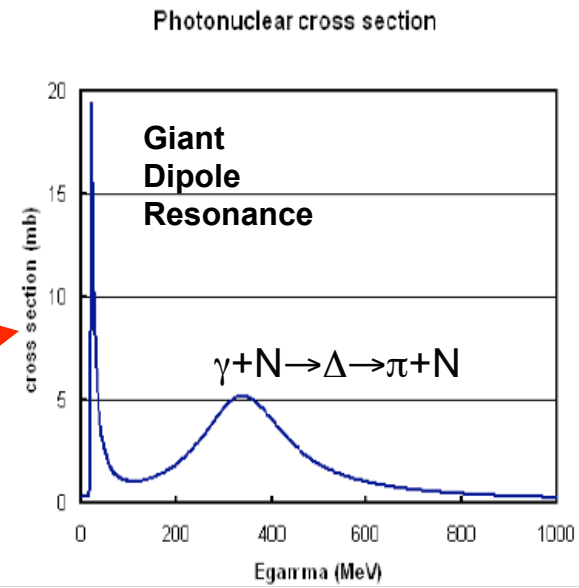
Has almost no effect above 475 MeV

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

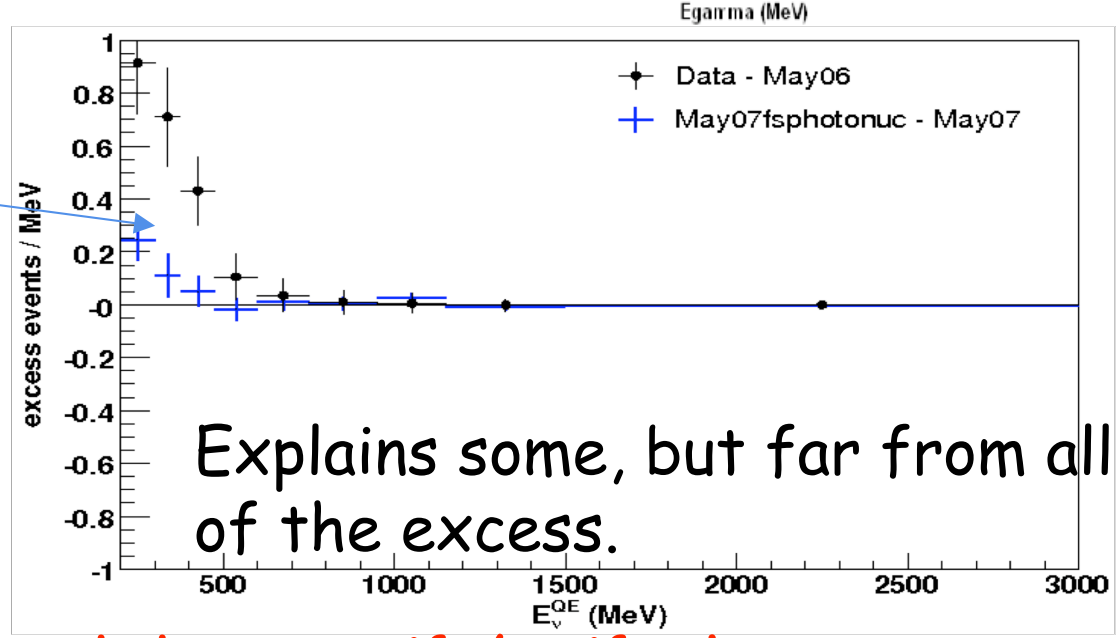
Processes that remove/absorb one of the gammas from a ν_μ-induced NC $\pi^0 \rightarrow \gamma\gamma$

- photonuclear absorption



Adding this into the MC

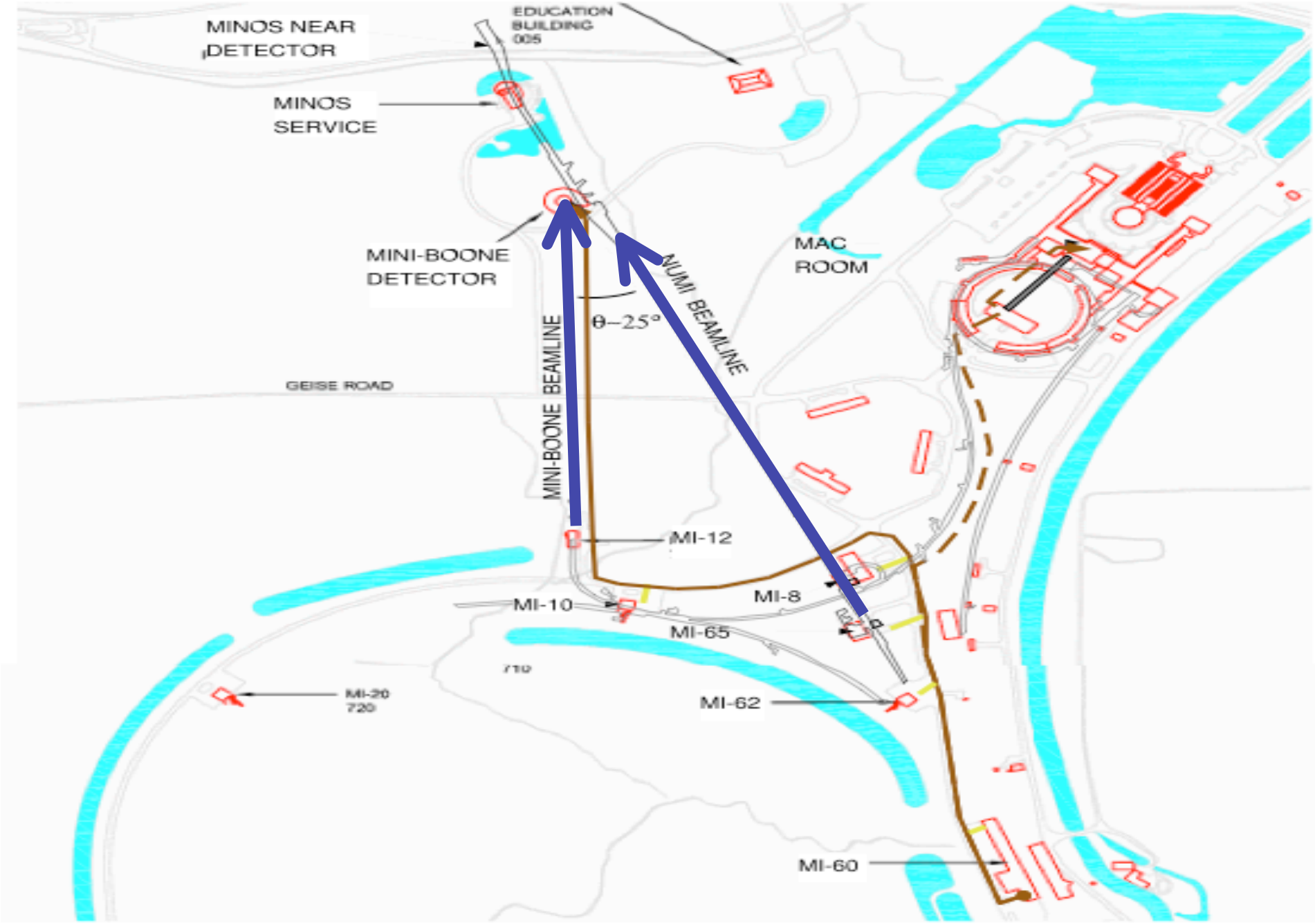
One and only correction so far!



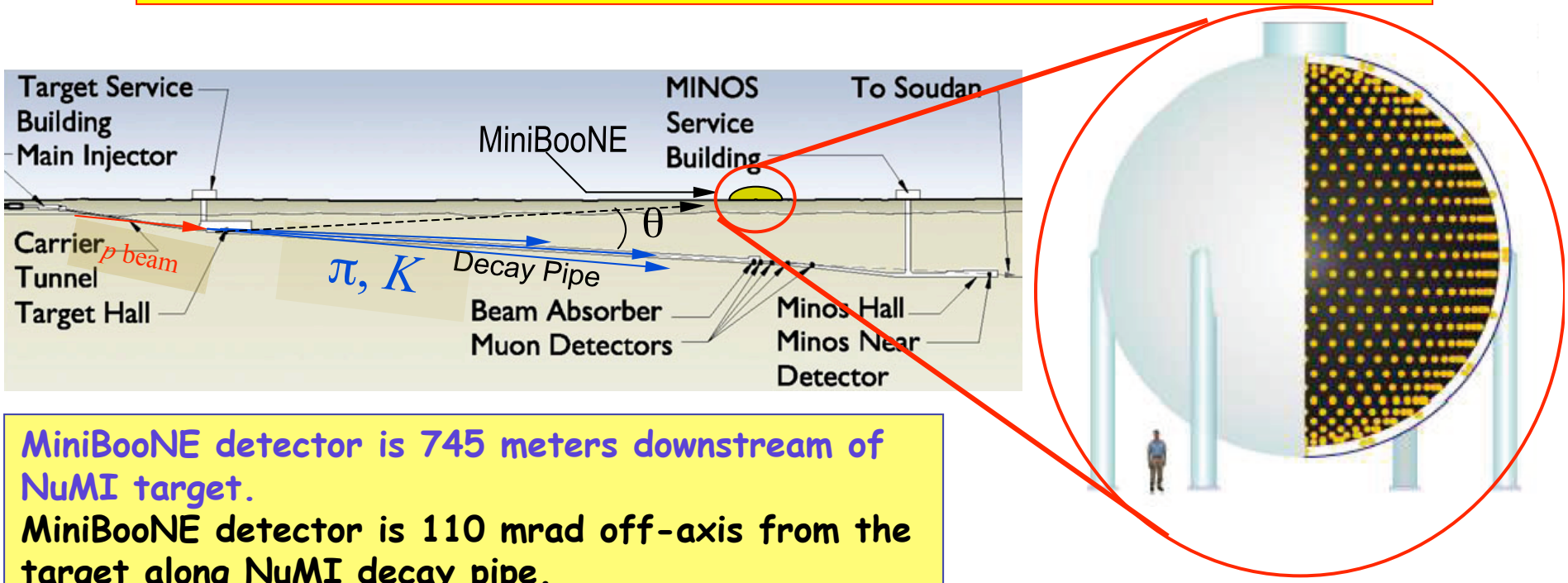
Clearly, more evidence is needed to quantify/verify the excess…

New Analysis:
Events from NuMI beamline

Fermilab Neutrino Beams



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.

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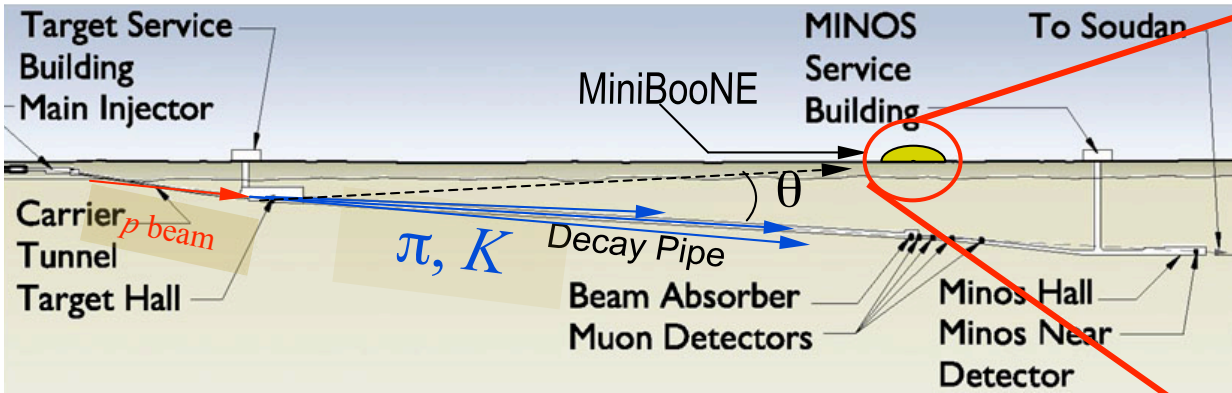

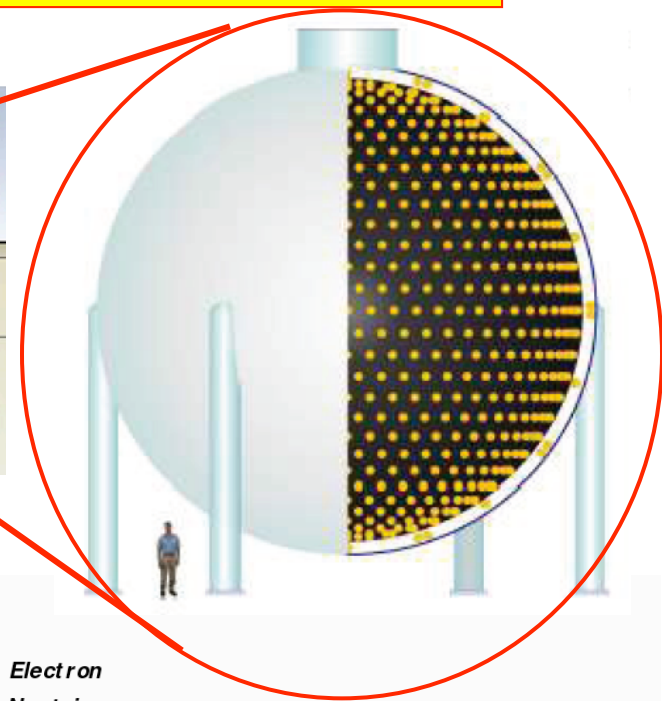

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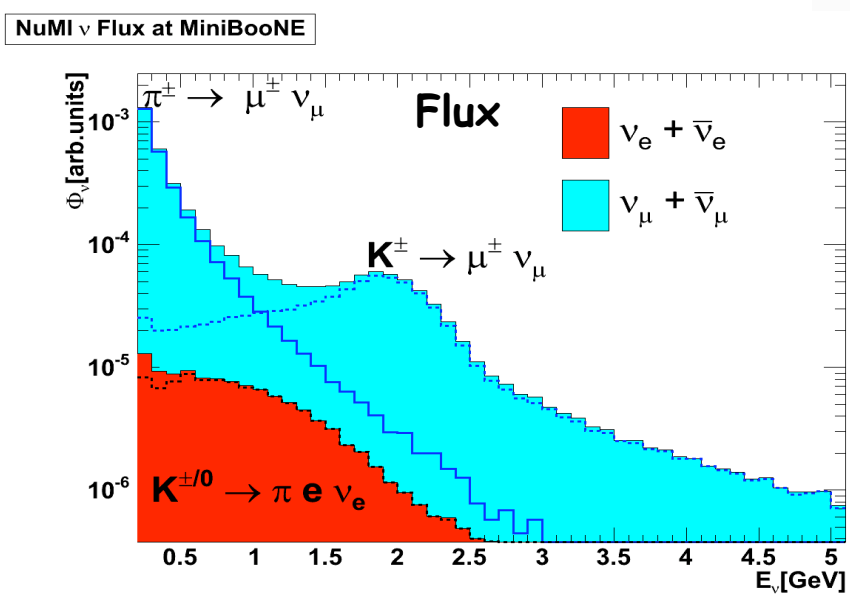
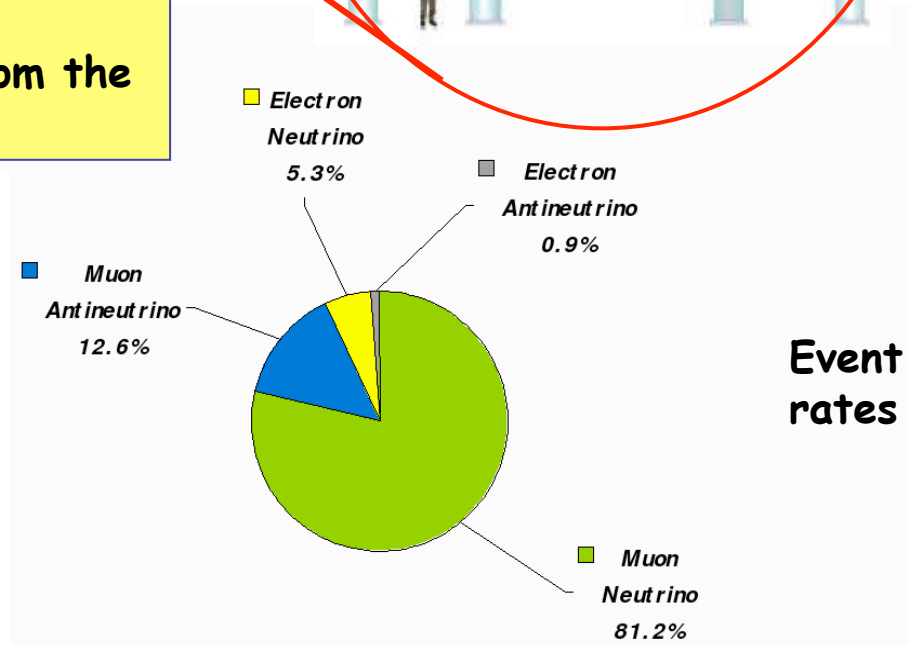




Event rates

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

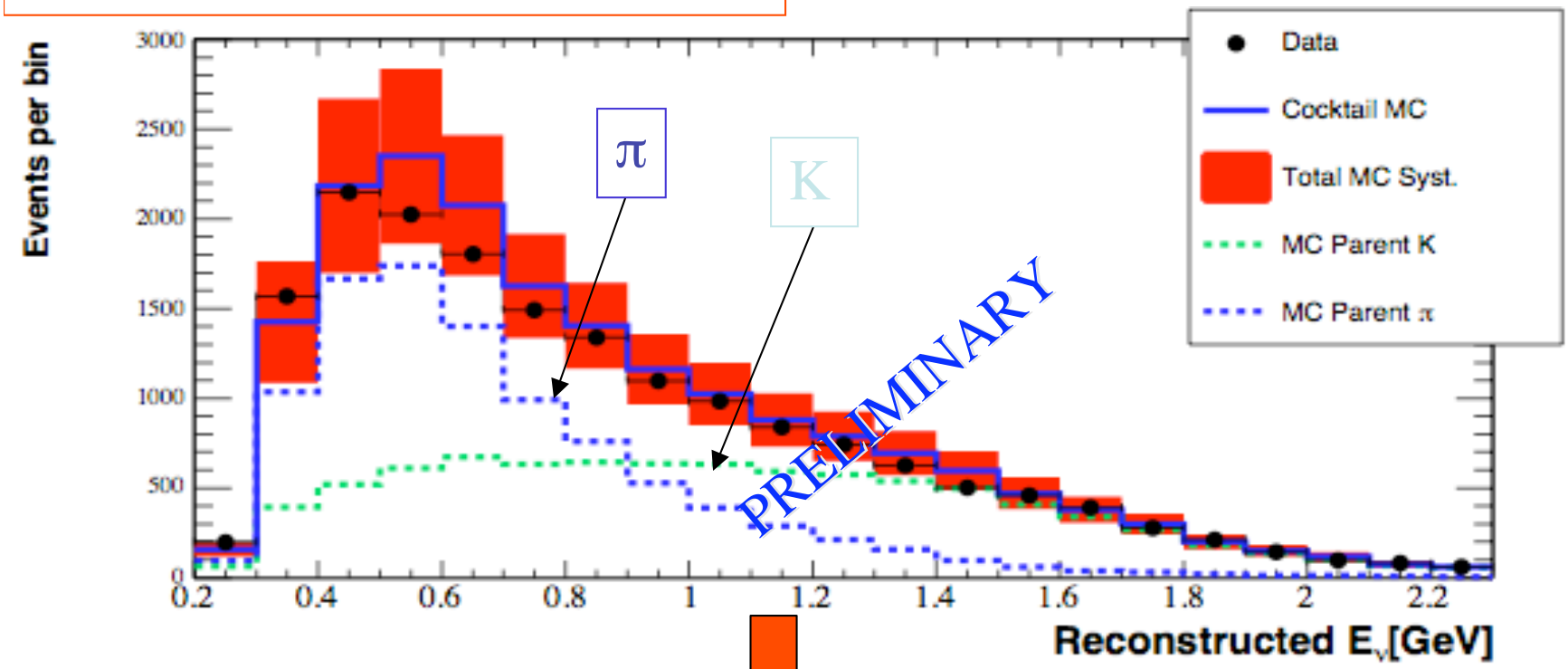
ν_μ CCQE Analysis

ν_μ CCQE sample: Reconstructed energy E_ν of incoming ν

ν_μ CCQE (ν+n → μ+p)

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

Reconstructed E_ν: from E_{lepton} ("visible energy") and lepton angle wrt neutrino direction



Understanding of the beam demonstrated:
MC is normalized to data POT number !

Conclusion from ν_μ CCQE analysis section

There is very good agreement between data and Monte Carlo:the MC tuned well.

This is the first demonstration of the off-axis principle.

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

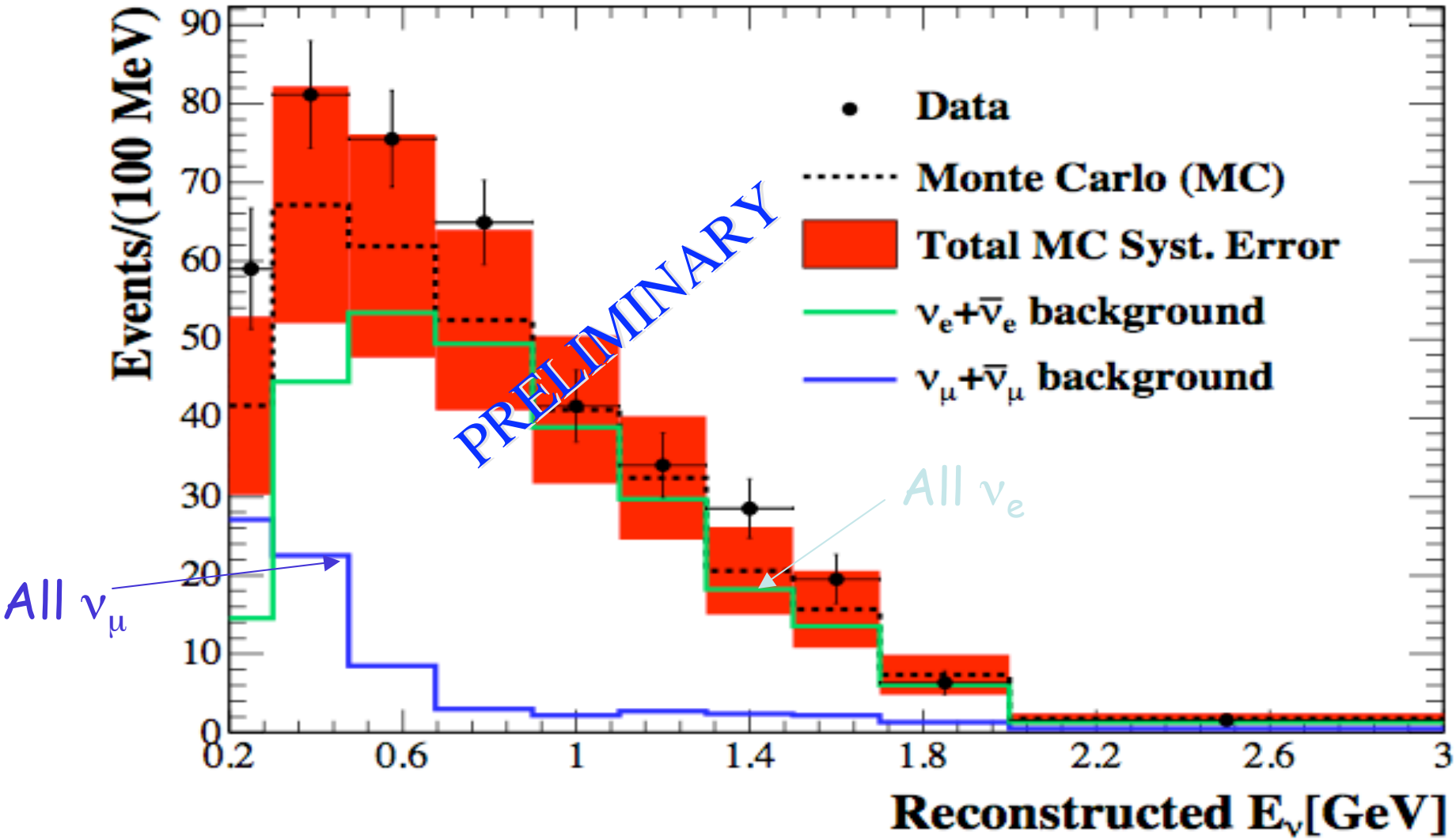
mis-id backgrounds for a ν_e analysis.

Now we want look into low energy excess …

ν_e CCQE Analysis

ν_e CCQE sample: Reconstructed energy E_ν of incoming ν

ν_e CCQE (ν+n → e+p)



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

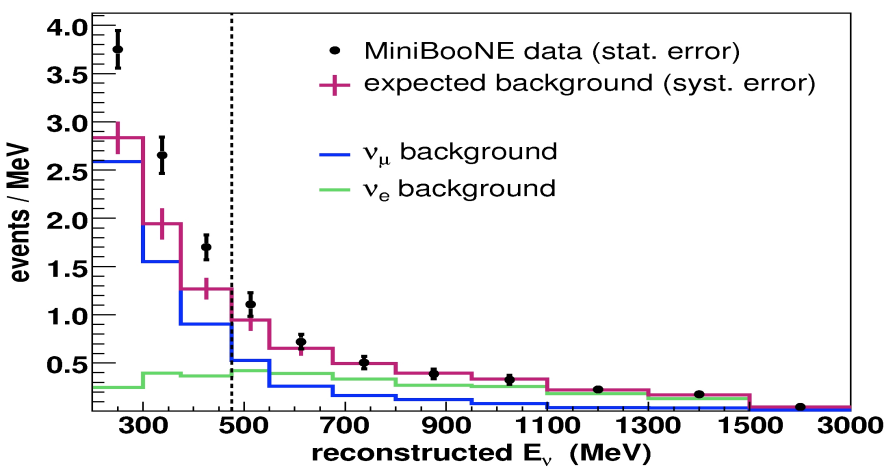
NuMI vs Booster Beam at MiniBooNE

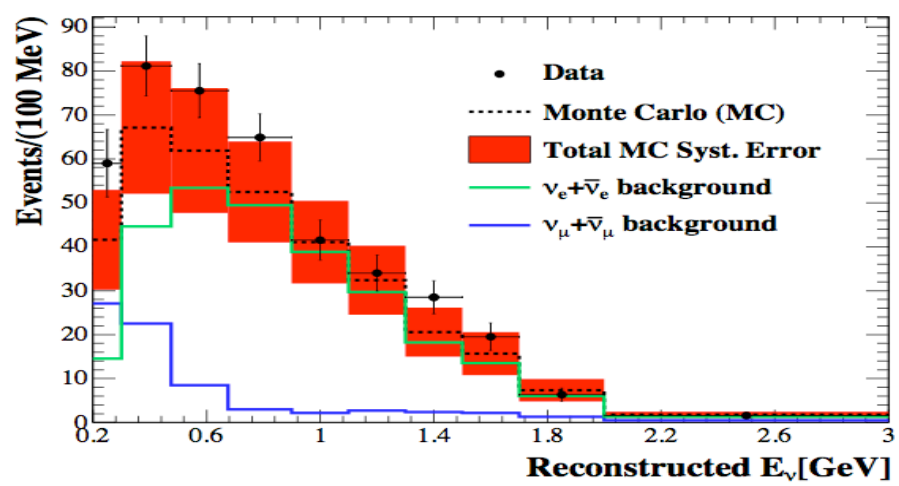
Recall:

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 L in Booster beam data is due to oscillation it should appear at 1.4E in the NuMI beam data at MiniBooNE.





Other Explanations?

Is there a physics explanation?

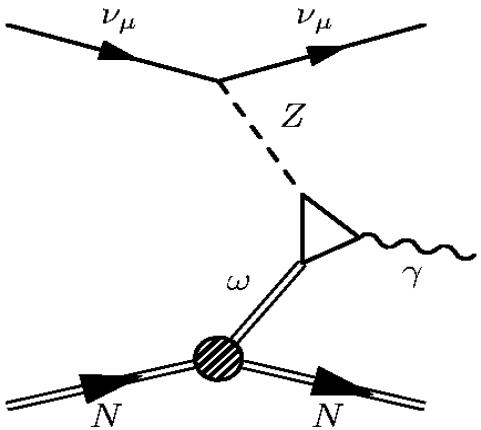
- Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density (arXiv:0708.1281: Jeffrey A. Harvey, Christopher T. Hill, Richard J. Hill)

- CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107

- Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017

- CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303

- New Light Gauge Boson: Nelson & Walsh, arXiv:0711.1363



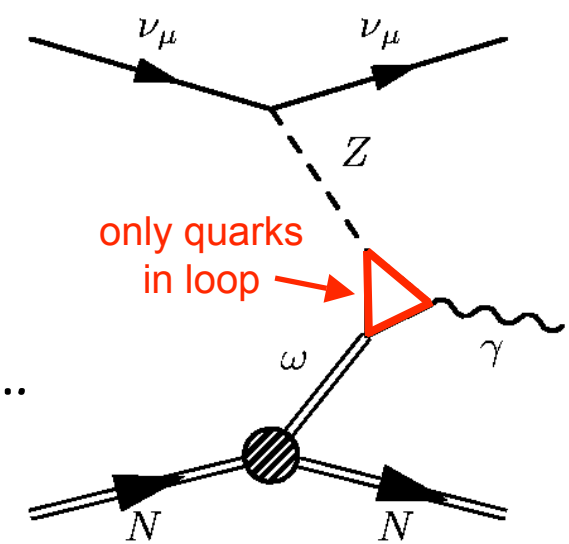
Possible Sources of Single Gamma Backgrounds

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.

Example: "Anomaly mediated neutrino-photon interactions at finite baryon density."
No quark vs. lepton cancellation in loop since only quarks can contribute
(Under active investigation)
(Harvey, Hill, and Hill, hep-ph0708.1281)

$$\sigma = \frac{\alpha g_\omega^4 G_F^2 E_\nu^6}{480\pi^6 m_\omega^4} \simeq 2.2\,\mathrm{x}10^{-41} (E_\nu/\mathrm{GeV})^6 (g_\omega/10.0)^4 \mathrm{cm}^2$$

if g_w~10, and E_ν were 700 MeV
this would produce a 115 event excess…
About the right level….

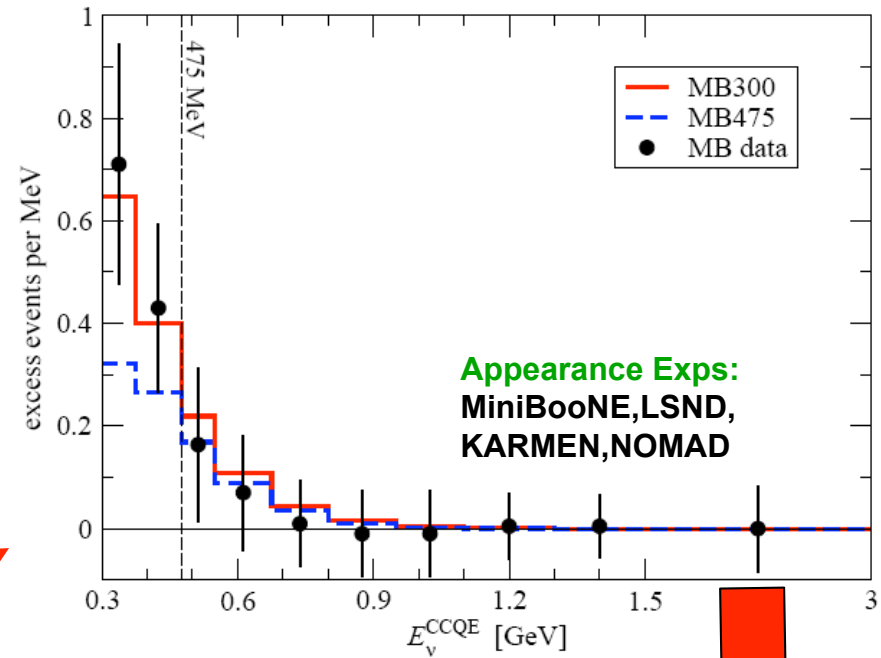


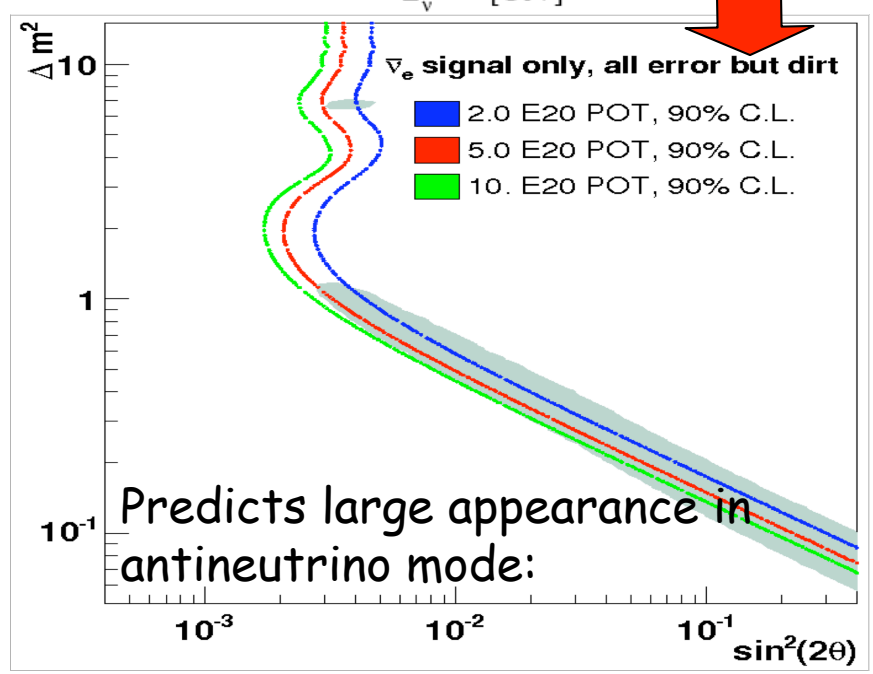
New Physics: Models With Sterile Neutrinos

- Models with 3 active and 1 sterile neutrino (3+1) are excluded by various ν_e and ν_μ disappearance measurements

- 3+2 models can give a good fit to appearance data but fit is discrepant with the disappearance results: Bugey,Chooz,PaloVerde,CDHS. (Appearance and disappearance incompatible at the 4σ level) (Maltoni and Schwetz, hep-ph0705.0107

- 3+2 models may also produce measurable effects in the Double Chooz experiment especially for the near detector (Bandyopadhyay and Choubey, hep-ph0707.2481)





New Physics: Gauge boson of Nelson and Walsh

arXiv:0711.1363, "Short Baseline Neutrino Oscillations and a New Light Gauge Boson", Ann Nelson & Jonathan Walsh

Obtained a low E anomaly about 40% of that seen by MB from an MSW-like potential in matter which affects low E neutrino oscillations.

The new light gauge vector boson ("paraphoton") has a mass of ~10 keV and a coupling strength of $g^2/e^2 \sim 10^{-9}$ coupling to B-L charge.

Because of low coupling strength, authors thought boson undetectable.

BR($P \rightarrow \nu\nu$) ~ 100%, BR($P \rightarrow \gamma\gamma\gamma$) ~ 10^{-7}. Lifetime ~2.5 ns.

The paraphotons can be produced by hadronic bremsstrahlung of the incident proton beam(~1%) [$x10^{-9}$] in the forward direction (~5-10mr) in inclusive reactions.

Assume PID & Fiducial Volume efficiency ~ 30%, and look for em shower.

Number of radiation lengths in MB ~ 5m/50cm = 10 [$x10^{-9}$].

See of the order of 10-20 events in the forward direction.

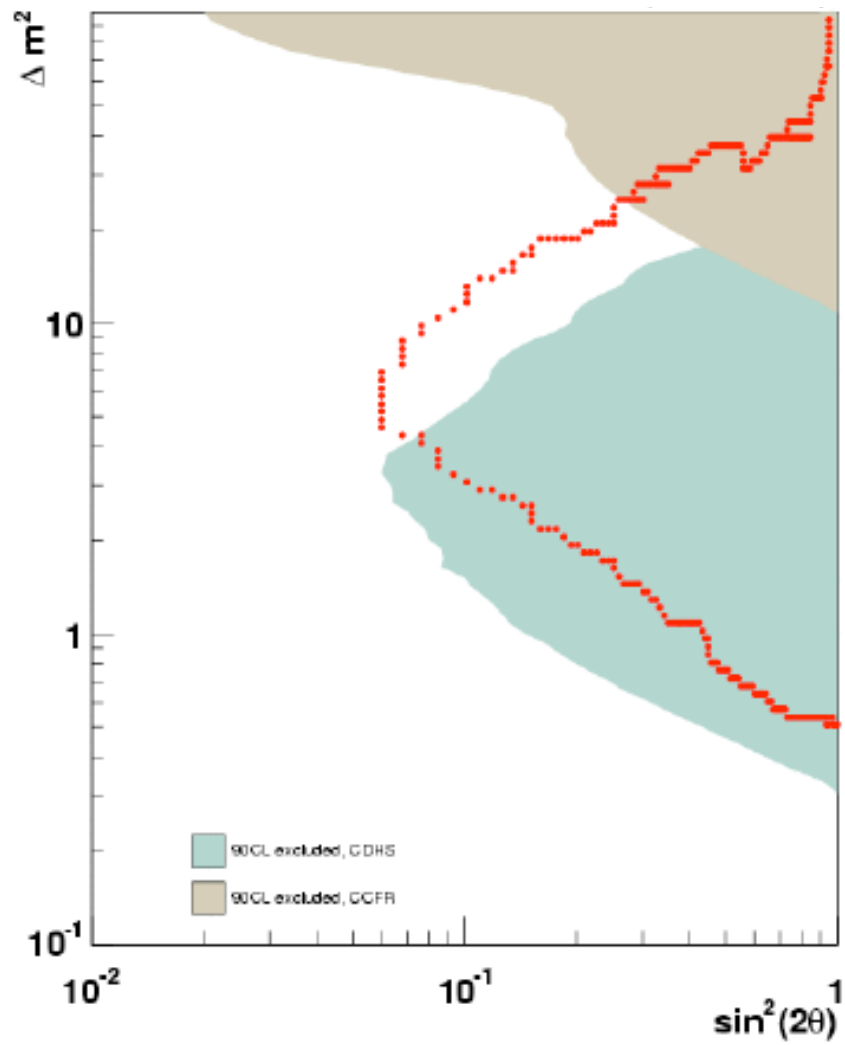
Examination of our present forward events is underway, but will need more events for definitive answer.

ν_μ *Disappearance at MiniBooNE*

ν_μ Disappearance: Ongoing Analysis

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

When we use SciBooNE as a near detector, we will be able to improve this sensitivity by reducing flux and cross section uncertainties



Anti-neutrinos at MiniBooNE

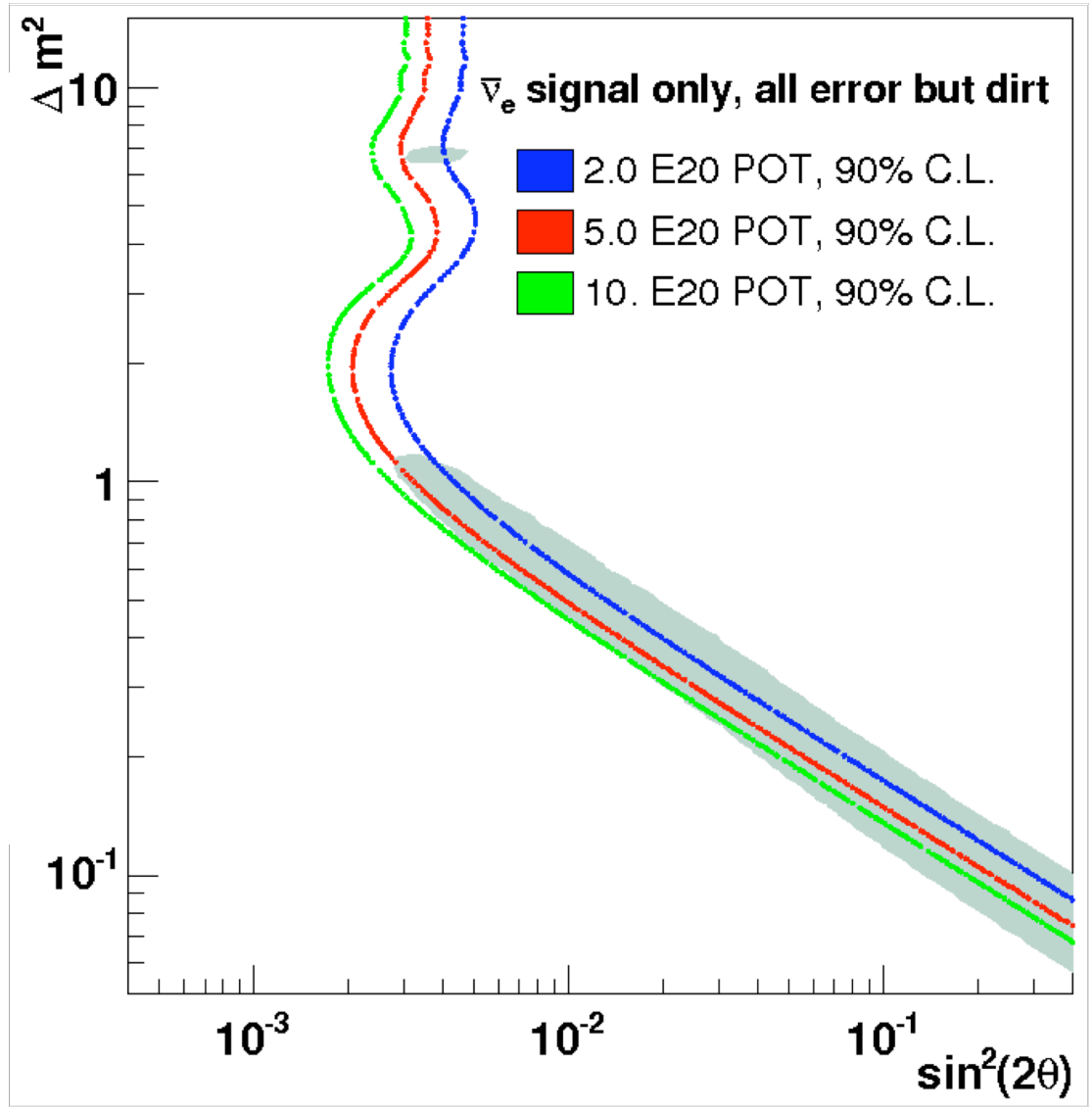
MiniBooNE Anti-neutrino Run

MiniBooNE is currently taking data in anti-neutrino mode. Collected ~2.5×10^{20} POT so far.

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.



Summary

-MiniBooNE first result show no evidence for $\nu_\mu \rightarrow \nu_e$ appearance-only oscillations in the analysis region above 475 MeV.

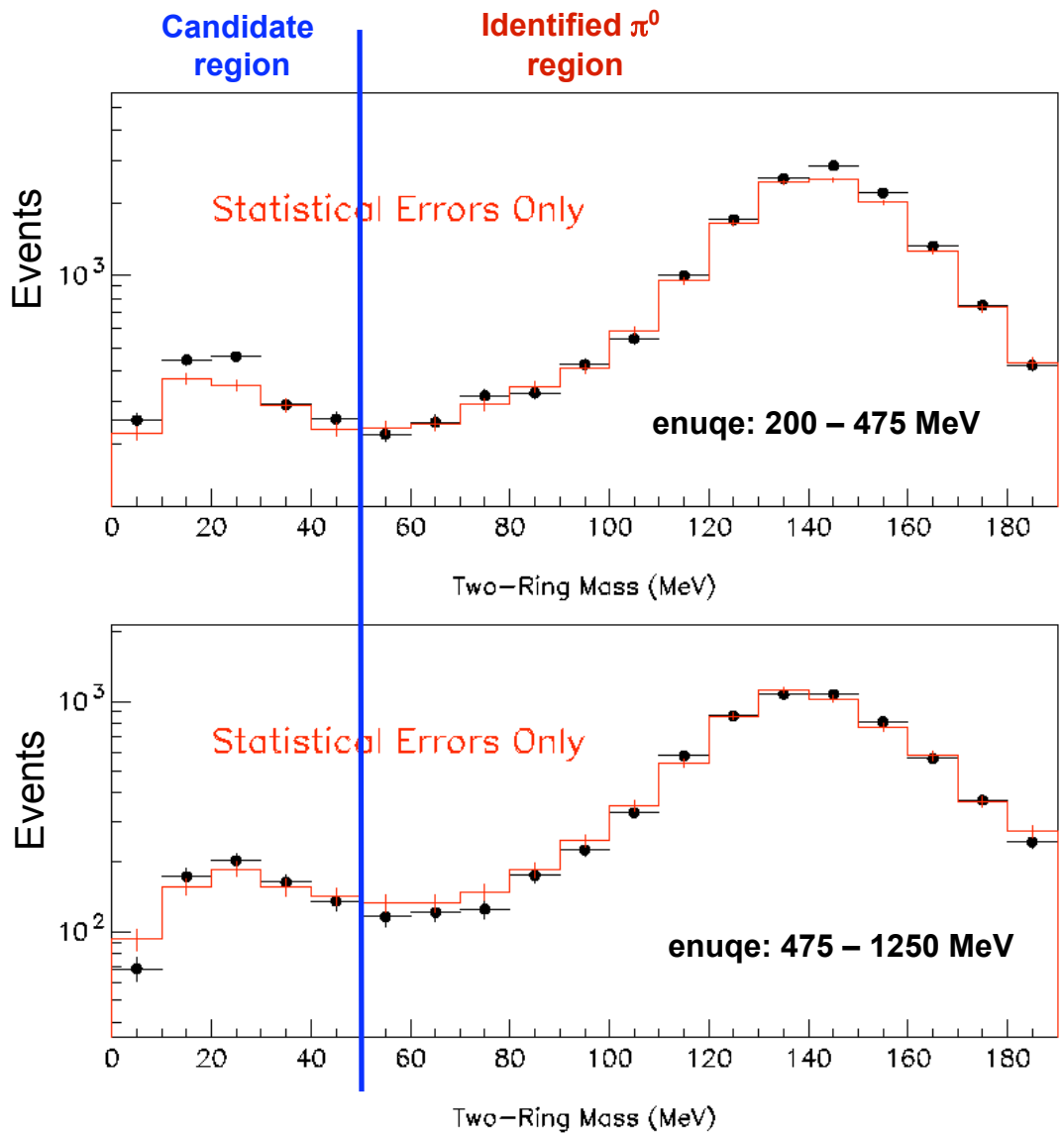
-However, at low energy (<475MeV) excess observed; thoroughly checked and not ruled out over last year. Expect update this summer!
-Interesting ideas to explain the excess appeared in community.

-We observed and analyzed the neutrino events from NuMI beamline at MiniBooNE.
-MiniBooNE is collecting more data from NuMI beamline.
-We are currently performing an analysis where ν_e CCQE sample systematics constrained by ν_μ CCQE sample: common systematics cancels.
-We are able to help resolution of the low energy excess observed in the first MiniBooNE results.
-We will perform an oscillation analysis with this data sample.

-ν_μ disappearance analysis is underway.

-MiniBooNE is currently taking data in anti-neutrino mode.
-Provides direct check of LSND result.
-Provides additional data set for low energy excess study.

How well does π^0 constraint work?



Results after removing ν_e's π^0 PID cut

- Good agreement in "Identified π^0 region"
- Excess for low energy sample clearly observed below 50 MeV

Excess cannot be explained by simply scaling up the π^0 and radiative Δ background

Black points: Data
Red histogram: Prediction