MiniBooNE Oscillation Report

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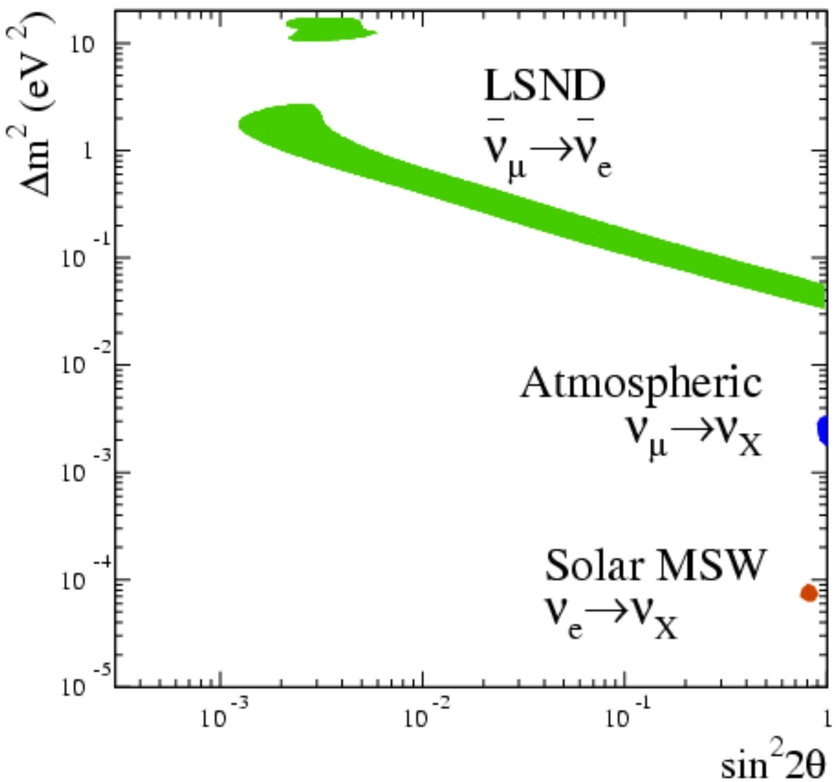
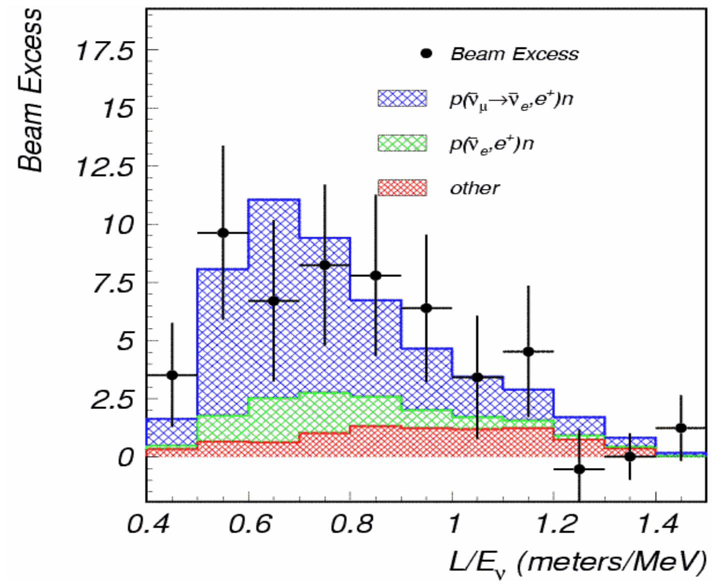
Outline

- MiniBooNE Experiment Description
- MiniBooNE's Neutrino Results
- (New) MiniBooNE's Anti-neutrino Results
- Summary

Oscillation Status After LSND

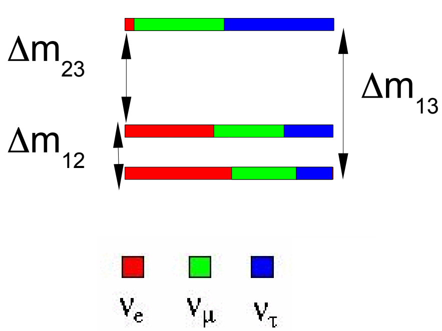




This signal looks very different from the others...

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

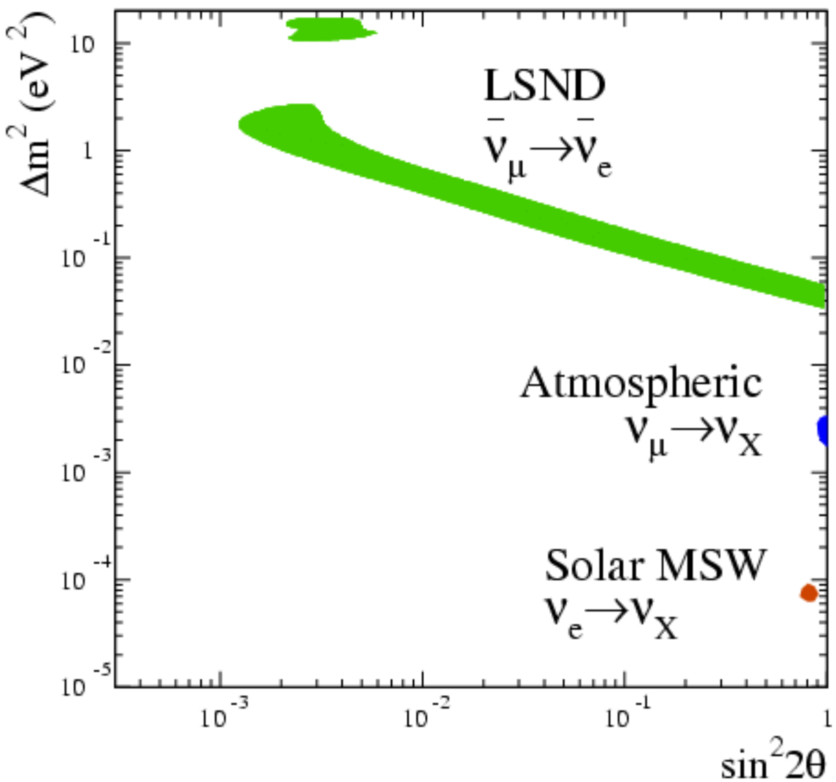
In SM there are only 3 neutrinos

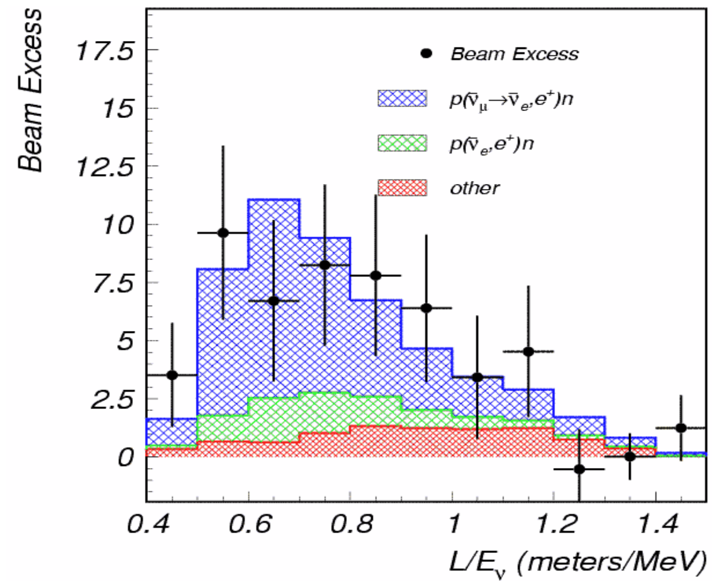


- Three distinct neutrino oscillation signals, with $\Delta m^2_{solar} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$
- For three neutrinos, expect $\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$

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

Oscillation Status After LSND





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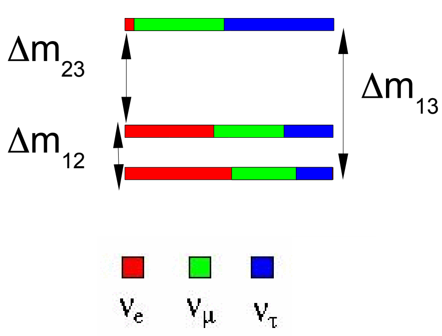
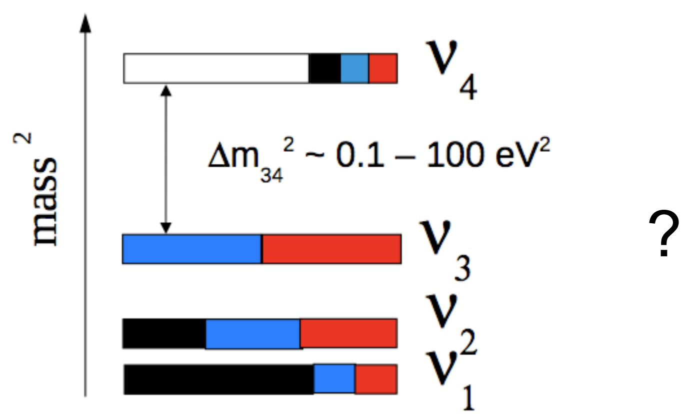
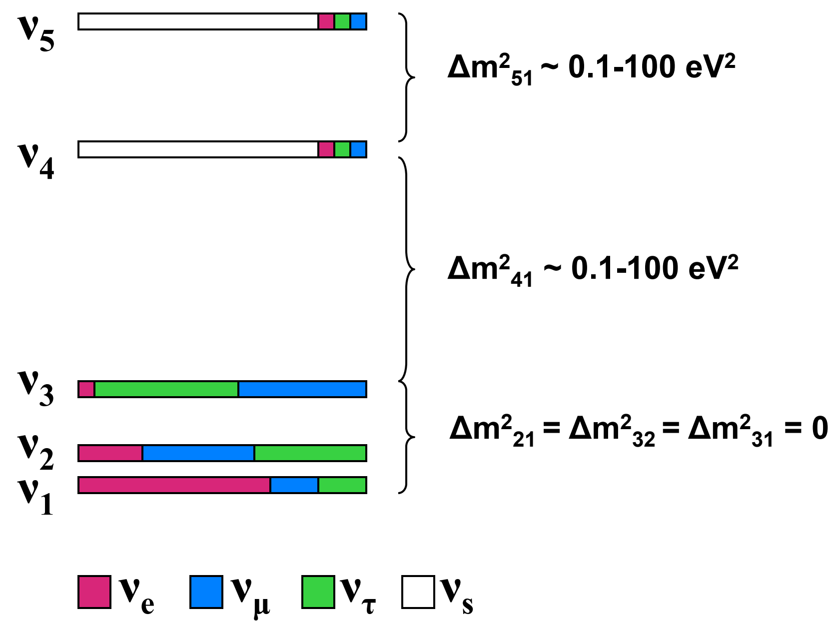




Oscillation explanation of LSND in conjunction with the atmospheric and solar oscillation results needed more than 3 ν's.

Models developed with 1 or more sterile ν's (or other new physics models).



Simplified 3+2 Models for $\nu_\mu \rightarrow \nu_e$:
2 independent Δm^2
3 mixing parameters
1 Dirac CP phase

It was important to check LSND what was left to MiniBooNE

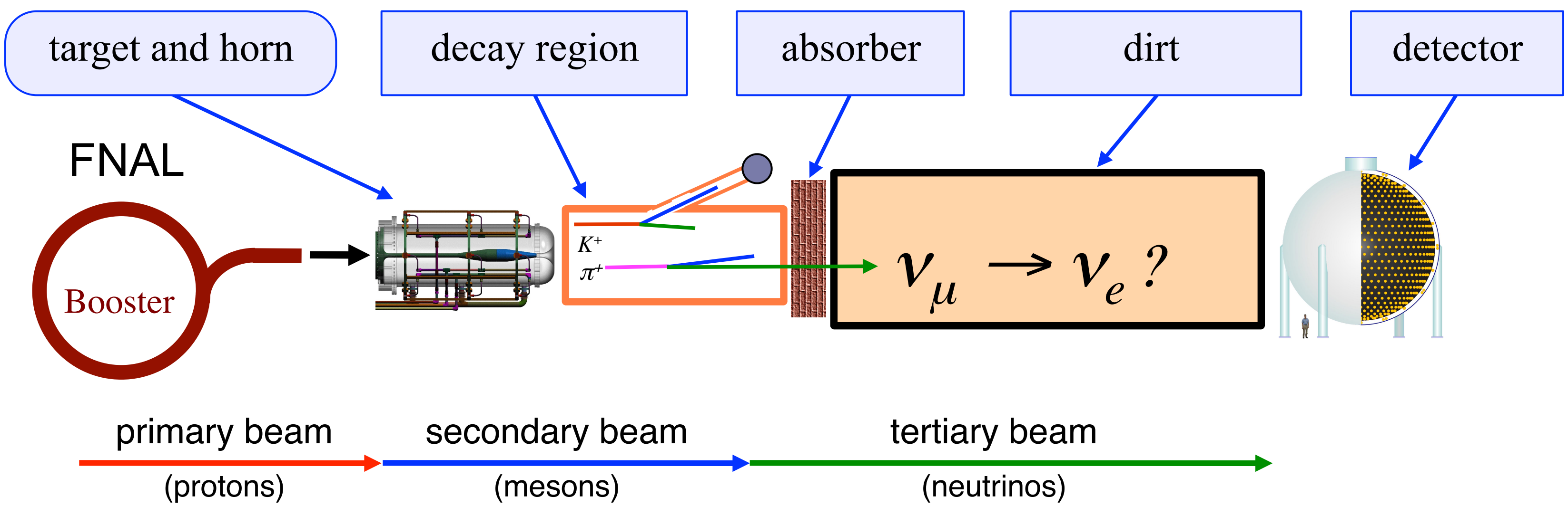
(Booster Neutrino Experiment)

MiniBooNE Setup

Keep L/E same as LSND while changing systematics, energy & event signature

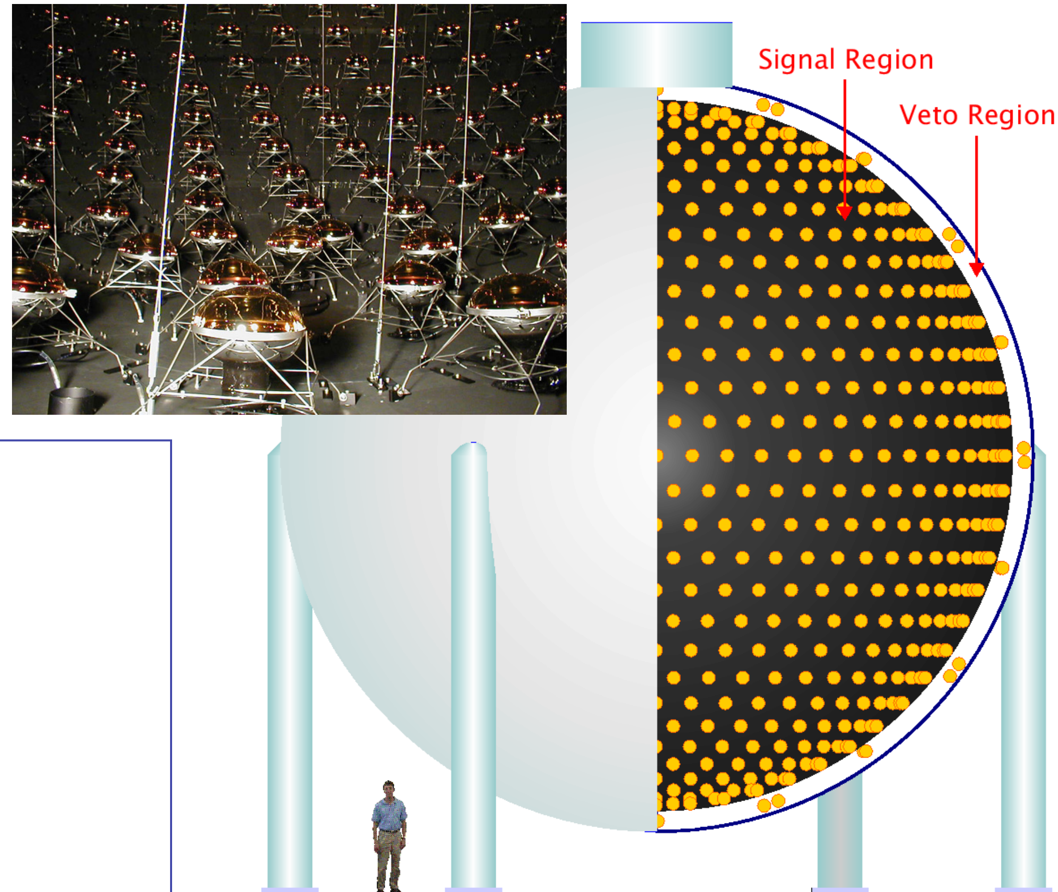
$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$ ➔ Two neutrino fits

LSND:	E ~30 MeV	L ~30 m	L/E ~1
MiniBooNE:	E ~500 MeV	L ~500 m	L/E ~1



Neutrino mode: search for $\nu_\mu \rightarrow \nu_e$ appearance with 6.5E20 POT → assumes CP/CPT conservation
Antineutrino mode: search for $\nu_\mu \rightarrow \nu_e$ appearance with 8.58E20 POT → direct test of LSND

MiniBooNE Detector

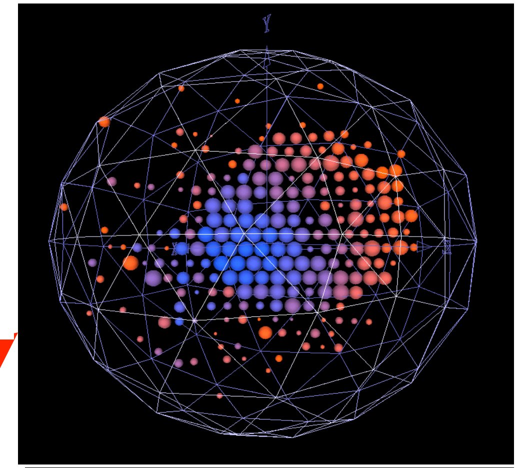


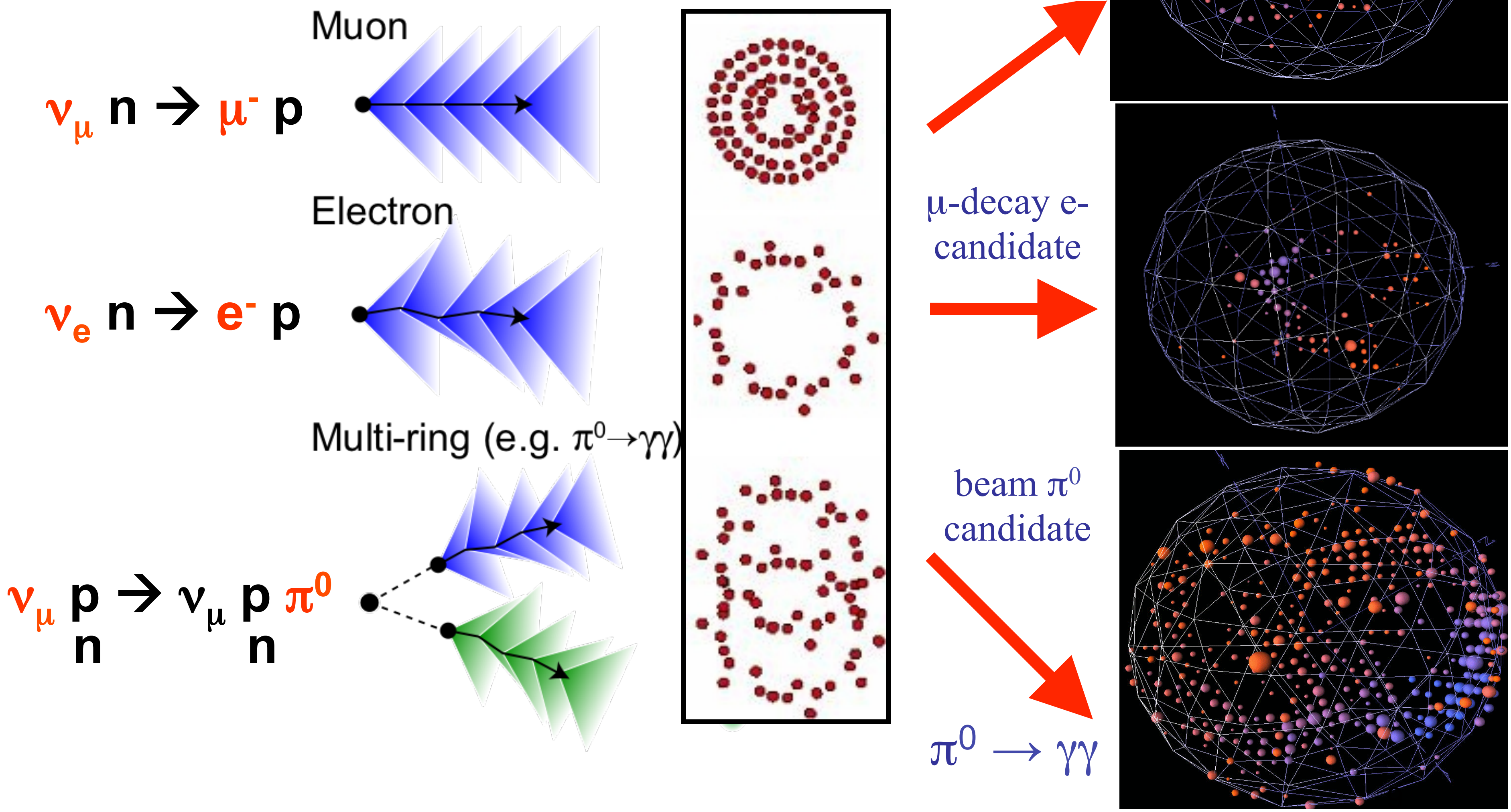
MiniBooNE Detector:
-12m diameter sphere
-950000 liters of oil(CH_2)
-1280 inner PMTs
-240 veto PMTs

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

Particle Identification

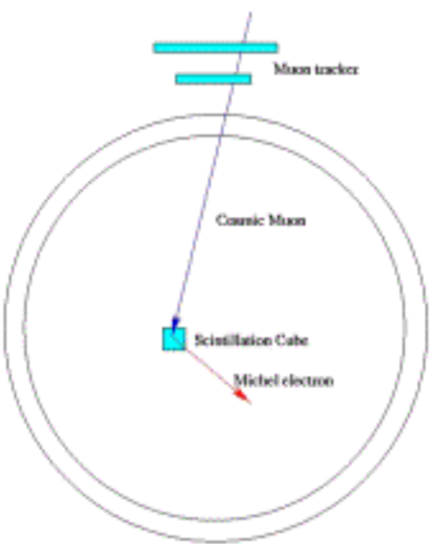
Čerenkov rings provide primary means of identifying products of ν interactions in the detector

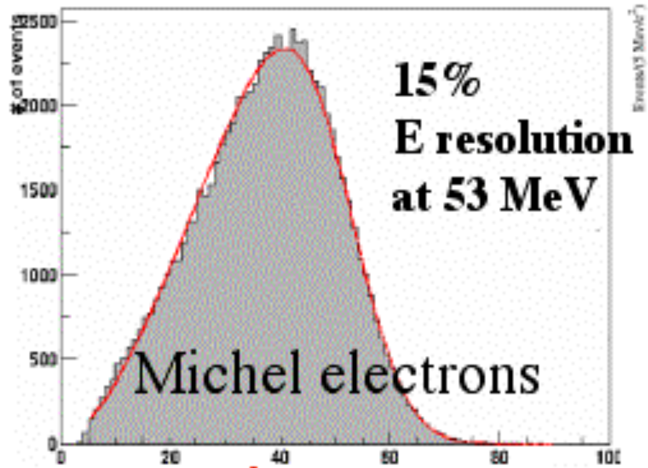


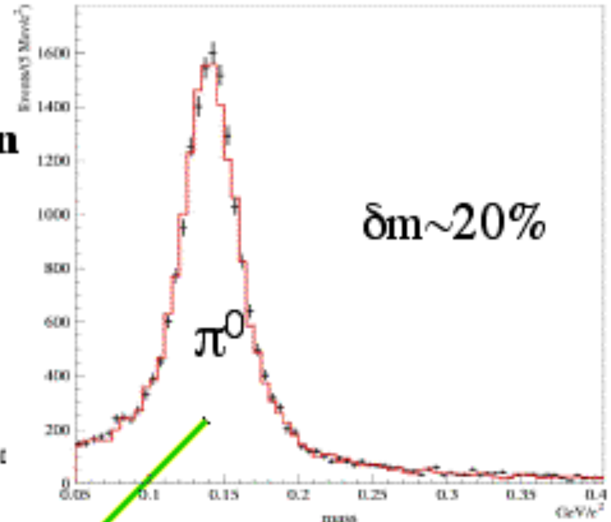


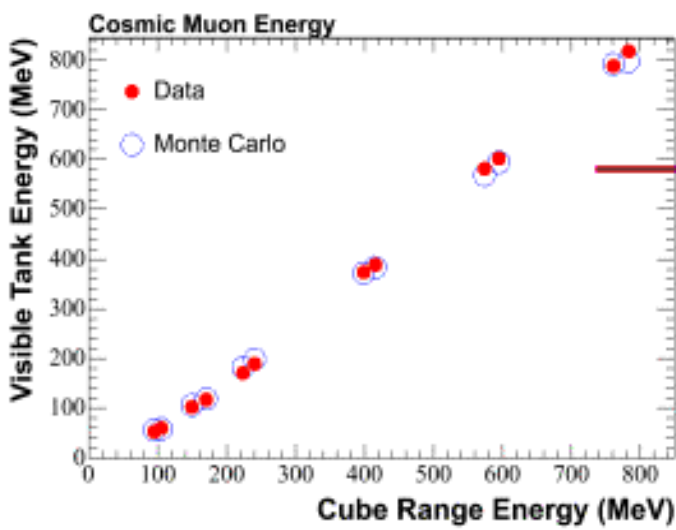
Energy Calibration

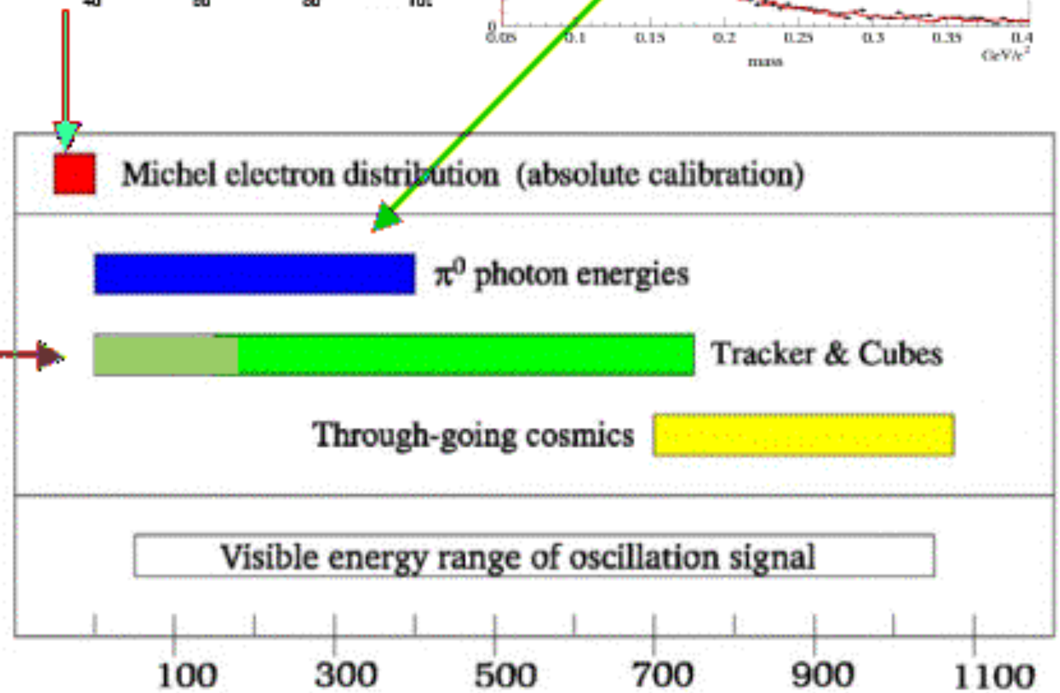
Tracker system





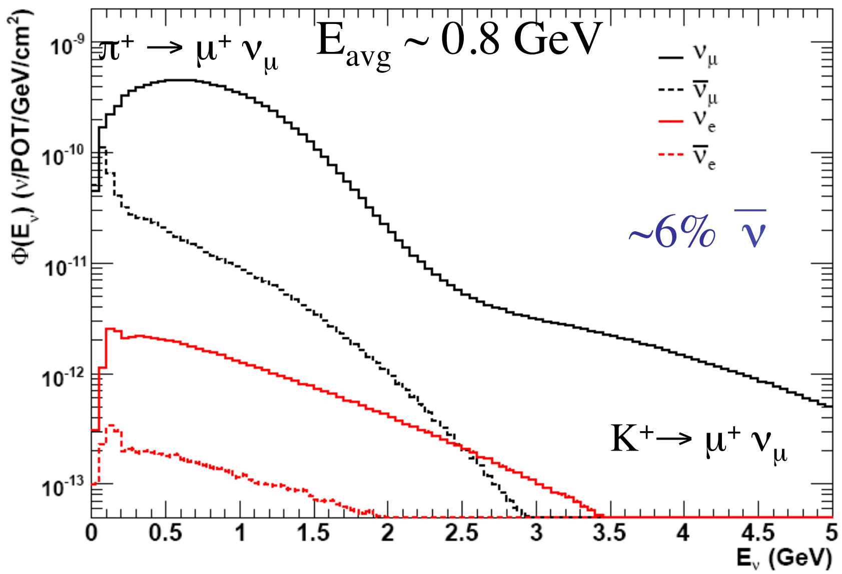




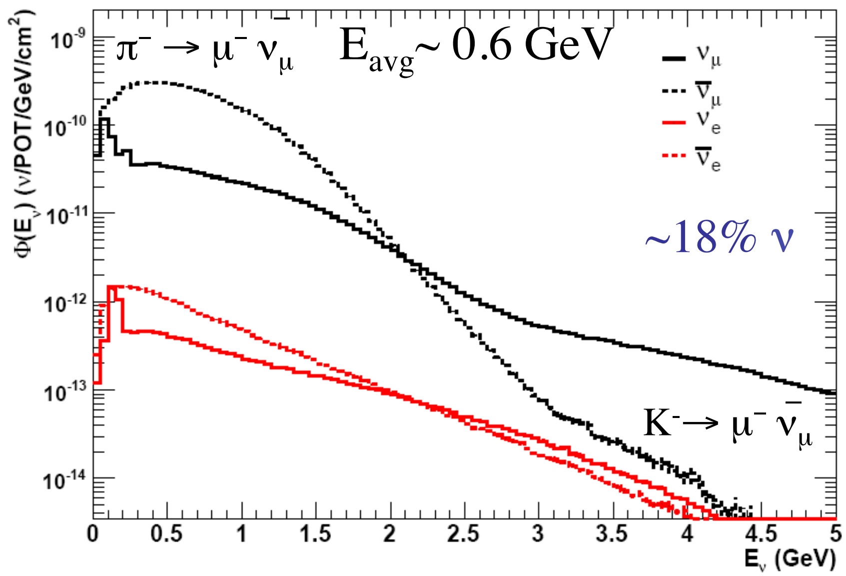


Booster Flux at MiniBooNE

Neutrino-Mode Flux



Antineutrino-Mode Flux



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

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

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

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

ν_e , $\bar{\nu}_e$ Event Rate Predictions

Events Rate = Flux x Cross-sections x Detector response

External measurements (HARP, etc)

ν_μ rate constrained by neutrino data

External and MiniBooNE Measurements

π^0, $\Delta \rightarrow N\gamma$, dirt, and intrinsic ν_e constrained from data.

Detailed detector simulation and PID

Checked with neutrino data and calibration sources.

- A. A. Aguilar-Arevalo et al., "Neutrino flux prediction at MiniBooNE", Phys. Rev. D79, 072002 (2009).
- A. A. Aguilar-Arevalo et al., "Measurement of Muon Neutrino Quasi-Elastic Scattering on Carbon", Phys. Rev. Lett. 100, 032301 (2008).
- A. Aguilar-Arevalo et al., "First Observation of Coherent π^0 Production in Neutrino Nucleus Interactions with Neutrino Energy <2 GeV", Phys. Lett. 664B, 41 (2008).
- A. A. Aguilar-Arevalo et al., "Measurement of the Ratio of the ν_u Charged-Current Single-Pion Production to Quasielastic Scattering with a 0.8 GeV Neutrino Beam on Mineral Oil", Phys. Rev. Lett. 103, 081801 (2009).
- A. A. Aguilar-Arevalo et al., "Measurement of ν_u and $\nu_{\underline{u}}$ induced neutral current single π^0 production cross sections on mineral oil at E_n ~ 1 GeV", Phys. Rev. D81, 013005 (2010).
- A. A. Aguilar-Arevalo et al, "Measurement of the ν_μ charged current π+ to quasi-elastic cross section ratio on mineral oil in a 0.8 GeV neutrino beam". Phys.Rev. Lett. 103:081801 (2010).
- A. A. Aguilar-Arevalo et al, "First Measurement of the Muon Neutrino Charged Current Quasielastic Double Differential Cross Section", Phys. Rev D81, 092005 (2010), arXiv: 1002.2680 [hep-ex].
- A. A. Aguilar-Arevalo et al, "Measurement of the Neutrino Neutral-Current Elastic Differential Cross Section", Phys. Rev. D82, 092005 (2010), arXiv:1007.4730 [hep-ex].
- A. A. Aguilar-Arevalo et al, "Measurement of ν_μ-induced charged-current neutral pion production cross sections on mineral oil at E_ν in 0.5-2.0 GeV", Phys. Rev. D83, 052009 (2011), arXiv:1010.3264 [hep-ex].
- A. A. A. Aguilar-Arevalo et al, "Measurement of neutrino-induced charged-current chraged pion production cross sections on mineral oil at E_ν ~ 1.0 GeV", Phys. Rev. D83, 052007 (2011), arXiv:1011.3572 [hep-ex].
- A. A. Aguilar-Arevalo et al, "Measurement of the neutrino component of an anti-neutrino beam observed by a non-magnetized detector", sumbitted to Phys. Rev. D, arXiv:1102.1964 [hep-ex].
- A. A. Aguilar-Arevalo et al., "The MiniBooNE Detector", Nucl. Instr. Meth. A599, 28 (2009).
- P. Adamson et al., "Measurement of ν_u and ν_e Events in an Off-Axis Horn-Focused Neutrino Beam", Phys. Rev. Lett. 102, 211801 (2009).
- R.B. Patterson et al, "The Extended-Track Event Reconstruction for MiniBooNE", Nucl. Instrum. Meth. A608, 206 (2009).

Dedicated x-sec talk by Bill Louis

Neutrino Mode MiniBooNE Results (2009)

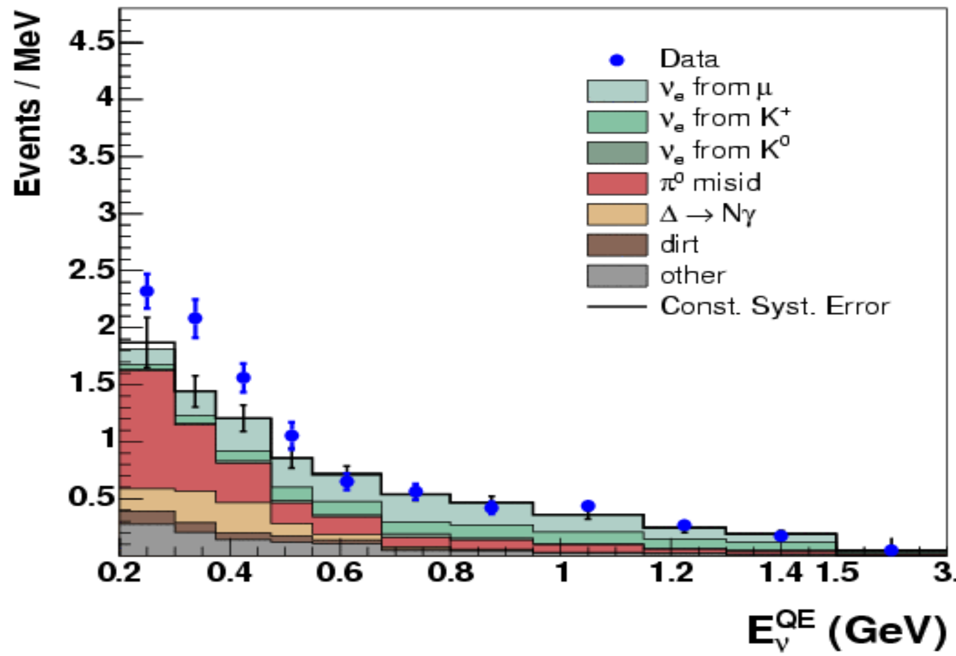
- 6.5E20 POT collected in neutrino mode
- E > 475 MeV data in good agreement with background prediction

  -Energy region has reduced backgrounds and maintains high sensitivity to LSND oscillations.

  -A two neutrino fit rules out LSND at the 90% CL assuming CP conservation.
- E < 475 MeV, statistically large (6σ) excess

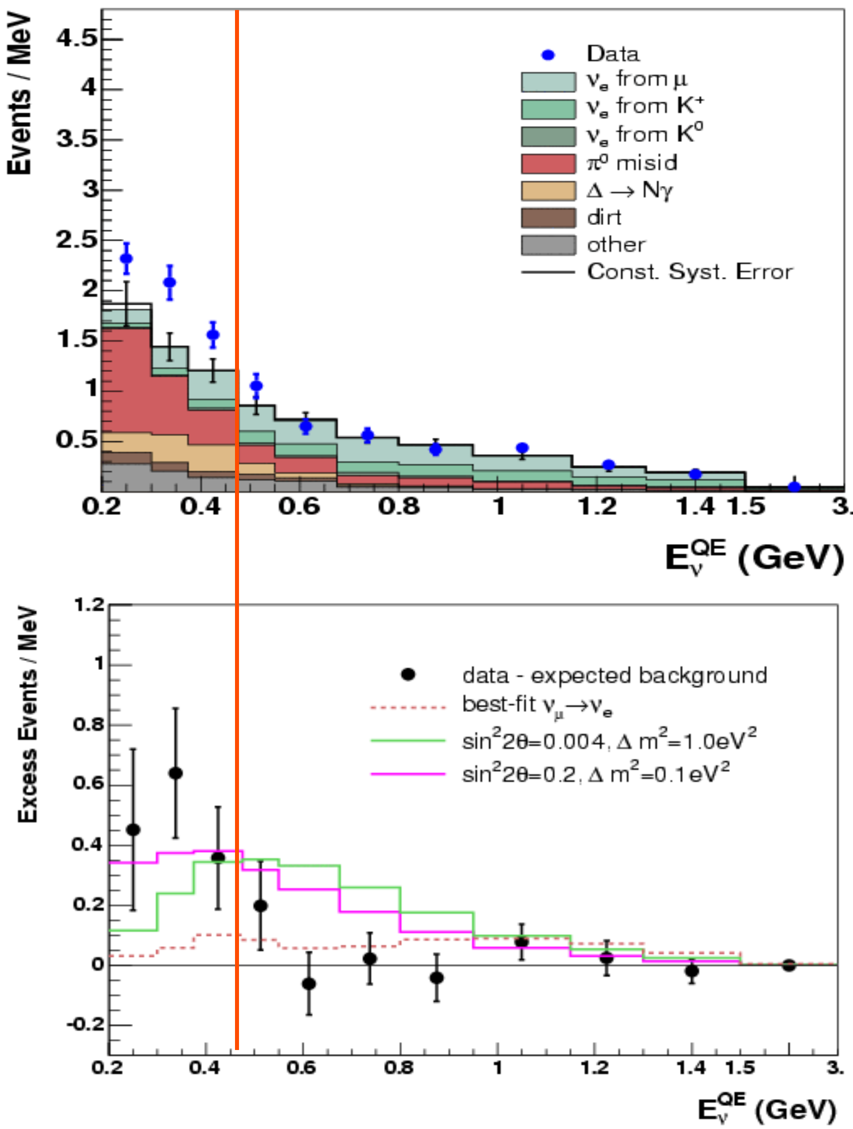
  -Reduced to 3σ after systematics, shape inconsistent with two neutrino oscillation interpretation of LSND. Excess of 129 +/- 43 (stat+sys) events is consistent with magnitude of LSND oscillations.

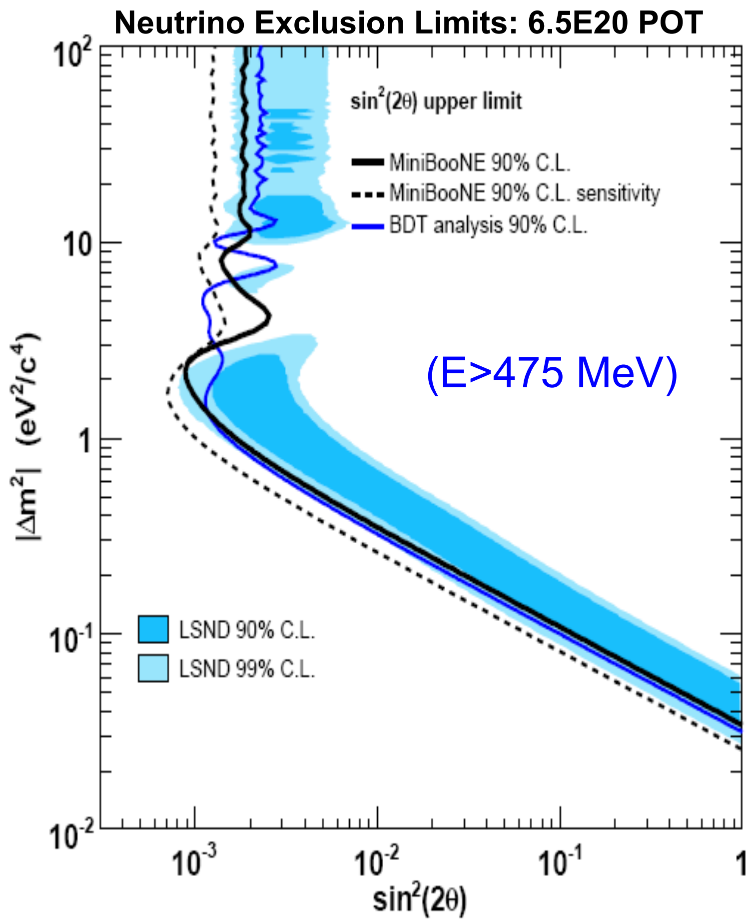
Published PRL 102,101802 (2009)



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

Neutrino Mode MiniBooNE Results (2009): Limit



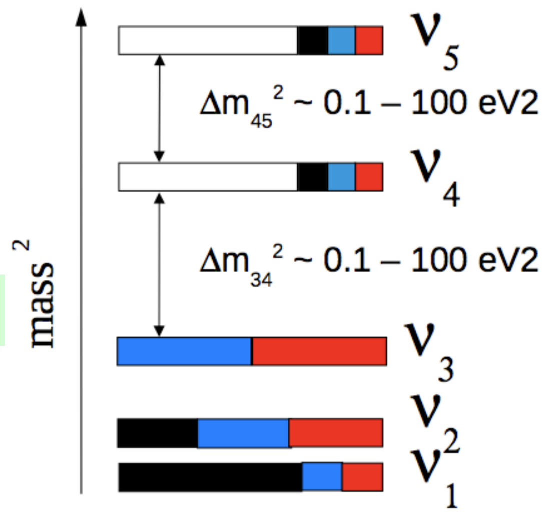


Range of possible explanations for observed excess

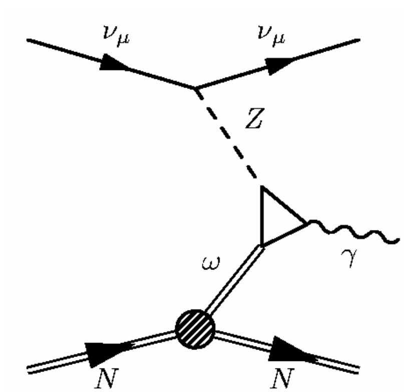
Several possible explanations have been put forth by the physics community, attempting to reconcile the MiniBooNE neutrino mode result with LSND and other appearance experiments…

- 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]
- …

Dedicated talk by Sergei Gninenko



$\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e$?



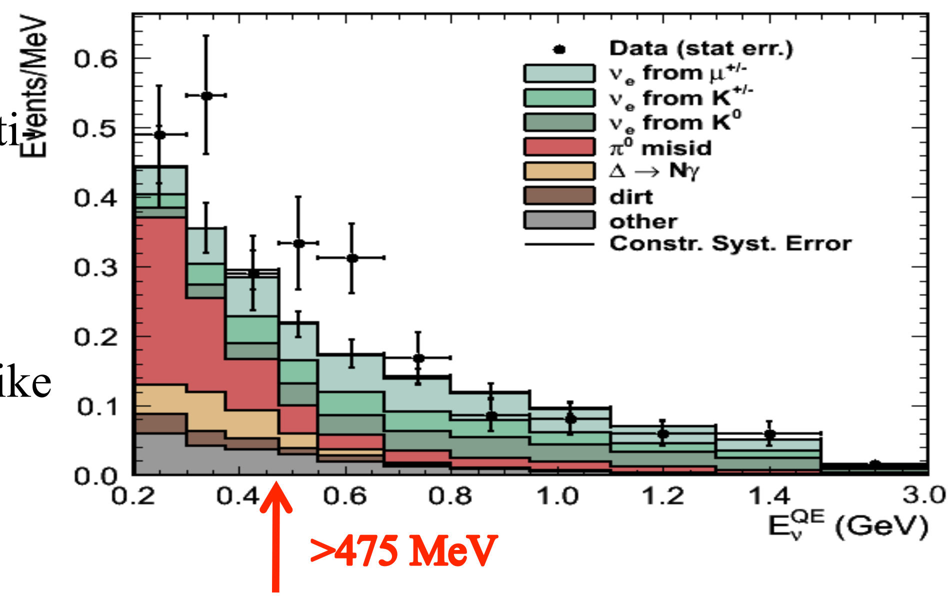
$\bar{\nu}_e$ Event Rate Predictions in Appearance Analysis

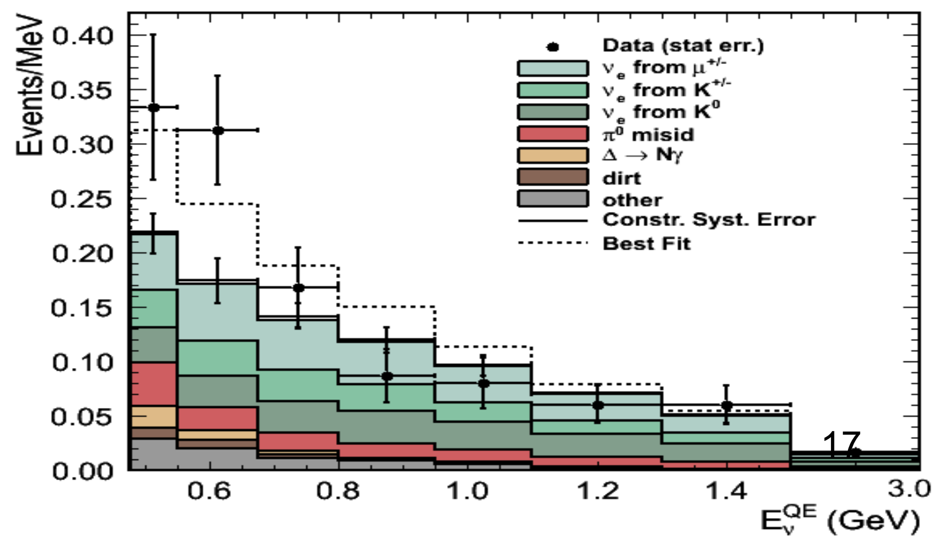
We have collected about ~1/5 the number of interactions as in neutrino mode when same POT considered.

- The flux per proton on target is lower (~×1.5) in $\bar{\nu}$ mode
- The cross section is lower (~×3) in $\bar{\nu}$ mode
- Background types and relative rates are similar for neutrino and antineutrino mode.
  - -except inclusion of 15.9% wrong-sign neutrino flux component in antineutrino mode
- Fit analysis and errors are similar.

Previous Antineutrino Mode Results (2010): 5.66E20 POT

- Results for 5.66E20 POT collected in anti-neutrino mode
- Only antineutrino's allowed to oscillate in fit
- In E < 475 MeV: A small 1.3σ electron-like excess.
- E > 475 MeV: An excess that is 3.0% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.





Published
Phys.Rev.Lett.105:181801,2010.
e-Print: **arXiv:1007.1150** [hep-ex])

Previous Anti-neutrino Mode Results (2010): 5.66E20 POT

Null excluded at 99.4% with respect to the two neutrino oscillation fit.

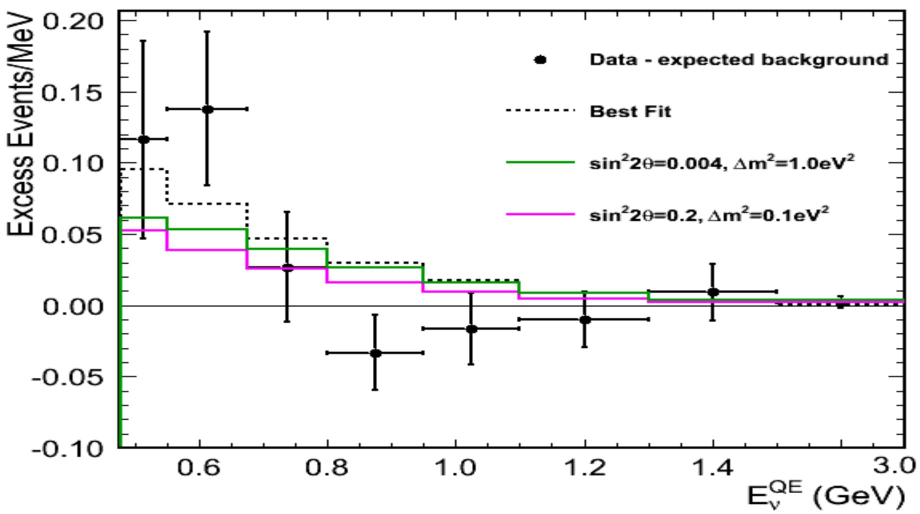
Best Fit Point

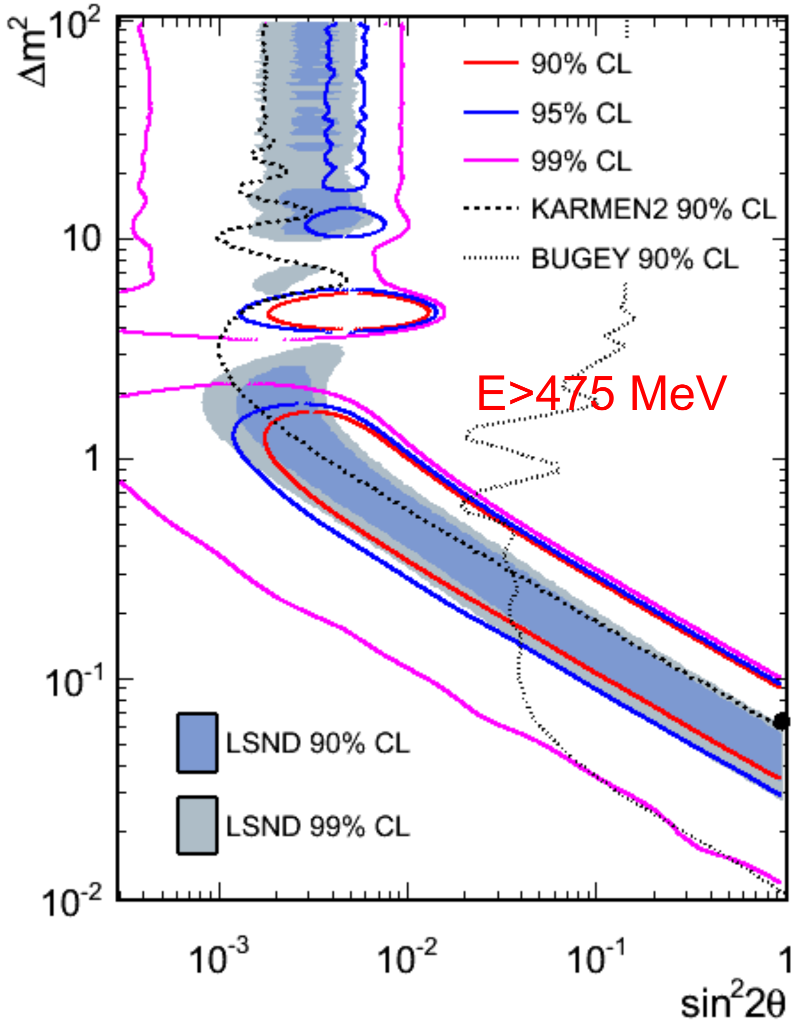
$(\Delta m^2, \sin^2 2\theta) =$

$(0.064\ eV^2, 0.96)$

$\chi^2/NDF = 7.96/3.89$

$P(\chi^2) = 8.7\%$

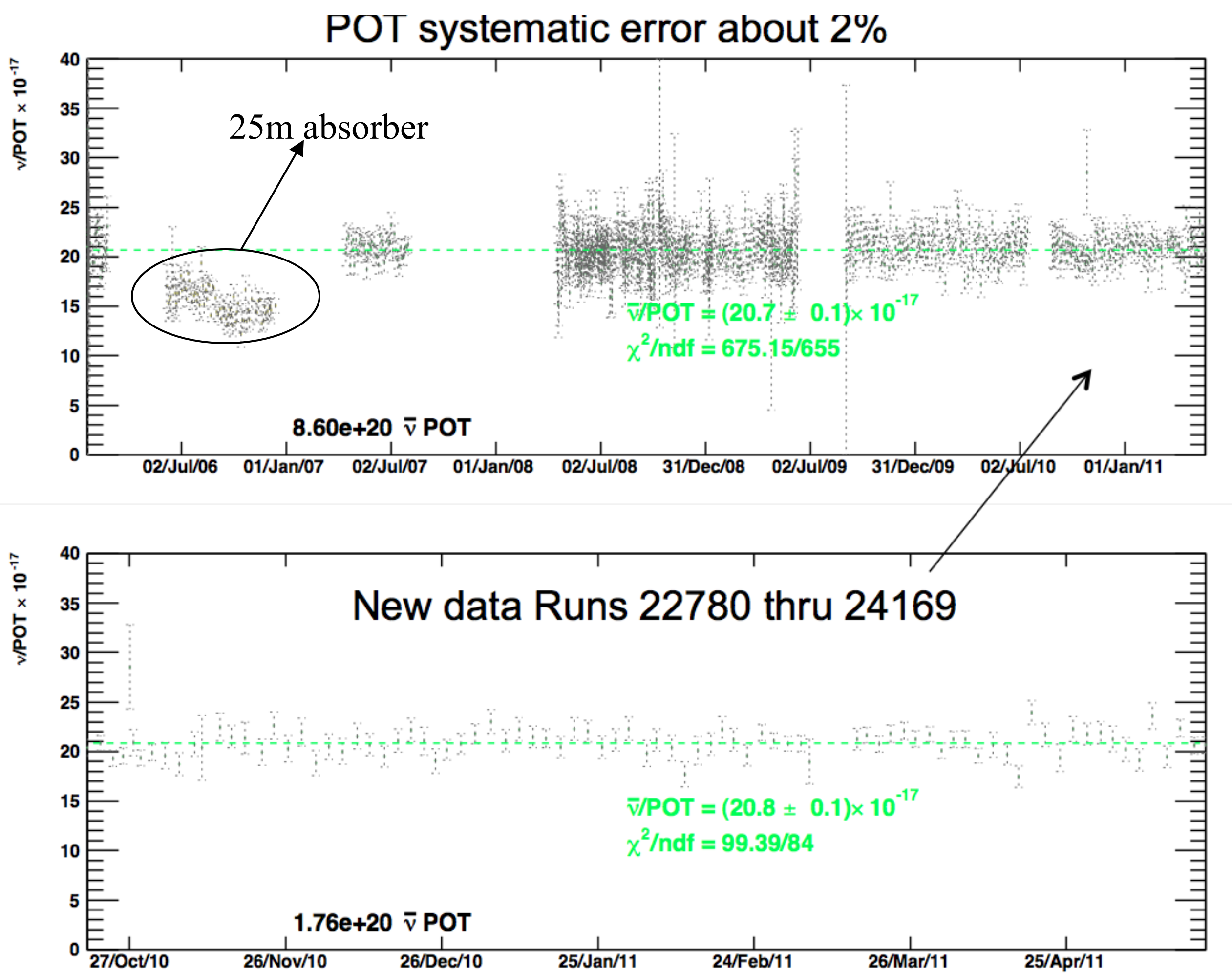




New Anti-neutrino mode results: 8.58E20 POT
(50% more data)

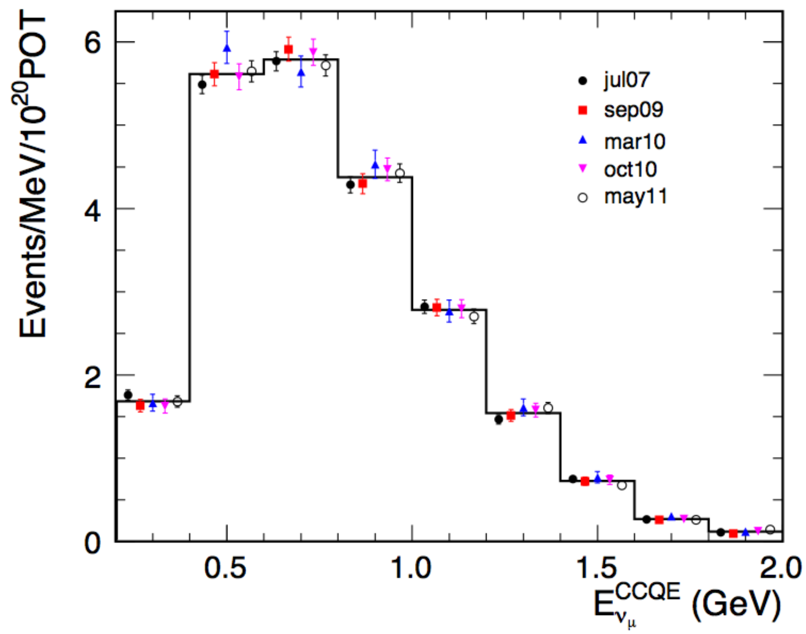
Data Checks

- Beam and Detector low level stability checks; beam stable to 2%, and detector energy response to 1%.



Data Checks

- $\bar{\nu}_\mu$ rates and energy stable over entire antineutrino run.

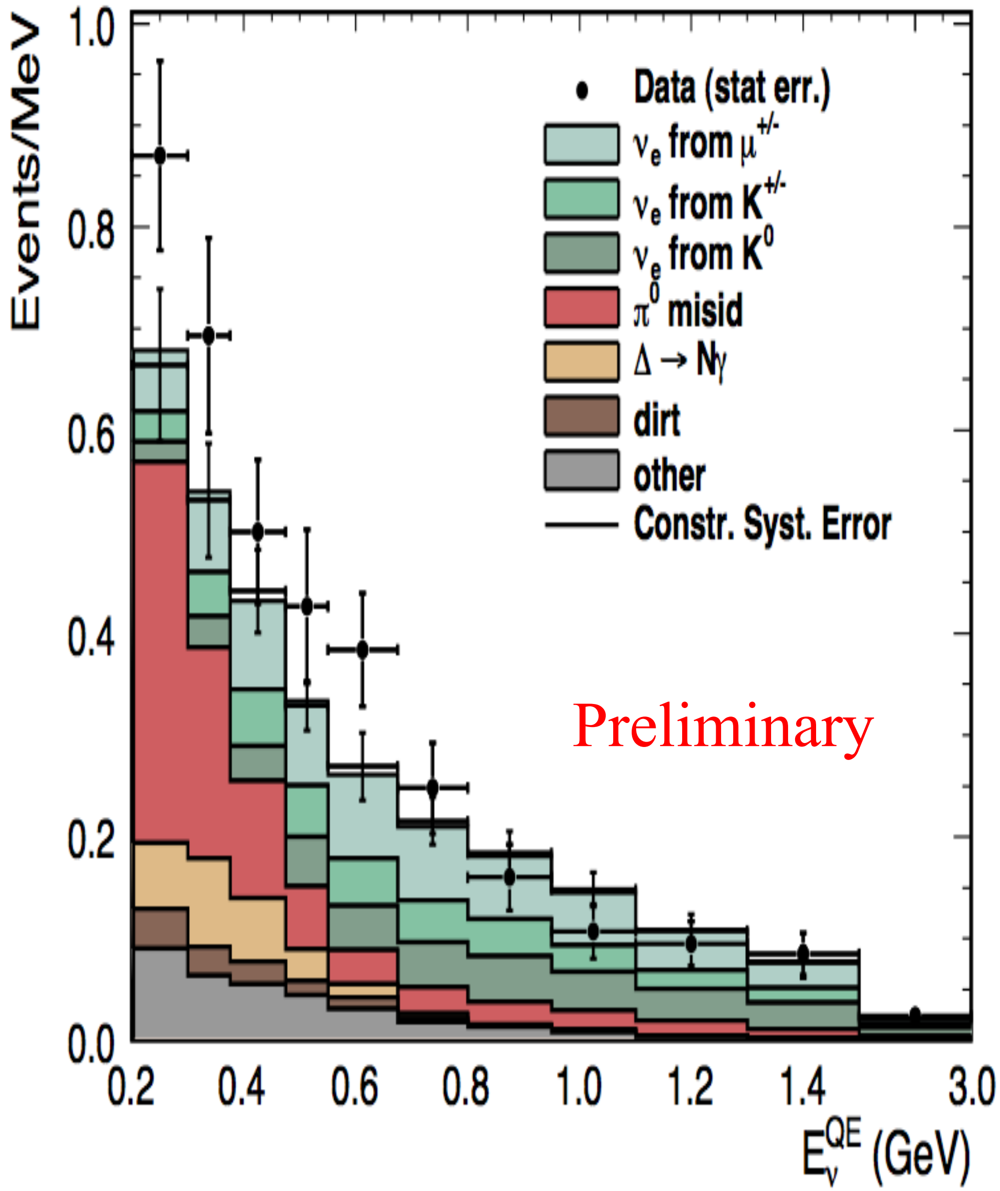


- New SciBooNE constraint on K^+ component of the Booster beam: Reduces this component of background by 3% and error by factor of 3 (e-print 1105.2871 [hep-ex], also see C. Mariani's SciBooNE talk).
- Other systematic errors, constrained by MiniBooNE data, reduced due to higher statistics in control samples:
  - -π-decay neutrino normalization factors
  - -Dirt neutrino background
  - -Neutral-current π^0 production.

New Anti-neutrino mode results: 8.58E20 POT

475MeV<E_ν<1250MeV:

- Expected events: 151.7±15.0 (syst) after fit constraints
- Observed events: 168.
- Observed Excess: 16.3±19.4 (total) →0.84σ
- Excess in oscillation serch region is reduced somewhat with new data.
- Low-energy excess is more significant and resembles neutrino-mode data.

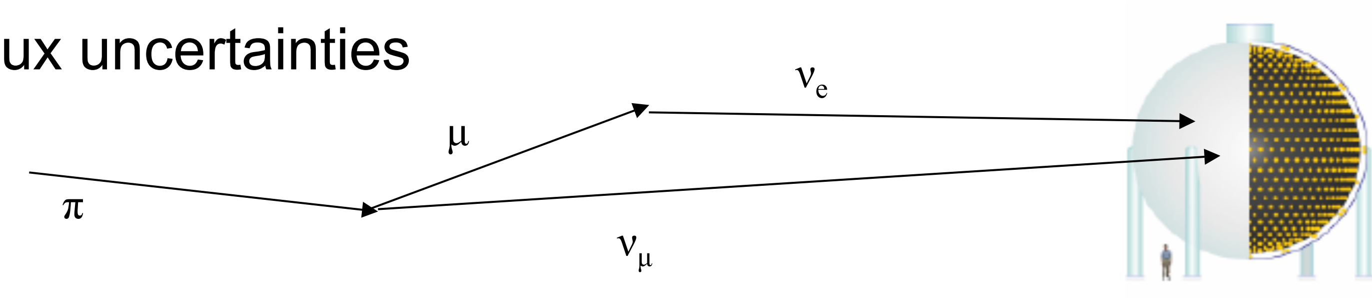


Oscillation Fit Method

- Identical to previous result
- Maximum likelihood fit:

$$-2\ln(L) = (x_1 - \mu_1, ...x_n - \mu_n)M^{-1}(x_1 - \mu_1, ...x_n - \mu_n)^T + \ln(|M|)$$

- Simultaneously fit
  - ν_e CCQE sample
  - High statistics ν_μ CCQE sample
- ν_μ CCQE sample constrains many of the uncertainties:
  - Flux uncertainties

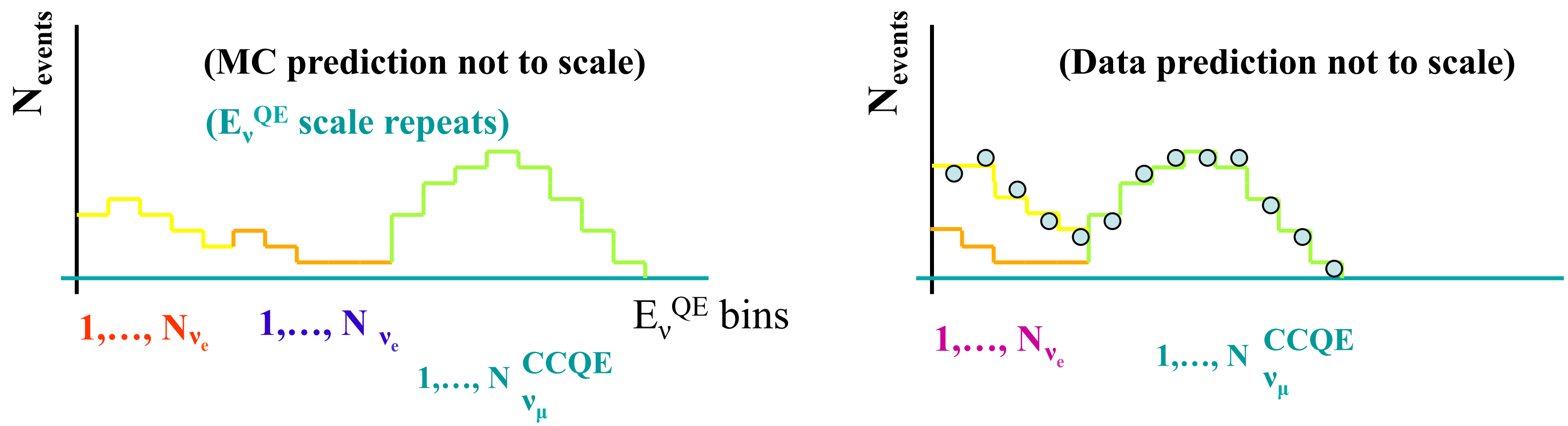


  - Cross section uncertainties (CCQE process)

Constrained Fit

The following three distinct samples are used in the oscillation fits:

1. Background to ν_e oscillations
2. ν_e Signal prediction (dependent on Δm^2, $\sin^2 2\theta$)
3. ν_μ CCQE sample, used to constrain ν_e prediction (signal+background)



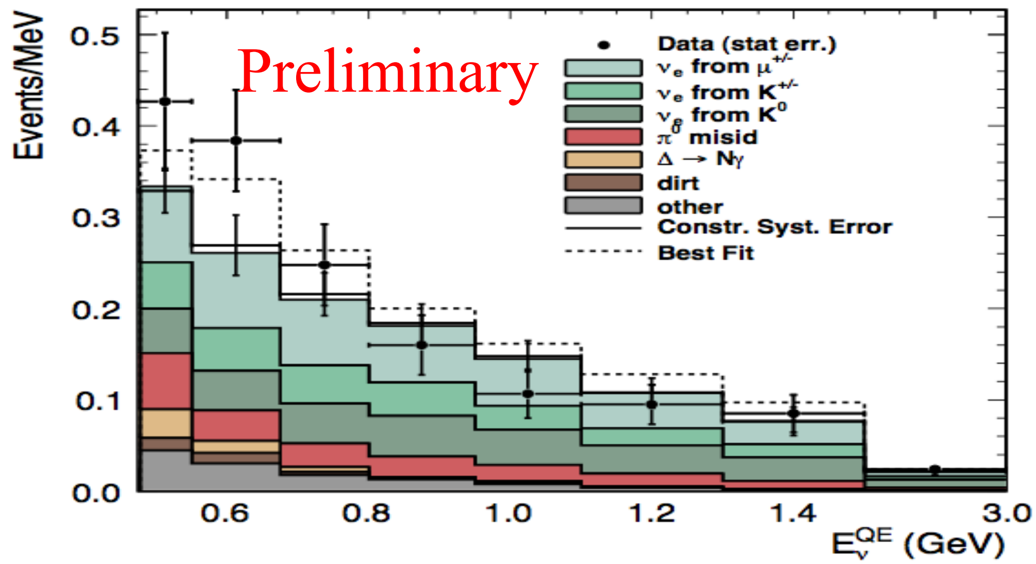
$$-2\ln(L) = (x_1 - \mu_1, ...x_n - \mu_n)M^{-1}(x_1 - \mu_1, ...x_n - \mu_n)^T + \ln(|M|)$$

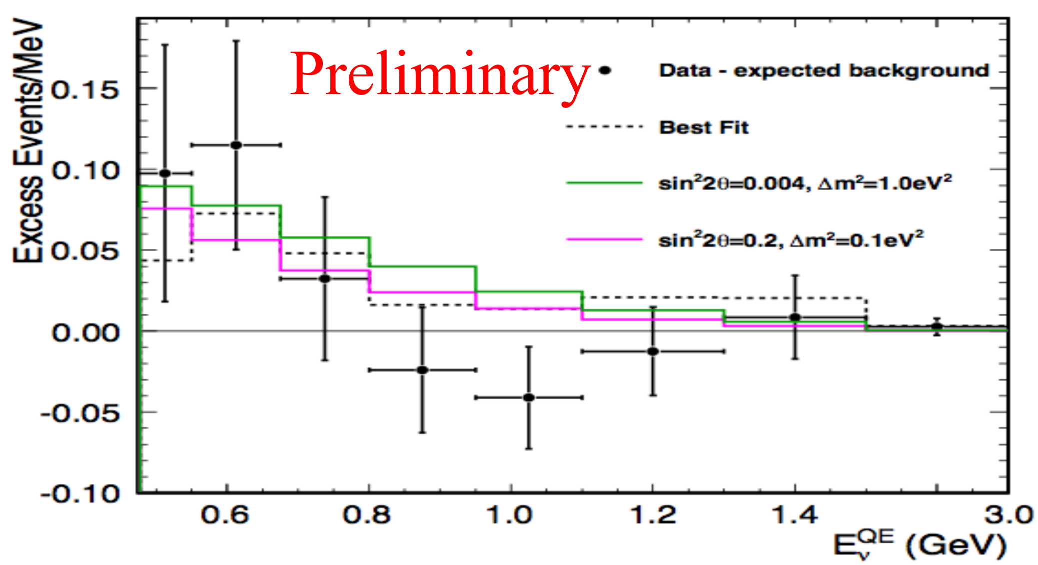
M_{ij} = full syst+stat covariance matrix at best fit prediction

logL calculated using both datasets (ν_e and ν_μ CCQE), and corresponding covariance matrix

Oscillation Fit

- Results for 8.58E20 POT.
- Maximum likelihood fit.
- Only antineutrinos allowed to oscillate.
- E > 475 MeV region is free of effects of low energy neutrino excess. This is the same official oscillation region as in neutrino mode.





Oscillation Fit

- Results for 8.58E20 POT
- Maximum likelihood fit.
- For the original osc energy region above 475 MeV, oscillations favored over background only (null) hypothesis at the 91.1% CL.
- Best Fit Point

  $(\Delta m^2, \sin^2 2\theta) = (4.6\ eV^2, 0.0045)$

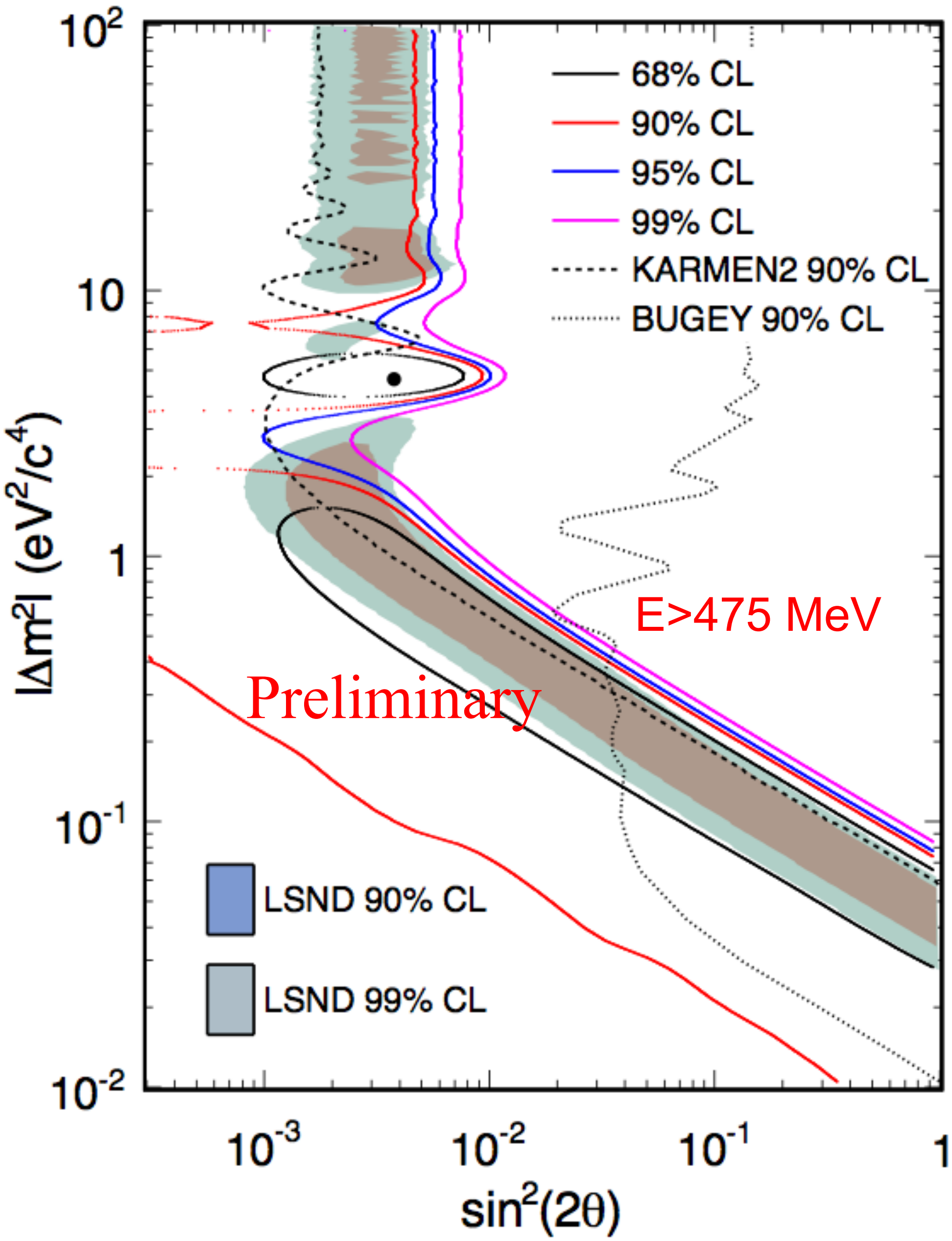
  $\chi^2_{BF}/NDF = 4.3/3.9$ with $P(\chi^2) = 35.5\%$

  $\chi^2_{NULL}/NDF = 9.3/5.9$ with $P(\chi^2) = 14.9\%$
- Consistent with LSND, though evidence for LSND-type oscillations less strong than previous published 5.66E20 result
- Previous result (5.66E20 POT) :

  Oscillation favored over null at 99.4%CL

  $\chi2_{BF}$ /NDF = 8.0/6 with $P(\chi^2)$ = 8.7%

  $\chi2_{NULL}$/NDF = 18.5/4 with $P(\chi^2)$ = 0.5%.

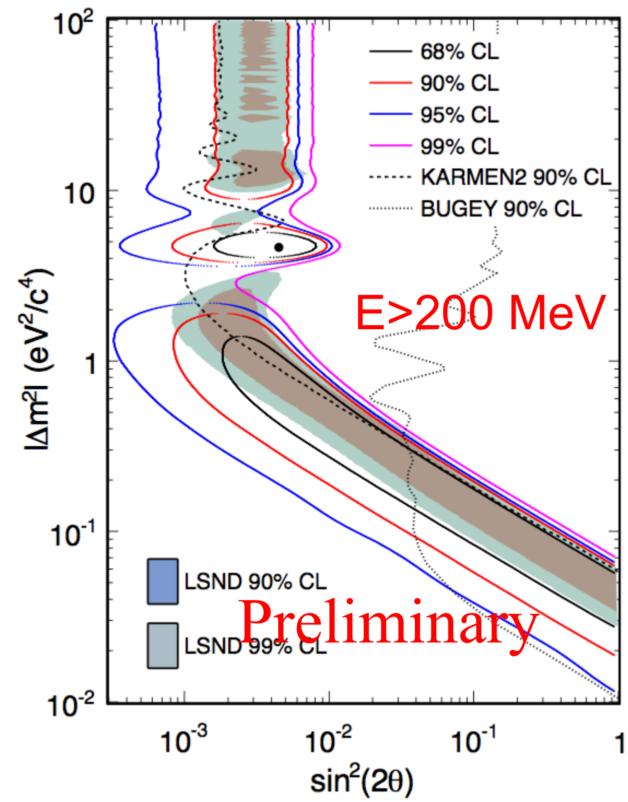


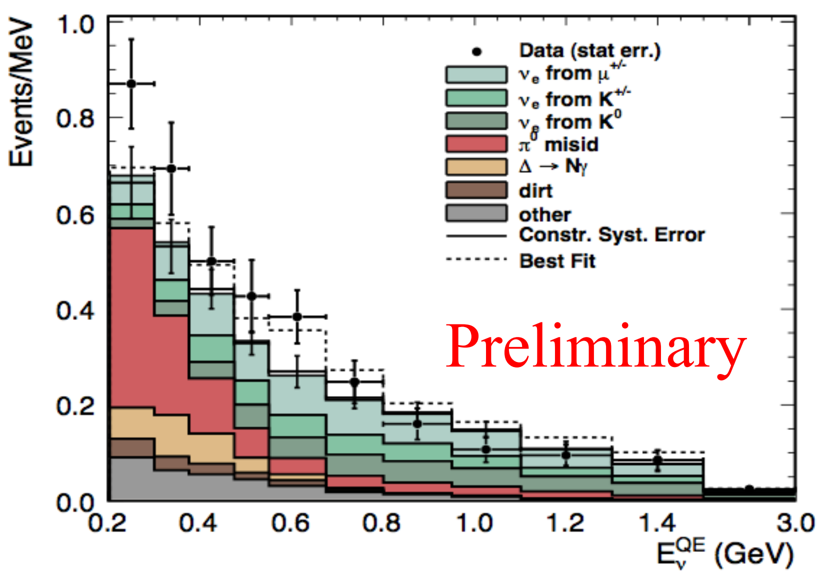
Oscillation Fit with E_ν > 200 MeV

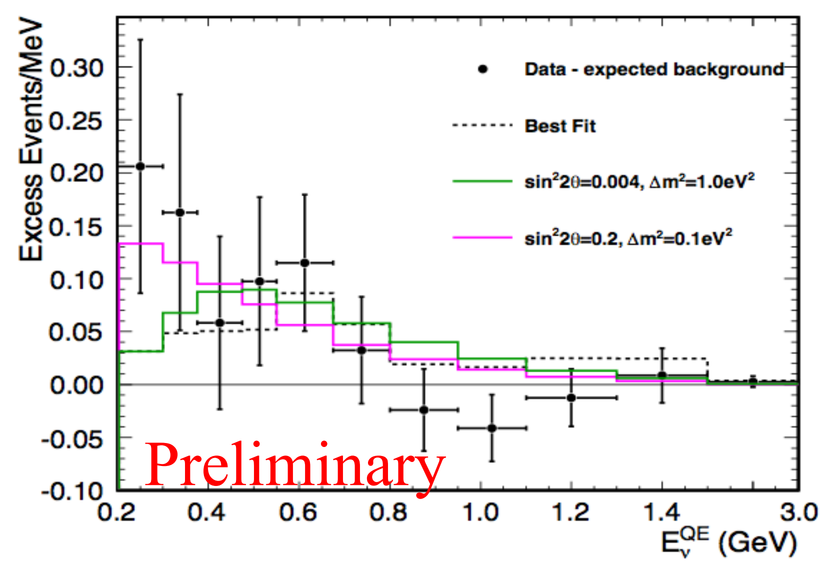
- Results for 8.58e20 POT.
- Use full energy range $200<E_\nu<2000$MeV in the fit.
- Does not include effects (subtraction) of neutrino low energy excess.
- For E< 475 MeV, excess = 38.6 ± 18.5 (For all energies, excess = 57.7 ± 28.5).
- Maximum likelihood fit method.
- Null excluded at 97.6% with respect to the two neutrino oscillation fit (model dependent).
- Best Fit Point (Δm^2, $\sin^2 2\theta$) = (4.6 eV^2, 0.0038)

χ^2_{BF}/NDF= 6.1/6.9, $P(\chi^2)$= 50.7%

χ^2_{NULL}/NDF= 14.5/8.9, $P(\chi^2)$= 10.1%

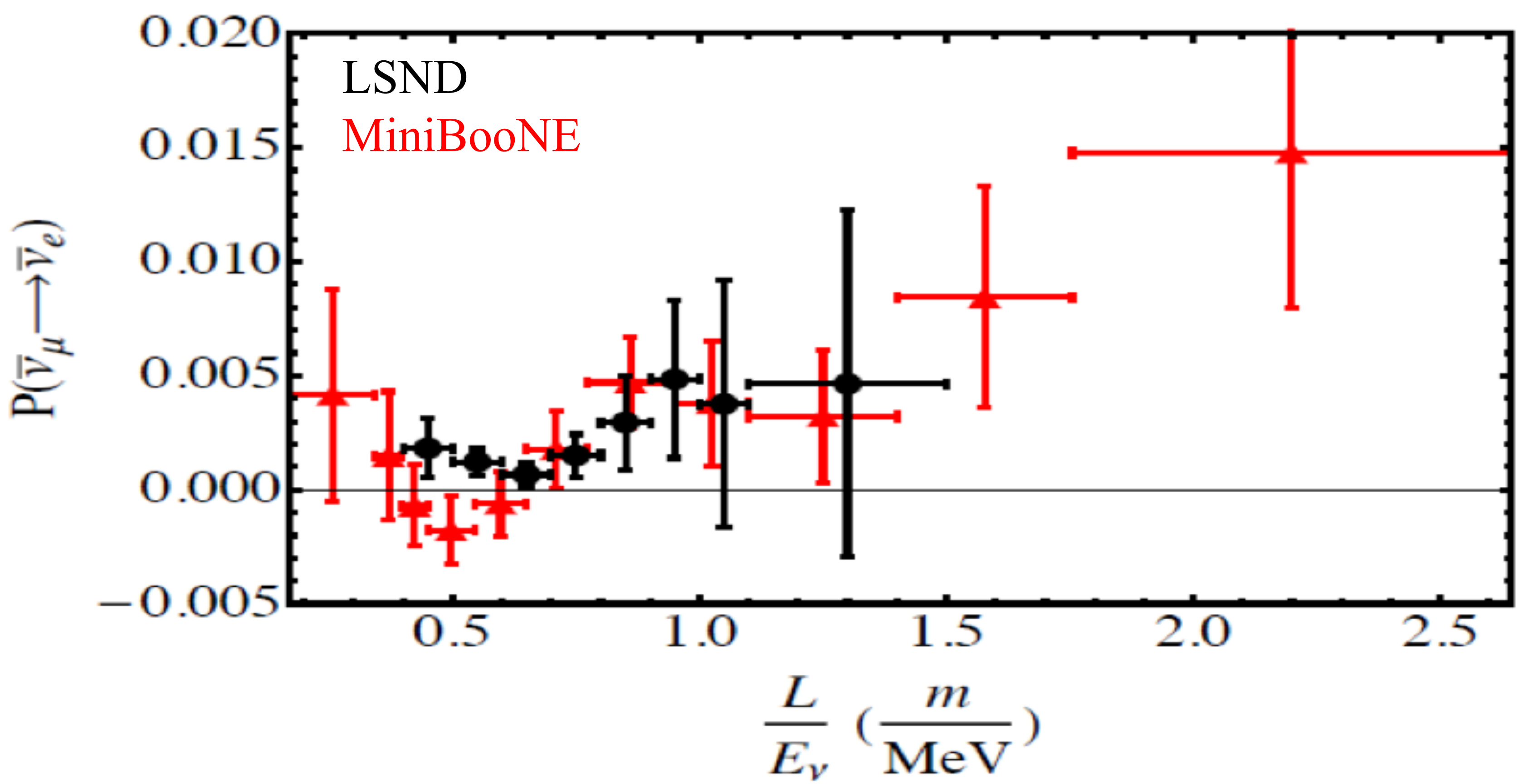






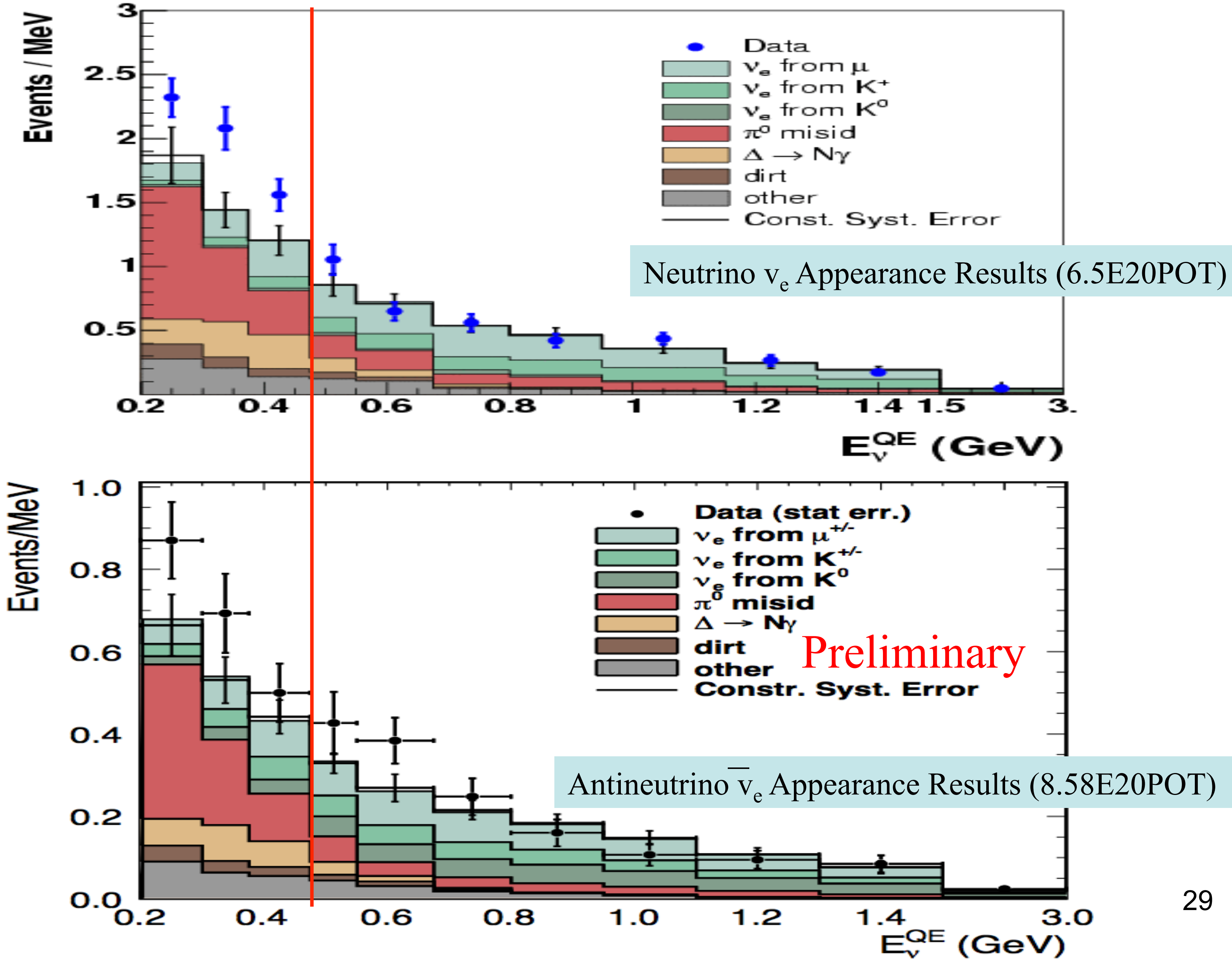
L/E Plot

- Data used for LSND and MiniBooNE correspond to $20<E_\nu<60$ MeV and $200<E_\nu<3000$ MeV, respectively.
- Oscillation probability is event excess divided by the number of events expected for 100% $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transformation.
-L is reconstructed distance travelled by the antineutrino from the mean neutrino production point to the interaction vertex; E_ν is the reconstructed antineutrino energy.



The data points include both statistical and systematic errors.

Comparison of ν_e and $\bar{\nu}_e$ Appearance Results



Summary of Results

- The MiniBooNE ν_e and $\overline{\nu}_e$ appearance picture is the following:

  1) Neutrino Mode:

     a) E < 475 MeV: An unexplained 3σ electron-like excess.

     b) E > 475 MeV: A two neutrino fit rules out LSND at the 98% CL.

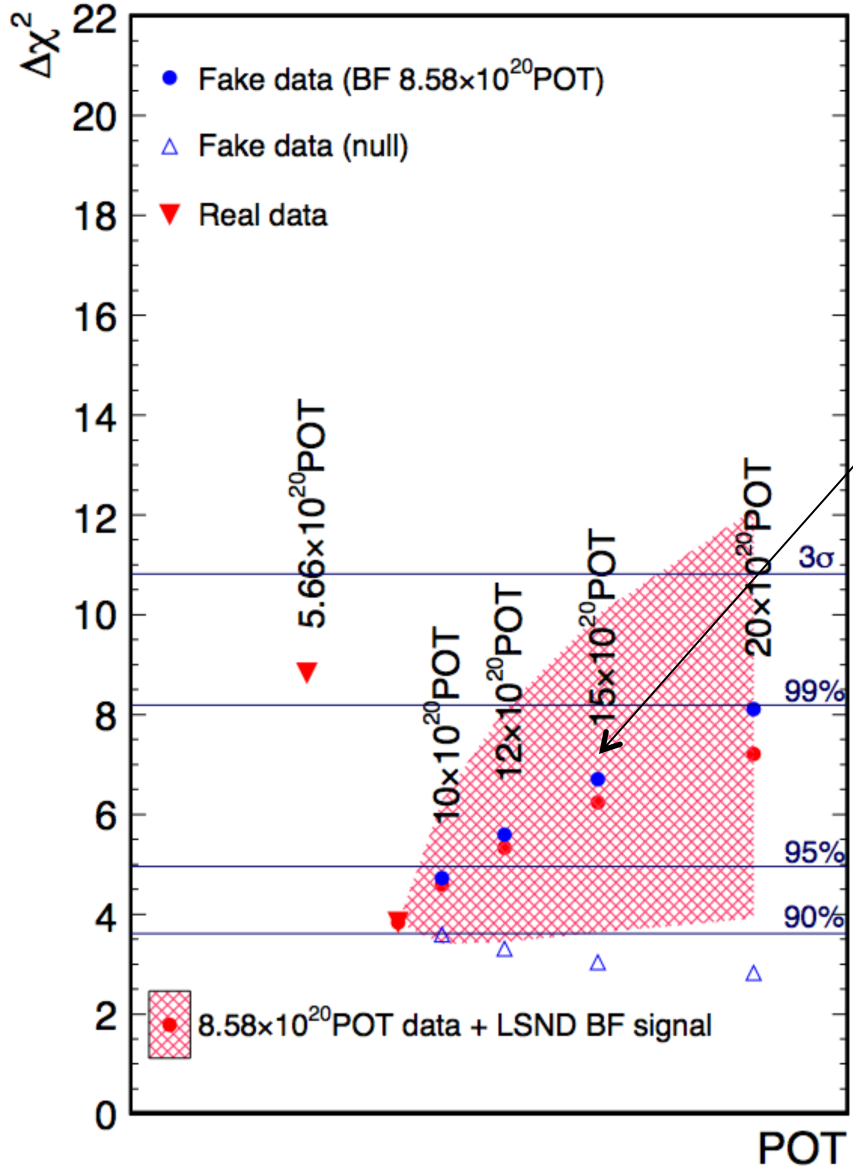
  2) Anti-neutrino Mode:

     a) E < 475 MeV: Electron-like excess = 38.6±18.5

     b) E > 475 MeV: An excess that is 14.9% consistent with null. Two neutrino oscillation fits consistent with LSND at 35.5% CL relative to null.

- Low energy excess now more prominent for anti-neutrino running than previous result.
- Perform a combined analysis of ν_e and $\overline{\nu}_e$ as next step.

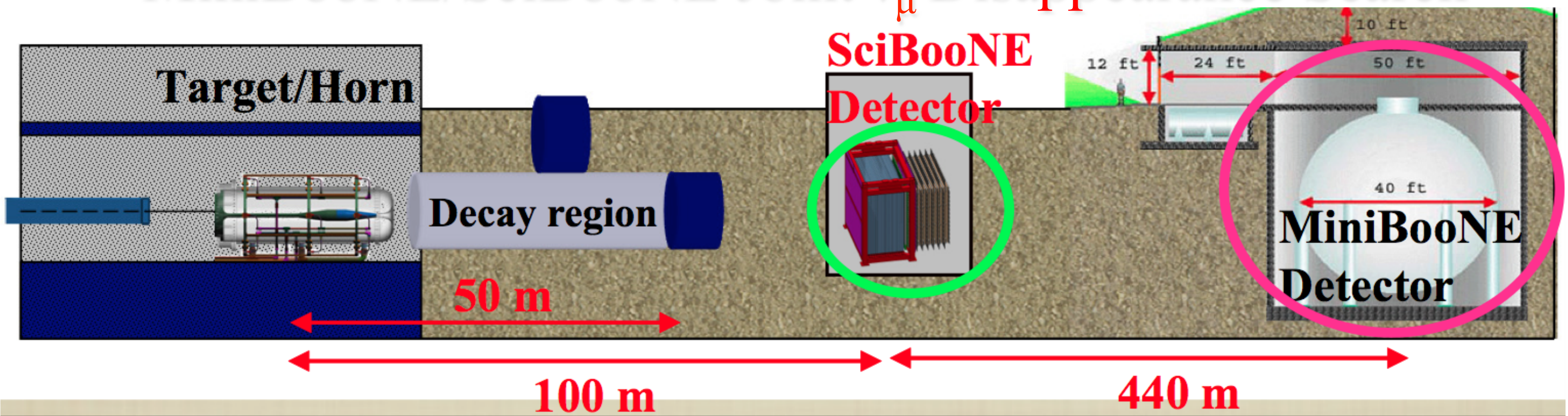
Future MiniBooNE Running

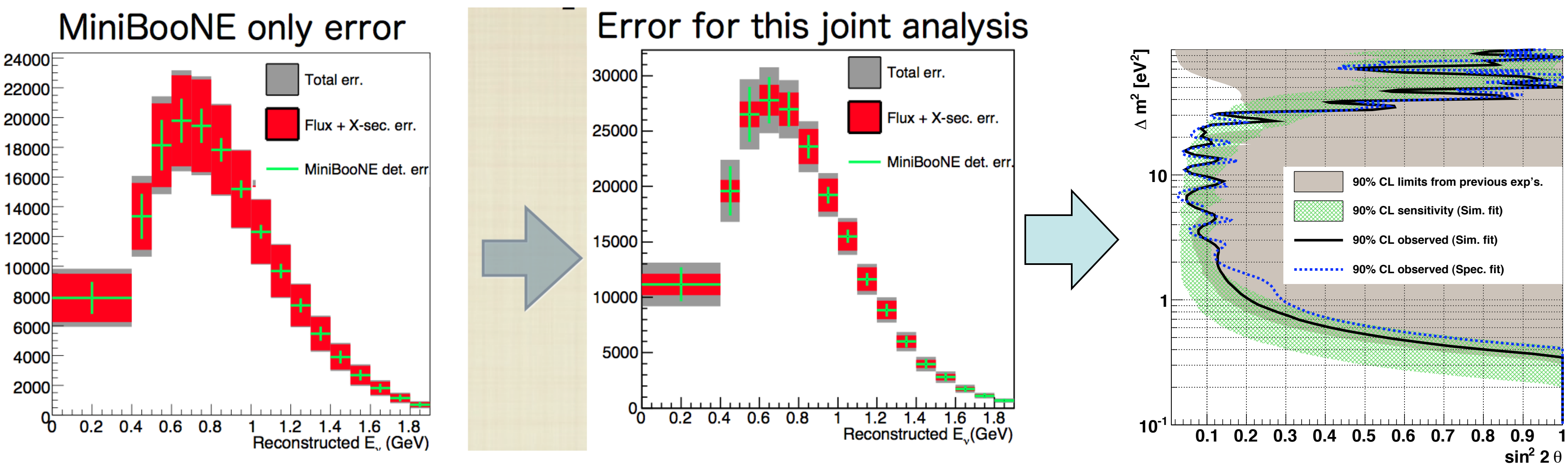


MiniBooNE Collaboration requested $15x10^{20}$ POT to complete the run in current configuration.

The data set will probe LSND signal at 2-3 σ level.

MiniBooNE/SciBooNE Joint ν_μ Disappearance Search





-No evidence for oscillations: Limit is better than other experiments in 10-30 eV^2 region.
-Results published: arXiv:1106.5685 [hep-ex], submitted to PRL.
-On-going effort: MiniBooNE/SciBooNE Joint $\bar{\nu}_\mu$ Disappearance Search.

Conclusions and Future Prospects

- Significant ν_e and $\bar{\nu}_e$ excesses above background are emerging in both neutrino mode and antineutrino mode in MiniBooNE.
- With new data update excess is indicated at low energy, as with neutrinos.
- Antineutrino data are consistent with LSND.
- Consistent with the "reactor anomaly" ?
- Antineutrino results are statistics-limited: MiniBooNE requested ~15×10^{20} POT to complete the run.

- There are possible follow-up experiments planned at FNAL and elsewhere
  - μBoone has CD-1 approval. Dedicated talk by B. Jones
  - BooNE (LOI). A MB-like near detector at 200 m (when MiniBooNE finished in current configuration).
  - Proposal for two detector LAr detector at CERN PS ring. Talk by F. Pietropaolo
  - Various other ideas (NOνA far detector with nearby accelerator, etc).

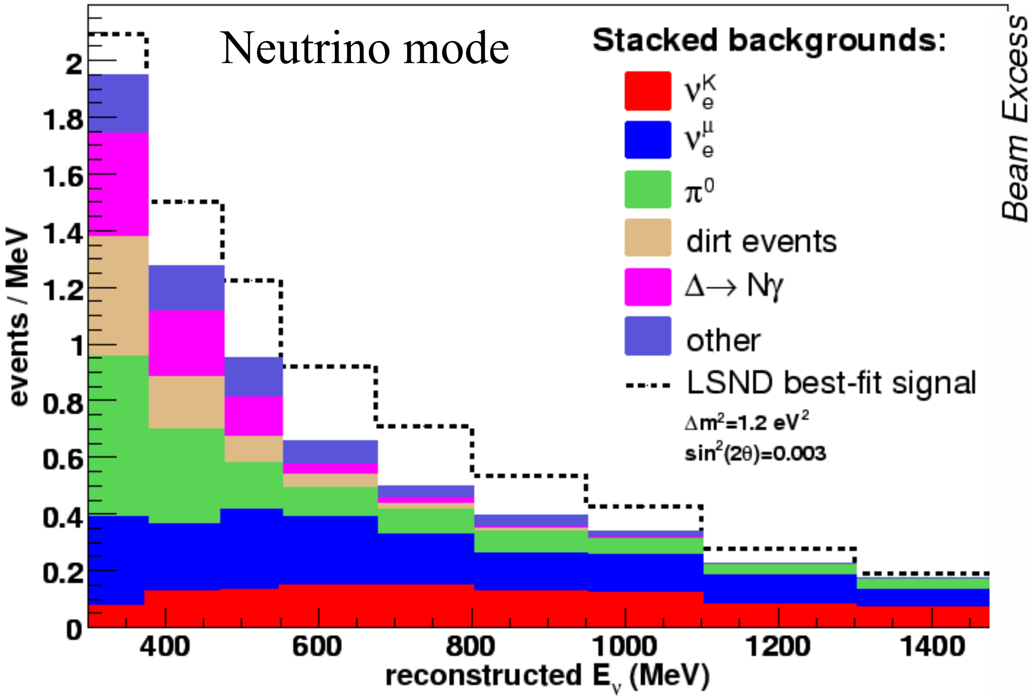
Dedicated short-baseline talk by Bill Louis

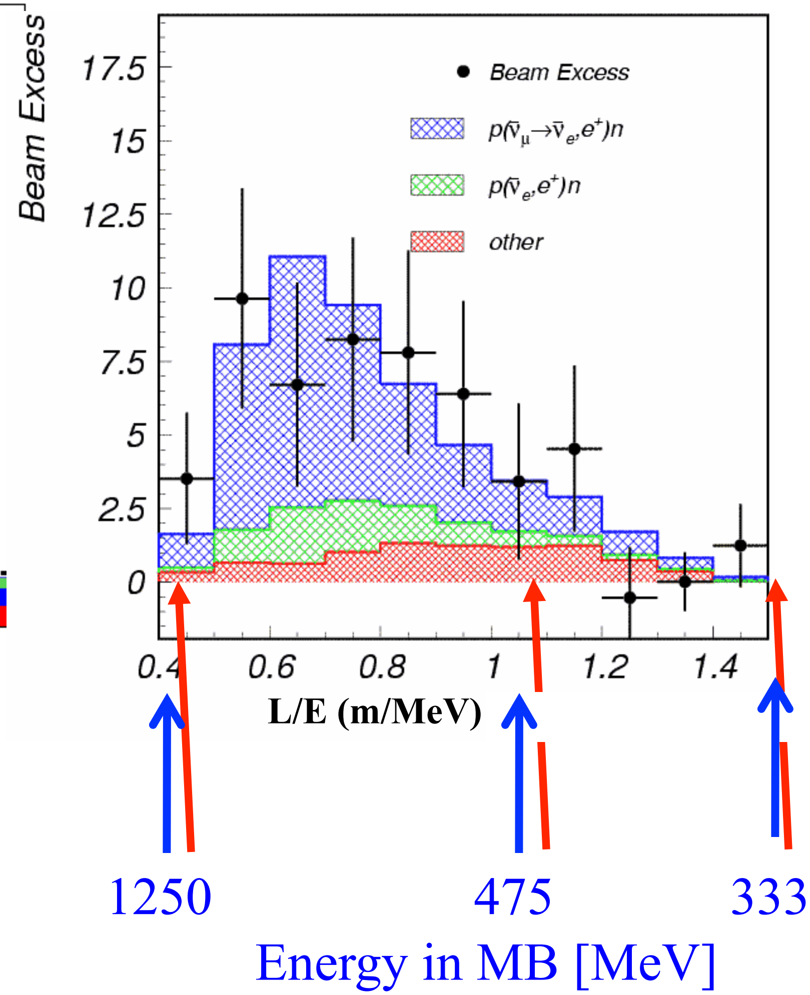
Thank you!

Backup Slides

Reminder of Some Pre-unblinding Choices

We are using energy range E_ν > 475 MeV in oscillation analysis.





- Why is the 200-475 MeV region unimportant for oscillation search?

  -Large backgrounds from mis-ids reduce S/B.

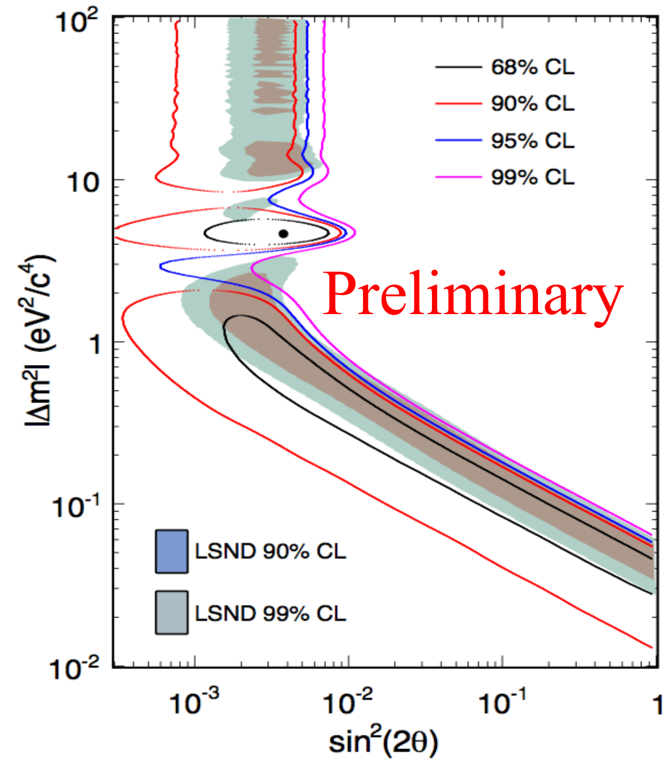
  -Many systematics grow at lower energies.

  -Most importantly, not a region of L/E where LSND observed a significant signal

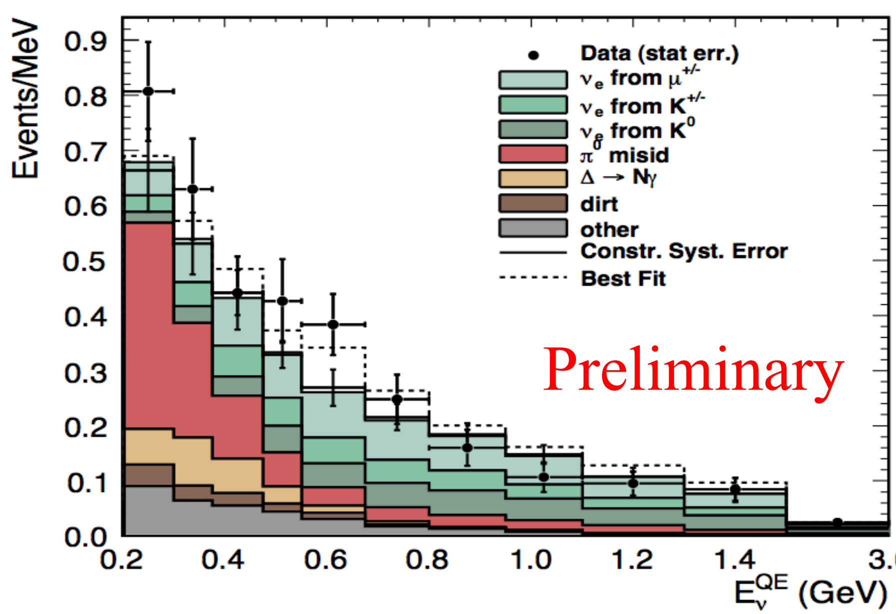
Low Energy Excess: How does it scale?

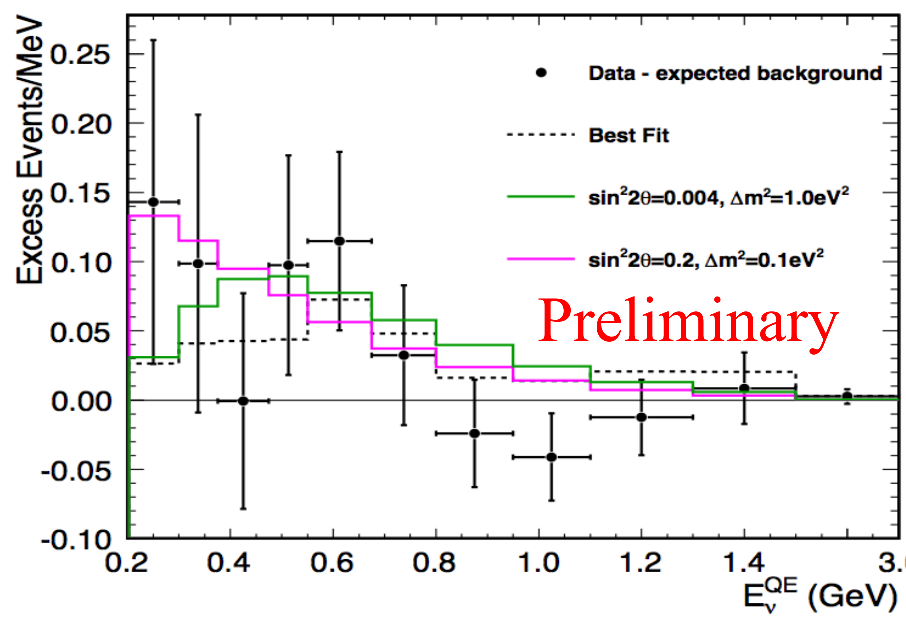
- Excess above background in $200<E<475$ MeV is 38.6 ± 18.5 events.
- Scaling from what is observed in neutrino mode we may test various hypotheses.
- Expected number of events in anti-neutrino mode assuming particular background as the source of low-E excess in neutrino mode:
  - -Total background: 50
  - - Neutrino contamination only: 17
  - - $\Delta\rightarrow N\gamma$ decays: 39
  - - Dirt: 46
  - - Protons on target (neutrals in secondary beam): 165
  - - K+ in secondary beam: 67
  - - NC $0: 48
  - - Inclusive CC: 59

Oscillation Fit with E_ν > 200 MeV
(include low E_ν ν-mode effects)

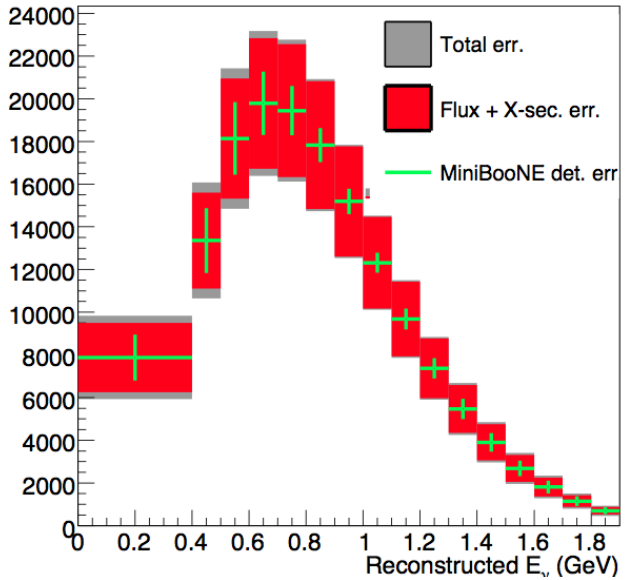


- Results for 8.58e20 POT.
- Assume simple scaling of neutrino low energy excess; subtract 17 events from low energy region (200-475 MeV).
- Maximum likelihood fit method.
- Best Fit Point (Δm^2, $\sin^2 2\theta$) = (4.6 eV^2, 0.0037)
  P(χ^2, BF)= 76.5%
  P(χ^2, NULL)= 28.3%





MiniBooNE only error



Error for this joint analysis