Results of MiniBooNE Experiment

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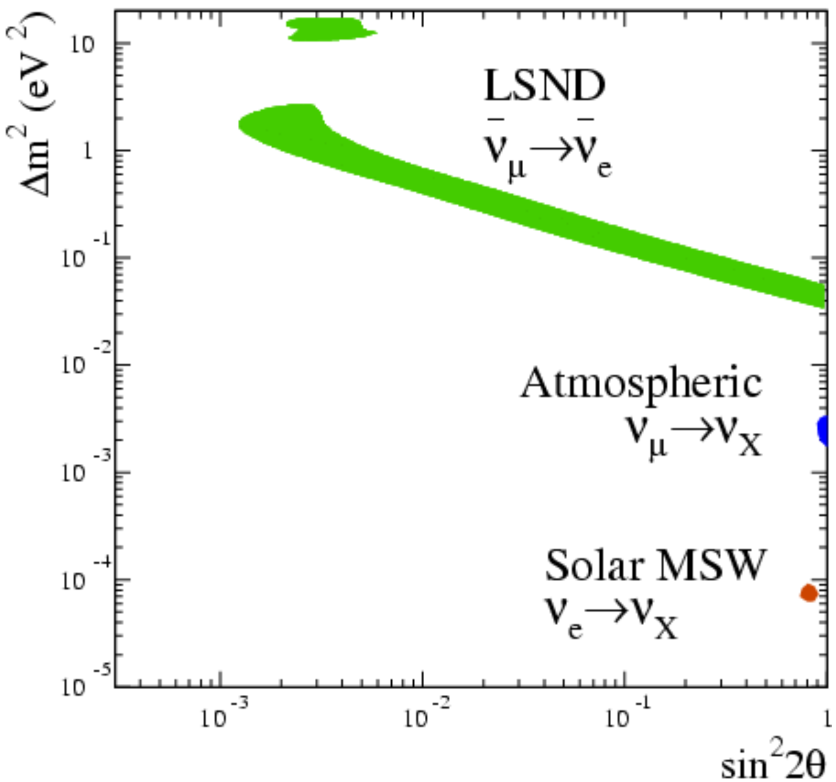
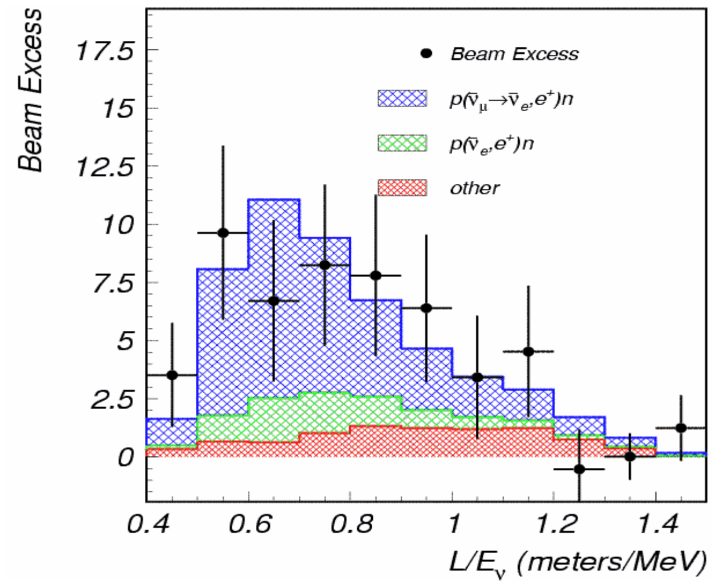
Outline

- MiniBooNE Experiment Description
- MiniBooNE's Neutrino Oscillation Search Results with Neutrinos
- MiniBooNE's Neutrino Oscillation Search Results with Anti-neutrinos
- Summary

Oscillation Status After LSND

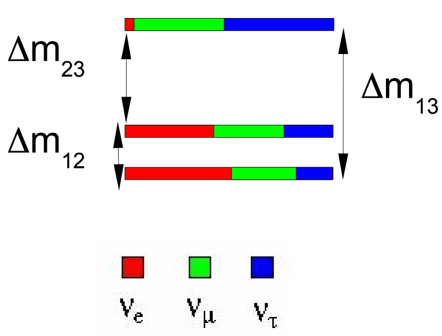




This signal looks very different from the others...

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

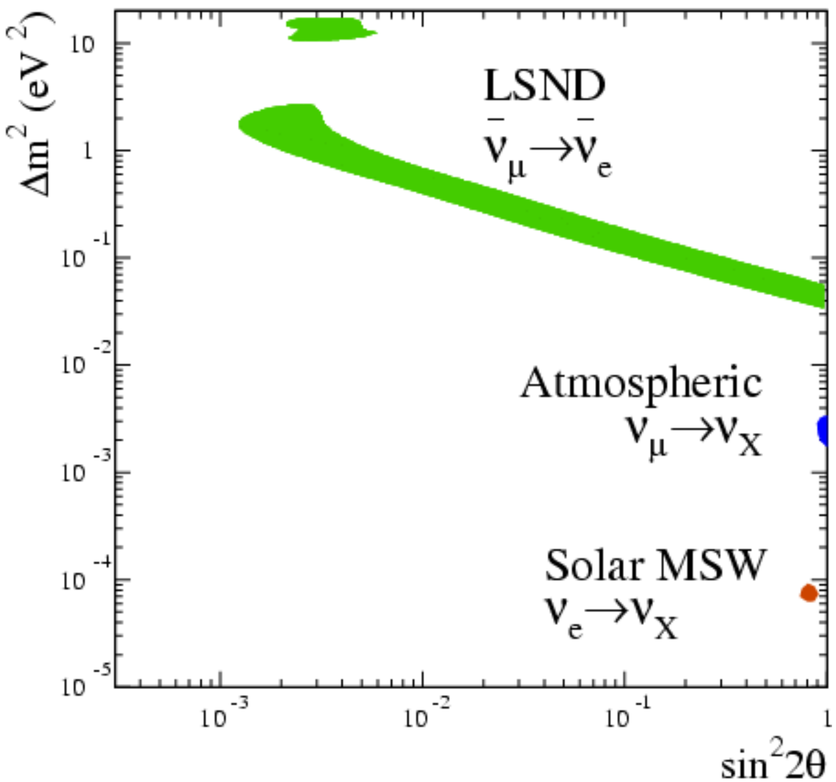
In SM there are only 3 neutrinos

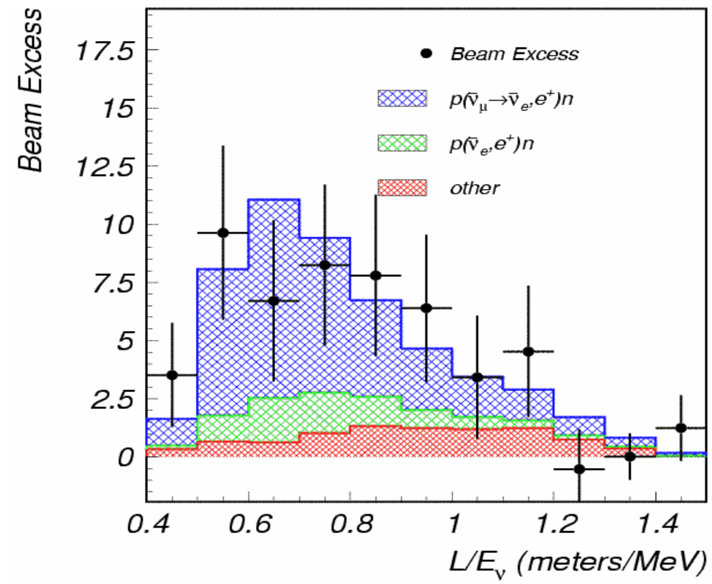


- Three distinct neutrino oscillation signals, with $\Delta m^2_{solar} + \Delta m^2_{atm} \neq \Delta m^2_{LSND}$
- For three neutrinos, expect $\Delta m^2_{21} + \Delta m^2_{32} = \Delta m^2_{31}$

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

Oscillation Status After LSND





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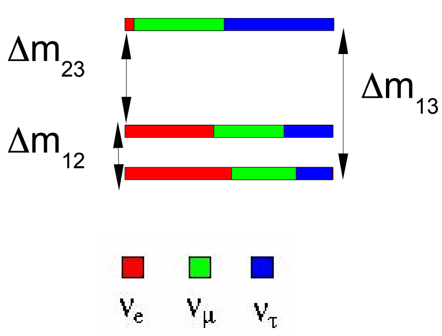
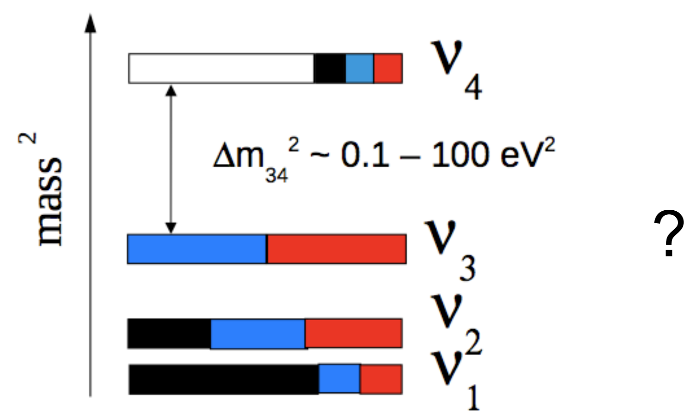
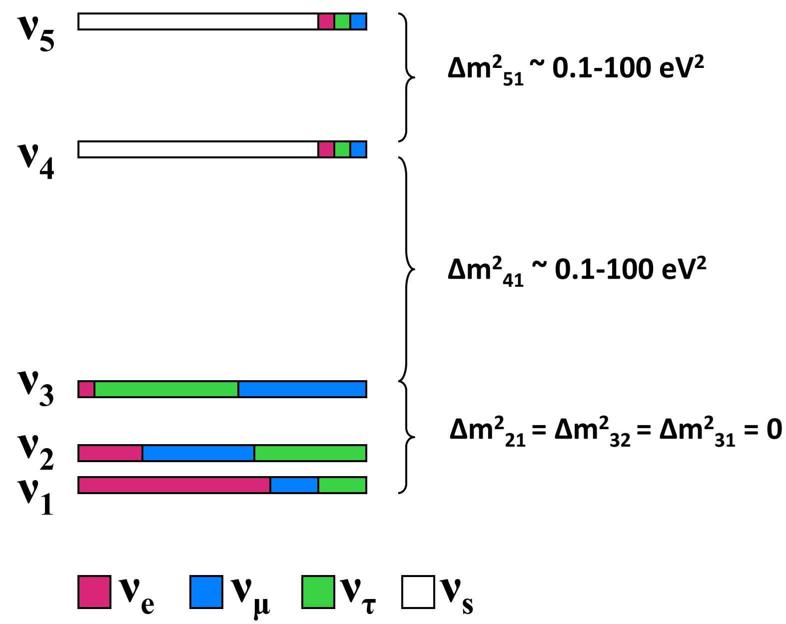




Oscillation explanation of LSND in conjunction with the atmospheric and solar oscillation results needed more than 3 ν' s.

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)

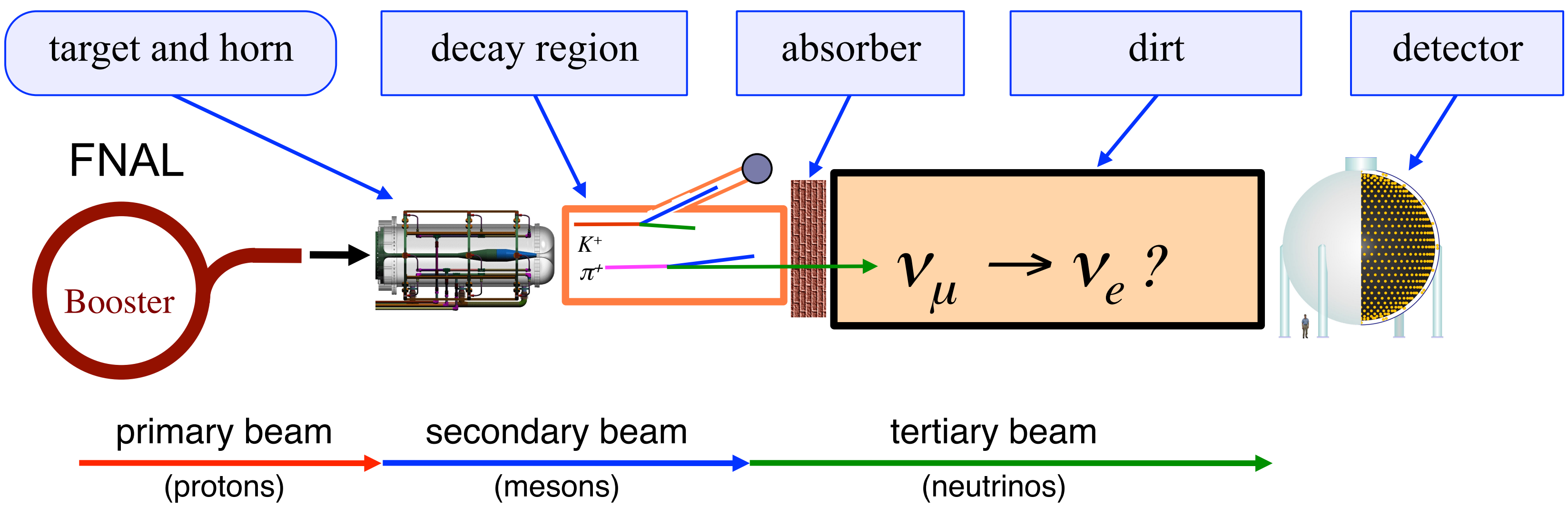
MiniBooNE Setup

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

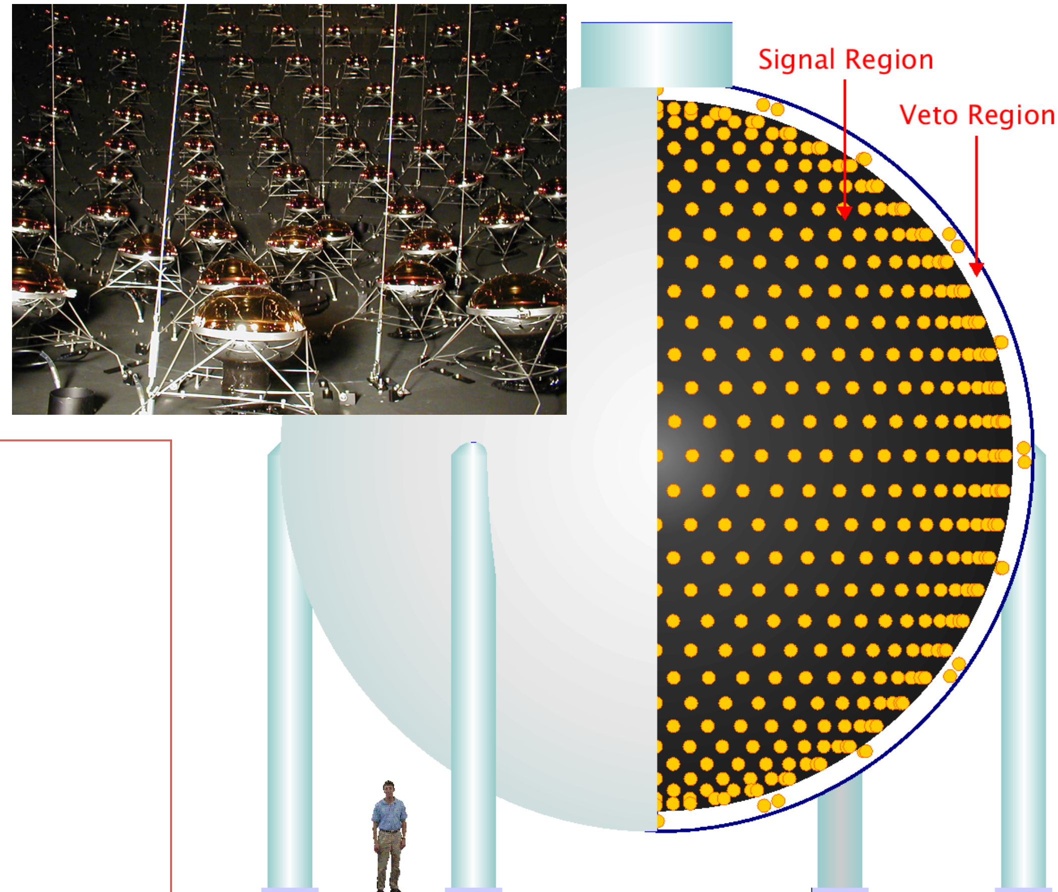
LSND: E ~30 MeV L ~30 m L/E ~1

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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance with 11.3E20 POT → direct test of LSND

MiniBooNE Detector

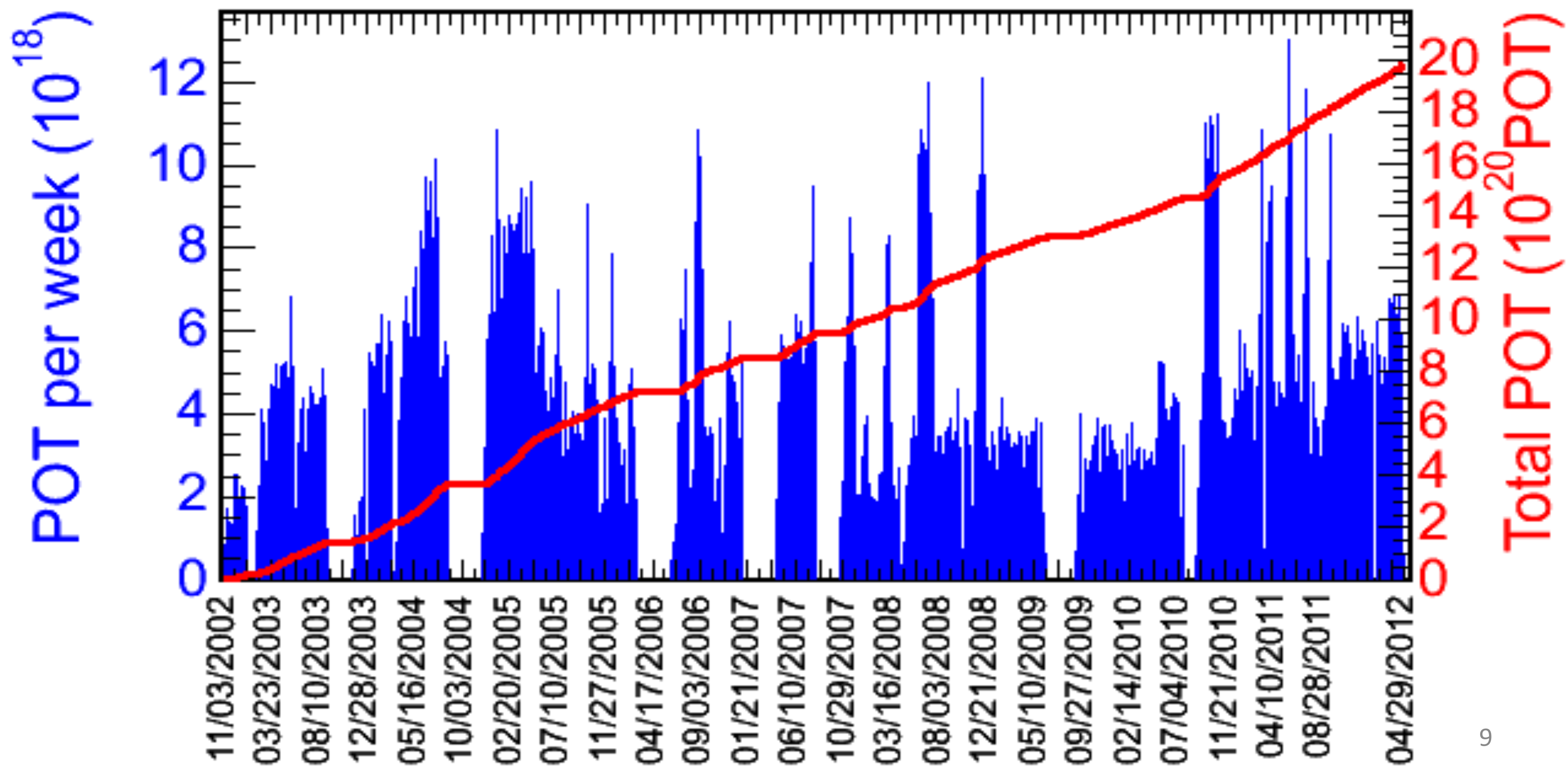


MiniBooNE Detector:
- -12m diameter sphere
- -950000 liters of oil(CH_2)
- -1280 inner PMTs
- -240 veto PMTs

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

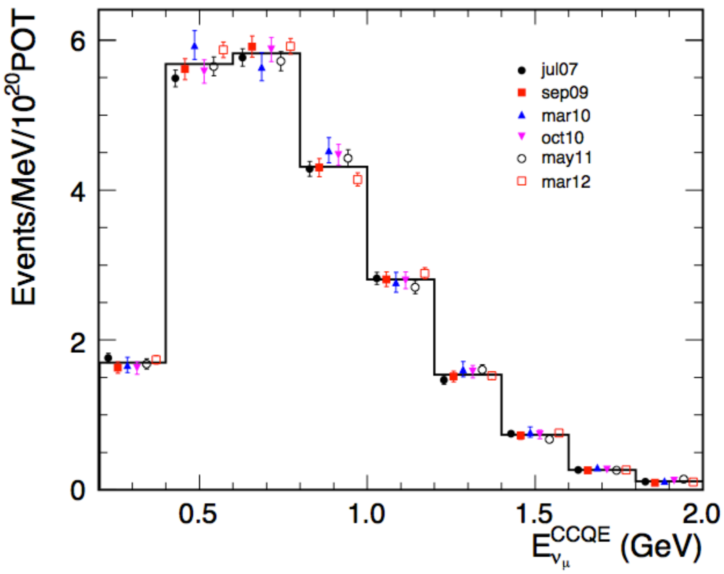
MiniBooNE Data

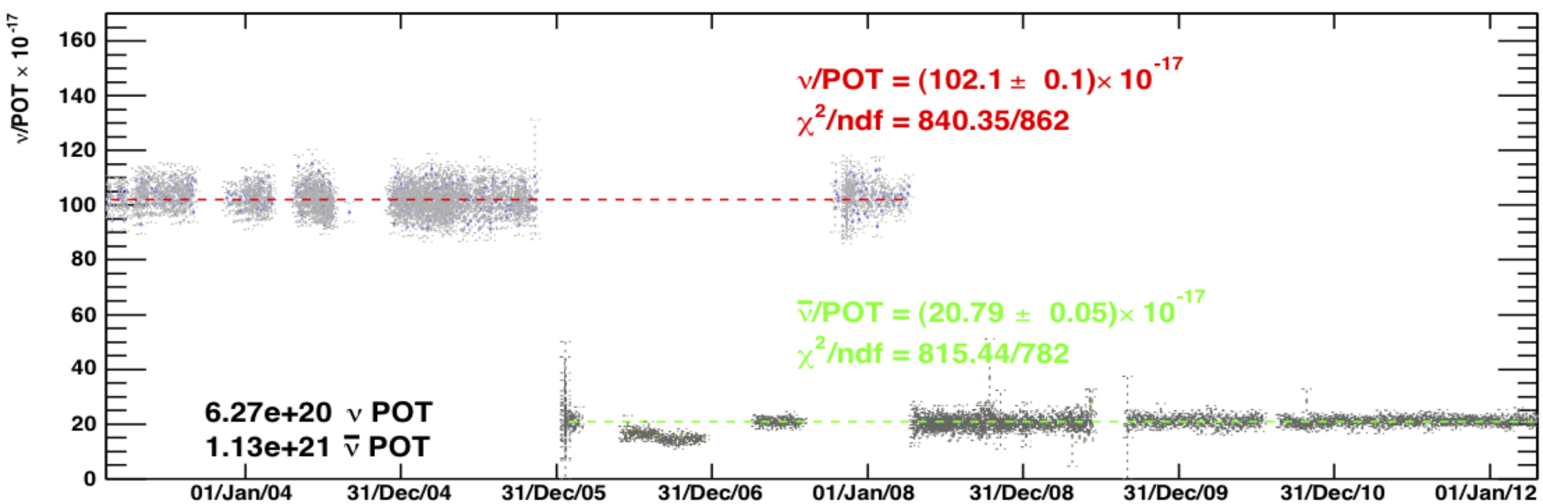
- Data taking: 2002-2012.
- Total POT collected 19.8×10^{20}.
- Neutrino mode: 6.5×10^{20} POT.
- Antineutrino mode: 11.3×10^{20} POT.



MiniBooNE Data

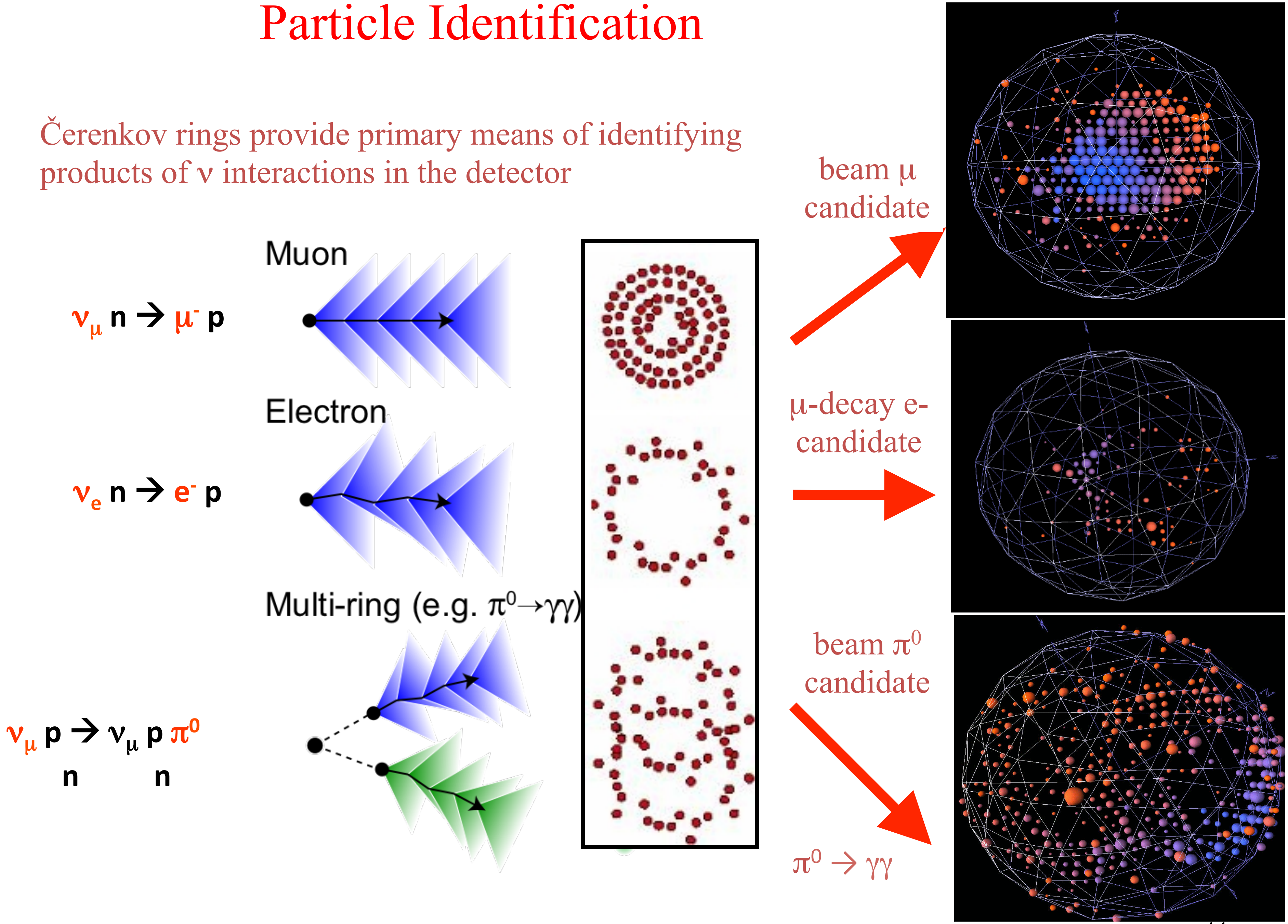
- Beam and Detector low level stability checks:
  -beam (neutrino/POT) stable to 2%
  -detector energy response to 1%.



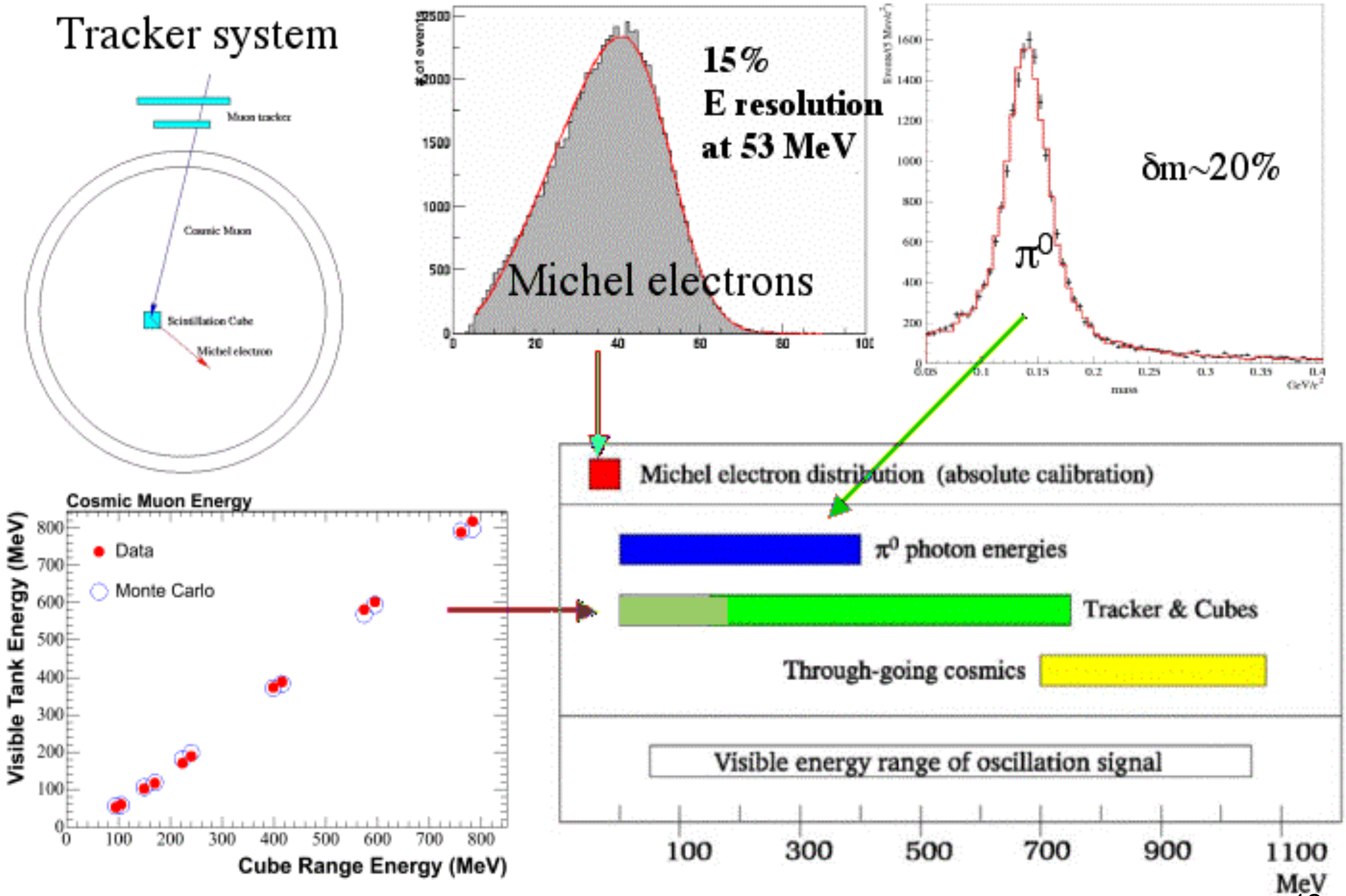


Particle Identification

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

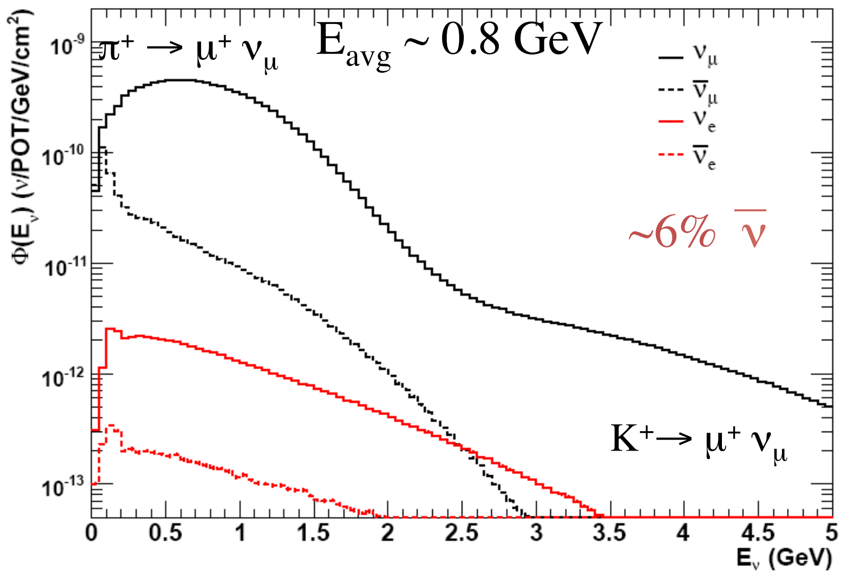


Energy Calibration

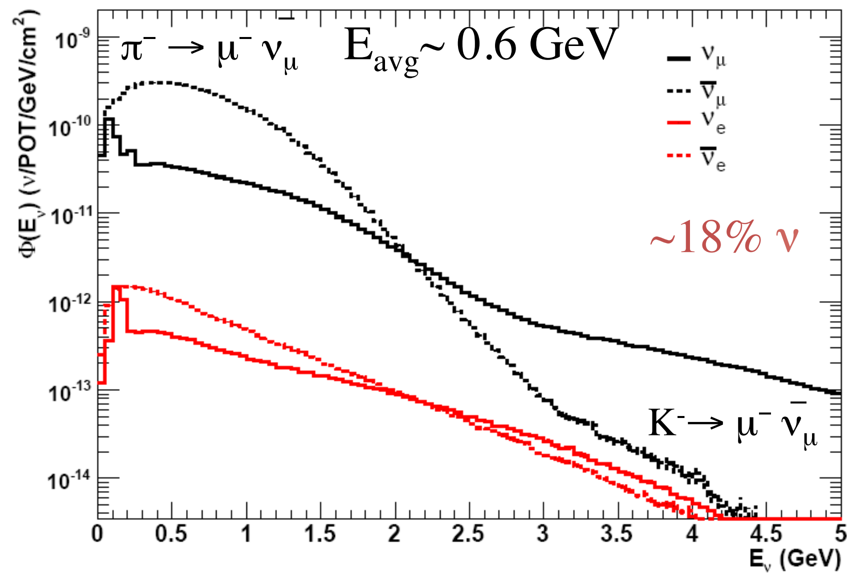


Booster Flux at MiniBooNE

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

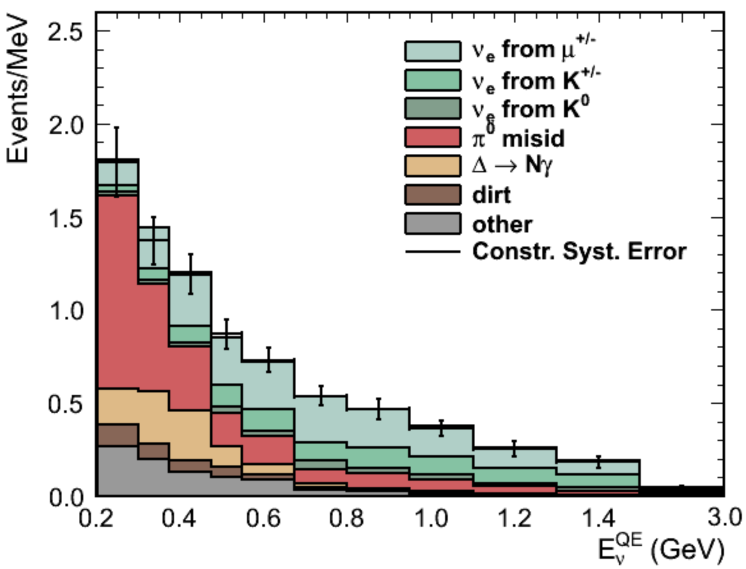
Checked with neutrino data and calibration sources.

- 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 charged 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", Phys. Rev. D84, 072005 (2011), 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).

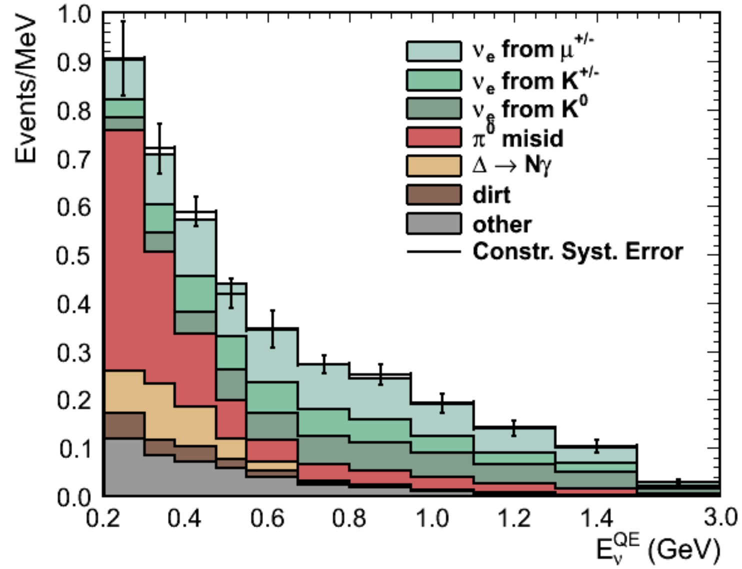
Background Prediction

-Similar backgrounds in neutrino and anti-neutrino mode.

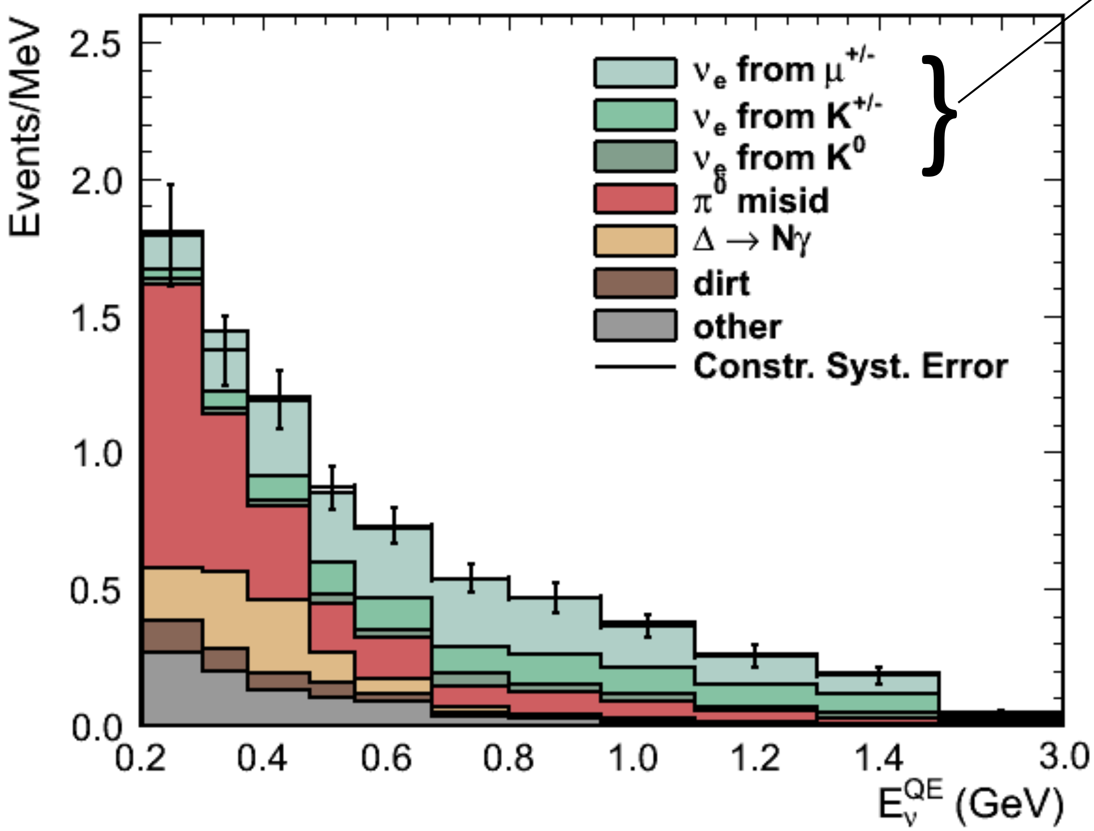
$\nu_\mu \rightarrow \nu_e$



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



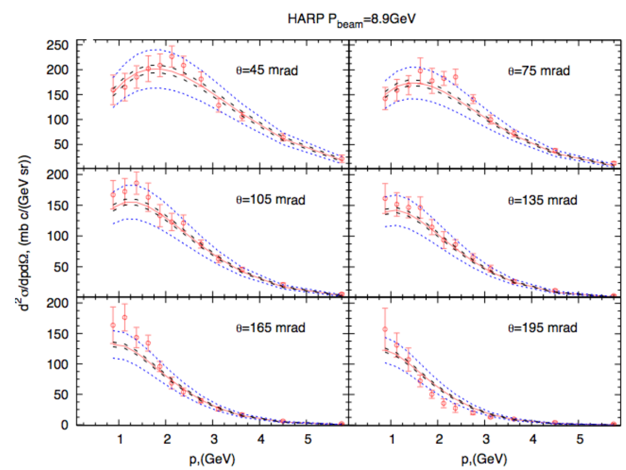
Background Prediction



- Intrinsic ν_e

  -External measurements

  -HARP p+Be for $\pi^{\pm}$



  -Sanford-Wang fits to world K^+/K^0 data

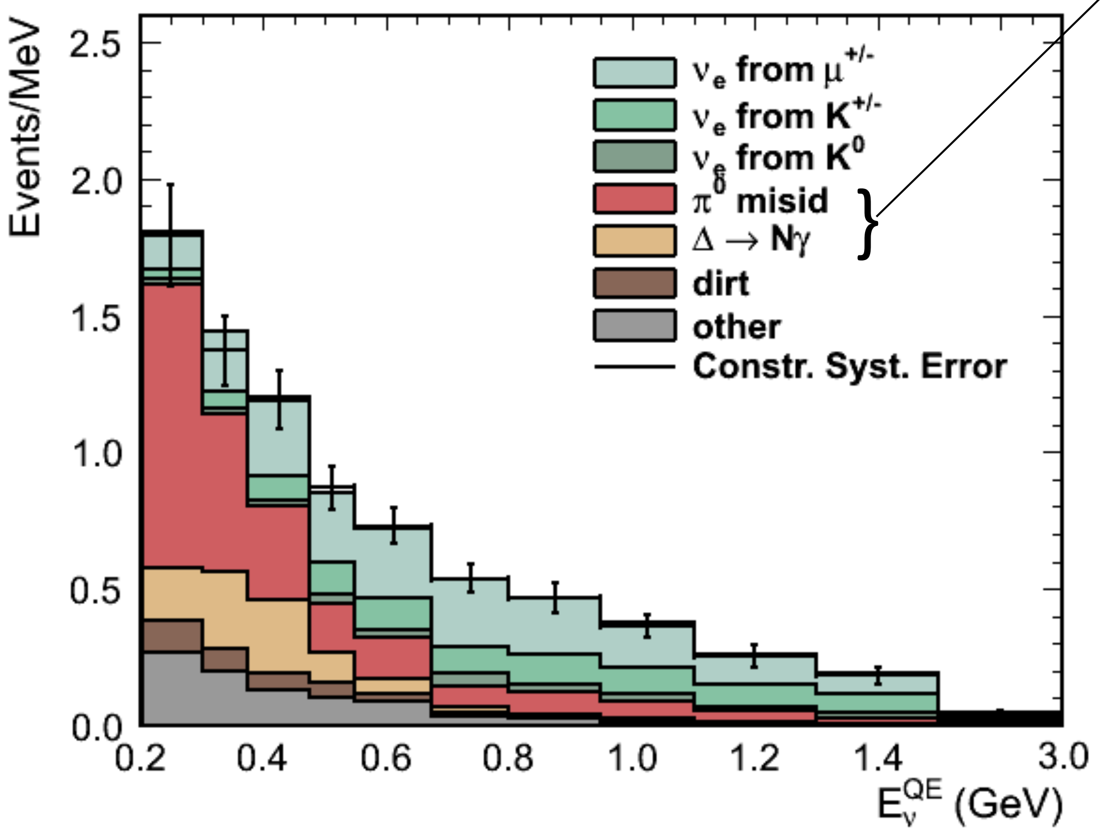
  Published PRD 79, 072002 (2009)

  -MiniBooNE data constrained

  -SciBooNE data constraint.

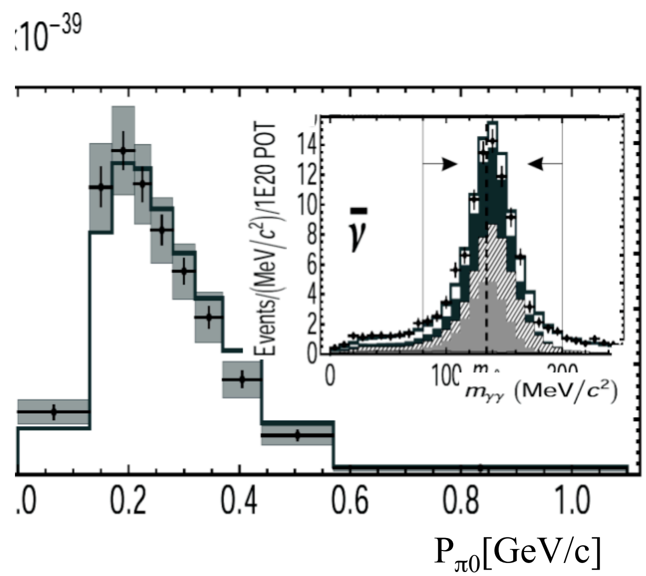
  Published PRD 84, 012009 (2011)

Background Prediction



Neutral Current π^0

MiniBooNE NC π^0 measurement

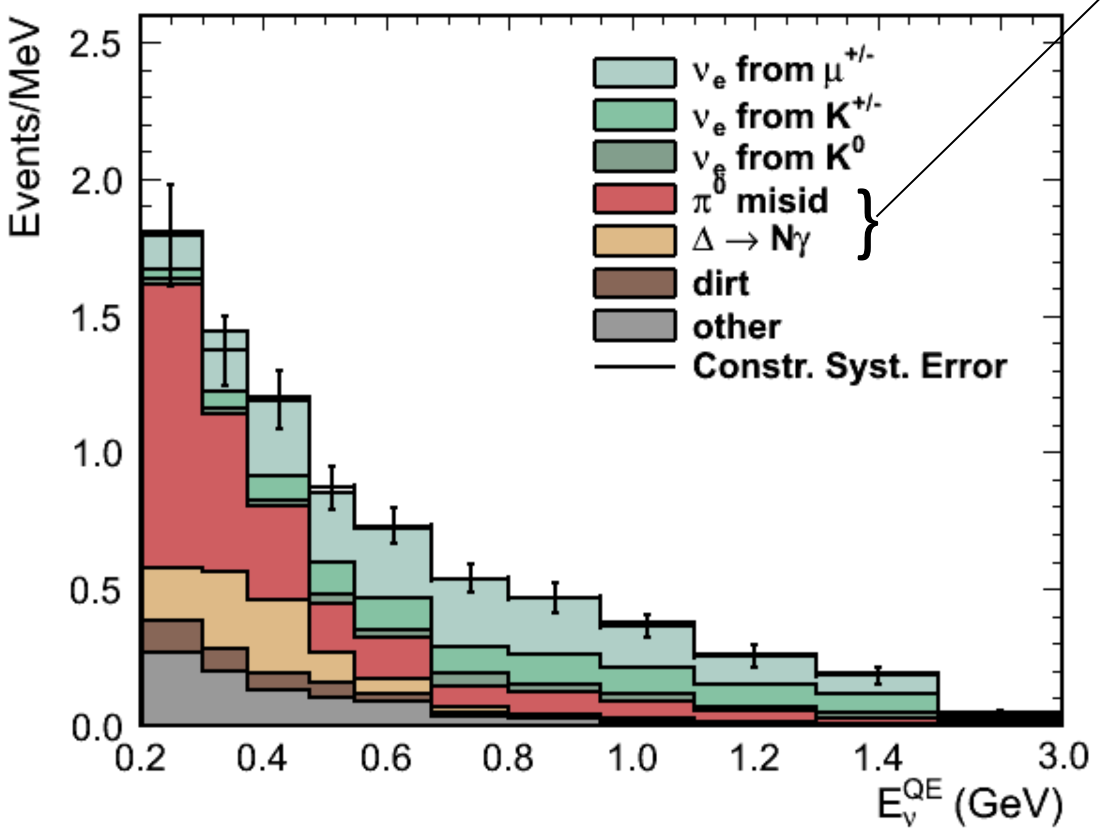


Published PRD 81, 013005 (2010)

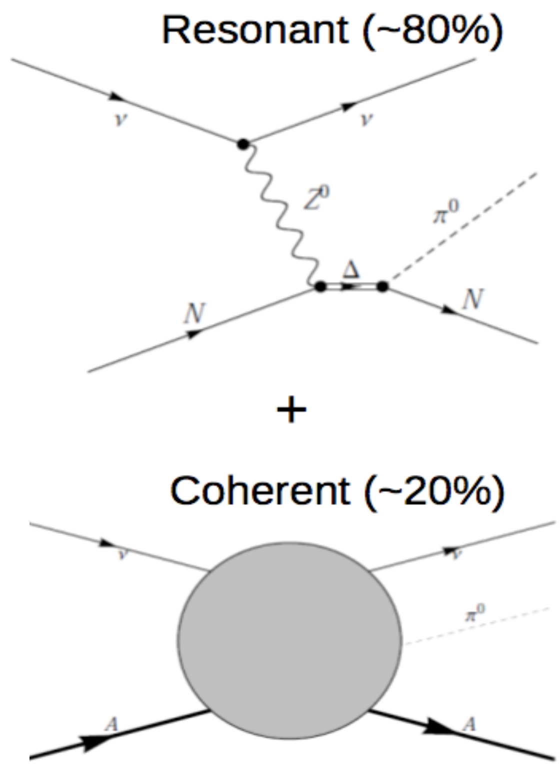
Constrains radiative

Δ decays as well

Background Prediction



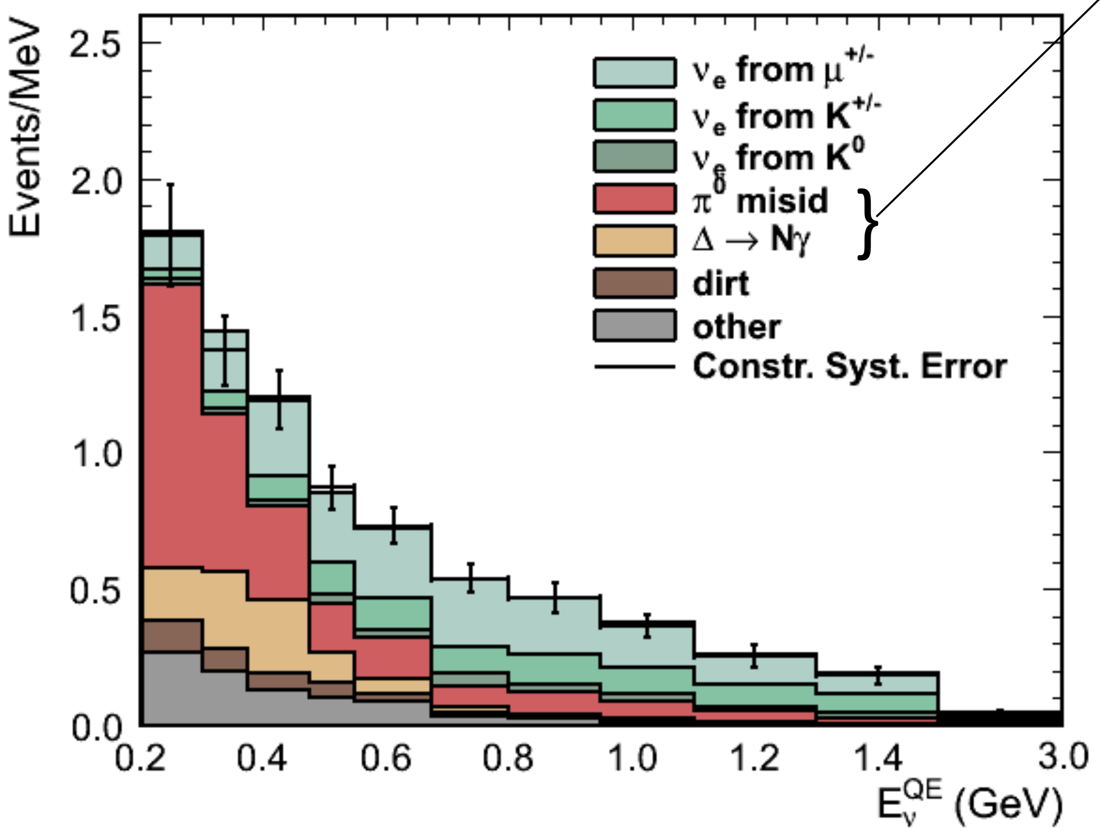
Neutral Current π^0



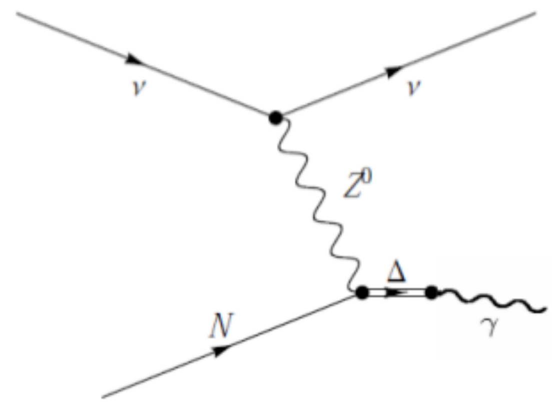
Published PLB 664, 41 (2008)

Measured Coherent/
Resonant Ratio

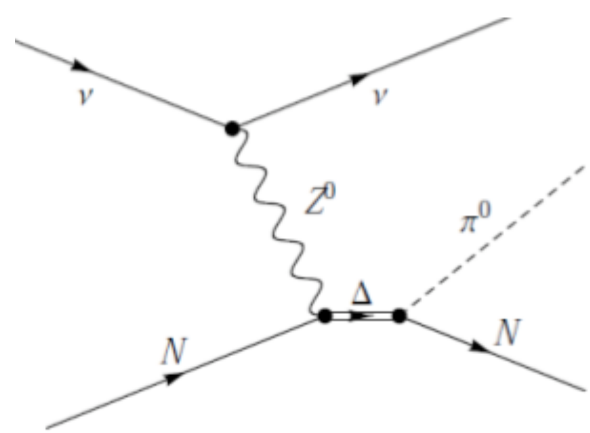
Background Prediction



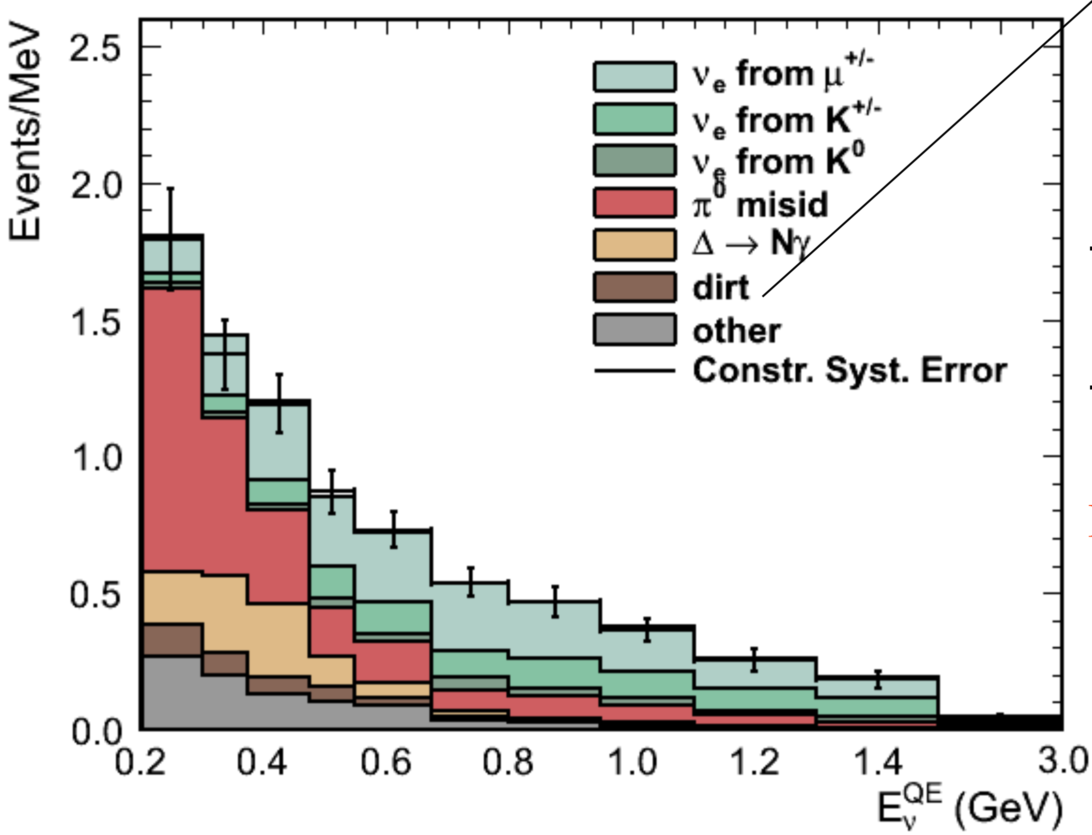
$\Delta \rightarrow N\gamma$



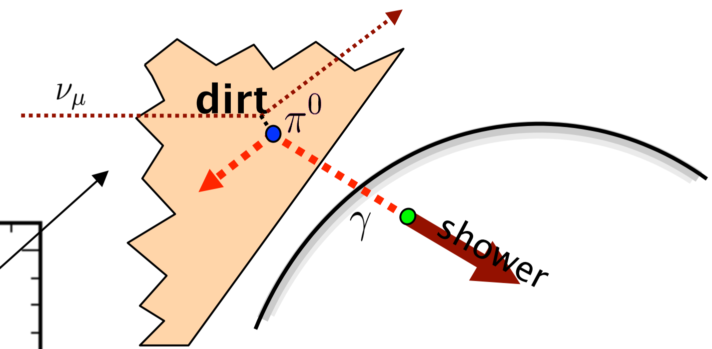
Use MiniBooNE NC π^0 measurement to constrain



Background Prediction



Dirt Events

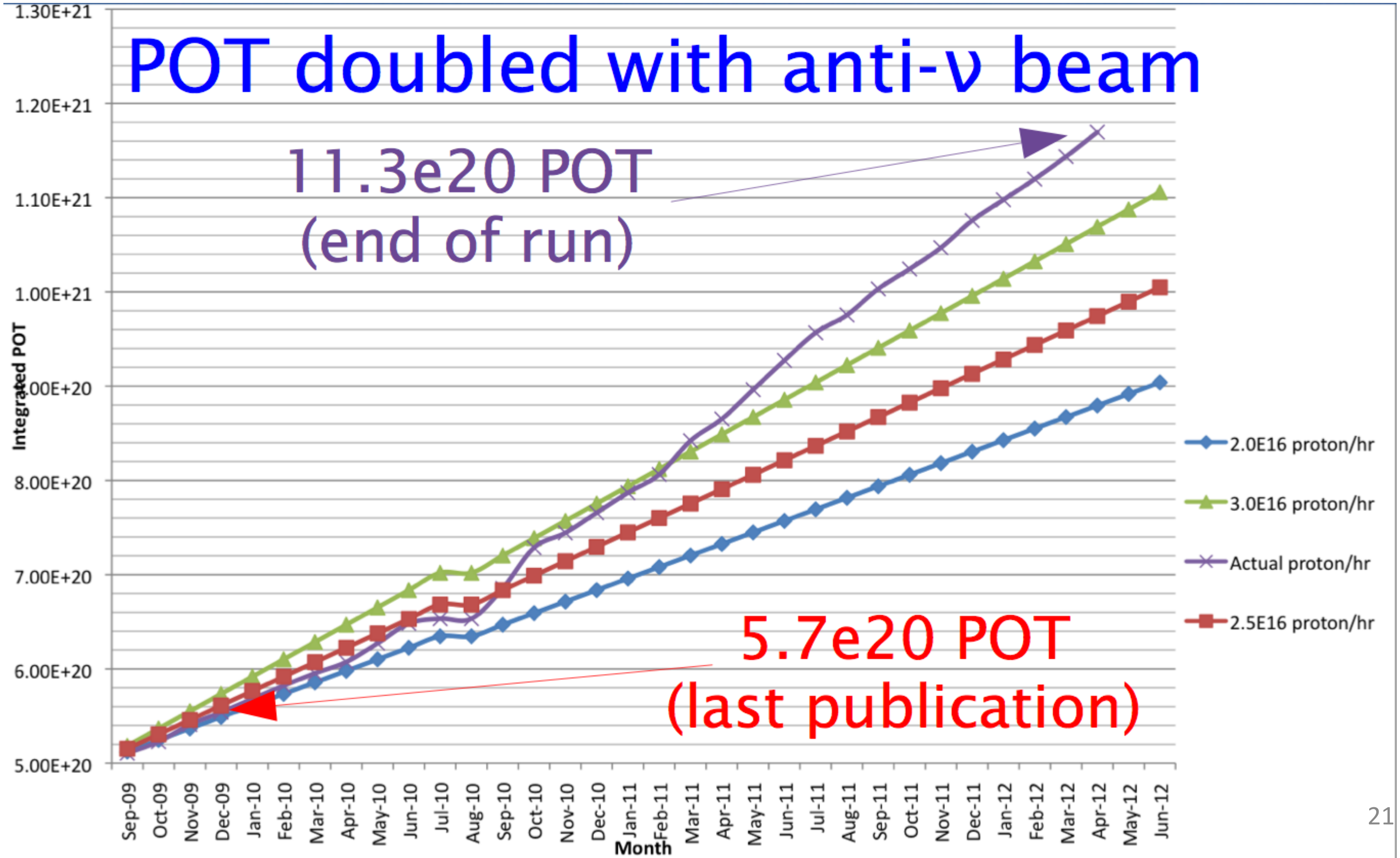


-Events at high radius
 pointing toward center
-low energy depositions

MiniBooNE measurement

Updates and news

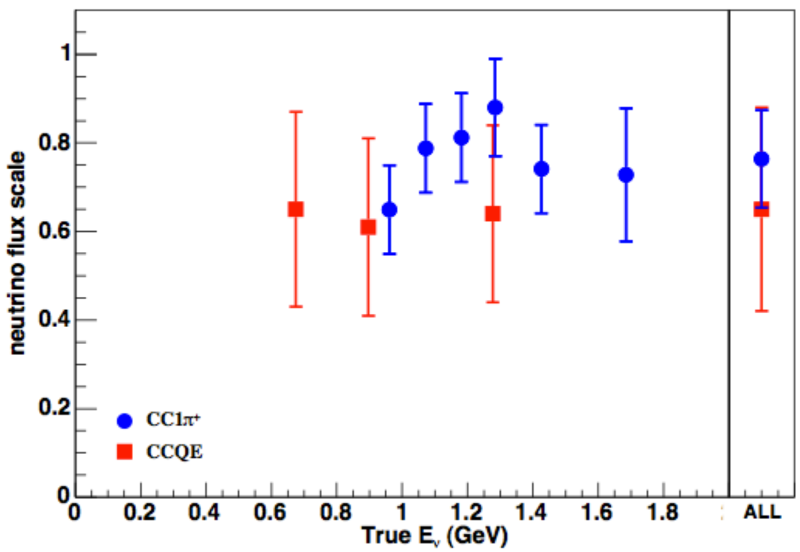
- Updated neutrino results.
- Full anti-neutrino mode results: 11.3×10^{20} POT compared to previous 5.7×10^{20} POT (Phys.Rev.Lett.105:181801, 2010.).

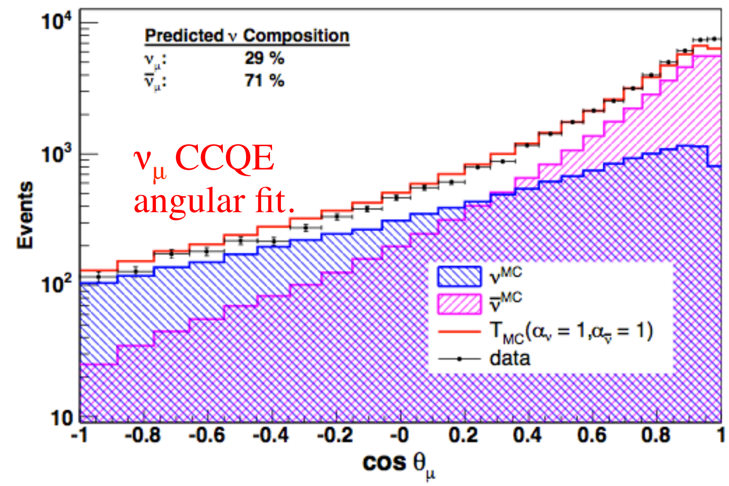


Analysis improvements since last publication

-In situ measurement of wrong-size contamination in $\bar{\nu}$ beam (PRD84, 072005 (2011)):

- ν_μ CCQE angular fit and,
- π^+ rate constraint.



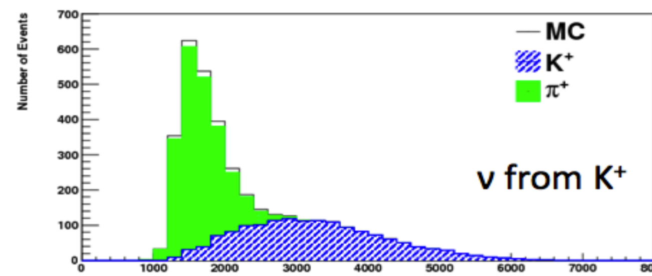


-New SciBooNE constraint on intrinsic ν_e from K^+:

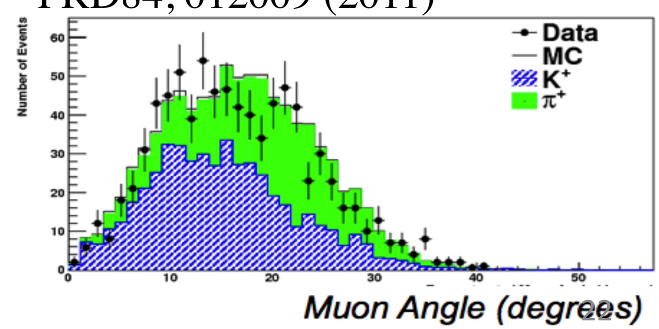
- found K^+ production to be 0.85±0.12 relative to prediction, consistent with original MiniBooNE assessment of 1.00±0.30.

-Combined with world K^+ production data, reduces error on K^+ flux to 9% in MiniBooNE energy range.

-Leading error on K^+ background becomes ~20% error on cross-section.



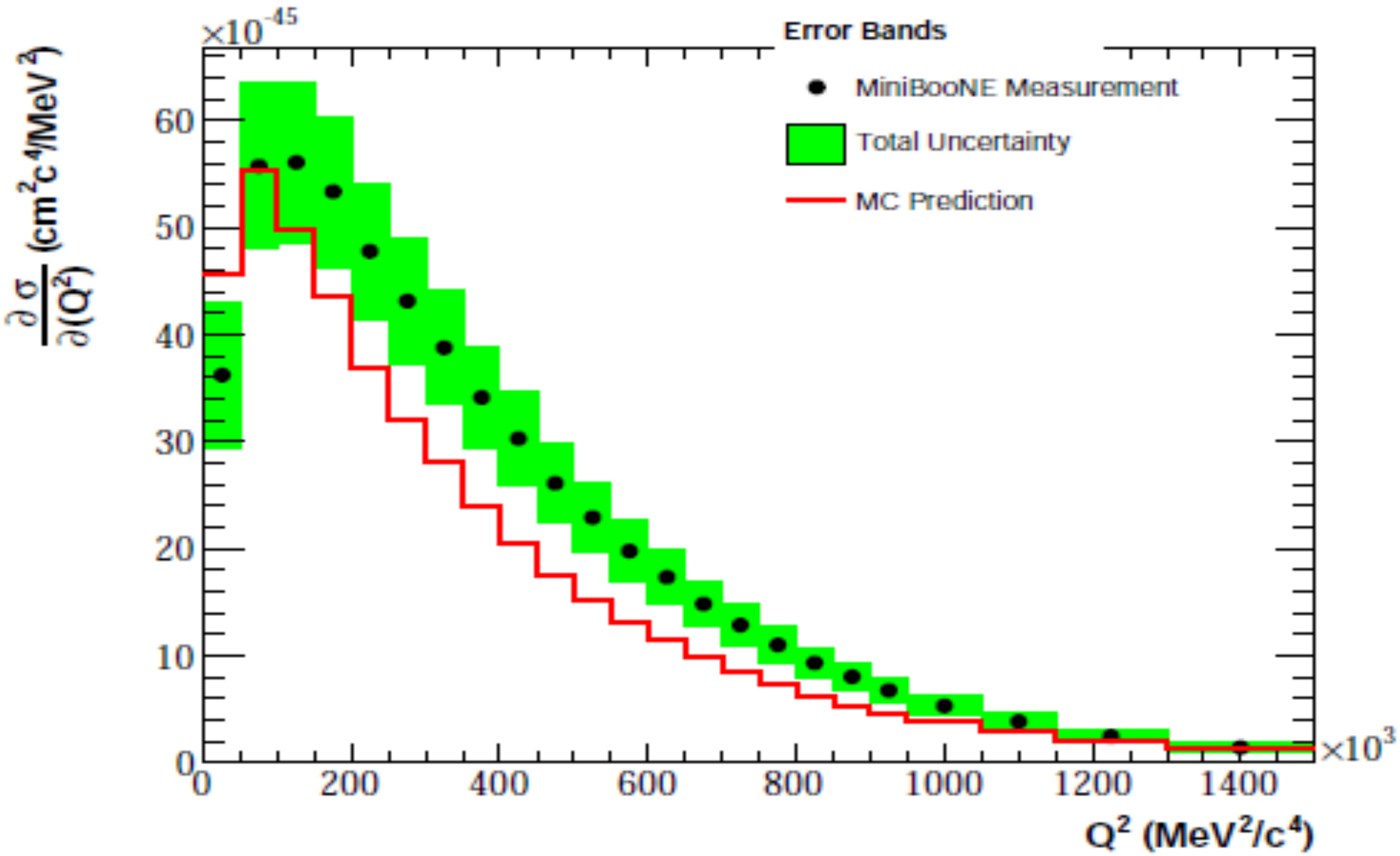
SciBooNE K samples.
PRD84, 012009 (2011)



Analysis improvements since last publication

-CC π^+ events (bkg for ν_μ CCQE sample when π^+ is absorbed) Q^2 reweighting applied based on internal MiniBooNE measurement).

-See PRD83, 052007 (2011) for details.

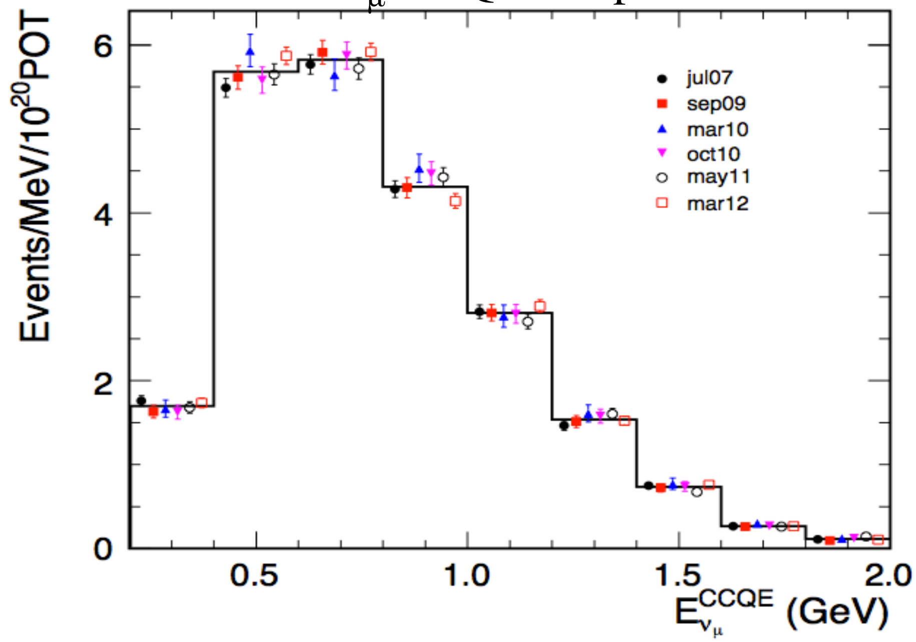


Analysis checks and improvements since last publication

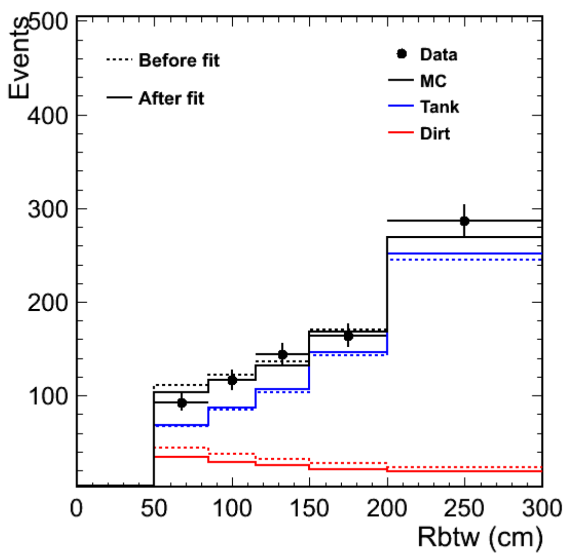
- $\bar{\nu}_\mu$ rates and energy stable over entire antineutrino run.

- Other systematic errors, constrained by MiniBooNE data, reduced due to higher statistics (doubled) in control samples:
  -Dirt neutrino background.
  -Neutral-current π^0 production.

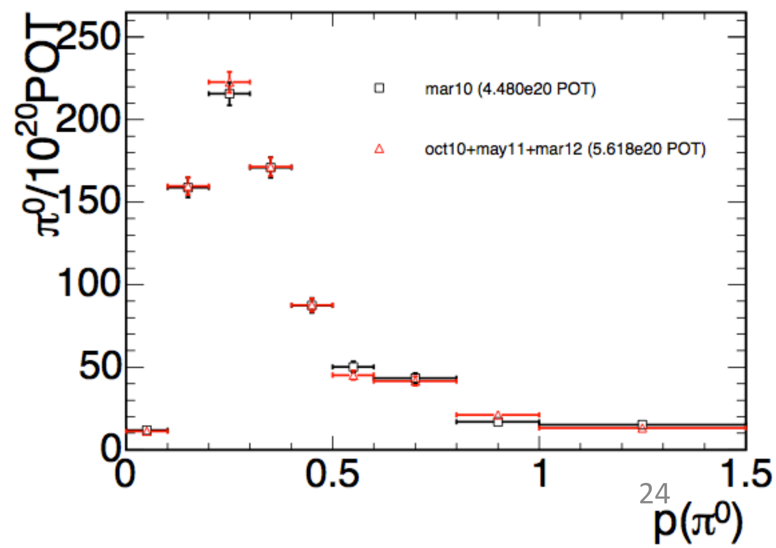
$\bar{\nu}_\mu$ CCQE sample



Dirt-enhanced sample



NC π^0 sample



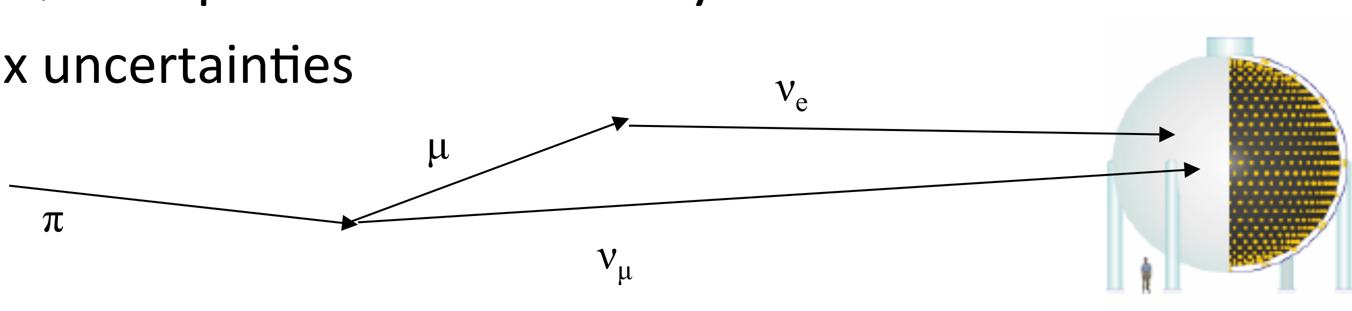
Oscillation Fit Method

- Identical to previous result
- Maximum likelihood fit:

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

$$M = M_{om} + M_{xsec} + M_{flux} + M\pi 0 + M_{dirt} + M_{K0} + ...$$

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

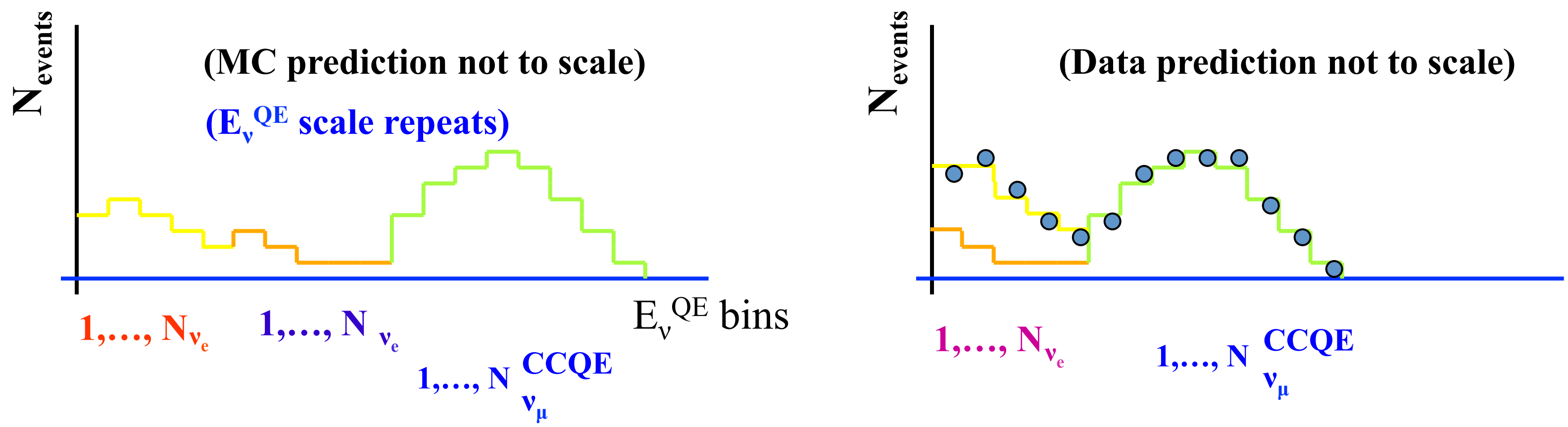


  - Cross section uncertainties (CCQE process)

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)

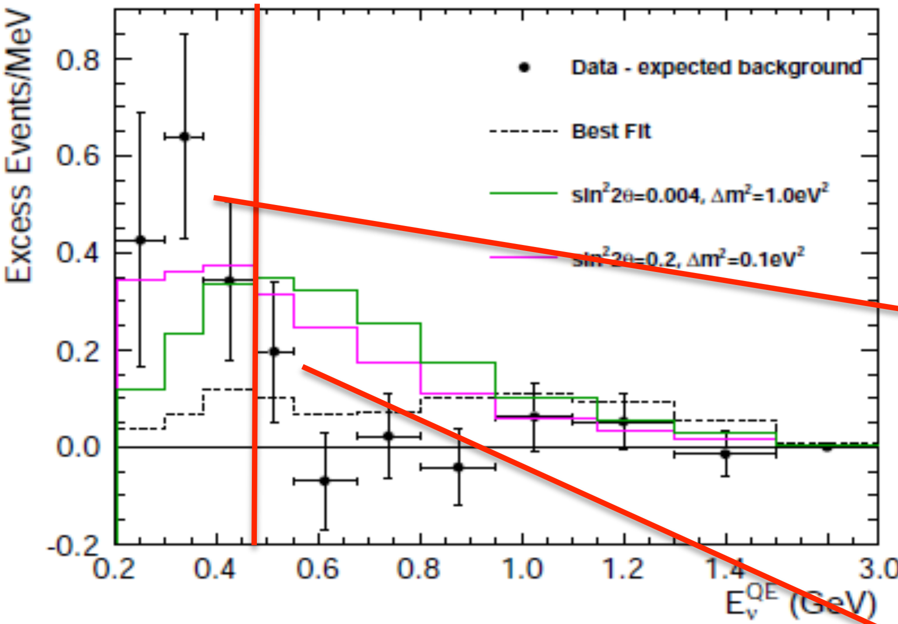


$$-2\ln(L) = (x_1 - \mu_1, ...x_n - \mu_n)M^{-1}(x_1 - \mu_1, ...x_n - \mu_n)^T + \ln(|M|)$$

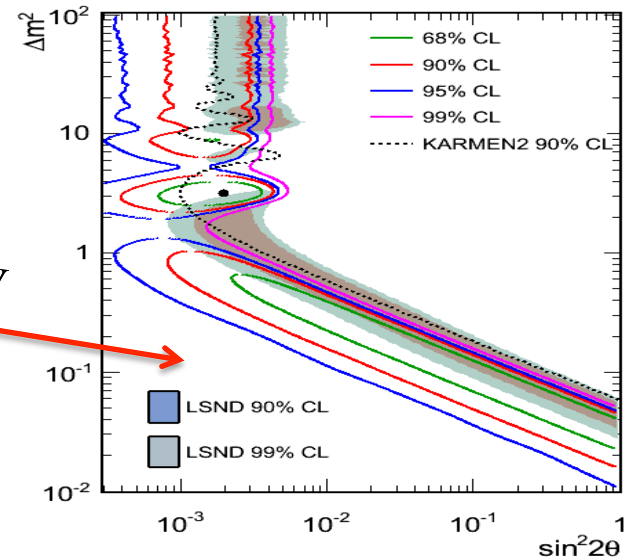
M_{ij} = full syst+stat covariance matrix at best fit prediction

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

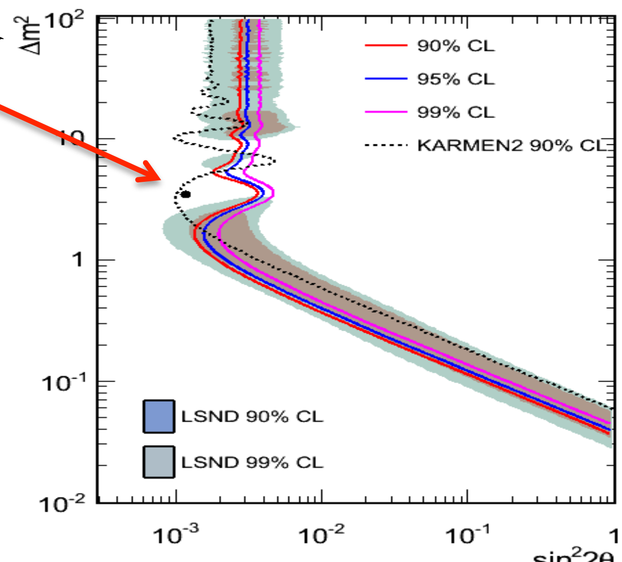
Updated Neutrino Appearance Results



E>200MeV



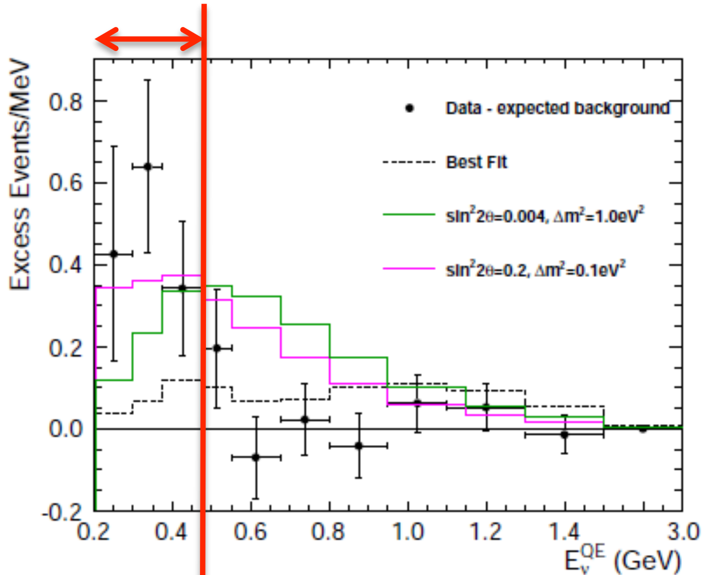
E>475MeV

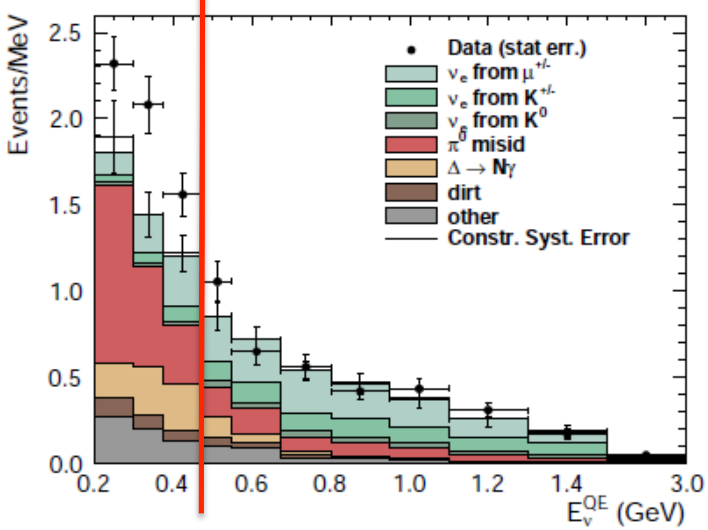


- Excess (200-1250 MeV): 146.3±28.4±40.2.
- Some tension between 3+1 model fits in two energy regions (1.4% probability to see 3.73 → 13.24 when including low E).

ν mode	E > 200 MeV	E > 475 MeV
χ^2(null)	22.81	6.35
Prob(null)	0.5%	36.6%
χ^2(bf)	13.24	3.73
Prob(bf)	6.12%	42.0%

Low Energy Excess





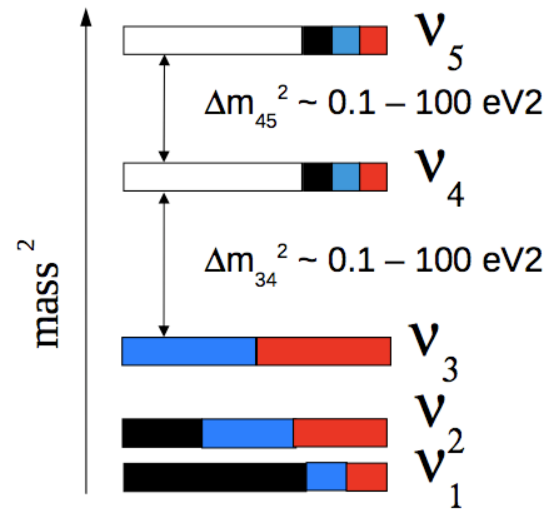
-What can we say about the low energy excess?

- Not a statistical fluctuation, statistical significance is 6σ.
- Unlikely to be intrinsic ν_e, small background at low E.
- NC π^0 background dominates.
  - -Reduces significance to 3σ.
  - -Heavily constrained by NC π^0 in situ measurement.
- Region where single γ can contribute.
  - -MB ties $\Delta \rightarrow N\,\gamma$ expected rate to be 1% of measured NC π^0 rate.
  - -Number of theory calculations exist for various single γ processes; all find total cross-section within 20% of MB ~5×10^{-42} cm^2/N.
  - -Would require nearly 300% change to account for excess.

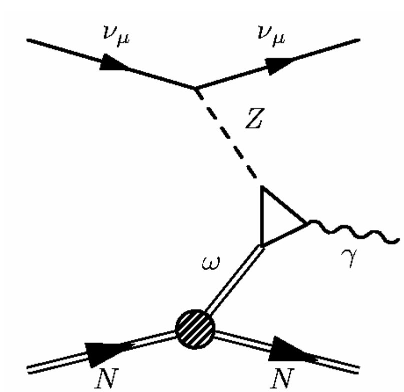
Range of possible explanations for observed excess

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]
- …



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

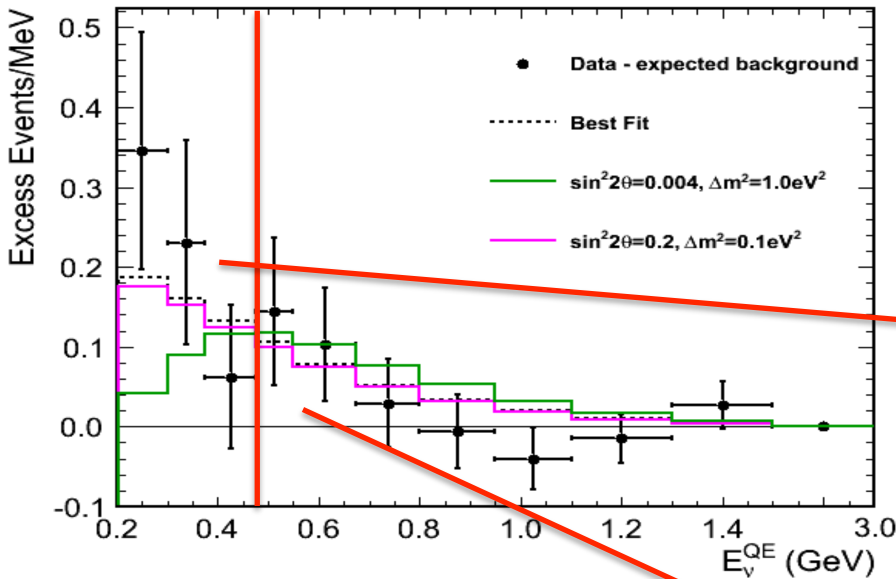


$\bar{\nu}_e$ Event Rate Predictions in Appearance Analysis

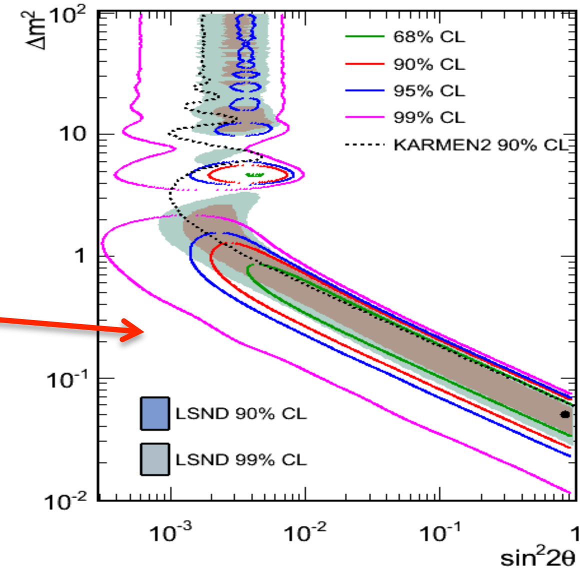
-We have collected about ~1/5 the number of interactions as in neutrino mode when same POT considered.
-Neutrino mode: $6.5\text{x}10^{20}$ POT.
-Antineutrino mode: $11.3\text{x}10^{20}$ POT.
→ expected number of candidates in anti-nu mode ~1/3 of nu-mode.

- 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 ~16% wrong-sign neutrino flux component in antineutrino mode
- Fit analysis and errors are similar.

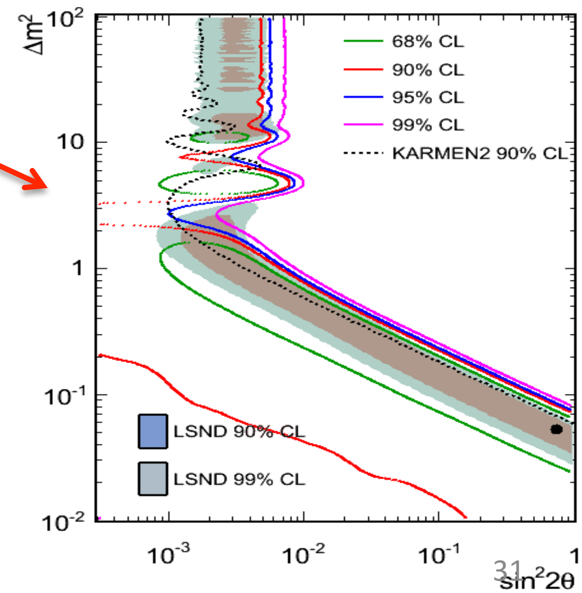
Antineutrino Appearance Results 11.3x10^{20} POT



E>200MeV



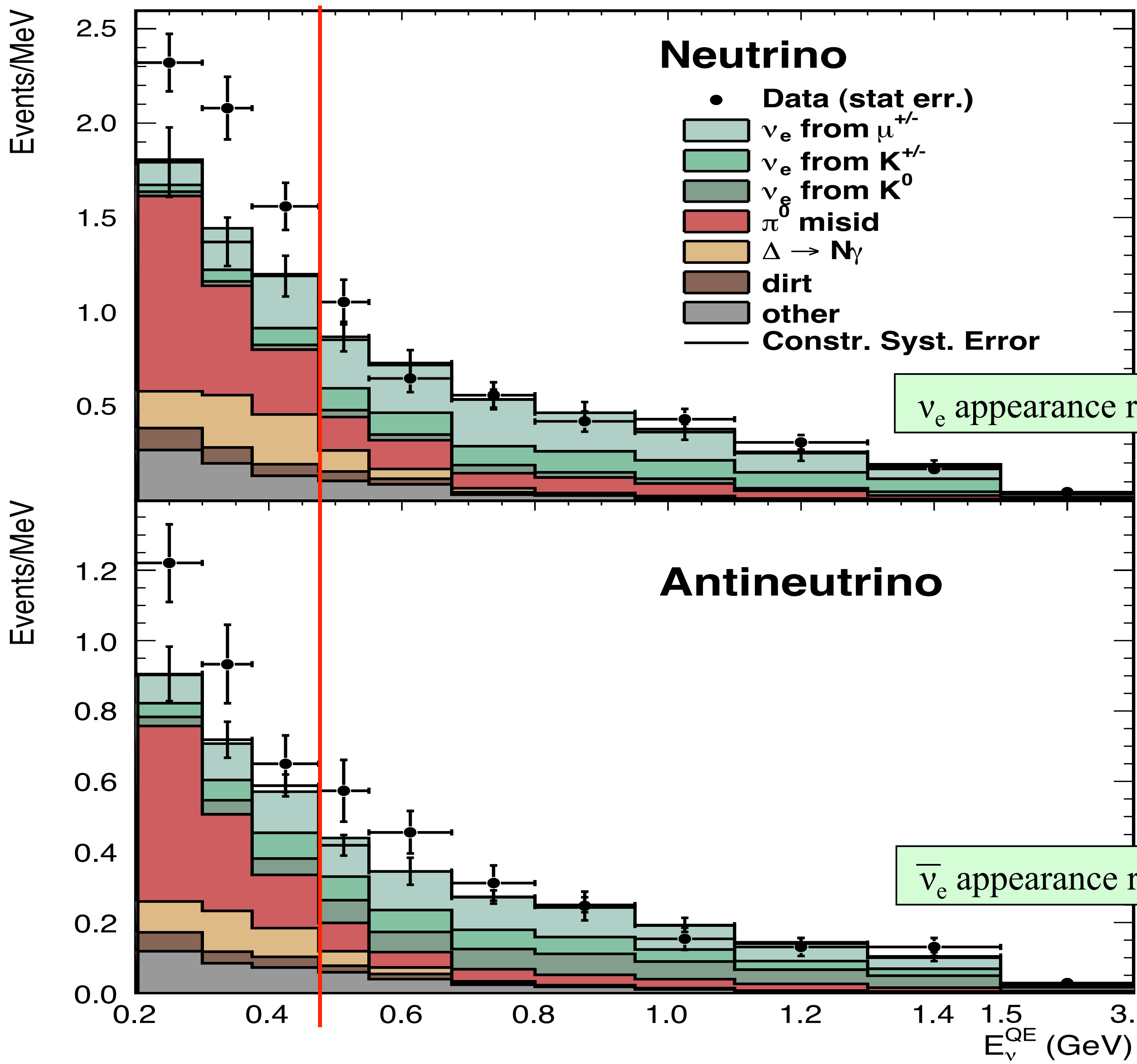
E>475MeV



- Wrong sign ν_μ assumed not to oscillate.
- Excess (200-1250 MeV): 78.2±20.0±23.4
- No tension between fits in two energy regions.

anti-ν mode	E > 200 MeV	E > 475 MeV
χ^2(null)	16.6	7.8
Prob(null)	5.4%	24.6%
χ^2(bf)	4.8	3.3
Prob(bf)	67.1%	49.2%

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



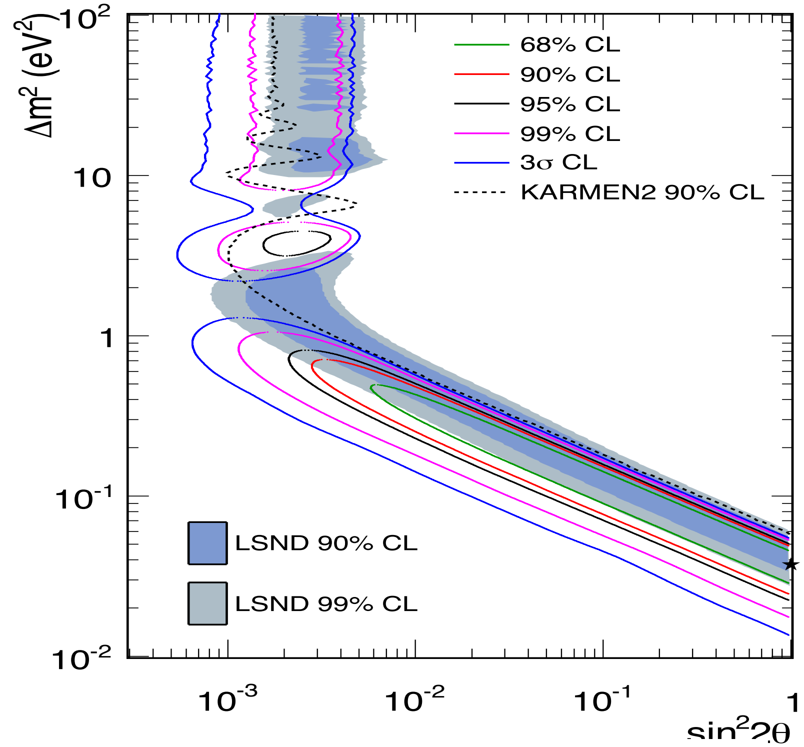
ν_e appearance results (6.5E20POT)

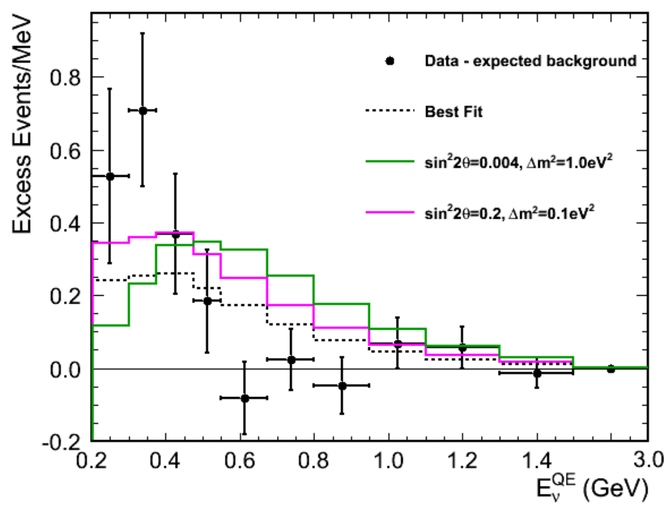
$\bar{\nu}_e$ appearance results (11.3E20POT)

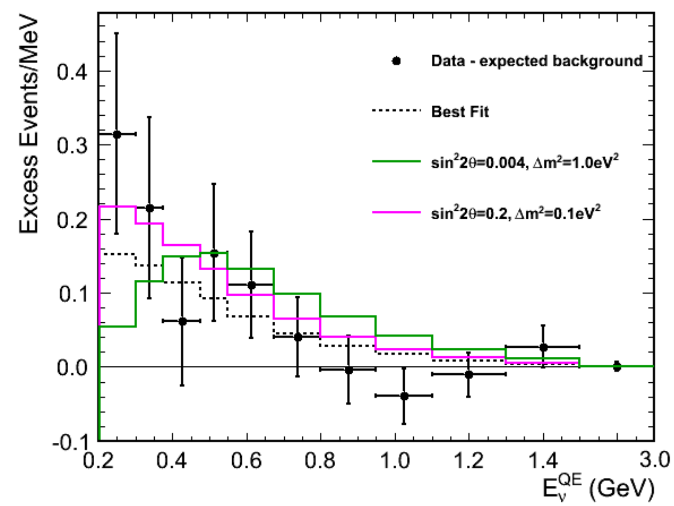
Combined ν_e and $\bar{\nu}_e$ Analysis

-Simultaneous fit of electron neutrino and electron antineutrino appearance candidates.
-Full correlated systematic error matrix used.
-Excess (200-1250 MeV): 240±34.5±52.6 (3.8 σ)
-Best fit preferred over null at 3.6 σ.

combined	E > 200 MeV	E > 475 MeV
χ^2(null)	42.53	12.87
Prob(null)	0.1%	35.8%
χ^2(bf)	24.72	10.67
Prob(bf)	6.7%	35.8%

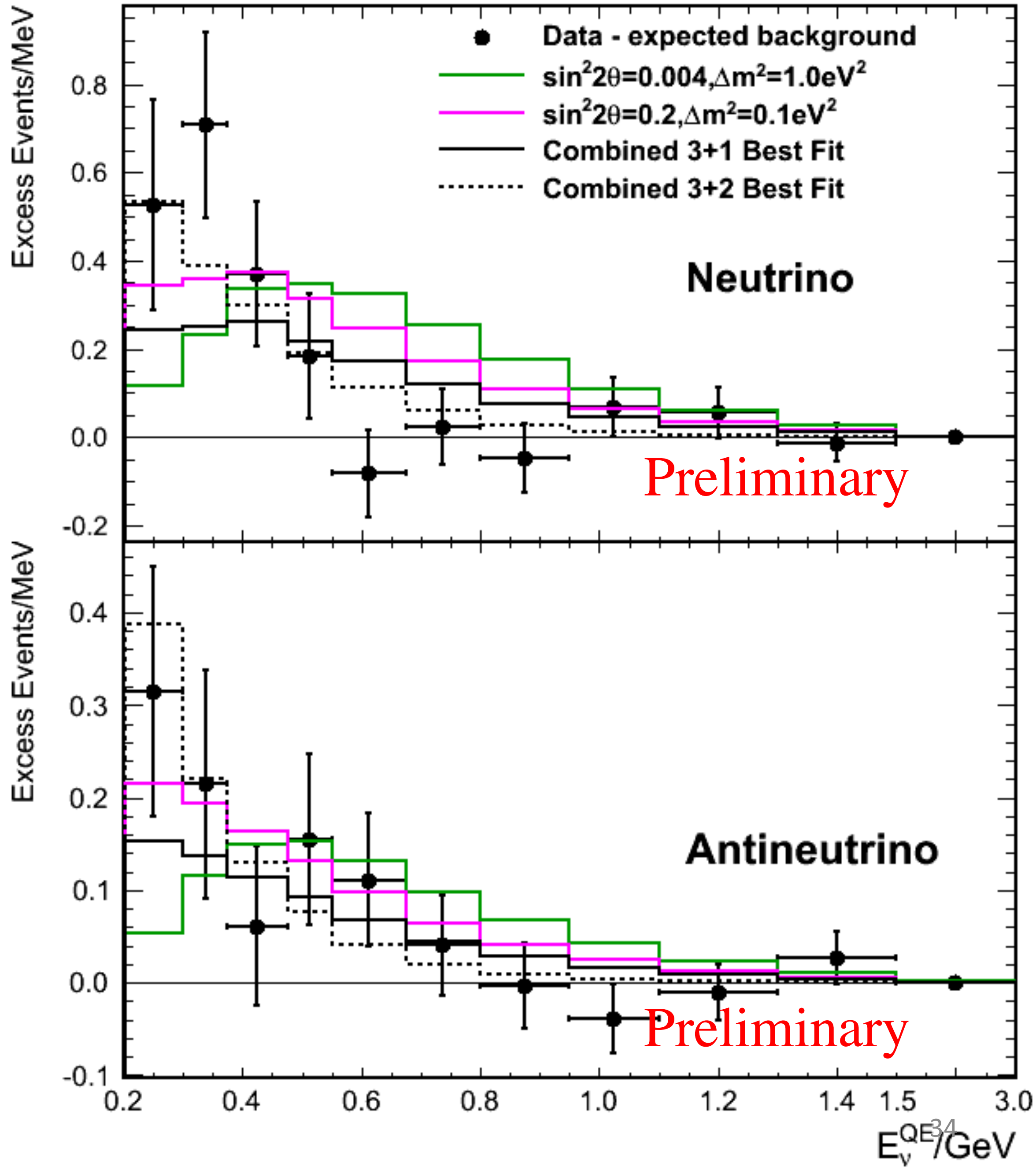






3 + 2 Model

- Allows CP-violation.
- Fits better the shape of MiniBooNE excess.
- Better fit to world data (see for example arXiv:1207.4765 for recent global fit.



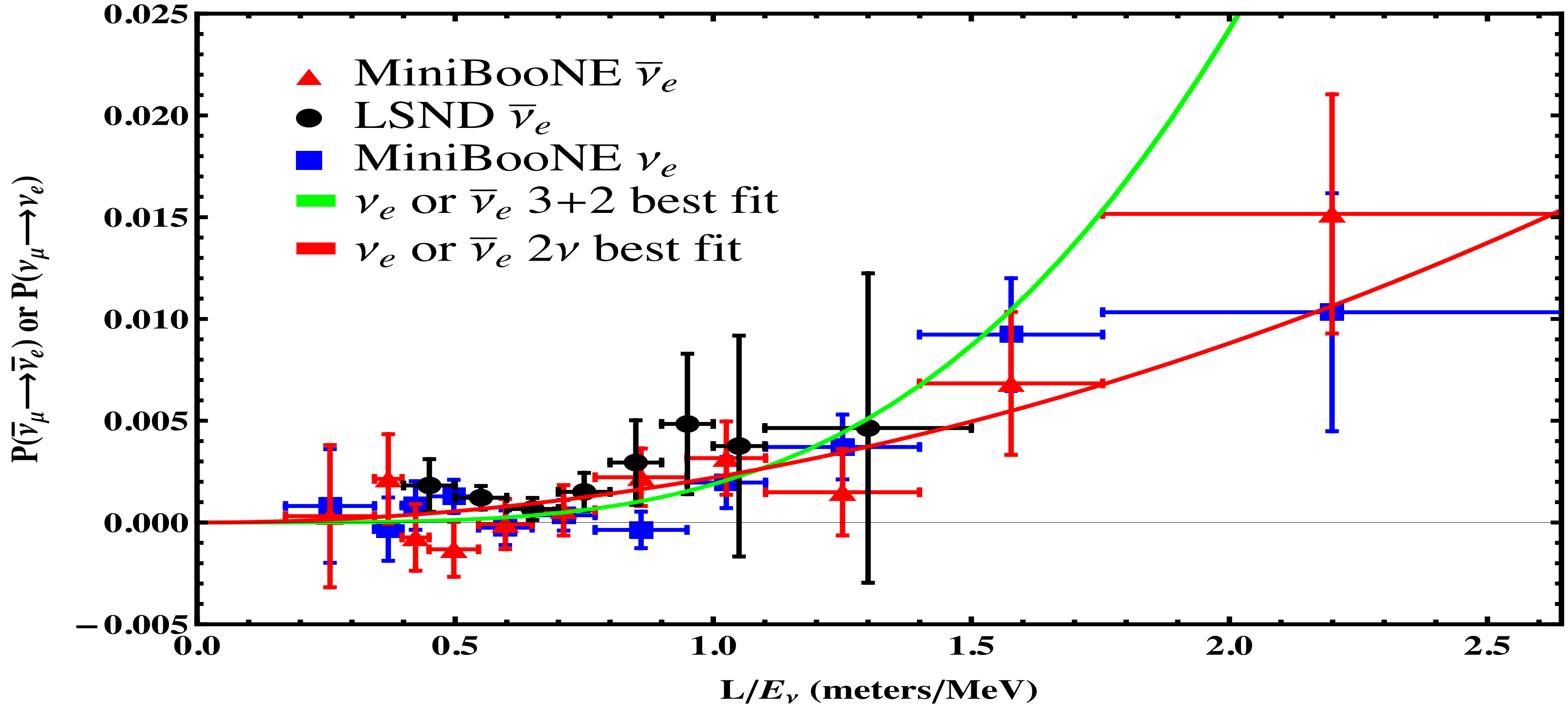
L/E dependence

-Model independent view of the results.

-Data used for LSND and MiniBooNE correspond to 20<E_ν<60 MeV and 200<E_ν<3000 MeV, respectively.

- Oscillation probability is event excess divided by the number of events expected for 100% $\nu_\mu \rightarrow \nu_e$ 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 excess as a function of L/E in MiniBooNE neutrino, antineutrino and LSND data is consistent.

Conclusions and Future Prospects

- MiniBooNE observes an excess of nue candidates in the 200-1250 MeV range in neutrino mode (3 σ) and in anti-neutrino mode (2.5 σ).
- The combined excess is 240 ± 34.5 ± 52.6 events (3.8 σ).
- Some tensions in data within simple 2 neutrino oscillation model (3 + 1).
- Much better fit 3 + 2 neutrino oscillation model.

- Running since 2002 in both neutrino and antineutrino mode, MiniBooNE has successfully accomplished primary goals and produced evidence that supports the claims of LSND oscillations.
- Being a one detector oscillations experiment, its systematic uncertainties now nearly dominate the total measurement error, therefore, more statistics in either neutrino or antineutrino mode do not significantly add new information to the question of oscillations.
- It is not yet known whether the MiniBooNE excesses are due to oscillations, some unrecognized NC γ background, or something else.

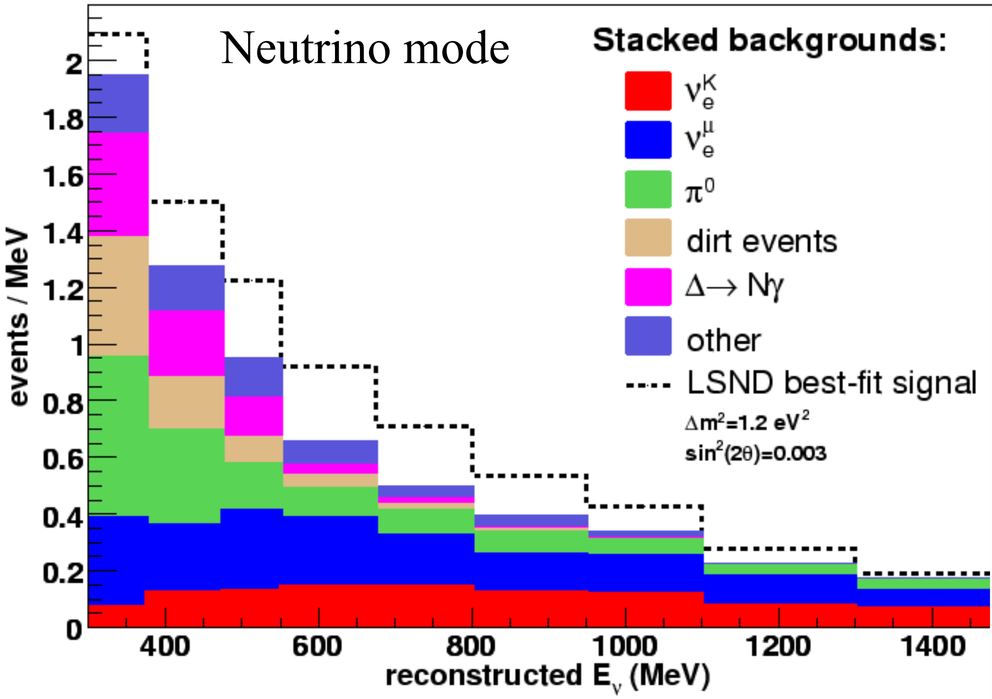
- Collaboration considering benefits of future running: running under various configurations possible (detector capabilities enhanced with addition of scintillator, beam off-target mode and with beam absorber).

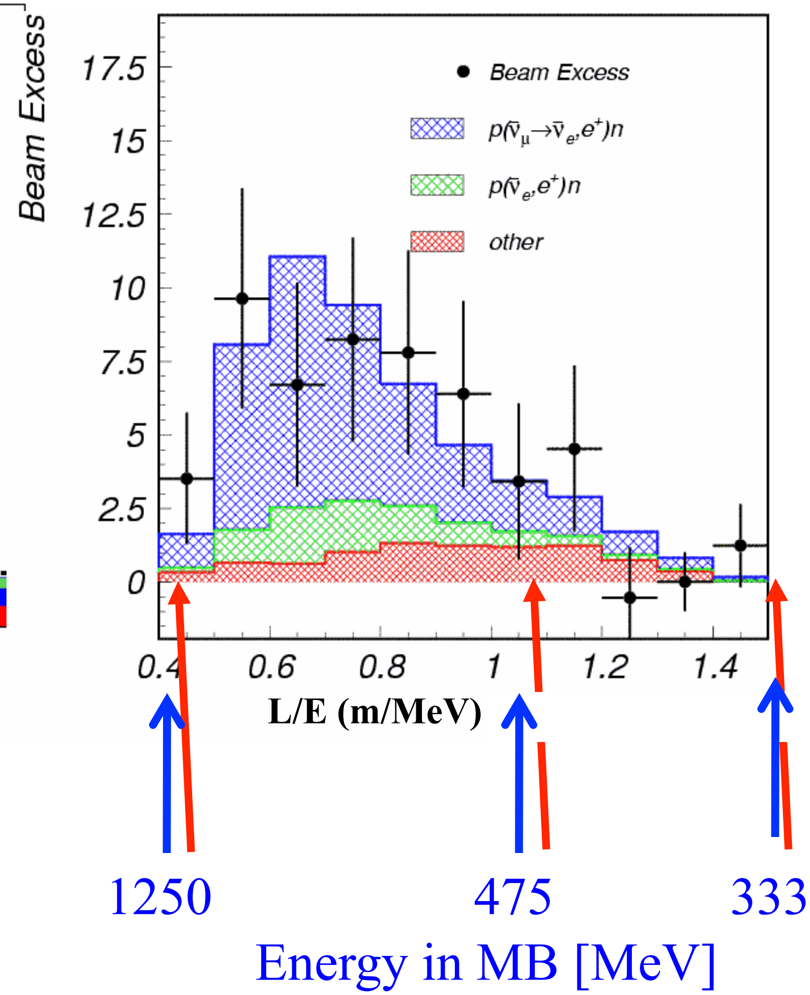
Thank you!

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.

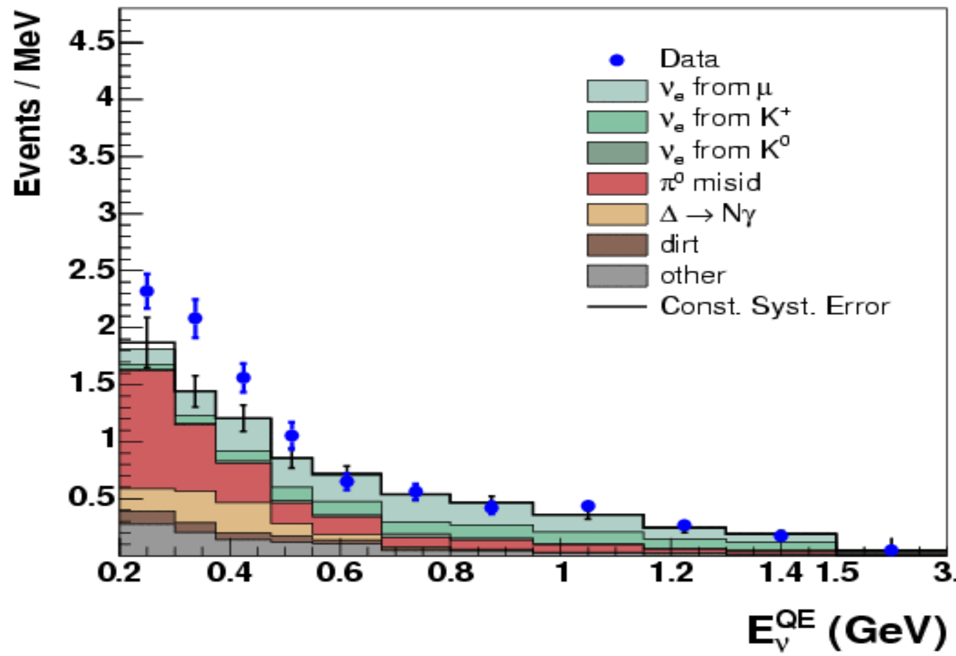
  -Many systematics grow at lower energies.

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

Neutrino Mode MiniBooNE Results (2009)

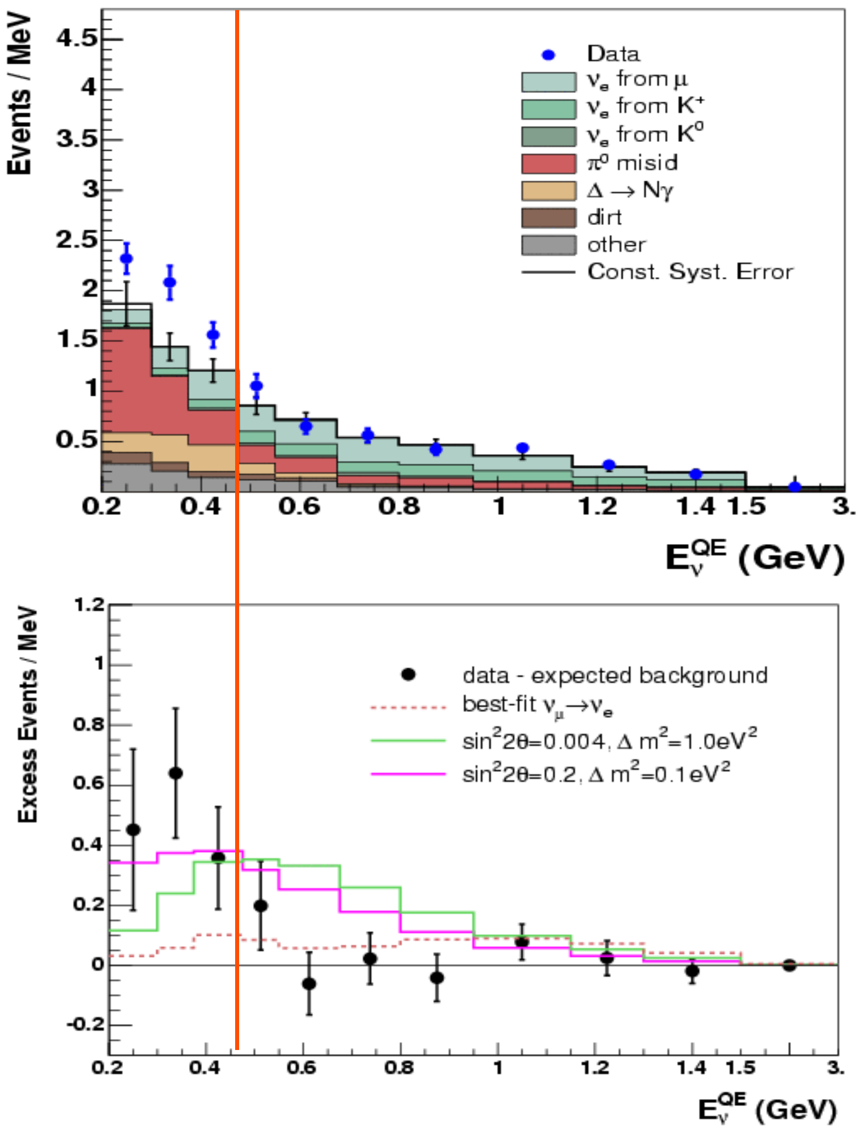
- 6.5E20 POT collected in neutrino mode
- E > 475 MeV data in good agreement with background prediction
  - -Energy region has reduced backgrounds and maintains high sensitivity to LSND oscillations.
  - -A two neutrino fit rules out LSND at the 90% CL assuming CP conservation.
- E < 475 MeV, statistically 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.

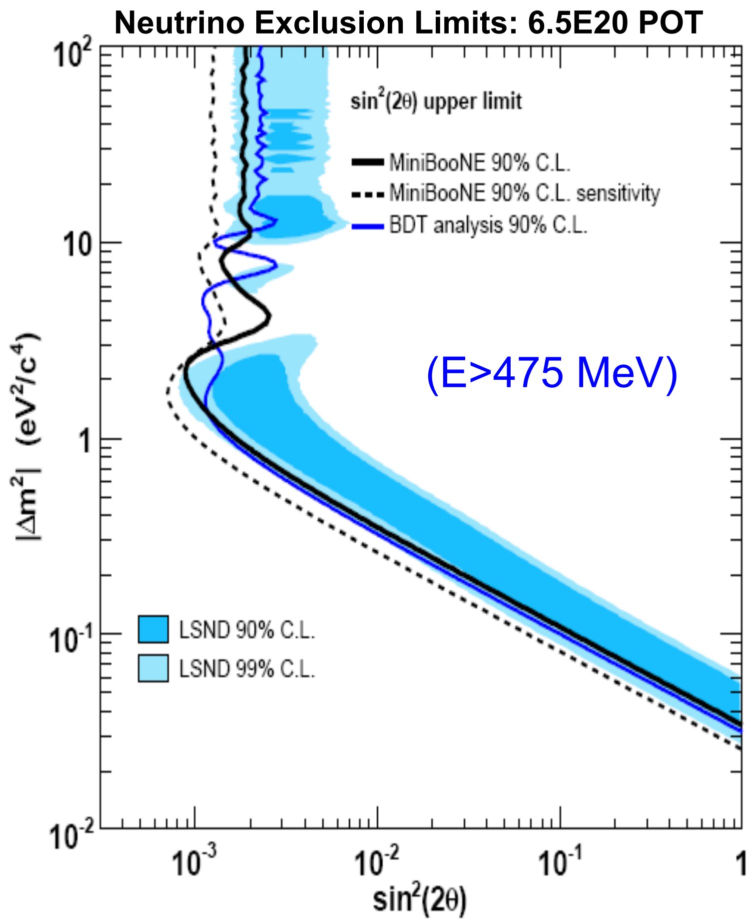
Published PRL 102,101802 (2009)



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 $\Delta \rightarrow N\gamma$	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

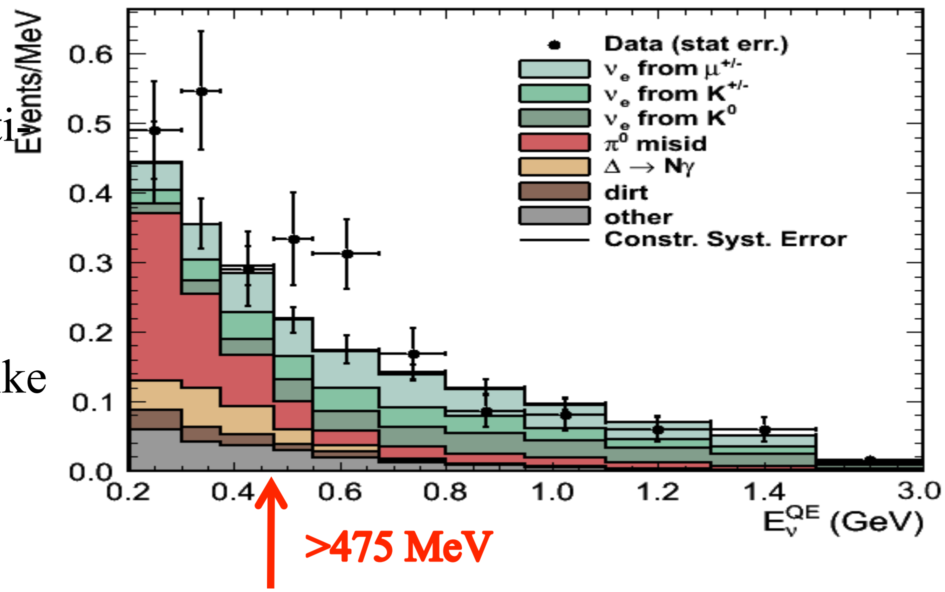
Neutrino Mode MiniBooNE Results (2009): Limit



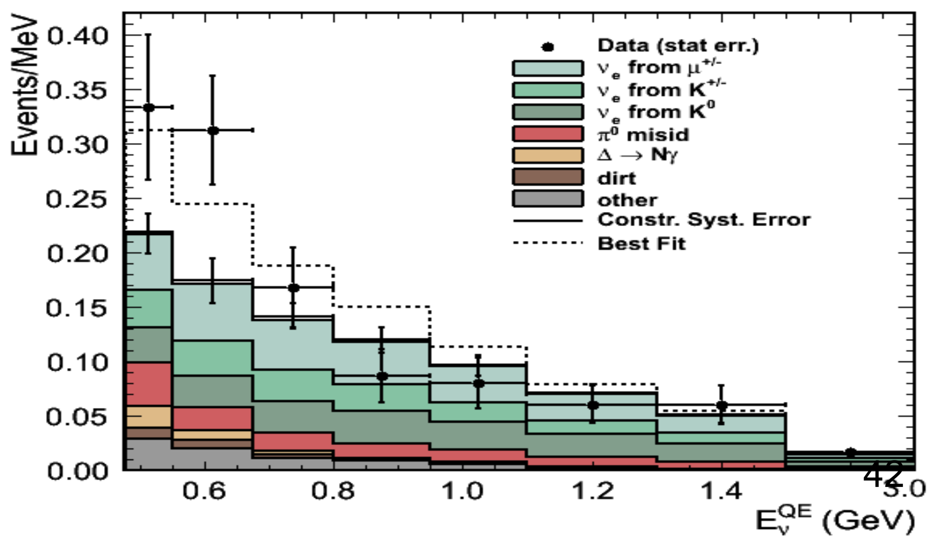


Previous Antineutrino Mode Results (2010): 5.66E20 POT

- Results for 5.66E20 POT collected in antineutrino 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.



Phys.Rev.Lett.105:181801, 2010.



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

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

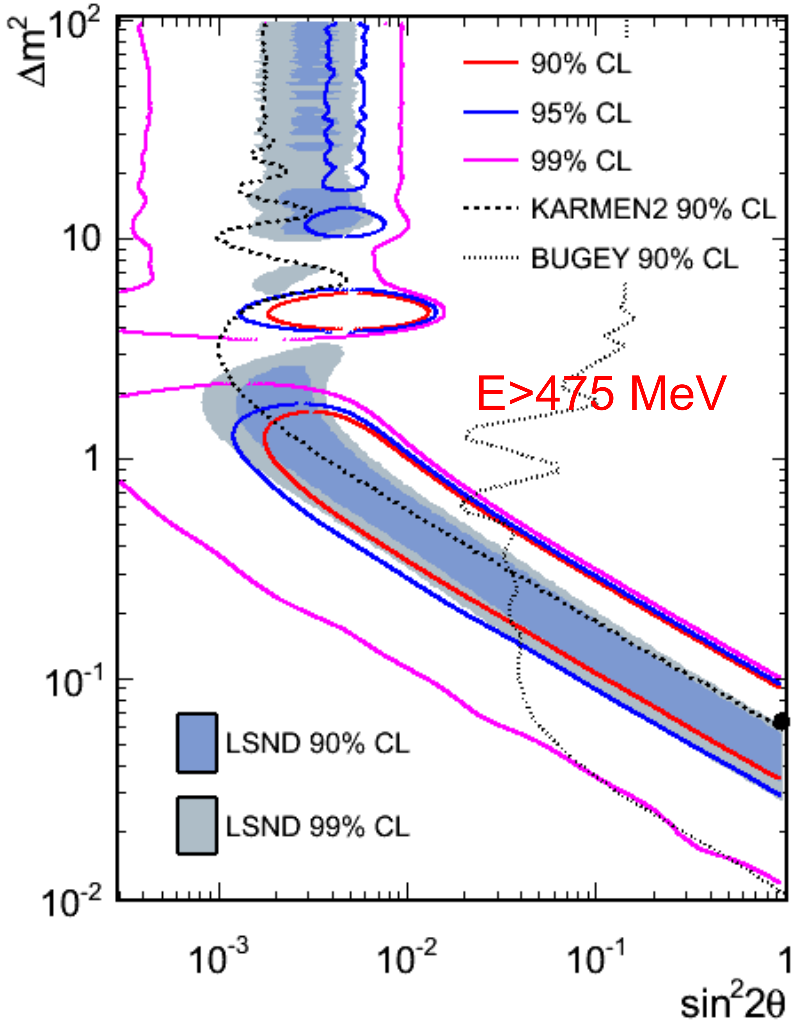
Best Fit Point

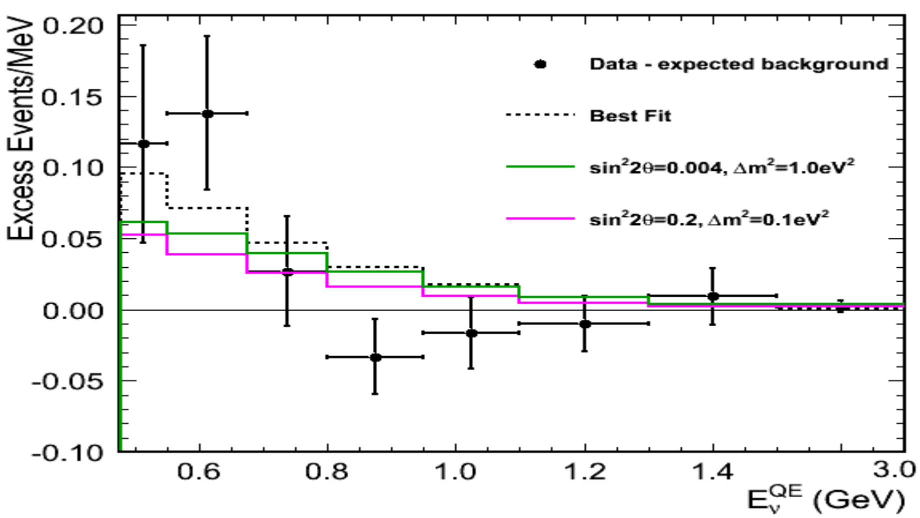
$(\Delta m^2, \sin^2 2\theta)$ =

(0.064 eV^2, 0.96)

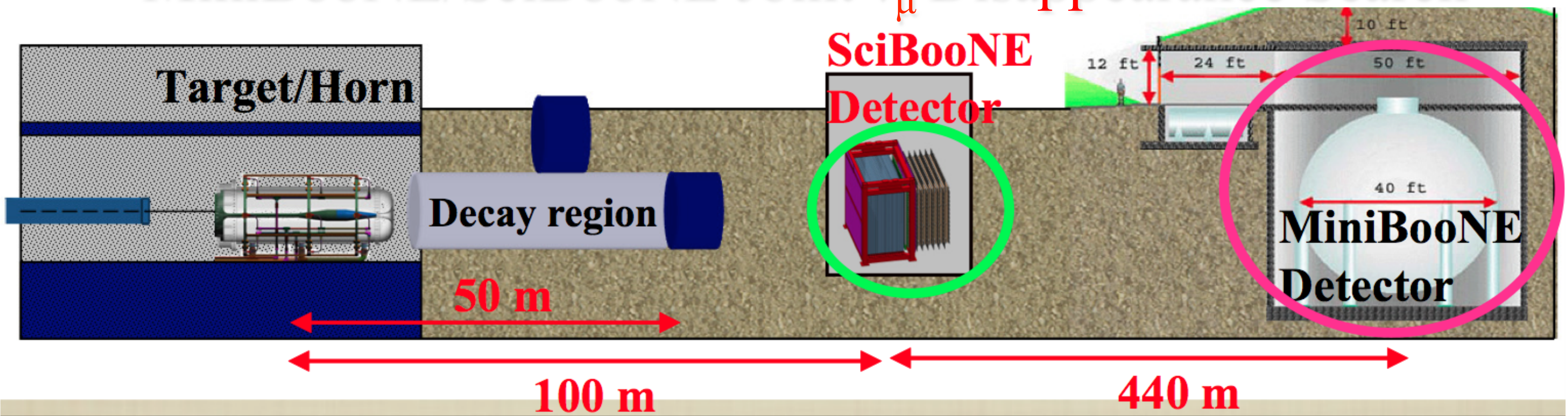
χ^2/NDF= 7.96/3.89

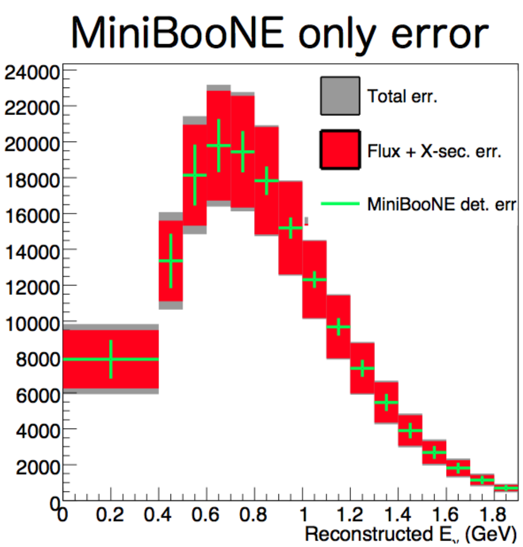
$P(\chi^2)$= 8.7%

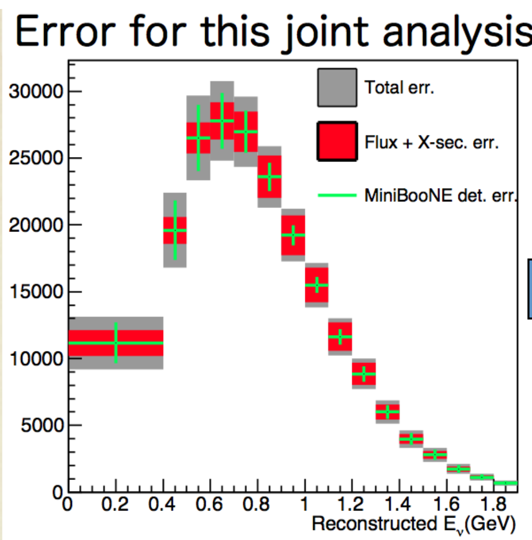


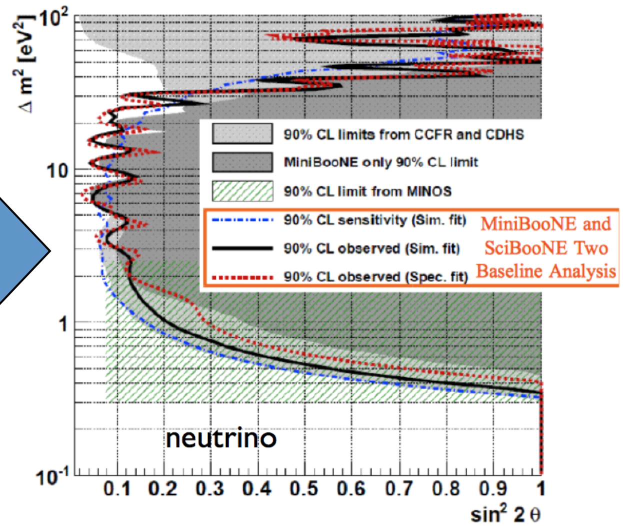


MiniBooNE/SciBooNE Joint ν_μ Disappearance Search



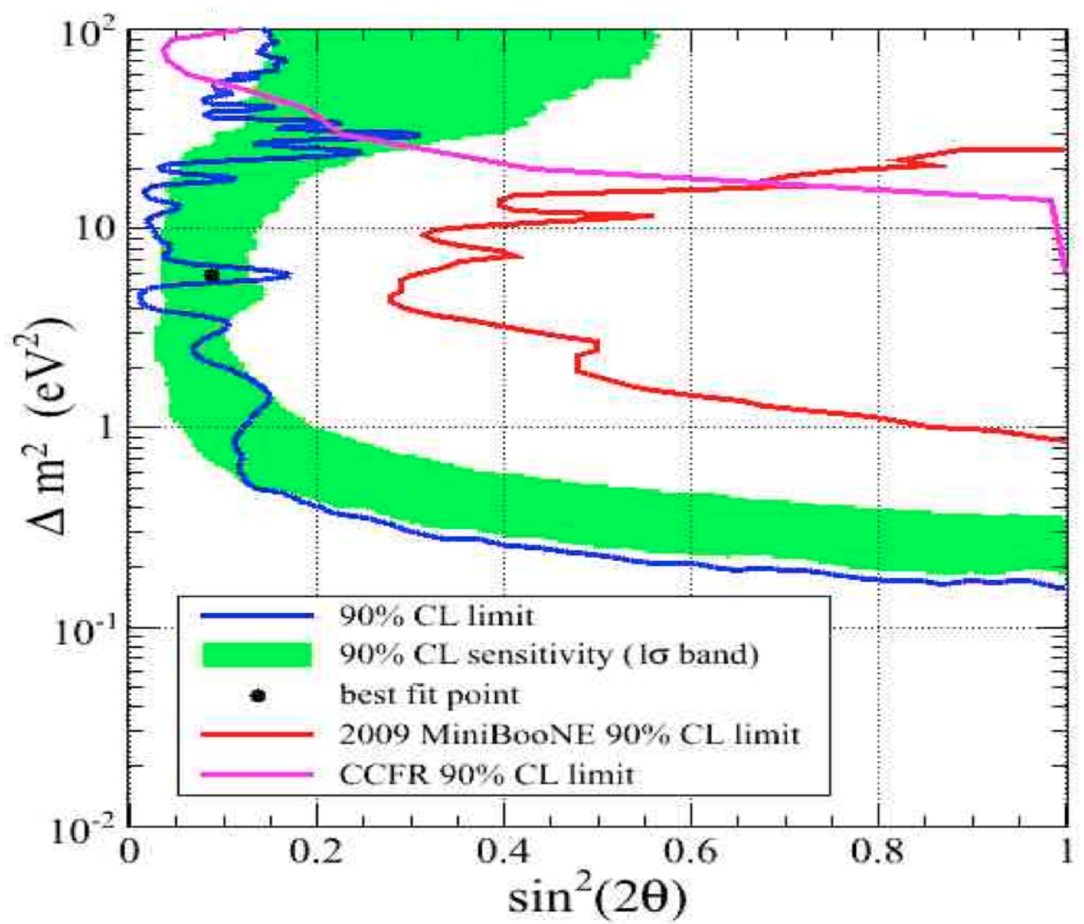






-No evidence for oscillations: Limit is better than other experiments in 10-30 eV^2 region.
-Results published: arXiv:1106.5685 [hep-ex], PRD 85, 032007 (2012).

MiniBooNE/SciBooNE Joint $\overline{\nu}_{\mu}$ Disappearance Search



-Significant improvement in sensitivity in muon antineutrino disappearance serch.
-No evidence for oscillations.
-Results published: arXiv:1208.0322 [hep-ex], accepted by PRD.