MiniBooNE

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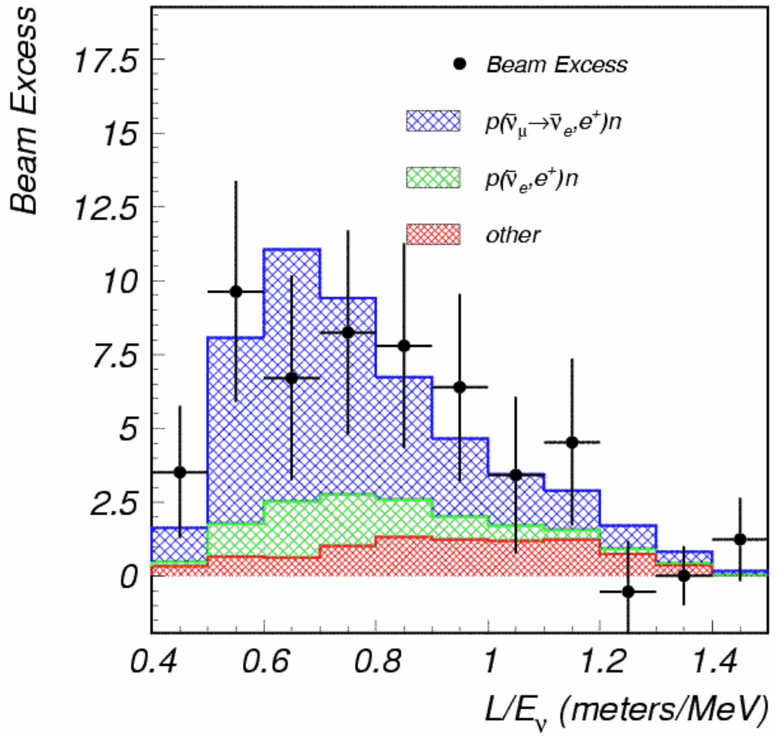
NuFact12, 24th July 2012
Williamsburg, VA

LSND

- Evidence for oscillations at higher Δm^2 than atmospheric and solar
- Stopped pion beam
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  $\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- $\bar{\nu}_e$ signature: Cherenkov light from e^+ with delayed n-capture
- Excess=87.9 ± 22.4 ± 6 (3.8σ)

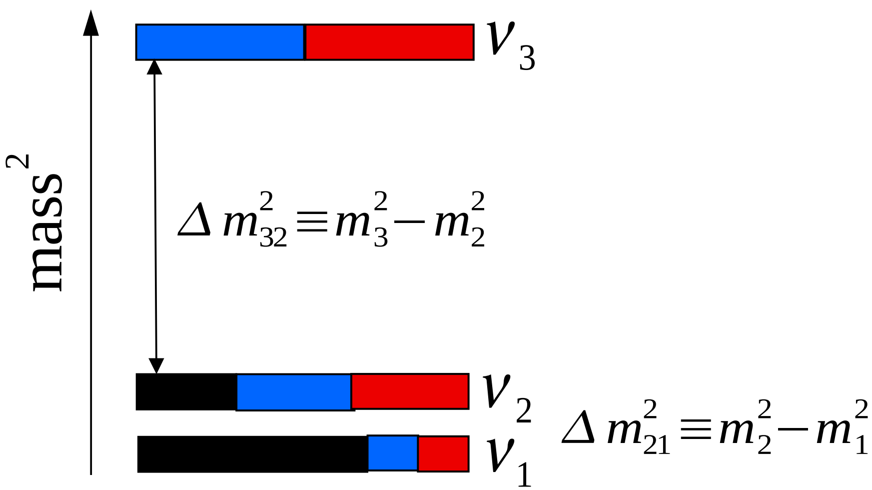


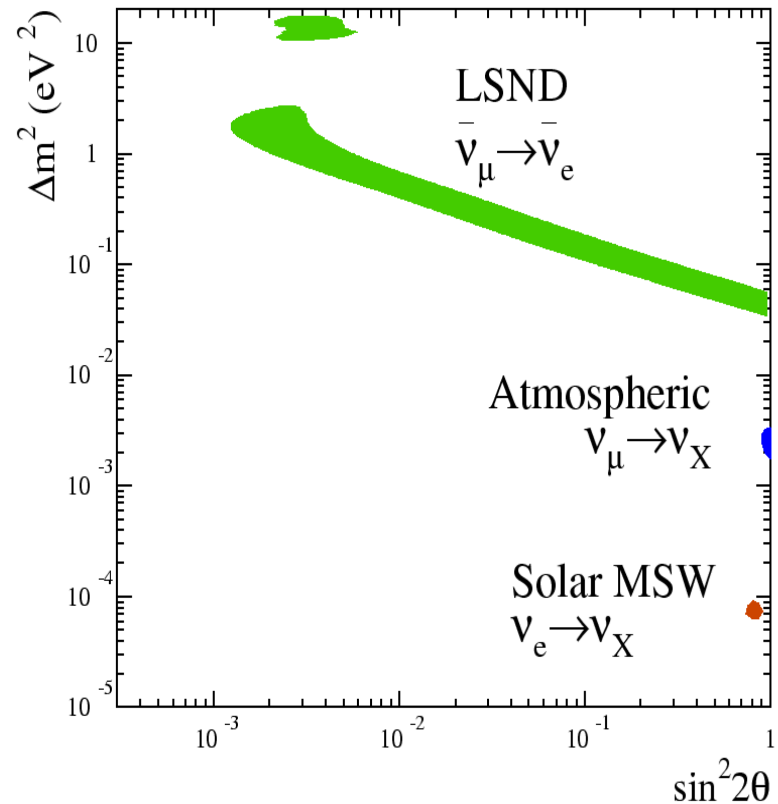
LSND signal

- Assuming two neutrino oscillations

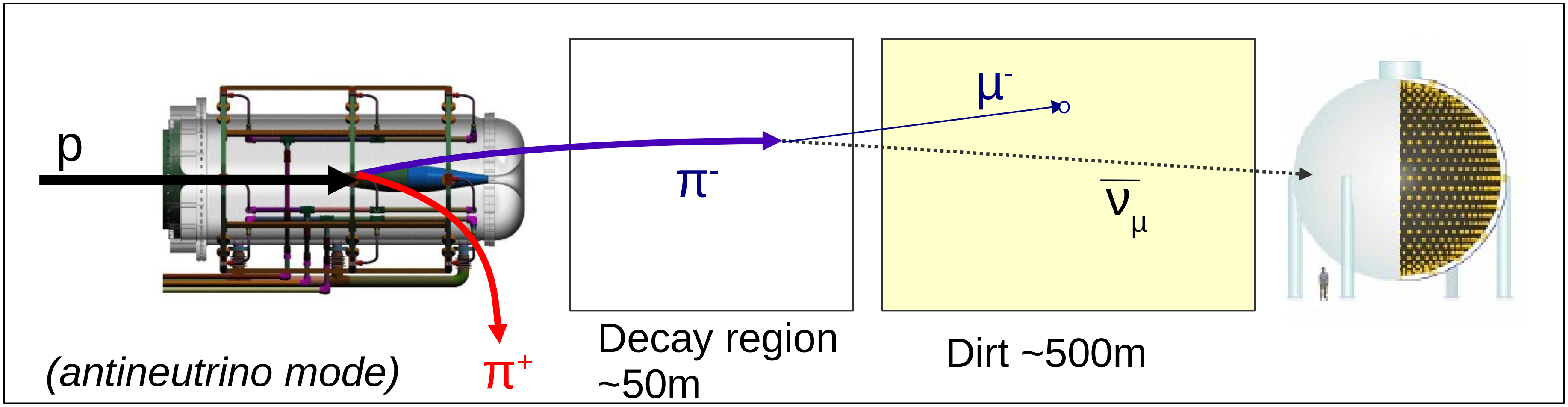
$$P(\bar{\nu}_\mu \to \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\ L\,\Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splitings





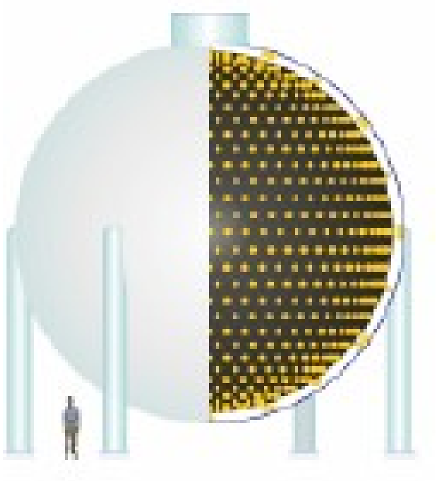
MiniBooNE experiment

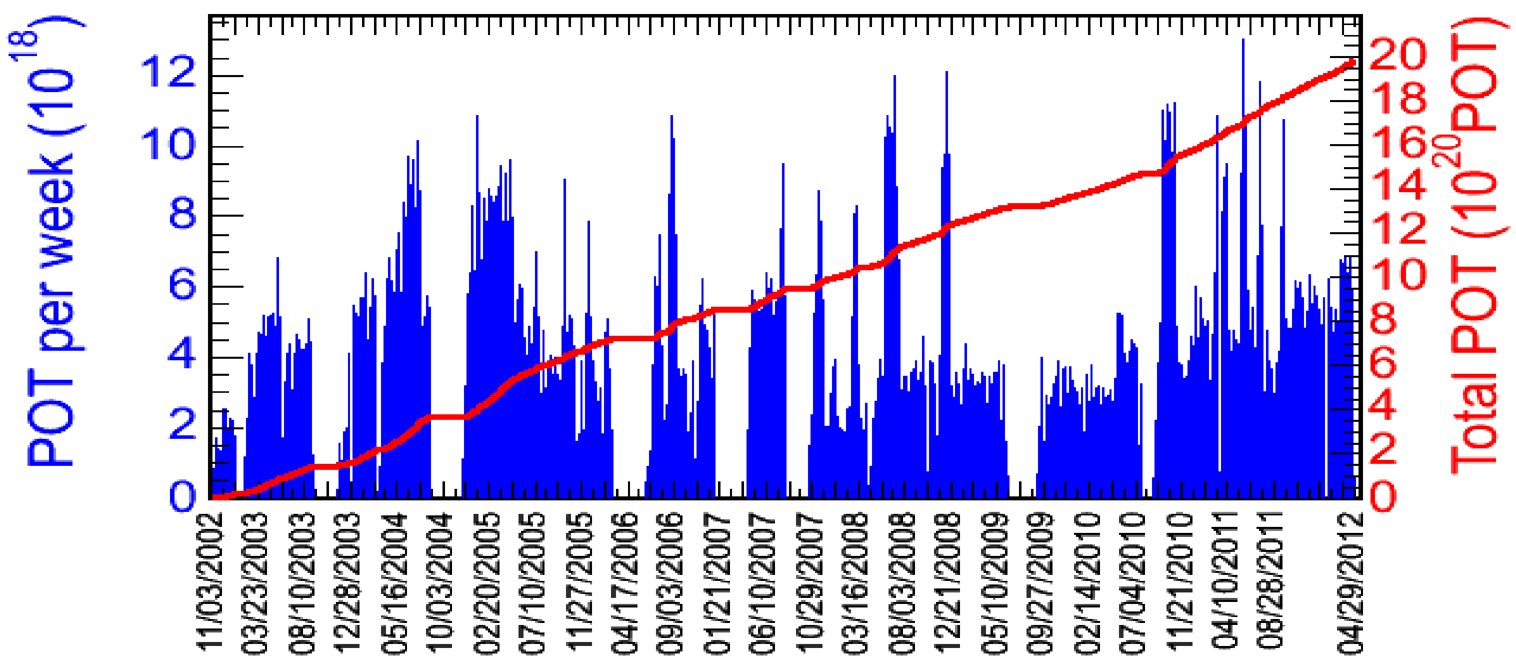


- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

Data

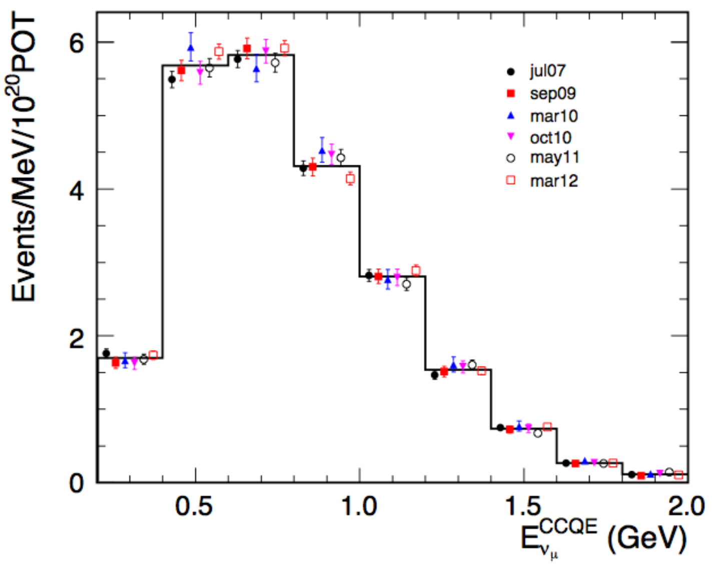
- Data taking: 2002-2012
- Total POT 19.8×10^{20}
- Neutrino: 6.5×10^{20}
- Antineutrino: 11.3×10^{20}

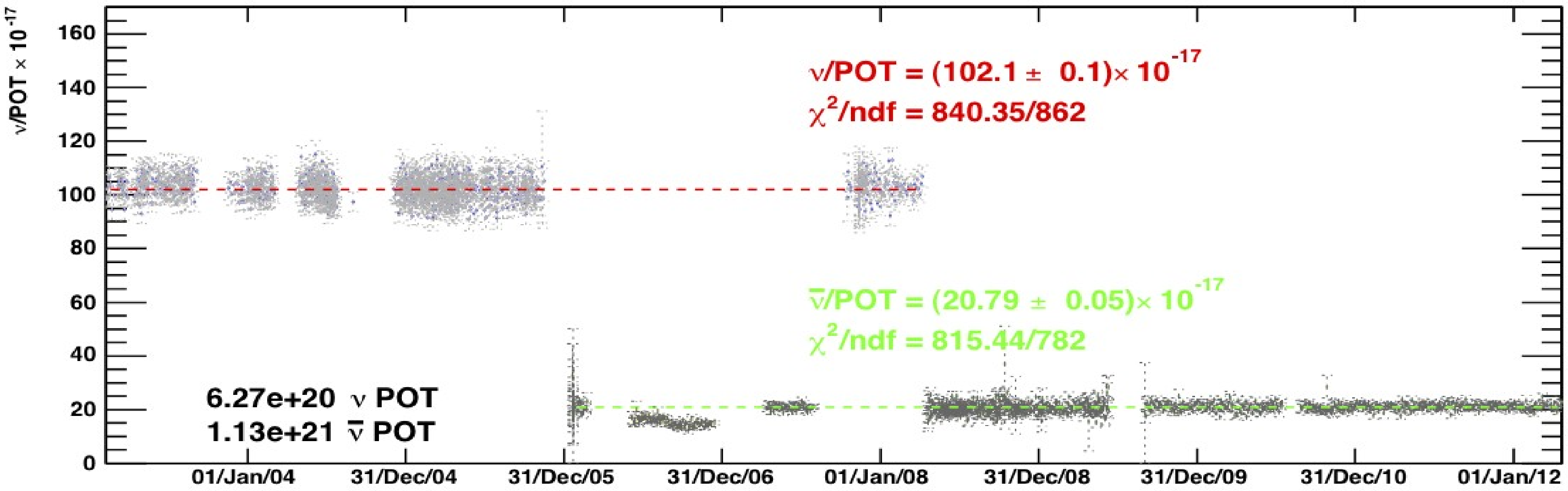




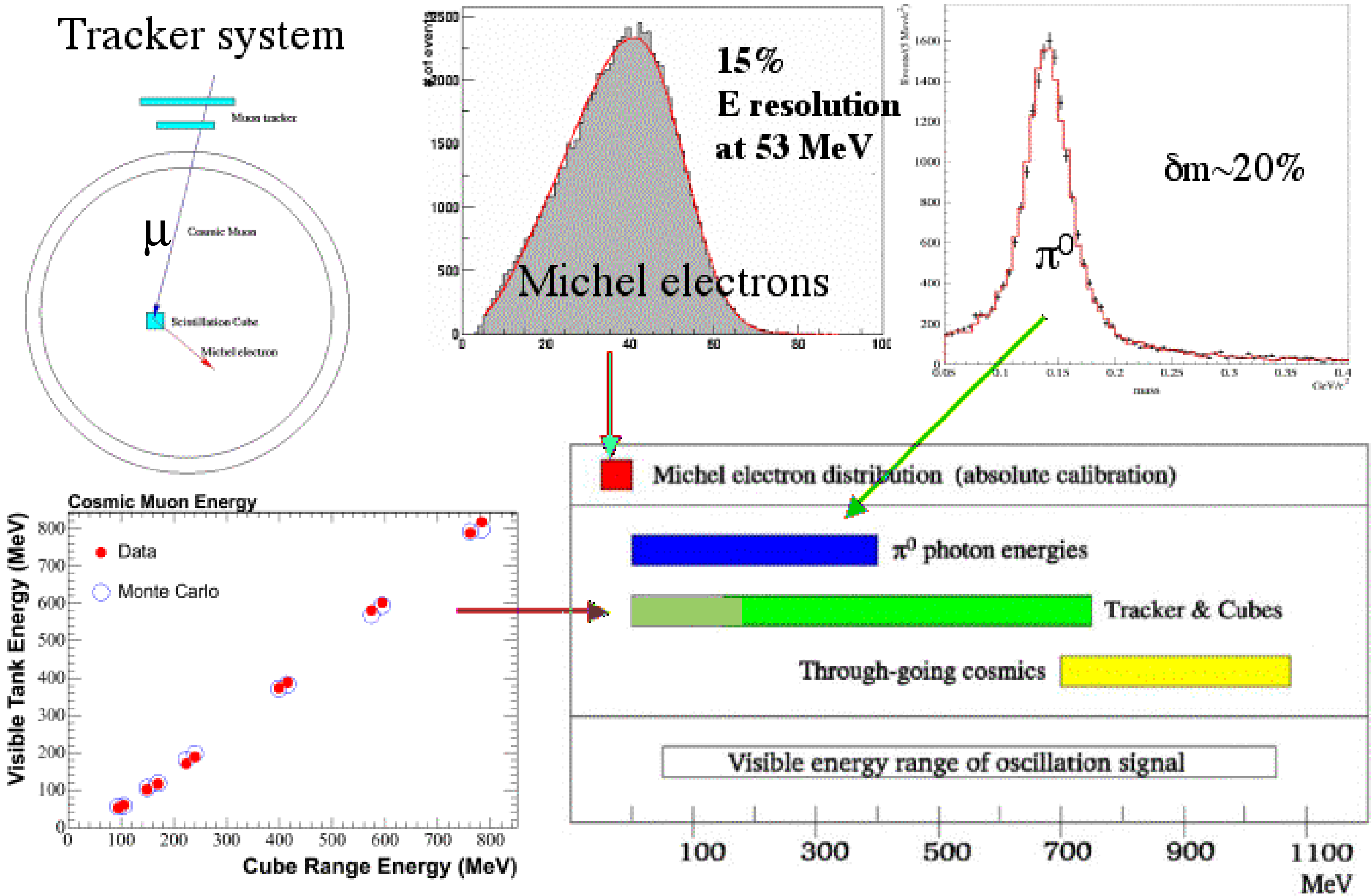
10 years of running

- Detector and beam extremely stable
- Neutrino/POT within 2%
- Detector calibration stable at 1% level





Calibration Sources



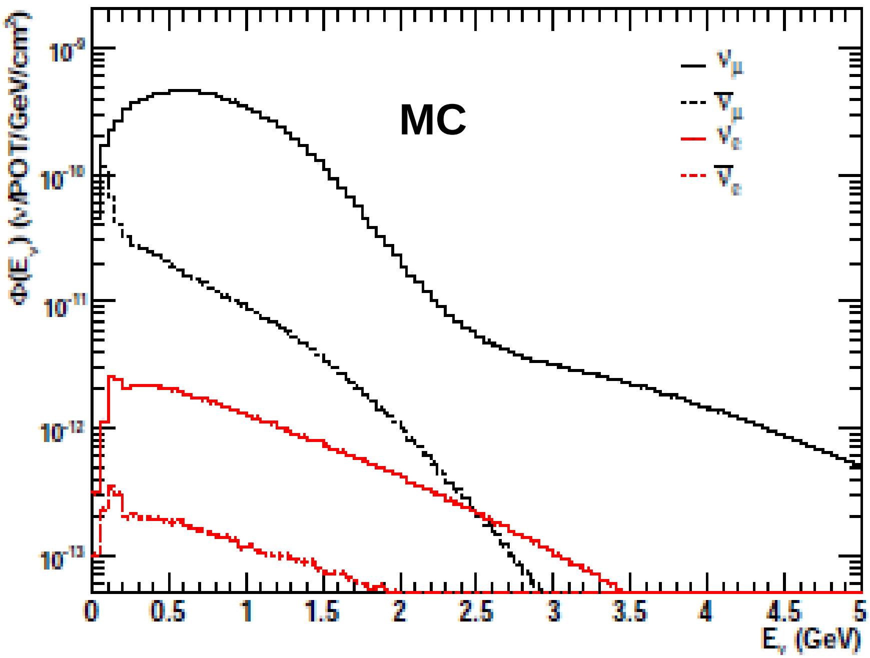
Predicted neutrino flux (MC)

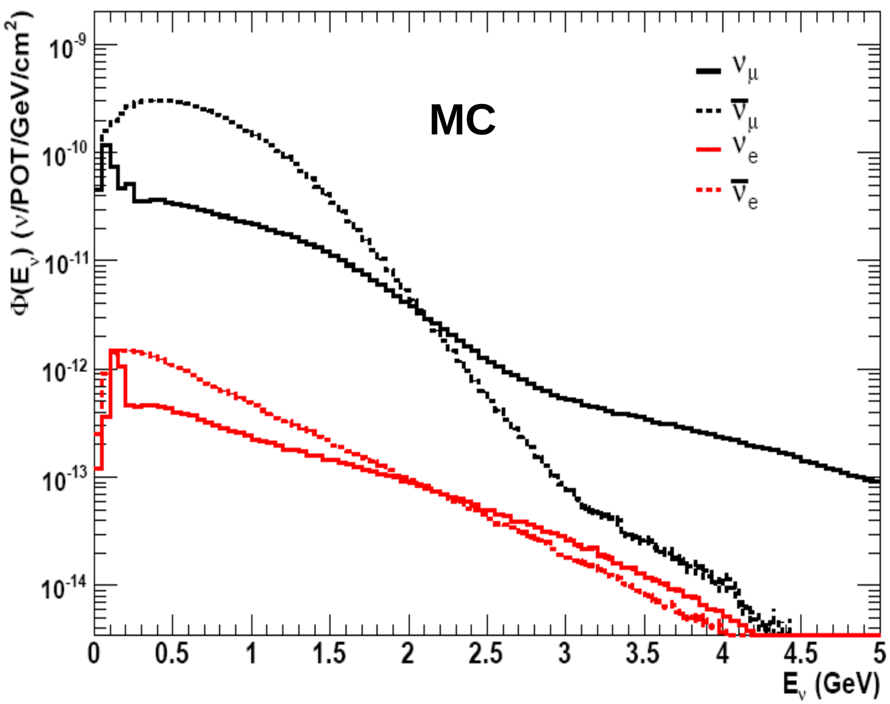
- Neutrino mode

ν_μ	93.6%
$\bar{\nu}_\mu$	5.8%
$\nu_e + \bar{\nu}_e$	0.6%

- Anti-neutrino mode

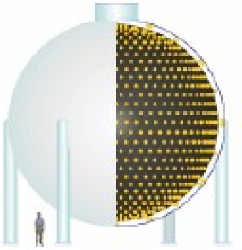
ν_μ	15.7%
$\bar{\nu}_\mu$	83.7%
$\nu_e + \bar{\nu}_e$	0.6%



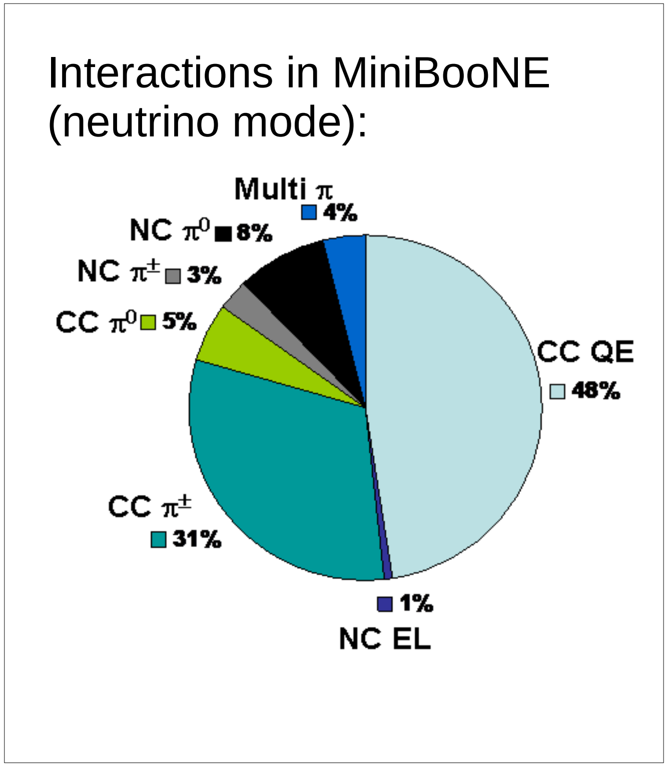


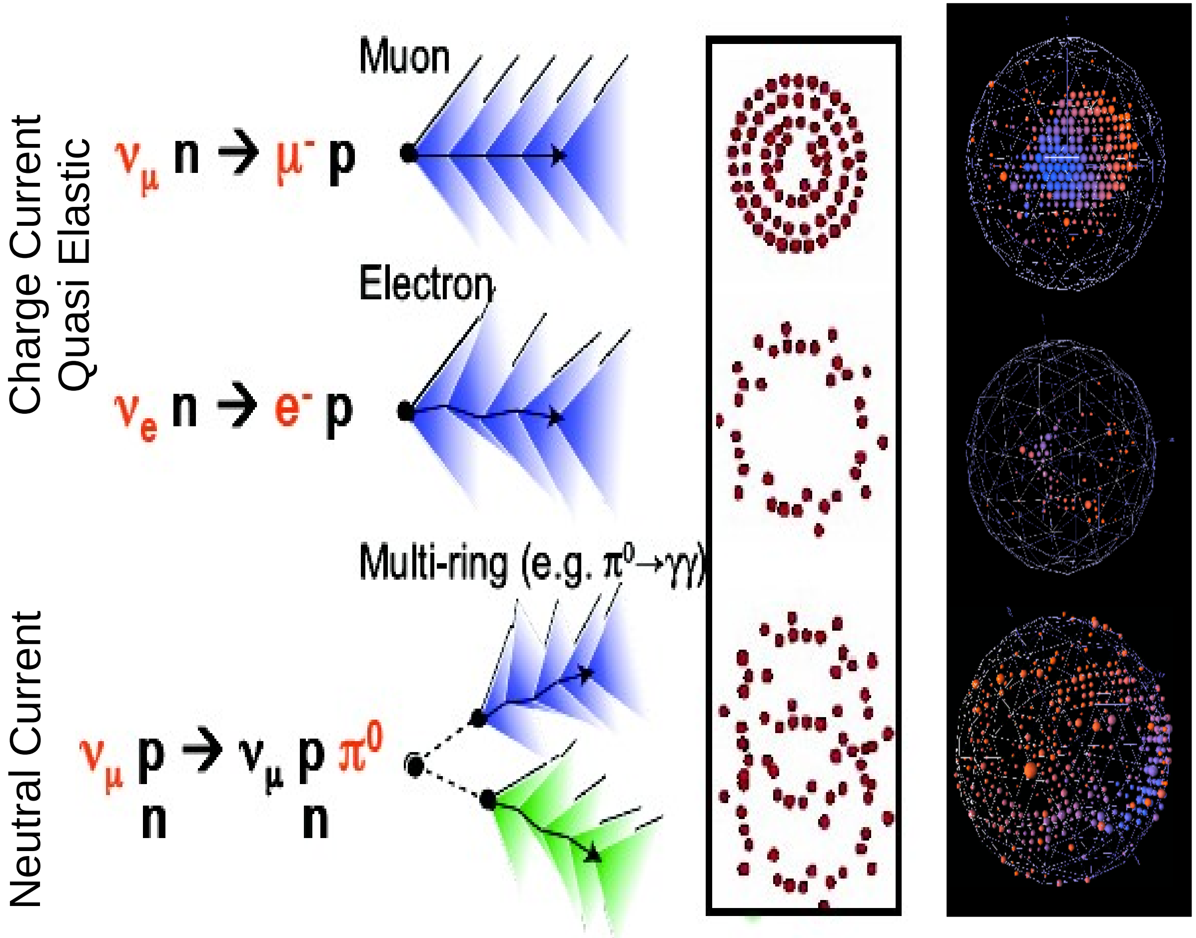
Phys. Rev. D79, 072002 (2009)

Events in MB



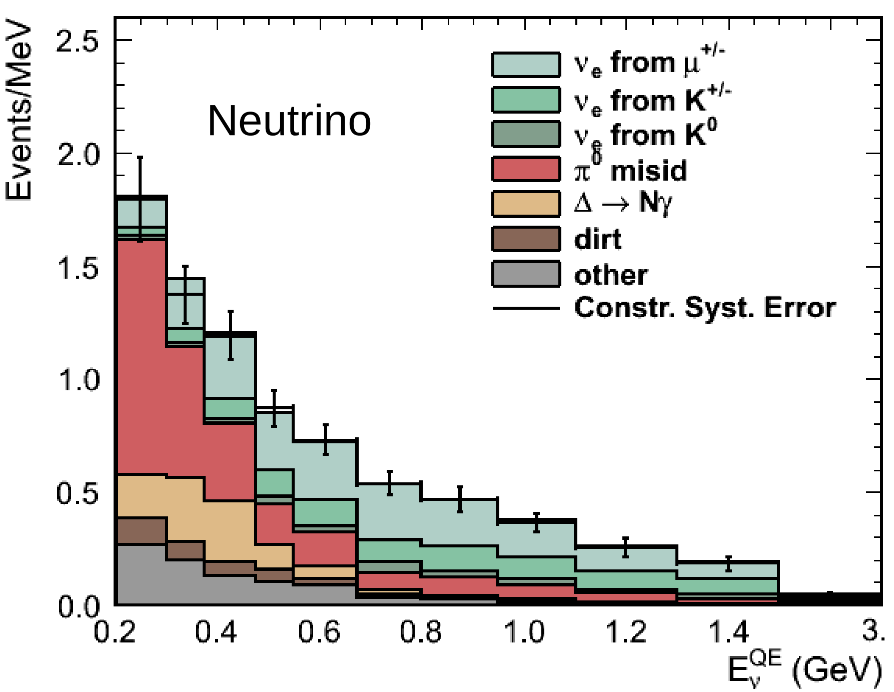
- Identify events using timing and hit topology
- Use primarily Cherenkov light

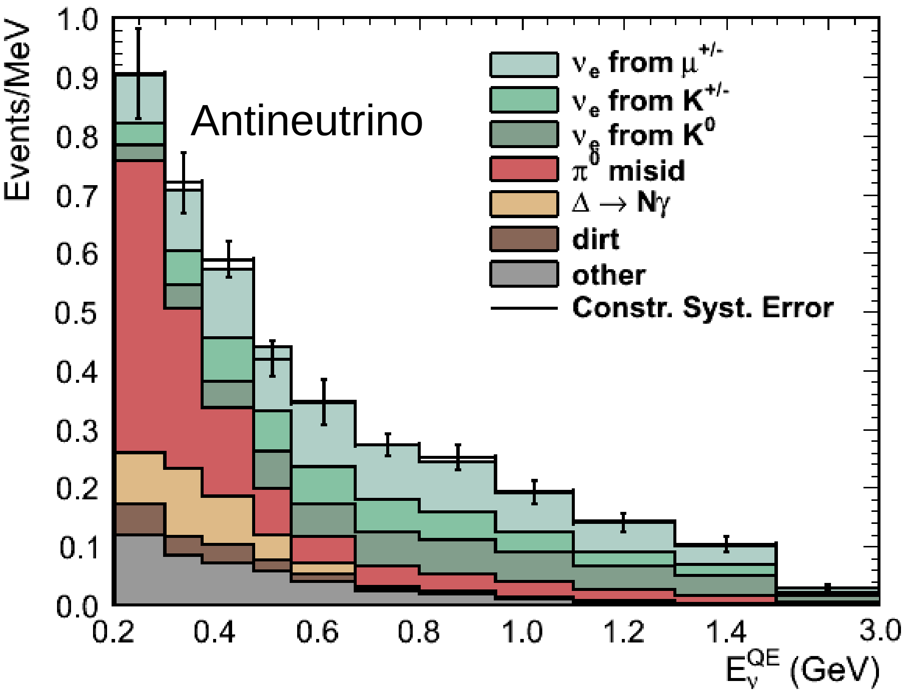




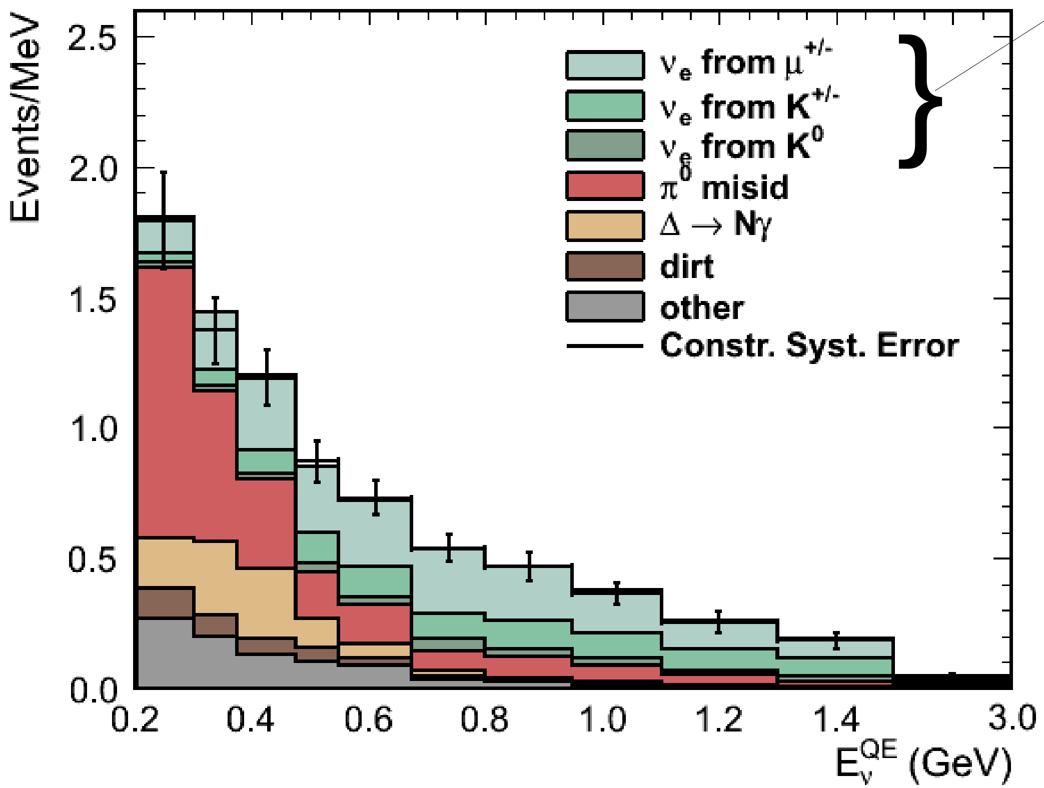
Background prediction

- Similar backgrounds in neutrino and anti-neutrino mode

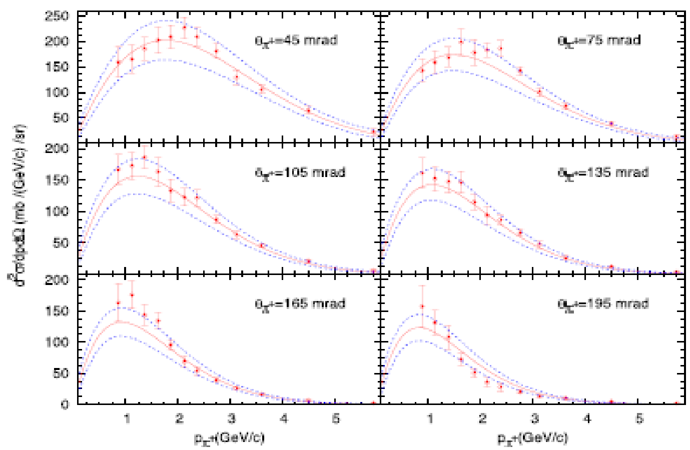




Background prediction



- Intrinsic ν_e
  - External measurements - HARP p+Be for $\pi^{\pm}$

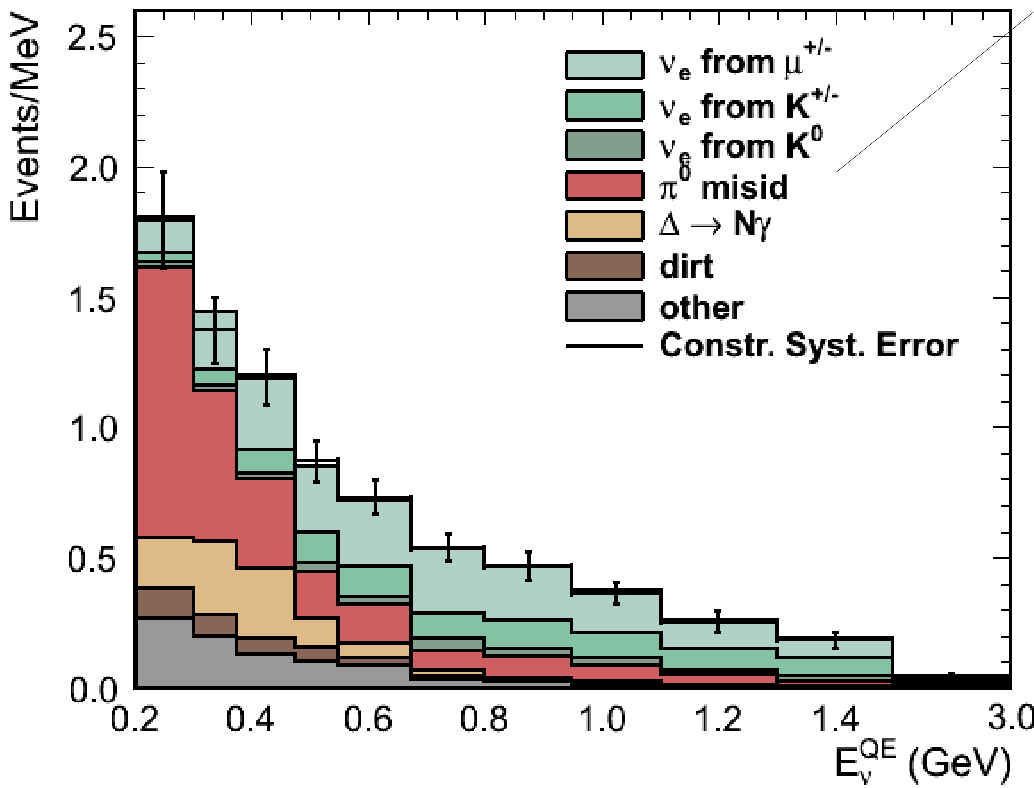


  - Fits to world K^+/K^0 data and Sciboone K^+ constraint

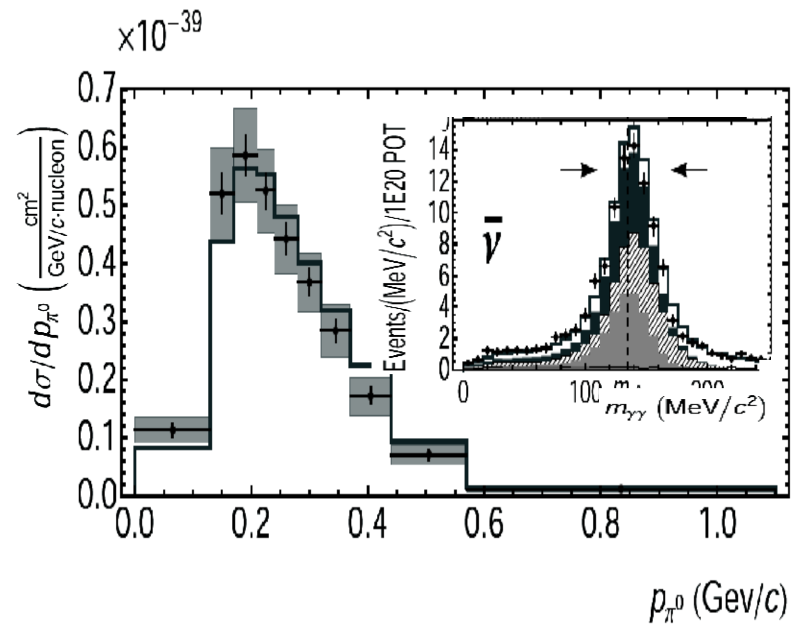
Phys. Rev. D79, 072002 (2009)
Phys. Rev. D84, 012009 (2011)

  - Constrained with MiniBooNE data

ν_e background prediction

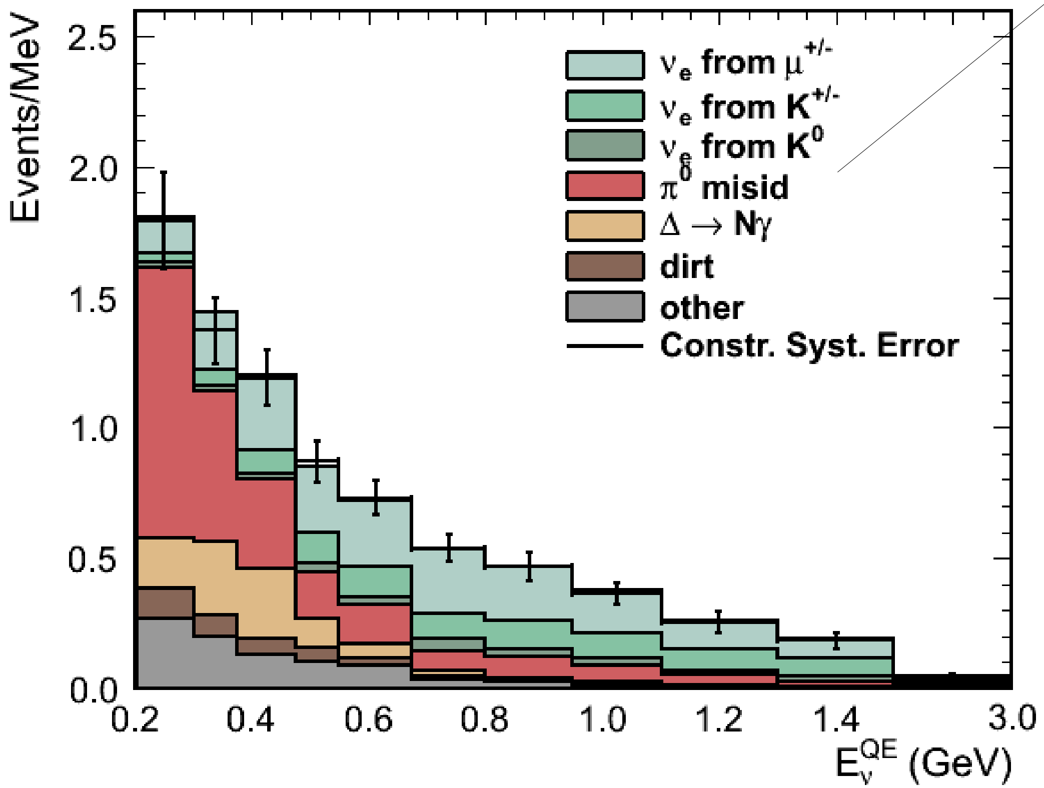


- NC π^0
  - MiniBooNE data

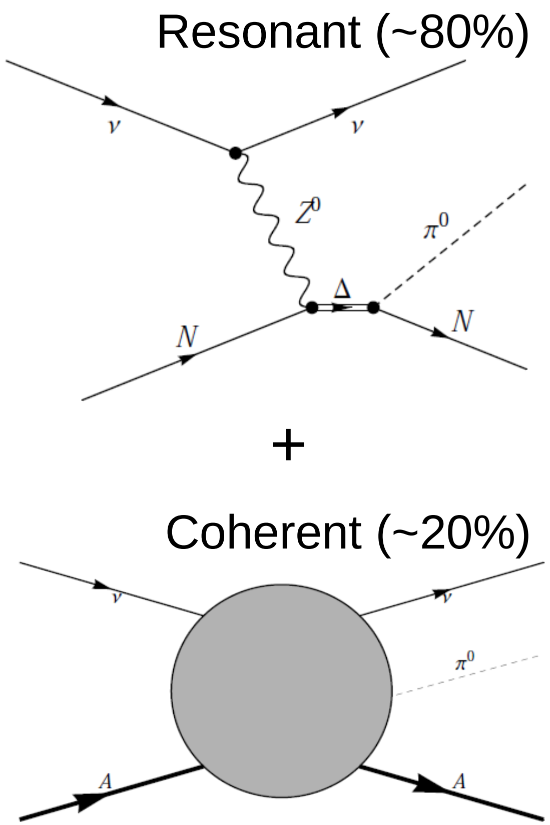


Phys. Rev. D81, 013005 (2010)

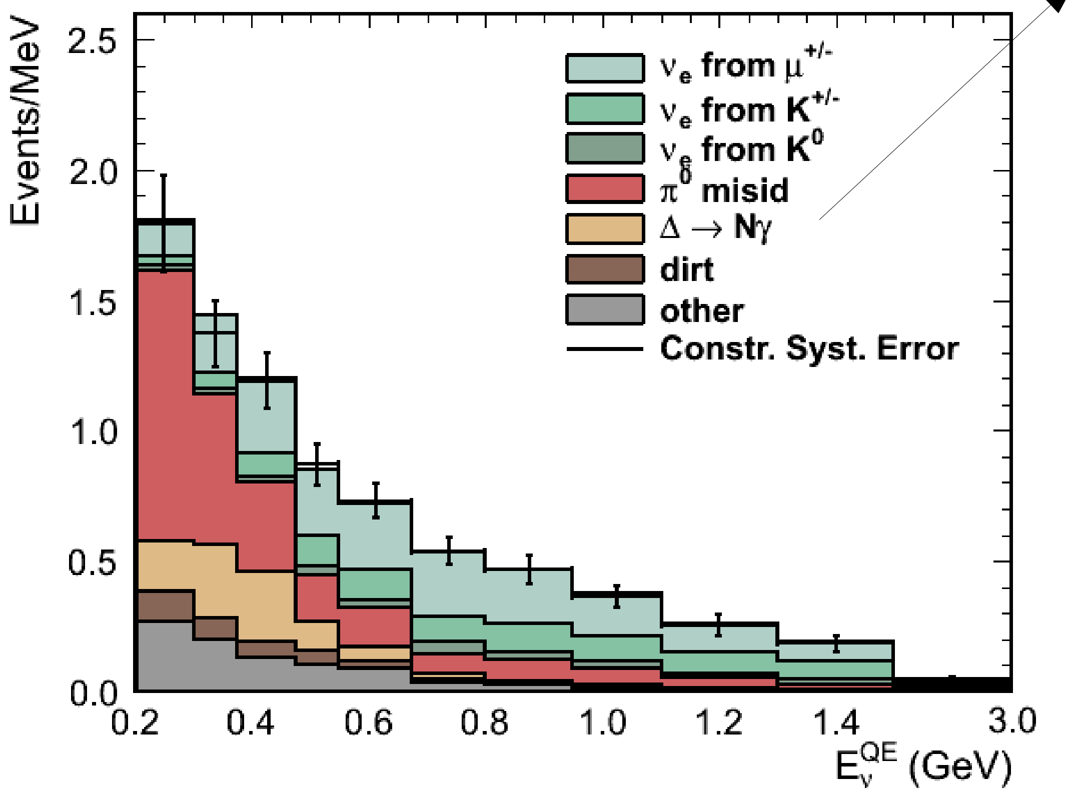
ν_e background prediction



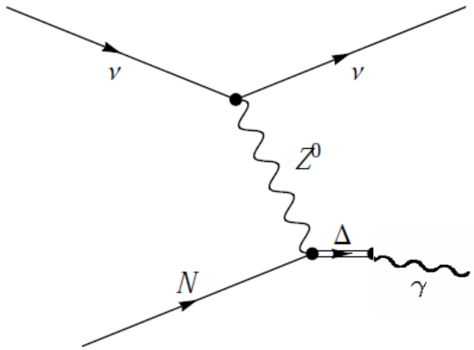
- NC π^0



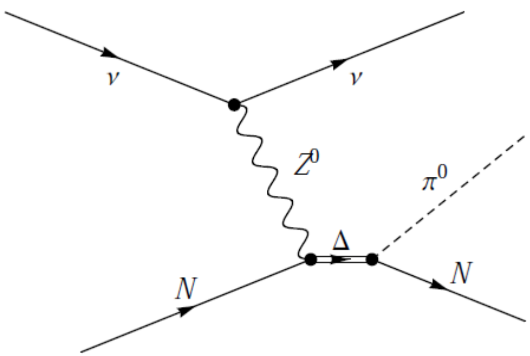
ν_e background prediction



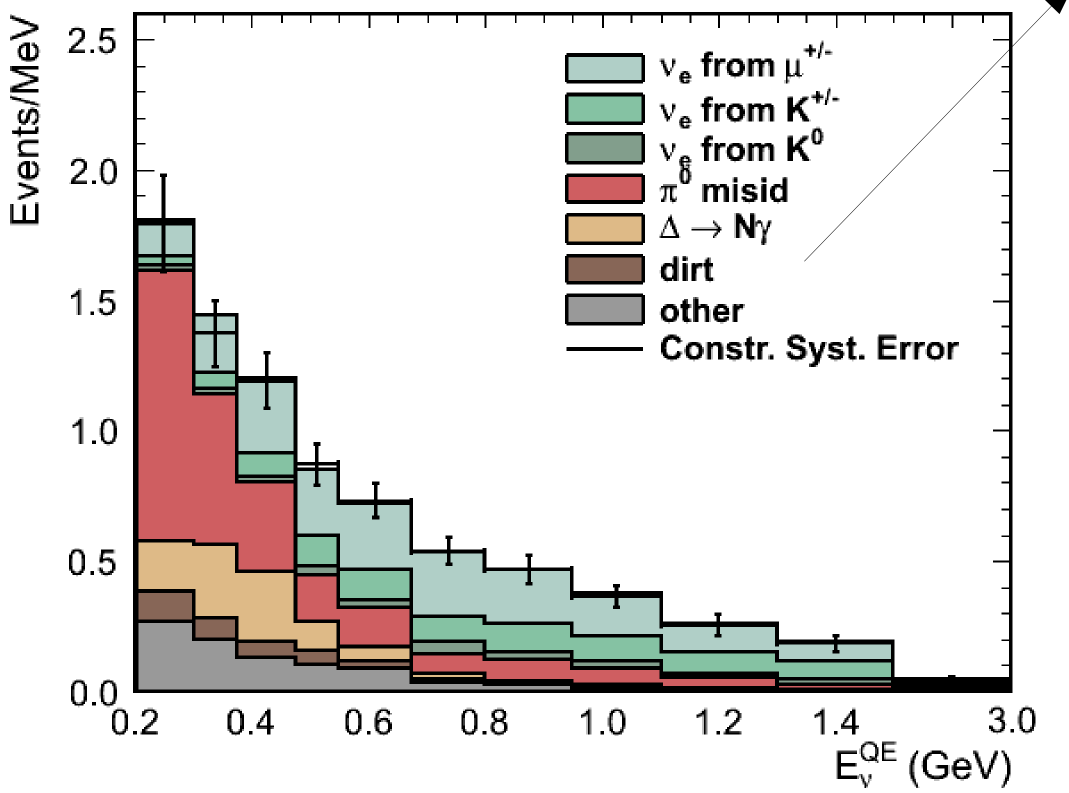
- $\Delta \rightarrow N\gamma$



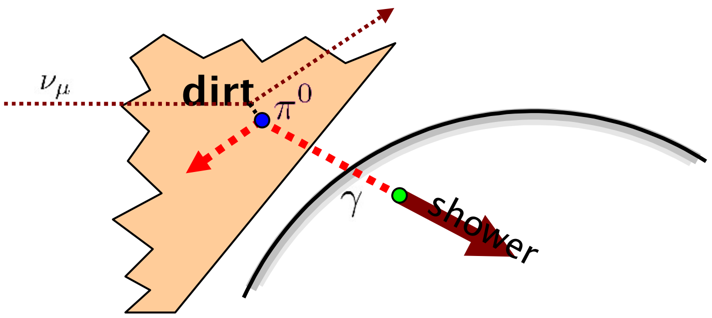
- constrained with π^0 data



ν_e background prediction



- Dirt:



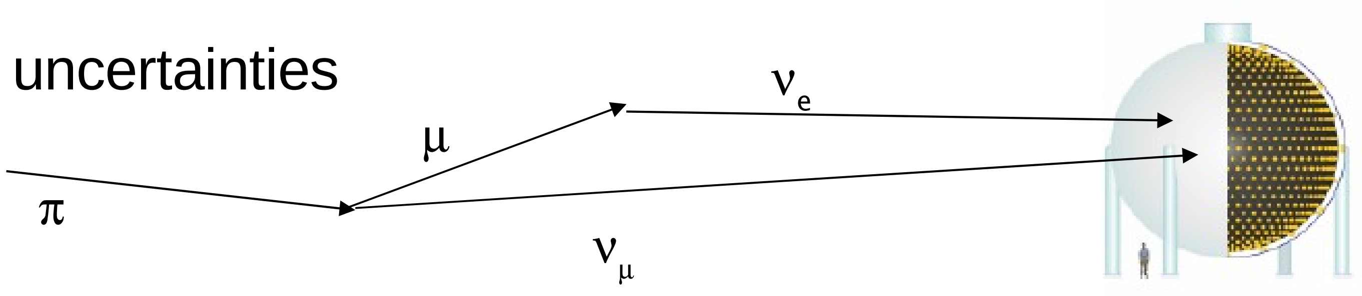
- Events at high R pointing toward center of detector
- MiniBooNE measurement

Oscillation Fit Method

- Maximum likelihood fit:

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

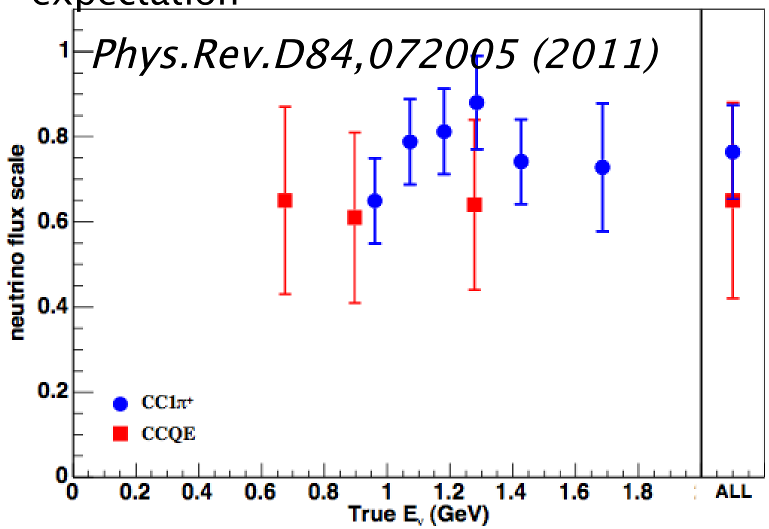
- Simultaneously fit
  - ν_e CCQE sample
  - High statistics ν_μ CCQE sample
- ν_μ CCQE sample constrains many of the uncertainties:
  - Flux uncertainties

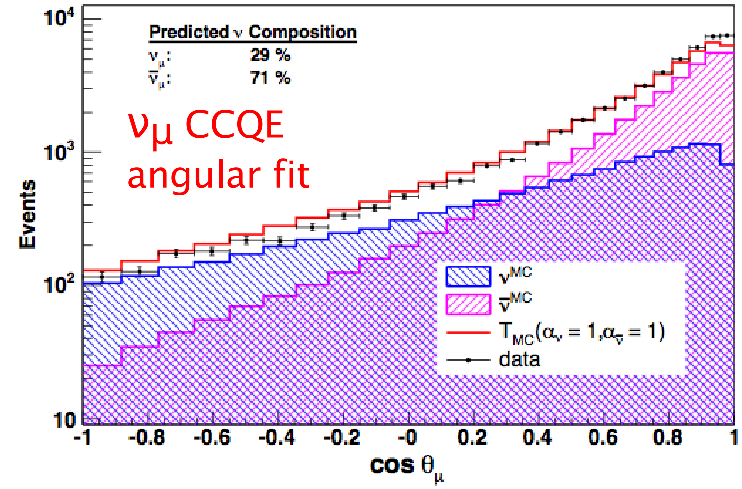


  - Cross section uncertainties

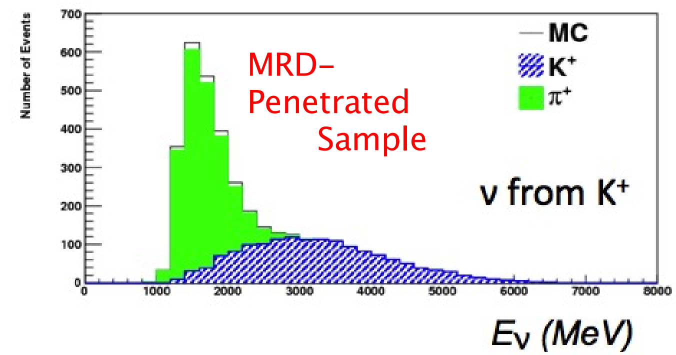
What's new since last oscillation publication?

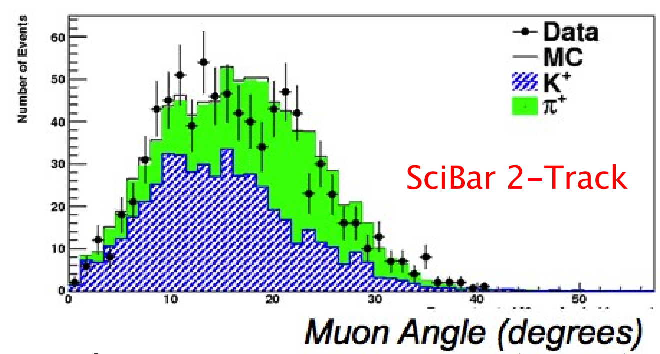
- *In situ* measurement of WS contamination in anti-ν beam
  - ν_μ CCQE angular fit, and new constrain from CCπ+ rate...good agreement with expectation





- New SciBooNE constraint on intrinsic ν_e from K+
  - Found K+ production to be 0.85 ± 0.12 relative to prediction, consistent with prior MiniBooNE assessment of 1.00 ± 0.30
  - Combined with world K+ production data, reduces error on K+ flux to 9% in MB En range
  - Leading error on K+ bkgs becomes ~20% error from cross-section

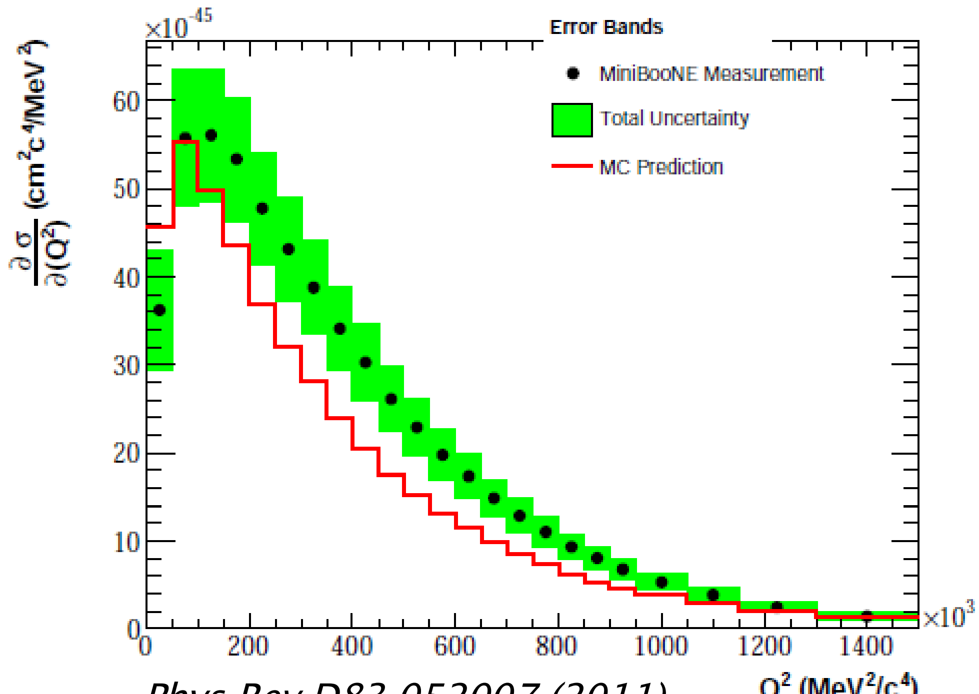




Phys.Rev.D84,012009 (2011)

What's new since last oscillation publication?

- Few other minor updates...
  - Higher stats for all MC samples, reduces fluctuations in error matrices
  - Added error matrix for intrinsic ν_e from K−
  - Improved smoothing algorithm that was being used to assess systematics due to discriminator thresholds and PMT response
  - CCπ+ events (bkg for ν_μ CCQE when π+ is absorbed) Q^2 reweighting applied based on internal MB measurement

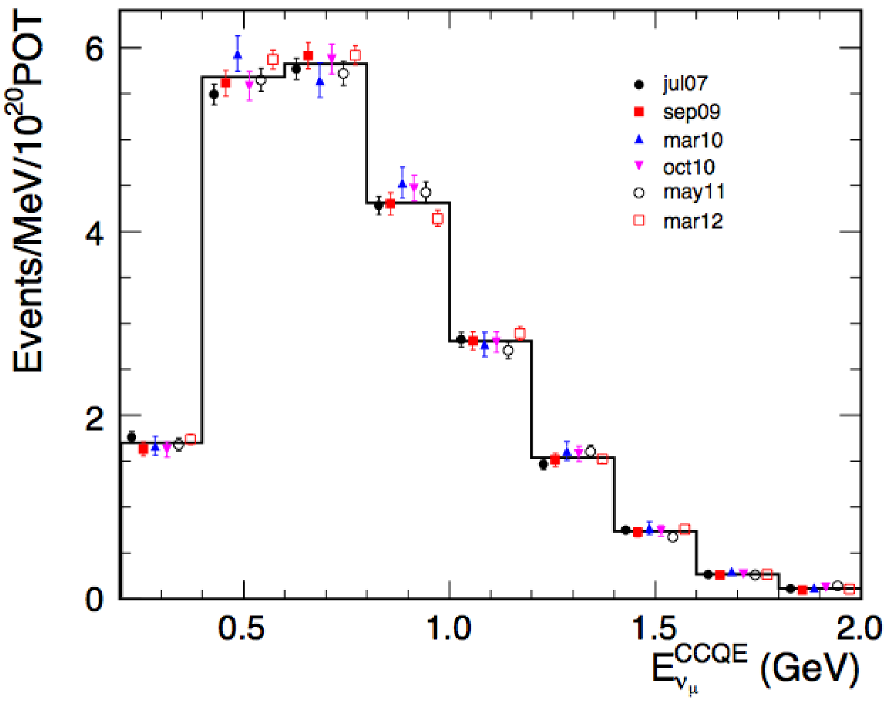


Phys.Rev.D83,052007 (2011)

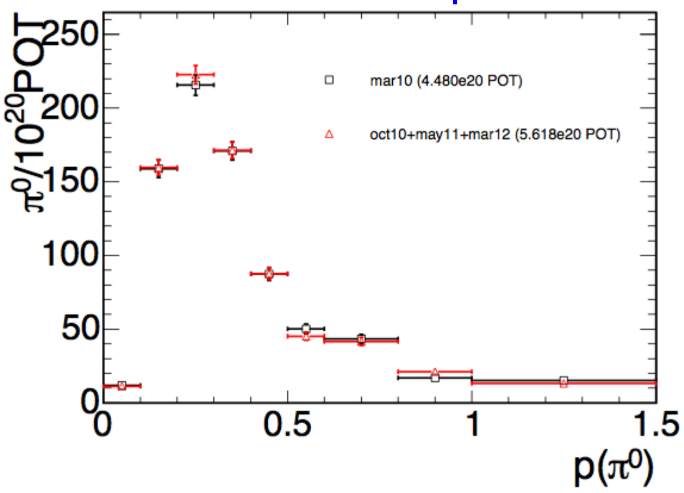
Main improvement...doubling of anti-ν stats

- Statistics of anti-neutrino running has doubled since *Phys.Rev.Lett.105 181801 (2010)*
  - 5.66e20 POT --> 11.3e20 POT
  - higher statistics in anti-ν_e appearance
  - ...and samples used for constraints

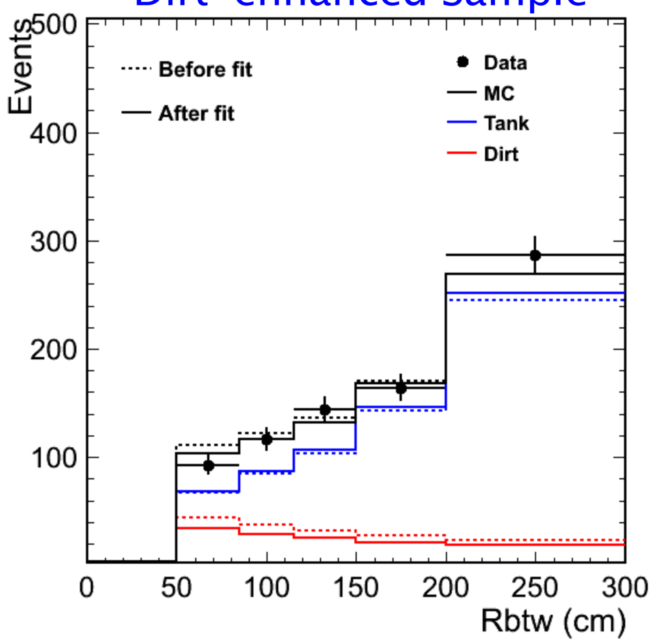
ν_μ CCQE Sample



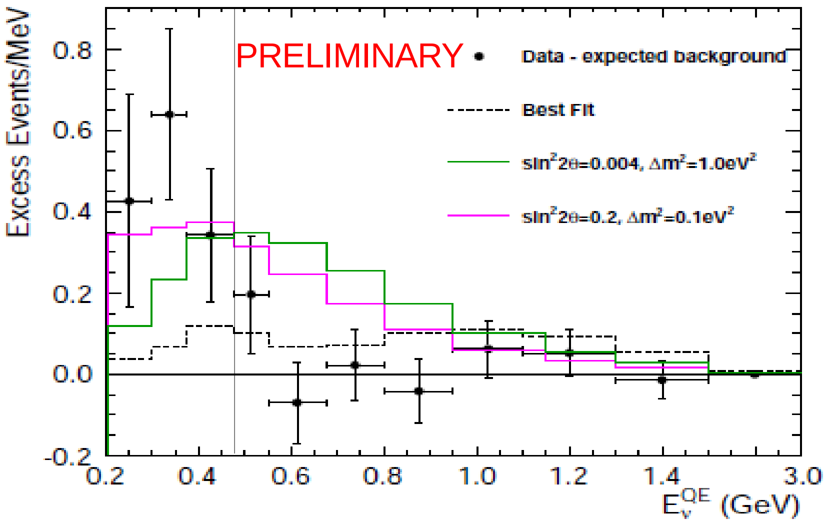
NC π^0 Sample



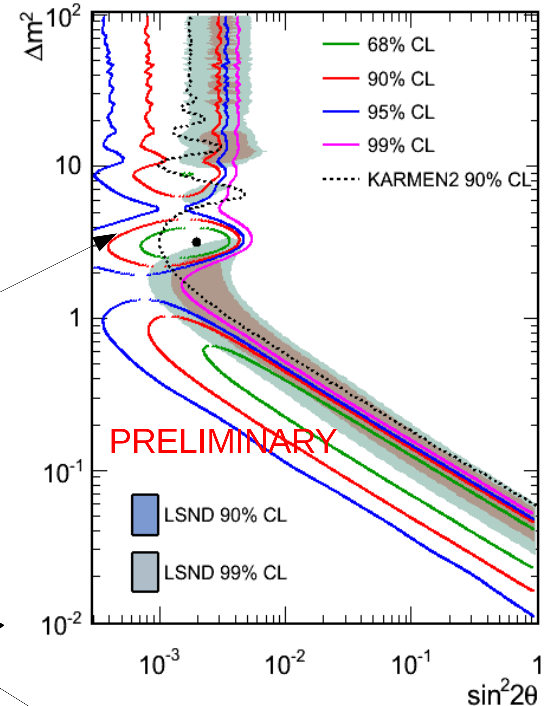
Dirt-enhanced Sample



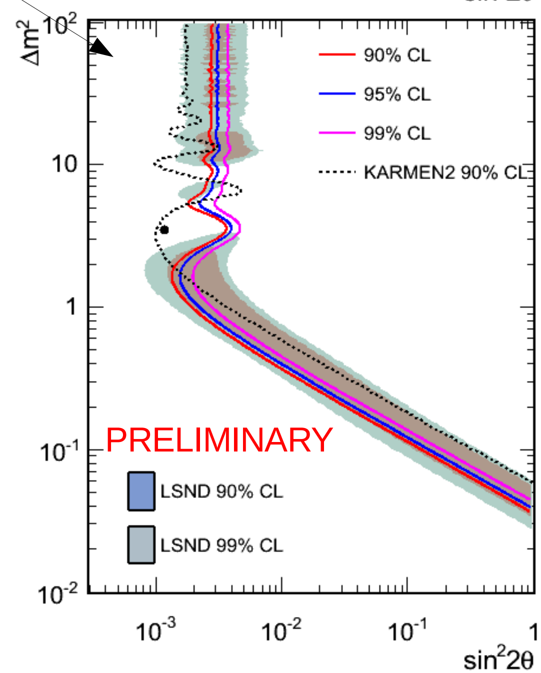
Updated Neutrino Appearance results



E>200 MeV



E>475 MeV

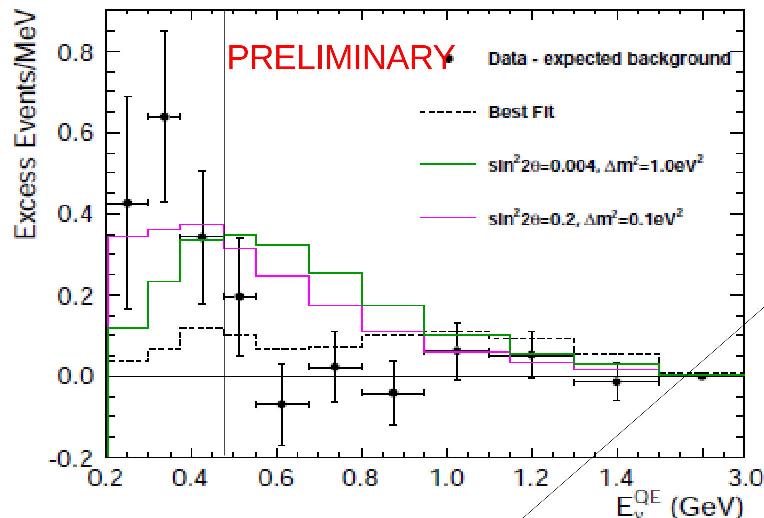


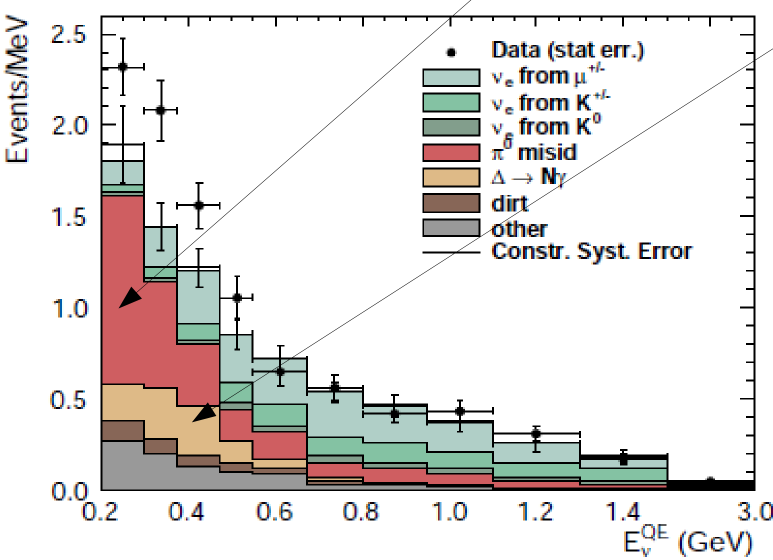
- Excess (200-1250 MeV): 146.3±28.4±40.2
- Some tension between 3+1 model fits in two energy regions (1.4% probability to see 3.73→13.24 when including low E)

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%

What can we say about low-E excess

Neutrino

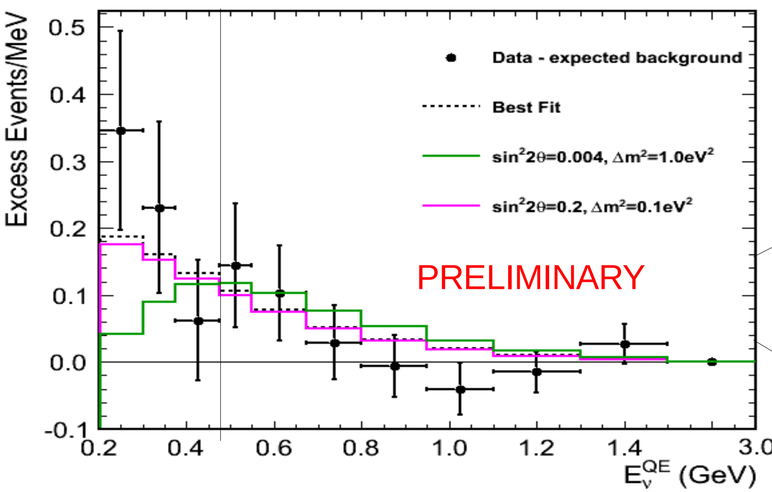




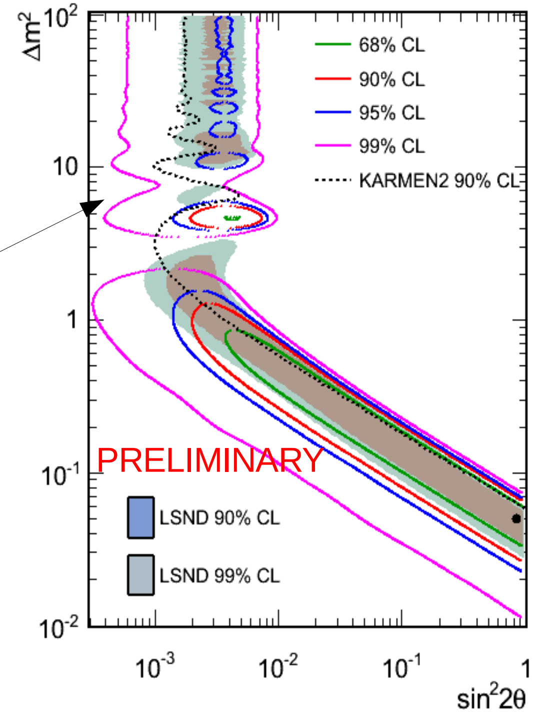
- Not a stat fluctuation, statistically 6σ
- Unlikely to be intrinsic ν_e, small bkg at low E
- NC π^0 background dominates
  - Reduces significance to 3σ
  - Heavily constrained by NC π^0 *in situ* measurement
- Region where single γ can contribute
- MB ties $\Delta \rightarrow N\gamma$ expected rate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

R. Hill, arxiv:0905.0291
Jenkins & Goldman, arxiv:0906.0984
Serot & Zhang, arxiv:1011.5913

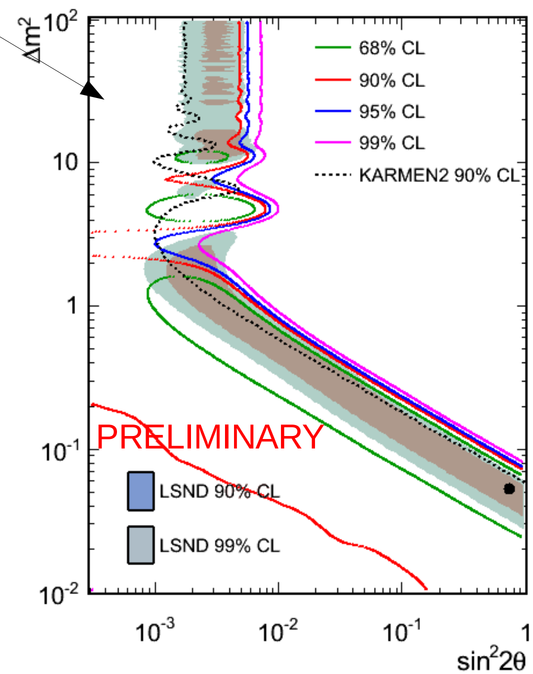
Antineutrino Appearance results 11.3x10^{20} POT



E>200 MeV



E>475 MeV

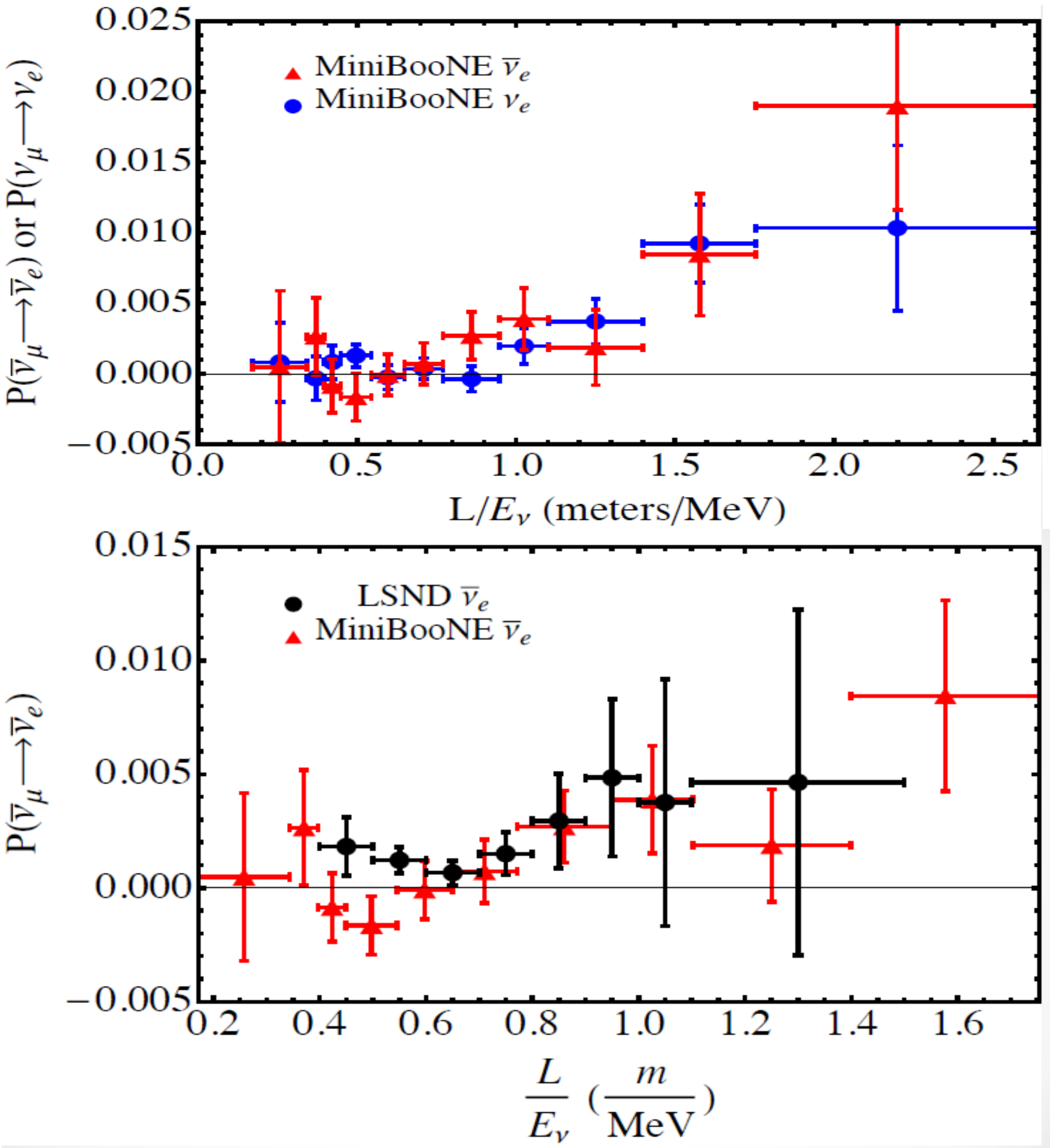


- Excess (200-1250 MeV):78.2±20.0±23.4
- No tension between fits in two energy regions
- Caveat: WS ν_μ assumed not to oscillate

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%

L/E dependence

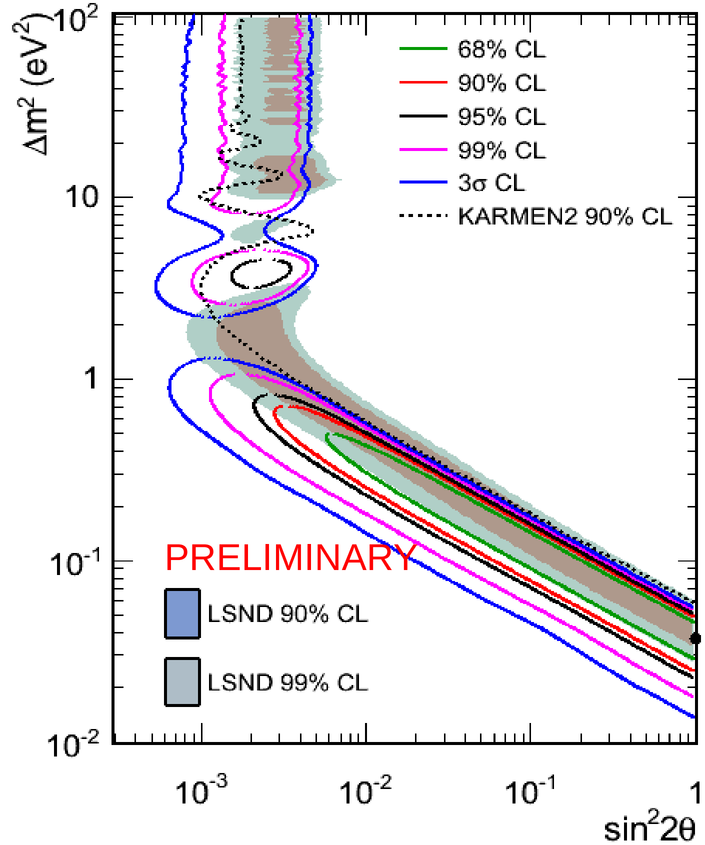
- Model independent look at the data
- The excess as a function of L/E in MiniBooNE neutrino, antineutrino and LSND data consistent

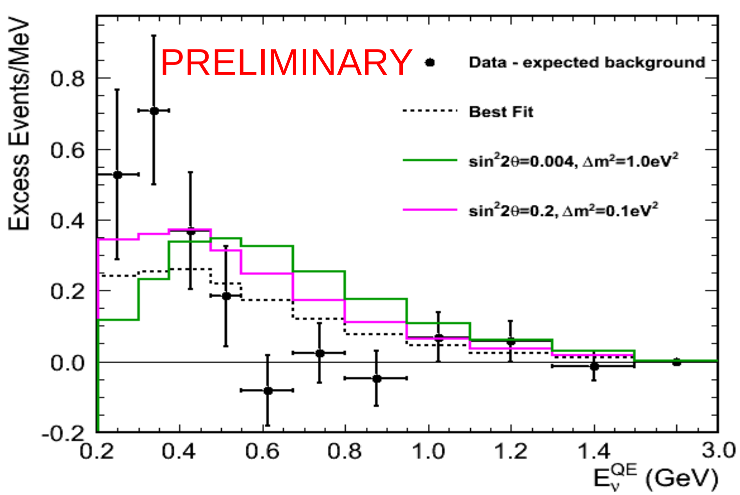


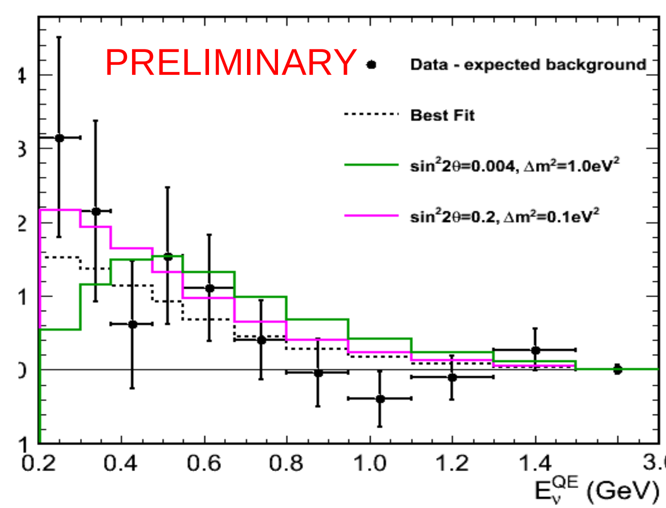
Combined ν and $\bar{\nu}$ analysis

- Consistent treatment of WS
- Full correlated systematic error matrix
- Excess (200-1250): 240±34.5±52.6 (3.8σ)
- Best Fit preferred over null at 3.6σ

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%

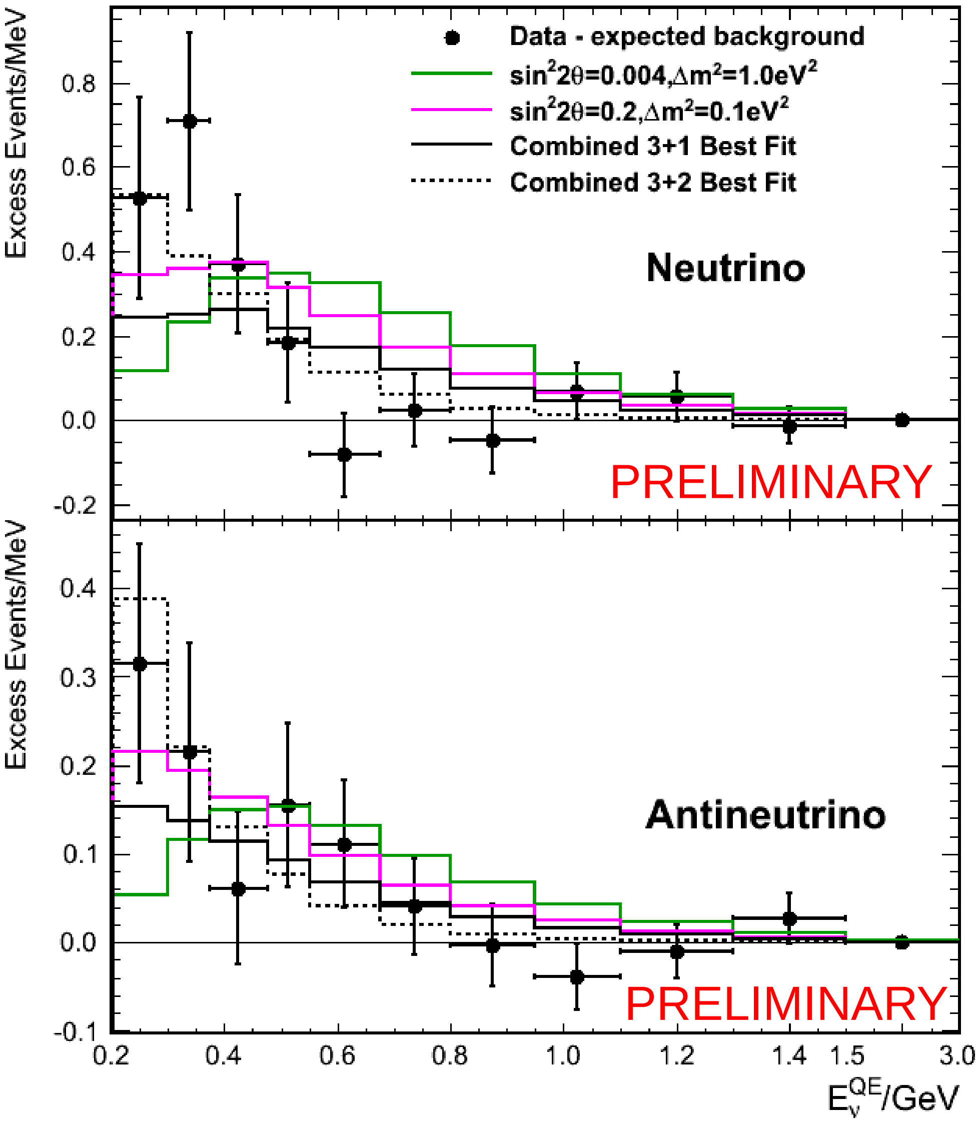






3+2 model

- 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)



Conclusion

- MiniBooNE observes an excess of nue candidates in the 200-1250 MeV energy range in neutrino mode (3.0σ) and in anti-neutrino mode (2.5σ)
- The combined excess is 240±34.5±52.6 (3.8σ)
- Some tensions in data within simple 2 neutrino oscillation model (3+1). Much better fit with 3+2 model.

- Collaboration considering merits of future running
  - Running under various configurations
  - Doubling neutrino mode POT running along with MicroBooNE

Backup

MiniBooNE Collaboration

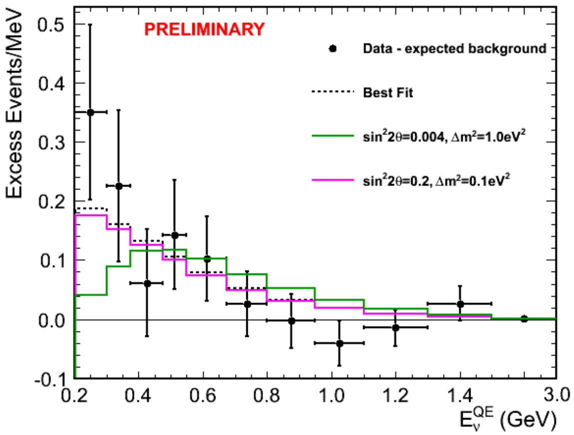
A. A. Aguilar-Arevalo[12], C. E. Anderson[15], S. J. Brice[6], B. C. Brown[6], L. Bugel[11], J. M. Conrad[11], Z. Djurcic[2], B. T. Fleming[15], R. Ford[6], F. G. Garcia[6], G. T. Garvey[9], J. Mirabal[9], J. Grange[7], J. A. Green[8,9], R. Imlay[10], R. A. Johnson[3], G. Karagiorgi[11], T. Katori[8,11], T. Kobilarcik[6], S. K. Linden[15], W. C. Louis[9], K. B. M. Mahn[5], W. Marsh[6], C. Mauger[9], W. Metcalf[10], G. B. Mills[9], C. D. Moore[6], J. Mousseau[7], R. H. Nelson[4], V. Nguyen[11], P. Nienaber[14], J. A. Nowak[10], B. Osmanov[7], Z. Pavlovic[9], D. Perevalov[1], C. C. Polly[6], H. Ray[7], B. P. Roe[13], A. D. Russell[6], M. H. Shaevitz[5], M. Sorel[5*], J. Spitz[15], I. Stancu[1], R. J. Stefanski[6], R. Tayloe[8], M. Tzanov[4], R. G. Van de Water[9], M. O. Wascko[10†], D. H. White[9], M. J. Wilking[4], G. P. Zeller[6], E. D. Zimmerman[4]

(The MiniBooNE Collaboration)

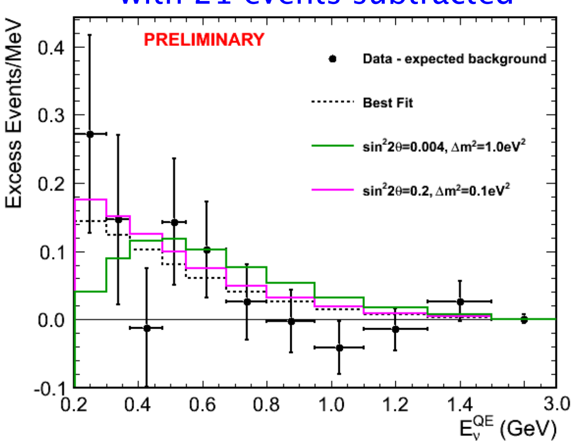
Account for neutrino low-E events

- Fits on prior page assume only anti-neutrinos are oscillating, but we know there is a low E excess in nu mode data
- Simplest scaling is to assume that there should be an excess in the low energy region proportional to the WS content (21 events)

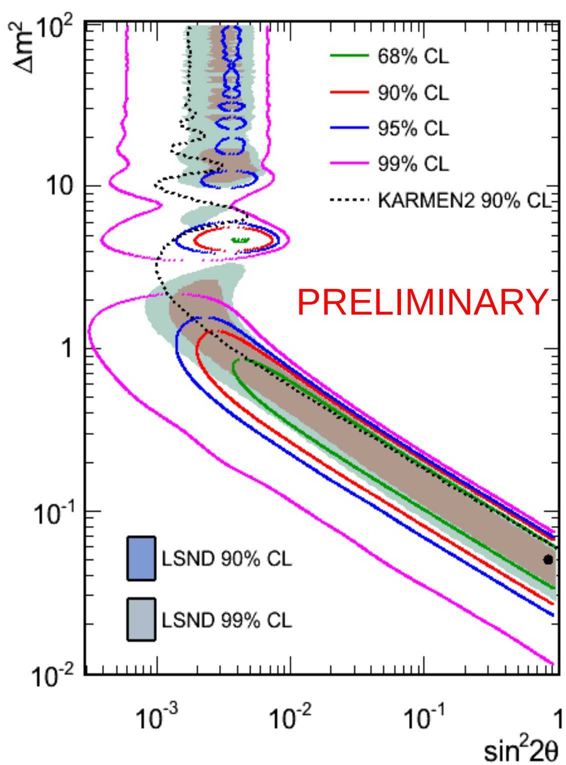
without 21 events subtracted



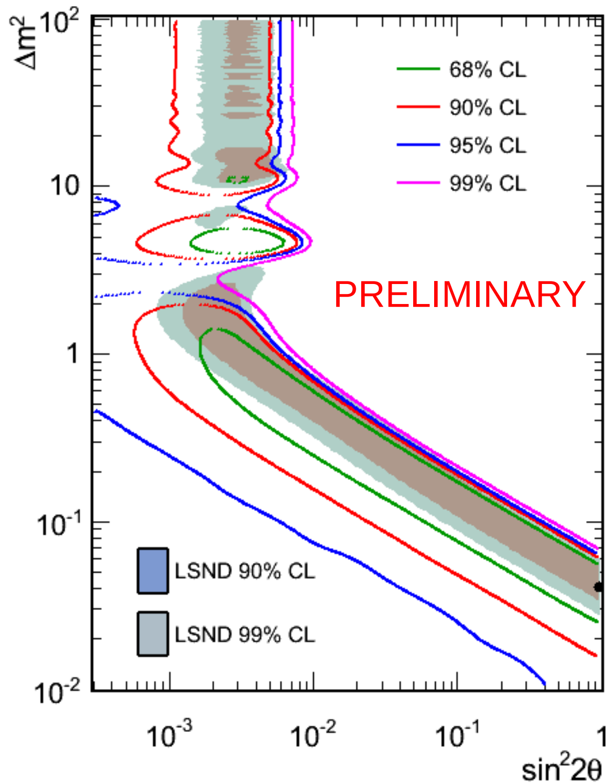
with 21 events subtracted



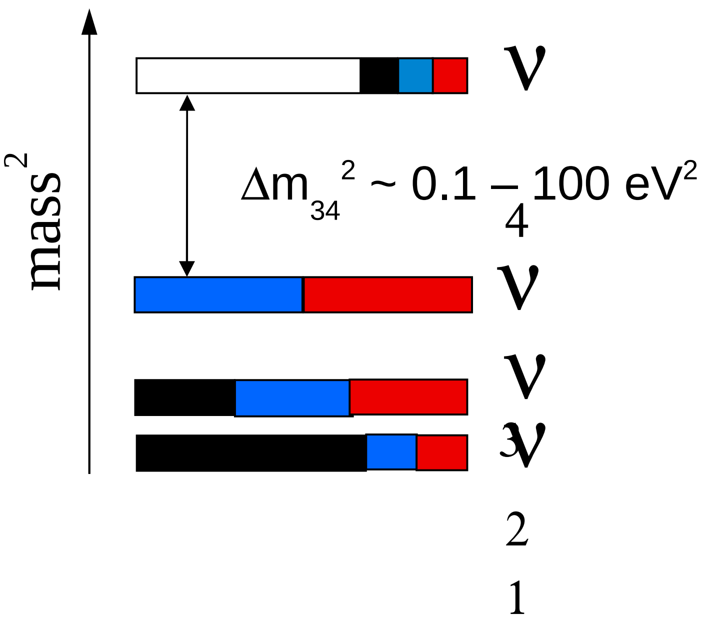
without 21 events subtracted



with 21 events subtracted



Sterile neutrinos



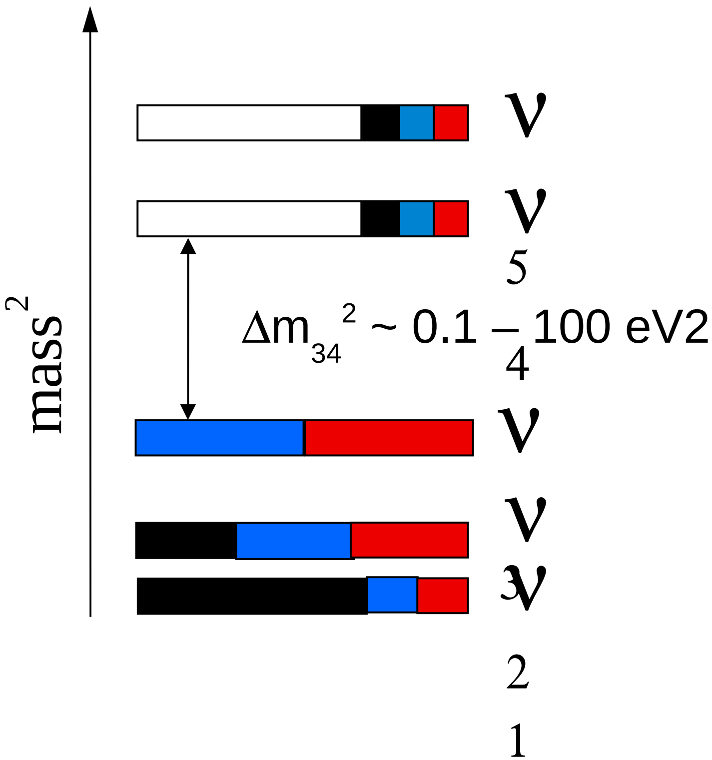
- 3 active neutrinos + 1 sterile neutrino
- Sterile neutrino has no Standard Model interactions
- Active neutrinos can oscillate into sterile
- 3 parameters relevant for short baseline exp.: Δm_{41}^2, $|U_{e4}|$ and $|U_{\mu4}|$

$$P(\nu_\mu \rightarrow \nu_e) = 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2(1.27\,\Delta m_{41}^2\, L/E)$$

$$P(\nu_e \rightarrow \nu_e) = 1 - 4|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \sin^2(1.27\,\Delta m_{41}^2\, L/E)$$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \sin^2(1.27\,\Delta m_{41}^2\, L/E)$$

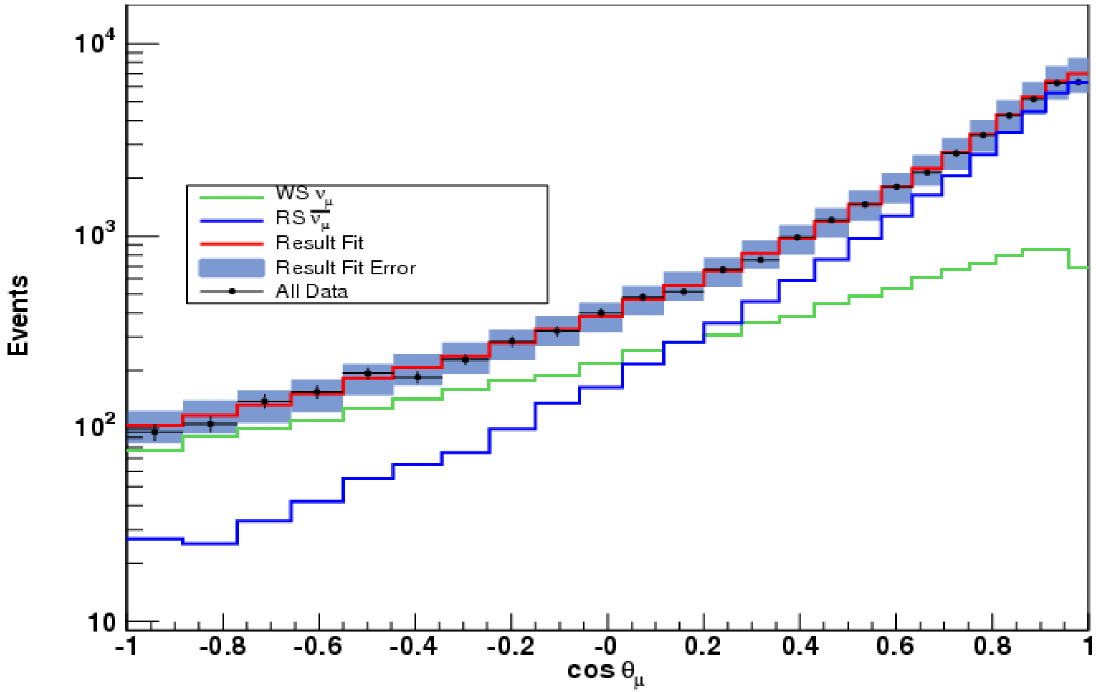
More sterile neutrinos

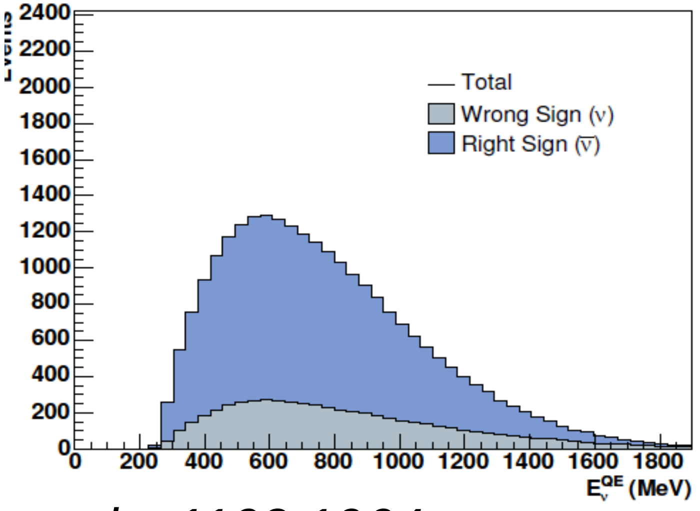


- Next minimal extension 3+2 models
- Favored by fits to world data
- Model allows CP violation
  - $\nu_\mu \rightarrow \overline{\nu}_e \neq \overline{\nu}_\mu \rightarrow \nu_e$

Signal prediction

- Assuming only right sign oscillates ($\bar{\nu}_\mu$)
- Need to know wrong sign vs right sign
- $\bar{\nu}_\mu$ CCQE gives more forward peaked muon





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