MiniBooNE/BooNE+

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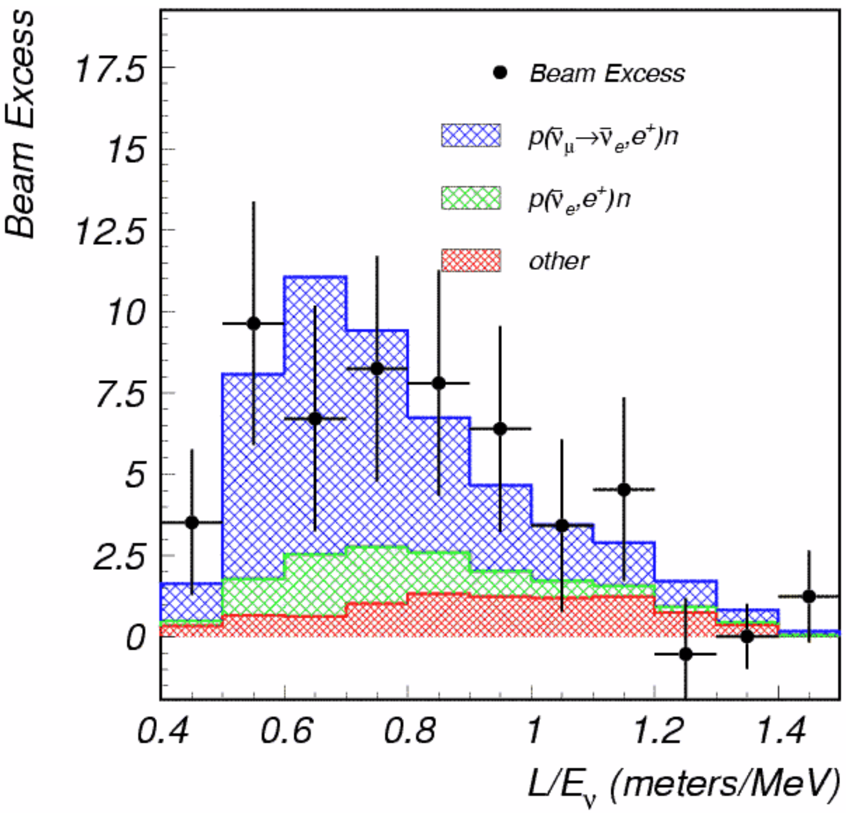
MiniBooNE motivation

- LSND
- Evidence for oscillations at higher Δm^2 than atmospheric and solar
- Stopped pion beam
  $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  $\quad\quad \hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- 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 (3.8s)

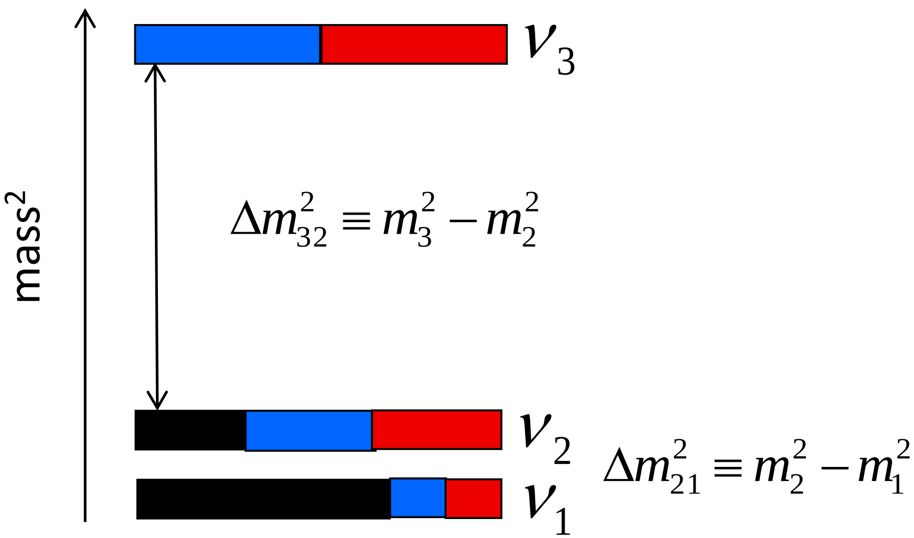


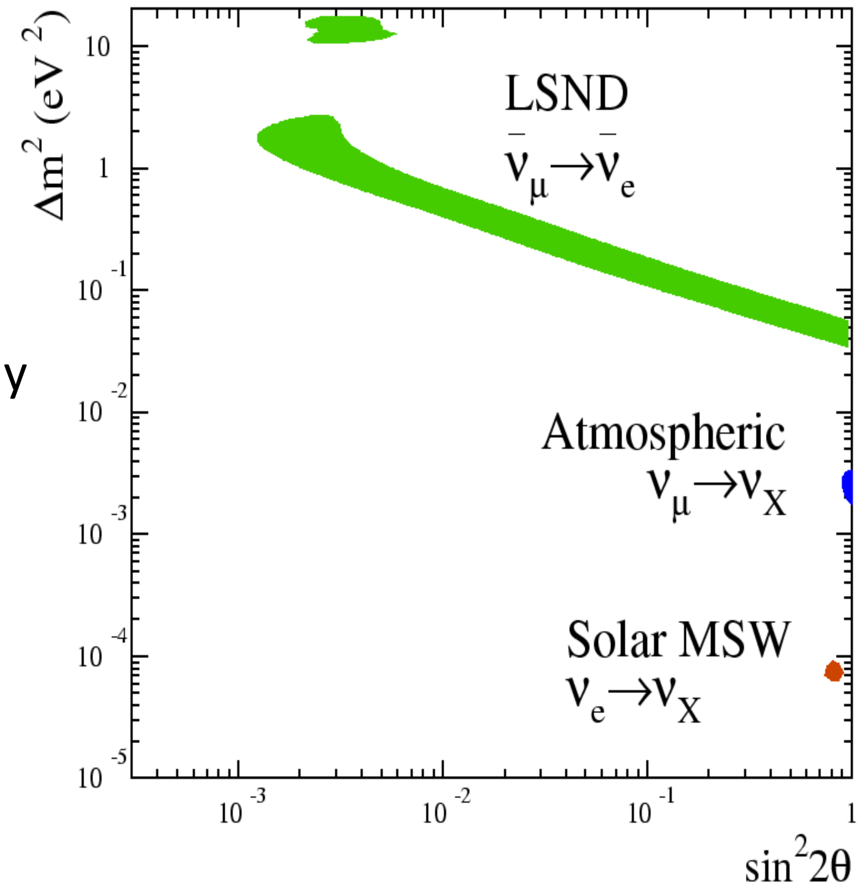
LSND signal

- Assuming two neutrino oscillations

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

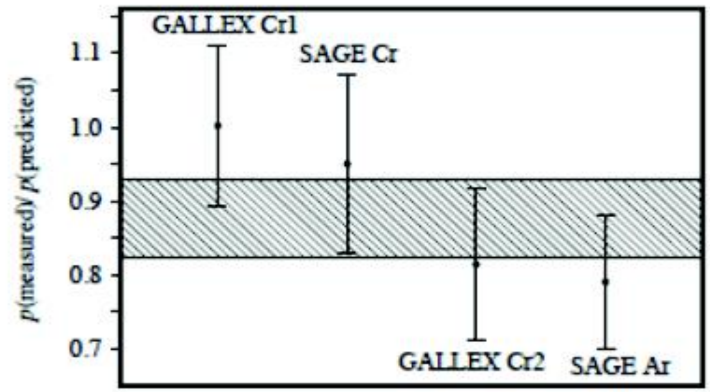
- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splitings

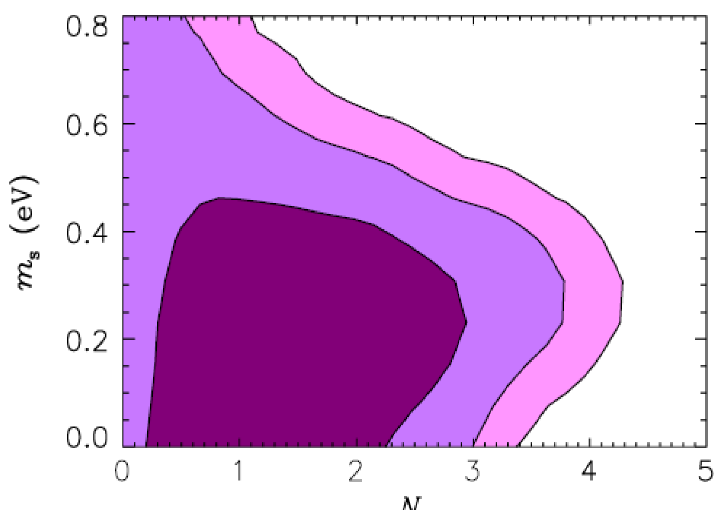




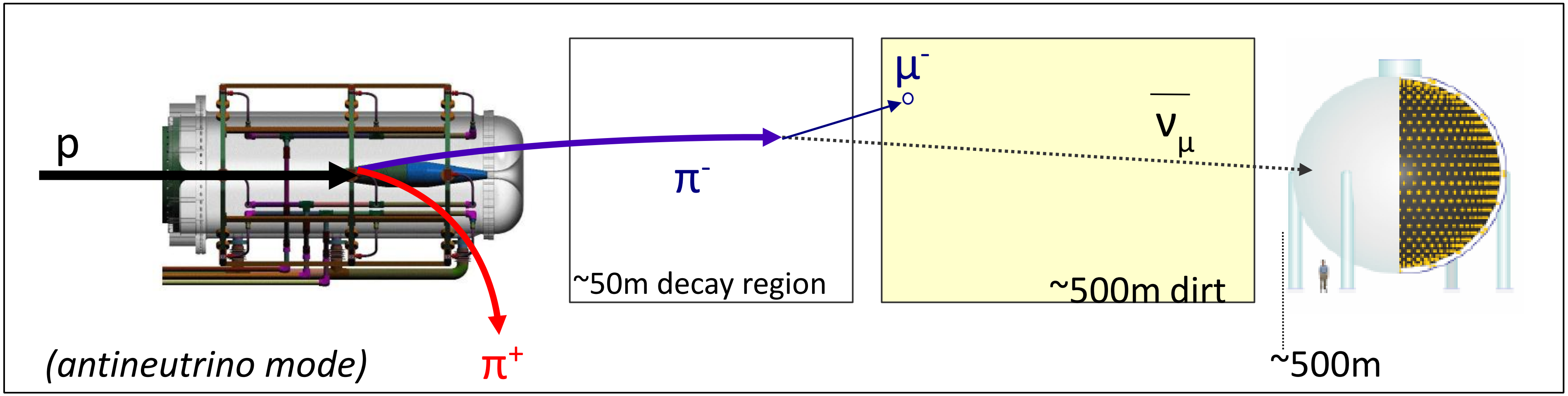
Other hints

- Reactor anomaly
  - R=meas/pred=0.943 ± 0.023
  - P_{osc}~10%, Δm^2~1eV^2
- Solar calibration experiments
  - R=meas/pred = 0.86 ± 0.06
- Cosmology





Booster Neutrino Beam



- 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

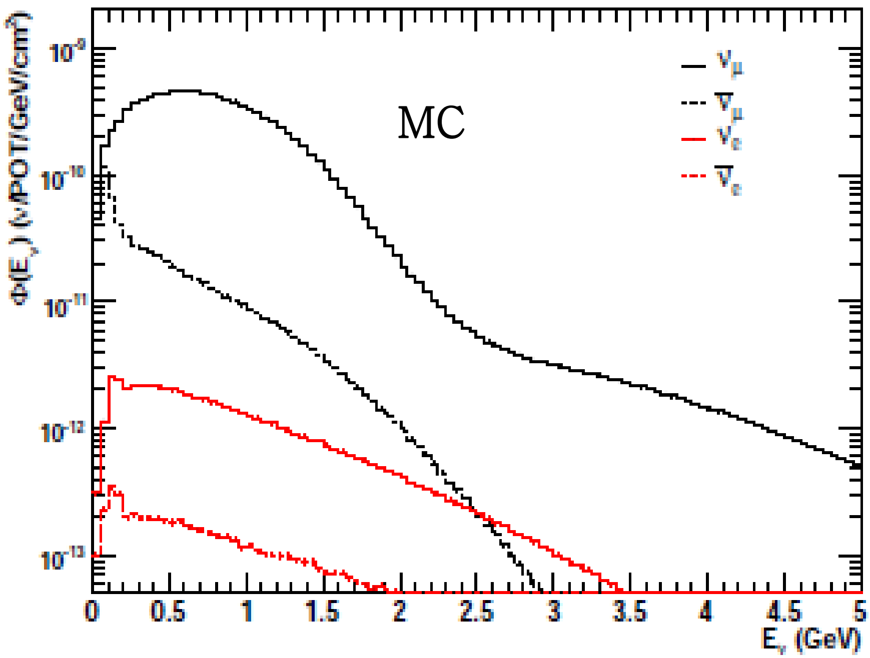
Predicted neutrino flux (MC)

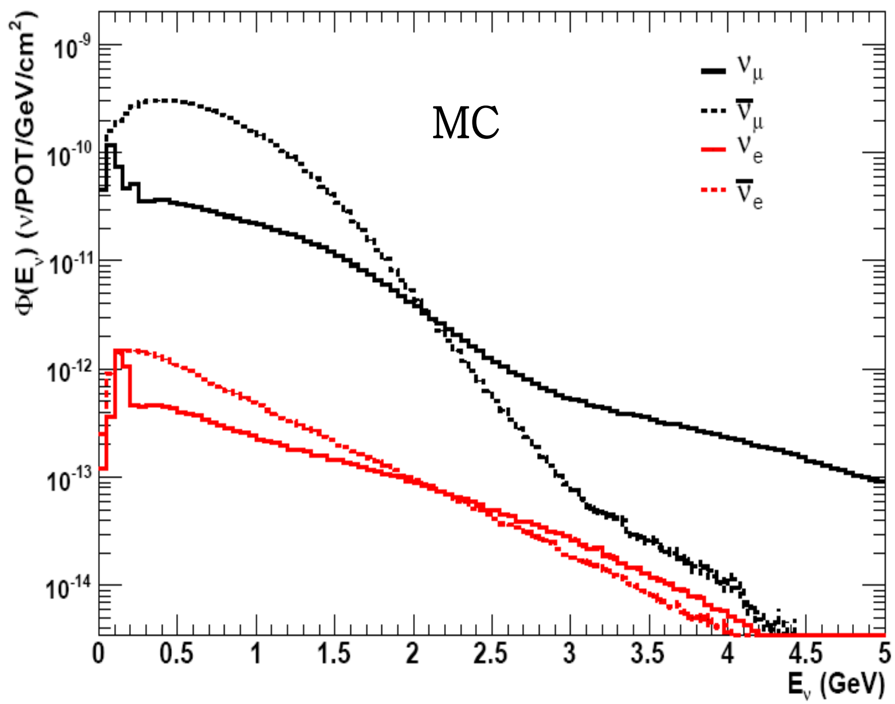
- Neutrino mode

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%

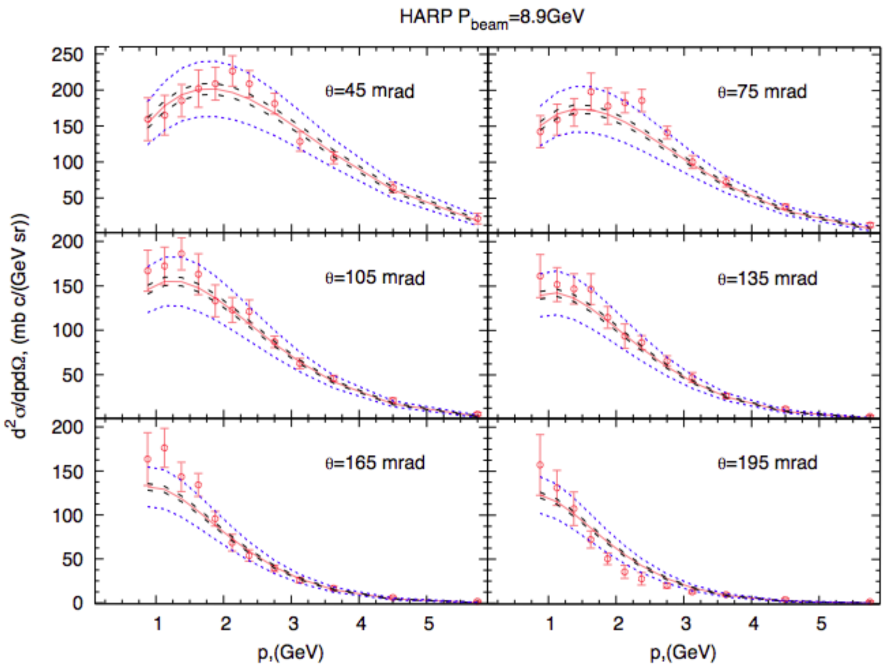




Phys. Rev. D79, 072002 (2009)

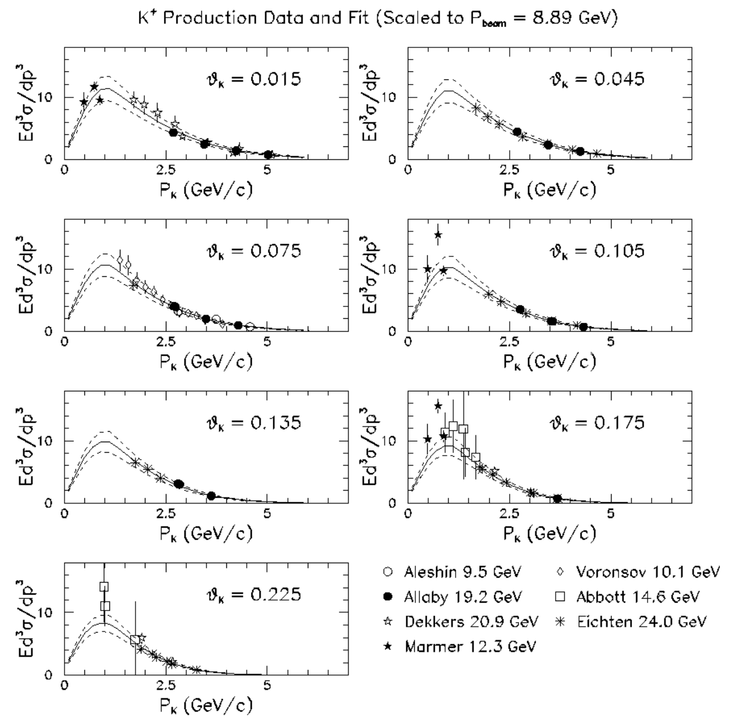
Hadron production

Pions



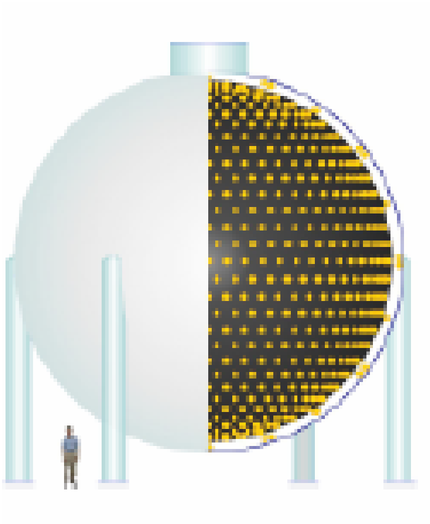
- Using HARP data
  - 8 GeV protons on 5% Be target
- Spline fits to parameterize the data

Kaons



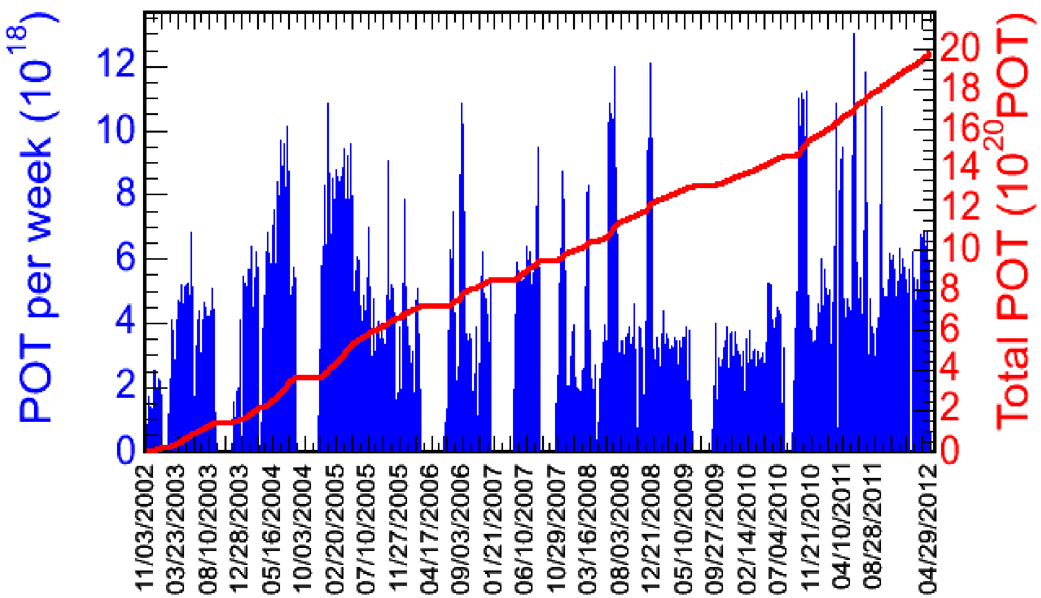
- Kaon data taken on multiple targets in 10-24 GeV range
- Fit to world data using Feynman scaling
- 30% overall uncertainty assesed

MiniBooNE



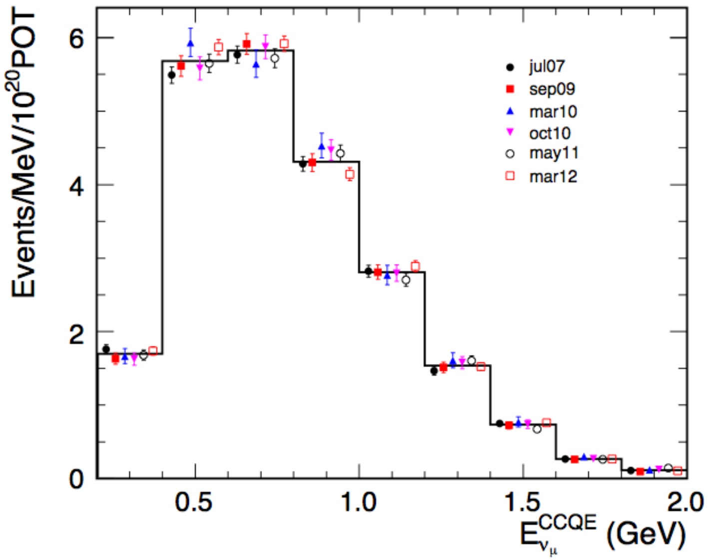
- One detector experiment
- 800t mineral oil Cherenkov detector
- 1520 PMTs in inner/outer region

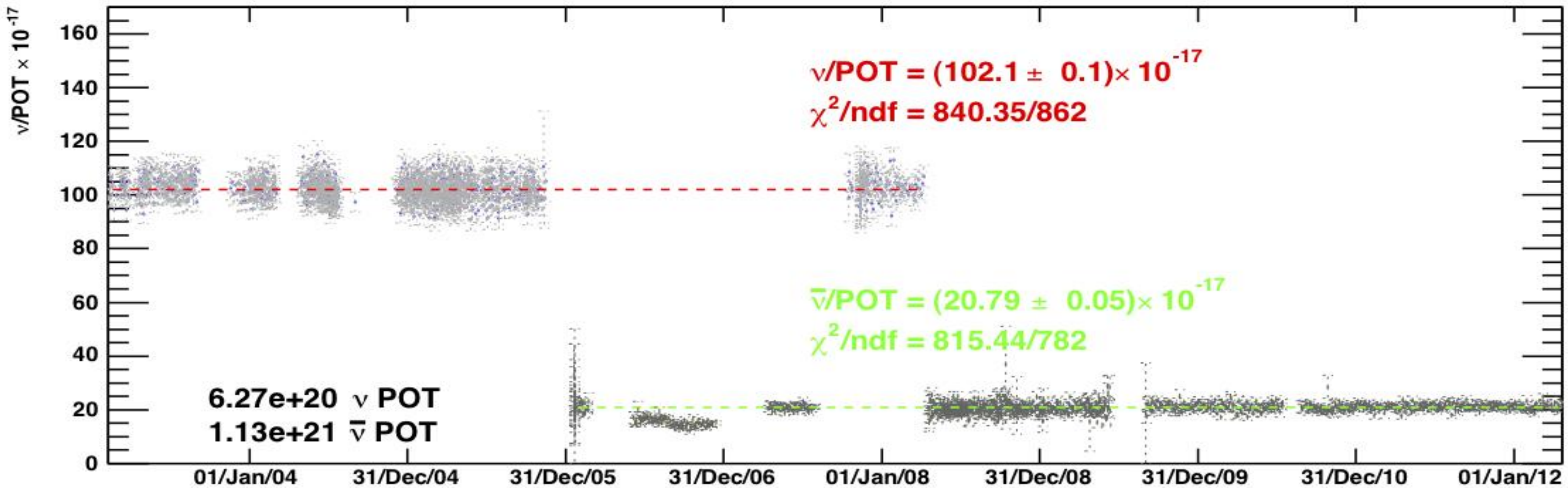
- Data taking: 2002-2012
- Total POT 19.8×10^{20}
- Neutrino: 6.5×10^{20}
- Antineutrino: 11.3×10^{20}



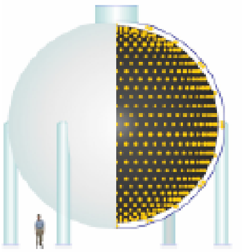
10 years of running

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



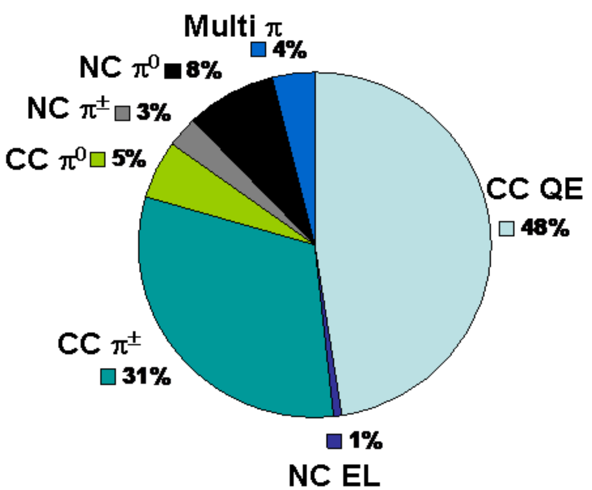


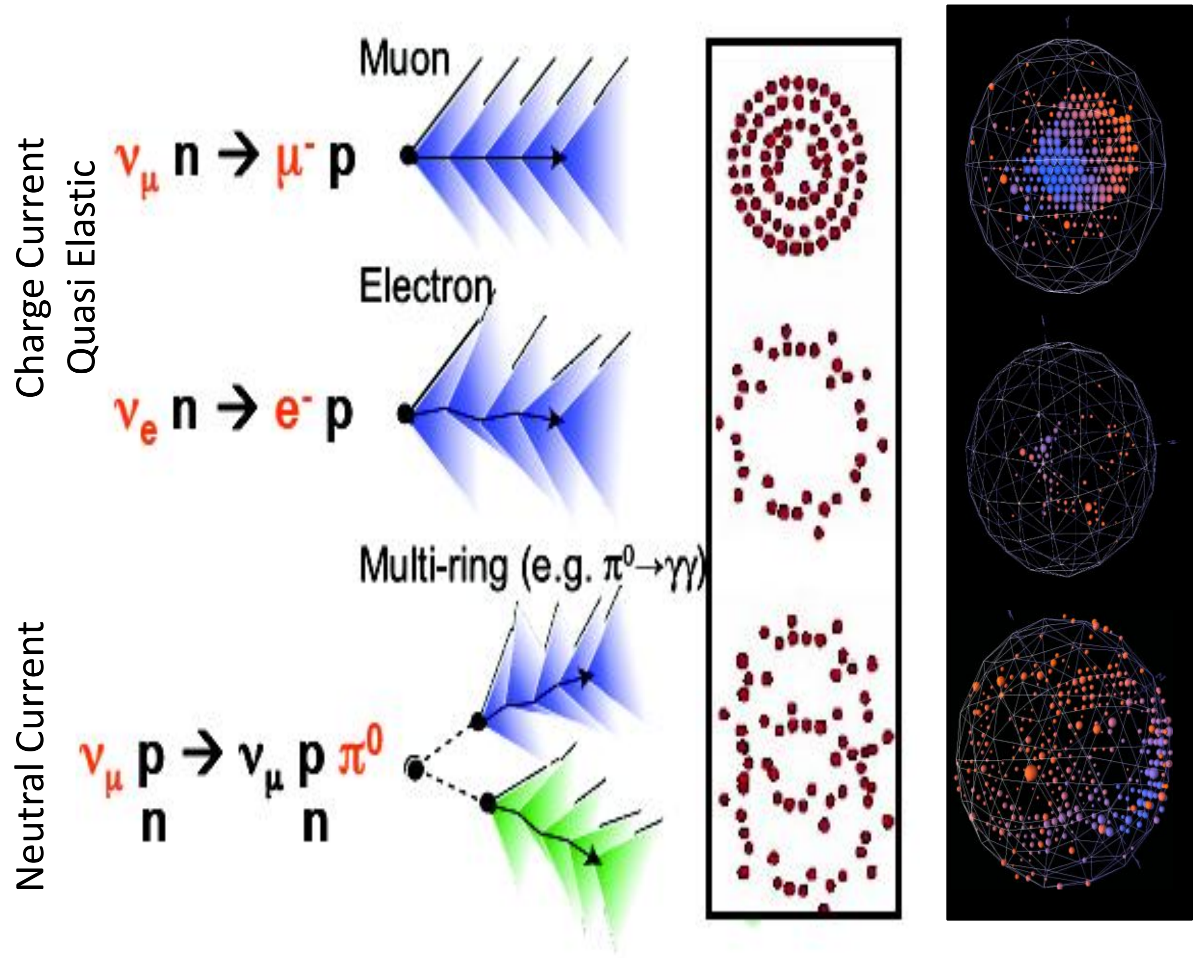
Events in MB



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

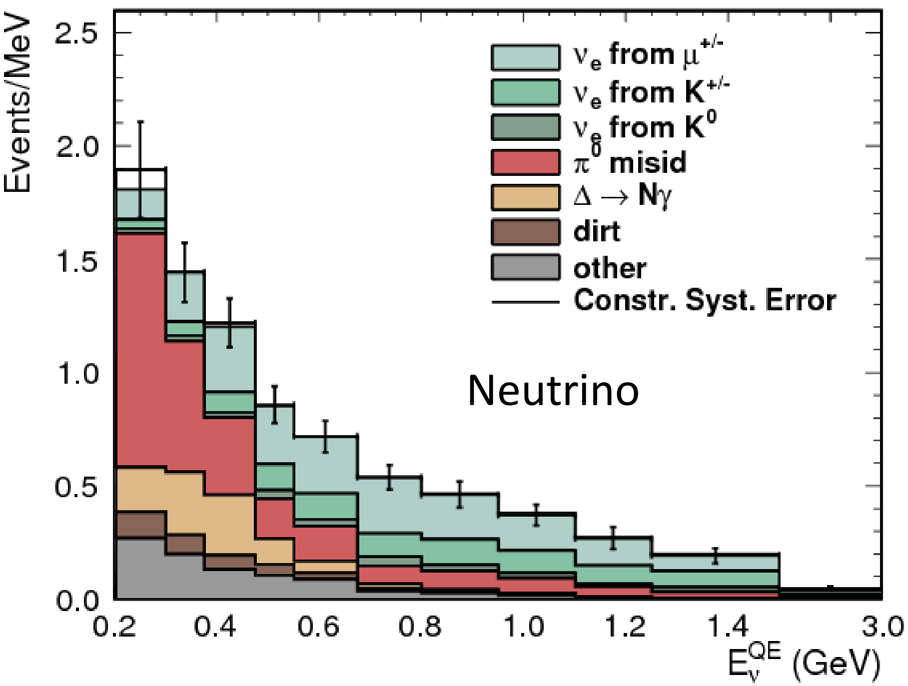
Interactions in MiniBooNE (neutrino mode):

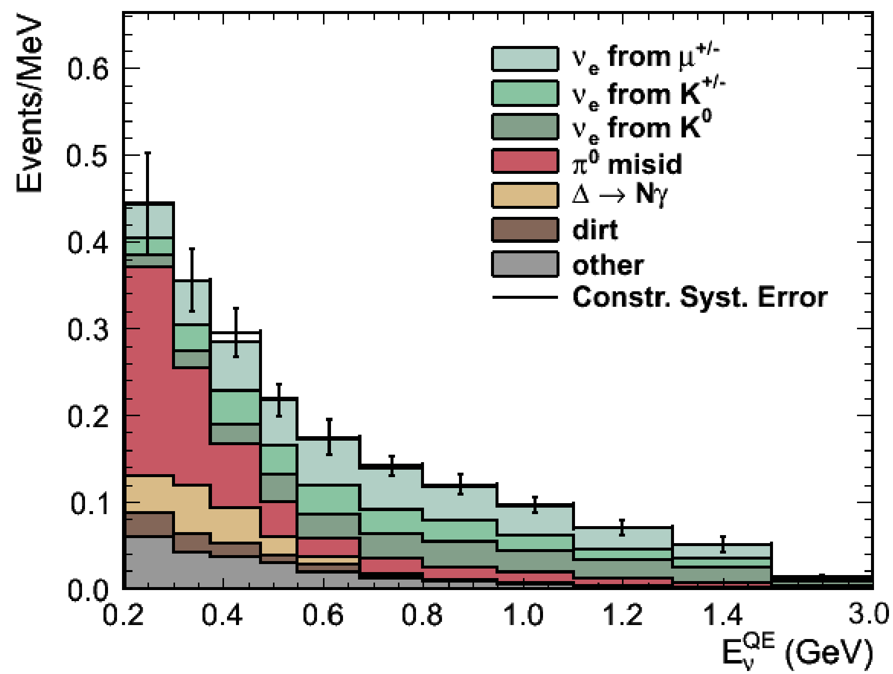




ν_e CCQE Backgrounds

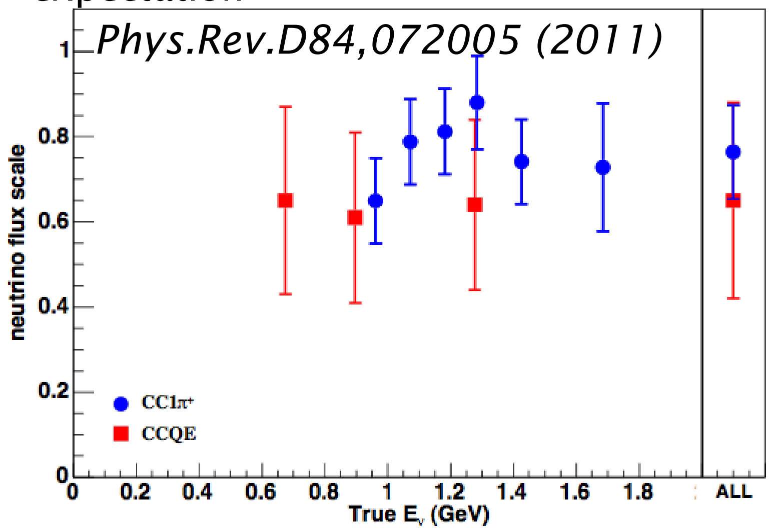
- Similar backgrounds in neutrino (left) and antineutrino mode (right)
- Use both MiniBooNE and external data to constrain each background

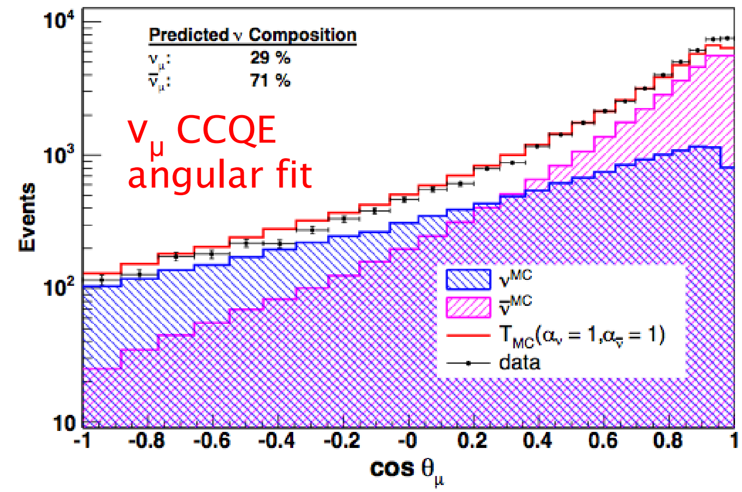




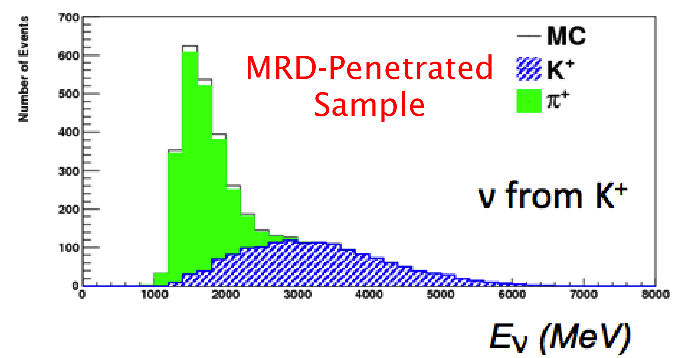
What's new since last oscillation publication?

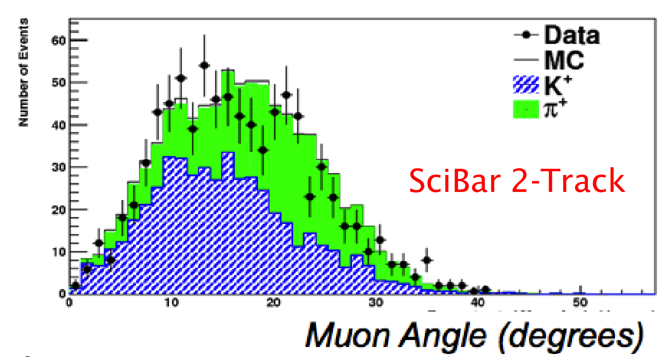
- *In situ* measurement of WS contamination in anti-ν beam
  - ν_μ CCQE angular fit, and new constrain from CCπ+ rate…good agreement with expectation





- 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

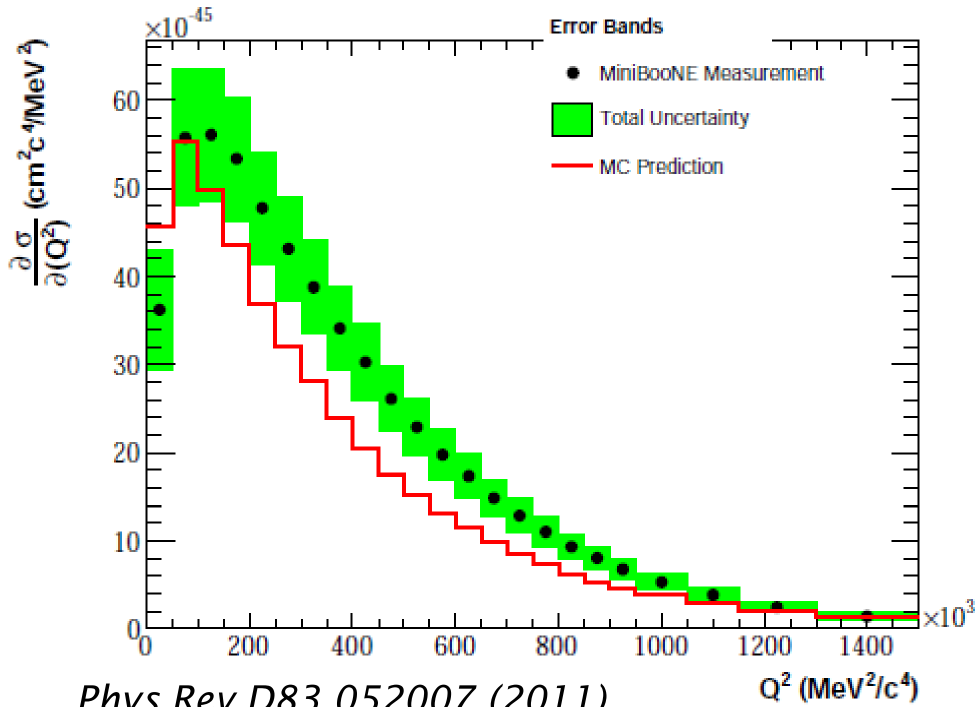




Phys.Rev.D84,012009 (2011)

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

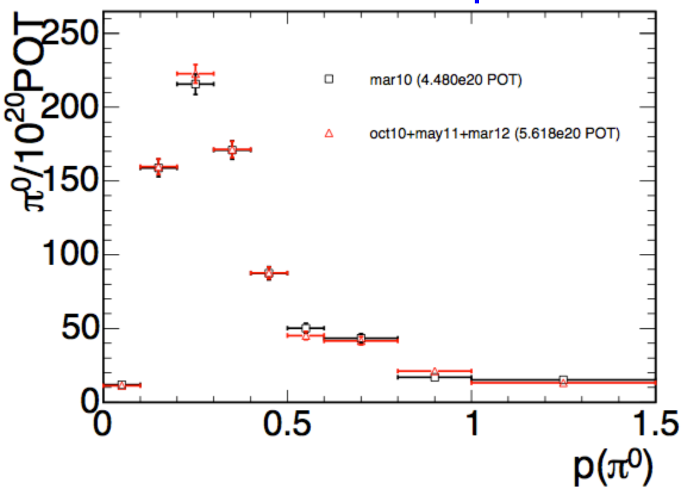


Phys.Rev.D83,052007 (2011)

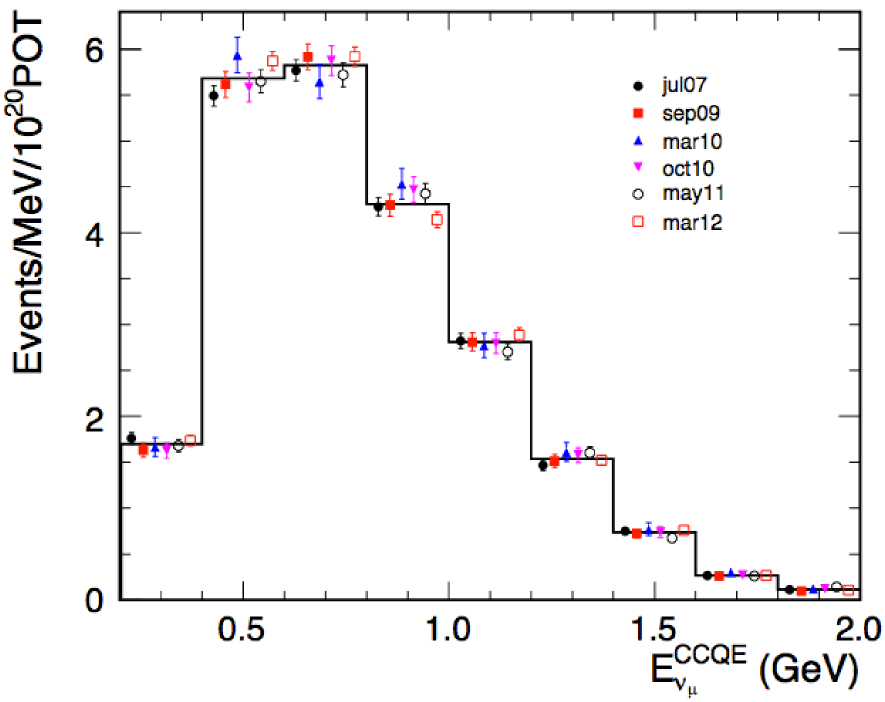
Main improvement…doubling of anti-ν stats

- 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

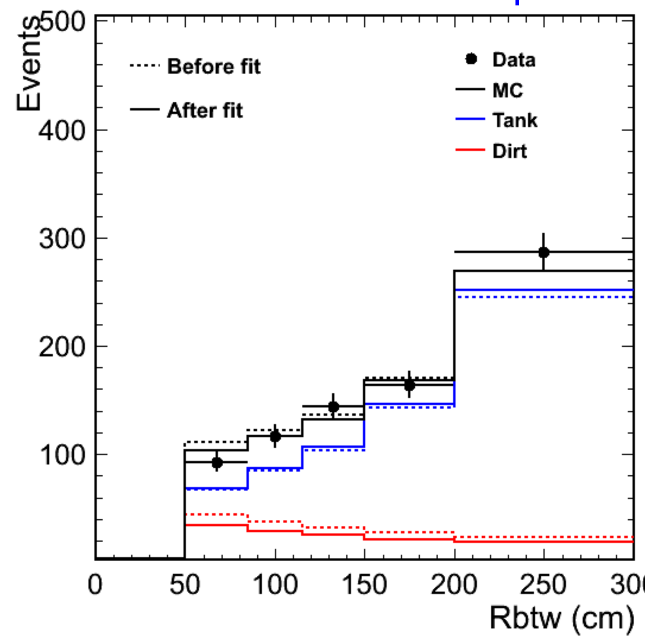
NC π^0 Sample



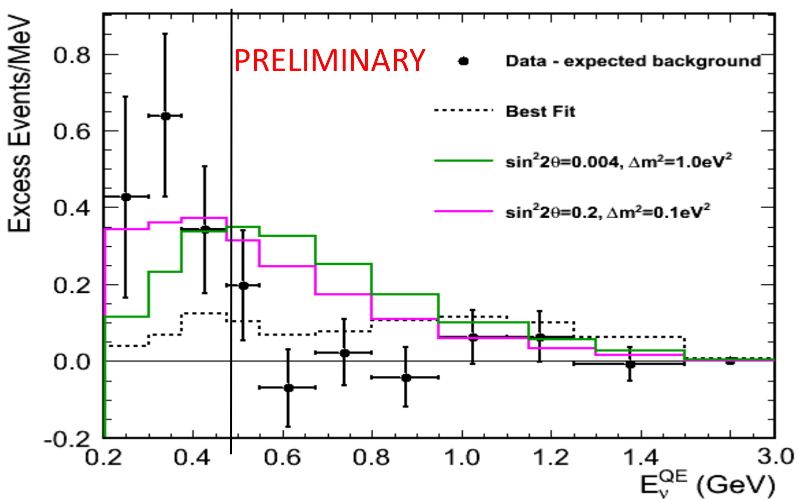
anti-ν_μ CCQE Sample

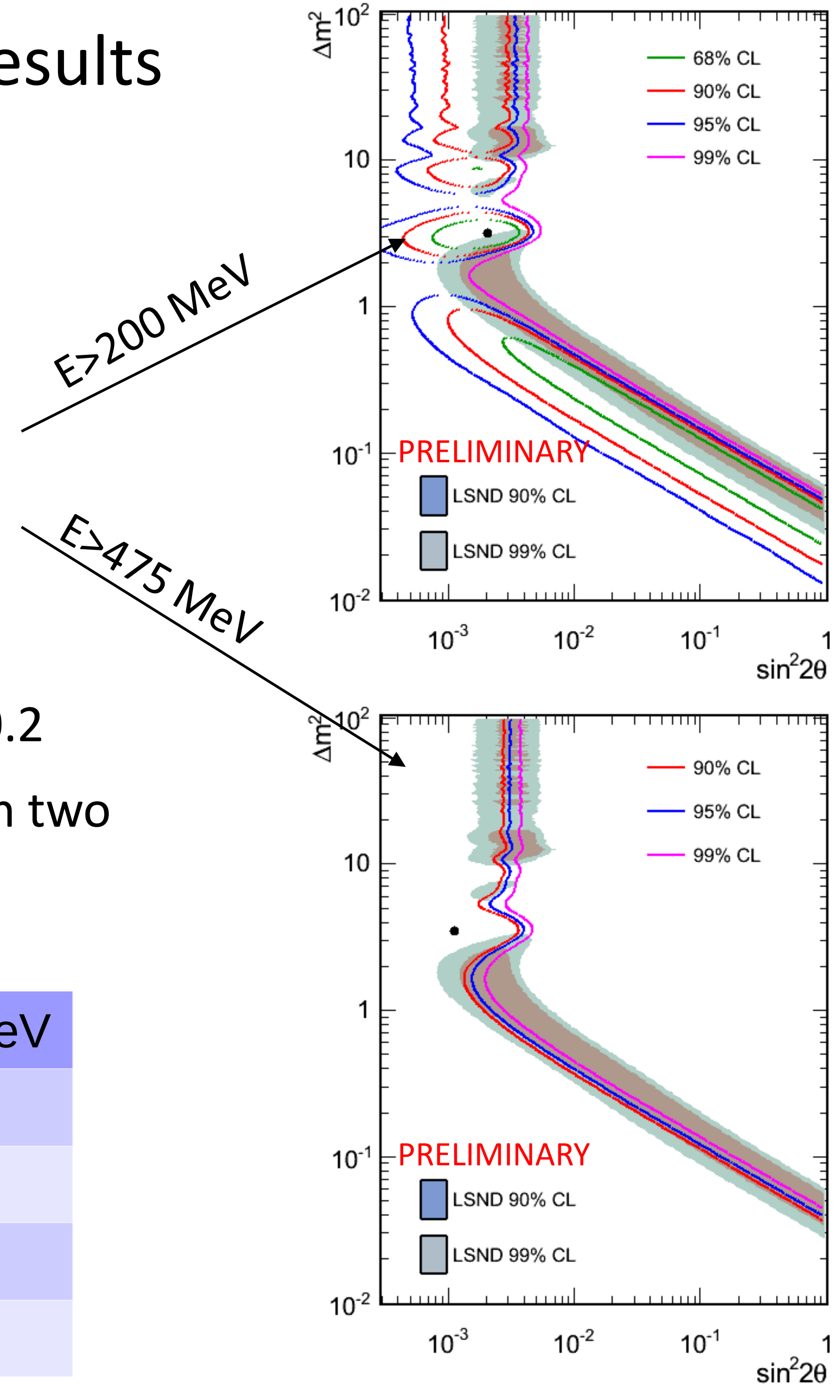


Dirt-enhanced Sample



Updated Neutrino Appearance results



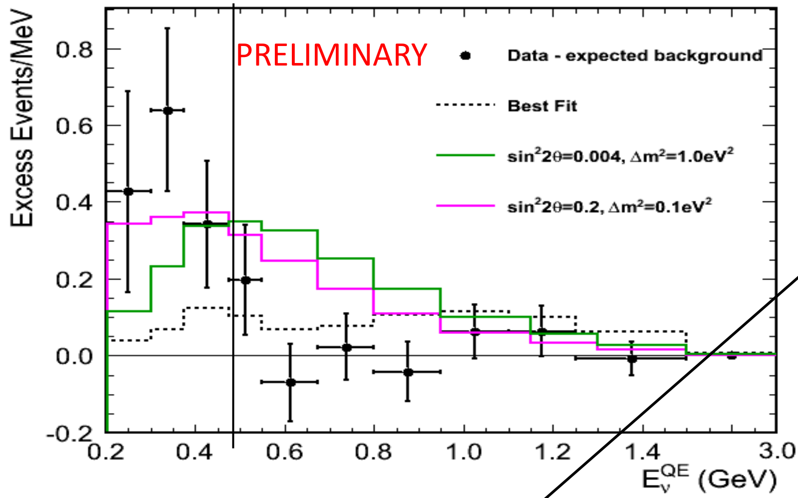


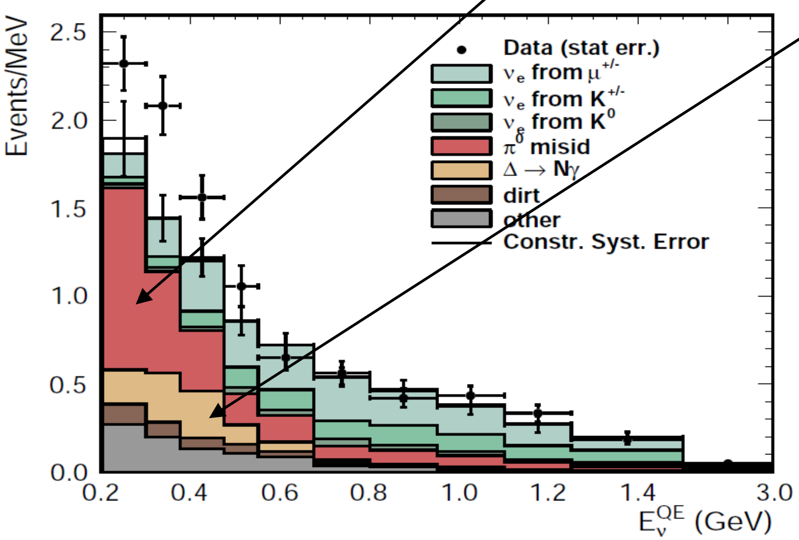
- Excess (200-1250 MeV): 146.3±28.4±40.2
- Some tension between 3+1 model fits in two energy regions (1.4% probability to see 3.73→13.24 when including low E)

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

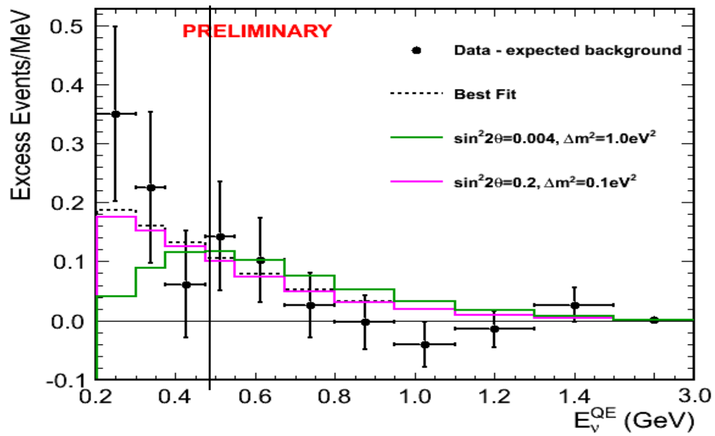




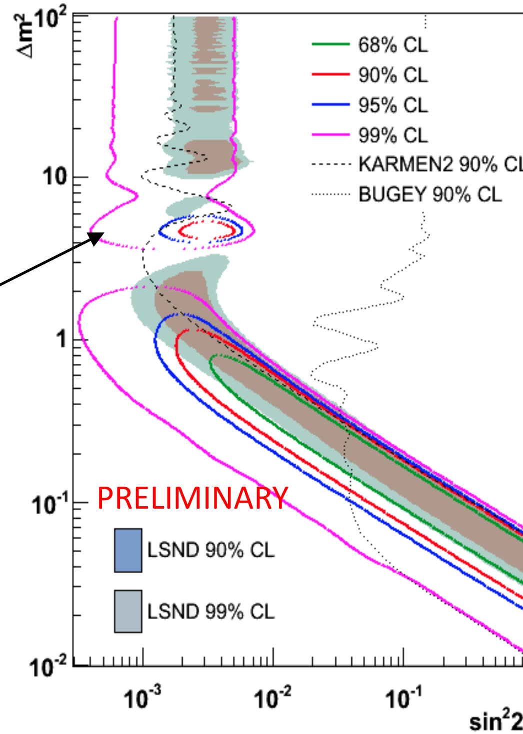
- Not a stat fluctuation, statistically 6σ
- Unlikely to be intrinsic ν_e, small bkg at low E
- NC π^0 background dominates
  - Reduces significance to 3σ
  - Heavily constrained by NC π^0 *in situ* measurement
- Region where single ・ can contribute
- MB ties $\Delta \rightarrow N\gamma$ expected rate to be 1% of measured NC π^0 rate
  - Number of theory calculations for various single ・ processes
  - All find total cross section within 20% of MB ~5x10^{-42} cm^2/N
  - Would need nearly 300% change

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

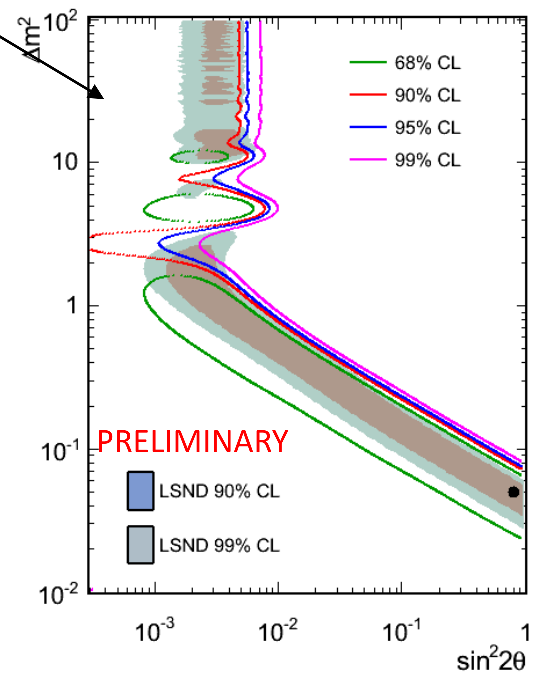
Antineutrino Appearance results
11.3×10^{20} POT



E>200 MeV



E>475 MeV

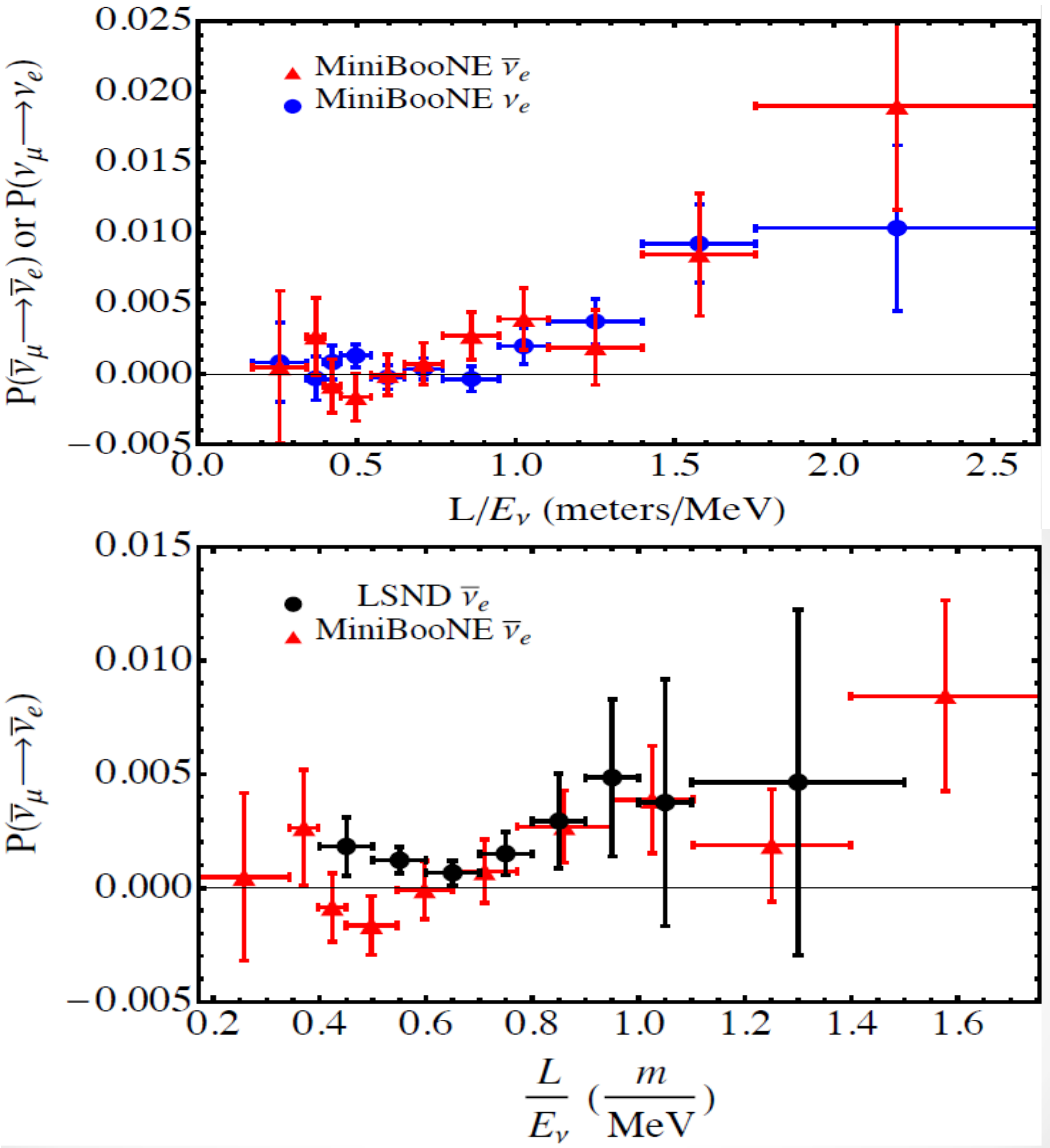


- Excess (200-1250 MeV):77.8±20.0±23.4
- No tension between fits in two energy regions
- Caveat: WS ν_μ assumed not to oscillate

anti-ν mode	E > 200 MeV	E > 475 MeV
χ^2(null)	16.3	7.59
Prob(null)	5.8%	26.4%
χ^2(bf)	4.76	3.23
Prob(bf)	67.5%	50.2%

L/E dependence

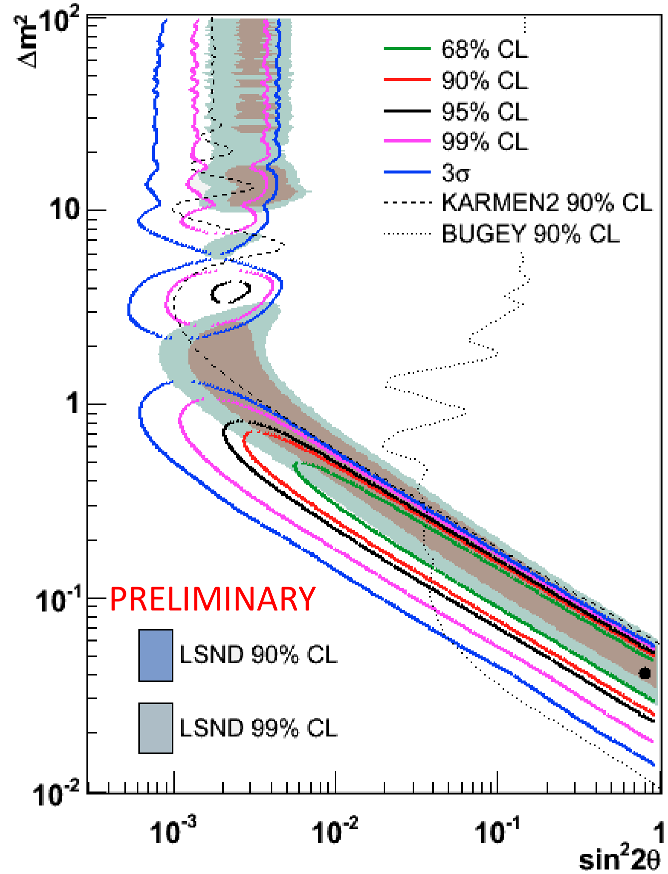
- Model independent look at the data
- The excess as a function of L/E in MiniBooNE neutrino, antineutrino and LSND data consistent

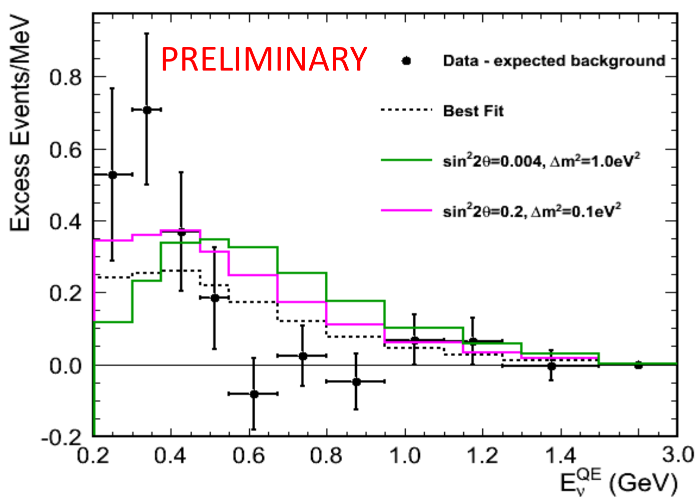


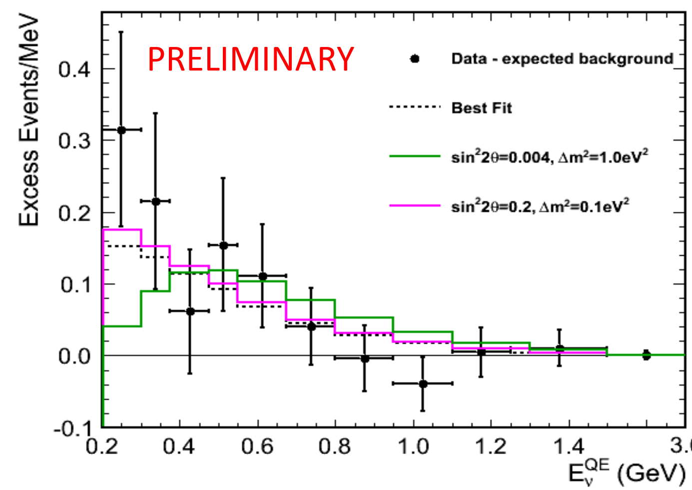
Combined ν and $\bar{\nu}$ analysis

- 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%

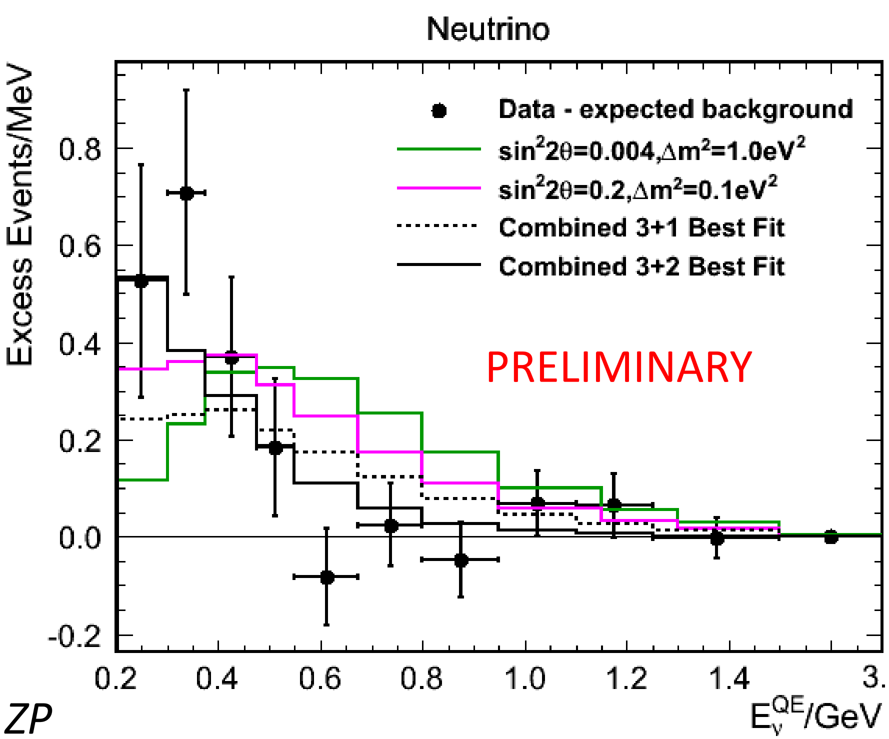


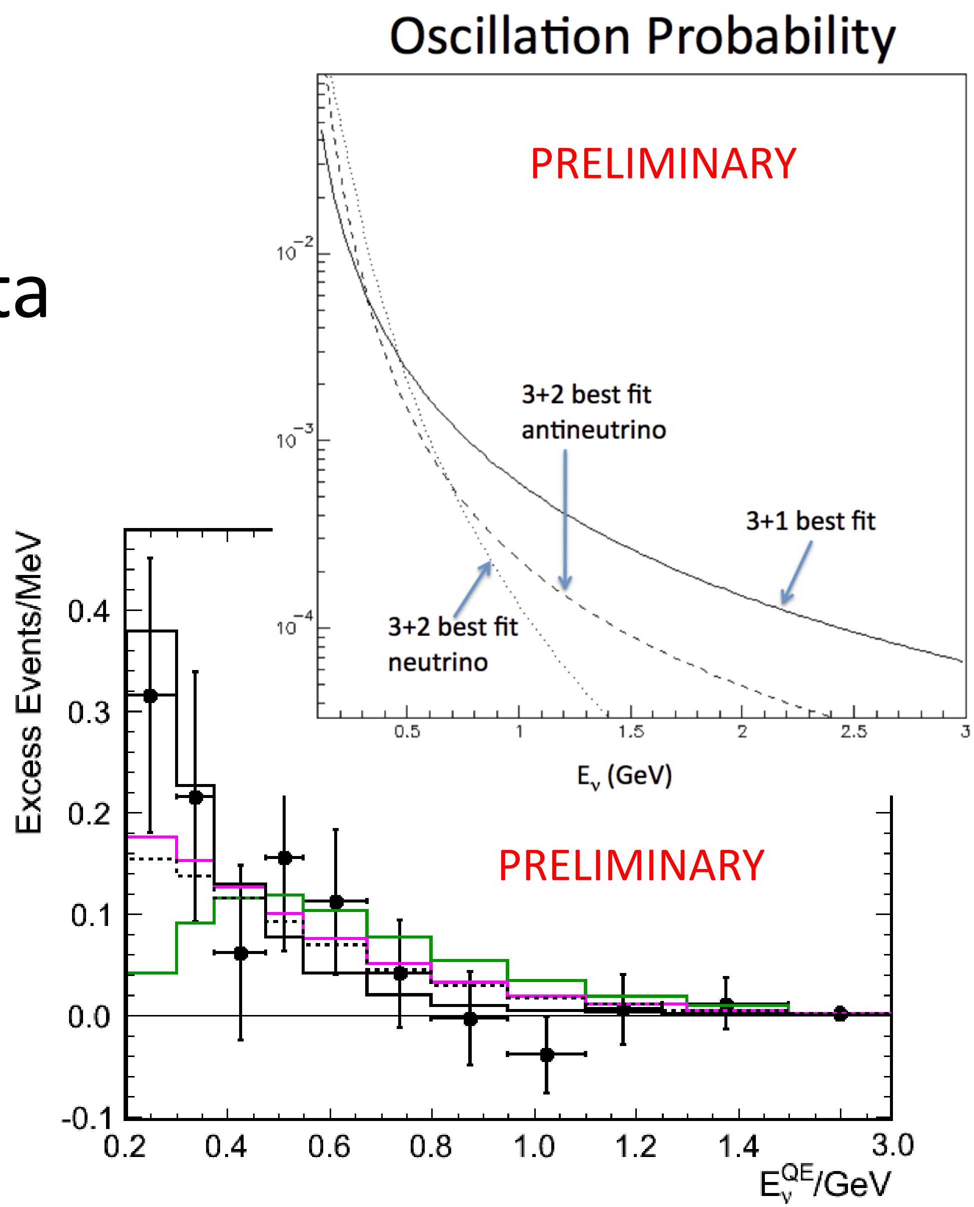




3+2 model

- CP violation
- Better fit to world data





ZP

3+N models require large ν_μ disappearance

- In general:

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) < \frac{1}{4} P(\overline{\nu}_\mu \to \overline{\nu}_x) P(\overline{\nu}_e \to \overline{\nu}_x)$$

- From reactor experiments:

$$P(\overline{\nu}_e \to \overline{\nu}_x) \sim 10\%$$

- From LSND/MiniBooNE:

$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \sim 0.25\%$$

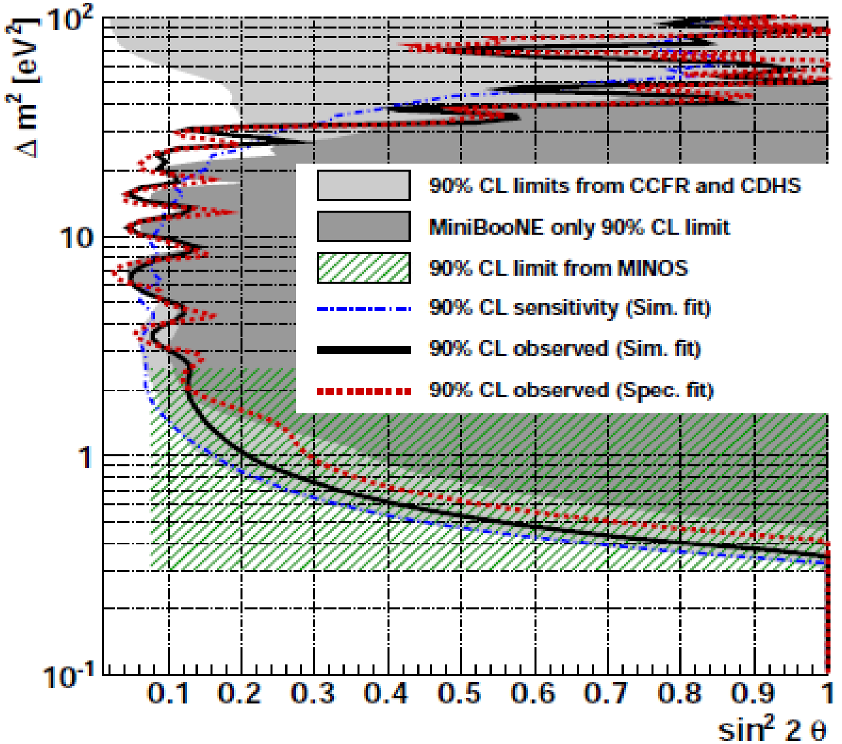
- Therefore:

$$P(\overline{\nu}_\mu \to \overline{\nu}_x) > 10\%$$

*Assuming light neutrinos are mostly active and sterile neutrinos are heavy

Combined ν_μ disappearance

- Joint SciBooNE/MiniBooNE analysis
- SciBooNE at 100m serves as near detector
- Compatible with no oscillations

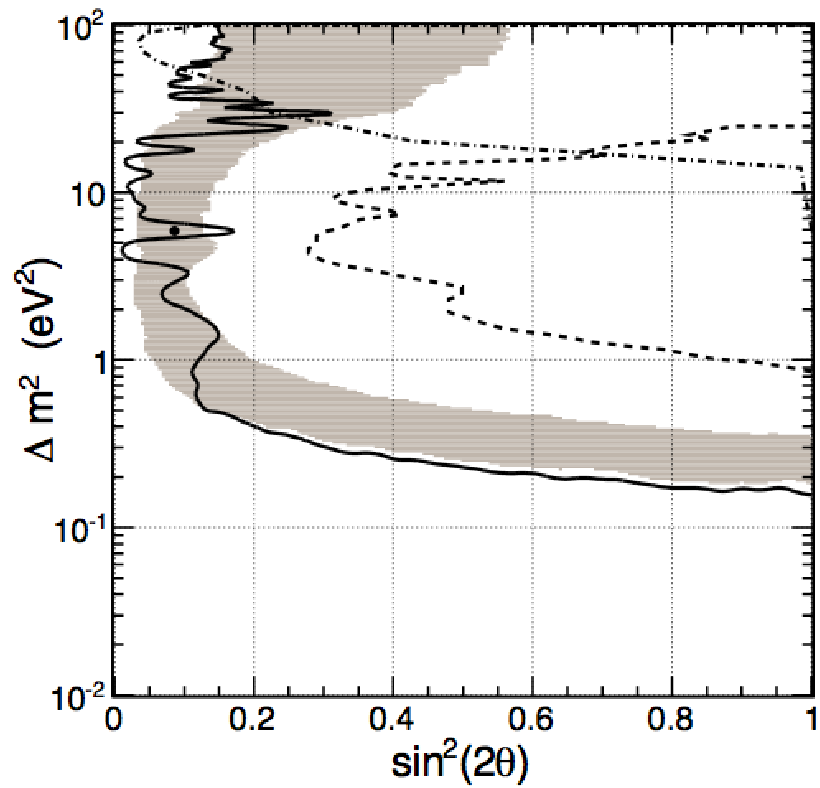


arxiv:1106.5685

Combined $\bar{\nu}_\mu$ disappearance

- Joint SciBooNE/MiniBooNE analysis
- Compatible with no oscillations
- BF point $\Delta m^2 = 5.9\ eV^2$, $\sin^2 2\theta = 0.086$
- $\chi^2 = 40.0$ (probability 47.1%) at the best fit point
- $\chi^2 = 43.5$ (probability 41.2%) for the null hypothesis

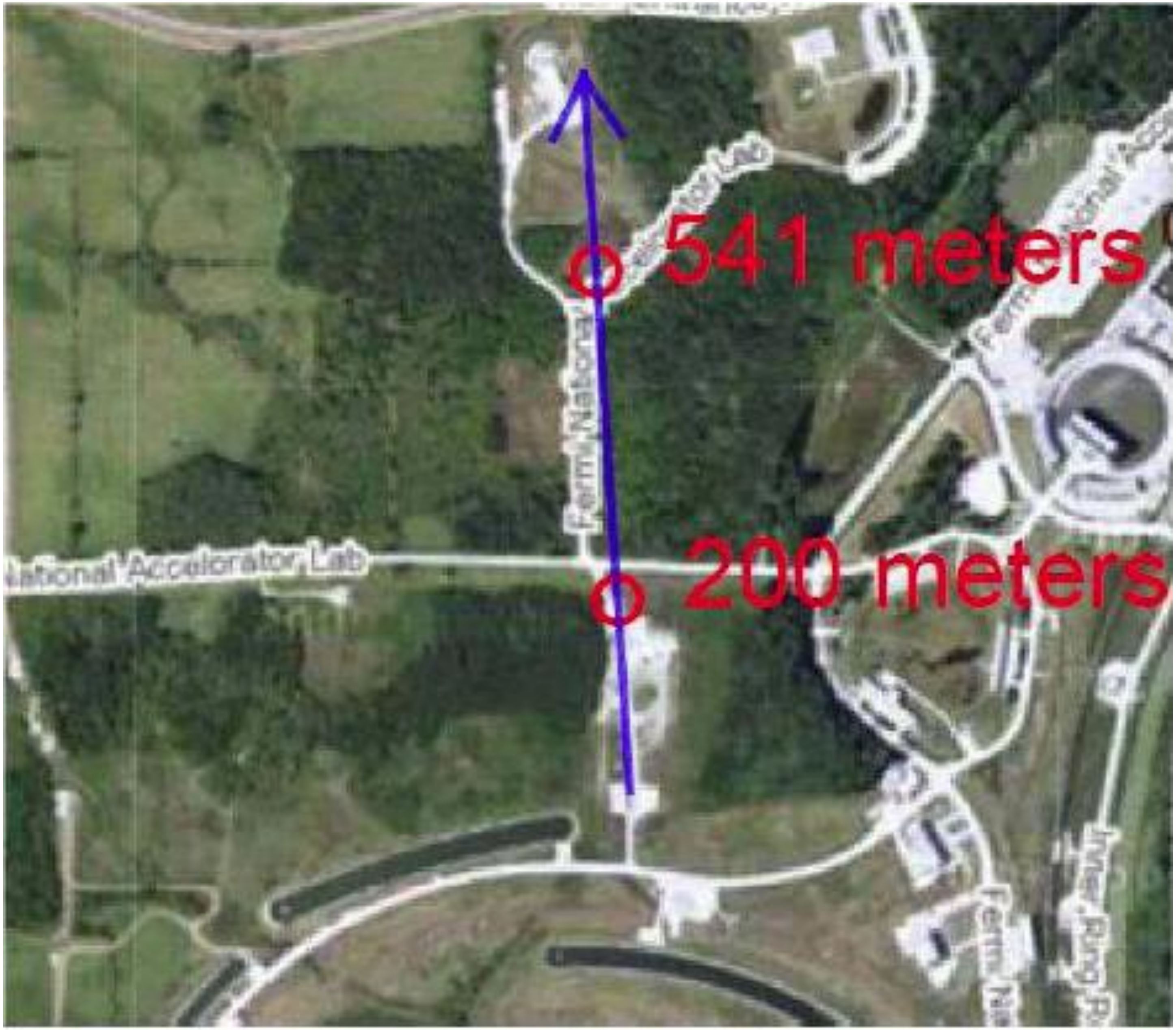
- Probabilities are based on fake data studies



G. Cheng, W. Huelsnitz

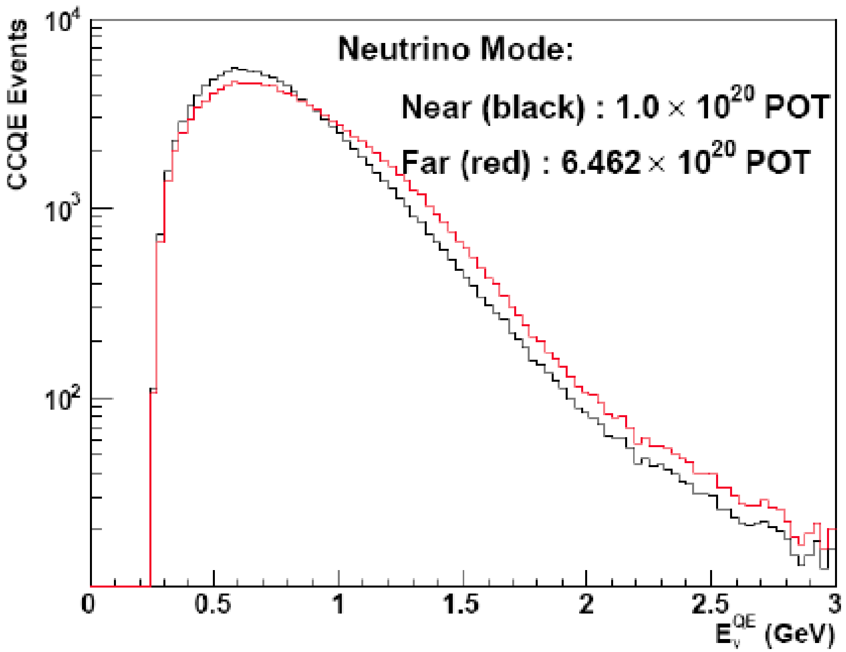
BooNE+

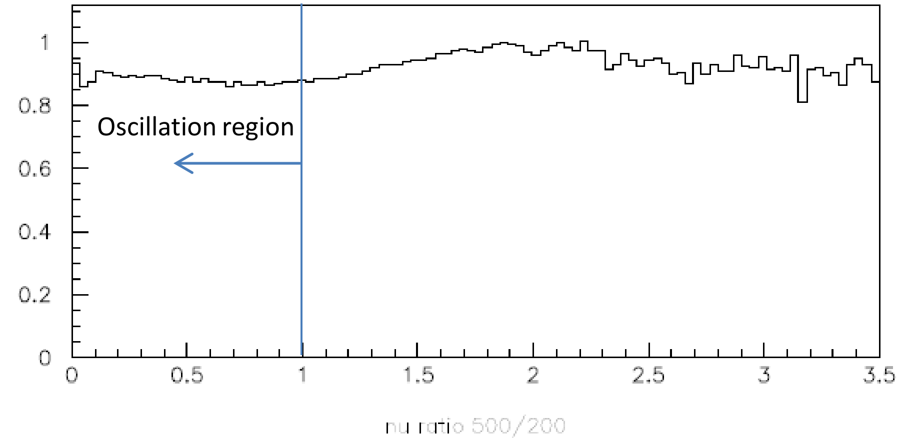
- Construct an "identical MiniBooNE" second detector at a distance ~200 meters downstream from target
- Measure MiniBooNE backgrounds directly
- Leverage 10 year of MiniBooNE running, analysis development, and operations experience
- With 1 year of running yield a dramatic improvement in sensitivity from $3\sigma \rightarrow 5\sigma$ in neutrino mode

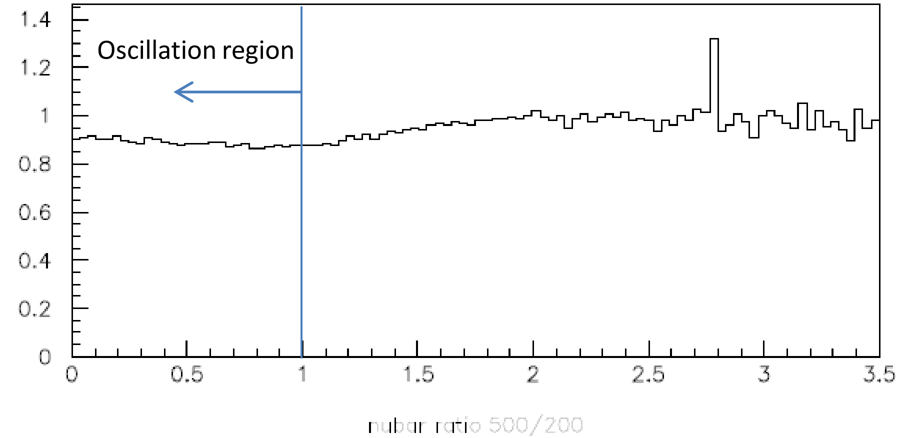

541 meters
200 meters
National Accelerator Lab
Fermi Nation

Flux

- Near detector at 200m
- Similar spectrum in Near and Far
- Far/Near flat in oscillation region







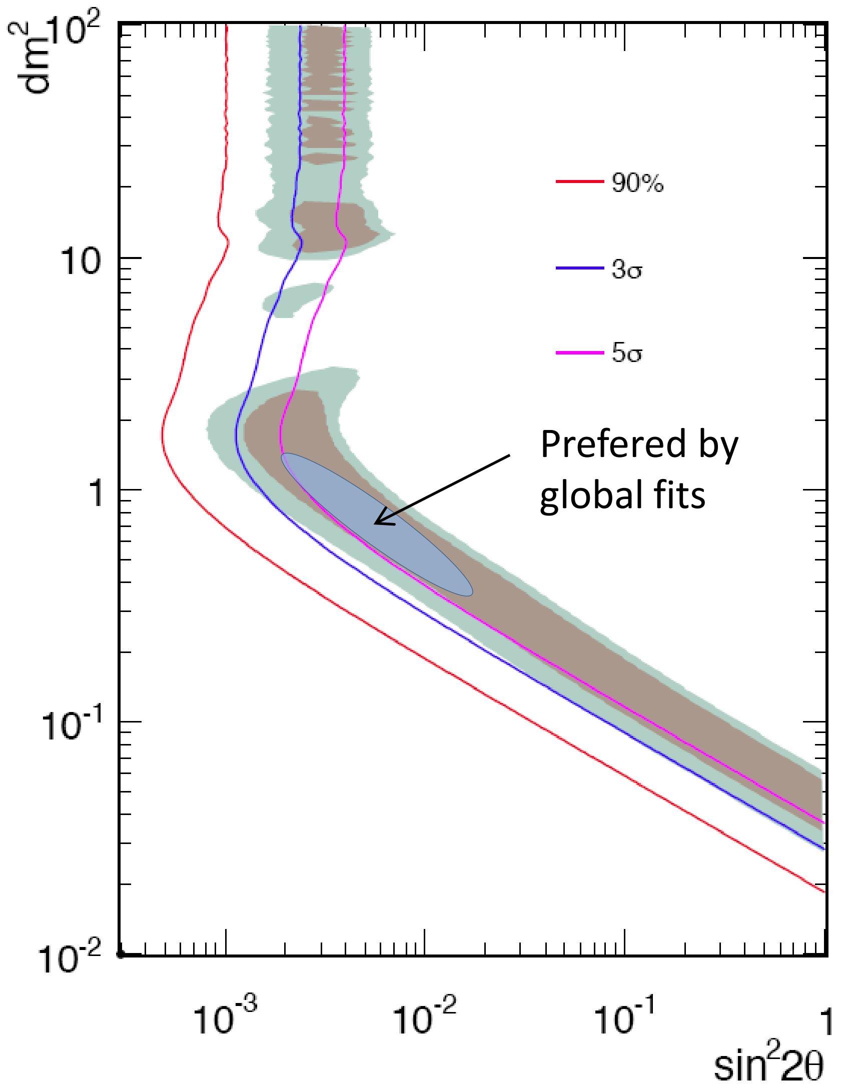
MiniBooNE uncertainties

Uncertainty (%)	200-475 MeV	475-1100 MeV
π+	0.4	0.8
π-	3.1	2.5
K+	0.7	1.4
K-	0.5	1.2
K0	1.9	5.3
Target and beam models	1.6	2.9
Cross sections	6.4	12.7
NC π0 yield	1.5	1.4
Hadronic interactions	0.4	0.2
Dirt	1	0.5
Electronics&DAQ model	4.2	4.3
Optical Model	8.2	3.1
Total	12.1%	15.4%

- Unconstrained nuebar background uncertainties
- Biggest contributors
  - Detector response
  - Cross sections

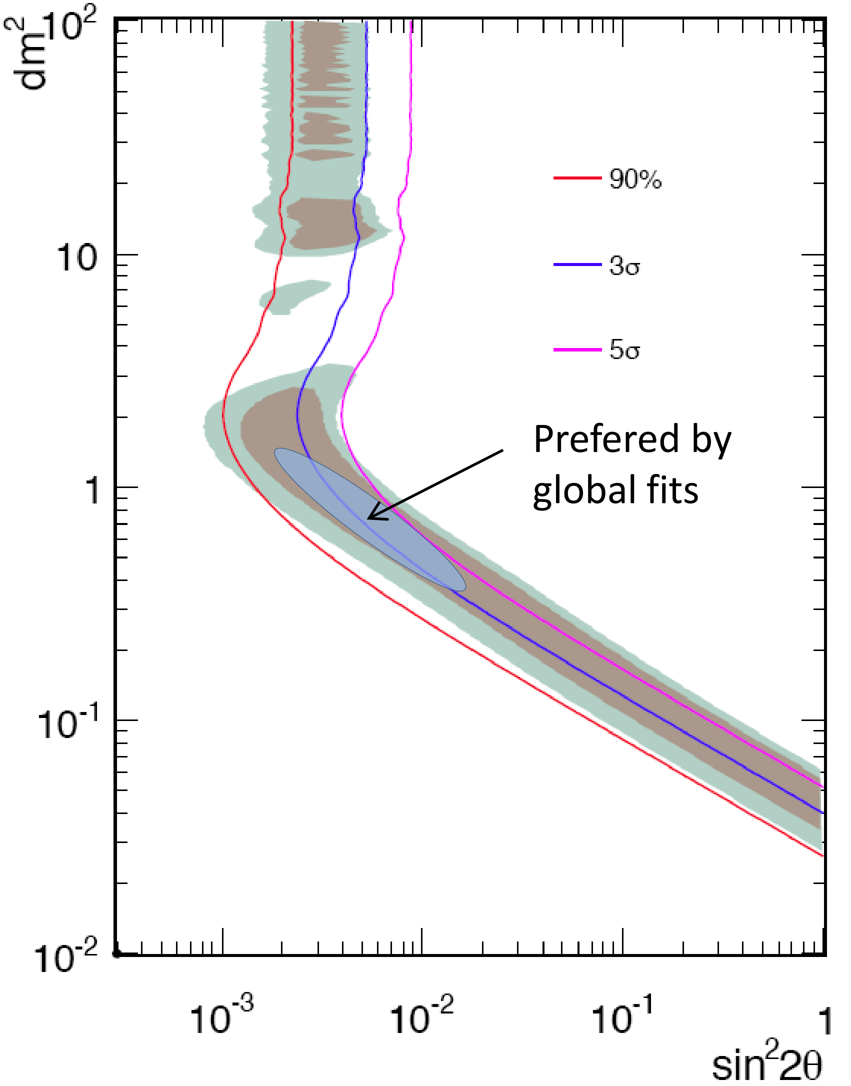
Appearance Sensitivity - neutrino

- Near location at 200 m
- $1x10^{20}$ POT in near detector
- Full systematic error analysis



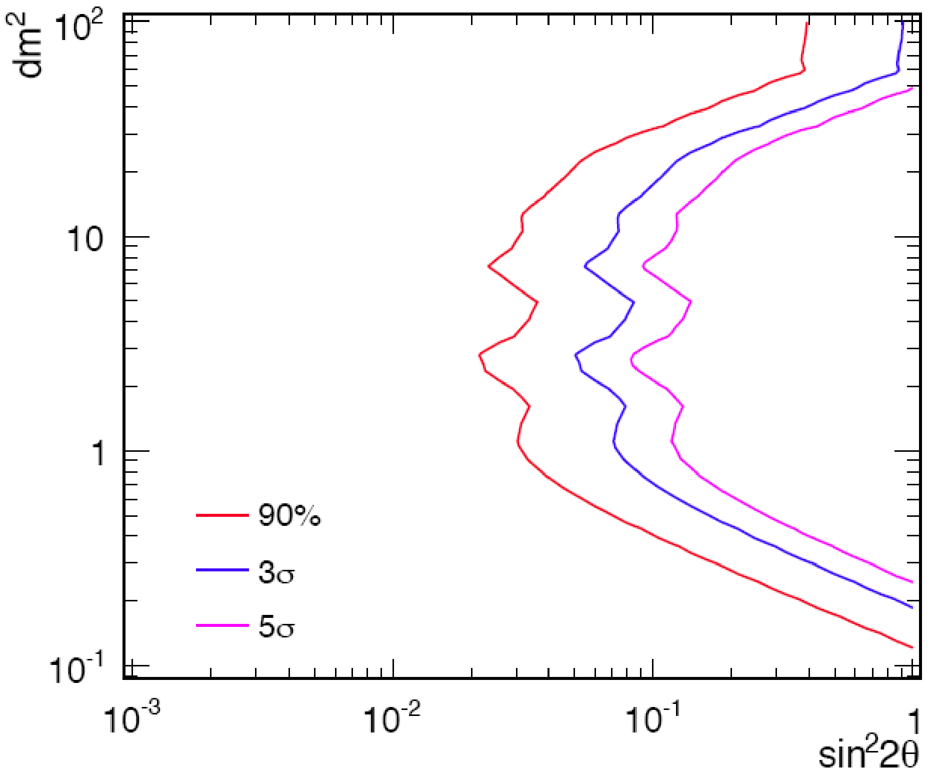
Appearance Sensitivity - antineutrino

- Near location at 200 m
- $1x10^{20}$ POT in near detector
- Full systematic error analysis



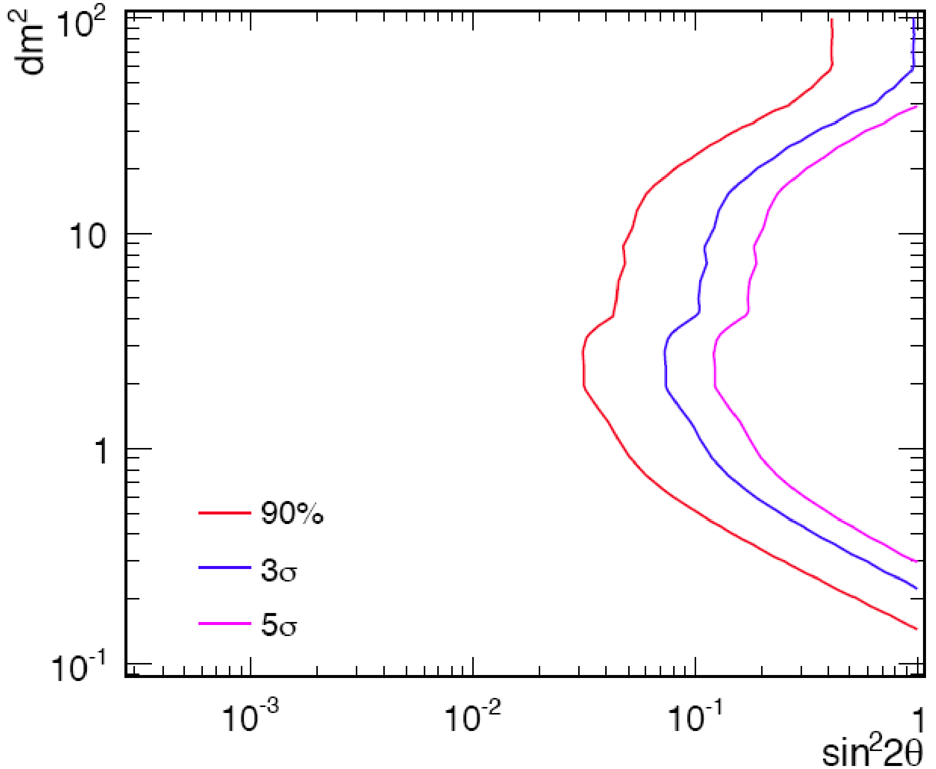
Disappearance Sensitivity - neutrino

- Look for ν_μ disappearance in CCQE sample
- Near location at 200 m
- $1x10^{20}$ POT in near detector
- Full systematic error analysis



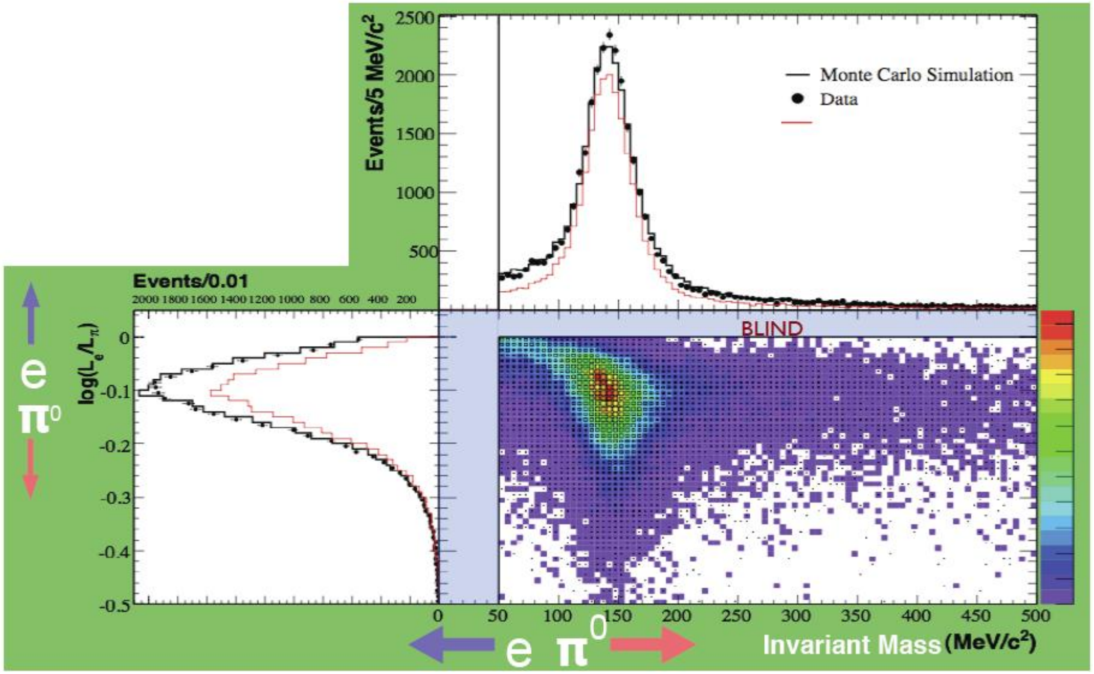
Disappearance Sensitivity - antineutrino

- Look for $\bar{\nu}_\mu$ disappearance in CCQE sample
- Near location at 200 m
- 1×10^{20} POT in near detector
- Full systematic error analysis



NC π^0 and NC elastic

- Change in rate of NC π^0s and NC elastic could verify sterile neutrino hypothesis
  - Clean selection, ~90000 NC elastic events in far detector
  - Clean selection, ~20000 NC π^0 events in far detector
  - Potential measurement at ~2-3% with near far comparison



Conclusion

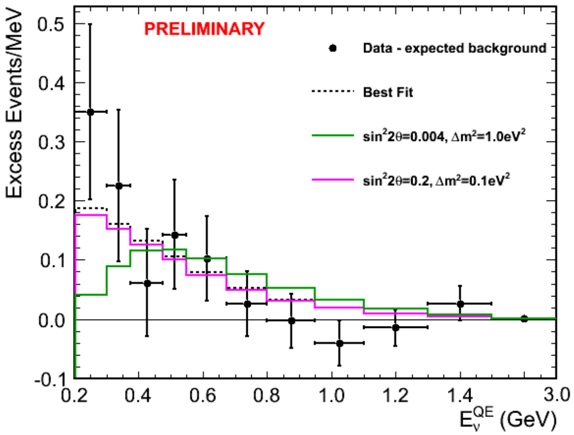
- MiniBooNE observes an excess of $\nu_e/\bar{\nu}_e$ events
- Combined neutrino antineutrino mode excess in 200-1250 MeV region is 240±34.5±52.6 (3.8σ) events
- No $\nu_\mu/\bar{\nu}_\mu$ disappearance observed in joint SciBooNE/MiniBooNE disappearance analysis
- Some tension between disappearance and appearance data in 3+N models

- We need to:
  - Improve sensitivity
  - Study L/E of observed excesses
- BooNE+ can measure neutrino oscillations with high significance (>5σ) and prove that sterile neutrinos exist

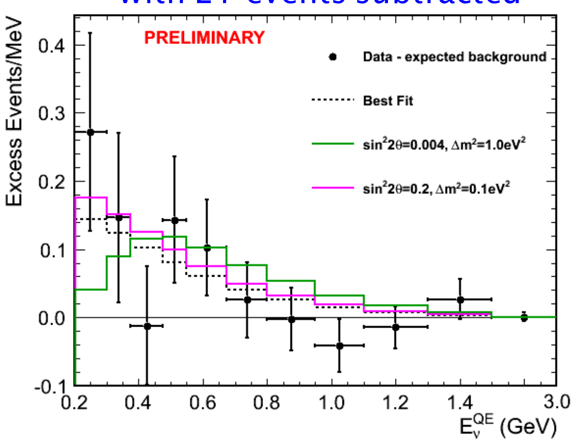
Account for neutrino low-E events

- 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)

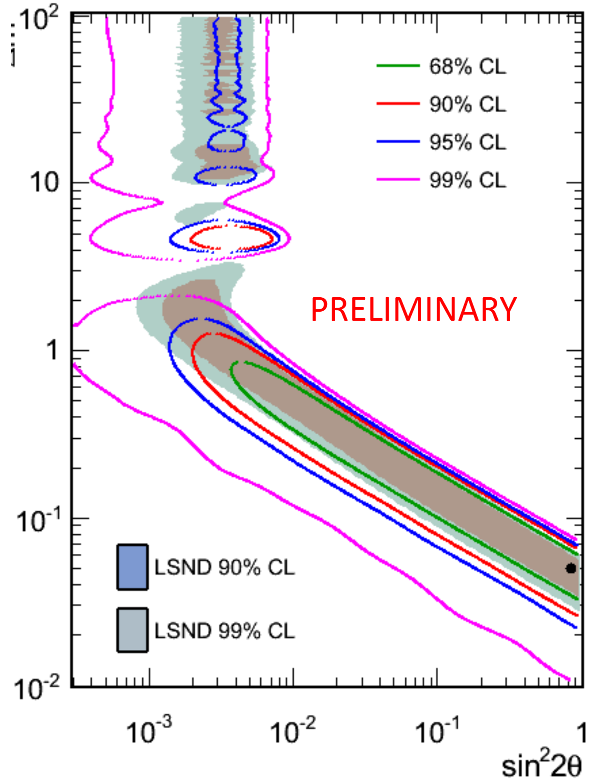
without 21 events subtracted



with 21 events subtracted



without 21 events subtracted



with 21 events subtracted