

# Short (& Long) Baseline Neutrino Oscillations

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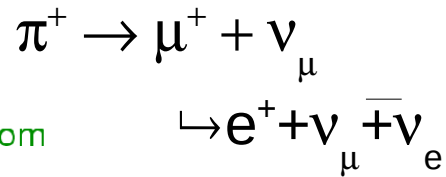
Nov 6 2012

# Outline

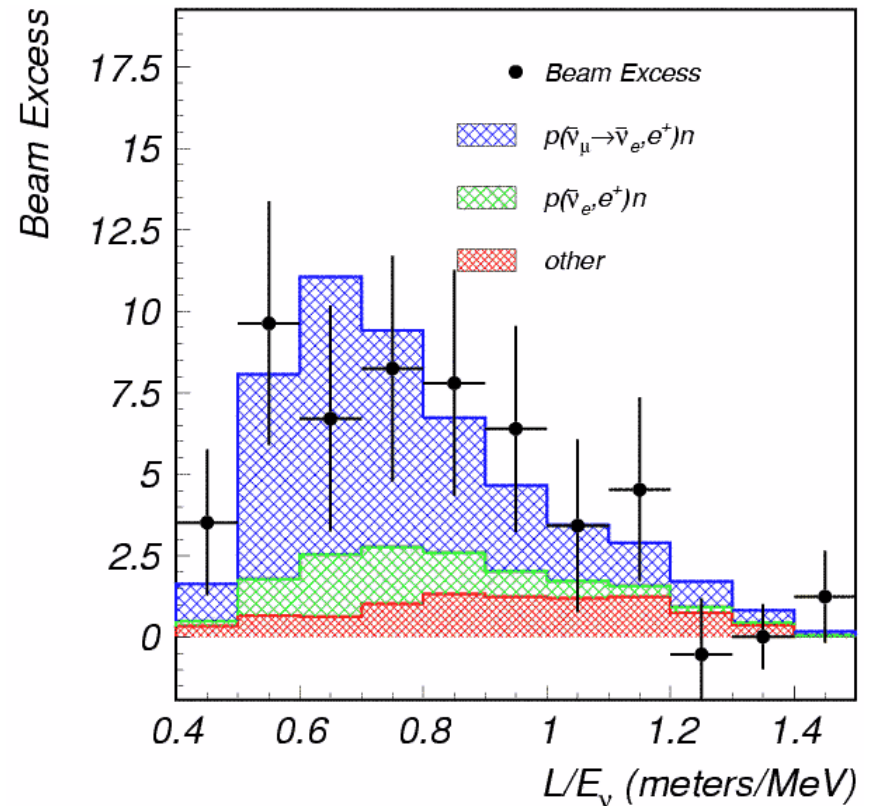
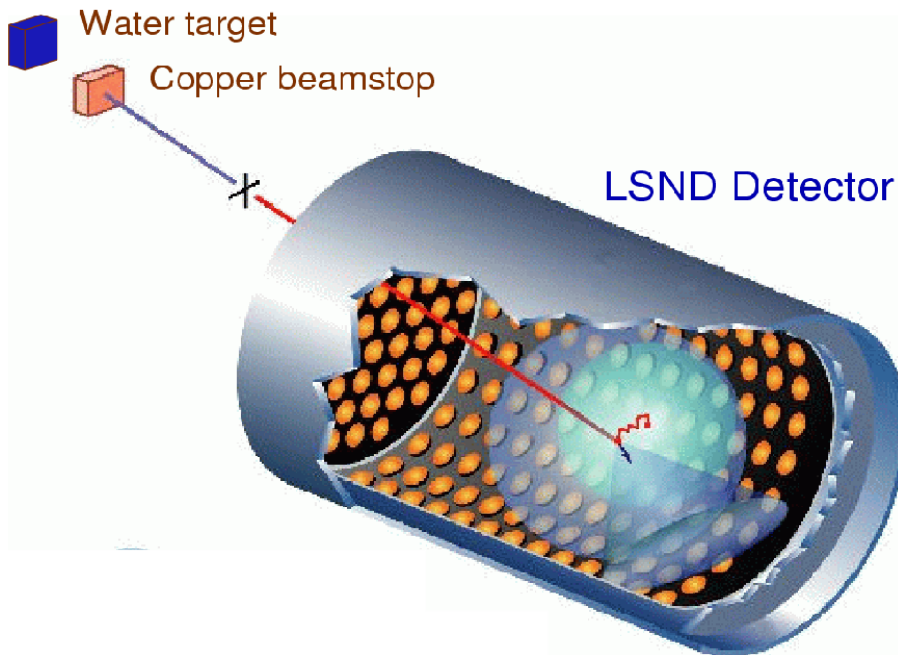
- Short baseline anomaly
  - Experimental evidence
  - Sterile neutrinos
- Global fits
- Future outlook
  - MicroBooNE

# LSND

- Liquid Scintillator Neutrino Detector at Los Alamos
- Evidence for oscillations at higher  $\Delta m^2$  than atmospheric and solar
- Excess of  $\bar{\nu}_e$  in  $\bar{\nu}_\mu$  beam:  $87.9 \pm 22.4 \pm 6$  ( $3.8\sigma$ )
- Stopped pion source:



800 MeV proton beam from  
LANSCE accelerator



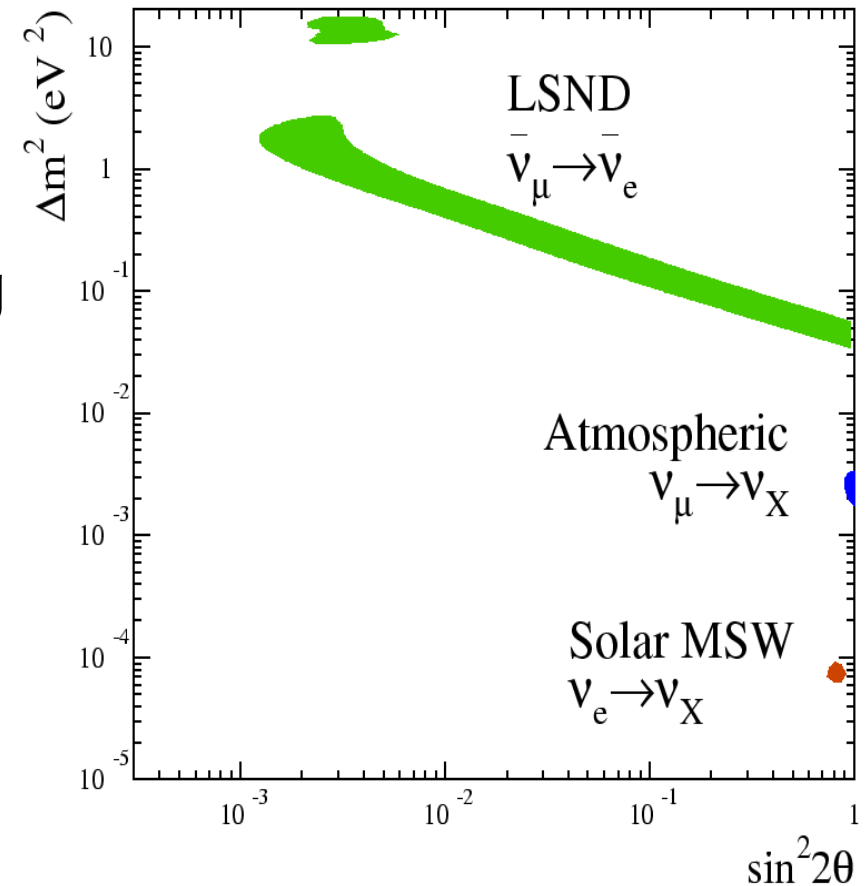
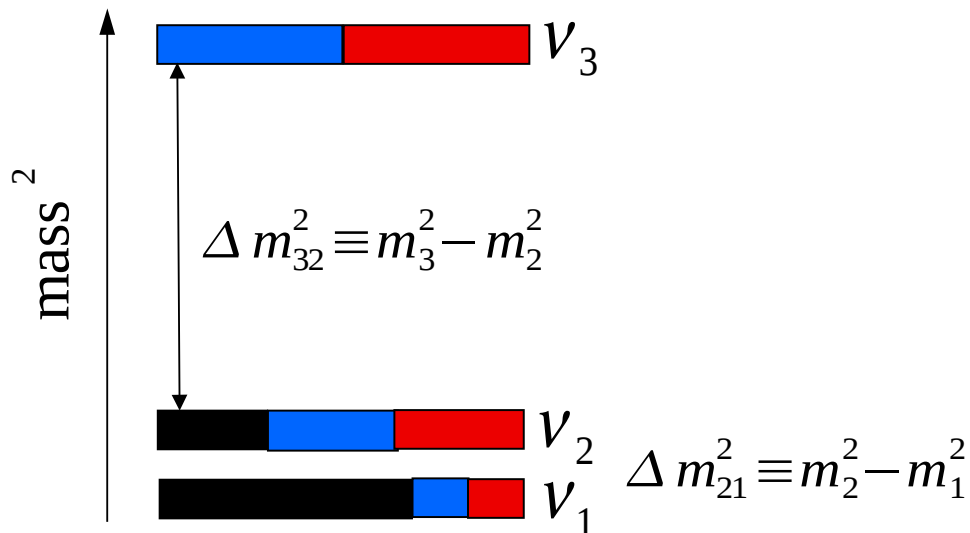
# LSND signal

- Assuming two neutrino oscillations

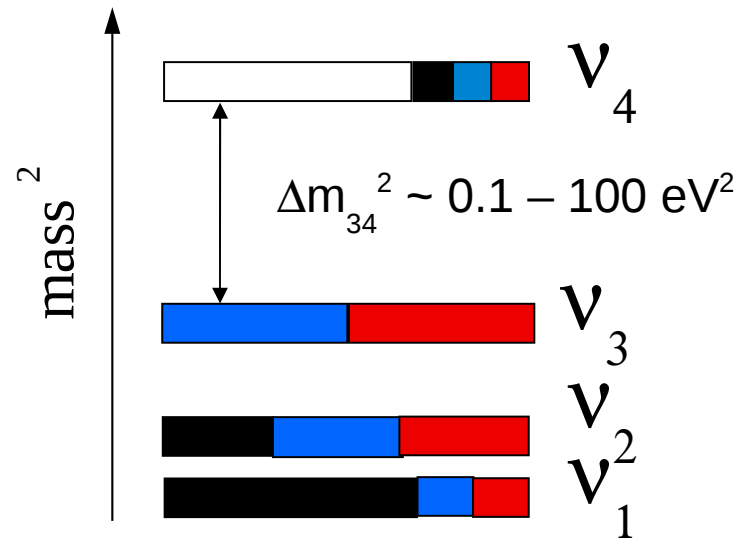
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta) \sin^2\left(\frac{1.27 L \Delta m^2}{E}\right)$$

$$= 0.245 \pm 0.067 \pm 0.045 \%$$

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



# Sterile neutrinos



- Sterile neutrinos have no Standard Model interactions but can oscillate into active neutrinos
- 3+N models (N=1, 2, ...)  
(short baseline CP violation for N>1)

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

- In 3+1 model 3 parameters relevant for short baseline exp.:

$$\Delta m_{41}^2, |U_{e4}| \text{ and } |U_{\mu 4}|$$

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

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

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) \sin^2(1.27 \Delta m_{41}^2 L/E) \quad 5$$

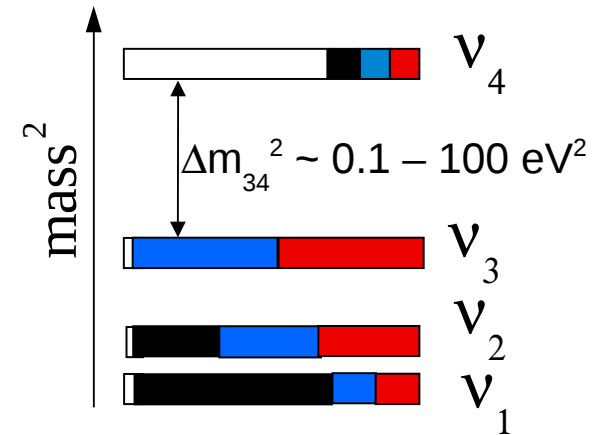
# CP violation

- Oscillation probability:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_i \sum_j |U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}| \sin^2(1.27 \Delta m_{ij}^2 L / E_\nu)$$

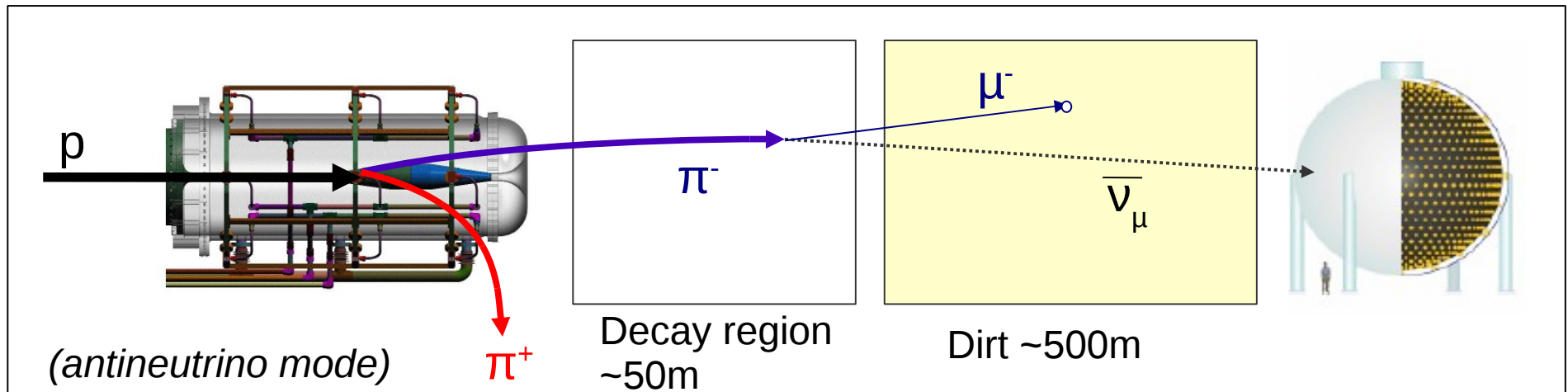
- As total number of neutrinos N increases, formalism rapidly gets complicated

N	# $\Delta m_{ij}^2$	# $\theta_{ij}$	#CP Phases
2	1	1	0
3	2	3	1
6	5	15	10



- Short baseline experiments not sensitive to active neutrino oscillations
  - 3 active neutrinos count as 1

# MiniBooNE experiment



- Similar L/E as LSND
  - MiniBooNE  $\sim 500\text{m}/\sim 500\text{MeV}$
  - LSND  $\sim 30\text{m}/\sim 30\text{MeV}$
- Horn focused neutrino beam ( $p+\text{Be}$ )
  - Horn polarity  $\rightarrow$  neutrino or anti-neutrino mode
- Mineral oil Cherenkov detector

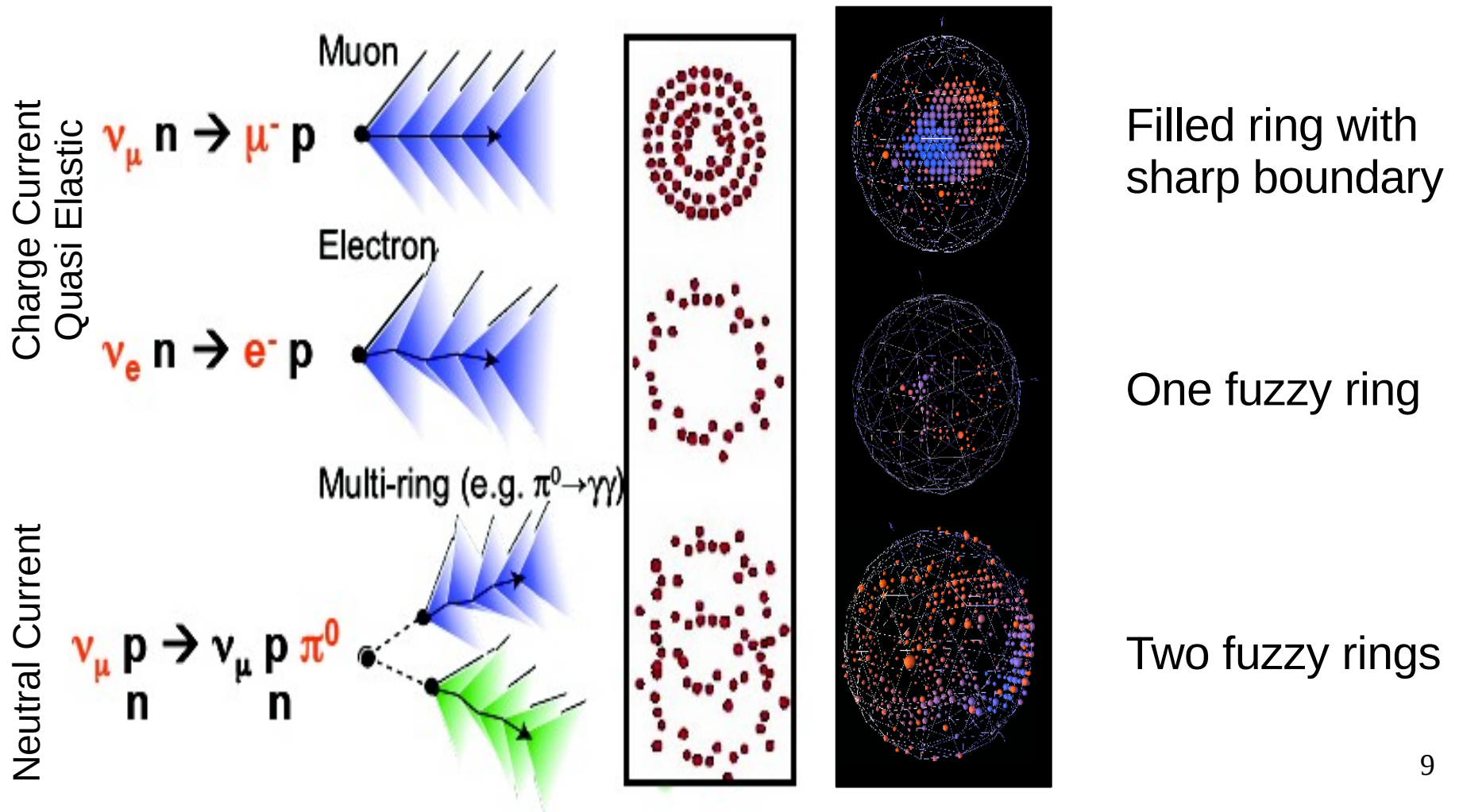
# MiniBooNE detector

- Sphere 12m in diameter
- 800t mineral oil
- 1280 inner PMTs +  
240 veto PMT



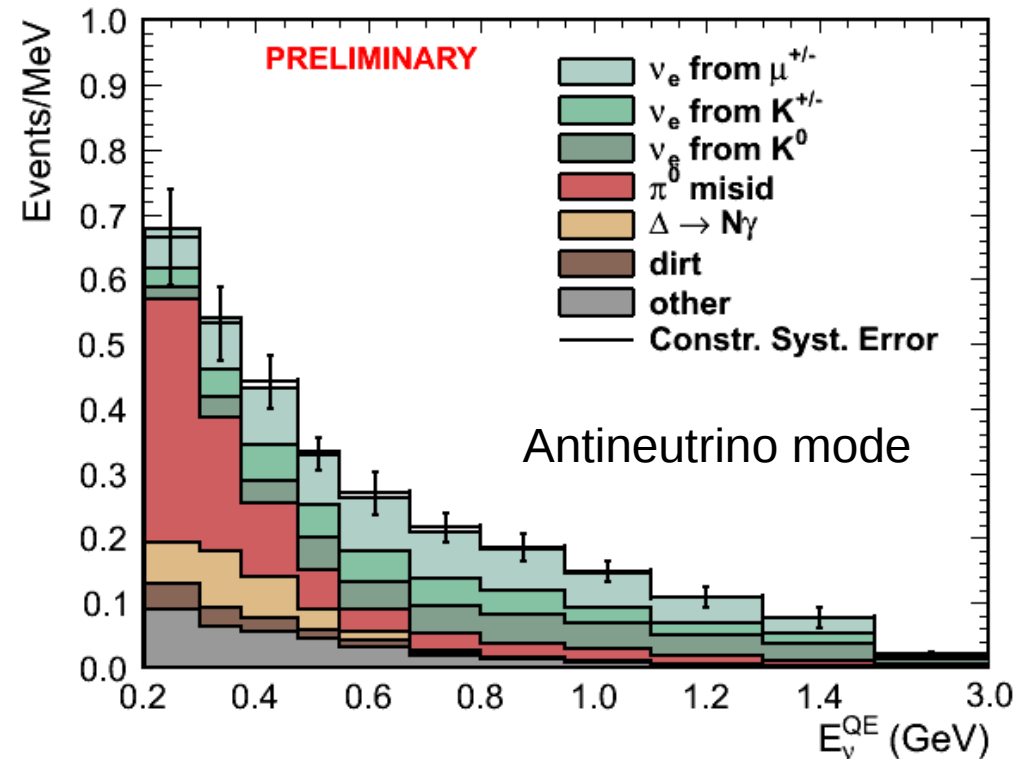
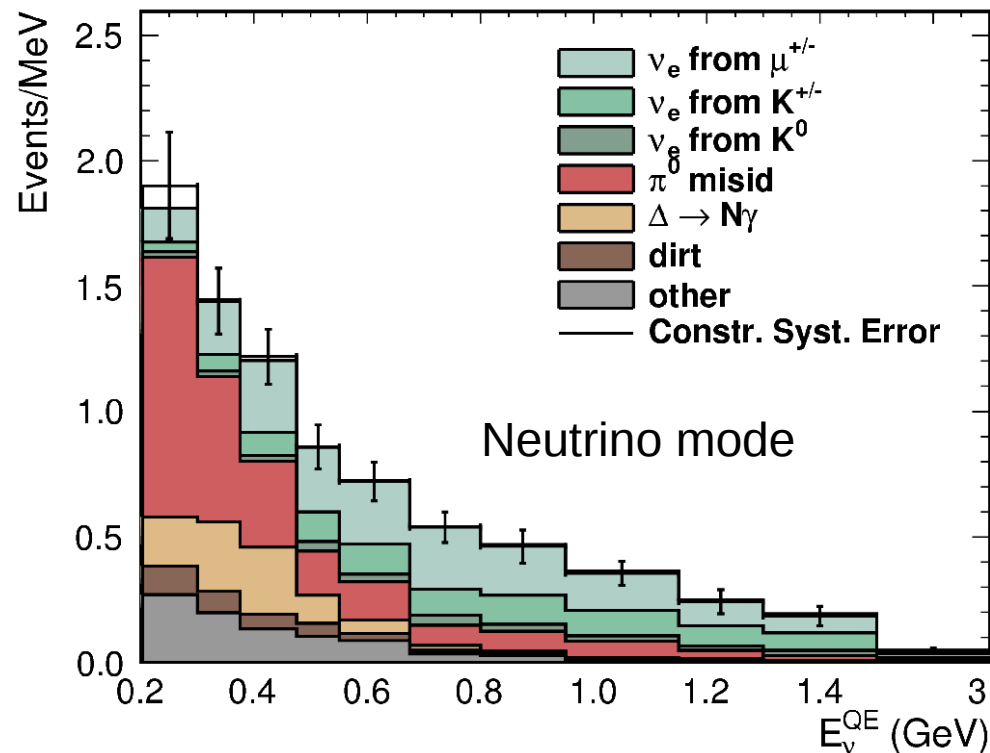
# Events in MiniBooNE

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



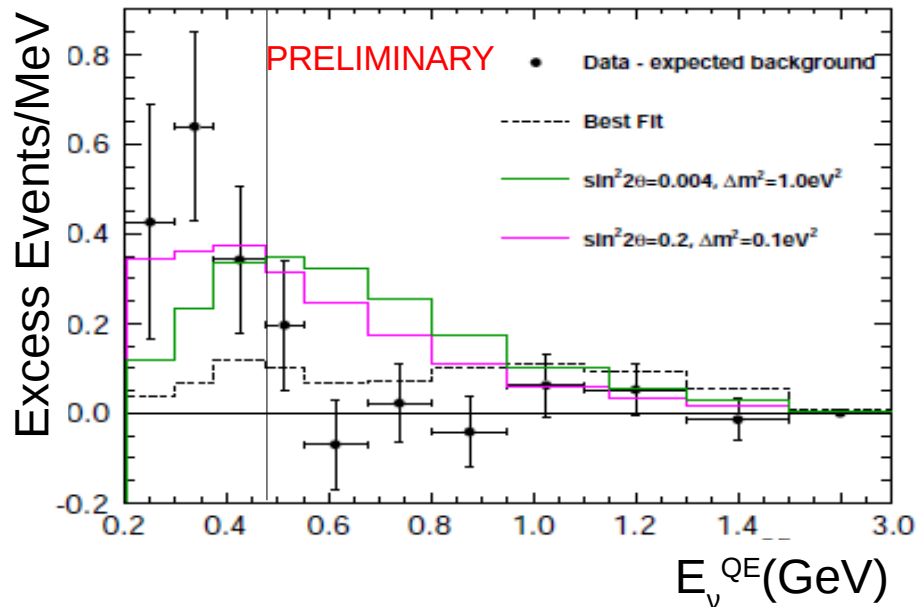
# Background events

- Backgrounds similar in neutrino (left) and antineutrino (right) mode
- Use MiniBooNE data to constrain backgrounds



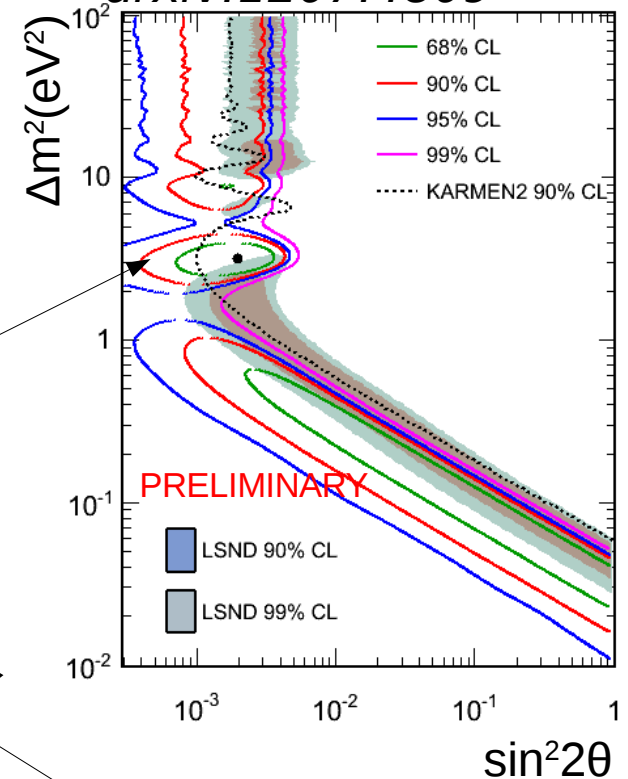
# Updated Neutrino Appearance results

arxiv:1207.4809



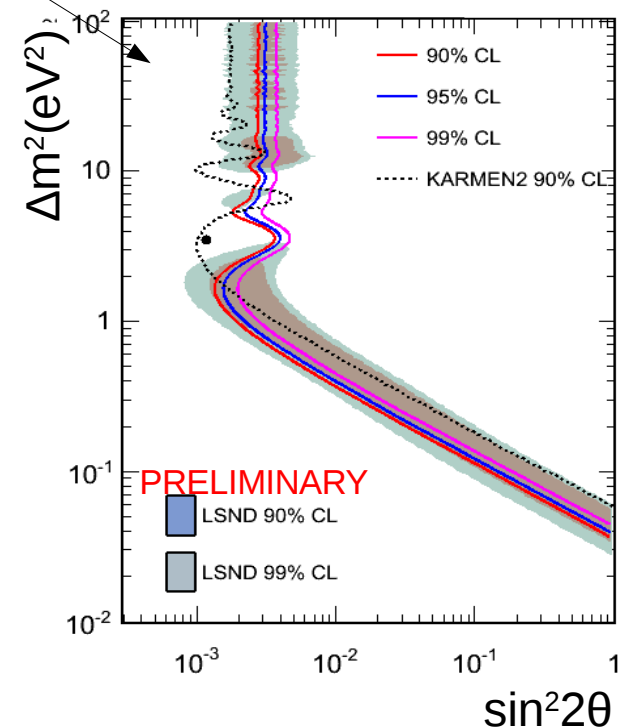
$E > 200 \text{ MeV}$

$E > 475 \text{ MeV}$



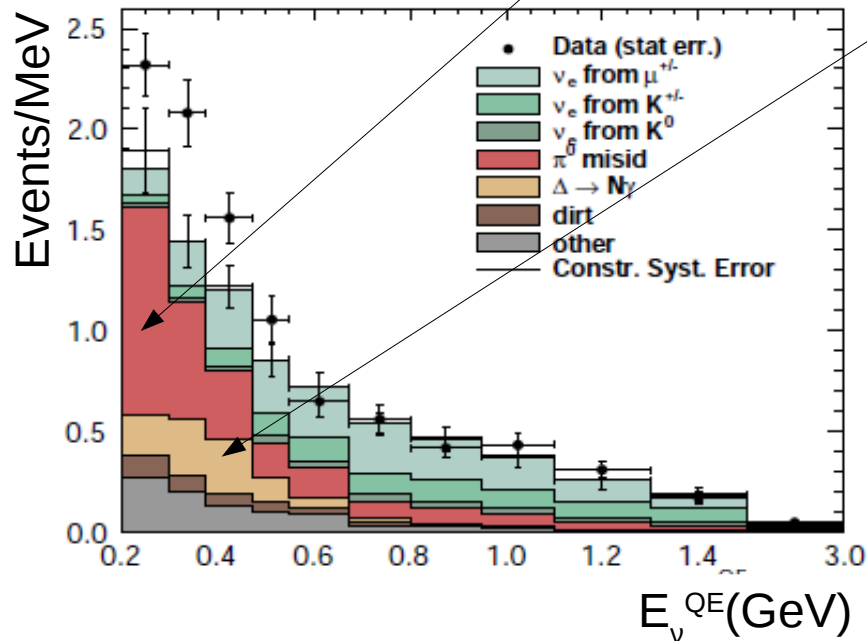
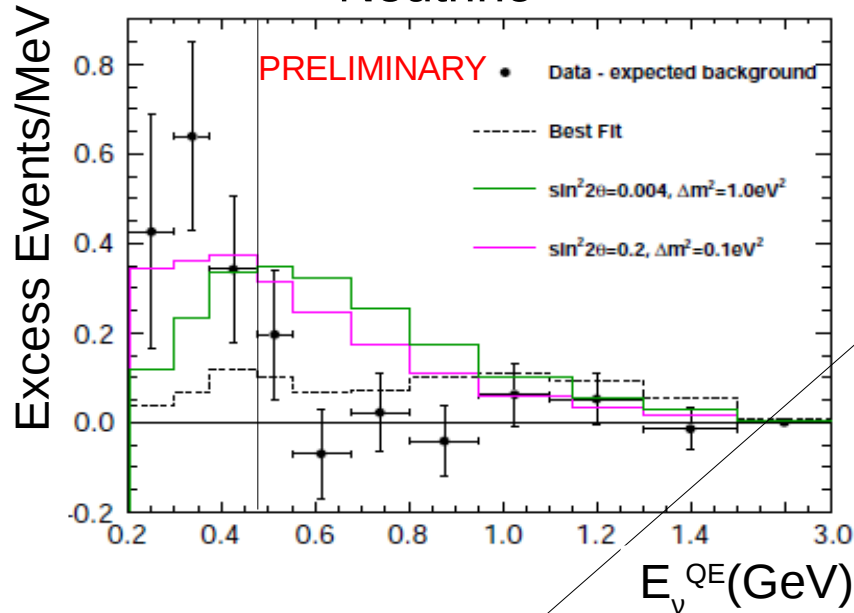
- Analysis energy range 200-1250 MeV
- Excess:  $162.0 \pm 28.1 \pm 38.7$  ( $3.4\sigma$ )
- Tension between 3+1 model fits in two energy regions

$\nu$ mode	$E > 200 \text{ MeV}$	$E > 475 \text{ MeV}$
$\chi^2(\text{no oscillations})$	22.81	6.35
Prob(no oscillations)	0.5%	36.6%
$\chi^2(\text{best fit})$	<b>13.24</b>	<b>3.73</b>
Prob(best fit)	<b>6.12%</b>	<b>42.0%</b>



# What can we say about low-E excess

## Neutrino



- Not a stat fluctuation, statistically  $7\sigma$
- Unlikely to be intrinsic  $\nu_e$ , small bkg at low E
- NC  $\pi^0$  background dominates
  - Reduces significance to  $3.7\sigma$
  - Heavily constrained by NC  $\pi^0$  *in situ* measurement
- Region where single  $\gamma$  can contribute
- MB ties  $\Delta \rightarrow N\gamma$  expected rate to be 1% of measured NC  $\pi^0$  rate
  - Number of theory calculations for various single  $\gamma$  processes
  - All find total cross section within 30% of MB  $\sim 5 \times 10^{-42} \text{ cm}^2/\text{N}$
  - Would need nearly 300% change

R. Hill, arxiv:0905.0291

Jenkins & Goldman, arxiv:0906.0984

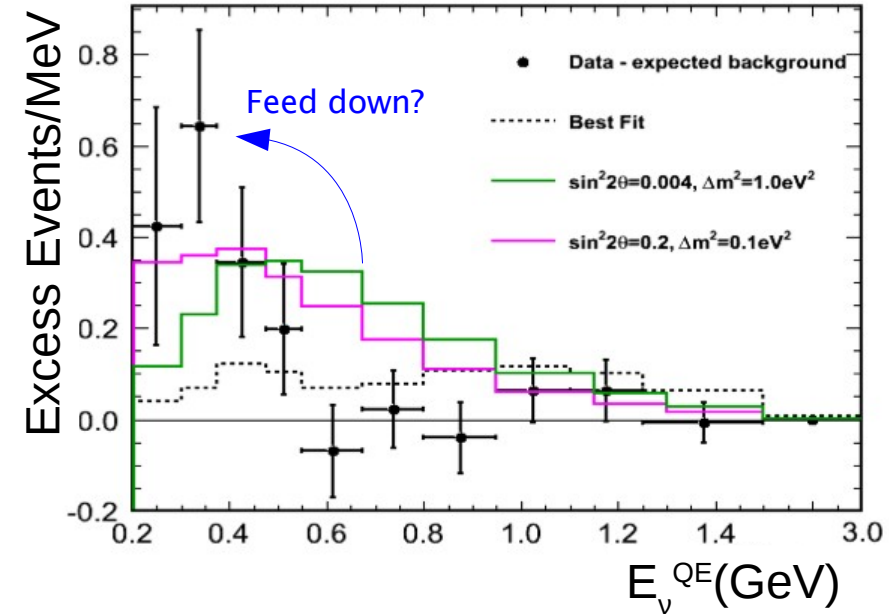
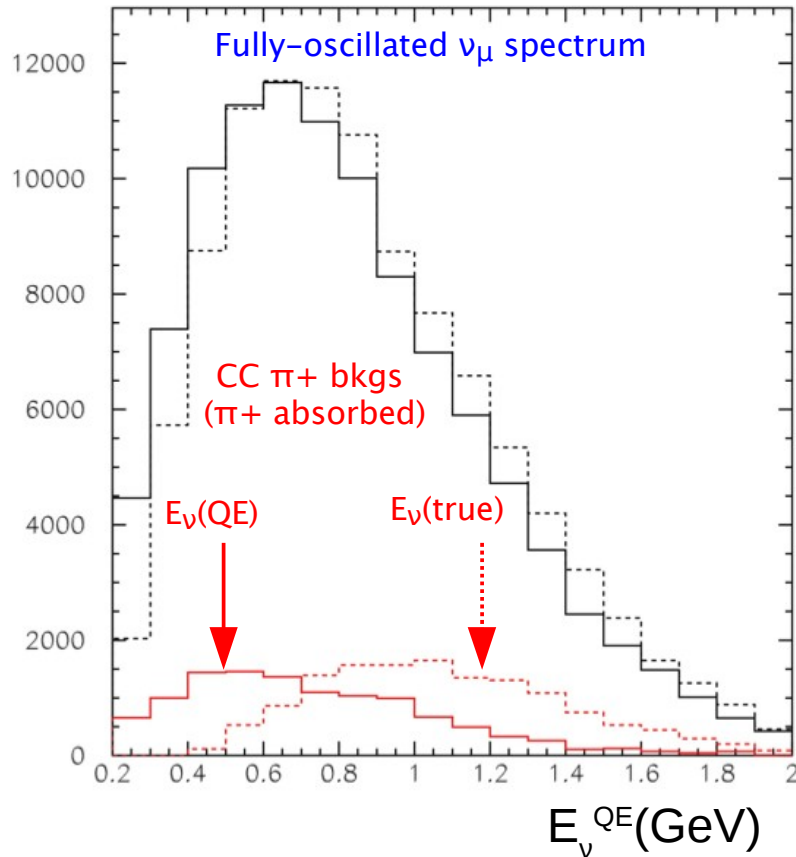
Serot & Zhang, arxiv:1011.5913, 1210.3610

# Nuclear effects & Reconstructed $E_\nu$

- This plot assumes CCQE-like reconstruction

$$E_\nu = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_n E_B + m_\mu^2 + \Delta M^2)}{2[(M_n - E_B) - E_\mu + p_\mu \cos \theta_\mu]}$$

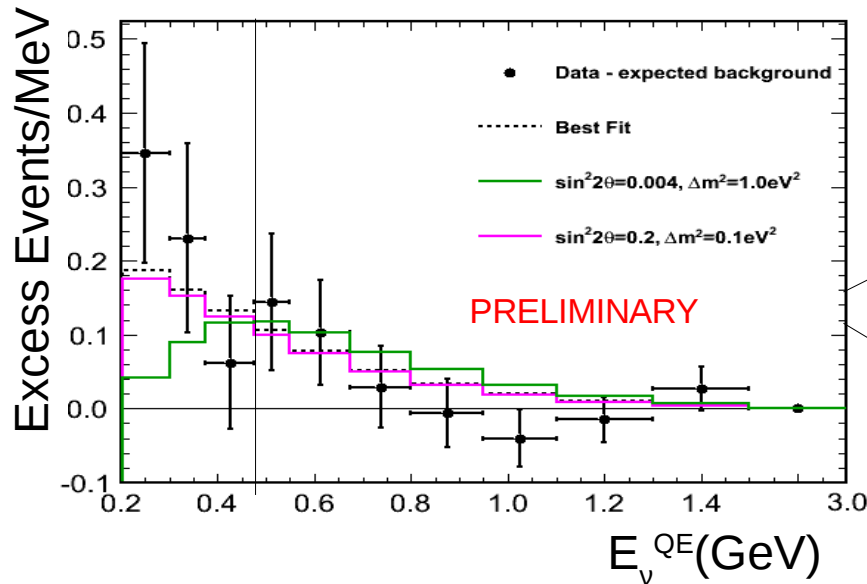
- Additional participants other than the outgoing lepton and struck nucleon will cause events to reconstruct at lower  $E_\nu$ (QE)



- MiniBooNE find a cross-section for CCQE that is 20-30% high
- Number of theorists suggesting this could arise from multi-nucleon correlations
- Fraction of oscillated  $\nu_e$  could be misreconstructed (similar to CC $\pi^+$  case)
- MiniBooNE corrects signal prediction based on the measured  $\nu_\mu$  spectrum

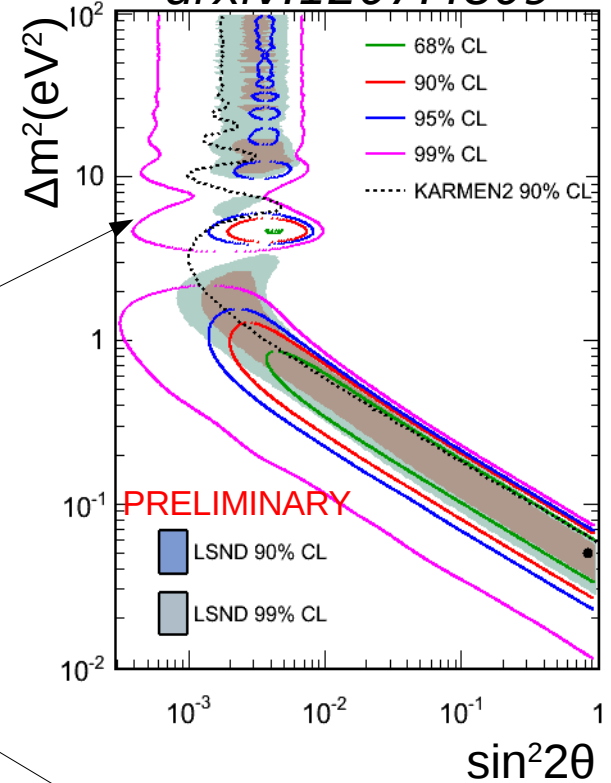
# Antineutrino Appearance results 11.3x10<sup>20</sup> POT

arxiv:1207.4809



E > 200 MeV

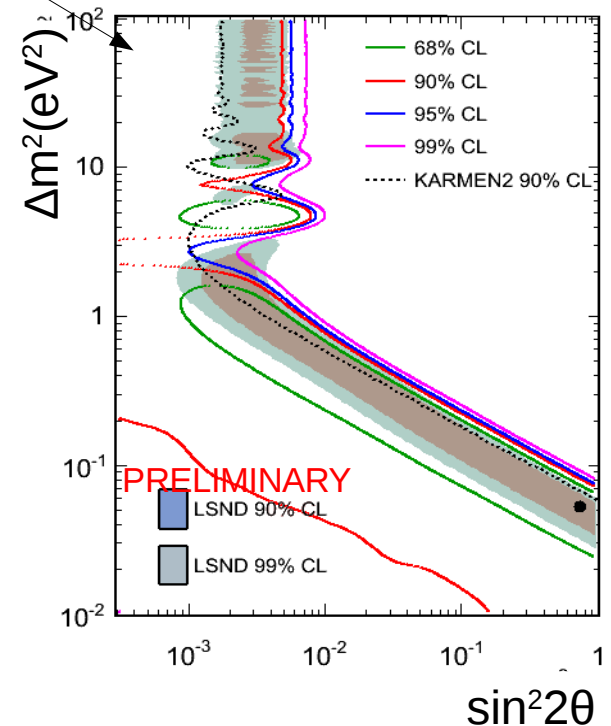
E > 475 MeV



- Excess (200-1250 MeV):  $78.4 \pm 20.0 \pm 20.3$  ( $2.8\sigma$ )
- Caveat: WS  $\nu_\mu$  assumed not to oscillate

anti- $\nu$ mode	E > 200 MeV	E > 475 MeV
$\chi^2$ (no oscillations)	16.6	7.8
Prob(no oscillations)	5.4%	24.6%
$\chi^2$ (best fit)	4.8	3.3
Prob(best fit)	67.1%	49.2%

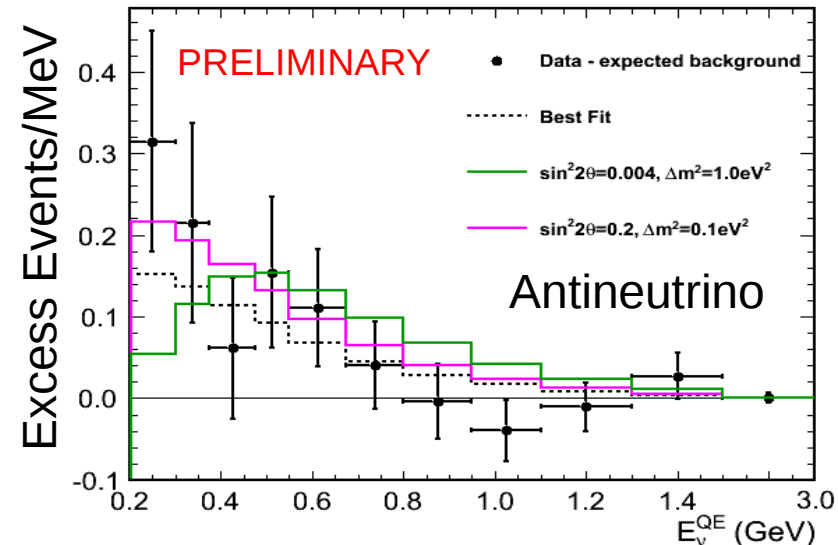
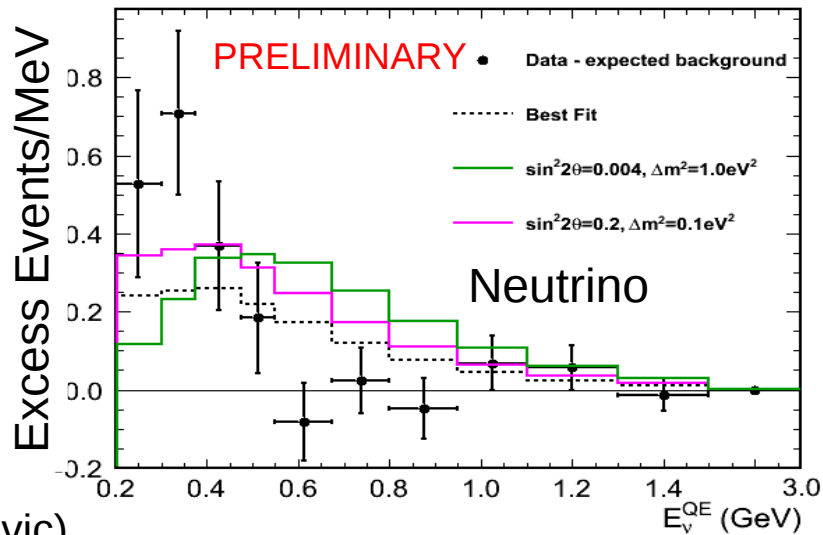
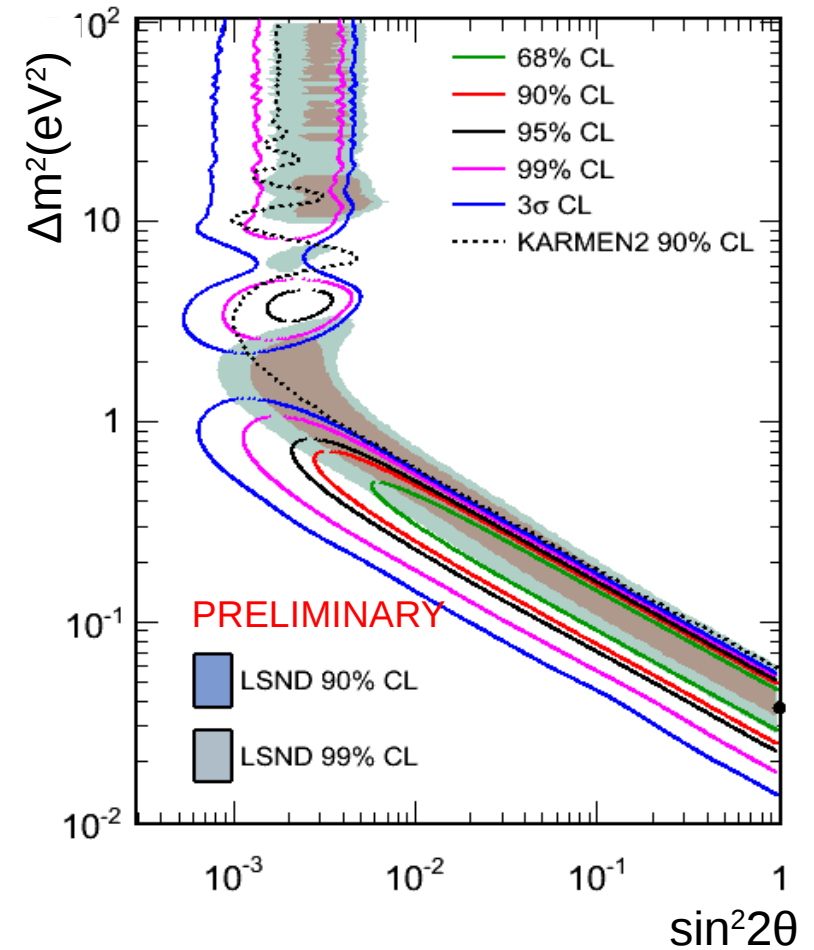
- cf. neutrino mode P(best fit) 6% and 42%



# Combined $\nu$ and $\bar{\nu}$ analysis

- Consistent treatment of neutrinos and antineutrinos
- Full correlated systematic error matrix
- Excess (200-1250):  $240 \pm 34.5 \pm 52.6$  ( $3.8\sigma$ )
- Best Fit preferred over null at  $3.6\sigma$

combined	$E > 200$ MeV	$E > 475$ MeV
$\chi^2(\text{null})$	42.53	12.87
Prob(null)	0.1%	35.8%
$\chi^2(\text{bf})$	24.72	10.67
Prob(bf)	<b>6.7%</b>	<b>35.8%</b>



# 3+2 model

- Allows CP violation at short baseline

$$P(\nu_{\mu} \rightarrow \nu_e) \neq P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e)$$

- Fits better the shape of MiniBooNE excess

$$|U_{\mu 4} U_{e 4}|^2 = 0.1844$$

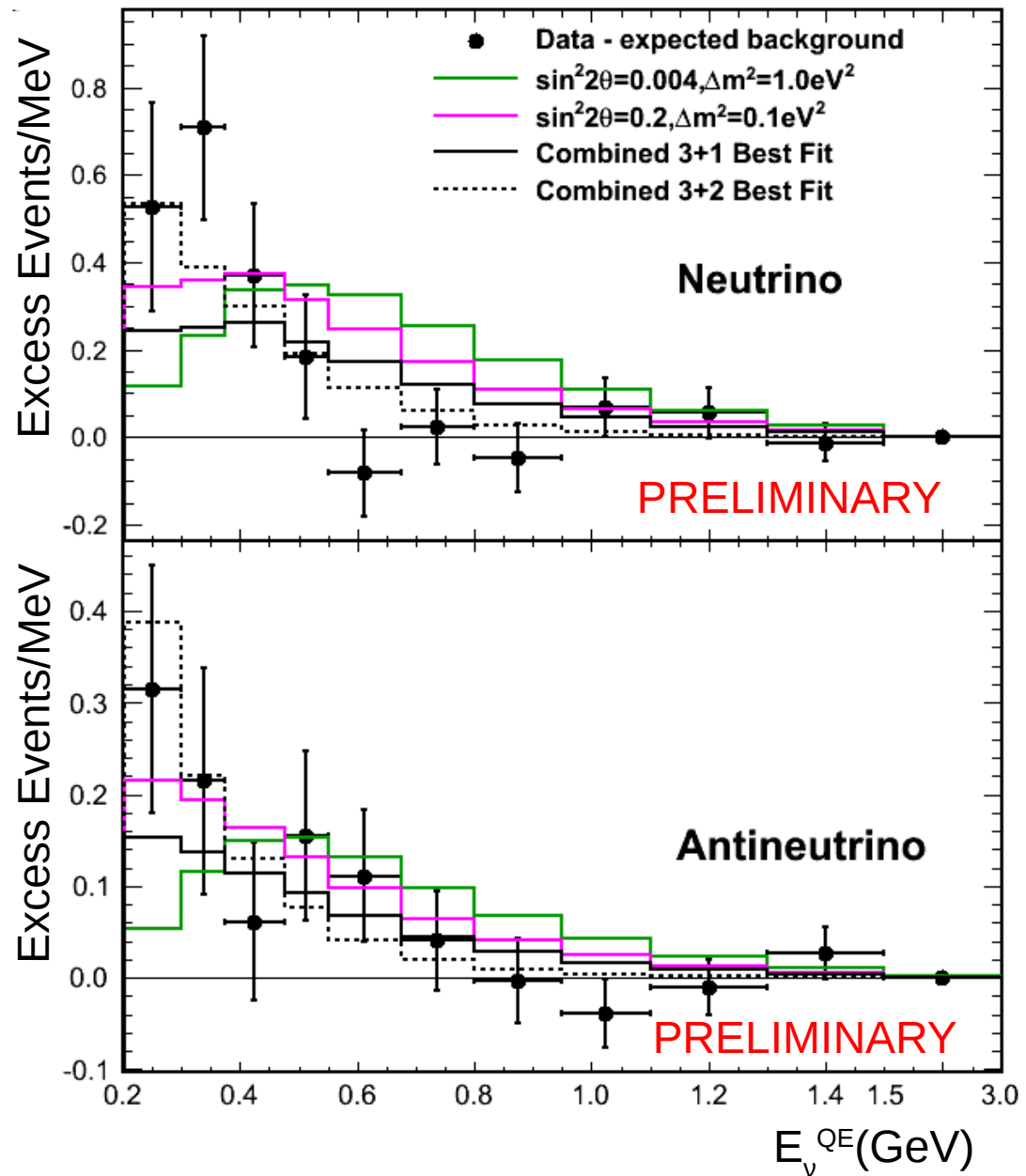
$$|U_{\mu 5} U_{e 5}|^2 = 0.00547$$

$$\Delta m_{41}^2 = 0.082$$

$$\Delta m_{51}^2 = 0.476$$

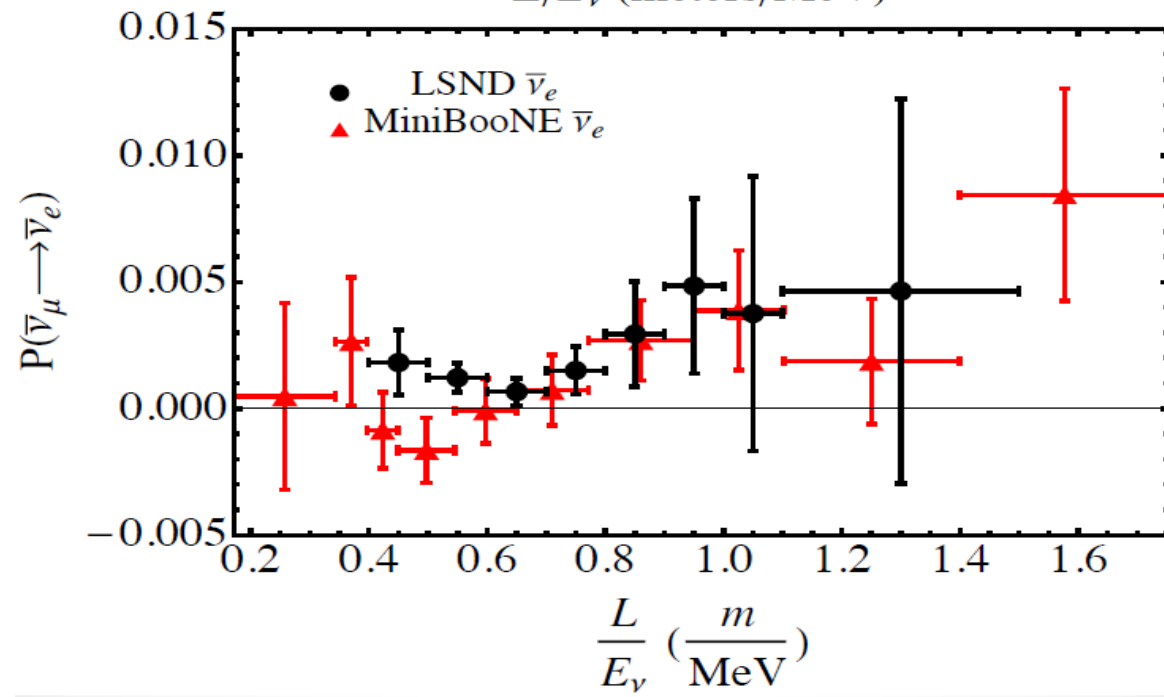
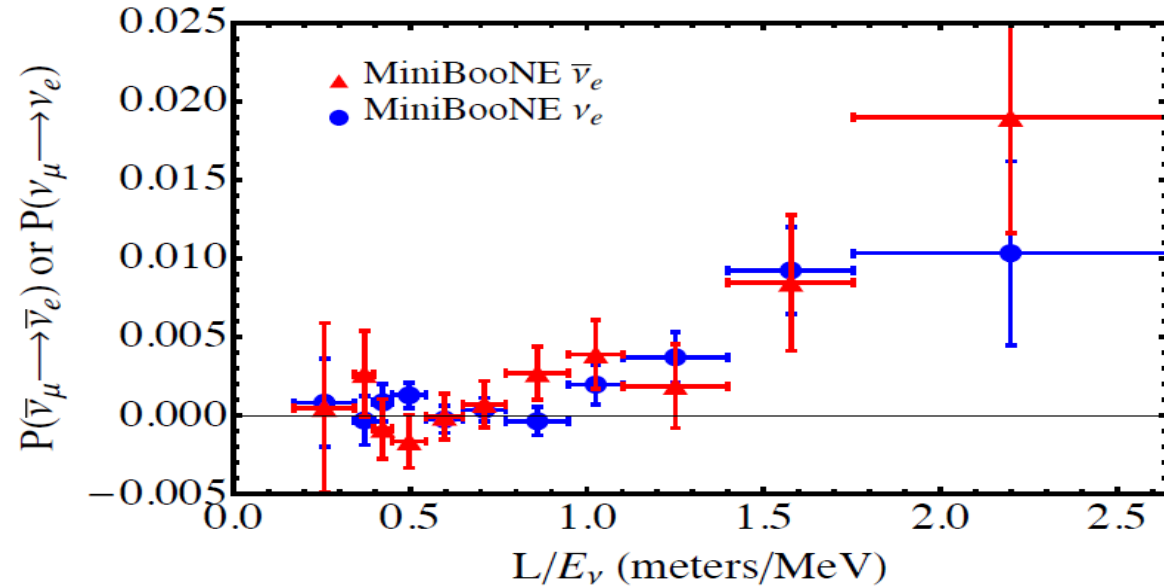
$$\phi = 1.0\pi$$

- Better fit to world data



# Probability vs L/E

- Fixed baseline L, vary energy  $E_\nu$
- Model independent look at the data
- The excess as a function of L/E in MiniBooNE neutrino, antineutrino and LSND data consistent

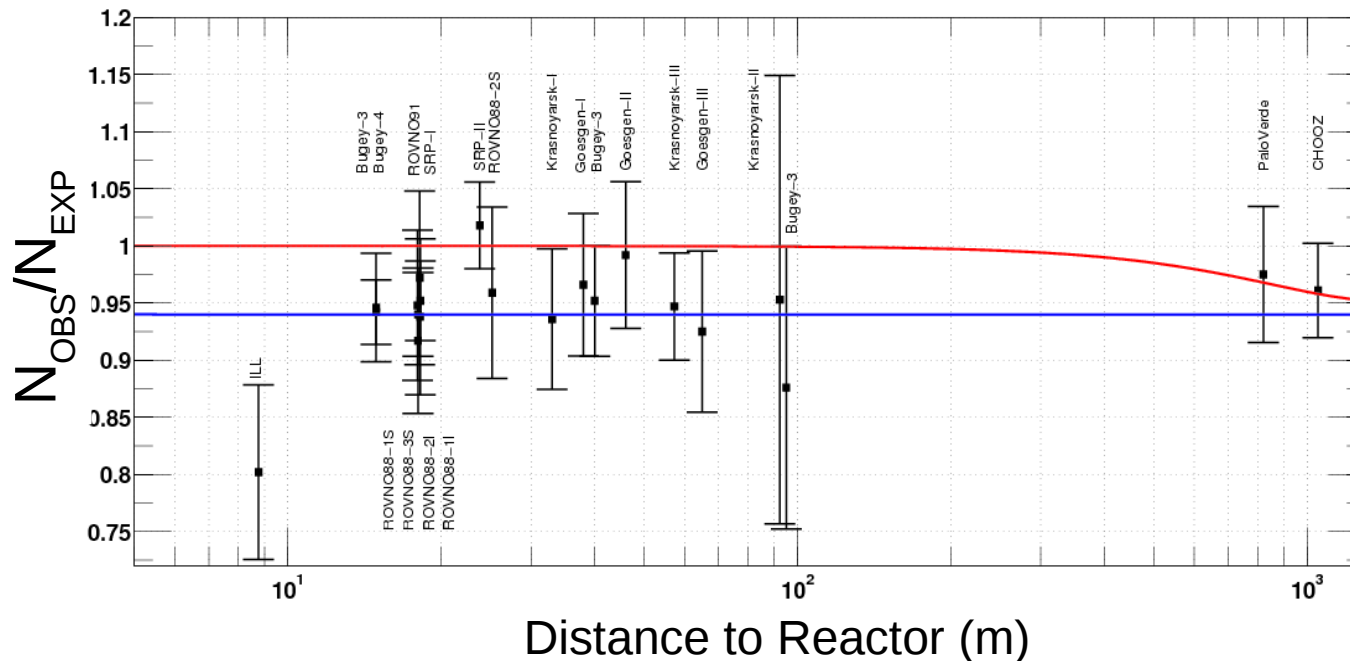


# Other short baseline anomalies?

- Reactor neutrino anomaly
- Gallium anomaly

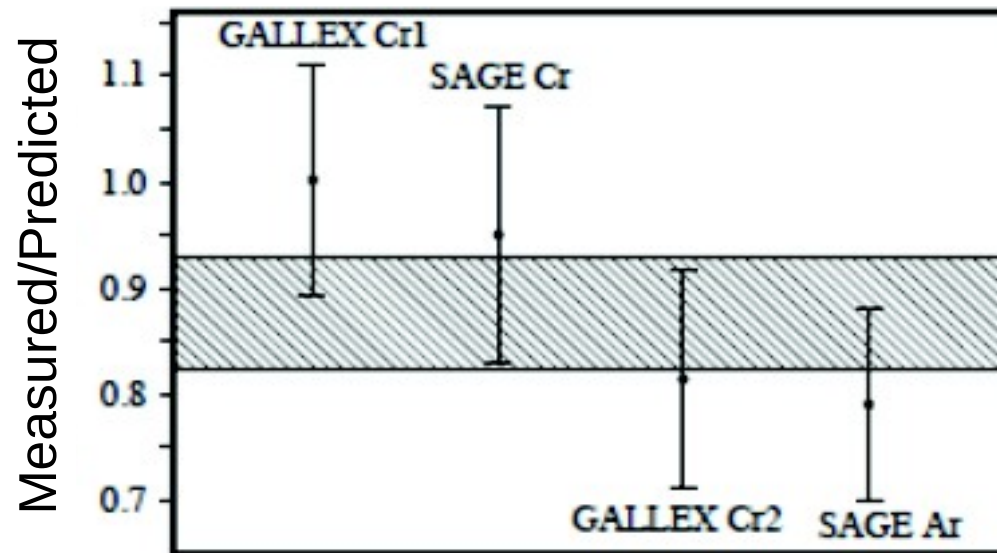
# Reactor anti-neutrino anomaly

- Recent re-evaluation of reactor fluxes  $\rightarrow +3\%$
- 7% deficit in observed flux from reactors
- Deviation from unity at 98.6% CL



# Gallium Anomaly

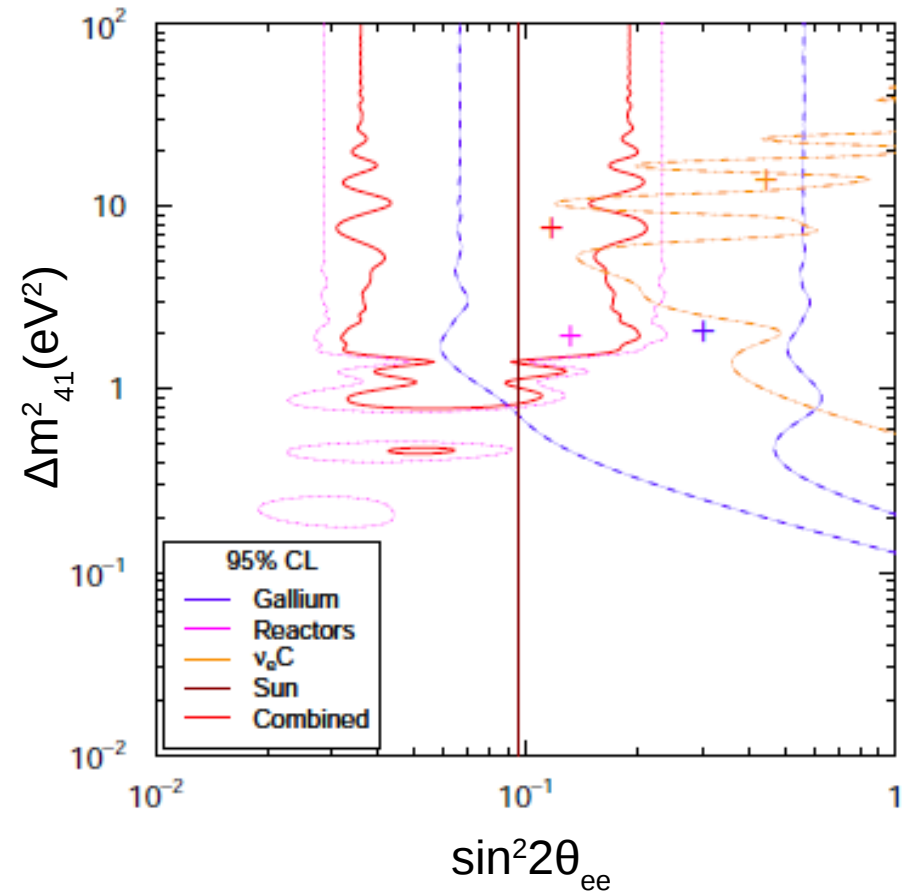
- GALLEX (LNGS) and SAGE (Baksan) looked at solar neutrinos
- Observed deficit during calibration runs with intense MCi sources ( $\nu_e$ )



- $R = \text{measured/predicted} = 0.86 \pm 0.06$

# Sterile neutrinos?

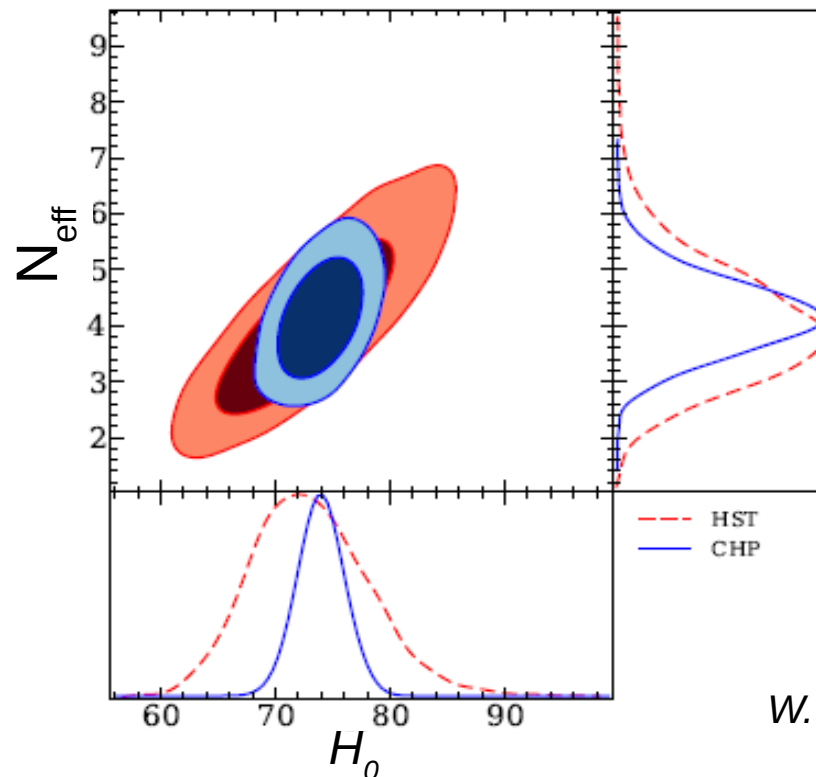
- Reactor data and GALLEX/SAGE
- Data consistent with sterile neutrino oscillations
- Limits on  $\nu_e$  disappearance using KARMEN and LSND  $\nu_e$ C scattering data (*arxiv:1106.5552*) and solar neutrino data



*Giunti, Laveder, Li, Liu, Long,*  
*arxiv:1210.5715*

# Cosmology

- Big Bang Nucleosynthesis (BBN), Cosmic Microwave Background (CMB), Large Scale Structures (LSS)
- Sensitive to sterile neutrinos
- Data consistent with extra relativistic degrees of freedom ( $N_{\text{eff}} > 3$ )
- Planck will provide much more precise measurement



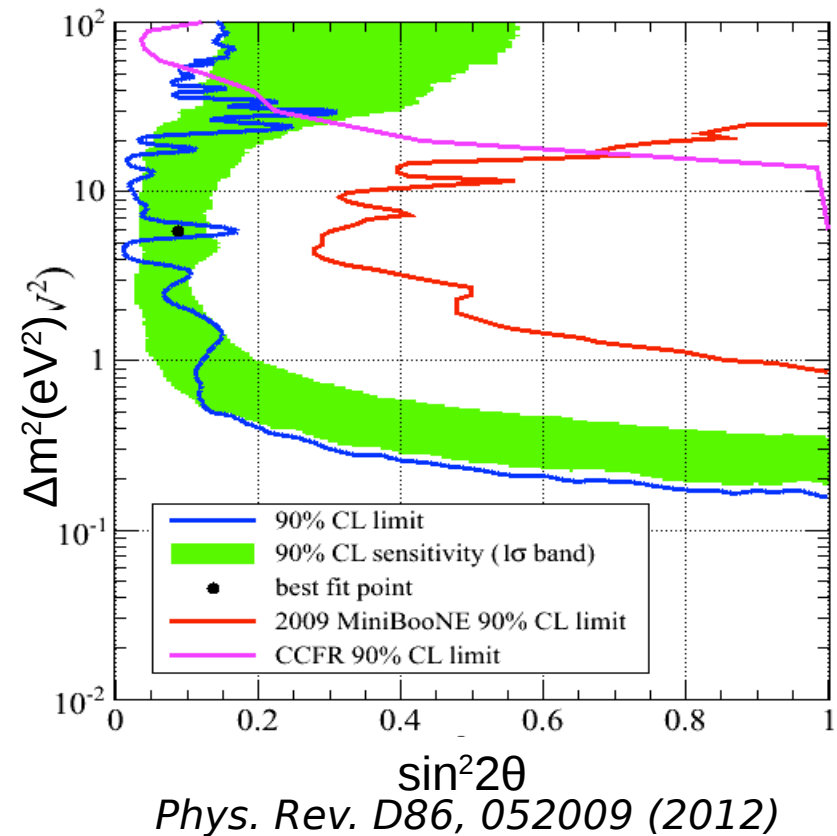
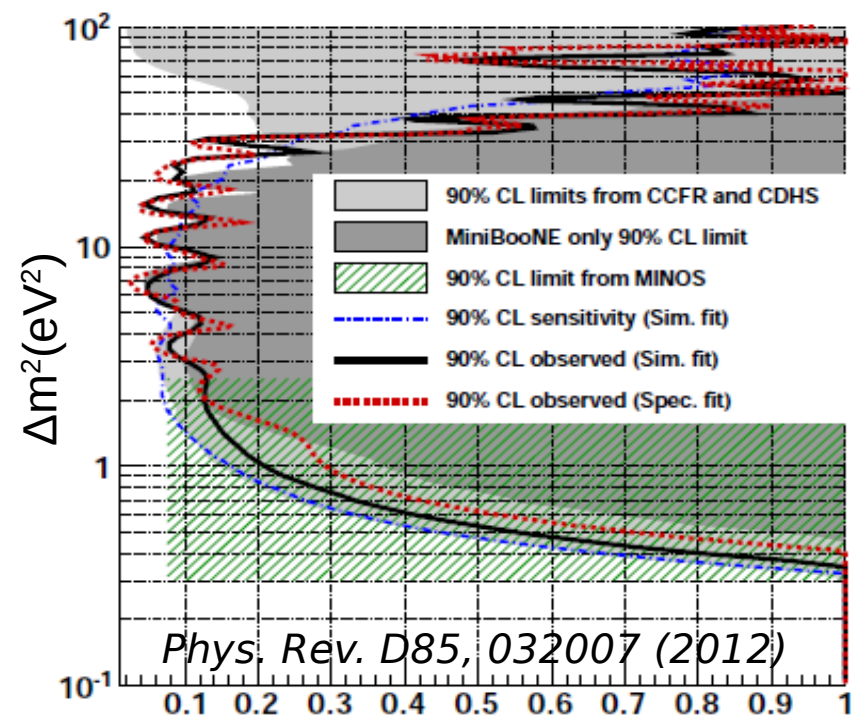
# 3+N models require large $\bar{\nu}_\mu$ disappearance

- In general:  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) P(\bar{\nu}_e \rightarrow \bar{\nu}_x)$
- From reactor experiments:  $P(\bar{\nu}_e \rightarrow \bar{\nu}_x) \sim 15\%$
- From LSND/MiniBooNE:  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\%$
- Therefore:  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 5\%$

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

# $\nu_{\mu}$ disappearance

- Neutrino (top) and Antineutrino (bottom)
- Limits from CCFR, CDHS, MiniBooNE & MINOS
- MiniBooNE used SciBooNE as near detector
- Under CPT  $\nu_{\mu}$  and  $\bar{\nu}_{\mu}$  disappearance probability is the same
- No disappearance observed yet



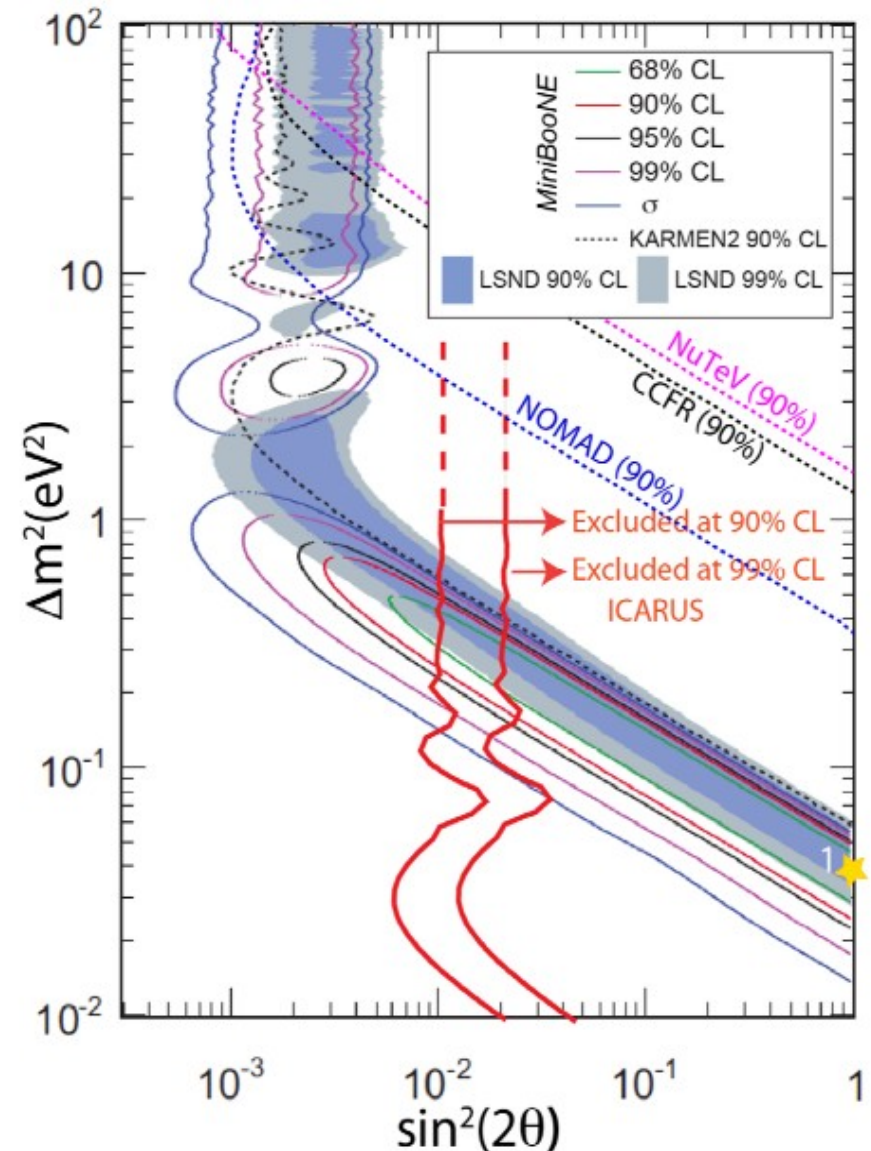
# Null results

- KARMEN

- Rutherford lab
- Stopped  $\pi$  source like LSND
- Detector at 17.7m
- Looked for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- Saw no evidence of oscillations

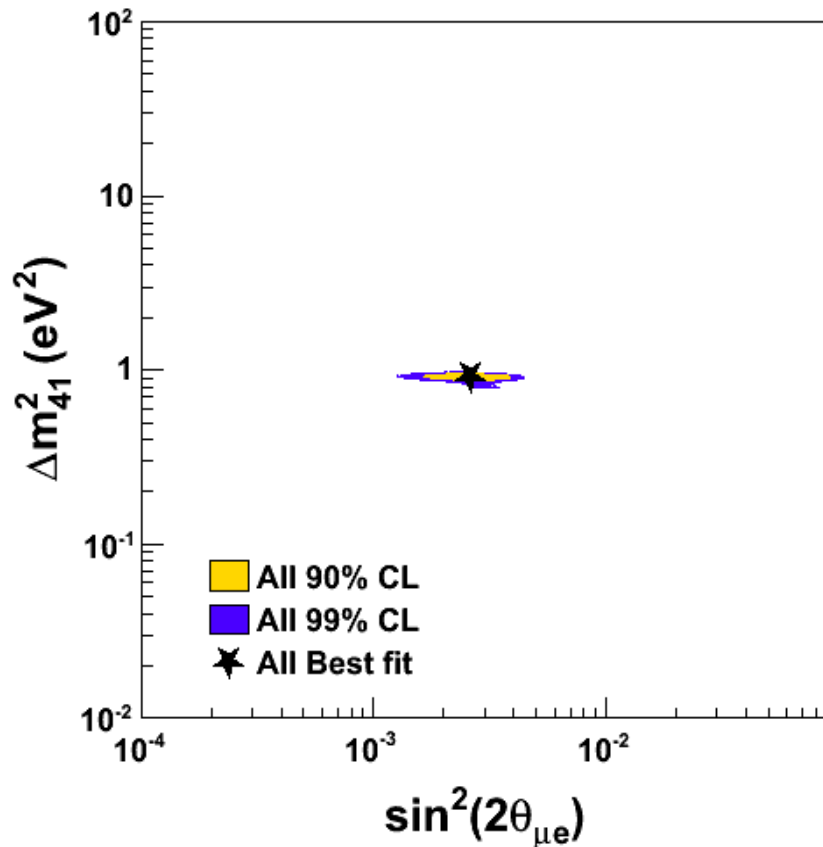
- ICARUS

- CERN to Gran Sasso neutrino beamline (730km)
- Looked for  $\nu_\mu \rightarrow \nu_e$
- Observed 2 events with expected background of 3.7



Does it all fit together?

# Global fits with 3+1 model

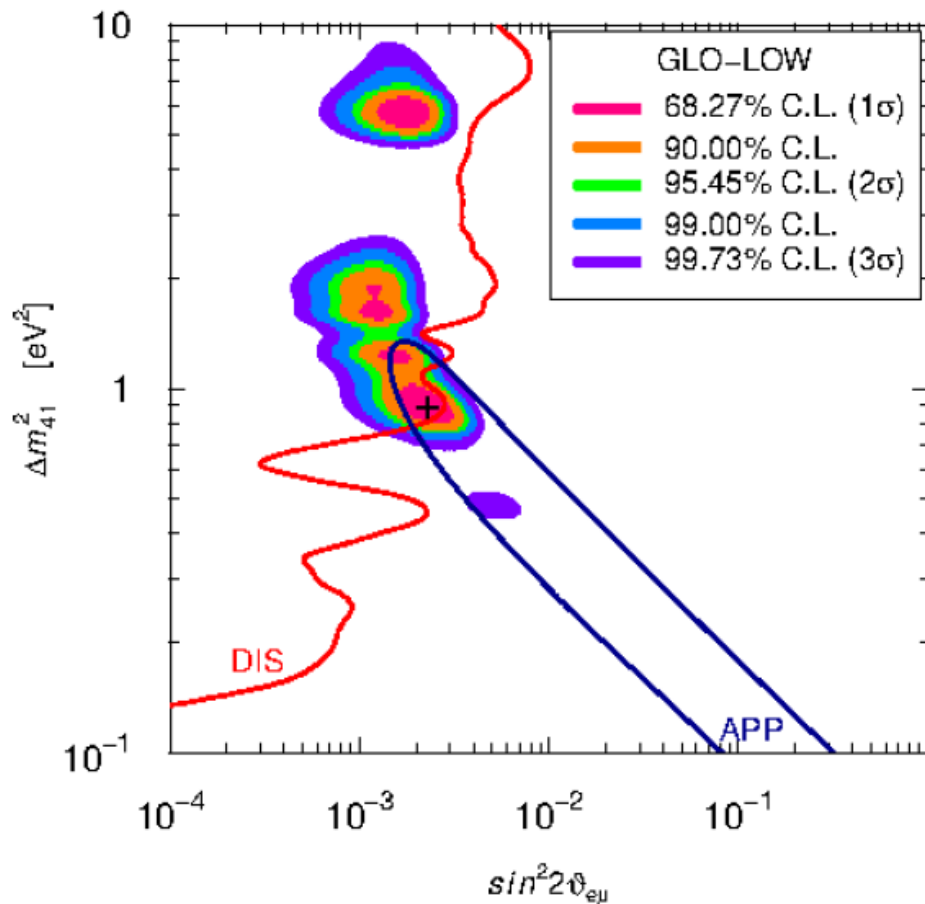


- Fit to all data
- 3 fit parameters
- Good  $\chi^2$  probability, however low parameter of goodness of fit (PG) indicates tensions in the data

$\chi^2(\text{dof})$	$\chi^2_{\text{null}}(\text{dof})$	gof	null gof	$\chi^2_{\text{PG}}(\text{dof})$	PG
233.9 (237)	286.5 (240)	55%	2.1%	54 (24)	0.043%

$$X^2_{\text{PG}} = X^2_{\text{min}; \text{combined}} - \sum_{\text{Experiments}} X^2_{\text{min}}$$

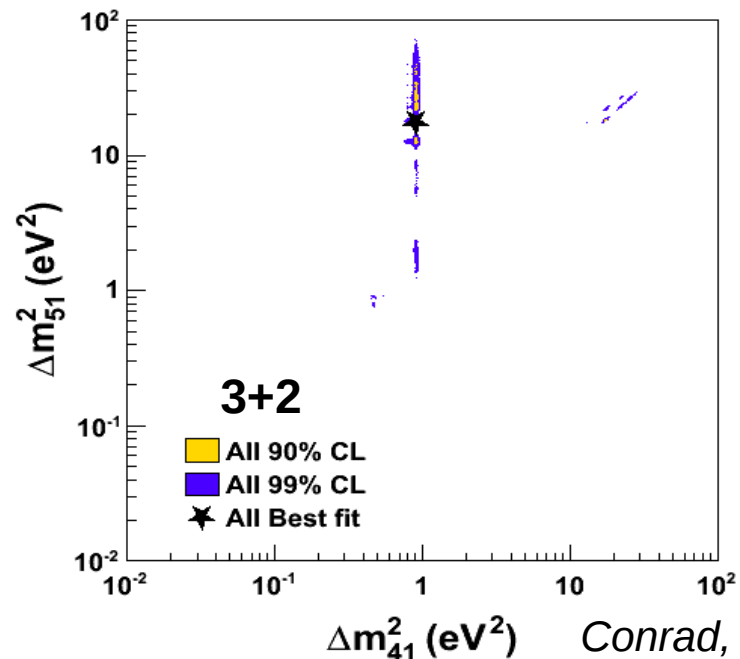
# Global fits with 3+1 model (cont'd)



- Tension between neutrino mode and antineutrino mode appearance experiments
- Tension between disappearance and appearance experiments
- All of the data cannot be fit simultaneously with 3+1 model

# 3+N fits ( $N > 1$ )

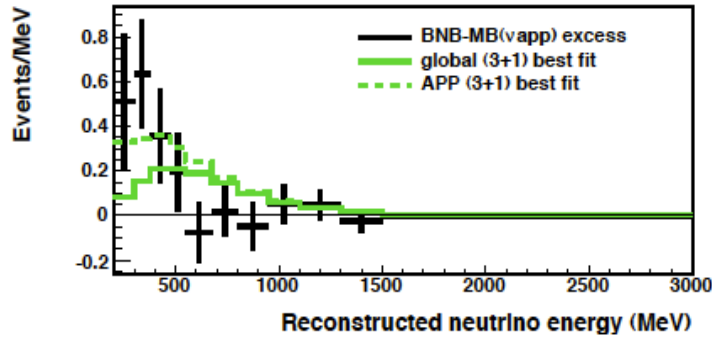
- 3+2 fits allow for CP violation – neutrino vs anti-neutrino appearance
- Tension relaxed with 3+2 fits and even more in 3+3 fits
- However, still some tension between appearance and disappearance even in 3+3 fits



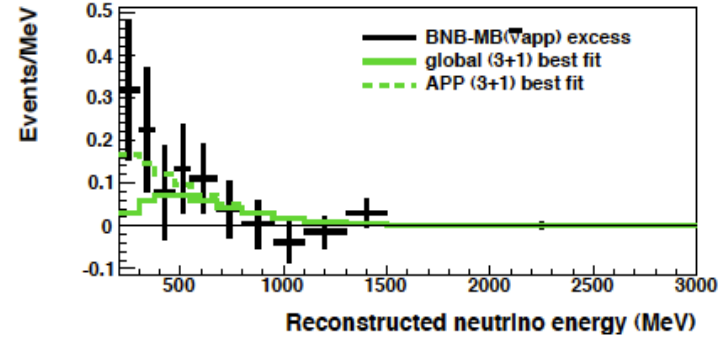
Conrad, Ignarra, Karagiorgi, Shaevitz & Spitz  
arxiv:1207.4765

# MiniBooNE low energy excess

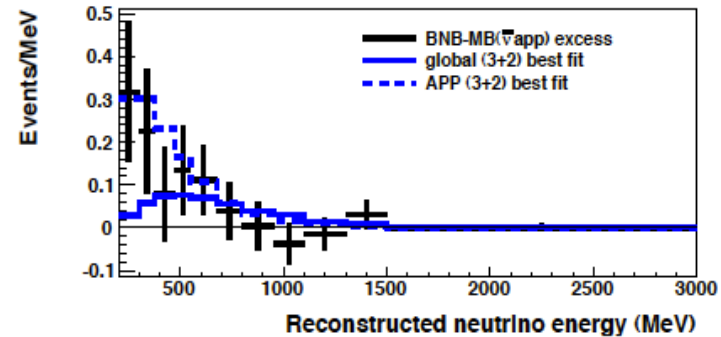
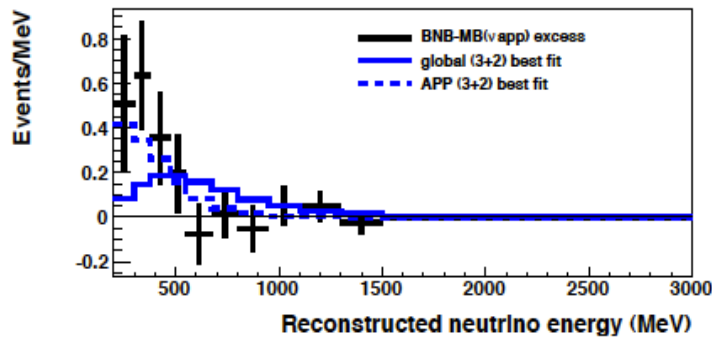
Neutrino



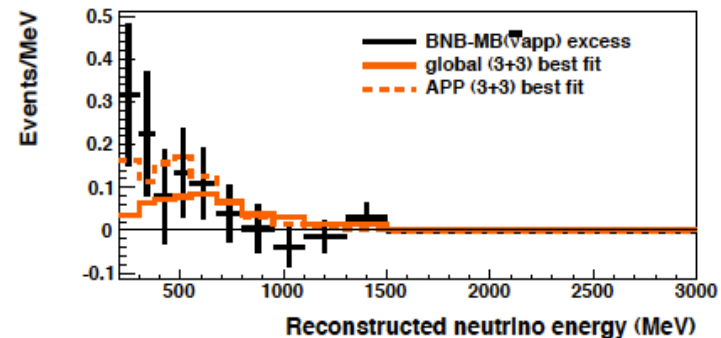
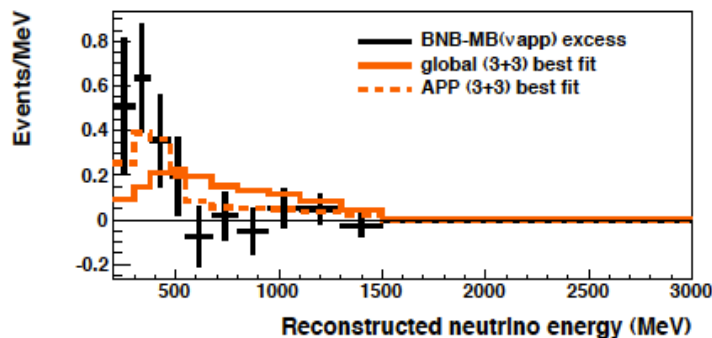
Antineutrino



3+1



3+2



3+3

# Future outlook

- Many proposals to test all of the anomalies and the sterile neutrino hypotheses:
  - Radioactive sources
  - Reactor neutrinos
  - Stopped  $\pi$  beam
  - Decay in flight beams
- MicroBooNE - resolve MiniBooNE low energy excess

# MicroBooNE Experiment

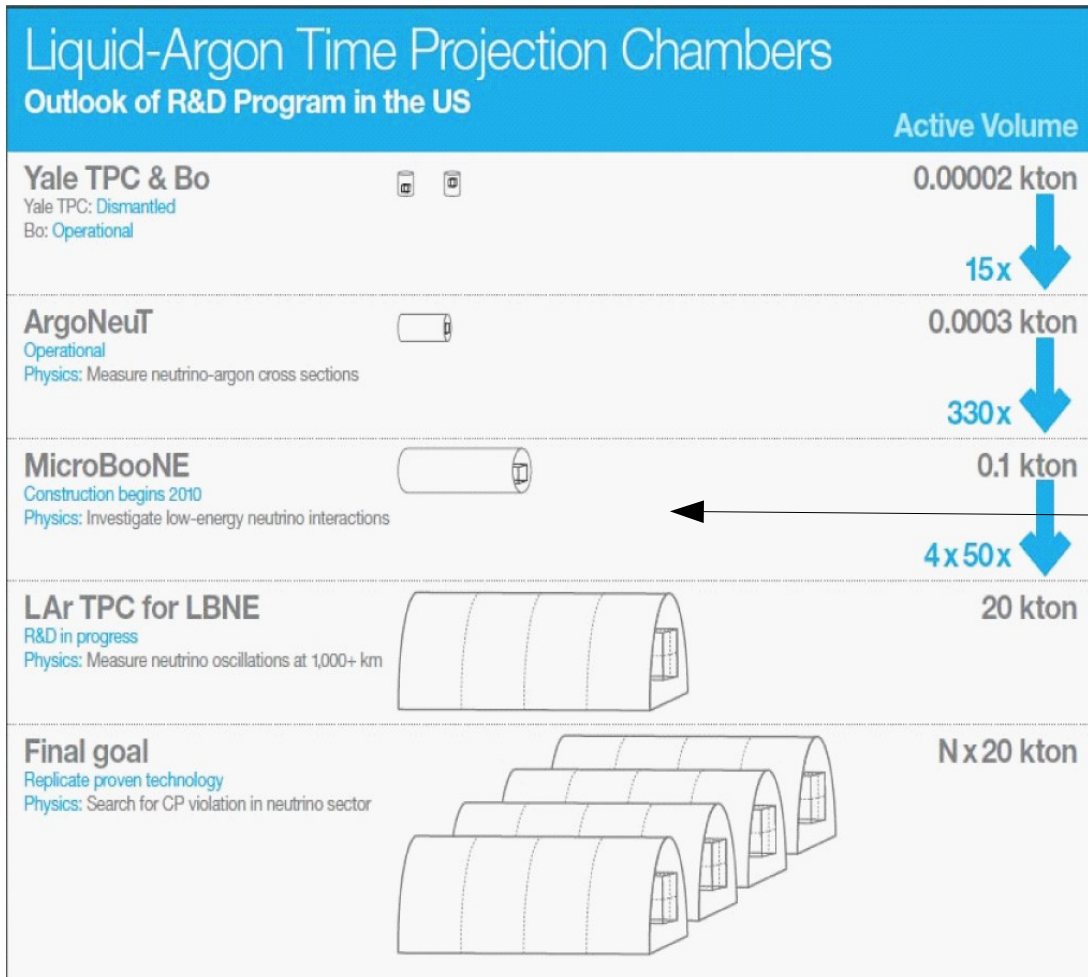
- Liquid Argon Time Projection Chamber (LArTPC)
  - 170t LAr (~84t active)
  - Fermilab's Booster Neutrino Beamline
- Start data taking in 2014



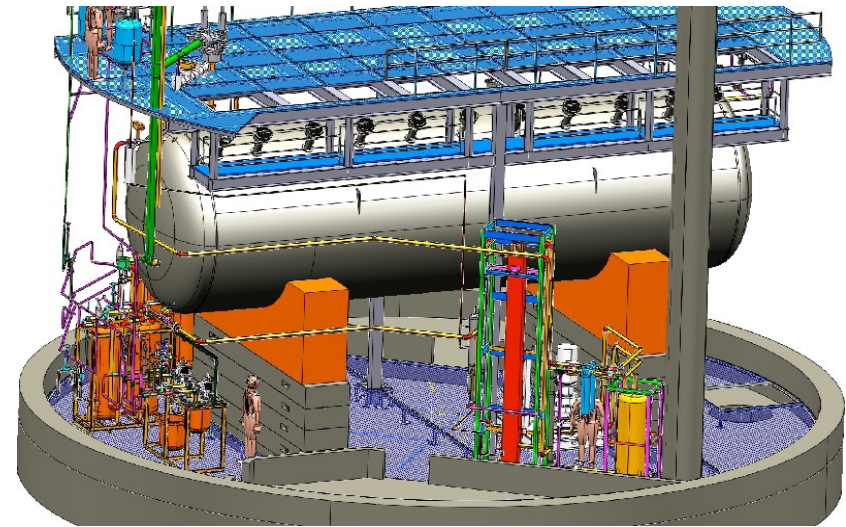
# MicroBooNE goals

- Physics goals
  - MiniBooNE low energy excess
    - MicroBooNE can distinguish between e and gamma
  - Cross sections
- R&D goals
  - Serve as a step toward multi-kton detectors
  - Test LArTPC technology
  - Development of full reconstruction of neutrino interactions in LArTPC

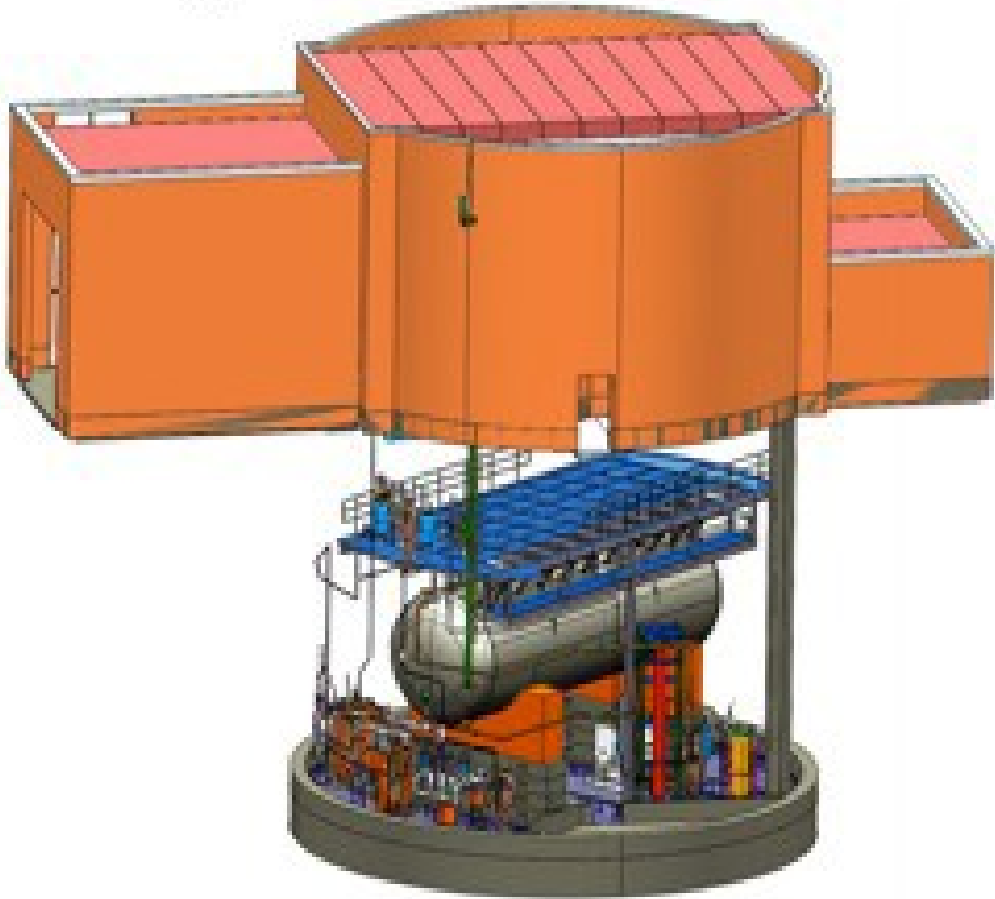
# LAr program



- Staged program toward multi-kiloton LAr detectors



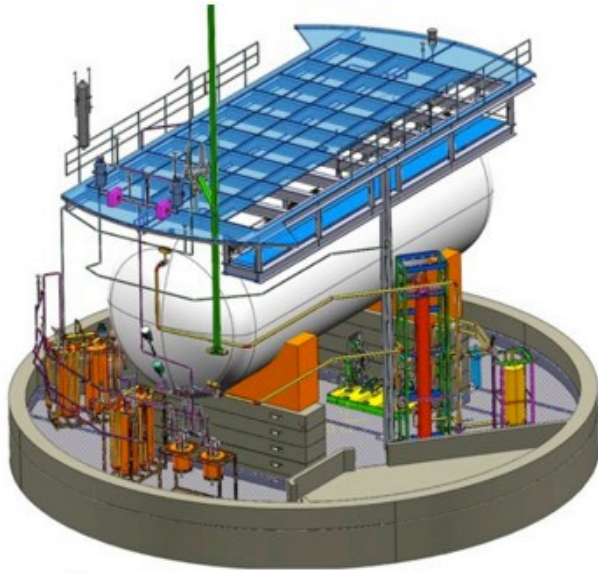
# Design/Construction



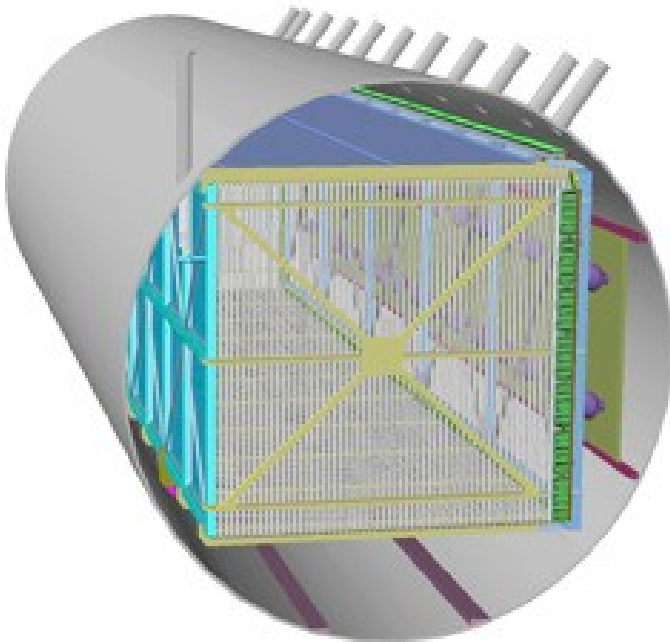
October 2012

- Start moving in  
~Spring 2013

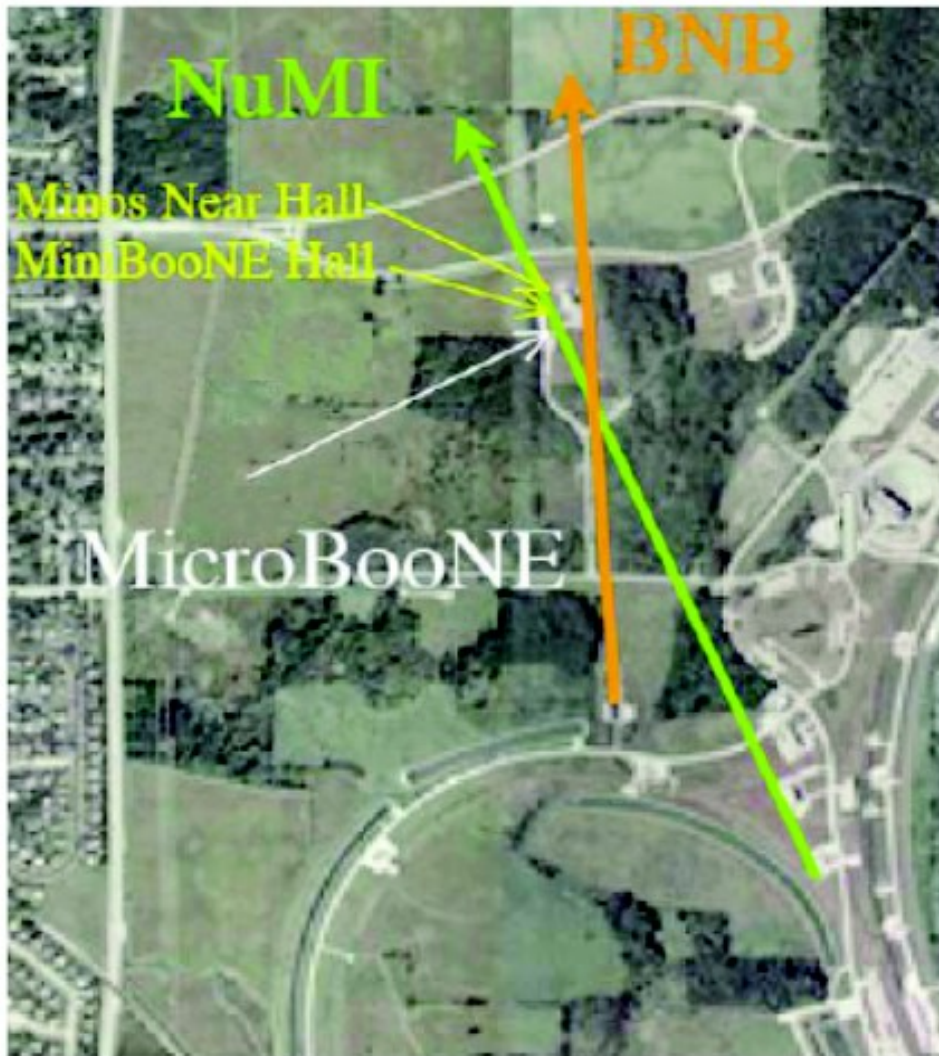
# Design/Construction



- TPC
  - $H \times W \times L = 2.33 \times 2.56 \times 10.37 \text{ m}$
  - 3 wire planes (2 induction, 1 collection)
  - 3mm wire pitch



# Neutrino beams



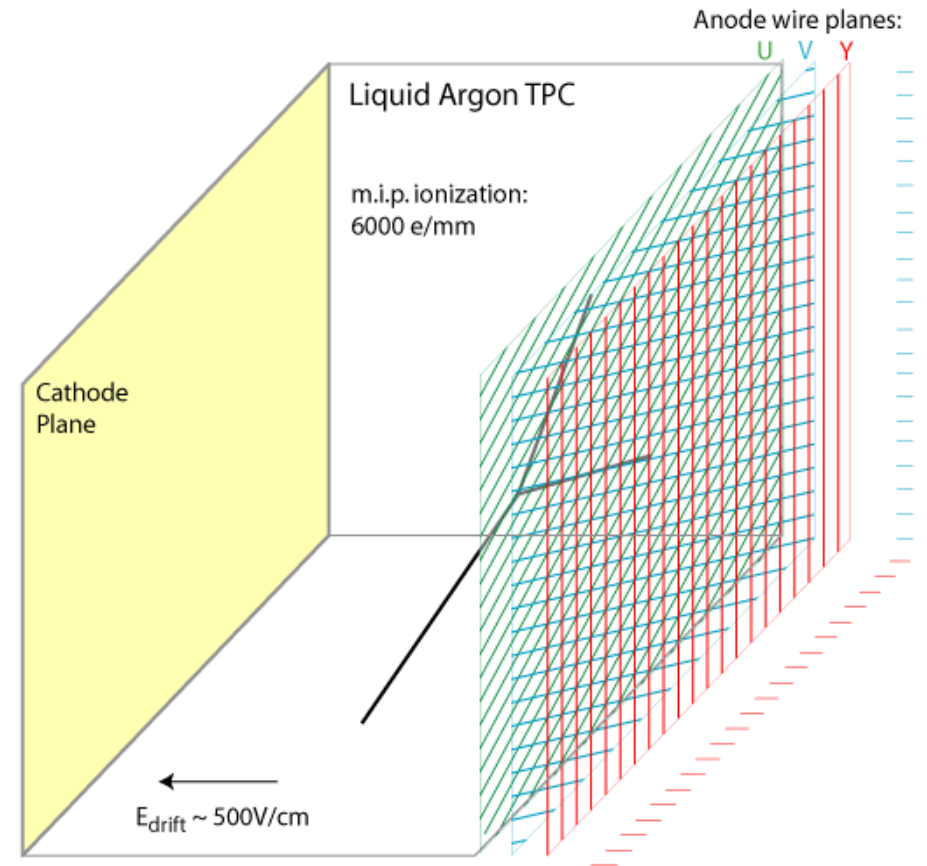
	BNB	NuMI
Total Events	145k	60k
$\nu_{\mu}$ CCQE	68k	25k
NC $\pi^0$	8k	3k
$\nu_e$ CCQE	0.4k	1.2k
POT	$6 \times 10^{20}$	$8 \times 10^{20}$

Projected Event Rates for MicroBooNE in 2-3 years.



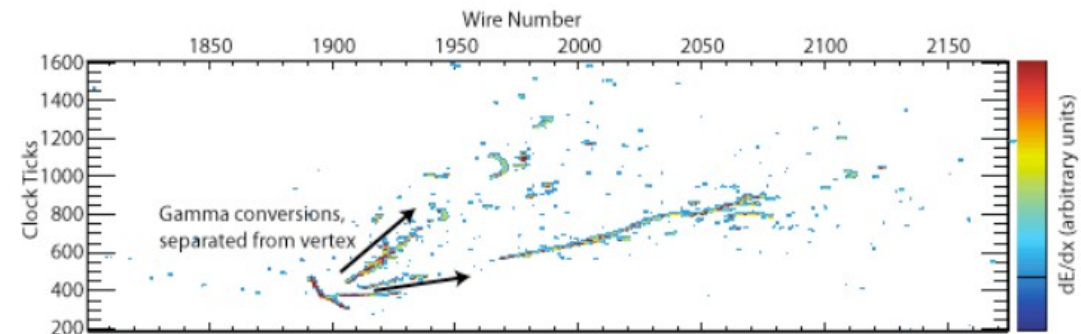
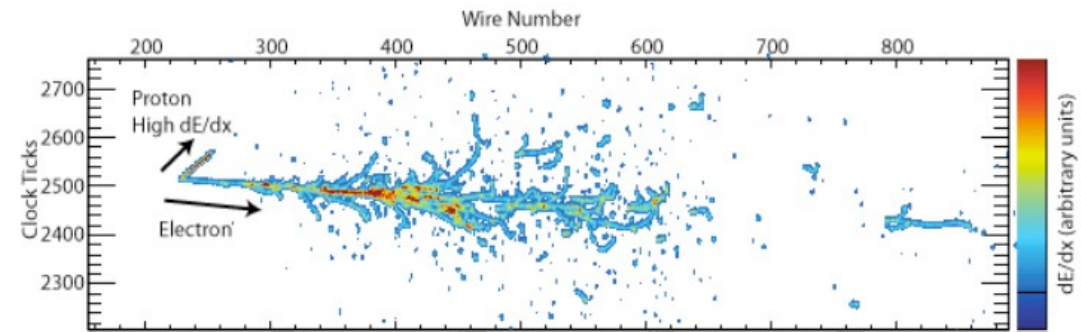
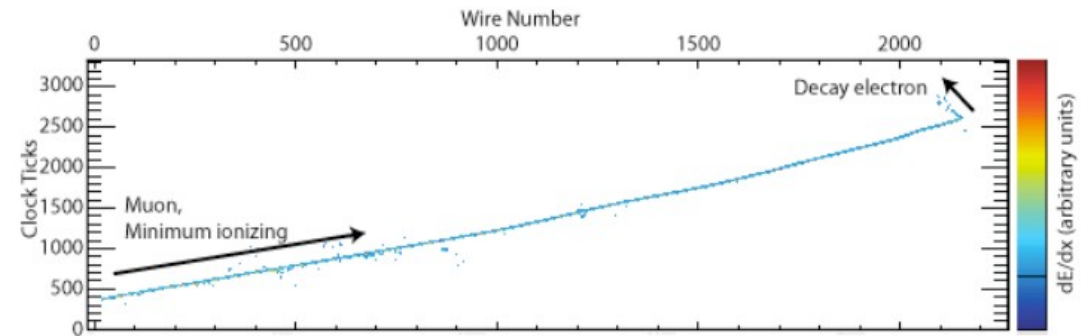
# LAr technology

- Charged particles ionize Ar
- Electric field drifts electrons to wire planes
- Induction/collection planes image charge



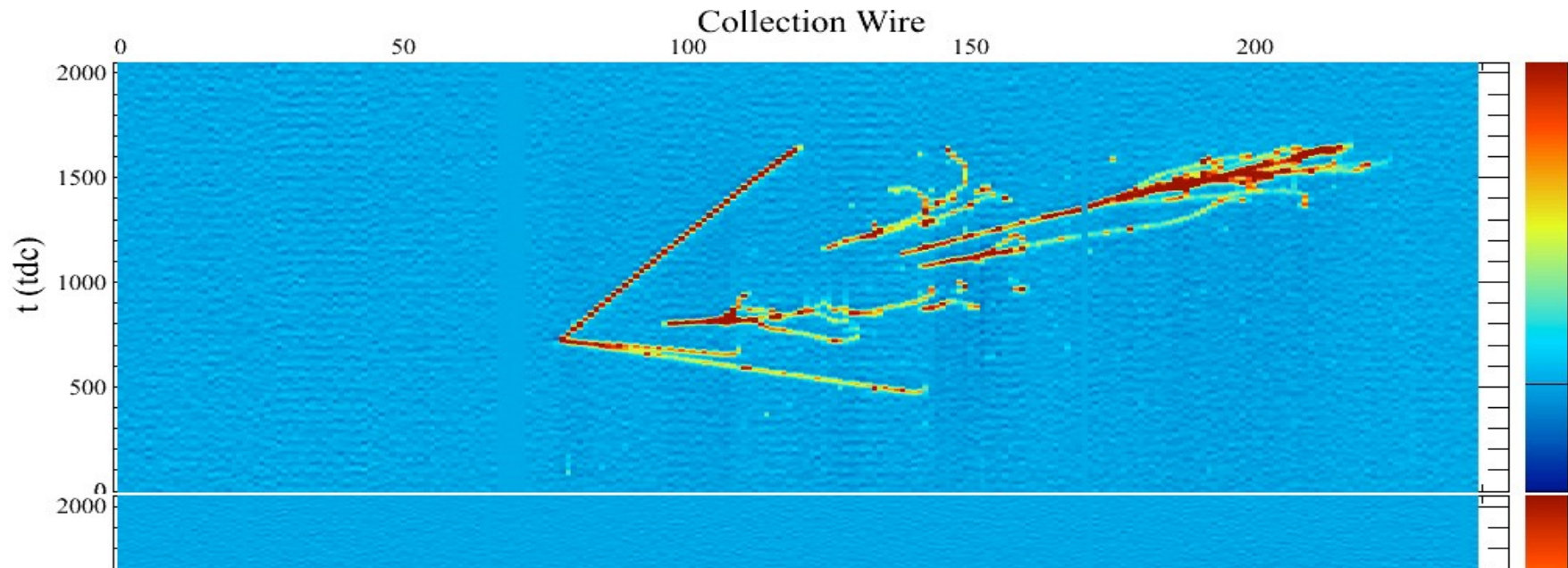
# Events in LArTPC

- mm scale resolution
- $dE/dx$  information
- Excellent PID and  $e/\gamma$  separation



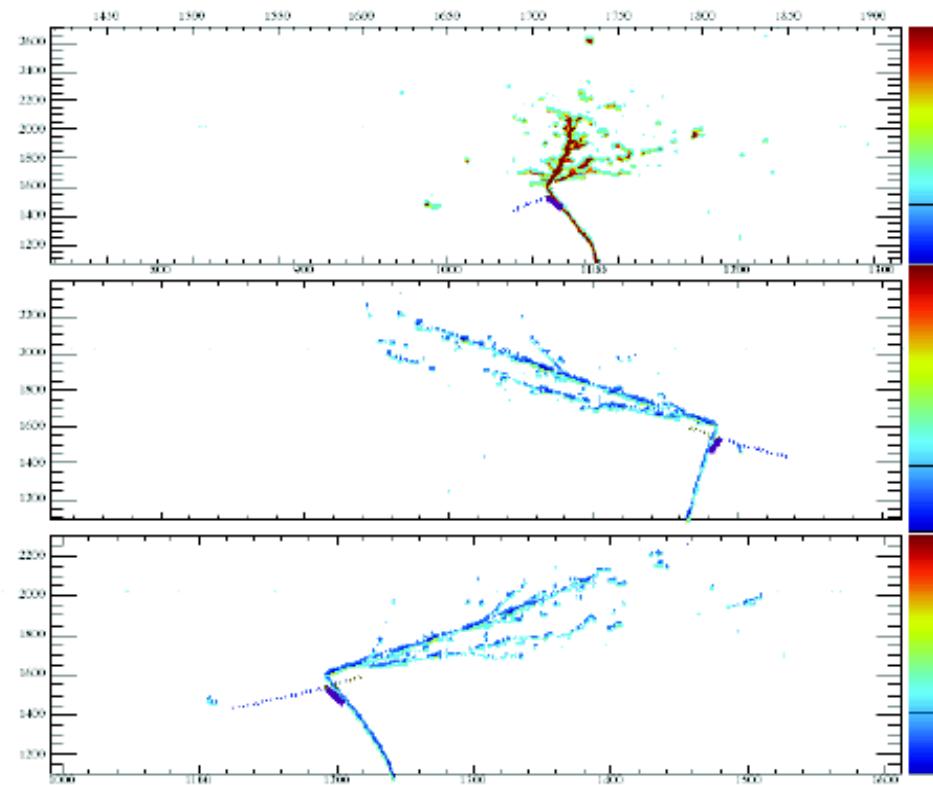
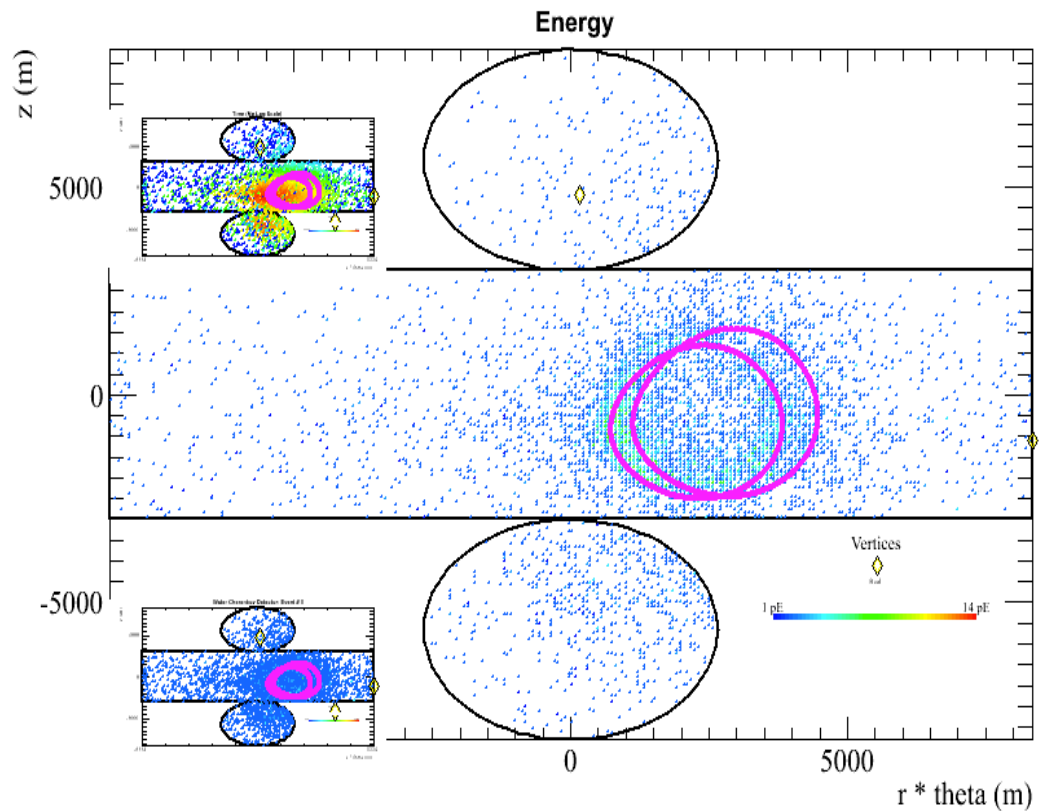
# Argoneut data

- $2 \pi^0$  event in Argoneut
  - Displaced vertices
  - High ionization at the beginning of gamma track



# Water Cherenkov vs LAr

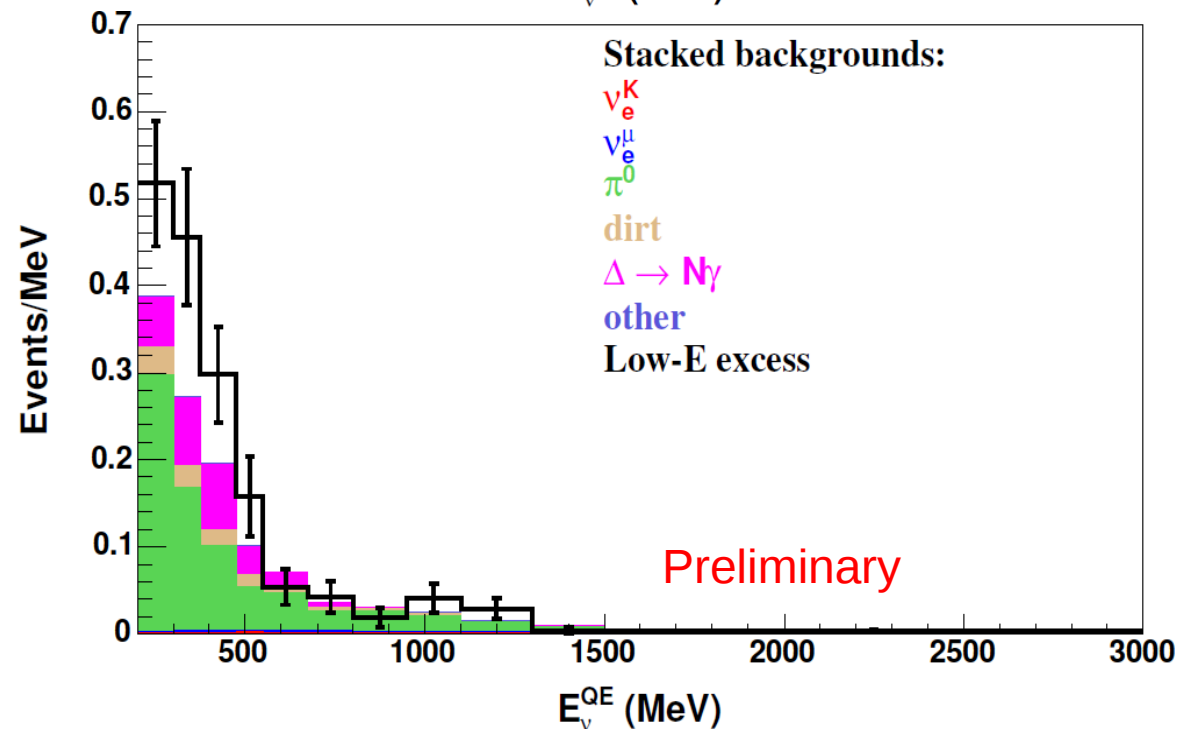
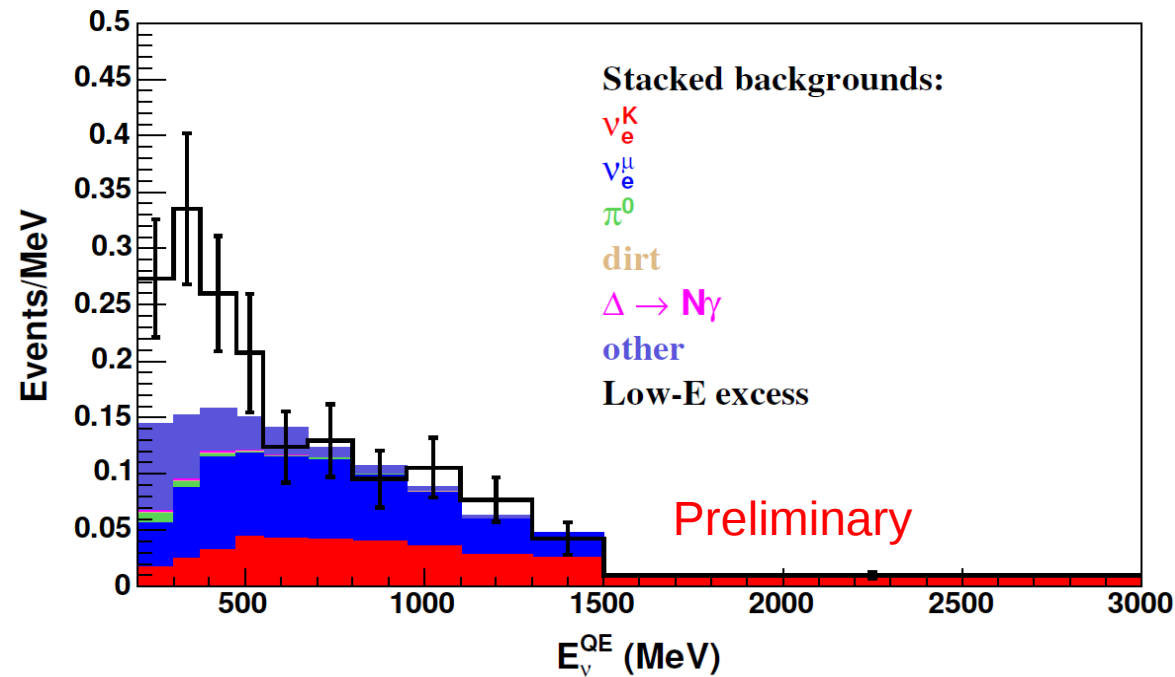
- Identical event simulated in Water Cherenkov detector and MicroBooNE



Courtesy J. Raaf

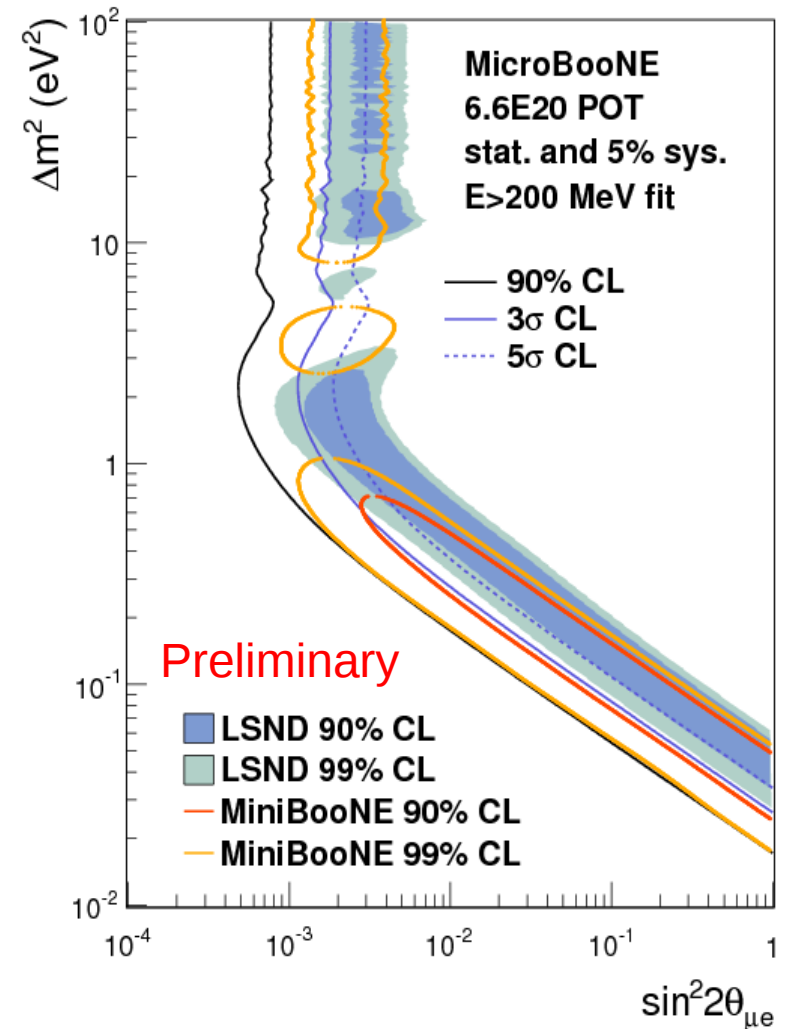
# e vs gamma

- In MicroBooNE low Energy excess will show in either electron like sample (top) or gamma like sample (bottom)
- If excess is due to electrons expect  $36.8 \pm 6.4$  ( $5.7\sigma$ )
- If excess is due to photons expect  $36.8 \pm 8.9$  ( $4.1\sigma$ )



# Sensitivity

- Additionally, MicroBooNE can also test oscillation hypothesis
- Sensitivity covers LSND preferred region at  $3\sigma$  level
- Smaller mass compared to MiniBooNE, but higher signal efficiency and background rejection



# My thoughts on combining MiniBooNE & MicroBooNE

- Use MicroBooNE to:
  - constrain the gamma backgrounds in low energy region (major source of uncertainty for MiniBooNE)
  - lower analysis energy threshold
  - study multinucleon effects and how it affects the reconstructed energy distribution in MiniBooNE
- MiniBooNE provides high statistics data sample
  - Excess in neutrino mode  $162.0 \pm 28.1 \pm 38.7$  ( $3.4\sigma$ )
  - Systematic error dominated by uncertainty in gamma backgrounds
- Combining the two results will increase the sensitivity in  $\Delta m^2 \sim 1\text{eV}^2$  region and allow reaching  $5\sigma$

# Opportunities with NuMI beam

- MicroBooNE at  $\sim 130$  mrad wrt NuMI beamline
- Given the large number of protons on target that are planned to be delivered to NOvA (NuMI), MicroBooNE will see more events from NuMI beam than from BNB
- Use NuMI events to:
  - Study muon antineutrino and electron neutrino interactions – large components compared to BNB
  - Reconstruction effects
  - Provide constraint to NOvA offaxis flux prediction

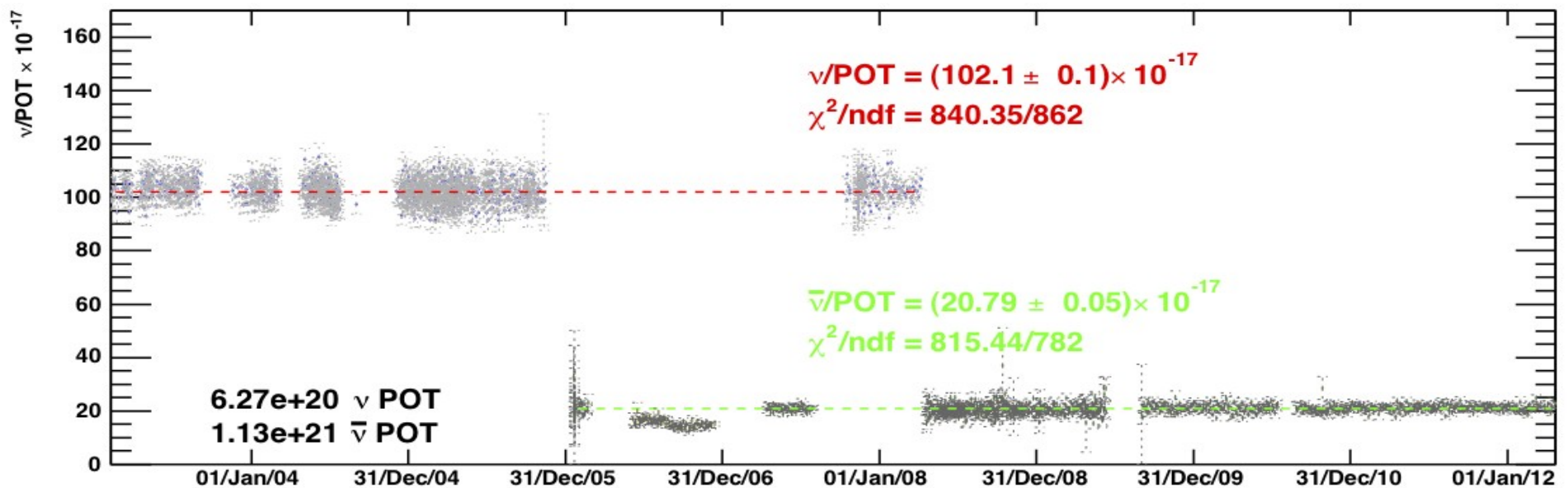
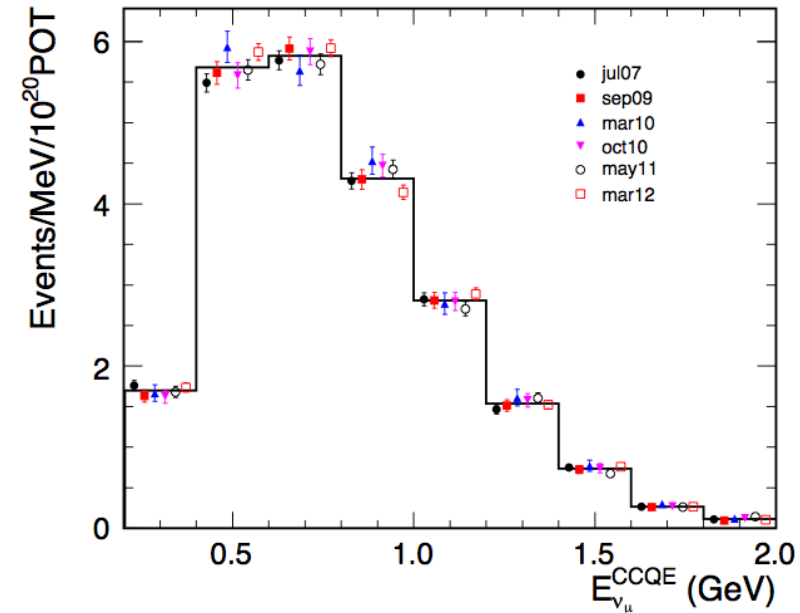
# Conclusion

- Increasing evidence for short baseline anomalies and existence of light sterile neutrinos, however not definite proof
- Important to find physics behind these anomalies
- Follow-up experiments being proposed and under construction
- Probe physics behind short baseline anomalies with high significance

Backup

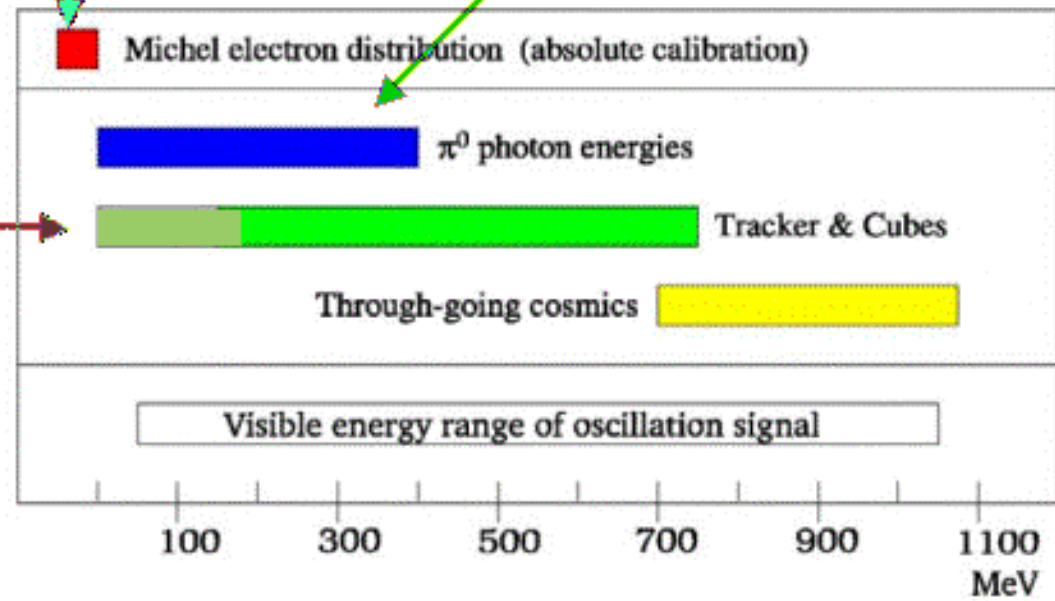
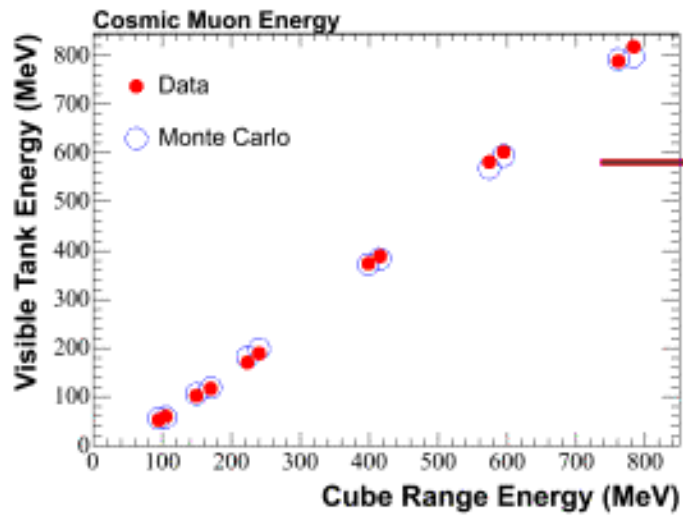
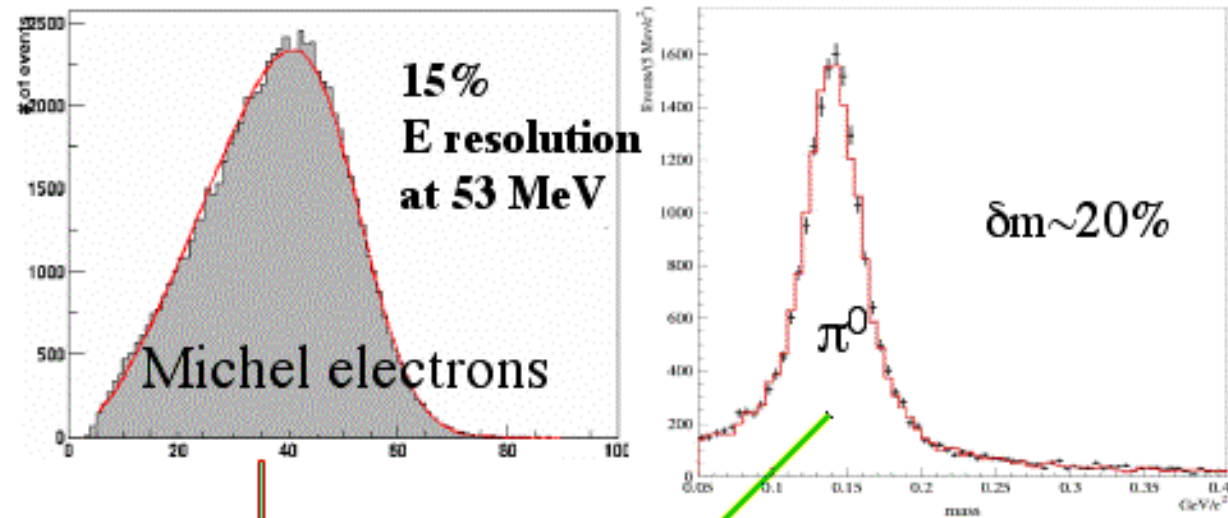
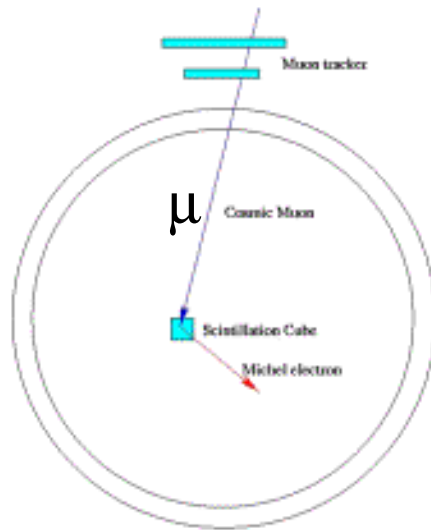
# 10 years of running

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



# Calibration Sources

## Tracker system



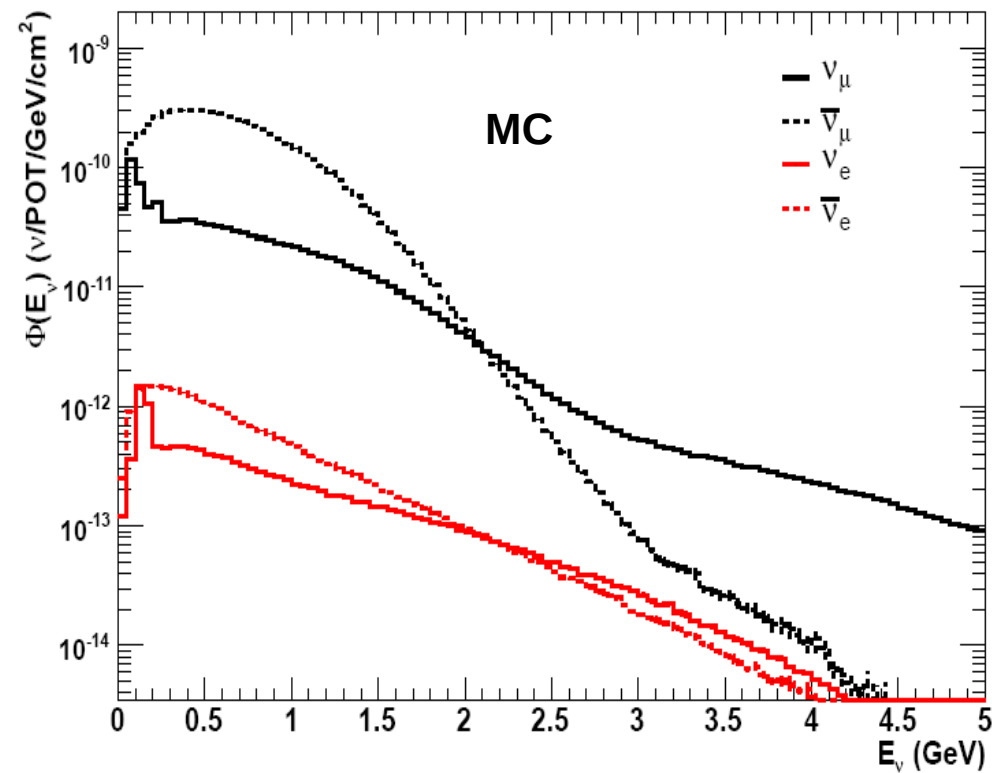
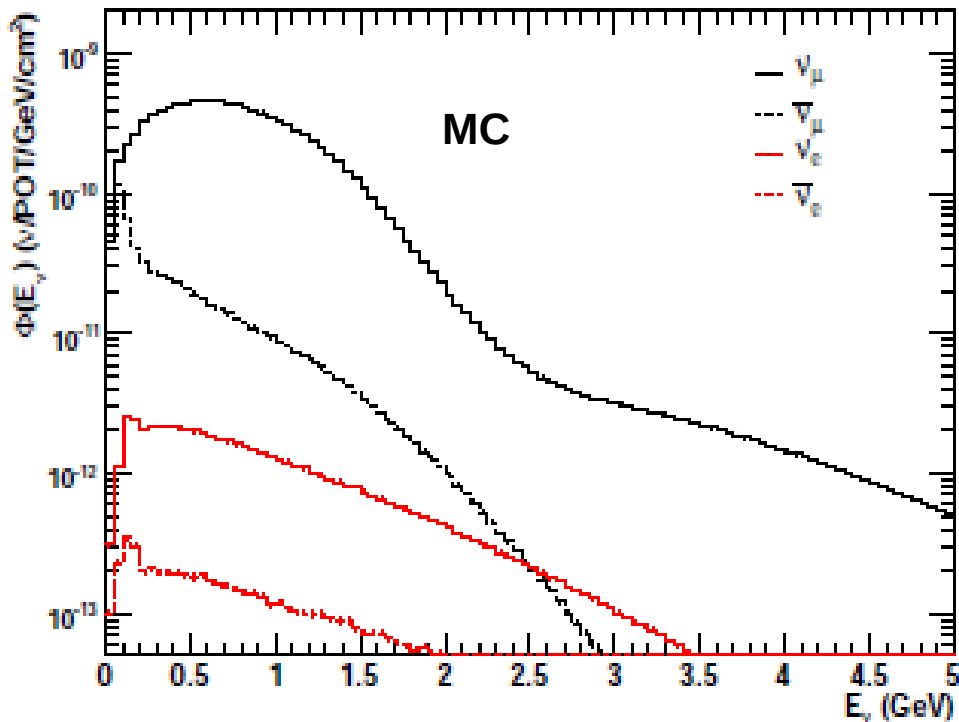
# Predicted BNB neutrino flux (MC)

- Neutrino mode

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

- Anti-neutrino mode

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



# Oscillation Fit Method

- Maximum likelihood fit:

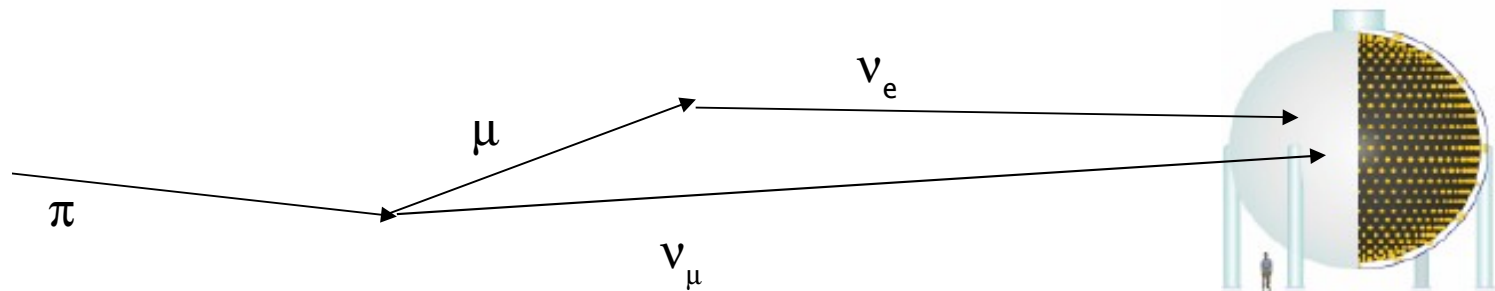
$$-2 \ln(L) = (x_1 - \mu_1, \dots, x_n - \mu_n) M^{-1} (x_1 - \mu_1, \dots, x_n - \mu_n)^T + \ln(|M|)$$

- Simultaneously fit

- $\nu_e$  CCQE sample
- High statistics  $\nu_\mu$  CCQE sample

- $\nu_\mu$  CCQE sample constrains many of the uncertainties:

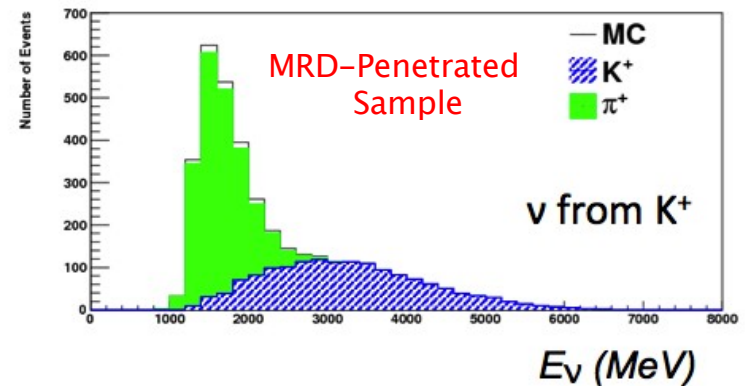
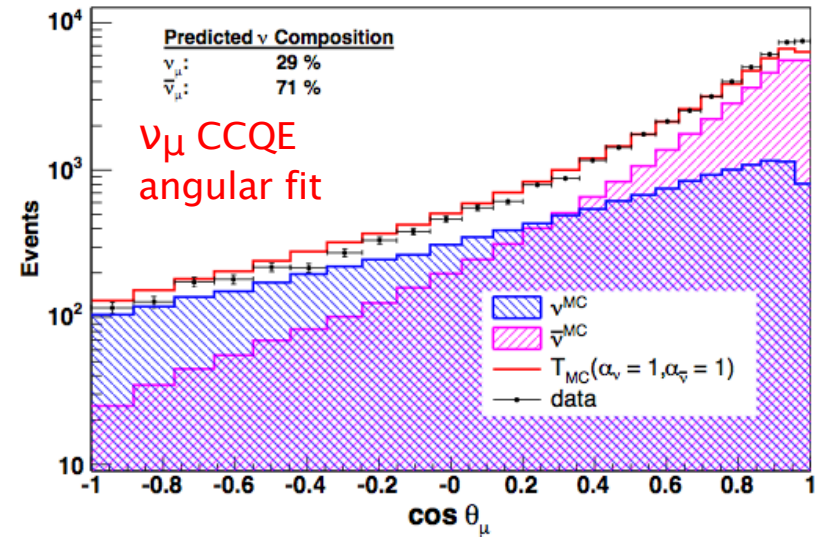
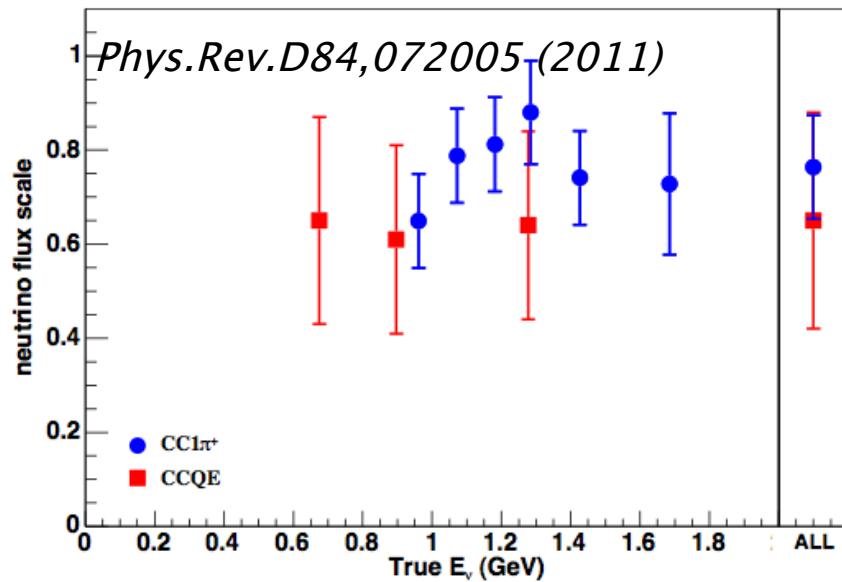
- Flux uncertainties



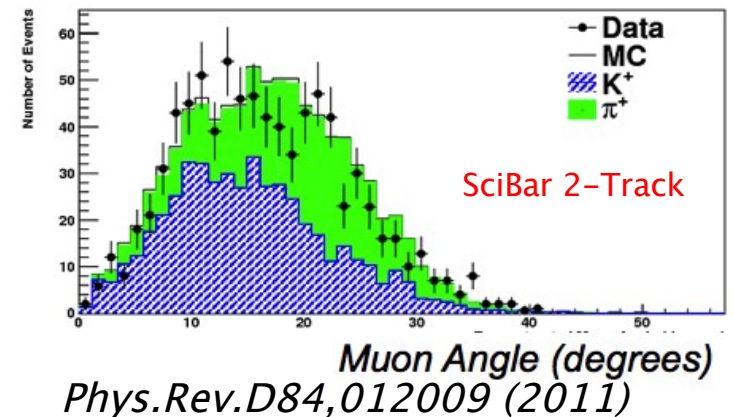
- Cross section uncertainties

# What's new since last oscillation publication?

- *In situ* measurement of WS contamination in anti- $\nu$  beam
  - $\nu_\mu$  CCQE angular fit, and new constrain from  $CC\pi^+$  rate...good agreement with expectation

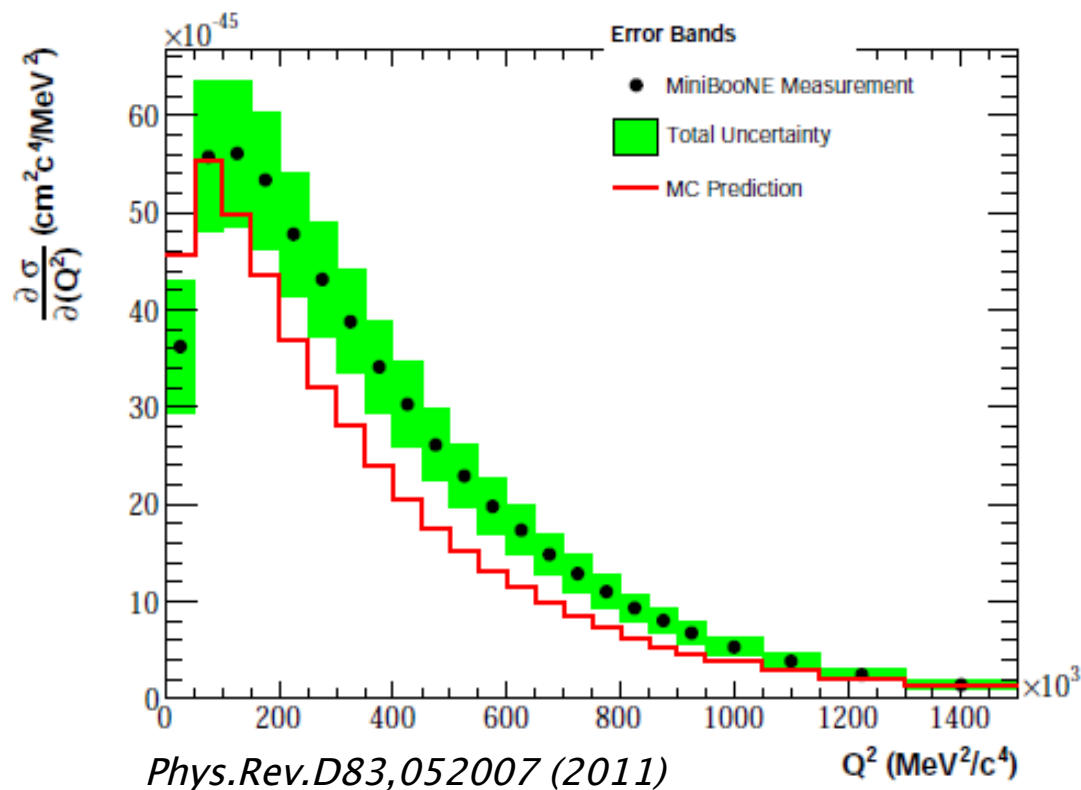


- New SciBooNE constraint on intrinsic  $\nu_e$  from  $K^+$ 
  - Found  $K^+$  production to be  $0.85 \pm 0.12$  relative to prediction, consistent with prior MiniBooNE assessment of  $1.00 \pm 0.30$
  - Leading error on  $K^+$  bkg becomes  $\sim 20\%$  error from cross-section



# What's new since last oscillation publication?

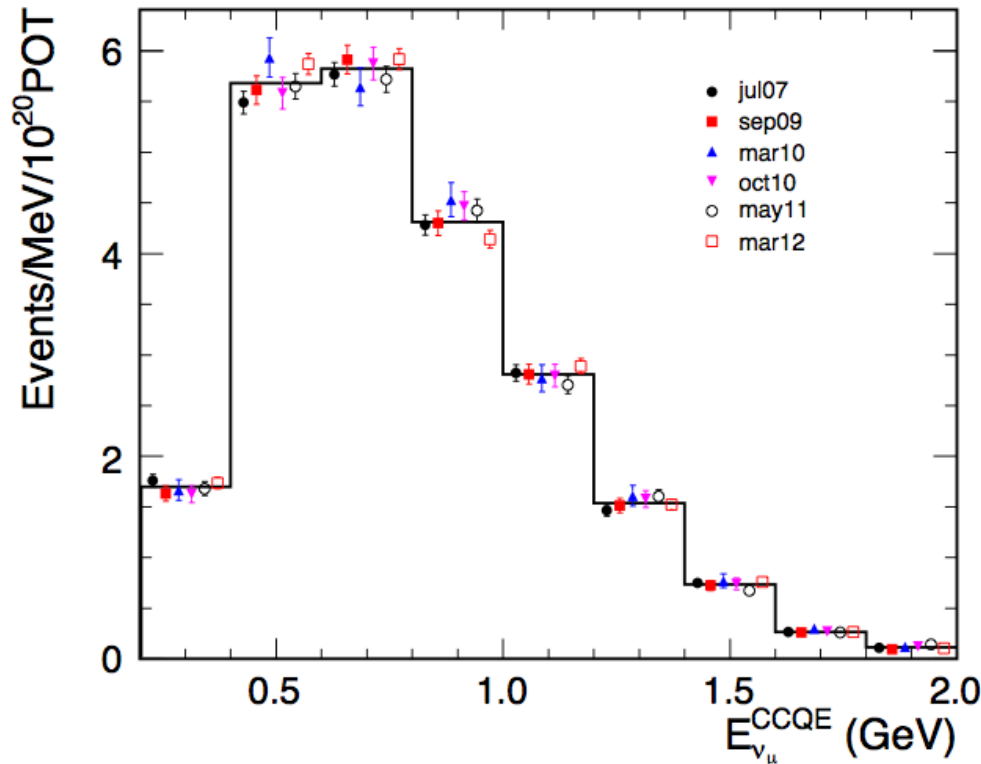
- Few other minor updates...
  - Higher stats for all MC samples, reduces fluctuations in error matrices
  - Added error matrix for intrinsic  $\nu_e$  from K-
  - Improved smoothing algorithm that was being used to assess systematics due to discriminator thresholds and PMT response
  - CC $\pi^+$  events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



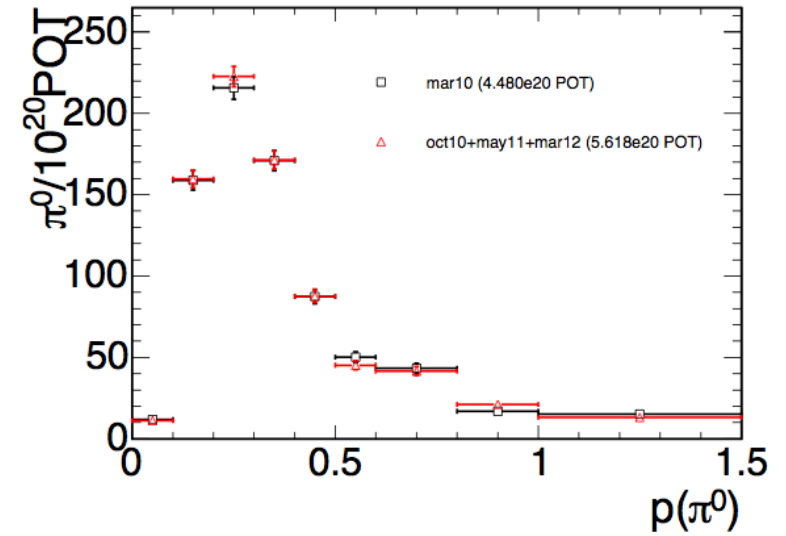
# Main improvement...doubling of anti- $\nu$ stats

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

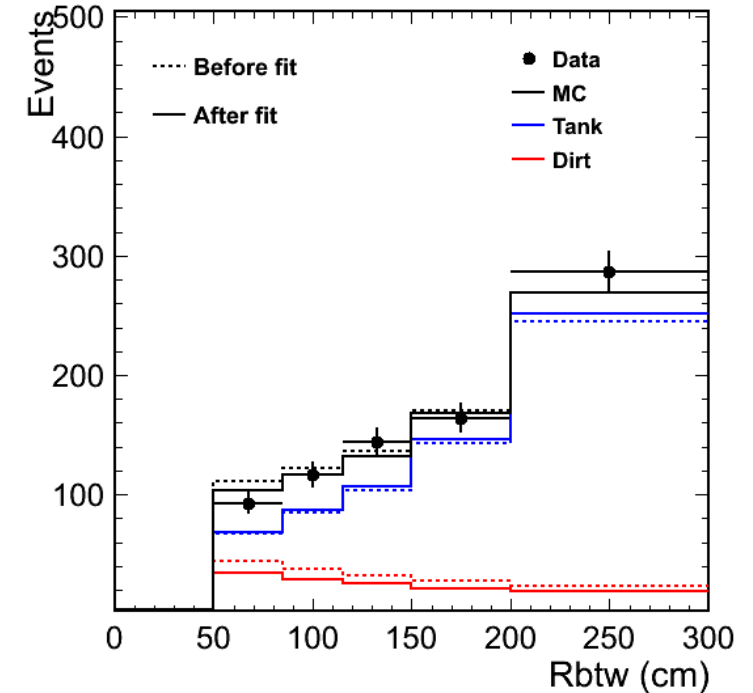
$\nu_\mu$  CCQE Sample



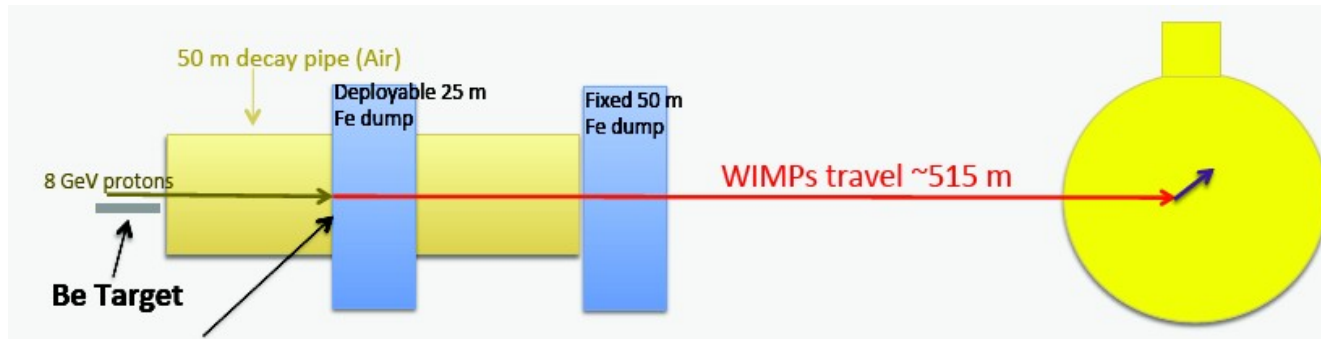
NC  $\pi^0$  Sample



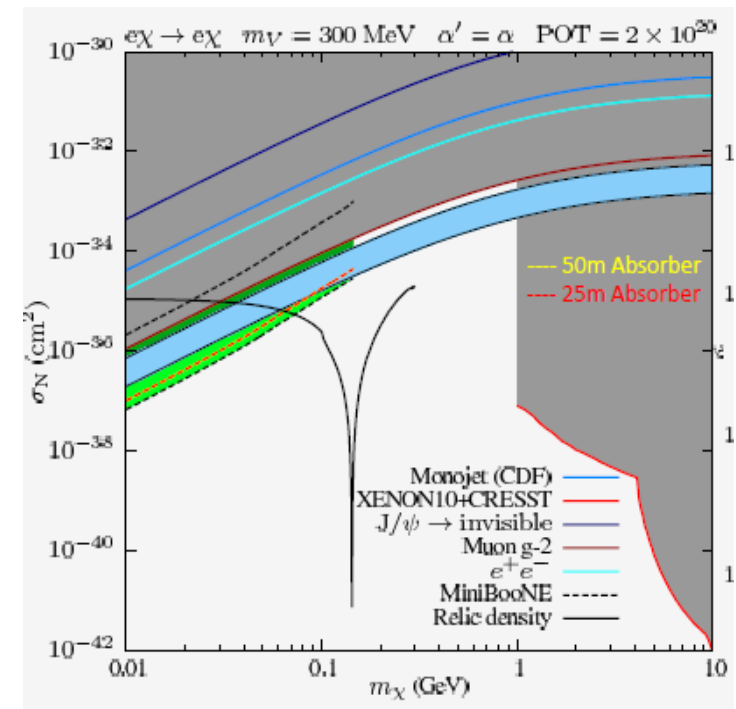
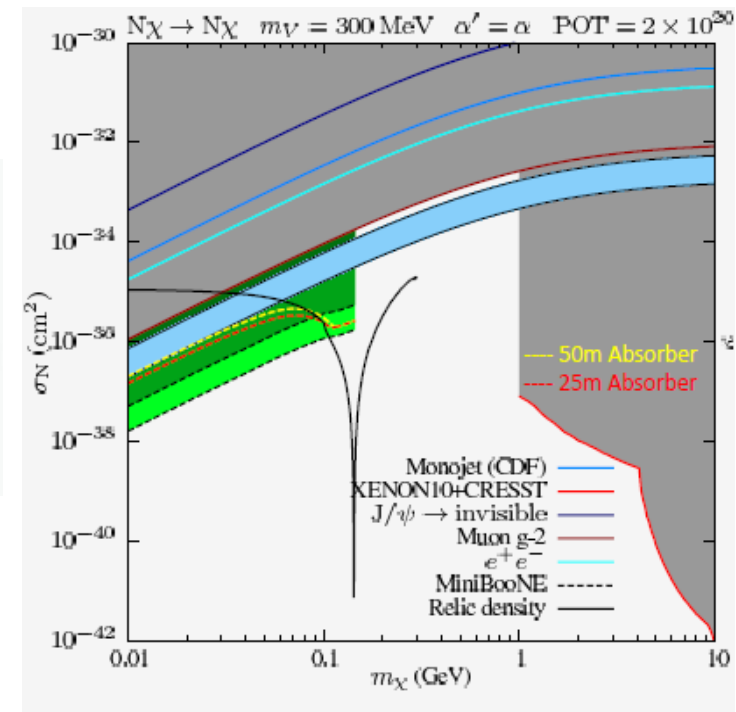
Dirt-enhanced Sample



# MB beam off target run

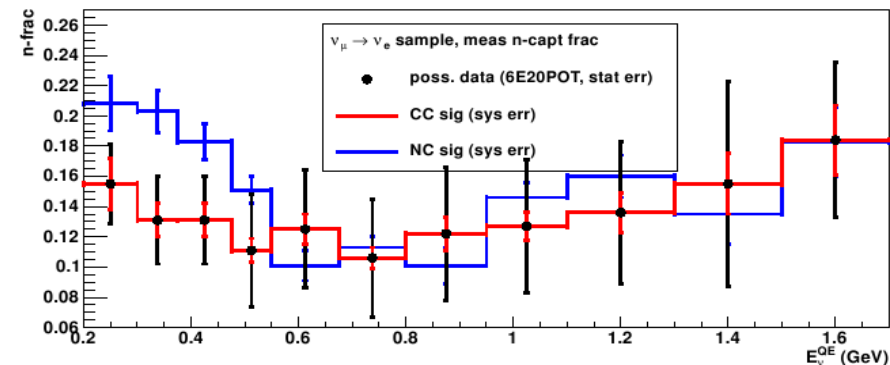
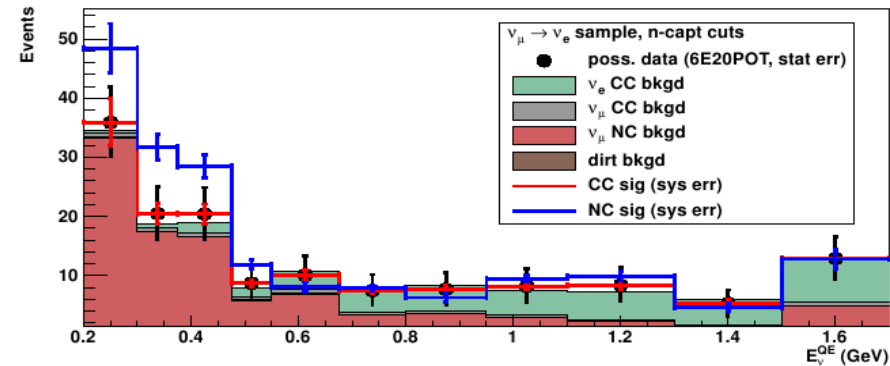
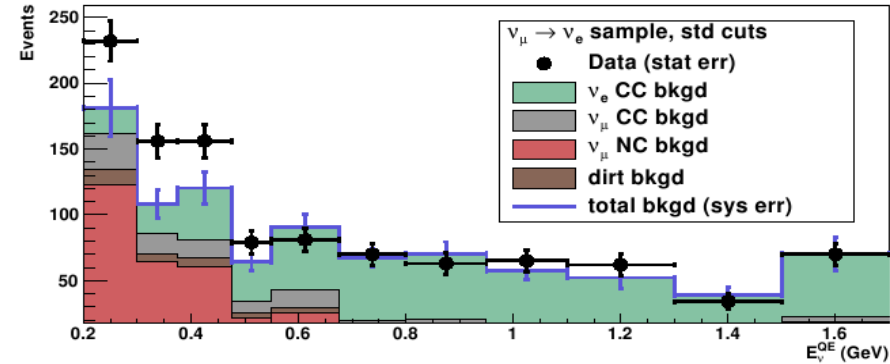


- $2e20$  POT w/ and w/o 25m absorber
- Shades of green indicate 1-10, 10-1000 and  $>1000$  signal events
- 90% CL sensitivity for estimated background
- Include timing info and  $\cos\theta_{\text{beam}}$  for electron sample
- Cover significant region of g-2 signal region



# MB with scintillator

- Add scintillator to MiniBooNE to enable reconstruction of 2.2 MeV n-capture photons
  - True CC events have only 1-10% neutrons
  - NC background has 50% neutrons (dominated by NC  $\Delta$  with equal branch to p/n decay)
- Other physics goals
  - p to n ratio in NC elastic scattering to measure  $\Delta s$  (s-quark contribution to nucleon spin)
  - Measurement of  $\nu_\mu C \rightarrow \mu N_{gs}$  tagged with  $N_{gs} \beta$  decay ( $\sim 15$  MeV endpoint enabled with scintillator); cross section known to  $\sim 2\%$  near threshold allows a low-E flux test
  - Test of QE assumption in neutrino energy reconstruction



# NC induced photon production

- Computed event rates in neutrino and antineutrino mode consistent with MiniBooNE estimate
- *“The difference between our upper bound and experimental estimate is not significant enough to explain the excess”*

$E_{QE}$ (GeV)	[0.2, 0.3]	[0.3, 0.475]	[0.475, 1.25]
coh	1.5 (2.9)	6.0 (9.2)	2.1 (8.0)
inc	12.0 (14.1)	25.5 (31.1)	12.6 (23.2)
H	4.1 (4.4)	10.6 (11.6)	4.6 (6.3)
Total	17.6 (21.4)	42.1 (51.9)	19.3 (37.5)
MiniBN	19.5	47.3	19.4
Excess	$42.6 \pm 25.3$	$82.2 \pm 23.3$	$21.5 \pm 34.9$

TABLE II:  $E_{QE}$  distribution of the NC photon events in the MiniBooNE neutrino run, comparing our estimate to the MiniBooNE estimate [1].