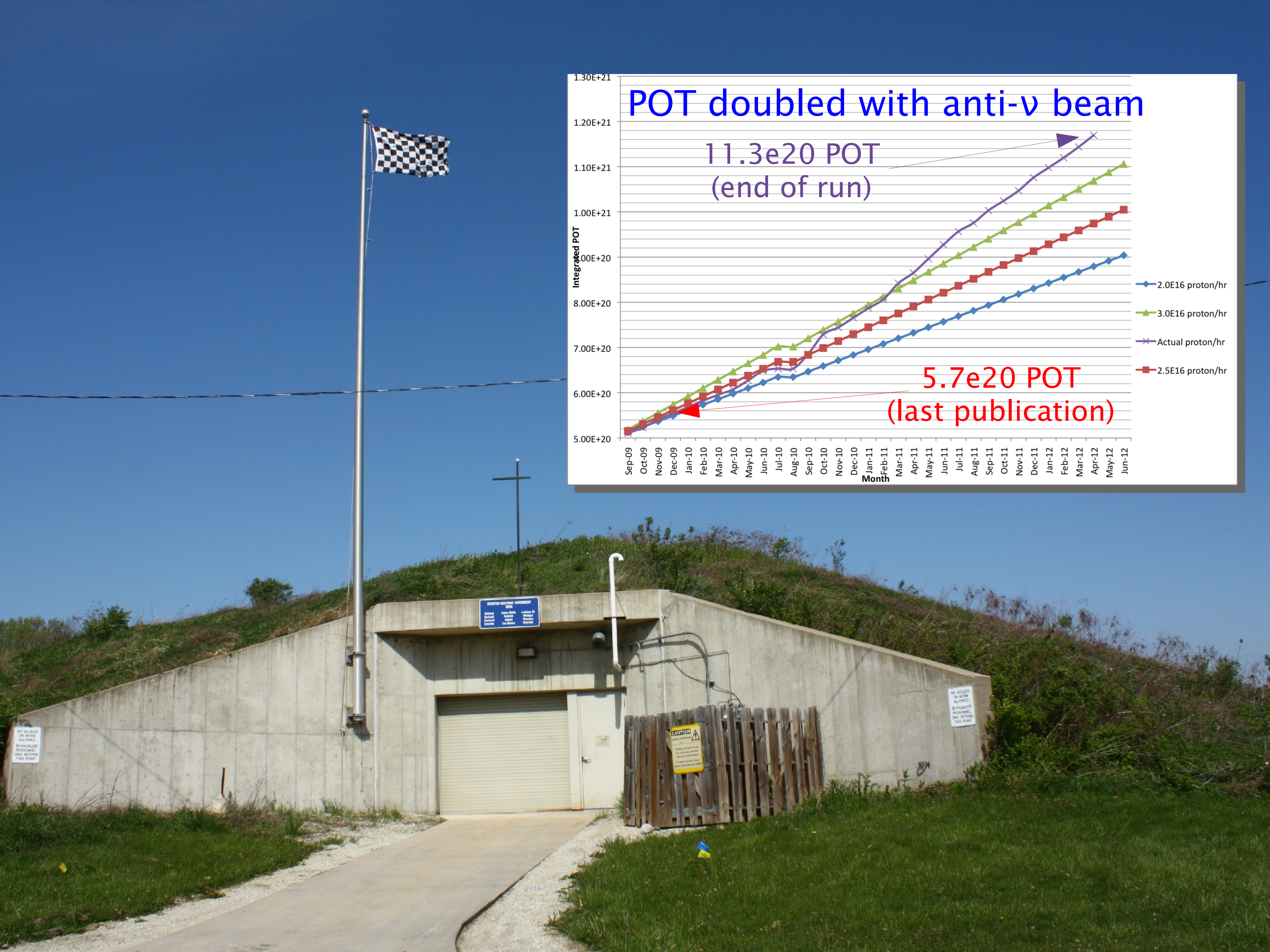
Updated Oscillation Results from MiniBooNE

Chris Polly, Fermilab



POT doubled with anti-ν beam
11.3e20 POT
(end of run)
5.7e20 POT
(last publication)
Integrated POT
Month
1.30E+21
1.20E+21
1.10E+21
1.00E+21
9.00E+20
8.00E+20
7.00E+20
6.00E+20
5.00E+20
Sep-09 Oct-09 Nov-09 Dec-09 Jan-10 Feb-10 Mar-10 Apr-10 May-10 Jun-10 Jul-10 Aug-10 Sep-10 Oct-10 Nov-10 Dec-10 Jan-11 Feb-11 Mar-11 Apr-11 May-11 Jun-11 Jul-11 Aug-11 Sep-11 Oct-11 Nov-11 Dec-11 Jan-12 Feb-12 Mar-12 Apr-12 May-12 Jun-12
2.0E16 proton/hr
3.0E16 proton/hr
Actual proton/hr
2.5E16 proton/hr
CAUTION

MiniBooNE is...

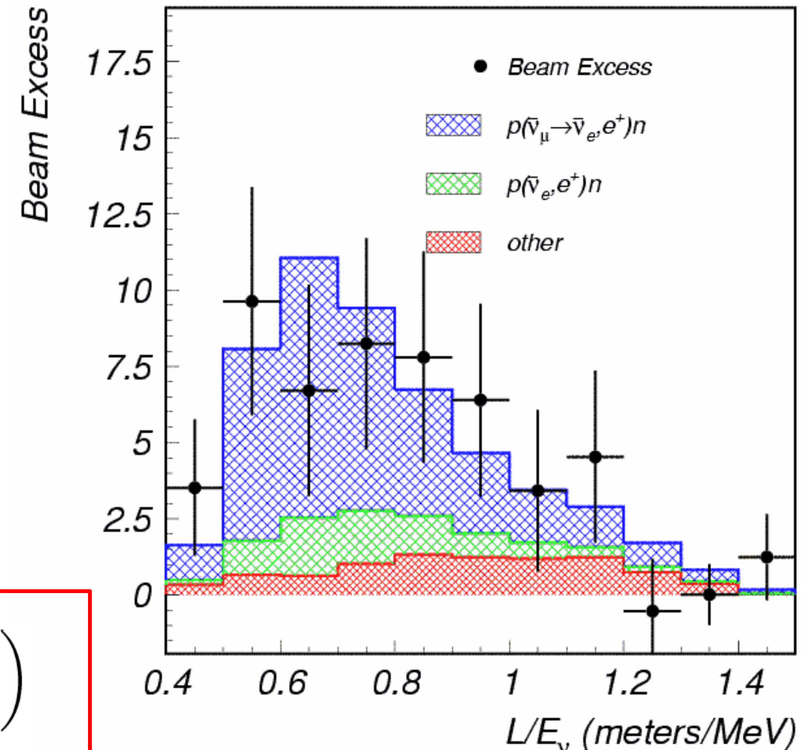
a single-detector experiment (CH_2) at Fermilab, short-baseline (500 m) experiment searching for ν_e (or anti-ν_e) appearing in ν_μ (or anti-ν_μ) beam.

...motivated by the LSND anomaly

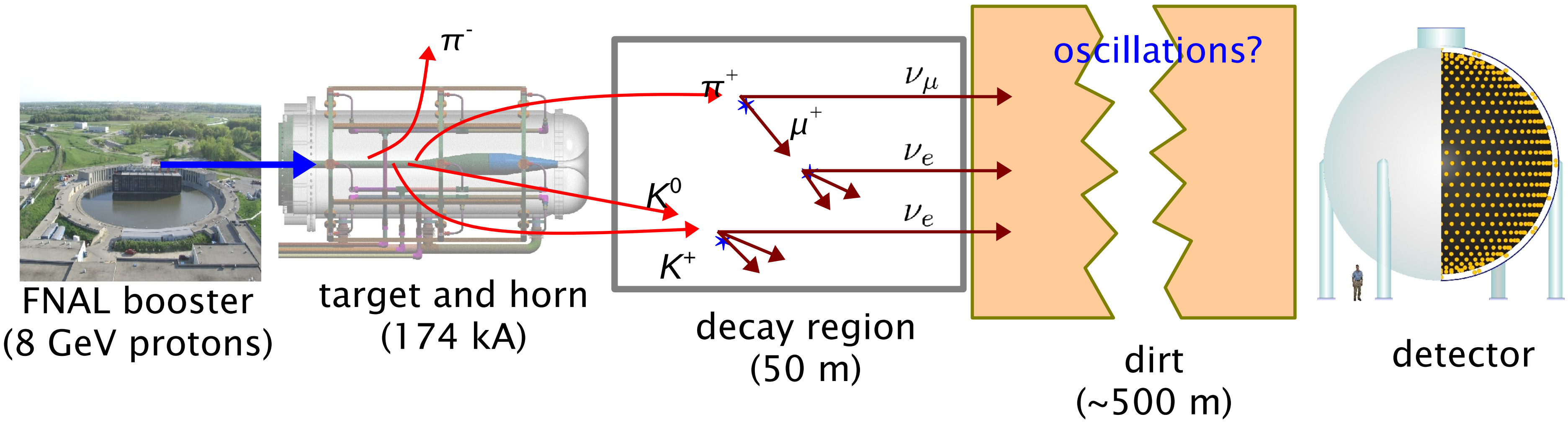
- LSND found an excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- Signature: Cerenkov & scin. light from e^+ with delayed n-capture (2.2 MeV)
- Excess: 87.9 ± 22.4 ± 6.0 (3.8σ)
- Under a 2ν mixing hypothesis:

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

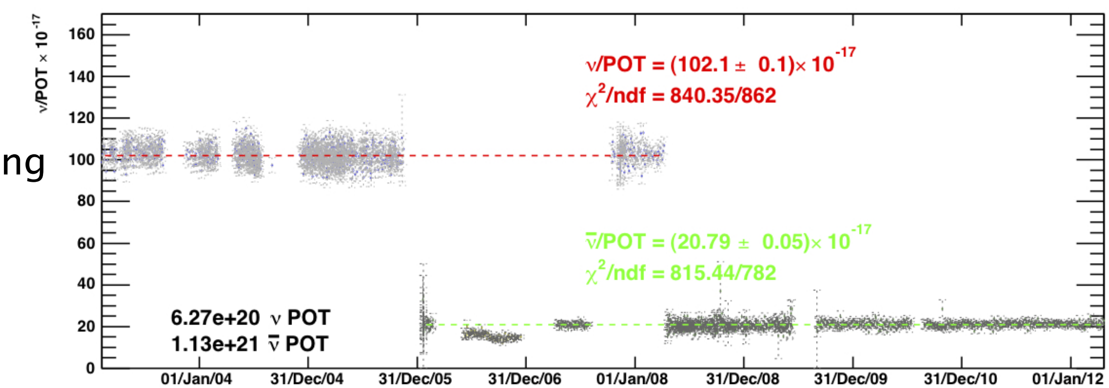
LSND data



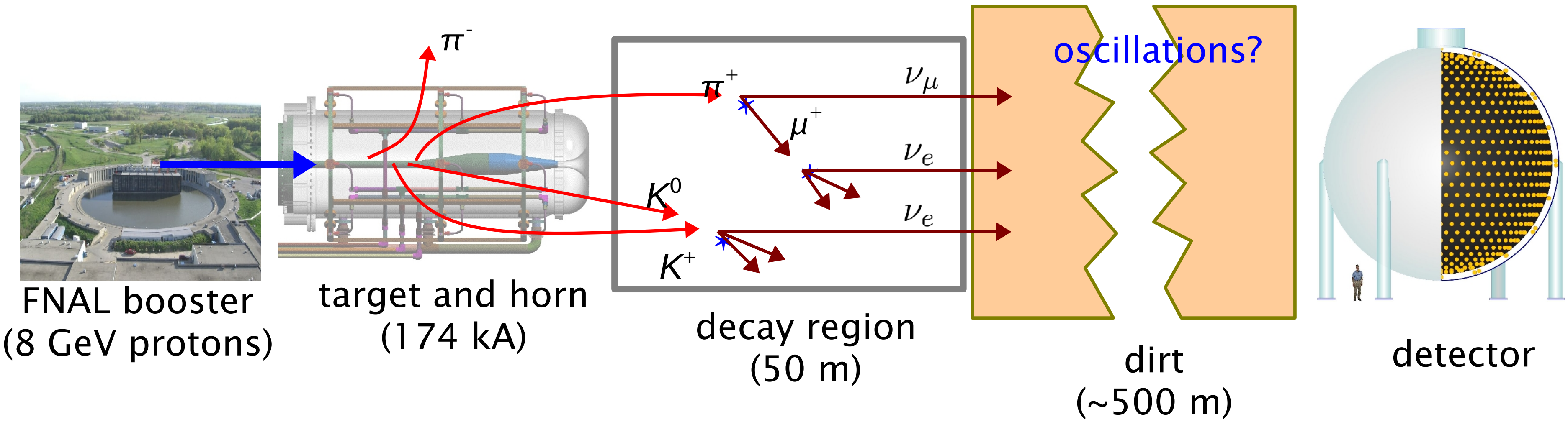
MiniBooNE design strategy...must have protons



- Early 90s, started looking for source of ν's intense enough to measure $P(\nu_\mu \rightarrow \nu_e)=0.25\%$
- 8 GeV FNAL Booster protons
  - 6.5e20 POT delivered for ν running
  - anti-ν running with 11.3e20 POT
- 174 kA focussing horn
  - Switch horn polarity to select π+/π− focus
  - Rate for anti-ν beam reduced by x5 from ν beam

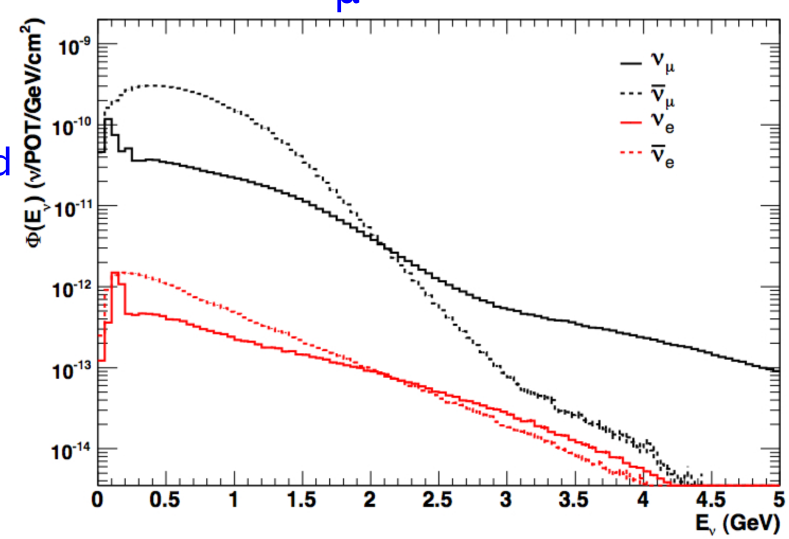


Implications of higher beam energy



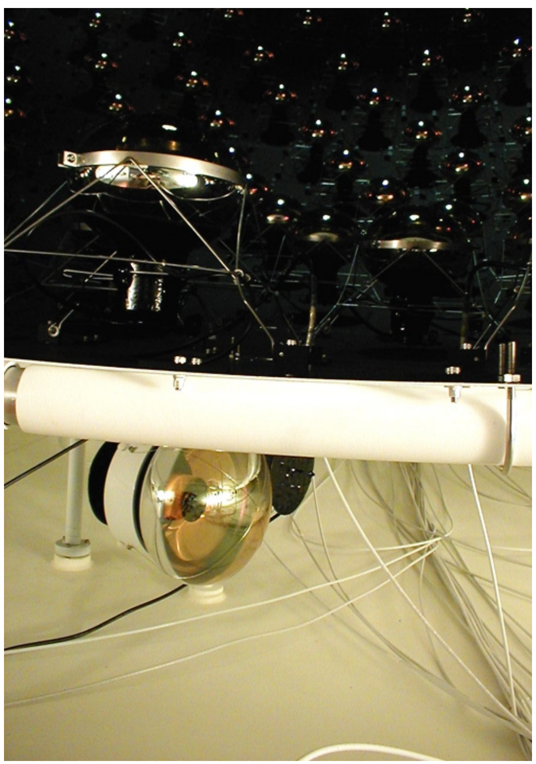
- Average MB E_ν ~800 MeV, LSND ~70 MeV
  - Gains an order of magnitude in cross-section
  - LSND anti-ν_μ's too low in E to make a μ or π
  - New bkgs in MiniBooNE: ν_μ CCQE and NC π^0 mis-id
- Higher energy protons make kaons
  - New bkgs in MiniBooNE: intrinsic ν_e from K
- In anti-neutrino mode, 20% of CCQE interactions come from WS neutrinos

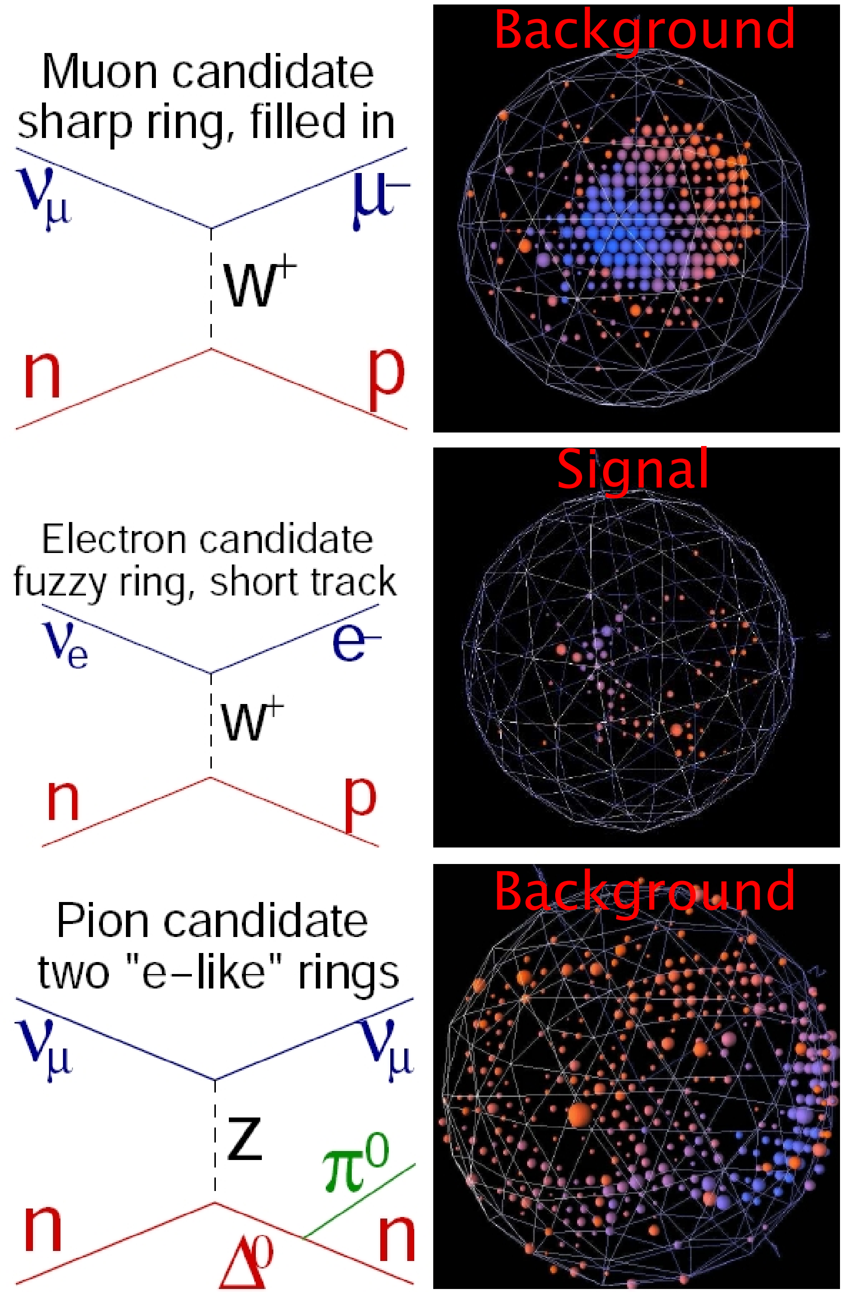
anti-ν_μ Mode Flux



Detector choices

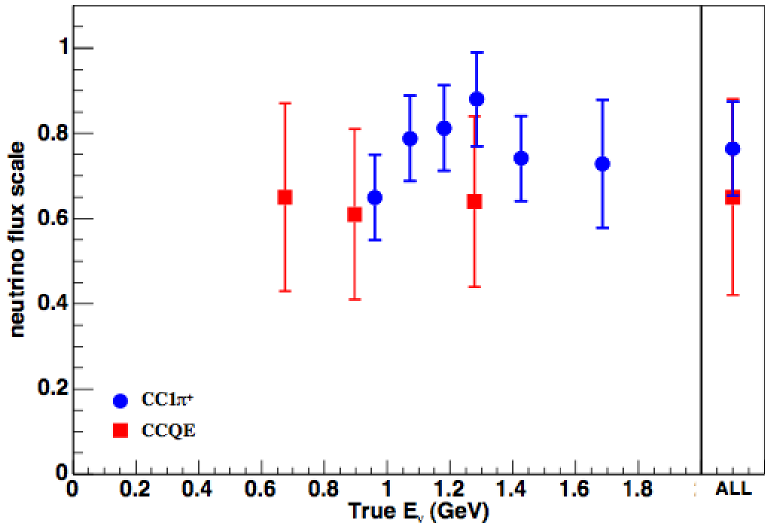
- Placed at 500 m to preserve LSND L/E
- 800-ton pure mineral oil (520 T fiducial)
  - Ring topology to separate e, μ, and π^0
  - Important Point: Can't distinguish e from γ
- Detector divided into inner/outer region
  - Ensures containment, reduces cosmic background to negligible level

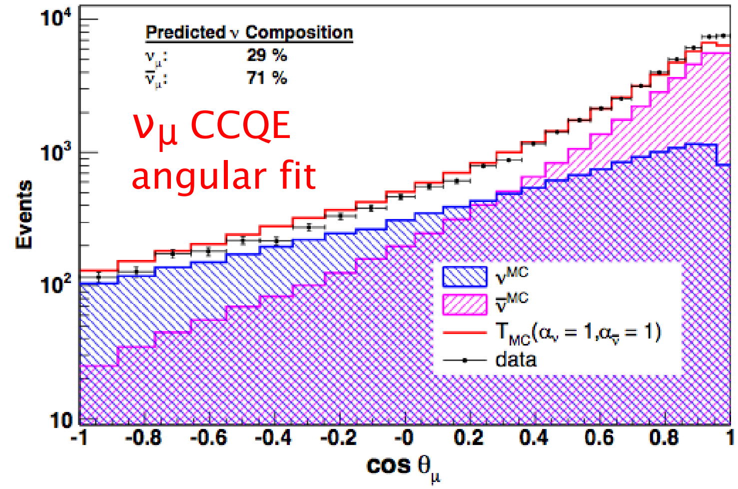




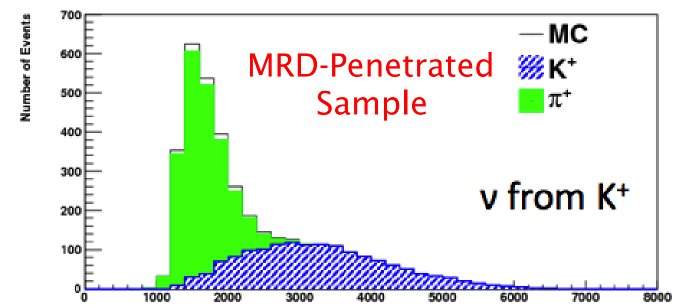
What's new since last oscillation publication?

- *In situ* measurement of WS contamination in anti-ν beam Phys.Rev.D84,072005 (2011)
  - ν_μ CCQE angular fit, and new constraint from CCπ+ rate...good agreement with expectation



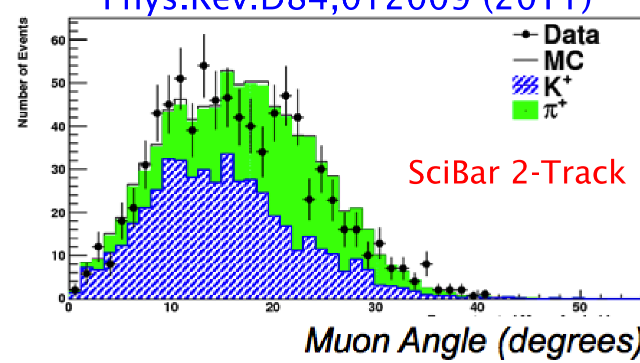


- New SciBooNE constraint on intrinsic ν_e from K+
  - Found K+ production to be 0.85 ± 0.12 relative to prediction, consistent with prior MiniBooNE assessment of 1.00 ± 0.30
  - Combined with world K+ production data, reduces error on K+ flux to 9% in MB Eν range
  - Leading error on K+ bkgs becomes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



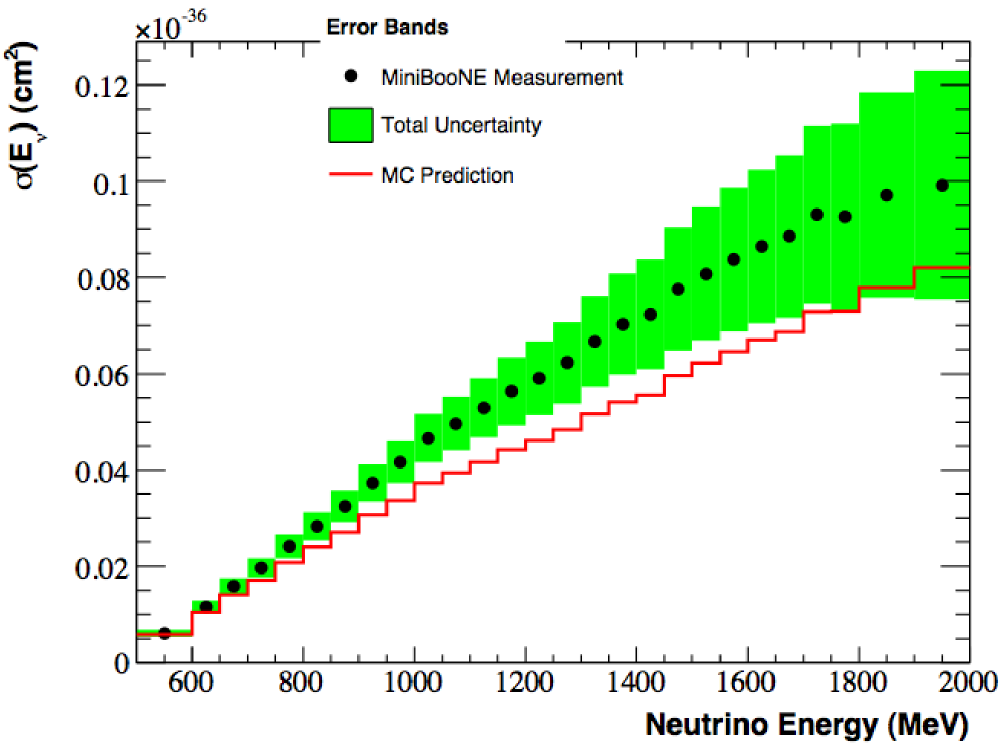
SciBooNE K+ Samples Eν (MeV)

Phys.Rev.D84,012009 (2011)



What's new since last oscillation publication?

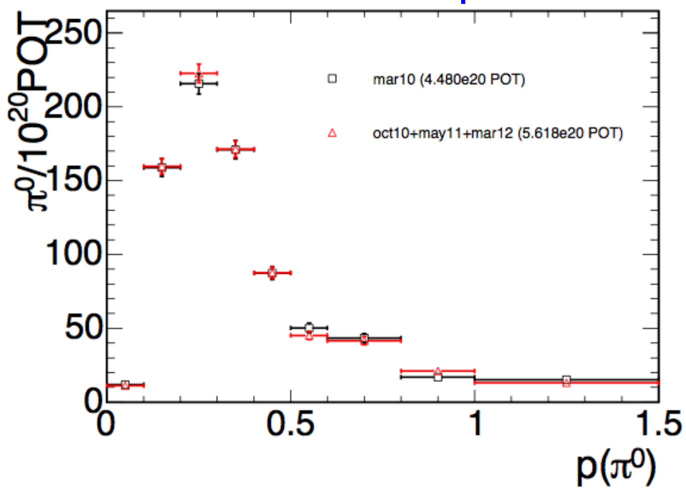
- Few other minor updates...
  - Added error matrix for intrinsic ν_e from K-
  - Improved smoothing algorithm that was being used to assess systematics due to discriminator thresholds and PMT response
  - $CC\pi+$ events (bkg for ν_μ CCQE when $\pi+$ is absorbed) Q^2 reweighting applied based on internal MB measurement...Phys.Rev.D83,052007 (2011)



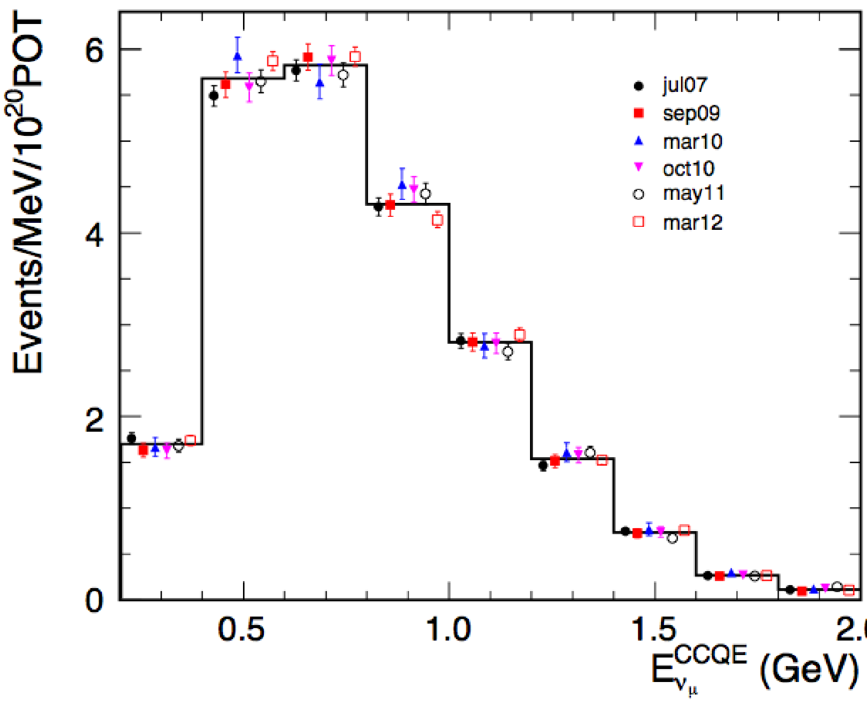
Main improvement...doubling of anti-ν stats

- 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

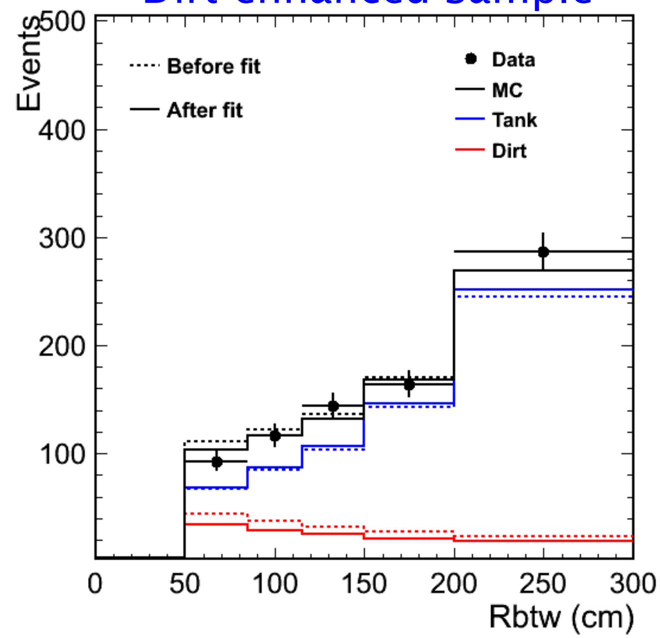
NC π^0 Sample



anti-ν_μ CCQE Sample

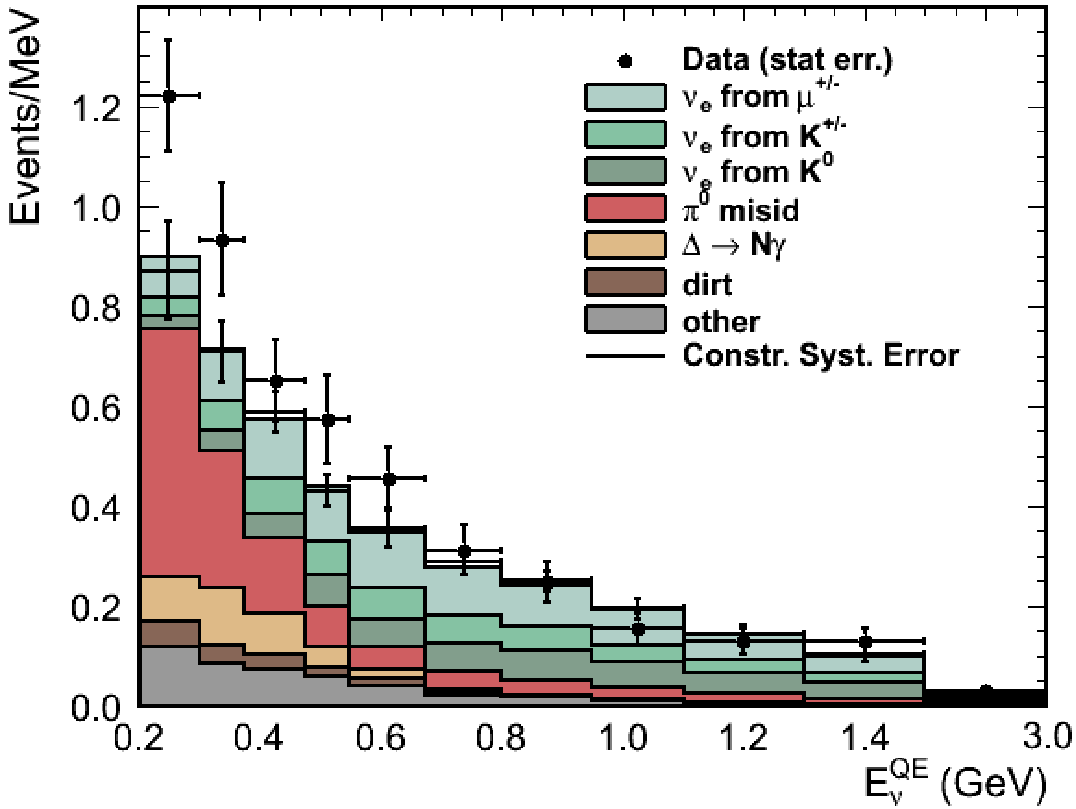


Dirt-enhanced Sample



First look at anti-neutrino data with full stats!

anti-ν_e CCQE signal candidates w/ 11.3e20 POT



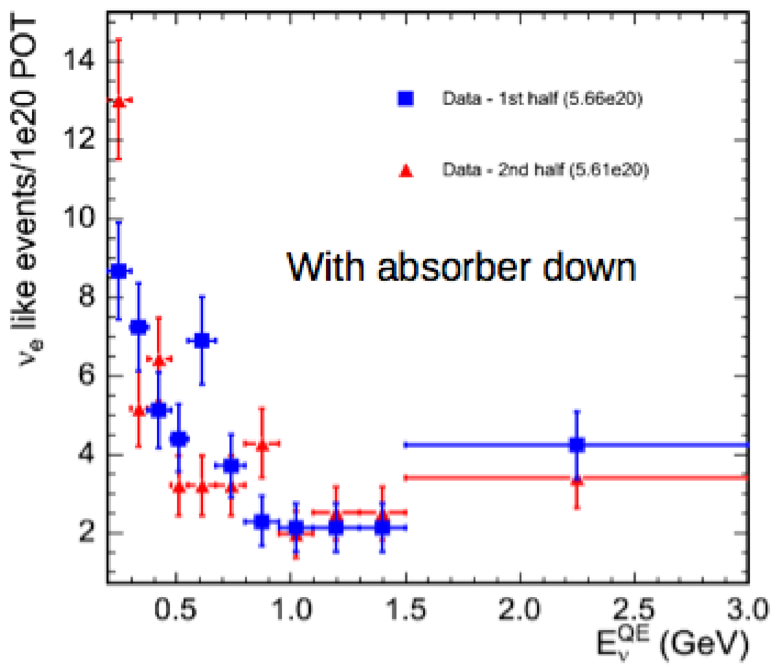
Higher stat anti-neutrino data is now much more consistent with what was observed in the data taken with a neutrino beam

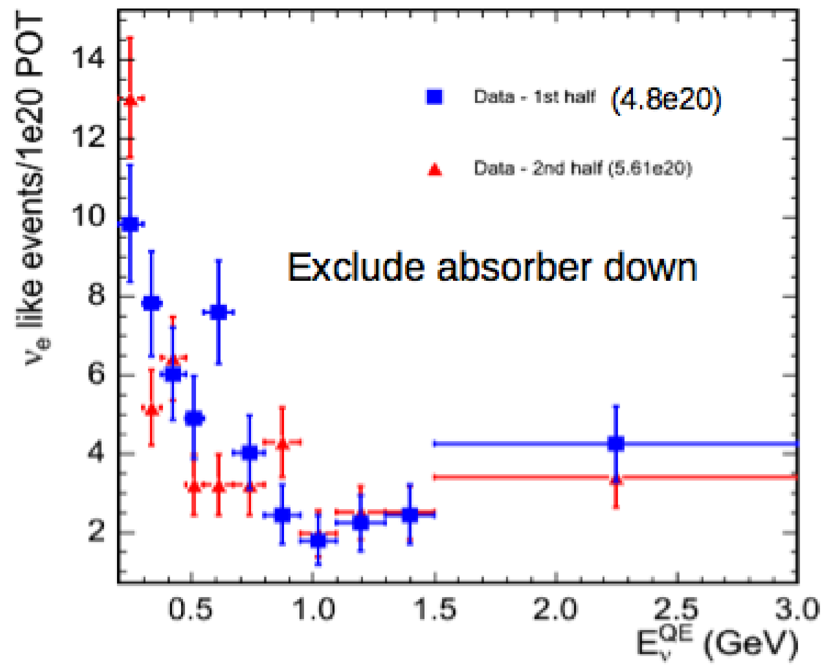
* Systematic error after all other data constraints applied, e.g. ν_μ CCQE, NC π^0 , dirt events, SciBooNE K^+

E_υ(QE) range	Data	Bkg ± stat ± syst*	Excess
200-475 MeV	257	199.1 ± 14.1 ± 16.3	57.9 ± 21.6 (2.7σ)
475-1250 MeV	221	201.1 ± 14.2 ± 17.9	19.9 ± 22.8 (0.9σ)
200-1250 MeV	478	400.2 ± 20.0 ± 23.4	77.8 ± 30.8 (2.5σ)

Compatibility of 1st and 2nd half of data

- KS test 17.8% (29.5% if exclude absorber down period)





		1st half			2nd half	
	data	mc	excess	data	mc	excess
200-475	119	100.5±14.3	18.5 (1.3s)	138	100.0±14.1	38 (2.7s)
475-1250	120	99.1±14.0	20.9 (1.5s)	101	103.1±14.4	-2.2 (-0.2s)

Combined fit of ν_μ and ν_e CCQE spectra

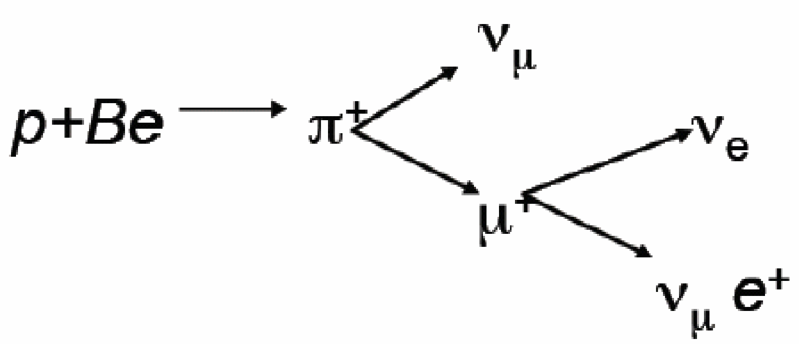
- Maximum likelihood fit:

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

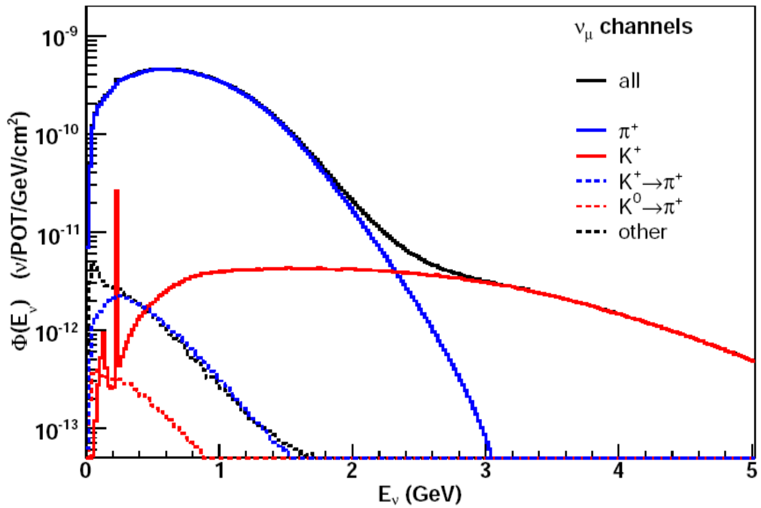
$M = M_{om} + M_{xsec} + M_{flux} + M_{\pi^0} + M_{dirt} + M_{K^0} + ...$

1000's of MC universes go into forming M

- Simultaneously fit (FC-corrected)
  - ν_e CCQE signal + high E ν_e sample
  - High statistics ν_μ CCQE sample
- ν_μ CCQE sample acts like a near detector, i.e. same flux as oscillation ν_e by definition, lepton universality + muon mass corrections fix relative cross-section

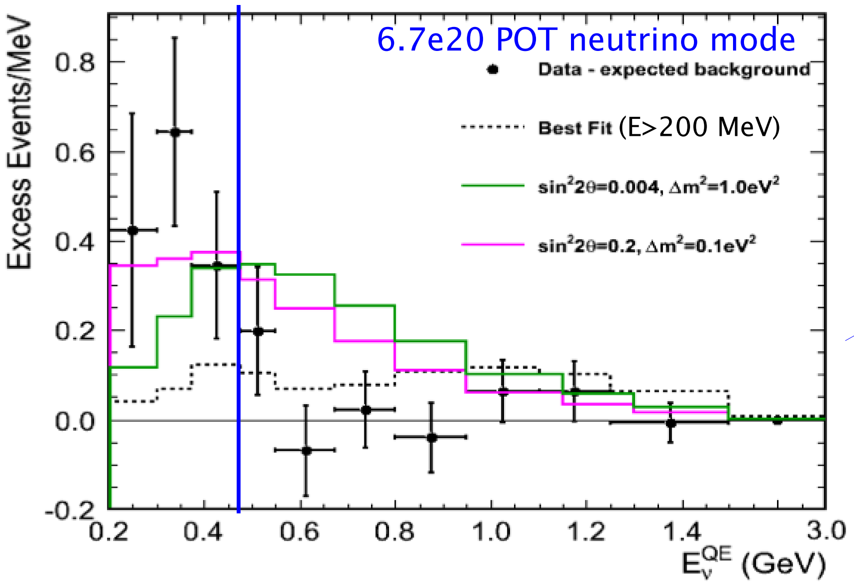


υ_μ flux through detector (υ mode)

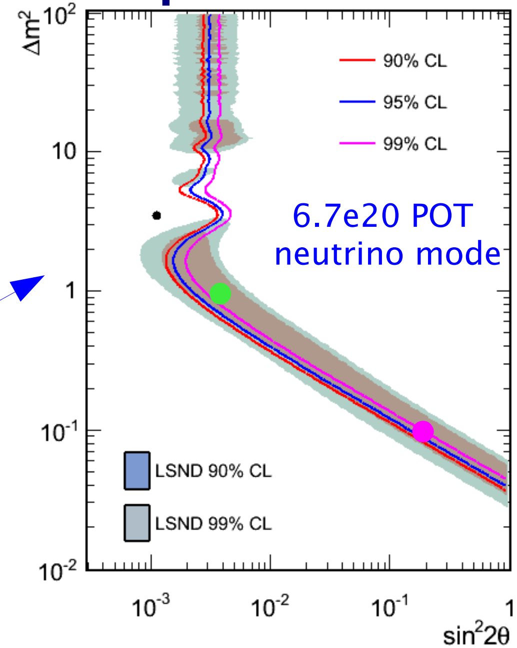


Neutrino mode 3+1 fits with all updates

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\,L\,\Delta m^2}{E}\right)$$



Fit E >475 MeV



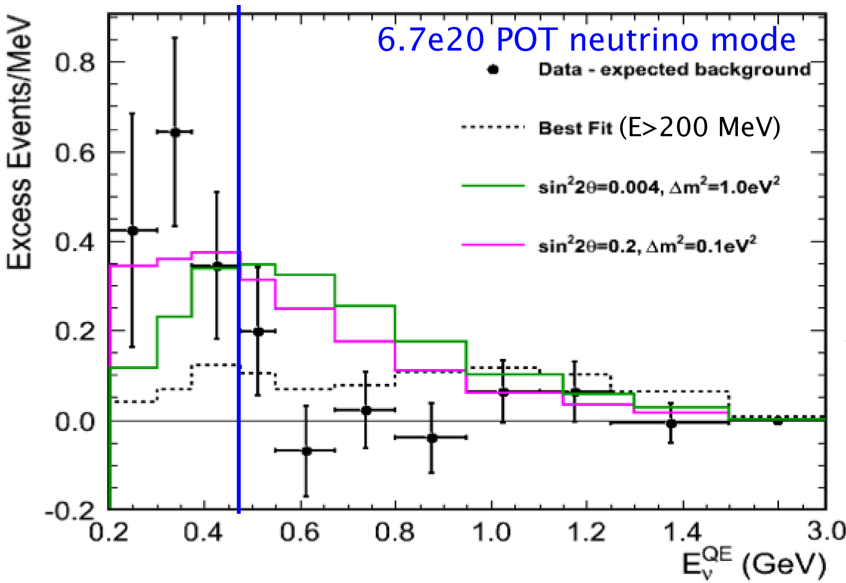
* All contours established from relative change in log-likelihood with Feldman-Cousins correction applied

- Fit region dilemma, circa 2007
  - Above 475 MeV almost no excess
  - Below 475 MeV large excess

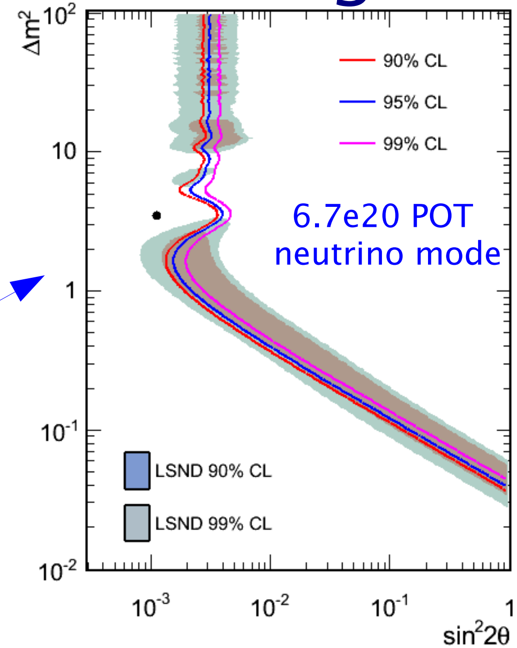
Caveat - all fits in this talk assume no ν_e disappearance

What happens if fit extended to full range?

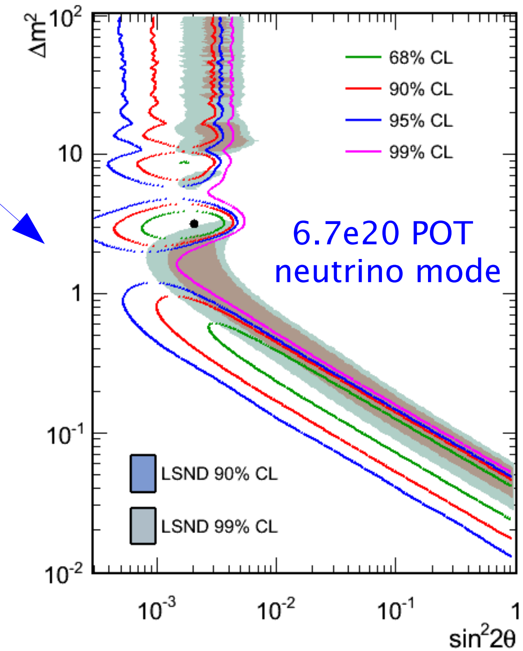
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\, L\, \Delta m^2}{E}\right)$$



Fit E >475 MeV



Fit E >200 MeV

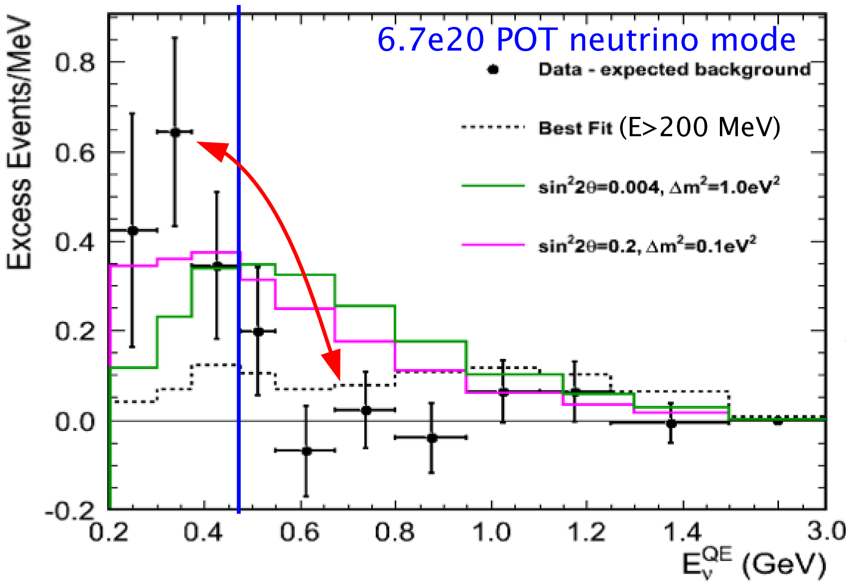


ν mode	E > 200 MeV	E > 475 MeV
χ^2(null)	22.81	6.35
Prob(null)	0.5%	36.6%
χ^2(bf)	13.24	3.73
Prob(bf)	6.12%	42.0%

Overall probability of bf 6%...not great,
but also not terrible

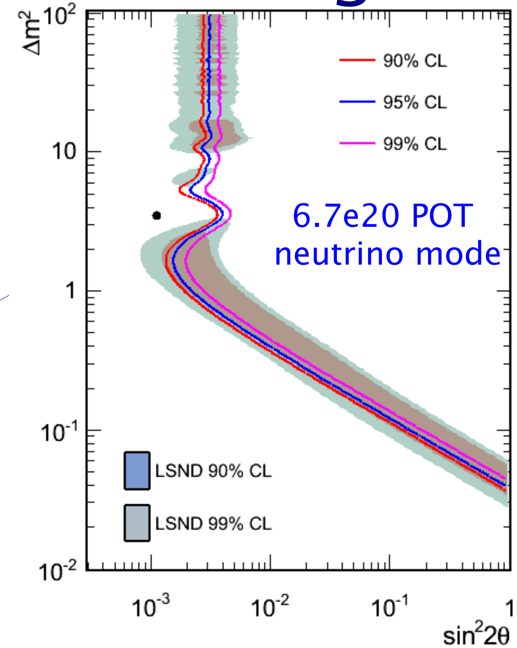
What happens if fit extended to full range?

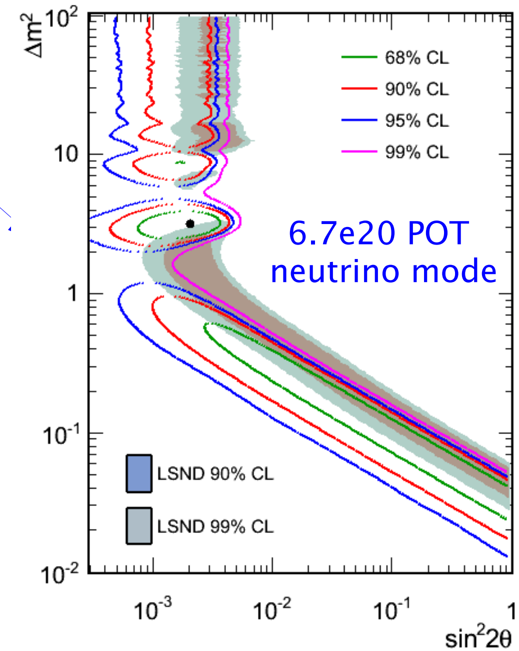
$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\, L\, \Delta m^2}{E}\right)$$



Fit E >475 MeV

Fit E >200 MeV





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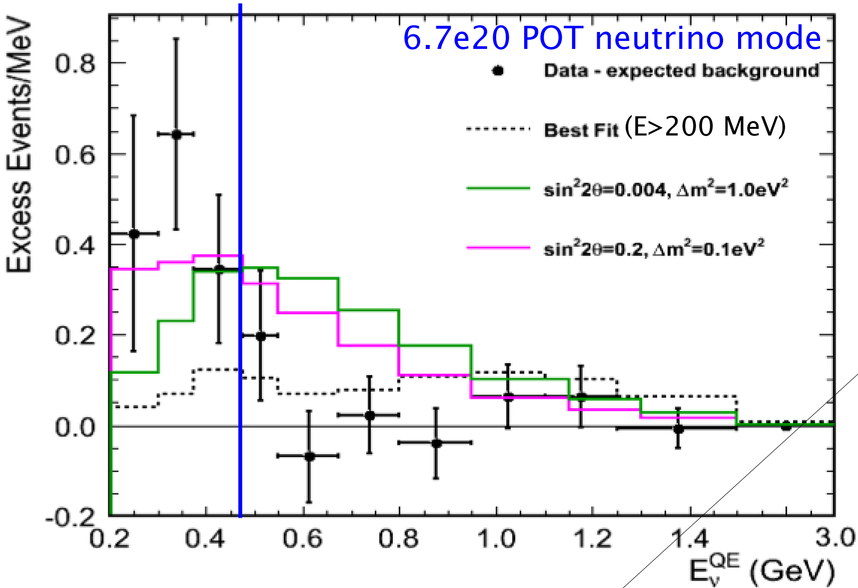
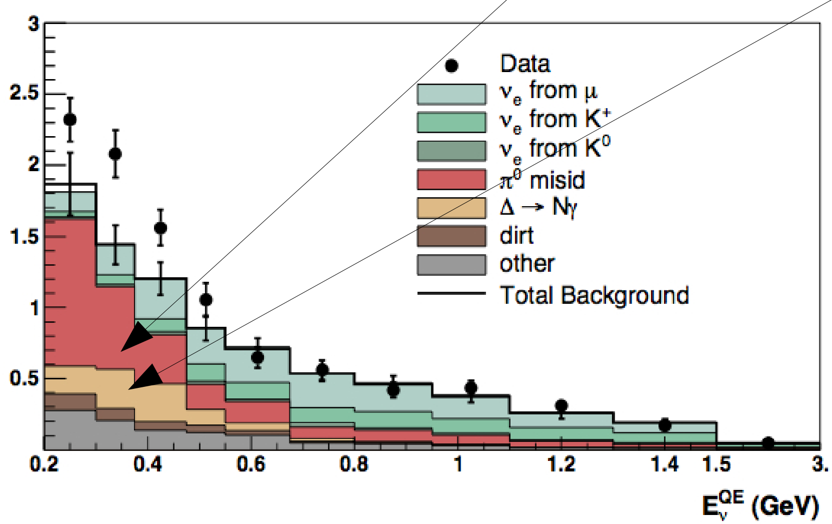
Tension between low and mid-range Eν, probability only 1.4% to see χ^2 3.73 → 13.24 (assuming E>200 MeV bf)

What can we say about low-E excess...





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

R. Hill, arXiv:0905.0291

Jenkins & Goldman, arXiv:0906.0984

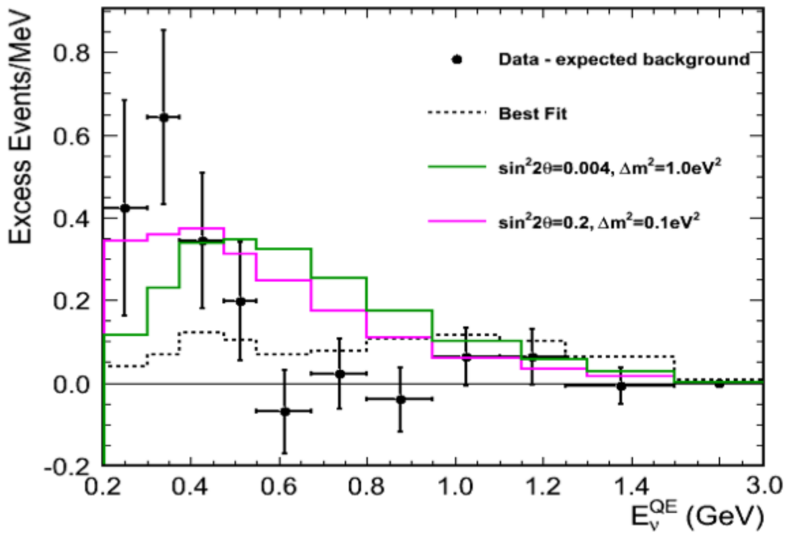
Serot & Zhang, arXiv:1011.5913

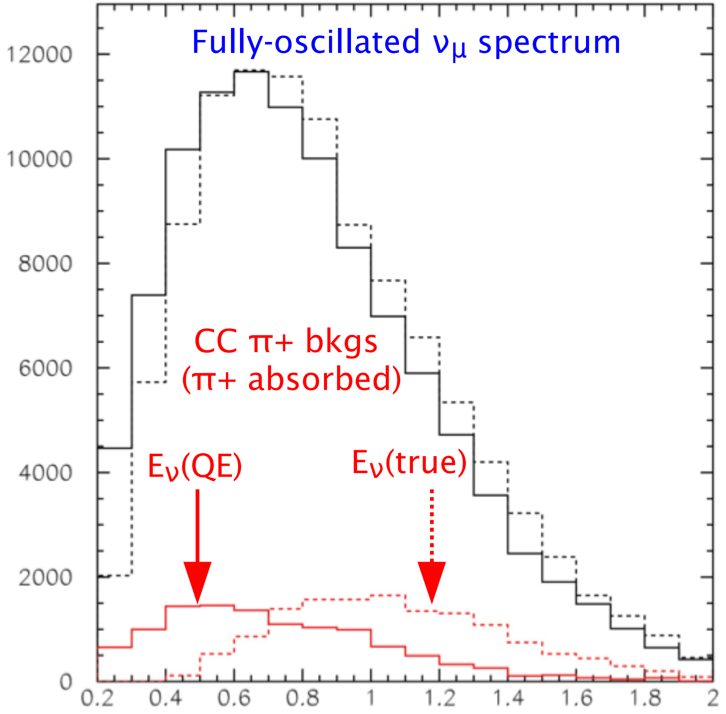
Something to consider...

- This plot assumes CCQE-like reconstruction

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

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





Something to consider...

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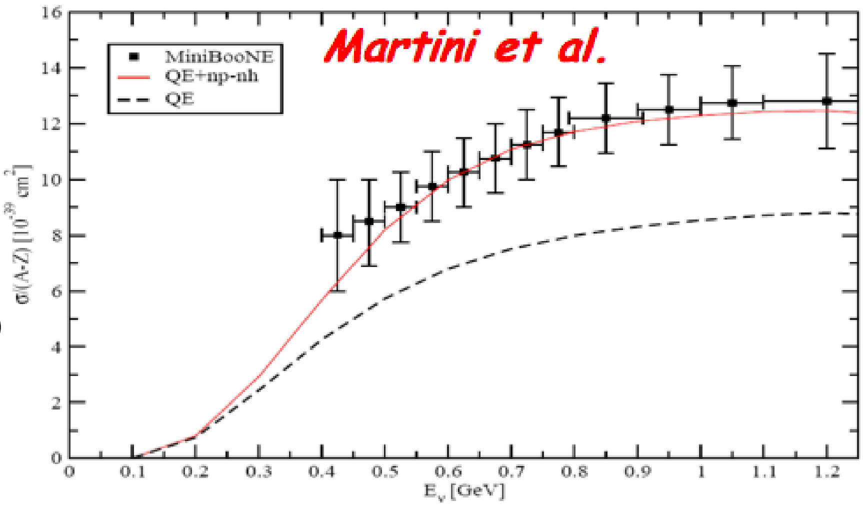
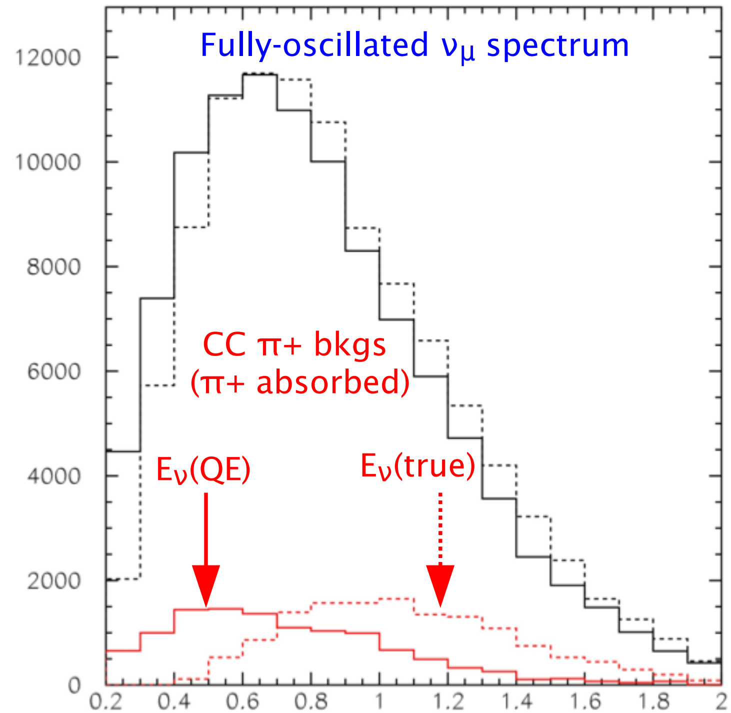
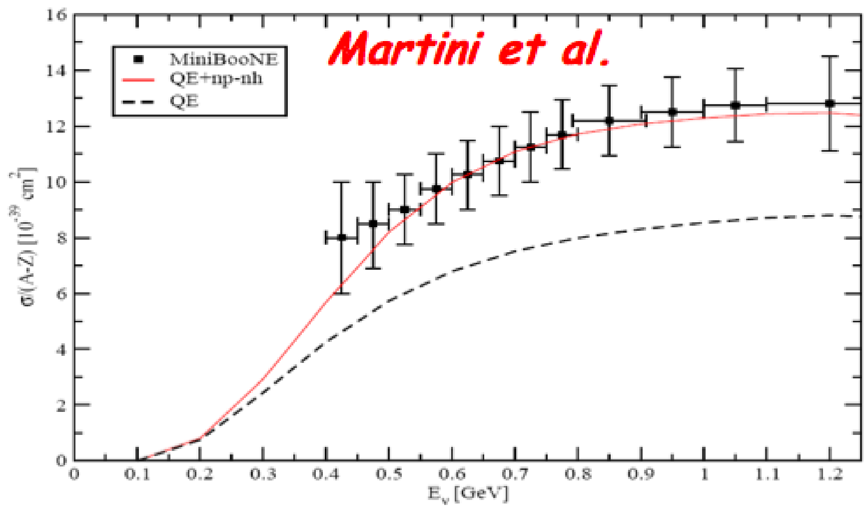
Martini *et al.*, PRC **80**, 065001 (2009)

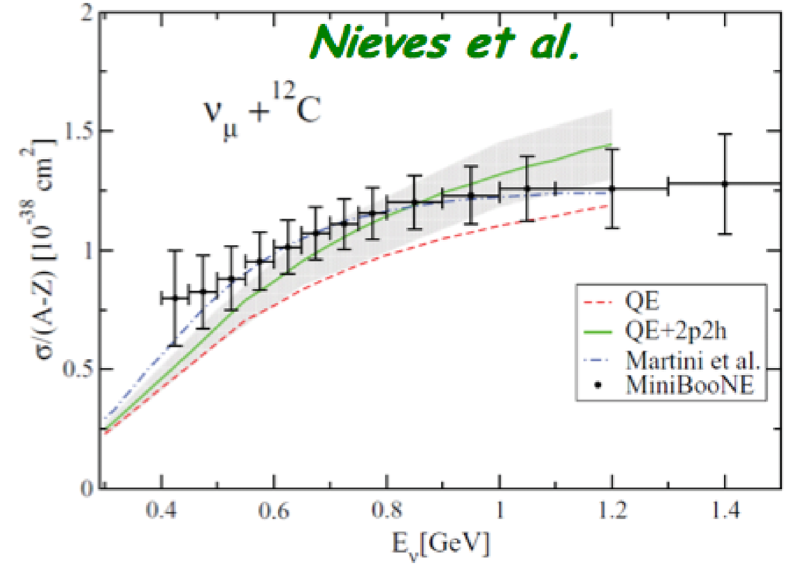


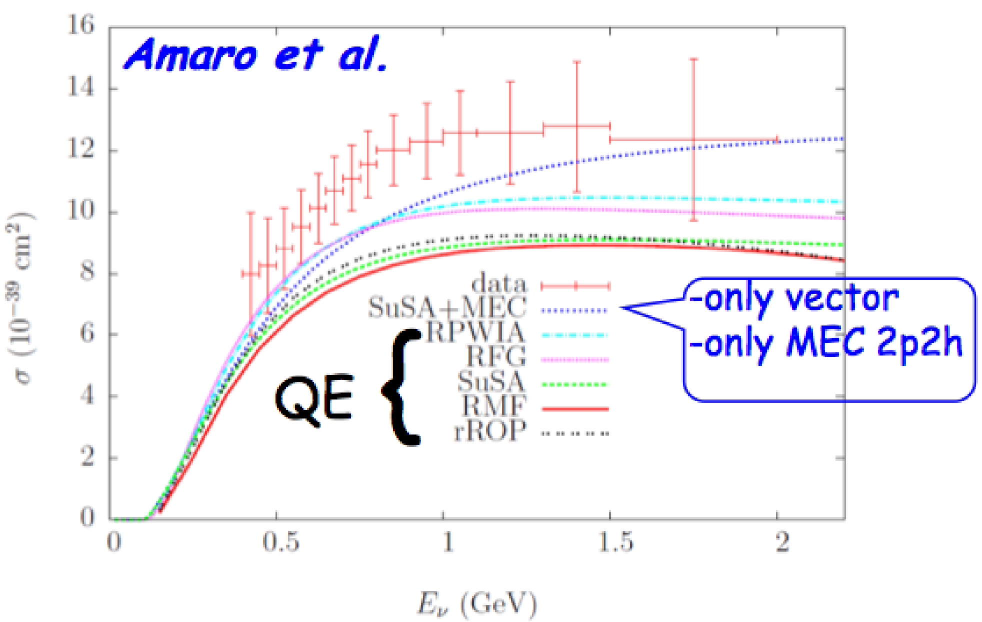


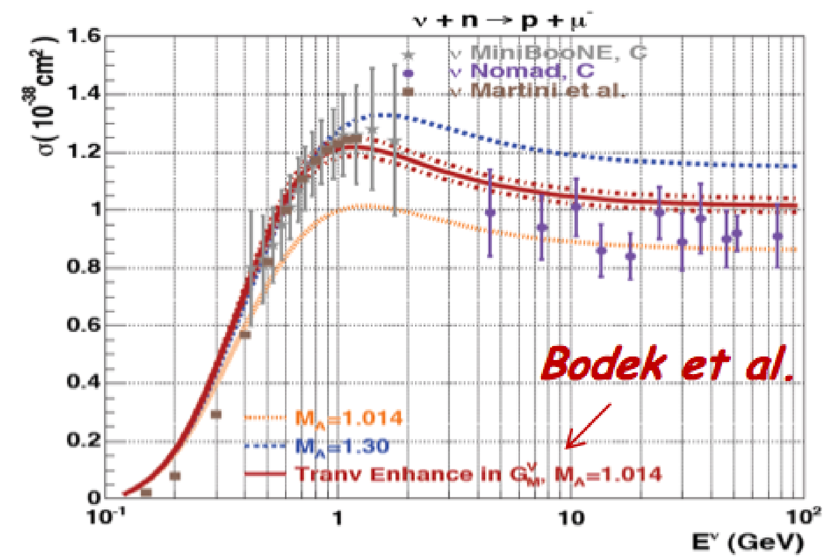
- MiniBooNE finds a cross-section for ν_μ CCQE that is 20-30% higher than expected
- Number of theorists suggesting this could arise from multi-nucleon correlations, observed many years ago in e-scattering
- Could help explain why MB xsec is higher than free nucleon, differences between expts where event selection can depend on final state nucleons

Comparison between models including np-nh

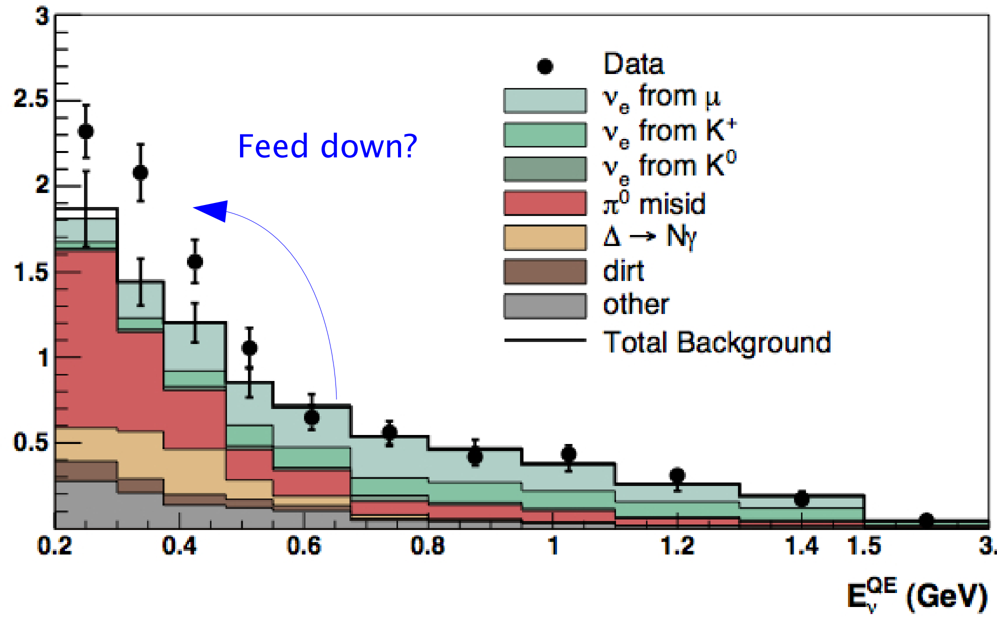


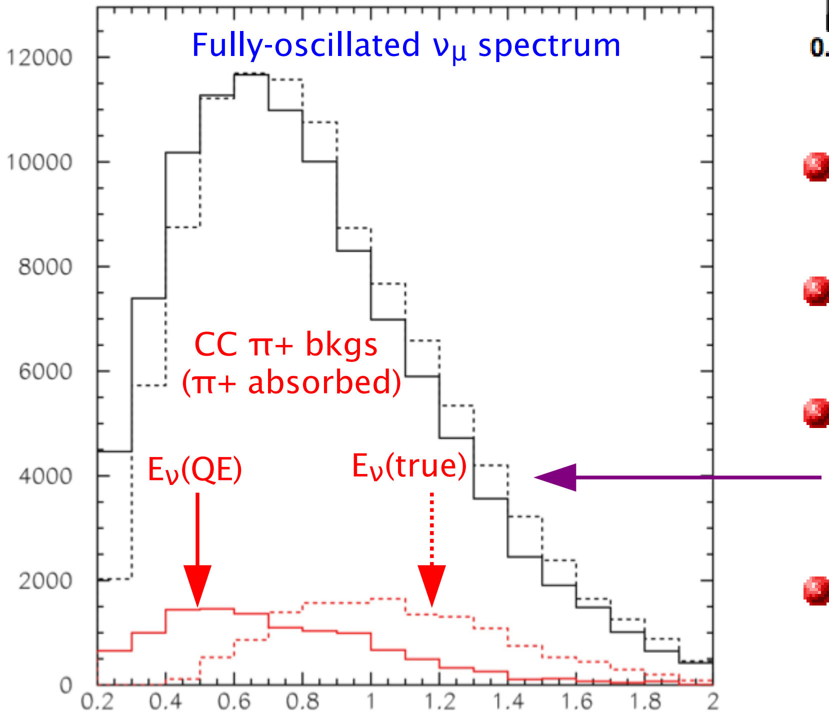






Relevant for oscillation analysis?



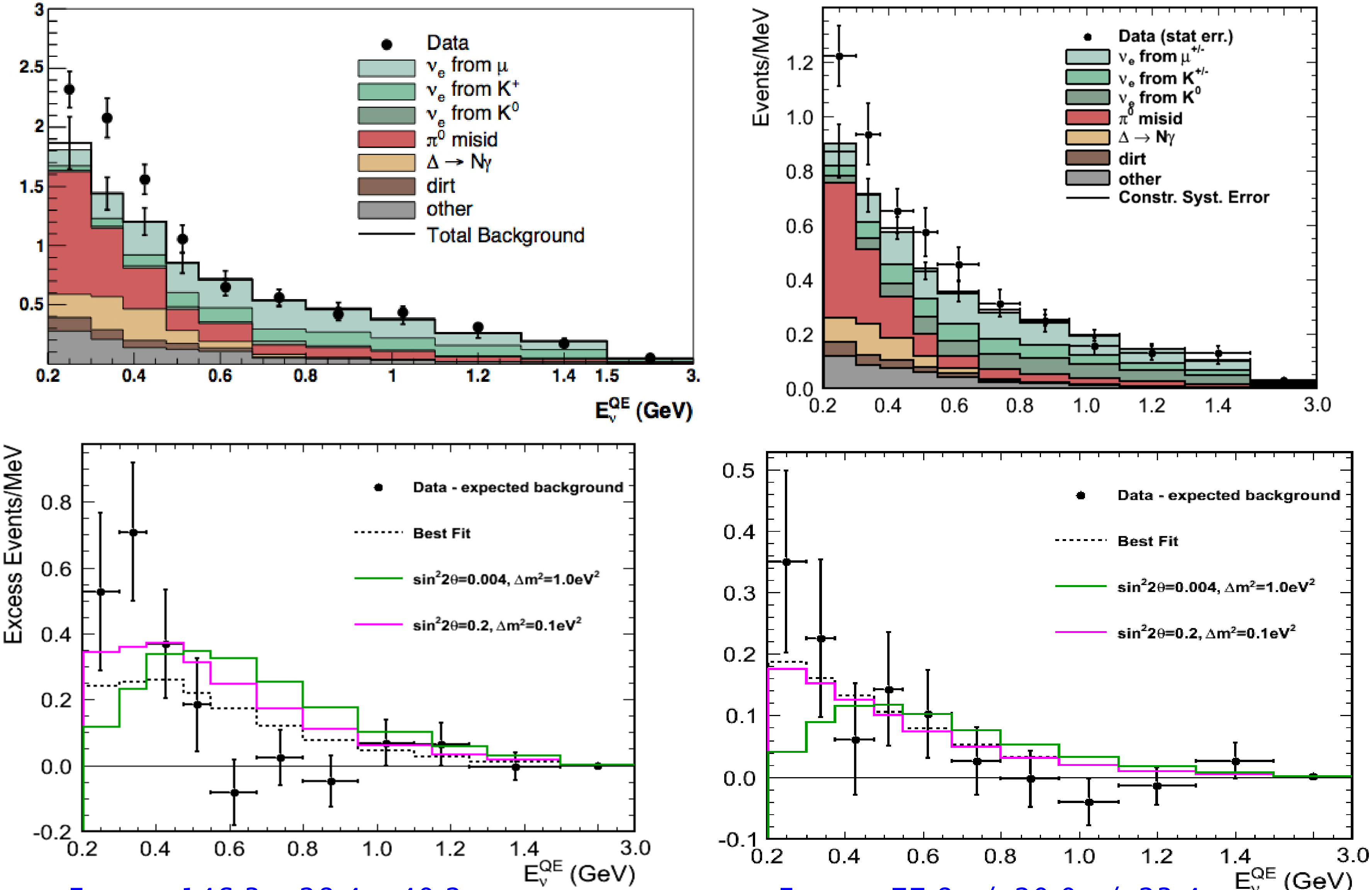


- Means a fraction of oscillated ν_e could be misreconstructed (similar to CCπ+ case)
- Could feed down help relax tension between low and mid range energies?
- Possible, but MiniBooNE corrects sig/bkg predictions based on the measured ν_μ spectrum
- Studies where we double the π+ absorption rate, and then retune sig/bkg predictions to match to CCQE...negligible impact

Comparing neutrino to anti-neutrino mode

6.7e20 POT neutrino mode

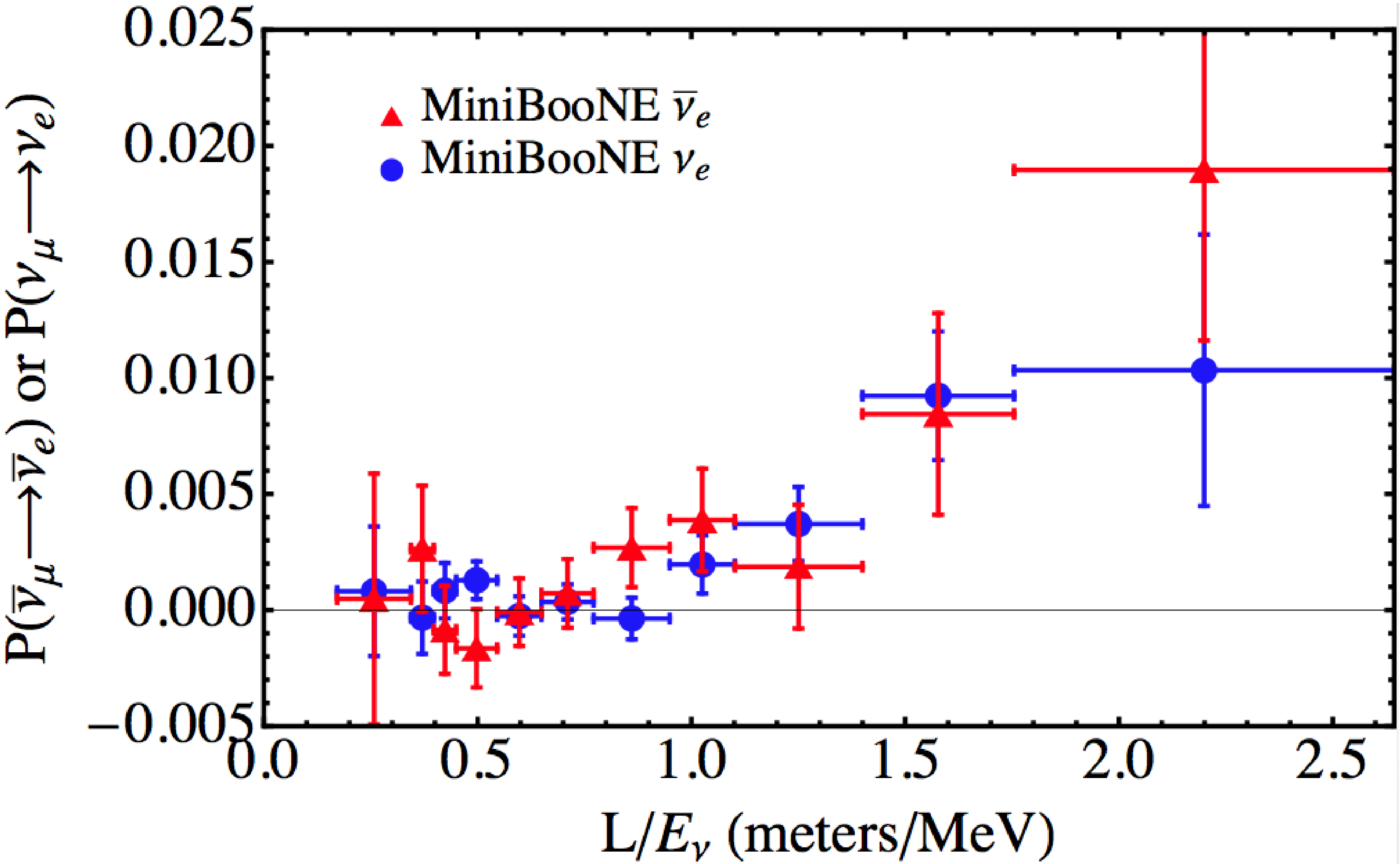
11.3e20 POT anti-neutrino mode



Excess: 146.3 ± 28.4 ± 40.2

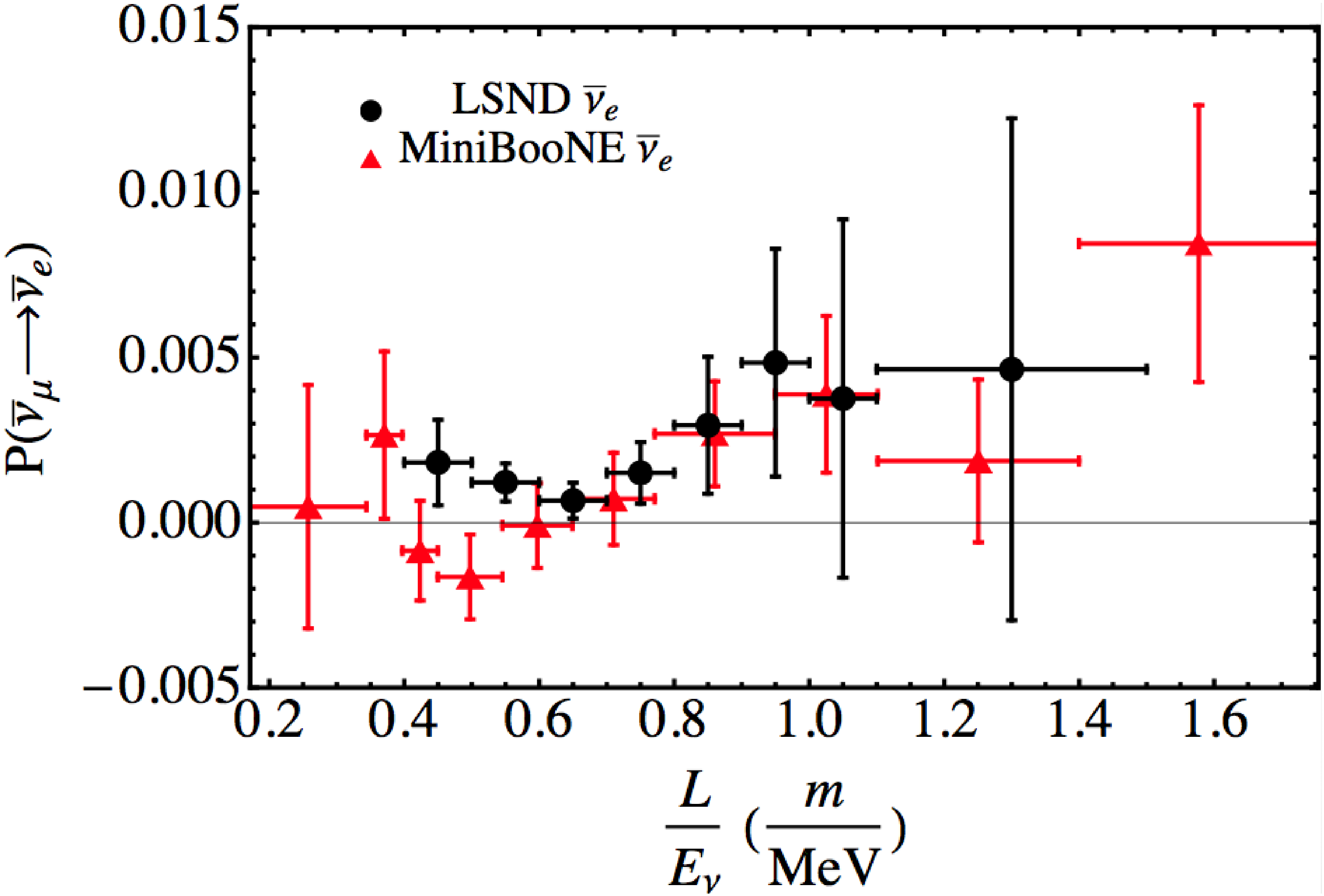
Excess: 77.8 +/- 20.0 +/- 23.4

Model-independent probability comparison

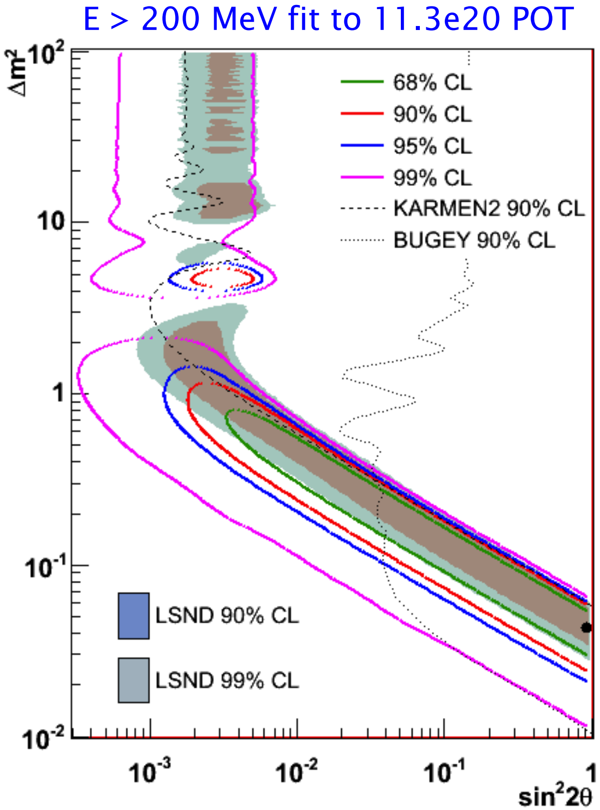


* Note this plot assumes that the excess events in anti-neutrino mode come only from the anti-neutrino beam content, P(osc) at highest 3 L/E bins would be reduced by 25% WS contamination were also included

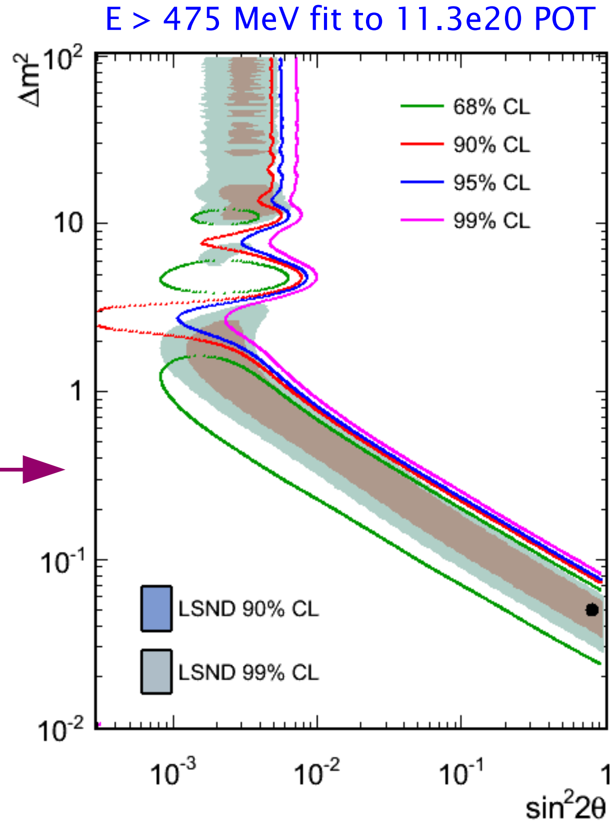
Can also compare to LSND P(osc)



Fitting anti-neutrino data to 2ν model



No tension



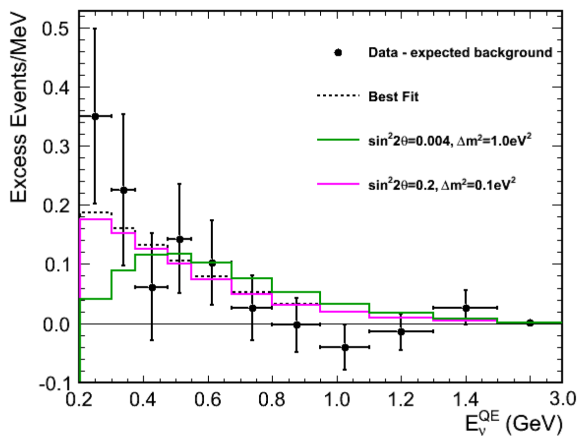
anti-ν mode	E > 200 MeV	E > 475 MeV
χ^2(null)	16.3	7.59
Prob(null)	5.8%	26.4%
χ^2(bf)	4.76 ↔	3.23
Prob(bf)	67.5%	50.2%

Caveat - for these fits, WS ν_μ are not assumed to oscillate

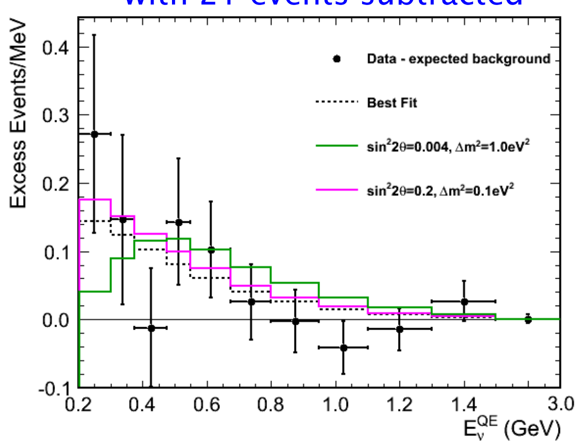
Account for neutrino low-E events

- 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)

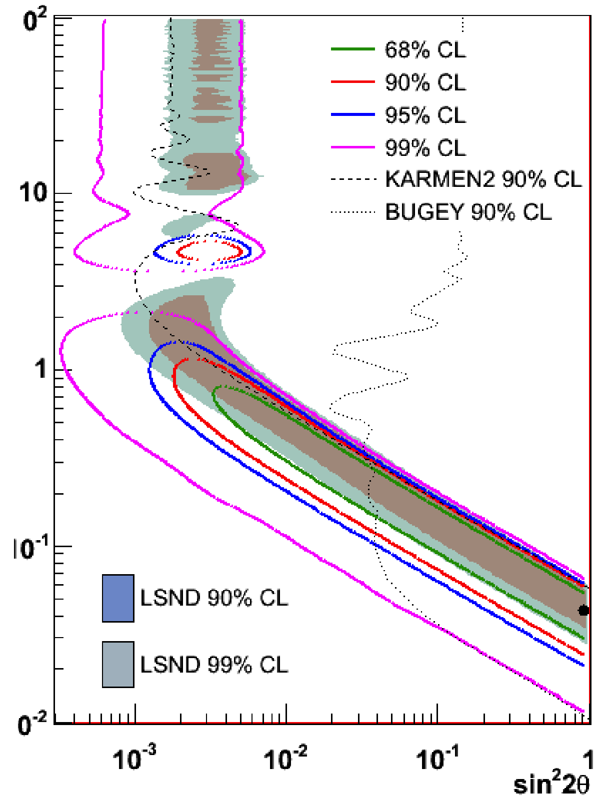
without 21 events subtracted



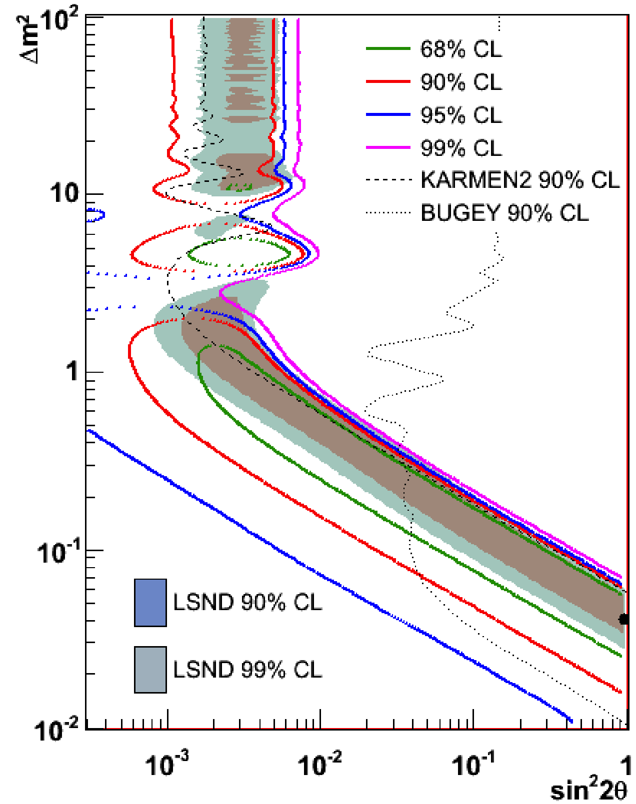
with 21 events subtracted



without 21 events subtracted

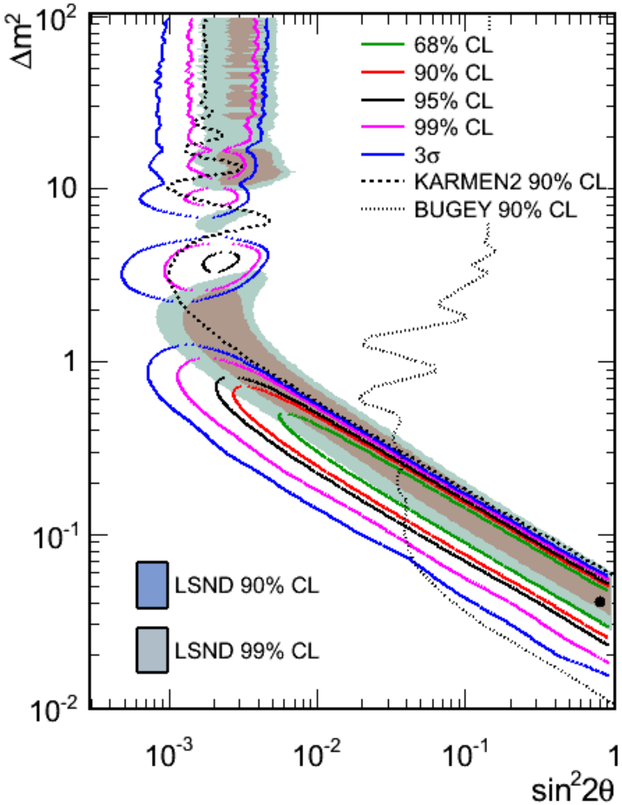


with 21 events subtracted



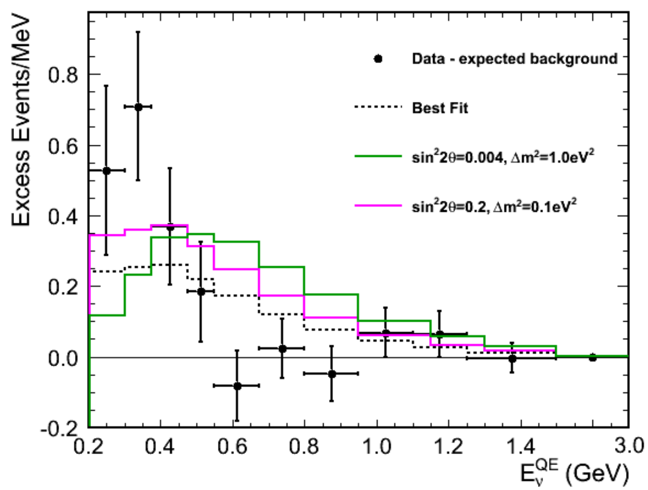
* E>200 MeV fits to full anti-neutrino statistics (11.3e20 POT)

Simultaneous 3+1 fit to ν and anti-ν data



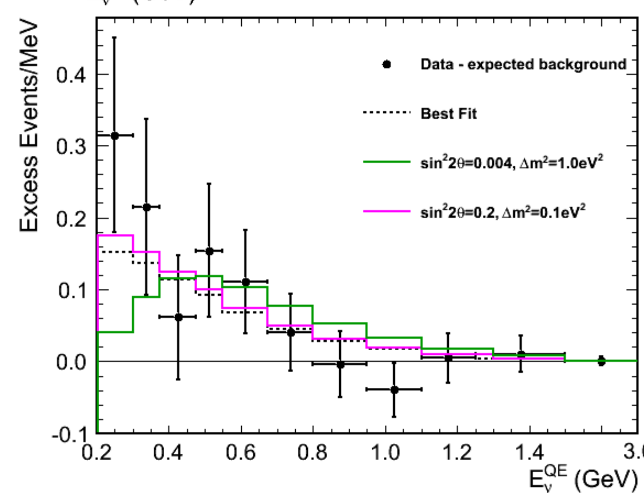
- WS accounted for properly
- Construction of correlated systematic error matrix (Z. Pavlovic)
- E>200 MeV BF preferred at 3.6σ over null

Total Excess: 240.3 +/- 34.5 +/- 52.6



* Simultaneous fit (E>200 MeV) with fully-correlated systematic to entire MB neutrino and anti-neutrino data

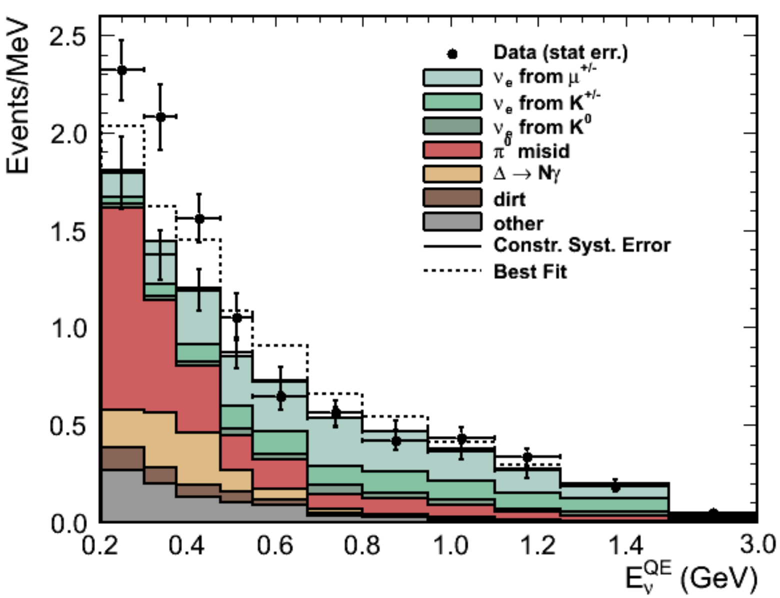
combined	E > 200 MeV	E > 475 MeV
χ^2(null)	42.53	12.87
Prob(null)	0.1%	35.8%
χ^2(bf)	24.72	10.67
Prob(bf)	6.7%	35.8%



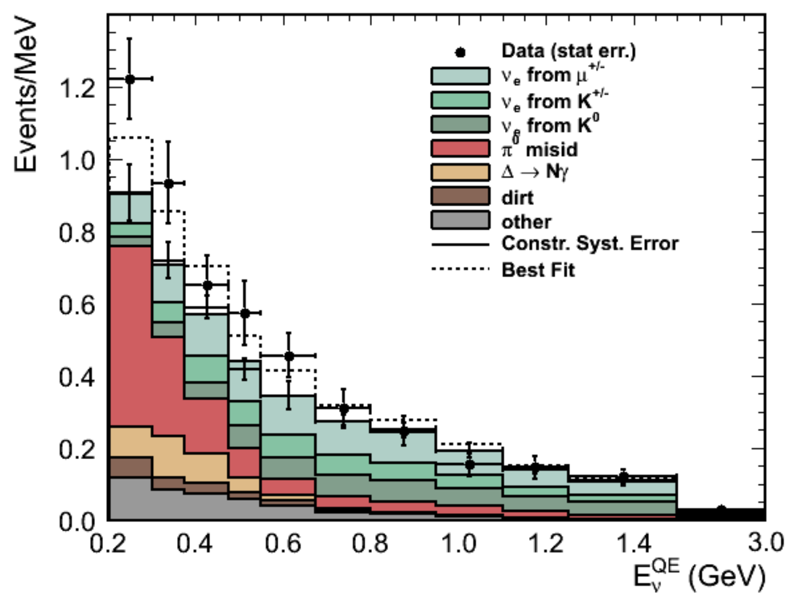
Conclusions

- MiniBooNE observes an excess of ν_e candidates in the 200-1250 MeV energy range in neutrino mode (3.0σ) and in anti-neutrino mode (2.5σ). The combined excess is 240.3 ± 34.5 ± 52.6 events (3.8σ)
- The event excess is concentrated in the 200-475 MeV region where NC π^0 and other processes leading to a single γ dominate
- Higher statistic anti-υ data is much more similar to the neutrino mode data
- It is not yet known whether the MiniBooNE excesses are due to oscillations, some unrecognized NC γ background, or something else

6.5e20 POT neutrino mode w/ 3+1 fit

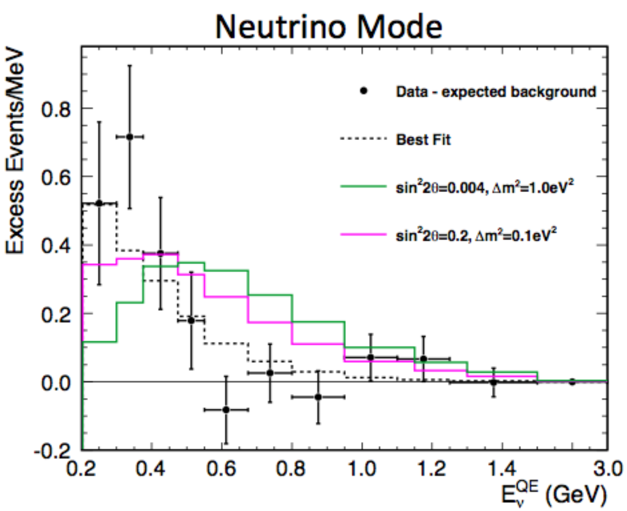


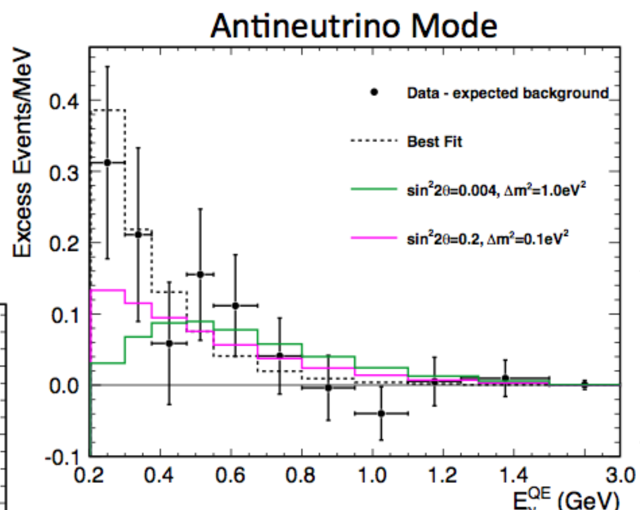
11.3e20 POT anti-neutrino mode w 3+1fit



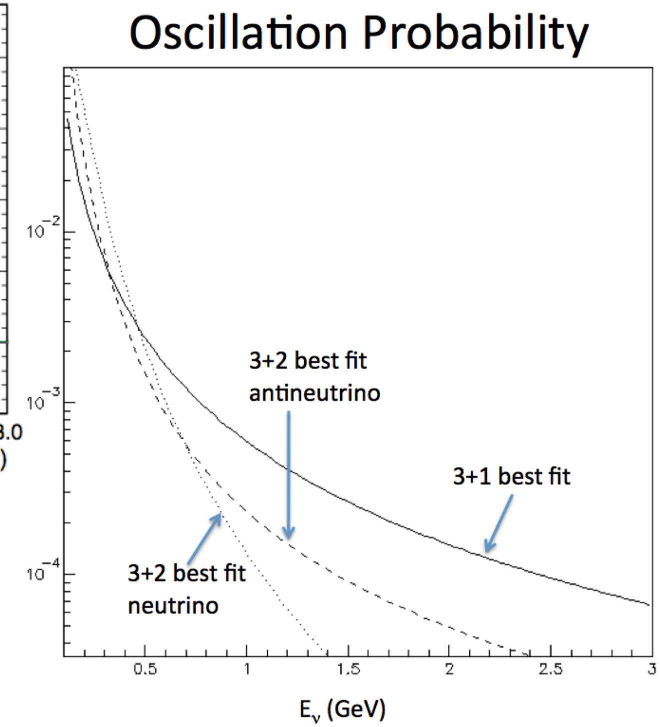
Advertisements...

- Please see Kendall Mahn's poster for recent progress in disappearance analyses
- MiniBooNE is through taking data for now, collaboration considering merits of keeping detector live during MicroBooNE run (doubling of neutrino data) under various configurations
- Fully-correlated systematic error matrix being incorporated into more exotic fits, e.g. 3+2 preview below



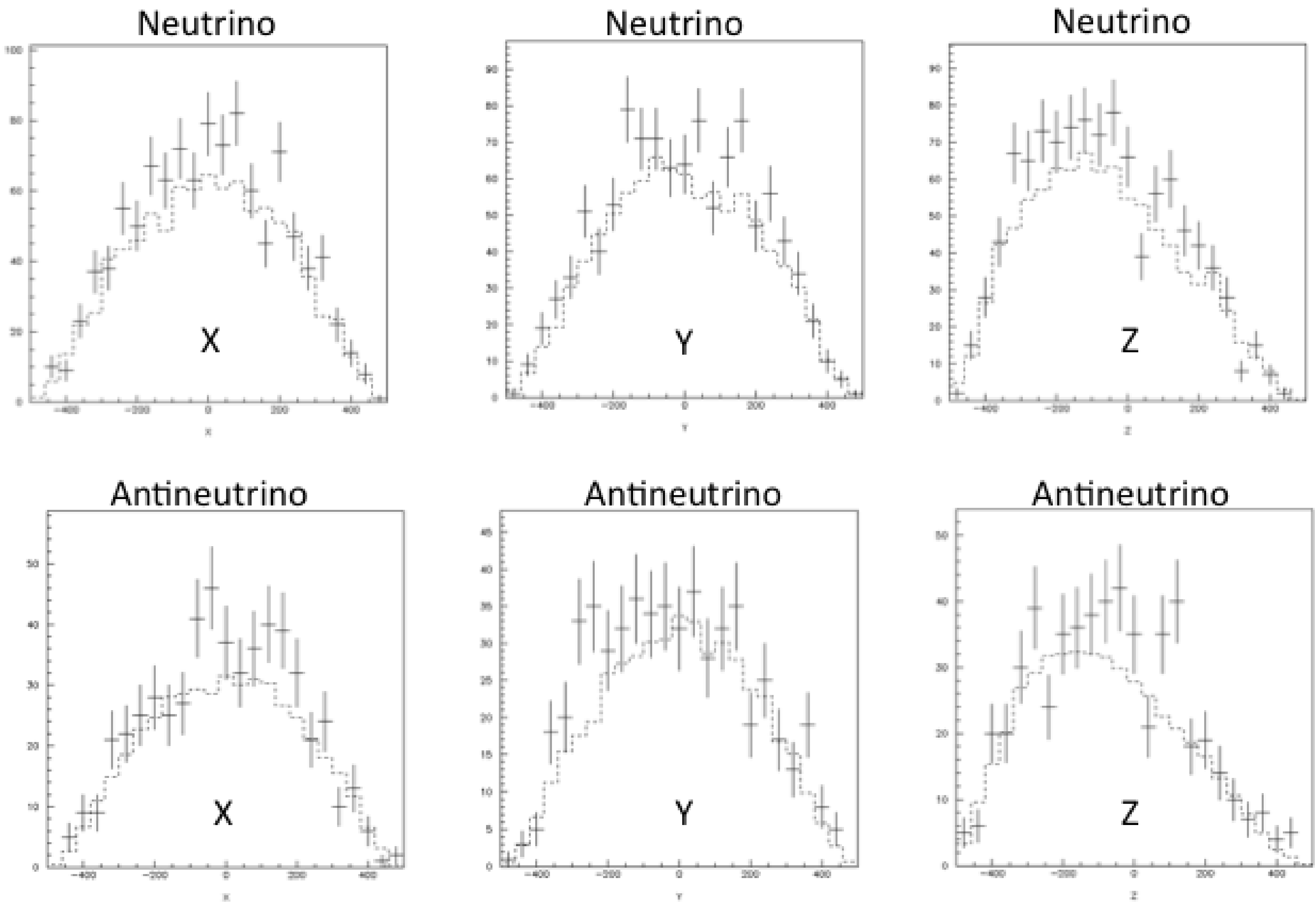


* Preliminary 3+2 fits



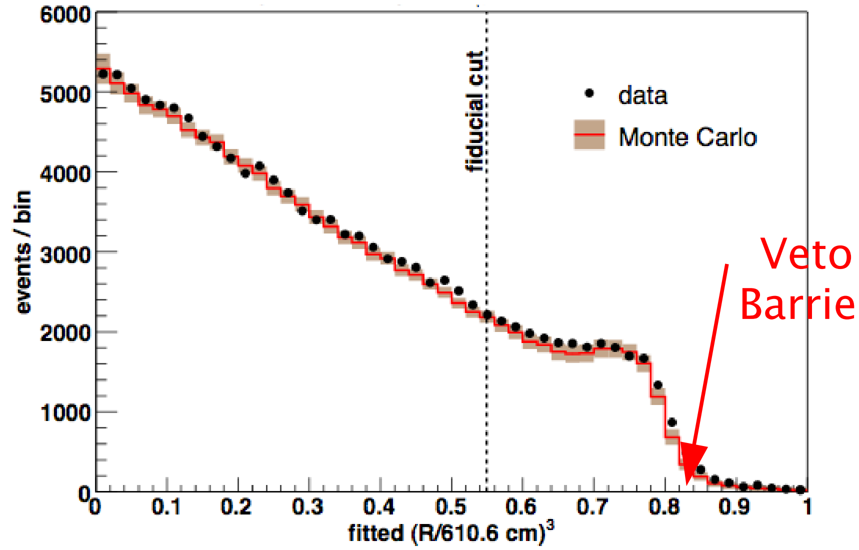
Backup slides

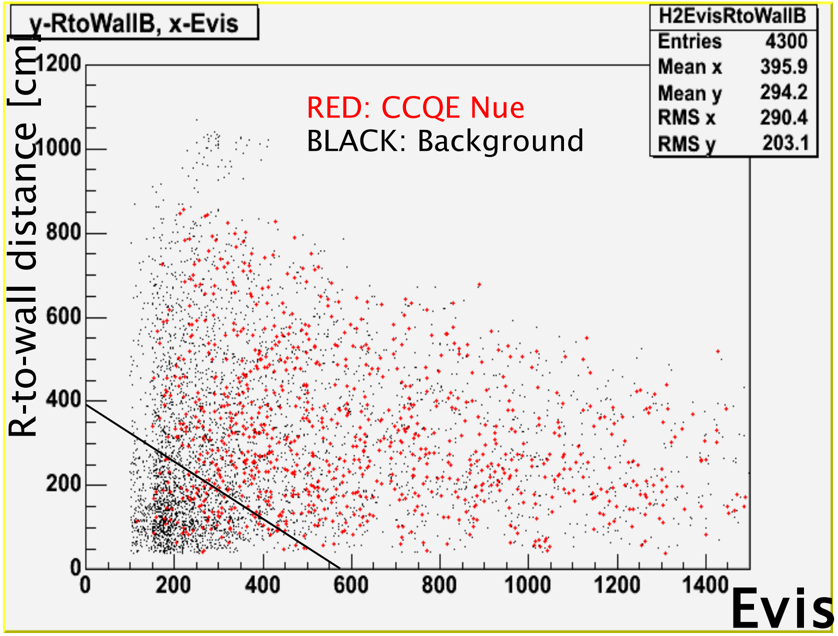
Spatial distributions (absolute norm)



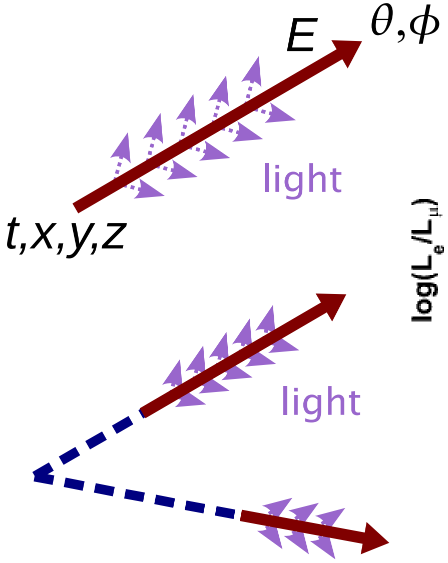
Signal selection in MiniBooNE

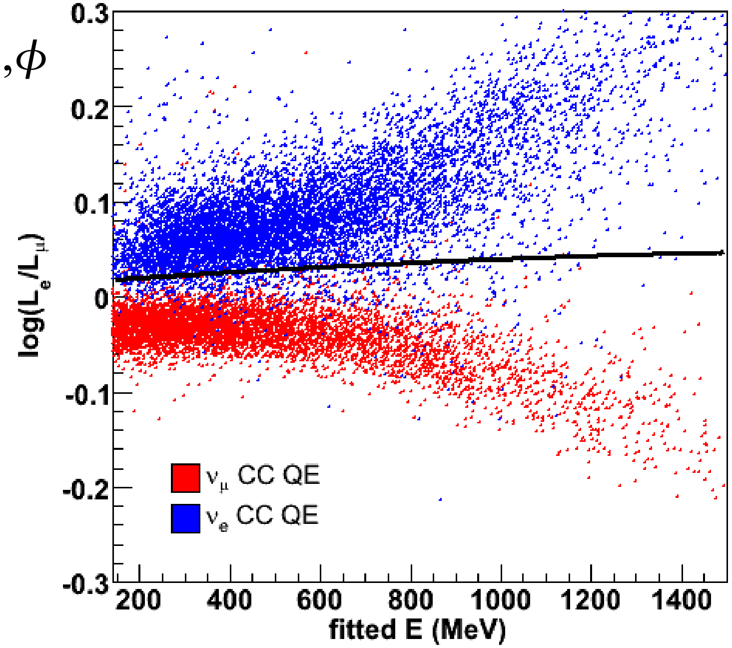
- Neutrino and anti-neutrino analyses are identical
- Start with pre-cuts
  - No late time activity, removes Michel electrons, cuts ~80% of ν_μ CCQE events
  - Veto hits < 6, contained & not a cosmic
  - Tank hits > 200 & visible E >140 MeV, removes NC elastic bkgs
  - Radius < 500 cm, far enough from PMTs to avoid area where light modeling becomes less certain
  - R-to-wall backward cut, removes bkgs (mainly γ's) from beam ν that interact in dirt outside the detector

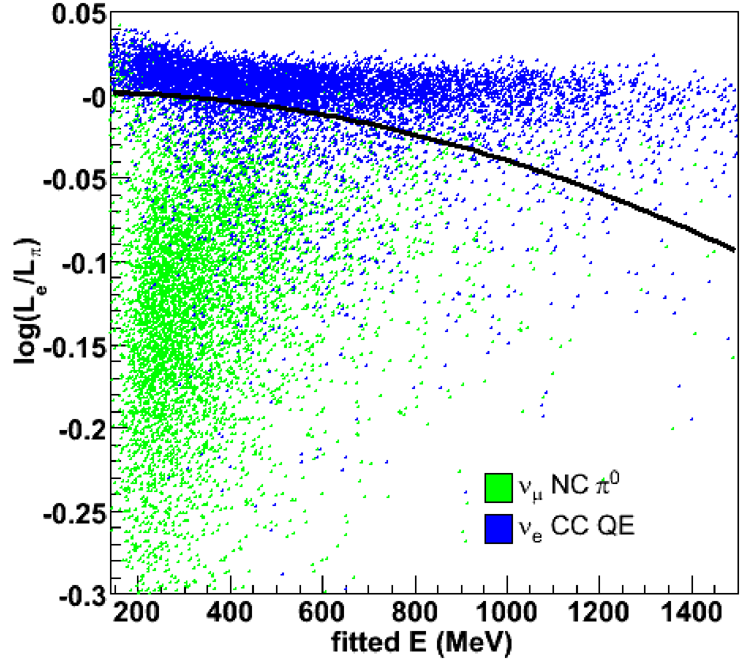


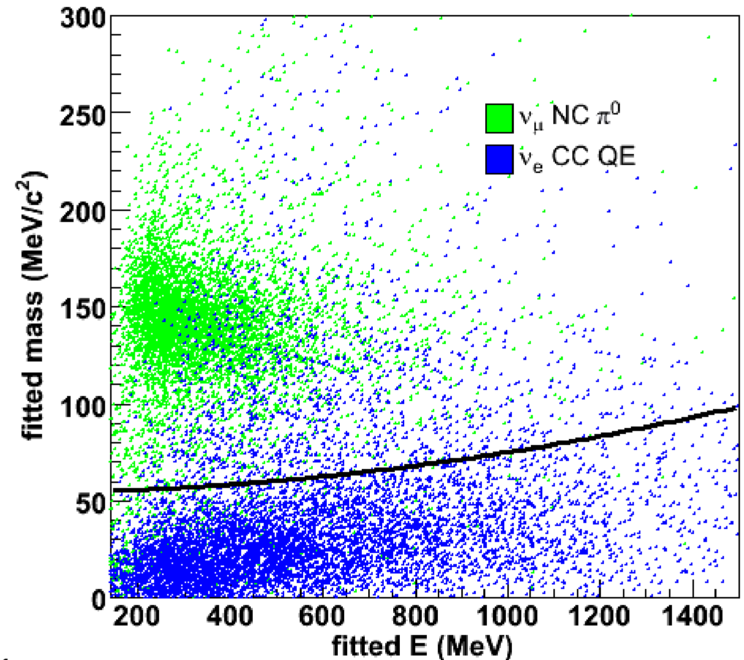


Track-based likelihoods









- Form sophisticated Q and T pdfs, and fit for track parameters under 3 hypotheses
  - The track is due to an electron
  - The track is coming from a muon
  - The "track" is a two-track(ring) π^0 event
- Apply energy-dependent cuts on L(e/μ), L(e/π), and the π^0 mass
- Plot remaining events versus E_ν(QE) and fit