Current Status of LSND and Reactor Anomalies and Future Prospects for Sterile Neutrino Searches

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Current Indications of Tension in the Standard 3 Neutrino Mixing Scheme

- Gallium: 2.7σ evidence for ν_e disappearance
- LSND: 3.8σ evidence for anti-ν_e appearance
- MiniBooNE: 3.8σ evidence for ν_e and anti-ν_e appearance
- Reactor: 3.0σ evidence for anti-ν_e disappearance

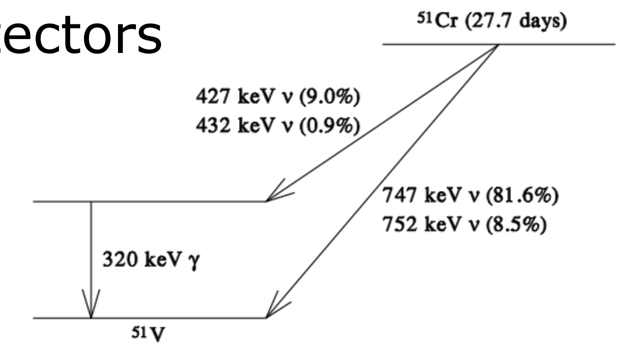
- Can be interpreted as a 4th neutrino state at eV scale mass

- Only 3 light, Weakly interacting neutrinos (LEP Z width)
- Oscillations with Δm^2_{solar} and Δm^2_{atm} are well established
- Therefore a 4th light state must be sterile

- Many thanks to K.Heeger, T. Lasserre, L.Huillier, C.Polly, M.Shaevitz for material

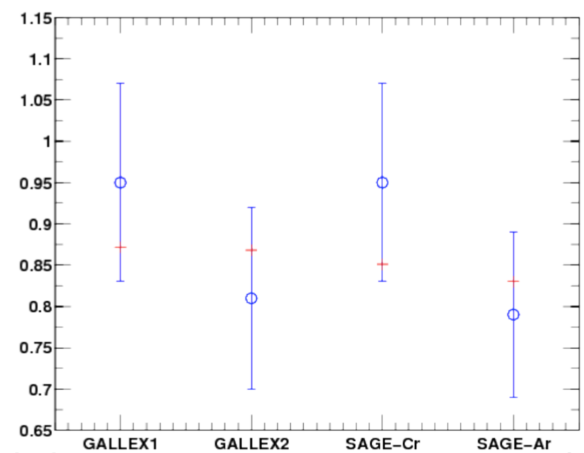
Gallium Anomaly

- Calibration of the Gallium Solar ν Detectors
- e-capture sources
  - ^{51}Cr (750 keV) & ^{37}Ar (810keV)



- The goal was to calibrate the production and extraction efficiency of the SAGE and GALLEX experiments

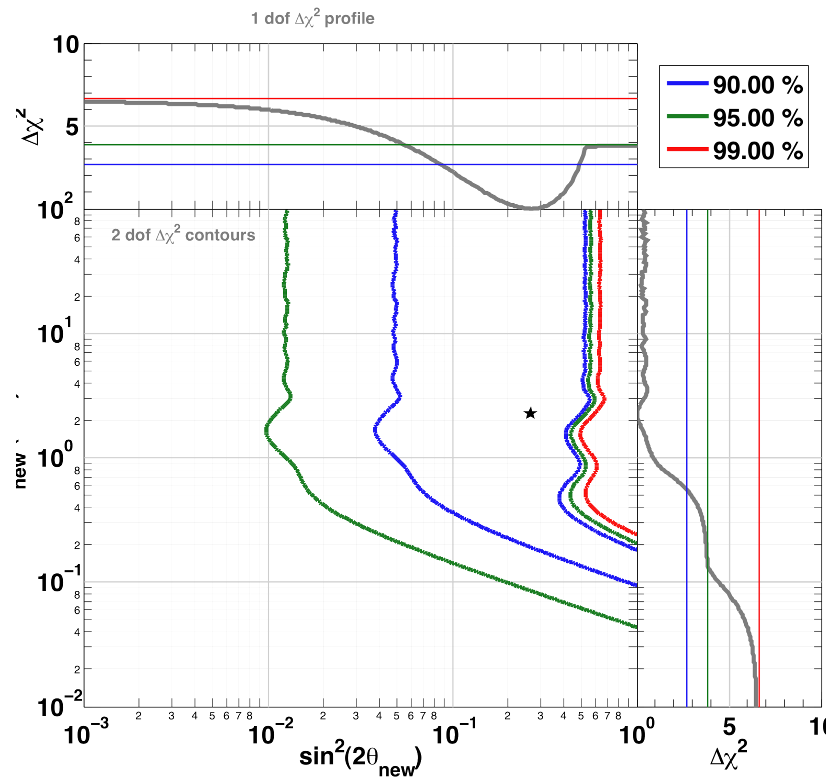
- Deficit observed
- $R_{obs/pred}$=0.86±0.05 ($\sigma_{Bahcall}$)
- $R_{obs/pred}$=0.76±0.085 (σ_{Haxton})



Gallium Anomaly

- No-oscillation hypothesis disfavored at 2.7σ (PRC 83 065504,2011)

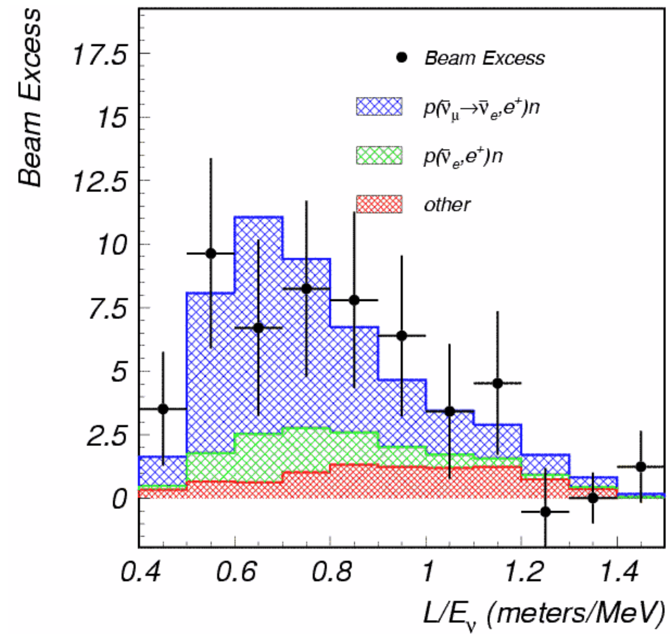
- Was not treated as evidence for new physics until the other anomalies appeared

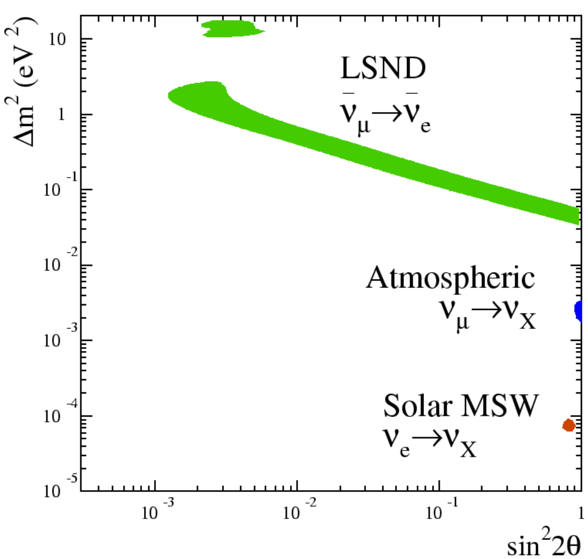


Plot from Th.Lasserre

LSND

- Used 800 MeV protons from LAMPF at Los Alamos in the 1990's
- Searched for anti-ν_e appearance in neutrino beam from pion decay at rest.



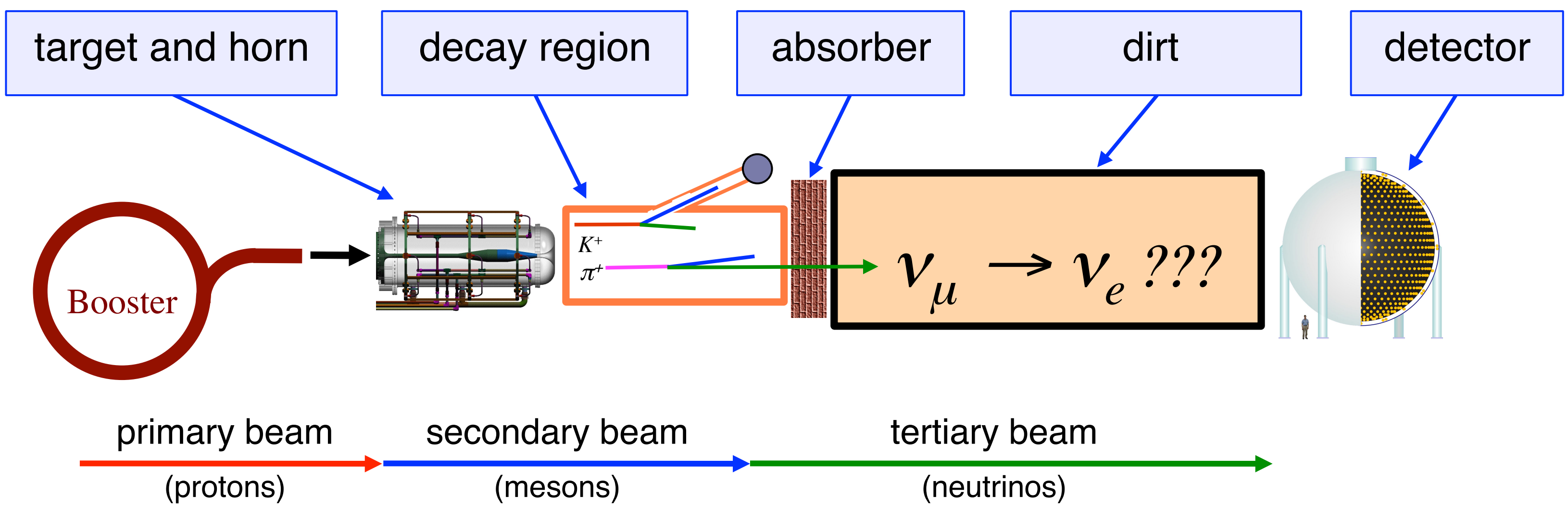


- Found an excess of anti-ν_e over background prediction
  - $87.9 \pm 22.4 \pm 6.0$ (3.8σ)

MiniBooNE

Keep L/E same as LSND
while changing systematics, energy & event signature

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27\Delta m^2 L/E)$$



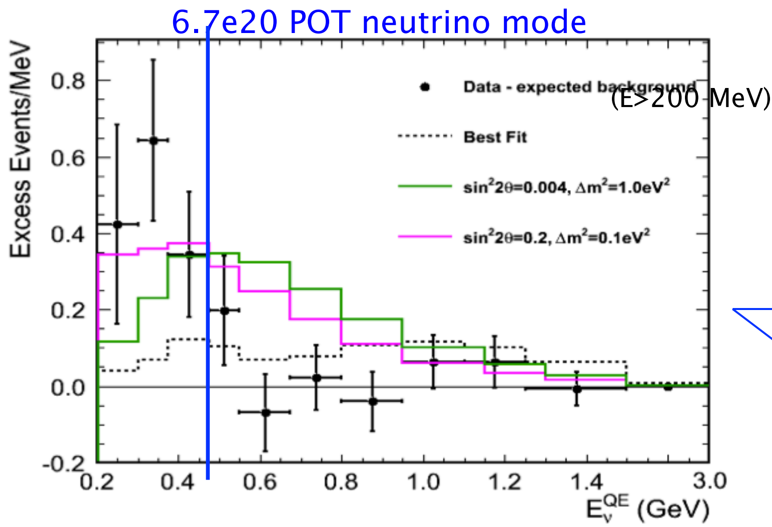
Order of magnitude
higher energy (~500 MeV)
than LSND (~30 MeV)

Order of magnitude
longer baseline (~500 m)
than LSND (~30 m)

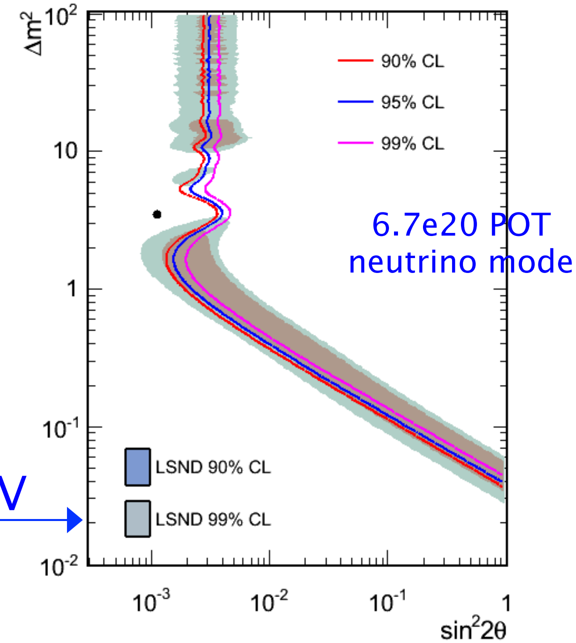
MiniBooNE Update

- 6.6×10^{20} POT in neutrino mode
  - No neutrino mode data added
- 11.3×10^{20} POT in anti-neutrino mode
  - Results updated in Kyoto with double the POT previously published
- Modest Improvements to the (anti-)nue analysis
  - *In situ* measurement of WS contamination in anti-ν beam
    Phys.Rev.D84,072005 (2011)
  - New SciBooNE constraint on intrinsic ν_e from K+
  - Added error matrix for intrinsic ν_e from K-
  - Improved smoothing algorithm 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)

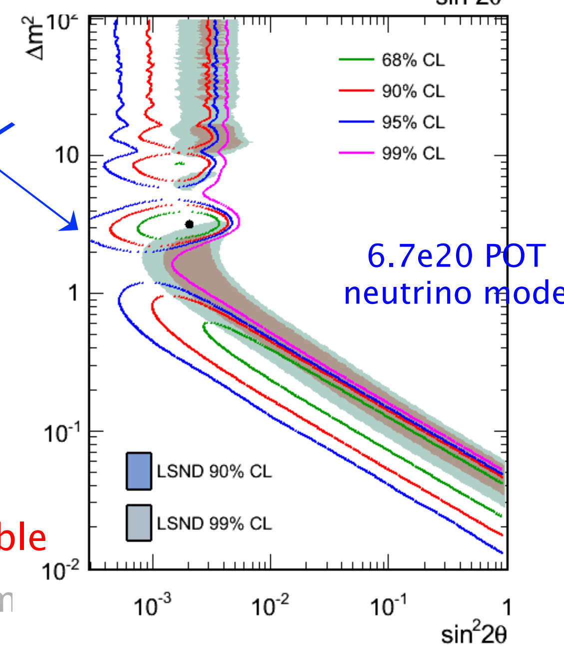
Neutrino mode 3+1 fits with all updates



Fit E >475 MeV



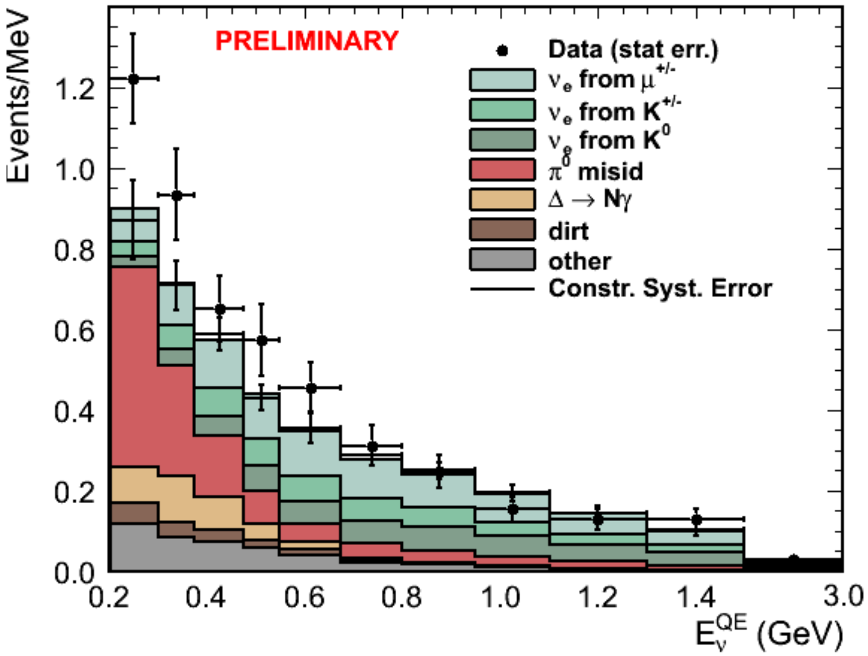
Fit E >200 MeV



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

Full Anti-neutrino dataset



anti-ν_e CCQE signal candidates with 11.3e20 POT

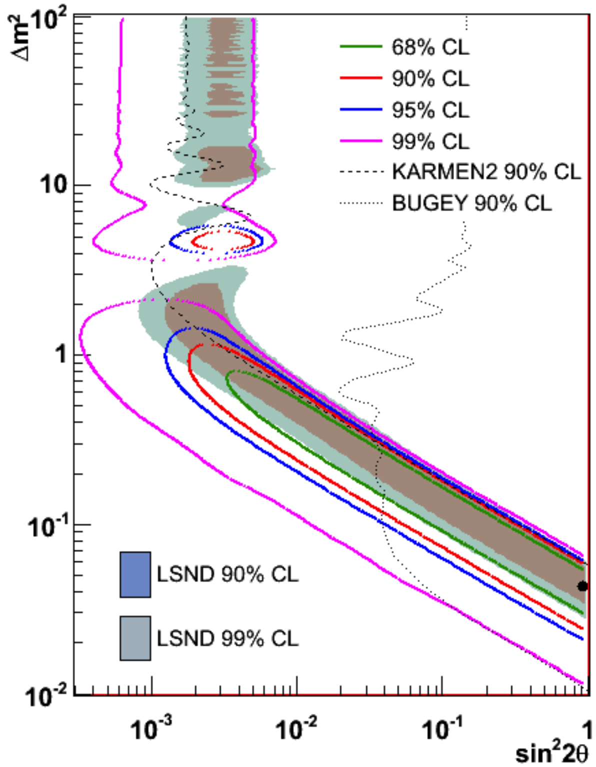
Higher stat anti-neutrino data is now much more consistent with what was observed in the data taken with a neutrino beam

* 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)

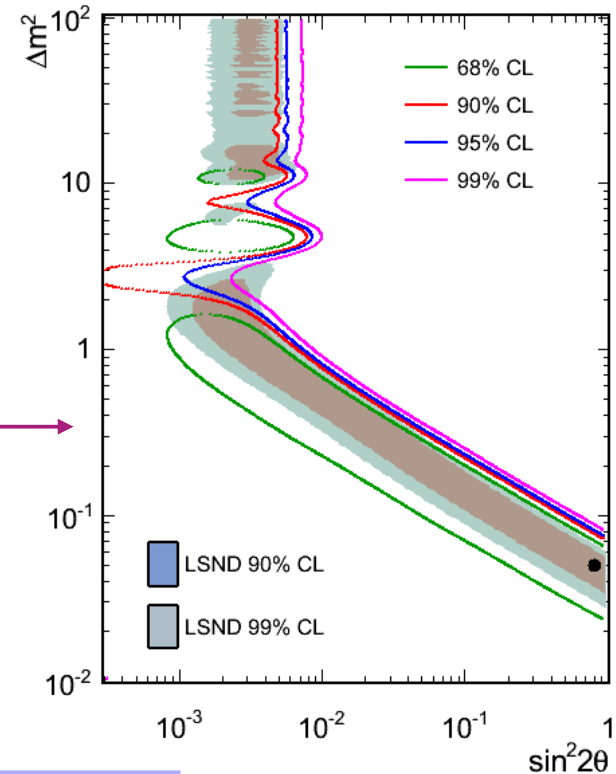
Fitting anti-neutrino data to 2ν model

E > 200 MeV fit to 11.3e20 POT



No tension

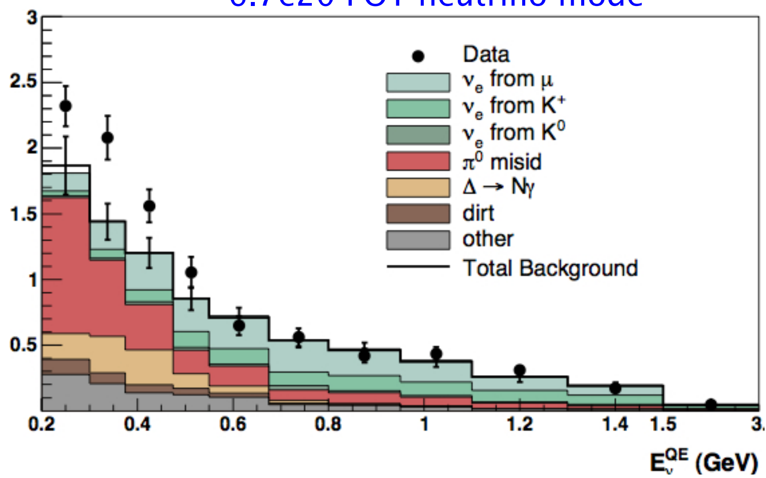
E > 475 MeV fit to 11.3e20 POT



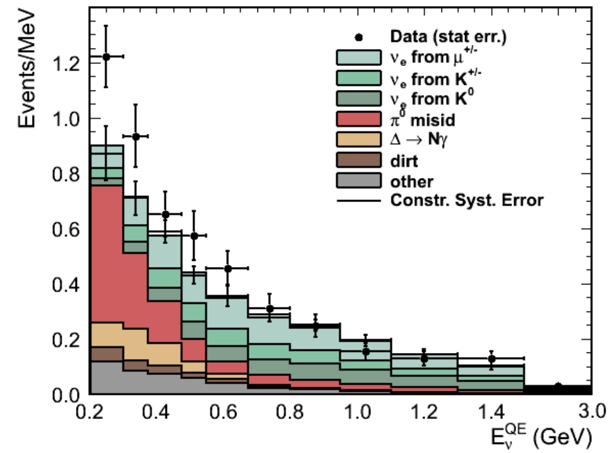
anti-ν mode	E > 200 MeV	E > 475 MeV
χ^2(null)	16.3	7.59
Prob(null)	5.8%	26.4%
χ^2(bf)	4.76	3.23
Prob(bf)	67.5%	50.2%

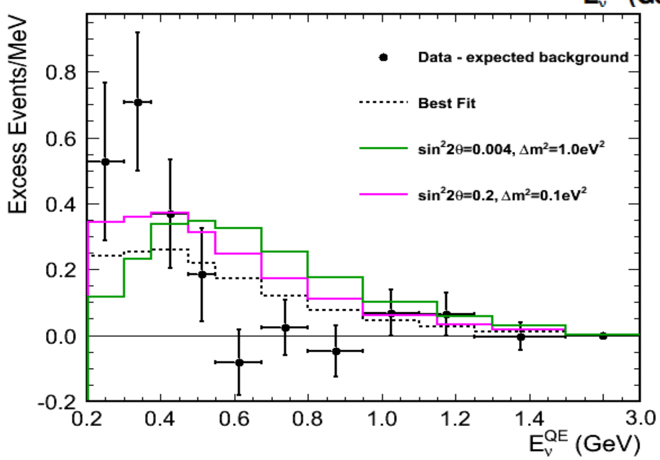
Comparing neutrino to anti-neutrino mode

6.7e20 POT neutrino mode

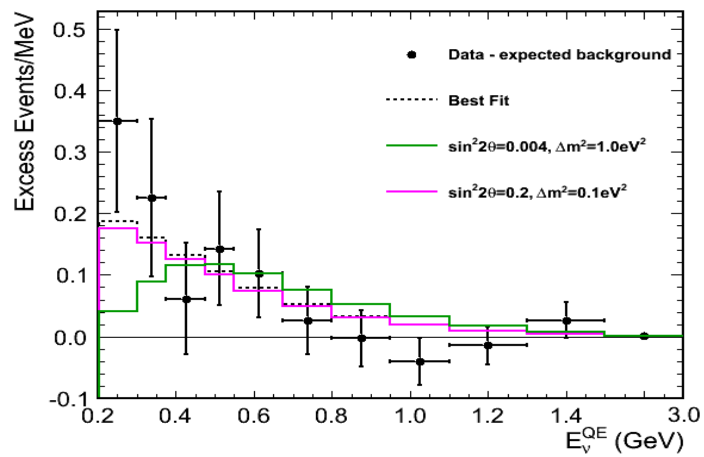


11.3e20 POT anti-neutrino mode



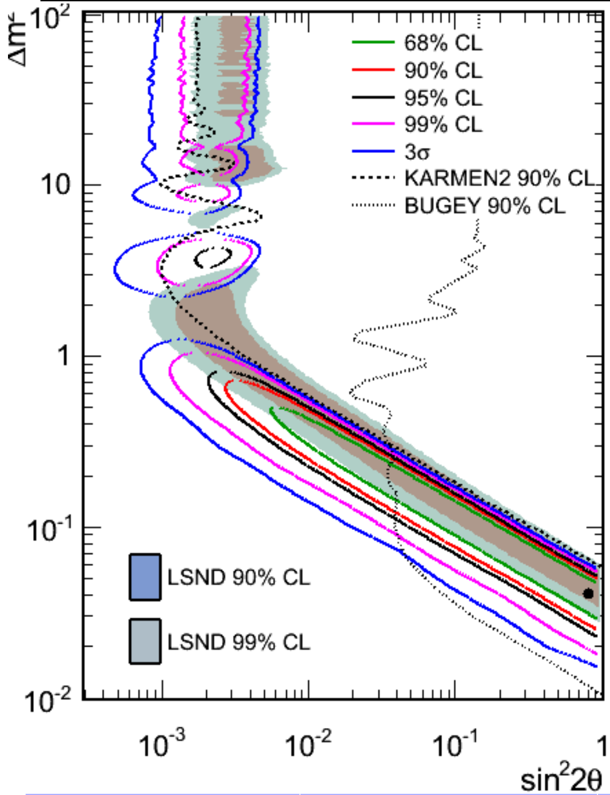


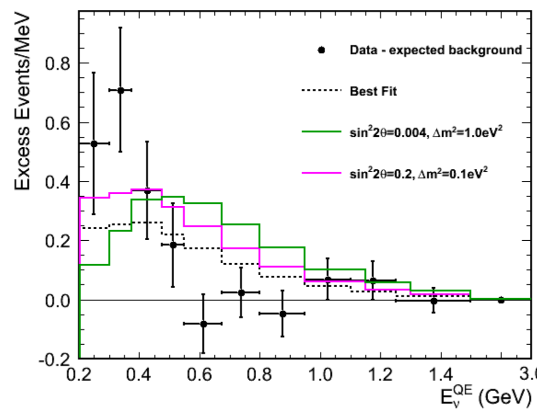
Excess: 146.3 ± 28.4 ± 40.2

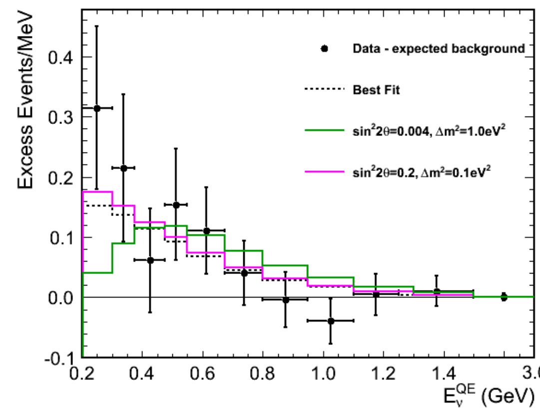


Excess: 77.8 +/- 20.0 +/- 23.4

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







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

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

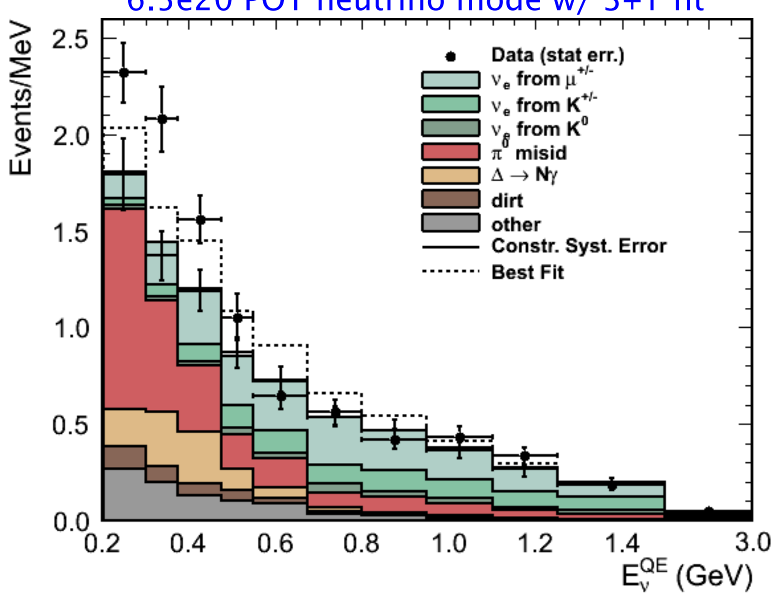
combined	E > 200 MeV	E > 475 MeV
χ^2(null)	42.53	12.87
Prob(null)	0.1%	35.8%
χ^2(bf)	24.72	10.67
Prob(bf)	6.7%	35.8%

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

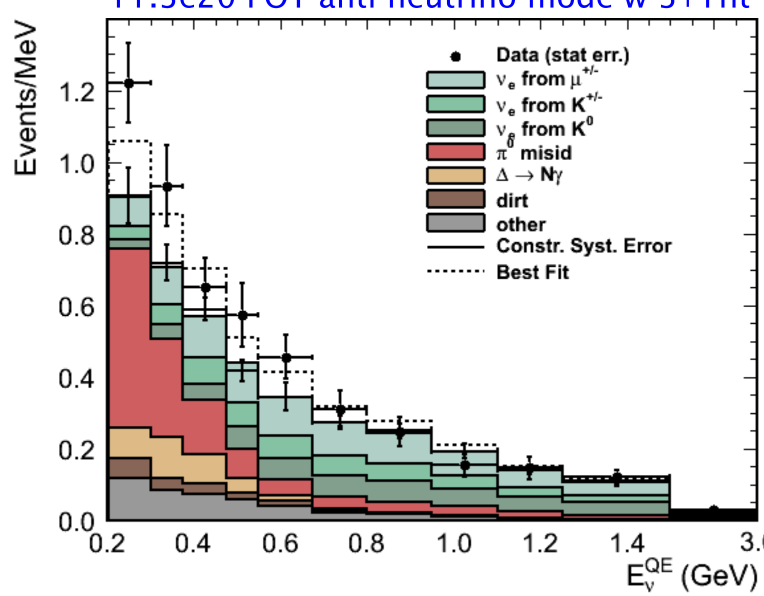
MiniBooNE Conclusions

- 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 statistics anti-υ data is now 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

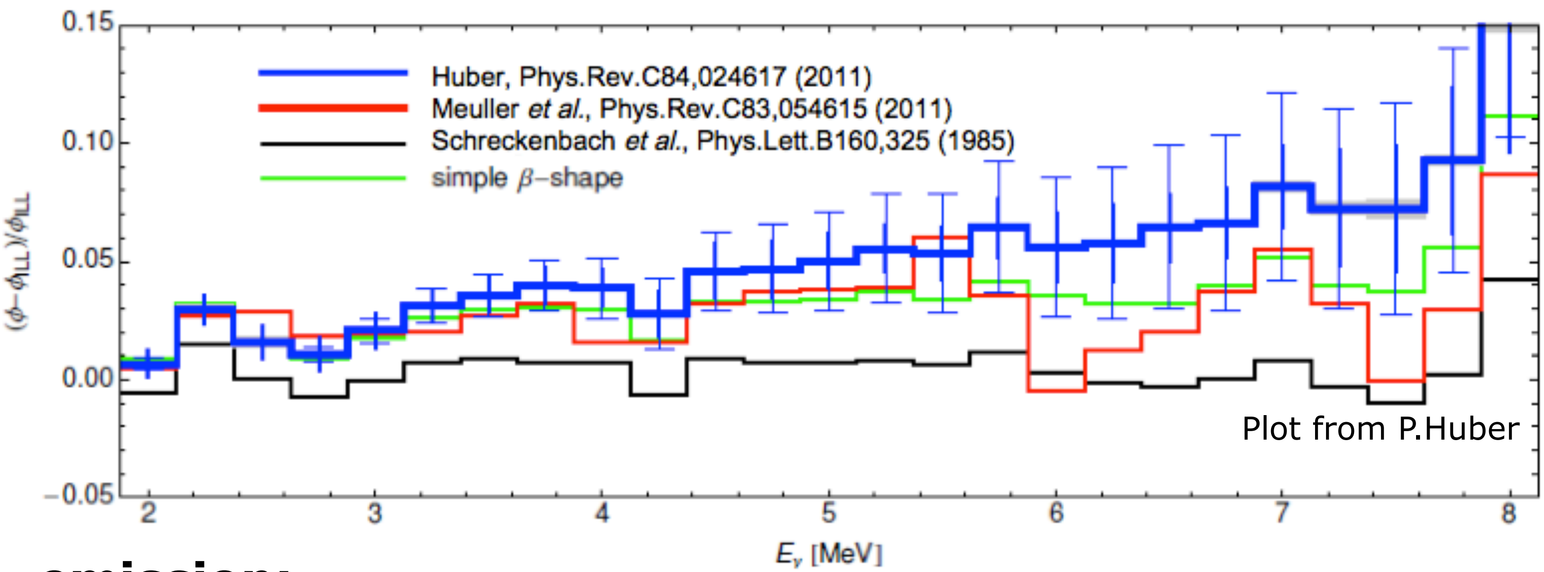
6.5e20 POT neutrino mode w/ 3+1 fit



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



Reactor Neutrino Anomaly



ν emission:

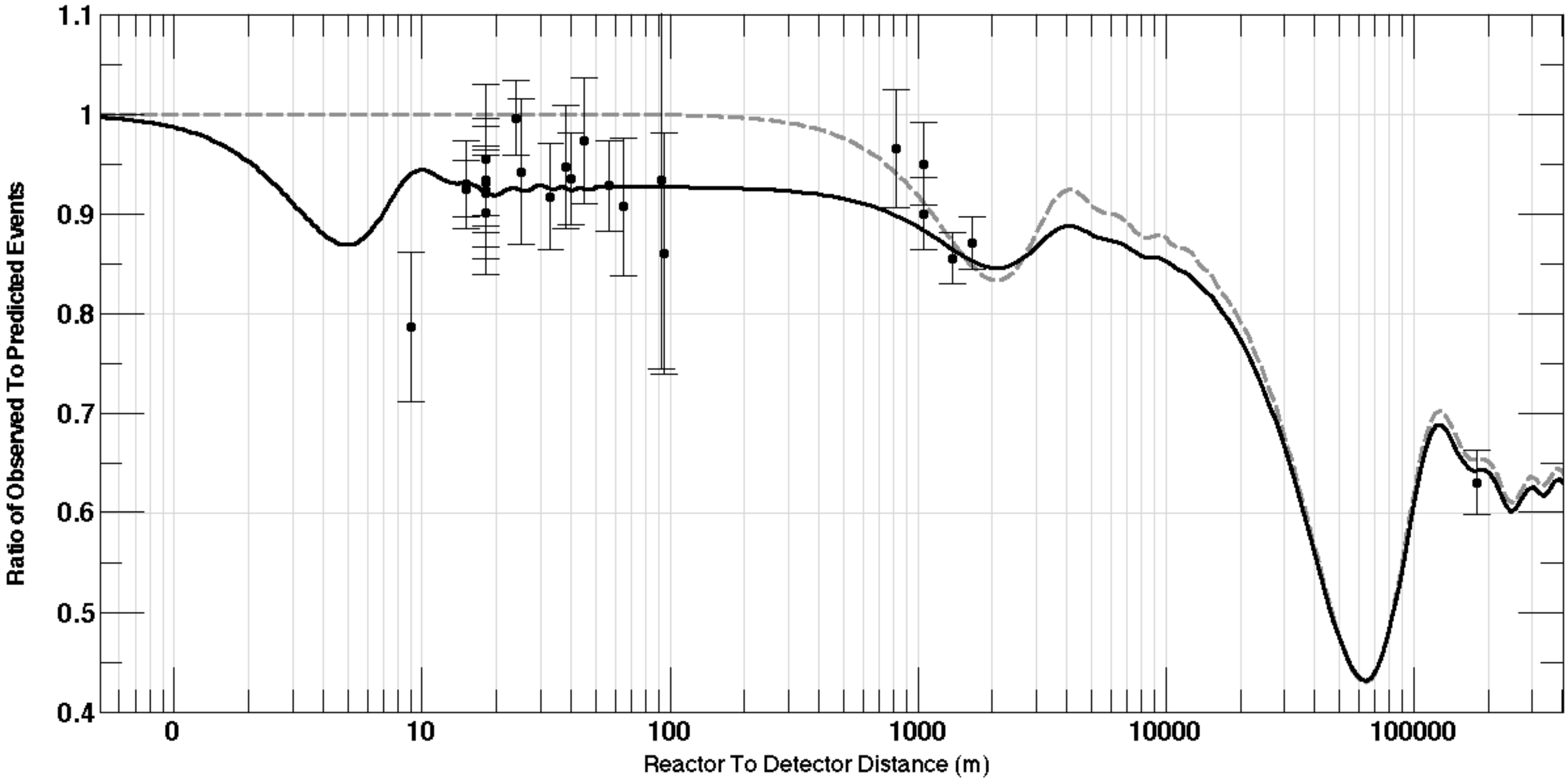
- Improved reactor neutrino spectra produces +3.5%
- Accounting for long-lived isotopes accumulating in reactors produces +1%
- PRC83, 054615 (2011)
- PRC84, 024617 (2011)

ν detection:

- Reevaluation of σ_{IBD} Improved neutron life time measurements produces +1%

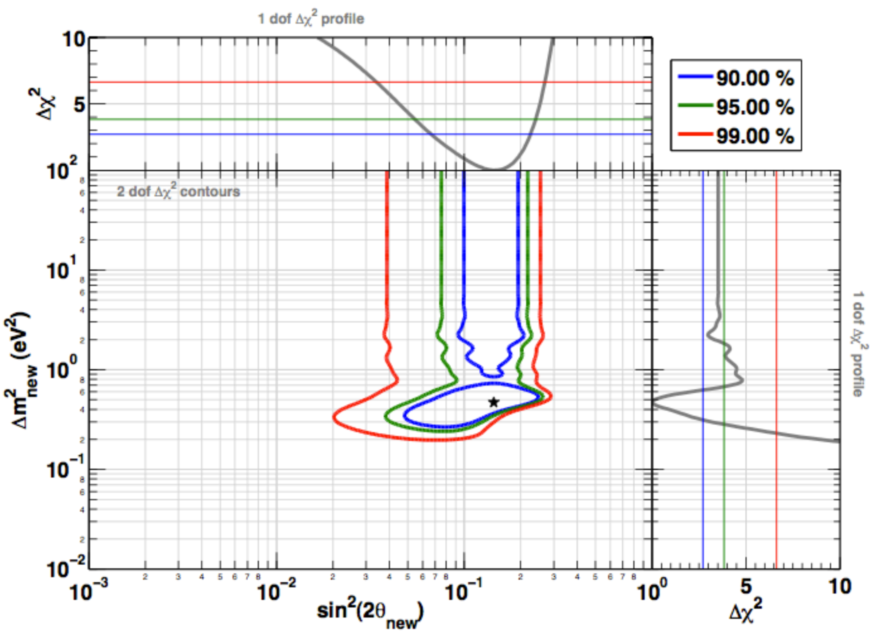
Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)

Interpreted as Oscillation with 4th State

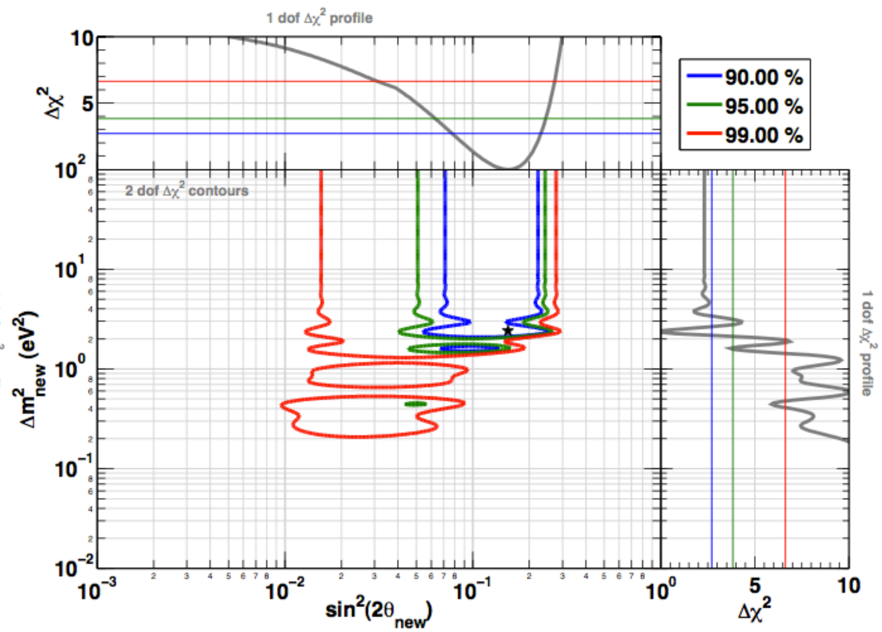


Interpreted as Oscillation with 4th State

Rate Analysis



Rate + Shape Analysis



Plot from G.Mention et al arXiv:1101.2755

Counter Evidence for 4th State

There are a number of results that are sensitive, but see no evidence for a 4th neutrino state with ~eV mass:-

– CDHS and MiniBooNE searches for ν_μ disappearance

– MiniBooNE search for $\bar{\nu}_\mu$ disappearance

– MINOS search for $\nu_\mu \rightarrow \nu_s$

– Karmen search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

It is hard (impossible?) to fit all data with a single oscillation hypothesis

Future Tests

- Need a definitive test(s) of the 4th neutrino hypothesis hinted at by the current anomalies

- Many tests proposed. They fall into three types:-
  1) Detector <15 m from compact nuclear reactor
  2) Accelerator based short baseline
  3) Intense sources close to or in detector

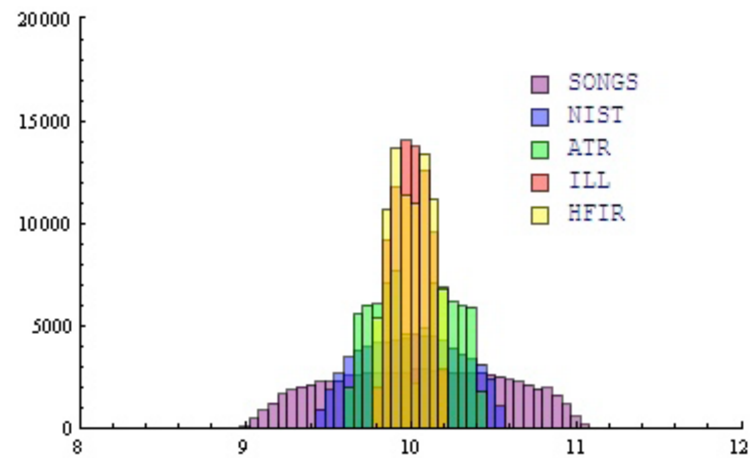
- For definitive test would like oscillation evidence in E and L and redundant cross-checks

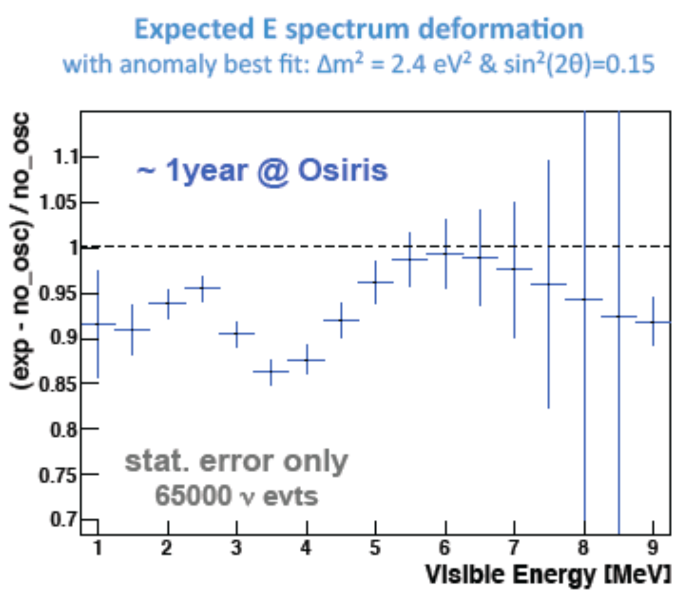
- See Sterile Neutrino White Paper
  - arXiv:1204.5379

- Upcoming report from Fermilab Short Baseline Working Group

Reactor Searches for 4th State

• Get a ton scale detector 2-10m from a compact core





• Look for depleted rate and altered shape

Proposed Reactor Short Baseline Experiments

Proposal	Reactor	Fuel (#fissions)	Core Size (m)	<L> (m)	Depth (mwe)	Status	Comment
Nucifer Saclay	Osiris 70 MW	^{235}U ON-OFF cycle	<1	7	5	Data Taking	Non proliferation 1 m^3 Gd-LS Mostly Rate + Shape?
Stereo Genoble	ILL 50 MW	^{235}U ON-OFF cycle	<1	10	10	Proposal	2 m^3 Gd-LS Rate + Mostly shape
SCRAMM (Ca)	San-Onofre 3 GW PWR	$^{235,238}U$ $^{239,241}Pu$	3x3.8	24	30	Proposal	2 m^3 Gd-LS Mostly Rate + Shape
SCRAMM (Idaho)	ATR 150 MW	^{235}U ON-OFF cycle	<1	12	15	Proposal	2 m^3 Gd-LS Rate + Mostly shape
DANSS (Russia)	KNPP 3 GW PWR	$^{235,238}U$ $^{239,241}Pu$	few	14	70	Being Built	Segmented detector 1 m^3 Rate + Shape?
NIST (US)	NCNR 20 MW	^{235}U ON-OFF cycle	≈1	4-11	0	Proposal	Rate + Mostly shape
Nu4 (Russia)	SM-3 100 MW	^{235}U ON-OFF cycle	0.35x0.42 x0.42	6-12	10	Being Built	14 m^3 Gd-LS Rate + shape

Table from T.Lasserre

Accelerator Based Short Baseline Search

- Wish (Requirements) list:-
  - Need significance at $>5\sigma$ level
  - Would like to see effect in L and E
  - Would like to have redundant crosschecks within an experiment
  - Would like to see a consistent picture with appearance and disappearance
- Four experiment types:-
  - Accelerator isotope production with large detector close by
  - Pion/Kaon decay at rest (C.F. LSND, Karmen)
  - Pion decay in flight (C.F. MiniBooNE)
  - Low energy neutrino factory

Accelerator Short Baseline Experiments

Isotope Source	Disapp	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest Source	Appearance & Disapp	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Accelerator $\overset{(-)}{\nu}$ using Pion Decay-in-Flight	Appearance & Disapp	$\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_\mu$, $\nu_e \rightarrow \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, CERN SPS
Low-Energy ν-Factory	Appearance & Disapp	$\nu_e \rightarrow \nu_\mu$, $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ $\nu_\mu \rightarrow \nu_\mu$, $\nu_e \rightarrow \nu_e$	νSTORM at Fermilab

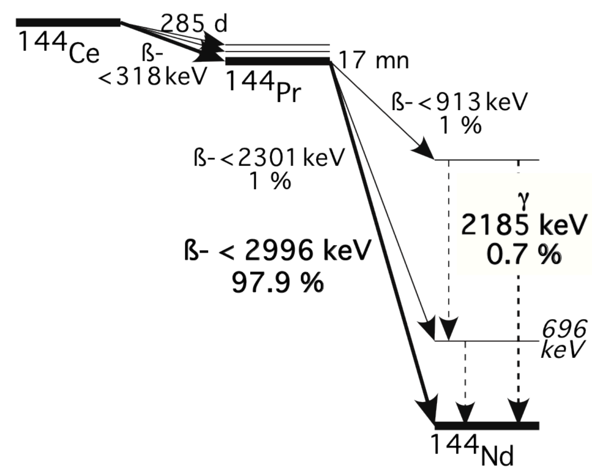
Table from M.Shaevitz

Intense Radioactive Sources

- Test 4th state hypothesis with ~MeV (anti-)neutrino sources placed a few meters from large low background detector
  - Similar to the ^{51}Cr calibrations of the SAGE and GALLEX solar ν detectors
  - Can use existing reactor/solar neutrino detectors
  - Can place source inside or just outside detector

- Can search for effect on energy spectrum and rate as a function of distance from source.

- Typically need compact MCi source
  - Technically non-trivial
  - e.g. ^{144}Ce



Proposals with Intense Radioactive Sources

Type	channel	Background	Source	Production	Activity (Mci)		Proposal
ν_e	$\nu_e e \to \nu_e e$ Compton edge 5% E_{res} 15cm R_{res}	radioactivity (managable) Solar ν (irreducible) ν-Source (out ok but in ?)	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	in	>3	Sage LENS
					out	5-10	SOX SNO+
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	in	>1	-
					out	5	Ricochet (NC)
$\bar{\nu}_e$	$\bar{\nu}_e p \to e^+ n$ E_{th}=1.8 MeV (e^+,n) Coincidence 5% E_{res} 15cm R_{res}	reactor ν & ν-Source → Background free!	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing	in	0.005-0.05	CeLAND SOX
					out	0.5	Daya-Bay
			^{90}Sr ^{106}Rh		-	-	-
			^{42}Ar	?	-	-	-

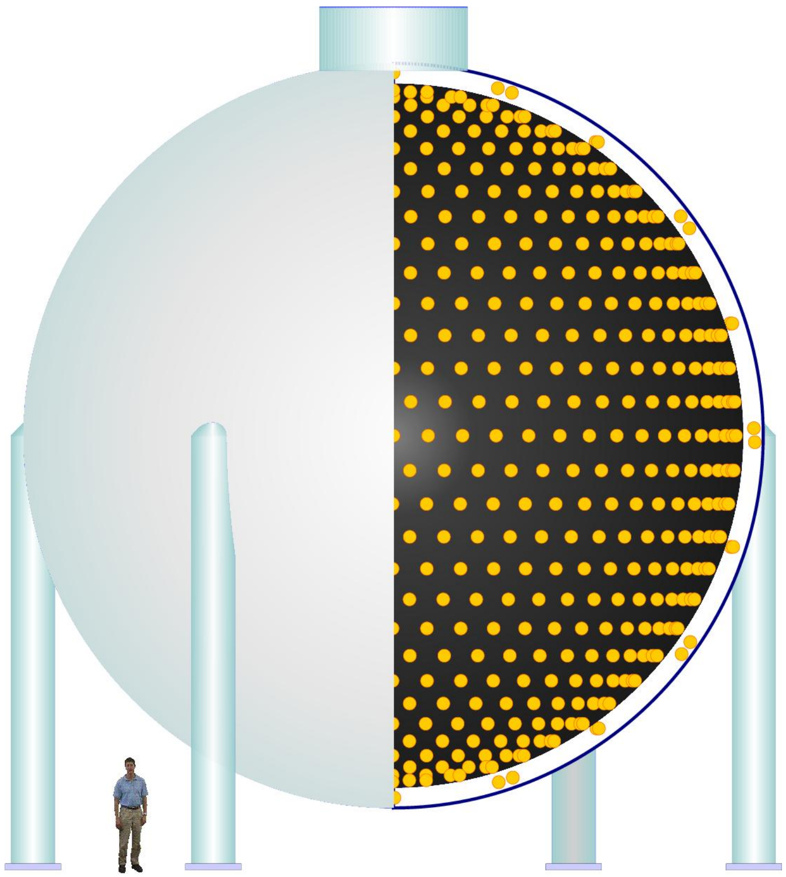
Table from T.Lasserre

Conclusions

- A number of intriguing hints at oscillations involving a 4^{th} ν state
- No single hint is compelling
- Much experimental evidence is in tension with such a 4^{th} state
- Nonetheless the situation cannot be ignored
- Definitive experiments are needed in more than one experimental domain
- Many proposals are on the table and some would be definitive

Backup slides

MiniBooNE Detector



541 meters downstream of target

3 meter overburden of dirt

12 meter diameter sphere

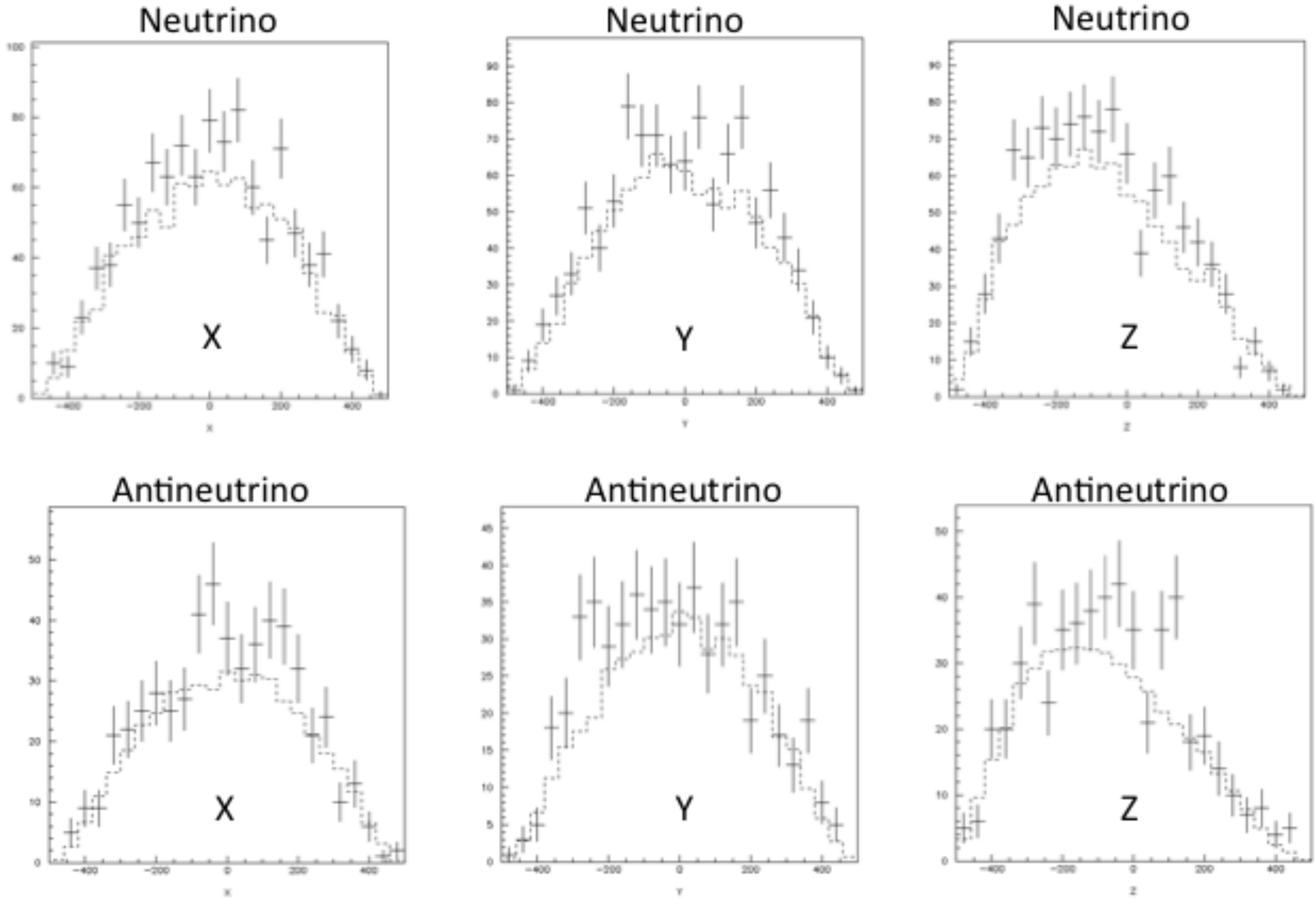
Filled with 800 t of pure mineral oil

(CH_2--density 0.86, n=1.47)

Fiducial volume: 450 t

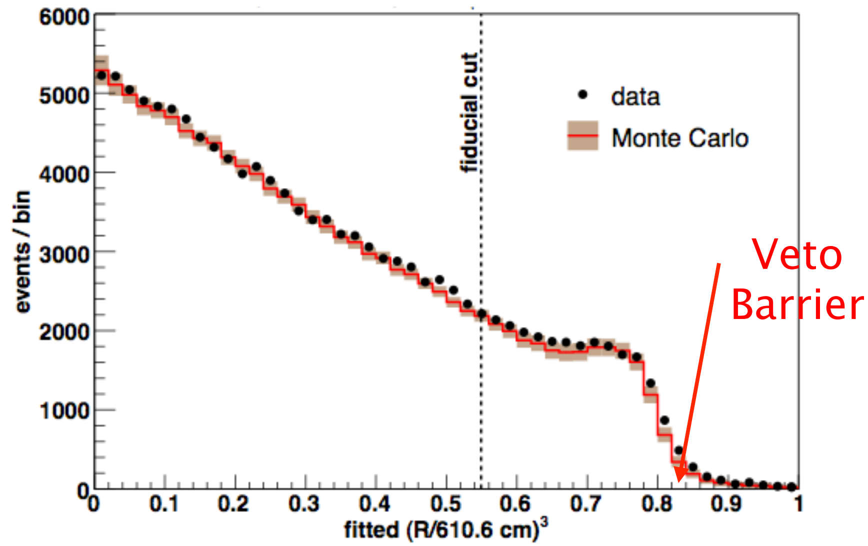
1280 inner 8” phototubes 10% coverage,

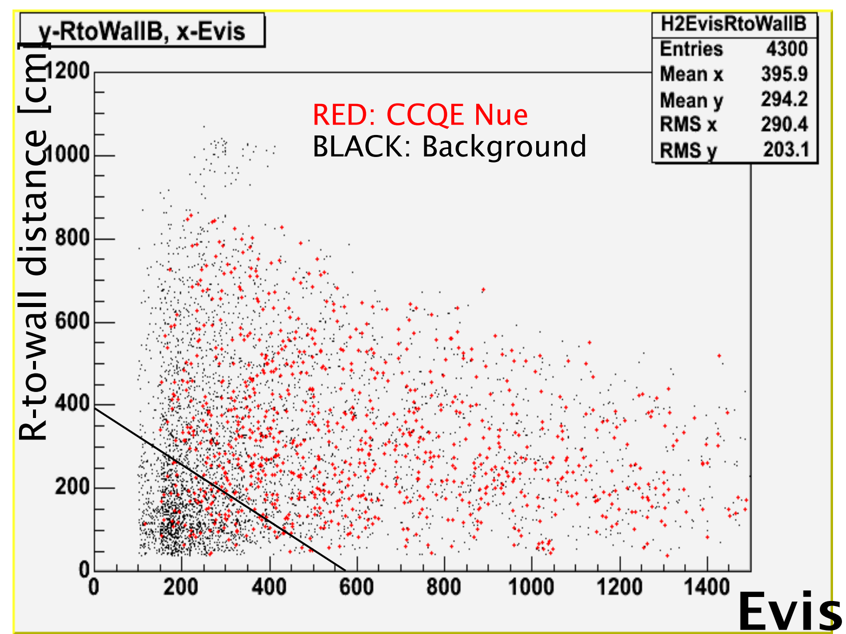
240 veto phototubes

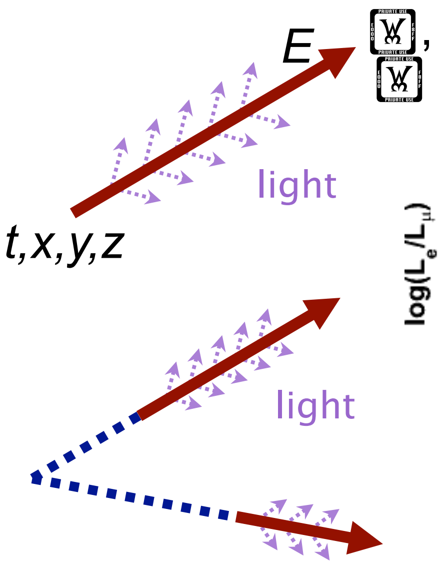

Neutrino
X
Neutrino
Y
Neutrino
Z
Antineutrino
X
Antineutrino
Y
Antineutrino
Z

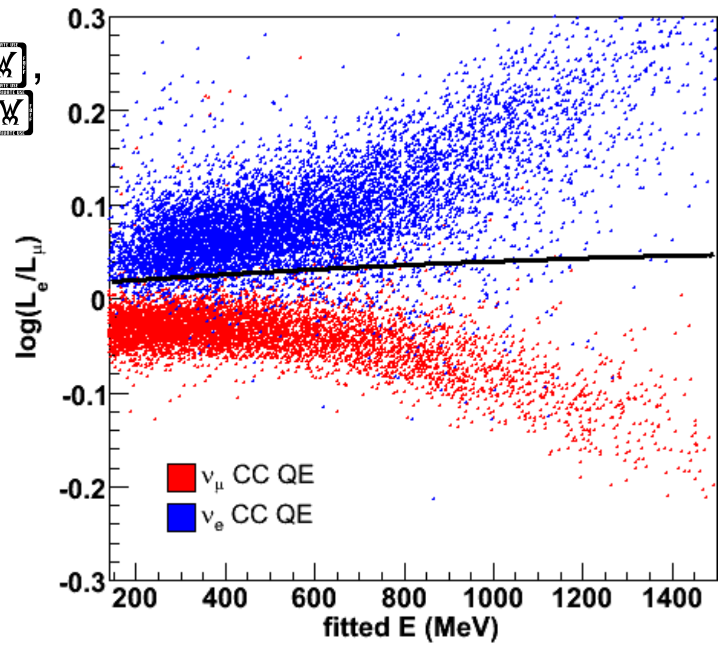
Signal selection in MiniBooNE

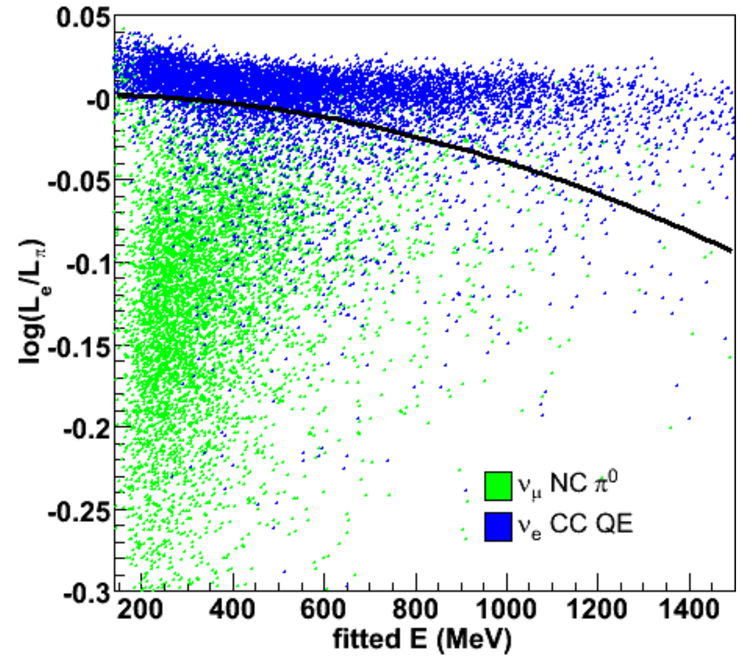
- Neutrino and anti-neutrino analyses are identical
- Start with pre-cuts
  - No late time activity, removes Michel electrons, cuts ~80% of ν_μ CCQE events
  - Veto hits < 6, contained & not a cosmic
  - Tank hits > 200 & visible E >140 MeV, removes NC elastic bkgs
  - Radius < 500 cm, far enough from 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

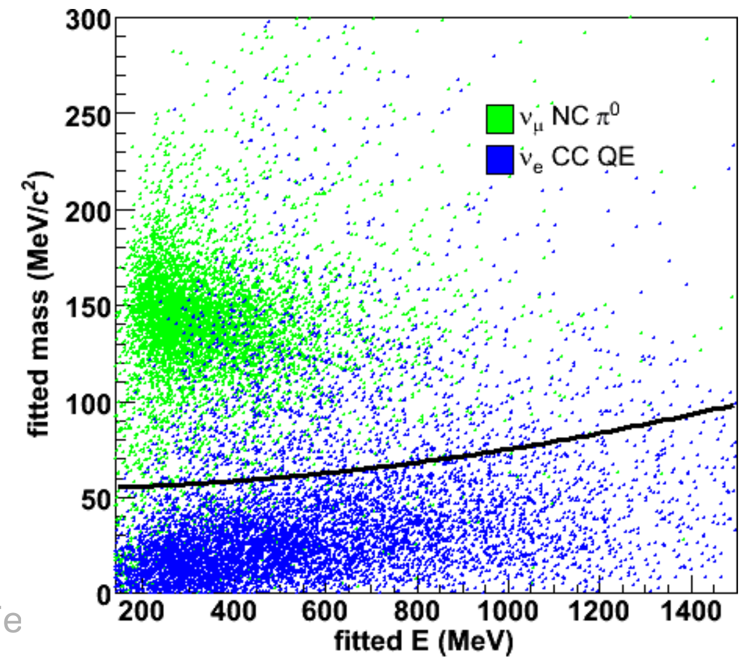






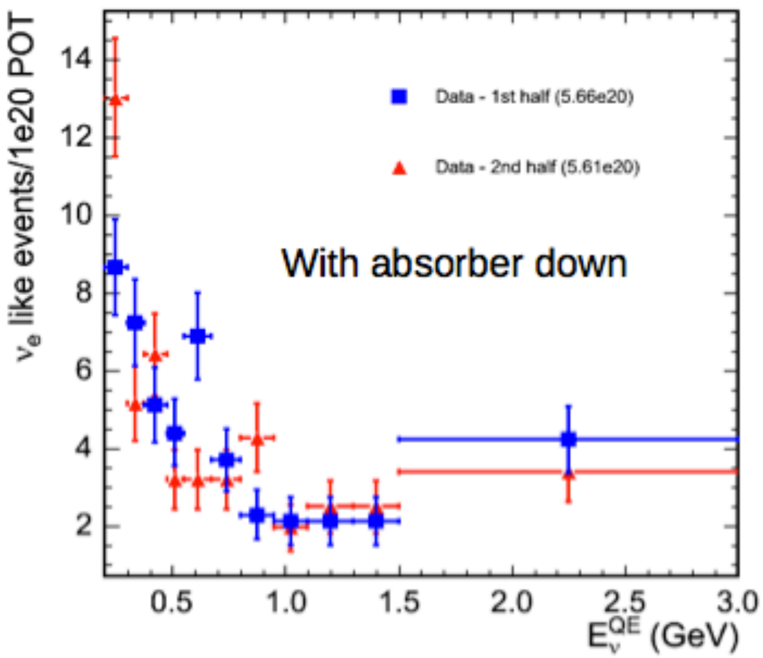


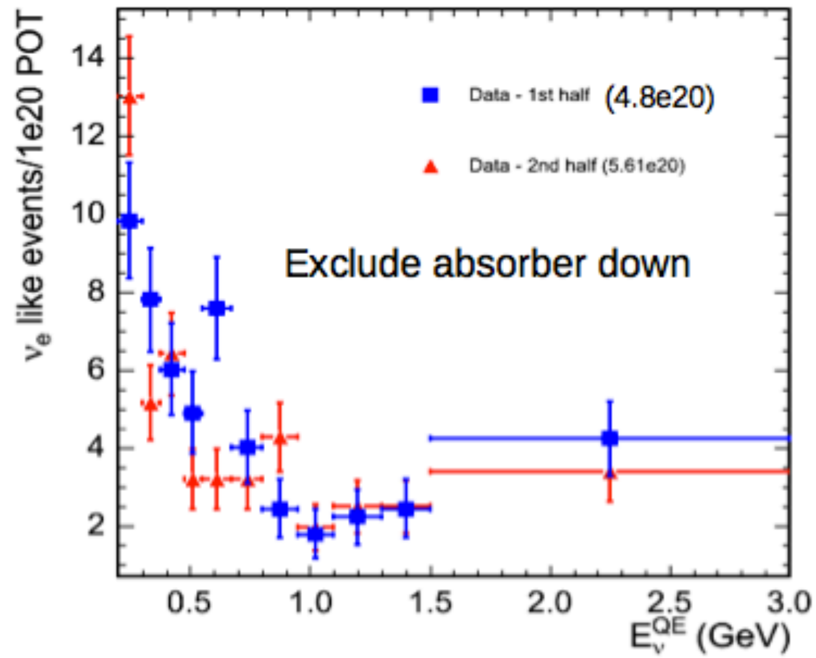




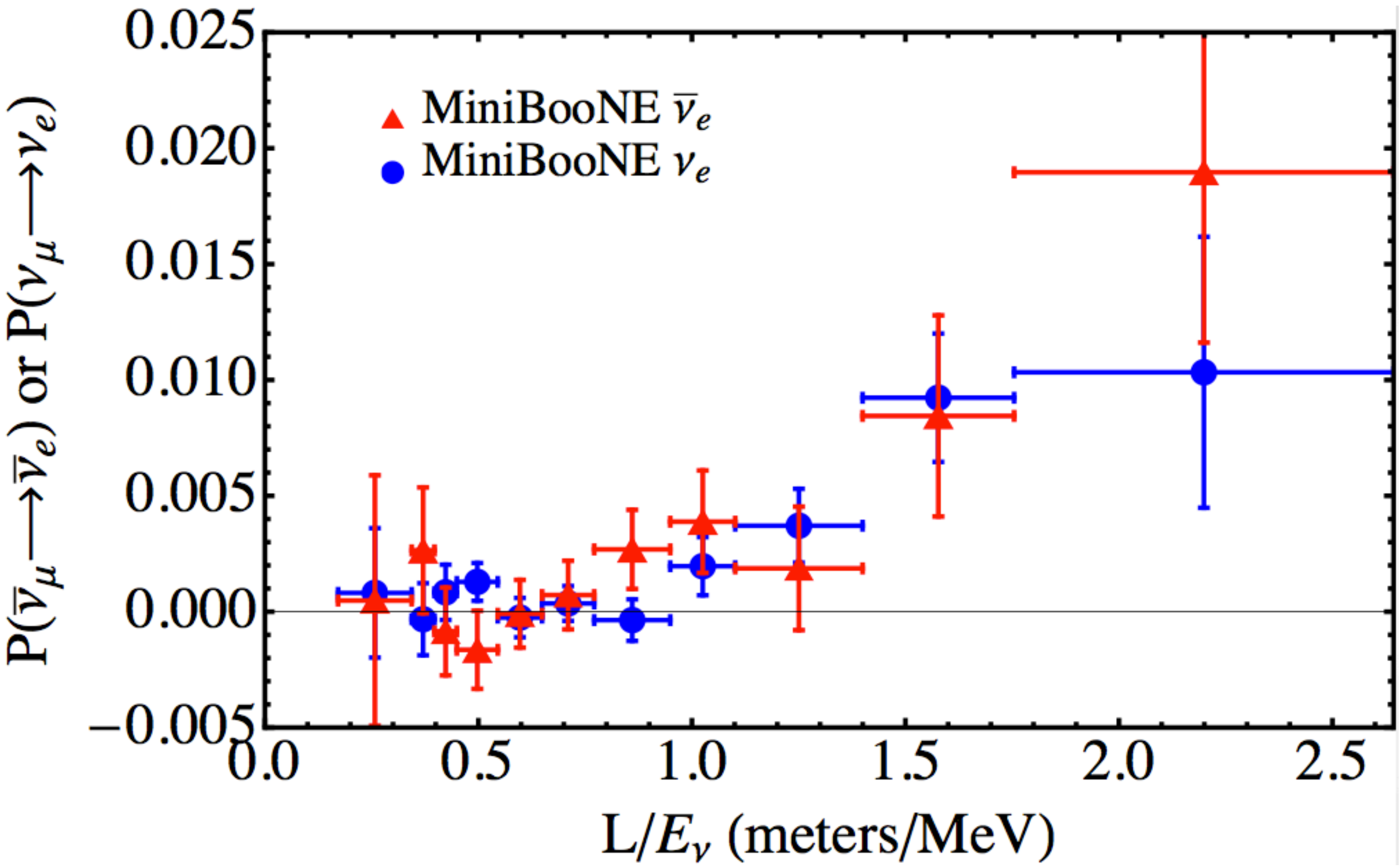
- Form sophisticated Q and T pdfs, and fit for track parameters under 3 hypotheses
  - The track is due to an electron
  - The track is coming from a muon
  - The "track" is a two-track(ring) π^0 event
- Apply energy-dependent cuts on L(e/μ), L(e/π), and the π^0 mass
- Plot remaining events versus E_ν(QE)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

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



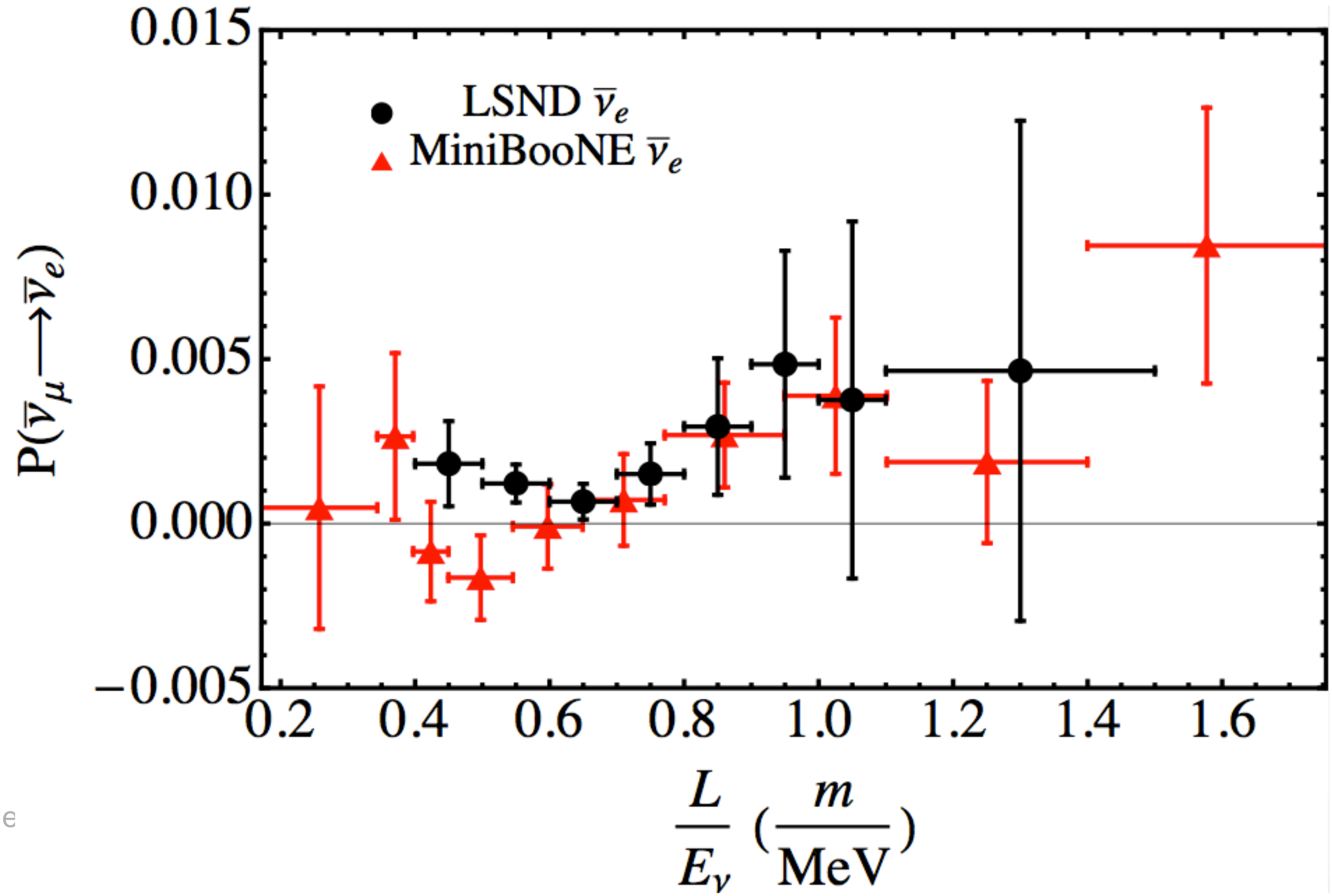


		1st half			2nd half	
	data	mc	excess	data	mc	excess
200-475	119	100.5±14.3	18.5 (1.3s)	138	100.0±14.1	38 (2.7s)
475-1250	120	99.1±14.0	20.9 (1.5s)	101	103.1±14.4	-2.2 (-0.2s)



* 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)



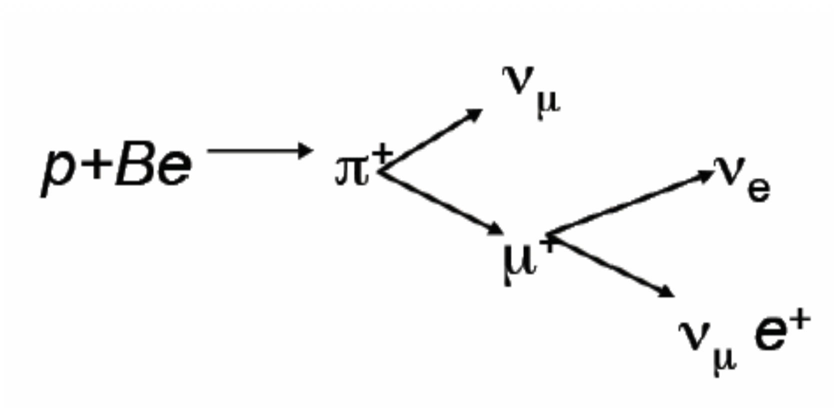
- Maximum likelihood fit:

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

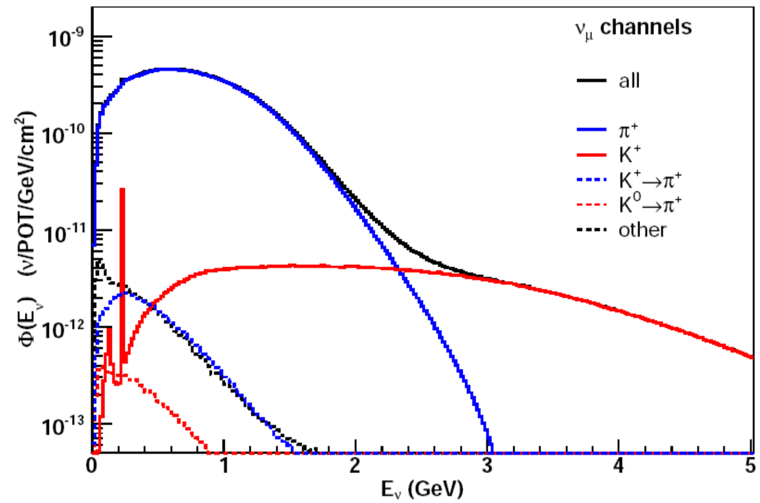
$M = M_{om} + M_{xsec} + M_{flux} + M_{\pi^0} + M_{dirt} + M_{K^0} + ...$

1000's of MC universes go into forming M

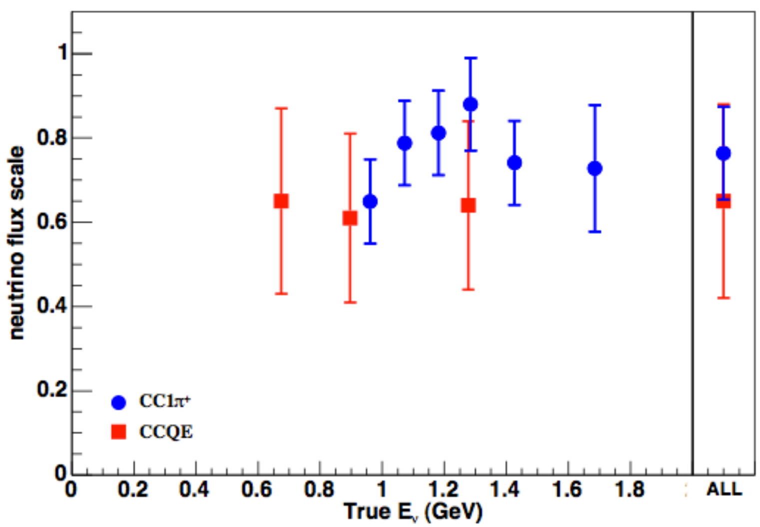
- Simultaneously fit (FC-corrected)
  - ν_e CCQE signal + high E ν_e sample
  - High statistics ν_μ CCQE sample
- ν_μ CCQE sample acts like a near detector, i.e. same flux as oscillation ν_e by definition, lepton universality + muon mass corrections fix relative cross-section

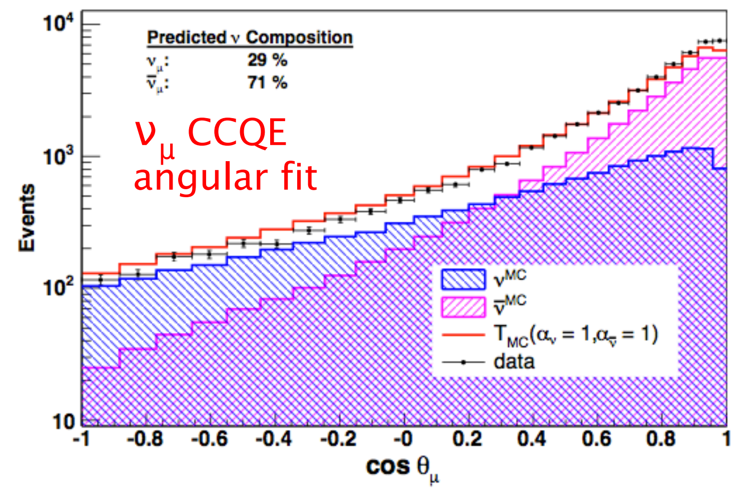


ν_μ flux through detector (ν mode)

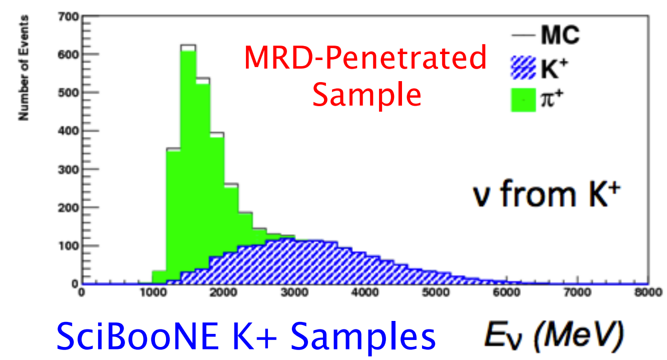


- *In situ* measurement of WS contamination in anti-ν beam Phys.Rev.D84,072005 (2011)
  - ν_μ CCQE angular fit, and new constraint from CCπ+ rate...good agreement with expectation

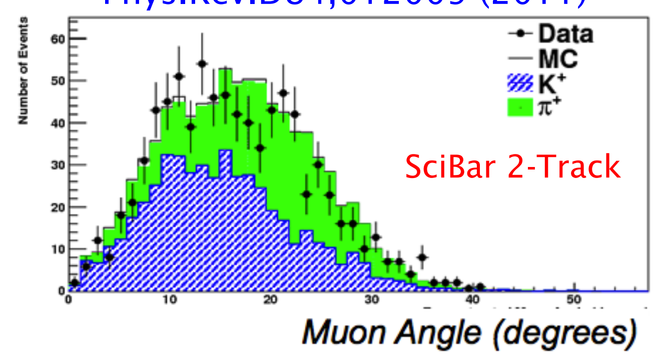




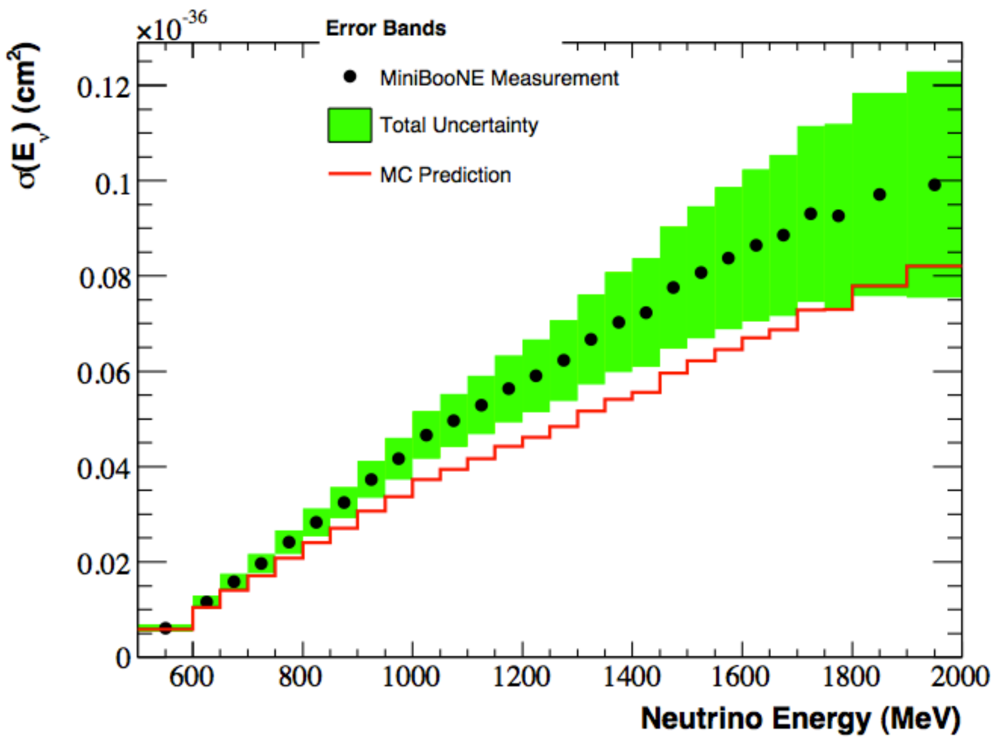
- New SciBooNE constraint on intrinsic ν_e from K+
  - Found K+ production to be 0.85 ± 0.12 relative to prediction, consistent with prior MiniBooNE assessment of 1.00 ± 0.30
  - Combined with world K+ production data, reduces error on K+ flux to 9% in MB Eν range
  - Leading error on K+ bkgs becomes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



SciBooNE K+ Samples
Phys.Rev.D84,012009 (2011)

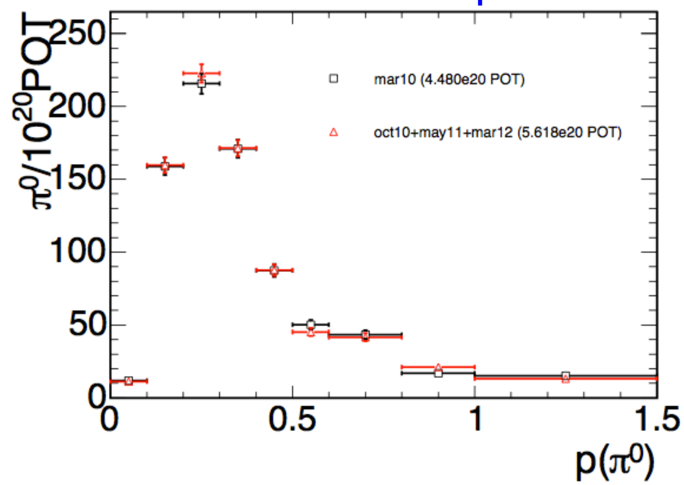


- Few other minor updates…
  - Added error matrix for intrinsic ν_e from K-
  - Improved smoothing algorithm that was being used to assess systematics due to discriminator thresholds and PMT response
  - CCπ+ events (bkg for ν_μ CCQE when π+ is absorbed) Q^2 reweighting applied based on internal MB measurement…Phys.Rev.D83,052007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

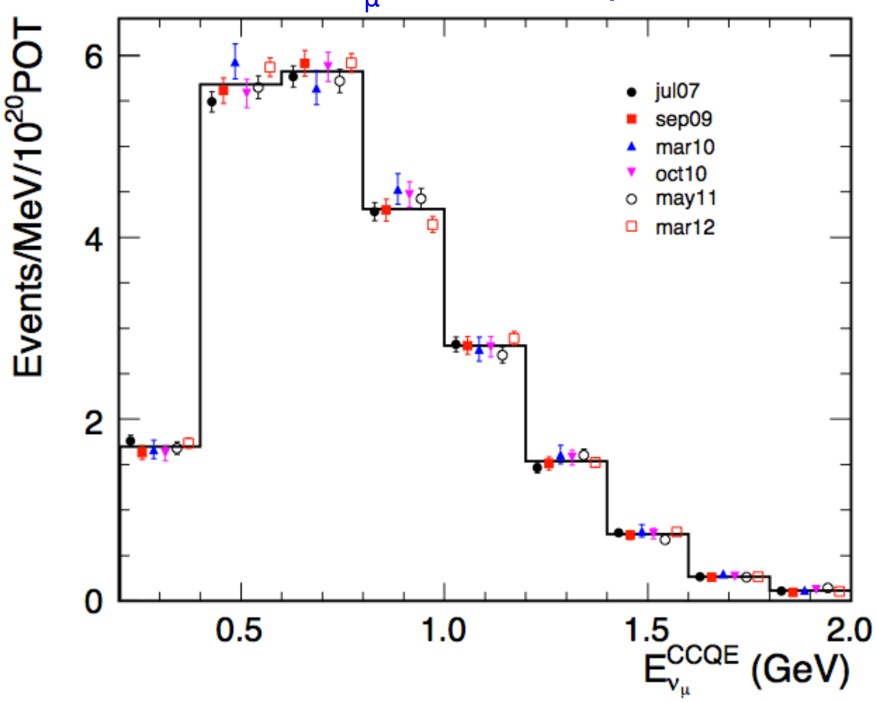


- Statistics of anti-neutrino running has doubled since Phys.Rev.Lett.105 181801 (2010)
  - 5.66e20 POT --> 11.3e20 POT
  - higher statistics in anti-ν_e appearance
  - ...and samples used for constraints

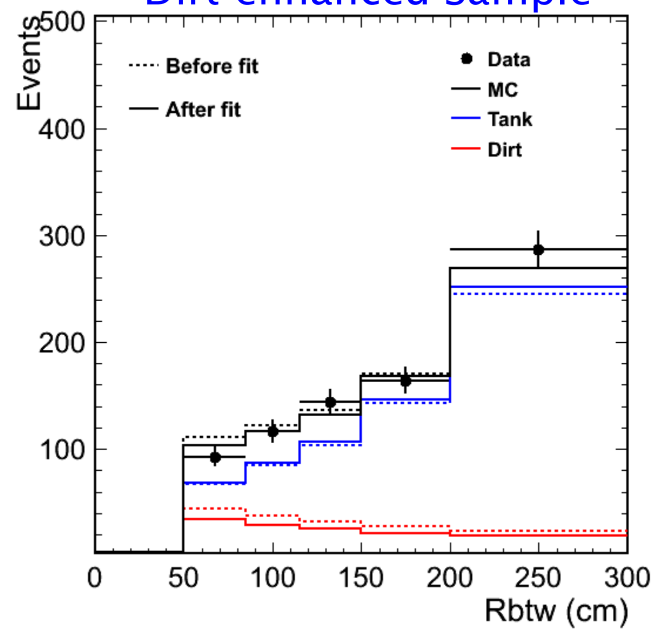
NC π^0 Sample

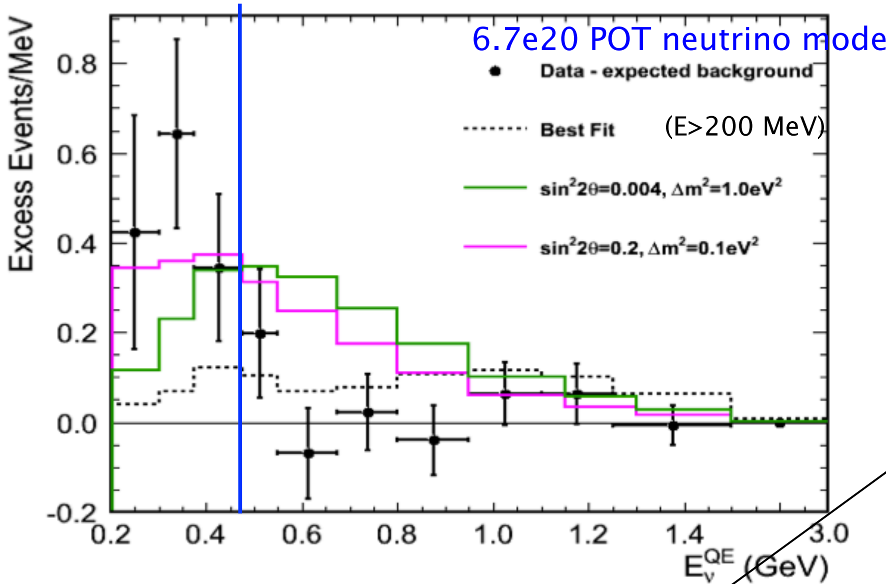


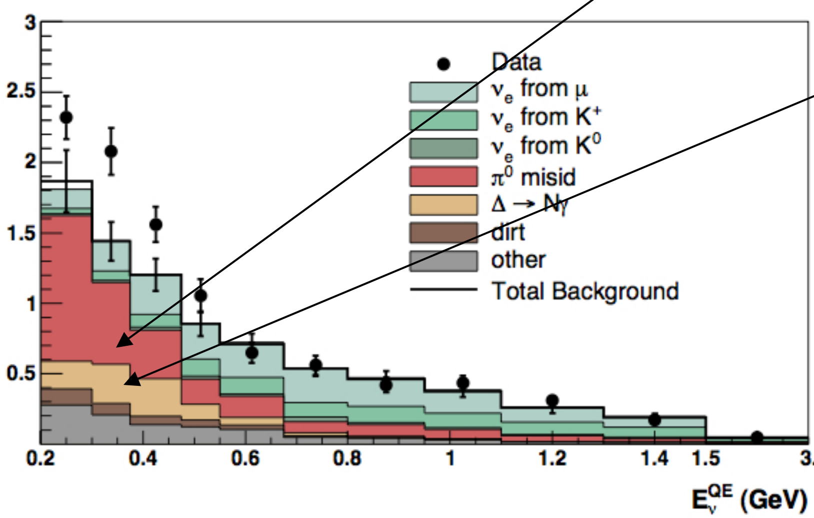
anti-ν_μ CCQE Sample



Dirt-enhanced Sample







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

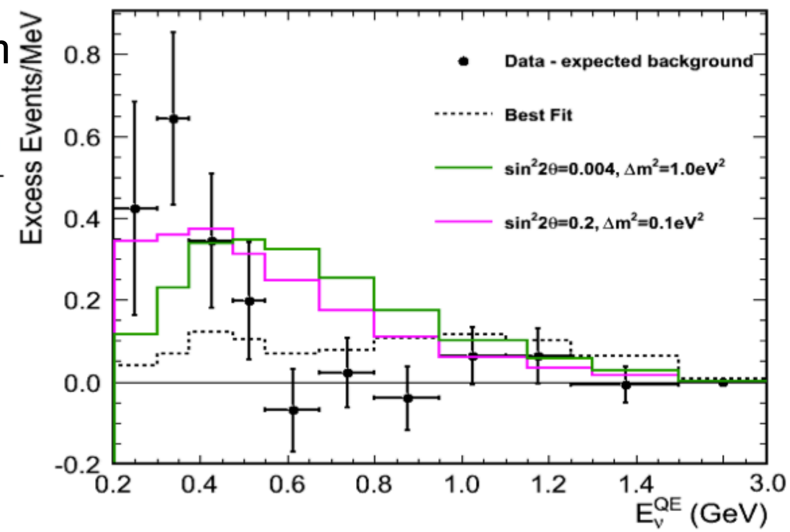
Jenkins & Goldman, arXiv:0906.0984

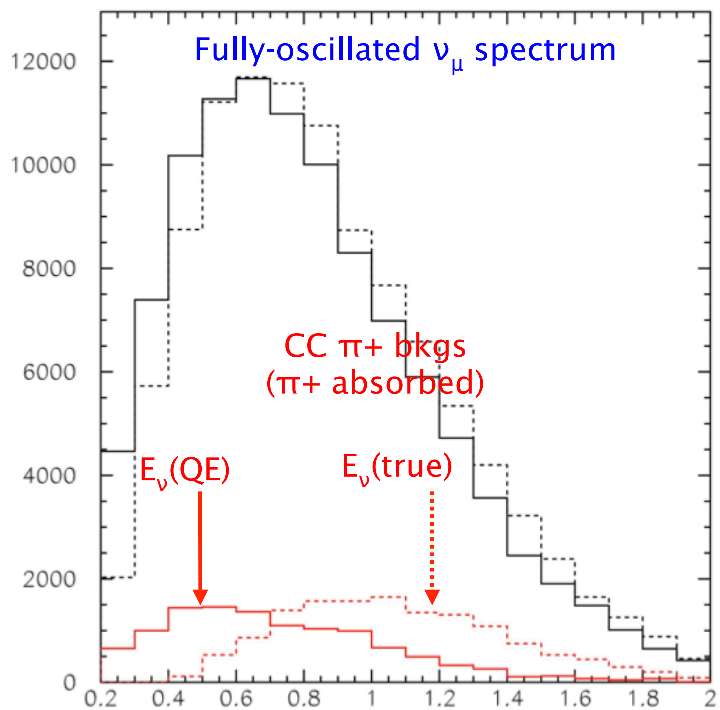
Serot & Zhang, arXiv:1011.5913

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)

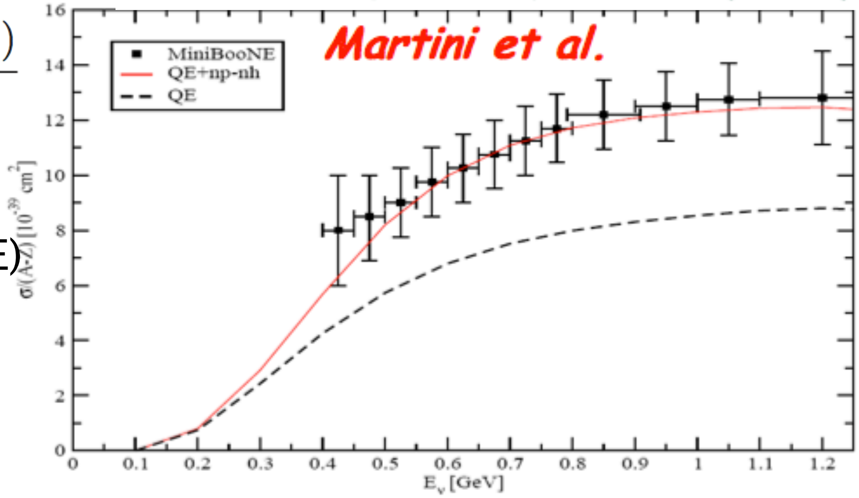
Something to consider...

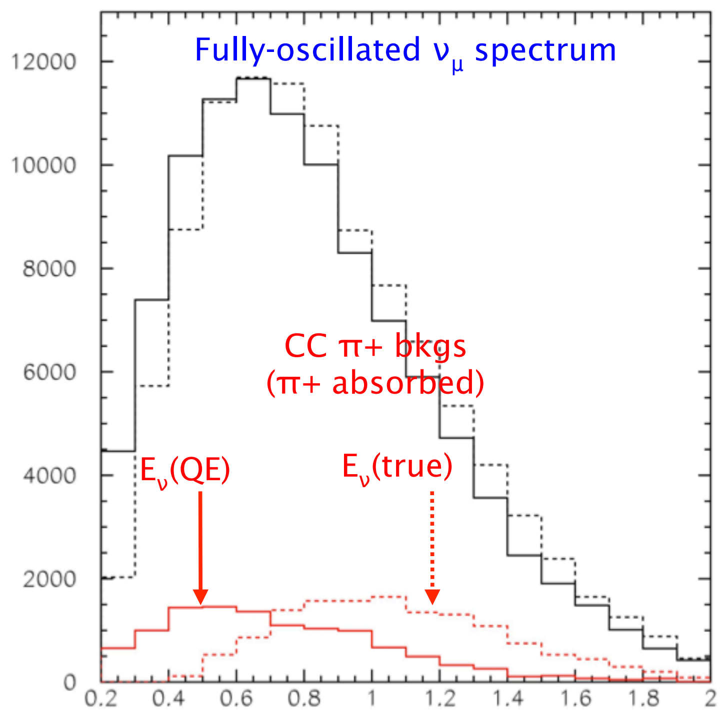
- This plot assumes CCQE-like reconstruction

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

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

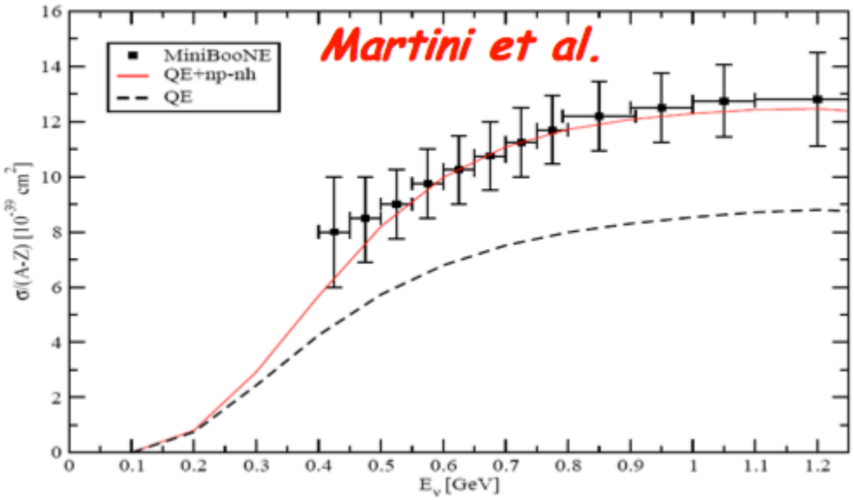
Martini *et al.*, PRC **80**, 065001 (2009)

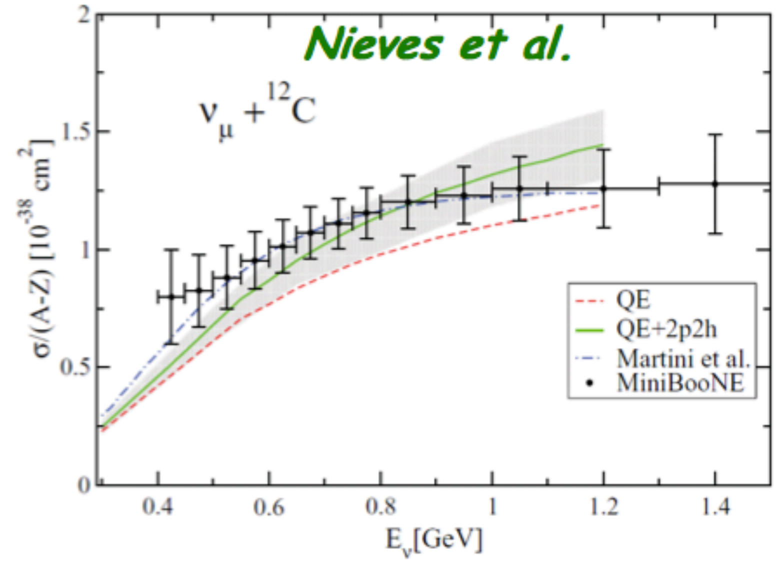


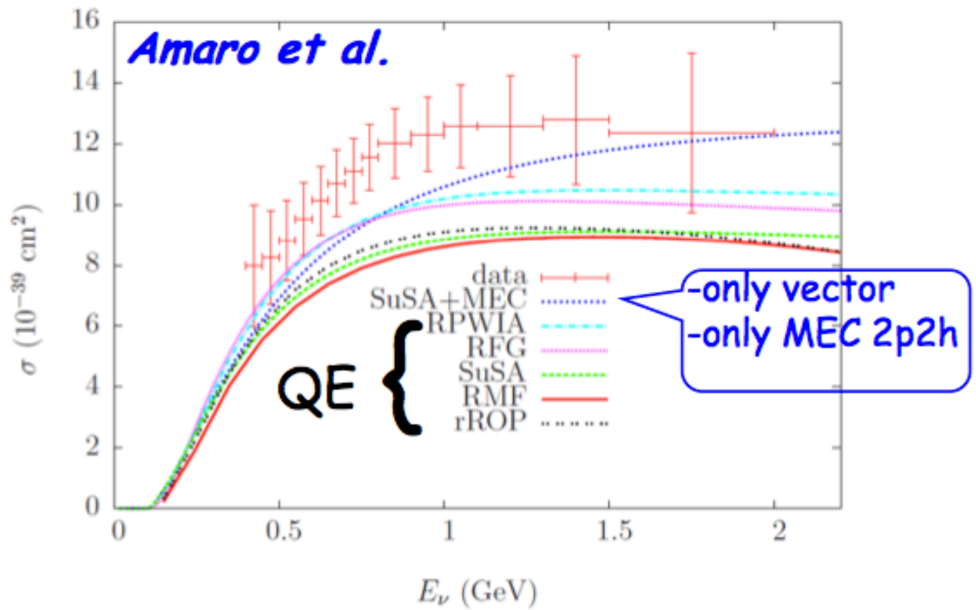


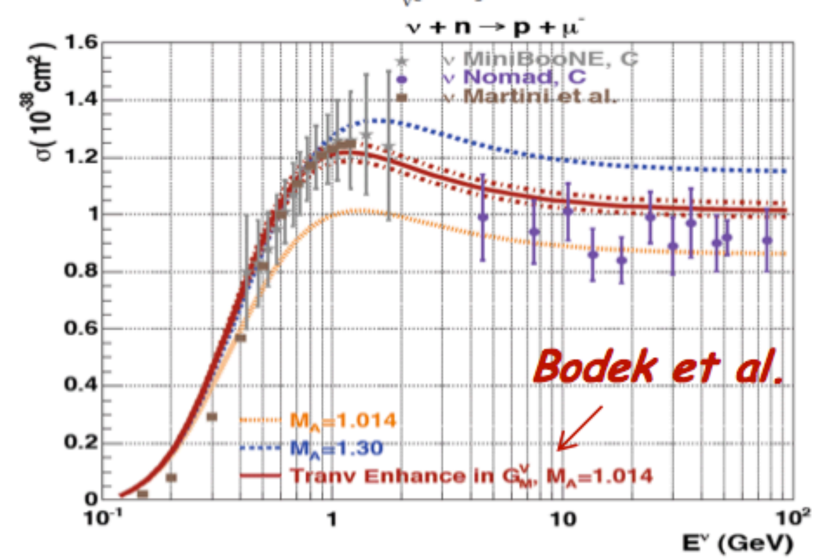
- MiniBooNE finds a cross-section for ν_μ CCQE that is 20-30% higher than expected
- Number of theorists suggesting this could arise from multi-nucleon correlations, observed many years ago in e-scattering
- Could help explain why MB xsec is higher than free nucleon, differences between expts where event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

Comparison between models including np-nh

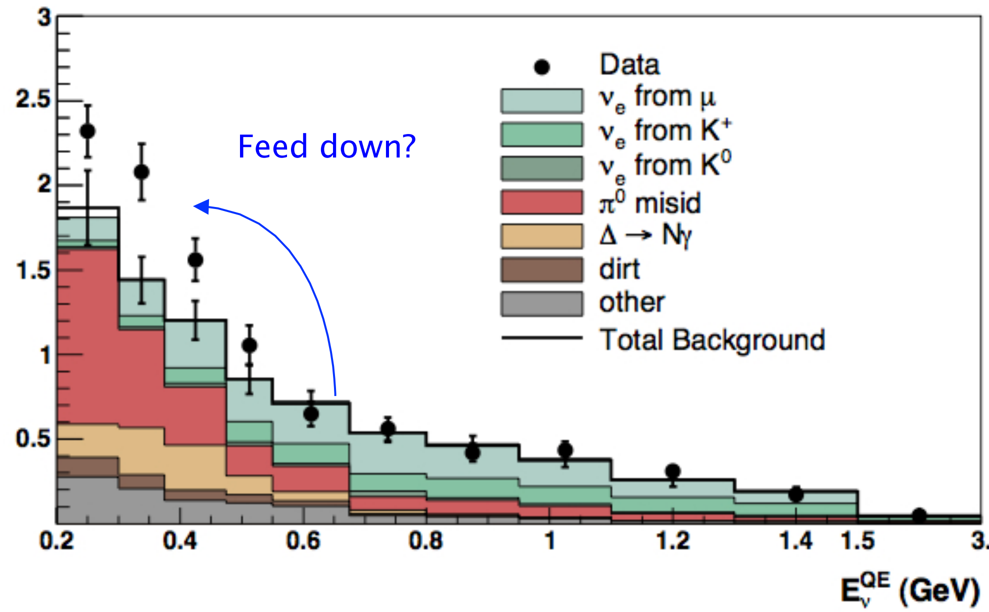


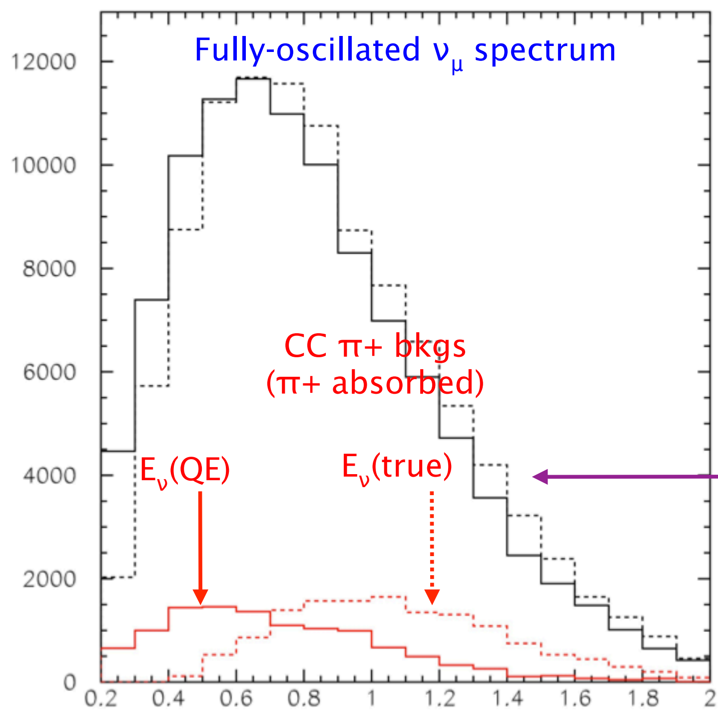






Relevant for oscillation analysis?



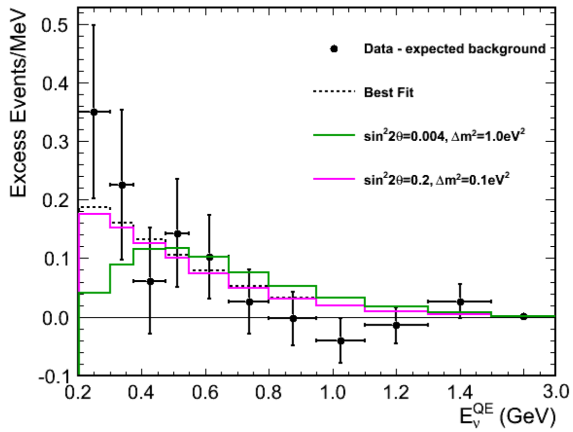


- Means a fraction of oscillated ν_e could be misreconstructed (similar to CCπ+ case)
- Could feed down help relax tension between low and mid range energies?
- Possible, but MiniBooNE corrects sig/bkg predictions based on the measured ν_μ spectrum
- Studies where we double the π+ absorption rate, and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

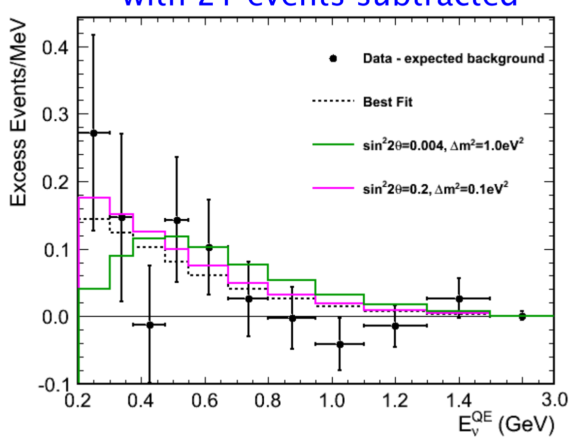
Account for neutrino low-E events

- 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)

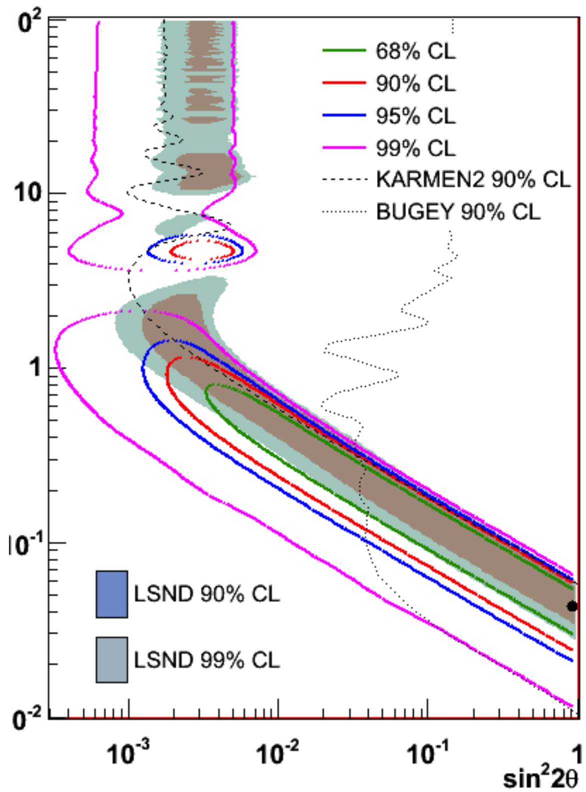
without 21 events subtracted



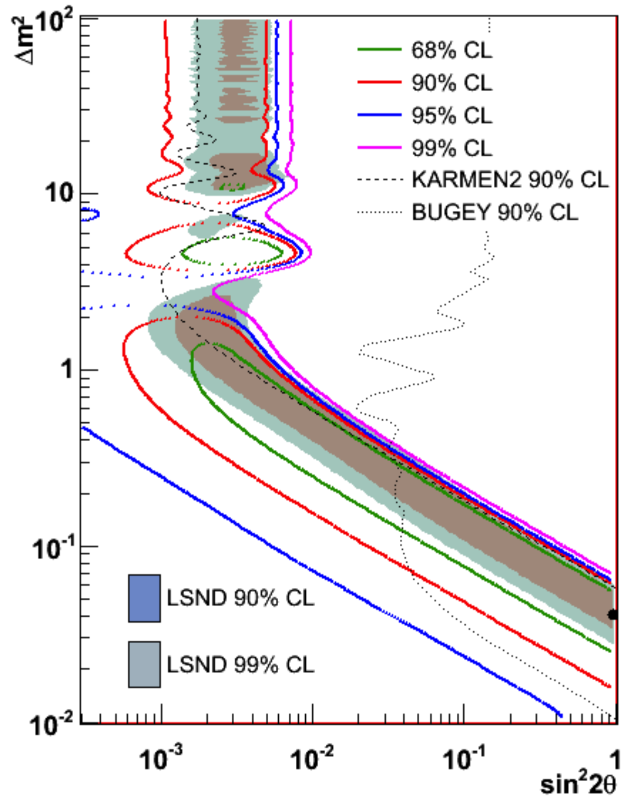
with 21 events subtracted



without 21 events subtracted



with 21 events subtracted



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

Reanalysis of Reactor Experiments

result	Det. type	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
Bugey-4	^{3}He+H_2O	888.7	0.538	0.328	0.078	0.056	0.987	0.926	3.0	3.0	15
ROVNO91	^{3}He+H_2O	888.6	0.614	0.274	0.074	0.038	0.985	0.924	3.9	3.0	18
Bugey-3-I	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.988	0.930	4.8	4.8	15
Bugey-3-II	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.994	0.936	4.9	4.8	40
Bugey-3-III	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.915	0.861	14.1	4.8	95
Goesgen-I	^{3}He+LS	897	0.620	0.274	0.074	0.042	1.018	0.949	6.5	6.0	38
Goesgen-II	^{3}He+LS	897	0.584	0.298	0.068	0.050	1.045	0.975	6.5	6.0	45
Goesgen-II	^{3}He+LS	897	0.543	0.329	0.070	0.058	0.975	0.909	7.6	6.0	65
ILL	^{3}He+LS	889	$\simeq 1$	—	—	—	0.832	0.7882	9.5	6.0	9
Krasn. I	^{3}He+PE	899	$\simeq 1$	—	—	—	1.013	0.920	5.8	4.9	33
Krasn. II	^{3}He+PE	899	$\simeq 1$	—	—	—	1.031	0.937	20.3	4.9	92
Krasn. III	^{3}He+PE	899	$\simeq 1$	—	—	—	0.989	0.931	4.9	4.9	57
SRP I	Gd-LS	887	$\simeq 1$	—	—	—	0.987	0.936	3.7	3.7	18
SRP II	Gd-LS	887	$\simeq 1$	—	—	—	1.055	1.001	3.8	3.7	24
ROVNO88-1I	^{3}He+PE	898.8	0.607	0.277	0.074	0.042	0.969	0.901	6.9	6.9	18
ROVNO88-2I	^{3}He+PE	898.8	0.603	0.276	0.076	0.045	1.001	0.932	6.9	6.9	18
ROVNO88-1S	Gd-LS	898.8	0.606	0.277	0.074	0.043	1.026	0.955	7.8	7.2	18
ROVNO88-2S	Gd-LS	898.8	0.557	0.313	0.076	0.054	1.013	0.943	7.8	7.2	25
ROVNO88-3S	Gd-LS	898.8	0.606	0.274	0.074	0.046	0.990	0.922	7.2	7.2	18

PRD83, 073006 (2011)