Significant Excess of Electron-Like Events from the MiniBooNE Short-Baseline Neutrino Experiment

W. C. Louis, LANL

August 2, 2018

- LSND Electron-Neutrino Appearance Results
- MiniBooNE Detector & BNB Neutrino Flux
- MiniBooNE Stability & Data/MC Agreement
- MiniBooNE Electron-Neutrino Appearance Results
- Allowed Regions for 2-Neutrino Oscillation Model
- Tension Between Appearance & Disappearance Results
- More Exotic Scenarios
- SBN Program at Fermilab
- CAPTAIN-Mills Experiment at LANL
- Conclusions

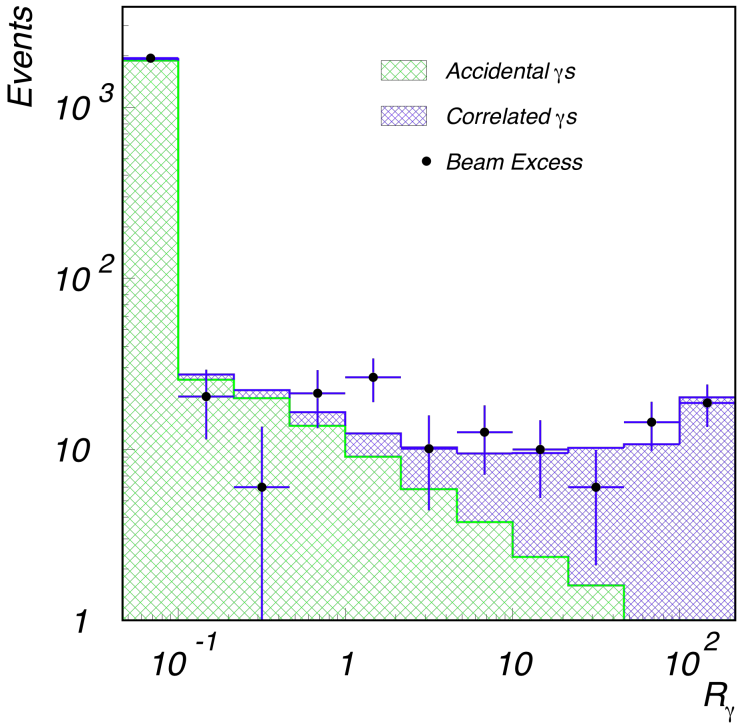
I thank in advance the slides from colleagues and from recent conferences!

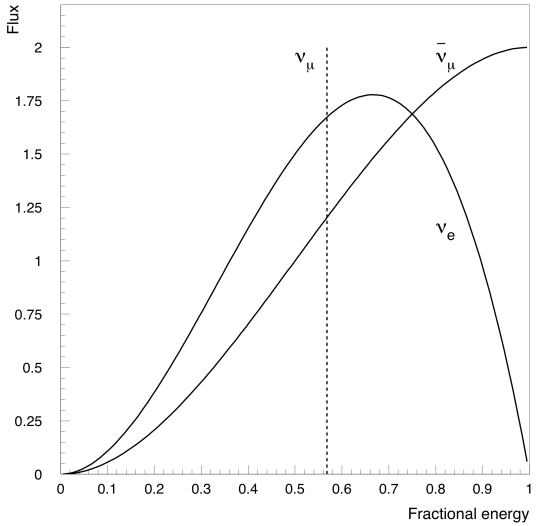
arXiv:1805.12028

LSND Event Excess

A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)

Correlated γ = 117.9+-22.4 events
Excess = 87.9+-22.4+-6.0 events



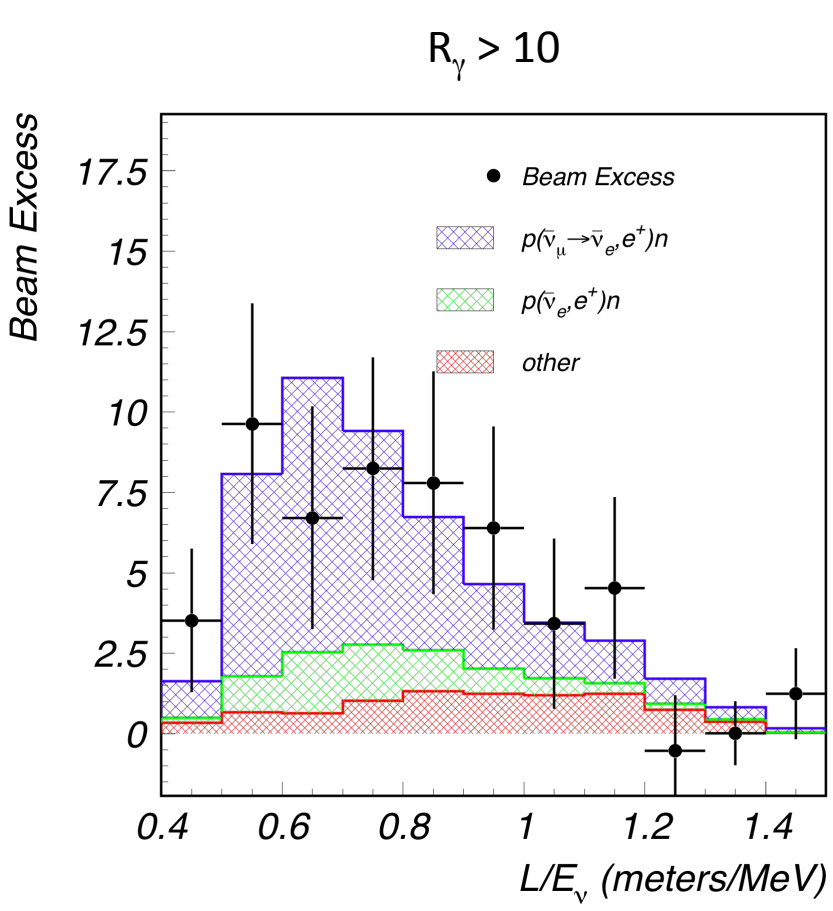


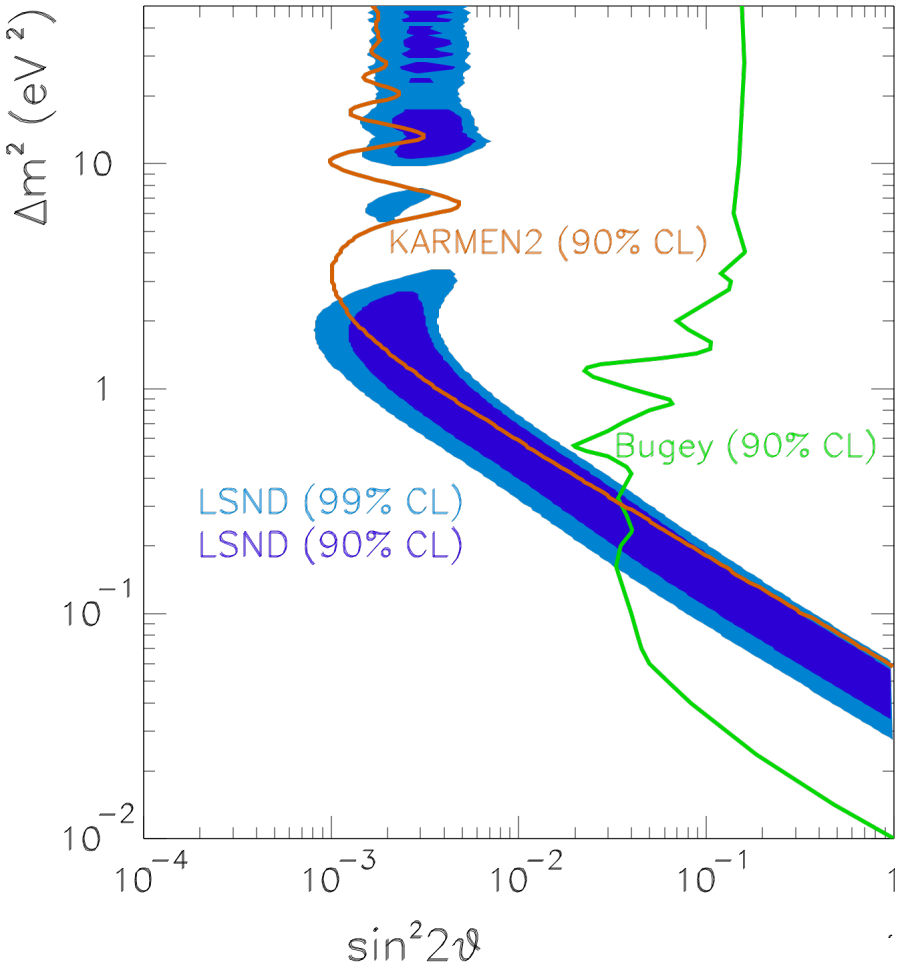
$\overline{\nu}_e$ p -> e^+ n, n p -> d γ(2.2 MeV)

LSND collected 28,896 C of protons on target and observed a 3.8 σ excess of events
Consistent with $\overline{\nu}_\mu$ -> $\overline{\nu}_e$ oscillations, corresponding to P_{osc} = (0.264+-0.067+-0.045)%

LSND Event Excesses

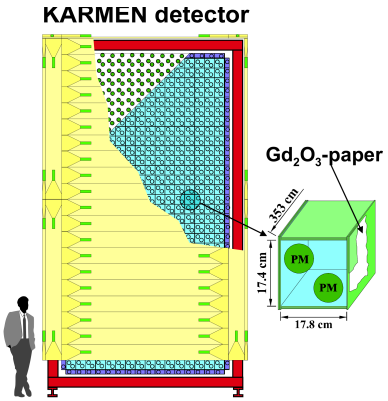
A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)





Joint LSND/KARMEN Analysis

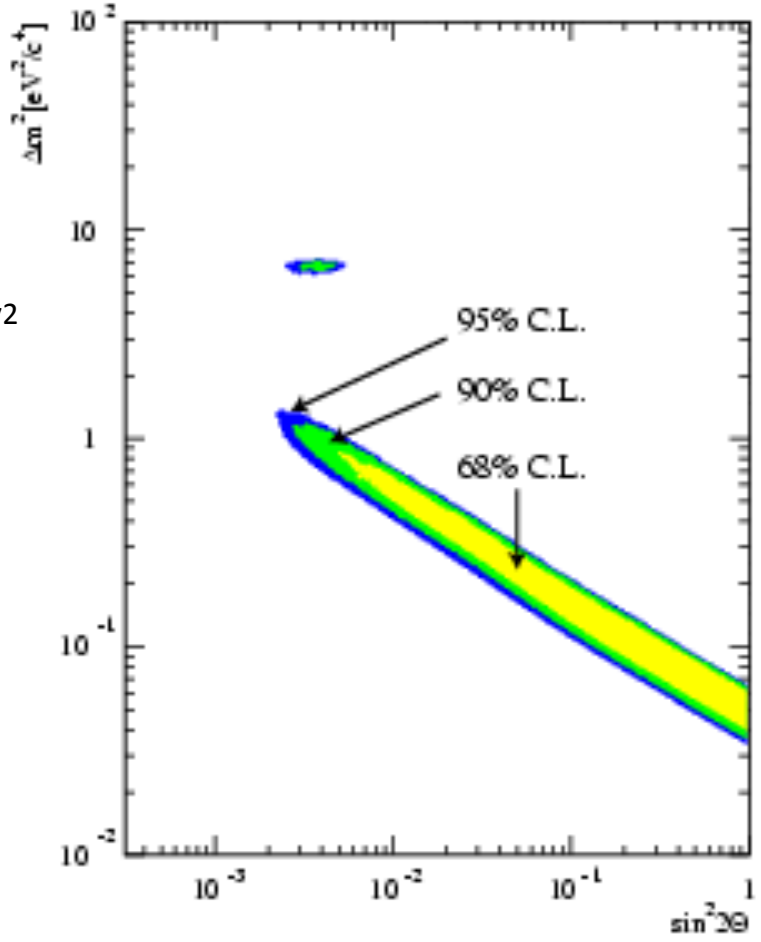
E. D. Church, K. Eitel, G. B. Mills, and M. Steidl, Phys. Rev. D66, 013001, (2002)

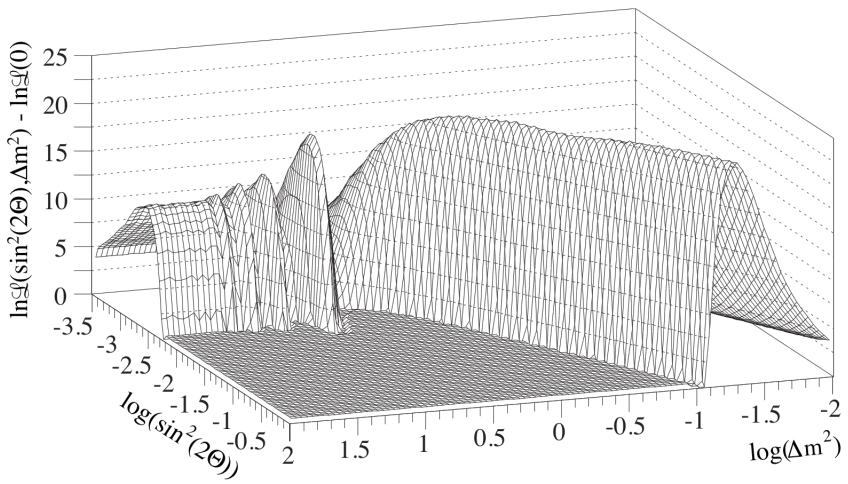


96% active volume of ^{12}C and p

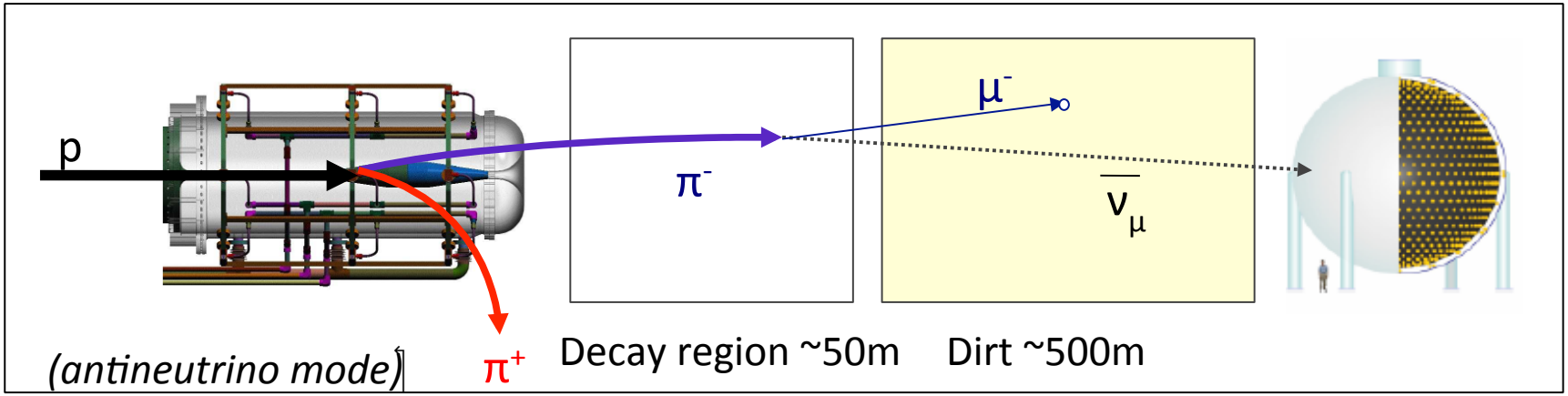
$$E \quad \frac{11.5\%}{\sqrt{E[MeV]}} \qquad t_{ISIS} \quad 2ns$$

KARMEN observed no event excess; however, a joint analysis of KARMEN (17.7m) & LSND (30m) reveals a favored region of $\Delta m^2 < 2\ eV^2$





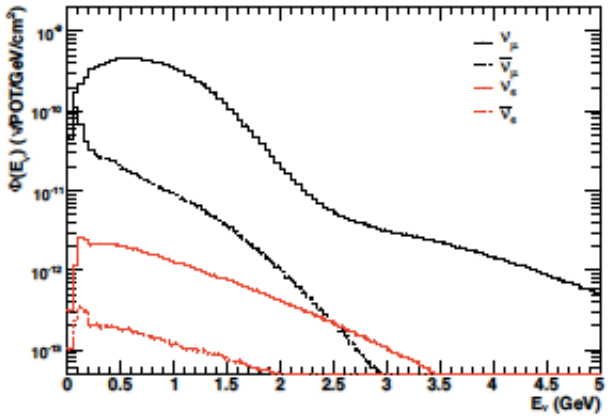
MiniBooNE Experiment



- Similar L/E as LSND for $\overline{\nu}_\mu$ -> $\overline{\nu}_e$ & ν_μ -> ν_e oscillations
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

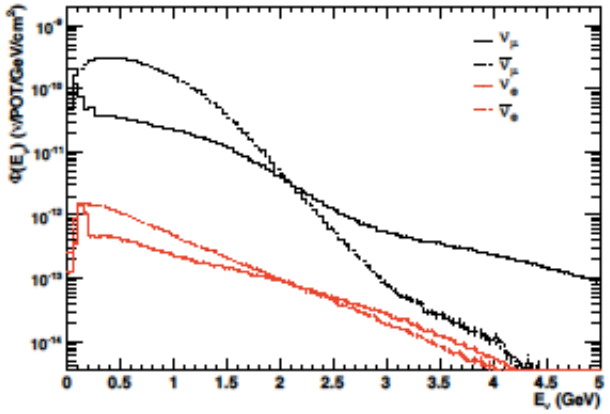
Booster Neutrino Beam (BNB)

arXiv:0806.1449v2 [hep-ex]



Neutrino Mode

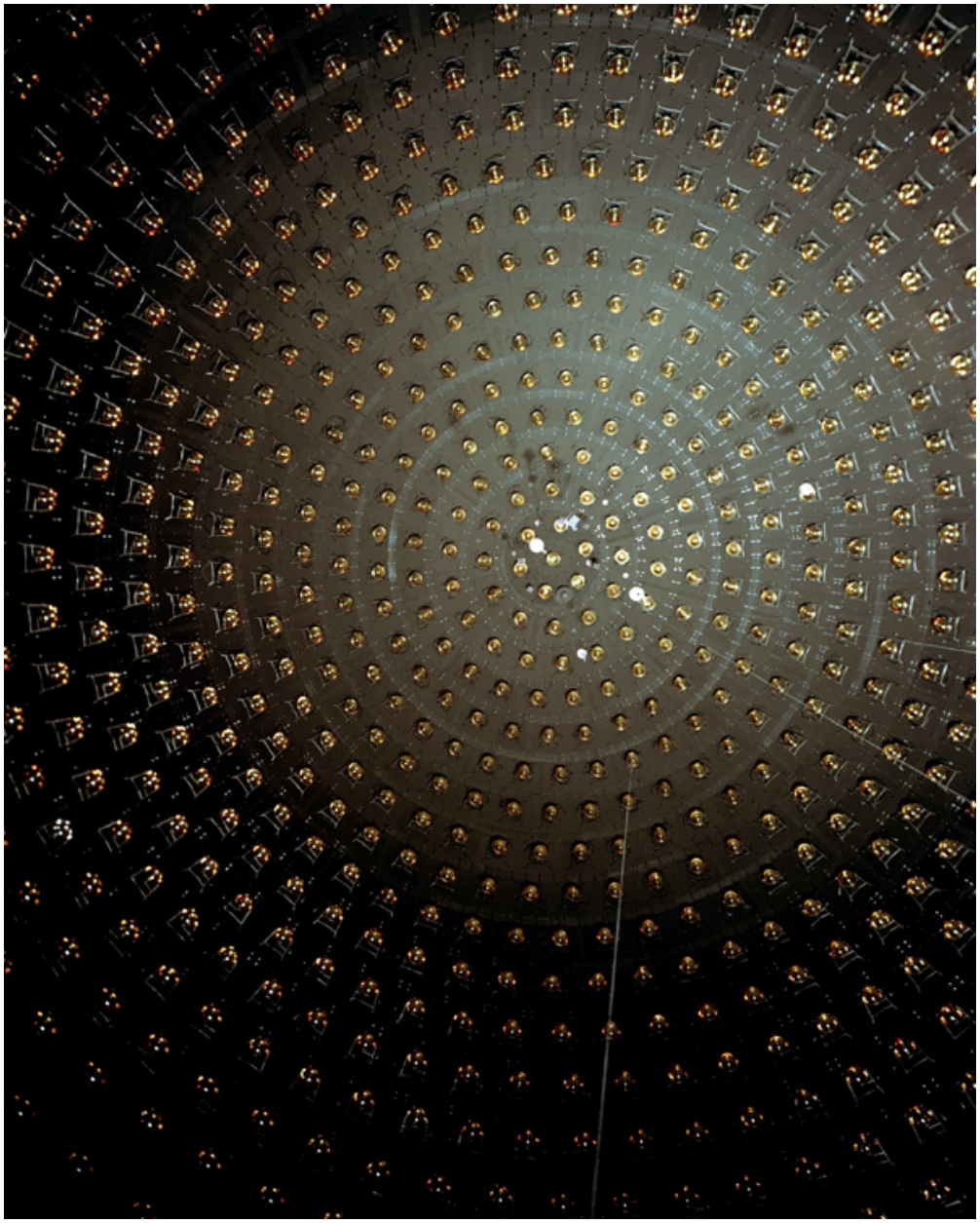
FIG. 27: Total predicted flux at the MiniBooNE detector by neutrino species with horn in neutrino mode.



Antineutrino Mode

FIG. 28: Total predicted flux at the MiniBooNE detector by neutrino species with horn in anti-neutrino mode.

MiniBooNE Detector Tank



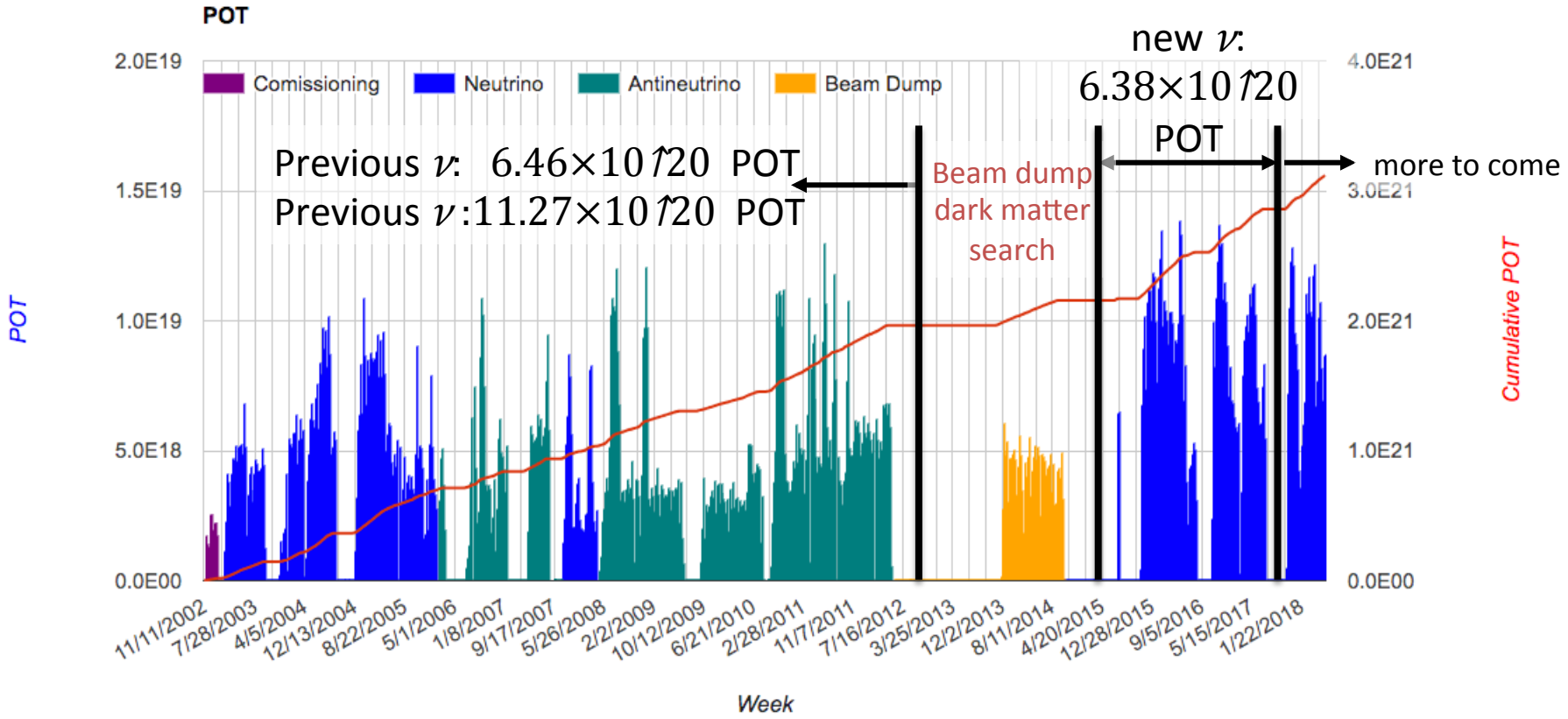
800 tons of mineral oil

10% Photocathode
coverage with 8” Hamamatsu
Phototubes: R1408, R5912

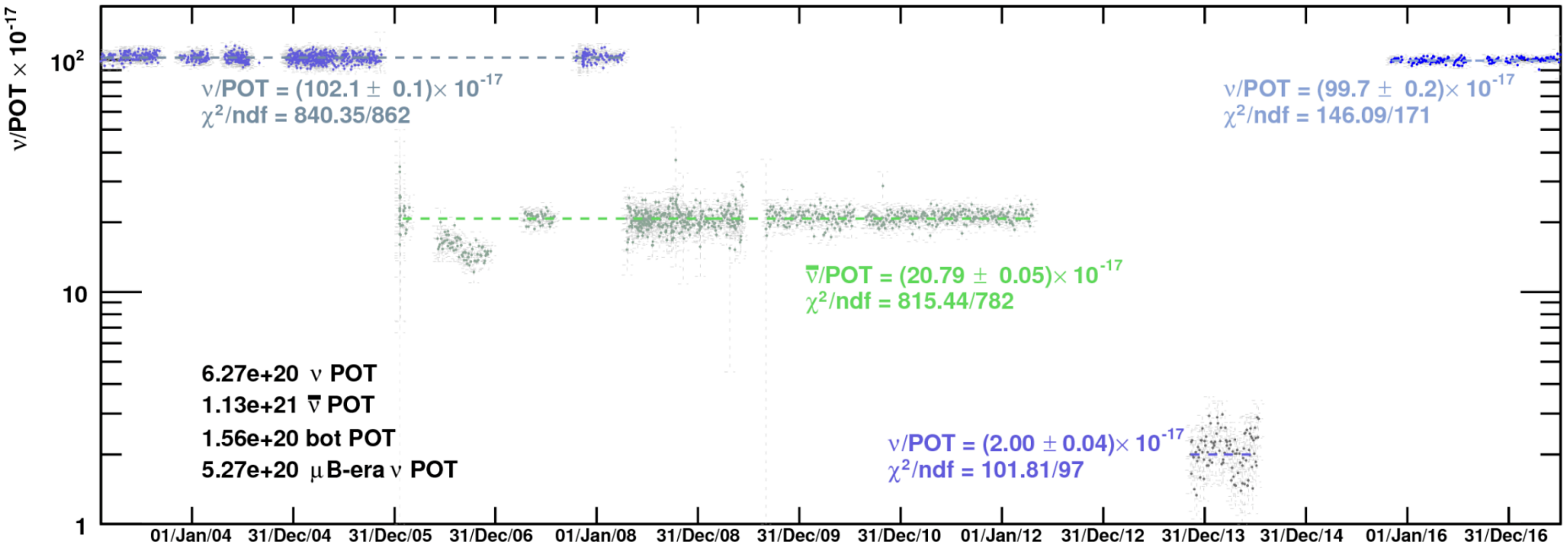
Charge Resolution:
1.4 PE, 0.5 PE
Time Resolution:
1.7 ns, 1.1ns

MiniBooNE Data Set

- 15+ years of running in neutrino, antineutrino, and beam dump mode. More POT to date.
- Result of a combined POT in mode + POT in mode is presented in this talk.

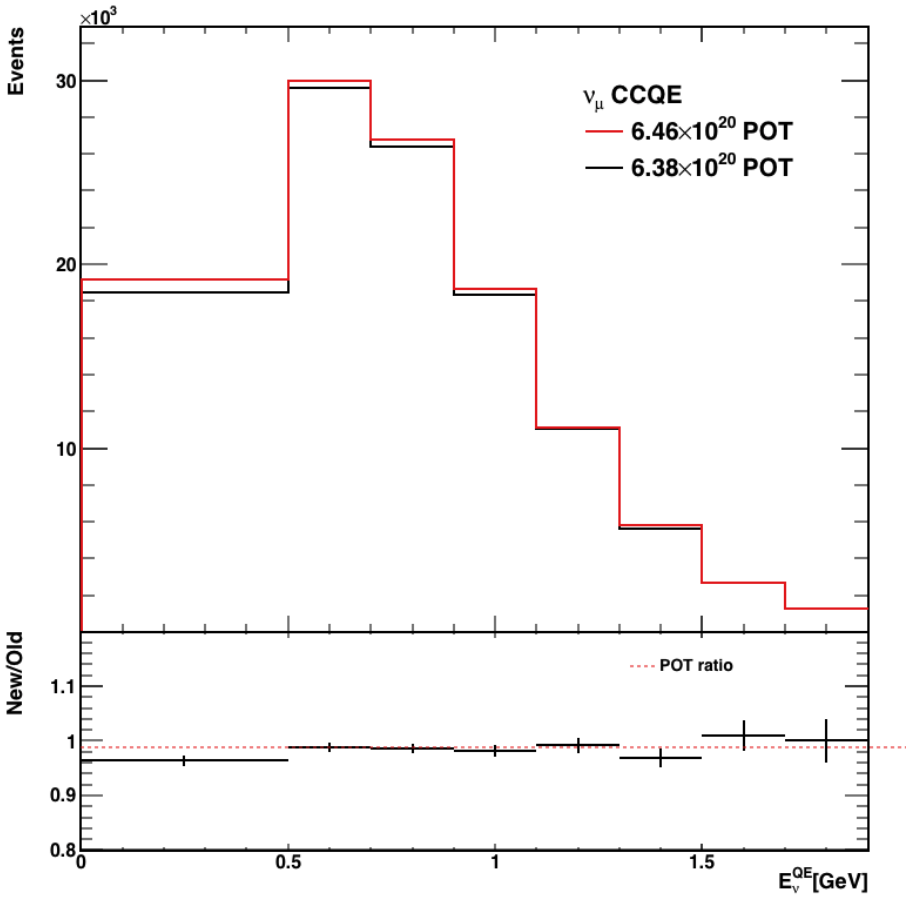


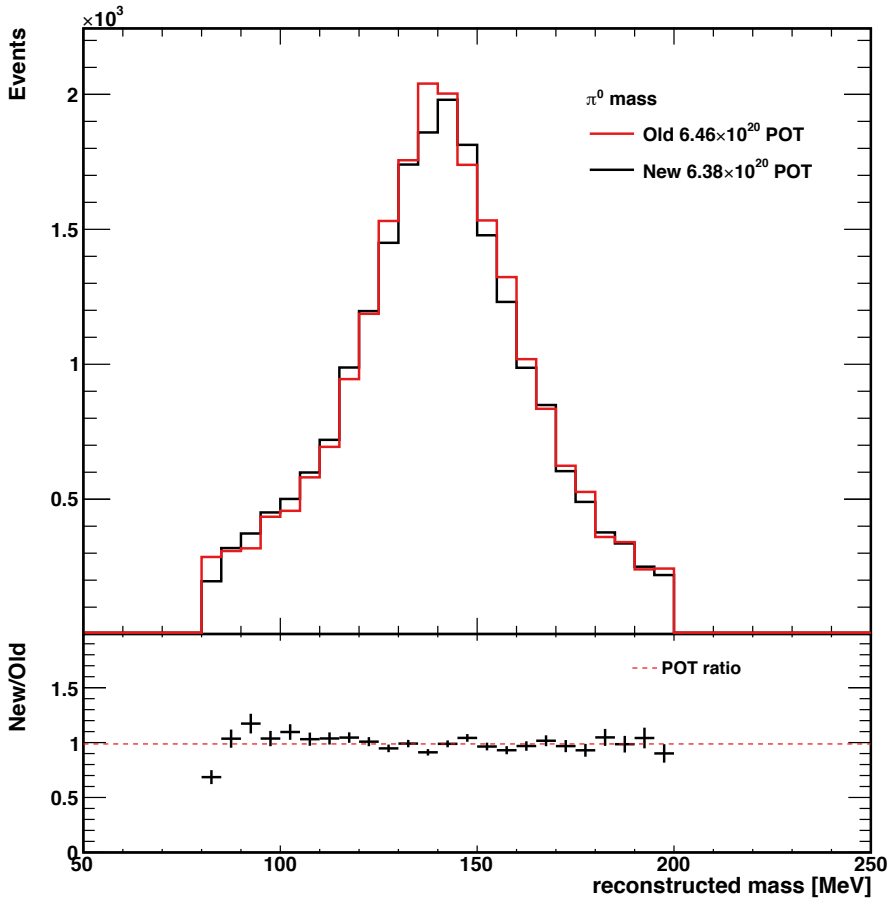
Neutrino Events/POT



- ν/POT remains stable

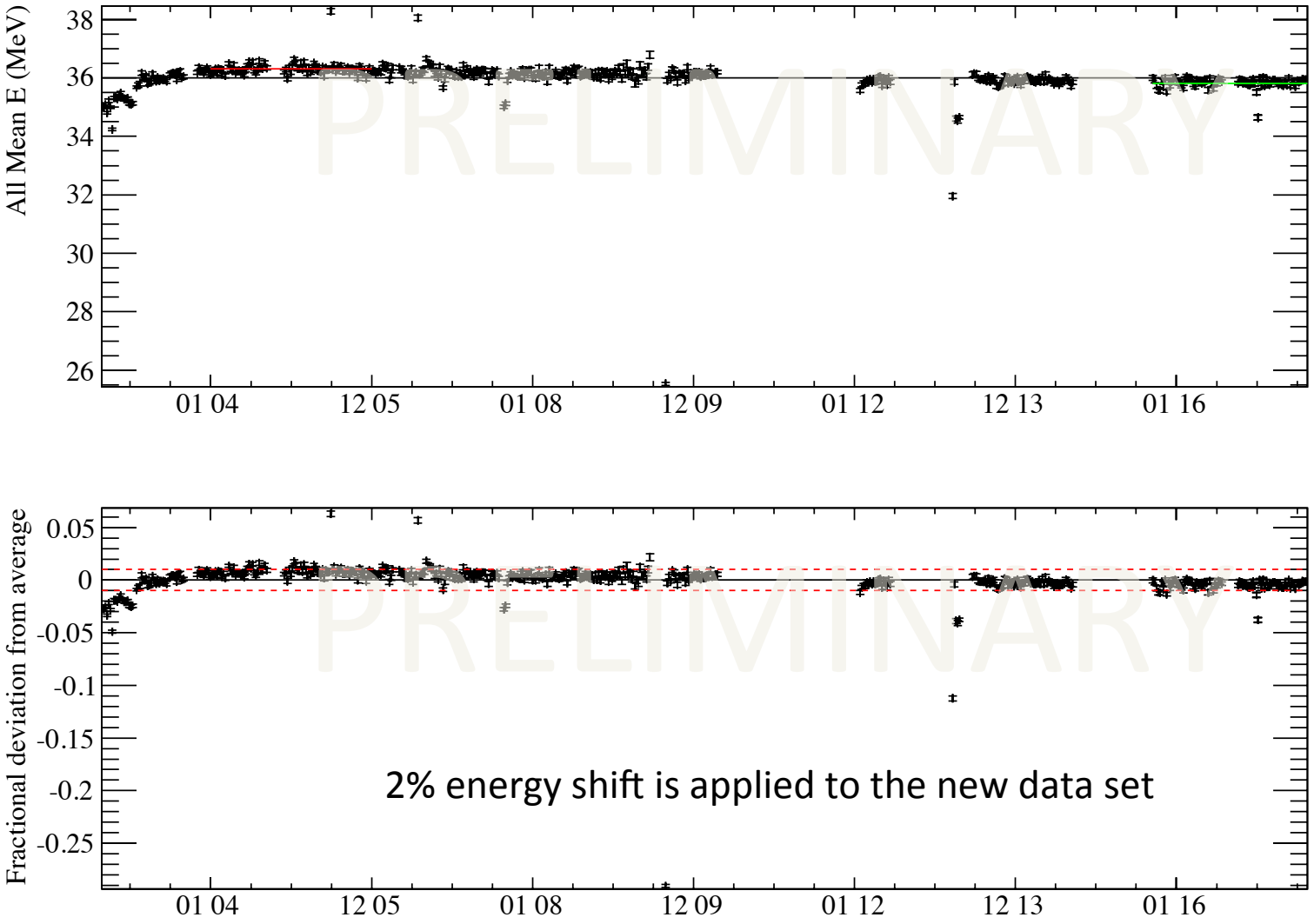
Detector & BNB Stability





- Detector remains stable within 2% for data sets separated by ~8 years
- Similar check is done for Michel electrons

Michel electron



Good Data vs MC Agreement

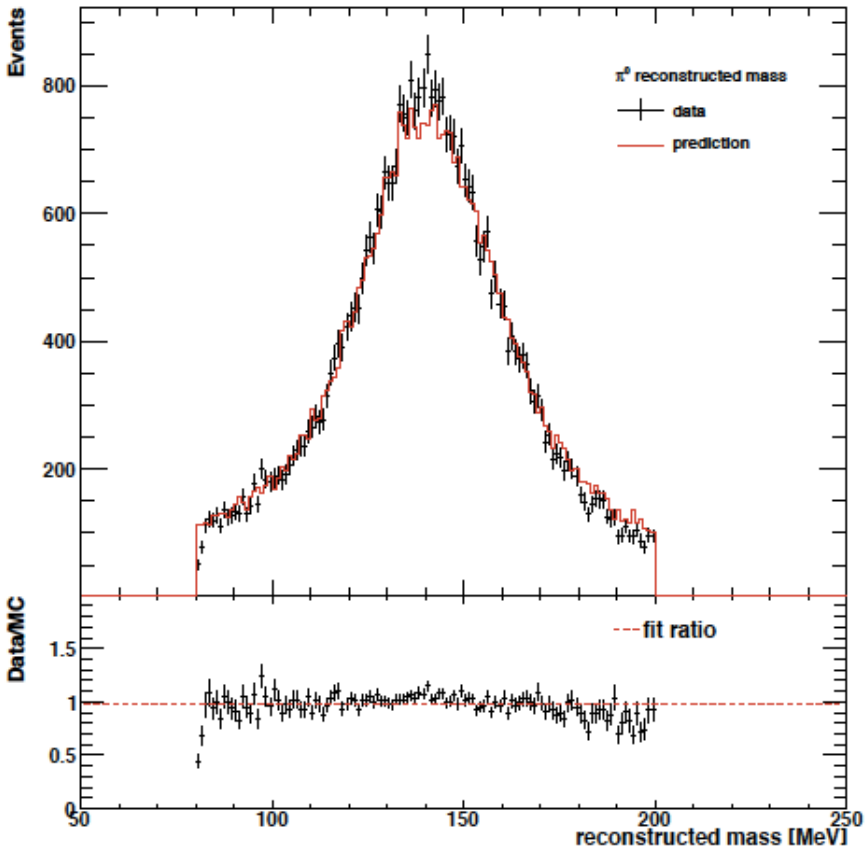


FIG. 7: An absolute comparison of the π^0 reconstructed mass distribution between the neutrino data (12.84×10^{20} POT) and the simulation for NC π^0 events (top). Also shown is the ratio between the data and Monte Carlo simulation (bottom).

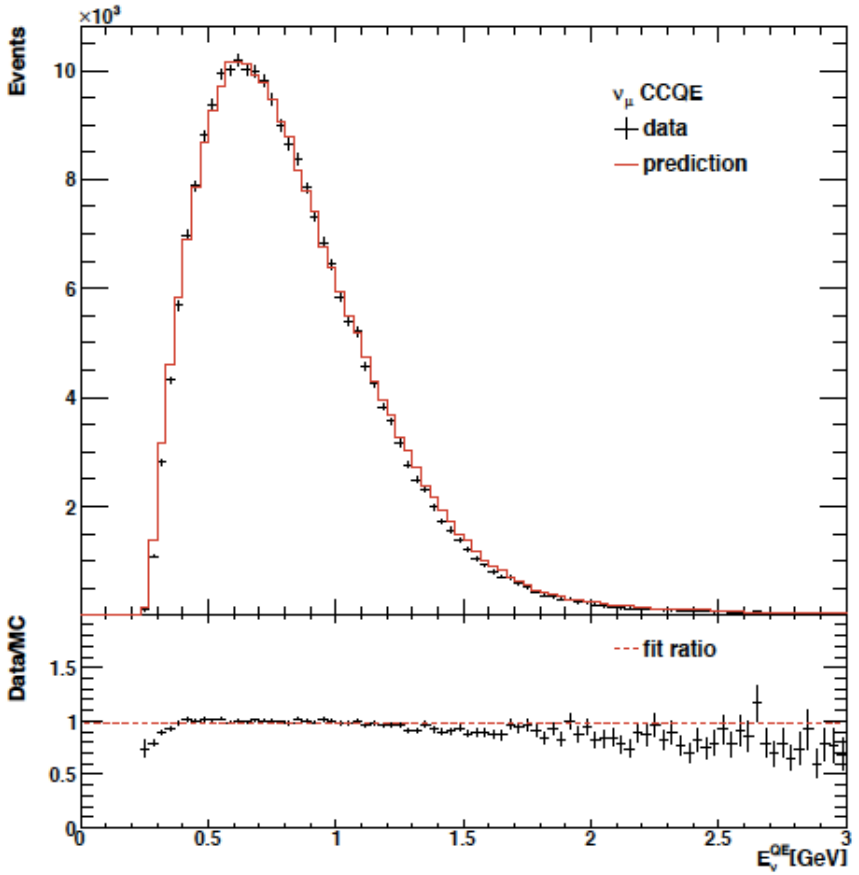
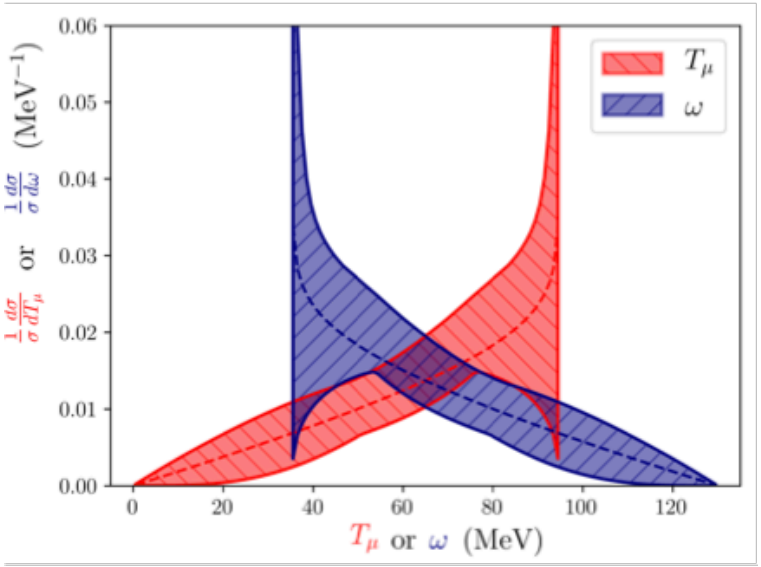


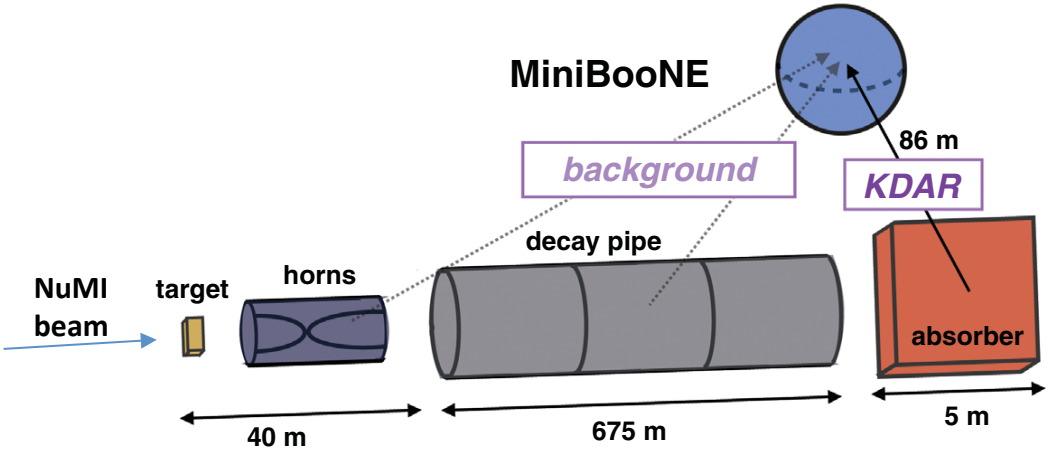
FIG. 8: An absolute comparison of the reconstructed neutrino energy distribution for CCQE events between the neutrino data (12.84×10^{20} POT) and the simulation (top). Also shown is the ratio between the data and Monte Carlo simulation (bottom).

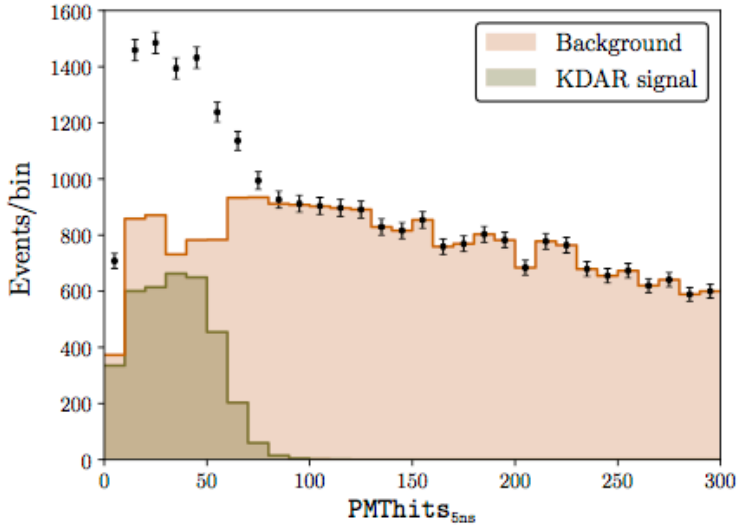
KDAR

"First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions", PRL 120 141802 (2018) (Editor's Suggestion)

- KDAR=Kaon Decay At Rest
- KDAR neutrinos from the NuMI beamline absorber have been isolated based on energy reconstruction and timing.
- First measurement of ω (energy transferred to the nucleus) with a known energy, weak-interaction-only nuclear probe.
- Results provide a standard candle for understanding CC events at a known energy (236 MeV).
- An associated data release website allows any model prediction (or) to be compared with the data.



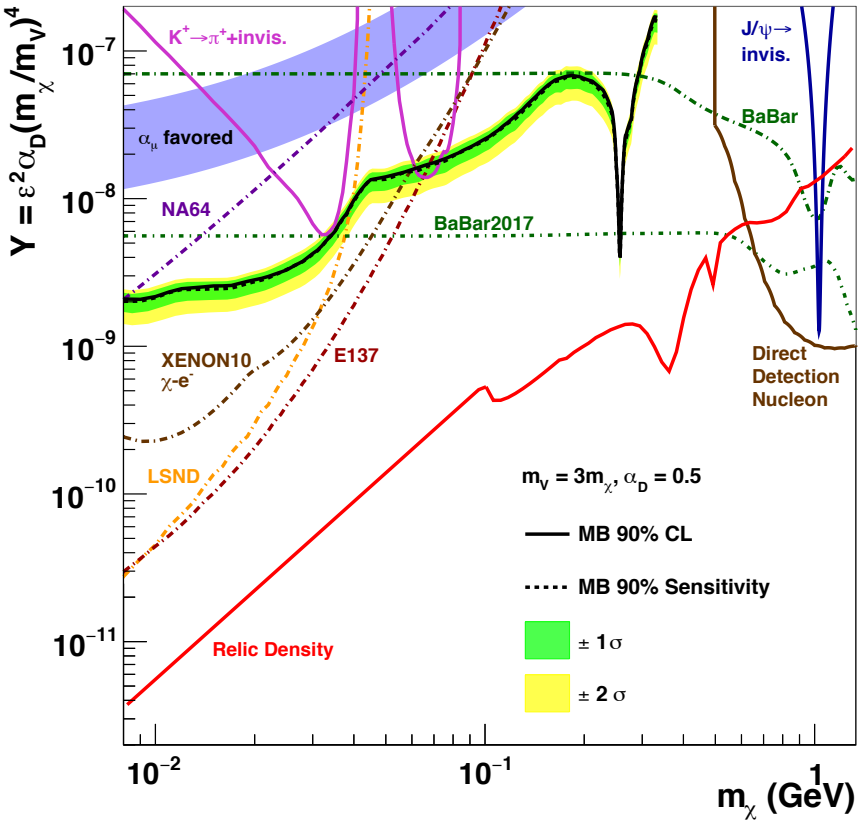


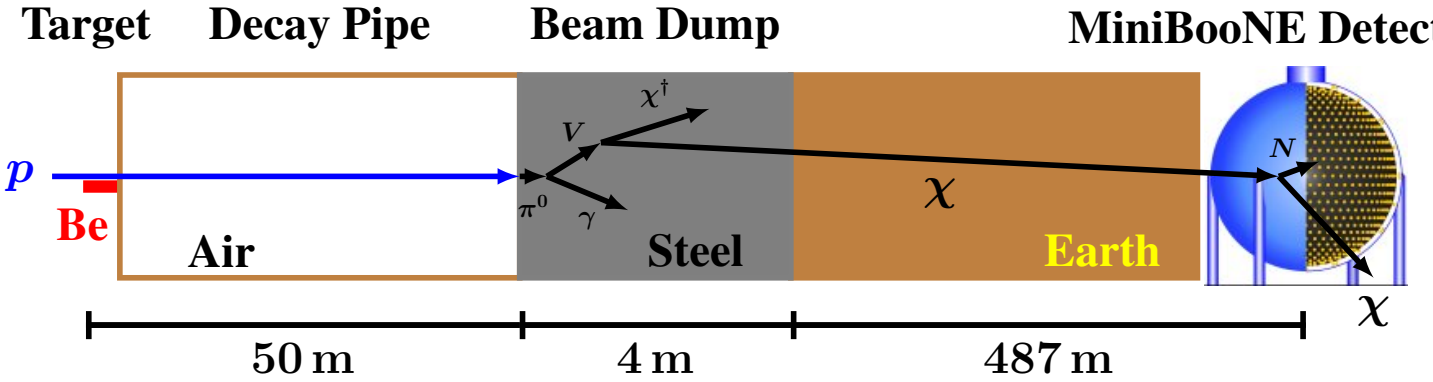


Dark Matter Search in Beam-Dump Mode

PRL 118, 221803 (2017)
Editor's Suggestion

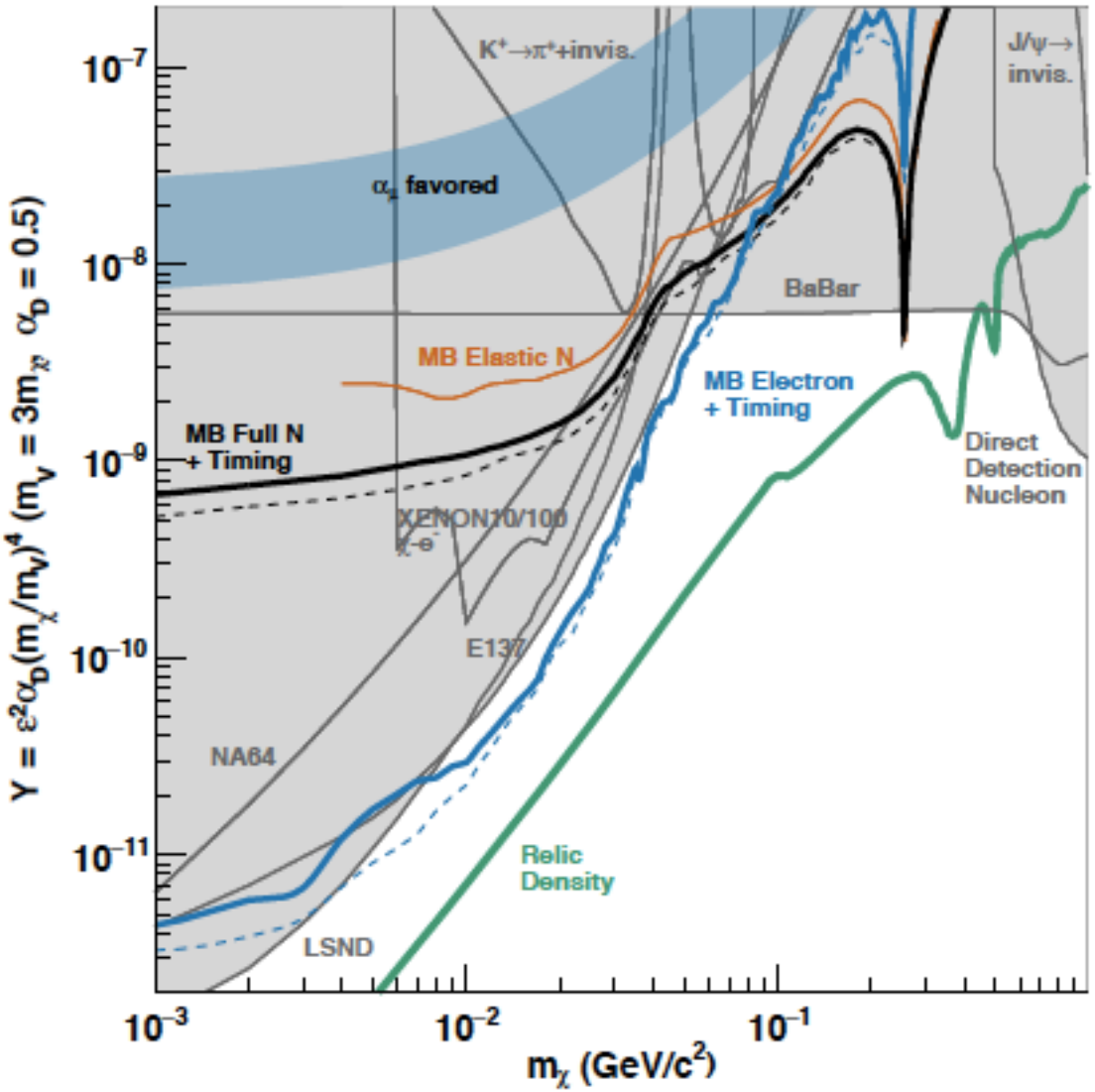
- First dedicated search for direct detection of accelerator-produced dark matter in a proton beamline
  - Searched for the dark matter to elastically scatter off nucleons
- Beam-dump mode reduced the flux by ~50
- The goal was to test **vector portal model** interpretation of g-2 (ruled out)
- At time of publication: set world leading limits in the vector portal dark matter model with a dark matter mass between 0.01 and 0.3 GeV
- New results are expected later in 2018
  - Inelastic scatter to produce s through decay
  - Elastic scattering off electrons





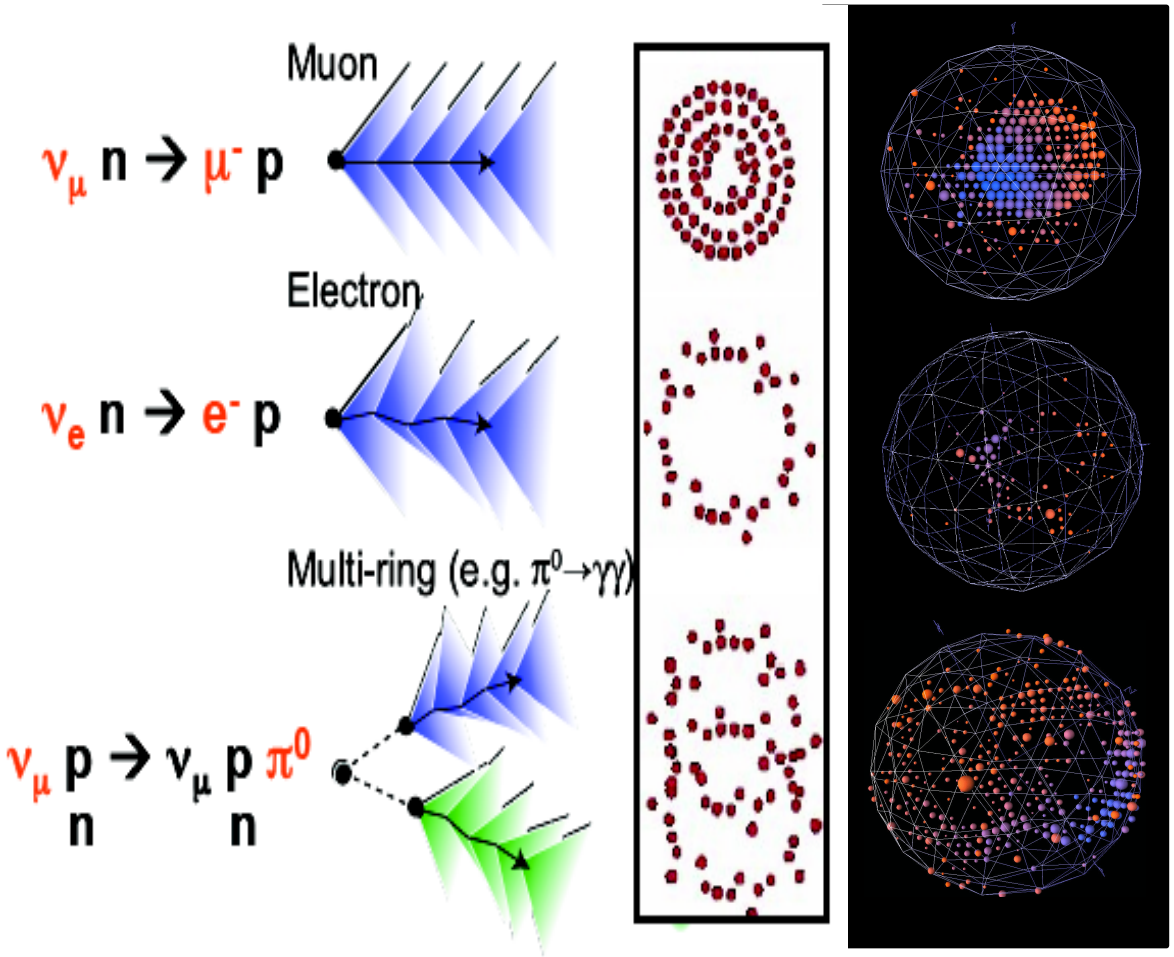
New Limits with Electron Events

arXiv:1807.06137



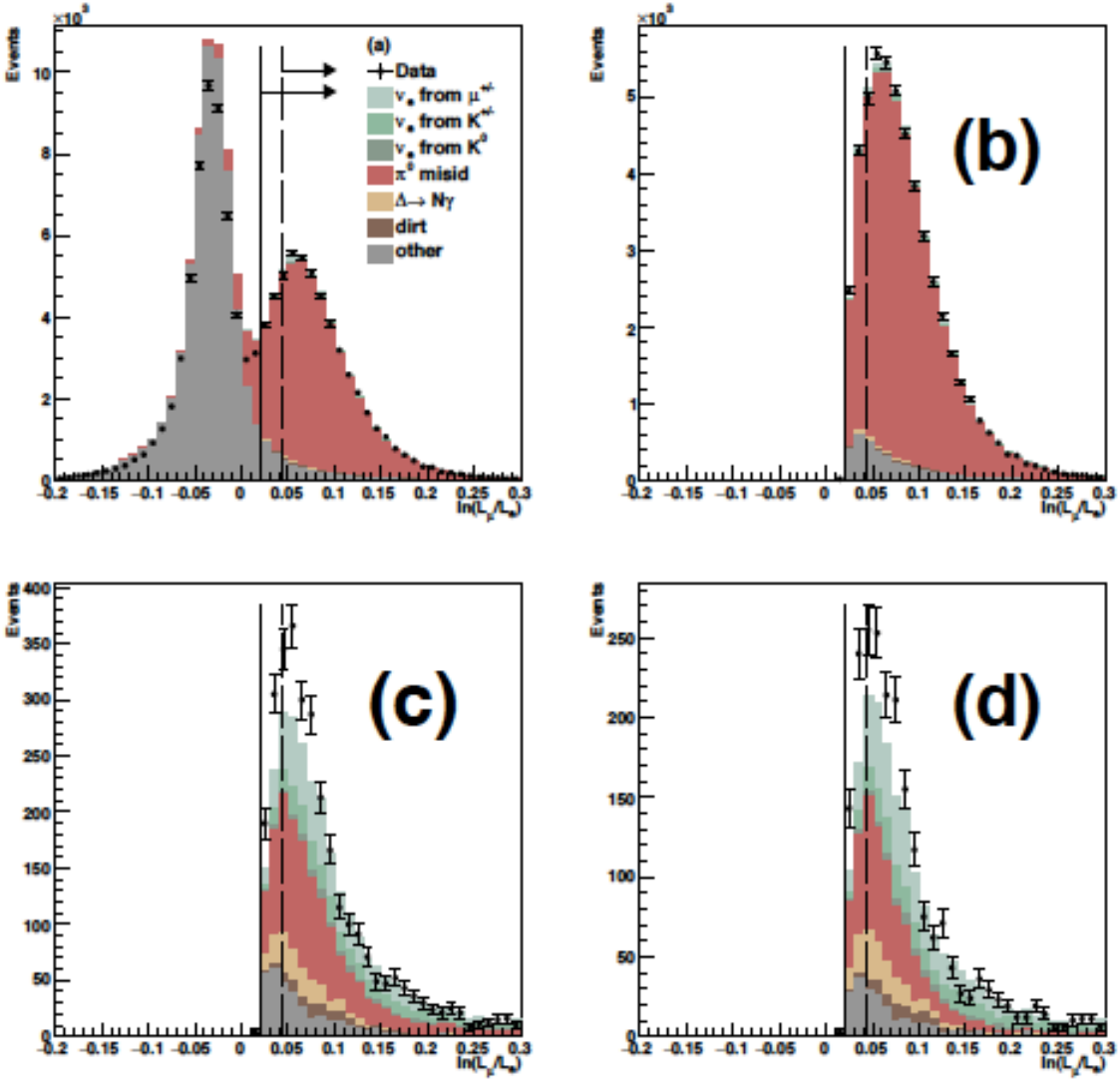
Event Signatures – PID from $L_{e\pi}$, $L_{e\mu}$, $M_{\pi 0}$

- Examples of ν_μ CCQE, ν_e CCQE, & NC π^0 event topologies
- Primarily use Cherenkov light
- Compare fits of different track reconstruction hypotheses for PID
- Insensitive to the difference between single photon and single electron



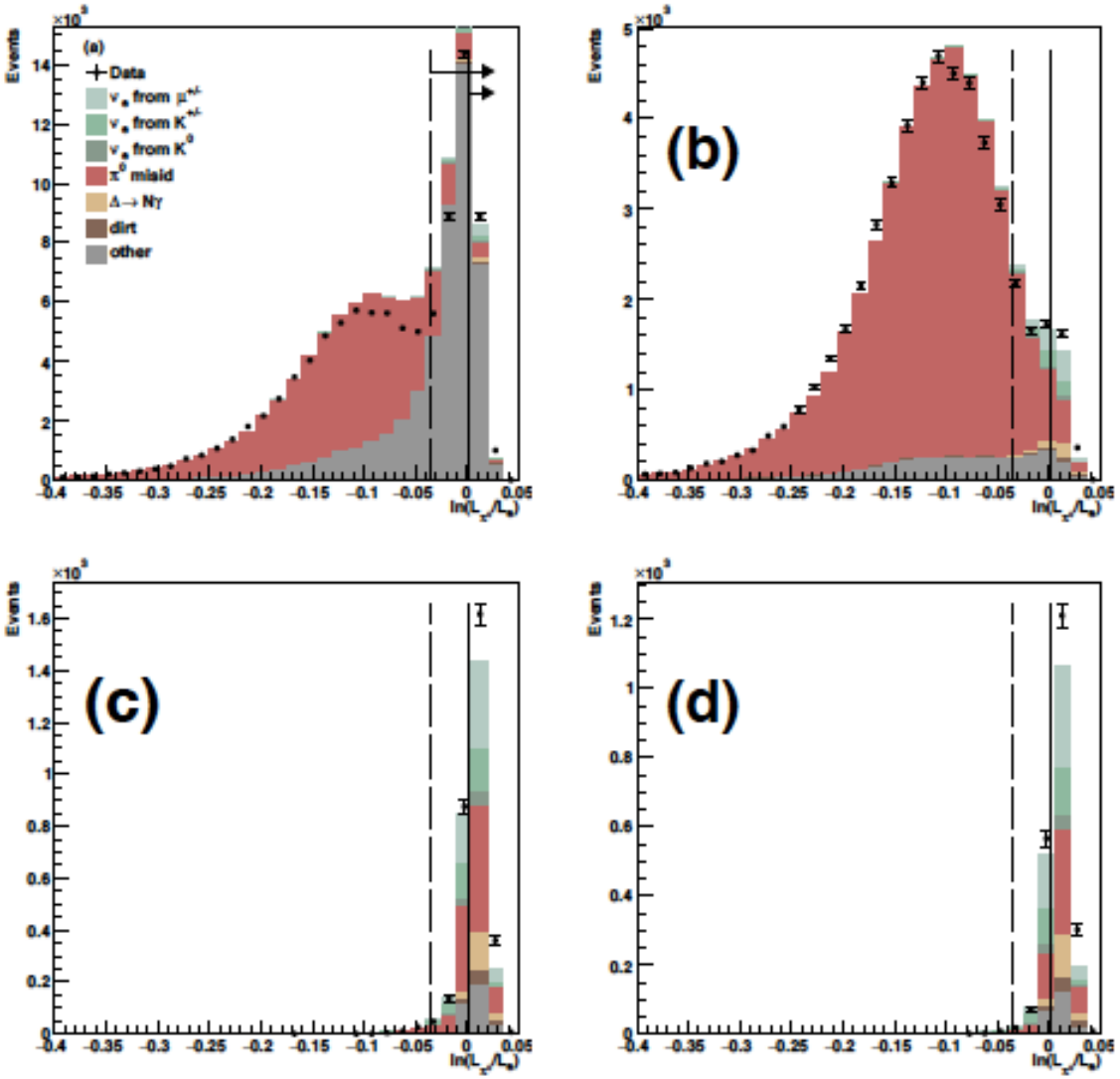
Data vs MC - $L_{e\mu}$

(a) No PID cuts
(b) $L_{e\mu}$ cut
(c) + $L_{e\pi}$ cut
(d) + M_{π} cut



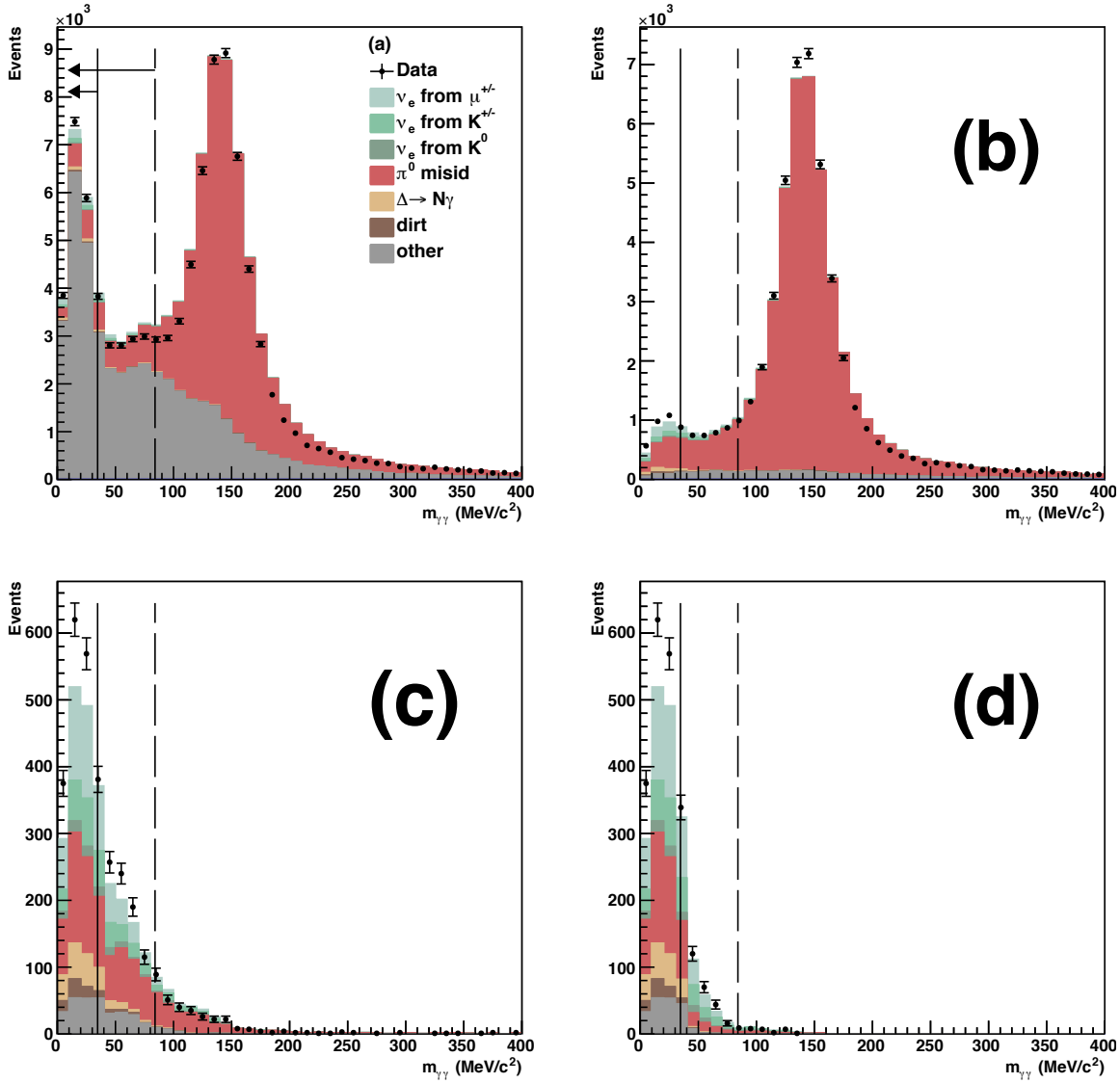
Data vs MC - $L_{e\pi}$

(a) No PID cuts
(b) $L_{e\mu}$ cut
(c) + $L_{e\pi}$ cut
(d) + M_{π} cut



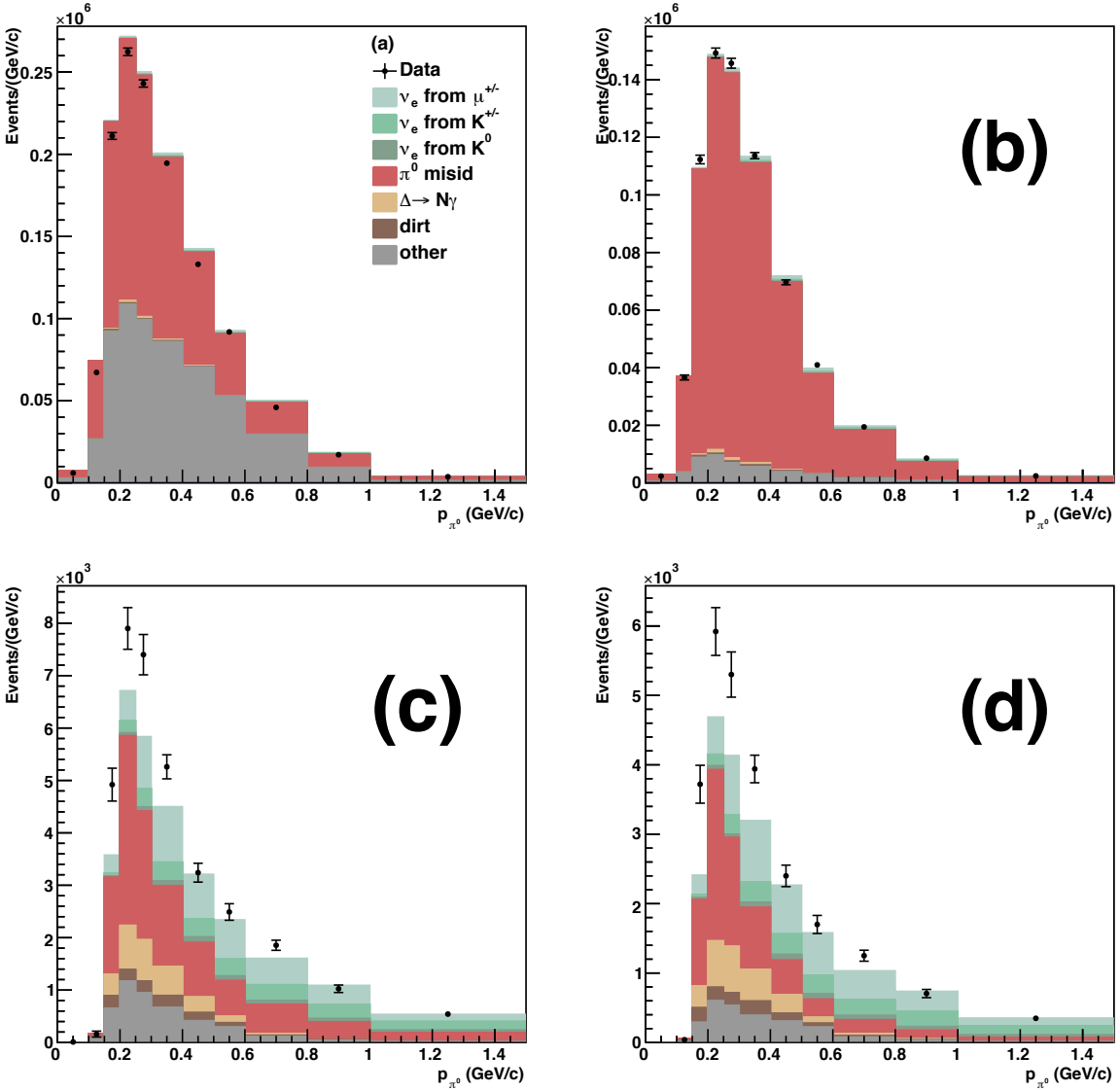
Data vs MC – $M_{\pi 0}$

(a) No PID cuts
(b) $L_{e\mu}$ cut
(c) + $L_{e\pi}$ cut
(d) + M_{π} cut



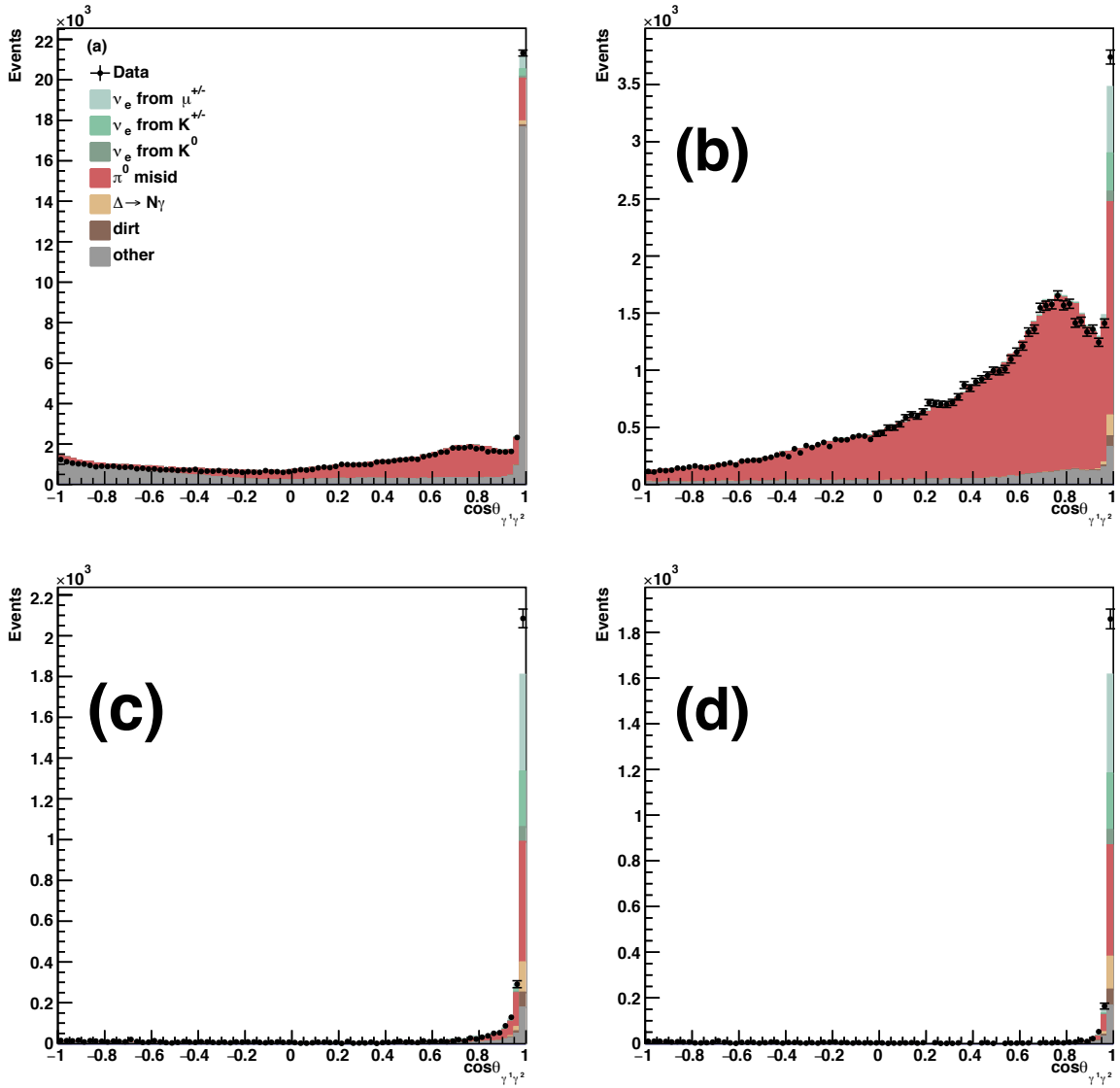
Data vs MC – P

(a) No PID cuts
(b) $L_{e\mu}$ cut
(c) + $L_{e\pi}$ cut
(d) + M_{π} cut



$\mathrm{Cos}(\theta_{\gamma\gamma})$ Distribution

(a) No PID cuts
(b) $L_{e\mu}$ cut
(c) + $L_{e\pi}$ cut
(d) + M_{π} cut

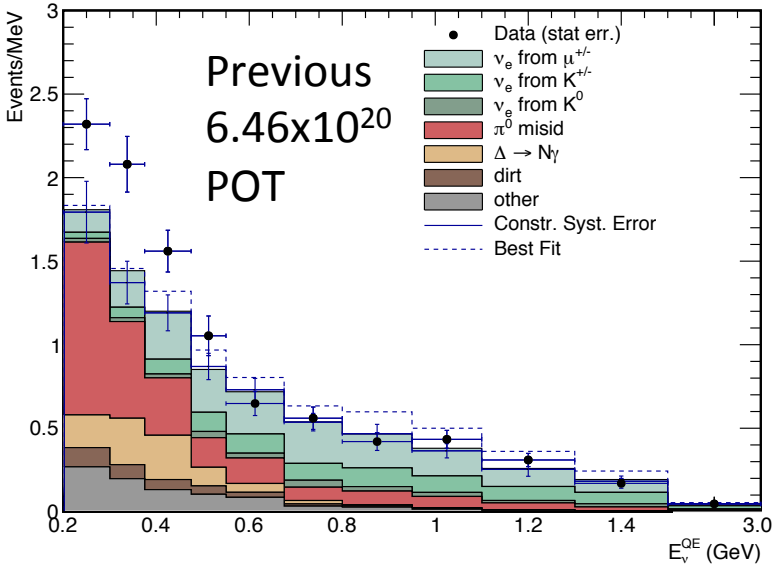


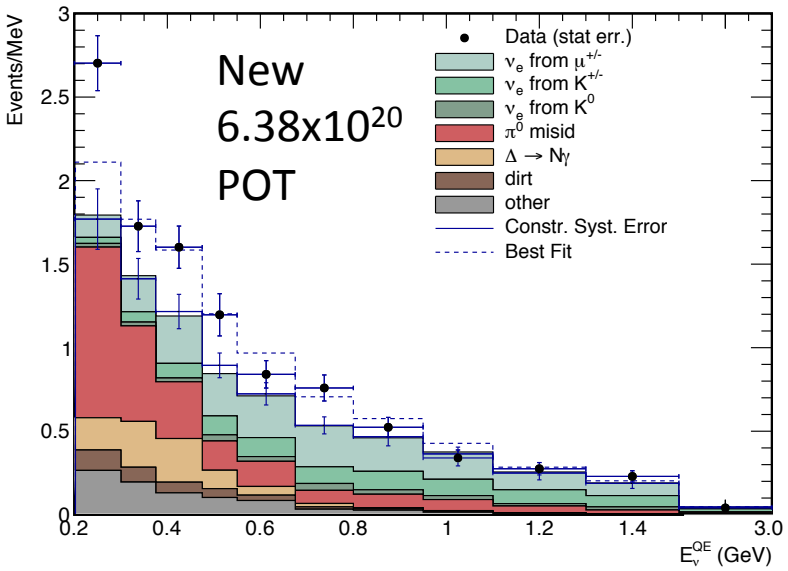
Electron-Neutrino Event Excess

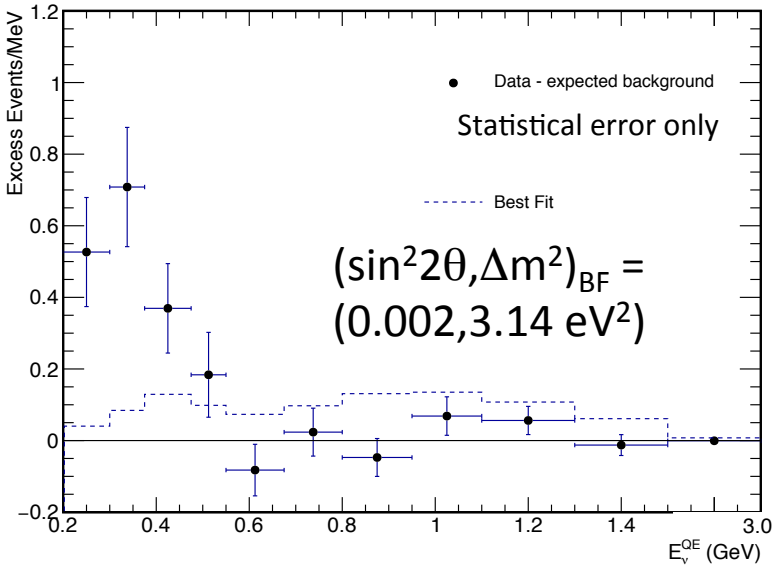
	Neutrino Mode POT	Antineutrino Mode POT	Combined
Data	1959	478	2437
Unconstrained Background	1590.5	398.2	1988.7
Constrained Background	1577.8	398.7	1976.5
Excess	381.2+-85.2 (4.5σ)	79.3+-28.6 (2.8σ)	460.5+-99.0 (4.7σ)
0.26% (LSND) ν_e Appearance	463.1	100.0	563.1

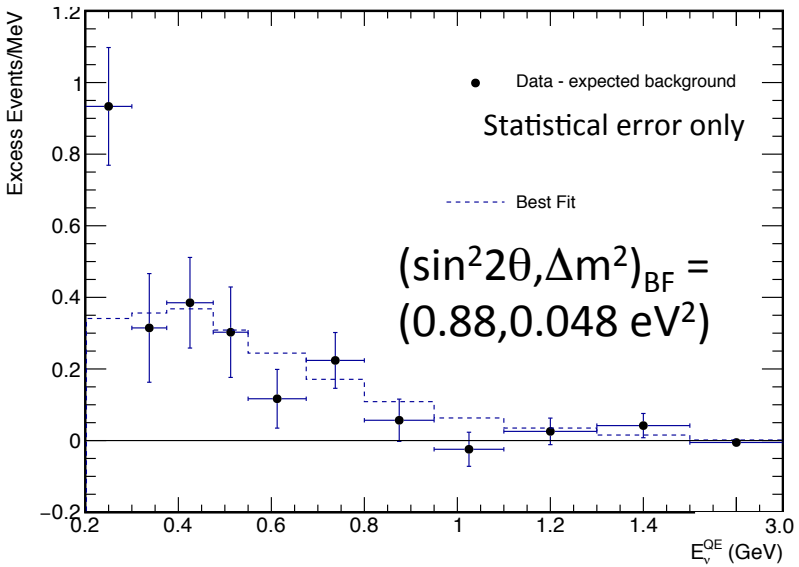
- Total excess for neutrino + antineutrino: 4.7σ
- Combined with LSND (3.8σ), total significance is at 6.0σ

Excess Old vs New Neutrino Data





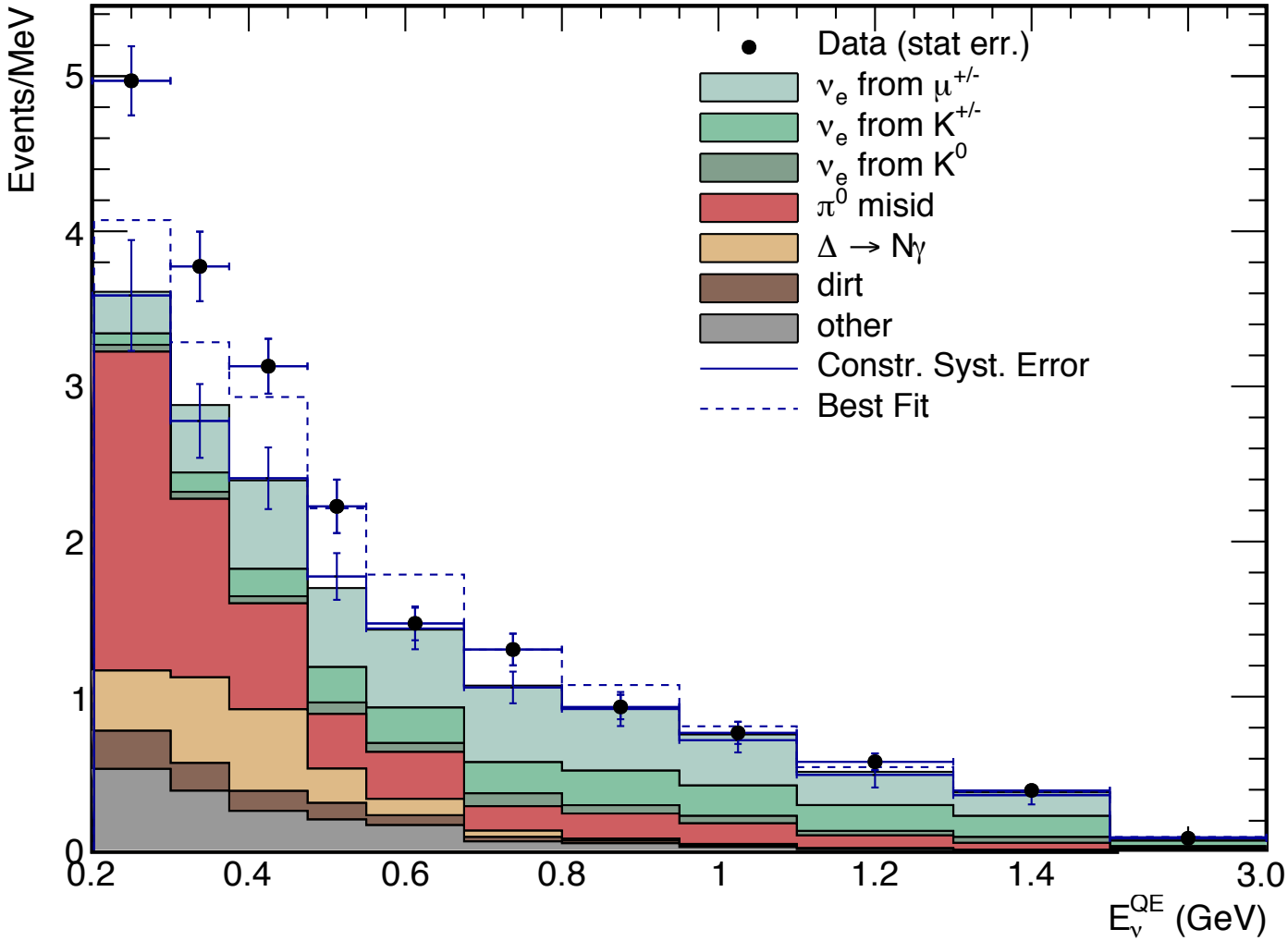




The observed ν_e spectra are statistically consistent between the new and previous data sets (KS probability = 76%)

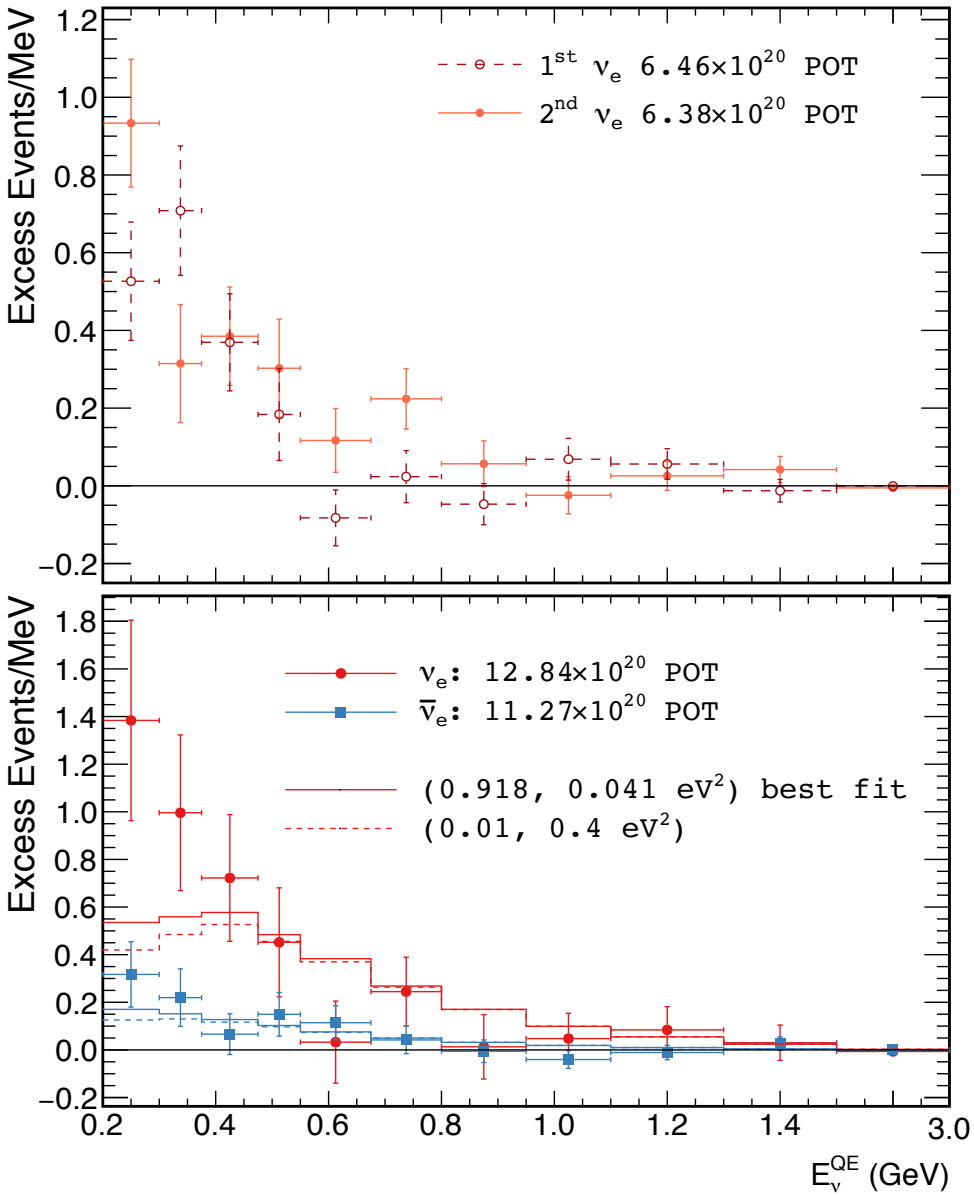
Total Neutrino Data

12.84 x 10^{20} POT

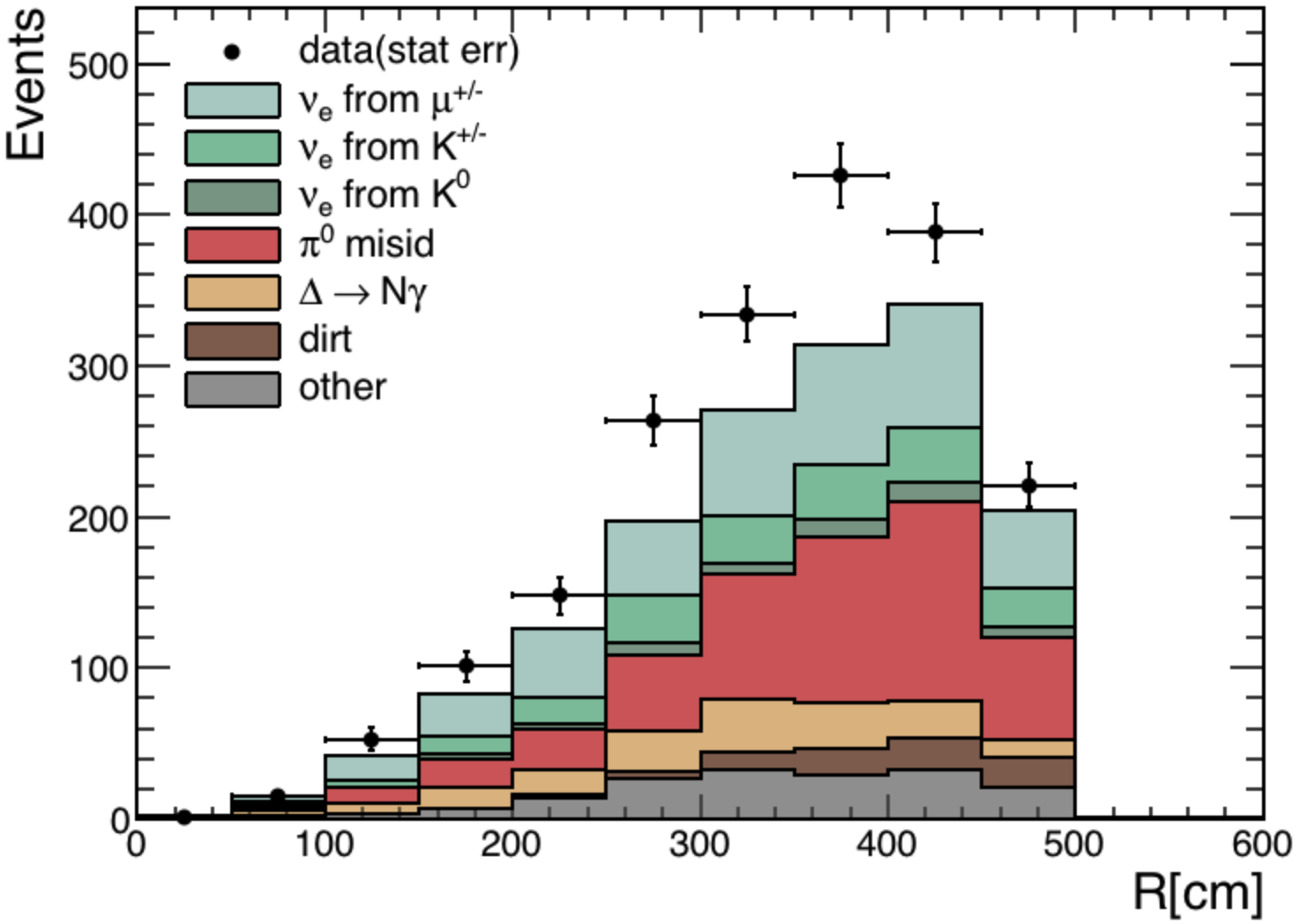


Excess Events: Neutrino & Antineutrino

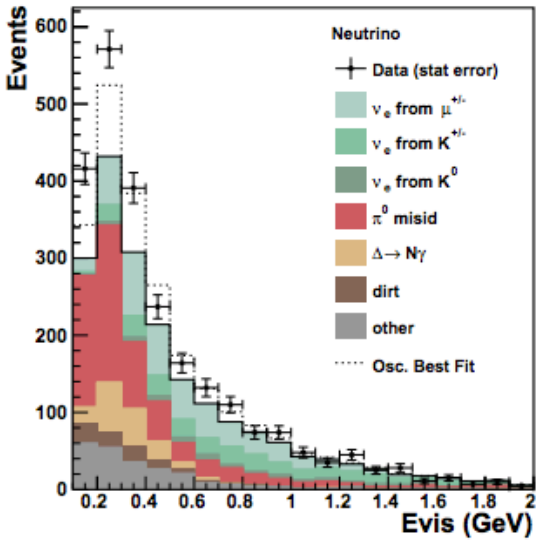
- Excesses in neutrino and antineutrino mode are qualitatively consistent

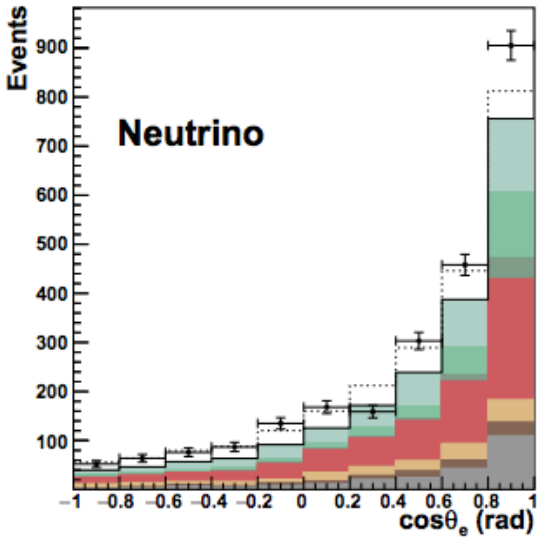


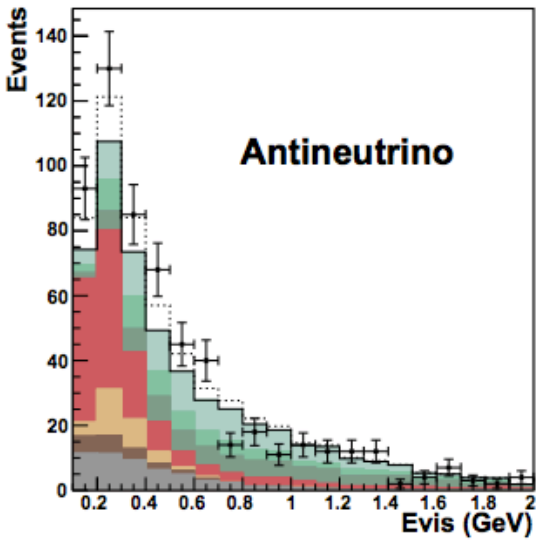
Neutrino Event Excess vs Radius

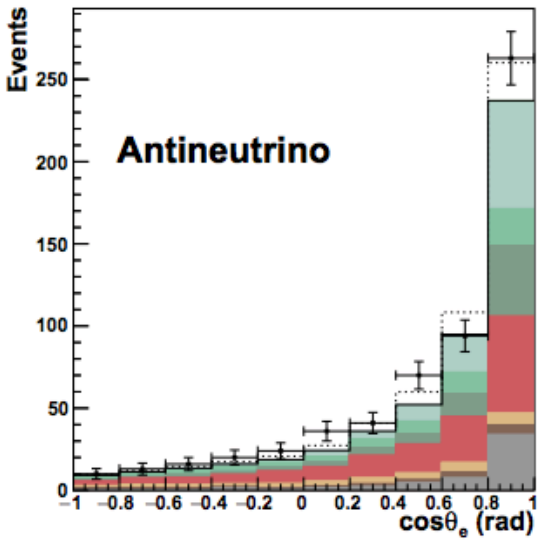


Event Excess vs Evis & UZ







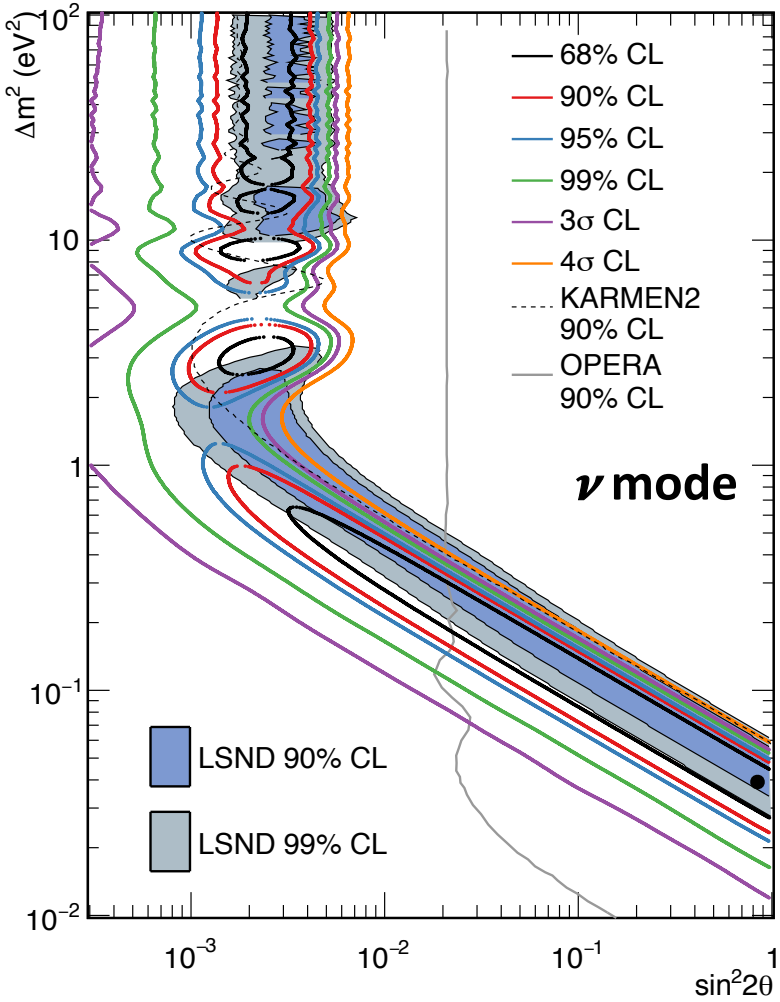


MiniBooNE Oscillation Analysis

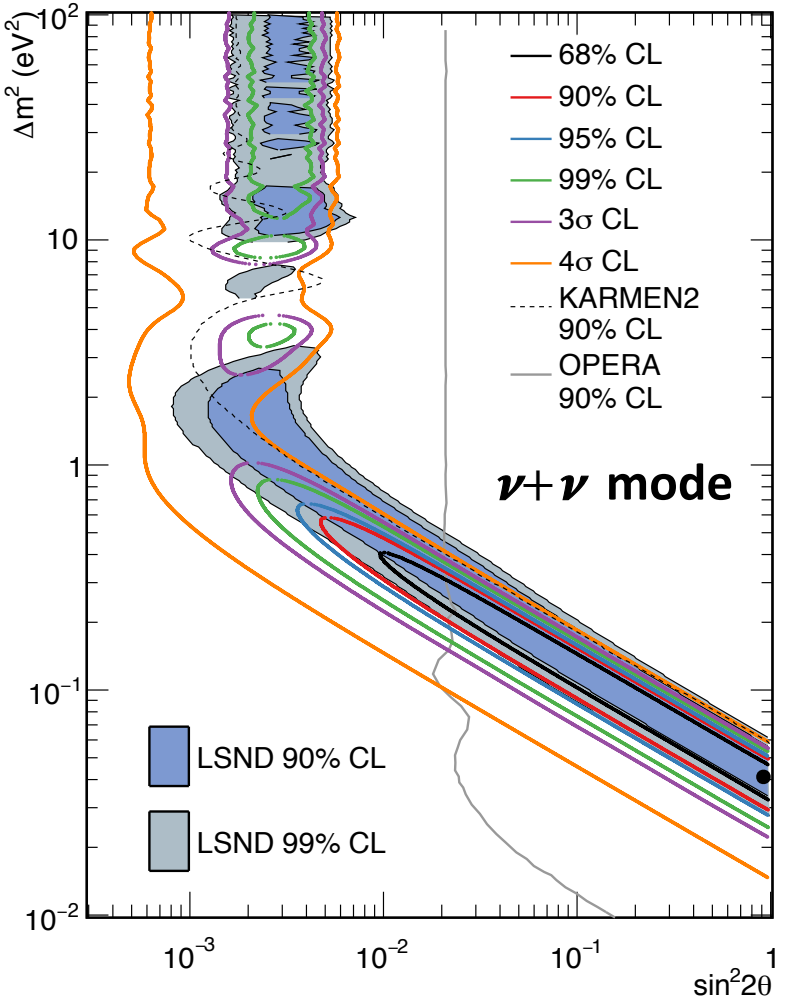
- Standard 2-neutrino oscillation model is used:

  $P = \sin^2(2\theta) \times \sin^2(1.267\Delta m^2 L/E)$
- The 2-neutrino oscillation model is probably not correct, but it serves as a way to compare LSND & MiniBooNE data.
- ν_e CCQE-like events are constrained by ν_μ CCQE-like events
- Maximum likelihood is used
- A simultaneous fit was conducted for ν_e and ν_μ distributions

Allowed Regions

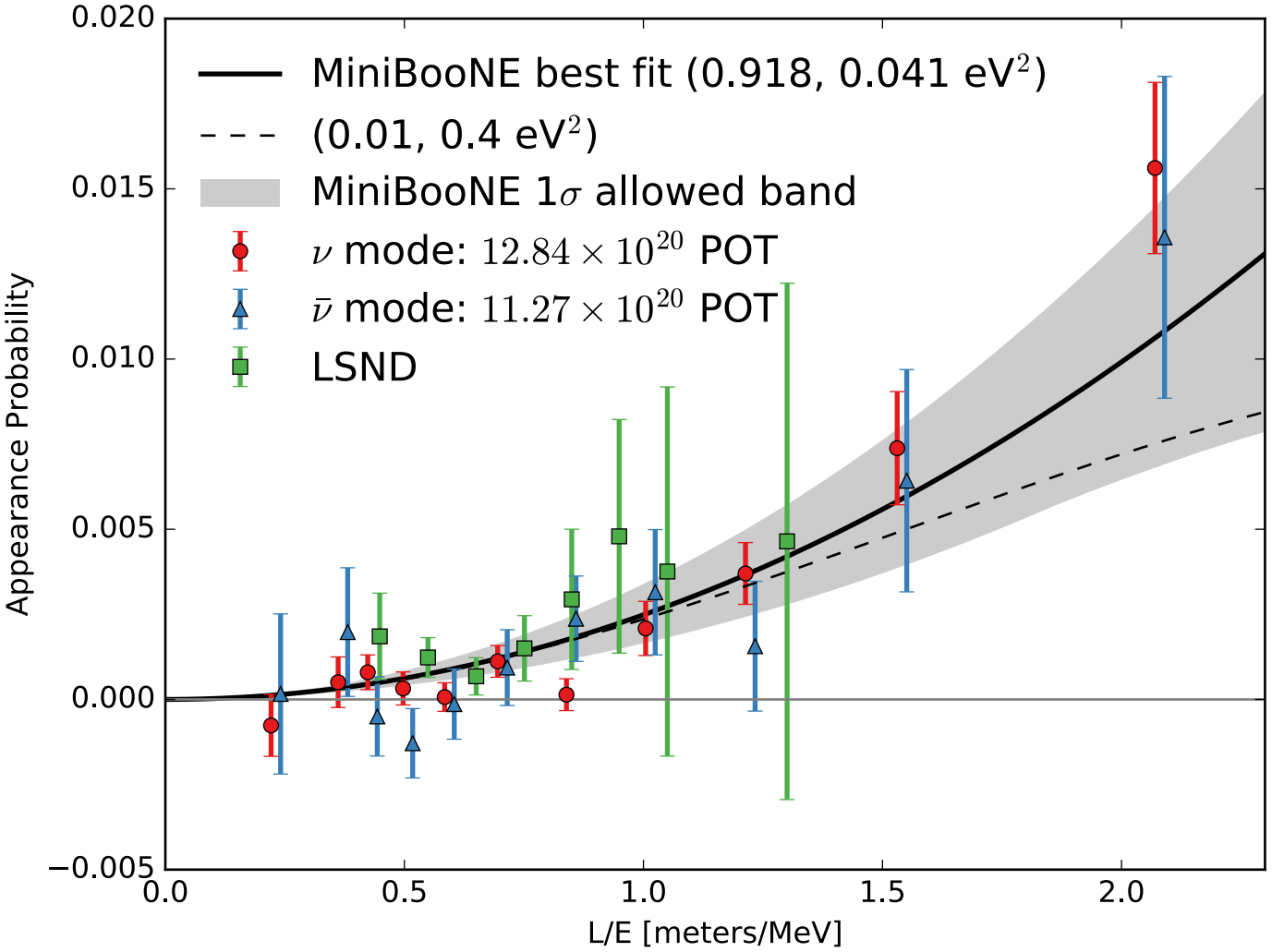


$(\Delta m^2, \sin^2 2\theta) = (0.039\ \text{eV}^2, 0.84)$
$\chi^2/\text{ndf} = 9.9/6.7$ (prob = 15.5%)



$(\Delta m^2, \sin^2 2\theta) = (0.041\ \text{eV}^2, 0.92)$
$\chi^2/\text{ndf} = 19.4/15.6$ (prob = 21.1%)

L/E

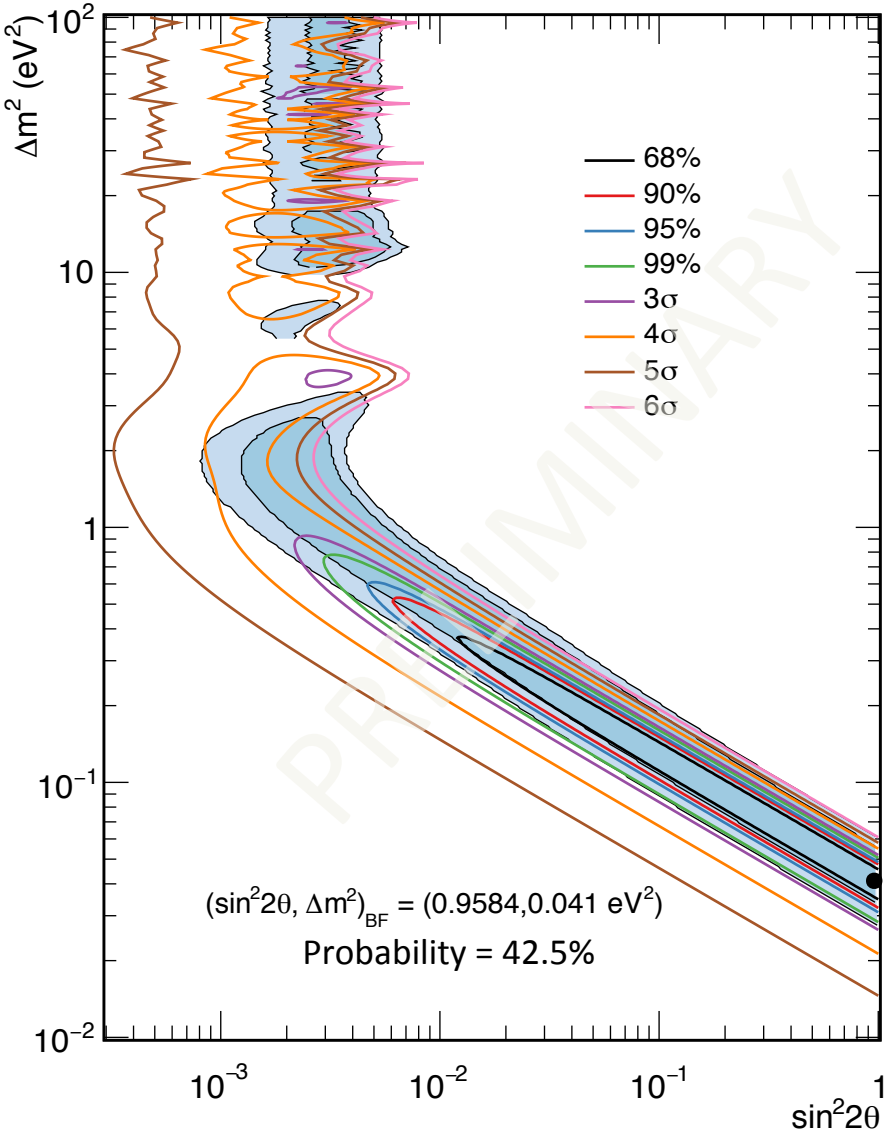


- MiniBooNE neutrino, MiniBooNE antineutrino, and LSND are **consistent** in appearance probability and L/E
- L/E caveats: arXiv:1407.3304

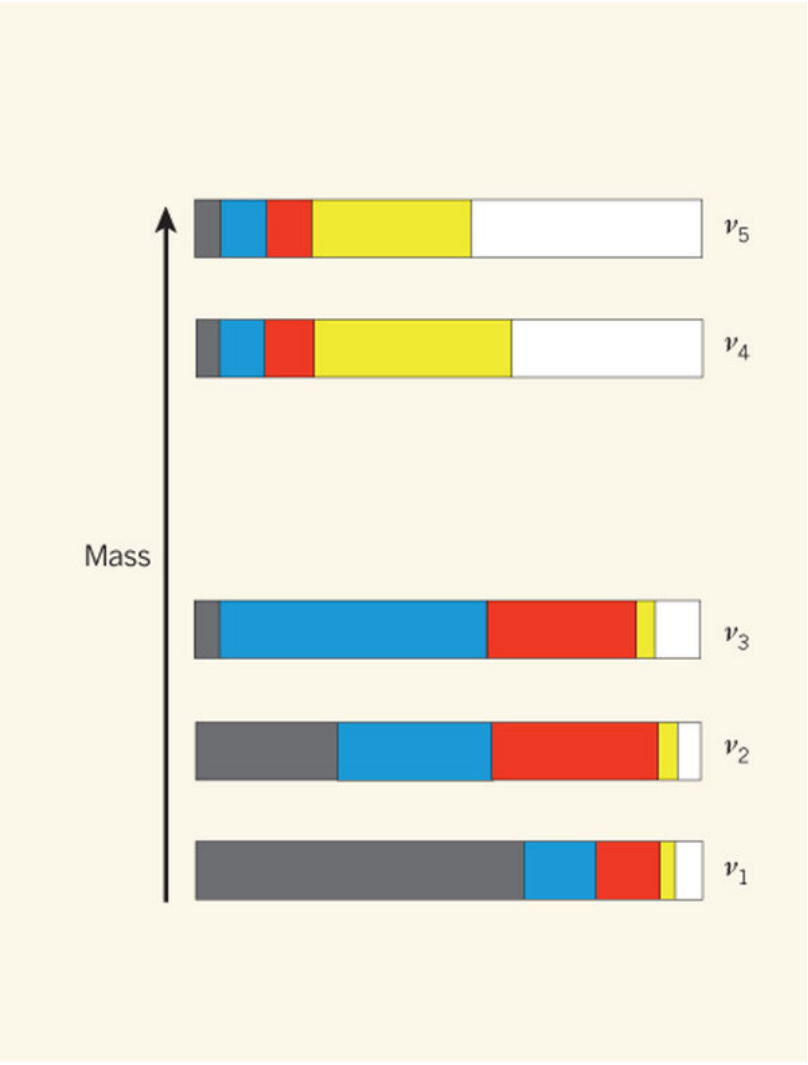
Combined Fit with LSND

However, the best fit at $\sin^2 2\theta \sim 1$ is ruled out by the other neutrino oscillation experiments, and there is tension between appearance & disappearance experiments!

More exotic models will probably need to be considered.



3+N Sterile Neutrino Models



- 3+N models
- N>1 allows CP violation for short baseline experiments
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e \neq \nu_\mu \rightarrow \nu_e$

Note: There are also other, more exotic possibilities

3+N Models With ν_e Appearance Require Large ν_e & ν_μ Disappearance!

In general, $P(\nu_\mu \rightarrow \nu_e) \sim \frac{1}{4} P(\nu_\mu \rightarrow \nu_x) P(\nu_e \rightarrow \nu_x)$

Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.

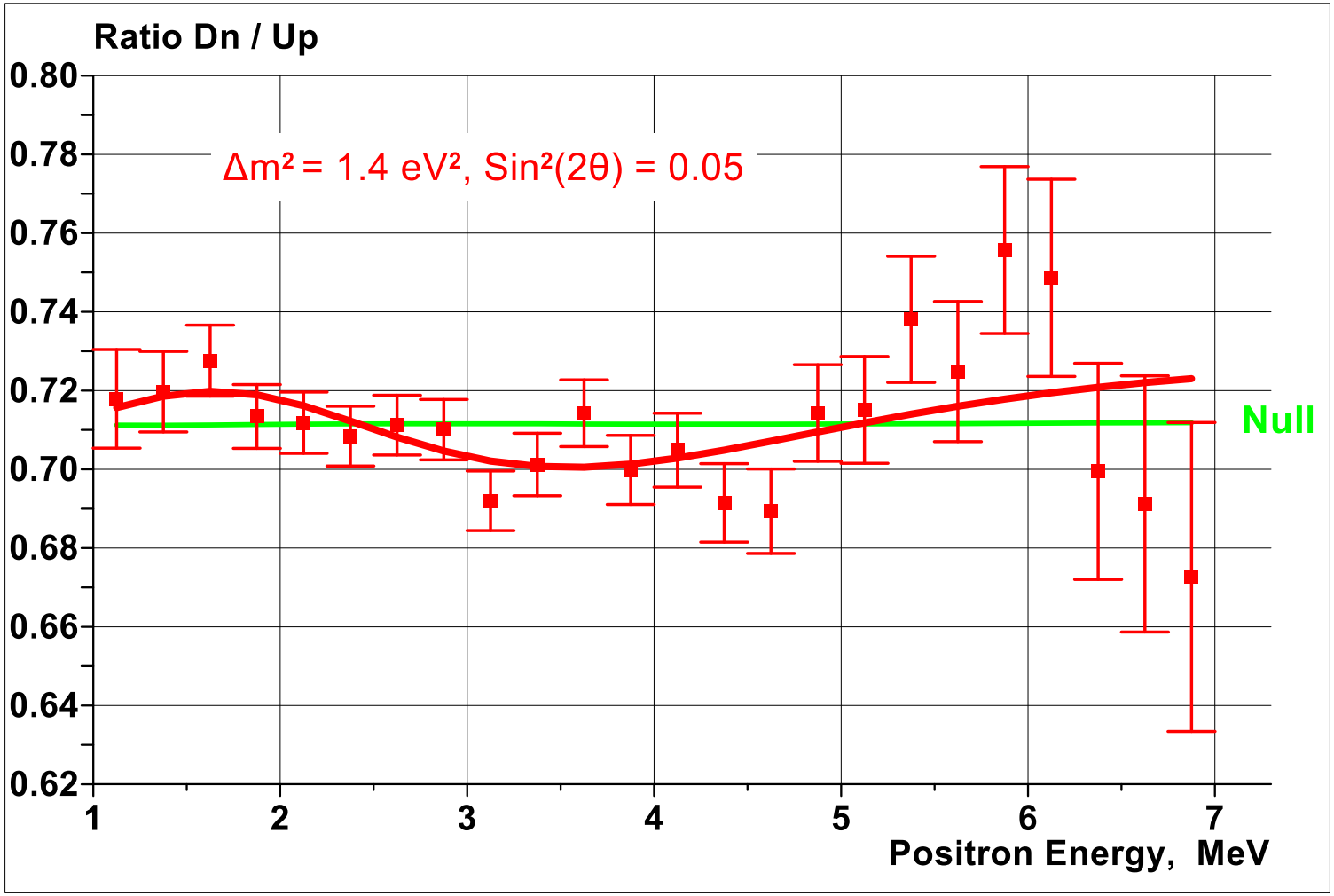
For 3+1 Models:
arXiv:1207.4765

$$P(\nu_\alpha \rightarrow \nu_\beta) \simeq 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E) \ ,$$

$$P(\nu_\alpha \rightarrow \nu_\alpha) \simeq 1 - 4(1 - |U_{\alpha 4}|^2)|U_{\alpha 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E) \ .$$

DANSS Reactor Neutrino Experiment

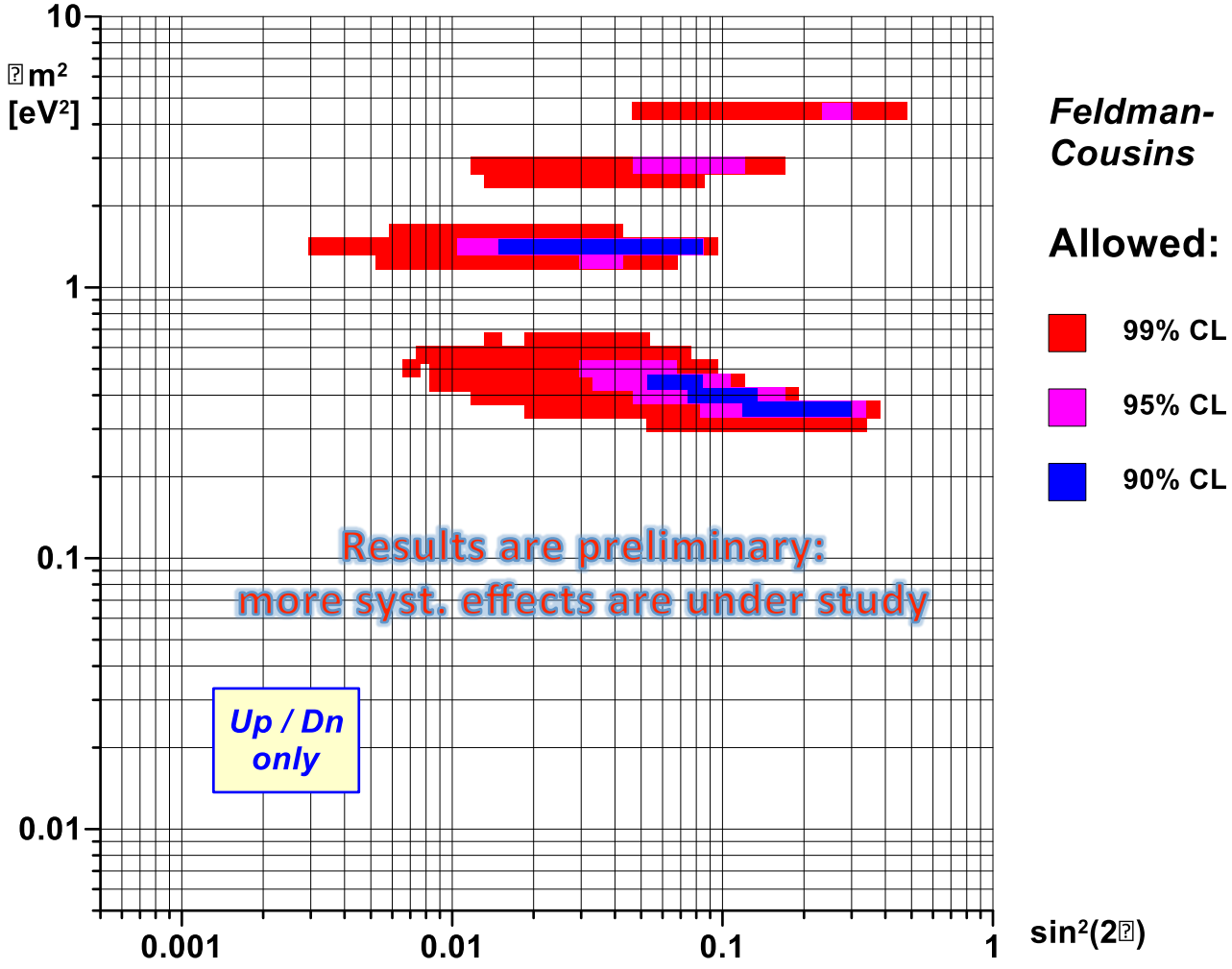
V.Egorov Talk at Neutrino 2018



DANSS best fit at ($\sin^2 2\theta, \Delta m^2$) = (0.05,1.4 eV^2) is 2.8σ better than null

DANSS Reactor Neutrino Experiment

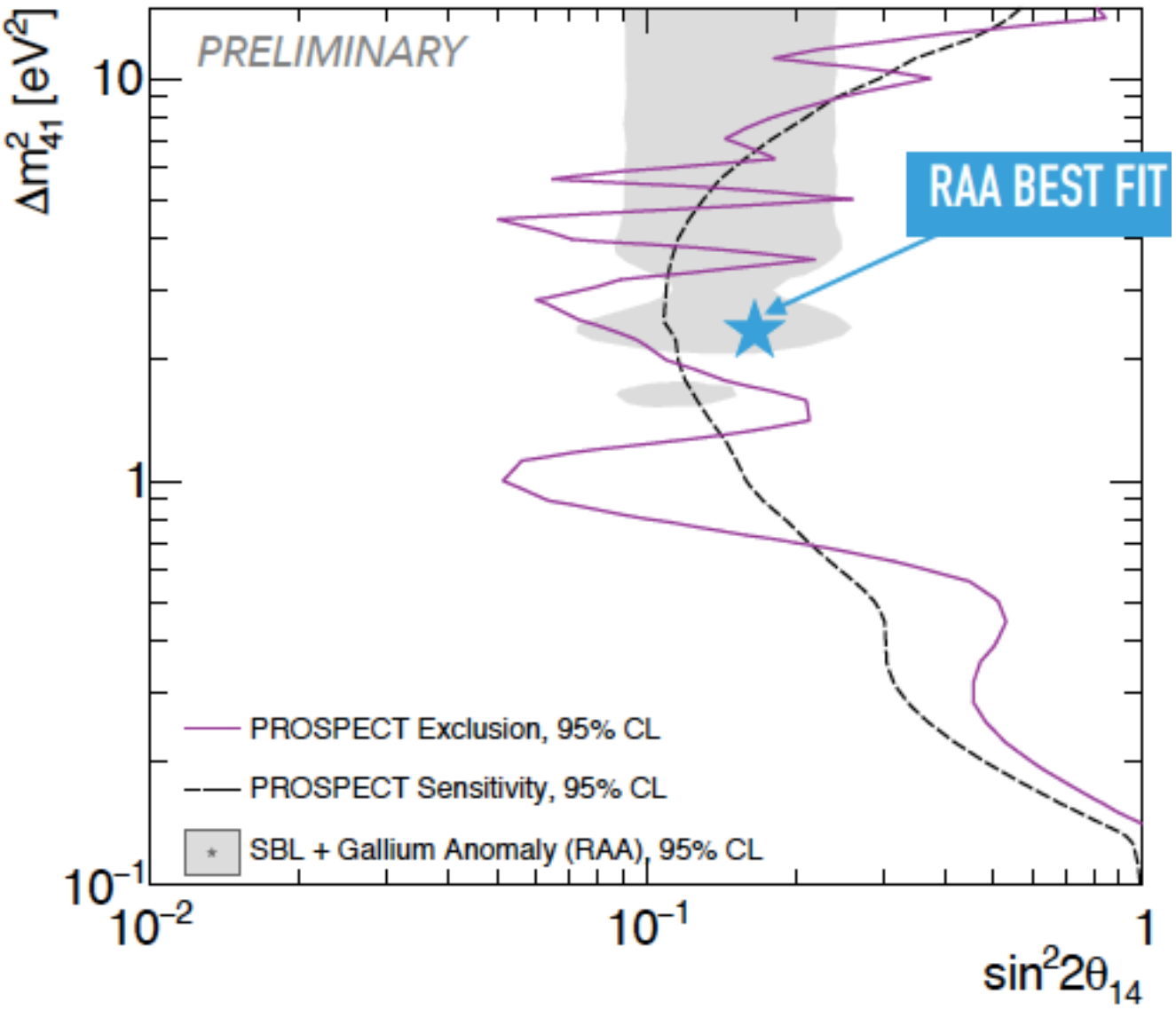
V. Egorov Talk at Neutrino 2018



DANSS best fit at $(\sin^2 2\theta, \Delta m^2) = (0.05, 1.4\ eV^2)$ is 2.8σ better than null

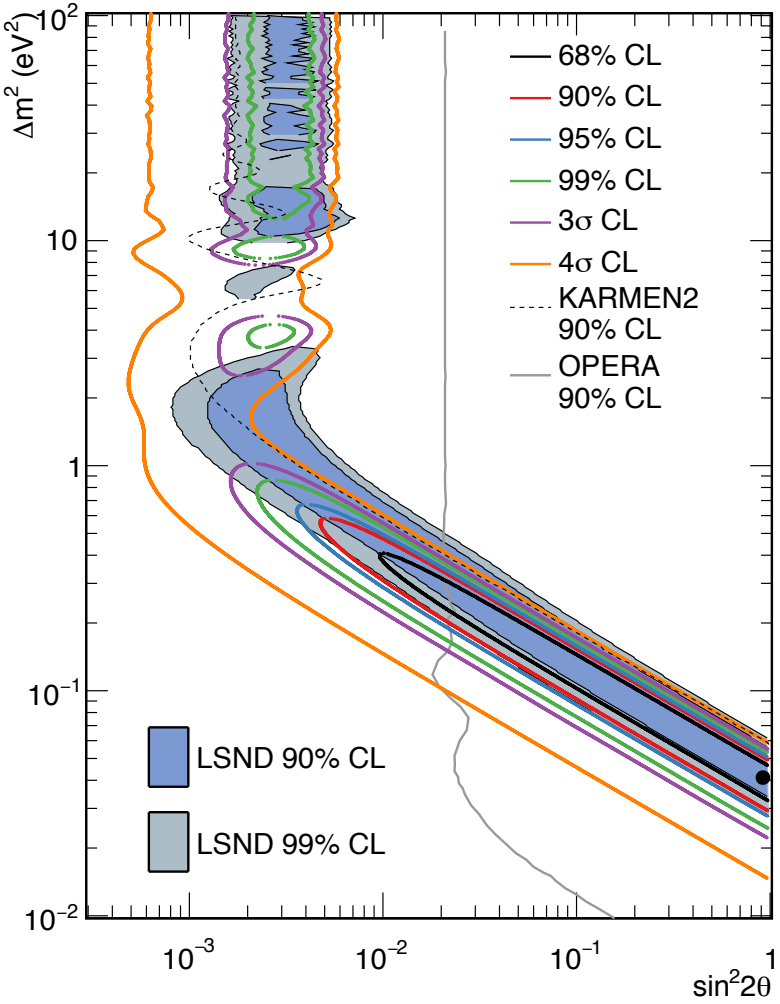
PROSPECT Reactor Neutrino Experiment

T. Langford Talk at Neutrino 2018

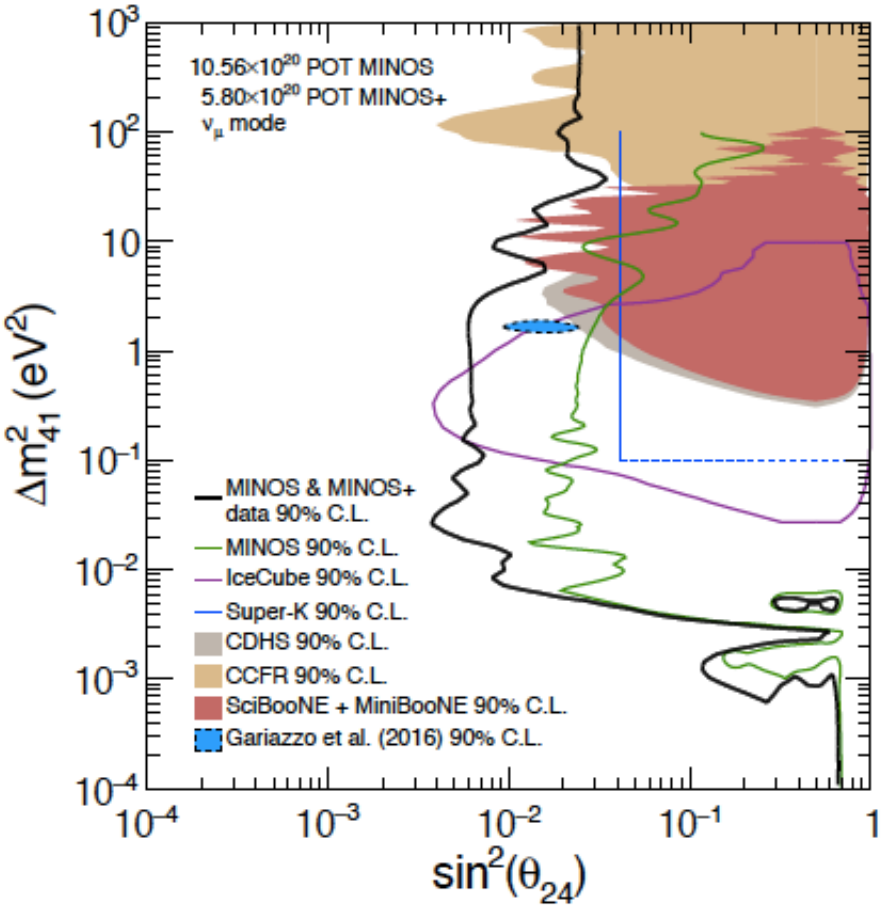


Tension Between Appearance & Disappearance Experiments in a 3+1 Model

Appearance



Disappearance



arXiv:1710.06488v2

More Exotic SBL Possibilities Than 3+N Models

(Sterile neutrinos may have other interactions!)

- Sterile Neutrino Decay
- Sterile Neutrino NSI & New Gauge Bosons
- Sterile Neutrinos with Resonant Oscillations
- Light WIMP Production (Light WIMPs can behave like neutrinos)
- Lorentz Violation & CPT Violation
- Extra Dimensions (active neutrinos are stuck on the brane, while sterile neutrinos can propagate in the bulk)
- Mass-Varying Neutrinos
- Neutrino Decoherence
- etc.

Impact of Nonstandard Interactions on Sterile-Neutrino Searches at IceCube

Jiajun Liao and Danny Marfatia
Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822, USA
(Received 2 March 2016; revised manuscript received 26 May 2016; published 8 August 2016)

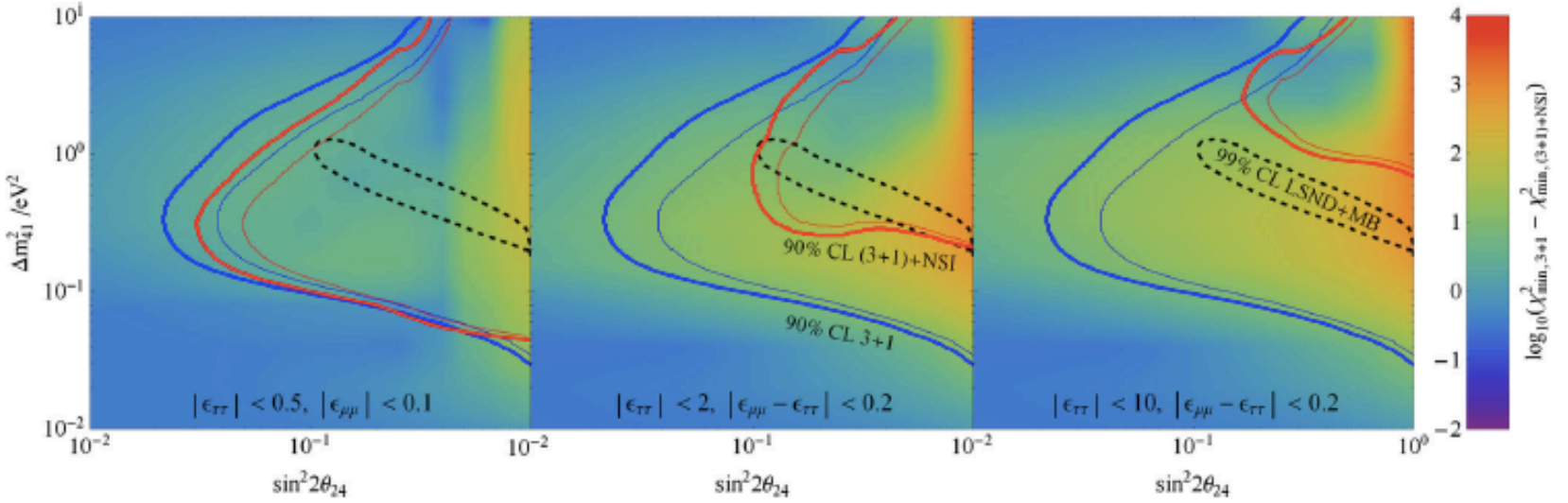


FIG. 4. The 90% and 99% C.L. exclusion bounds for the $3+1$ scenario from IceCube data are shown in blue; the regions to the right of the curves are excluded. The corresponding bounds for the $3+1$ scenario with NSI parameters in three different ranges are shown in red; all other NSI parameters are set to zero. The black dashed curve encloses the 99% C.L. allowed region for the combined LSND and MiniBooNE appearance analysis with $\sin^2\theta_{14} = 0.023$ [24]. The shading shows the effect of NSIs on $3+1$ oscillations.

Three Twin Neutrinos: Evidence from LSND and MiniBooNE

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[a] *Department of Physics, University of Wisconsin-Madison, Madison, WI 53706, USA*

[b] *Instituto de Física Corpuscular, Universidad de Valencia CSIC, Valencia 46071, Spain*

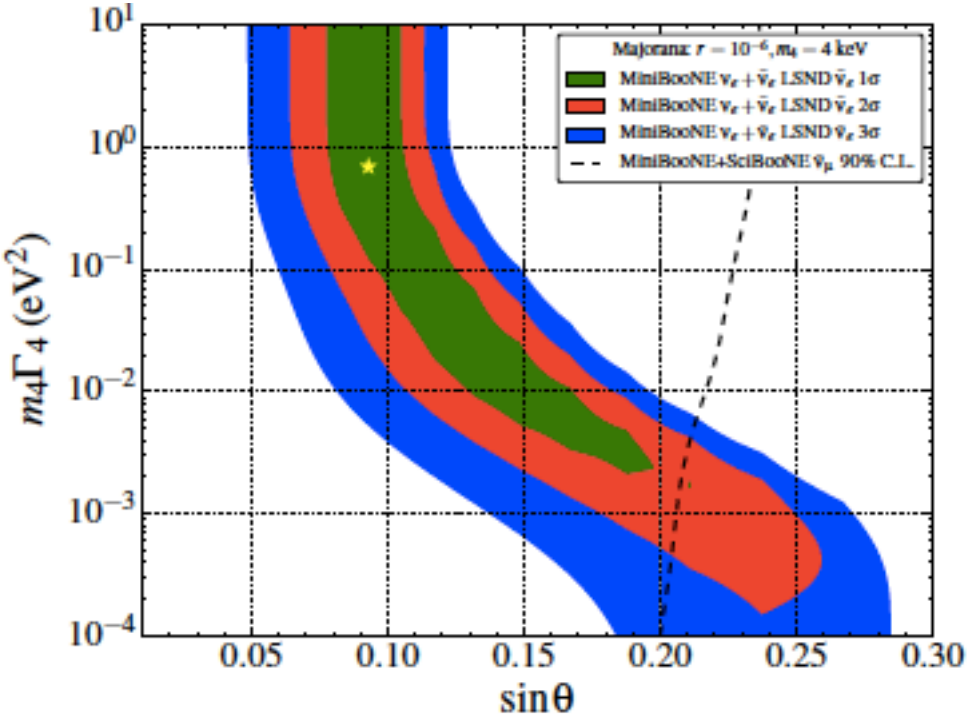

FIG. 7: The allowed Majorana model parameter space in $\sin\theta$ and $m_4\Gamma_4$ for fixed values of r and m_4. The vertical dashed line at $\sin\theta = 0.20$ is the constraint line (its left side is allowed) from unitarity of the three active neutrinos. The yellow star is the best fit point of our model, which has $\Delta\chi^2 = 22.5$ compared to the no twin neutrino assumption.

Phys. Rev. D 93, 073004 (2016)

FERMILAB-PUB-18-336-T
OSU-HEP-18-04

A Dark Neutrino Portal to Explain MiniBooNE

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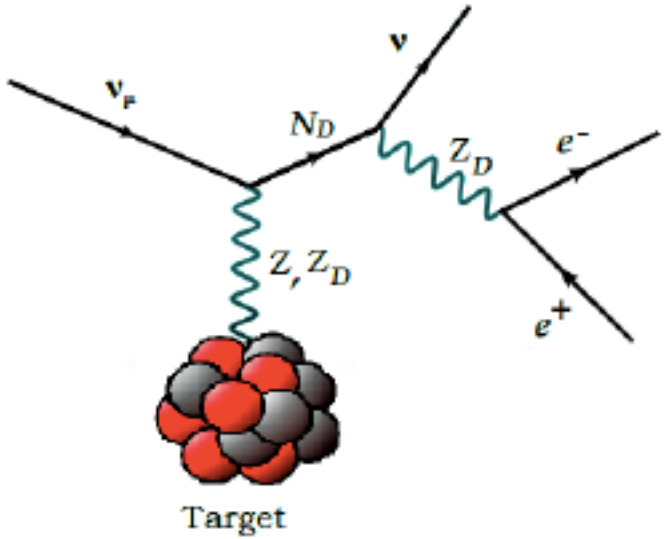
[1] *Departamento de Física Matemática, Instituto de Física Universidade de São Paulo, C.P. 66.318, São Paulo, 05315-970, Brazil*
[2] *Department of Physics and Oklahoma Center for High Energy Physics, Oklahoma State University, Stillwater, OK 74078-3072, USA*
[3] *Theory Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA*

(Dated: July 27, 2018)

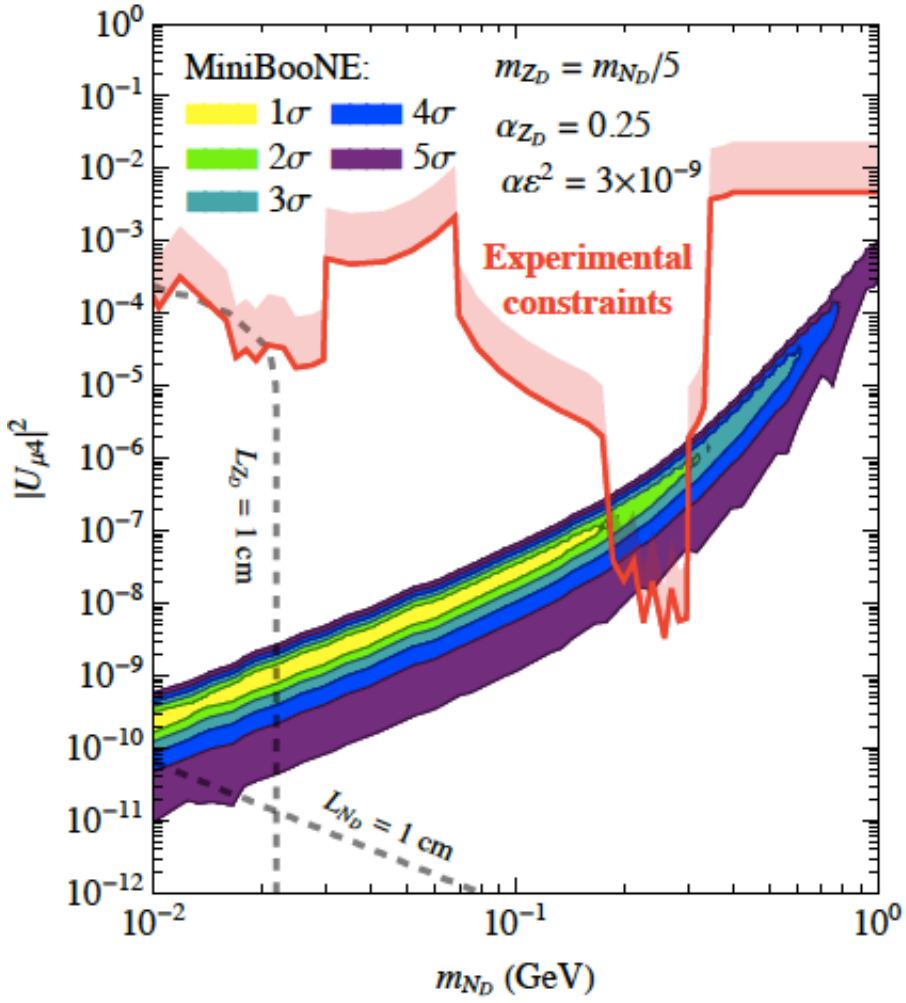
We present a novel framework that provides an explanation to the long-standing excess of electron-like events in the MiniBooNE experiment at Fermilab. We suggest a new dark sector containing a dark neutrino and a dark gauge boson, both with masses between a few tens and a few hundreds of MeV. Dark neutrinos are produced via neutrino-nucleus scattering, followed by their decay to the dark gauge boson, which in turn gives rise to electron-like events. This mechanism provides an excellent fit to MiniBooNE energy spectra and angular distributions.

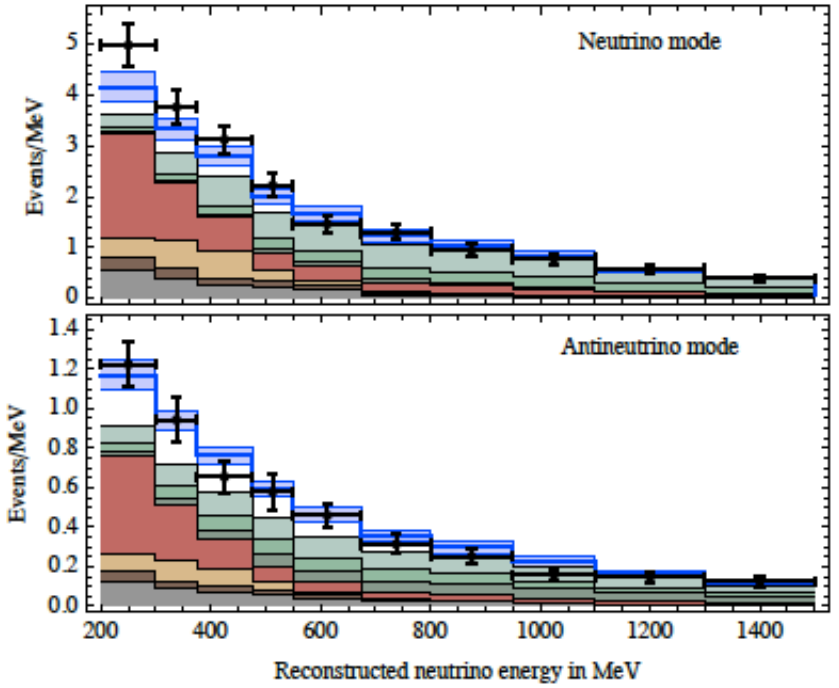
arXiv:1807.09877

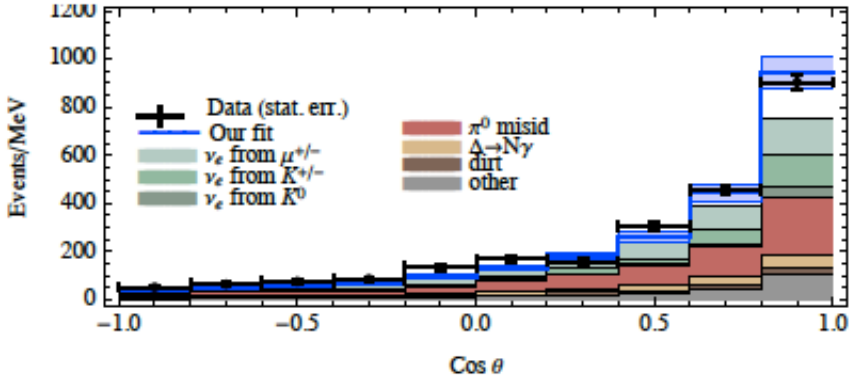


A Dark Neutrino Portal to Explain MiniBooNE

arXiv:1807.09877







Example of an Empirical Exotic Model: An MSW-Like Resonance

$C = \sqrt{\cos^2 2\theta (1 - E/E_{res})^2 + \sin^2 2\theta}$

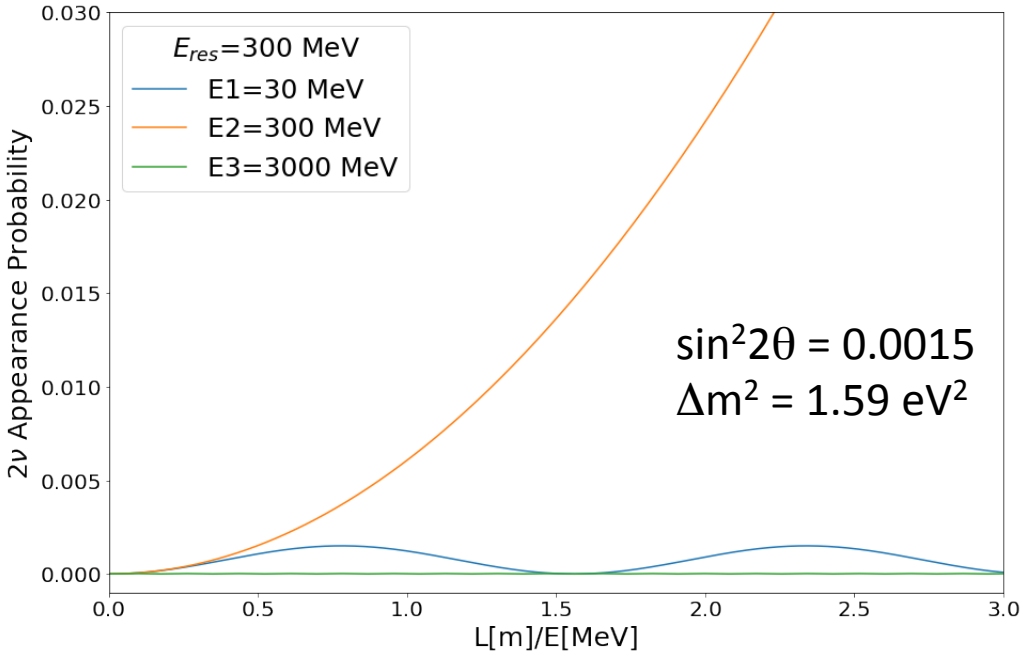
$\sin^2 2\theta_M = \sin^2 2\theta / C^2$

$\Delta m_M^2 = C \Delta m^2$

$P(E \ll E_{res}) \sim \sin^2 2\theta \times \sin^2(1.267 \Delta m^2 L/E)$

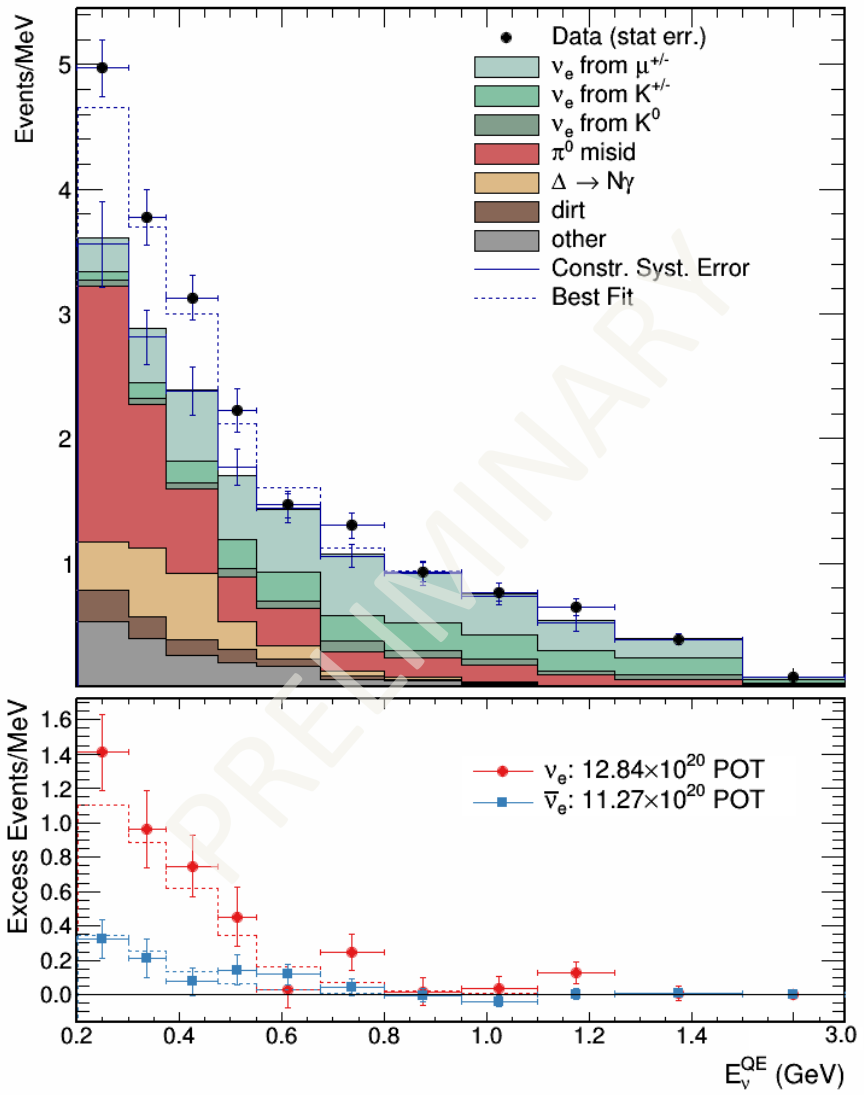
$P(E \sim E_{res}) \sim \sin^2 2\theta_M \times \sin^2(1.267 \Delta m_M^2 L/E)$

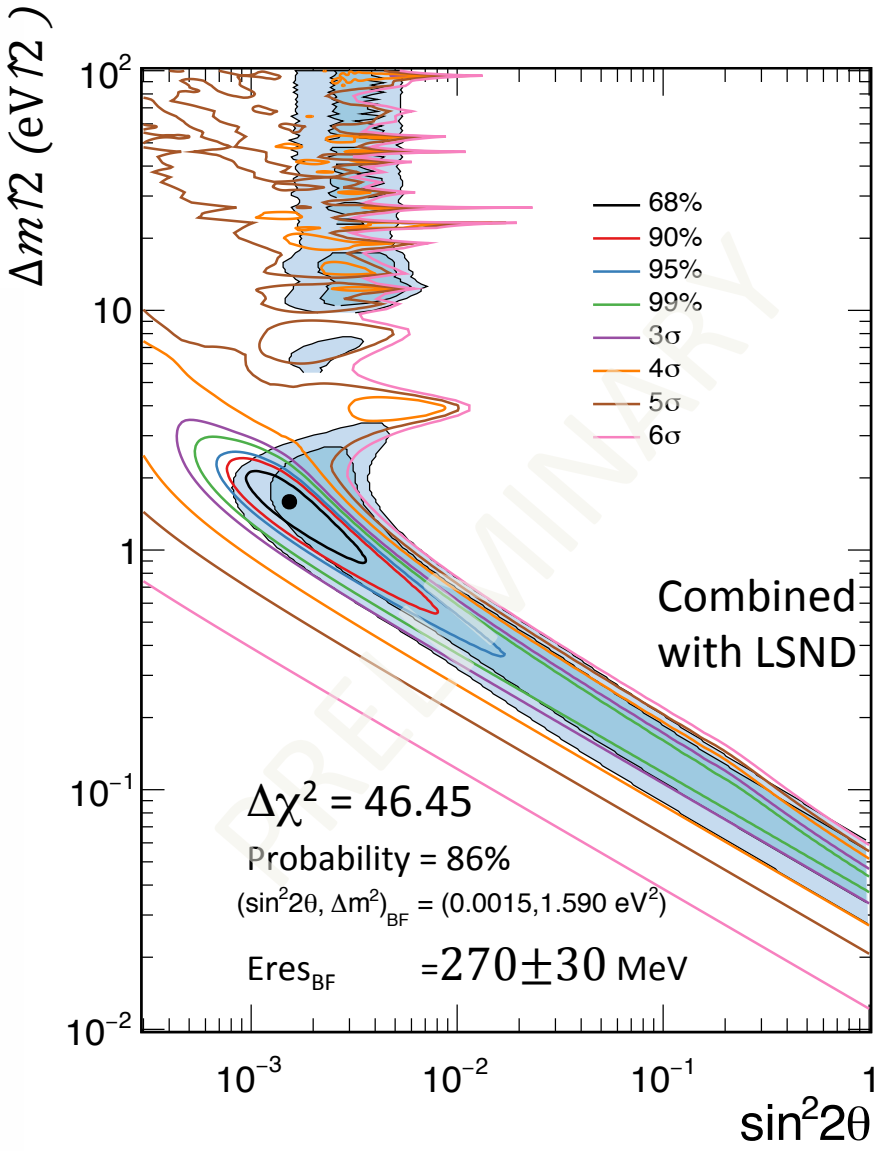
$P(E \gg E_{res}) \sim 0$



Inspired by:
J. Assadi, E. Church, R. Guenette, B. J. P. Jones, & A. M. Szelc, PRD 97, 075021 (2018);
G. Karagiorgi, M. H. Shaevitz, & J. M. Conrad, arXiv:1202.1024;
Heinrich Paes, Sandip Pakvasa, & Thomas J. Weiler, PRD 72, 095017 (2005).

An Empirical MSW-Like Resonance Model

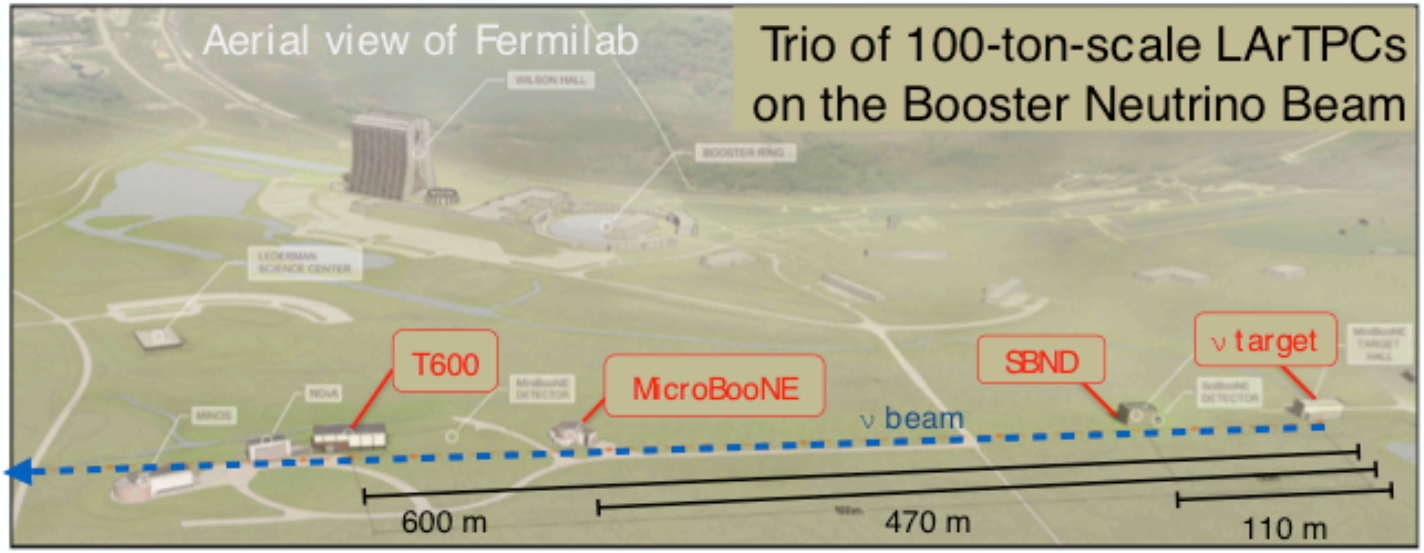


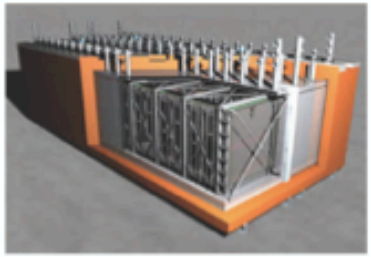


An MSW-Like model provides a better fit to the MiniBooNE & LSND data

Short Baseline Neutrino (SBN) Program

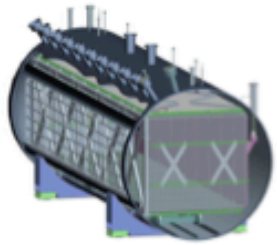
See talk by D. Schmitz





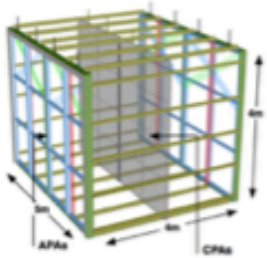
ICARUS-T600

476 tons



MicroBooNE

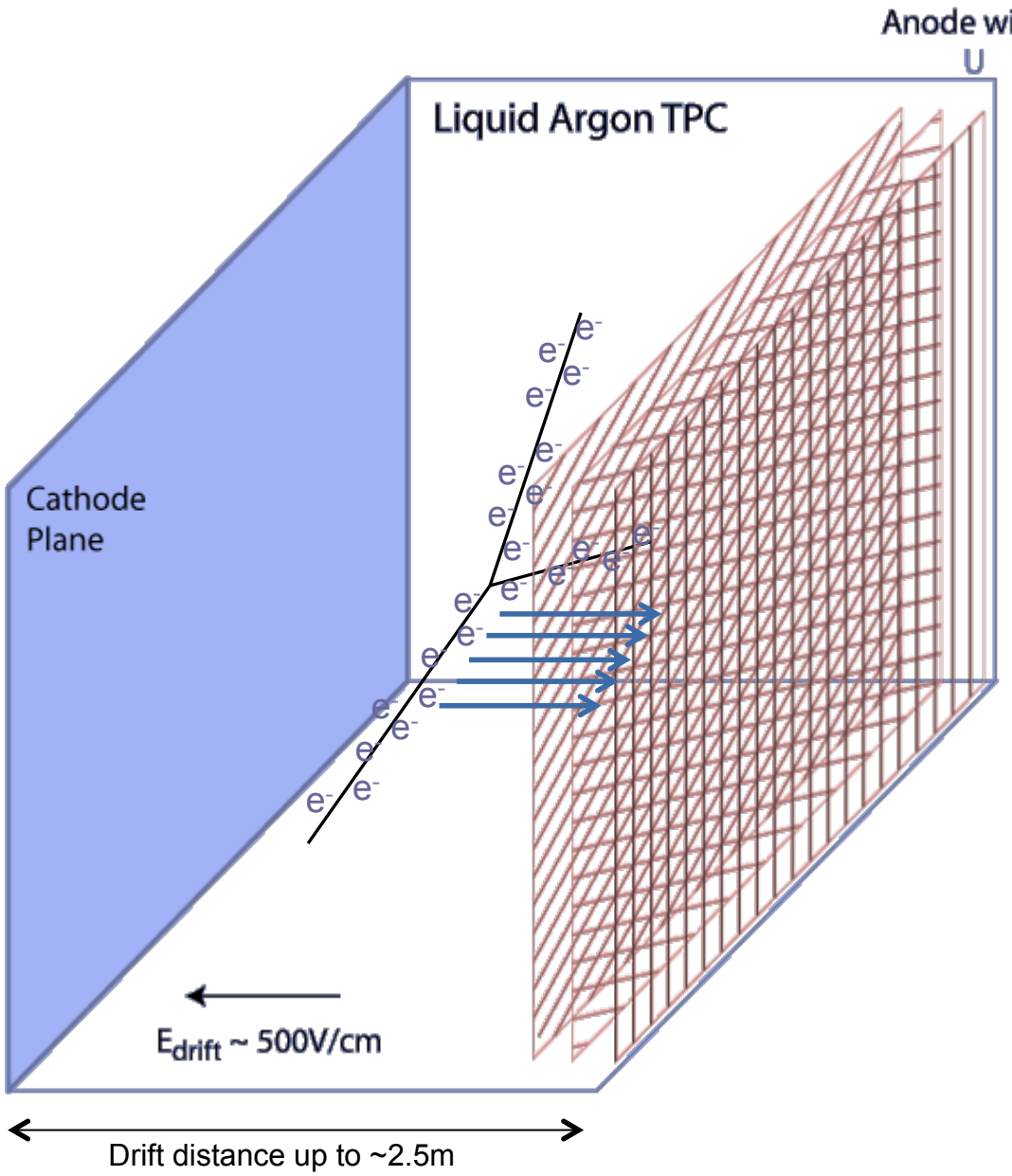
89 tons



Short Baseline Near Detector (SBND)

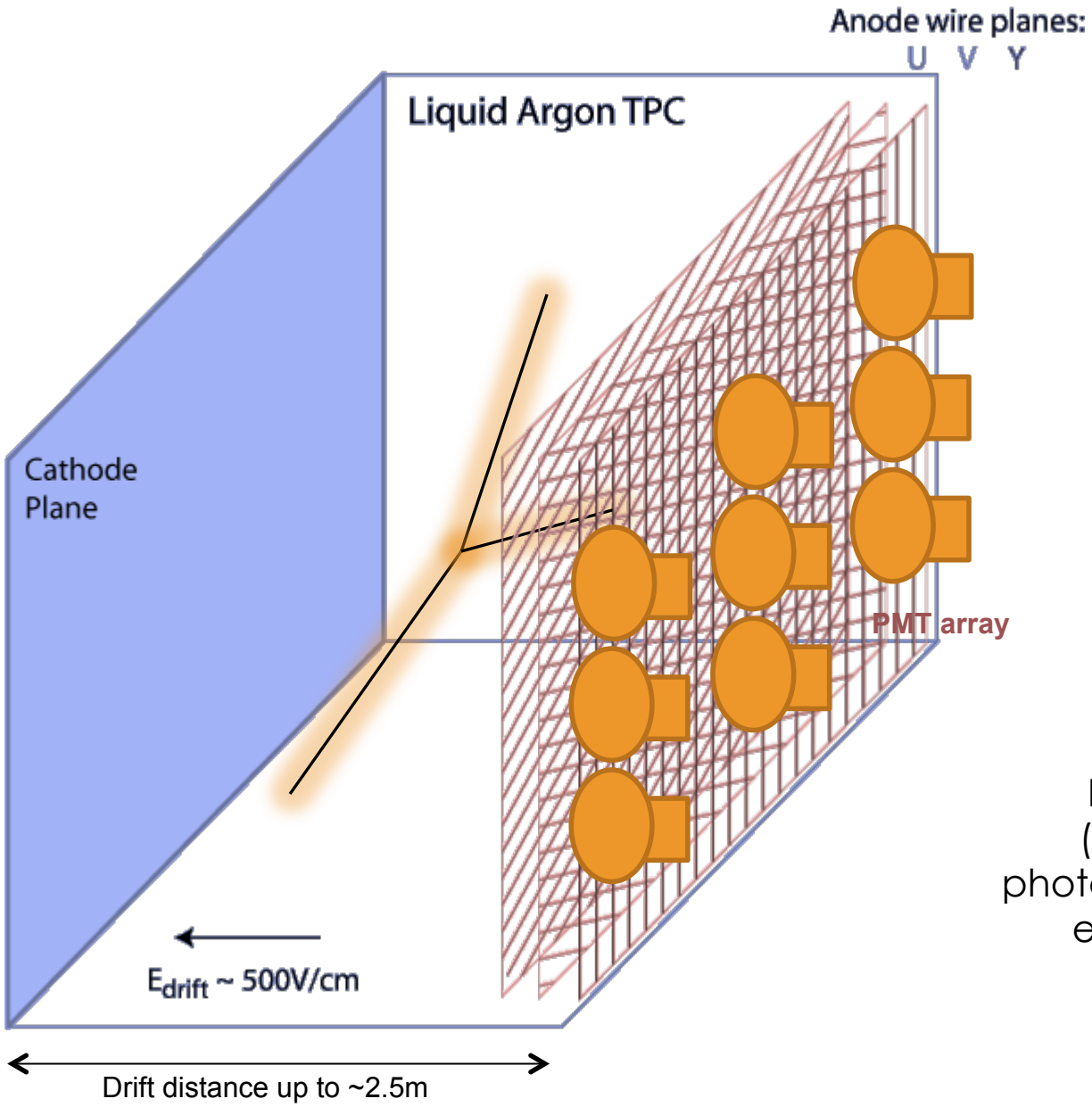
112 tons

LArTPC working principle



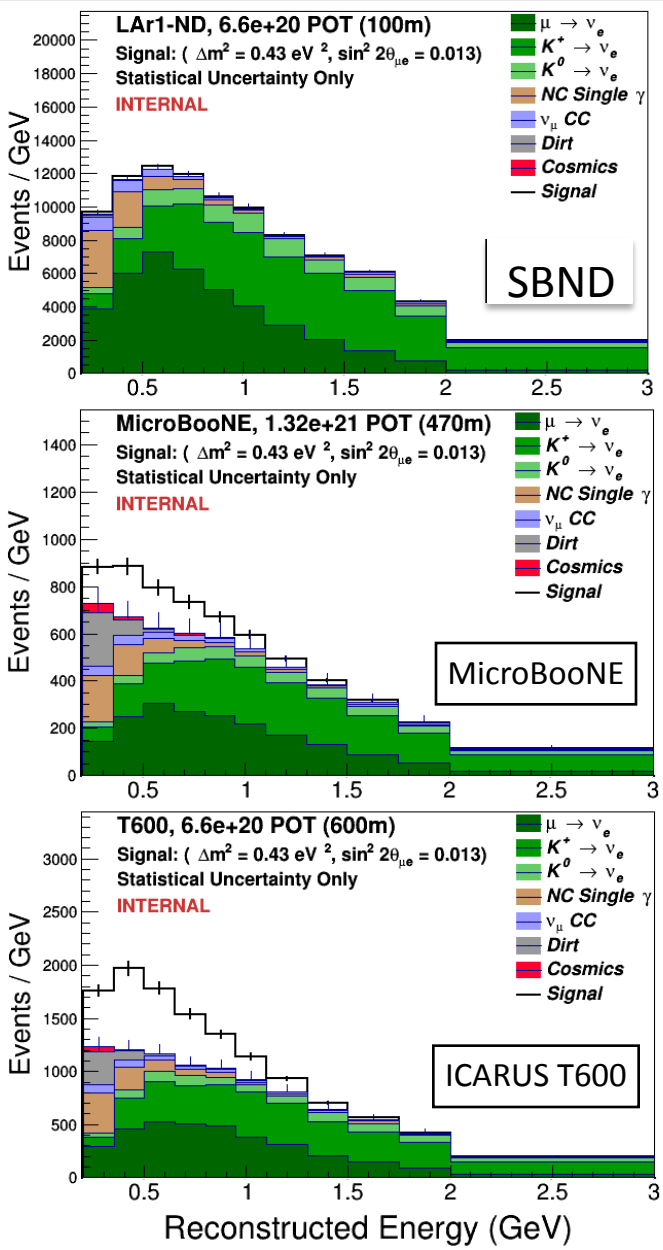
Charged particle tracks produced in neutrino interactions ionize argon atoms; **ionization charge** drifts to **finely segmented charge collection planes** over ~1-few ms.

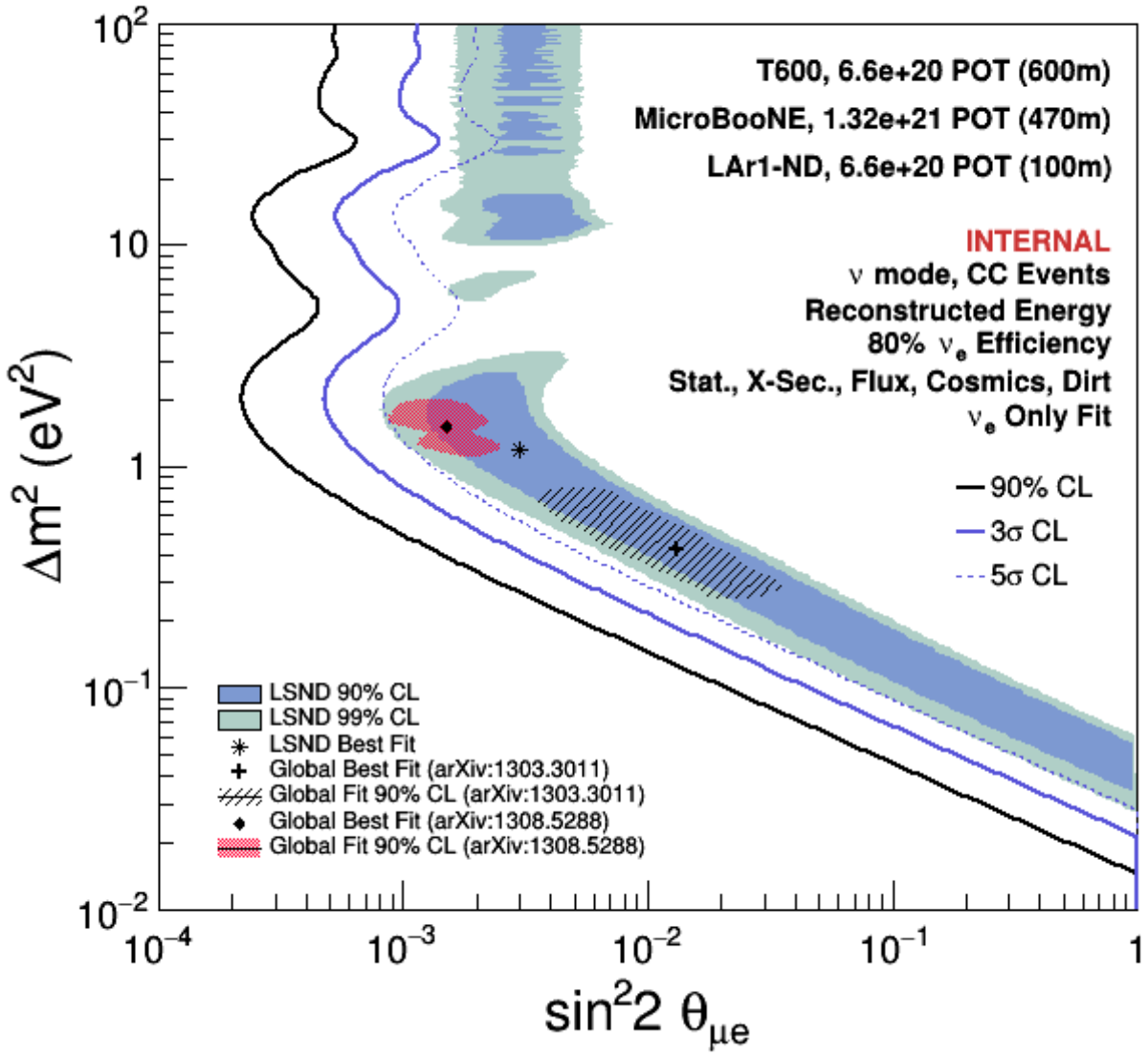
LArTPC working principle



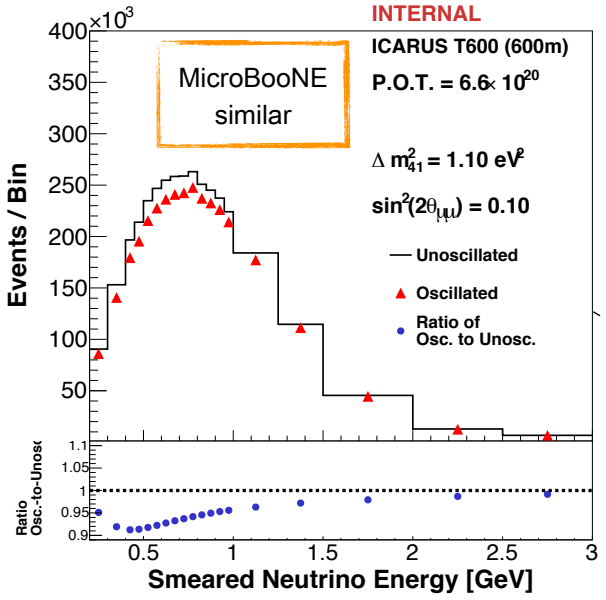
Prompt **scintillation light** (~few ns) is detected by photo-sensitive detectors for event t_0, drift coordinate determination, and triggering

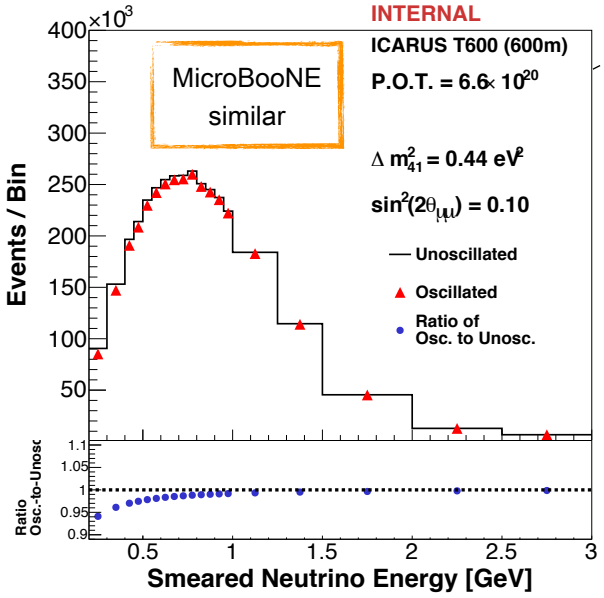
ν_e Appearance Sensitivity

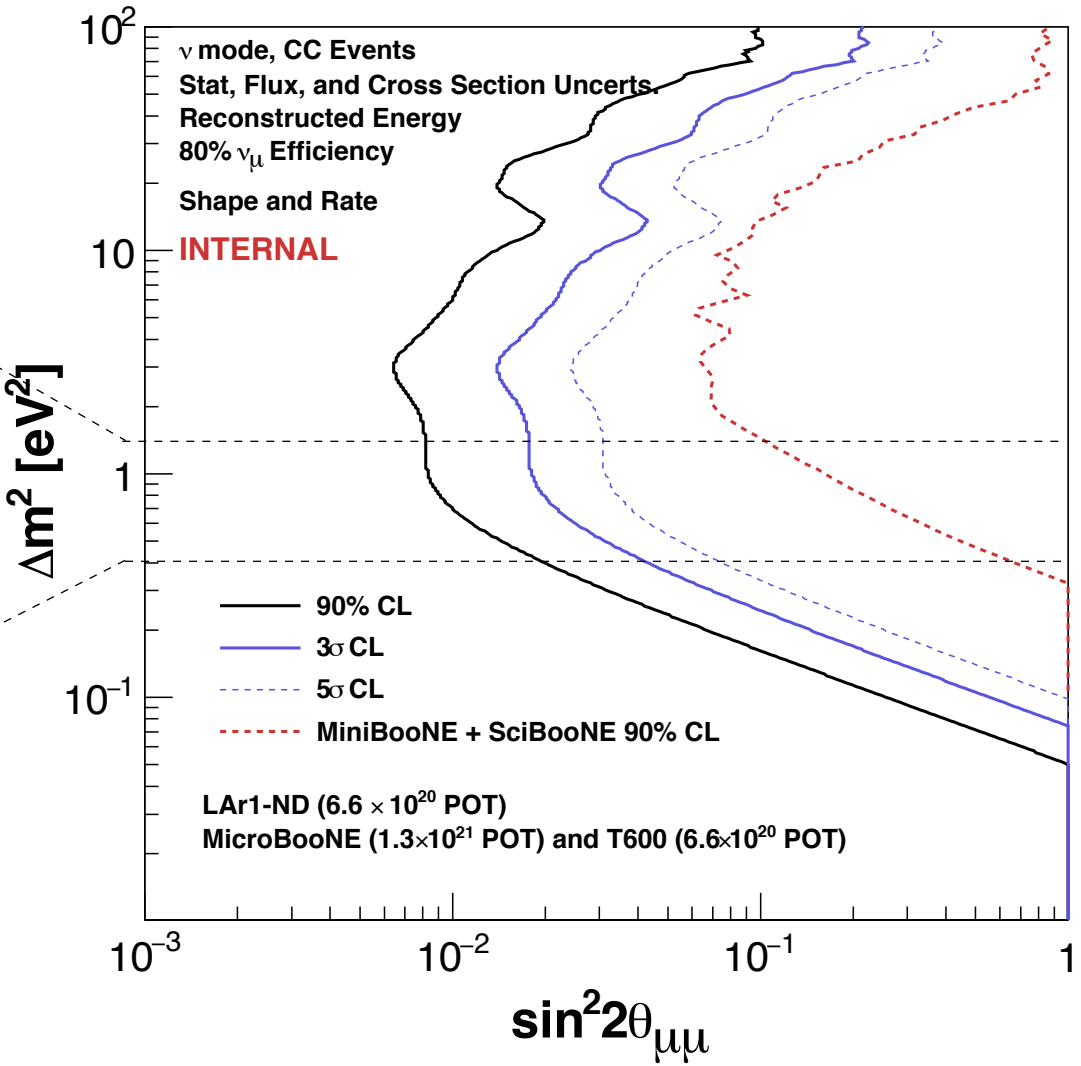




ν_μ Disappearance Sensitivity







Sensitivity includes full flux and cross section systematics, but not detector systematics at this time.

Coherent CAPTAIN-Mills Experiment

- Search the muon disappearance channel : $\nu_\mu \rightarrow \nu_s$
- Monoenergetic neutrinos from pion decay at rest:

$$\mu^+ \longleftarrow \pi^+ \xrightarrow[E_{\nu_\mu} = 30\ \mathrm{MeV}]{\nu_\mu}$$

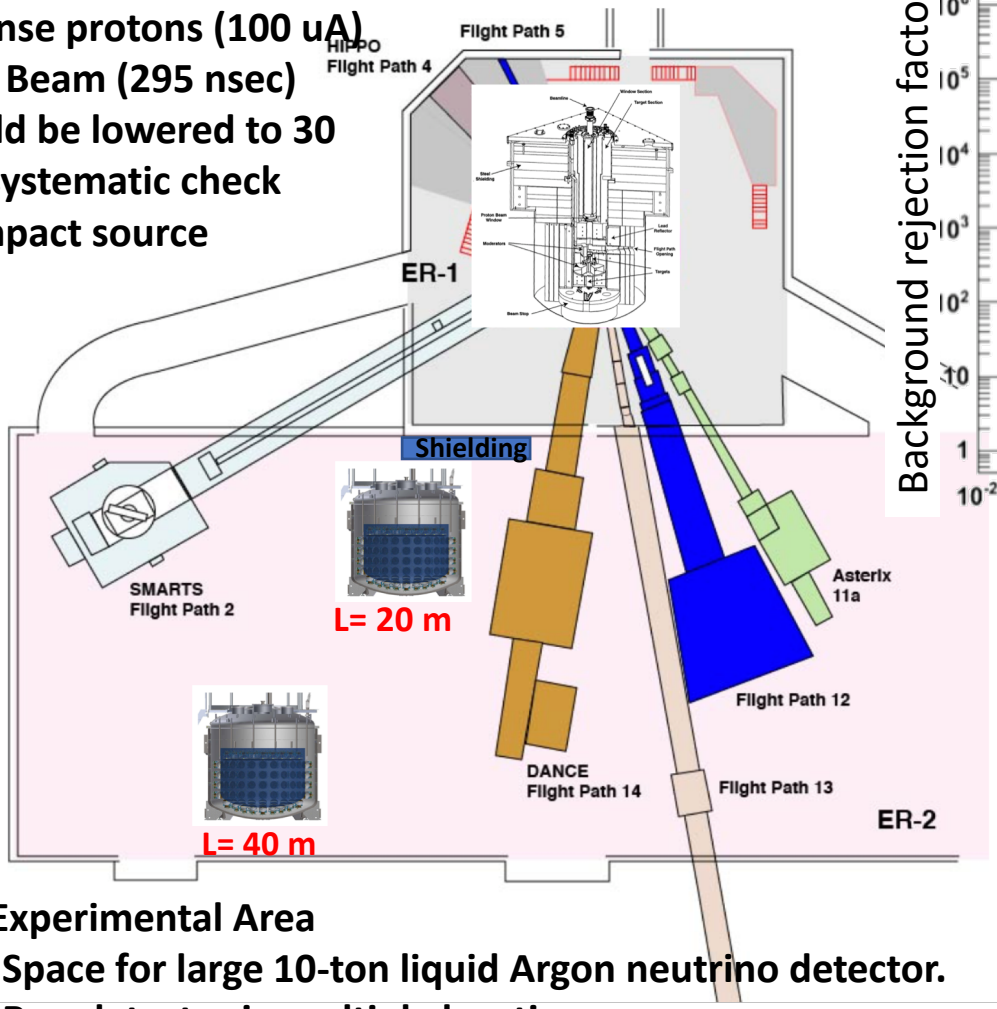
- Using Coherent Elastic Neutrino-Nucleus Scattering (CEvNS):

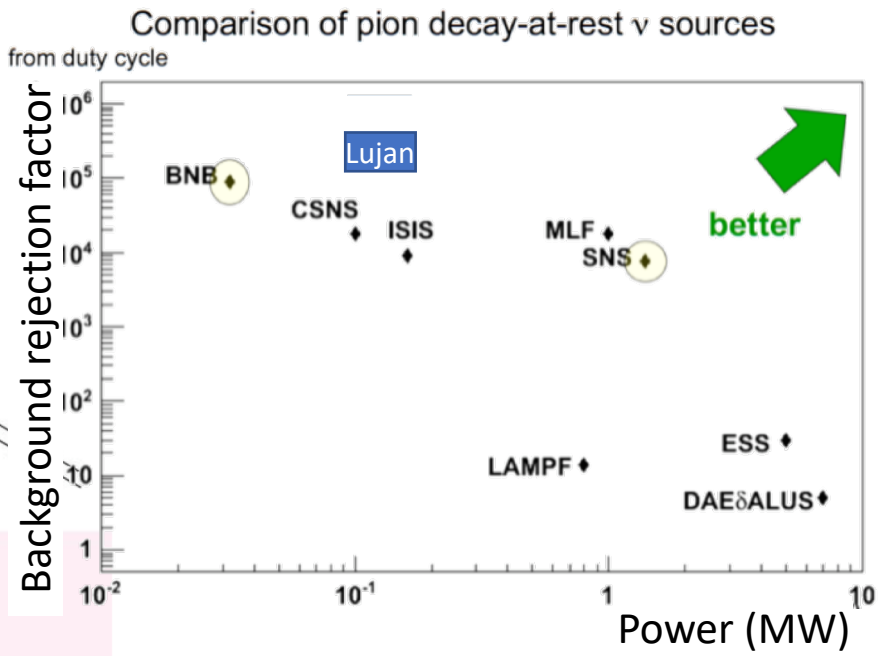
- Movable detector for baseline between 20-40m
  - L/E between 0.65 – 1.35

Lujan Center @ Los Alamos

Lujan Target

- **Intense protons (100 uA)**
- **Fast Beam (295 nsec)**
- **Could be lowered to 30 ns for systematic check**
- **Compact source**



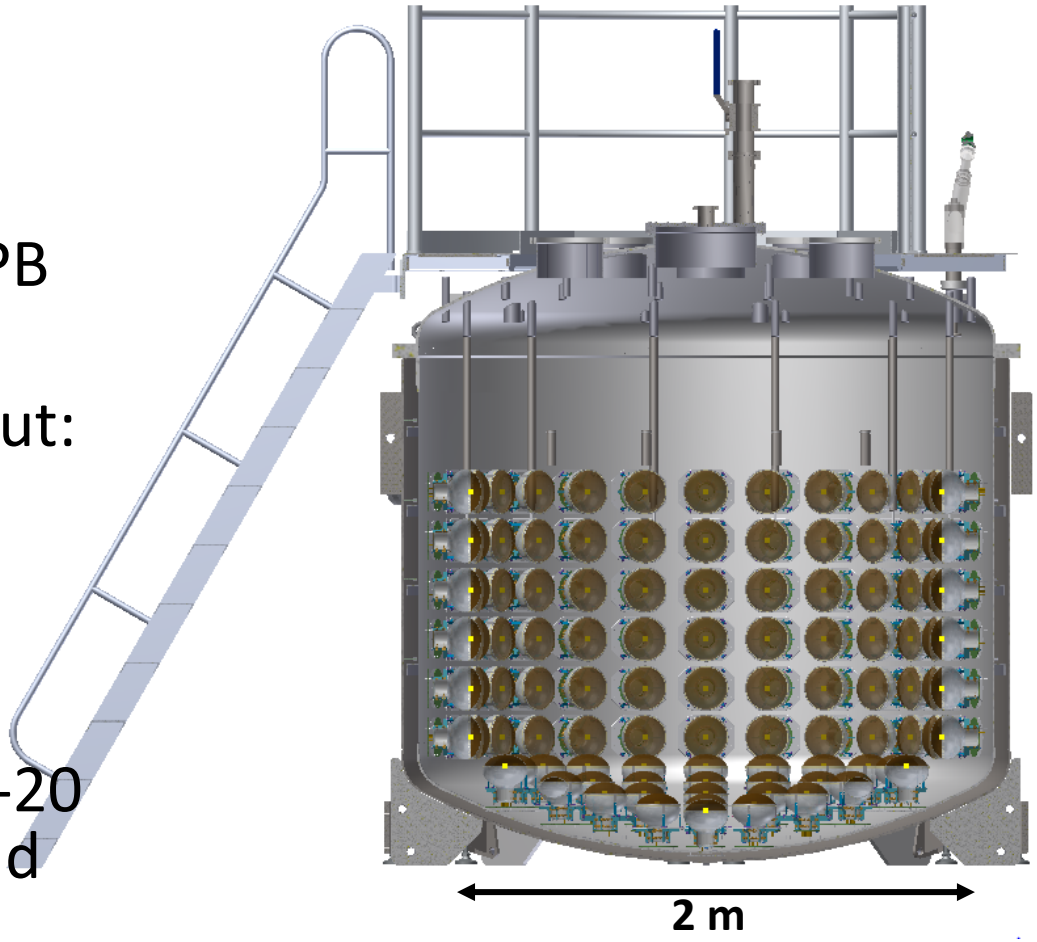


Lujan Experimental Area

- **Space for large 10-ton liquid Argon neutrino detector.**
- **Run detector in multiple locations**
- **Room for shielding, large overhead crane**

Coherent Captain Mills: Detector

- 7 tons LAr fiducial volume, 3 tons LAr veto (2-3 radiation length)
- 220 R5912 PMTs
- Wavelength shifting TPB foils
- Scintillation Light output: 40 photons/keV
  - Fast: 6 ns
  - Slow: 1 μs
- Detailed RAT/GEANT4 simulation predicts 10-20 keV detection threshold



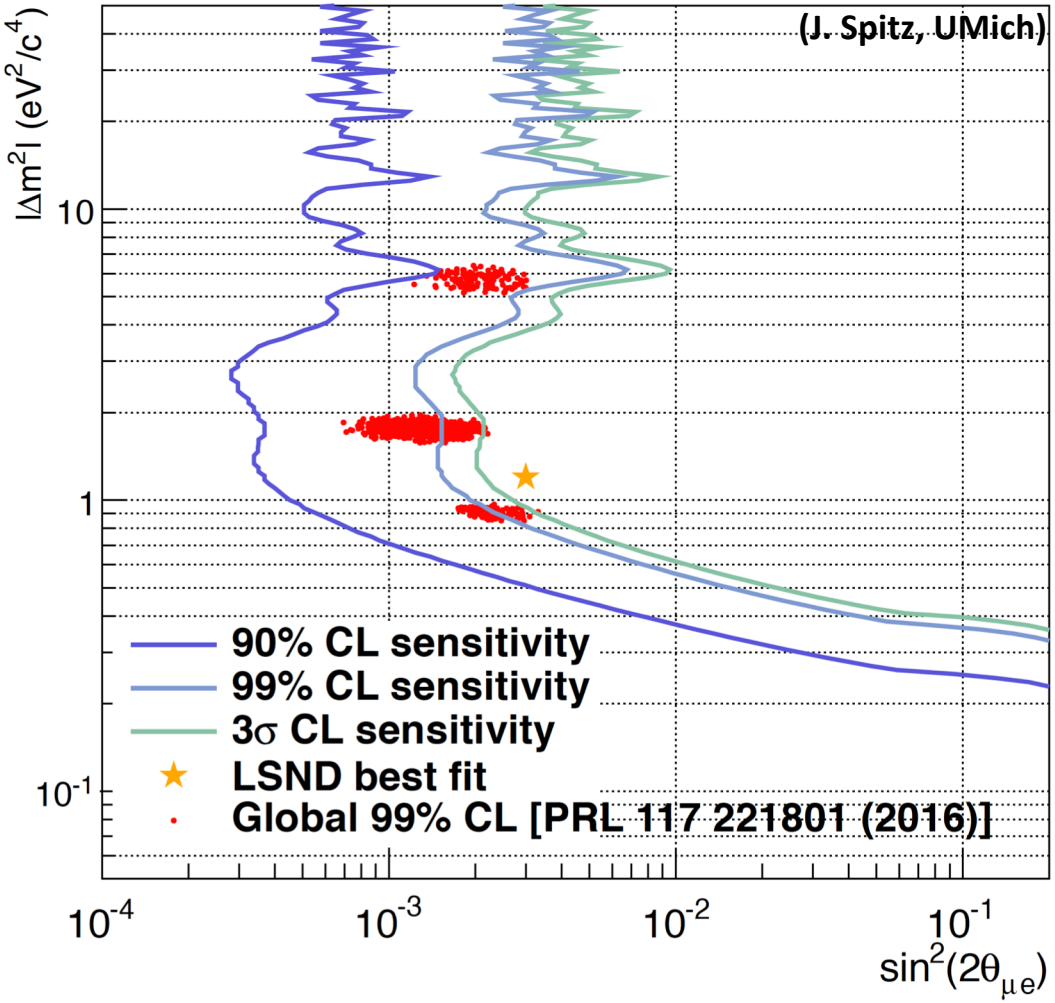
Expected Event Rates(Preliminary)

- 80 kW @ 1 beam year, 7 tons fiducial LAr

Reaction	L = 20 m (events/yr)	L = 40 m (events/yr)
Coherent ν_μ (E = 30 MeV)	2709	677
Coherent $\nu_e + \bar{\nu}_\mu$	9482	2370
Charged Current ν_e	257	64
Neutral Current ν_μ	36	18
Neutral Current $\bar{\nu}_\mu$	79	20

Large LAr **coherent elastic neutrino-nucleus scattering (CEvNS**) cross sections -> 1000's events!

Sensitivity



- **~3σ sensitivity for 3 year run at LSND best fit point**
- **5σ for five year run**
- **Can rule out world best fit at better than 90%**

Conclusions

- MiniBooNE confirms LSND excess at 4.7σ, with a combined significance of 6.0σ.
- MiniBooNE continues data-taking, and analysis in the future will include time-of-flight information to better constrain backgrounds.
- MicroBooNE will confirm whether excess is due to electrons or photons.
- SBN will confirm whether the excess is due to neutrino oscillations.
- CCM will search for ν_μ disappearance with 30 MeV monoenergetic neutrinos.
- Thanks to Fermilab for 15 years of MiniBooNE operation & for great beam delivery (approaching 3x10^{21} POT)!

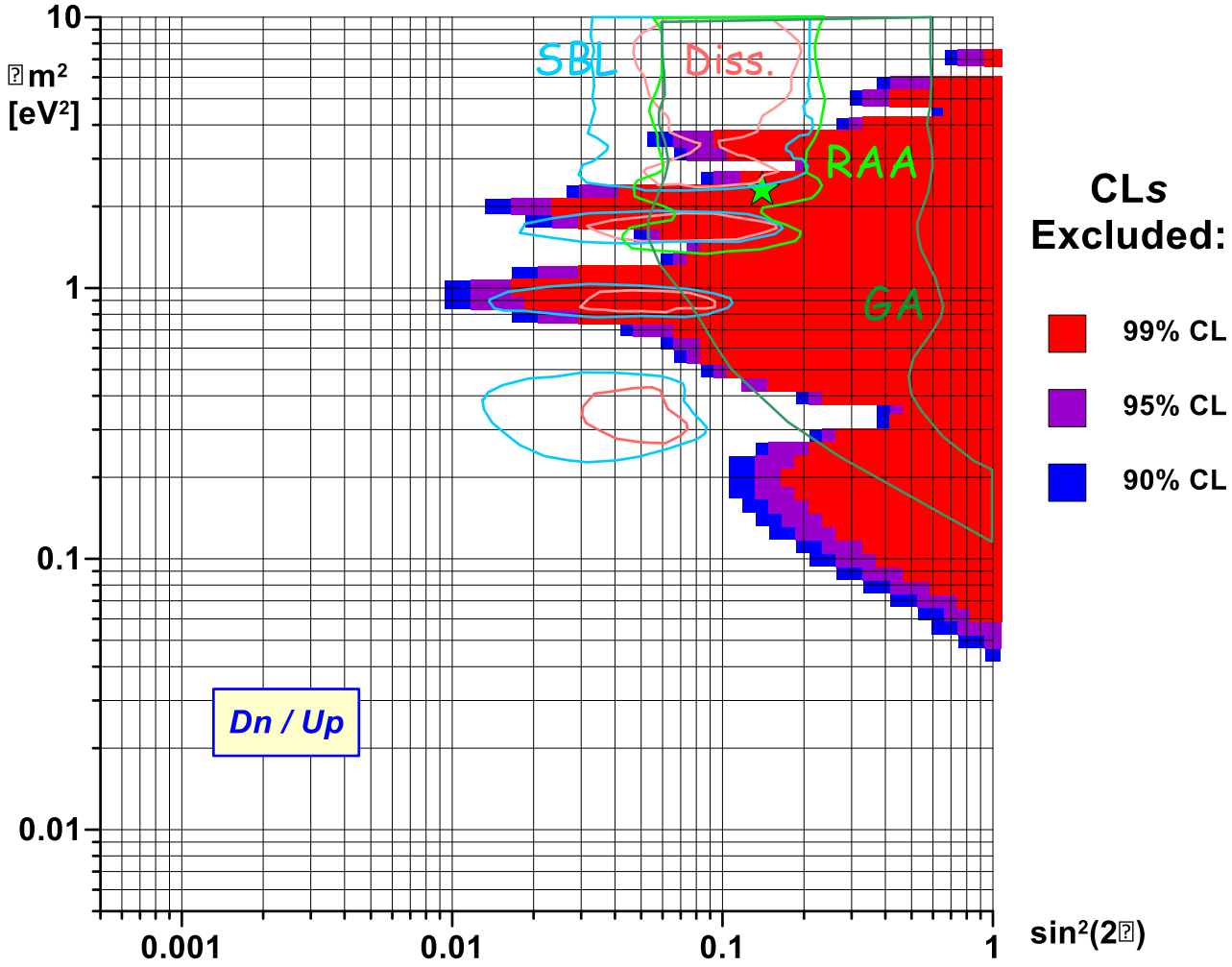
Backup

TABLE I: *The expected (unconstrained) number of events for the* $200 < E_\nu^{QE} < 1250$ *MeV neutrino energy range from all of the backgrounds in the* ν_e *and* $\bar{\nu}_e$ *appearance analysis before using the constraint from the CC* ν_μ *events. Also shown are the constrained background, as well as the expected number of events corresponding to the LSND best fit oscillation probability of 0.26%, assuming oscillations at large* Δm^2*. The table shows the diagonal-element systematic plus statistical uncertainties, which become substantially reduced in the oscillation fits when correlations between energy bins and between the electron and muon neutrino events are included. The antineutrino numbers are from a previous analysis [3].*

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \rightarrow N\gamma$	172.5 ± 24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	425.3 ± 100.2	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	192.2 ± 41.9	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K_L^0 Decay	54.5 ± 20.5	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	6.0 ± 3.2	6.7 ± 6.0
Unconstrained Bkgd.	1590.6 ± 176.9	398.2 ± 49.7
Constrained Bkgd.	1577.8 ± 85.2	398.7 ± 28.6
Total Data	1959	478
Excess	381.2 ± 85.2	79.3 ± 28.6
0.26% (LSND) $\nu_\mu \rightarrow \nu_e$	463.1	100.0

DANSS Reactor Neutrino Experiment

V.Egorov Talk at Neutrino 2018



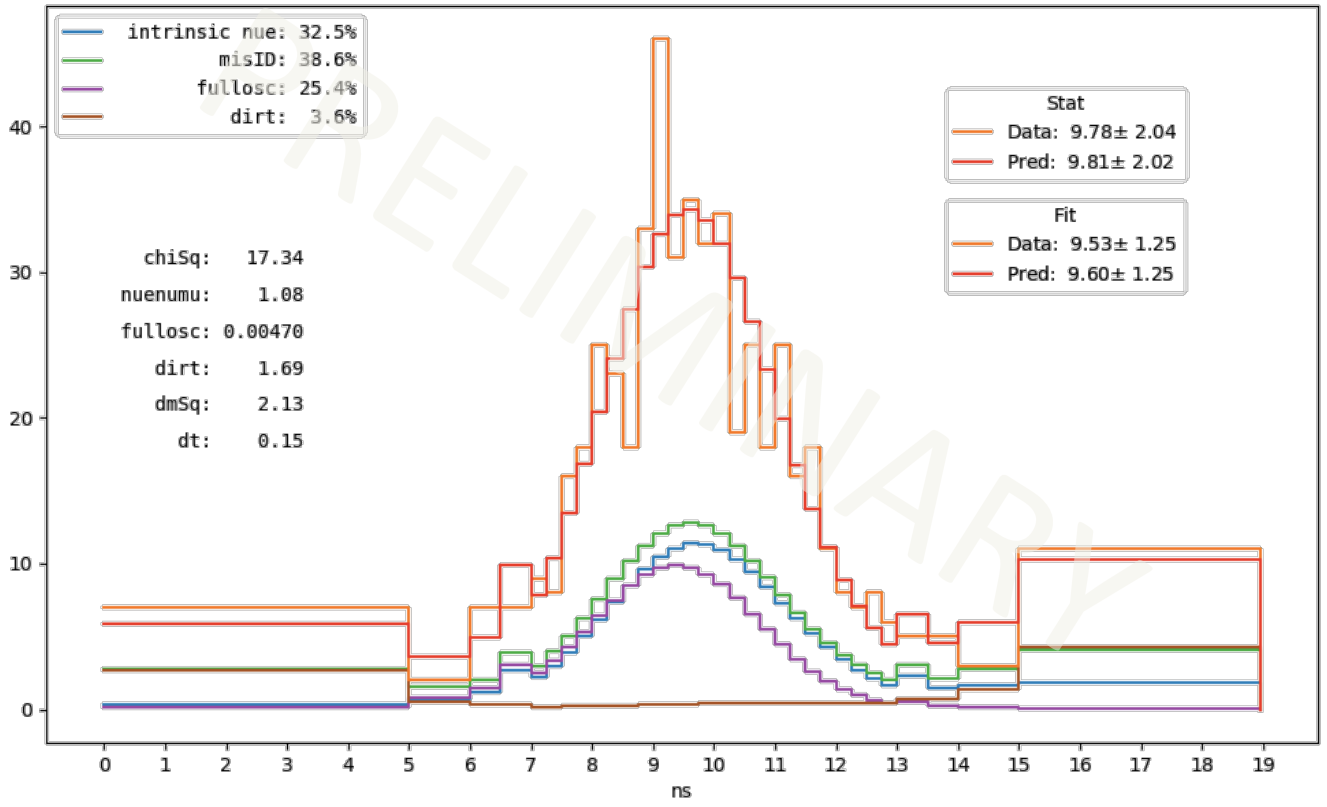
DANSS best fit at ($\sin^2 2\theta, \Delta m^2$) = (0.05,1.4 eV^2) is 2.8σ better than null

New vs Old Excess

- Excess in old $6.46\times10\hat{}20$: $162.0\pm28.1\pm38.7$
- Excess in new $6.38\times10\hat{}20$: $235.8\pm28.1\pm38.1$
- Average excess$\approx200\pm30$
- Previous dataset sees a -1σ excess, while current dataset sees a +1σ excess

Could it be Dirt?

- Constrained at ~10% by internal measurements
- Time-of-flight measurement is consistent with dirt background estimate of 4%



Could it be Pi0?

Phys.Rev.D81:013005,2010

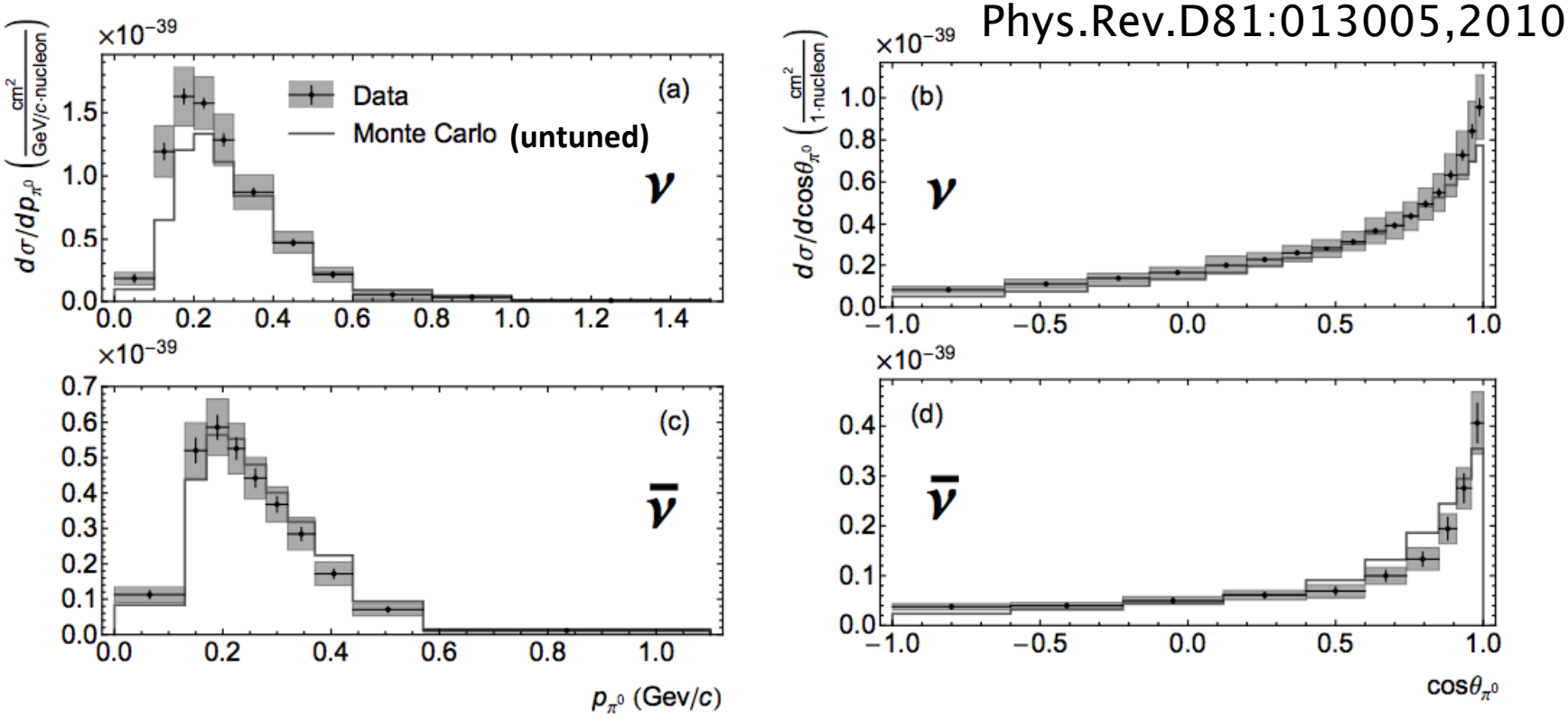


FIG. 7: Flux-averaged absolute differential cross sections for NC $1\pi^0$ production on CH_2 including the effects of FSI. Data are shown as black dots with statistical error bars and systematic error boxes. The dark-gray line is the Monte Carlo prediction[33] using R-S models of single pion production[2, 5] modified as described in the text. (a) $\frac{d\sigma}{dp_{\pi^0}}$ for ν_μ-induced production. (b) $\frac{d\sigma}{d\cos\theta_{\pi^0}}$ for ν_μ-induced production. (c) $\frac{d\sigma}{dp_{\pi^0}}$ for $\bar{\nu}_\mu$-induced production. (d) $\frac{d\sigma}{d\cos\theta_{\pi^0}}$ for $\bar{\nu}_\mu$-induced production. The numerical values for the cross sections appear in Appendix C and are also available at the MiniBooNE website[43].

Could it be Nue?

- Nue has small contribution at low energy
- Nue is constrained from SciBooNE measurements of Kaon decay
- Nue is constrained by well-measured Numu

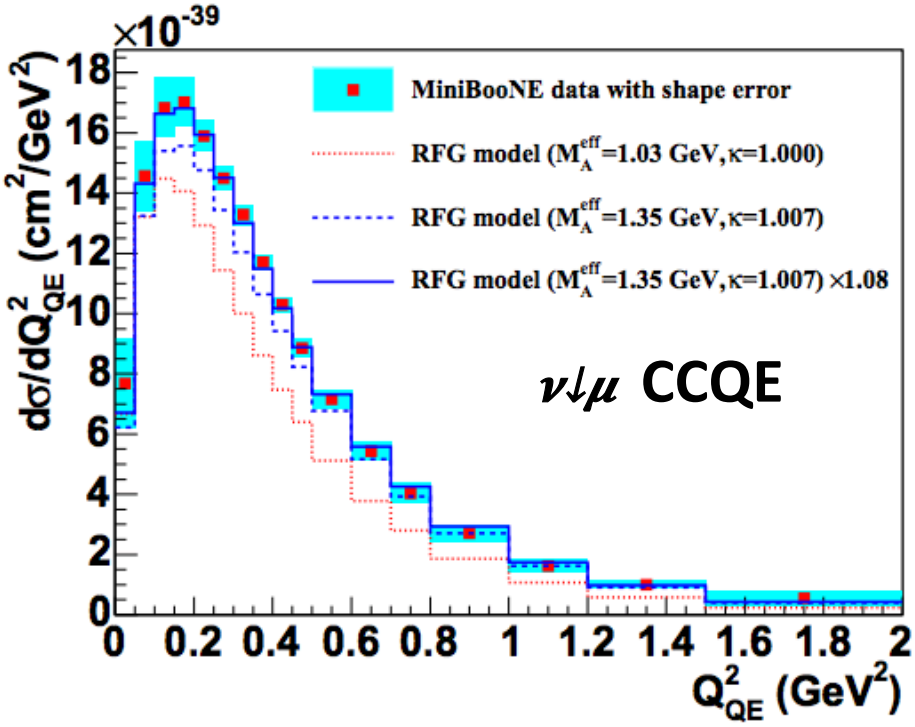


FIG. 14: (Color online). Flux-integrated single differential cross section per target neutron for the ν_μ CCQE process. The measured values are shown as points with the shape error as shaded bars. Calculations from the NUANCE RFG model with different assumptions for the model parameters are shown as histograms. Numerical values are provided in Table IX in the Appendix.

Phys.Rev.D81:092005,2010

Could it be NC gamma?

Table 2
E_ν^{QE} distributions of the NCγ events at MiniBooNE. Our predictions for the different partial contributions, their sum with the 68% CL error band, and the results without N^* are displayed. In addition, the lower $(\Delta + N)$ and upper (Full) limits in the calculation of Ref. [14] and the MiniBooNE estimate are shown. The asterisk (*) stands for figures obtained with $E_\nu^{QE} < 1.25$ GeV rather than 1.3 GeV.

E_ν^{QE} (GeV)	ν mode			$\bar{\nu}$ mode		
	[0.2, 0.3]	[0.3, 0.475]	[0.475, 1.3]	[0.2, 0.3]	[0.3, 0.475]	[0.475, 1.3]
p(ν_μ)	2.94	9.11	4.69	0.31	0.95	0.58
inc(ν_μ)	11.01	32.70	22.47	1.16	3.38	2.67
coh(ν_μ)	1.38	5.83	1.52	0.15	0.59	0.16
p($\bar{\nu}_\mu$)	0.03	0.11	0.06	0.85	2.76	1.23
inc($\bar{\nu}_\mu$)	0.14	0.38	0.23	3.26	9.35	5.09
coh($\bar{\nu}_\mu$)	0.03	0.10	0.02	0.85	2.53	0.47
Total	15.54	48.23	29.98	6.58	19.55	10.16
Error band	[12.96, 18.12]	[42.42, 54.03]	[25.79, 33.48]	[5.04, 8.12]	[16.63, 22.48]	[8.80, 12.25]
no N^*	15.27	47.31	26.60	6.36	19.09	9.03
Zhang($\Delta + N$) [14]	17.6	43.1	19.3*	6.8	16.7	6.0*
Zhang (Full) [14]	21.4	51.9	37.5*	9.1	22.0	18.0*
MiniBooNE [20]	19.5	47.4	19.9	8.8	16.9	6.9

Theoretical Estimates for NC gamma production
agree well with MiniBooNE estimates

Could it be NC gamma?

Table 4
E_γ distribution of the NC photon events in the MiniBooNE neutrino run, comparing our estimate to the MiniBooNE estimate [1,35].

E_γ (GeV)	coh	inc	H	Total	MiniBN	Excess
[0.1, 0.2]	0.72 (1.5)	14.0 (15.0)	4.4 (4.6)	19.1 (21.1)	10.6	52.5
[0.2, 0.3]	3.2 (5.5)	22.7 (25.2)	7.8 (8.5)	33.7 (39.2)	32.5	61.2
[0.3, 0.4]	3.7 (5.4)	12.7 (15.0)	5.0 (5.6)	21.4 (26.0)	24.7	58.4
[0.4, 0.5]	1.0 (1.7)	5.4 (7.3)	2.1 (2.4)	8.5 (11.4)	12.7	−9.7
[0.5, 0.6]	0.32 (1.0)	2.3 (3.9)	0.75 (1.0)	3.4 (5.9)	4.4	10.5

Table 5
E_γ distribution of the NC photon events in the MiniBooNE antineutrino run, comparing our estimate to the MiniBooNE estimate [1,35].

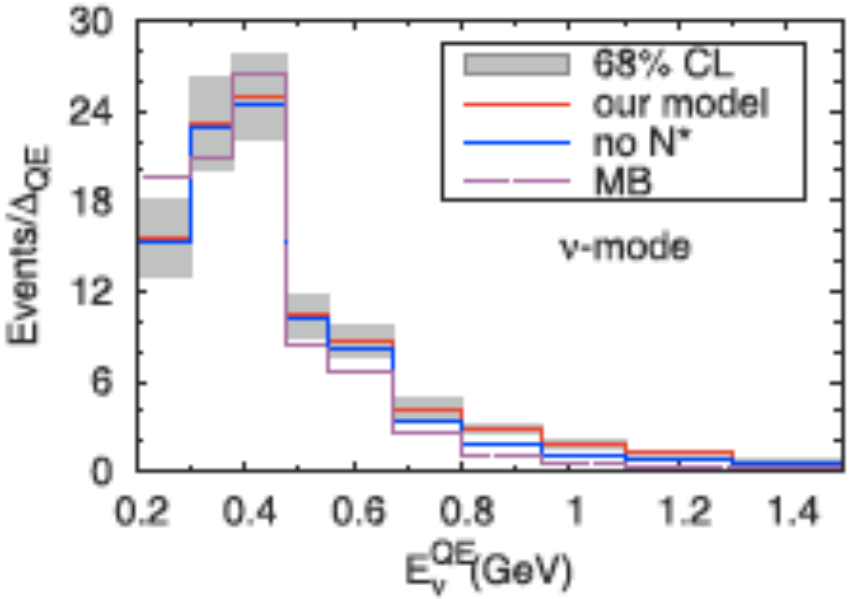
E_γ (GeV)	coh	inc	H	Total	MiniBN	Excess
[0.1, 0.2]	0.55 (1.2)	4.9 (5.5)	1.4 (1.6)	6.9 (8.3)	4.3	18.8
[0.2, 0.3]	2.0 (3.8)	8.7 (10.3)	2.9 (3.3)	13.6 (17.4)	14.3	22.6
[0.3, 0.4]	1.8 (3.0)	4.0 (5.4)	1.5 (1.8)	7.3 (10.2)	9.1	11.5
[0.4, 0.5]	0.36 (1.0)	1.3 (2.6)	0.43 (0.66)	2.1 (4.3)	3.6	18.7
[0.5, 0.6]	0.10 (0.72)	0.51 (1.7)	0.14 (0.36)	0.75 (2.8)	1.1	8.4

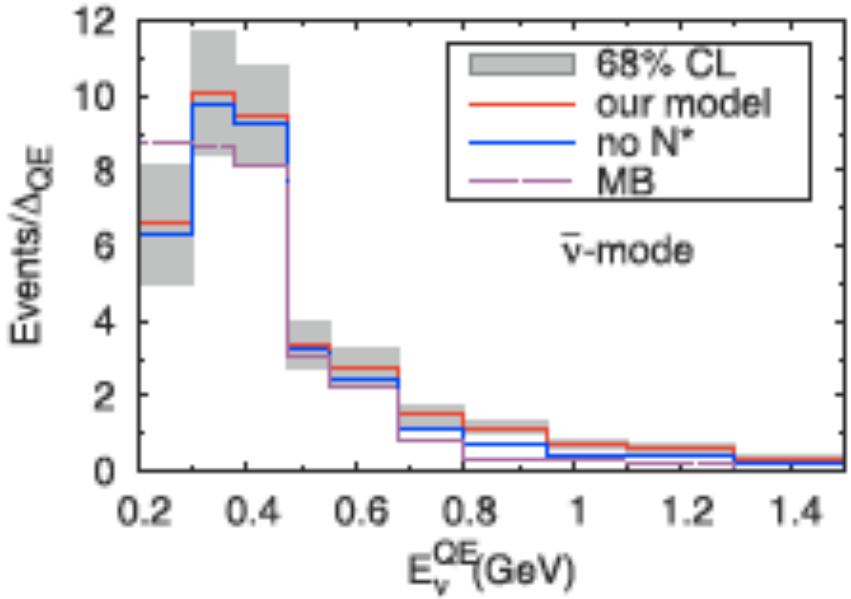
Could it be NC gamma?

Single photon events from neutral current interactions at MiniBooNE

En Wang, Luis Alvarez-Ruso*, Juan Nieves

Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia, Institutos de Investigación de Paterna, Apartado 22085, E-46071 Valencia, Spain



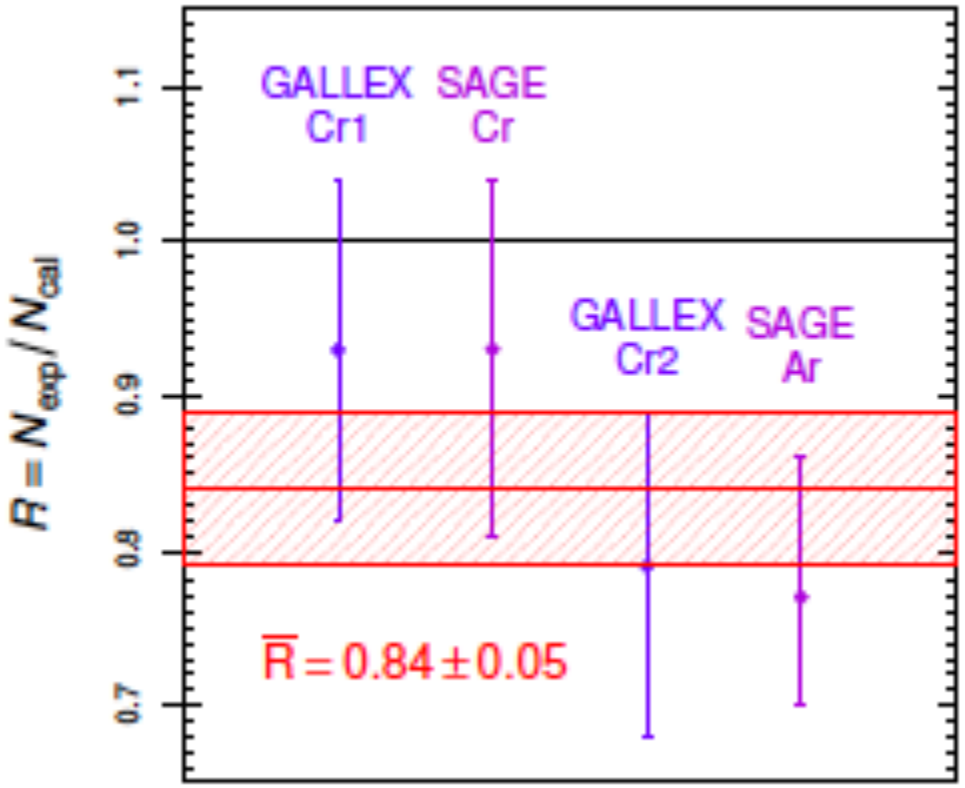


Theoretical Estimates of Single γ Production

- B. D. Serot and X. Zhang, arXiv:1110.2760 [nucl-th].
- B. D. Serot and X. Zhang, Phys. Rev. C 86, 015501 (2012) [arXiv:1206.3812 [nucl-th]].
- X. Zhang and B. D. Serot, Phys. Rev. C 86, 035504 (2012) [arXiv:1208.1553 [nucl-th]].
- X. Zhang and B. D. Serot, Phys. Rev. C 86, 035502 (2012) [arXiv:1206.6324 [nucl-th]].
- X. Zhang and B. D. Serot, Phys. Lett. B 719, 409 (2013) [arXiv: 1210.3610 [nucl-th]].

Gallium Anomaly

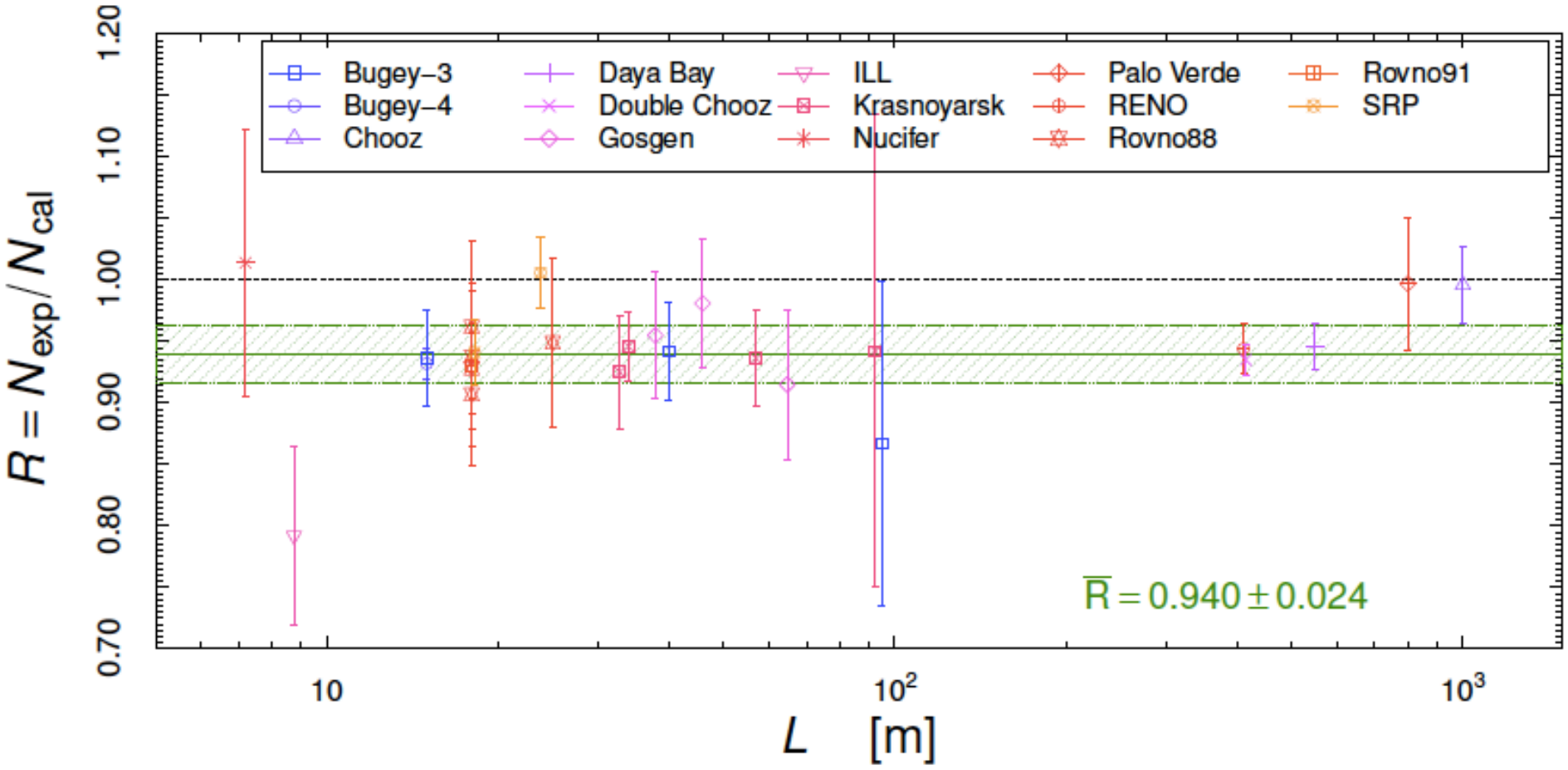
S. Gariazzo, C. Giunti, M. Laveder, Y. F. Li, & E. M. Zavanin, arXiv:1507.08204



GALLEX & SAGE observe fewer events than expected from their calibration measurements, consistent with ν_e disappearance to sterile neutrinos

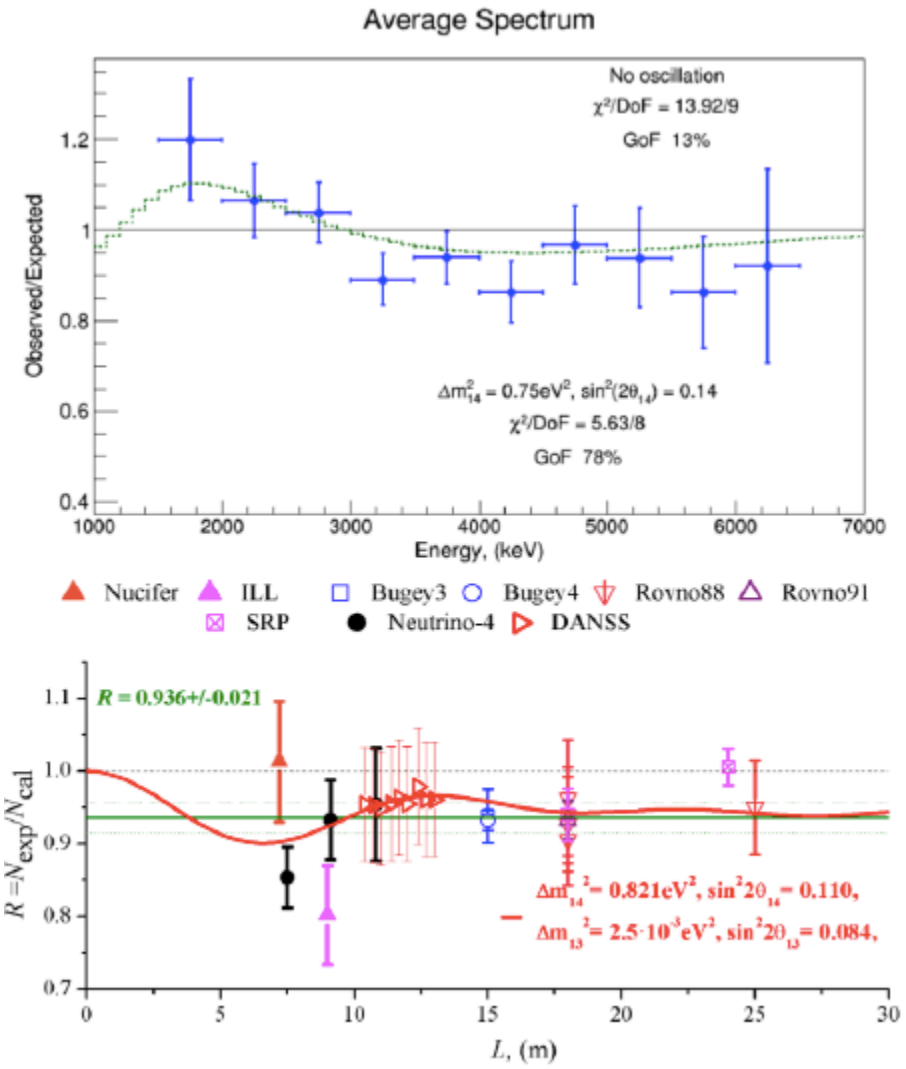
Reactor Neutrino Anomaly

S. Gariazzo, C. Giunti, M. Laveder, & Y. F. Li, arXiv:1703.00860



Neutrino-4 Results

arXiv:1708.00421



$\Delta m^2_{14} \approx 0.75 eV^2$

$\sin^2 2\theta_{14} \approx 0.14$

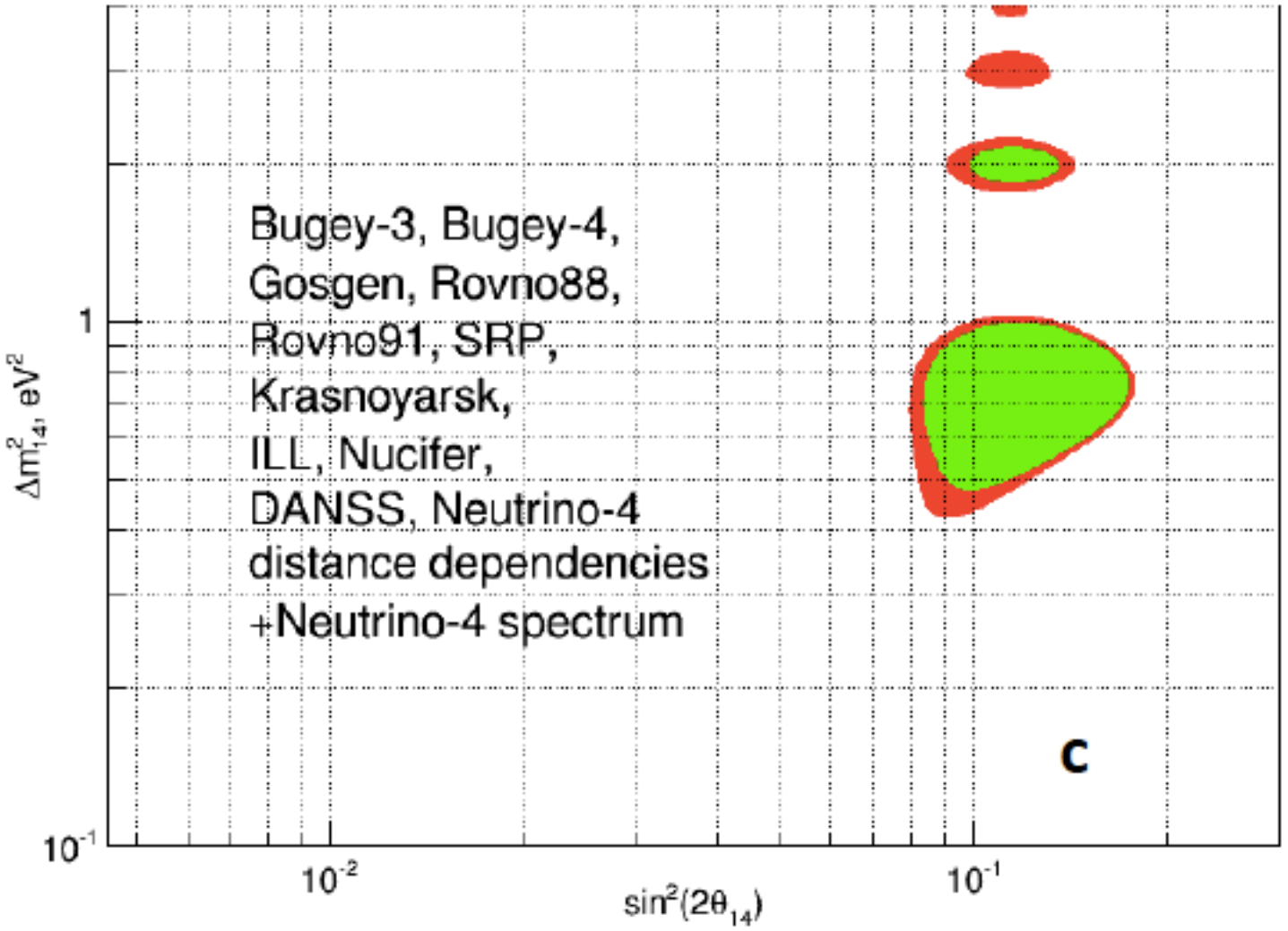
? !

$\Delta m^2_{14} \approx 0.82 eV^2$

$\sin^2 2\theta_{14} \approx 0.11$

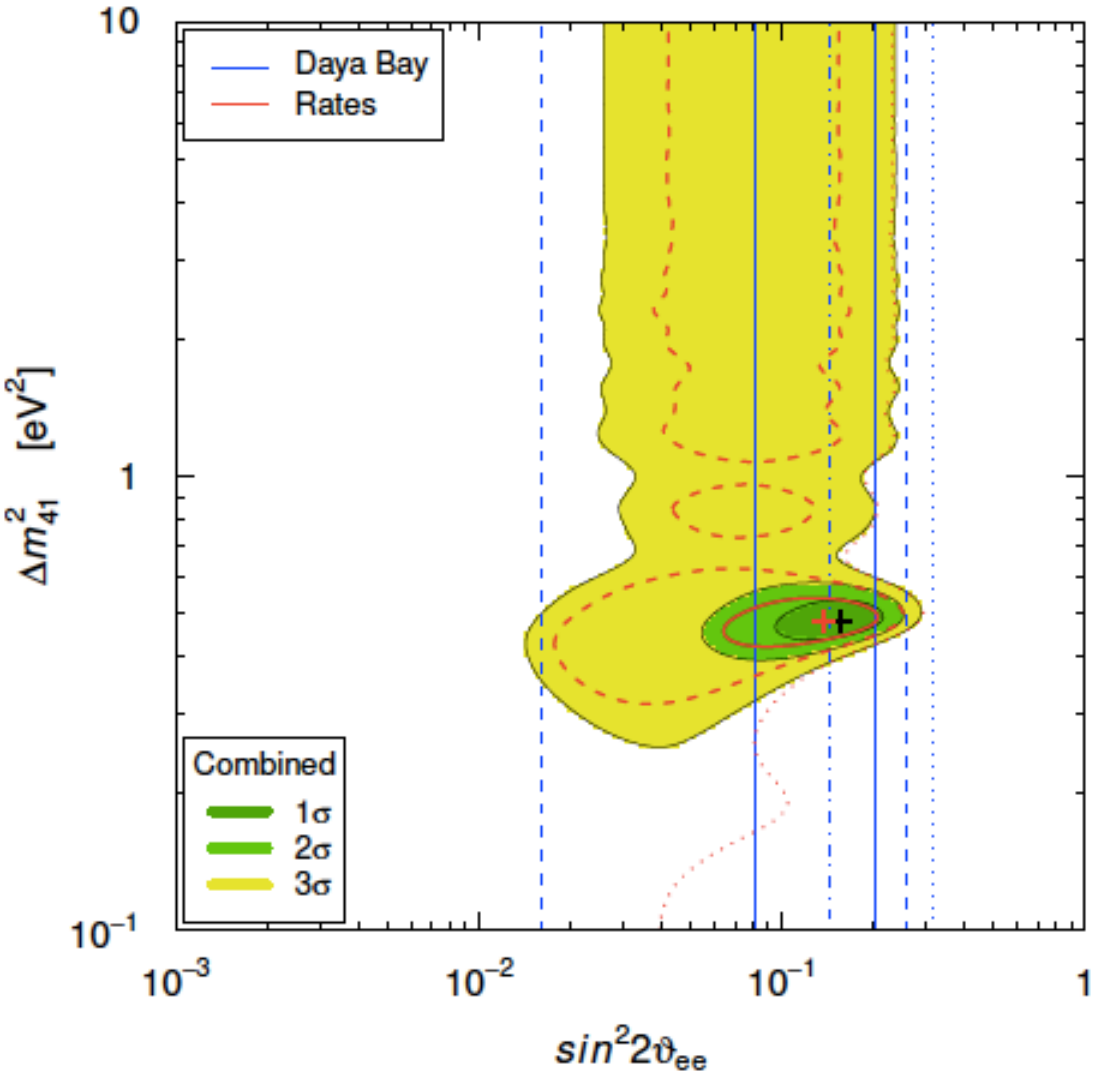
Neutrino-4 Results

arXiv:1708.00421



Reactor Fuel Fraction Information on the Antineutrino Anomaly

Giunti, Ji, Laveder, Li, & Littlejohn, arXiv:1708.01133



Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\Sigma_i\Sigma_j \left|U_{\alpha i}\, U^*_{\beta i}\, U^*_{\alpha j}\, U_{\beta j}\right| \sin^2(1.27\Delta m^2_{ij} L/E_\nu)$$

As #ν increases, the formalism gets rapidly more complicated!

#ν	#Δm^2_{ij}	#θ_{ij}	#CP Phases
2	1	1	0
3	2	3	1
4	3	6	3
5	4	10	6
6	5	15	10

Therefore, there needs to be ≥ 3 neutrino mixing for CP Violation!

3+N Models With ν_e Appearance Require Large ν_e & ν_μ Disappearance!

In general, $P(\nu_\mu \rightarrow \nu_e) \sim \frac{1}{4} P(\nu_\mu \rightarrow \nu_x) P(\nu_e \rightarrow \nu_x)$

Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.

For 3+2 Models:
arXiv:1207.4765

$$
\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\beta) \simeq & -4|U_{\alpha 5}||U_{\beta 5}||U_{\alpha 4}||U_{\beta 4}| \cos\phi_{54} \sin^2(1.27\Delta m^2_{54} L/E) \\
& +4(|U_{\alpha 4}||U_{\beta 4}| + |U_{\alpha 5}||U_{\beta 5}| \cos\phi_{54})|U_{\alpha 4}||U_{\beta 4}| \sin^2(1.27\Delta m^2_{41} L/E) \\
& +4(|U_{\alpha 4}||U_{\beta 4}| \cos\phi_{54} + |U_{\alpha 5}||U_{\beta 5}|)|U_{\alpha 5}||U_{\beta 5}| \sin^2(1.27\Delta m^2_{51} L/E) \\
& +2|U_{\beta 5}||U_{\alpha 5}||U_{\beta 4}||U_{\alpha 4}| \sin\phi_{54} \sin(2.53\Delta m^2_{54} L/E) \\
& +2(|U_{\alpha 5}||U_{\beta 5}| \sin\phi_{54})|U_{\alpha 4}||U_{\beta 4}| \sin(2.53\Delta m^2_{41} L/E) \\
& +2(-|U_{\alpha 4}||U_{\beta 4}| \sin\phi_{54})|U_{\alpha 5}||U_{\beta 5}| \sin(2.53\Delta m^2_{51} L/E) \ ,
\end{aligned}
$$

ϕ_{54} is the CP Phase angle

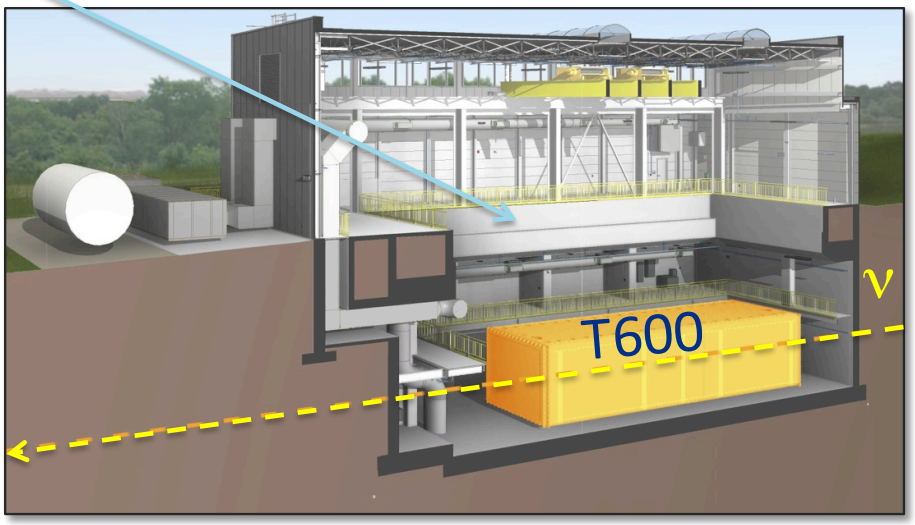
$$
\begin{aligned}
P(\nu_\alpha \rightarrow \nu_\alpha) \simeq & \ 1 - 4|U_{\alpha 4}|^2|U_{\alpha 5}|^2 \sin^2(1.27\Delta m^2_{54} L/E) \\
& -4(1 - |U_{\alpha 4}|^2 - |U_{\alpha 5}|^2)(|U_{\alpha 4}|^2 \sin^2(1.27\Delta m^2_{41} L/E) \\
& +|U_{\alpha 5}|^2 \sin^2(1.27\Delta m^2_{51} L/E)) \ .
\end{aligned}
$$

MicroBooNE Liquid Argon TPC

Far Detector Building - GPP

- Close cooperation between ICARUS, CERN and Fermilab on design requirements and review.
- Designed for 3m concrete overburden over detector to mitigate cosmogenic backgrounds for near surface operation
- Milestones:
  - ✓ Aug 2014 Start preliminary design
  - ✓ Mar 2015 Design complete
  - ✓ July 2015 Construction Start
  - ✓ Sept 2015 Excavation complete
  - ✓ June 2016 Concrete complete
  - ✓ Nov 2016 Building envelope complete
  - ❑ Dec 2016 Beneficial Occupancy
  - ❑ Jan 2017 Project Complete

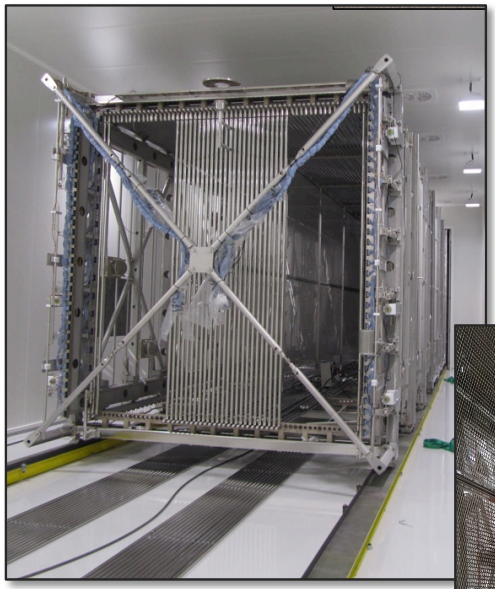
On track for completion on Budget



ICARUS Refurbishing at CERN (WA104)

- 1st TPC Module almost complete:
  - ✓ New cold vessel complete
  - ✓ Flattened cathodes
  - ✓ Replace internal TPC cabling
  - ✓ New 8” PMTs (90 per wire plane)
  - – Push into cold vessel (12/20)
  - – HV decoupling boards:
    - Technical problems: delay into 2017
- 2nd TPC module ready to start
  - – Cold vessel being welded
  - – Parts at CERN
  - – Start in January
- Ship both TPCs in cold vessels to Fermilab in April 2017
- New TPC readout electronics
  - – Ready to award fabrication contract

First TPC Module in CERN Cleanroom

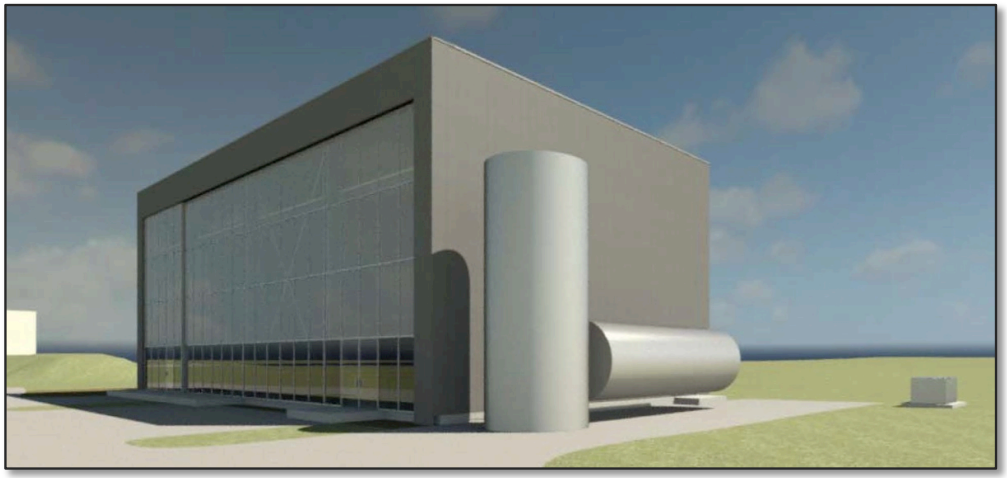


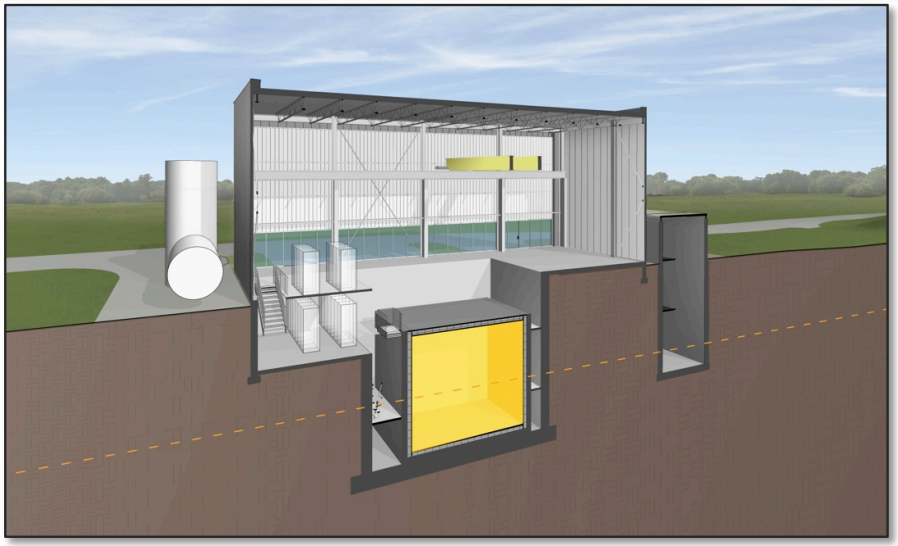
Tour of TPC 1
11/17/16

Near Detector Building - GPP

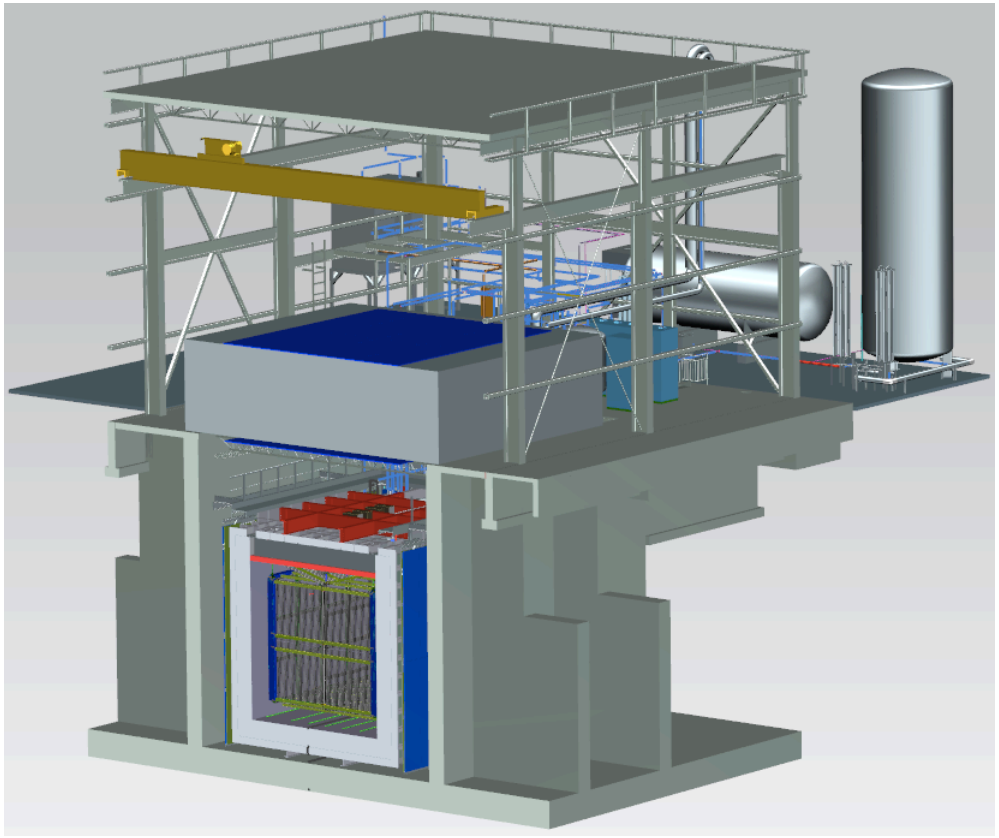
- Designed for 3m concrete overburden inside building to mitigate cosmogenic backgrounds for near surface operation
- Milestones:
  - ✓ Jan 2015 Design start
  - ✓ July 2015 Final design review
  - ✓ Aug 2015 Design complete
  - ✓ Mar 2016 Construction start
  - ✓ Sep 2016 Concrete Complete
  - ✓ Oct 2016 Structure Complete
  - ❑ Dec 2016 Envelope Complete
  - ❑ Feb 2017 Beneficial Occupancy
  - ❑ Mar 2017 Project Complete

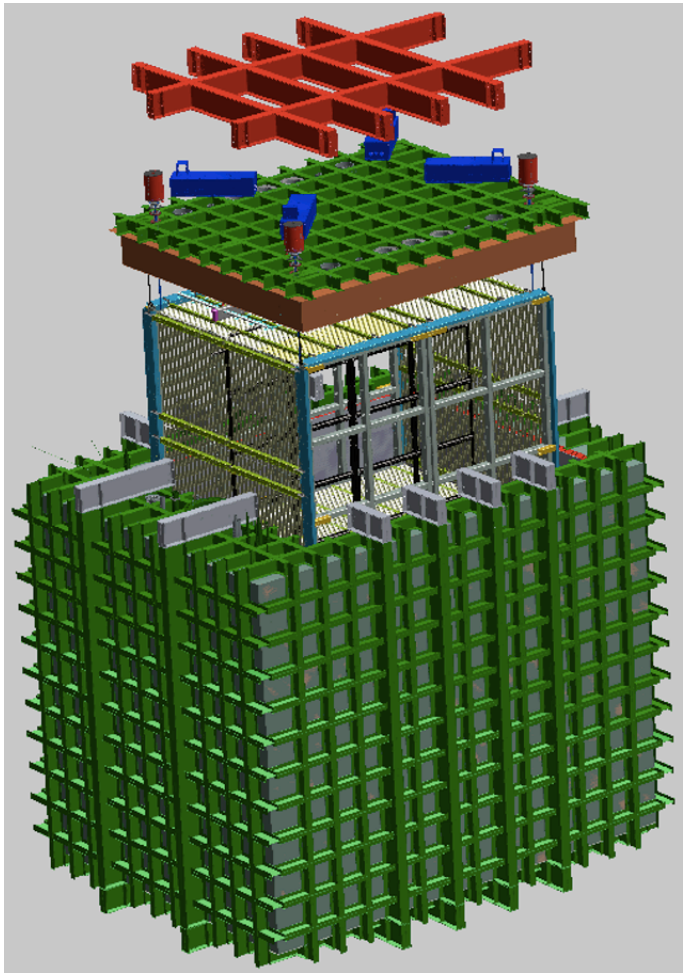
On track for completion on Budget



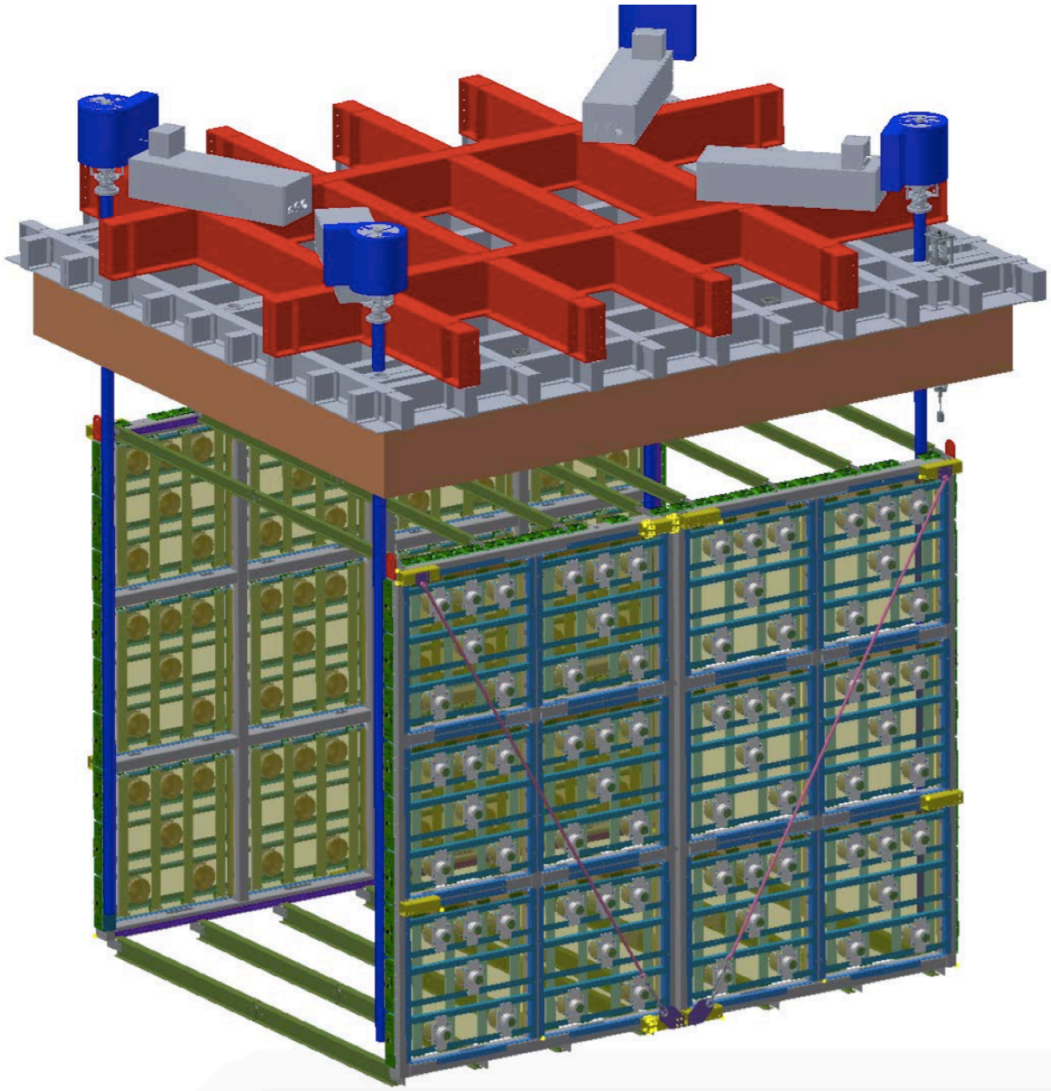


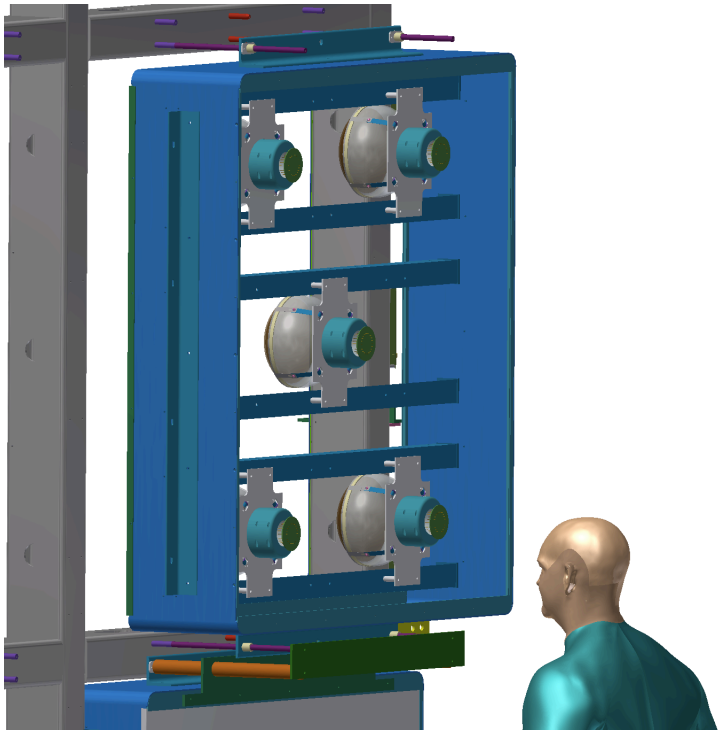
SBND LAr TPC

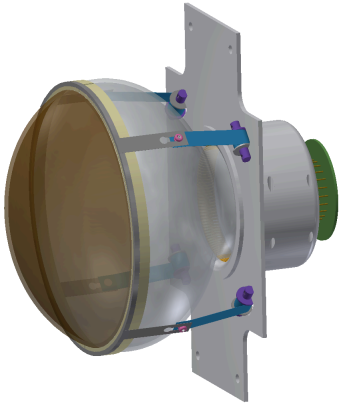




LANL Is Building SBND Photon Detection System







DUNE Is Affected by 3+N Models

Gandhi, Kayser, Masud, & Prakash, arXiv:1508.06275

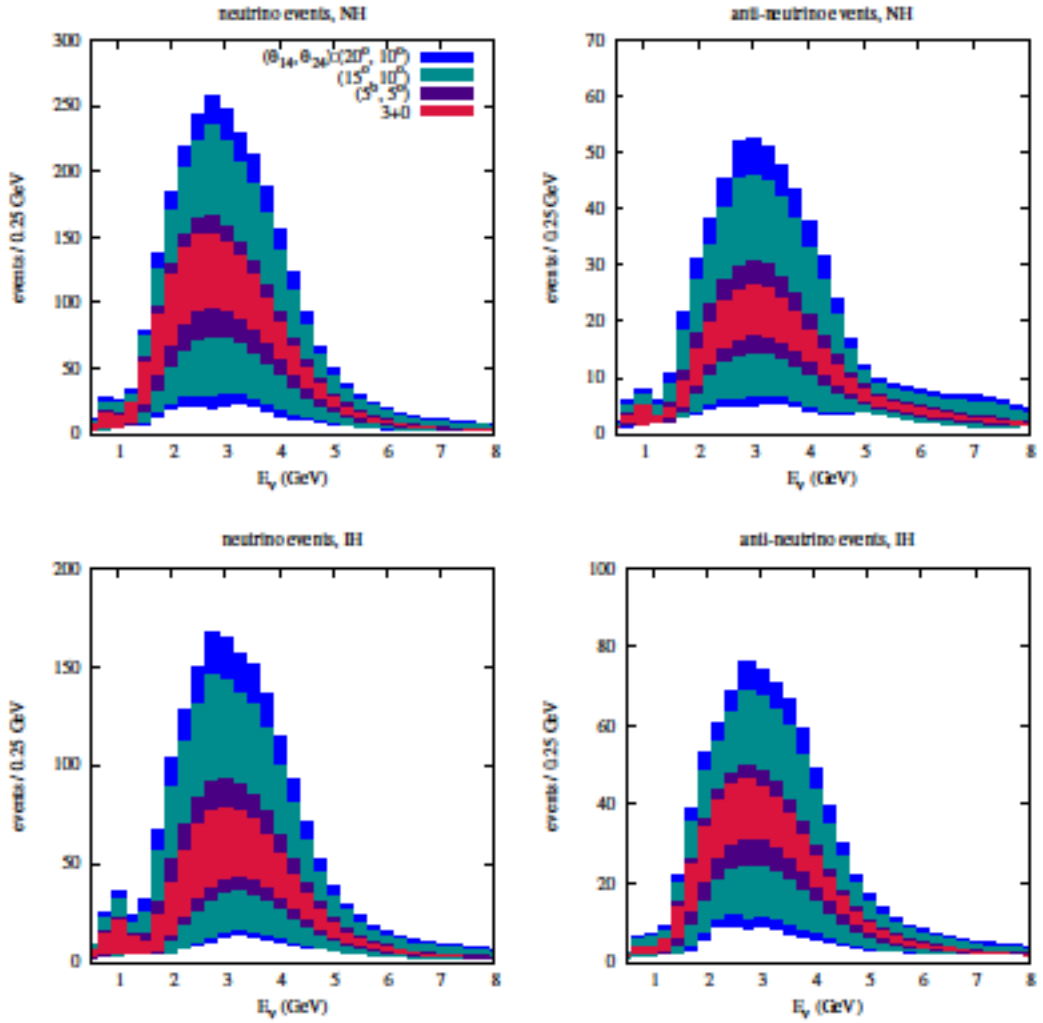


Figure 4: Neutrino and anti-neutrino event rates in DUNE plotted as a function of the reconstructed neutrino energy. The vertical spread for a given color for an energy bin shows the maximum and the minimum events rates possible.

Solar Measurements

(Errors still too large to give competitive limits)

arXiv:1707.09279