Is there a right-handed (‘sterile’) neutrino in the eV range?

Where it started

Phys.Rev.D64:112007,2001

DOI: 10.1103/PhysRevD.64.112007

Report number: LAUR-01-2390/UCR-HEP-E306

LA-UR-01-2390/UCRHEP-E306

Evidence for Neutrino Oscillations from the Observation of $\bar{\nu}_e$ Appearance in a $\bar{\nu}_\mu$ Beam

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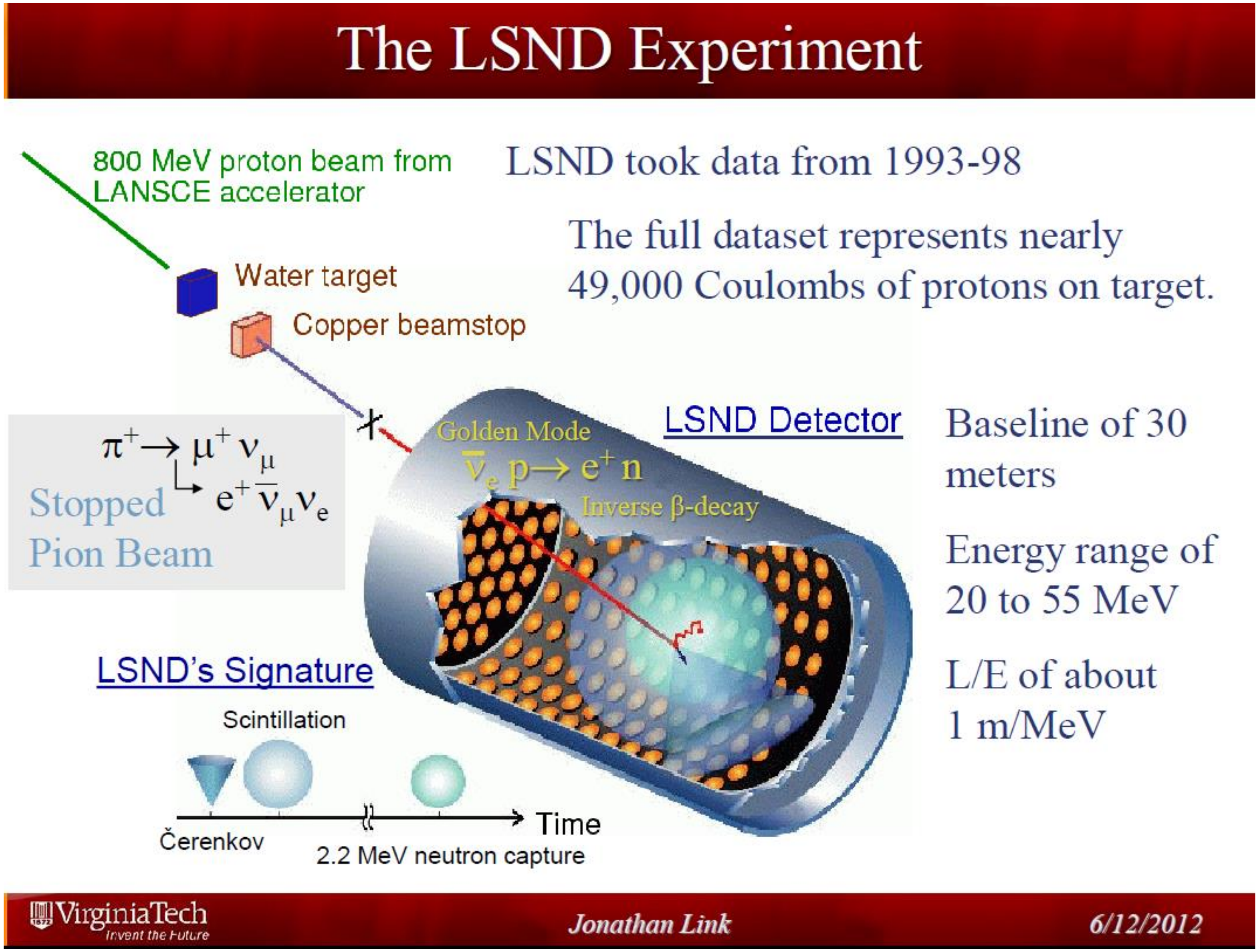
(LSND Collaboration)

arXiv:hep-ex/0104049v3

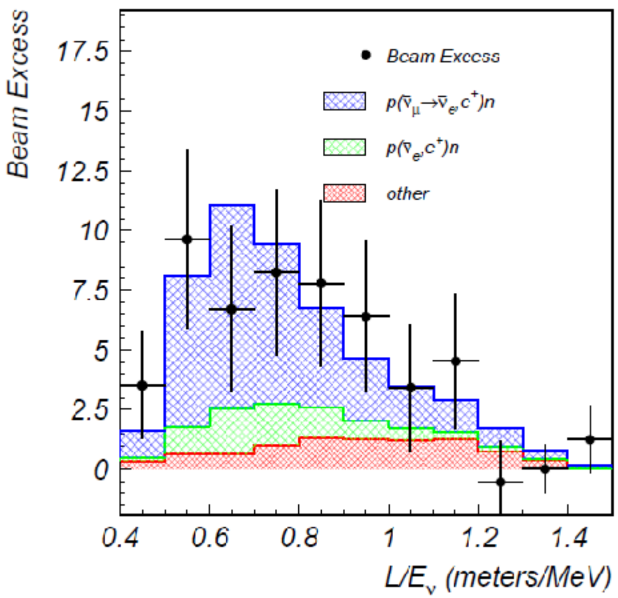


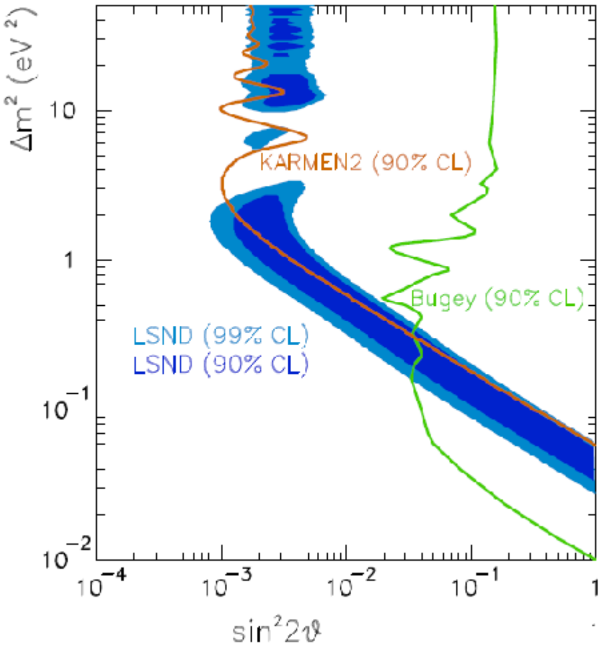
At the basis of the experiment: background to golden channel is low, because there is no known neutrino interaction that produces a fast electromagnetic signal followed by a 'slow neutron' capture signal

However *we do not know* all neutrino reactions at these low energies.

LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance

Aguilar-Arevalo *et al.*, Phys.Rev. D64, 112007 (2001)





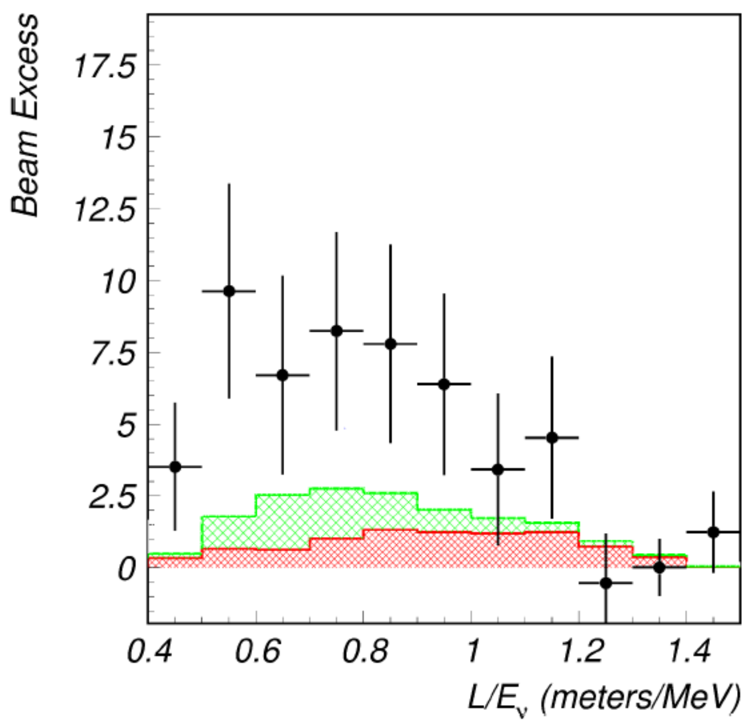
Event Excess: 32.2 ± 9.4 ± 2.3

Can be fit by oscillation signal

LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e \qquad 20\,\text{MeV} \leq E \leq 52.8\,\text{MeV}$



- Well-known and pure source of $\bar{\nu}_\mu$

$$p + \text{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$$

$$\mu^+ \xrightarrow[\text{at rest}]{} e^+ + \nu_e + \bar{\nu}_\mu$$

$L \simeq 30\,\text{m}$

$$\bar{\nu}_e + p \to n + e^+$$

Well-known detection process of $\bar{\nu}_e$

- $\approx 3.8\sigma$ excess
- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

[PRD 65 (2002) 112001]

Intrinsic issues with LSND (data taken 1992-1999) claim of $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillation

-- mainly the problem is due to the fact that there is only one detector.
➔ it is hard to tell if effect observed is $\bar{\nu}_e$ appearance of some photon + neutron background

-- the beam is made of $\pi^\pm \rightarrow \mu^\pm (\nu_\mu / \bar{\nu}_\mu)$ followed by $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ or much less $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$
from a continuous delivery (it is not a pulsed beam where the pion decay (26 ns) and muon decay (2.2 μs) would be separated.

-- some pions decay at rest (DAR) and some in flight (DIF)
-- beam target is made of water + copper dump or «High Z» + copper dump.
-- there are uncertainties on the relative rate of DIF and DAR related to the interaction length of pions in water and dump (and various spaces)
DIF of negative pions creates backgrounds for $\bar{\nu}_e$ from muon decay.

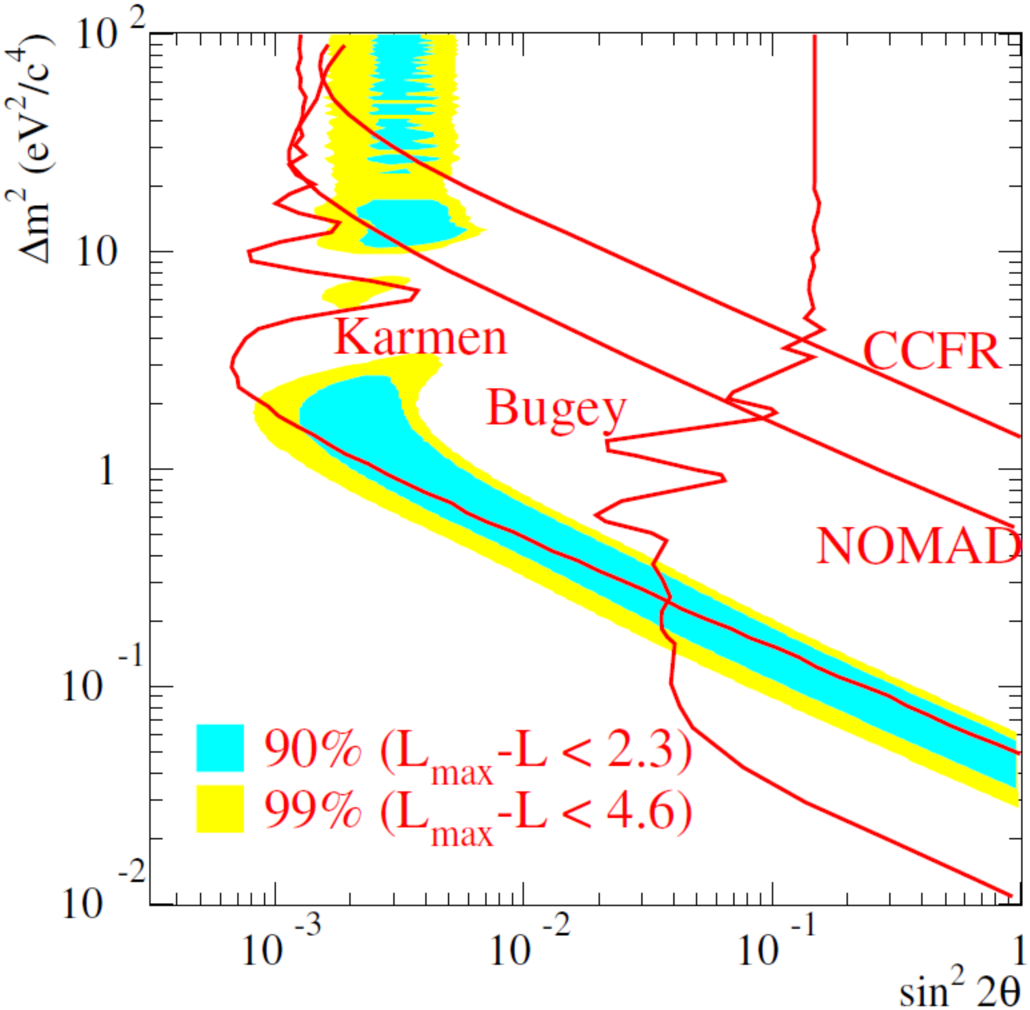
Here is what is said of the ‘various’ backgrounds

There are additional backgrounds from $\bar{\nu}_e$ produced by $\mu^- \to e^- \nu_\mu \bar{\nu}_e$ and $\pi^- \to e^- \bar{\nu}_e$ DIF. These $\bar{\nu}_e$ can interact on either C or a free proton to yield the oscillation signature of a positron and a recoil neutron. For $20 < E_e < 60$ MeV, 0.1 ± 0.1 events are estimated. The reactions $\nu_e\ {}^{12}C \to e^- n X$ and $\nu_e\ {}^{13}C \to e^- n X$ are negligible (< 0.1 events) over the $20 < E_e < 60$ energy range and cannot occur for $E_e > 20$ MeV and $E_e > 36$ MeV, respectively. Other backgrounds, for example $\nu_\mu C \to \nu_\mu n \gamma X$ with $E_\gamma > 20$ MeV, $\nu_e C \to e^- p X$ followed by ${}^{13}C(p,n)\ {}^{13}N$, and $\nu_\mu C \to \mu^- X$ followed by μ^- capture, are also negligible.

<u>there is no reference for the calculated backgrounds or further discussion or cross-checks</u>
The signal is not very large (down to $2 10^{-3}$) and background are of order few 10^{-4} .
It is notable that these are many sources of backgrounds and they are eliminated
by an energy cut.
<u>How many neglected negligible backgrounds would be enough to make the signal?</u>

-- in particular it is not clear if the NC γ+n background is calculated for muon neutrinos and ${}^{12}C$ only or if it is calculated for all three species and including for ${}^{13}C$ and for the DIF which have a larger momentum? ${}^{13}C$ has a very low binding energy
(1.1% of natural carbon and 4 MeV E_b
- - which is why they can populate the region above 20 MeV
-- I asked these questions with no success.
<u>In absence of a near-far detector set-up it is impossible to conclude.</u>

-- note that the Karmen experiment with a pulsed beam at RAL never saw anything.



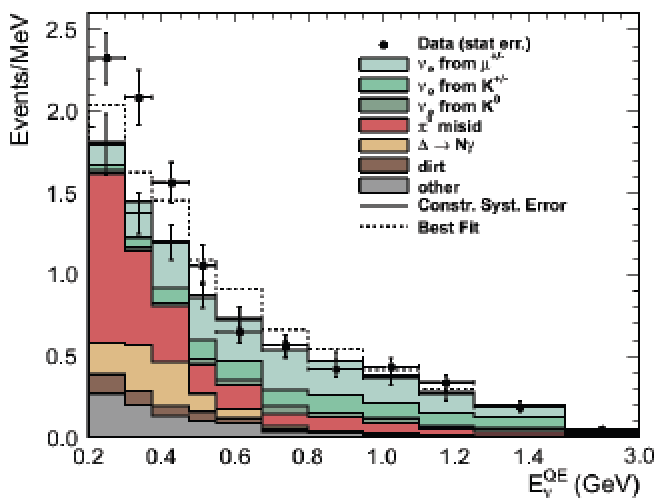
$$\Delta m^2_{\mathrm{SBL}} \gtrsim 3 \times 10^{-2}\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{ATM}} \simeq 2.5 \times 10^{-3}\,\mathrm{eV}^2 \gg \Delta m^2_{\mathrm{SOL}}$$

Next came another experiment with no near detector ☹

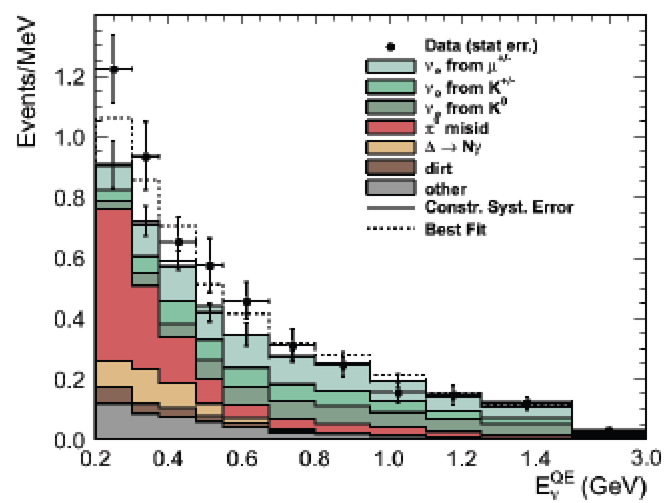
BOONE proposal was supposed to check the LSND ‘anomaly’. It had 2 detectors
lack of money or interest → downgraded to miniBOONE with only one detector.
This was, in my opinion, a very serious mistake at managerial level.

If an experiment is worth doing it it worth doing well.

6.5e20 POT neutrino mode w/ 3+1 fit



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



MiniBooNE observes an excess of ve 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)
It is not yet known whether the MiniBooNE excesses are due to oscillations.

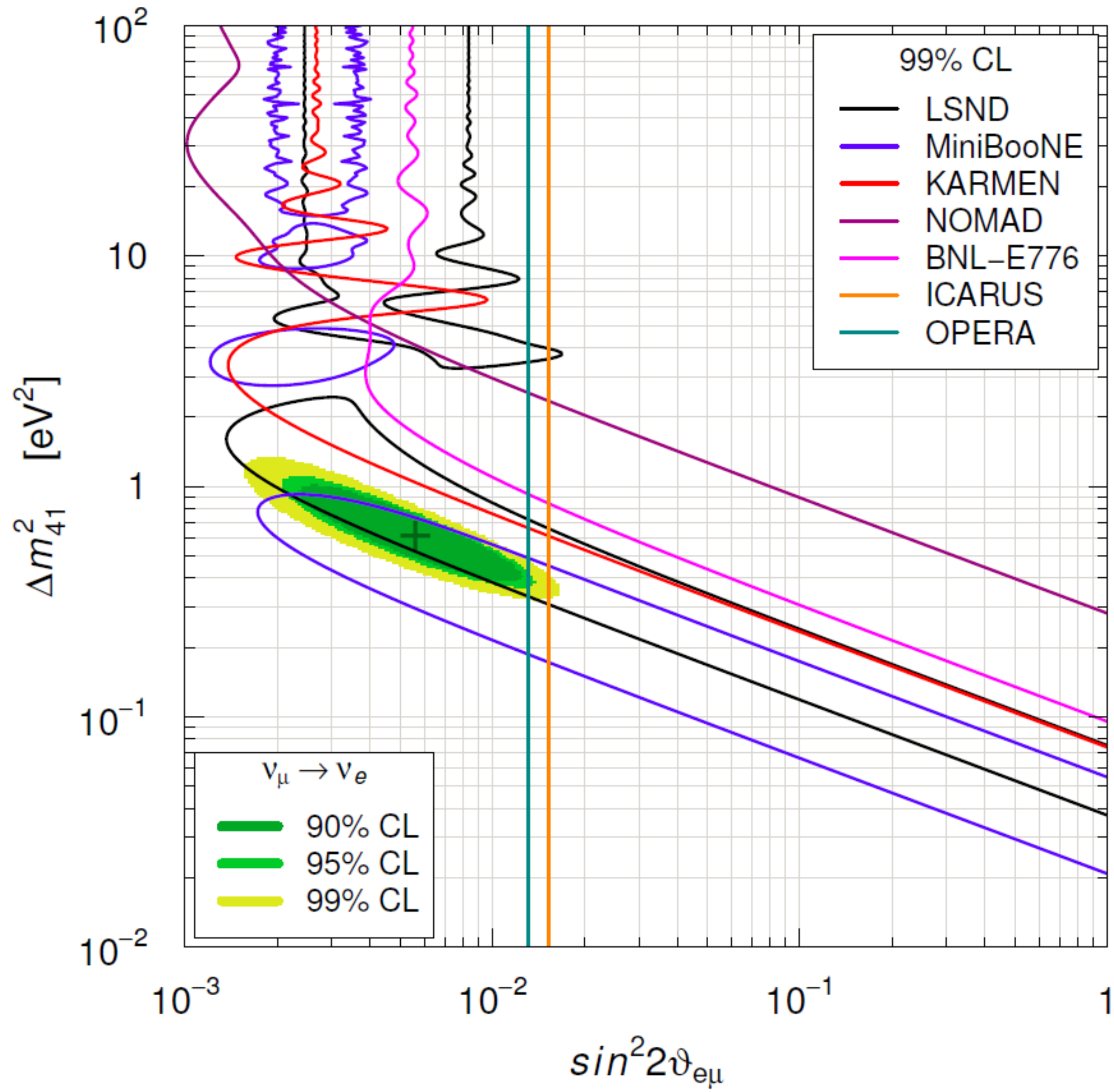
C. Polly

Anomaly	Type	Channel	Significance
LSND	DAR	$\bar{\nu}$ CC	3.8 σ
MiniBooNE	SBL accelerator	ν CC	3.0 σ
MiniBooNE	SBL accelerator	$\bar{\nu}$ CC	1.7σ
Gallium/Sage	Source - e capture	ν CC	2.7σ
Reactor	Beta-decay	$\bar{\nu}$	3.0σ

New MiniBooNE
Combined ν + $\bar{\nu}$
Now 3.8 σ

M. Shaevitz

$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ Appearance



looks interesting….

final results.

Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment

A. A. Aguilar-Arevalo[13], B. C. Brown[6], L. Bugel[12], G. Cheng[5], J. M. Conrad[12], R. L. Cooper[10,15], R. Dharmapalan[1,2], A. Diaz[12], Z. Djurcic[2], D. A. Finley[6], R. Ford[6], F. G. Garcia[6], G. T. Garvey[10], J. Grange[7], E.-C. Huang[10], W. Huelsnitz[10], C. Ignarra[12], R. A. Johnson[3], G. Karagiorgi[5], T. Katori[12,16], T. Kobilarcik[6], W. C. Louis[10], C. Mariani[19], W. Marsh[6], G. B. Mills[10,†], J. Mirabal[10], J. Monroe[18], C. D. Moore[6], J. Mousseau[14], P. Nienaber[17], J. Nowak[9], B. Osmanov[7], Z. Pavlovic[6], D. Perevalov[6], H. Ray[7], B. P. Roe[14], A. D. Russell[6], M. H. Shaevitz[5], J. Spitz[14], I. Stancu[1], R. Tayloe[8], R. T. Thornton[10], M. Tzanov[4,11], R. G. Van de Water[10], D. H. White[10], D. A. Wickremasinghe[3], E. D. Zimmerman[4]

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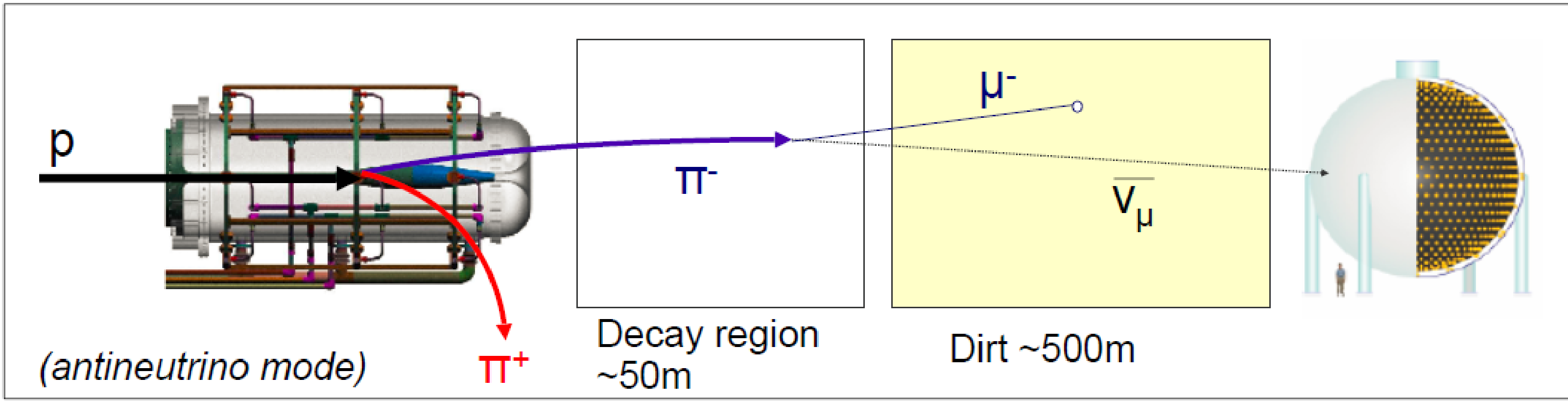
(Dated: May 31, 2018)

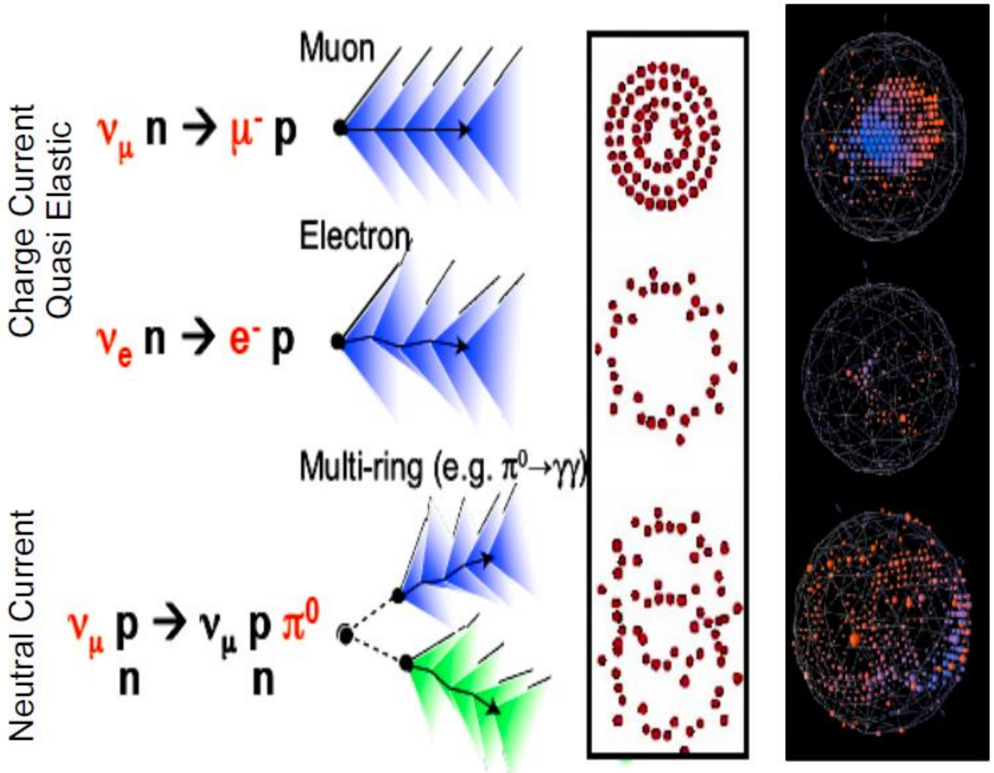
The MiniBooNE experiment at Fermilab reports results from an analysis of ν_e appearance data from 12.84×10^{20} protons on target in neutrino mode, an increase of approximately a factor of two over previously reported results. A ν_e charged-current quasi-elastic event excess of 381.2 ± 85.2 events (4.5σ) is observed in the energy range $200 < E_\nu^{QE} < 1250$ MeV. Combining these data with the $\bar{\nu}_e$ appearance data from 11.27×10^{20} protons on target in antineutrino mode, a total ν_e plus $\bar{\nu}_e$ charged-current quasi-elastic event excess of 460.5 ± 95.8 events (4.8σ) is observed. If interpreted in a standard two-neutrino oscillation model, $\nu_\mu \to \nu_e$, the best oscillation fit to the excess has a probability of 20.1% while the background-only fit has a χ^2-probability of 5×10^{-7} relative to the best fit. The MiniBooNE data are consistent in energy and magnitude with the excess of events reported by the Liquid Scintillator Neutrino Detector (LSND), and the significance of the combined LSND and MiniBooNE excesses is 6.1σ. All of the major backgrounds are constrained by in-situ event measurements, so non-oscillation explanations would need to invoke new anomalous background processes. Although the data are fit with a standard oscillation model, other models may provide better fits to the data.

MiniBooNE experiment



- Similar L/E as LSND
  - MiniBooNE ~500m/~500MeV
  - LSND ~30m/~30MeV
- Horn focused neutrino beam (p+Be)
  - Horn polarity → neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

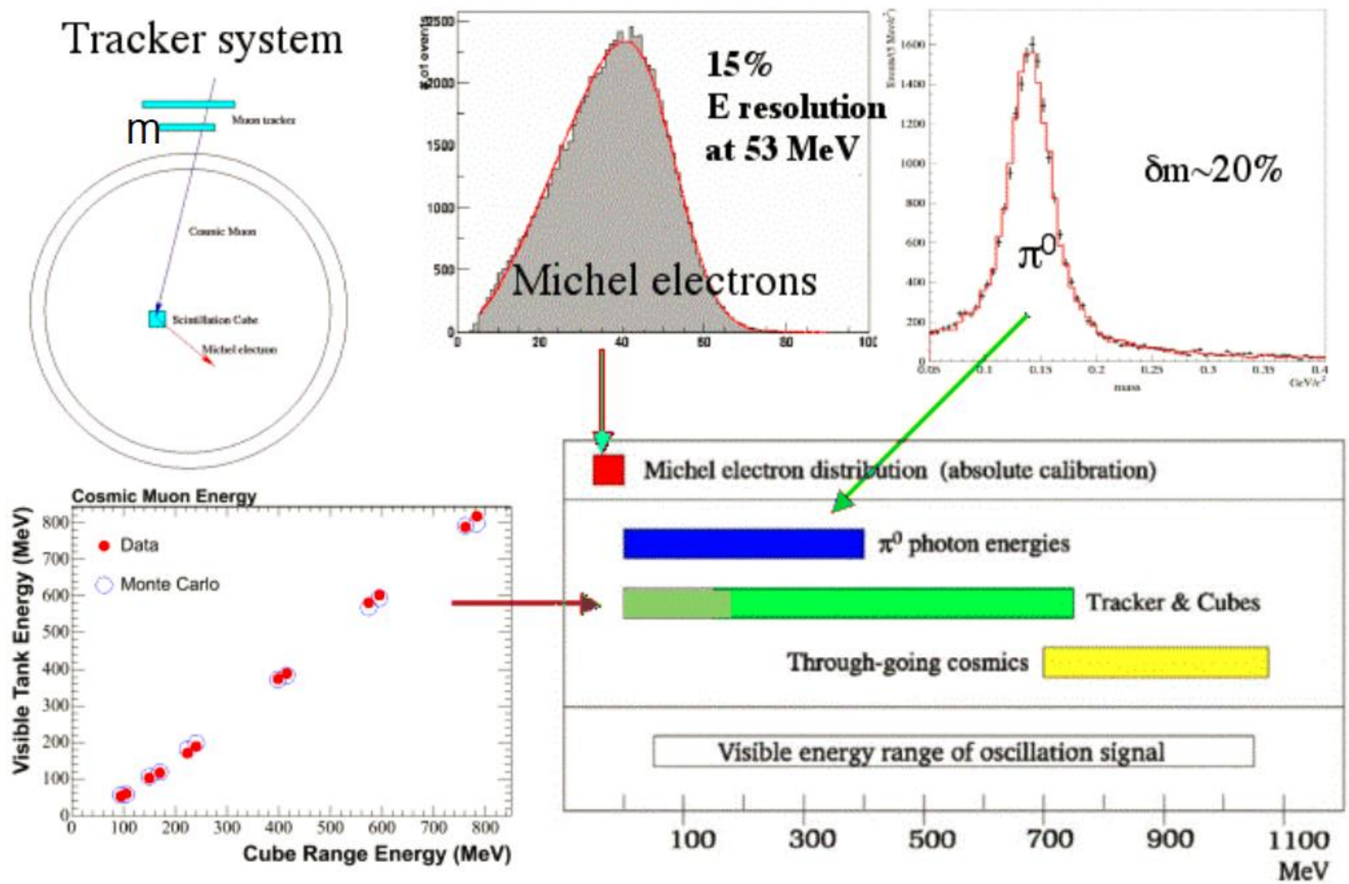
Events in MiniBooNE



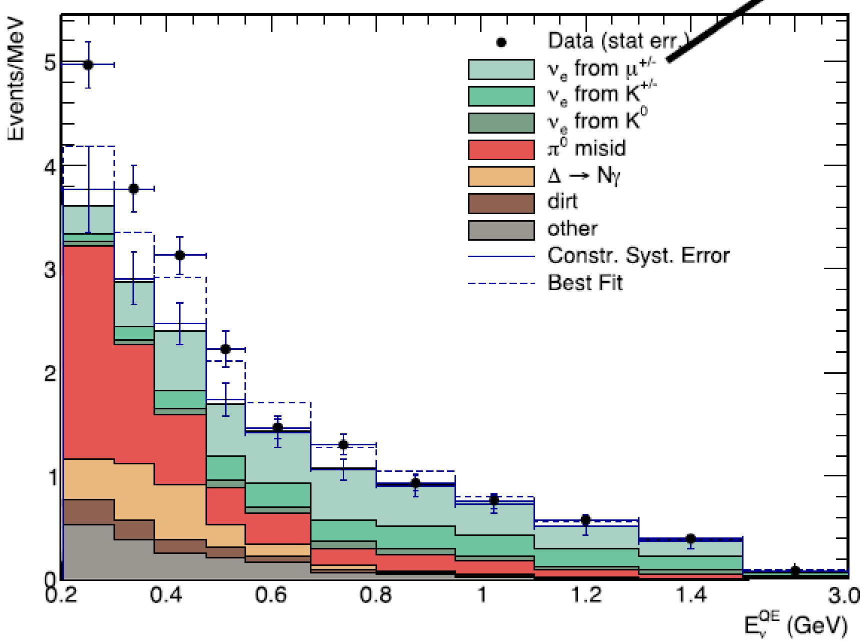
- Identified using timing and hit topology
- Use primarily Cherenkov light
- ID based on ratio of fit likelihoods under different particles hypothesis

how about gammas?

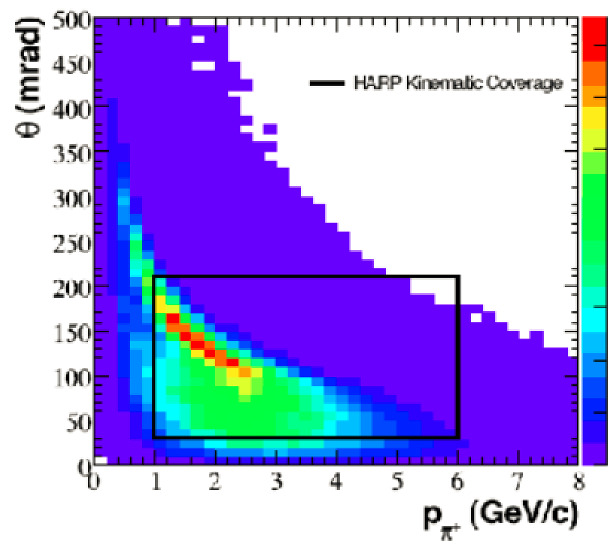
Detector calibration



Background prediction



- External measurements - HARP & BNL E910 p+Be -> $\pi^\pm$



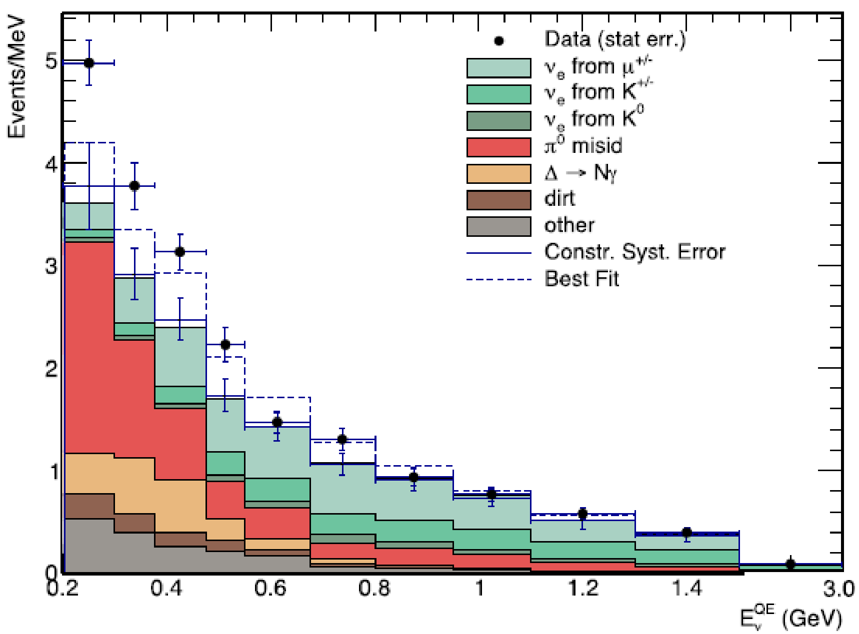
note that most of excess is in region of gammas (π^0 misid, γ)
γ is assumed to originate from Δ resonance)

Phys. Rev. D79, 072002 (2009)

- Covers phase space contributing to 78% of neutrino flux from pi+ (76% from pi- in antineutrino mode)

NB replica target data were taken in HARP but not used or if used not clear how?

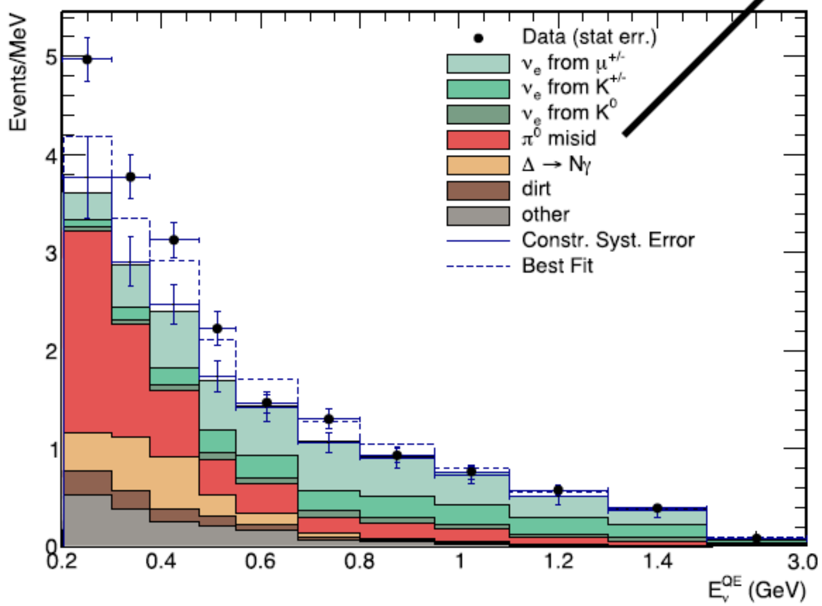
ν_e sample



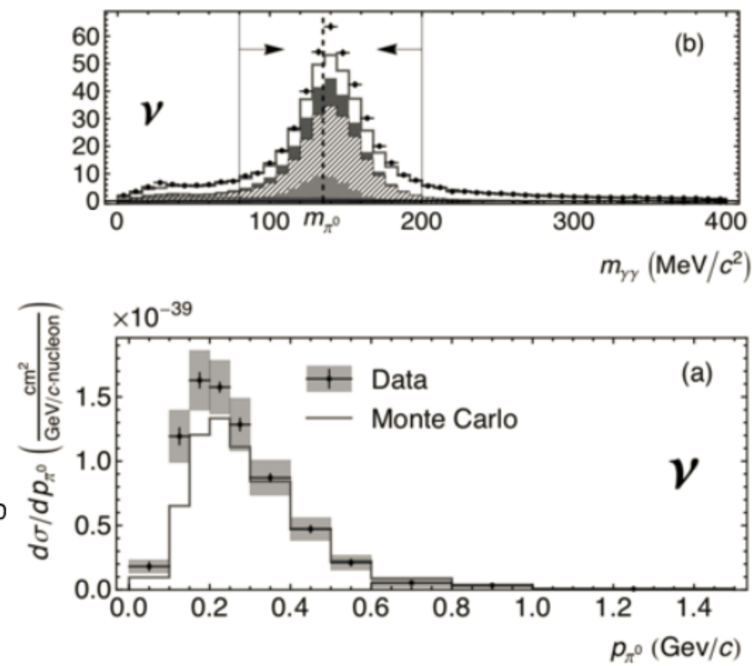
	Process	Neutrino Mode	Antineutrino Mode
misID	ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
	NC π^0	501.5 ± 65.4	112.3 ± 11.5
	NC $\Delta \to N\gamma$	172.5 ± 24.1	34.7 ± 5.4
	External Events	75.2 ± 10.9	15.3 ± 2.8
	Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
Intrinsic	ν_e & $\bar{\nu}_e$ 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^0_L 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.	1590.5 ± 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) $\nu_\mu \to \nu_e$	463.1	100.0

seems to confirm LSND

Background prediction

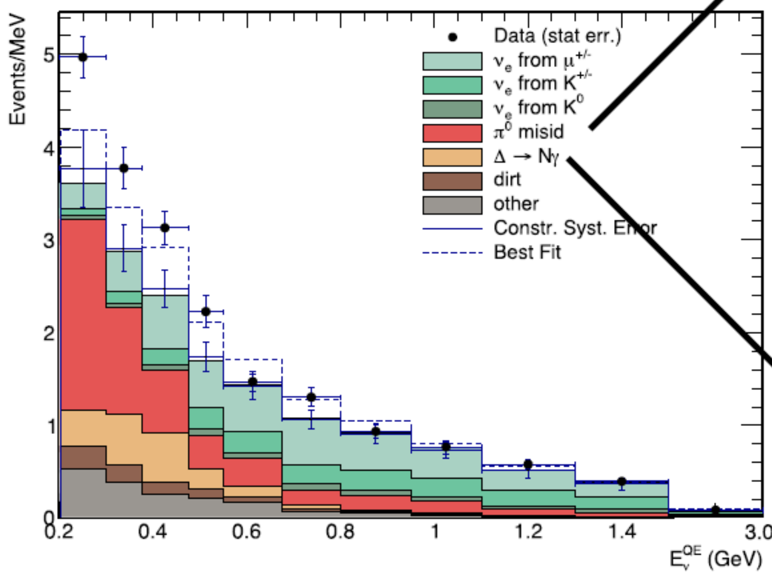


- NC π^0 MiniBooNE measurement



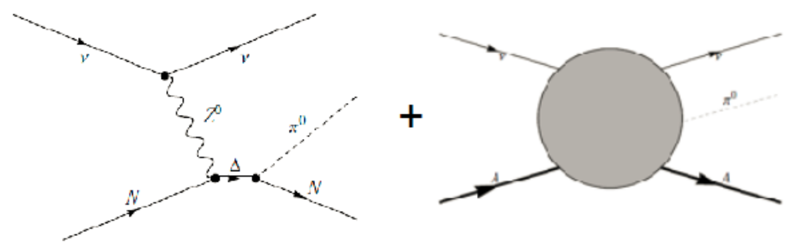
Phys. Rev. D81, 013005 (2010)

Background prediction

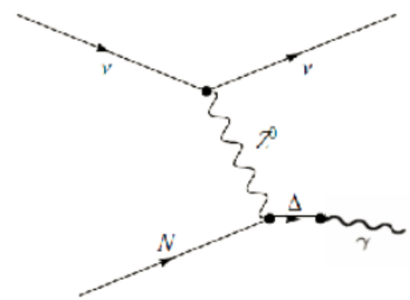


- NC π^0 MiniBooNE measurement

Resonant (~80%) + Coherent (~20%)

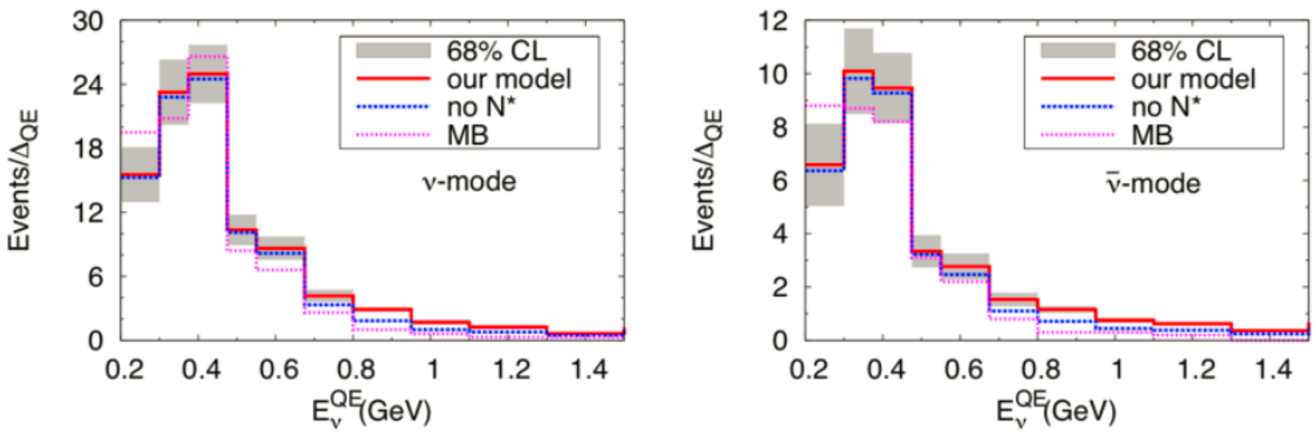


- Constrain radiative Δ decays



fundamental assumption needed: single gamma originates from Δ resonance and can be related to π^0 production.
What if both LSND and miniBOONE simply discovered a new source of gammas?
in absence of a near-far detector ratio is is impossible to separate sterile neutrino and this 'mundane' explanation.

NC gamma

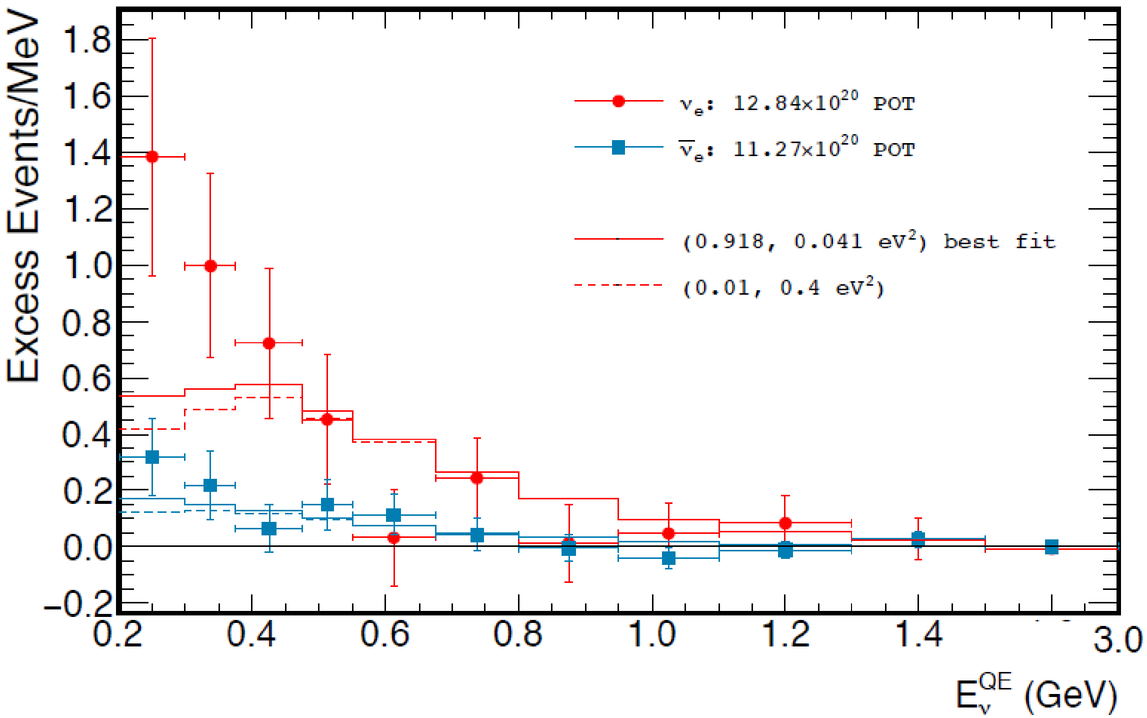


Phys. Lett. B740, 16 (2015).

- Several theoretical calculations:
  - Computed event rates in neutrino and antineutrino mode consistent with MiniBooNE estimate

[2] E. Wang, L. Alvarez-Ruso and J. Nieves, Phys.Rev. C89, (2014)015503 [arXiv:1311.2151]
[3] R. J. Hill, Phys.Rev. D81, (2010)013008 [arXiv:0905.0291]
[4] X. Zhang, B. D. Serot, Phys.Lett. B719, (2013)409 [arXiv:1210.3610]
[10] Y. Hayato, Acta Phys.Polon. B40 (2009)2477
[11] C. Andreopoulos *et al.* Nucl.Instrum.Meth. A614 (2010)87 [arXiv:0905.2517]
[12] D. Casper, Nucl.Phys.Proc.Suppl. 112 (2002)161 [arXiv:0208030]

Two-neutrino model



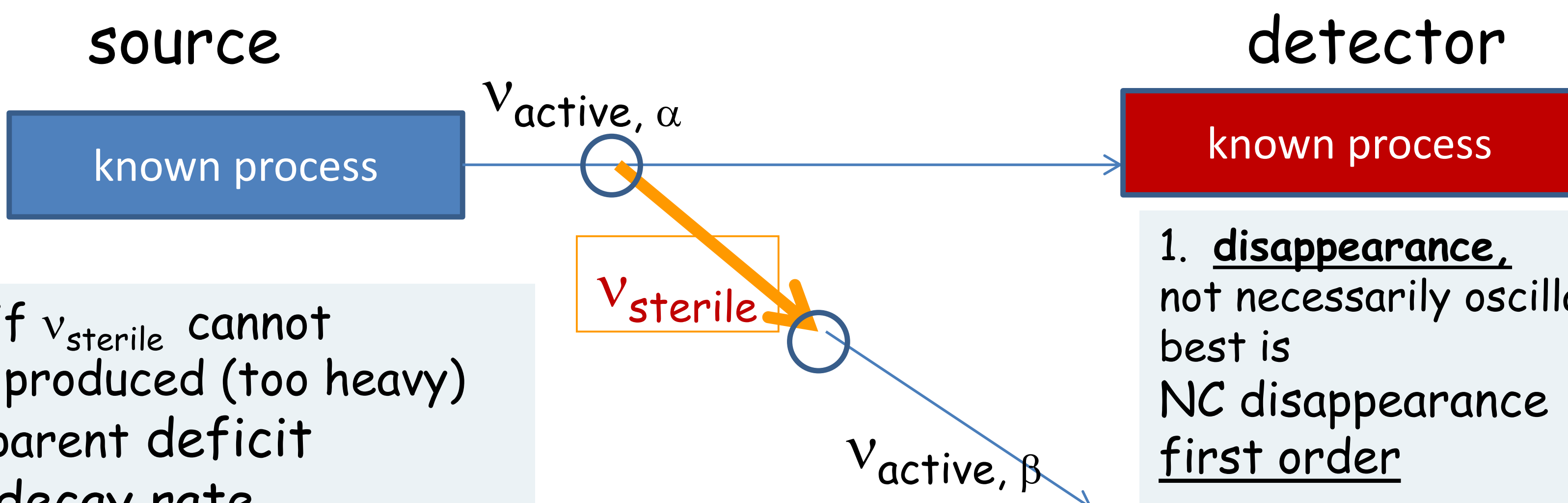
- Excess qualitatively consistent in neutrino and anti-neutrino modes

note that the significance is not

Sterile neutrino search: a global view:

Detected by mixing between sterile and active neutrino

ideal experiments:



0. if ν_{sterile} cannot be produced (too heavy) apparent deficit in decay rate

1. **disappearance,**
not necessarily oscillatory
best is
NC disappearance
first order

2. $\nu_\alpha \rightarrow \nu_\beta$ **appearance**
(at higher order)

☑ Oscillation channels are related:

$$P_{\nu_e \to \nu_e} \simeq 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - 2|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2)$$

$$P_{\nu_\mu \to \nu_e} \simeq 2|U_{e4}|^2|U_{\mu 4}|^2$$

(for $4\pi E/\Delta m^2_{41} \ll L \ll 4\pi E/\Delta m^2_{31}$)

if you want to see appearance you must see both disapearances!

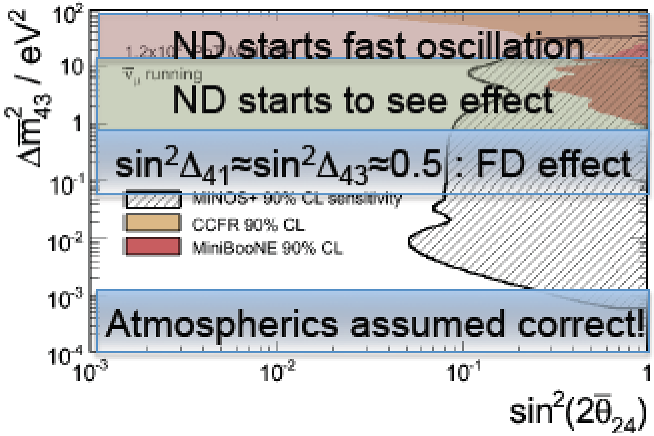
MINOS+ sterile reach

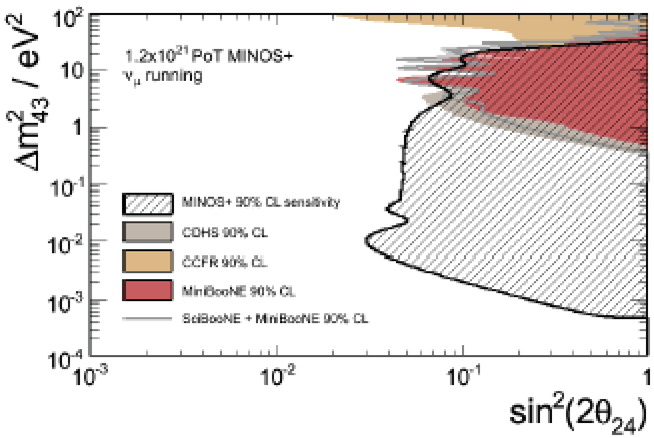
(http://lanl.arxiv.org/abs/1109.4033)

$|U_{e4}|^2 = \sin^2\theta_{14}$

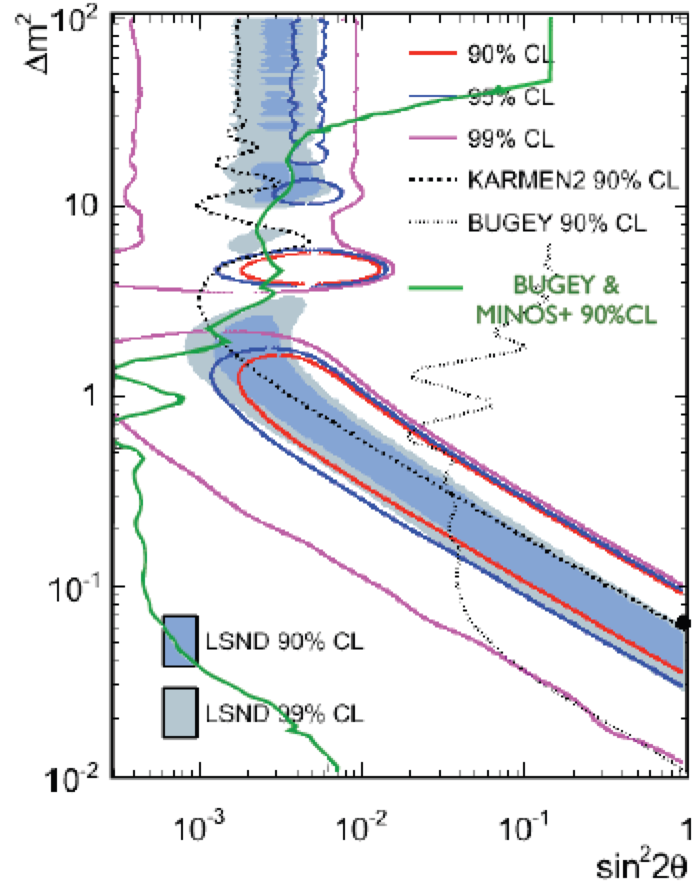
$|U_{\mu 4}|^2 = \cos^2\theta_{24} * \sin^2\theta_{24}$

$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$





A.Sousa



$\sin^2(2\theta_{\mu e}) = 4|U_{e4}|^2 * |U_{\mu 4}|^2$

Is the interpretation of the 3.8 σ LSND effect as ‘sterile neutrino’ the correct one?

arXiv:1607.01177

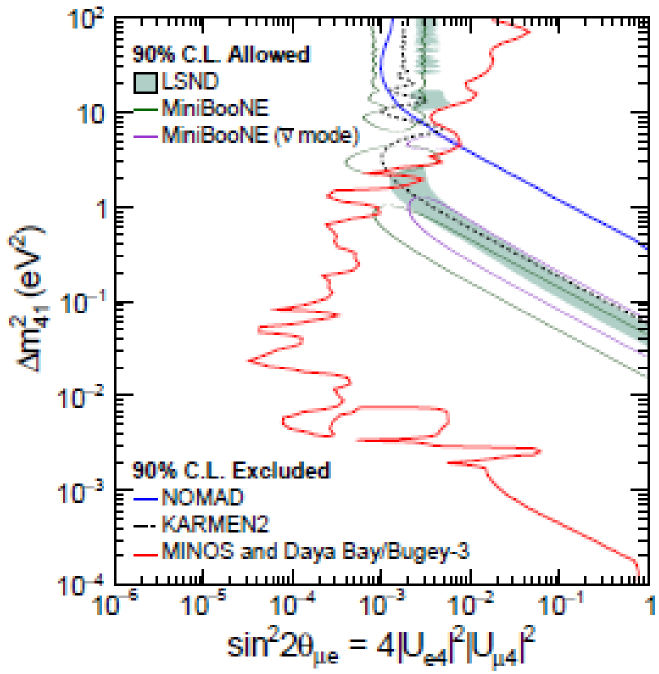


FIG. 4. MINOS and Daya Bay/Bugey-3 combined 90% C.L. limit on $\sin^2 2\theta_{\mu e}$ compared to the LSND and MiniBooNE 90% C.L. allowed regions. Regions of parameter space to the right of the red contour are excluded. The regions excluded at 90% C.L. by KARMEN2 [43] and NOMAD [44] are also shown.

both in 3+1 hypothesis

MINOS + DAYA Bay (+ Bugey)
no disppearance

arXiv:1605.01990

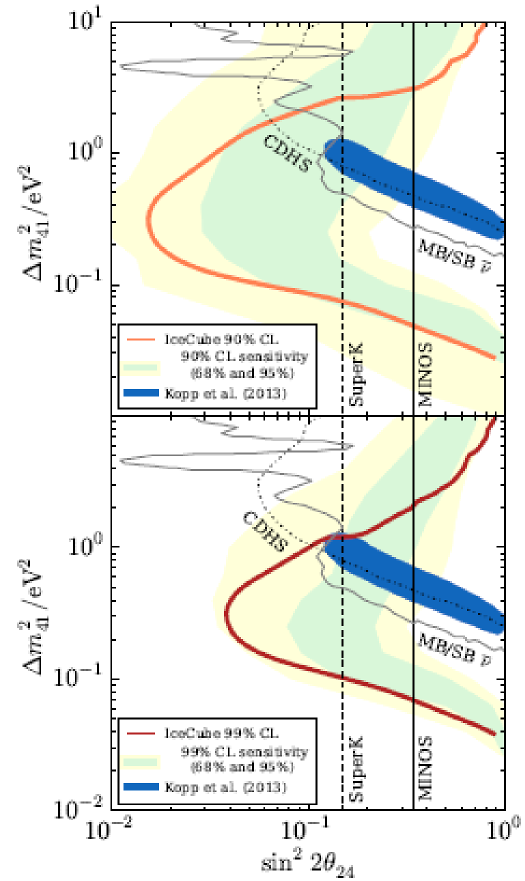
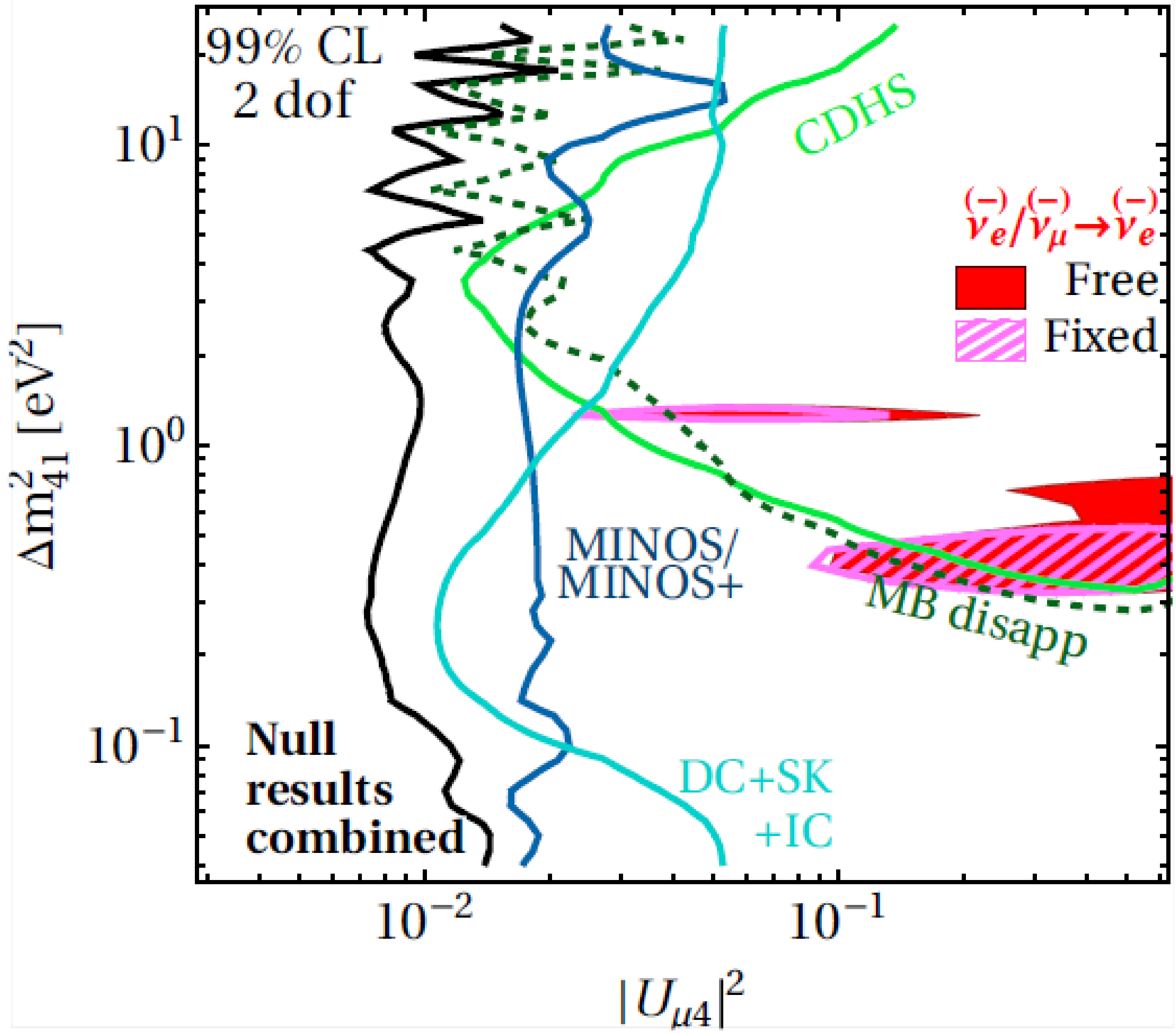


FIG. 5. Results from the IceCube search. (Top) The 90% (orange solid line) CL contour is shown with bands containing 68% (green) and 95% (yellow) of the 90% contours in simulated pseudo-experiments, respectively. (Bottom) The 99% (red solid line) CL contour is shown with bands containing 68% (green) and 95% (yellow) of the 99% contours in simulated pseudo-experiments, respectively. The contours and bands are overlaid on 90% CL exclusions from previous experiments [7–10], and the MiniBooNE / LSND 90% CL allowed region from [12, 13, 21] assuming $|U_{e4}|^2 = 0.023$.

IceCube in atmospheric neutrinos
no sterile neutrino effect

With new result from MINOS + (run with high energy beam for NOvA)



The light sterile neutrino seems very much dead.

MITP/18-023, FERMILAB-PUB-18-086-T, IFT-UAM/CSIC-18-033

Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos

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We discuss the possibility to explain the anomalies in short-baseline neutrino oscillation experiments in terms of sterile neutrinos. We work in a $3+1$ framework and pay special attention to recent new data from reactor experiments, IceCube and MINOS+. We find that results from the DANSS and NEOS reactor experiments support the sterile neutrino explanation of the reactor anomaly, based on an analysis that relies solely on the relative comparison of measured reactor spectra. Global data from the ν_e disappearance channel favour sterile neutrino oscillations at the 3σ level with $\Delta m^2_{41} \approx 1.3$ eV^2 and $|U_{e4}| \approx 0.1$, even without any assumptions on predicted reactor fluxes. In contrast, the anomalies in the ν_e appearance channel (dominated by LSND) are in strong tension with improved bounds on ν_μ disappearance, mostly driven by MINOS+ and IceCube. Under the sterile neutrino oscillation hypothesis, the p-value for those data sets being consistent is less than 2.6×10^{-6}. Therefore, an explanation of the LSND anomaly in terms of sterile neutrino oscillations in the $3+1$ scenario is excluded at the 4.7σ level. This result is robust with respect to variations in the analysis and used data, in particular it depends neither on the theoretically predicted reactor neutrino fluxes, nor on constraints from any single experiment. Irrespective of the anomalies, we provide updated constraints on the allowed mixing strengths $|U_{\alpha 4}|$ ($\alpha = e, \mu, \tau$) of active neutrinos with a fourth neutrino mass state in the eV range.

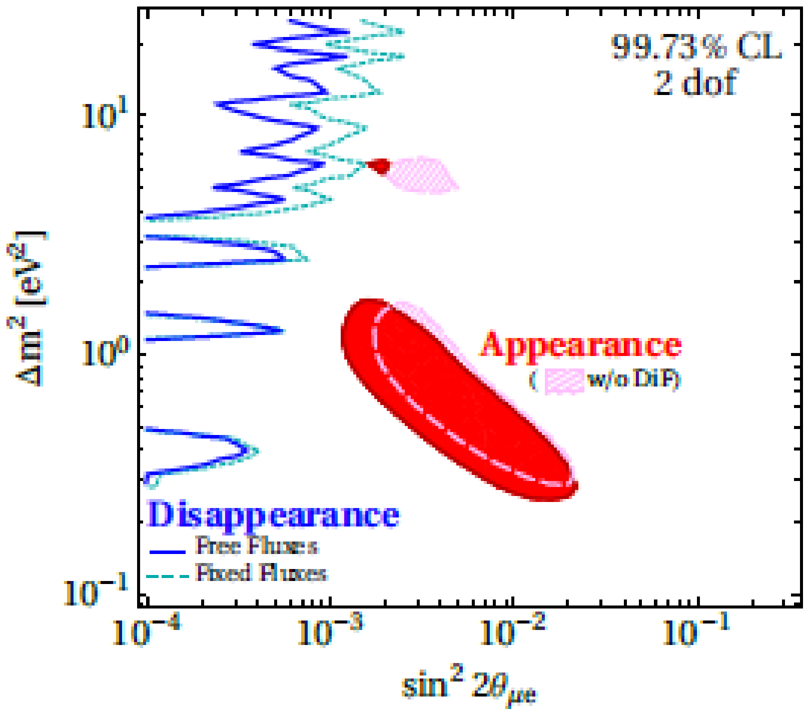

FIG. 7. Appearance versus disappearance data in the plane spanned by the effective mixing angle $\sin^2 2\theta_{\mu e} \equiv 4|U_{e4}U_{\mu 4}|^2$ and the mass squared difference Δm^2_{41}. The blue curves show limits from the disappearance data sets using free reactor fluxes (solid) or fixed reactor fluxes (dashed), while the shaded contours are based on the appearance data sets using LSND DaR+DiF (red) and LSND DaR (pink hatched). All contours are at 99.73% CL for 2 dof.