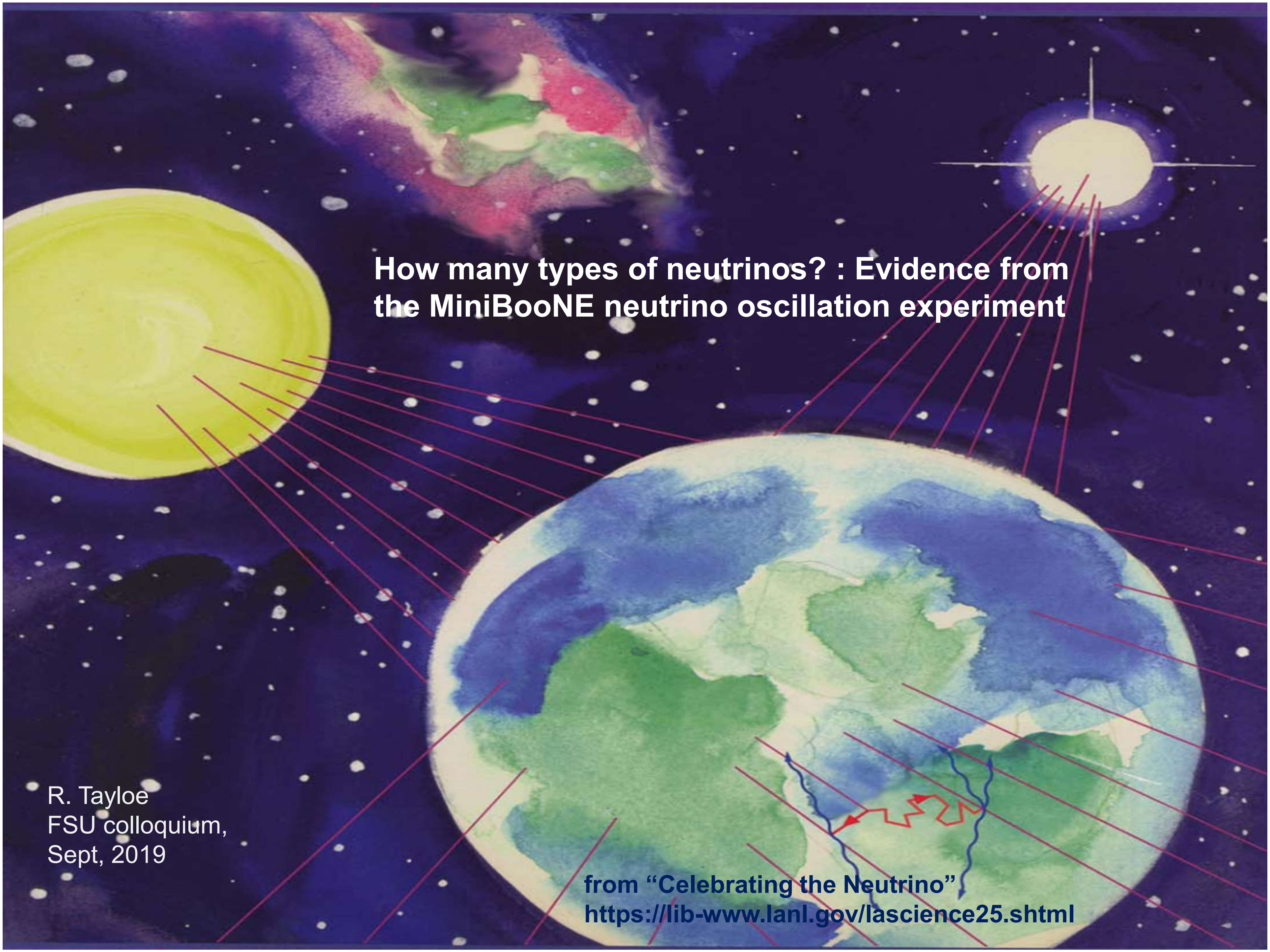
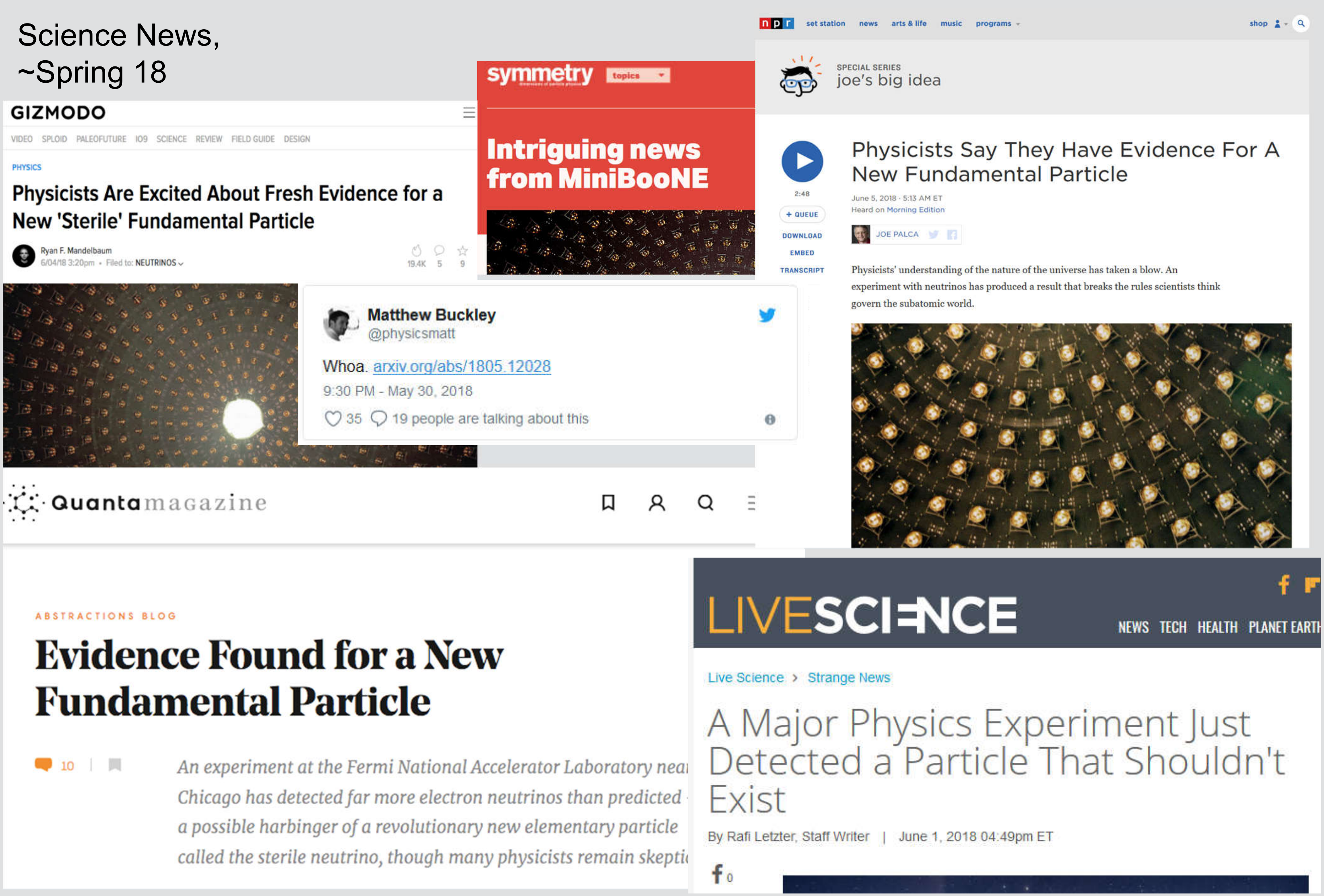
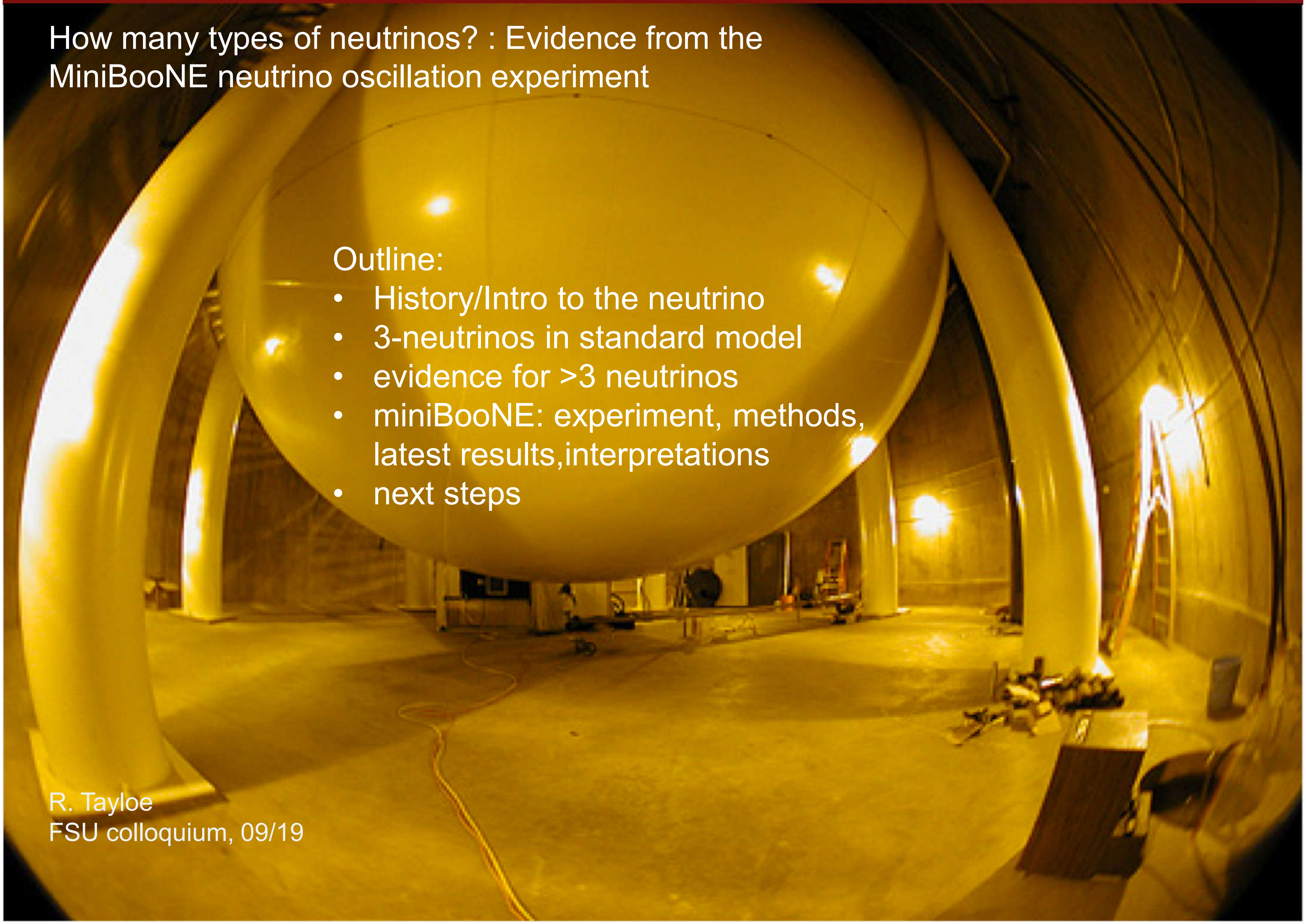

How many types of neutrinos? : Evidence from the MiniBooNE neutrino oscillation experiment
R. Tayloe
FSU colloquium,
Sept, 2019
from “Celebrating the Neutrino”
https://lib-www.lanl.gov/lascience25.shtml

Science News,
~Spring 18





How many types of neutrinos? : Evidence from the MiniBooNE neutrino oscillation experiment

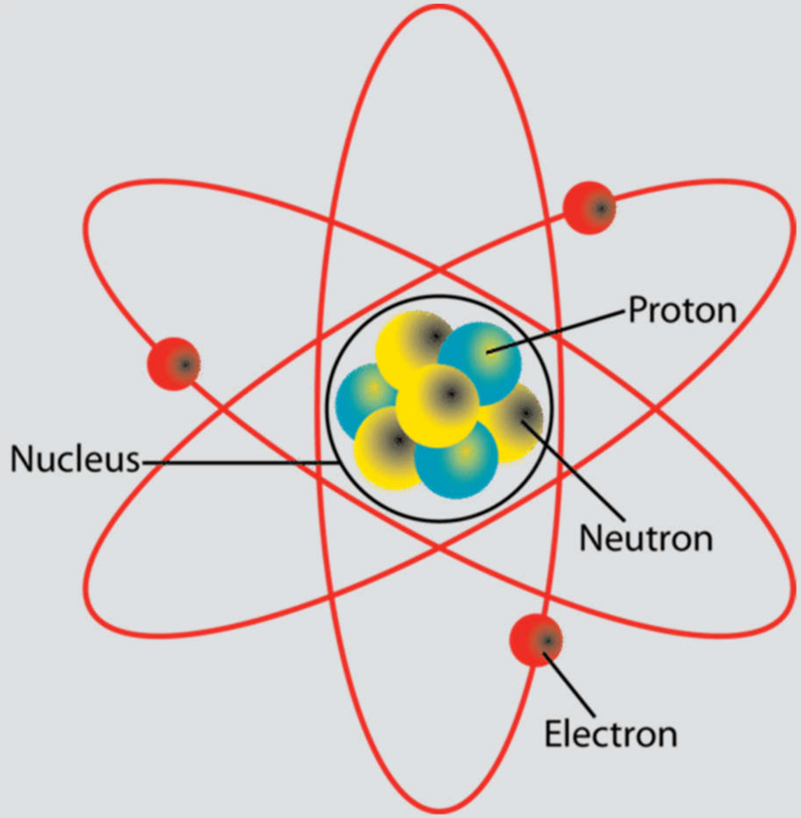
Outline:

- History/Intro to the neutrino
- 3-neutrinos in standard model
- evidence for >3 neutrinos
- miniBooNE: experiment, methods, latest results,interpretations
- next steps

R. Tayloe
FSU colloquium, 09/19

Introduction: ν history

First….the atom (early 1900s)

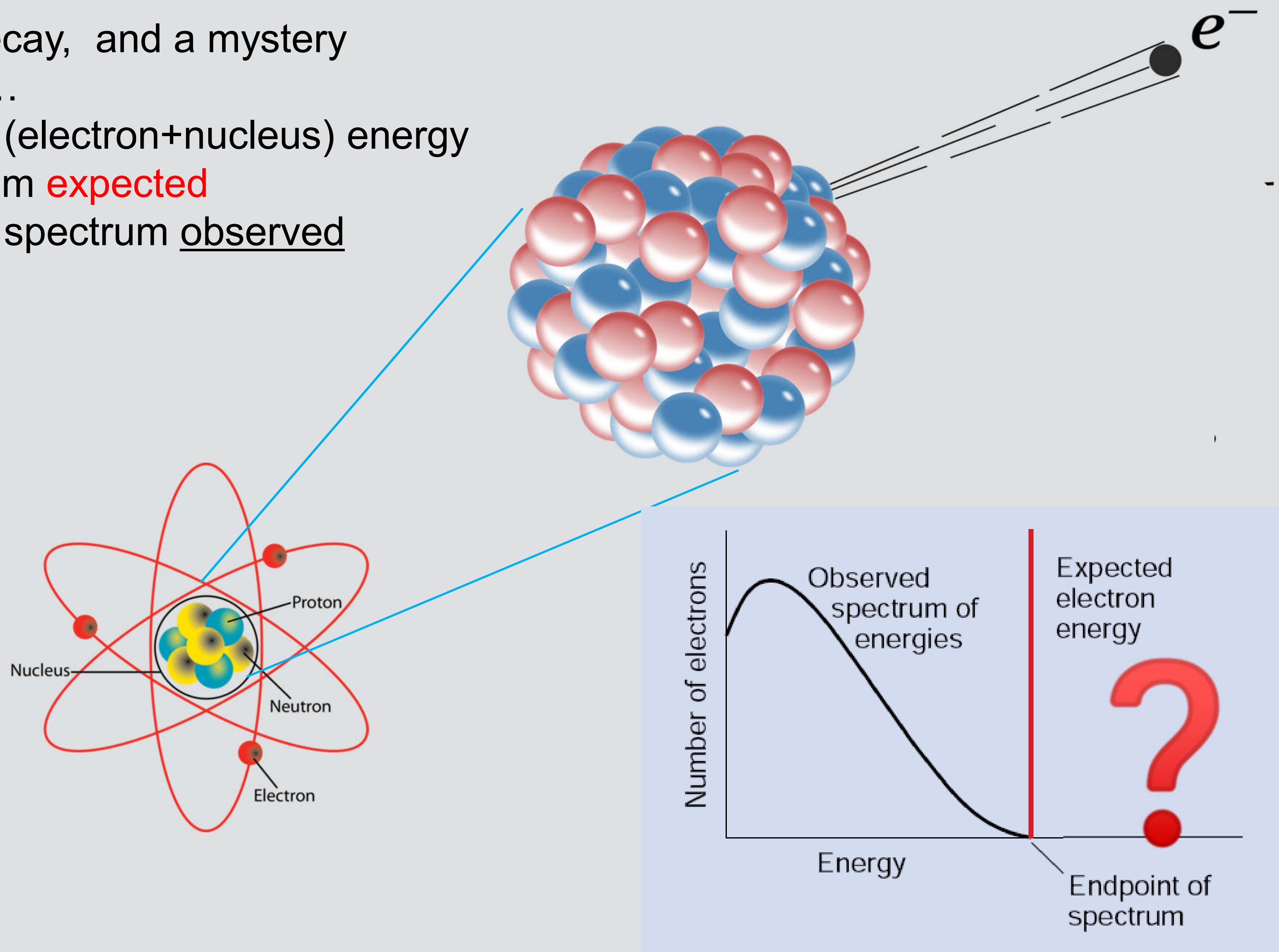


(ok, the full picture of nucleus, with protons and neutrons wasn't yet known at that time)

Introduction: ν history

Then β-decay, and a mystery (~1930s)…

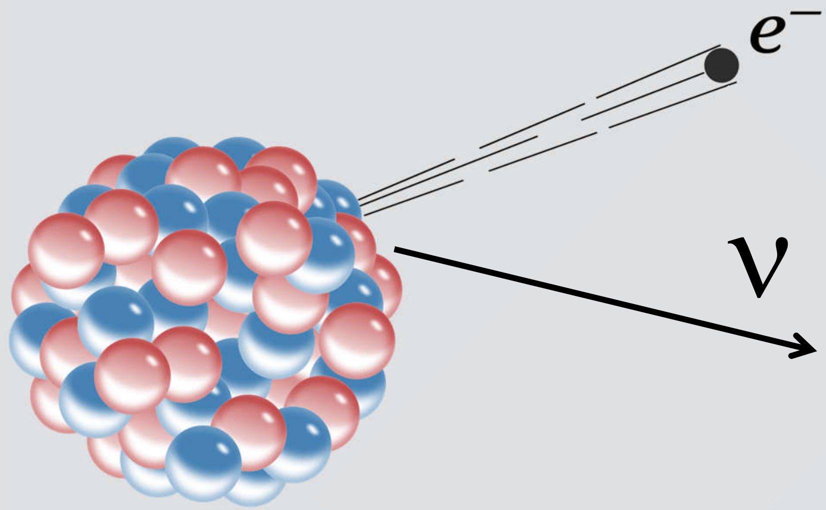
- 2-body (electron+nucleus) energy spectrum expected
- 3-body spectrum observed

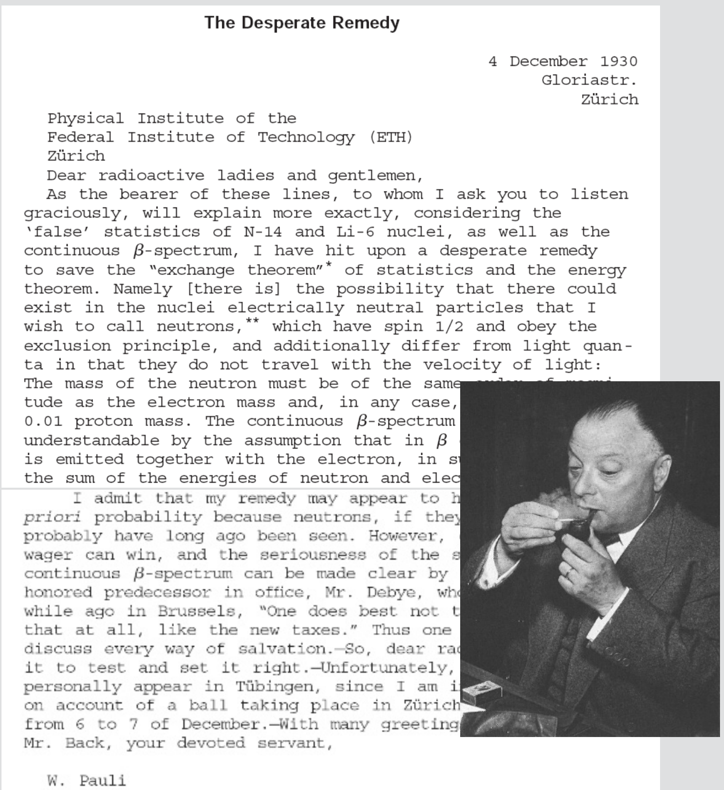


Introduction: ν history

Then β-decay, and a mystery (~1930s)…

- Pauli's hypothesis of the neutrino (to solve β-decay problem)





The Desperate Remedy

4 December 1930
Gloriastr.
Zürich

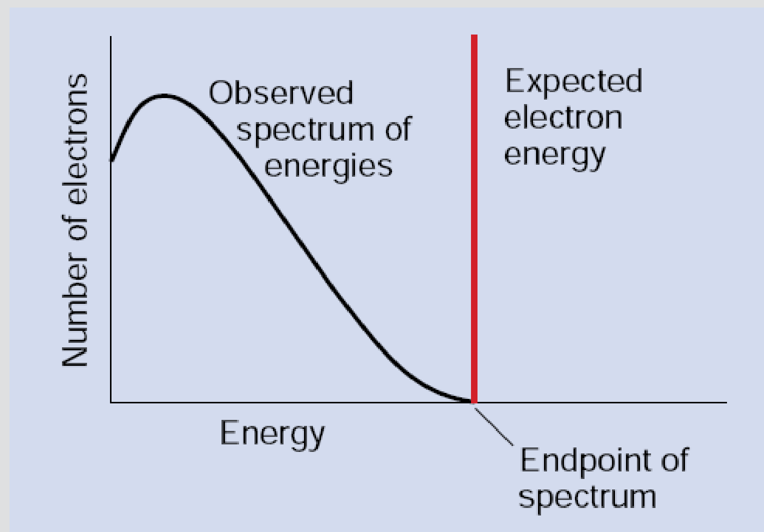
Physical Institute of the
Federal Institute of Technology (ETH)
Zürich

Dear radioactive ladies and gentlemen,

As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem"* of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons,** which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same
tude as the electron mass and, in any case,
0.01 proton mass. The continuous β-spectrum
understandable by the assumption that in β
is emitted together with the electron, in s
the sum of the energies of neutron and elec

I admit that my remedy may appear to h
priori probability because neutrons, if they
probably have long ago been seen. However,
wager can win, and the seriousness of the s
continuous β-spectrum can be made clear by
honored predecessor in office, Mr. Debye, wh
while ago in Brussels, "One does best not t
that at all, like the new taxes." Thus one
discuss every way of salvation.—So, dear ra
it to test and set it right.—Unfortunately,
personally appear in Tübingen, since I am i
on account of a ball taking place in Zürich
from 6 to 7 of December.—With many greeting
Mr. Back, your devoted servant,

W. Pauli

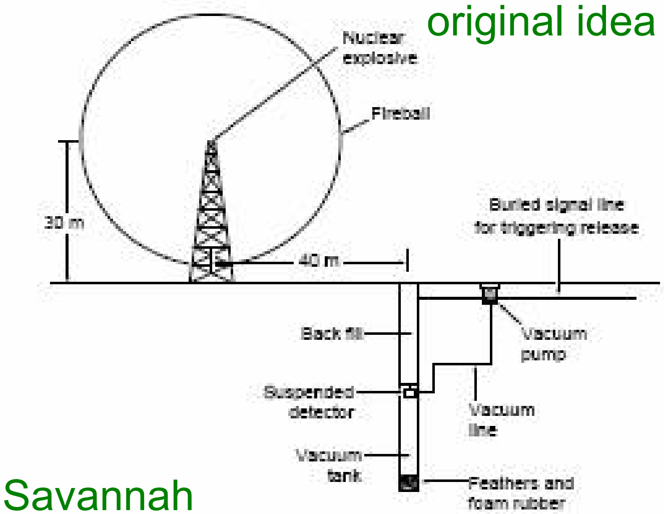


Introduction: ν history

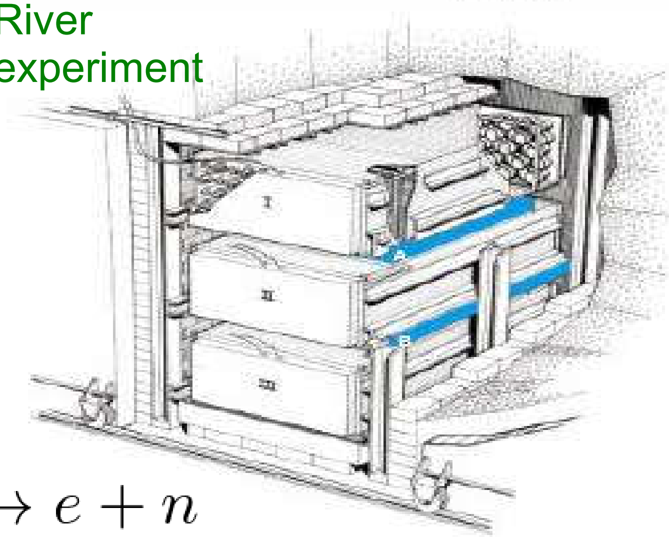
~25 years later (~1955),
the neutrino was discovered
by a team from Los Alamos Nat'l Lab

Fred Reines and Clyde Cowan. 1995 Nobel to Reines for the detection of the neutrino

original idea



Savannah River experiment



$$\nu + p \rightarrow e + n$$

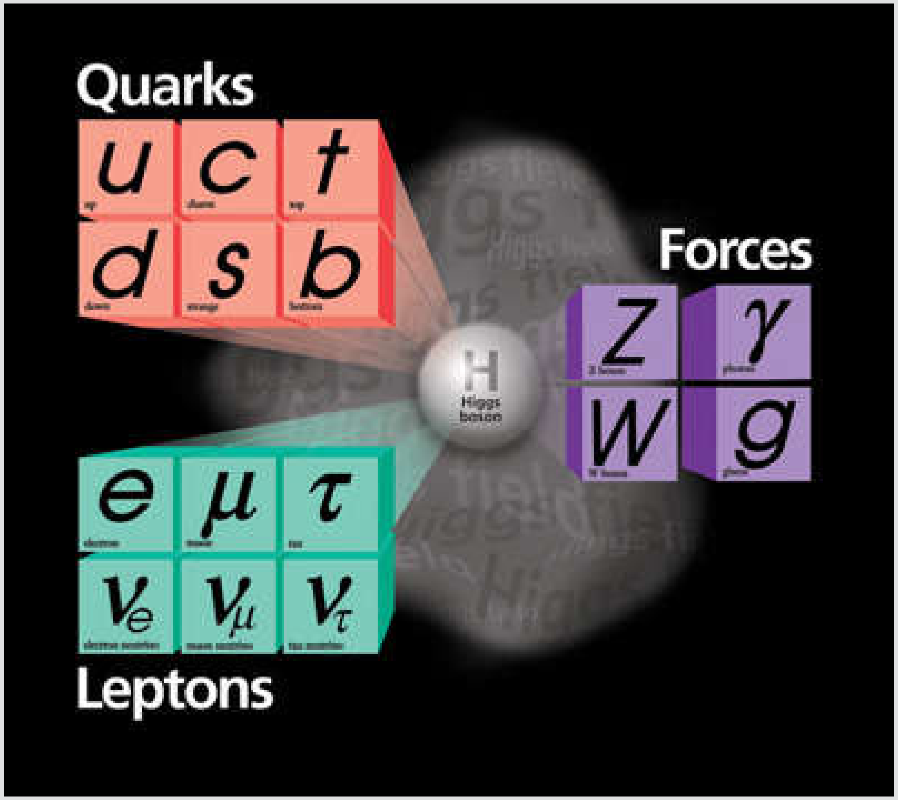
Introduction: ν and the SM

~60 years later (now),

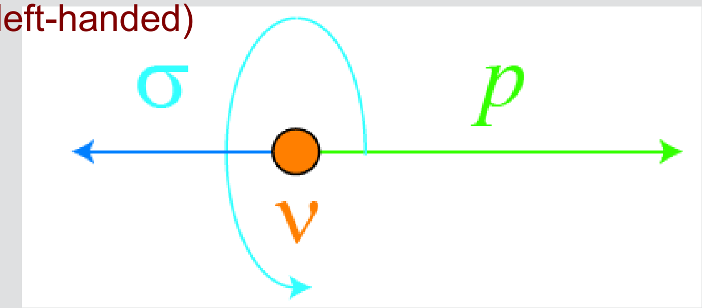
The neutrino arranged with other fundamental particles into the standard model of of particle physics…

.. with 3 generations of quarks, leptons, and 3 different forces mediating their interactions, and..

with 3, very light, almost massless, left-handed neutrinos…



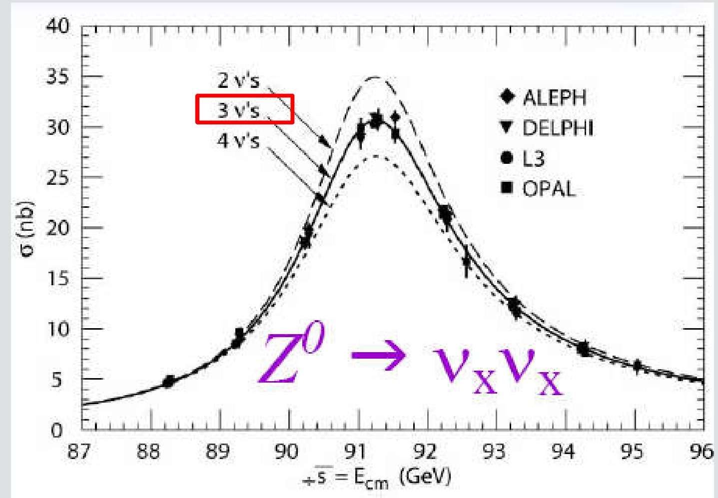
ν spin is in direction opposite to momentum (left-handed)



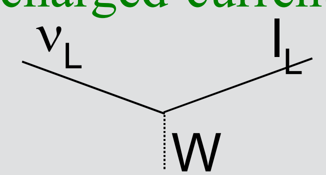
Introduction: ν and the SM

- Z-decay data show there are only 3 neutrinos with the "standard" electroweak (EW) interaction mediated by W and Z bosons

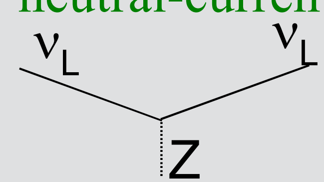
- cosmological observations support N(ν)~3



"charged-current"



"neutral-current"

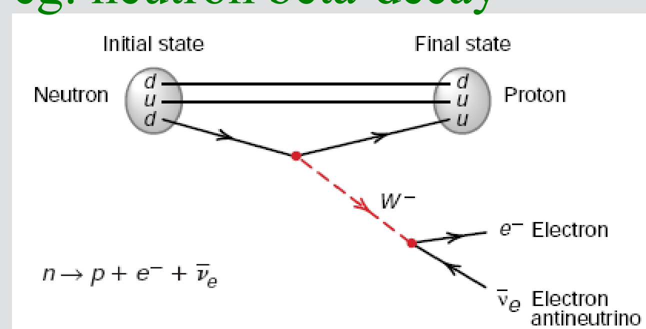


Neutrinos: they are very small
They have no charge; they have no mass;
they do not interact at all.
The Earth is just a silly ball
to them, through which they simply pass...

true to good approximation!

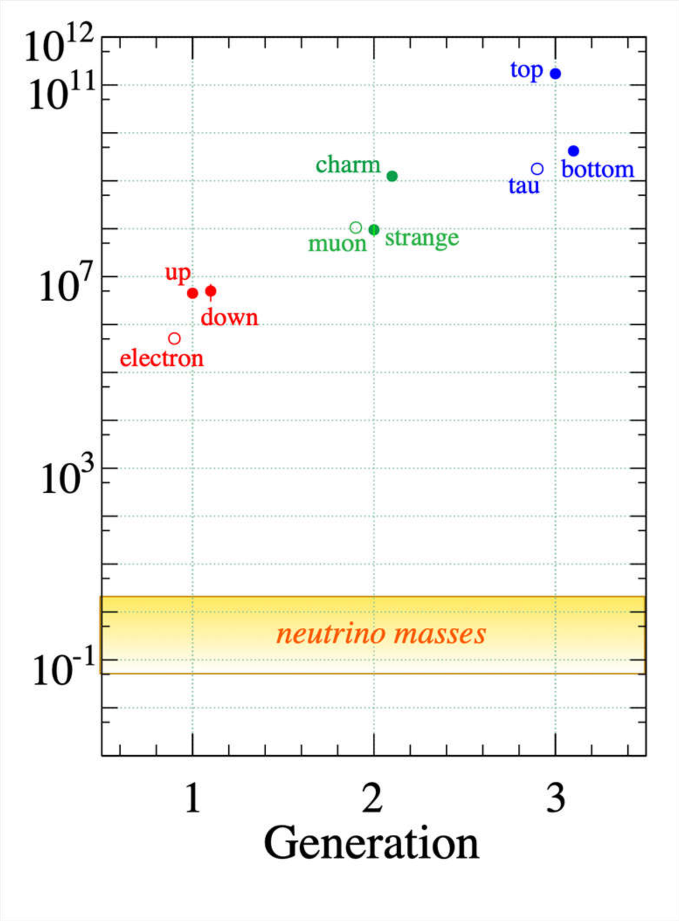
excerpt from Telephones Poles and other Poems, John Updike

eg: neutron beta-decay



Introduction: ν mass…

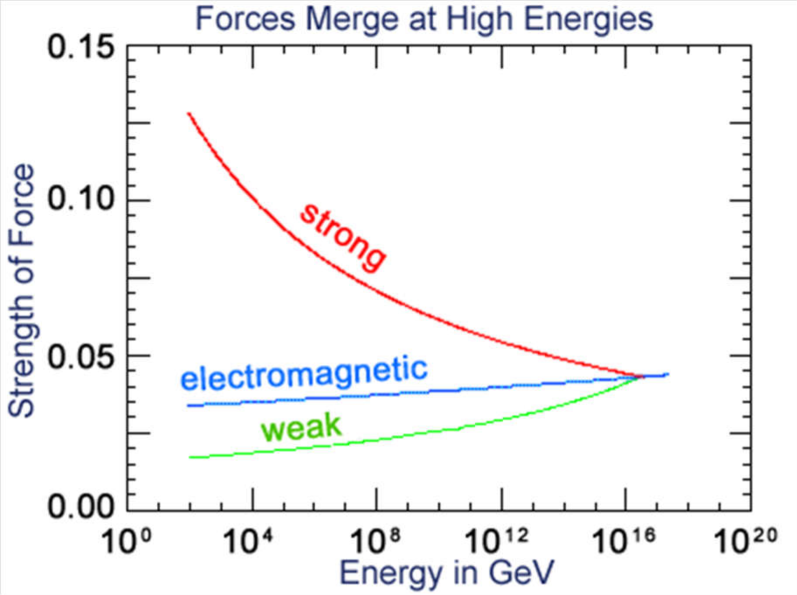
Neutrinos: neutral, ~massless particles, a possible window into beyond-the-standard-model physics…



see-saw mechanism

$$\mathcal{L}_{\rm mass} = \left[\begin{array}{cc} \nu_L & \nu_R \end{array} \right] \left[\begin{array}{cc} 0 & m \\ m & M \end{array} \right] \left[\begin{array}{c} \nu_L \\ \nu_R \end{array} \right]$$

$$\lambda \simeq \frac{m^2}{M} \simeq \frac{(100 \text{ GeV})^2}{10^{15} \text{ GeV}} = 0.01 \text{ eV}$$

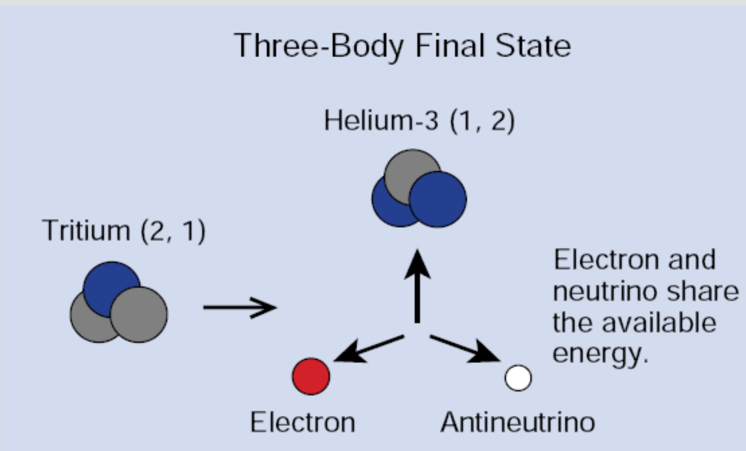


credit: M. Messier, IU

Introduction: ν mass

So how do you weigh a ν ?

Direct-mass measurements:
Use a spectrometer to measure the missing energy of the ν and infer the mass.



THE
PHYSICAL REVIEW
A journal of experimental and theoretical physics established by E. L. Nichols in 1893
SECOND SERIES, VOL. 88, No. 4 NOVEMBER 15, 1952

The Beta-Spectrum of Tritium and the Mass of the Neutrino*

L. M. LANGER AND R. J. D. MOFFAT
Department of Physics, Indiana University, Bloomington, Indiana
(Received June 23, 1952)

A direct determination of the beta-spectrum of H^3 has been made in a high resolution magnetic spectrometer. The experimental data are fitted by a straight line Fermi plot from 5.5 kev to the maximum energy at 17.95±0.10 kev. An upper limit of 250 volts or 0.05 percent of the mass of the electron is obtained for the rest mass of the neutrino. New estimates are obtained for the H^3 comparative half-life, the neutron half-life, and the value of the Fermi universal constant of beta-decay.

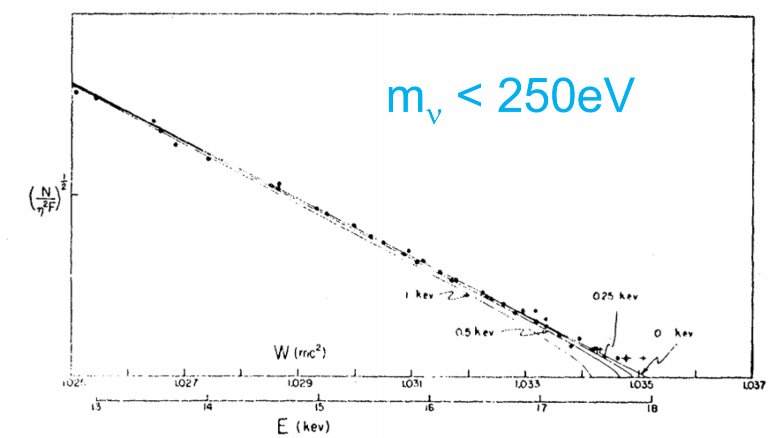


FIG. 5. Expanded Fermi plot of the tritium spectrum in the region near the end point. The curves are the theoretical plots expected for the indicated rest mass of the neutrino.

Early IU neutrino measurements: tritium beta decay

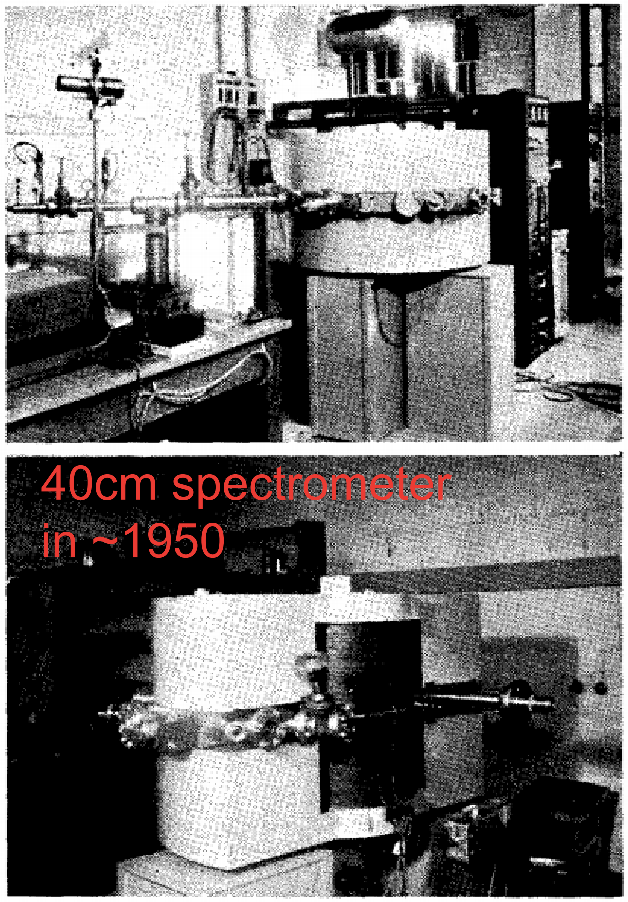


FIG. 3. Front and rear views of complete spectrometer

THE

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Early IU neutrino measurements: tritium beta decay

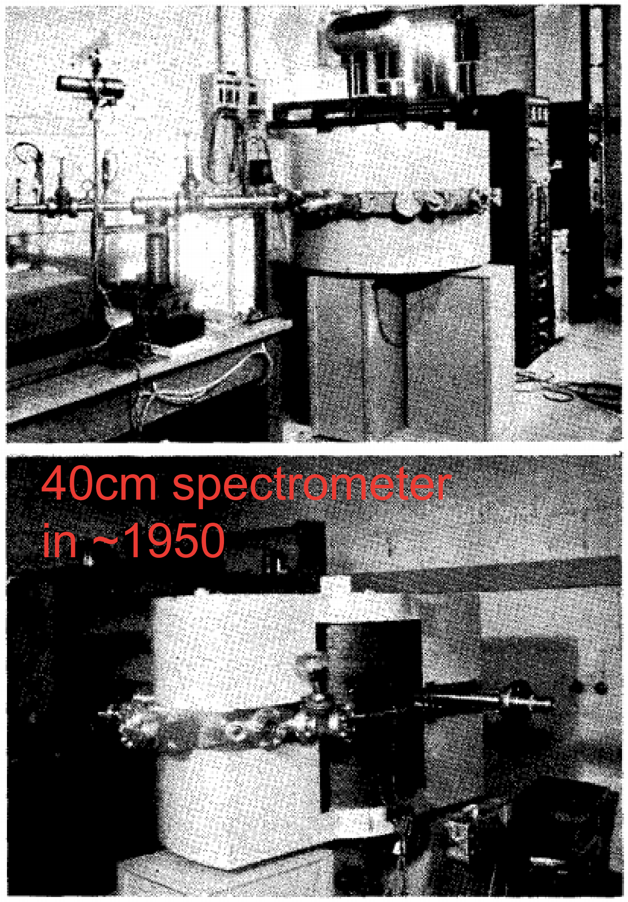
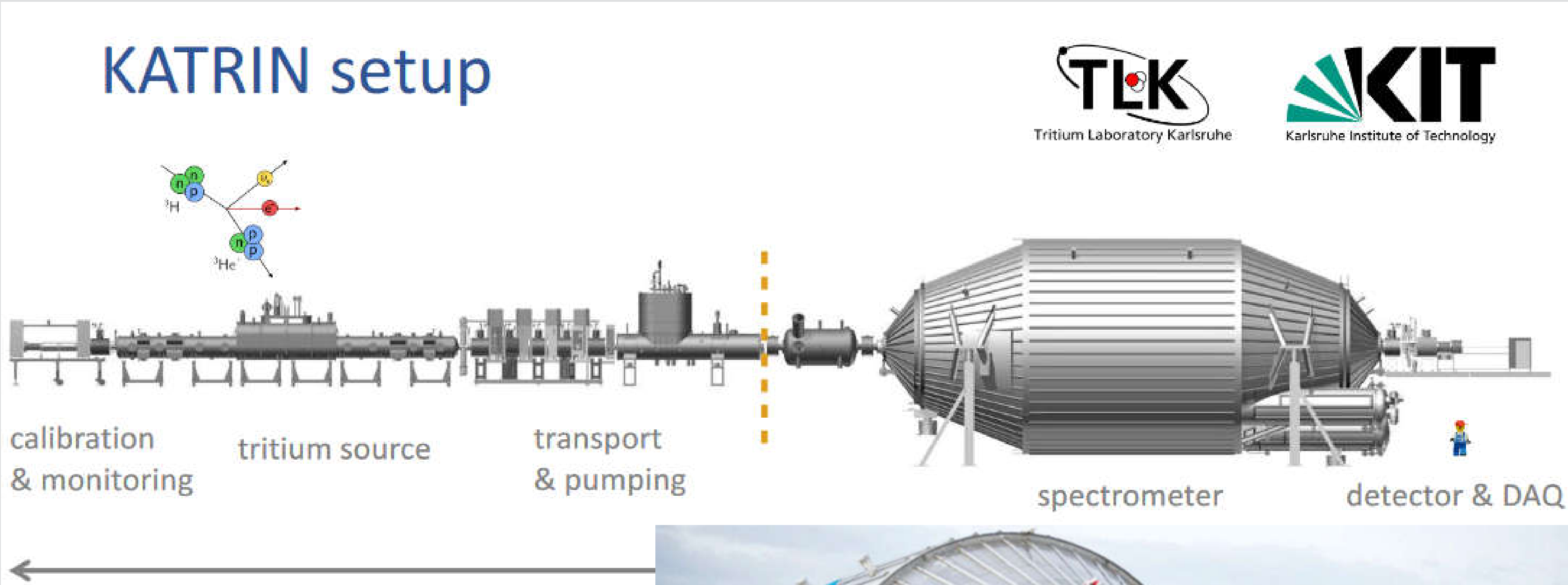


FIG. 3. Front and rear views of complete spectrometer



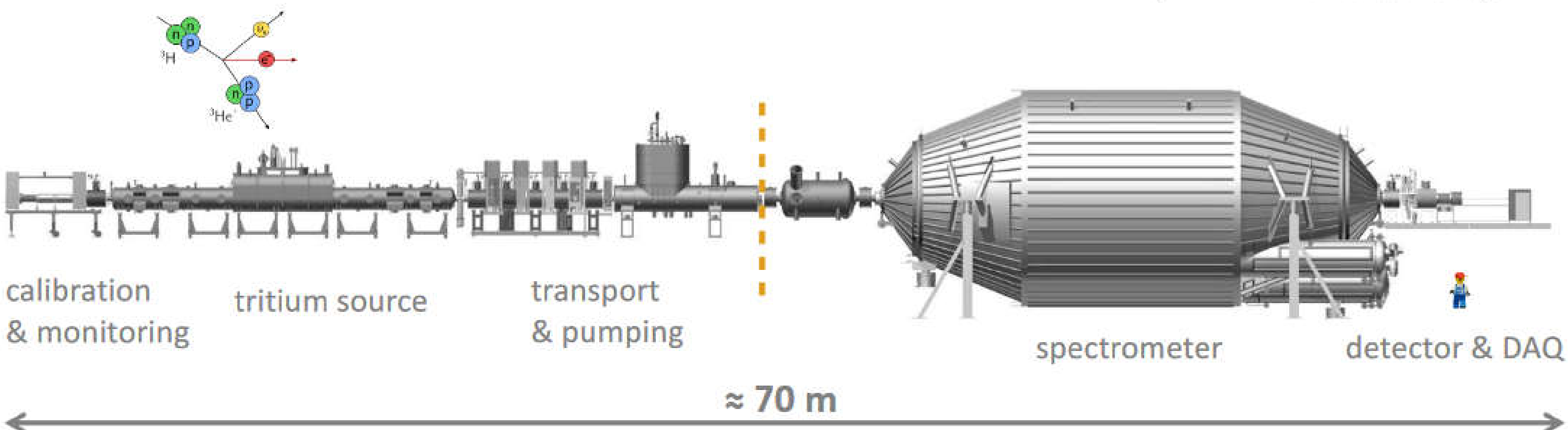
on a slightly larger scale….

…and tritium beta decay measurements continue…

KATRIN setup

Tritium Laboratory Karlsruhe

Karlsruhe Institute of Technology



arXiv.org > hep-ex > arXiv:1909.06048

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High Energy Physics - Experiment

An improved upper limit on the neutrino mass from a direct kinematic method by KATRIN

$m_\nu < 1.1$eV

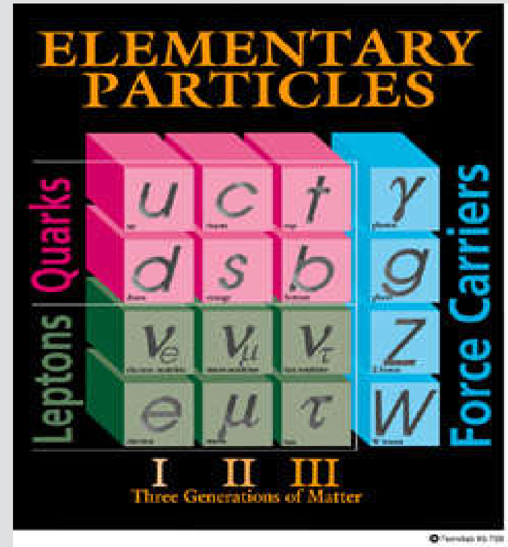
M. Aker, K. Altenmüller, M. Arenz, M. Babutzka, J. Barrett, S. Bauer, M. Beck, A. Beglarian, J. Behrens, T. Bergmann, U. Besserer, K. Blaum, F. Block, S. Bobien, K. Bokeloh (nee Hugenberg), J. Bonn, B. Bornschein, L. Bornschein, H. Bouquet, T. Brunst, T. S. Caldwell, L. La Cascio, S. Chilingaryan, W. Choi, T. J. Corona, K. Debowski, M. Deffert, M. Descher, P. J. Doe, O. Dragoun, G. Drexlin, J. A. Dunmore, S. Dyba, F. Edzards, L. Eisenblätter, K. Eitel, E. Ellinger, R. Engel, S. Enomoto, M. Erhard, D. Eversheim, M. Fedkevych, A. Felden, S. Fischer, B. Flatt, J. A. Formaggio, F. M. Fränkle, G. B. Franklin, H. Frankrone, F. Friedel, D. Fuchs, A. Fulst, D. Furse, K. Gauda, H. Gemmeke, W. Gil, F. Glück, S. Görhardt, S. Groh, S. Grohmann, R. Grössle, R. Gumbsheimer, M. Ha Minh, M. Hackenjos, V. Hannen, F. Harms, J. Hartmann, N. Haußmann, F. Heizmann, K. Helbing, S. Hickford, D. Hilk, B. Hillen, D. Hillesheimer, D. Hinz, T. Höhn, B. Holzapfel, S. Holzmann, T. Houdy, M. A. Howe, A. Huber, A. Jansen, A. Kaboth, C. Karl, O. Kazachenko, J. Kellerer, N. Kernert, L. Kippenbrock, M. Kleesiek (nee Haag), M. Klein, C. Köhler, L. Köllenberger, A. Kopmann, M. Korzeczek, A. Kosmider, A. Kovalí, B. Krasch, M. Kraus, H. Krause, L. Kuckert et al. (109 additional authors not shown)

(Submitted on 13 Sep 2019)

We report on the neutrino mass measurement result from the first four-week science run of the Karlsruhe Tritium Neutrino experiment KATRIN in spring 2019. Beta-decay electrons from a high-purity gaseous molecular tritium source are energy analyzed by a high-resolution MAC-E filter. A fit of the integrated electron spectrum over a narrow interval around the kinematic endpoint at 18.57 keV gives an effective neutrino mass square value of $(-1.0^{+0.9}_{-1.1})$ eV^2. From this we derive an upper limit of 1.1 eV (90% confidence level) on the absolute mass scale of neutrinos. This value coincides with the KATRIN sensitivity. It improves upon previous mass limits from kinematic measurements by almost a factor of two and provides model-independent input to cosmological studies of structure formation.

Introduction: ν oscillations

- Neutrinos: neutral, ~massless particles,a possible window into beyond-the-standard-model physics…



…Can study via an interferometric technique, et phenomena of neutrino oscillations:

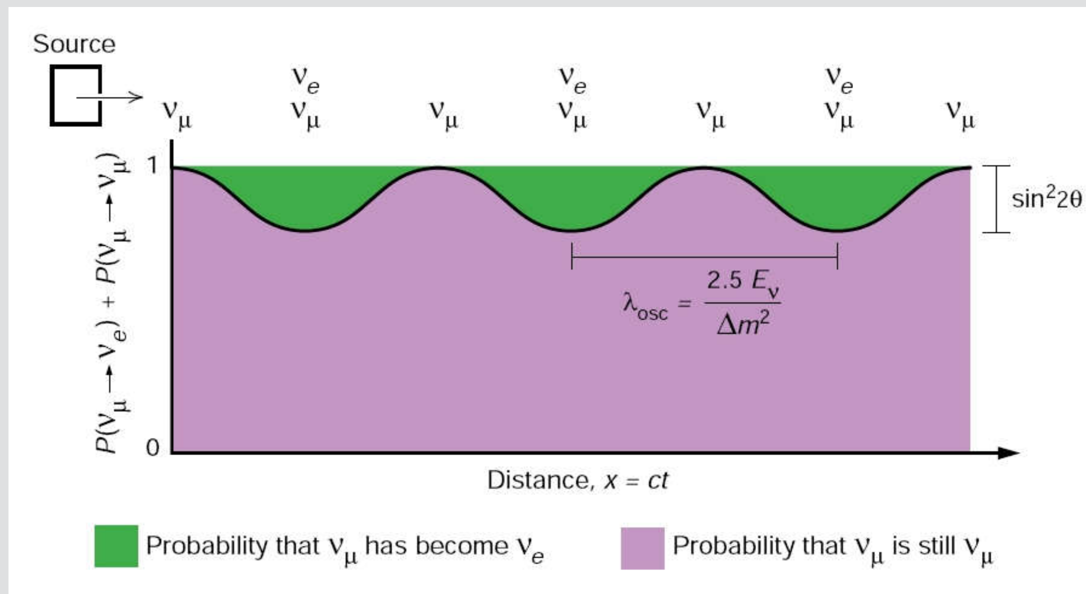
eg: for 2 generations:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

$$|\nu_\mu(t)\rangle = -\sin\theta\exp[-i(E_1/\hbar)t]/\nu_1\rangle + \cos\theta\exp[-i(E_2/\hbar)t]/\nu_2\rangle$$

$$P(\nu_\mu\to\nu_e) = \sin^2 2\theta\,\sin^2\left(\frac{\pi x}{\lambda_{osc}}\right)$$

$$\lambda_{osc} = 2.5E_\nu/\Delta m^2$$

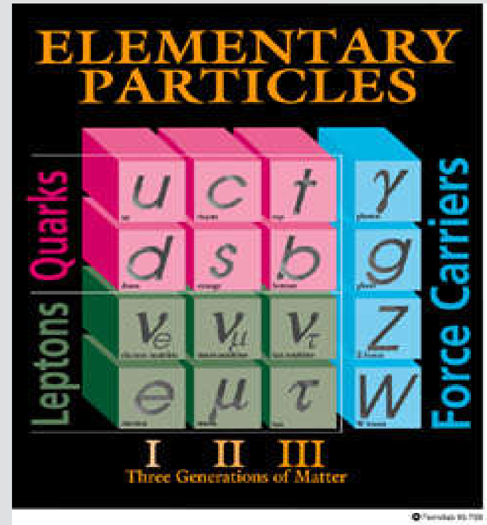


- and experiments are sensitive to ~ eV mass differences

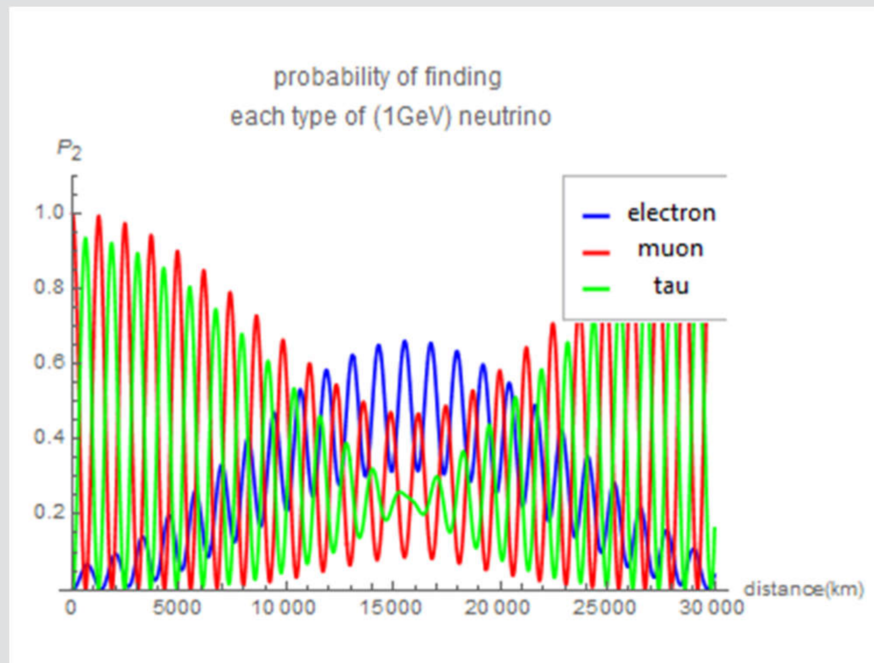
Introduction: ν oscillations…

- More completely, for 3 generations:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P$$
$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & c_{13}c_{23} \end{pmatrix} P\ .$$



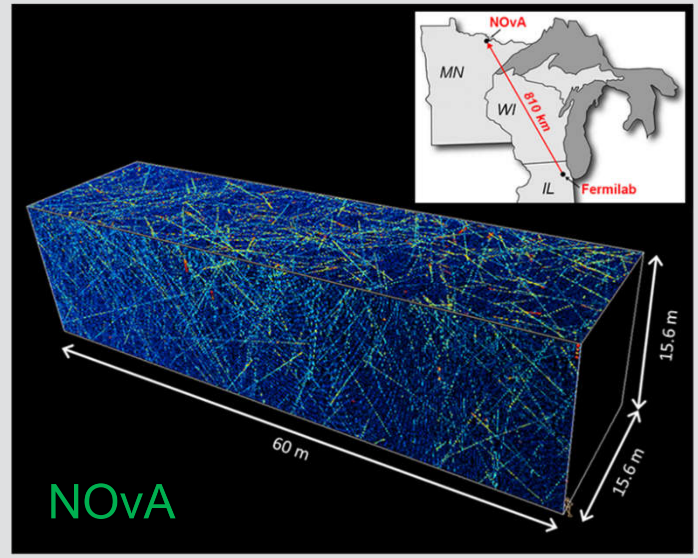
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j} {\rm Re}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right]\sin^2\left(\frac{\Delta m^2_{ji}L}{4E}\right) + 2\sum_{i<j} {\rm Im}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right]\sin\left(\frac{\Delta m^2_{ji}L}{2E}\right),$$



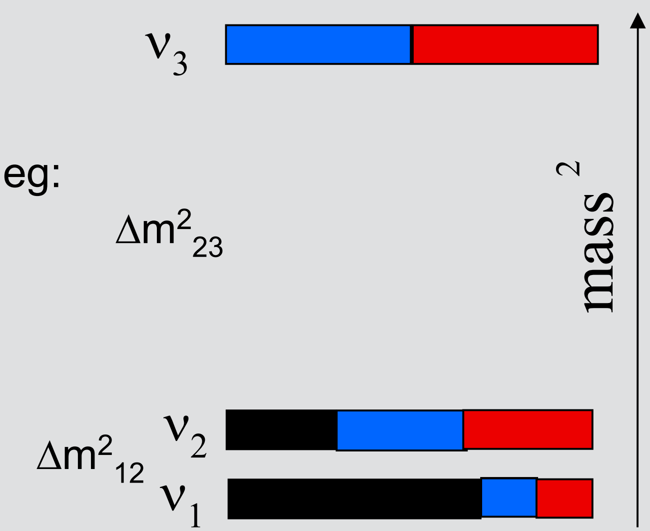
Introduction: ν oscillations…

- Evidence for ν oscillations exist at
  - $\Delta m^2 \sim 10^{-5}\ eV^2$ (“solar”) and
  - $\Delta m^2 \sim 10^{-4}\ eV^2$ (“atmospheric”) .

And has been verified in multiple experiments:
MINOS, KamLAND, Super-K, NOvA ,T2K.
(and DUNE, in future)



- This evidence is well-explained with 3ν mass model and these Δm^2_{12} , Δm^2_{23}
- and these efforts explore additional important questions, eg:
  - ν mass ordering,
  - matter-antimatter asymmetry
- However, there is the LSND result…

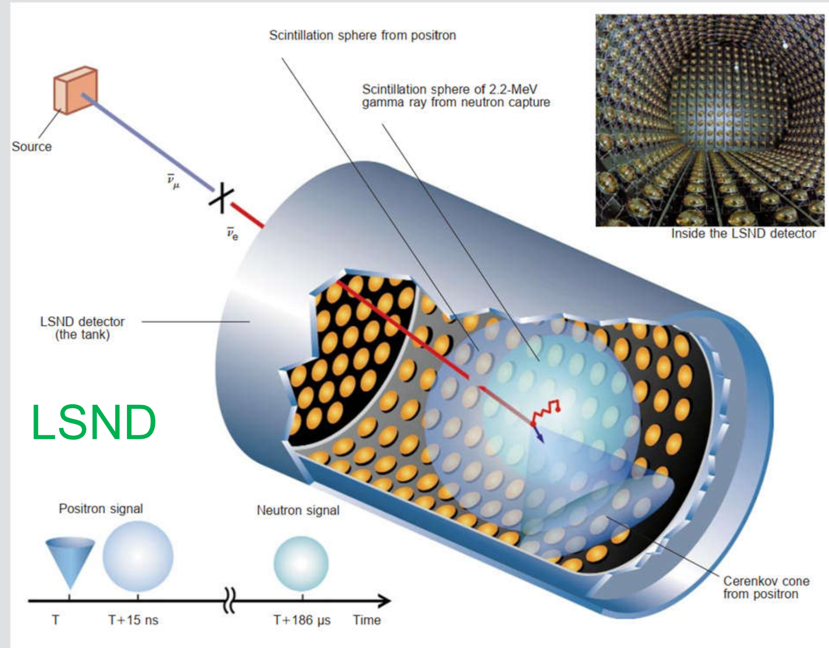


Introduction: LSND

- Liquid Scintillator Neutrino Detector
- at Los Alamos Natl Lab in 1994-1999
- baseline distance: L~20m
- neutrino energy: E~20MeV
- L/E~1 so looking for Δm^2~1 ev^2

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \, \sin^2\left(\frac{\pi x}{\lambda_{osc}}\right)$$

$$\lambda_{osc} = 2.5 E_\nu / \Delta m^2$$



- used same detection method as original 1955 experiment

$$\nu + p \to e + n$$

Left to right: Rex Tayloe, Geoffrey Mills, Hywel White, Vern Sandberg, Bill Louis, and Gerry Garvey. For biographies of Hywel White, Vern Sandberg, and Bill Louis, see "A Thousand Eyes." For a biography of Gerry Garvey, see "The Oscillating Neutrino."

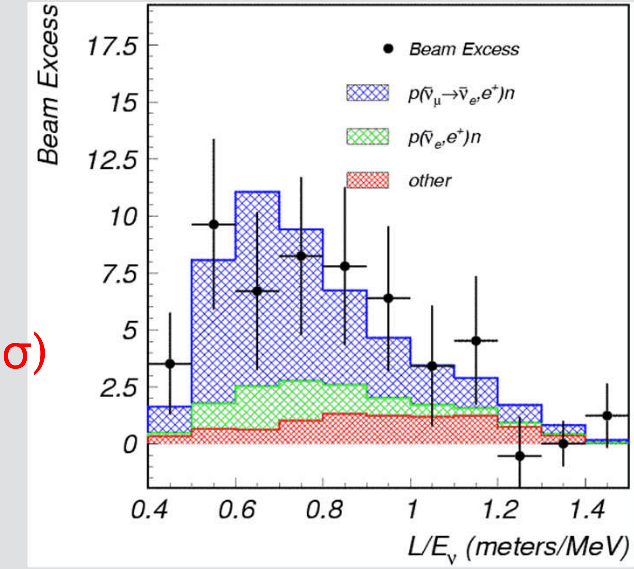
Introduction: LSND

- observed excess of $\bar{\nu}_e$ in beam of $\bar{\nu}_\mu$

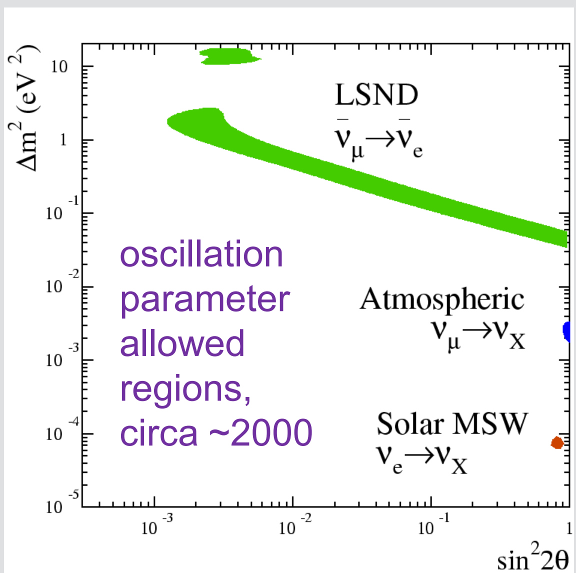
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\pi x}{\lambda_{osc}}\right)$$

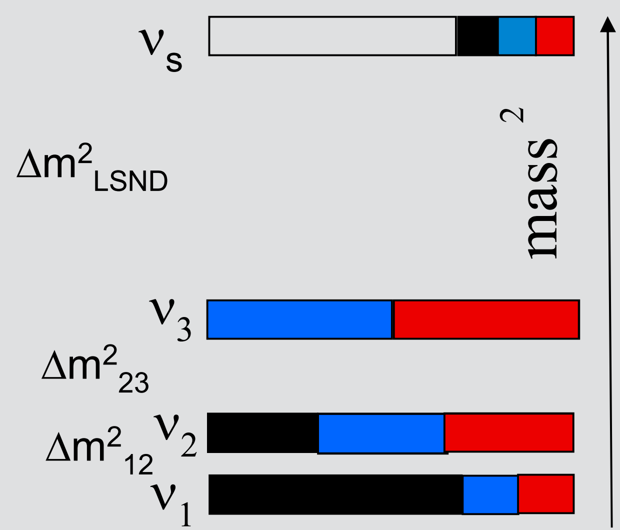
$$\lambda_{osc} = 2.5 E_\nu / \Delta m^2$$

Excess over background:
87.9 ± 22.4 ± 6.0 (3.8σ)



- LSND result, with other established results, implies a third Δm^2 and at least 1 more generation of neutrinos



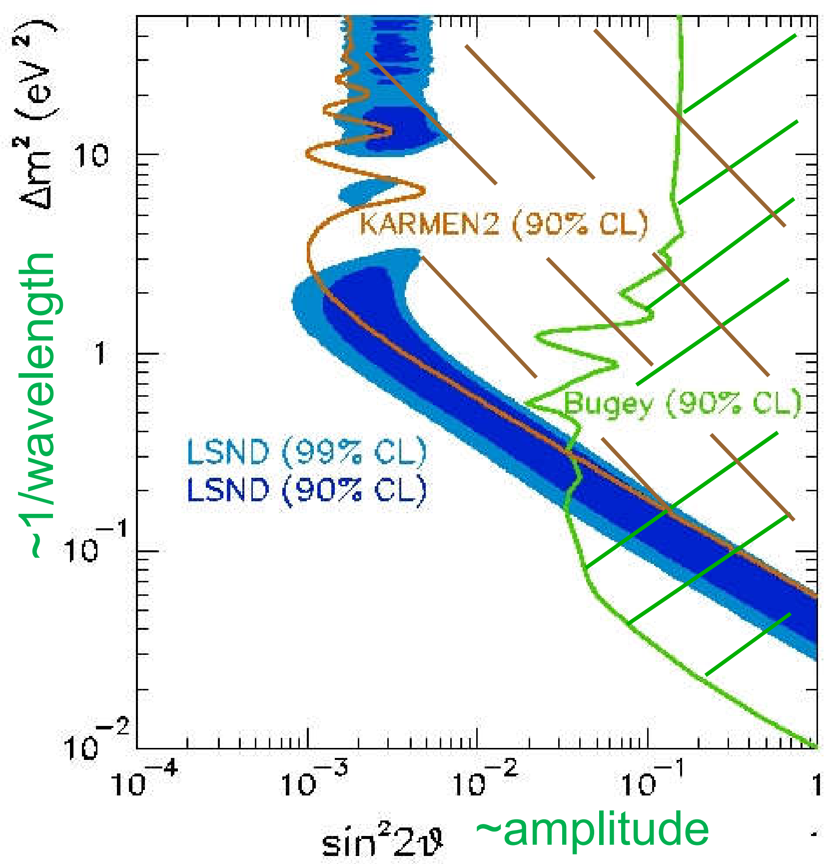


Aside: Measuring ν Oscillations, allowed and limit regions

- ν oscillation experiments measure wavelength/amplitude of oscillations
- allows extraction of Δm^2 , $\sin^2 2\theta$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(\frac{\pi X}{\lambda_{osc}})$$

$$\lambda_{osc} = 2.5 E_\nu / \Delta m^2$$



Example:

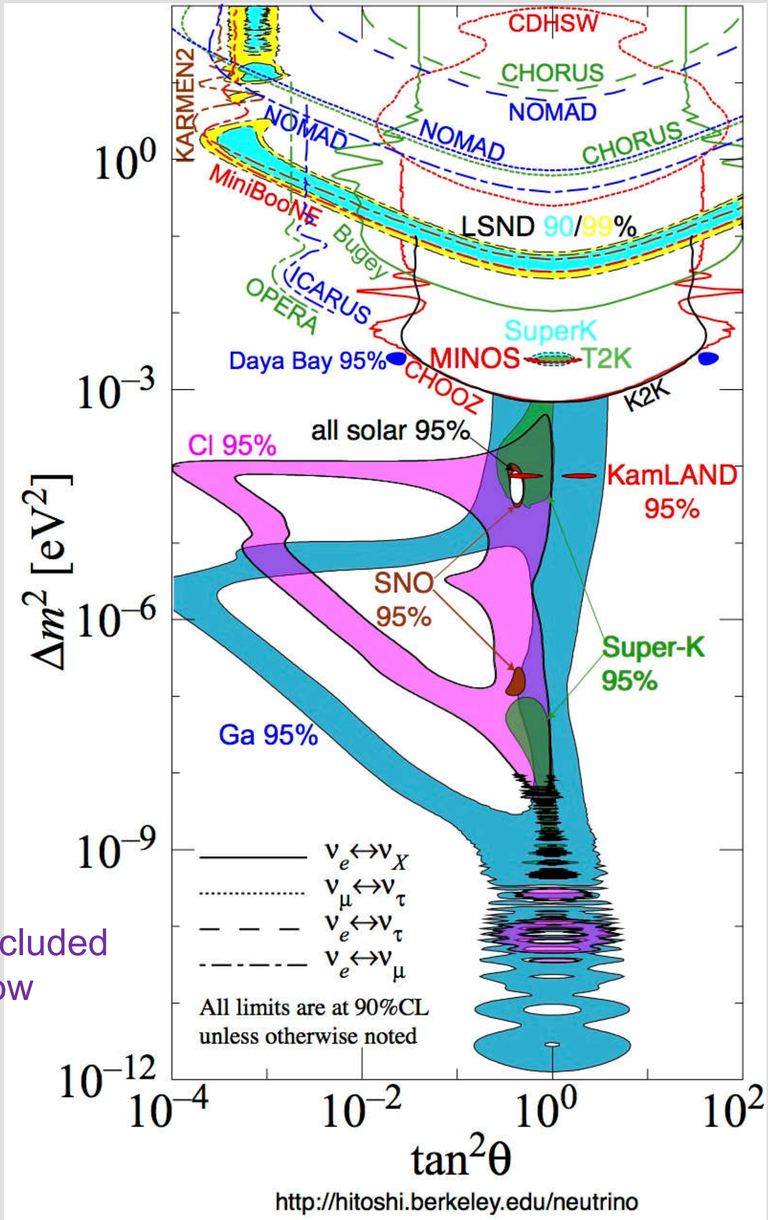
- The **LSND** experiment observed a signal for oscillations, resulting in allowed region (in blue)

- **KARMEN2** and **Bugey** did not, resulting in lines that delimit excluded regions (to right of brown/green lines)

Introduction: ν oscillations…

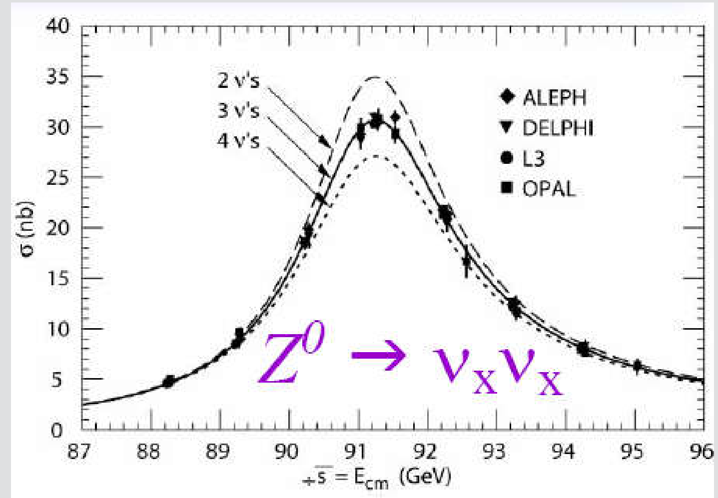
… and continued efforts add more information

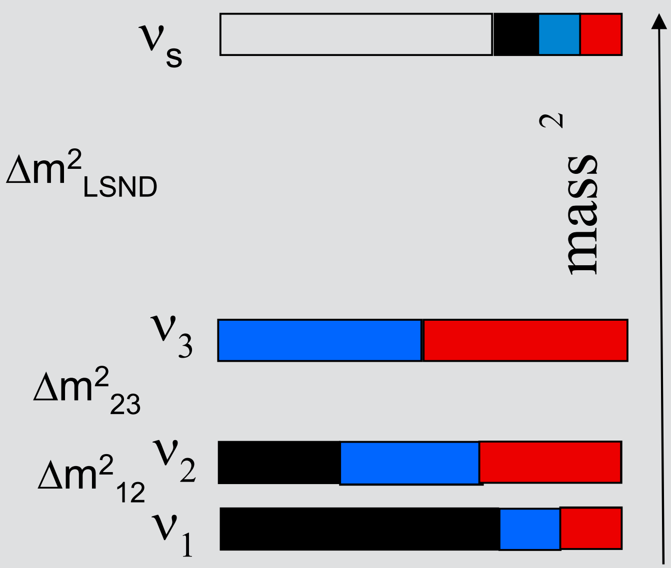
oscillation parameter allowed/excluded regions, now

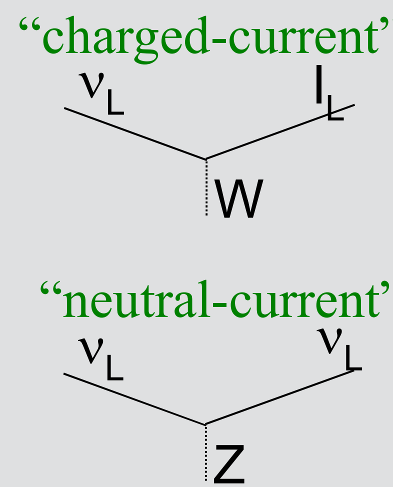


Introduction: "sterile" ν

Since various measurements (Z-decay, cosmology) limit N(ν) < 3 , then any more ν must not interact via standard ("electoweak") fashion, thus "sterile" (as opposed to "active")





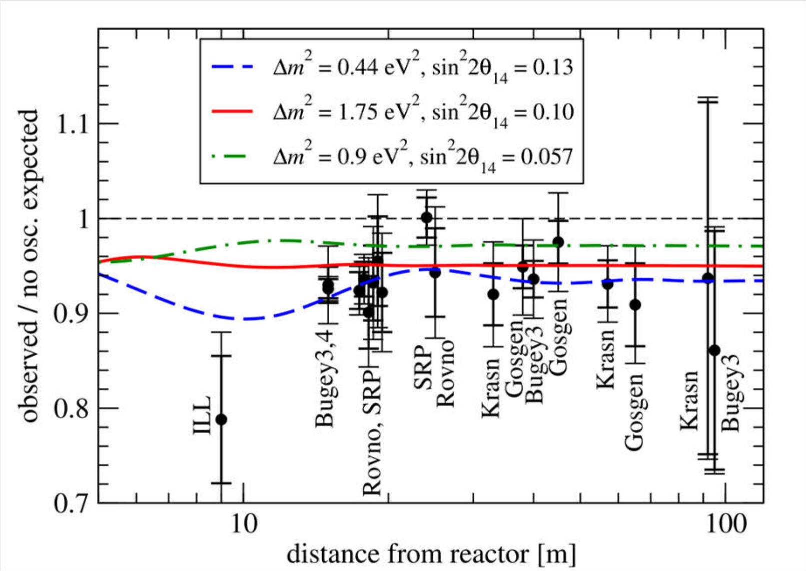


electroweak interaction

Introduction: ν oscillations…

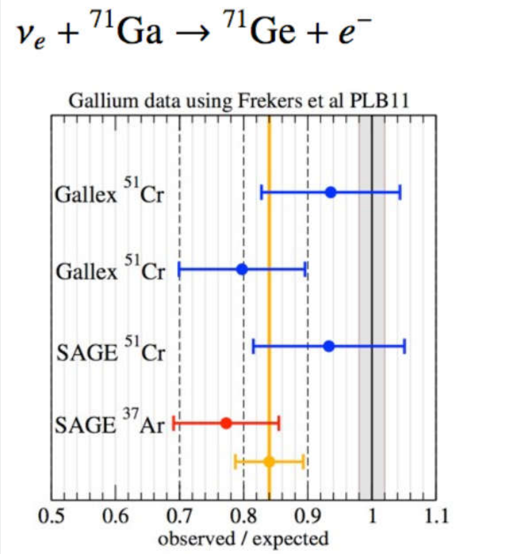
Other anomalies/evidence for sterile neutrinos:

- reactor $\bar{\nu}_e$ measured rates ~5% lower than prediction



J. High Energy Phys. **2013**, 50 (2013).

- Gallium (solar ν) experiments see deficit of ν_e from calibration sources.



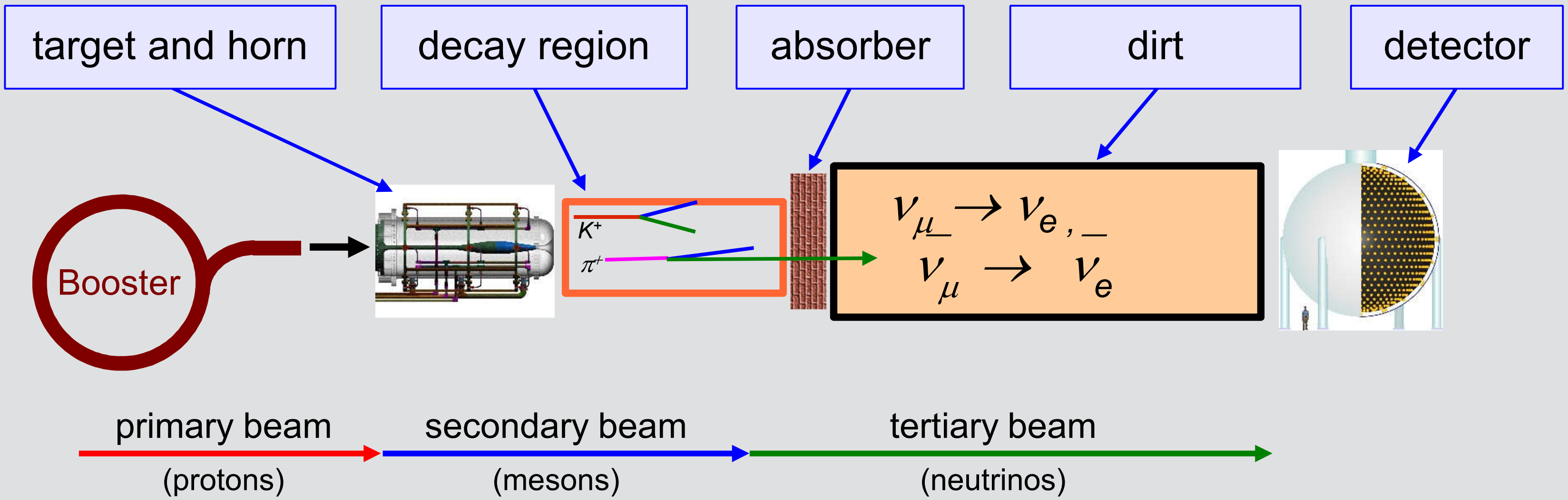
Phys.Rev. C83 (2011) 065504

T. Schwetz et al. talk @ APC, 2013

- deficits due to oscillation to sterile ν ?

MiniBooNE experiment: overview

- Designed and built to search for electron-appearance oscillations ($\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$) and to study ν interactions

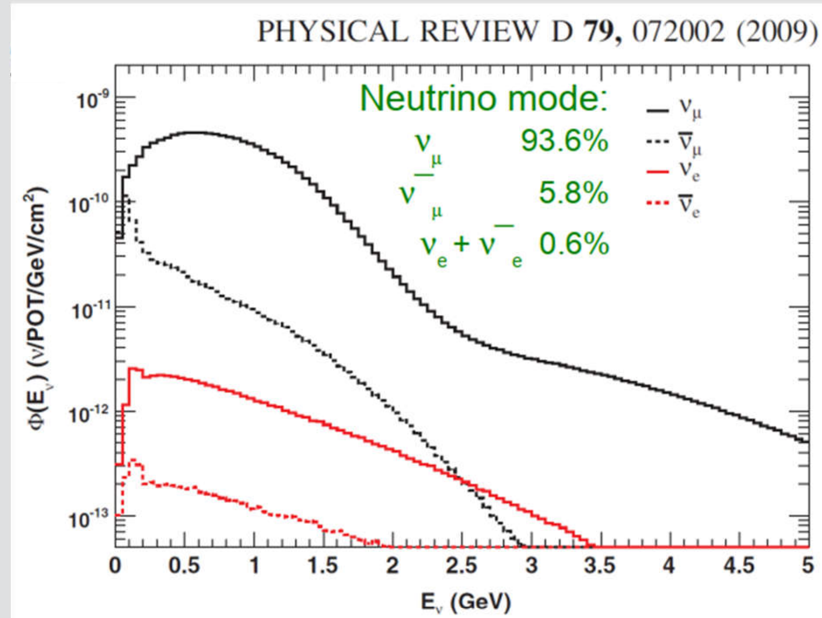


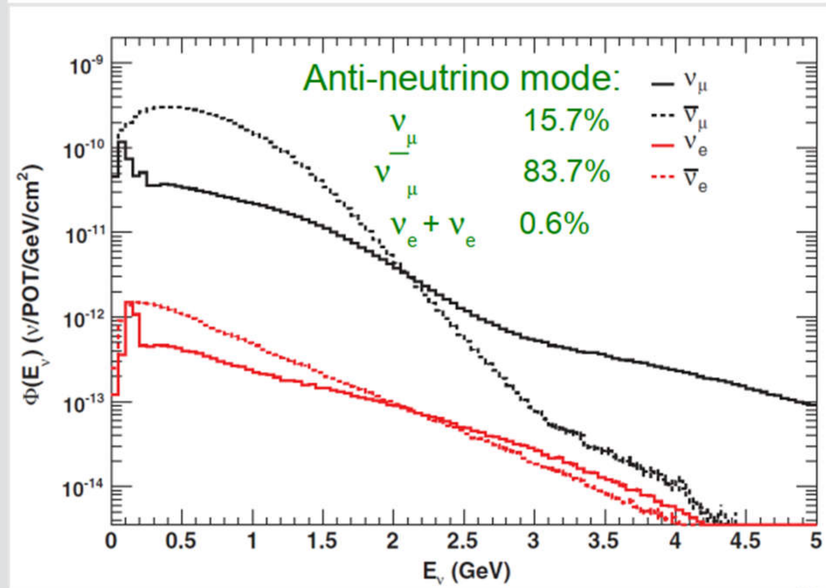
- Uses the Fermilab Booster Neutrino Beamline (BNB)
- $E_\nu \approx 500$ MeV, detector at 500m, ($L/E_\nu \approx 1$)
- ran 2002-2019
- last beam taken 7/17/19

MiniBooNE experiment: ν flux

- 8GeV protons on a 1.7 int. length Be target…
- within a magnetic horn (2.5 kV, 174 kA), can focus pos. (neutrino mode) or neg. (antineutrino mode) mesons
- flux predicted from π production measurements plus detailed MC simulations of target+horn (PRD79(2009)072002)
- most important π production measurements from HARP (at CERN) at 8.9 GeV/c beam momentum (as MB), 5% int. length Be target (Eur.Phys.J.C52(2007)29)
- also measured in-situ, including the "intrinsic" ν_e
- $<E_\nu> \approx$ 800 MeV

Magnetic focusing horn



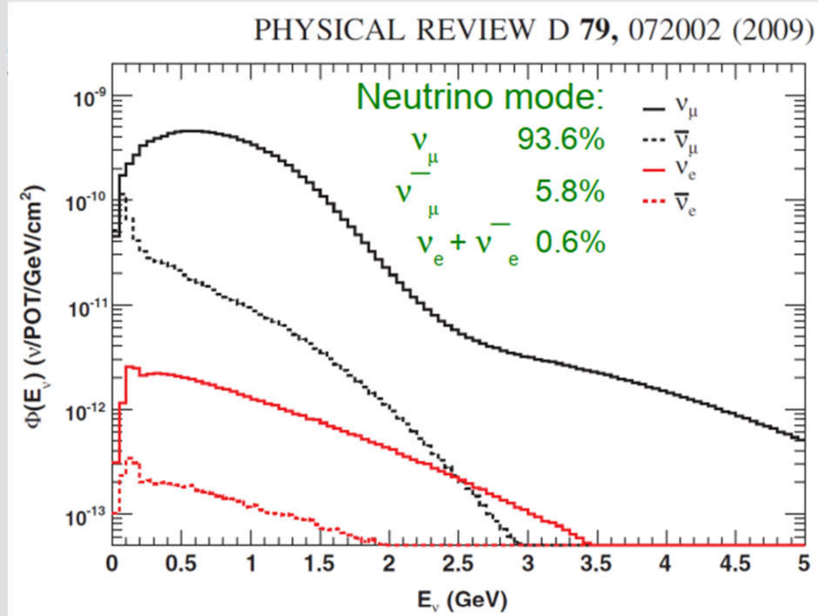


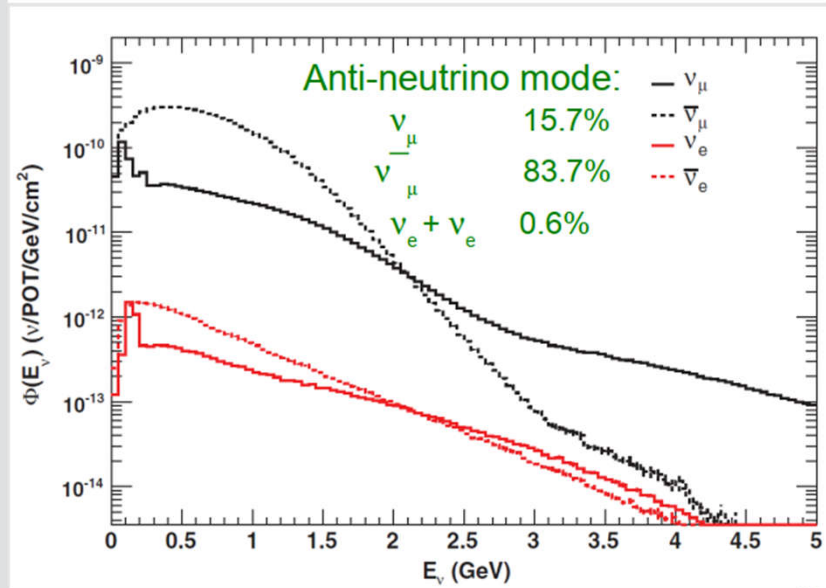
MiniBooNE experiment: ν flux

- 8GeV protons on a 1.7 int. length Be target…
- within a magnetic horn (2.5 kV, 174 kA), can focus pos. (neutrino mode) or neg. (antineutrino mode) mesons
- flux predicted from π prod… …ements plus detailed MC sim… …get+horn (PRD79(2009)…
- most i… …production measurements from HAR… …RN) at 8.9 GeV/c beam momentum (as MB), 5% int. length Be target (Eur.Phys.J.C52(2007)29)
- also measured in-situ, including the "intrinsic" ν_e
- $<E_\nu> \approx$ 800 MeV

ie: we know the ν flux

Magnetic focusing horn

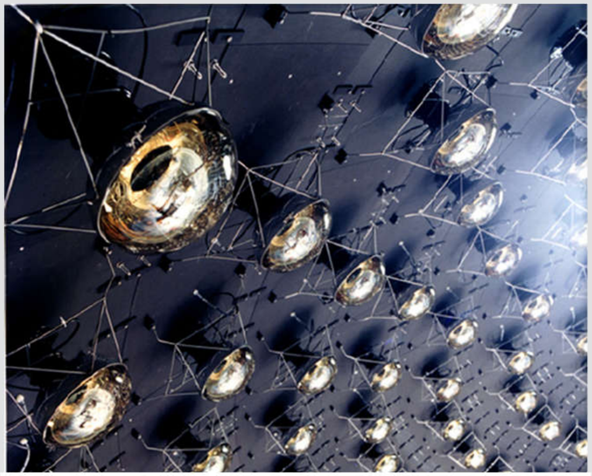


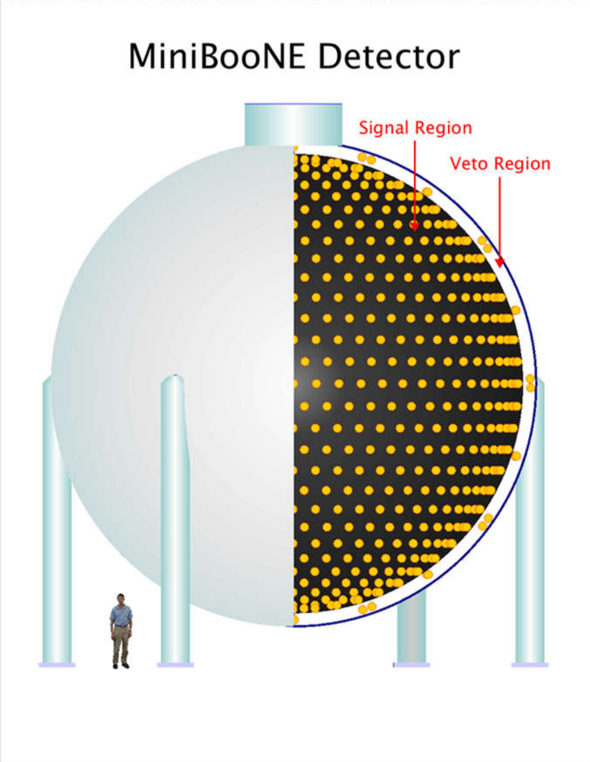


MiniBooNE experiment: detector

A mineral oil (CH_2) cherenkov detector:

- 541 meters from target
- 12 meter diameter sphere
- 800 tons mineral oil (CH_2)
- 3 m overburden
- includes 35 cm veto region
- viewed by 1280 8” PMTs
- (10% coverage) + 240 veto





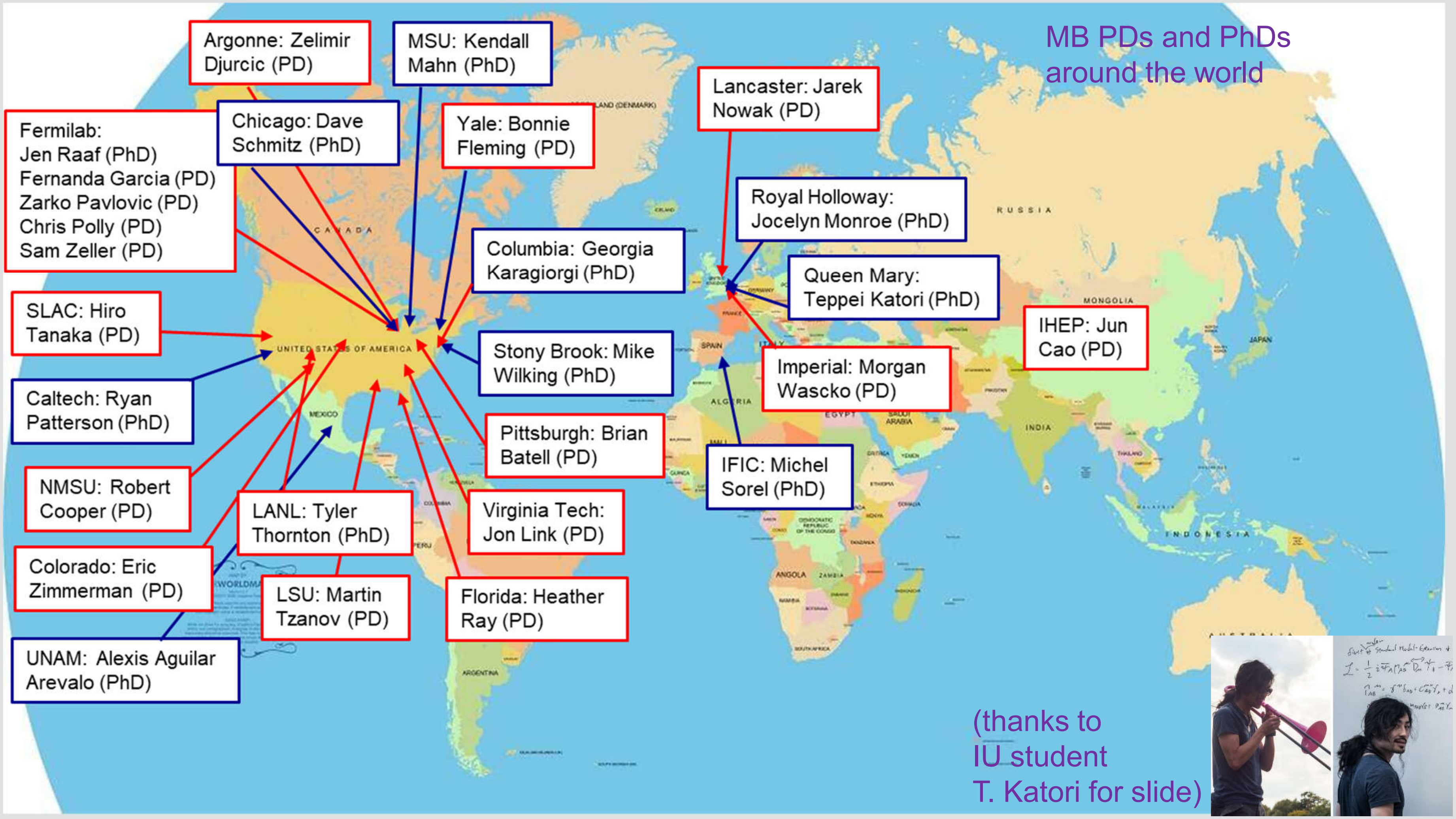
MiniBooNE experiment: collaboration

A hardy collaboration, spanning ~20 yrs…

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]

MiniBooNE experiment: collaboration

… training many excellent young scientists



MiniBooNE experiment: collaboration

… and inspiring rock-n-roll….

symmetry
dimensions of particle physics

home | departments | science topics | image bank | archives

Photo by Reidar Hahn, Fermilab

signal to background

August 09, 2013

Miniboone the band meets MiniBooNE the experiment

A New York rock band named after a Fermilab neutrino experiment recently visited their namesake for the first time.

By Laura Dattaro

PDF download

Related symmetry content

Doug Schrashun once wrote a song named after a concept in quantum mechanics for a band named after a neutrino experiment.

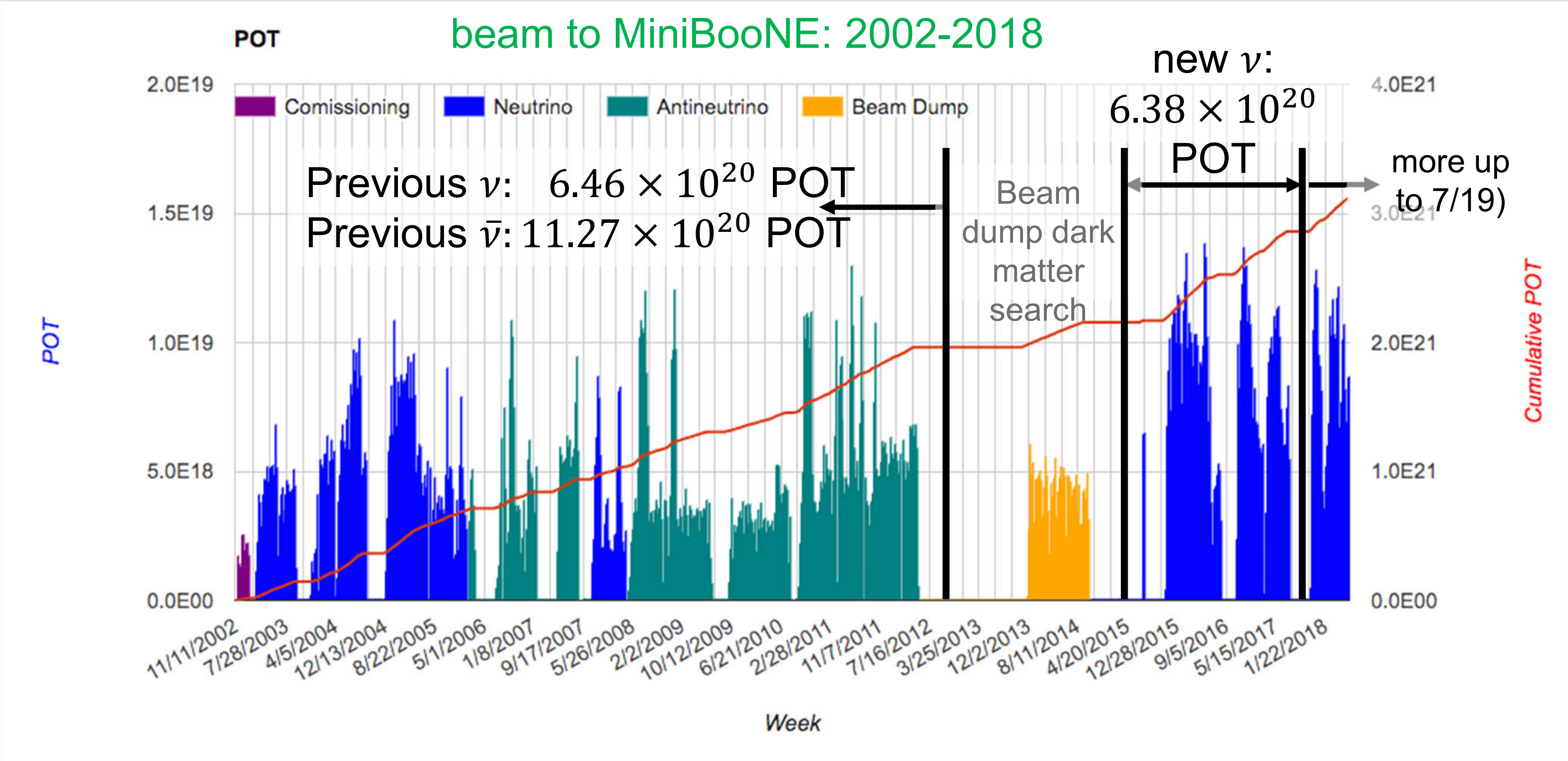
But he is not, by any means, a scientist.

Schrashun is a financial consultant and a founding member of the band Miniboone, which shares a name with the first phase of the Booster Neutrino Experiment at Fermilab. Miniboone the band recently visited MiniBooNE the experiment for the first time.

MiniBooNE experiment: data

- 2002-2005, 2007 in ν_μ mode,
- 2005-2006, 2008-2012 $\bar{\nu}_\mu$ mode
- 2014 χ (dark matter) mode
- 2016-2017 ν_μ mode

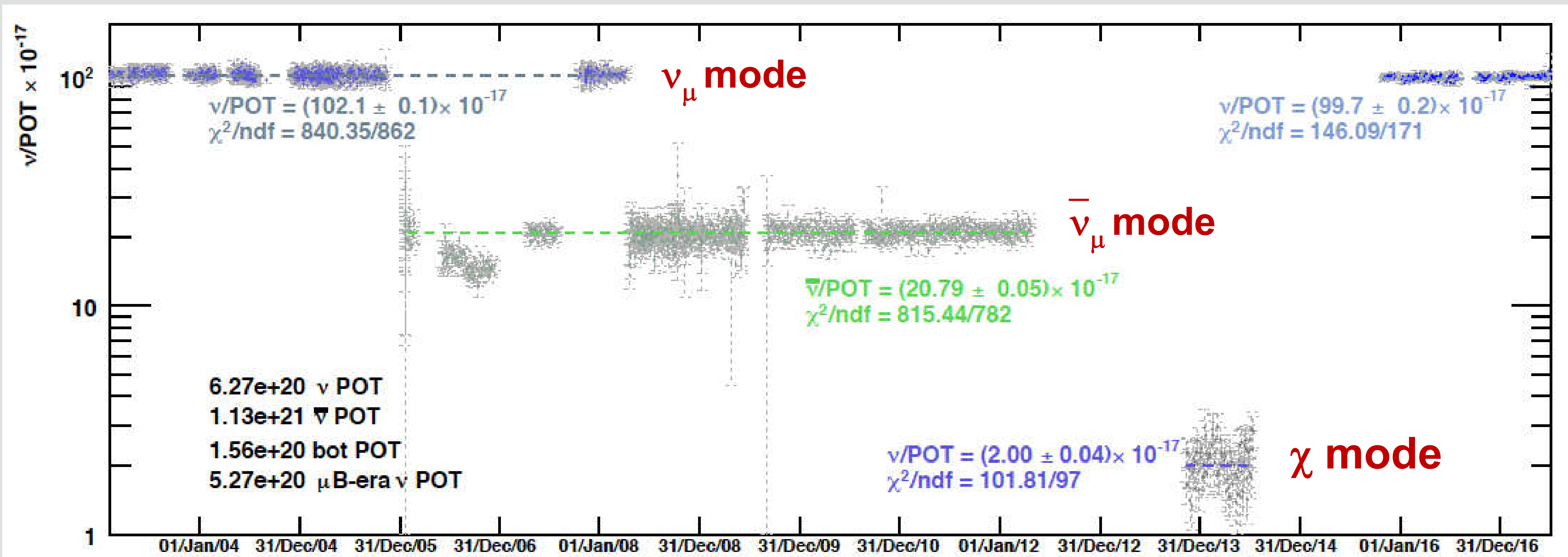
"POT"=protons on target



MiniBooNE experiment: data

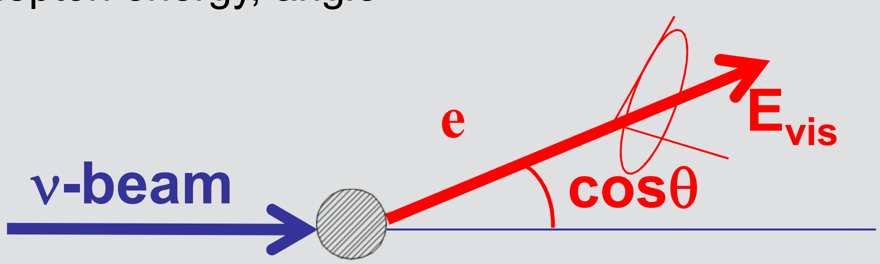
- event rate stable over 15 years of running

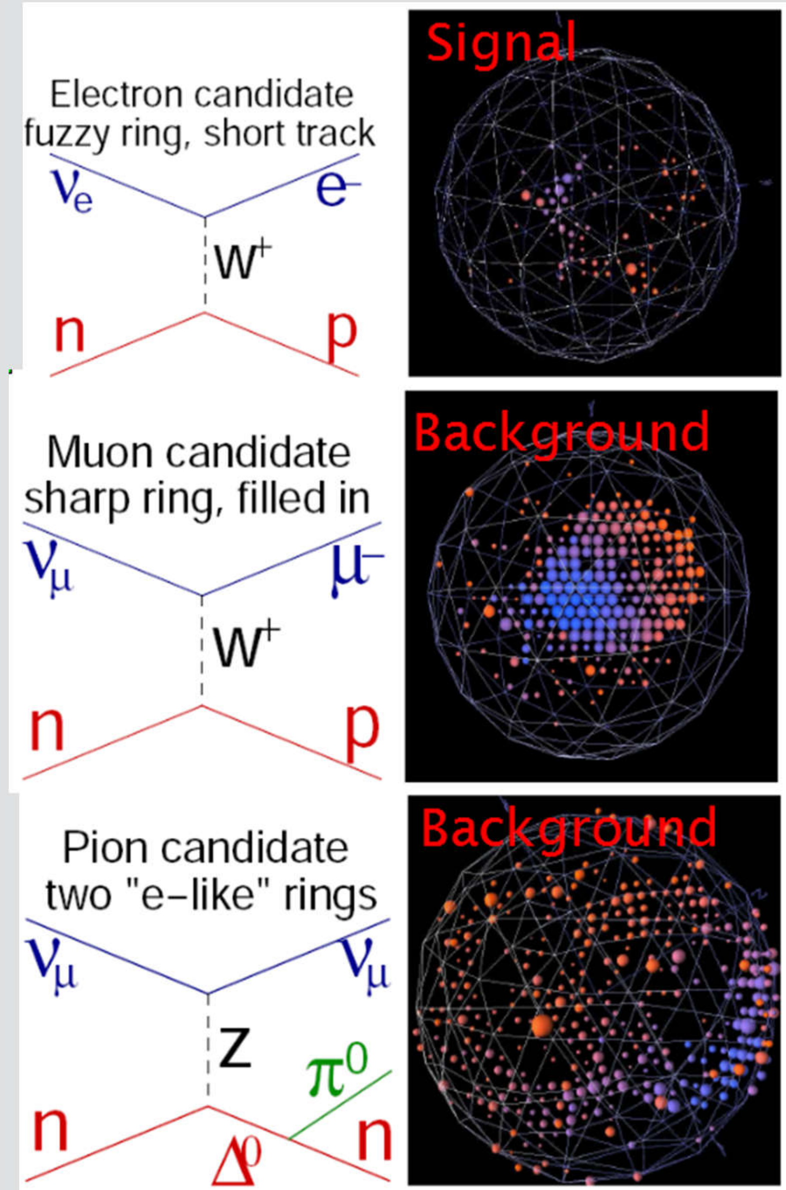
neutrino event in MiniBooNE: 2002-2018



MiniBooNE experiment: analysis

- charged particles in MB create Cherenkov light and small amount of scintillation light.
- Tracks reconstructed (energy, direction, position, type) with likelihood method utilizing time, charge of PMT hits (NIM, A 608 (2009), pp. 206-224)
- in addition, muon, charged pion decays are seen by recording PMT info for 20μs around 2μs beam spill
- can ID ν_e, $\bar{\nu}_e$ oscillation-candidate events and separate from backgrounds
- Measure neutrino enegy E_ν^{QE} via lepton energy, angle





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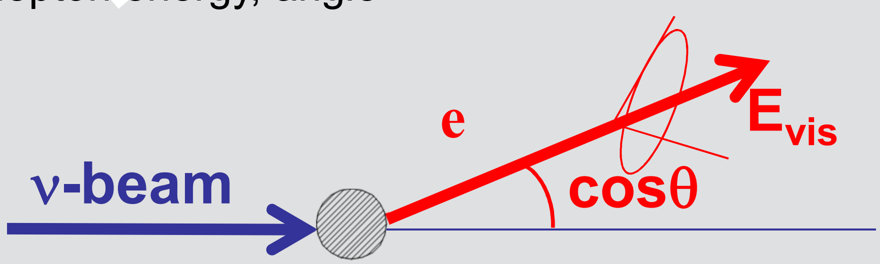
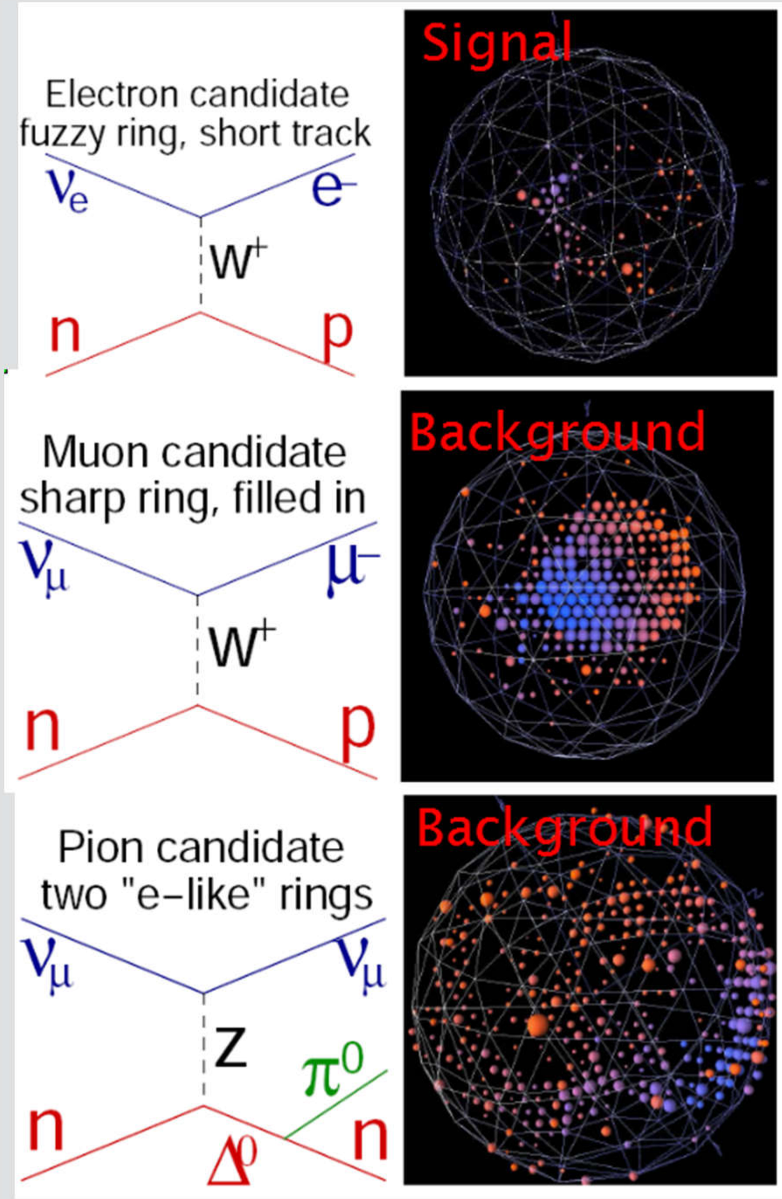
- can ID ν_e... ...llation-candidate events and separat... ...backgrounds
- M... ...neutrino enegy E_ν^{QE} via lepton energy, angle

ie: can measure signal/background





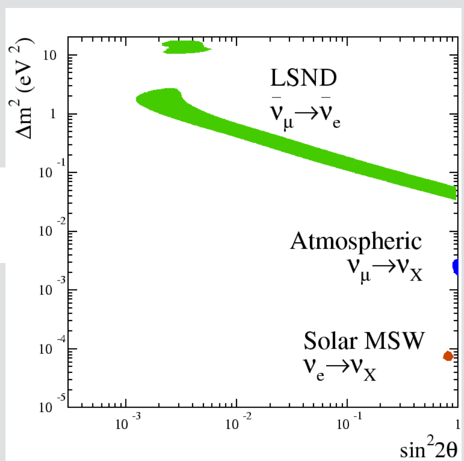
MiniBooNE experiment: analysis

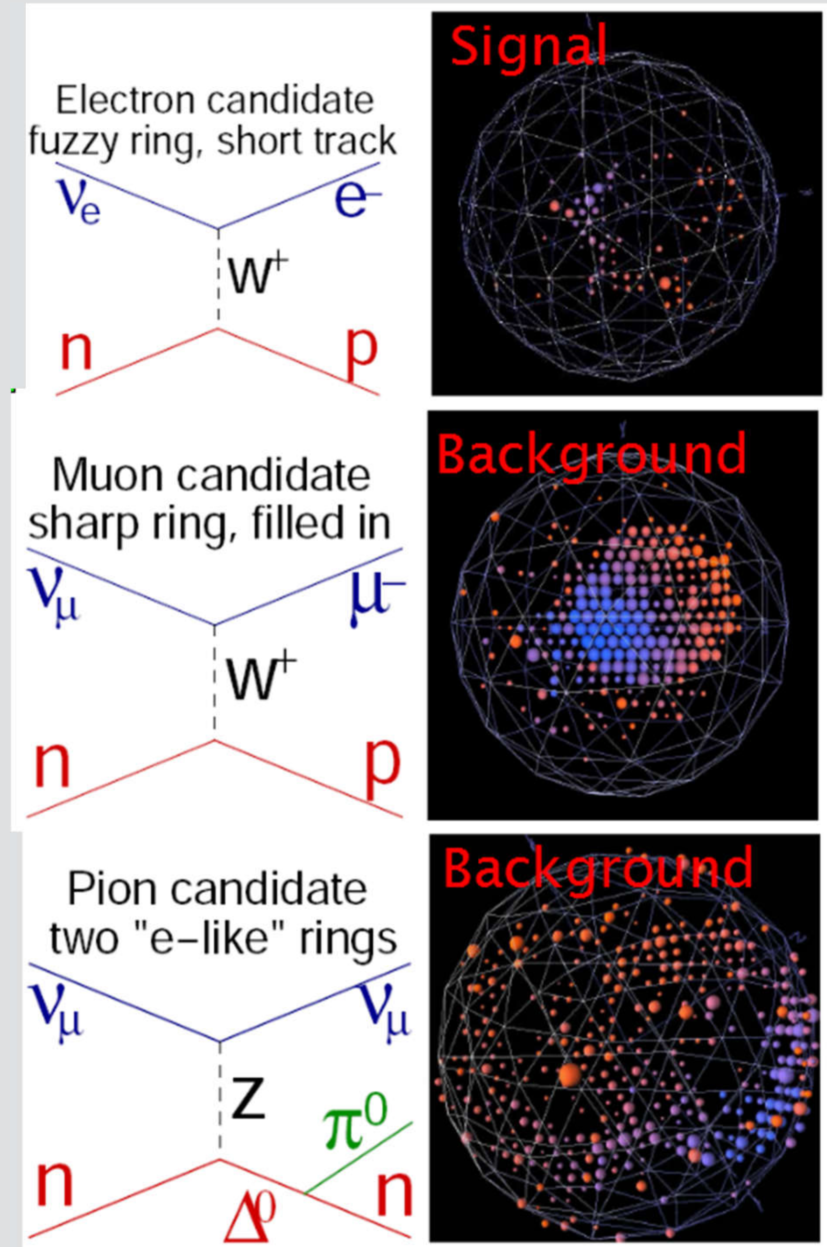
Additional details:

- 1-detector experiment so must normalize (flux)x(cross section) with ν_μ events
- virtually all backgrounds measured in miniBooNE data and “constrained” (fit at same time) in the oscillation fits
- looking for 1 in 1000 ν_μ oscillating to ν_e

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2\left(\frac{\pi x}{\lambda_{osc}}\right)$$

$$\lambda_{osc} = 2.5 E_\nu / \Delta m^2$$





MiniBooNE: latest results

Significant Excess of ElectronLike Events in the MiniBooNE Short-Baseline Neutrino Experiment

MiniBooNE Collaboration (A.A. Aguilar-Arevalo (Mexico U., ICN) *et al.*) Show all 47 authors

May 30, 2018 - 7 pages

Phys.Rev.Lett. 121 (2018) no.22, 221801
(2018-11-27)
DOI: 10.1103/PhysRevLett.121.221801
LA-UR-18-24586, FERMILAB-PUB-18-219
e-Print: arXiv:1805.12028 [hep-ex] | PDF
Experiment: FNAL-E-0898

- neutrino data set has doubled since previous publication
  (PhysRevLett.110.161801, arXiv:1207.4809 [hep-ex])
- combined with full antineutrino data set
- using same analysis and cuts as previously published

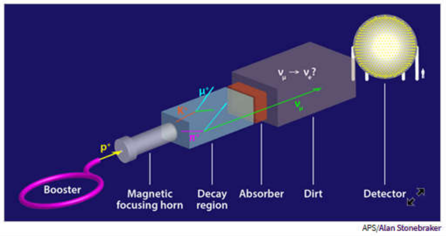
Physics ABOUT BROWSE PRESS COLLECTIONS

Viewpoint: The Plot Thickens for a Fourth Neutrino

Joachim Kopp, Theoretical Physics Department, CERN, Geneva, Switzerland, and PRISMA Cluster of Excellence, Mainz, Germany

November 26, 2018 • *Physics* 11, 122

Confirming previous controversial results, the MiniBooNE experiment detects a signal that is incompatible with neutrino oscillations involving just the three known flavors of neutrinos.

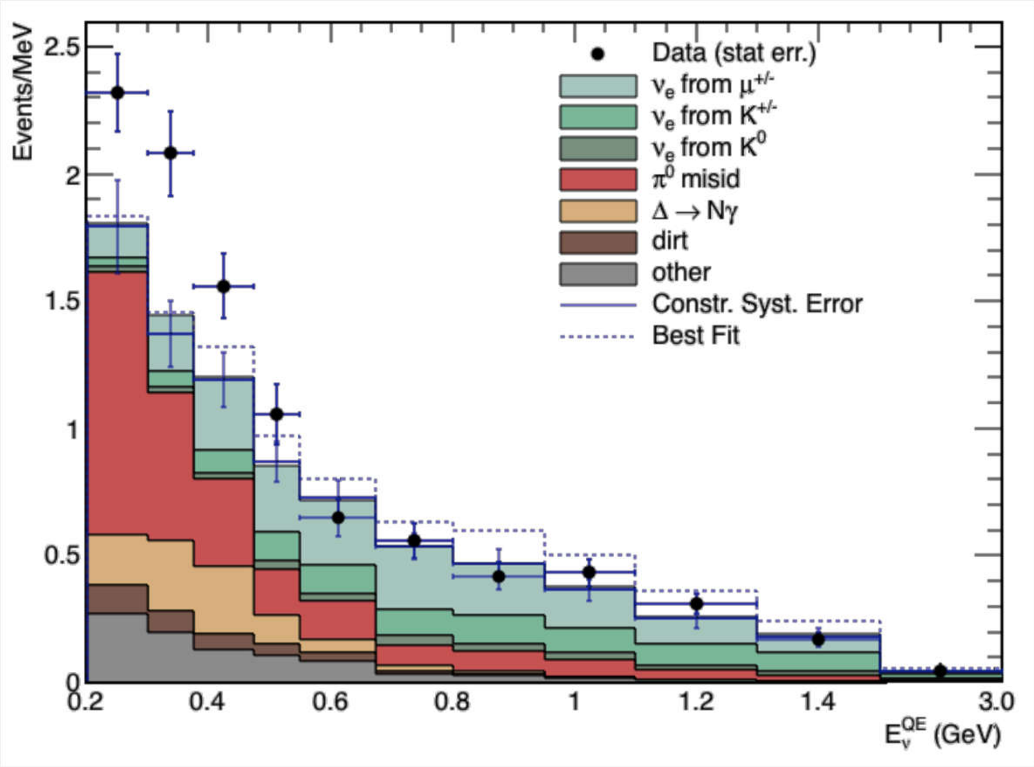


MiniBooNE: previous results

First, previous neutrino results previous pub'd data.

Oscillation results:
2002-2007 data: 6.46× 10^{20} POT

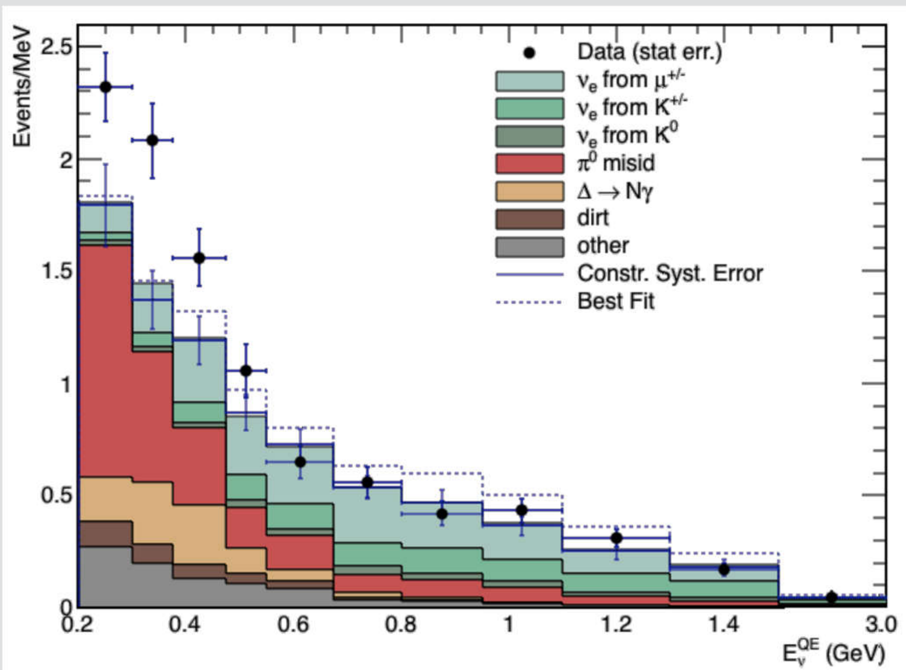
excess over background:
162 ± 47.8 events (3.4σ)



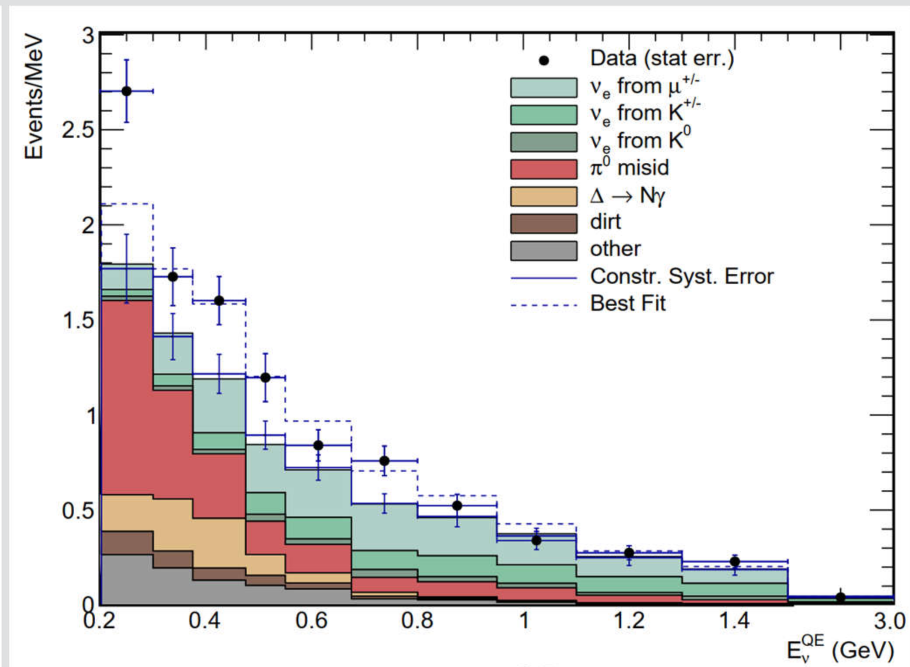
MiniBooNE: new results

Oscillation results:

2002-2007 data: 6.46$\times 10^{20}$ POT



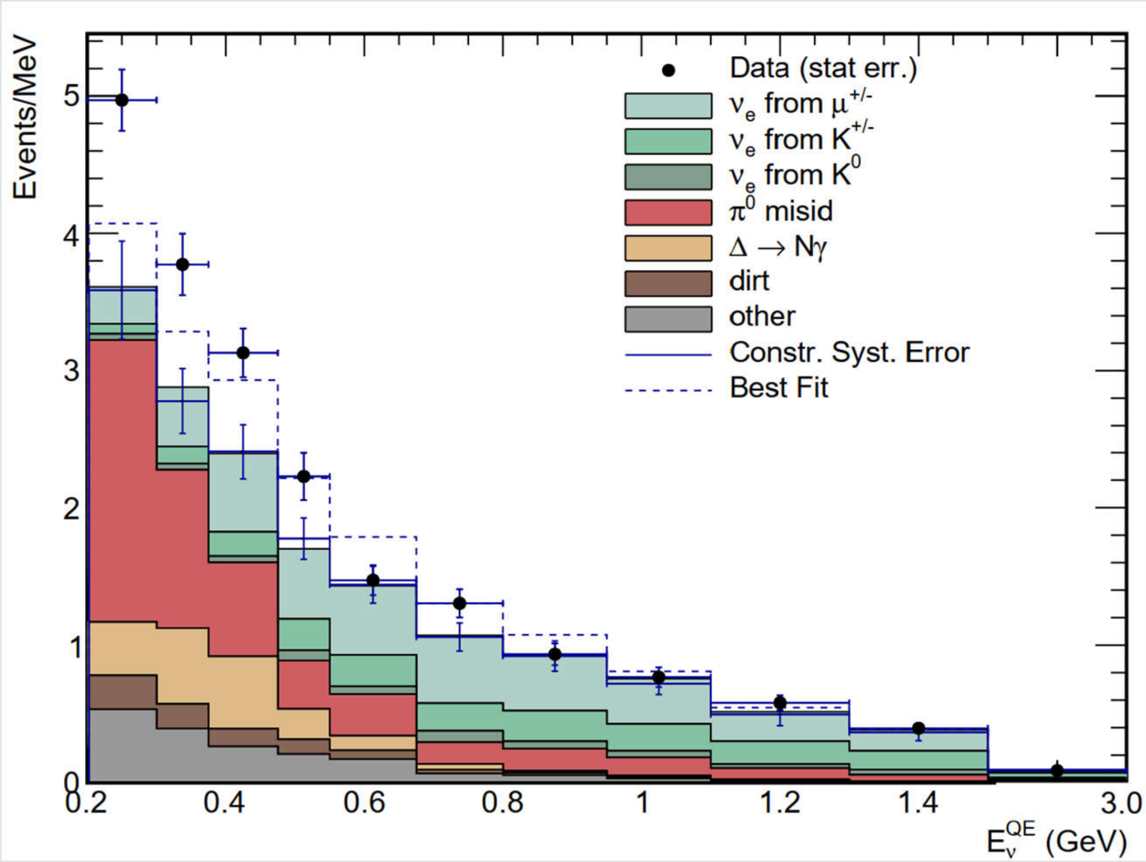
2016-2017 data: 6.38$\times 10^{20}$ POT



MiniBooNE: new results

Full neutrino data set:
12.84$\times 10^{20}$ POT

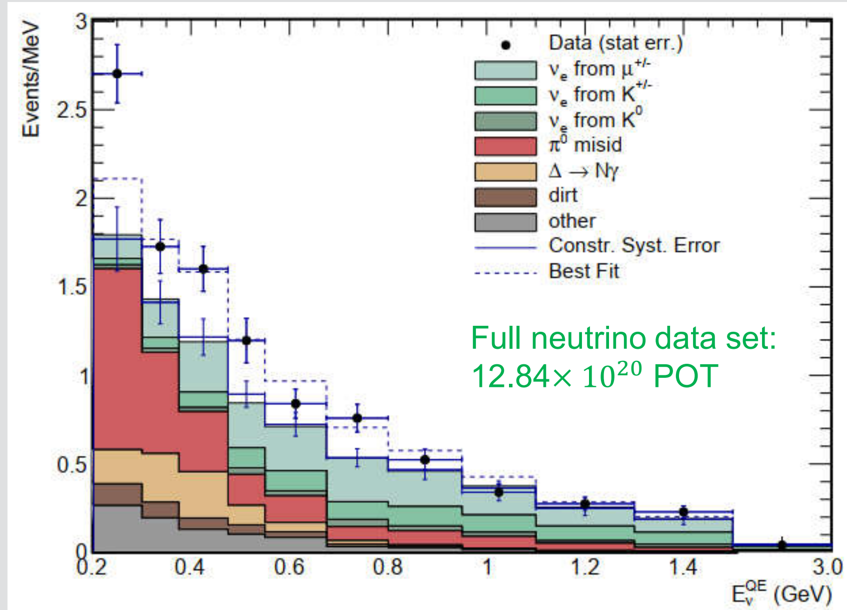
total excess over background:
381 ± 85 events (4.5σ)



MiniBooNE: new results

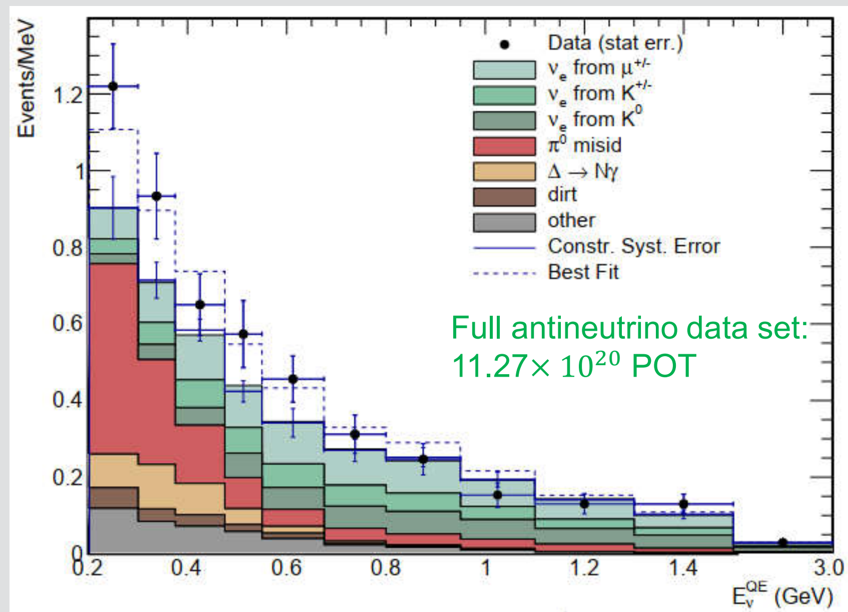
Combine with antineutrino results:
11.27× 10^{20} POT

total excess over background:
460 ± 96 events (4.8σ)



full MB oscillation event table

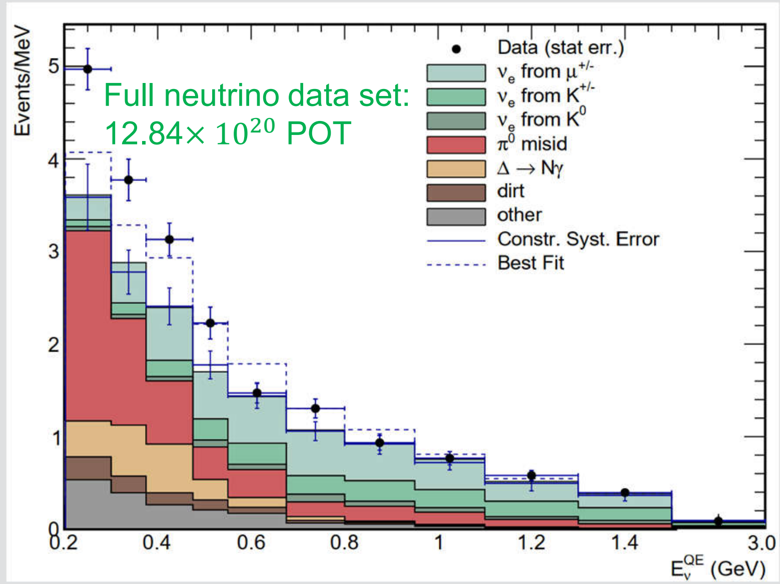
Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
NC π^0	501.5 ± 65.4	112.3 ± 11.5
NC $\Delta \rightarrow N\gamma$	172.5 ±24.1	34.7 ± 5.4
External Events	75.2 ± 10.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	89.6 ± 22.9	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ 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^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	398.2
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



MiniBooNE: backgrounds

"Intrinsic":

- higher energy
- ν_e from K decay : measured with SciBooNE high energy ν_μ event measurement
- ν_e from μ decay : measured by ν_μ CCQE measurement



"misID":

- External Events: measured from *in-situ* data sample

  (more on next slides...)
- NC π^0: from *in-situ* measurement of NC π^0 rate
- NC Δ→Nγ resonance: Δ production from measured NC π^0 rate, Nγ from calculation

full MB oscillation event table

misID

Intrinsic

Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	73.7 ± 19.3	12.9 ± 4.3
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Unconstrained Bkgd.	1590.5 ± 176.9	398.2 ± 49.7
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MiniBooNE: backgrounds

"Intrinsic":

- higher energy
- ν_e from K decay : measured with SciBooNE high energy ν_μ event measurement
- ν_e from μ decay : measured … CCQE measurement

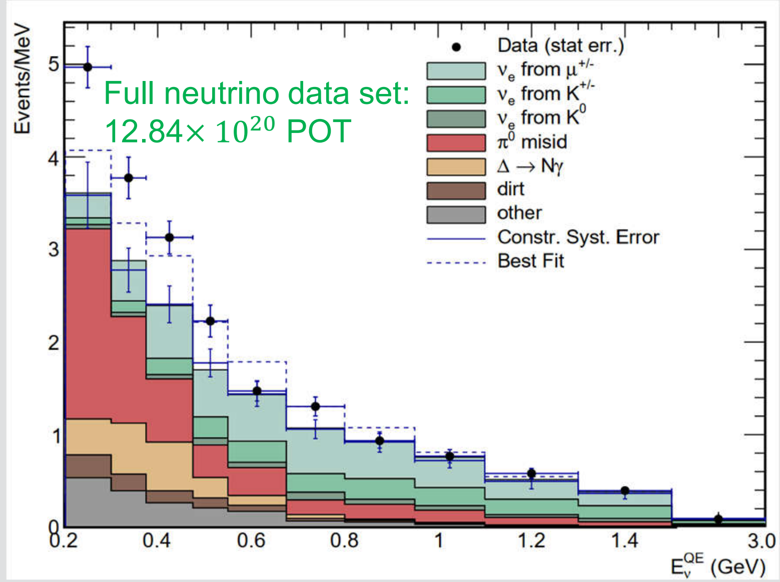
"misID":

- External … measured from *in-situ* d… …mple

(… on next slides...)

- … π^0: from *in-situ* measurement of NC π^0 rate
- NC Δ→Nγ resonance: Δ production from measured NC π^0 rate, Nγ from calculation

ie: backgrounds are carefully measured



full MB oscillation event table

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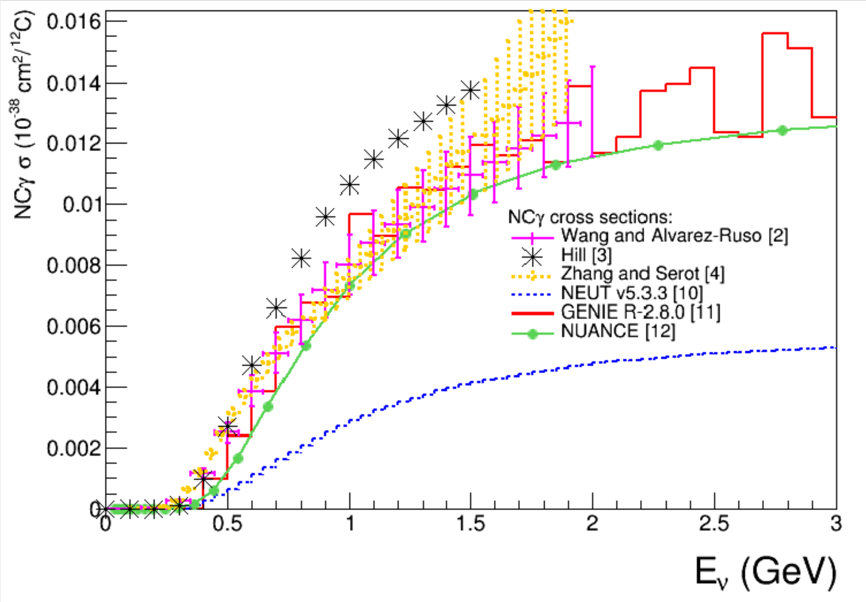
MiniBooNE: background details

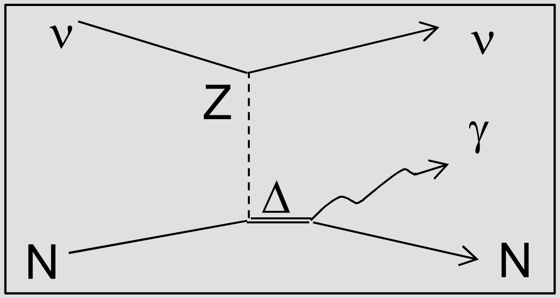
NCγ production?

- initial calculations claimed triangle anomaly was large
- further work by that group and others reach concensus that these terms are small and Δ production does indeed dominate as MB assumes...

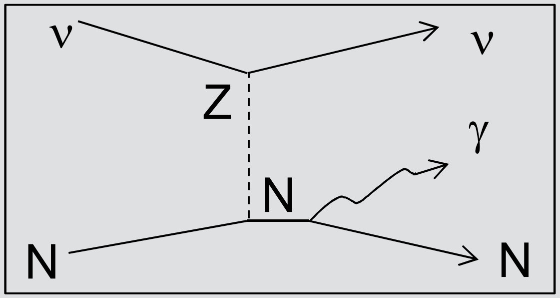


[2] E. Wang, L. Alvarez-Ruso and J. Nieves, Phys.Rev. **C89**, (2014)015503 [arXiv:1311.2151]
[3] R. J. Hill, Phys.Rev. **D81**, (2010)013008 [arXiv:0905.0291]
[4] X. Zhang, B. D. Serot, Phys.Lett. **B719**, (2013)409 [arXiv:1210.3610]
[10] Y. Hayato, Acta Phys.Polon. **B40** (2009)2477
[11] C. Andreopoulos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

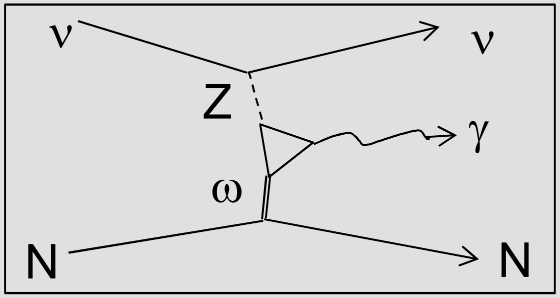
radiative Δ-decay



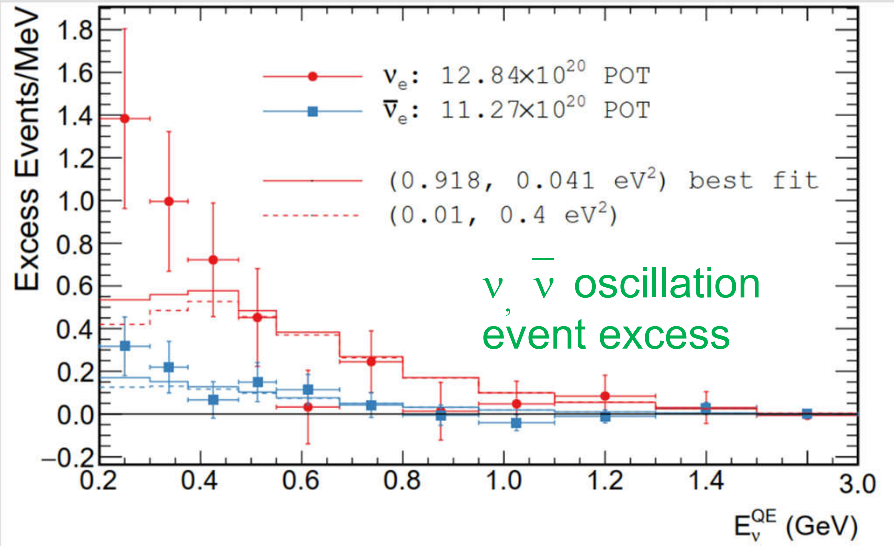
generalized Compton scattering

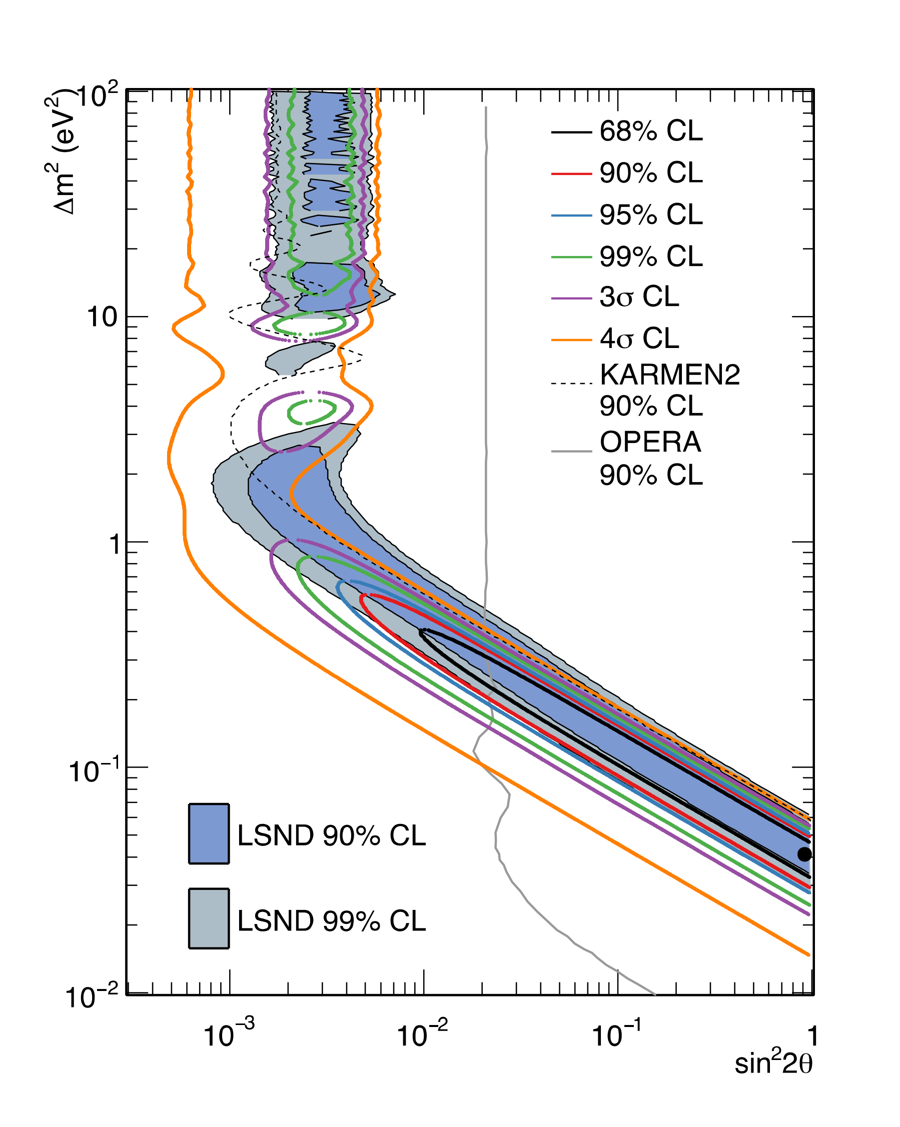


anomaly mediated triangle diagram



MiniBooNE: oscillation fits





best fit point:

$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.918)$

$\chi^2/ndf = 19.4/15.6$ (prob = 21.1%)

background-only:

$\chi^2/ndf = 47.1/17.3$ (prob = .02%)

Sterile neutrinos?

Oscillations with 1 extra "sterile" neutrino, "3+1" model:

extend mixing matrix:

$$\begin{pmatrix} \nu_e(x) \\ \nu_\mu(x) \\ \nu_\tau(x) \\ \nu_s(x) \end{pmatrix}_L = U \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \\ \nu_3(x) \\ \nu_4(x) \end{pmatrix}_L = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1(x) \\ \nu_2(x) \\ \nu_3(x) \\ \nu_4(x) \end{pmatrix}_L$$

then, short-baseline appearance, eg MB:

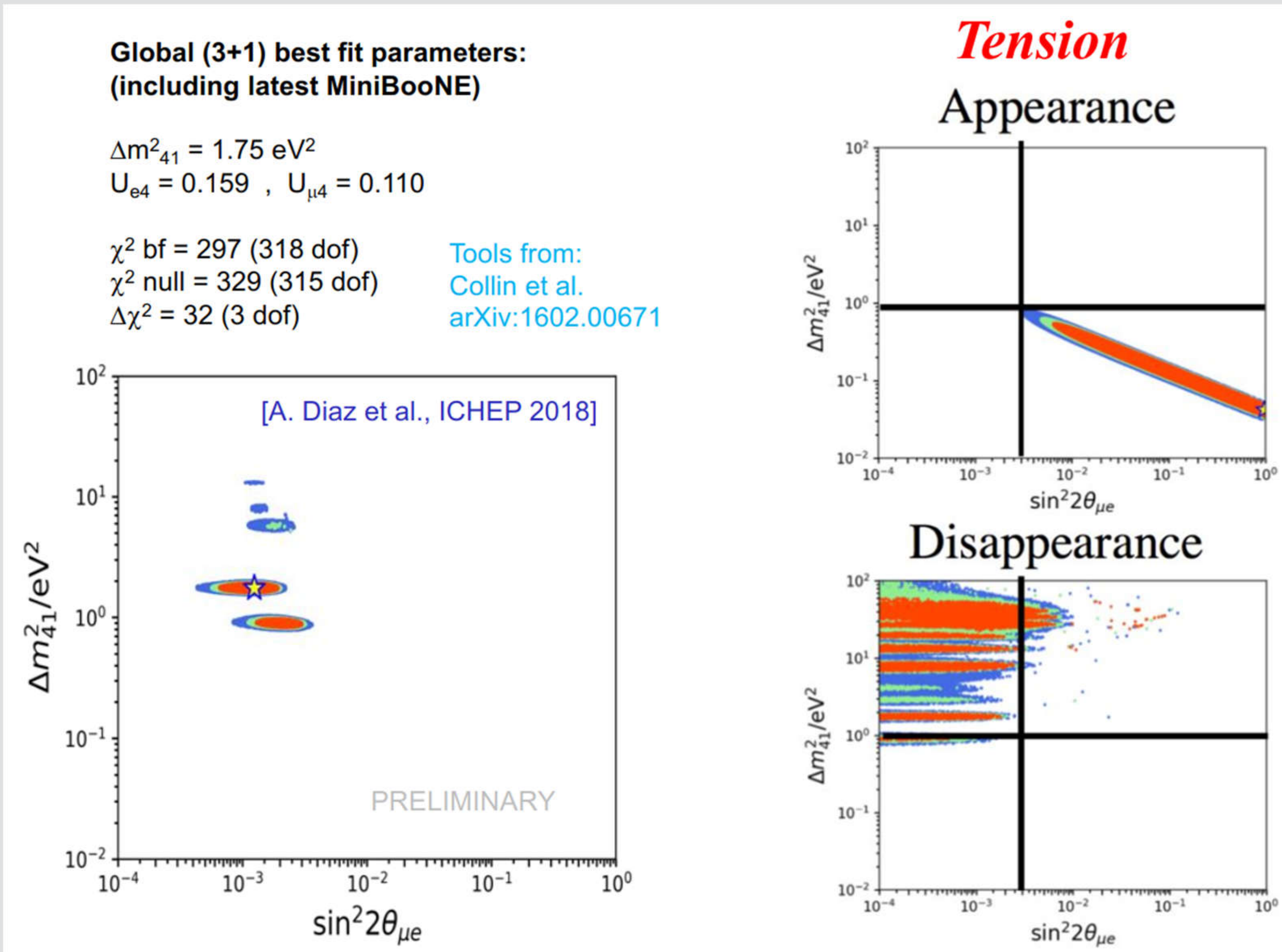
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta^{\rm SBL}_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right), \qquad \sin^2 2\theta^{\rm SBL}_{\alpha\beta} \equiv 4\,|U_{\alpha4}U_{\beta4}|^2 \qquad (\beta \neq \alpha),$$

and would predict effects in other other experiments:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta^{\rm SBL}_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right), \qquad \sin^2 2\theta^{\rm SBL}_{\alpha\alpha} \equiv 4\,|U_{\alpha4}|^2\left(1 - |U_{\alpha4}|^2\right), \qquad (73)$$

Sterile neutrinos?

Perhaps, but 3+1 models don't describe all experiments well
(eg: from Shaevitz, NOW18)

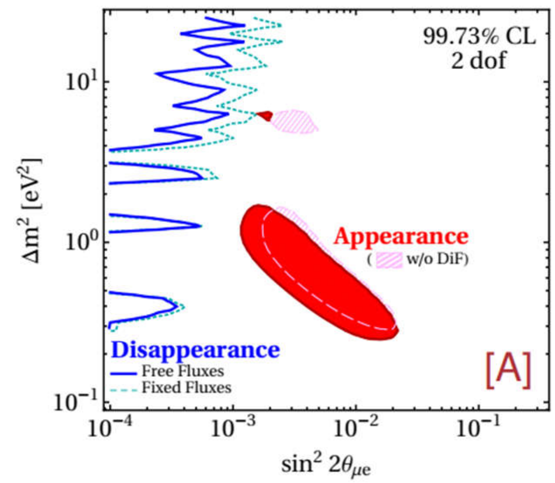


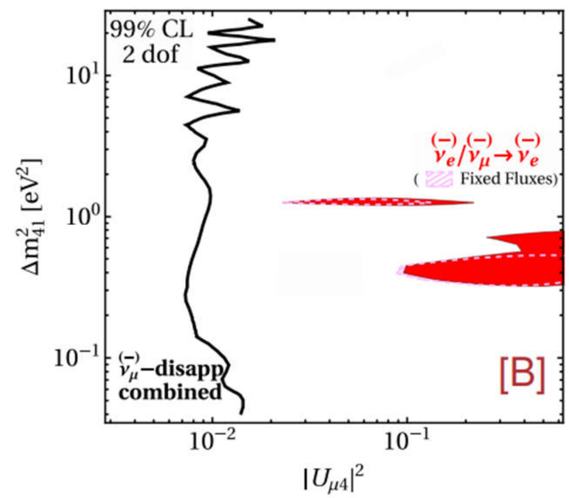
Sterile neutrinos?

…and:

(3+1): tension among data samples

- Limits on $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$ disappearance imply a bound on the $\nu_\mu \to \nu_e$ appearance probability;
- such bound is stronger than what is required to explain the LSND and MiniBooNe excesses [A];
- hence, severe tension arises between **APP** and **DIS** data: $\chi^2_{\text{PG}}/\text{dof} = 29.6/2 \Rightarrow \text{PG} = 3.7 \times 10^{-7}$ [17];
- a similar result is visible when comparing "ν_e-data" ($\nu_e \to \nu_e$ and $\nu_\mu \to \nu_e$) and "ν_μ-data" ($\nu_\mu \to \nu_\mu$) [B];
- note: tension between **APP** and **DIS** data first pointed out in 1999 [34]. Full global fit in 2001 [35] cornered (3+1) models. No conceptual change since then…





[17] M. Dentler *et al.*, arXiv:1803.10661.
[34] S.M. Bilenky *et al.*, PRD **60** (1999) 073007 [hep-ph/9903454].
[35] MM, Schwetz, Valle, PLB **518** (2001) 252 [hep-ph/0107150].

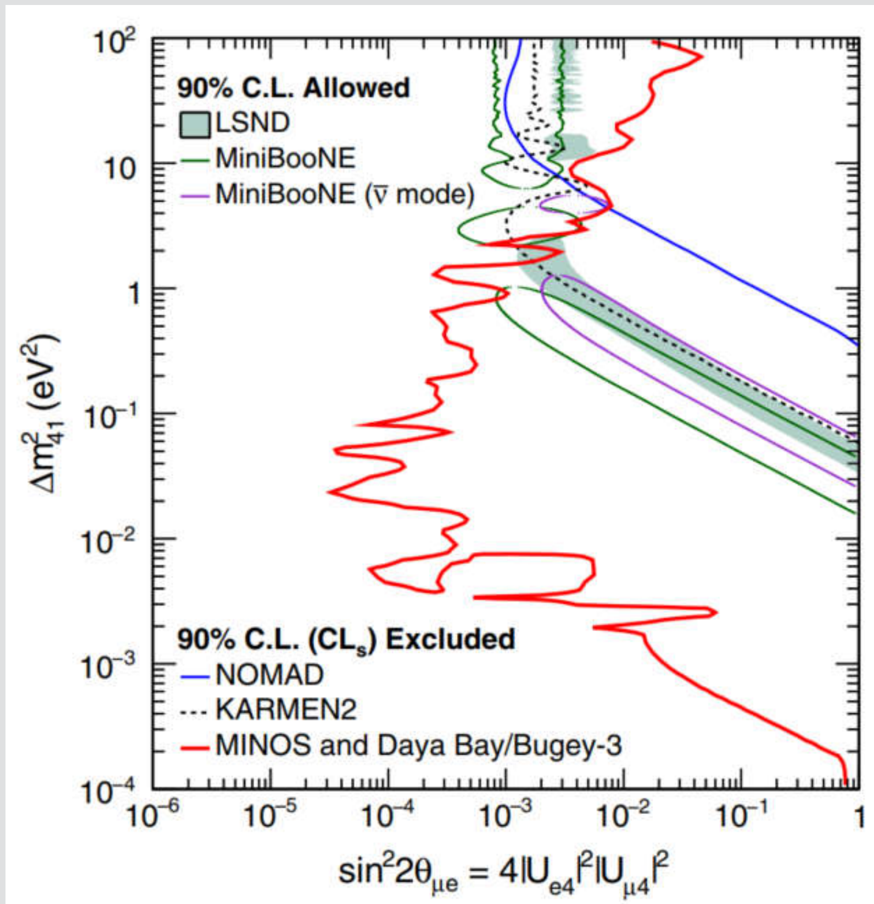
Michele Maltoni <michele.maltoni@csic.es>
NEUTRINO 2018, 8/06/2018

Sterile neutrinos?

…and:

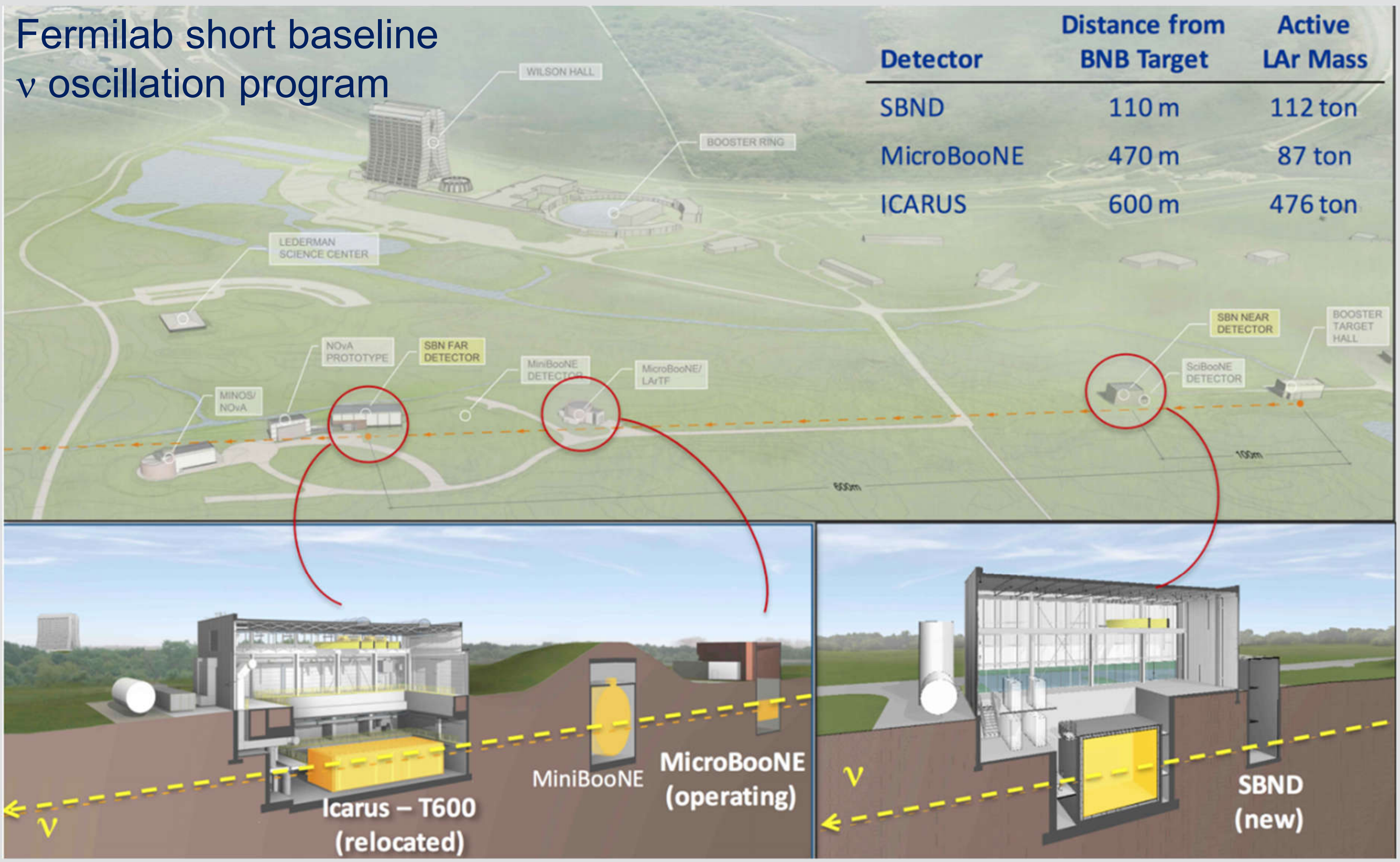
PRL **117,** 151801 (2016) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2016

Limits on Active to Sterile Neutrino Oscillations from Disappearance Searches in the MINOS, Daya Bay, and Bugey-3 Experiments

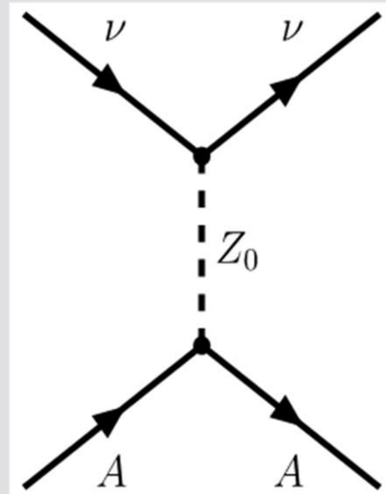


Future experiments

Perhaps miniBooNE is observing sterile neutrinos but explanation of all experiments still lacking.
Need futher tests: eg: short-baseline program at Fermilab, Prospect at ORNL, JSNS2 at JPARC, etal.



COHERENT experiment at ORNL-SNS has recently discovered the elusive coherent elastic neutrino nucleus scattering process (CEvNS) in CsI detector



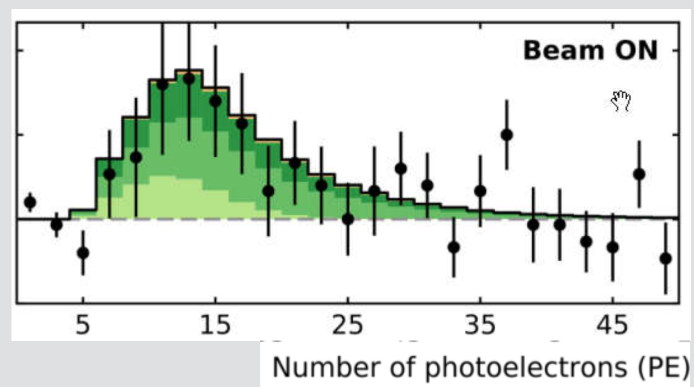
Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdy...

+ See all authors and affiliations

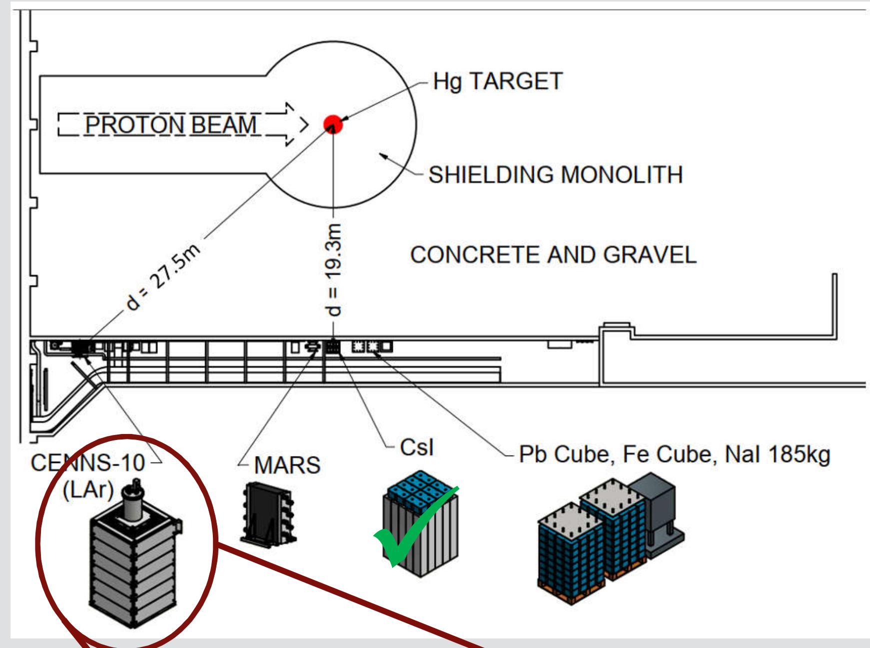
Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

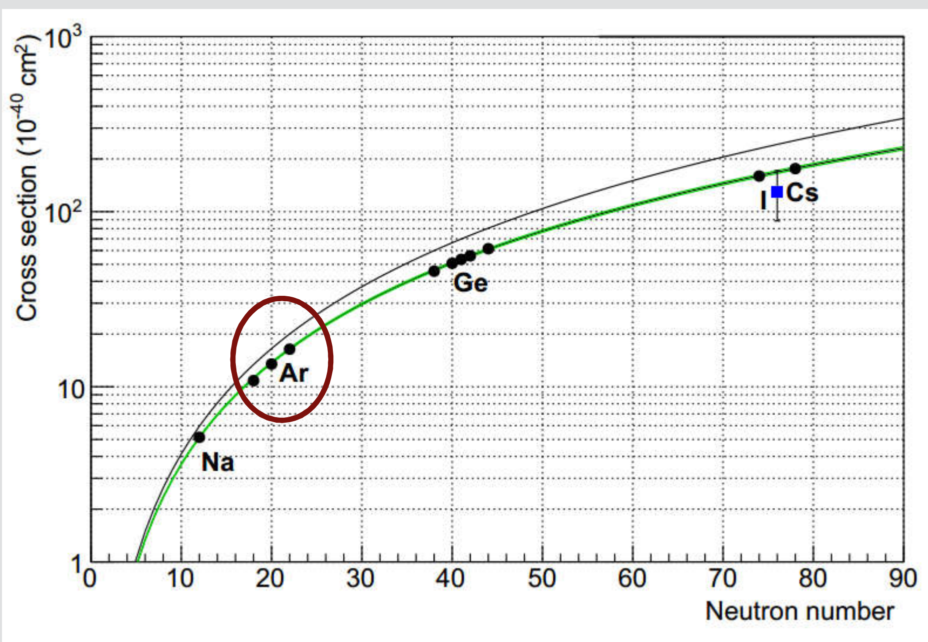
Peer Reviewed

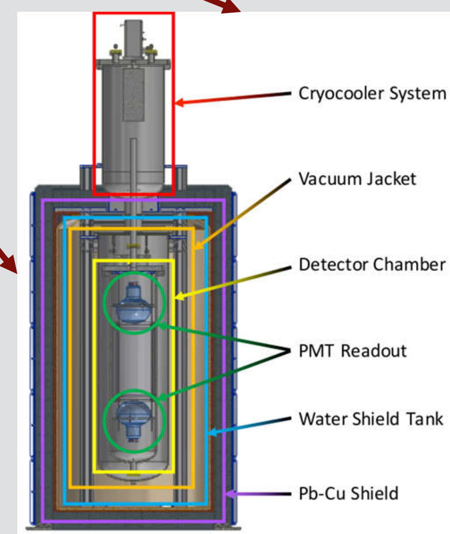


COHERENT experiment

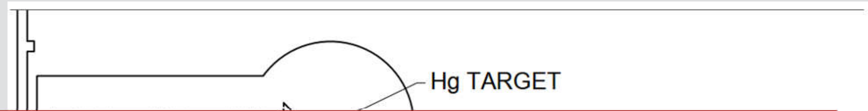
- Next goal, demonstrate N^2 dependence of CEvNS
- with CENNS-10 (liquid argon, LAr), currently running…







COHERENT experiment



arXiv.org > hep-ex > arXiv:1909.05913

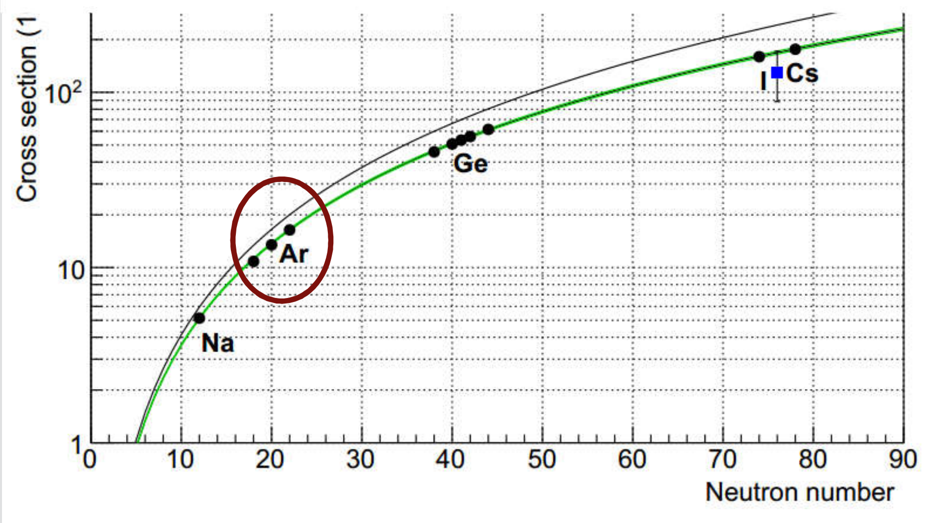
High Energy Physics - Experiment

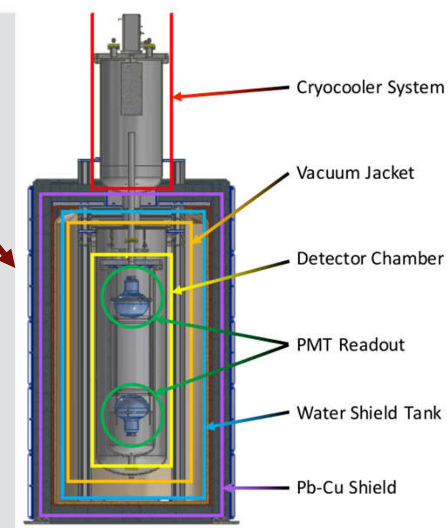
First Constraint on Coherent Elastic Neutrino-Nucleus Scattering in Argon

COHERENT Collaboration: D. Akimov, J. B. Albert, P. An, C. Awe, P. S. Barbeau, B. Becker, V. Belov, M. A. Blackston, A. Bolozdynya, B. Cabrera-Palmer, M. Cervantes, J. I. Collar, R. L. Cooper, J. Daughhetee, M. del Valle Coello, J. A. Detwiler, M. D'Onofrio, Y. Efremenko, E. M. Erkela, S. R. Elliott, L. Fabris, M. Febbraro, W. Fox, A. Galindo-Uribarri, M. P. Green, K. S. Hansen, M. R. Heath, S. Hedges, T. Johnson, M. Kaemingk, L. J. Kaufman, A. Khromov, A. Konovalov, E. Kozlova, A. Kumpan, L. Li, J. T. Librande, J. M. Link, J. Liu, K. Mann, D. M. Markoff, H. Moreno, P. E. Mueller, J. Newby, D. S. Parno, S. Penttila, D. Pershey, D. Radford, R. Rapp, H. Ray, J. Raybern, O. Razuvaeva, D. Reyna, G. C. Rich, D. Rudik, J. Runge, D. J. Salvat, K. Scholberg, A. Shakirov, G. Simakov, G. Sinev, W. M. Snow, V. Sosnovtsev, B. Suh, R. Tayloe, K. Tellez-Giron-Flores, R. T. Thornton, I. Tolstukhin, J. Vanderwerp, R. L. Varner, C. J. Virtue, G. Visser, C. Wiseman, T. Wongjirad, J. Yang, Y.-R. Yen, J. Yoo, C.-H. Yu, J. Zettlemoyer

(Submitted on 12 Sep 2019)

Coherent elastic neutrino-nucleus scattering (CEvNS) is the dominant neutrino scattering channel for neutrinos of energy $E_\nu < 100$ MeV. We report a limit for this process using data collected in an engineering run of the 29 kg CENNS-10 liquid argon detector located 27.5 m from the Oak Ridge National Laboratory Spallation Neutron Source (SNS) Hg target with 4.2×10^{22} protons on target. The dataset yielded < 7.4 observed CEvNS events implying a cross section for the process, averaged over the SNS pion decay-at-rest flux, of $< 3.4 \times 10^{-39}$ cm^2, a limit within twice the Standard Model prediction. This is the first limit on CEvNS from an argon nucleus and confirms the earlier CsI non-standard neutrino interaction constraints from the collaboration. This run demonstrated the feasibility of the ongoing experimental effort to detect CEvNS with liquid argon.

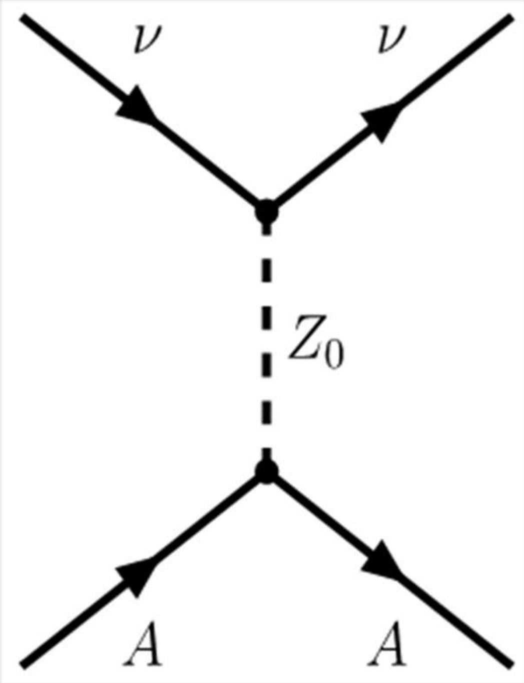




Coherent Elastic ν-Nucleus Scattering:

Physics reach of CEvNS:

- Understanding supernovae (SN):
  - Expected to be important in core-collapse SN and
  - possible SN detection channel.
- Standard Model tests, eg: NSI, $\sin^2\theta_W$, neutrino magnetic moments
- Nuclear Physics: neutron skin
- ν oscillations: A possible ν_s detection channel
- reactor monitoring (non-proliferation)
- Dark Matter:
  - Important background for O(10-ton) direct searches
  - detectors sensitive for accelerator produced DM…



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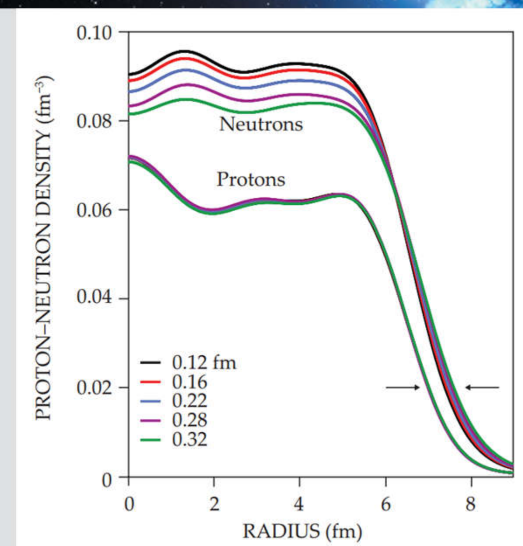

Neutron-rich matter in heaven and on Earth
Jorge Piekarewicz, and Farrukh J. Fattoyev

Citation: Physics Today **72**, 7, 30 (2019); doi: 10.1063/PT.3.4247
View online: https://doi.org/10.1063/PT.3.4247

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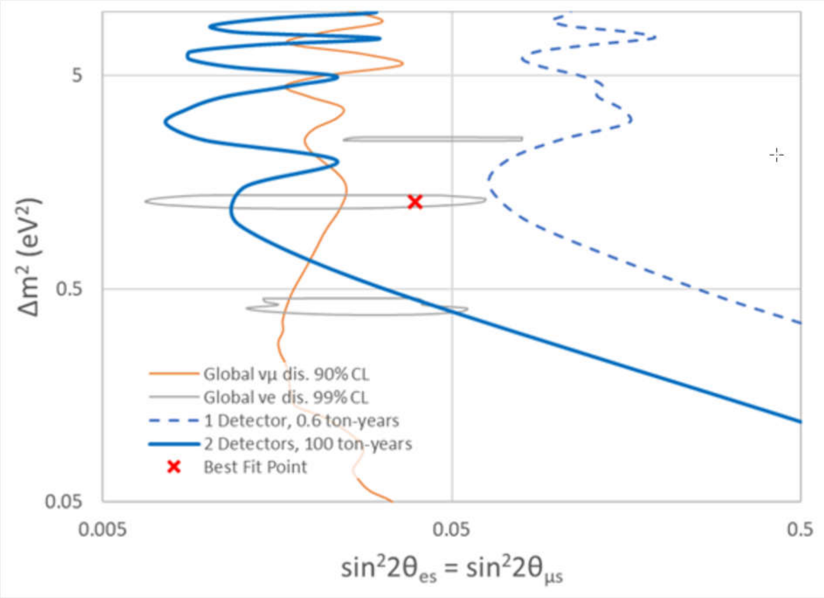
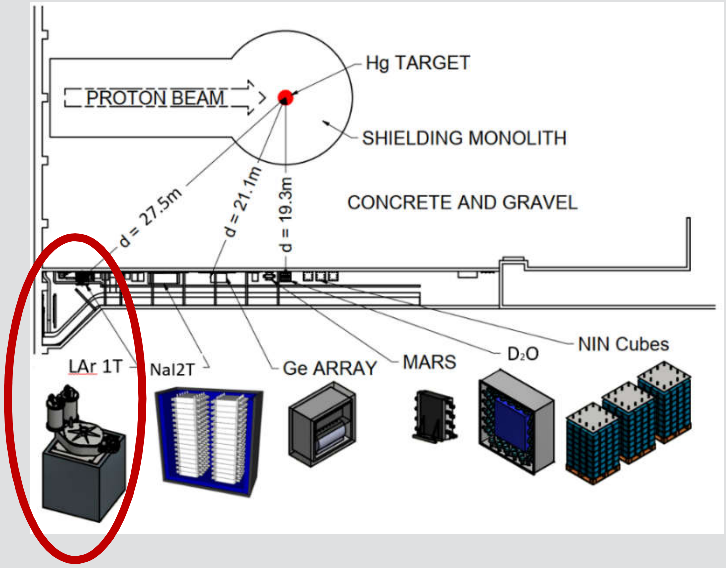
COHERENT, Large LAr neutrino oscillation search

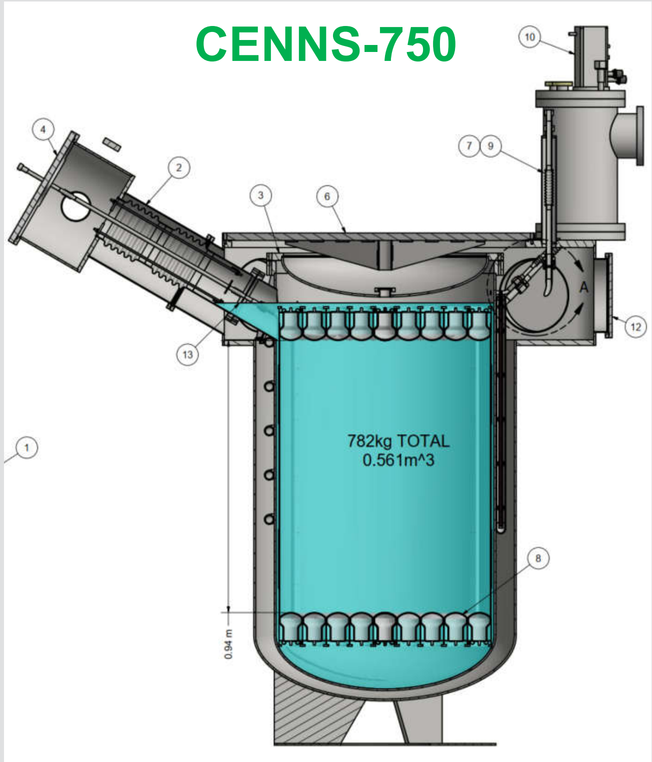


COHERENT future, large LAr detector

CENNS-750:

- Single-phase LAr (scintillation-only) calorimeter, 750/**610kg** total/**fiducial**
- ⇒ 3000 CEvNS, 440 inelastic CC/NC events/yr !

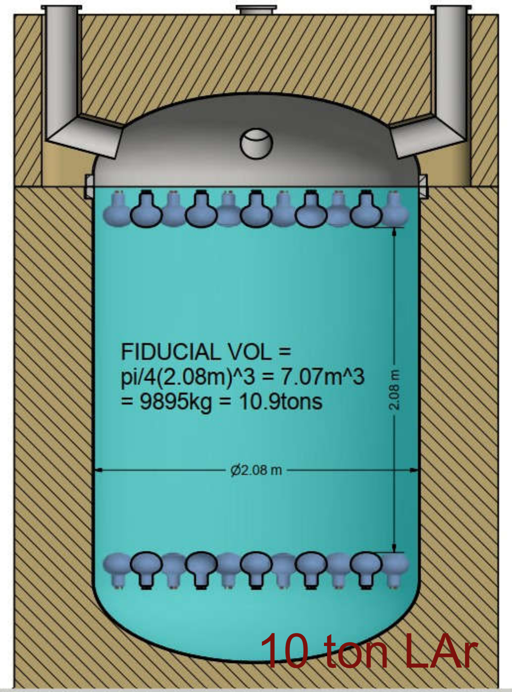


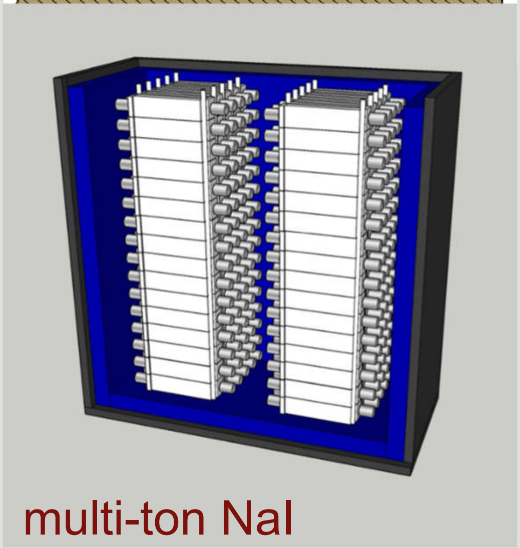


COHERENT future, beyond ν-alley

Search for accelerator-produced, low-mass, dark matter + oscillations and other physics topics.

10-ton LAr or ~2-ton cryogenic NaI detector downstream (ideally) from high power neutron target, eg ORNL SNS 2nd target station (under consideration)

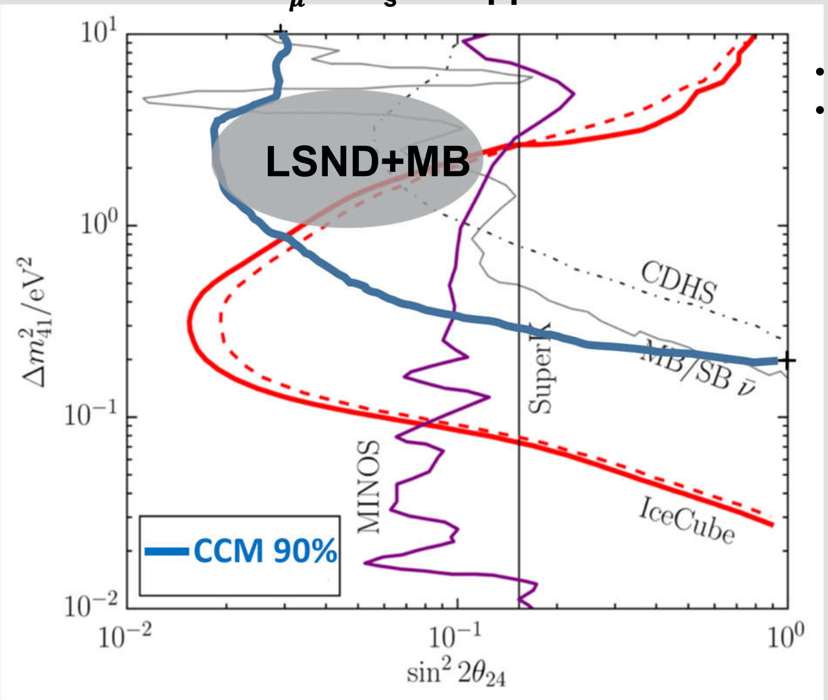




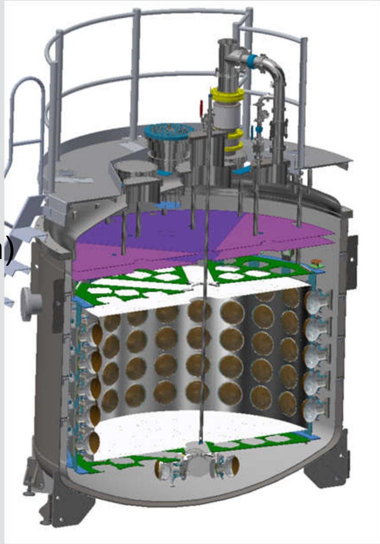
<u>Another sterile neutrino search: at LANL</u>

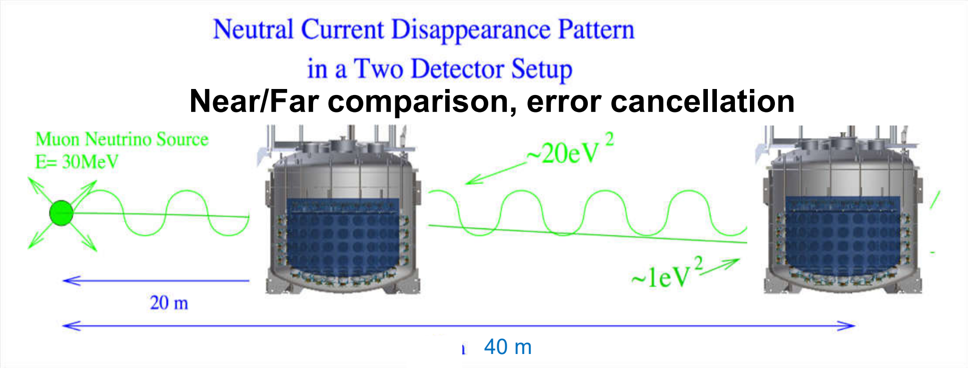
Convincing Search for Sterile Neutrinos – and Dark Matter - at LANL
Coherent Captain-Mills (CCM) Experiment

$\nu_\mu \rightarrow \nu_s$ Disappearance



- Prompt 30 MeV monoenergetic muon neutrinos (from LANL Lujan beam)
- Delayed neutrinos
- Neutral Current Coherent Ar Scattering:





credit: R. Vandewater, LANL

Summary

- MiniBooNE recently updated oscillation search continues to observe excess of events over backgrounds, consistent with LSND.
- Sterile neutrinos? Perhaps, but tension in various observations exists. Not a simple interpretation. Maybe multiple new neutrino states?
- Future experiments will need to confirm sterile neutrino hypothesis.

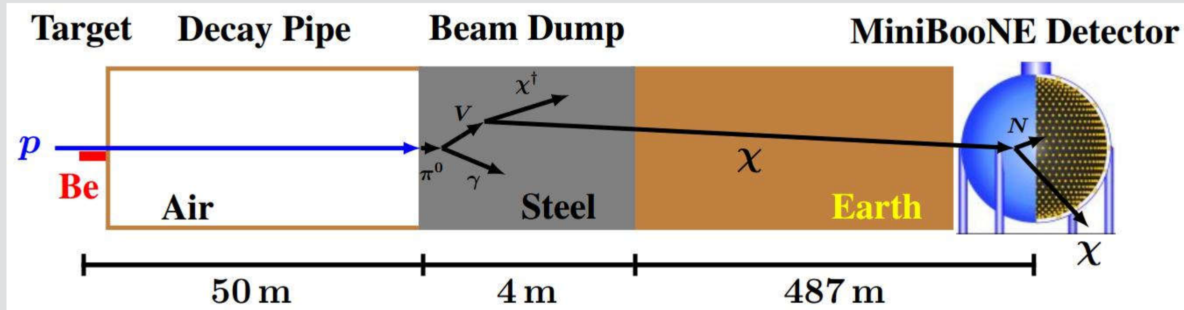
Thanks to colleagues for many plots/slides!

Find all papers at:

- inspirehep.net/search?p=collaboration:'MiniBooNE'
- inspirehep.net/search?p=collaboration:'LSND'

backups

MiniBooNE: Dark matter search in proton beam dump



Experiment:

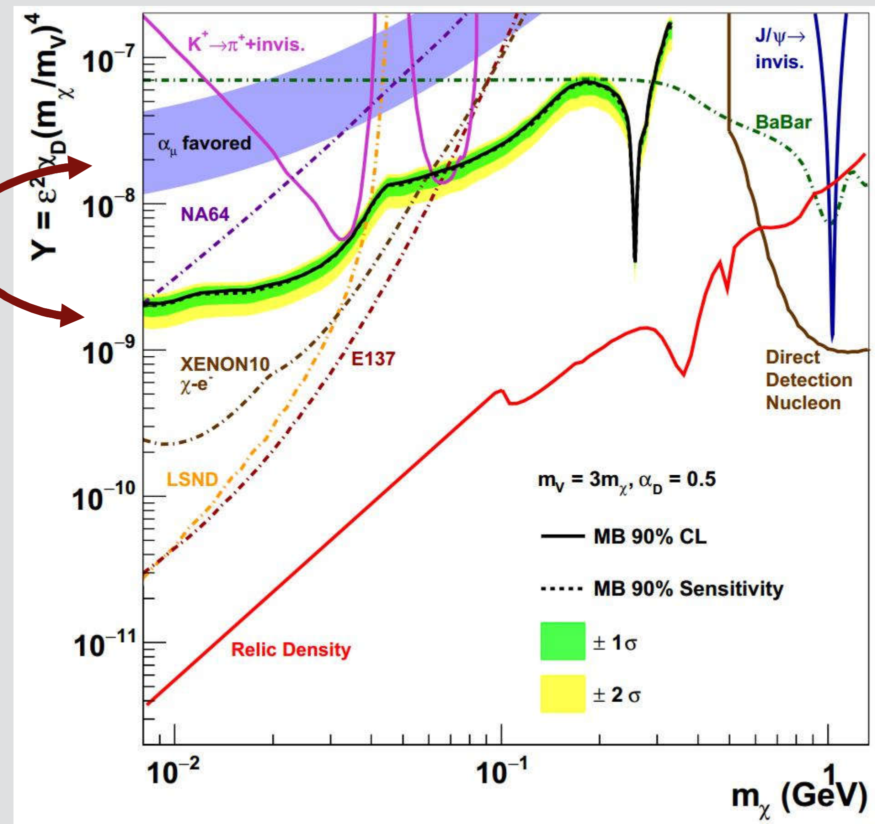
- dark matter, χ , may couple to ordinary matter via dark photon (V_μ)
- V_μ kinetically mixed with γ from π^0 decay in Fermilab Booster Neutrino beam dump
- χ from V decays detected via elastic scattering in MiniBooNE ν detector

Results:

- resulting limit (in dimensionless cross section scaling parameter, Y) from 2×10^{20} protons delivered in 2014
- extends dark matter limits to smaller m_χ
- excludes a vector mediator solution to g-2 anomaly
- most stringent limit in $0.08<m_\chi< 0.3$ GeV
- **Phys. Rev. Lett. 118, 221803 (2017).**

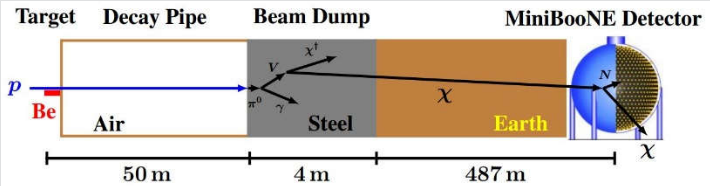
Future:

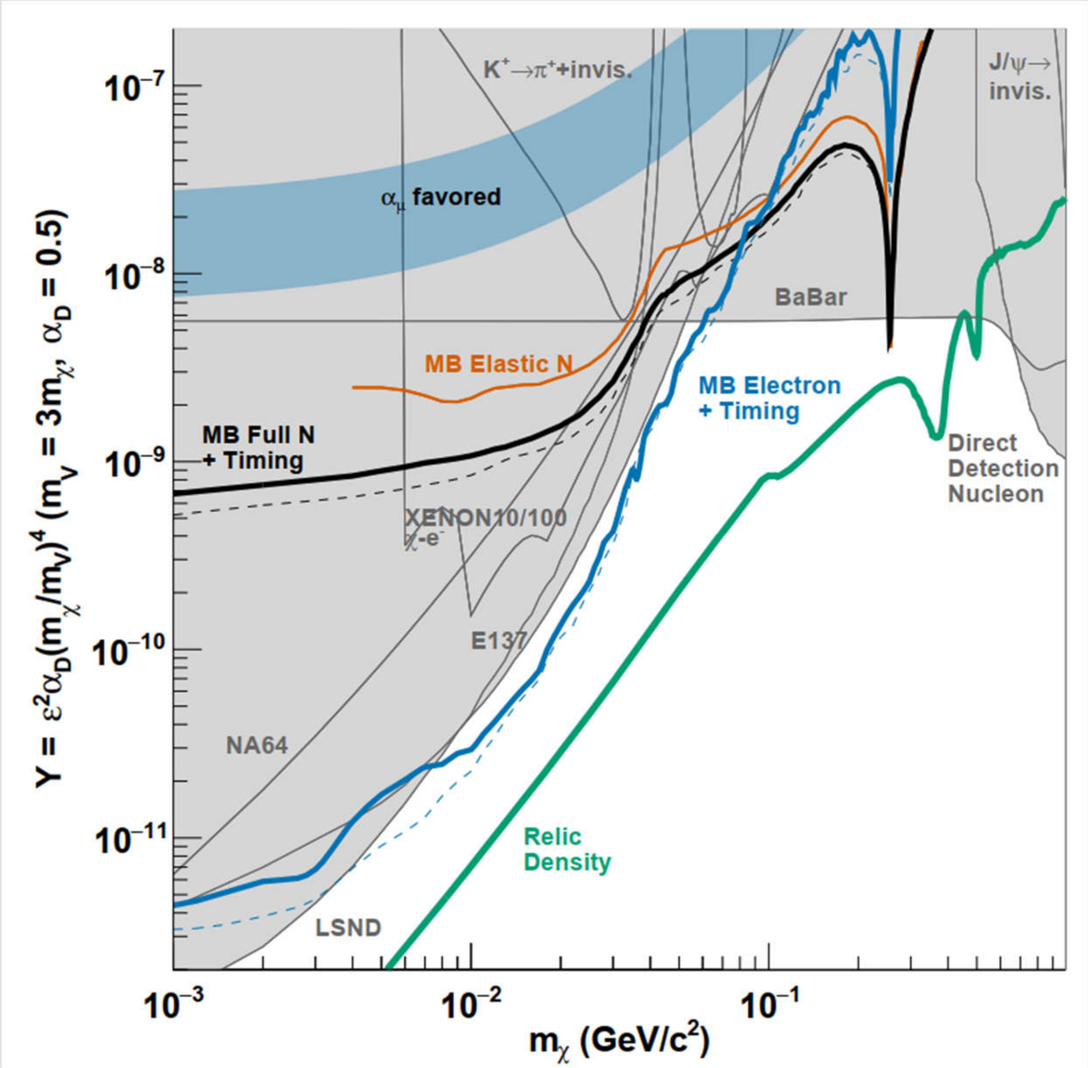
- Searches with upcoming short-baseline ν detectors will push sensitivity to cover Relic Density solution



MiniBooNE: Dark matter search in proton beam dump

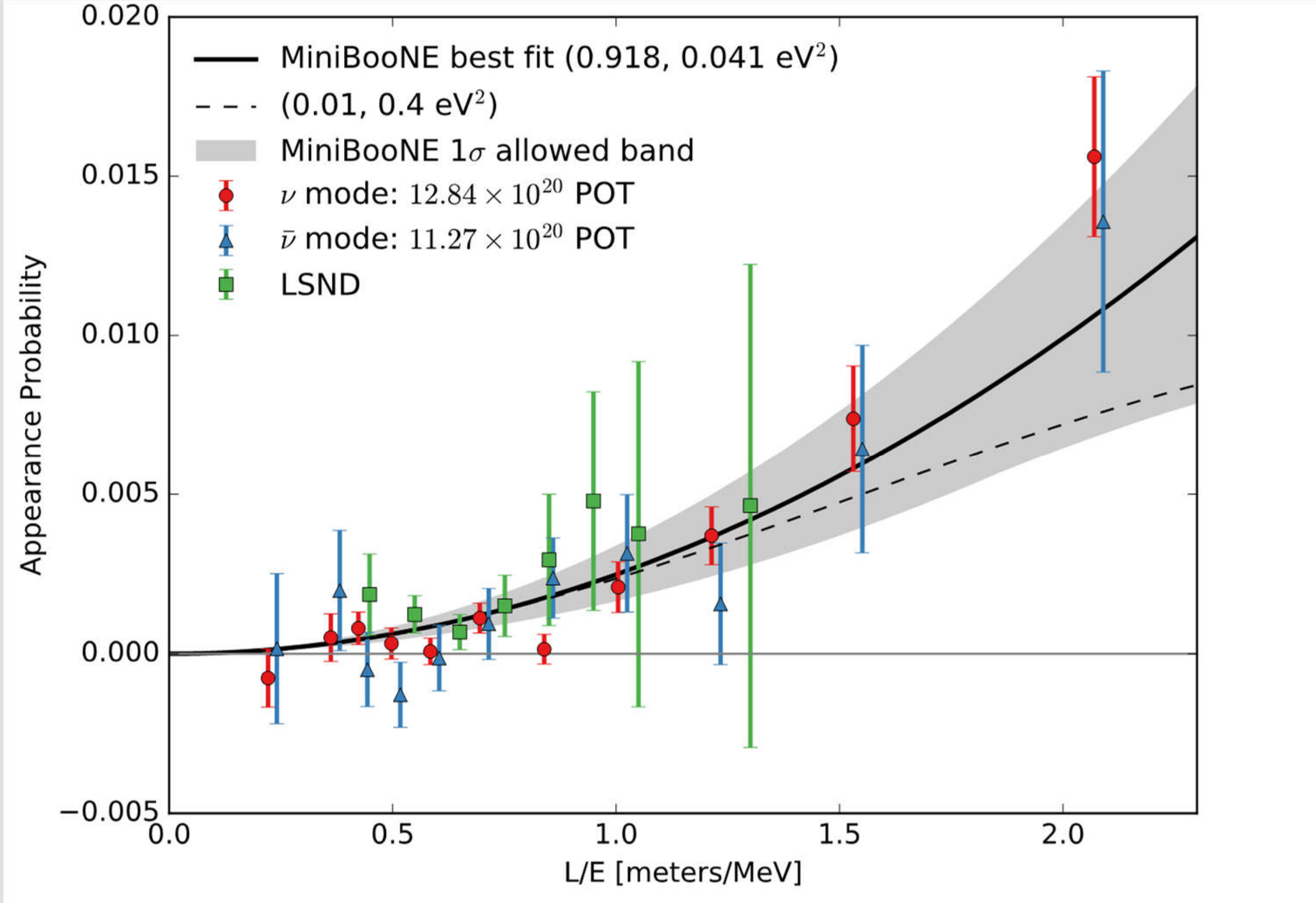
… and recent extension of this work (arXiv:1807.06137), adding resonance and electron channels





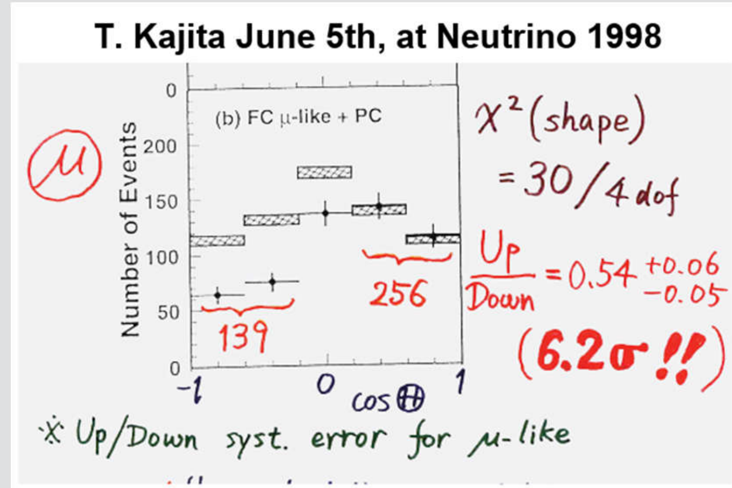
MiniBooNE: L/E

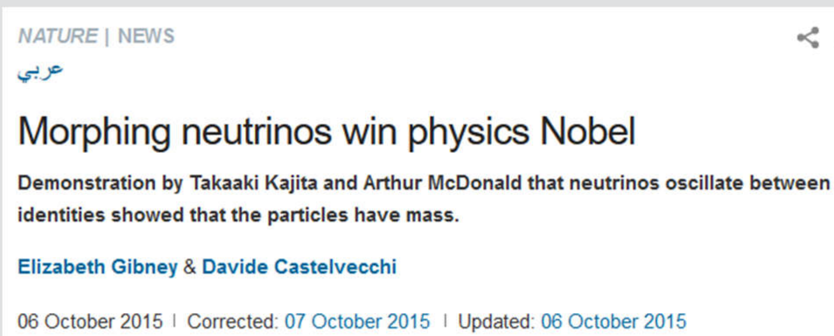
- Average E_ν^{QE} of each bin is used
- MiniBooNE neutrino, MiniBooNE antineutrino and LSND are **consistent** in appearance probability and L/E
- (For some caveats of using L/E plot, please see arXiv:1407.3304)



Introduction: ν oscillations…

- Evidence for ν oscillations exist in...
  - “solar” ($\Delta m^2 \sim 10^{-5}$ eV^2) and
  - “atmospheric” ($\Delta m^2 \sim 10^{-4}$ eV^2)




NATURE | NEWS

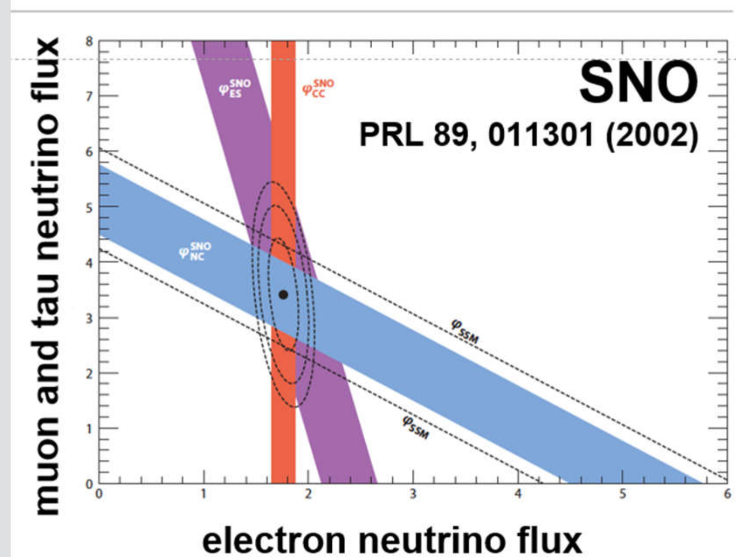
عربي

Morphing neutrinos win physics Nobel

Demonstration by Takaaki Kajita and Arthur McDonald that neutrinos oscillate between identities showed that the particles have mass.

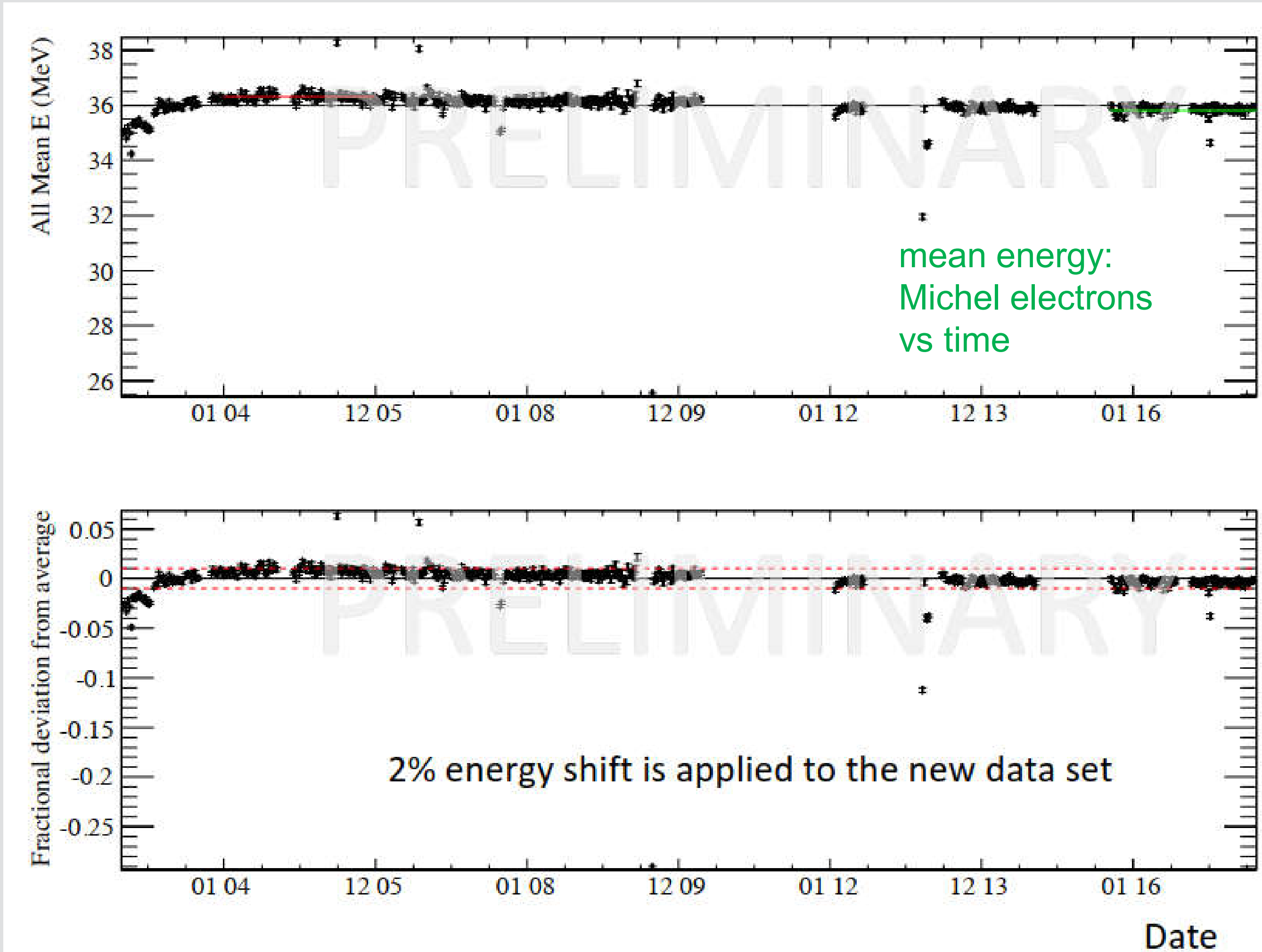
Elizabeth Gibney & Davide Castelvecchi

06 October 2015 | Corrected: 07 October 2015 | Updated: 06 October 2015



MiniBooNE experiment: data stability

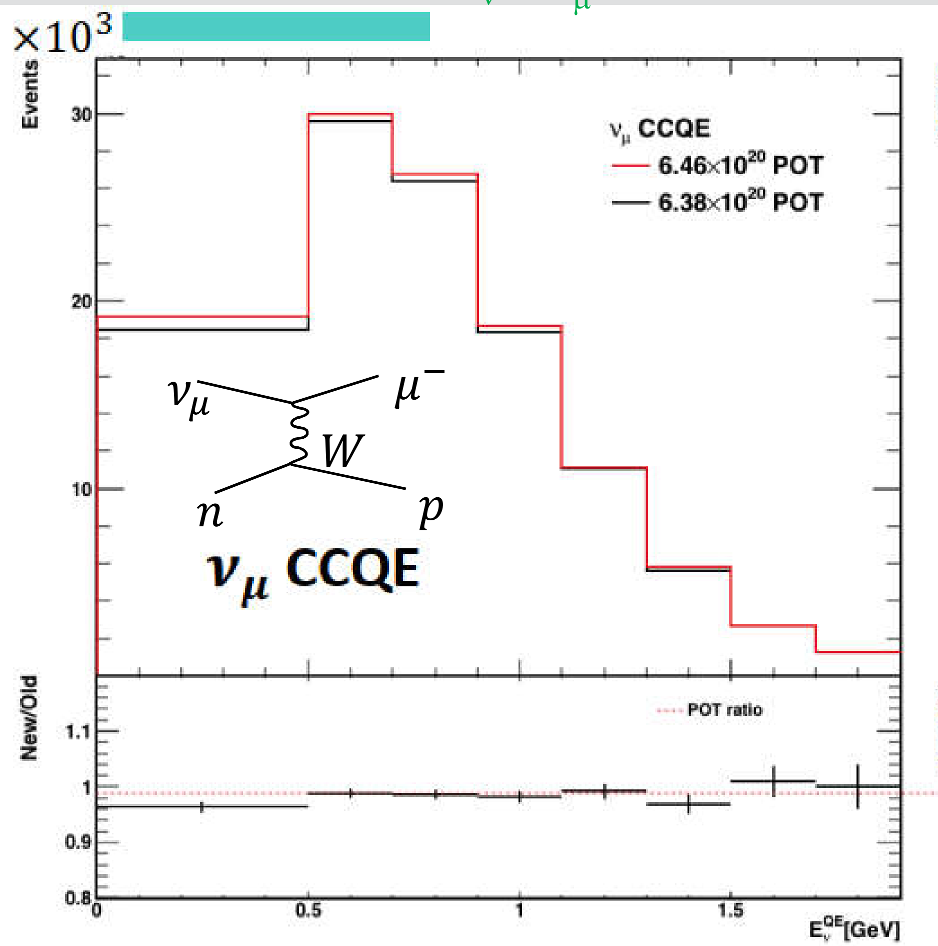
- mean energy of “Michels”, muon-decay electrons (calibration source)
- 2% energy calibration difference in most recent data



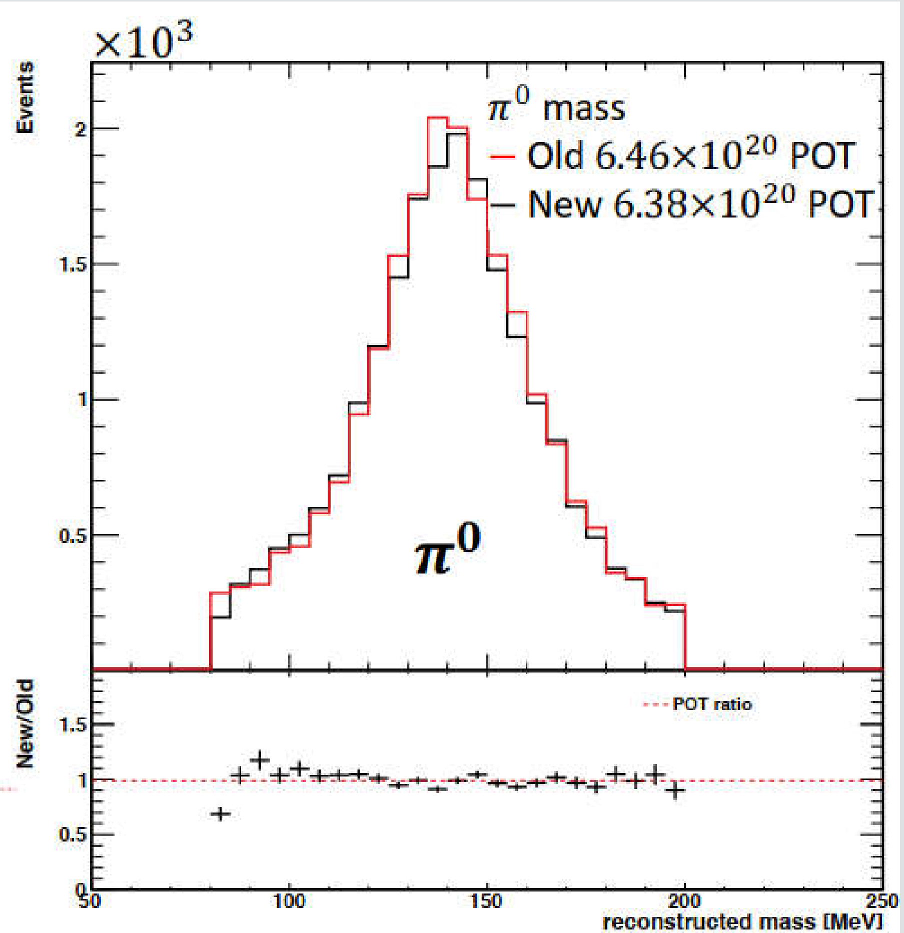
MiniBooNE experiment: data stability

- neutrino data sets separated by 8 years (!)

reconstructed $E_\nu - \nu_\mu$ CCQE events



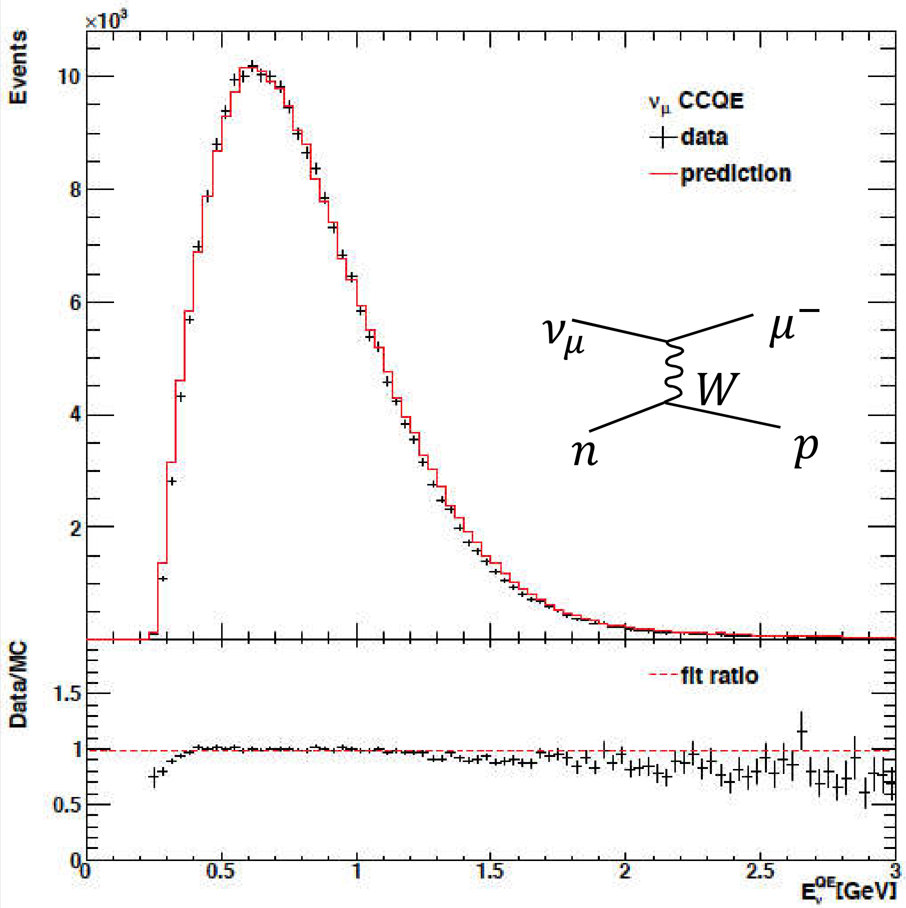
π^0 reconstructed mass



MiniBooNE experiment: data stability

- data/MC comparisons

reconstructed E_ν numu CCQE



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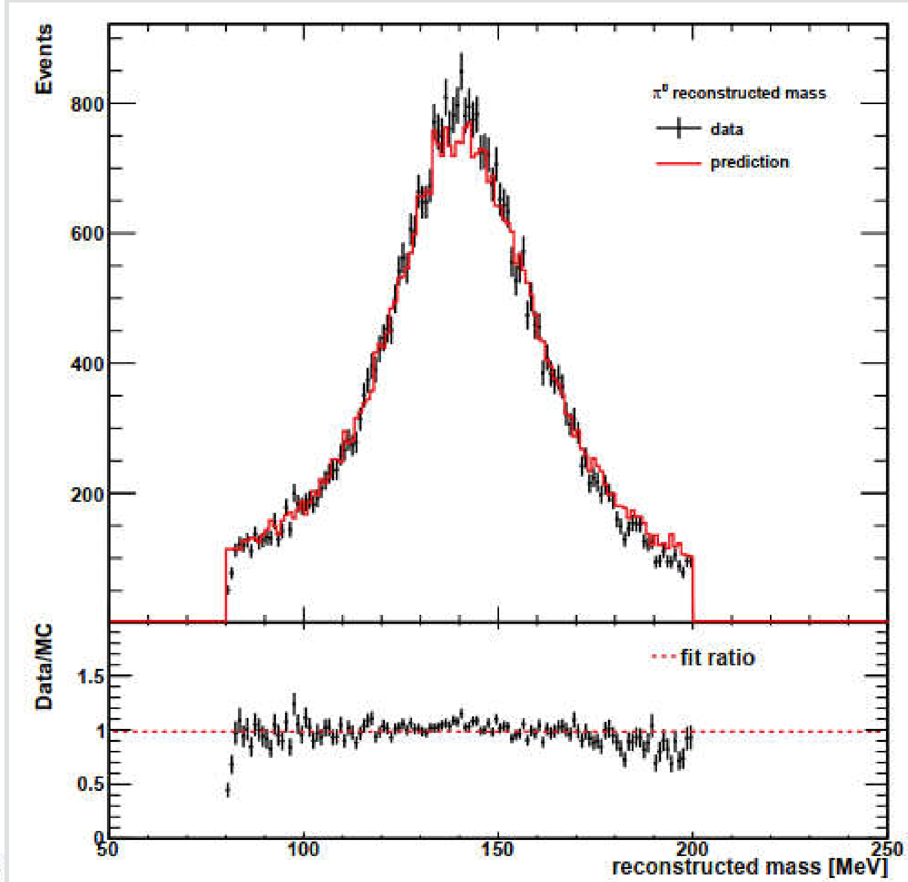
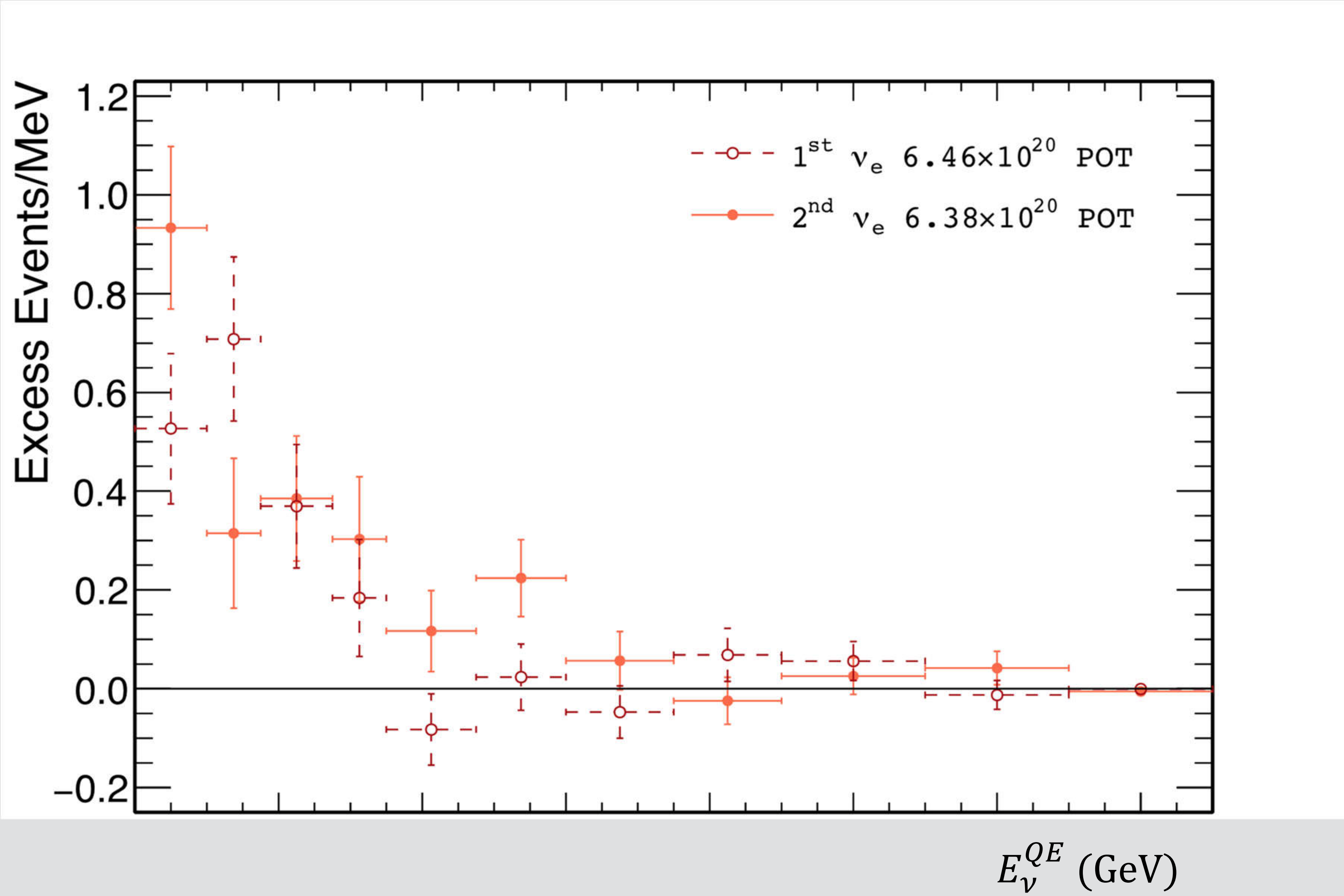


MiniBooNE: new results

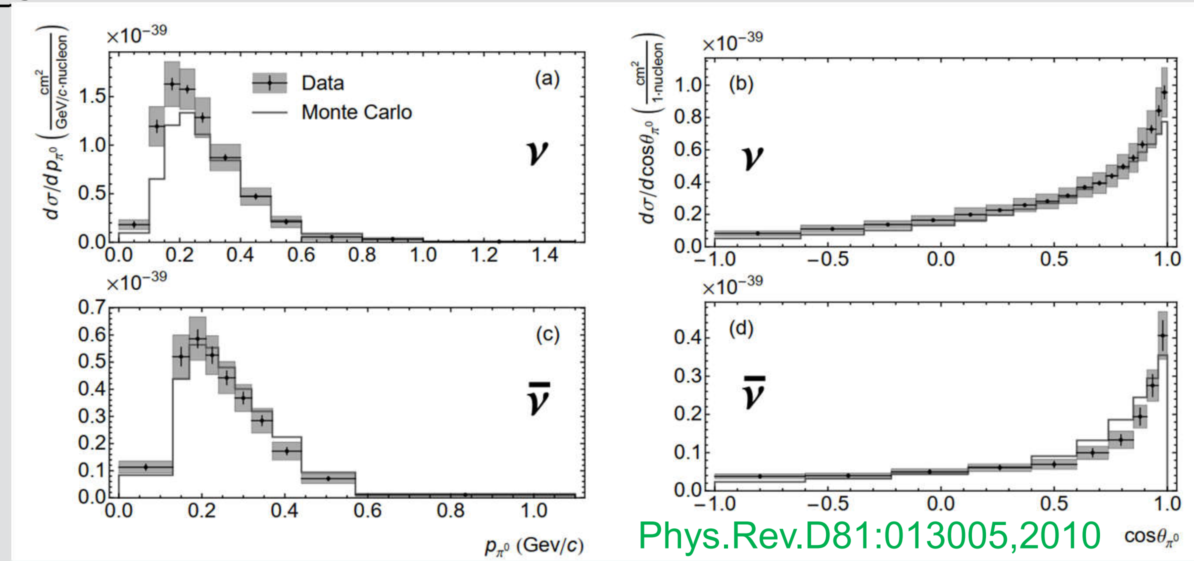
Oscillation event excess: Old, new data sets consistent

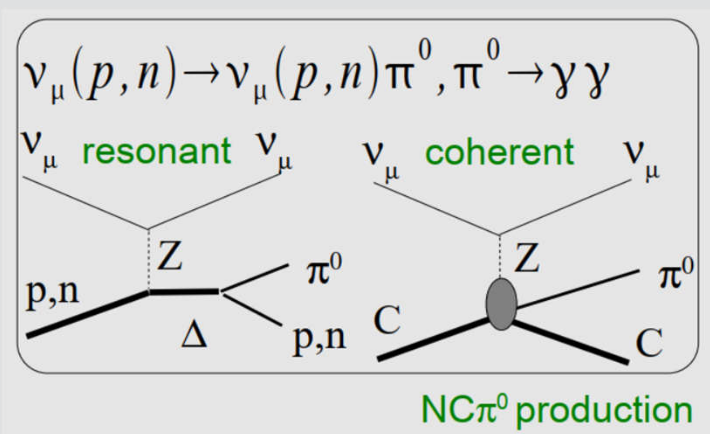


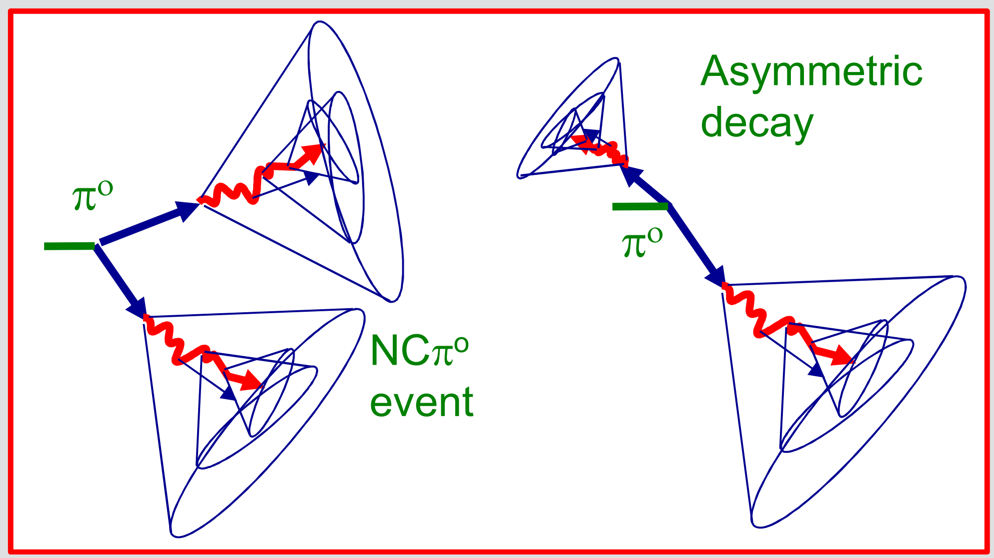
MiniBooNE: background details

NC π^0 misID:

- from *in-situ* measurement of NC π^0 rate
- missed π^0 in oscillation sample are mostly asym. decays, straightforward to simulate







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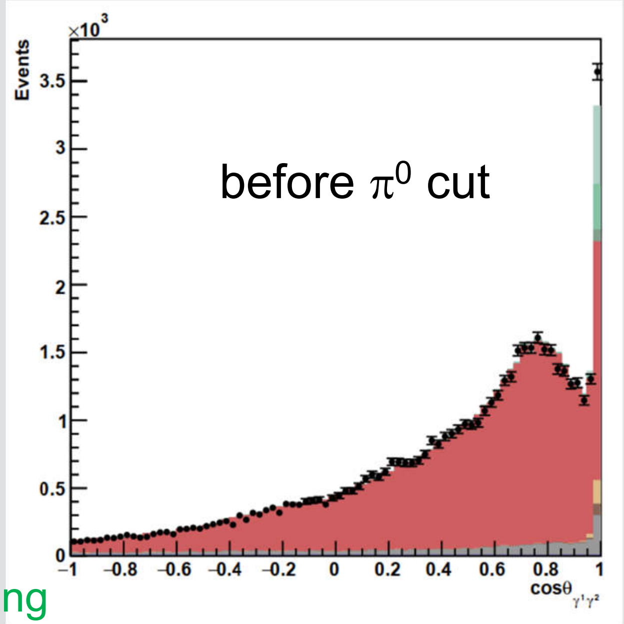
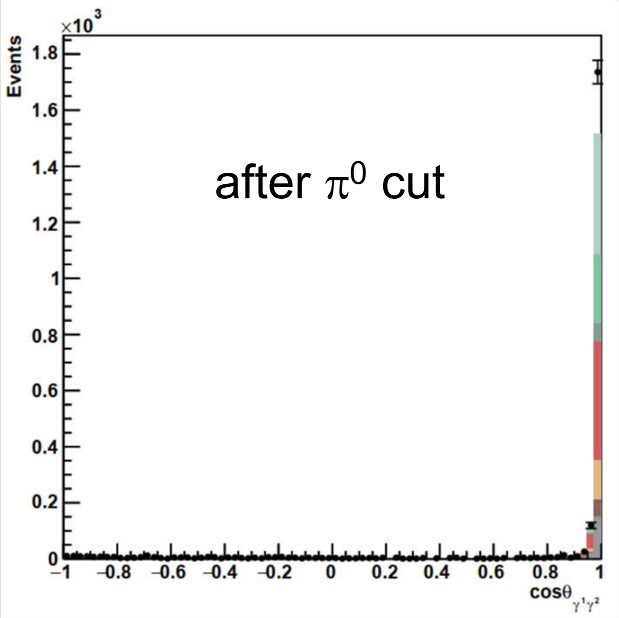
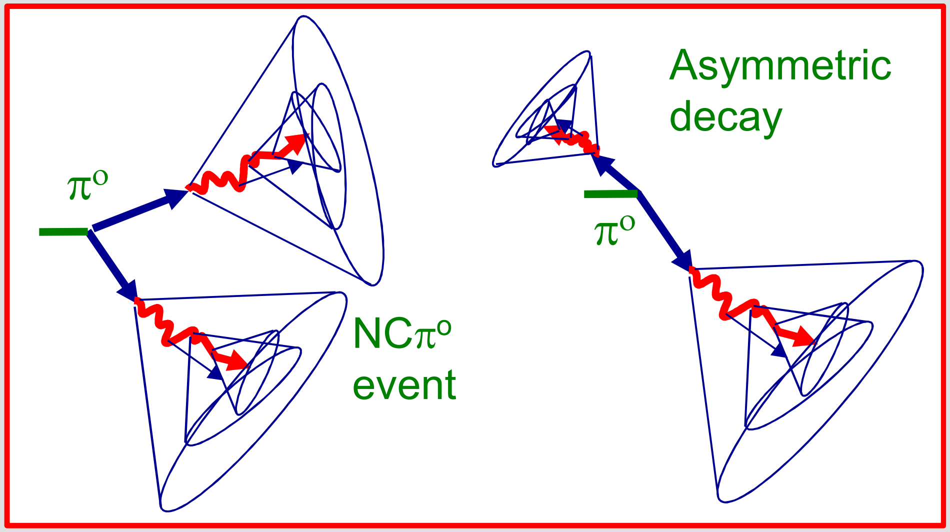


pion decay opening angle: $\cos\theta_{\gamma^1\gamma^2}$



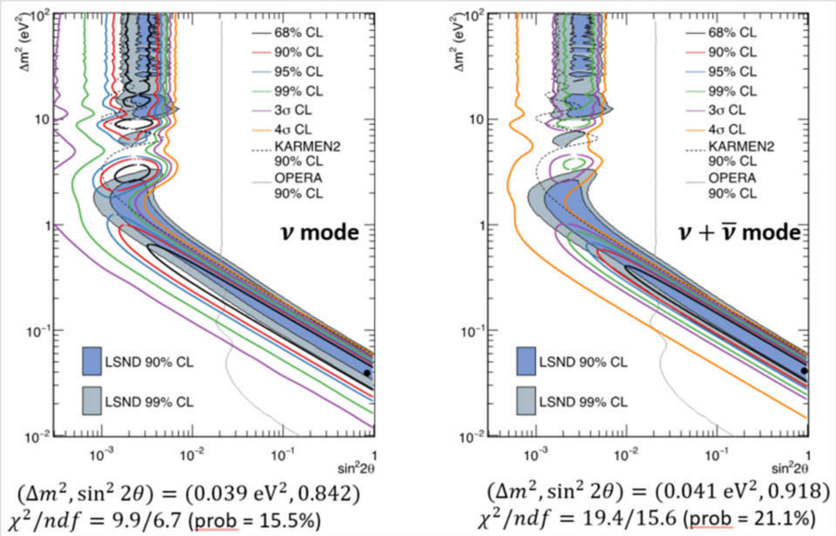


MiniBooNE: oscillation fits

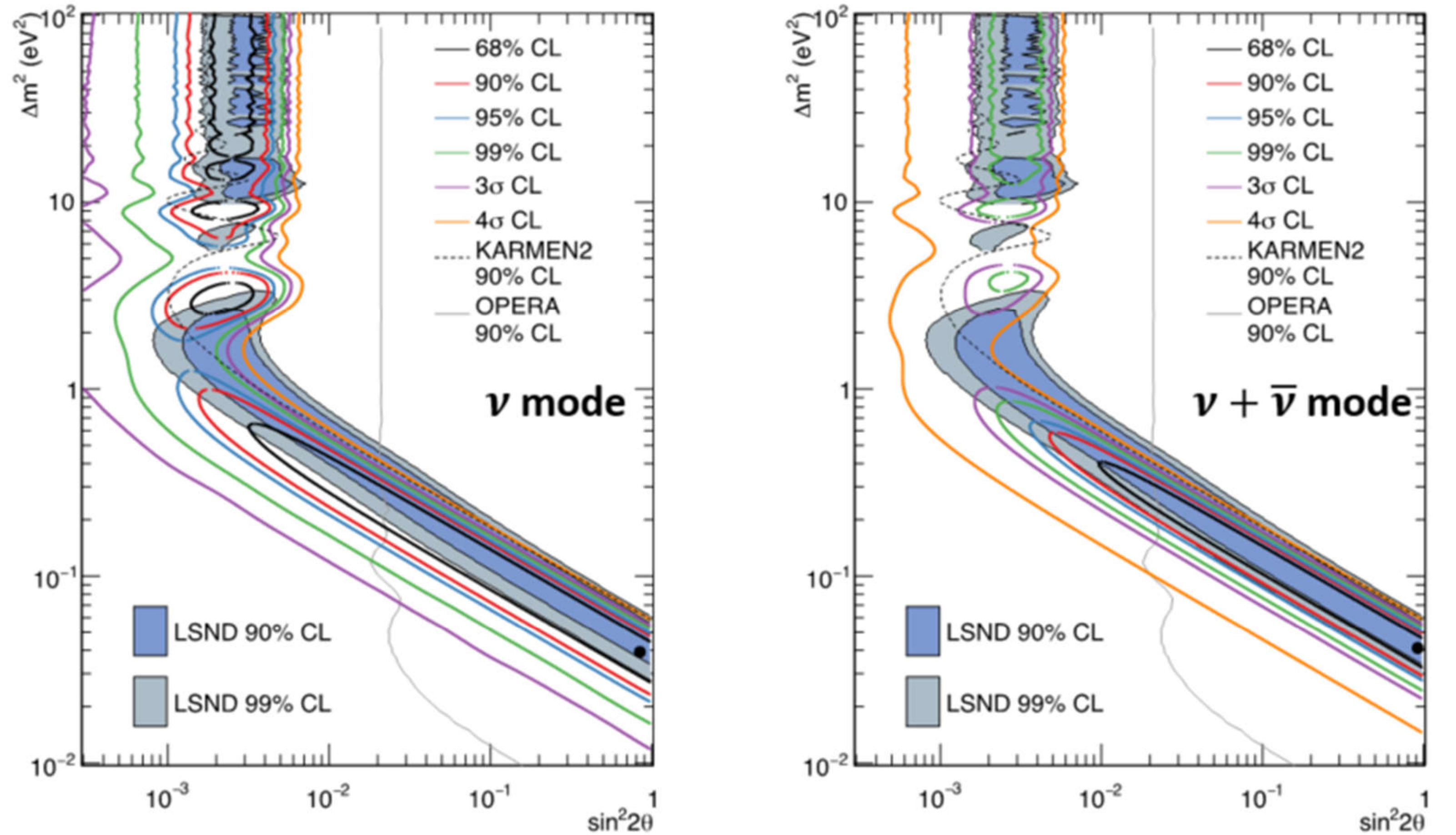
- Standard $2-\nu$ oscillation model is used:

$$P(L,E) = \sin^2 2\theta \times \sin^2(1.267\Delta m^2 L/E)$$

  - (In a 2 neutrino model, $\nu_\mu/\bar{\nu}_\mu$ disappearance is negligible)
- ν_e CCQE-like events are constrained by the ν_μ CCQE-like events
- Maximum likelihood is used
  - For a $\nu + \bar{\nu}$ analysis, a simultaneous fit was conducted for $\nu_e, \nu_\mu, \bar{\nu}_e,$ and $\bar{\nu}_\mu$ distributions
  - Oscillation is only applied to $\nu_e/\bar{\nu}_e$ but not to $\nu_\mu/\bar{\nu}_\mu$
- In a 3+1 model, $\sin^2 2\theta_{\mu e} \approx 4|U_{\mu 4}|^2 |U_{e4}|^2$ at the MiniBooNE mass splitting range



MiniBooNE: oscillation fits



$(\Delta m^2, \sin^2 2\theta) = (0.039\ \text{eV}^2, 0.842)$
$\chi^2/ndf = 9.9/6.7$ (prob = 15.5%)

$(\Delta m^2, \sin^2 2\theta) = (0.041\ \text{eV}^2, 0.918)$
$\chi^2/ndf = 19.4/15.6$ (prob = 21.1%)

- Consistent with LSND!