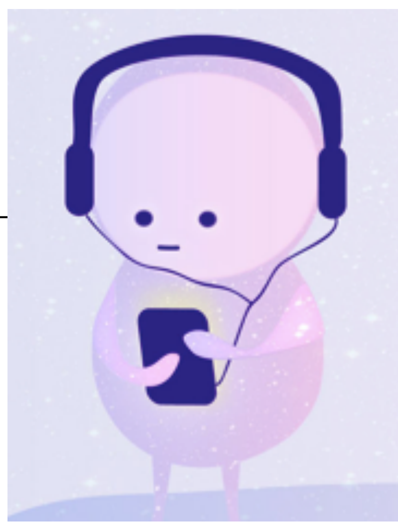
BSM Searches with Neutrinos from MeV to PeV Energies

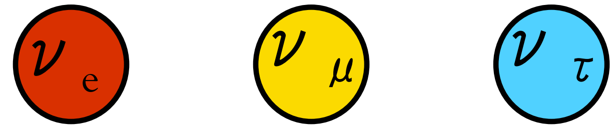
Janet Conrad,
Santa Barbara
April 11, 2018



I really wanted to talk about
more than sterile neutrinos.
But there is so much to say about them!

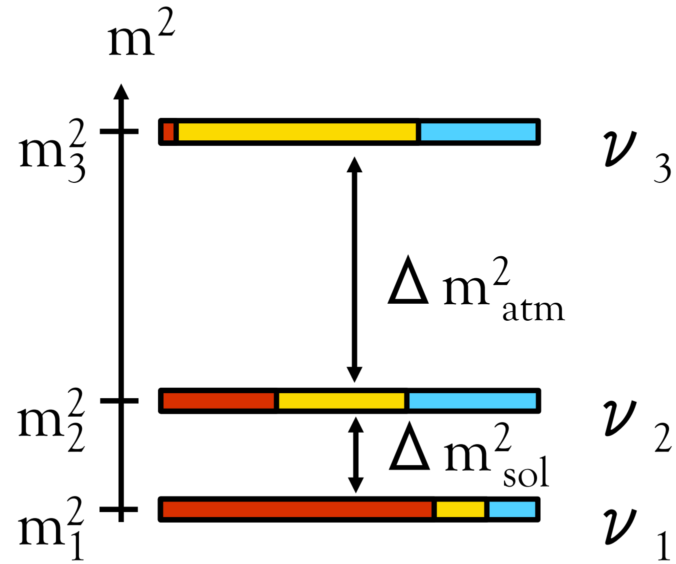
So that plan just didn't work out...

The 3 Neutrino Model:



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left(\begin{matrix} U_{\text{PMNS}} \\ 3\times 3 \end{matrix} \right) \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

oscillations: $\theta_{12}, \theta_{23}, \theta_{13}, \delta^{\text{CP}}$



Surprisingly well constrained!
Main experimental focus now: mass hierarchy and CP violation.

Question for theorists: *What larger questions get answered?*

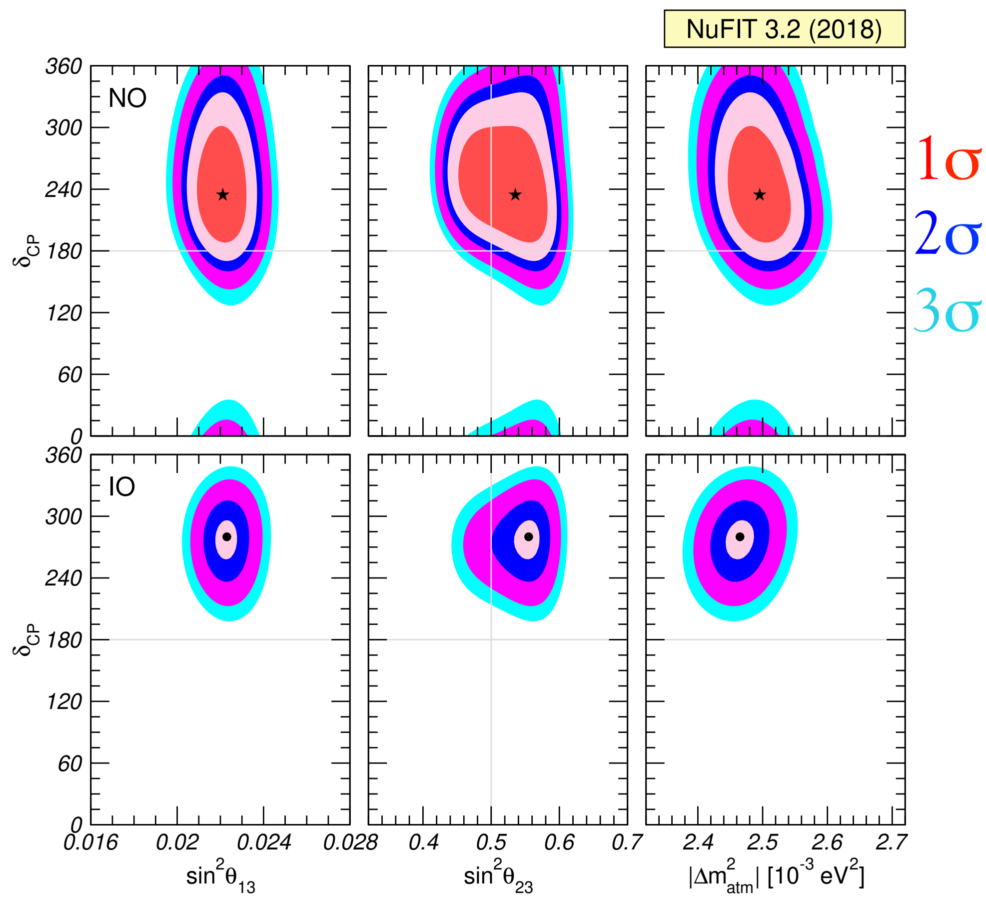
Question for experimentalists: *How close are we to answers?*

I think global fits will get us to answers soon,
combining solar, atmospheric, reactor and accelerator data.

www.nu-fit.org

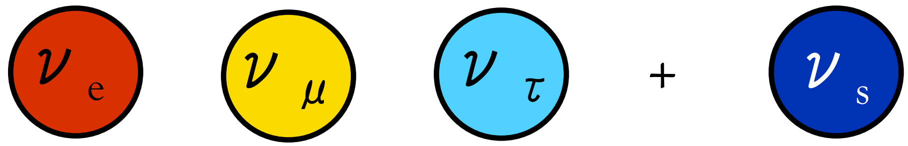
January 2018,
Correlations between
δ_{CP} and other parameters:

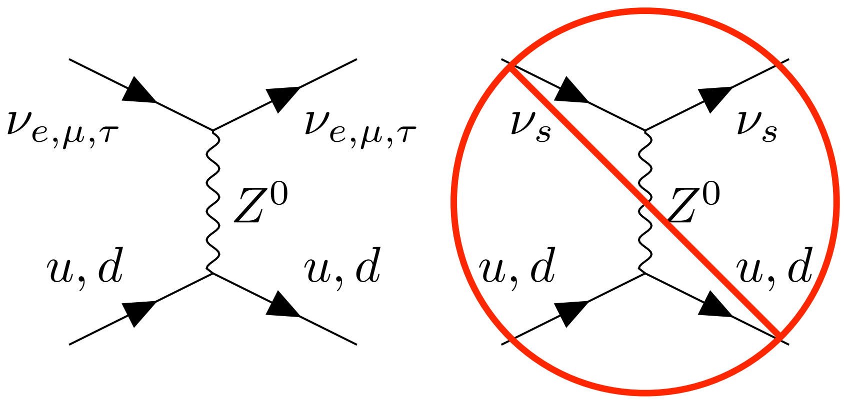
A lot more data is coming
within the next 2 years,
and even as soon as June!



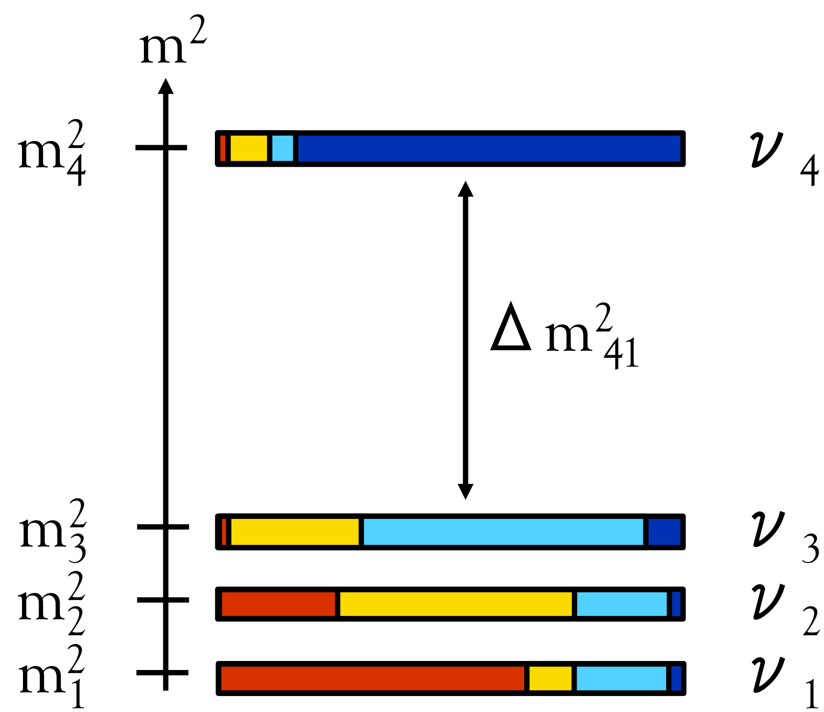
Artwork by Sandbox Studio, Chicago

Motivation:
Anomalies (>2σ signals) consistent w/ $\Delta m^2 \sim 1$ eV^2 oscillations → "3+1"





$$U_{3+1} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ \vdots & & \vdots & U_{\mu 4} \\ \vdots & & \vdots & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix},$$



A 3+1 model is already constrained (barely) by measurements

$$|U| = \begin{bmatrix} 0.79 \to 0.83 & 0.53 \to 0.57 & 0.14 \to 0.15 & 0.13\,(0.17) \to 0.20\,(0.21) \\ 0.25 \to 0.50 & 0.46 \to 0.66 & 0.64 \to 0.77 & 0.09\,(0.10) \to 0.15\,(0.13) \\ 0.26 \to 0.54 & 0.48 \to 0.69 & 0.56 \to 0.75 & 0.0\,(0.0) \to 0.7\,(0.05) \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix}$$

Vacuum oscillations: $\nu_\mu \to \nu_e$, $\nu_e \to \nu_e$, $\nu_\mu \to \nu_\mu$ ⇒ $U_{e4}\,,\ U_{\mu4}\,,\ \Delta m^2$

Matter Effects: ν_μ disappearance ⇒ $U_{\tau 4}$ also

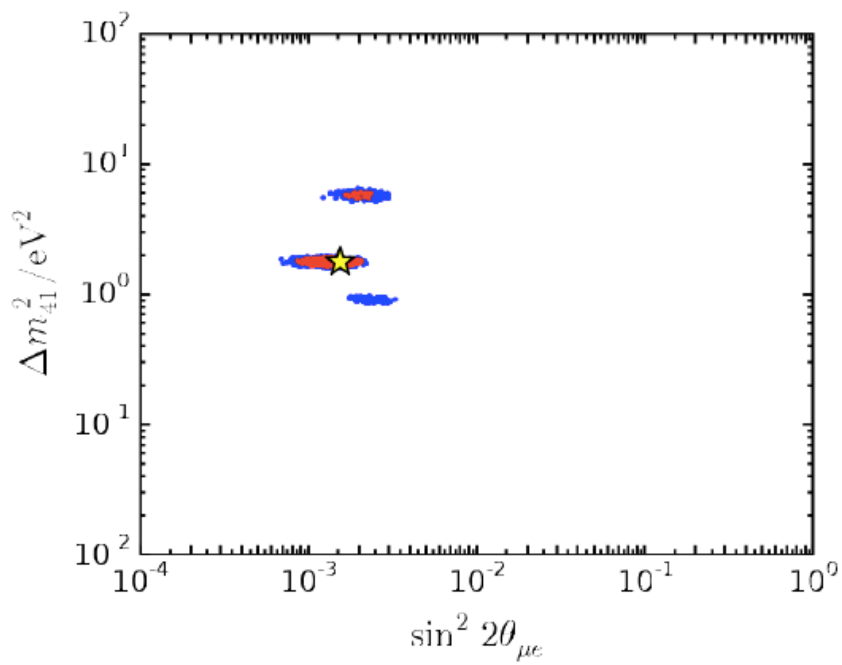
First Constraints on the Complete Neutrino Mixing Matrix with a Sterile Neutrino
G.H. Collin, C.A. Argüelles, J.M. Conrad (MIT), M.H. Shaevitz (Columbia U.). Jun 30, 2016. 6 pp.
Published in **Phys.Rev.Lett. 117 (2016) no.22, 221801**

This model yields a good $\Delta\chi^2$/dof

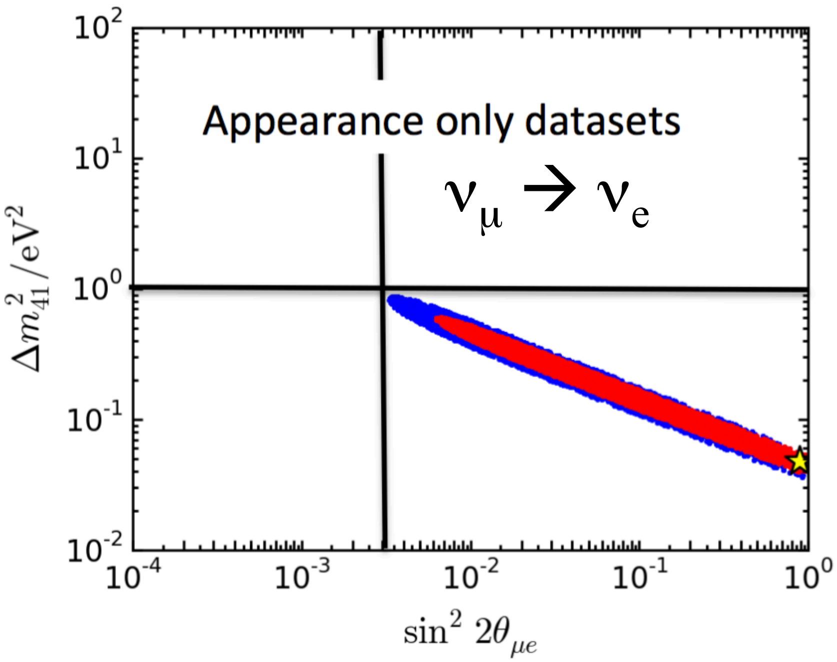
3+1	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\tau 4}\rvert$	N_{bins}	$\chi^2_{\min}$	χ^2_{null}	$\Delta\chi^2$ (dof)
SBL	1.75	0.163	0.117	-	315	306.81	359.15	52.34 (3)
SBL+IC	1.75	0.164	0.119	0.00	524	518.23	568.84	50.61 (4)
IC	5.62	-	0.314	-	209	207.11	209.69	2.58 (2)

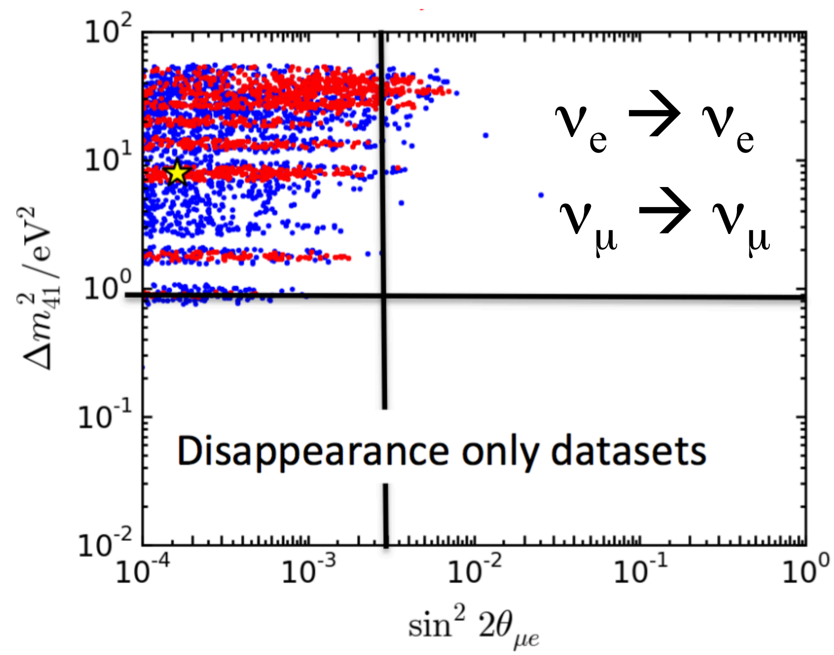
Vac
Vac+Matter
Matter only

$\Delta\chi^2$ should address problems like un-necessary bins…



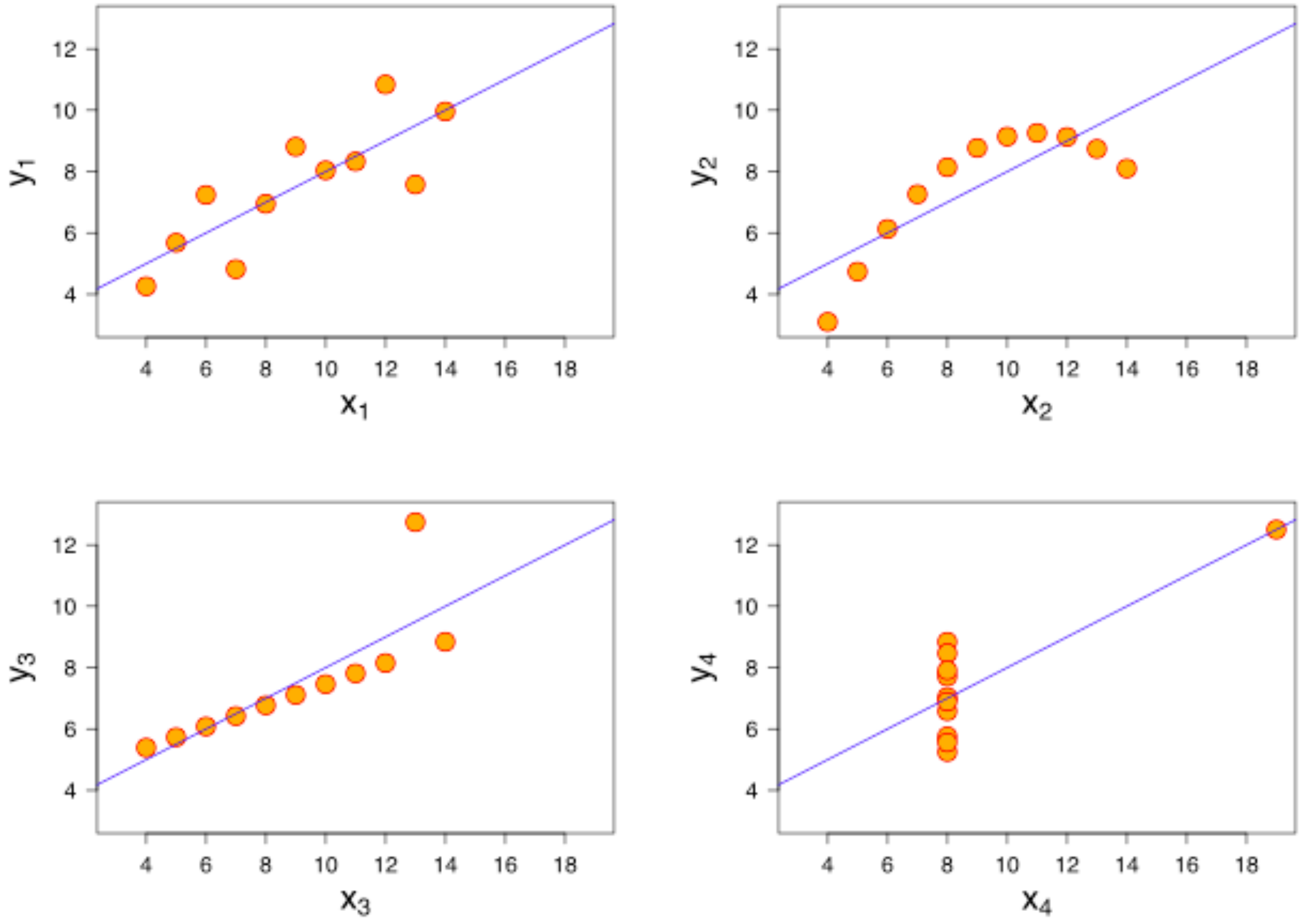
But fits seems to be internally inconsistent





$$P_{\nu_e \to \nu_e} = 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) \ ,$$
$$P_{\nu_\mu \to \nu_\mu} = 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) \ ,$$
$$P_{\nu_\mu \to \nu_e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E).$$

Anscombe's Quartet



All four sets are identical in mean of x, mean of y, and variance of y. The all have the same χ^2.

We have an alternative: Parameter Goodness of Fit

M. Maltoni and T. Schwetz, Phys. Rev. D **68**, 033020 (2003) [hep-ph/0304176].

$$\chi^2_{PG} = \chi^2_{glob} - (\chi^2_{app} + \chi^2_{dis}).$$

$$N_{PG} = (N_{app} + N_{dis}) - N_{glob}$$

PG probabilities for 3+1 fits are very low (<1%)

PG test is less sensitive to most systematic errors…
But it can miss a case where there is a signal.

Signal with parameters x,y,z

+

A systematic shift in a background

produces a signature that looks like

Signal with parameters x',y',z'

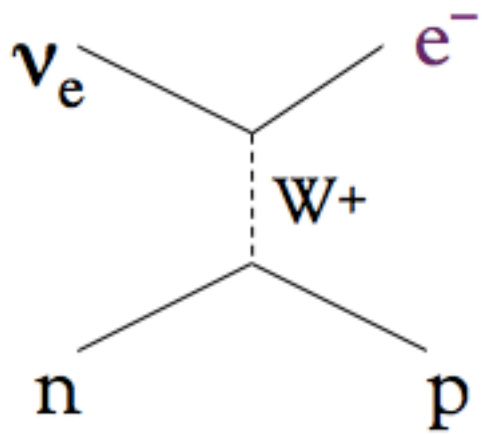
and this can happen!

Sterile Neutrinos: An Introduction to Experiments
J.M. Conrad (MIT), M.H. Shaevitz (Columbia U.). Sep 25, 2016. 46 pp.
e-Print: arXiv:1609.07803 [hep-ex] | PDF

Can you come up w/ a better test?

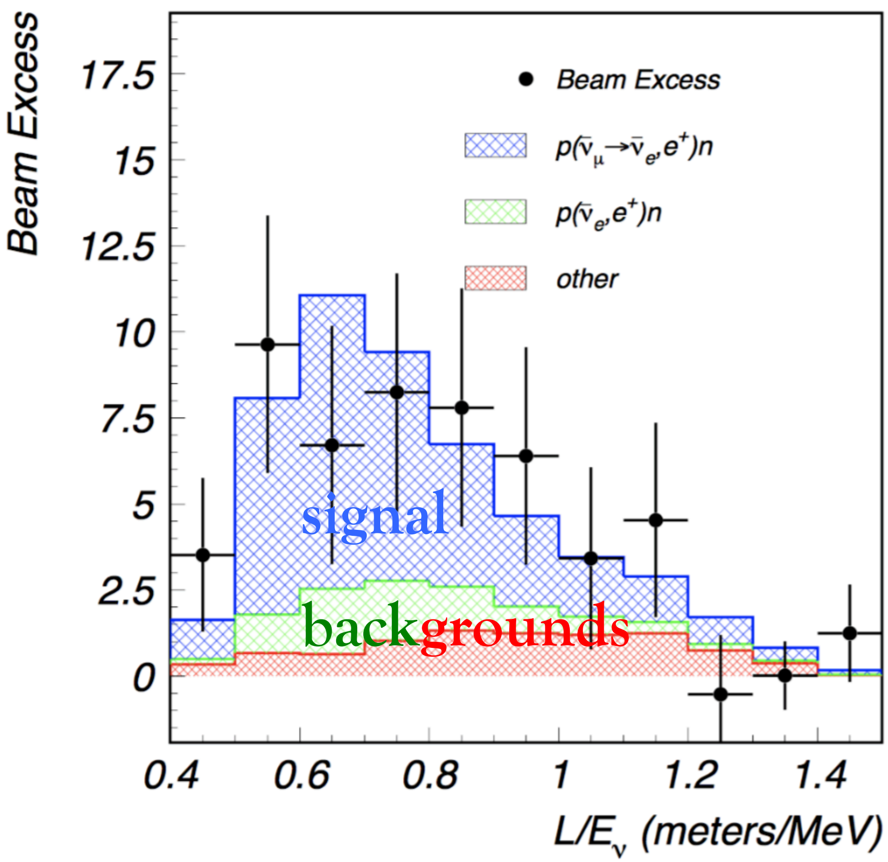
$\nu_\mu \rightarrow \nu_e$

In these experiments you are looking for electron neutrino interactions in a sea of interactions from muon neutrinos

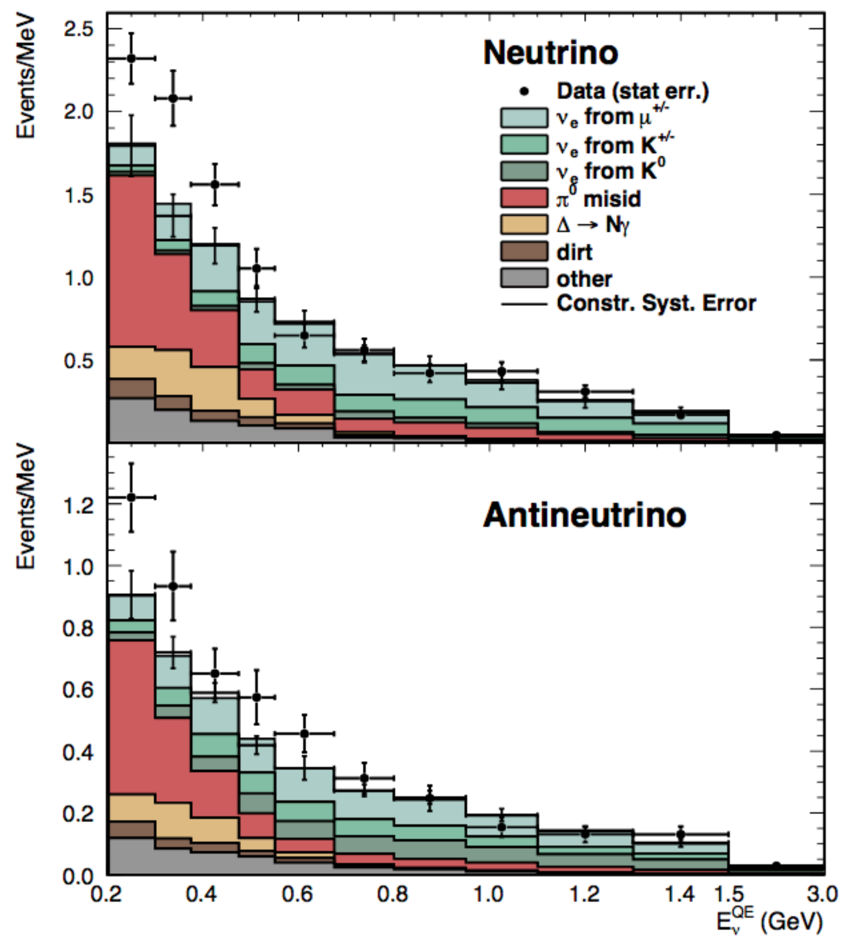


There are 2 experiments with $\nu_\mu \rightarrow \nu_e$ anomalies:

LSND

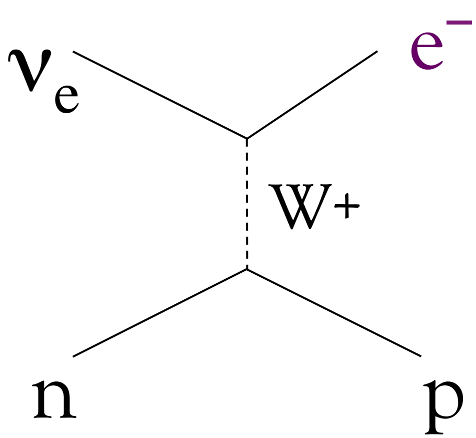


MiniBooNE in 2 modes



Most conventional beams range in energy from a few 100 MeV to a few GeV...

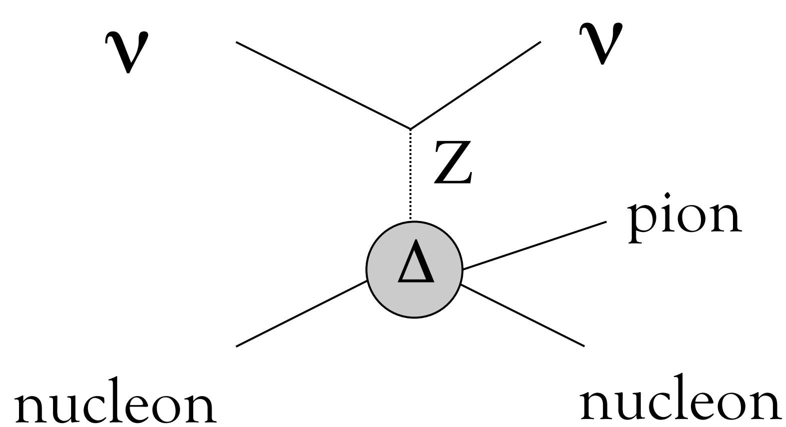
In those ranges you get this...



CCQE Charged Current
Quasi-Elastic

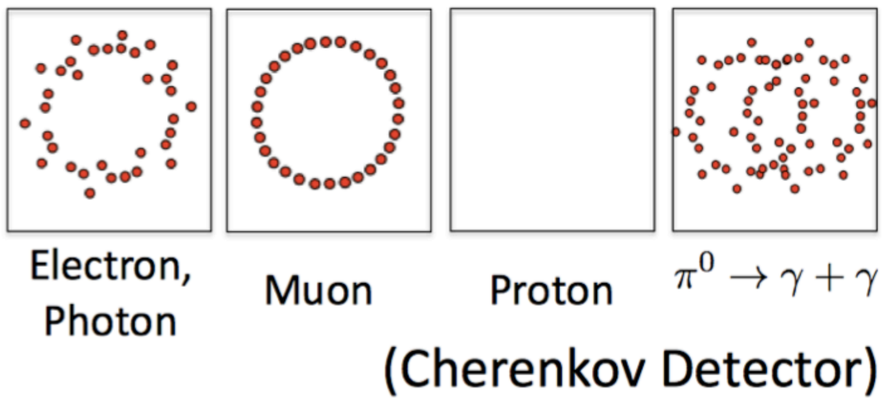
signal

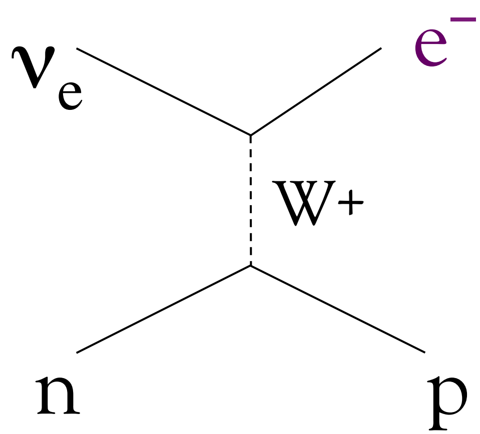
And you also get
(along with other events)...

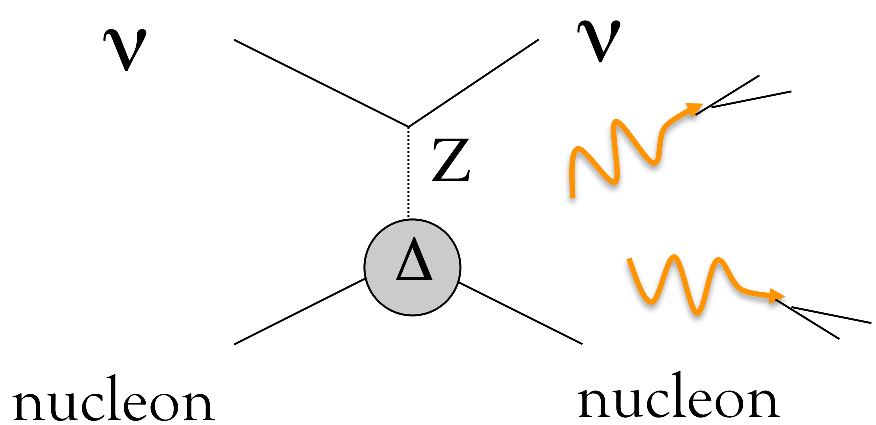


Neutral Current
Resonant Production

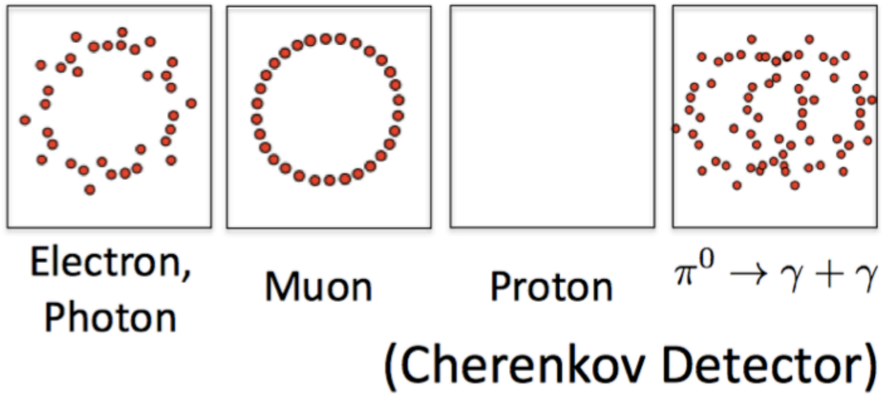
background

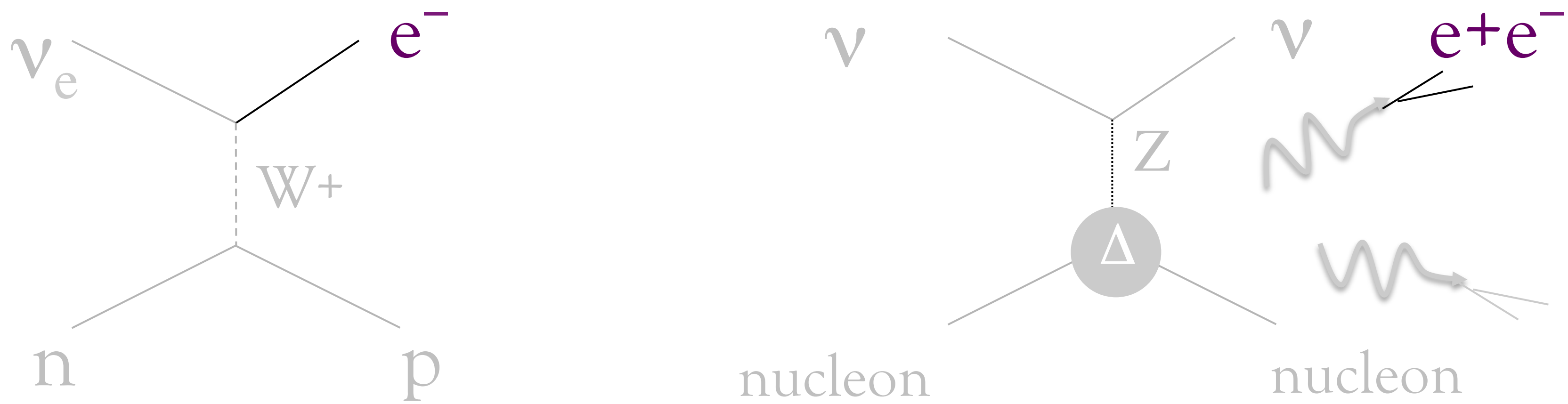






The worry: MiniBooNE can confuse these signals





The worry: MiniBooNE can confuse these signals

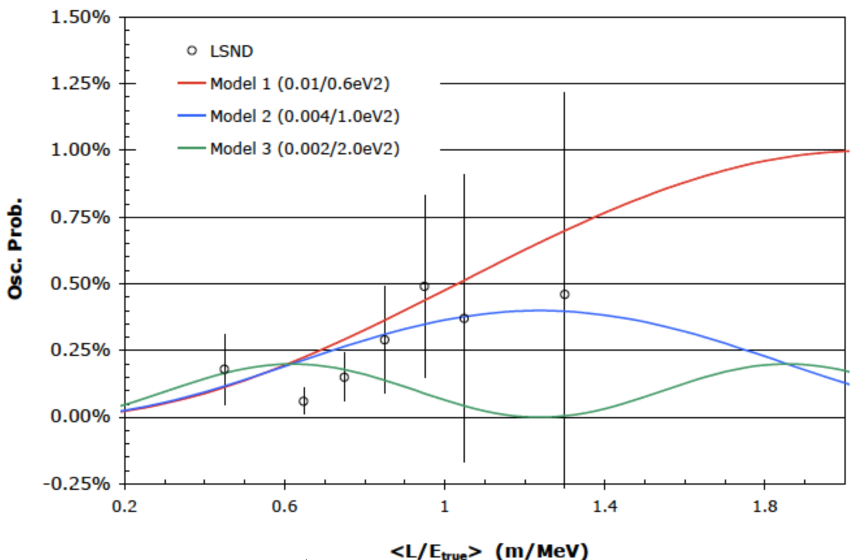
A small admixture of additional mis-id π^0 + a real signal → fake signal.
This is the case where the PG test will fail.

Comparing to oscillation models

$$P_{\nu_\mu \to \nu_e} = \sin^2 2\theta_{e\mu} \sin^2(1.27 \Delta m^2_{41} L/E)$$

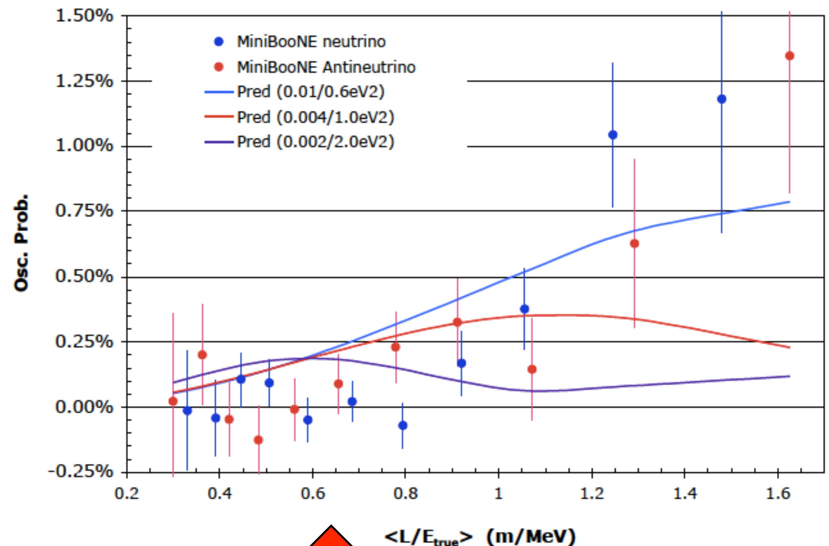
High data points, some π^0?

LSND



Low data points

MiniBooNE



Low data points

A lot of 3+1 issues come from $\nu_\mu \rightarrow \nu_e$

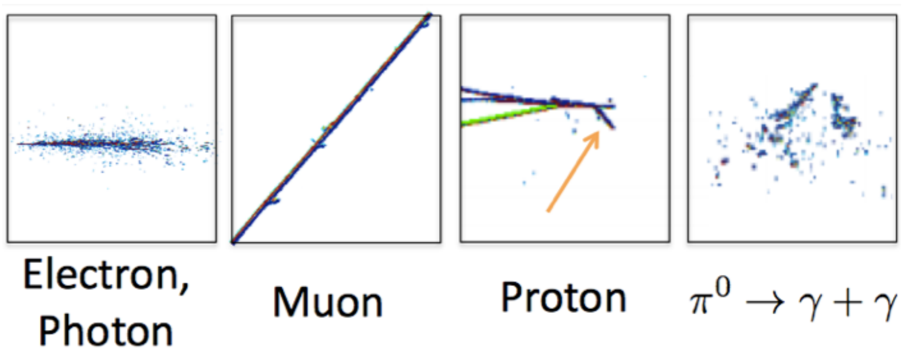
Some instructions on how to make these plots: **Using L/E Oscillation Probability Distributions**
MiniBooNE Collaboration (A.A. Aguilar-Arevalo (Mexico U., CEN) *et al.*).
FERMILAB-FN-0984-AD-PPD
e-Print: arXiv:1407.3304 [hep-ex] | PDF

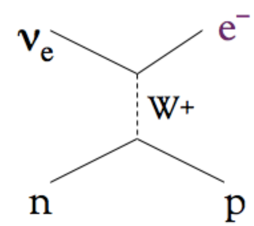
Coming Soon!

At Neutrino 2018: MiniBooNE running has continued.
Data set is now doubled.
If signal remains in new data set,

MiniBooNE → about 5σ

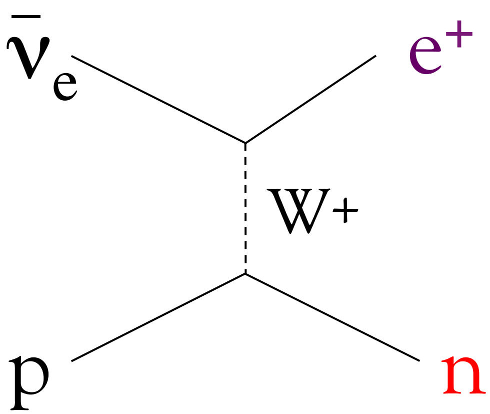
Later (hopefully not too much later): MicroBooNE

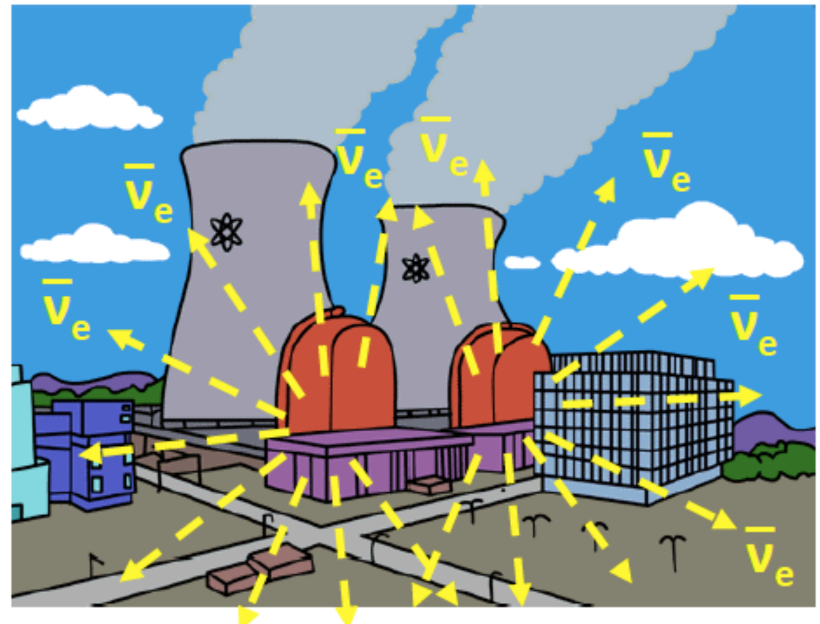




Can distinguish photons from electrons at ~85% level
(A lot better than 0% as in Cherenkov detector case.)

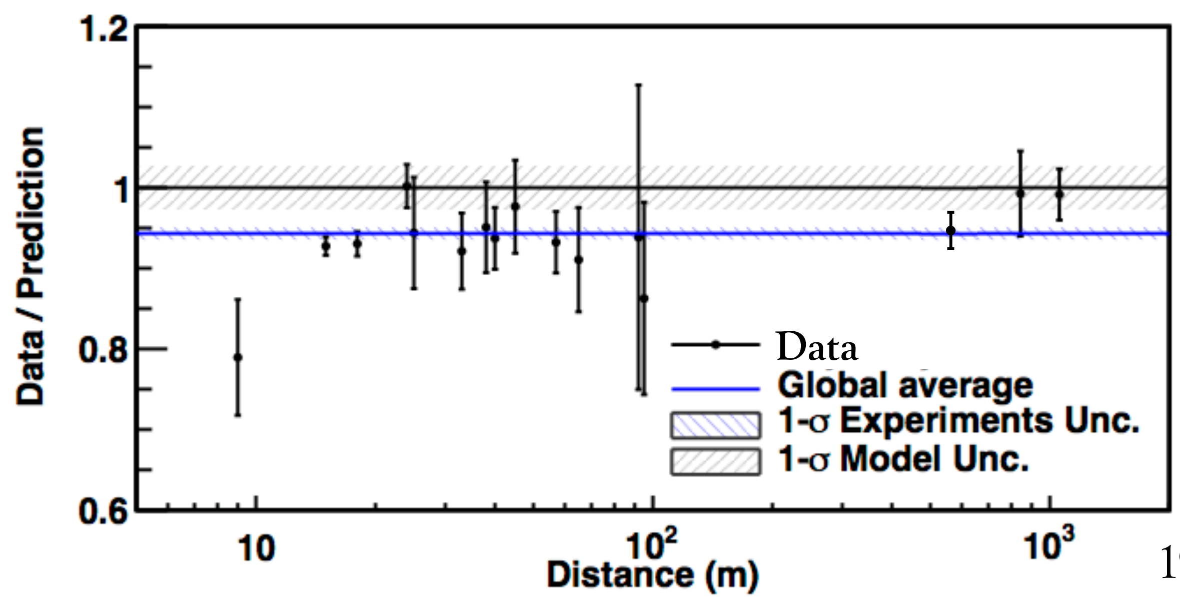
$\nu_e \rightarrow \nu_e$



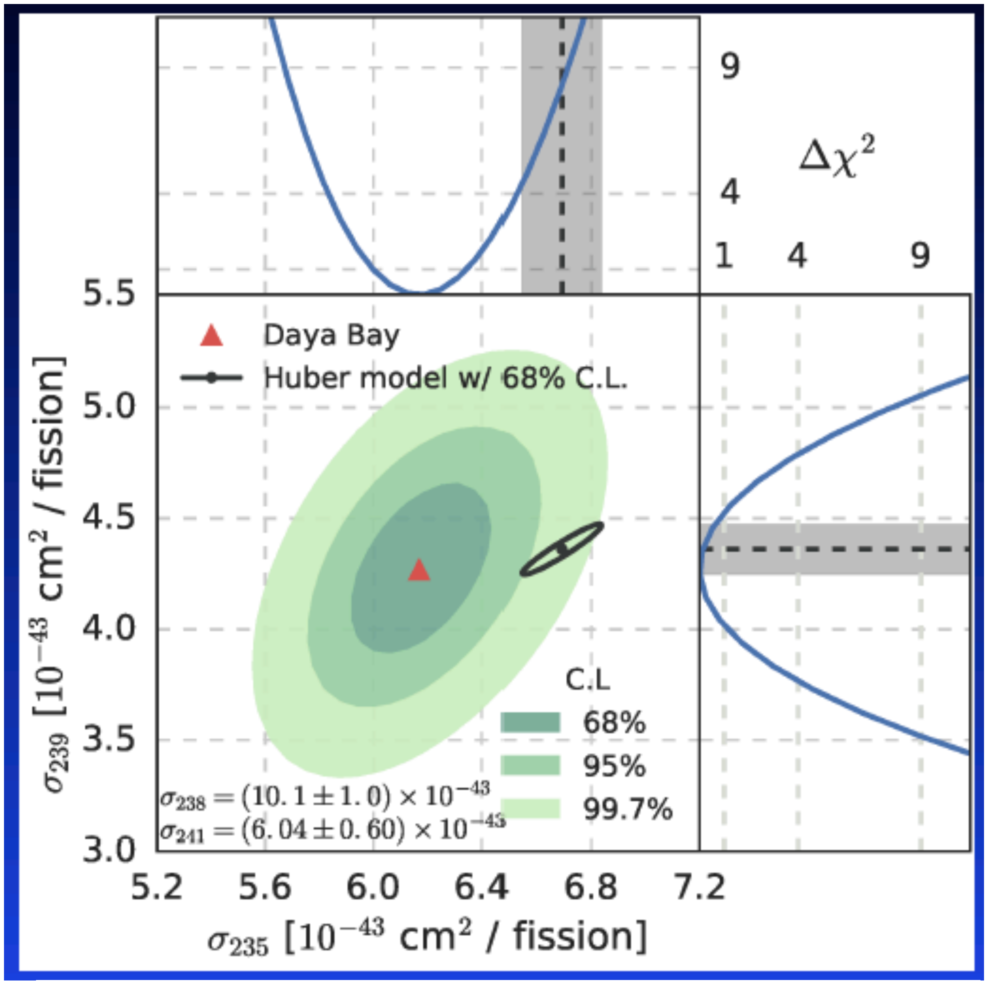


"Reactor Anomaly" appeared when modern experiments updated reactor fluxes

→ We must think more about limits!



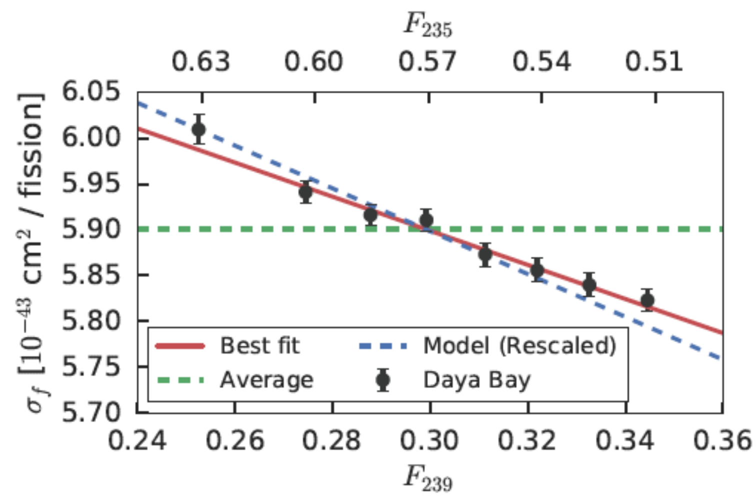
If this offset is due to oscillations,
the effect will occur throughout the reactor burn cycle



Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay
Daya Bay Collaboration (F.P. An (East China U. Sci. Tech., Shanghai) *et al.*). Apr 4, 2017. 8 pp.
Published in **Phys.Rev.Lett. 118 (2017) no.25, 251801**

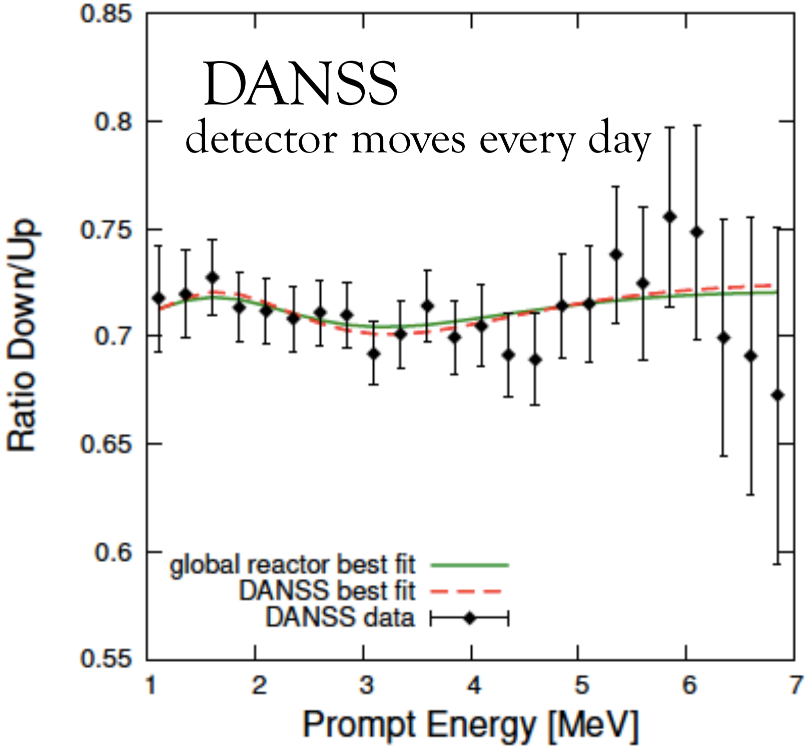
U-235 shows an effect,
Pu-239 doesn't??

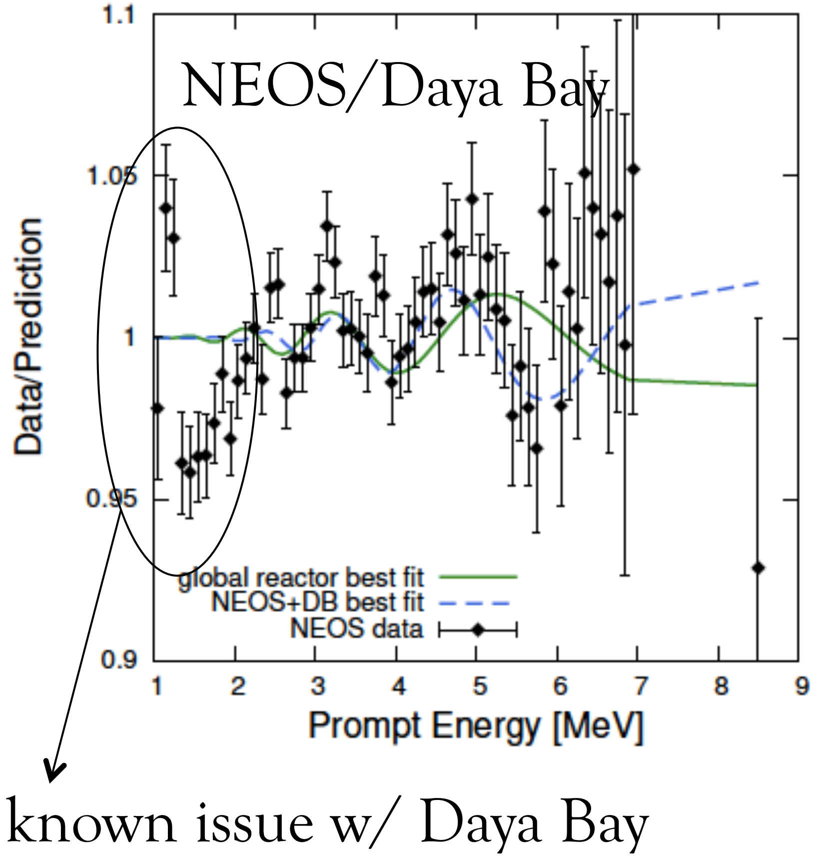
This is controversial!



Assumes **no** other
time-dependent
flux contributions

The newest generation of reactor experiments is testing the energy dependence for the shape!



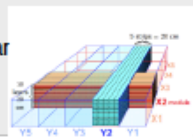
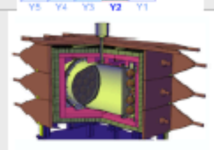
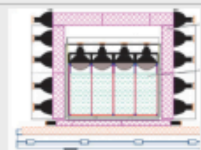
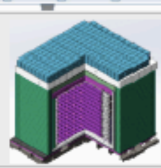
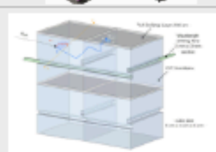
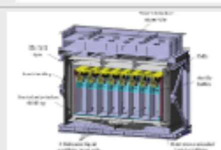


Both experiments will be updating at Neutrino 2018

. **Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos**
Mona Dentler, Álvaro Hernández-Cabezudo, Joachim Kopp, Pedro A.N. Machado, Michele Maltoni, Ivan Martinez-Soler, Thomas Schwetz. Mar 28, 2018. 32 pp.
MITP/18-023, FERMILAB-PUB-18-086-T, IFT-UAM/CSIC-18-033, MITP-18-023, FERMILAB-PUB-18-086-T, IFT-UAM-CSIC-18-033
e-Print: arXiv:1803.10661 [hep-ph] | PDF

Coming Soon!

A slew of results on $\nu_e \rightarrow \nu_e$

Experiment		Reactor/Fuel	Baseline (m)	Mobility	Detection Material	Segmentation	Readout	Energy Resolution	PID	Status
DANSS Kalinin nuclear reactor (Russia)		3000 MWth LEU	10.7-12.7	Yes	PS+Gd Sheets	2D, 5mm	WLS fibers + SiPM and PMT	25%/√E	Topology	Collecting data
NEOS Hanbit nuclear power complex (Korea)		2800 MWth LEU	~24	No	GdLS	-	PMT Double-ended	5% @ 1 MeV	Recoil PSD	Phase-1 complete
Neutrino-4 SM-3 reactor (Russia)		100 MWth HEU	6-12	Yes	GdLS	2D, 10 cm	PMT Single-ended	Not available	Topology	Phase-1 complete
PROSPECT High Flux Isotope Reactor (USA)		**85 MWth HEU**	**7-12**	**Yes**	**^{6}LiLS**	**2D, 14.6 cm**	**PMT Double-ended**	**4.5%/√E**	**Topology + recoil and capture PSD**	**Commissioning and installation in progress**
Solid BR2 research reactor (Belgium)		40-80 MWth HEU	6-9	No	PVT cubes+ ^{6}Li:ZnS(Ag) sheets	3D, 5 cm	WLS fibers + SiPM	20%/√E	Topology + capture PSD	Collecting data
STEREO ILL research reactor (France)		58 MWth HEU	9-11	No	GdLS	2D, 25 cm	PMT Single-ended	12% @ 2 MeV	Recoil PSD	Collecting data

Some values from Mauro Mezzetto, neutrino 2016

Reactor Experiments Everywhere!

$\nu_\mu \rightarrow \nu_\mu$ (Vacuum Oscillations)

Because there are only limits – unlike $\nu_e \rightarrow \nu_e$ or $\nu_\mu \rightarrow \nu_e$
These results are, comparatively, really poorly vetted

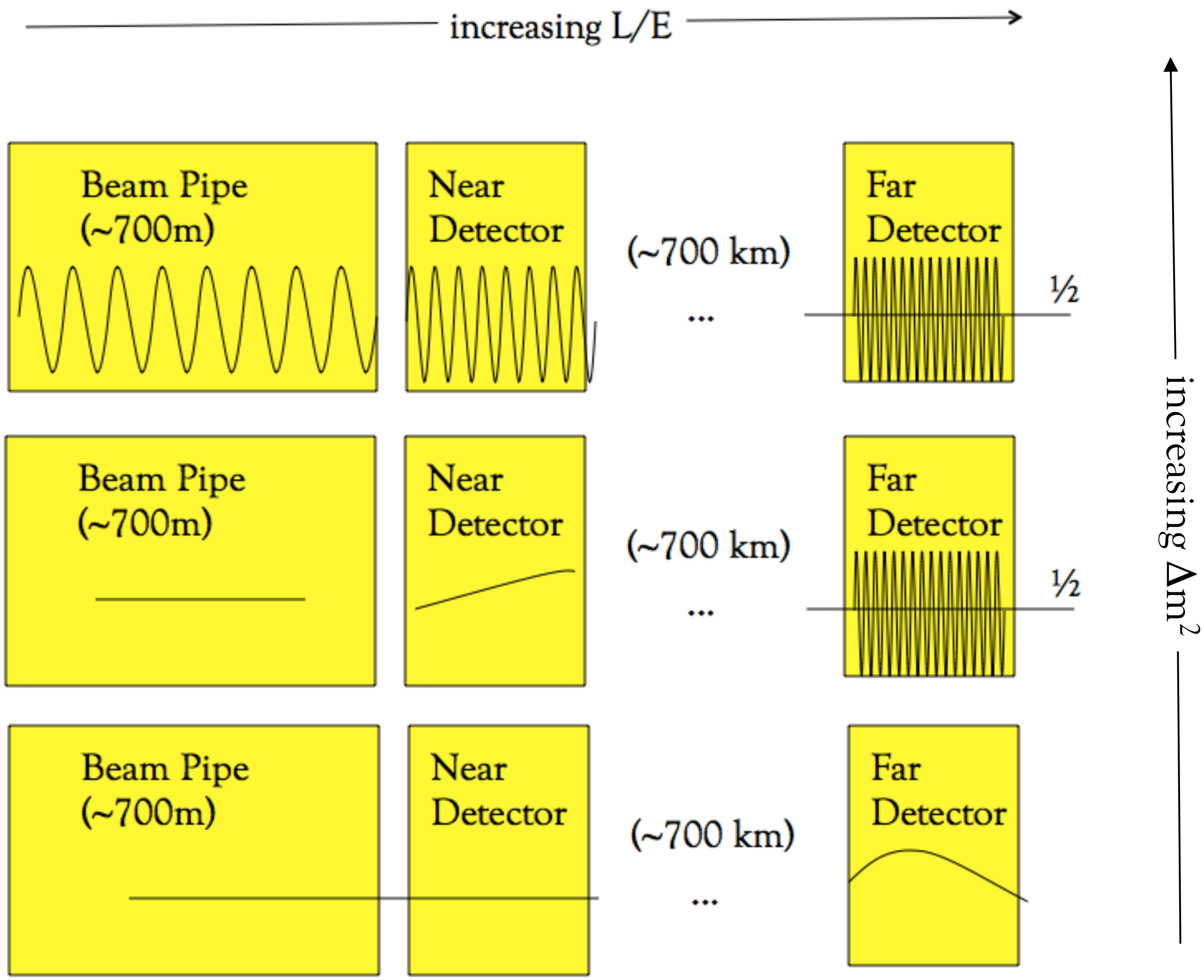
I want to spend time on the latest 3+1 limits presented by MINOS/MINOS+

arXiv.org > hep-ex > arXiv:1710.06488

High Energy Physics – Experiment

Search for sterile neutrinos in MINOS and MINOS+ using a two-detector fit

There is something seriously wrong with this result.
It is showing non-SM behavior in the limit.
→ This limit cannot be taken at face value!



At higher Δm^2 you must use absolute flux, xsec preds.
→ worse limit

in between, turnover of limit

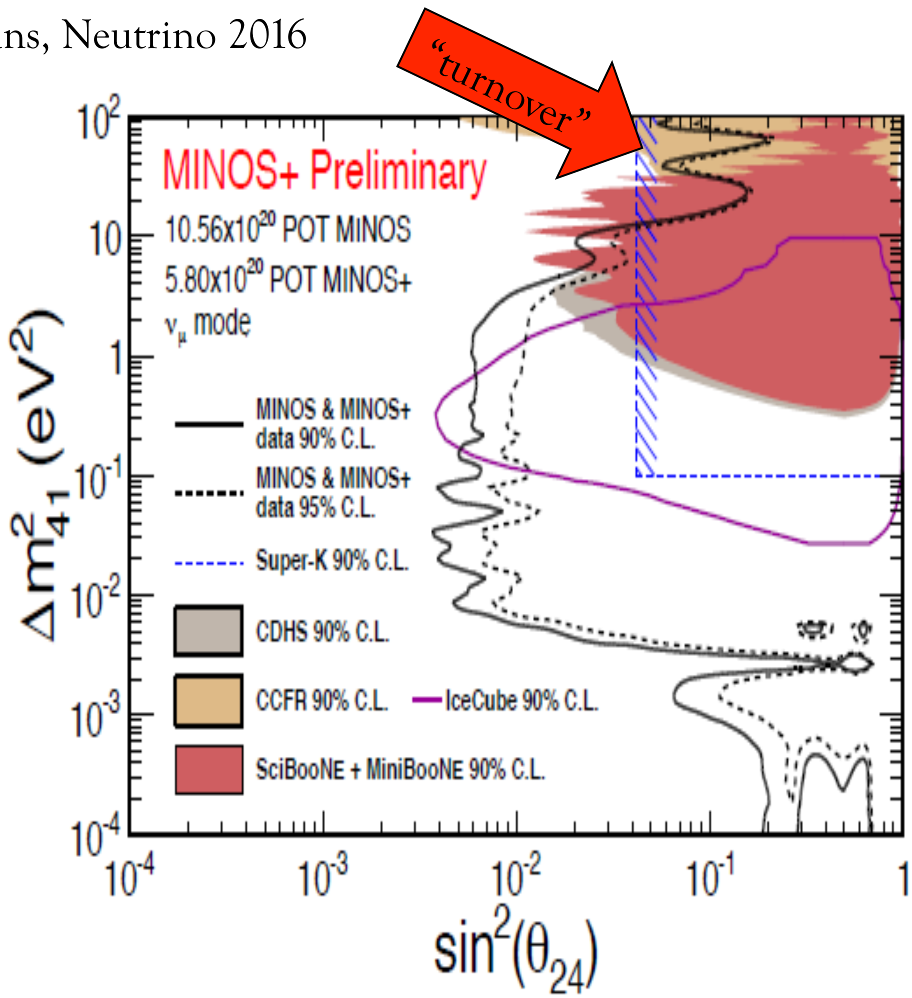
At lower Δm^2 you can use the near/far ratio and many systematics cancel
→ better limit

Minos is in the NuMI Beam

Basically what this should look like – a high sensitivity region where the near/far ratio works well, and a "turnover" at high Δm^2

Justin Evans, Neutrino 2016

This limit
is strange in
that it corresponds
to ~1% error
in the near/far
ratio.



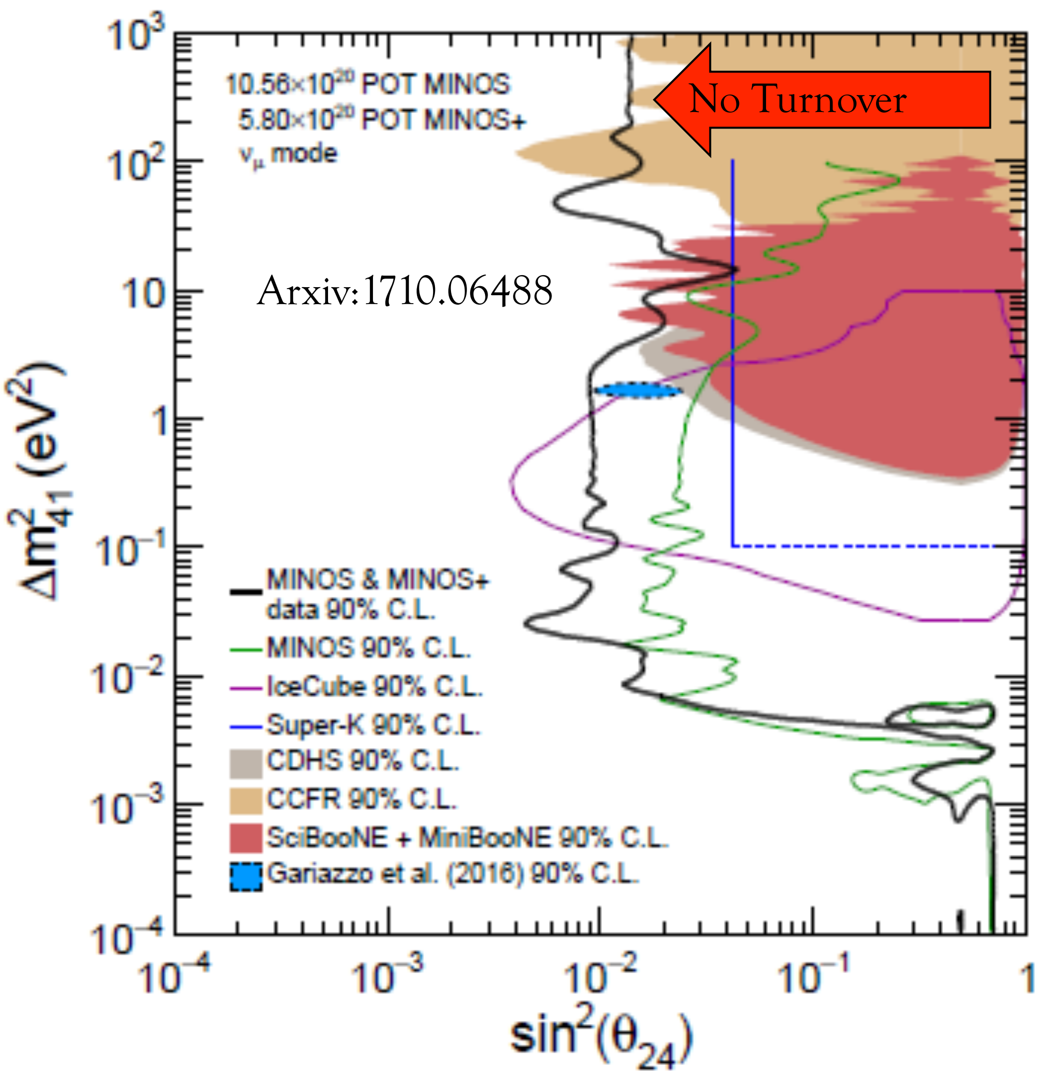
poor limit here
because of
atm. signal

The latest MINOS/+ version has lost its turn-over!
There is now only a small indentation.

Same data.
New analysis.
No longer
"preliminary"

Wrong high Δm^2 behavior

What happened?
They changed to the
"MINERvA Flux"

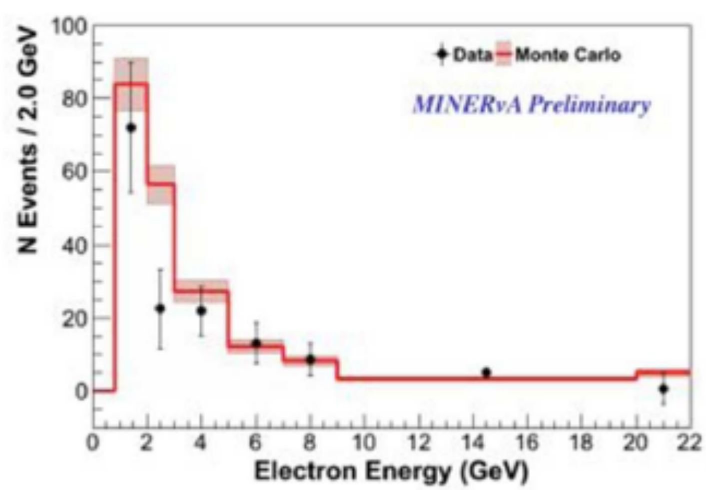


Marco Laveder realized: the new MINERvA flux is not 1st principles.

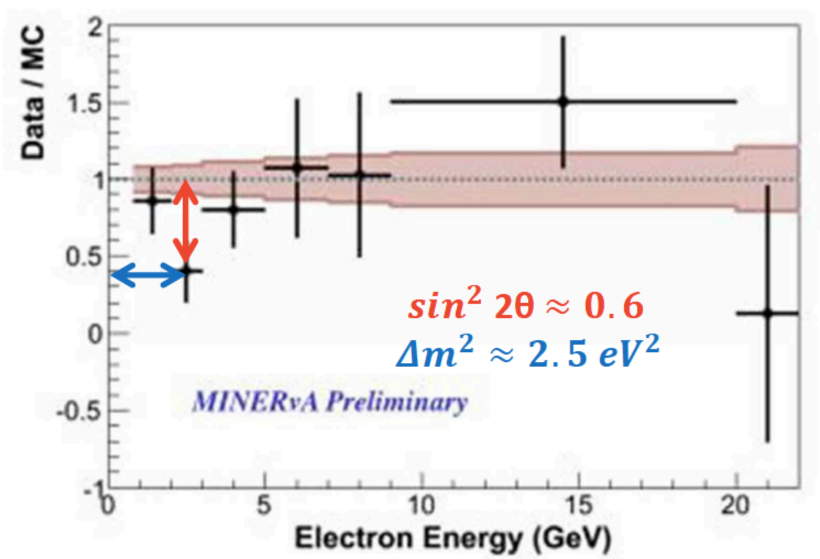
It uses ν–e data from the NuMI line (same as MINOS) as a constraint

This leads to two issues…

1. MINOS/+ limit is circular argument:
   The measured flux is used to test the measured flux
2. The MINERvA ν-e scattering lowers the ab initio prediction,
   & has E-dependence.



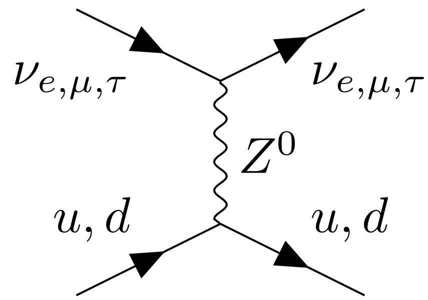
arxiv: 1512.07699

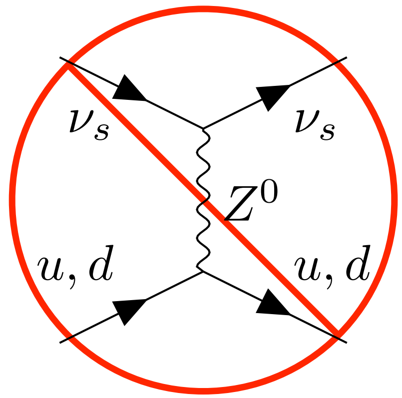


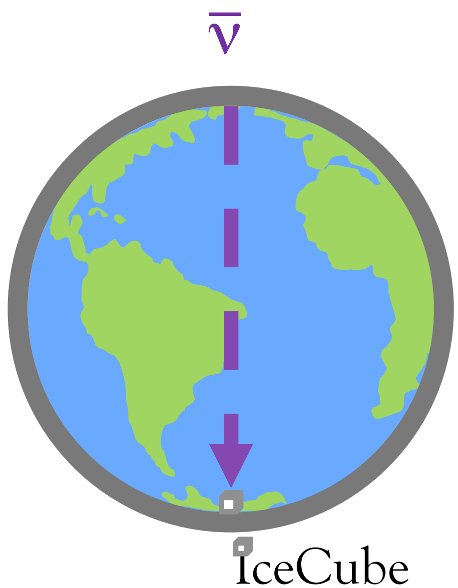
J.Park – FNAL seminar, Dec 20, 2013

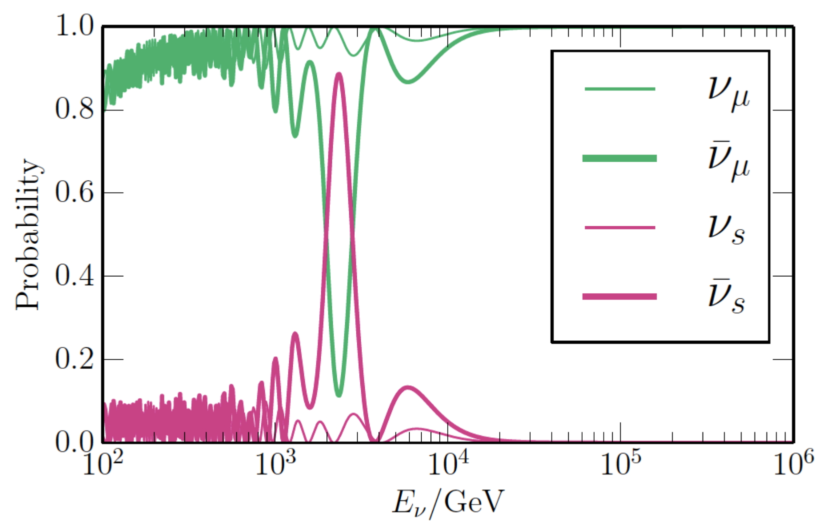
If we are ever to discover anything, we have to be as critical of limits as we are with signals!

ν_μ disappearance from matter effects



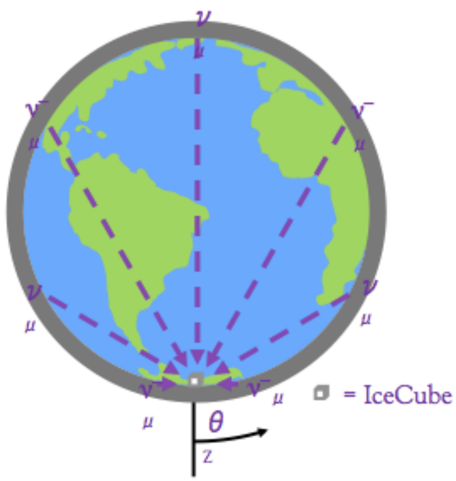


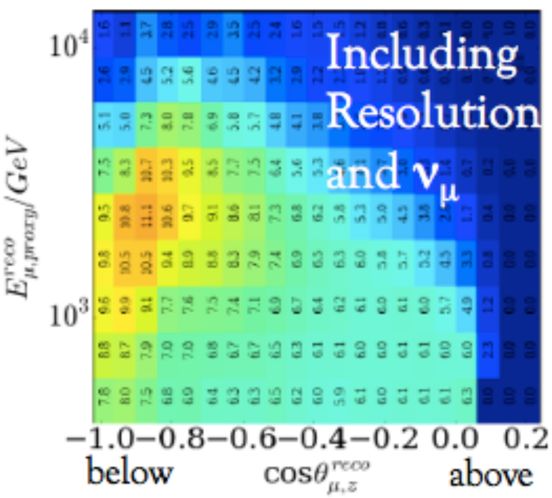


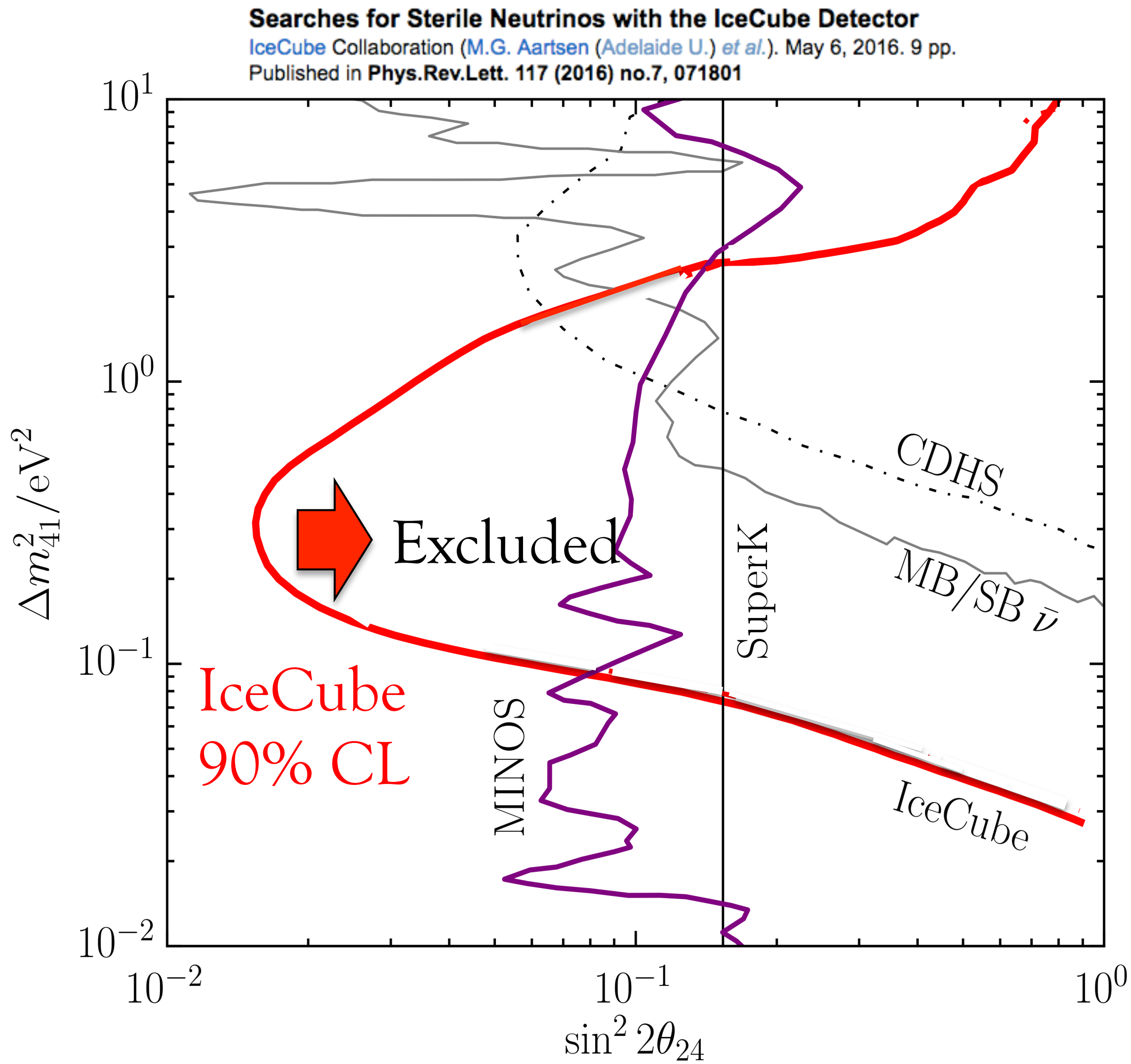


$\Delta m^2_{41} = 1\ \mathrm{eV}^2,\ \sin^2 2\theta_{24} = 0.1$

Use both $\cos\theta_z$ and E → no signal observed, set limit

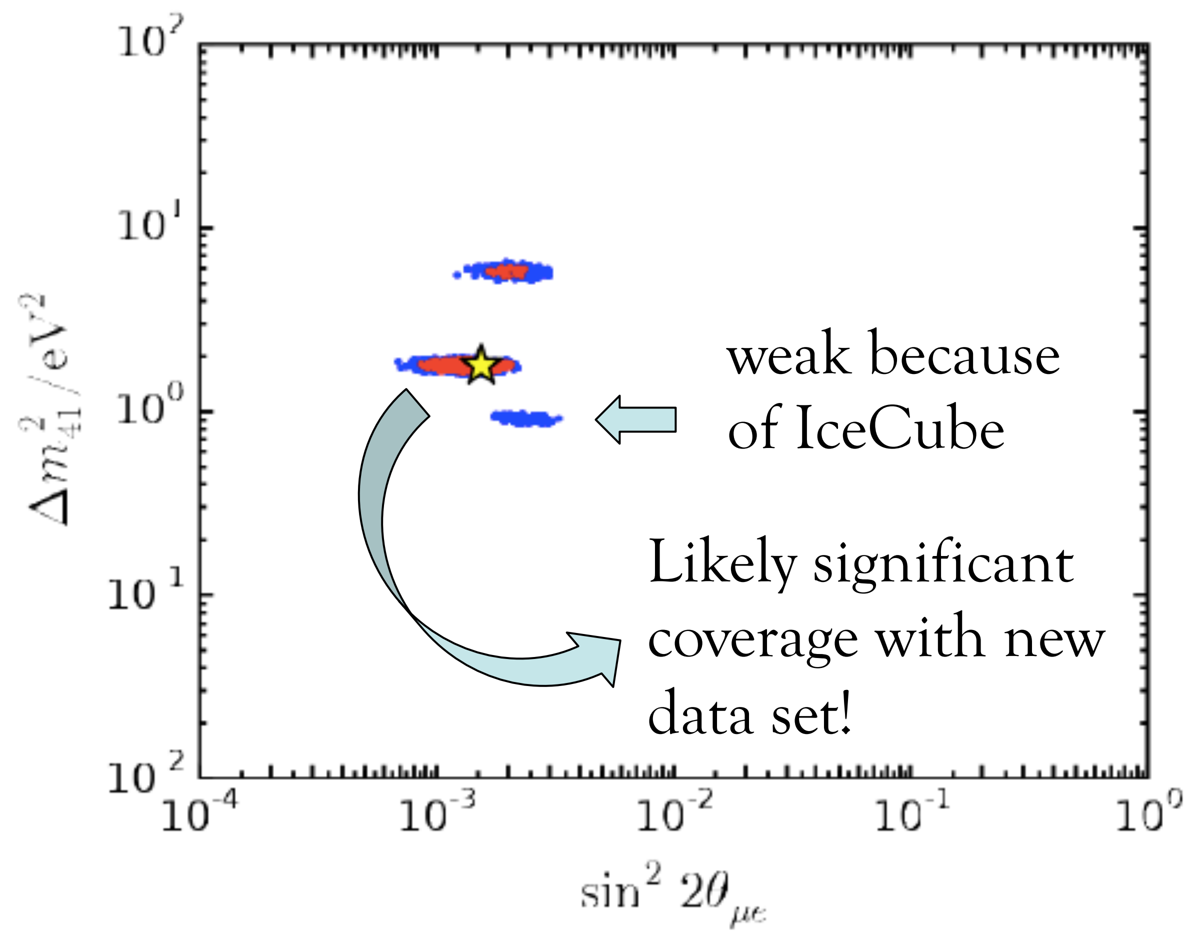






Coming Soon!

More than 6 times the IceCube data – ready end of summer?



3+1 is a highly challenged model!

But the experimental results have staying-power.

MiniBooNE is headed to 5σ

The number of anomalies (with wiggles) grows…

NEOS/DANSS

Potentially the NuMI flux has an anomaly

Appearing across orders of magnitude in energy

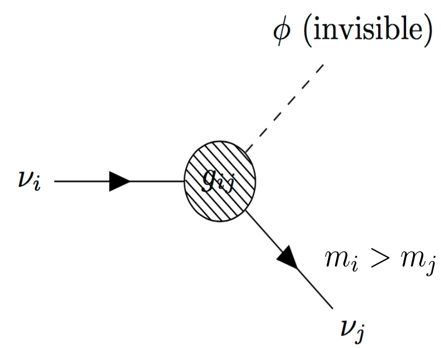
The basics are pretty uniform:

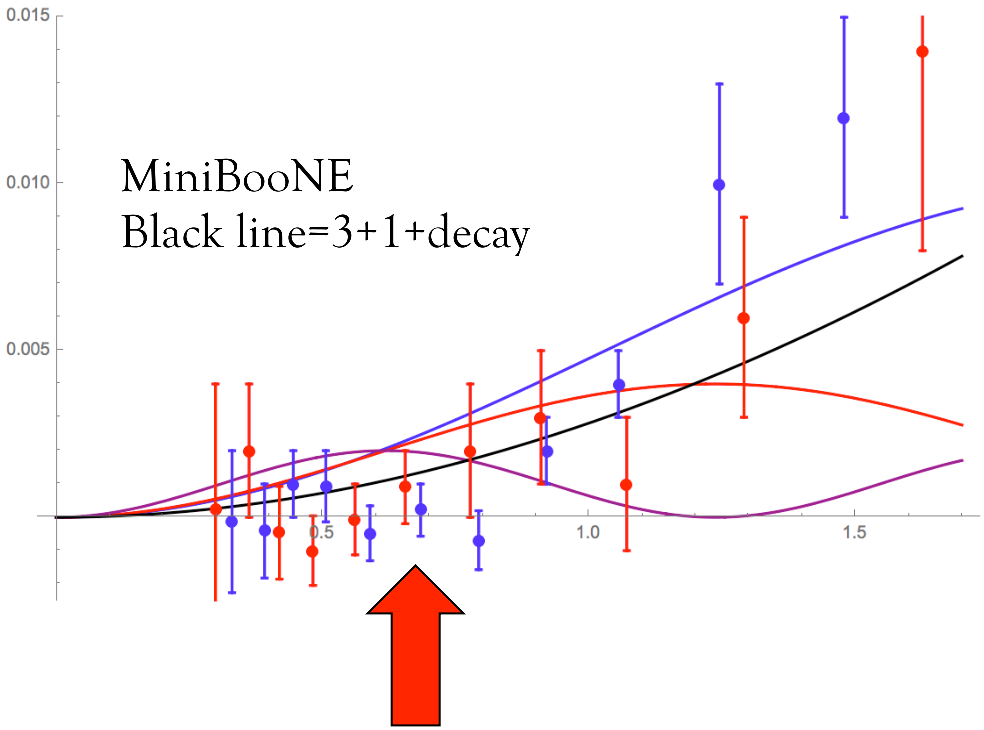
Observed oscillations are in 1 to 10 eV^2

We need better models!
We need to think beyond ν_s

I have spent a lot of time on 3+2 and 3+3 models.
Simple ones (one CP parameter) give little improvement.
Adding additional parameters may be needed…

My favorite model at the moment: 3+1+decay





And it greatly loosens the ν_μ disappearance limits

. **Exploring a nonminimal sterile neutrino model involving decay at IceCube**
Zander Moss, Marjon H. Moulai (MIT, Cambridge, Dept. Phys.), Carlos A. Argüelles, Janet M. Conrad (MIT, Cambridge, Dept. Phys. & MIT, Cambridge, Dept. Phys. & MIT, Cambridge, Dept. Phys.). Nov 15, 2017. 12 pp.
Published in **Phys.Rev. D97 (2018) no.5, 055017**

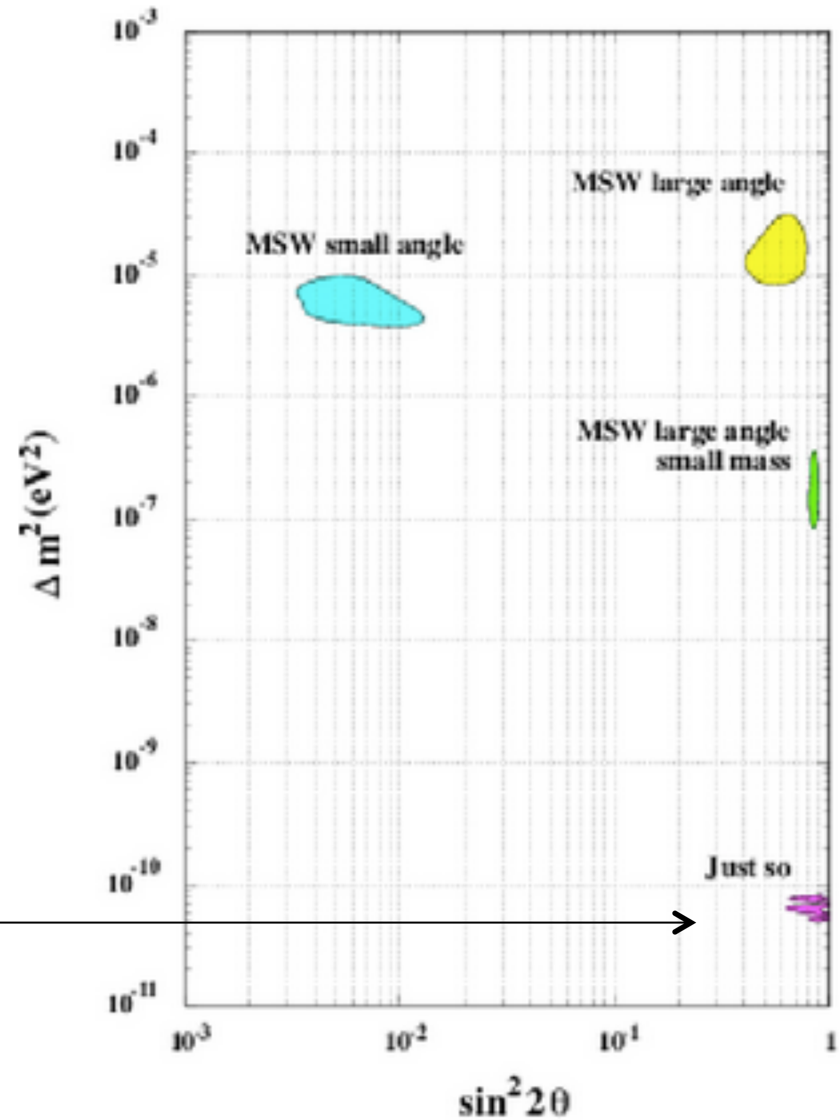
Is it crazy to have a more complex model than simple oscillations?

No.

If we had stuck to the oscillation-only view for 3 neutrinos,

We would be in a *giant mess* right now.

Because we would be thinking solar neutrinos had to oscillate with $\Delta m^2 = 10^{-10}$ eV^2



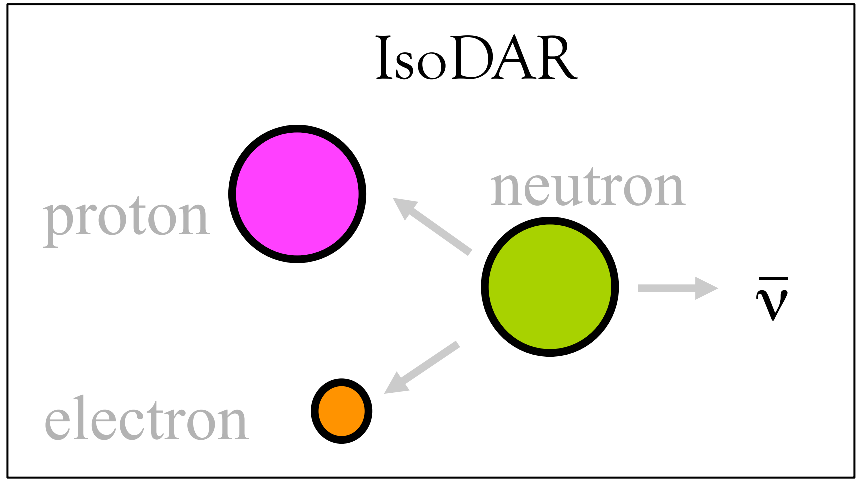
We also need better experiments

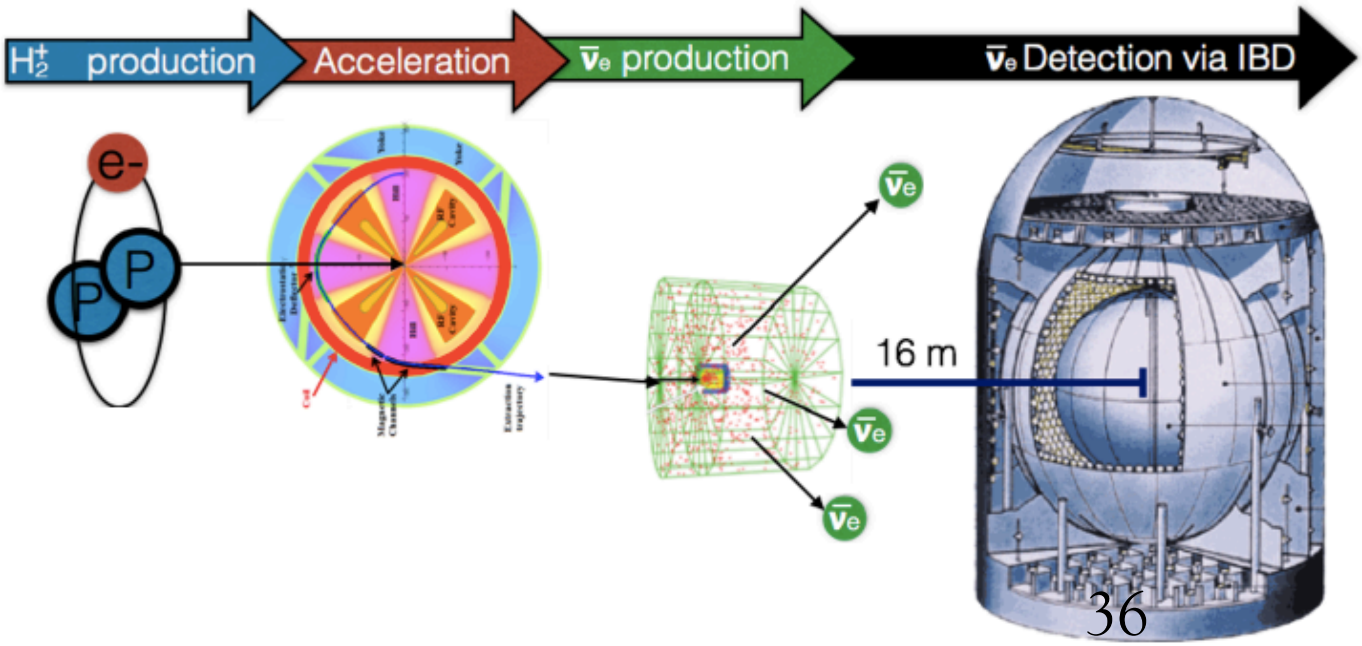
All signals are at the margins of sensitivity.
This is almost always true of a discovery.
Witness: the Higgs.

The Higgs signature was its mass peak.
Higher mass → Higher energy… Tactic: Bigger Collider

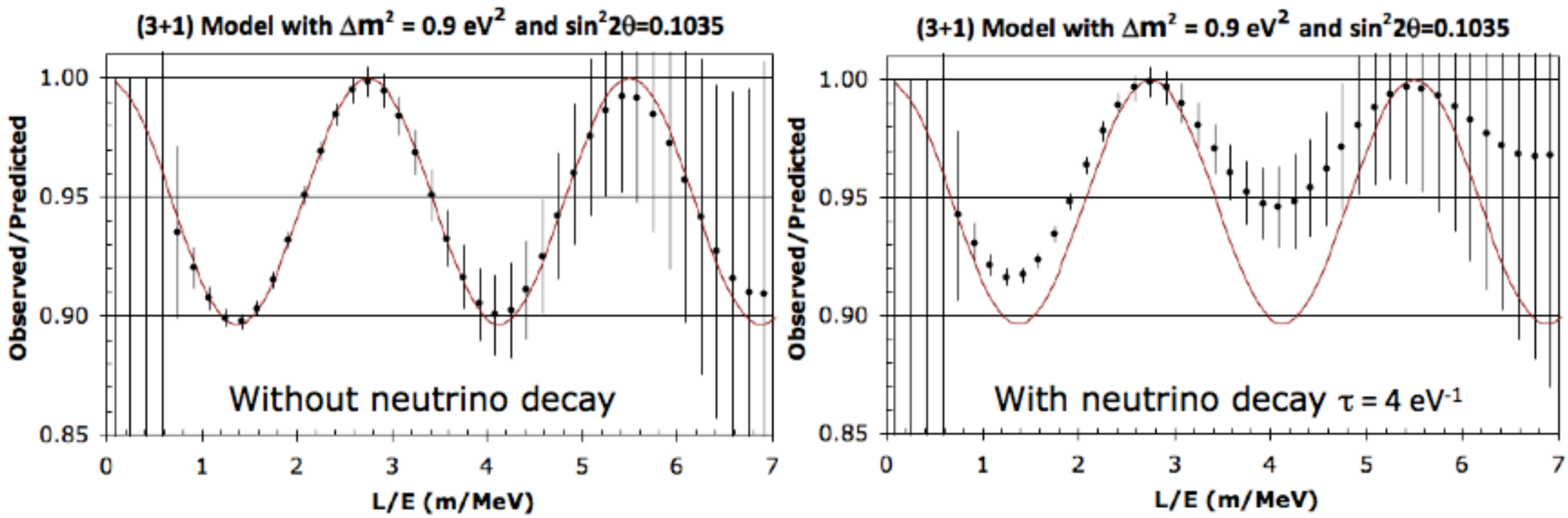
The signature of this anomaly, whatever it is,
is the oscillation wiggle of different flavors.

Tactic: Experiments that trace the oscillation wiggle


IsoDAR
proton
neutron
$\bar{\nu}$
electron


H_2^+ production
Acceleration
$\bar{\nu}_e$ production
$\bar{\nu}_e$ Detection via IBD
e-
P
P
$\bar{\nu}_e$
$\bar{\nu}_e$
$\bar{\nu}_e$
16 m
36

Comparison: 3+1 without and with decay



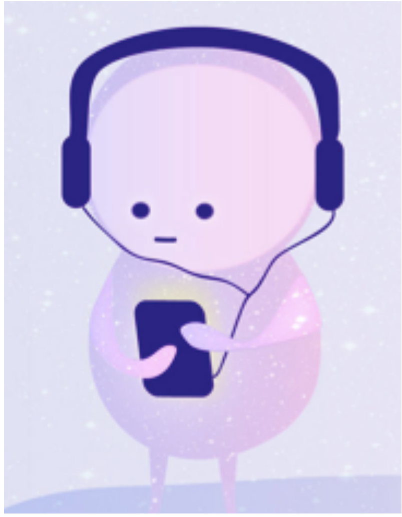
This shows the power of experiments that can trace the oscillation wave to high precision!

IsoDAR really needs your help!

We are working toward a major proposal to NSF.

Please support our primary goal!
Please help us expand our physics program, too.

Concluding thoughts



My title was:
BSM Searches with Neutrinos from MeV to PeV Energies.
And I really meant to cover more subjects!

So… Please check out IceCube's really great new LV search

Neutrino Interferometry for High-Precision Tests of Lorentz Symmetry with IceCube
IceCube Collaboration (M.G. Aartsen (Adelaide U.) *et al.*). Sep 11, 2017. 12 pp.
e-Print: **arXiv:1709.03434 [hep-ex]** | **PDF**

And also a great paper on neutrino-dark matter scattering by my postdoc Carlos Argüelles:

Imaging Galactic Dark Matter with High-Energy Cosmic Neutrinos
Carlos A. Argüelles (MIT), Ali Kheirandish (Wisconsin U., Madison), Aaron C. Vincent (Imperial Coll., London).
Published in **Phys.Rev.Lett. 119 (2017) no.20, 201801**

Ask me about other BSM work and ideas at coffee!

… Thank You!

Back up slides

The latest 3ν parameters

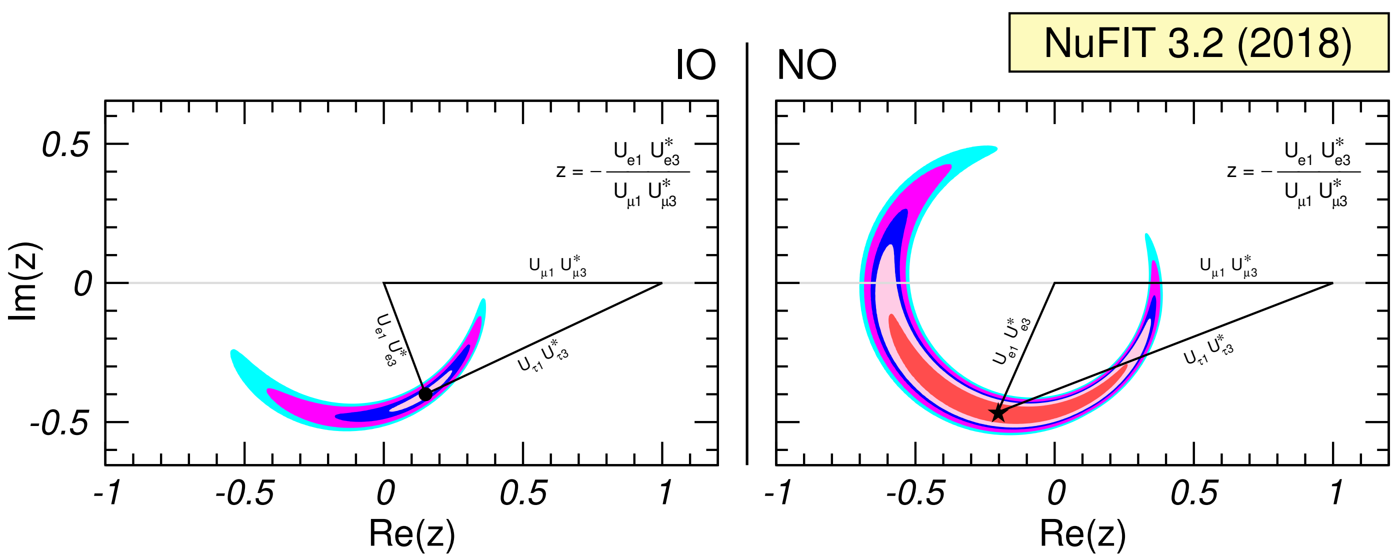
NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{\mathrm{CP}}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix}+2.399 \to +2.593 \\ -2.536 \to -2.395\end{bmatrix}$

We will hit 3σ soon on both δ_{CP} and hierarchy.
CP violation is likely to be large,
The hierarchy is likely to be normal.

Where does the 3-neutrino program go from here?

We have unprecedented precision, what will we do with it?



Doesn't cosmology make the anomalies uninteresting?

I could say all this:

First Constraints on the Complete Neutrino Mixing Matrix with a Sterile Neutrino
G.H. Collin, C.A. Argüelles, J.M. Conrad (MIT), M.H. Shaevitz (Columbia U.). Jun 30, 2016. 6 pp.
Published in Phys.Rev.Lett. 117 (2016) no.22, 221801

These fits also do not include data from cosmology because the CMB and large scale structure (LSS) constraints on the presence of a fourth neutrino are model dependent. The dependencies include assuming a "standard" thermal history for the Universe [39]. Sterile neutrino thermalization can be suppressed a number of plausible ways [40–48]. In fact, thermalization may not occur when one considers models with full four-neutrino mixing [49]. Introducing the assumption that sterile neutrinos have very weak pseudoscalar interactions that are unobservable in the short baseline data not only resolves the apparent disagreement between the 3+1 models and CMB, it also predicts a Hubble constant in agreement with local measurements [50]. Changes in the assumption of the influence of dark energy on the expansion history and growth structure also influences the comological results [39]. Based on this, rather than include cosmology in the fit, what is most interesting is to fit the cosmological data separately from the oscillation experiments, and then consider the meaning of discrepancies.

Instead, I will say: by definition, anomalies don't fit our prejudices.
Cosmology makes the anomalies more interesting.

Cheat sheet: Connecting all matrix elements and angles...

$$
\begin{aligned}
P_{\nu_e \to \nu_e} &= 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) \ , \\
P_{\nu_\mu \to \nu_\mu} &= 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) \ , \\
P_{\nu_\mu \to \nu_e} &= 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E).
\end{aligned}
$$

$$
\begin{aligned}
P_{\nu_e \to \nu_e} &= 1 - \sin^2 2\theta_{ee} \sin^2(1.27 \Delta m^2_{41} L/E), \\
P_{\nu_\mu \to \nu_\mu} &= 1 - \sin^2 2\theta_{\mu\mu} \sin^2(1.27 \Delta m^2_{42} L/E), \\
P_{\nu_\mu \to \nu_e} &= \sin^2 2\theta_{e\mu} \sin^2(1.27 \Delta m^2_{41} L/E),
\end{aligned}
$$

$$
\begin{aligned}
\sin^2 2\theta_{ee} &= 4(1 - |U_{e4}|^2)|U_{e4}|^2, \\
\sin^2 2\theta_{\mu\mu} &= 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2, \\
\sin^2 2\theta_{e\mu} &= 4|U_{e4}|^2|U_{\mu 4}|^2.
\end{aligned}
$$

$$\sin^2 2\theta_{ee} = \sin^2 2\theta_{14}$$

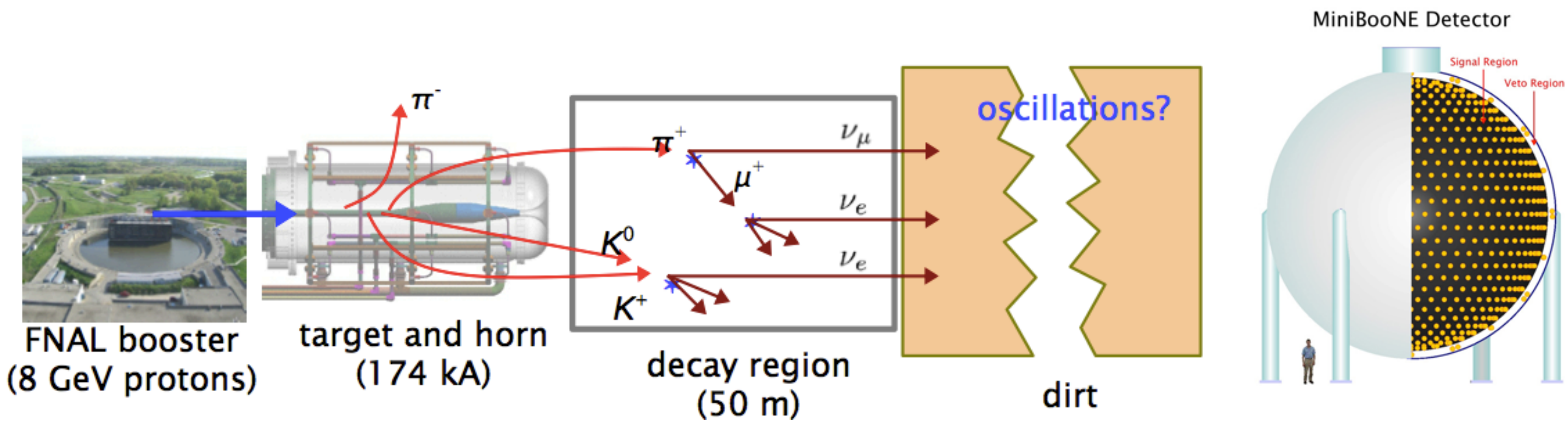
$$\sin^2 2\theta_{\mu\mu} = 4\cos^2\theta_{14}\sin^2\theta_{24}(1 - \cos^2\theta_{14}\sin^2\theta_{24})$$

$$\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{14}\sin^2\theta_{24}$$

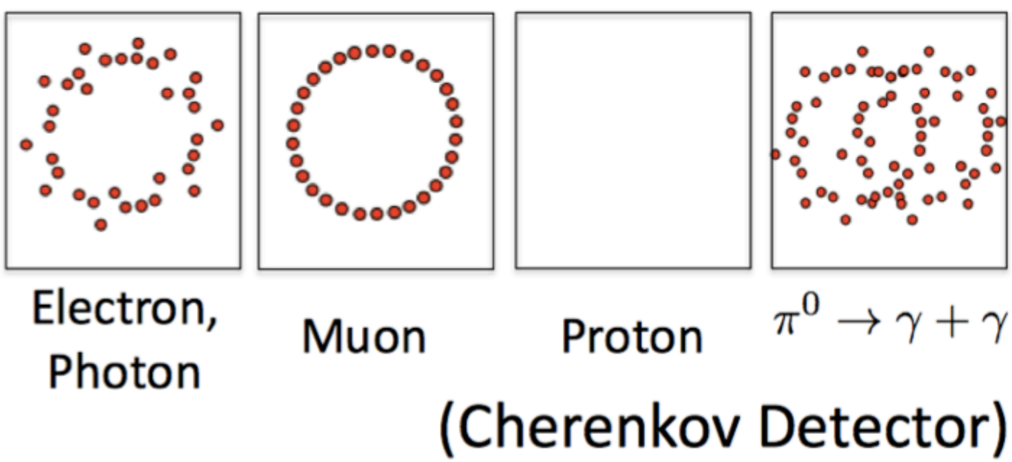
$$\sin^2 2\theta_{e\tau} = \sin^2 2\theta_{14}\cos^2 2\theta_{24}\sin^2\theta_{34}$$

$$\sin^2 2\theta_{\mu\tau} = \sin^2 2\theta_{24}\cos^4\theta_{14}\sin^2\theta_{34}$$

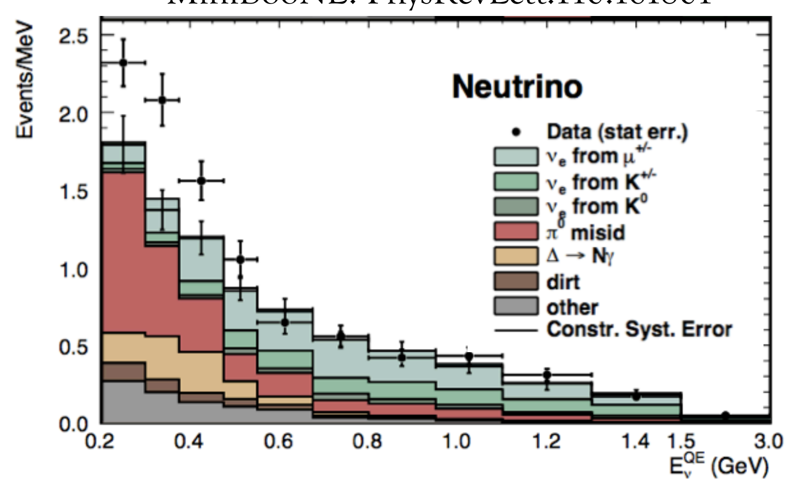
MiniBooNE Experiment



~ 500 m $(L/E \sim 1$ m/MeV$)$



MiniBooNE: PhysRevLett.110.161801



An excess of electron-like events in a muon neutrino beam

With that said,
Attributing 100% of the MiniBooNE signal to misidentified π^0's is probably wrong.

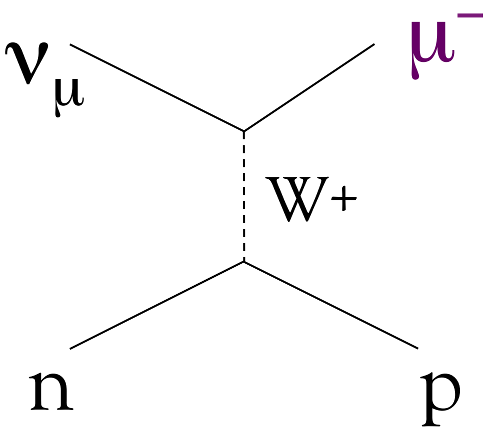
MiniBooNE constrains the mis-id rate very well with identified π^0's.

Level of increase required to explain excess in ν running is very large

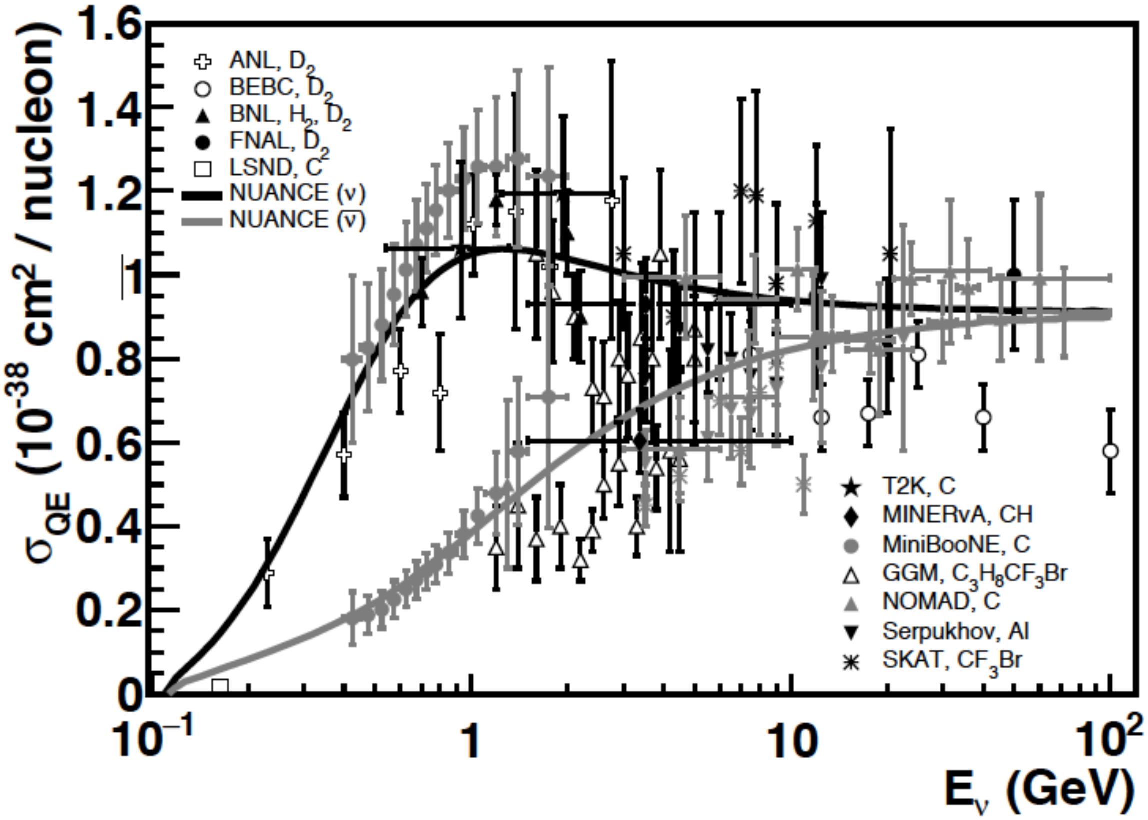
Process	$\chi^2(cos\theta)/9$ DF	$\chi^2(Q^2)/6$ DF	Factor Increase
NC π^0	13.46	2.18	2.0
$\Delta \to N\gamma$	16.85	4.46	2.7
$\nu_e C \to e^- X$	14.58	8.72	2.4
$\bar{\nu}_e C \to e^+ X$	10.11	2.44	65.4

Unexplained Excess of Electron-Like Events From a 1-GeV Neutrino Beam
MiniBooNE Collaboration (A.A. Aguilar-Arevalo (Columbia U.) *et al.*). Dec 2008. 12 pp.
Published in **Phys.Rev.Lett. 102 (2009) 101802**

& the predicted rate in $\bar{\nu}$ mode is not correct.

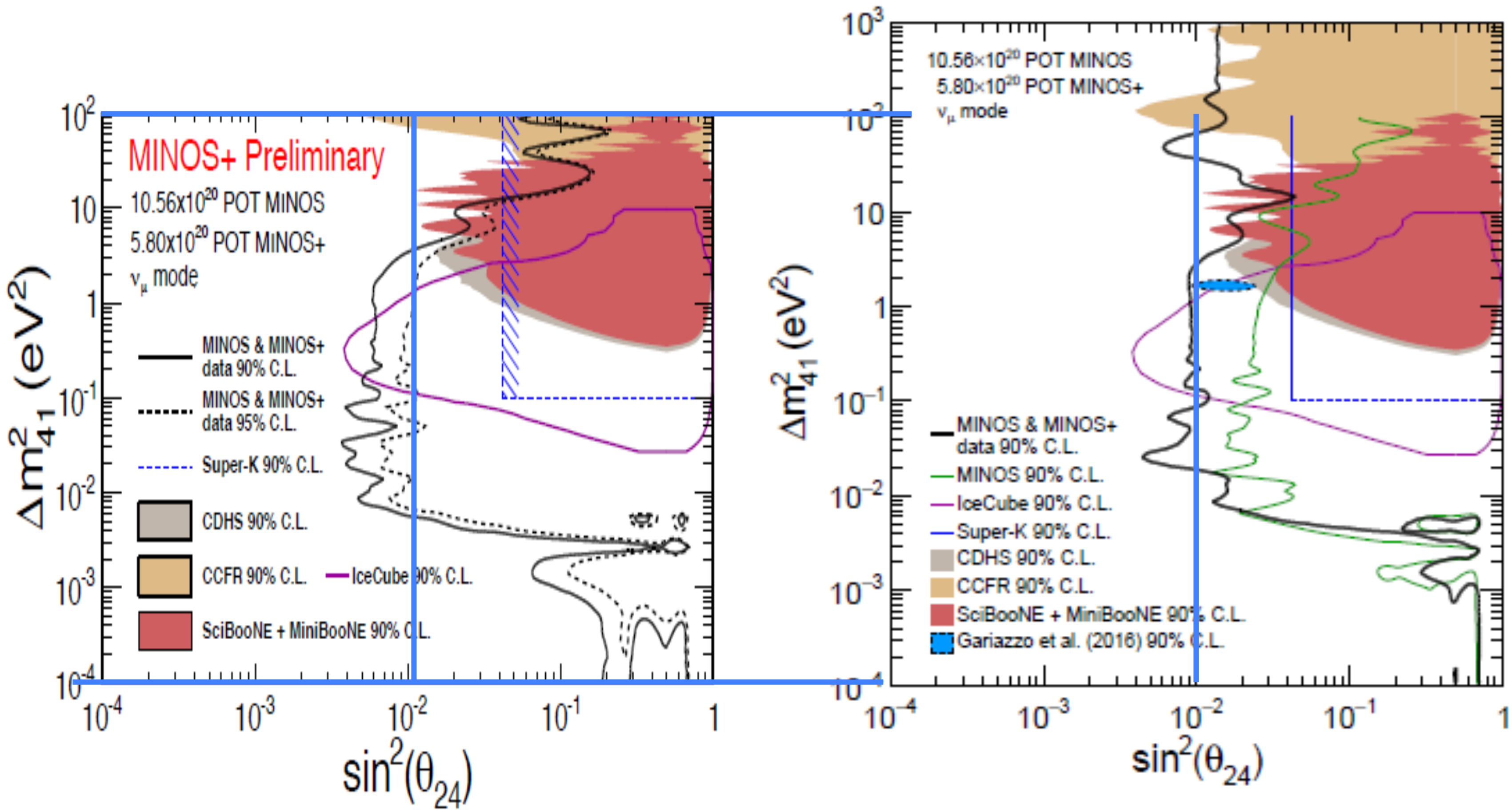


νμ
μ⁻
W+
n
p



ANL, D2
BEBC, D2
BNL, H2, D2
FNAL, D2
LSND, C
NUANCE (ν)
NUANCE (ν̄)
T2K, C
MINERvA, CH
MiniBooNE, C
GGM, C3H8CF3Br
NOMAD, C
Serpukhov, Al
SKAT, CF3Br
σQE (10⁻³⁸ cm² / nucleon)
Eν (GeV)

Let's compare the 2 plots side by side,
with blue lines added to guide the eye

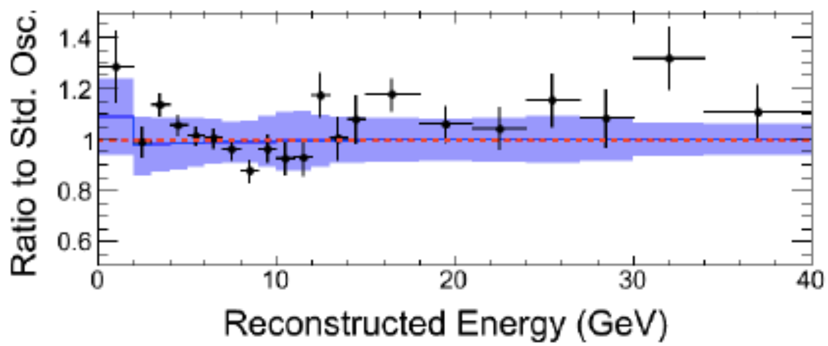


The newest MINOS/+ result:
has incorrect high Δm^2 behavior

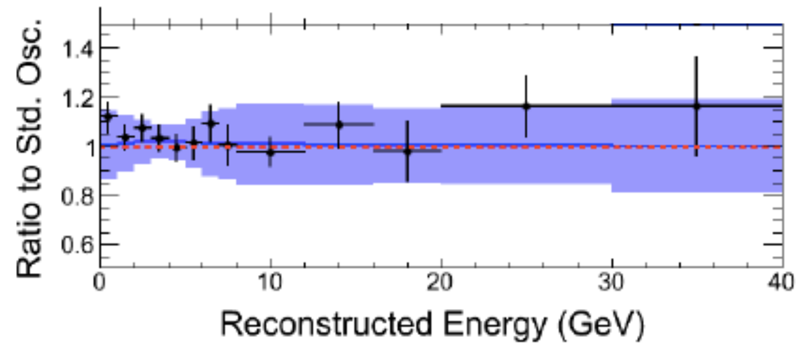
What is going on?

The MINERvA Flux leads to a large under-prediction for MINOS/+

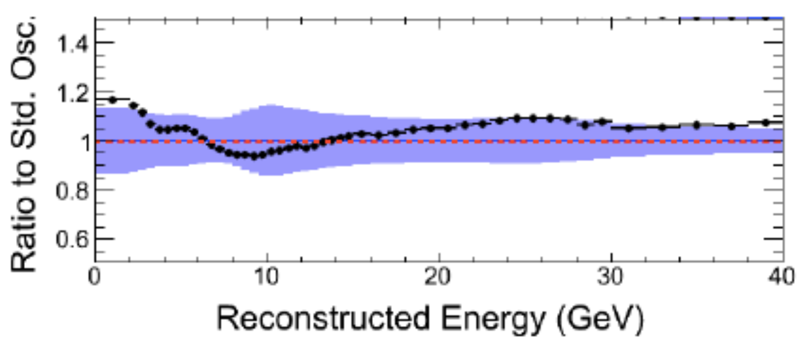
The MINOS+ Far detector CC:



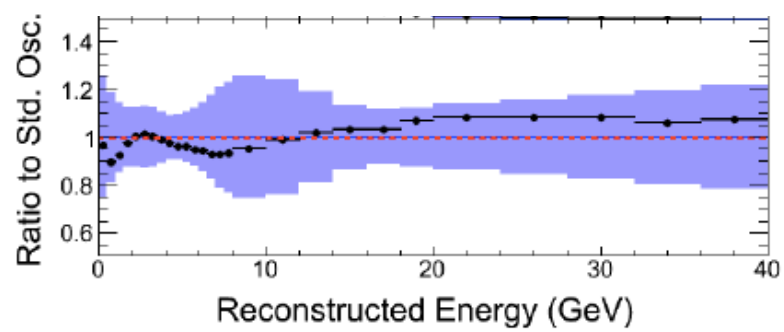
The MINOS+ far NC



The MINOS+ near detector CC:



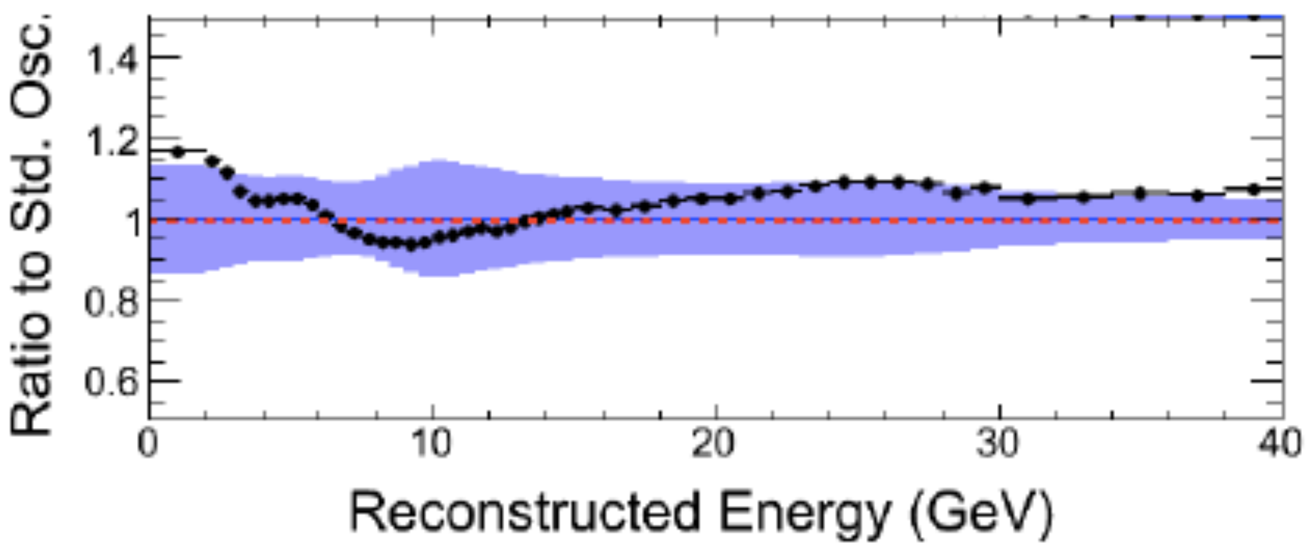
The MINOS+ near NC



This systematic error makes an observed deficit highly unlikely, making the limit artificially good.

These are the UNCONSTRAINED ERRORS.
The analysis uses a correlated error matrix.
When the errors are constrained, they are apparently much reduced.

The MINOS+ near detector CC:



Bill Louis' arxiv article on the MINOS/+ problem

Problems With the MINOS/MINOS+ Sterile Neutrino Muon-Neutrino Disappearance Result
William C. Louis. Mar 30, 2018. 2 pp.
e-Print: arXiv:1803.11488 [hep-ex] | PDF

1) The ratio of NC events in near/far: $R = 1.062 \pm 0.019$,
(stat only errors) – this is a 3.3σ effect

2) The $\sin^2 2\theta$ limit can be converted to an error on
the oscillation probability. At 1 eV^2 MINOS/+
is claiming an error of ~1%. Even with the ratio
that seems implausible.

From:

Neutrino Flux Predictions for the Low Energy NuMI Beam – Supplemental

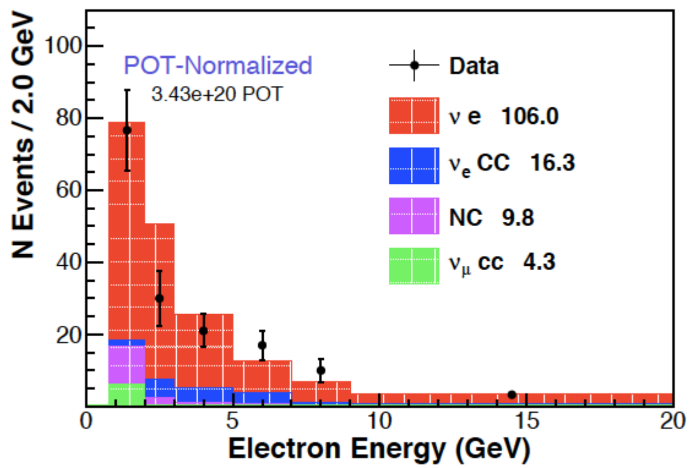
The MINERvA Collaboration

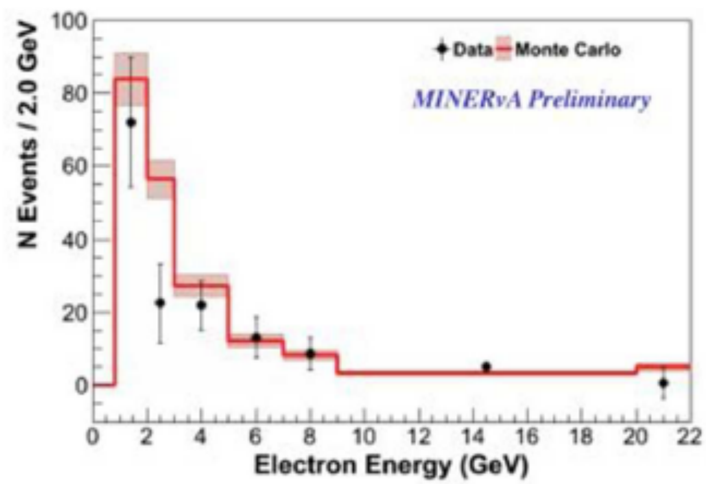
(Dated: May 13, 2016)

The fluxes are averaged over the MINERvA fiducial volume. The have been corrected using a suite of hadron production data as described in the accompanying paper. They have also been constrained using the $\nu e \to \nu e$ scattering measurement described briefly in the paper and also in `arXiv:1512.07699`.

This flux assumed no oscillation!

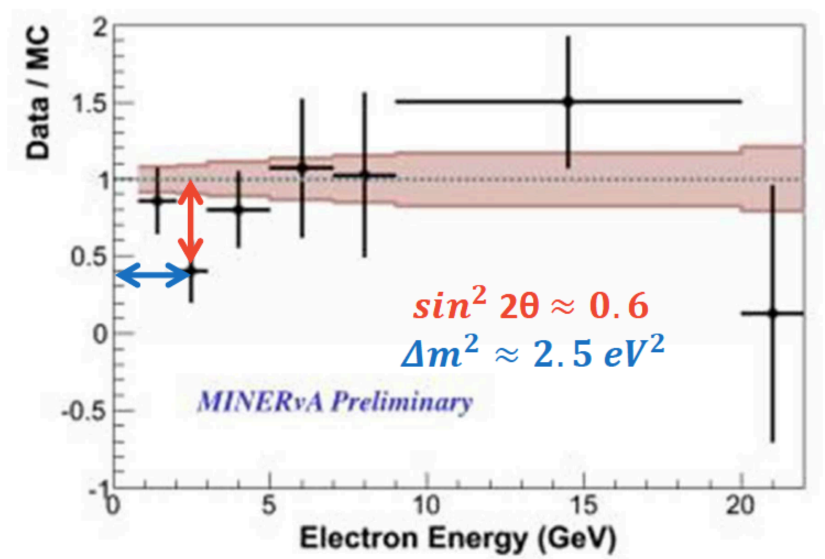
The new MINERvA flux is not *ab initio*.
It uses ν–e data from the NuMI line as a constraint





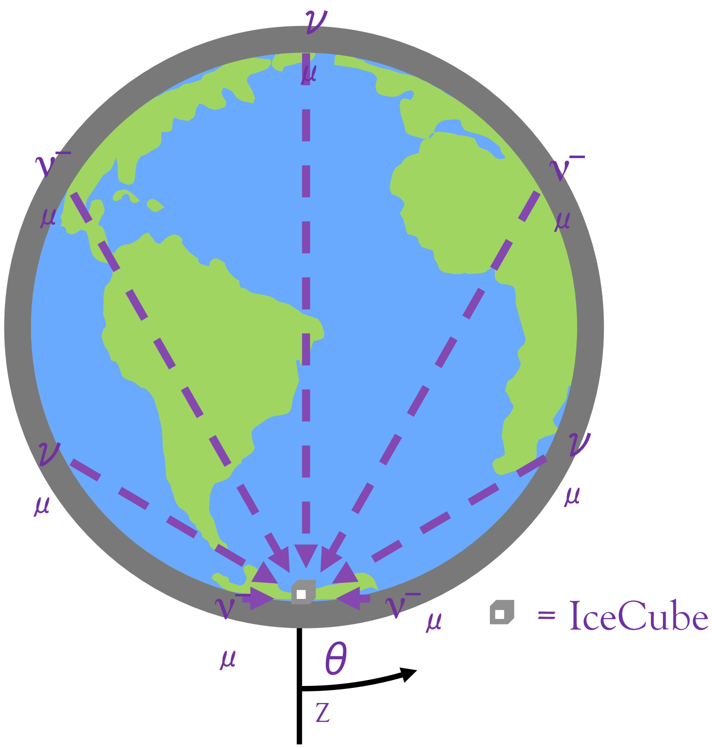
When this data is used to constrain the flux, the flux prediction is significantly lowered.

Also, the cross section has a "shape"

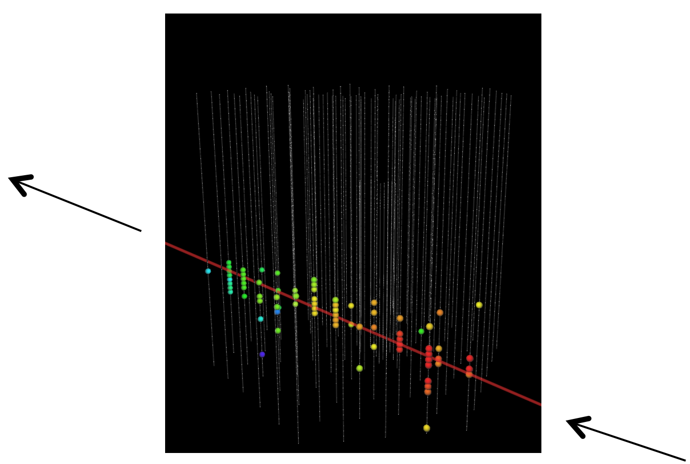


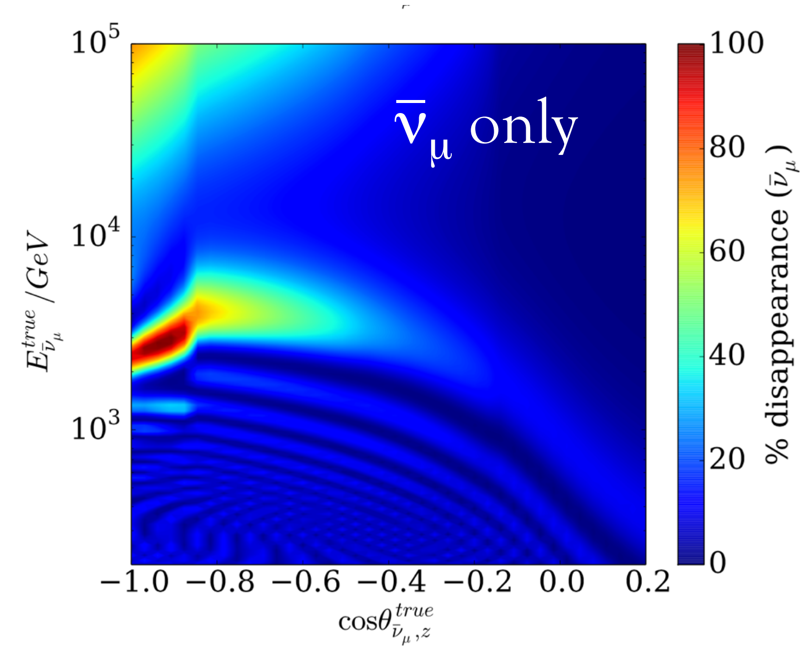
arxiv: 1512.07699

J.Park – FNAL seminar, Dec 20, 2013

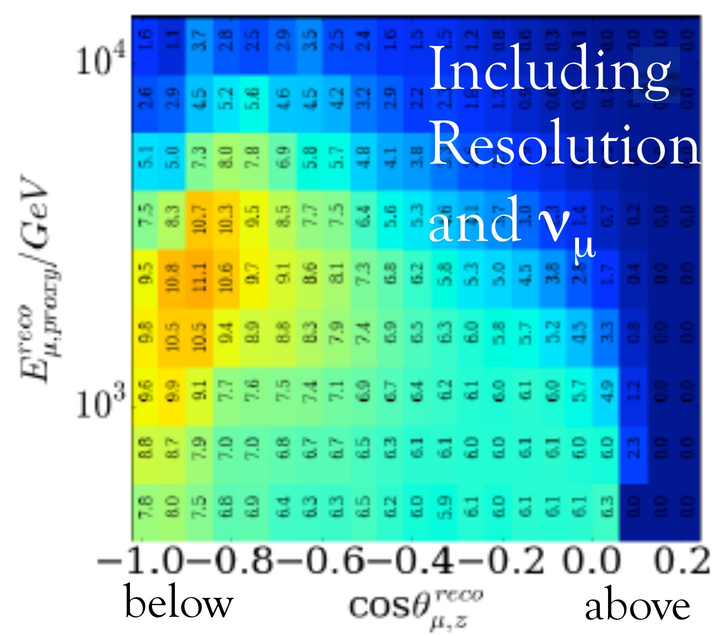


ν_μ
$\bar{\nu}_\mu$
= IceCube
θ
z





$\bar{\nu}_\mu$ only
$E^{true}_{\bar{\nu}_\mu}/GeV$
$\cos\theta^{true}_{\bar{\nu}_\mu,z}$
% disappearance ($\bar{\nu}_\mu$)

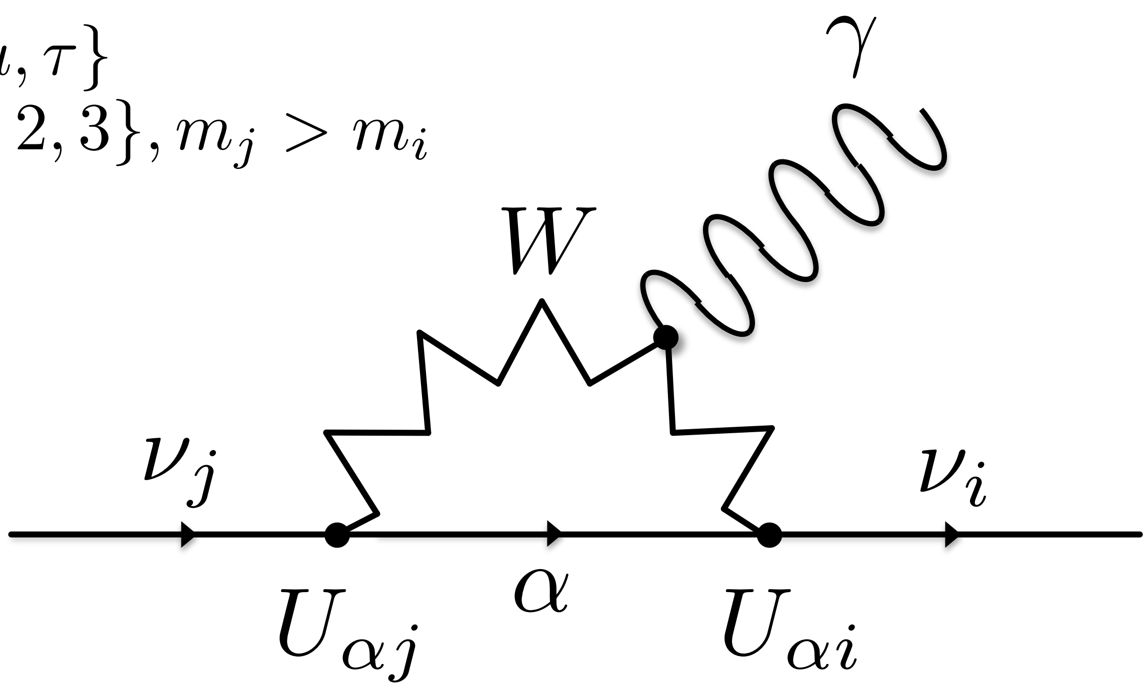


Including Resolution and ν_μ
$E^{reco}_{\mu,proxy}/GeV$
below
$\cos\theta^{reco}_{\mu,z}$
above

Standard Model Neutrino Decay

slides from talk by Marjon Moulai

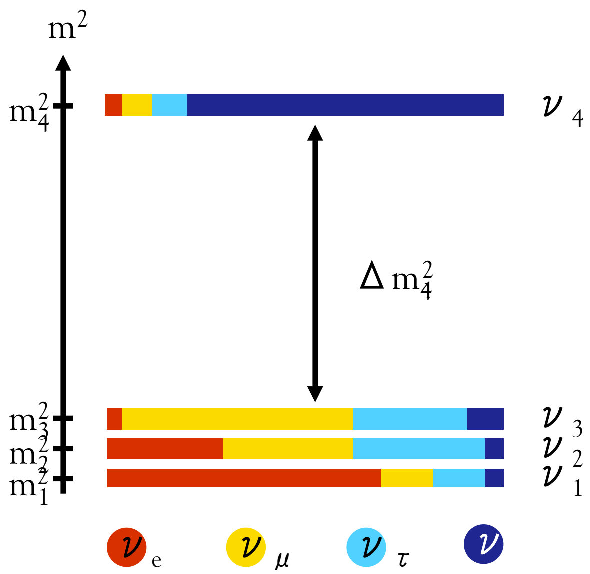
$\alpha \in \{e, \mu, \tau\}$
$i, j \in \{1, 2, 3\}, m_j > m_i$



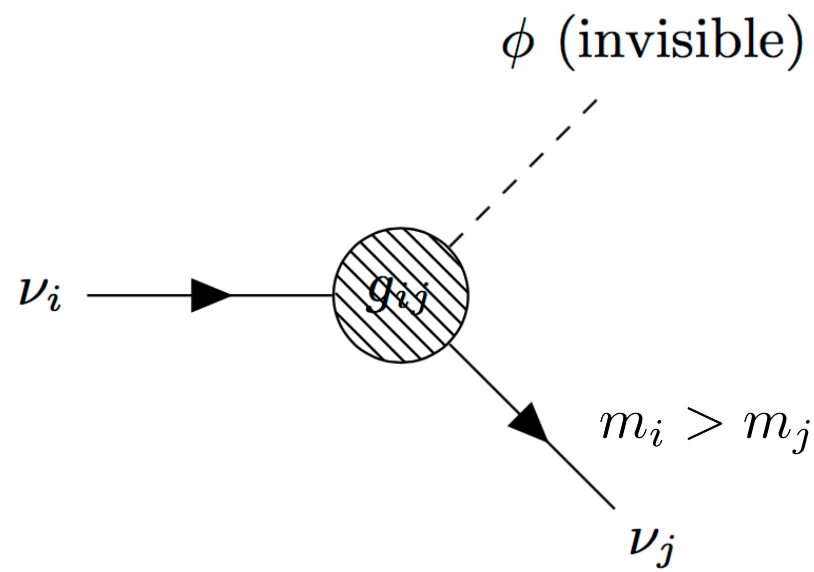
$$\nu_i \to \nu_j + \gamma : \qquad \tau \simeq 10^{36}(m_i/eV)^{-5} yr$$
$$\nu_i \to \nu_j + \gamma + \gamma : \qquad \tau \simeq 10^{57}(m_i/eV)^{-9} yr$$
$$\nu_i \to \nu_j + \nu_l + \bar{\nu}_k : \qquad \tau \simeq 10^{55}(m_i/eV)^{-5} yr$$

3+1 with Neutrino Decay

slides from talk by Marjon Moulai



(not to scale...)

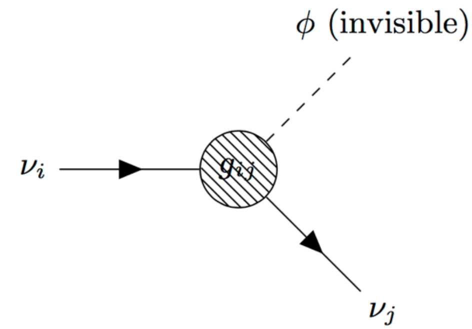


- Assume 3+1 sterile neutrino, normal hierarchy:
- Interested in decays that could mask steriles in IceCube.

  ⇒ For now, we only consider the channel $\nu_4 \longrightarrow \nu_3\ \phi$, with lifetime τ_4.

slides from talk by Marjon Moulai

Neutrino Decay Model



$$\frac{\partial \rho}{\partial x} = -i[H_0, \rho] - \frac{1}{2}\{\Gamma, \rho\} + \mathcal{R}$$

Neutrino ensemble in density matrix formalism

Hamiltonian for standard oscillations in matter

Decay operator

Neutrino regeneration (very subdominant)

$$\Gamma(E) = \sum_i \Gamma_i(E)\Pi_i, \quad 1/\Gamma = \tau$$

Neutrino lifetime

Projector to i[th] mass eigenstate

$$\mathcal{R}(E) = \sum_{i,j} \int_E^{E*x_{ij}^2} d\tilde{E}\ \mathrm{Tr}\left[\rho(\tilde{E})\Pi_i(\tilde{E})\right] \left(\frac{d\Gamma_{ij}}{dE}\right)^{\mathrm{CPP}} \Pi_j(E)$$

$$\mathcal{R}(E) += \sum_{i,j} \int_E^{E*x_{ij}^2} d\tilde{E}\ \mathrm{Tr}\left[\bar{\rho}(\tilde{E})\bar{\Pi}_i(\tilde{E})\right] \left(\frac{d\Gamma_{ij}}{dE}\right)^{\mathrm{CVP}} \Pi_j(E)$$

Regeneration terms

Decay daughter energy distribution

$x_{ij} \equiv m_i/m_j$

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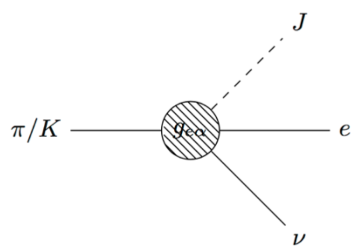
Flavor-dependent bounds

Bound from meson decays:

$$\sum_\alpha |g_{e\alpha}|^2 < 3 \times 10^{-5}$$



$$g_{\alpha\beta} = \sum_{i,j} g_{ij} U_{\alpha i} U^*_{j\beta}$$

$$g_{\alpha\beta} = g_{4j} U_{\alpha 4} U^*_{j\beta}$$

Assume only one g_{4j} is non-zero:

From SBL fits: $U_{\alpha 4} \sim \mathcal{O}(0.1)$

$U_{j\beta} \sim \mathcal{O}(0.1)$

$\Rightarrow g_{4j} < \mathcal{O}(0.1)$

From standard measurements:

$$\Gamma_{ij} = g_{ij}^2 m_i / 32\pi$$

$$\tau_{ij} > 10^4 / m_i$$

But if more than one g_{4j} is non-zero, cancellations may occur, decreasing the constraint on decay rate.

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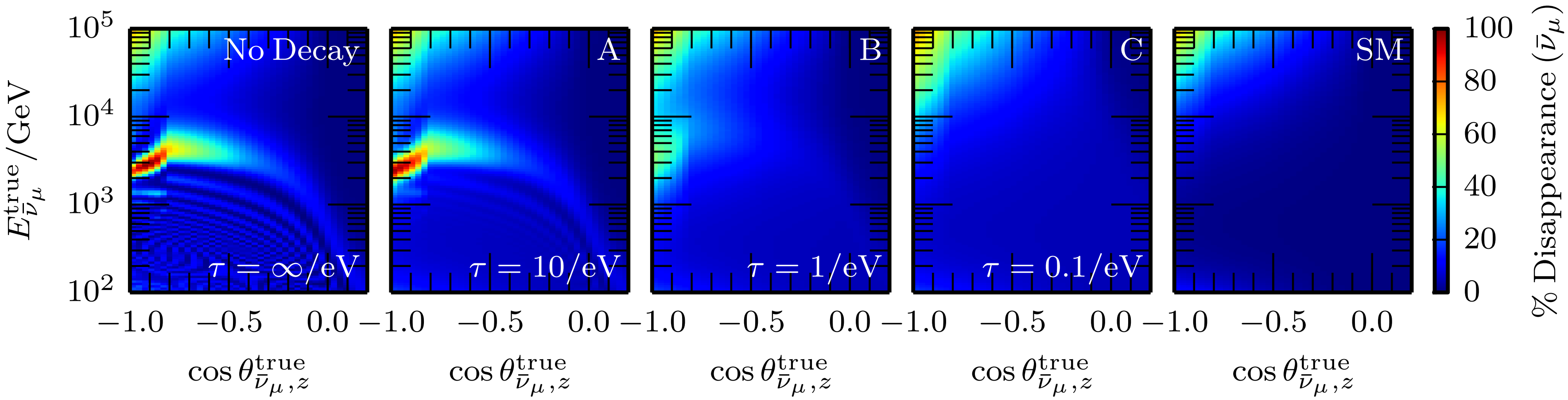
Oscillograms for: $\Delta m^2_{41} = 1\ \mathrm{eV}^2$, $\sin^2 2\theta_{24} = 0.1$, $\nu_4 \longrightarrow \nu_3 \phi$



- Decreasing lifetime ⟶
- For τ=1/eV, hc$\tau \approx 1\mu$m

$$d_{\mathrm{osc}} \sim E/\Delta m^2_{4j}$$

$$d_{\mathrm{decay}} \sim E\tau_4/m_4$$

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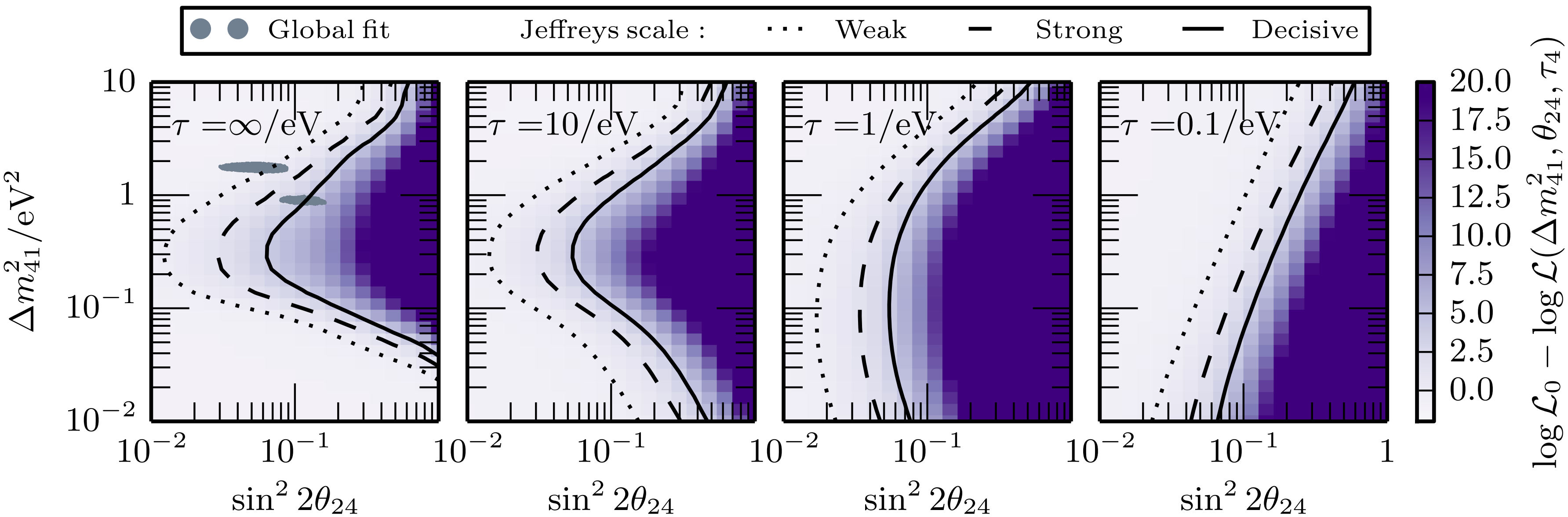
Model comparison of 3+1 and 3 ν's



- Decreasing lifetime ⟶
- For τ ∼ 0.1/eV, regions favored by global-fit under no-decay hypothesis are no longer disfavored

  ⇒ IceCube results can be significantly changed.

Null = 3 ν