Three, four or more?
The status and future of sterile neutrino fits.

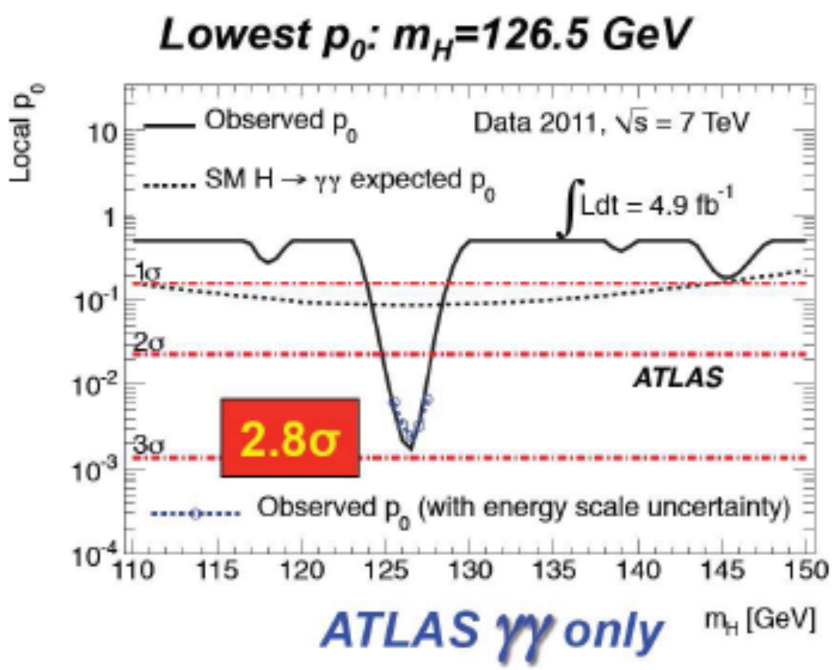
Janet Conrad
MIT
Nov. 10, 2014

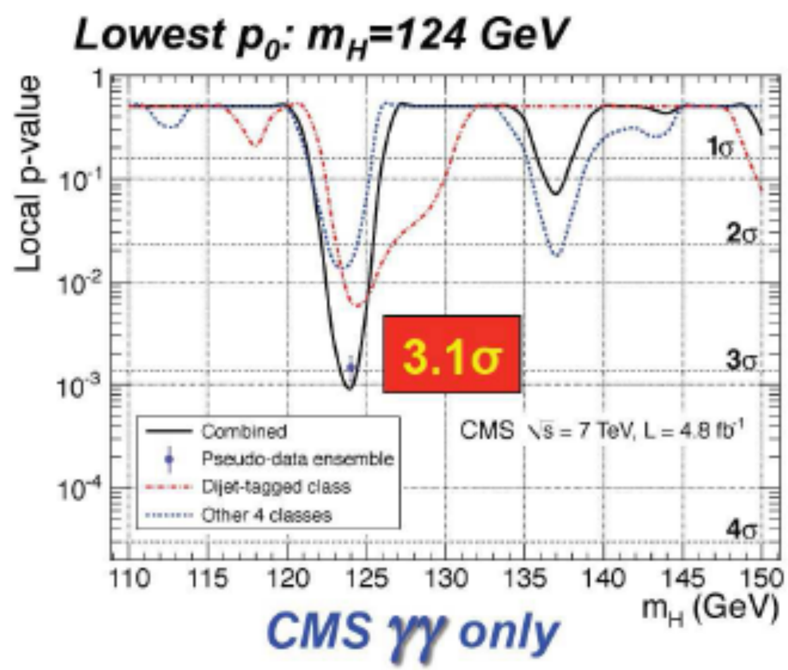
Including work by Mike Shaevitz, Gabriel Collin
(and, in the past, Christina Ignarra, Georgia Karagiorgi, Michel Sorel)

"Why are you wasting my time?
low sigma signals always go away!"

Oh really?

Fall 2011 LHC data release



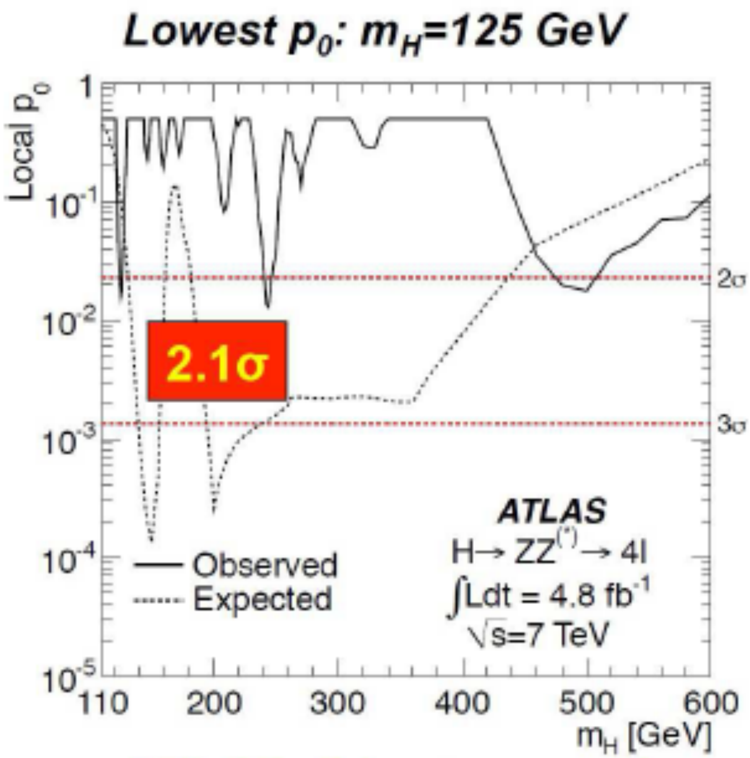


Lower significance than:

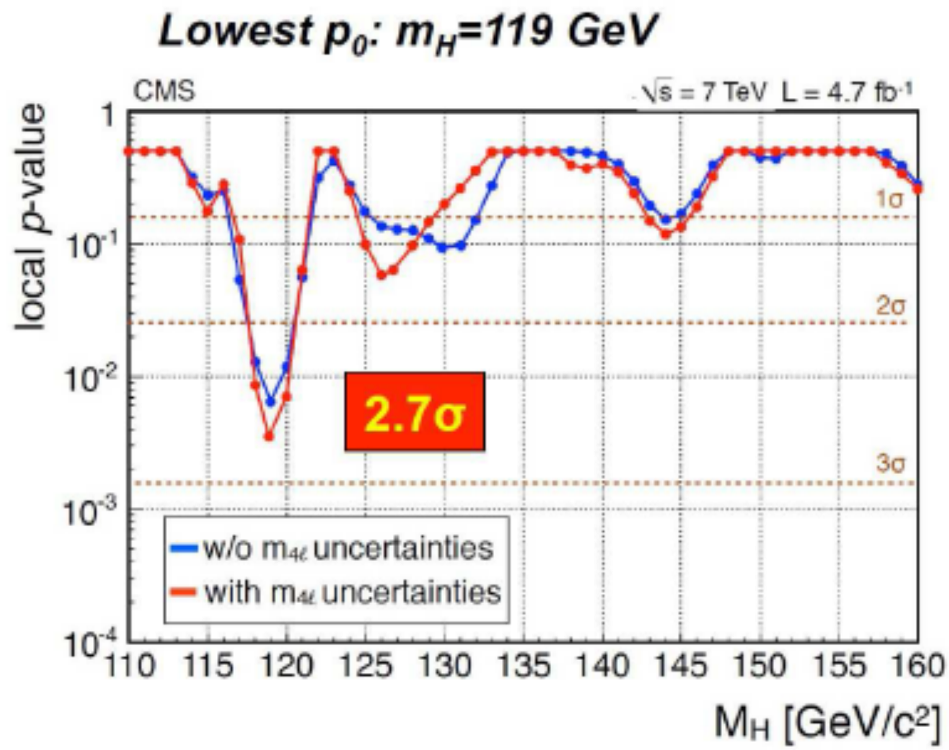
LSND: 3.8 σ

MiniBooNE nu: 3.4 σ

Fall 2011 LHC data release



ATLAS 4-leptons only



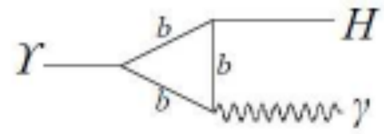
CMS 4-leptons only

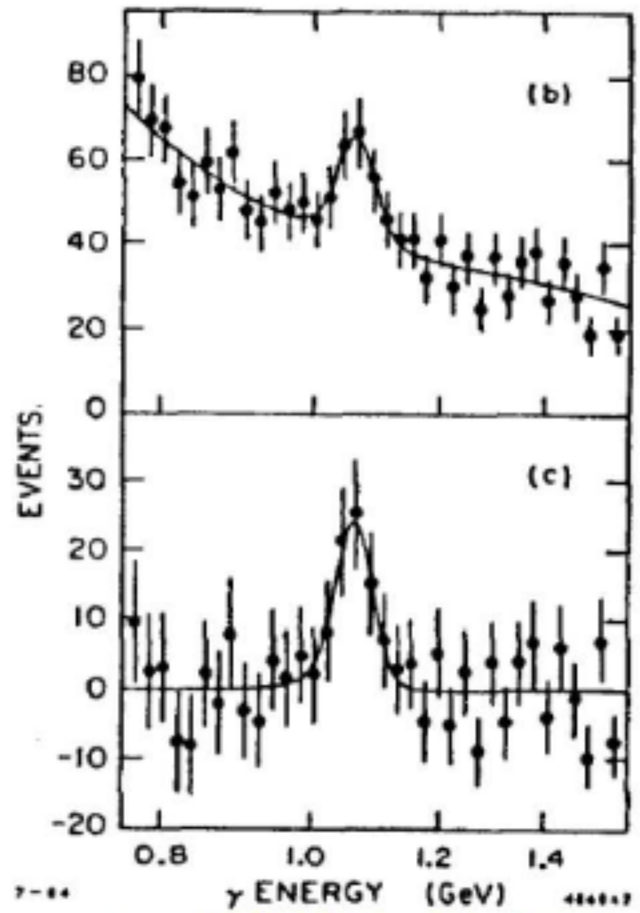
Reactor and radioactive sources are in the >2σ range.

The original Higgs signal
from the 1980's

(In fact,
signals do go away…

>5σ single-channel
Signals go away!)





Top: *inclusive γ spectrum*
Bottom: *bkg-subtracted spectrum*

“I meant that low sigma UNEXPECTED signals always go away!”

Oh really?

Which of these unexpected signals were first reported at $<3\sigma$?

- ☐ Observation of neutrinos
- ☐ Regeneration of Ks
- ☐ The LMA solar solution
- ☐ $\sin^2 2\theta_{13}=0.1$ (i.e. large)

Oh really?

Which of these unexpected signals were first reported at $<3\sigma$?

- ☑ Observation of neutrinos

  Cowen and Reines, 1953

- ☑ Regeneration of Ks

  Adair group, 1962

- ☑ The LMA solar solution

  See Bahcall fits, 2001

- ☑ $\sin^2 2\theta_{13}=0.1$ (i.e. large)

  Double Chooz Collab, 2011

"I meant that low sigma UNEXPECTED signals
which are in tension with limits
and associated with controversy
go away"

You mean like the discovery of the tau?

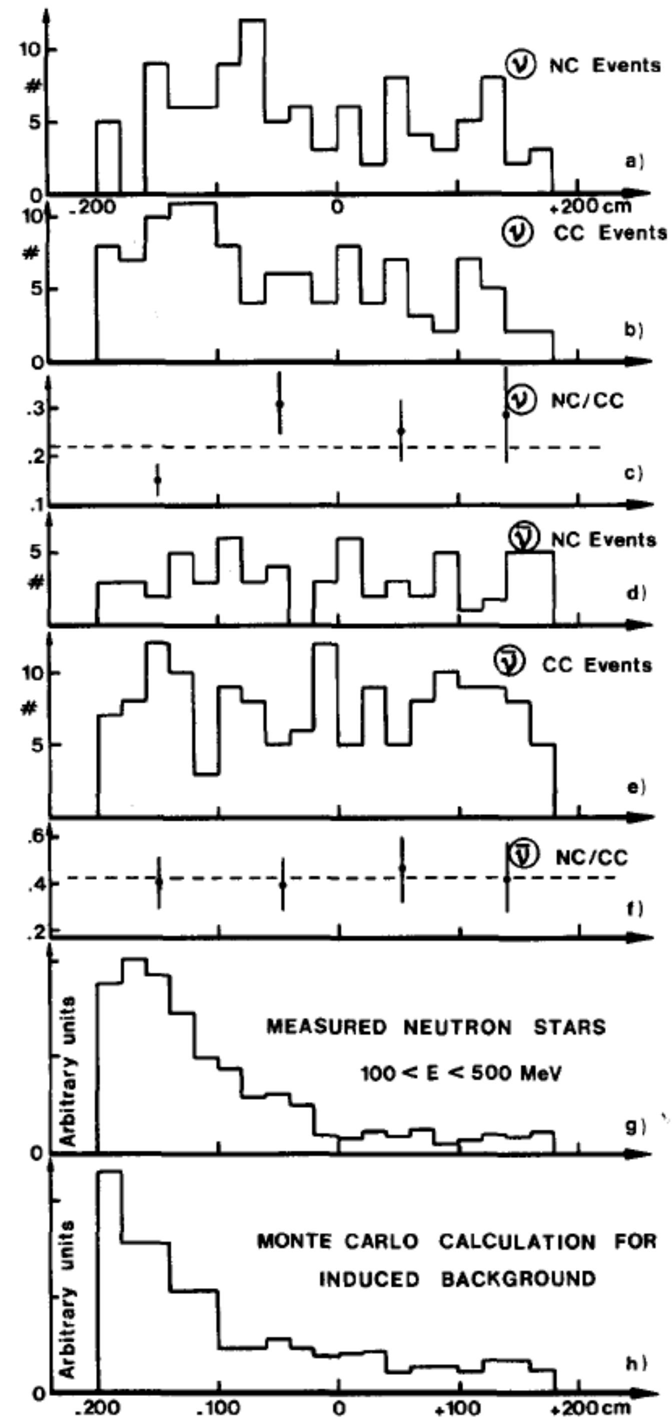
THE DISCOVERY OF THE TAU LEPTON*

MARTIN L. PERL
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

Our first publication was followed by several years of confusion and uncertainty about the validity of our data and its interpretation. It is hard to explain this confusion a decade later when we know that τ pair production is 20% of the e^+e^- annihilation cross section below the Z^0, and when τ pair events stand out so clearly at the Z^0.

There were several reasons for the uncertainties of that period. It was hard to believe that both a new quark, charm, and a new lepton, tau, would be found in the same narrow range of energies. And, while the existence of a fourth quark was required by theory, there was no such requirement for a third charged lepton. So there were claims that the $e\mu$ events were the complicated result of the decays of charm quarks. There were claims that the other predicted decay modes of tau pairs such as $e-$hadron and $\mu-$hadron events could not be found. Indeed finding such events was just at the limit of the particle identification capability of the detectors of the mid-1970's.

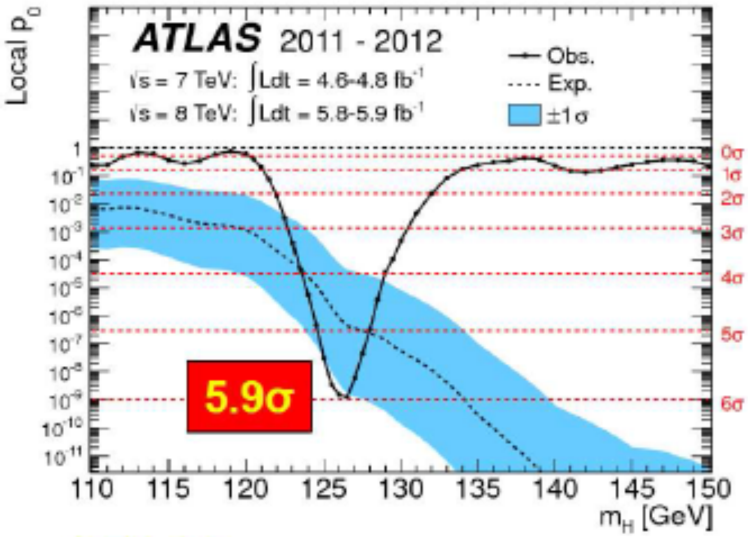
Or maybe
you mean
like the like discovery
of neutral current
interactions?

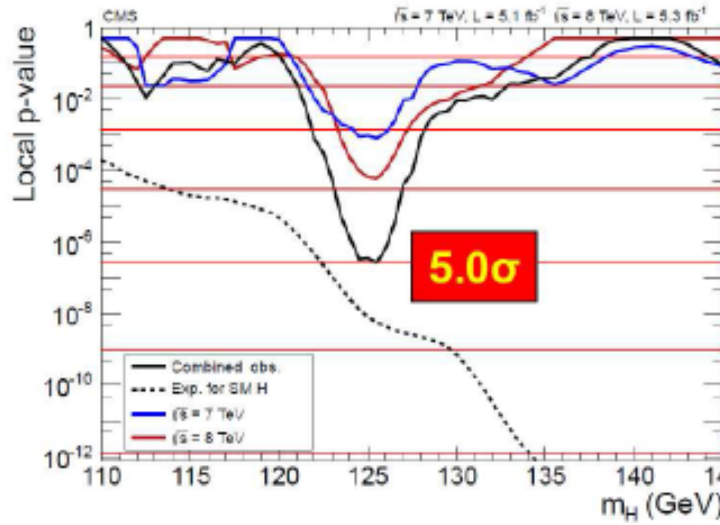


Or maybe
you mean
like discovery
of neutrino
oscillations?

"Look, If you have to fit a bunch of signals to get 5σ,
then I don't believe it!"

Oh really?





ATLAS PLB 716 (2012) 1-29, *Sept 17 (2012)*

Largest local excess:

5.9σ at m_H= 126.5 GeV

H→γγ, bb, ττ, WW(lνlν, lνqq), ZZ(4l, llνν, llqq)

CMS PLB 716 (2012) 30-61, *Sept 17 (2012)*

Largest local excess:

5.0σ at m_H= 125.5 GeV

H→γγ, bb, ττ, WW(lνlν), ZZ(4l, llττ, llνν, llqq)

Sizes of the individual excesses in 2012:

γγ:	4.5σ (Atlas);	4.1σ (CMS)
4 leptons:	3.4σ	3.2σ

(BTW, this fit has > 1000 pull parameters.)

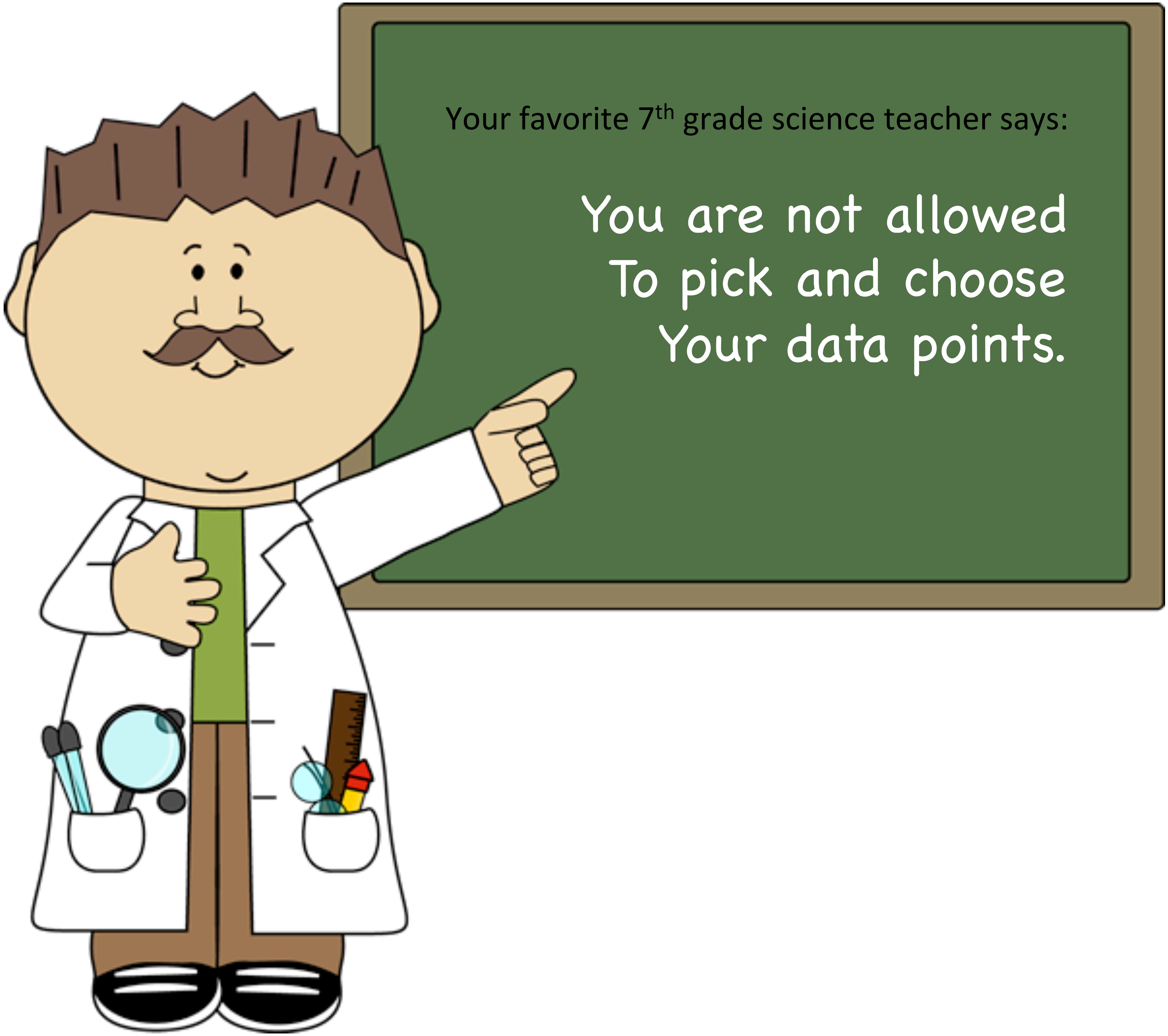
Applause, applause!
July 4, 2012

“Look,

data set x rules out data set y at 90% CL,

so why are we even discussing global fits

to more data?”


Your favorite 7th grade science teacher says:
You are not allowed
To pick and choose
Your data points.

"The problem with fits is that
With 4 parameters I can fit an elephant
And with 5, I can make his trunk wiggle."

Actually, this one could be true…

Drawing an elephant with four complex parameters

Jürgen Mayer
Max Planck Institute of Molecular Cell Biology and Genetics, Pfotenhauerstr. 108, 01307 Dresden, Germany

Khaled Khairy
European Molecular Biology Laboratory, Meyerhofstraße. 1, 69117 Heidelberg, Germany

Jonathon Howard
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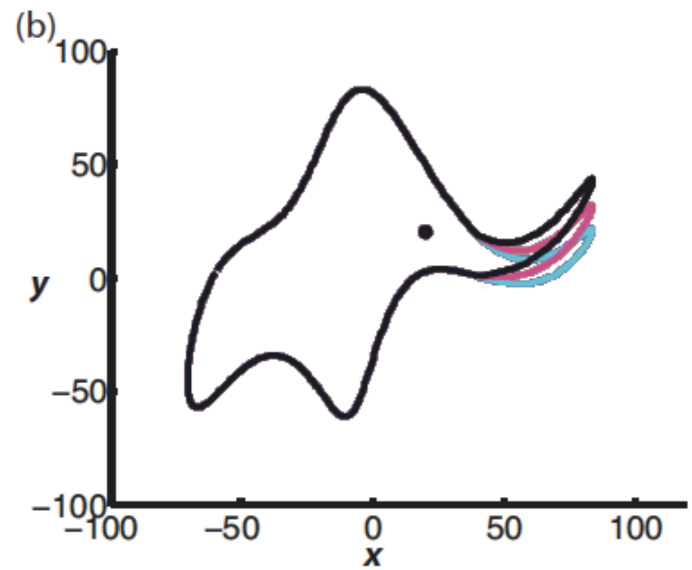
(Received 20 August 2008; accepted 5 October 2009)

We define four complex numbers representing the parameters needed to specify an elephantine shape. The real and imaginary parts of these complex numbers are the coefficients of a Fourier coordinate expansion, a powerful tool for reducing the data required to define shapes.
[DOI: 10.1119/1.3254017]

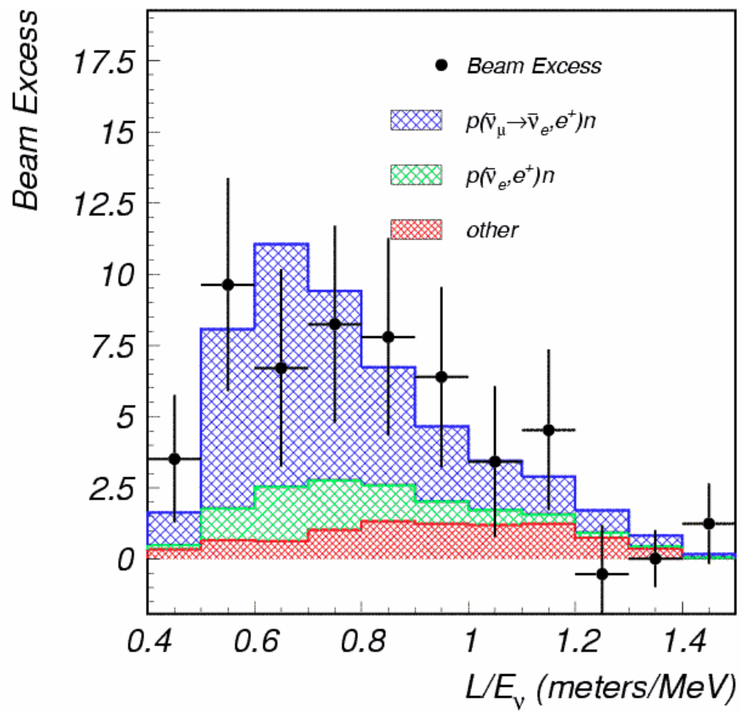
5th parameter makes his nose wiggle

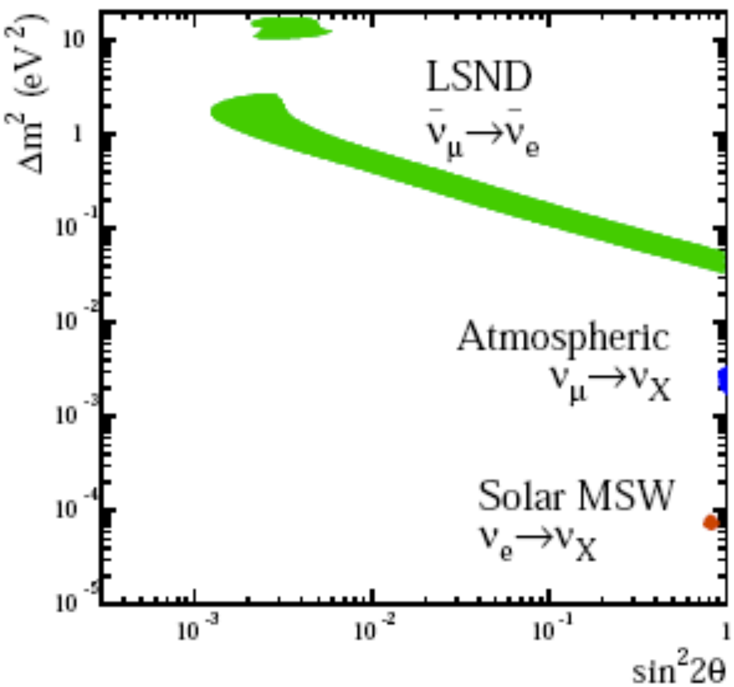


Lets discuss

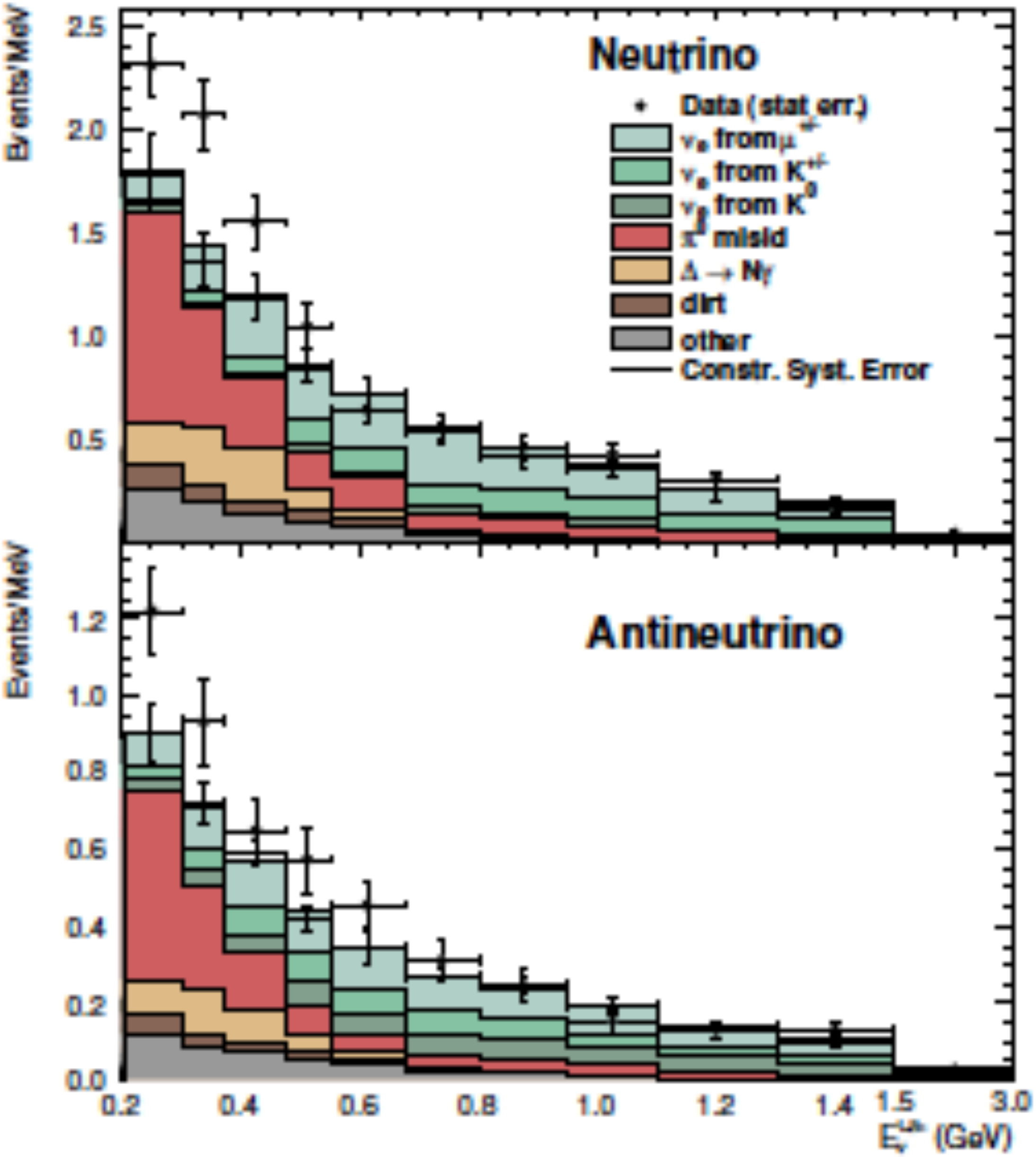
Global fits for sterile neutrinos

LSND

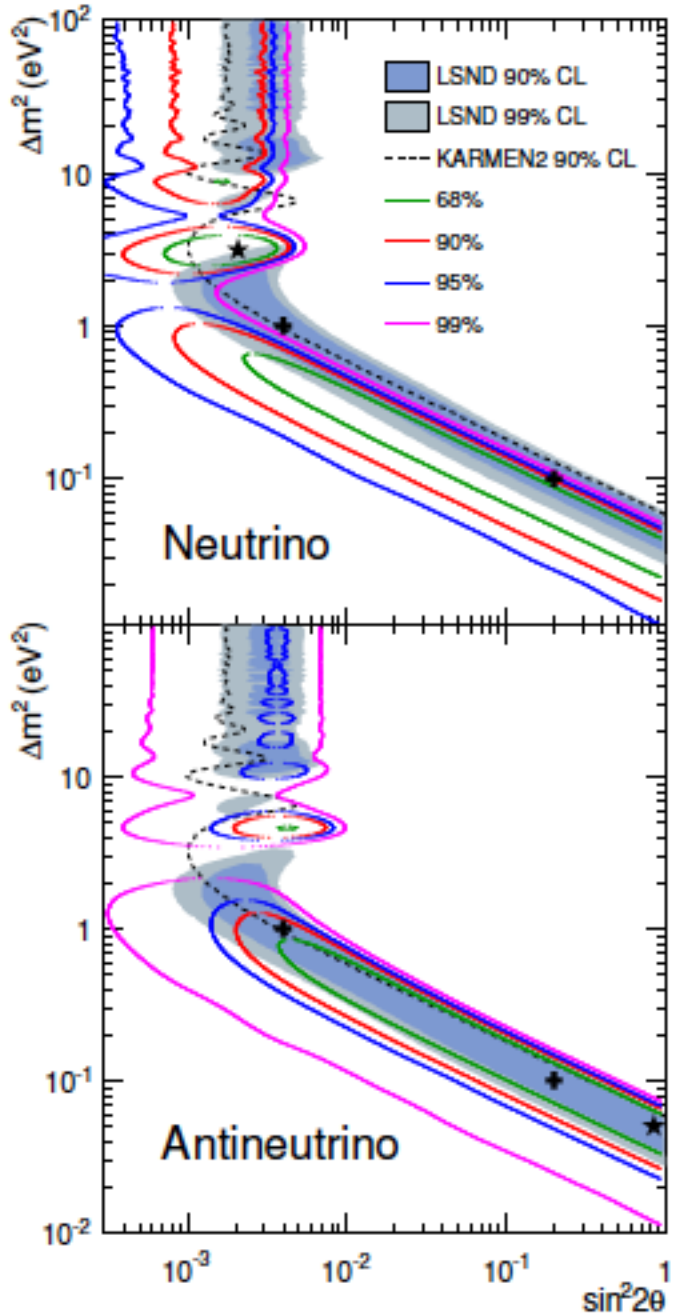

Beam Excess
17.5
15
12.5
10
7.5
5
2.5
0
0.4
0.6
0.8
1
1.2
1.4
L/E$_\nu$ (meters/MeV)
Beam Excess
$p(\bar{\nu}_\mu \rightarrow \bar{\nu}_e, e^+)n$
$p(\bar{\nu}_e, e^+)n$
other


Δm^2 (eV^2)
LSND
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Atmospheric
$\nu_\mu \rightarrow \nu_X$
Solar MSW
$\nu_e \rightarrow \nu_X$
$\sin^2 2\theta$

MiniBooNE

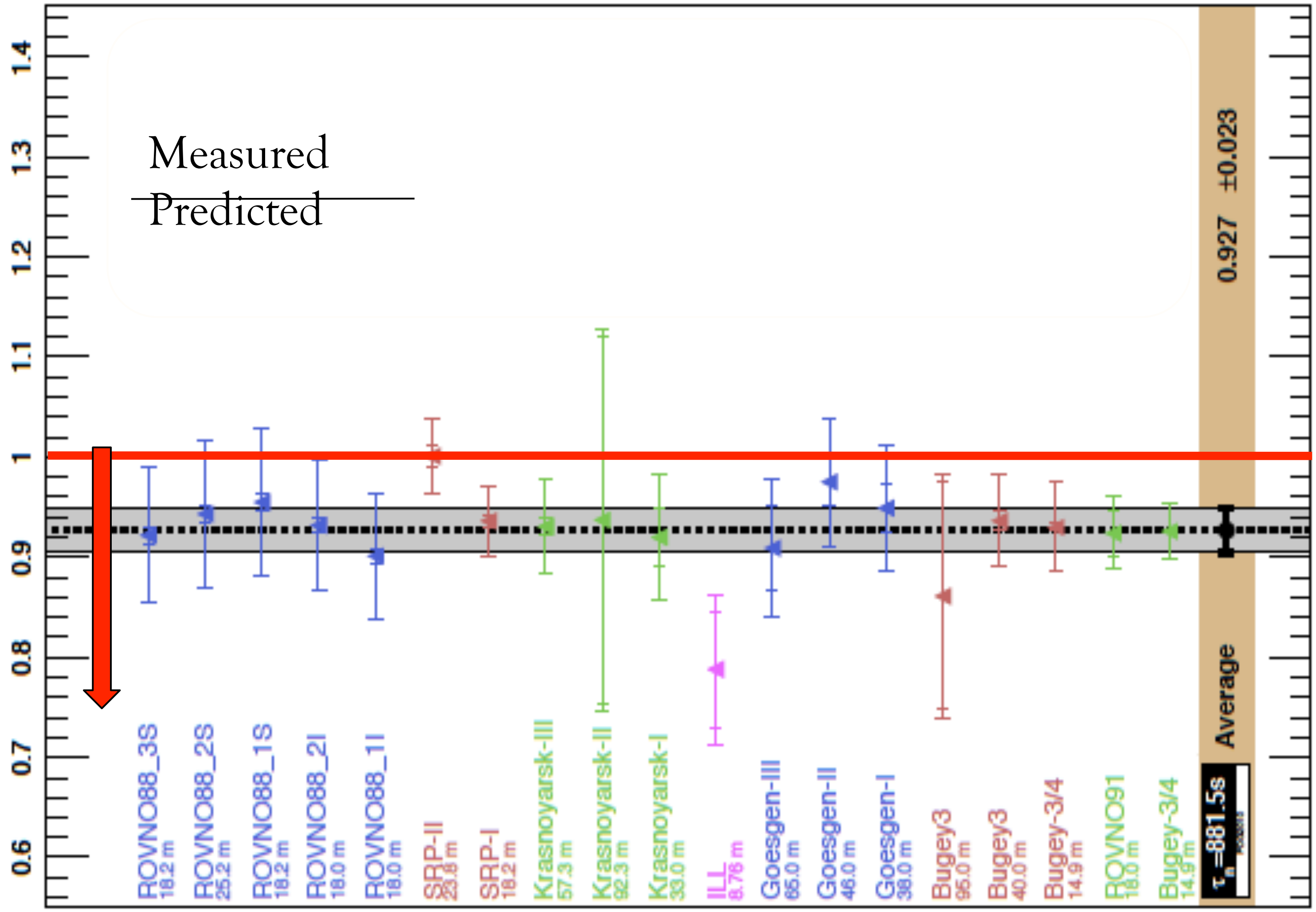


Neutrino
Data (stat err.)
ν_e from $\mu^{+/-}$
ν_e from $K^{+/-}$
ν_e from K^0
π^0 misid
$\Delta \rightarrow N\gamma$
dirt
other
Constr. Syst. Error
Antineutrino
Events/MeV
E_ν^{QE} (GeV)

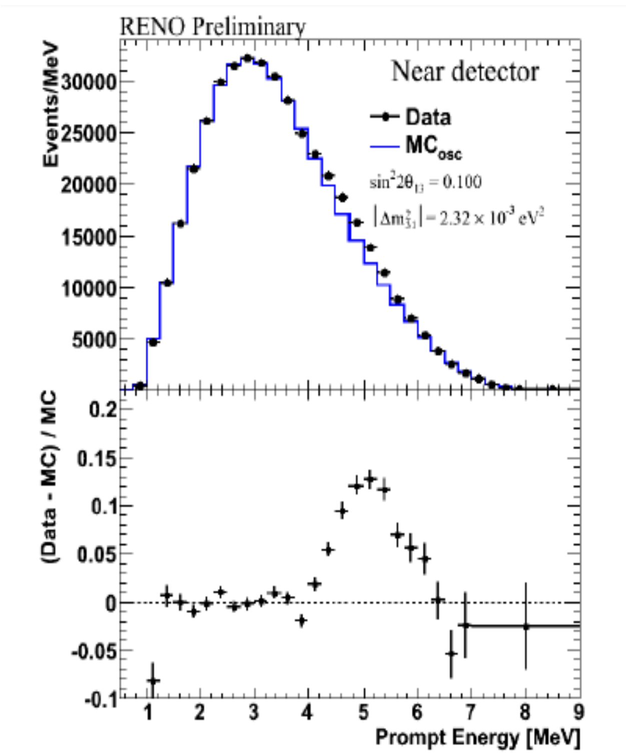


LSND 90% CL
LSND 99% CL
KARMEN2 90% CL
68%
90%
95%
99%
Neutrino
Antineutrino
Δm² (eV²)
sin²2θ

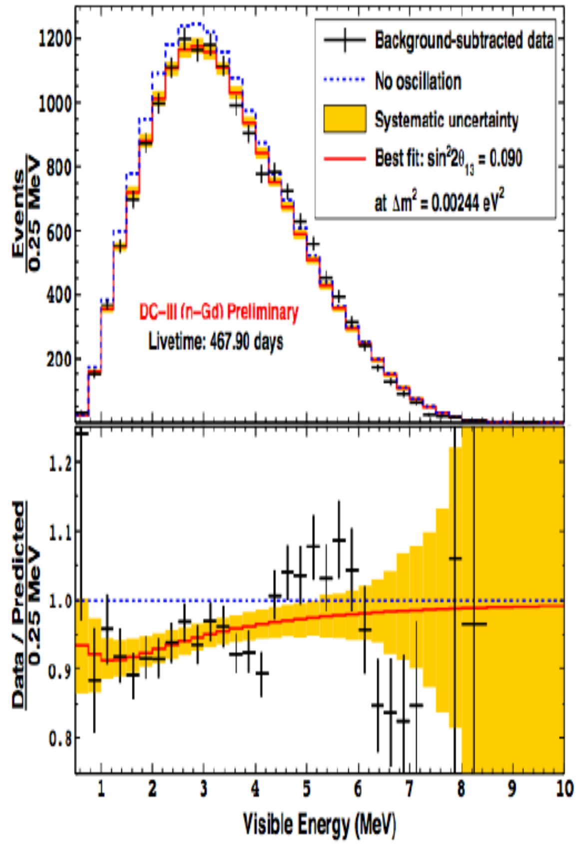
$$
\begin{aligned}
P = & \qquad (\sin^2\theta_{23}\sin^2 2\theta_{13})\ (\sin^2\Delta_{31}) \\
& \mp \sin\delta\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \cos\delta\ (\sin 2\theta_{13}\sin 2\theta_{23}\sin 2\theta_{12})\ (\sin\Delta_{31}\cos\Delta_{31}\sin\Delta_{21}) \\
& \qquad + (\cos^2\theta_{23}\sin^2 2\theta_{12})\ (\sin^2\Delta_{21}).
\end{aligned}
$$


Measured
Predicted
0.927 ±0.023
Average
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
ROVNO88_3S 18.2 m
ROVNO88_2S 25.2 m
ROVNO88_1S 18.2 m
ROVNO88_2I 18.0 m
ROVNO88_1I 18.0 m
SRP-II 23.8 m
SRP-I 18.2 m
Krasnoyarsk-III 57.3 m
Krasnoyarsk-II 92.3 m
Krasnoyarsk-I 33.0 m
ILL 8.76 m
Goesgen-III 65.0 m
Goesgen-II 46.0 m
Goesgen-I 38.0 m
Bugey3 95.0 m
Bugey3 40.0 m
Bugey-3/4 14.9 m
ROVNO91 18.0 m
Bugey-3/4 14.9 m
τ_n=881.5s

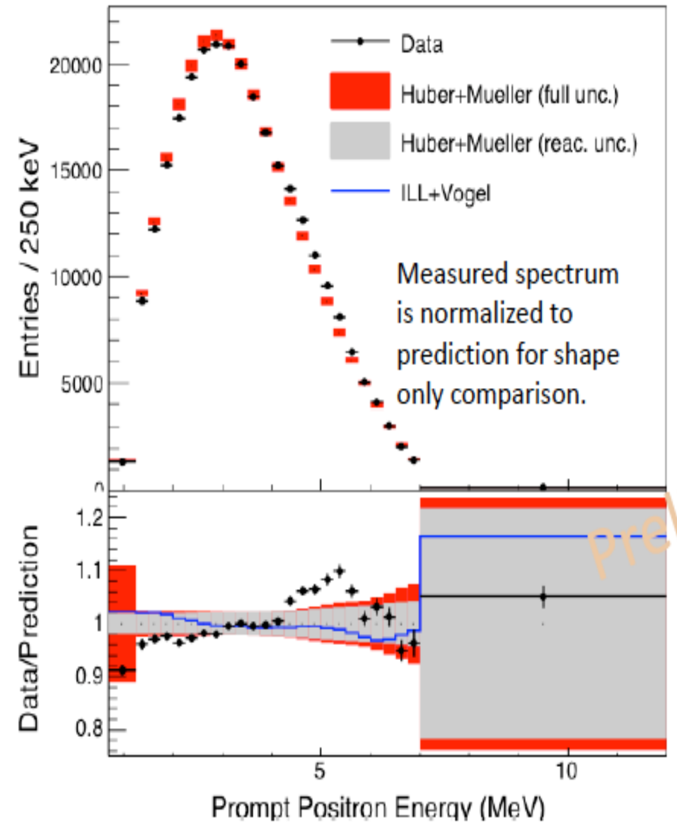
RENO



Double Chooz



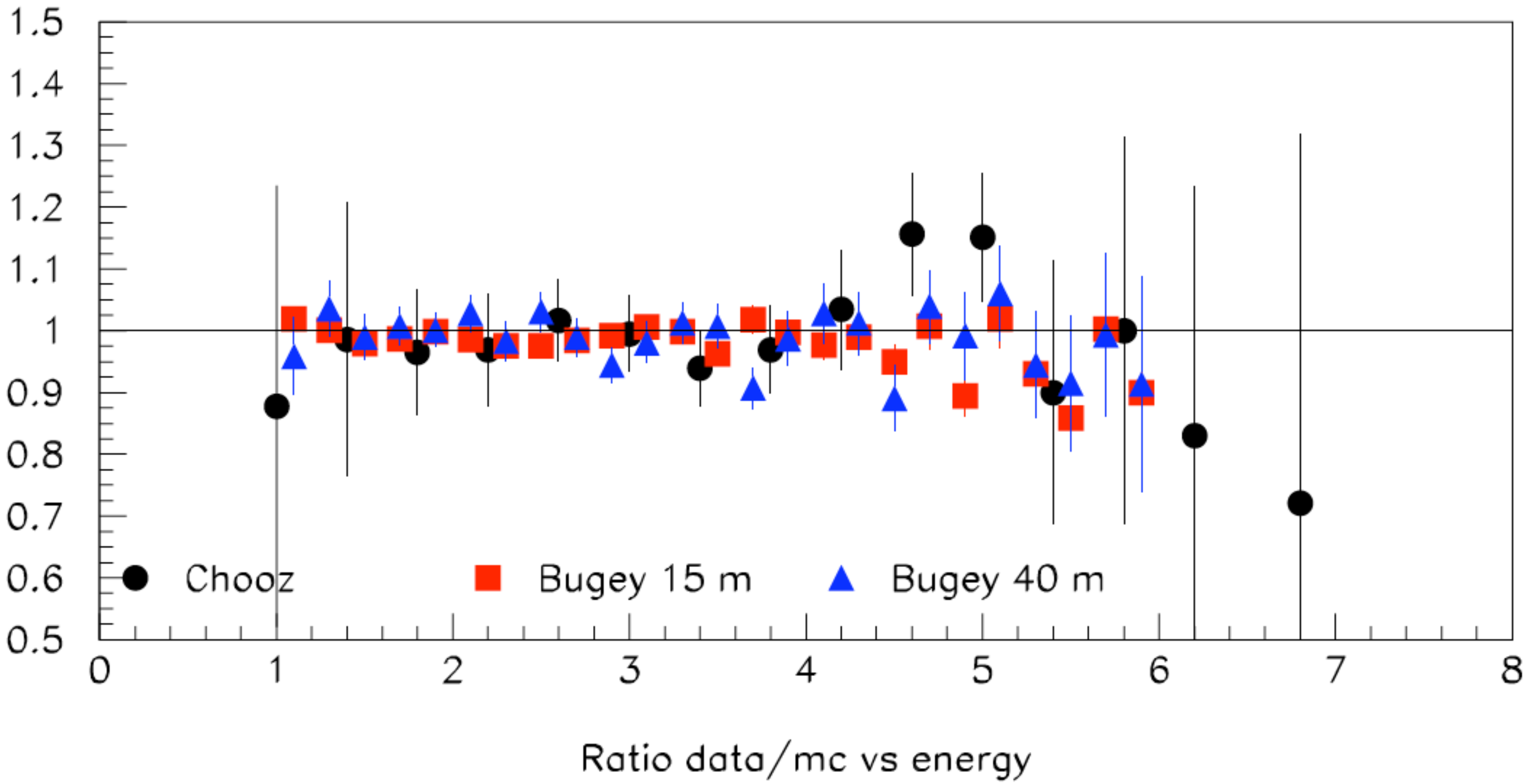
Daya Bay

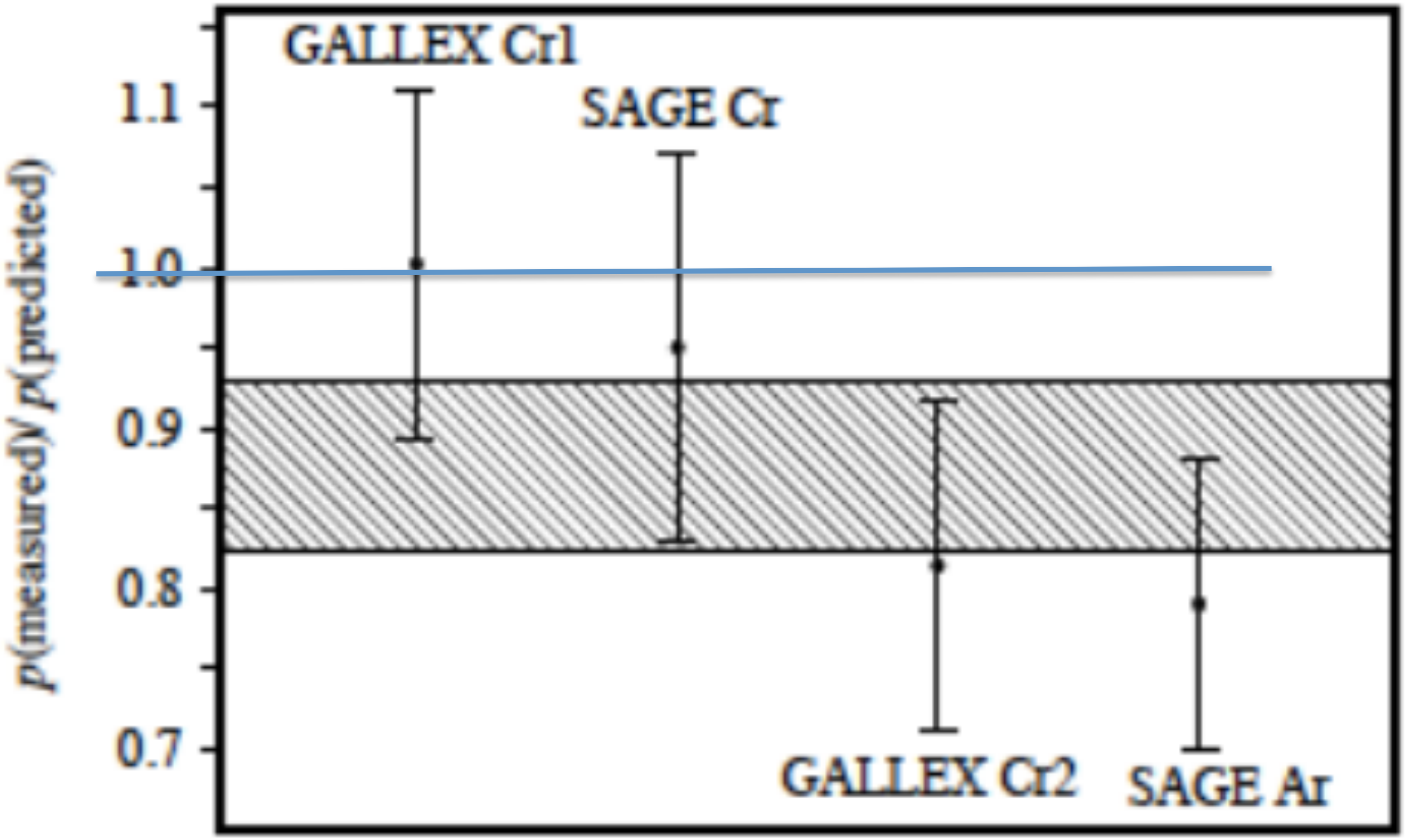


Dwyer and Langford (arXiv:1407.1281)

Suggests decays that may be the origin of the bump

This plot has the pre-anomaly prediction for normalization!




GALLEX Cr1
SAGE Cr
GALLEX Cr2
SAGE Ar
1.1
1.0
0.9
0.8
0.7
p(measured)/ p(predicted)

http://arxiv.org/abs/arXiv:1210.5715

TABLE IV. Gallium cross section (in units of 10^{-46} cm^2) and its ratio with the corresponding Bahcall cross section (Eqs. (6) and (7)) for ^{51}Cr and ^{37}Ar neutrinos in the three cases discussed in the text.

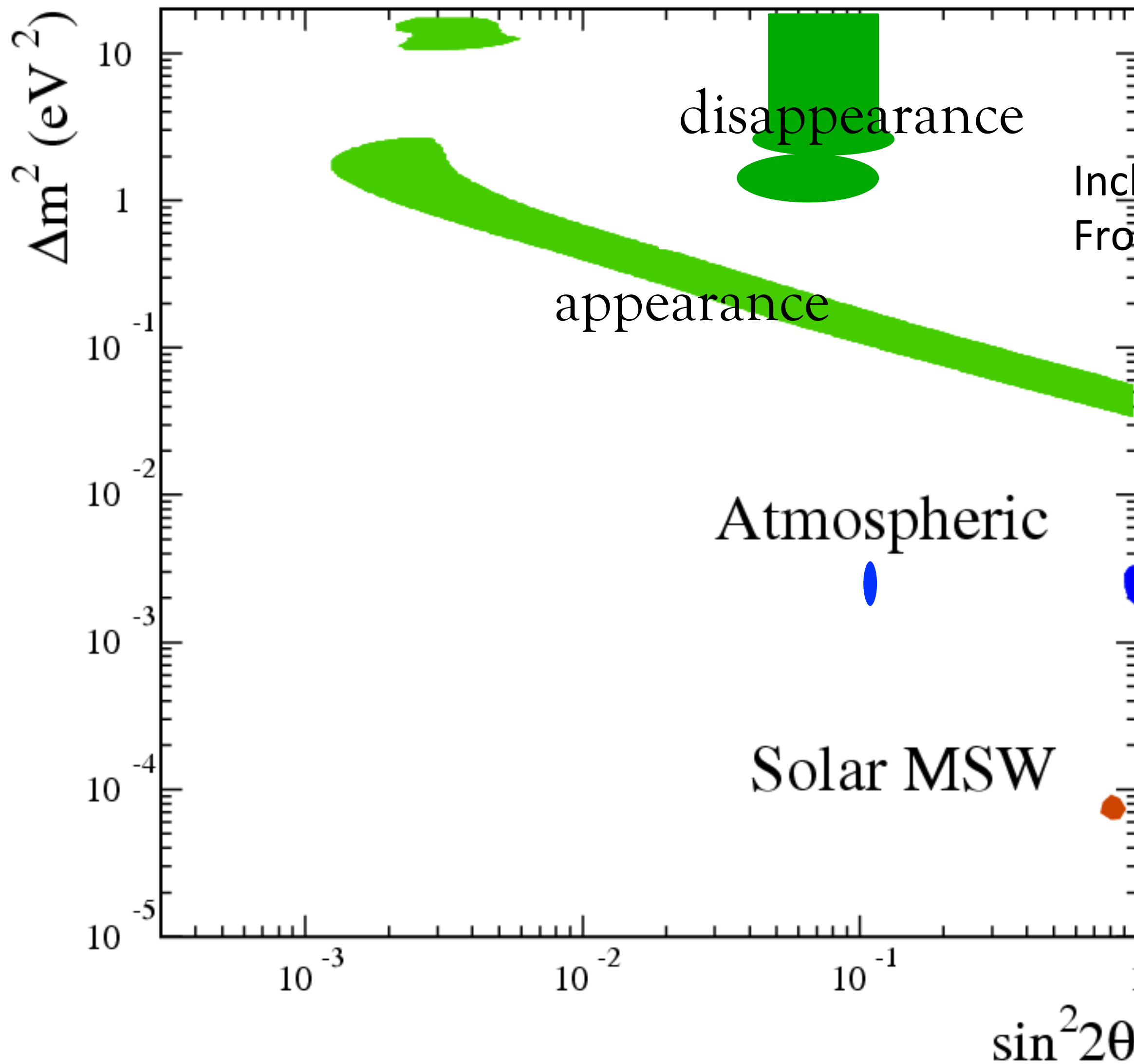
	^{51}Cr		^{37}Ar	
	σ	σ/σ_B	σ	σ/σ_B
HK	63.9 ± 6.5	1.10 ± 0.11	77.2 ± 8.1	1.10 ± 0.12
FF	59.2 ± 1.1	1.02 ± 0.02	71.5 ± 1.4	1.02 ± 0.02
HF	64.9 ± 6.5	1.12 ± 0.11	78.5 ± 8.1	1.12 ± 0.12

TABLE V. Values of χ^2, goodness-of-fit (GoF) for 2 degrees of freedom and best-fit values of the 3+1 oscillation parameters obtained from the three fits of Gallium data described in the text.

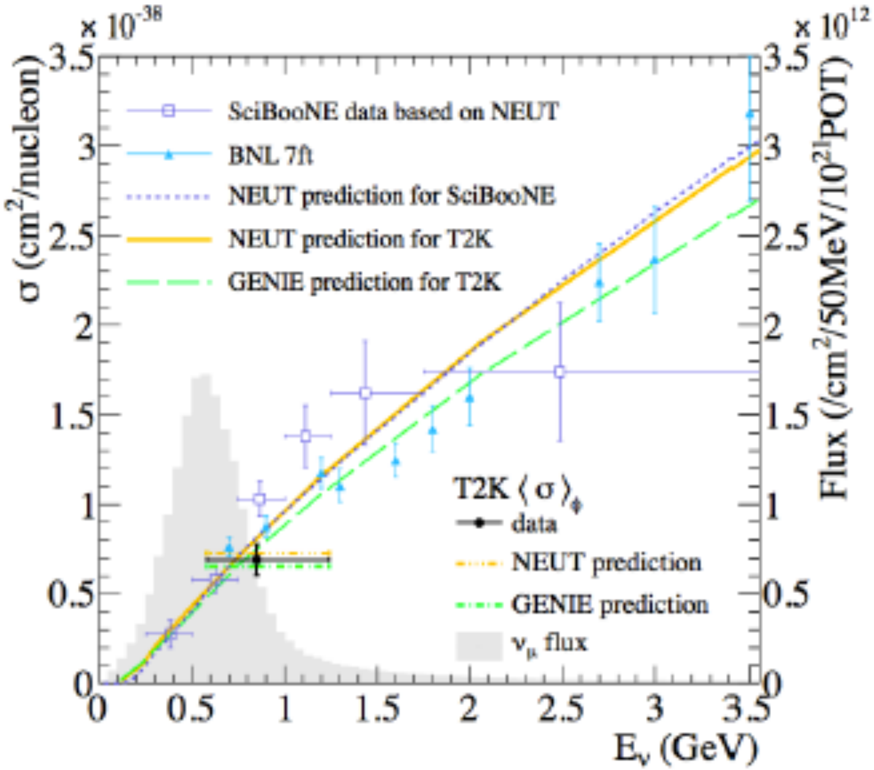
	HK	FF	HF
$\chi^2_{\rm min}$	4.8	7.9	4.6
GoF	9.1%	1.9%	9.9%
$\Delta m^2_{41}[\rm eV^2]$	2.24	2.1	2.24
$\sin^2 2\vartheta_{ee}$	0.50	0.30	0.52

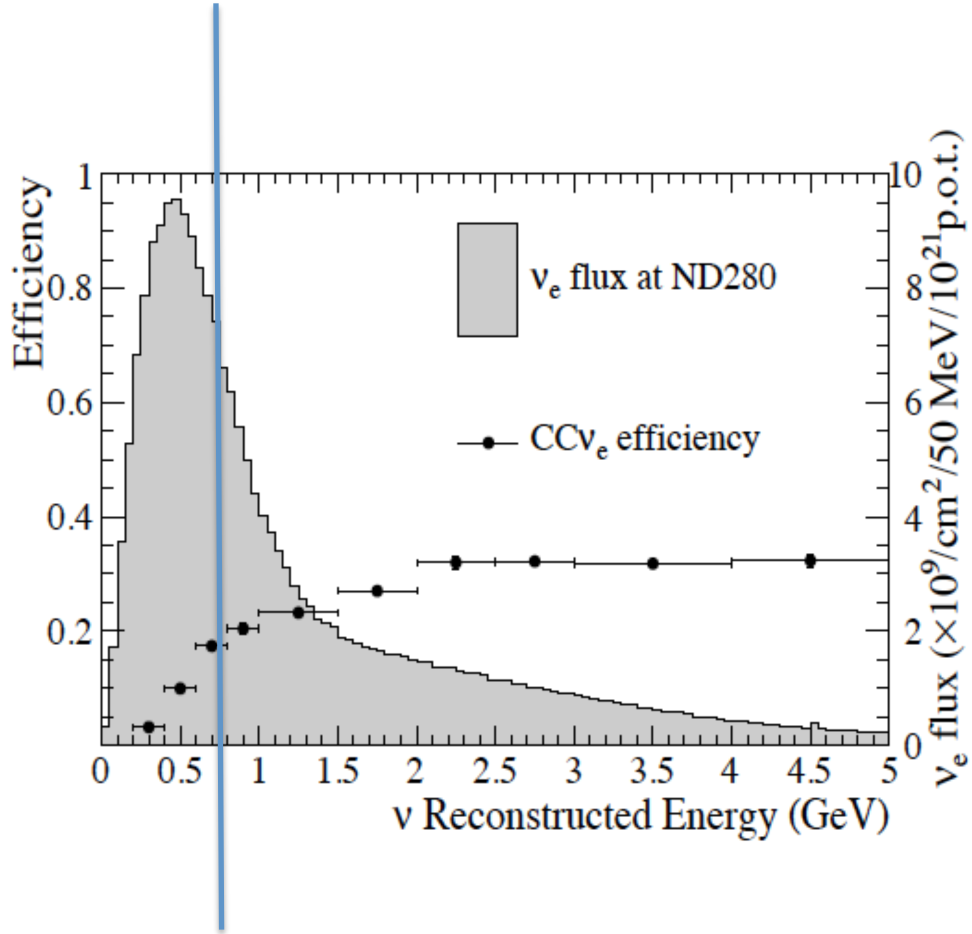
Add this uncertainty as a systematic?

Signals: LSND, MB (nu and nubar), Reactor, Gallium

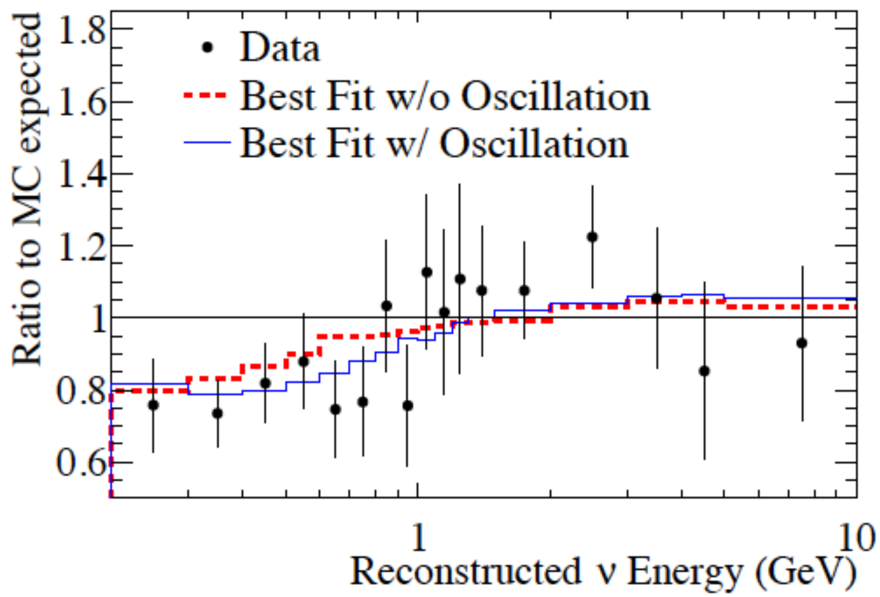


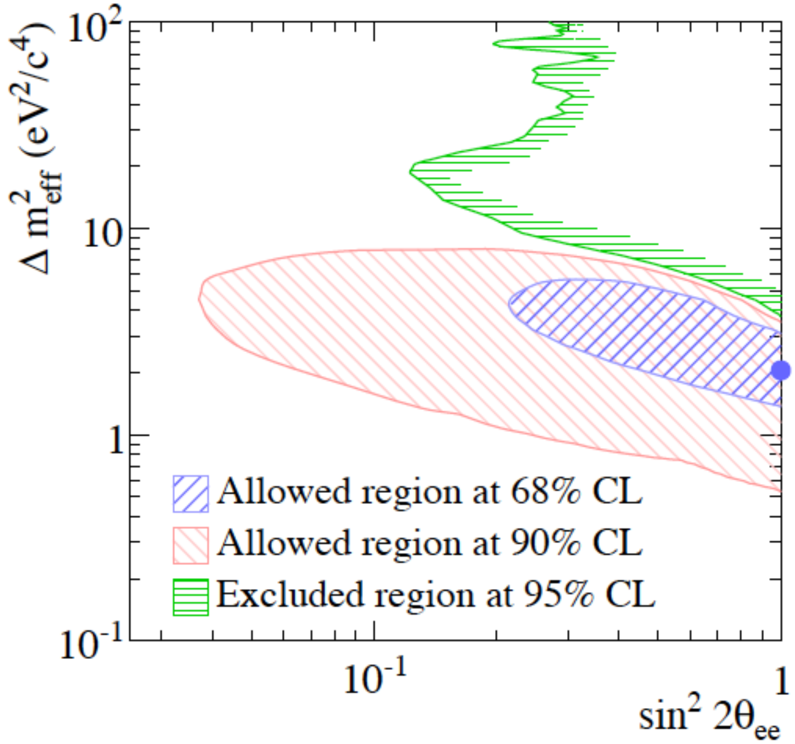
Includes constraints
From null expts


× 10⁻³⁸
σ (cm²/nucleon)
× 10¹²
Flux (/cm²/50MeV/10²¹POT)
SciBooNE data based on NEUT
BNL 7ft
NEUT prediction for SciBooNE
NEUT prediction for T2K
GENIE prediction for T2K
T2K ⟨σ⟩ϕ
data
NEUT prediction
GENIE prediction
νμ flux
Eν (GeV)


Efficiency
νe flux at ND280
CCνe efficiency
ν Reconstructed Energy (GeV)
νe flux (×10⁹/cm²/50 MeV/10²¹p.o.t.)

T2K ν_e disappearance: 1410.8811





Data Release for A.A. Aguilar-Arevalo et al., "A Search for Electron Neutrino Appearance at the Δm^2 ~1 eV^2 Scale", arXiv:0704.1500 [hep-ex], Phys. Rev. Lett. 98, 231801 (2007)

The following MiniBooNE information from the first oscillation paper in 2007 is made available to the public:

- **Energy Range for Default Oscillation Fit (475 MeV - 3000 MeV reconstructed neutrino energy)**
  - ntuple file of official MiniBooNE $\sin^2$(2theta) sensitivity and upper limit curves as a function of Dm^2, for a 2-neutrino muon-to-electron oscillation fit, and 90% and 3sigma confidence levels. The file contains 100 rows, one for each Dm^2 value in the range $10^{-2} < Dm^2 (eV^2) < 10^2$, and 5 columns per row with the following format:

    (Dm^2 (eV^2), $\sin^2(2th)_{max, 90\% CL}$, $\sin^2(2th)_{max, 3sigma CL}$, $\sin^2(2th)_{sens, 90\% CL}$, $\sin^2(2th)_{sens, 3sigma CL}$)
    where $\sin^2(2th)_{max}$ and $\sin^2(2th)_{sens}$ indicate the upper limit and sensitivity, respectively, and 90% and 3sigma CL indicate the confidence levels corresponding to those numbers.

  - ntuple file of official MiniBooNE 2-dimensional chi2 surface as a function of (Dm^2, $\sin^2$(2theta)) in the range ($10^{-2} < Dm^2 (eV^2) < 10^2$, $3\cdot10^{-4} < \sin^2(2theta) < 1$). The file contains 20,000 rows, one for each (Dm^2, $\sin^2$(2theta)) pair of values, and 3 columns per row with the following format:

    (Dm^2 (eV^2), $\sin^2$(2th), chi2)
    Note: the value quoted in the third column is the total, and not the reduced, chi2 value (*ie*, it has not been divided by the number of degrees of freedom)

  - 1D array of bin boundaries in electron neutrino reconstructed neutrino energy
  - 1D array of observed electron neutrino candidate events per reconstructed neutrino energy bin
  - 1D array of predicted background electron neutrino candidate events per reconstructed neutrino energy bin
  - 2D array of (systematic + statistical uncertainty) predicted background fractional covariance matrix per reconstructed neutrino energy bins
  - ntuple file of 9,934 predicted muon-to-electron full transmutation events, containing information on reconstructed neutrino energy, true neutrino energy, neutrino baseline, and event weight for each event
  - 2D array of (systematic uncertainty only) predicted muon-to-electron full transmutation fractional covariance matrix per reconstructed neutrino energy bins
- **Low Energy Threshold Range (300 MeV - 3000 MeV reconstructed neutrino energy)**
  - 1D array of bin boundaries in electron neutrino reconstructed neutrino energy
  - 1D array of observed electron neutrino candidate events per reconstructed neutrino energy bin
  - 1D array of predicted background electron neutrino candidate events per reconstructed neutrino energy bin
  - 2D array of (systematic + statistical uncertainty) predicted background fractional covariance matrix per reconstructed neutrino energy bins
  - ntuple file of 9934 predicted muon-to-electron full transmutation events, containing information on reconstructed neutrino energy, true neutrino energy, neutrino baseline, and event weight for each event (same file as one for default energy range)
  - 2D array of (systematic uncertainty only) predicted muon-to-electron full transmutation fractional covariance matrix per reconstructed neutrino energy bins

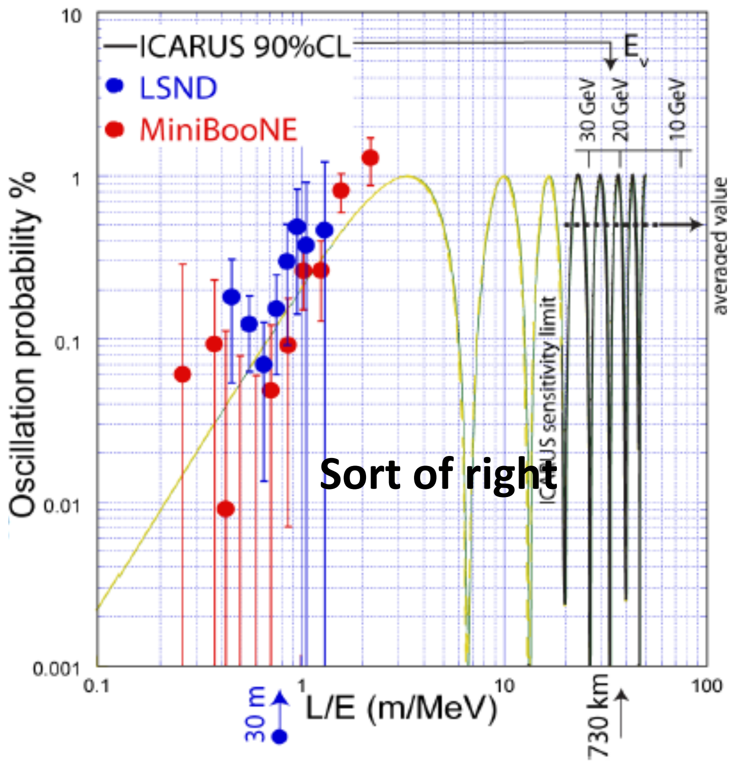
Instructions

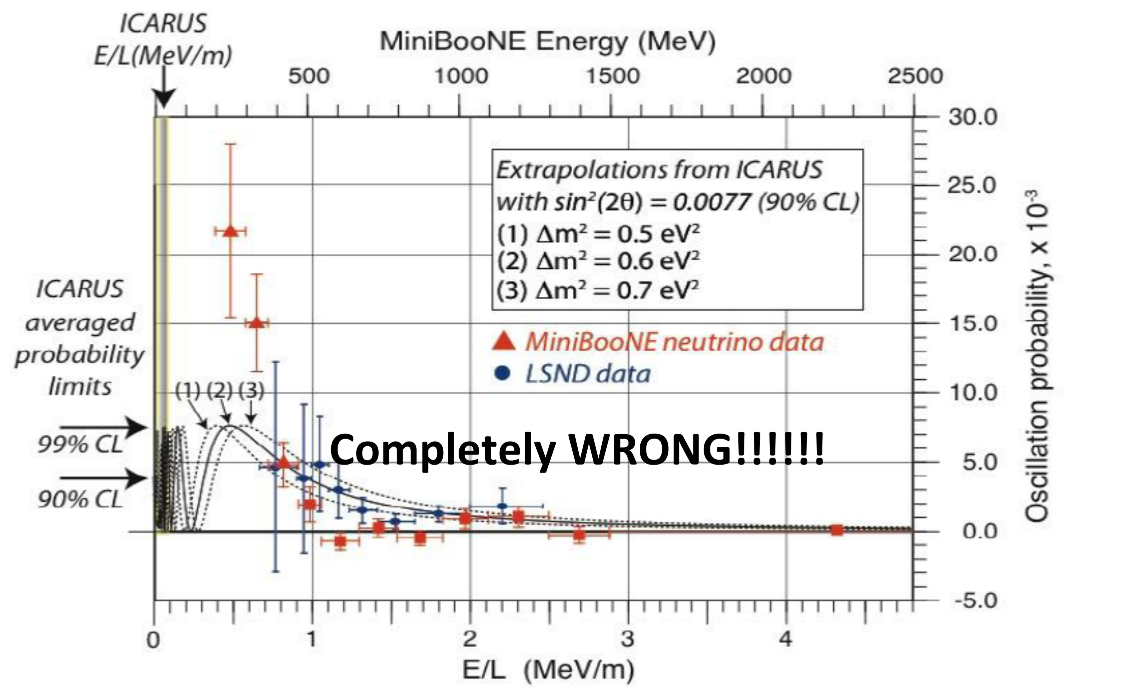
Instructions on how to use this information can be found here. A FORTRAN program implementing these instructions to perform an example oscillation fit can be found here (note: you will need CERNLIB libraries, including LAPACK libraries, to build this program).

Contact Information

- For clarifications on how to use MiniBooNE public data or for enquiries about additional data not linked from this page, please contact: Steve Brice or Richard Van de Water

Two completely contradictory plots from same ICARUS Nu2014 talk

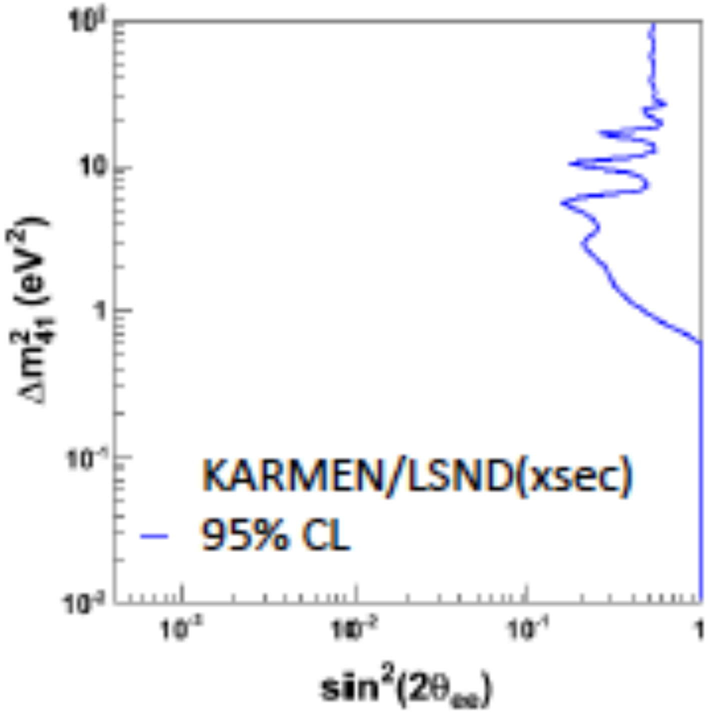




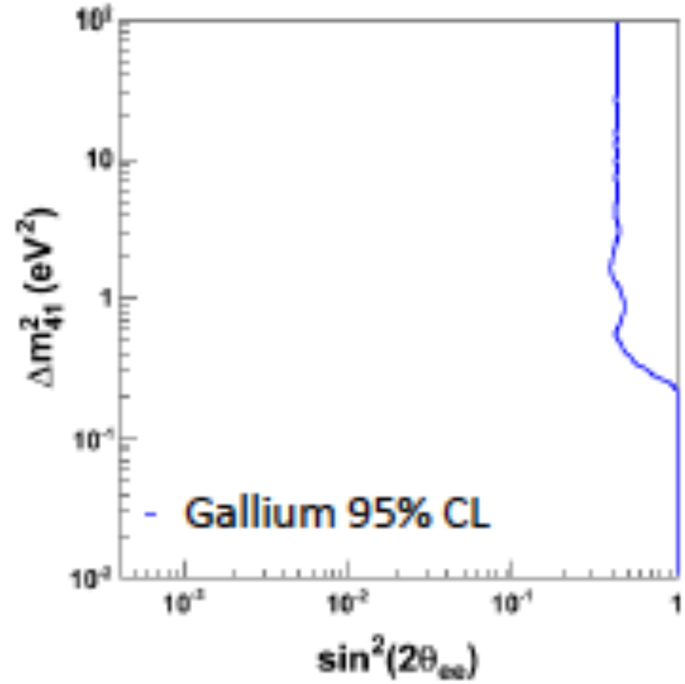
Using L/E Oscillation Probability Distributions

http://arxiv.org/abs/arXiv:1407.3304

This paper explores the use of L/E oscillation probability distributions to compare experimental measurements and to evaluate oscillation models. In this case, L is the distance of neutrino travel and E is a measure of the interacting neutrino's energy. While comparisons using allowed and excluded regions for oscillation model parameters are likely the only rigorous method for these comparisons, the L/E distributions are shown to give qualitative information on the agreement of an experiment's data with a simple two-neutrino oscillation model. In more detail, this paper also outlines how the L/E distributions can be best calculated and used for model comparisons. Specifically, the paper presents the L/E data points for the final MiniBooNE data samples and, in the Appendix, explains and corrects the mistaken analysis published by the ICARUS collaboration.



KARMEN/LSND(xsec)
95% CL
Δm^2_{41} (eV^2)
$\sin^2(2\theta_{ee})$



Gallium 95% CL
Δm^2_{41} (eV^2)
$\sin^2(2\theta_{ee})$

2012 data sets

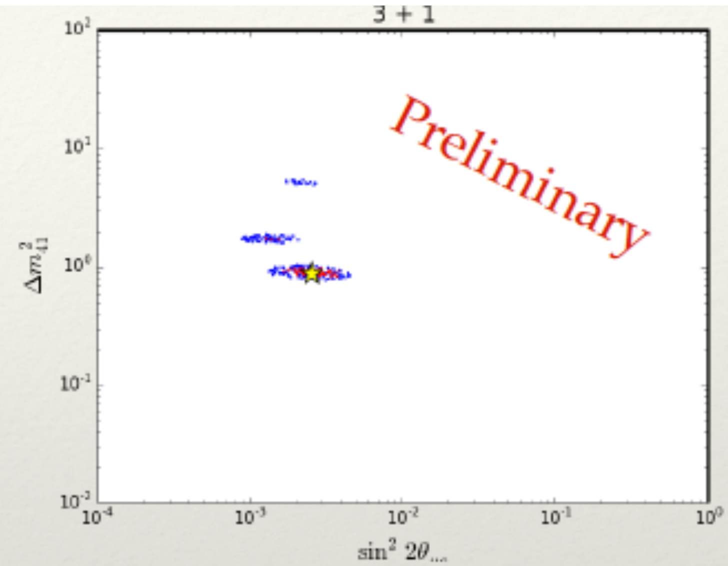
- Appearance:
  - MiniBooNE-BNB: $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$
  - MiniBooNE-NuMI,
  - NOMAD,
  - LSND,
  - KARMEN,
- Disappearance:
  - MiniBooNE-BNB: $\nu_\mu \to \nu_\mu$
  - GALLEX/SAGE,
  - KARMEN/LSND xsec,
  - CCFR84,
  - CDHS,
  - Atmospheric,
  - Bugey,
  - MINOS

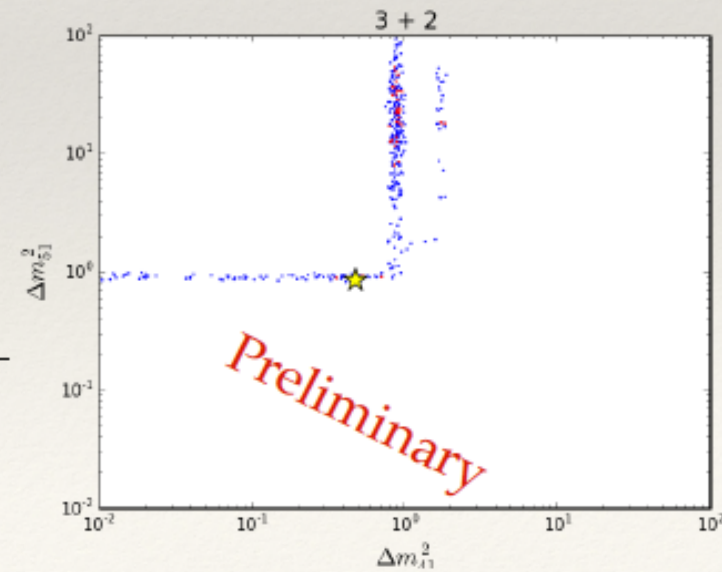
Red: 90% CL

Blue: 99% CL

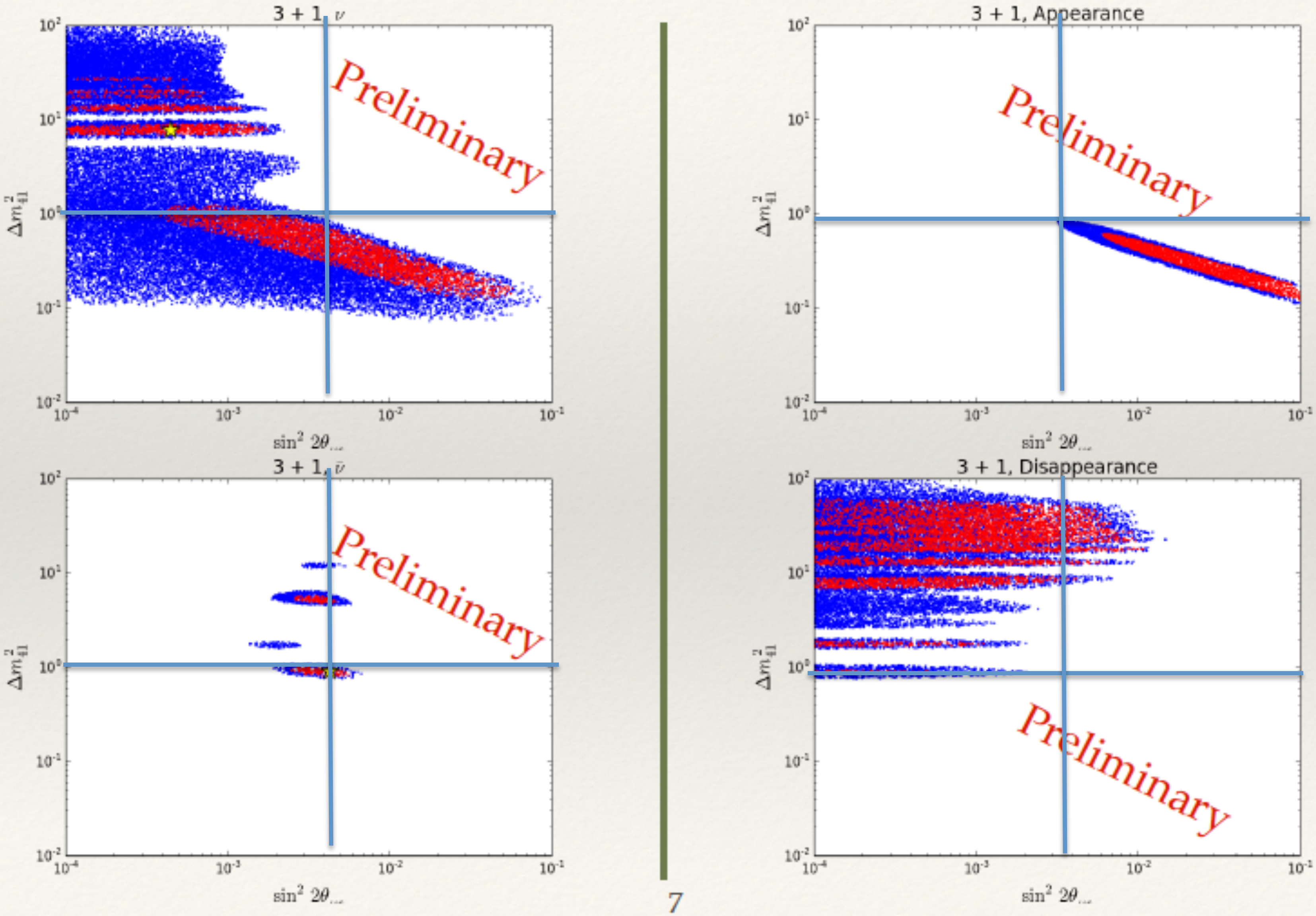
	χ^2_{best}	Pr
Null	290	1.5%
3+1	240	43%
3+2	235	45%

6



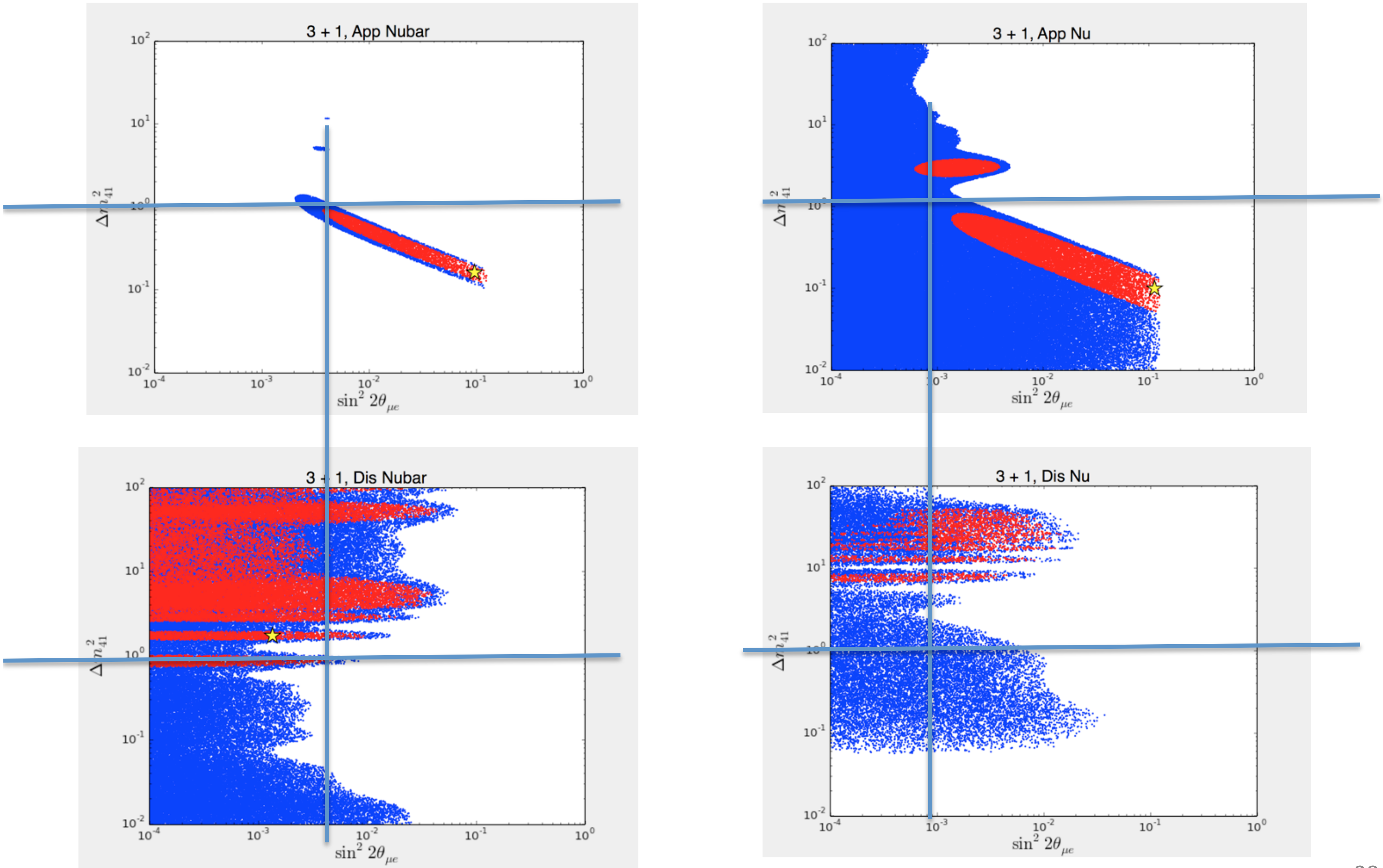


Compare Allowed Regions for Nu/Nubar and Appearance/Disappearance

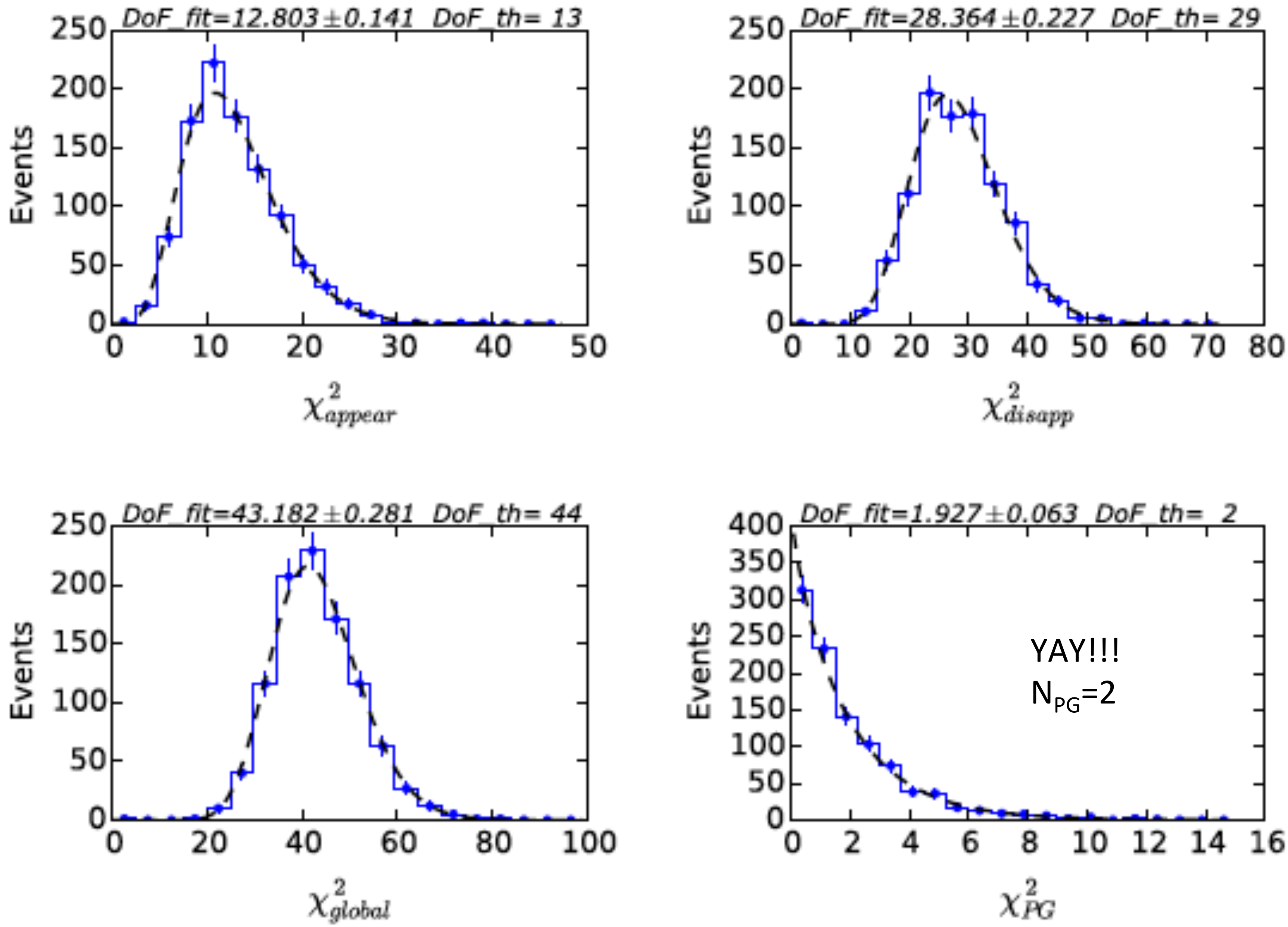


Appearance vs Disappearance in 3+1 separately for nu and nubar…

Nubar 3+1 Nu 3+1



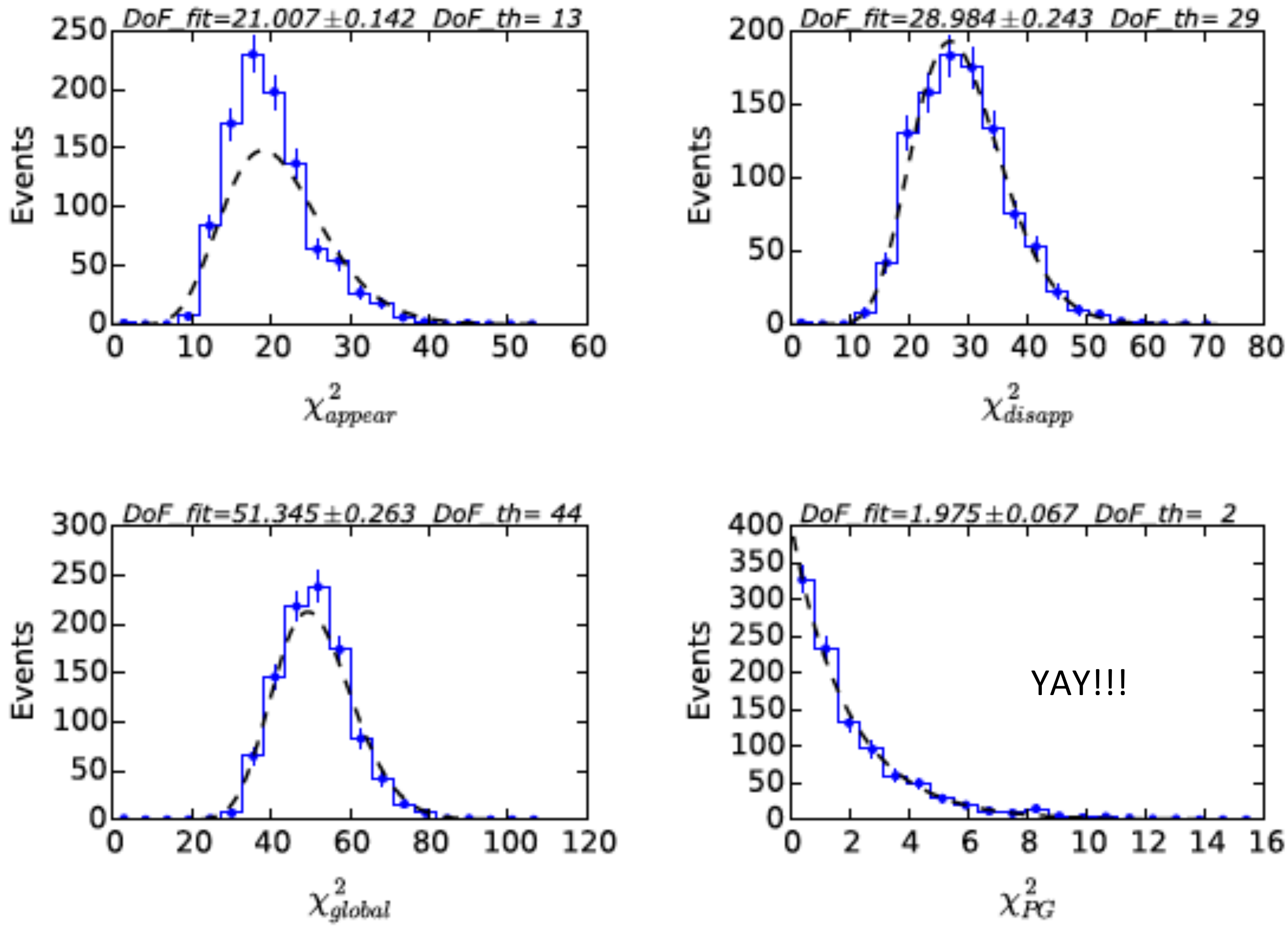
Just statistics, no underlying systematic



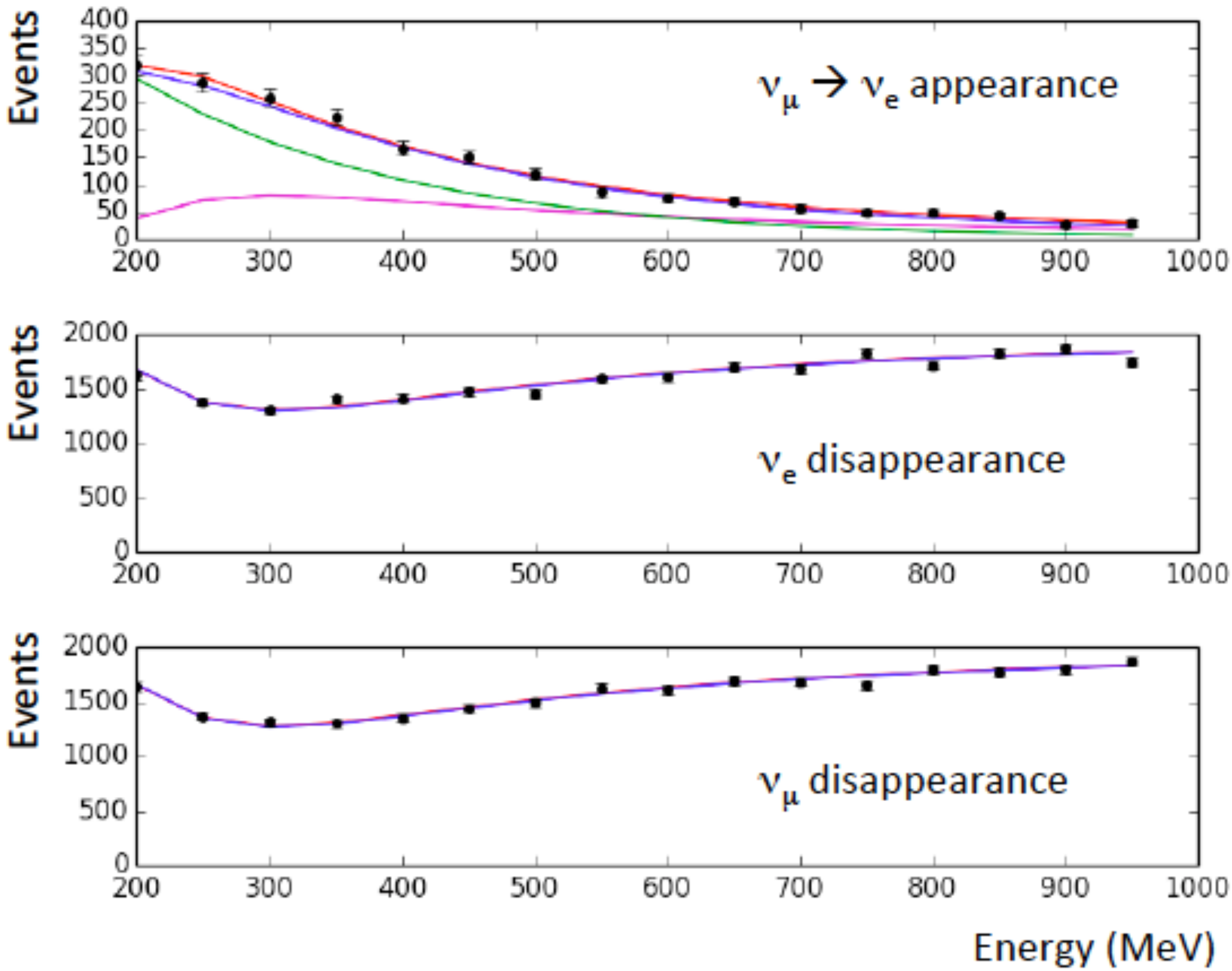
$$\chi^2_{\nu_e app} = \sum_{i=1}^{16} \frac{\left(d_i^{\nu_e app} - \left(osc_i^{\nu_e app} + b_i^{\nu_e app}\left(A_{fit}\right)\right)\right)^2}{\left(\sigma_i^{\nu_e app}\right)^2} + \frac{\left(A_{fit} - A_{exp}\right)^2}{\sigma^2_{A_{exp}}}$$

$$\chi^2_{disapp} = \sum_{i=1}^{16} \frac{\left(d_i^{\nu_\mu disapp} - osc_i^{\nu_\mu disapp}\right)^2}{\left(\sigma_i^{\nu_\mu disapp}\right)^2} + \sum_{i=1}^{16} \frac{\left(d_i^{\nu_e disapp} - osc_i^{\nu_e disapp}\right)^2}{\left(\sigma_i^{\nu_e disapp}\right)^2}$$

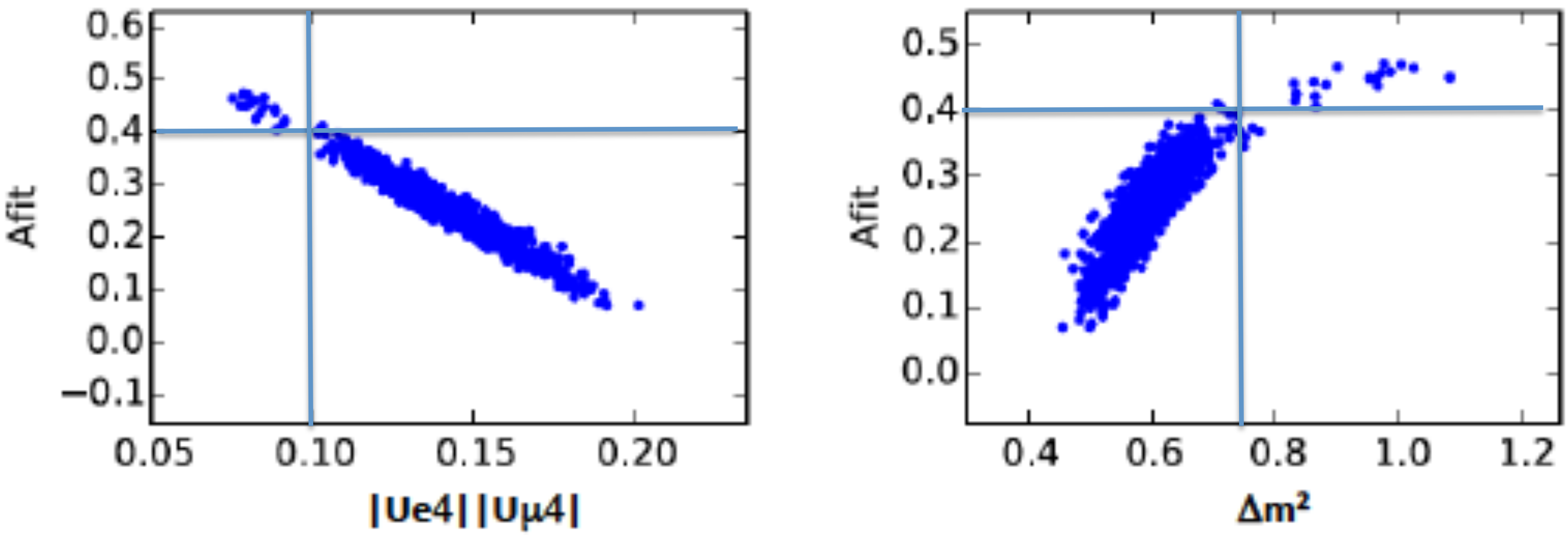
$$\chi^2_{global} = \sum_{i=1}^{16} \frac{\left(d_i^{\nu_e app} - \left(osc_i^{\nu_e app} + b_i^{\nu_e app}\left(A_{fit}\right)\right)\right)^2}{\left(\sigma_i^{\nu_e app}\right)^2} + \frac{\left(A_{fit} - A_{exp}\right)^2}{\sigma^2_{A_{exp}}} + \sum_{i=1}^{16} \frac{\left(d_i^{\nu_\mu disapp} - osc_i^{\nu_\mu disapp}\right)^2}{\left(\sigma_i^{\nu_\mu disapp}\right)^2} + \sum_{i=1}^{16} \frac{\left(d_i^{\nu_e disapp} - osc_i^{\nu_e disapp}\right)^2}{\left(\sigma_i^{\nu_e disapp}\right)^2}$$

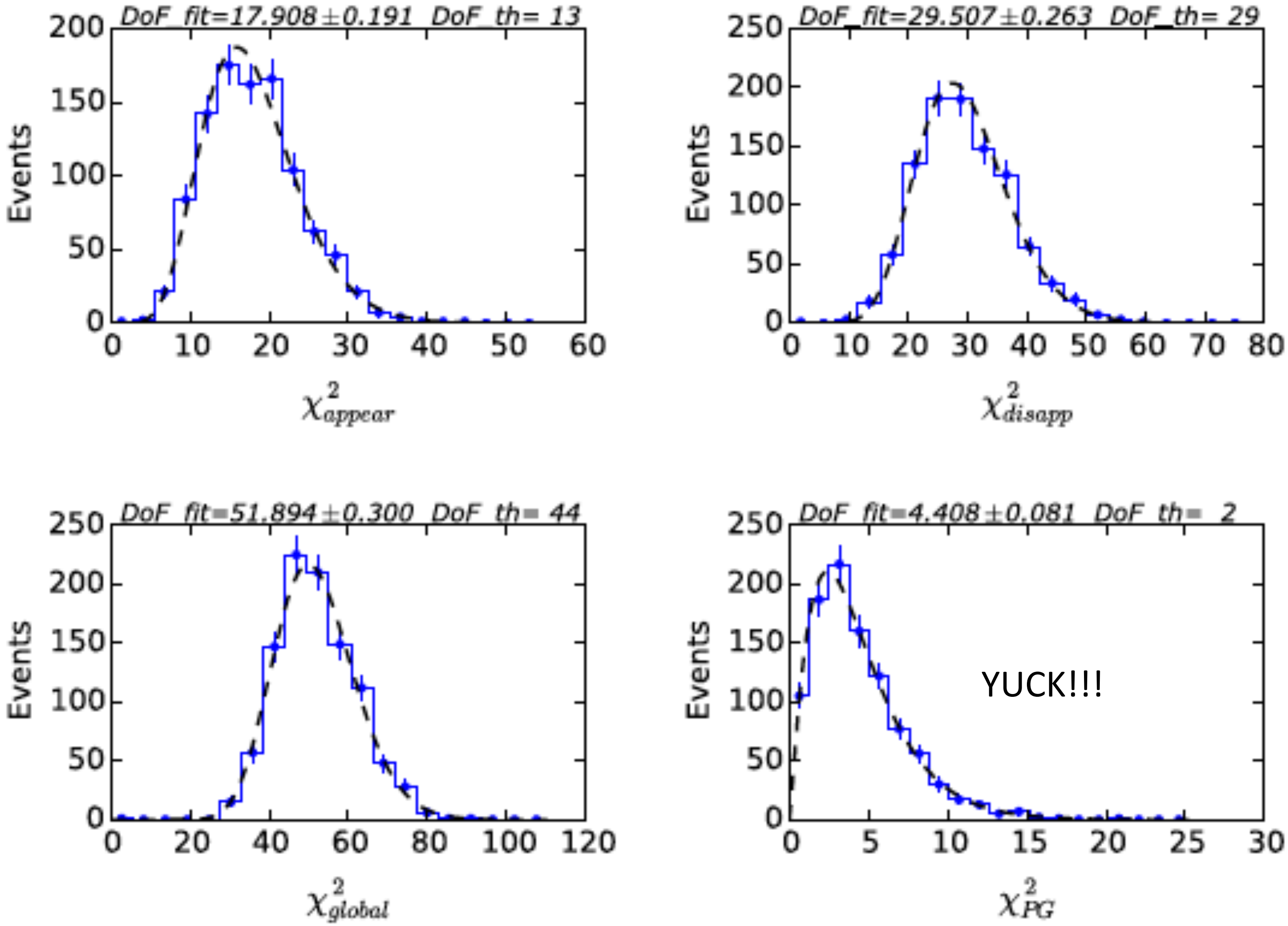


True even for very large normalization of residual background, Atrue



Events
$\nu_\mu \rightarrow \nu_e$ appearance
Events
ν_e disappearance
Events
ν_μ disappearance
Energy (MeV)


0.6
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
Afit
0.05
0.10
0.15
0.20
|Ue4||Uμ4|
0.5
0.4
0.3
0.2
0.1
0.0
Afit
0.4
0.6
0.8
1.0
1.2
Δm²


DoF_fit=17.908±0.191 DoF_th= 13
Events
χ^2_{appear}
DoF_fit=29.507±0.263 DoF_th= 29
Events
χ^2_{disapp}
DoF_fit=51.894±0.300 DoF_th= 44
Events
χ^2_{global}
DoF_fit=4.408±0.081 DoF_th= 2
Events
YUCK!!!
χ^2_{PG}

1408.7075

September 1, 2014

FITTING THEORY TO DATA IN THE PRESENCE OF BACKGROUND UNCERTAINTIES

BYRON ROE

8. Summary

Methods are given for using the χ^2 method when regression correlations between the shapes of backgrounds and theoretical models being fitted occur. These methods are appropriate whenever these correlations exist.

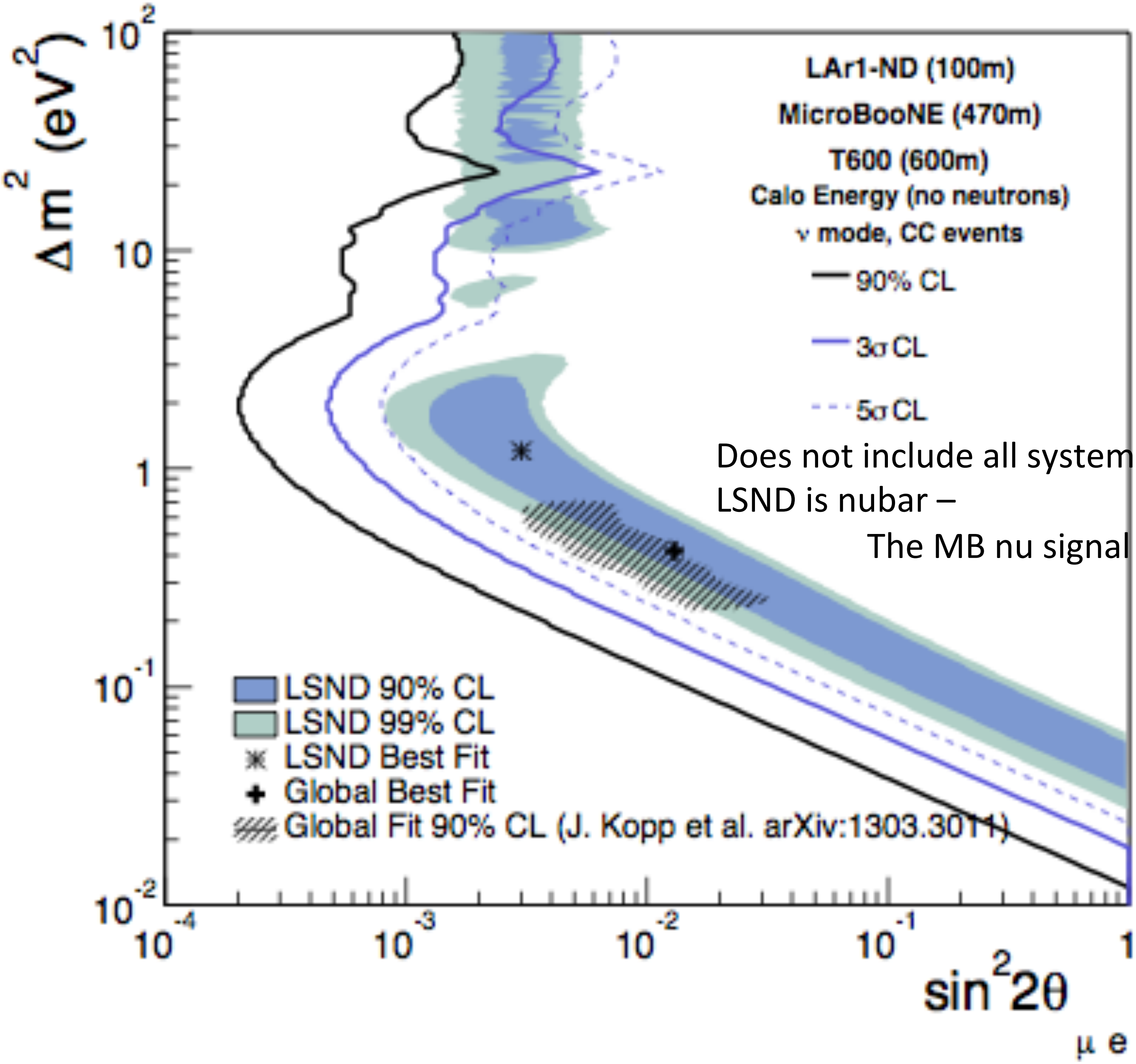
(1) If the background shape correlations with the theoretical model are not taken into account, χ^2 fits will not give correct results. The experimental χ^2 usually will not have a χ^2 distribution.

(2) Fake data studies without including these correlations will not be optimum. The use of "effective number of degrees of freedom" will help the situation, but will not be as precise as the methodology introduced here.

(3) One must use caution in applying the Maltoni-Schwetz theorem to find the compatibility of two sets of data to a theoretical model hypothesis. The theorem may incorrectly indicate incompatibility if there are correlations between the backgrounds and the theoretical model and/or if there are problems with the estimations of background variables.

“Why would you want to reach 5σ in less than a year?
It is like killing puppies with elephant guns…”

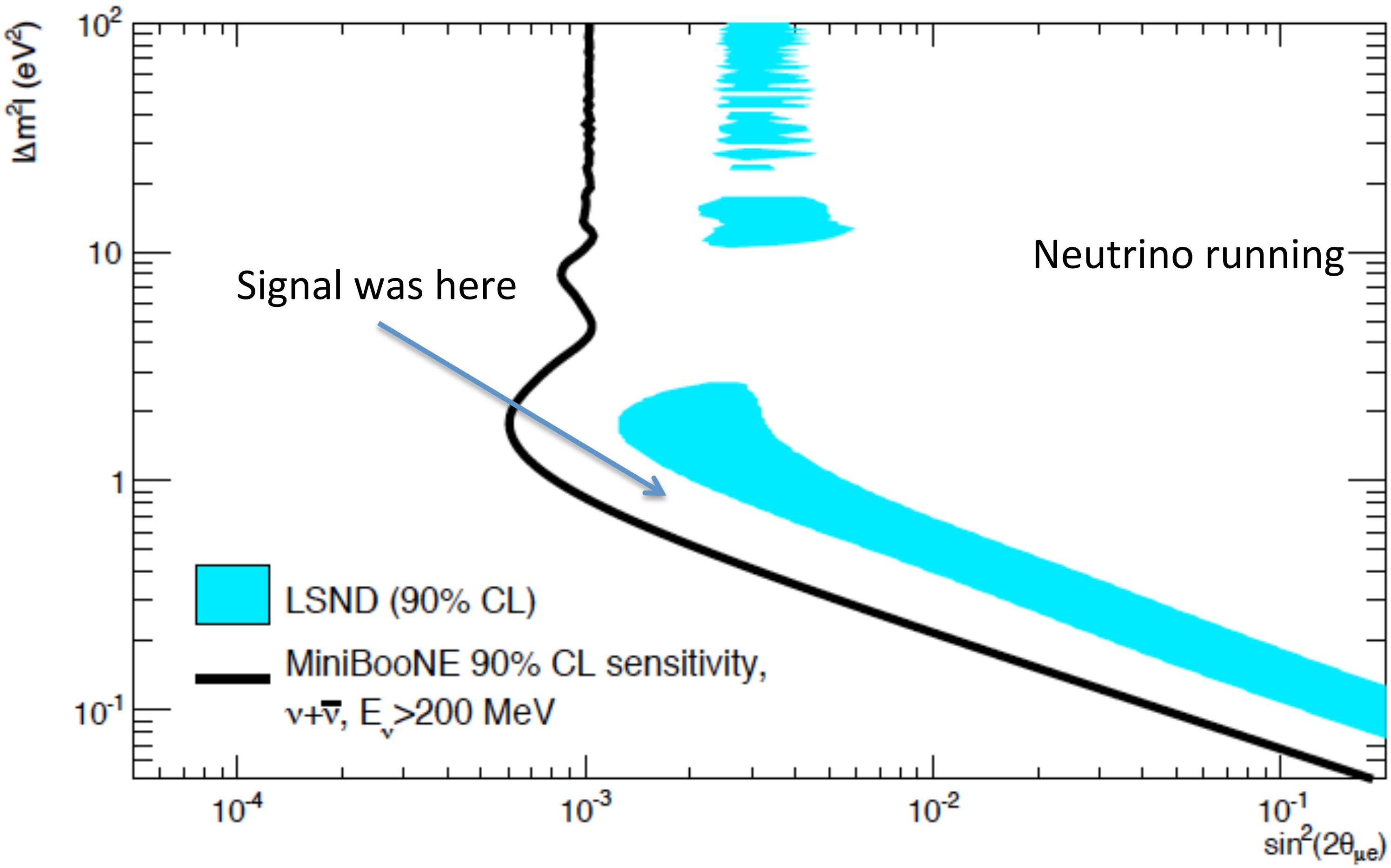
-Dave Wark

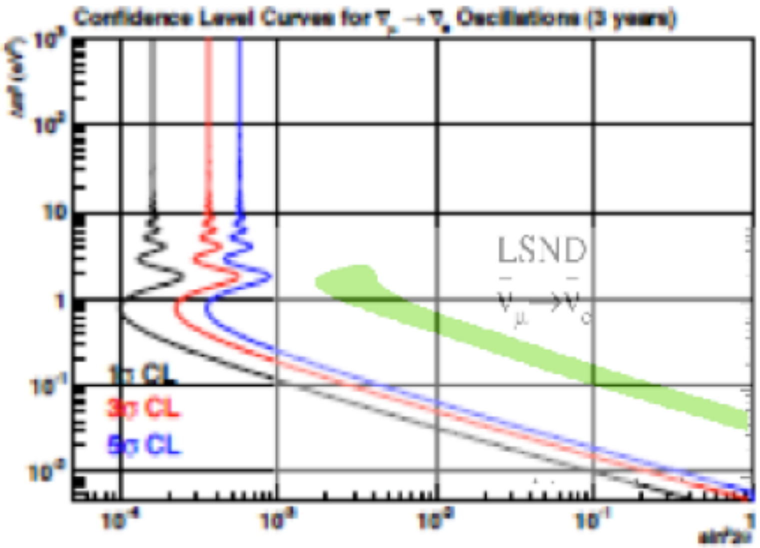


Does not include all systematics yet!
LSND is nubar –
The MB nu signal is to the left

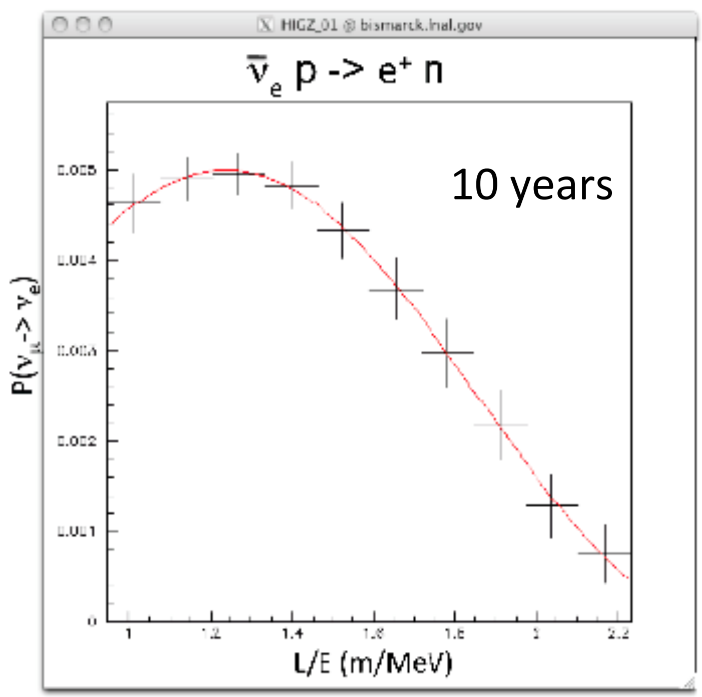
What was MiniBooNE's sensitivity*?

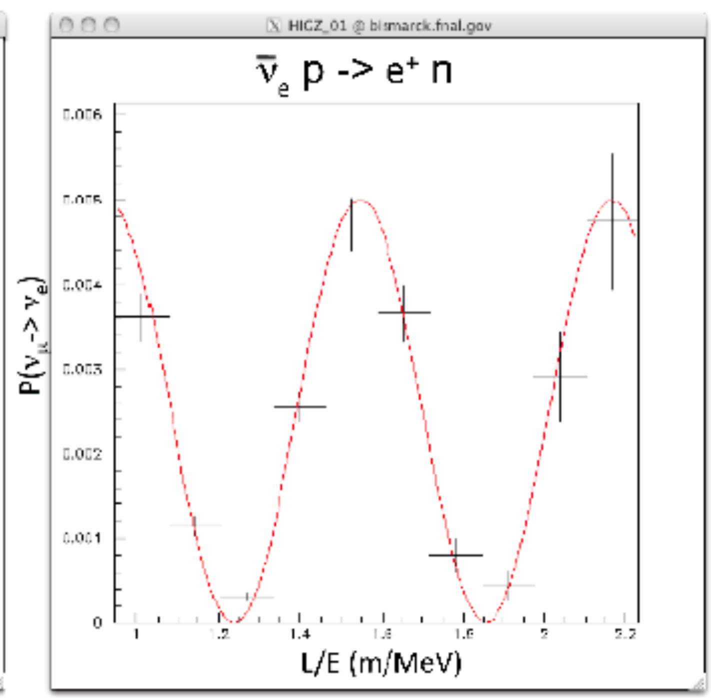
*The *actual* experimental sensitivity achieved (not from the proposal)



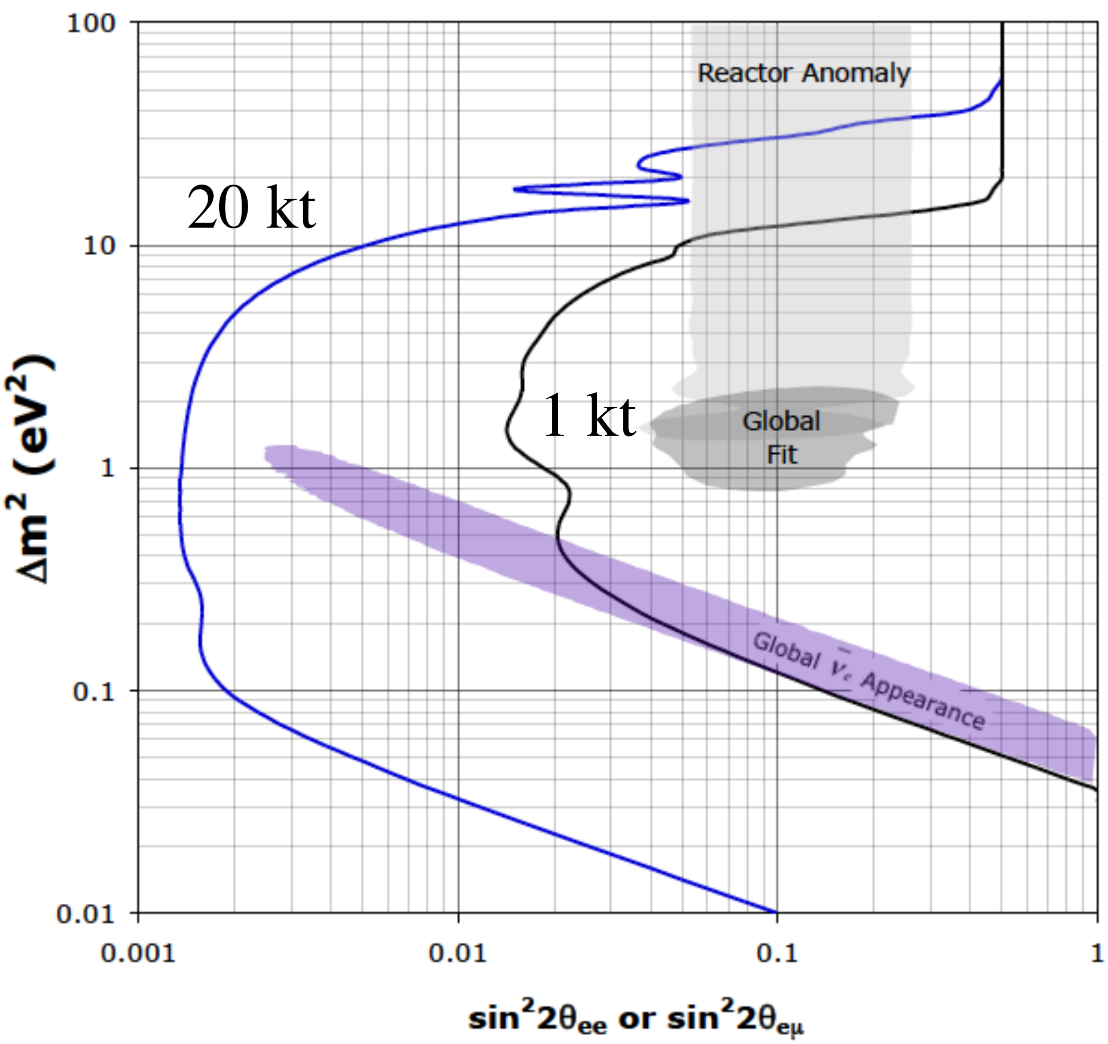

Confidence Level Curves for $\bar{\nu}_\mu \to \bar{\nu}_e$ Oscillations (3 years)
1σ CL
3σ CL
5σ CL
LSND
$\bar{\nu}_\mu \to \bar{\nu}_e$

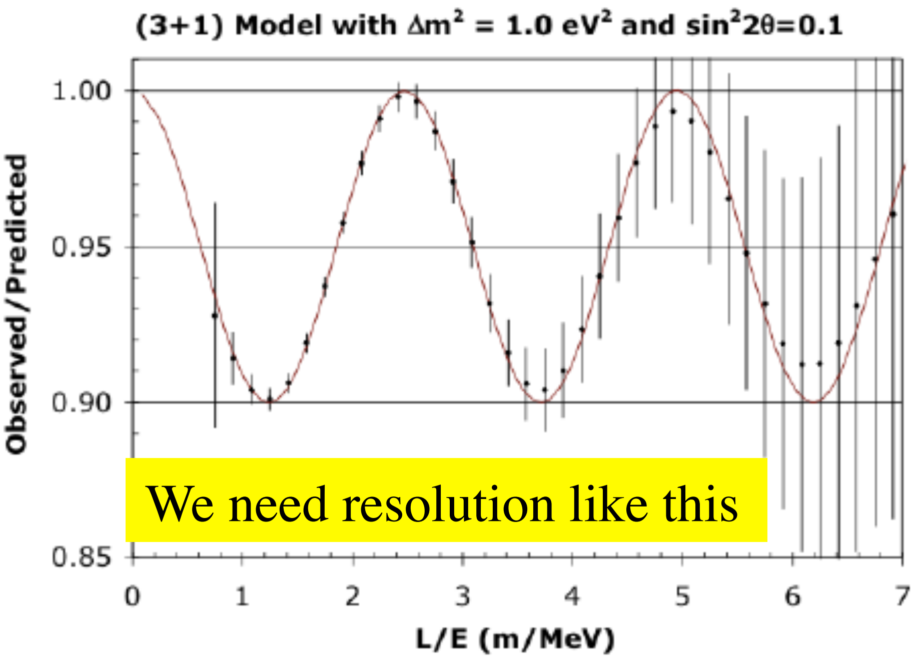
3 years

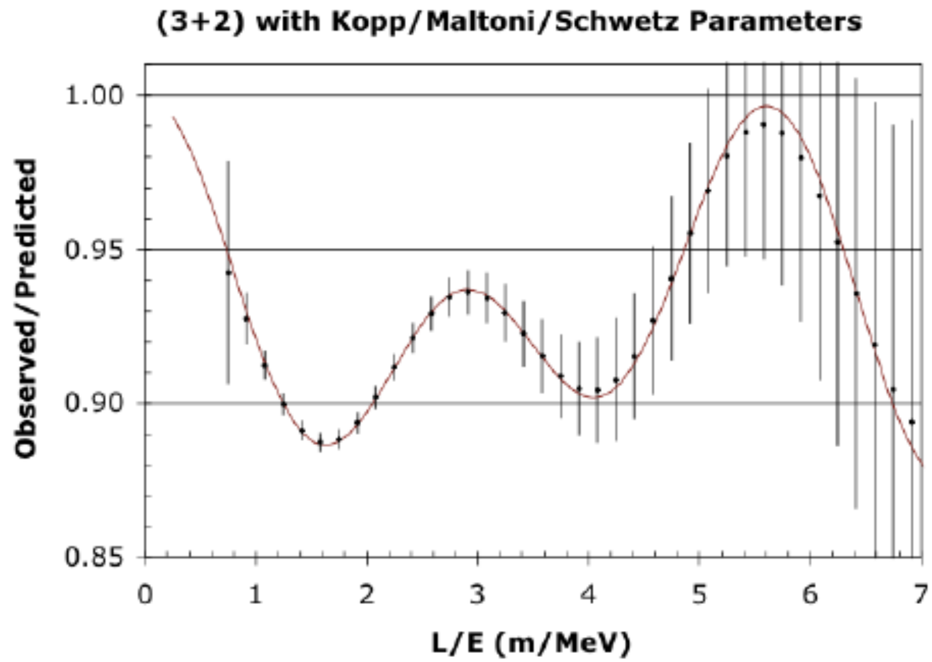

HIGZ_01 @ bismarck.fnal.gov
$\bar{\nu}_e$ p -> e+ n
10 years
P(ν_μ -> ν_e)
L/E (m/MeV)


HIGZ_01 @ bismarck.fnal.gov
$\bar{\nu}_e$ p -> e+ n
P(ν_μ -> ν_e)
L/E (m/MeV)

IsoDAR -- Fully doped scintillator – 5σ




(3+1) Model with Δm² = 1.0 eV² and sin²2θ=0.1
Observed/Predicted
L/E (m/MeV)
We need resolution like this


(3+2) with Kopp/Maltoni/Schwetz Parameters
Observed/Predicted
L/E (m/MeV)

5 years