Title: News from nu's -- Interpretations of recent neutrino anomalies

Date: May 27, 2011 01:00 PM

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Abstract: Recently, several neutrino physics has witnessed an accumulation of anomalous results. In the first part of this talk, we will discuss the tension that the MINOS experiments has seen between oscillations of neutrinos and anti-neutrinos. We will show that, phenomenologically, this tension can be explained if neutrinos are hypothesized to have new interactions mediated by higher-dimensional operators, but we will also show that problems arise when one attempts to embed these operators into renormalizable models. In the second part of the talk, we will address several results hinting at the existence of sterile neutrinos. We will present results from a global fit to worldwide neutrino oscillation data, and will show that one sterile neutrino is not enough to reconcile all data sets, and that 5-neutrino models, while being in much better agreement with the data, still have some tension.

News from ν's

Interpretations of recent neutrino anomalies

Joachim Kopp

Perimeter Institute, May 27, 2011

Fermilab

based on work done in collaboration with
Pedro Machado, Michele Maltoni, Stephen Parke, Thomas Schwetz

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Outline

1. The MINOS experiment and its results—a hint for CPT violation?
   - The MINOS experiments and (some of) its results
   - Explanation attempts

2. MiniBooNE and the reactor anti-neutrino anomaly—sterile neutrinos?
   - The reactor anti-neutrino anomaly
   - LSND and MiniBooNE
   - The Gallium anomaly
   - Global fit

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Hinchcliffe's theorem

"When a title is in the form of a question, the answer is always NO."

see, however:

IS HINCHLIFFE'S RULE TRUE?

Boris Peon

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Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

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The MINOS experiment

Beam:

- ν_μ ($\bar{\nu}_\mu$) from decay in flight of π^+ (π^-)
- Intrinsic backgrounds: wrong-sign ν_μ, ν_e from π, K, μ decays

Far detector:

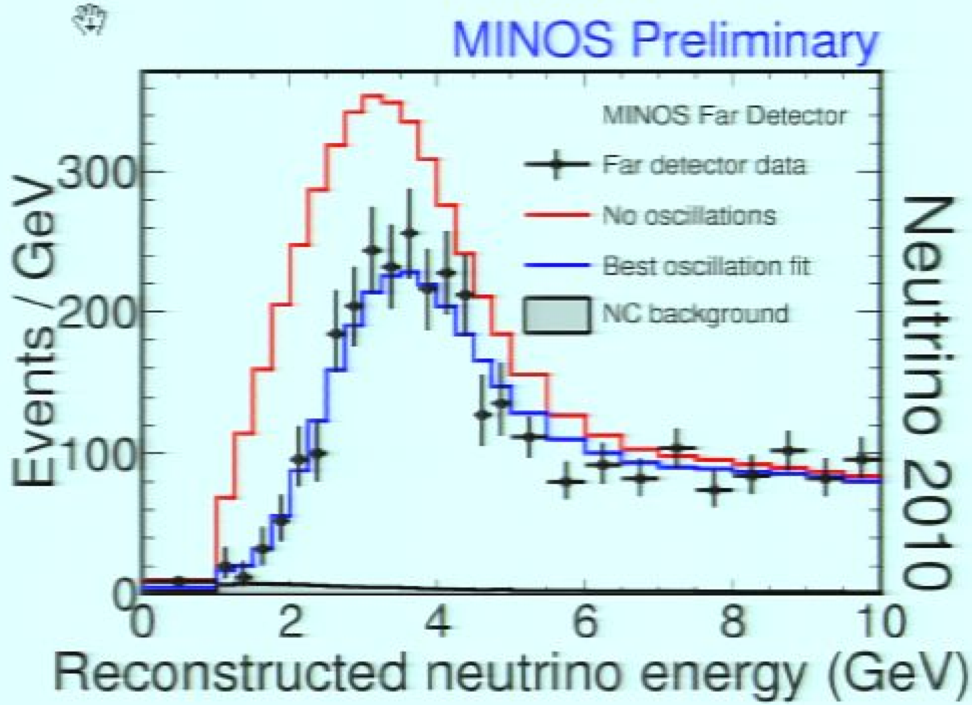
- 5.4 kt magnetized iron / solid scintillator

Near detector:

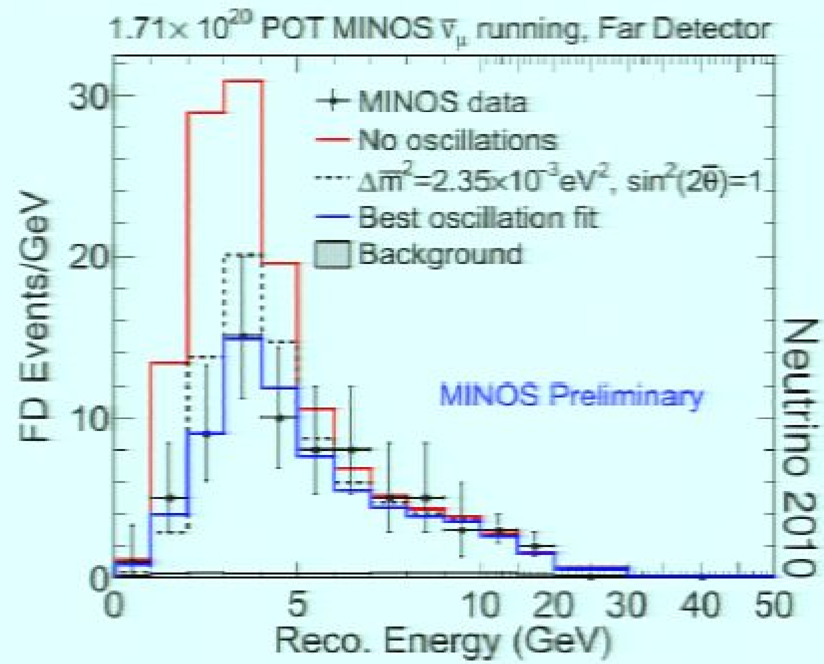
- Similar to the far detector but smaller
- Goal: Reduction of systematic uncertainties

Image credit: MINOS collaboration, http://www-numi.fnal.gov/

MINOS ν_μ, $\bar{\nu}_\mu$ disappearance data



ν_μ



$\bar{\nu}_\mu$

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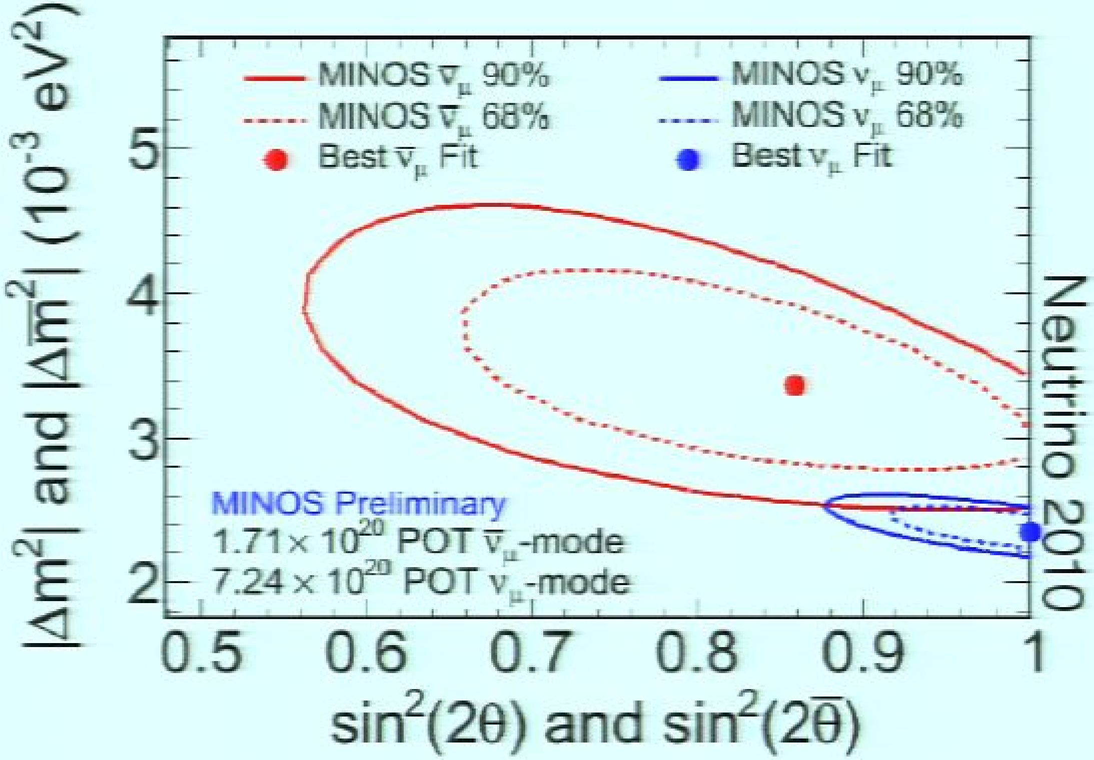
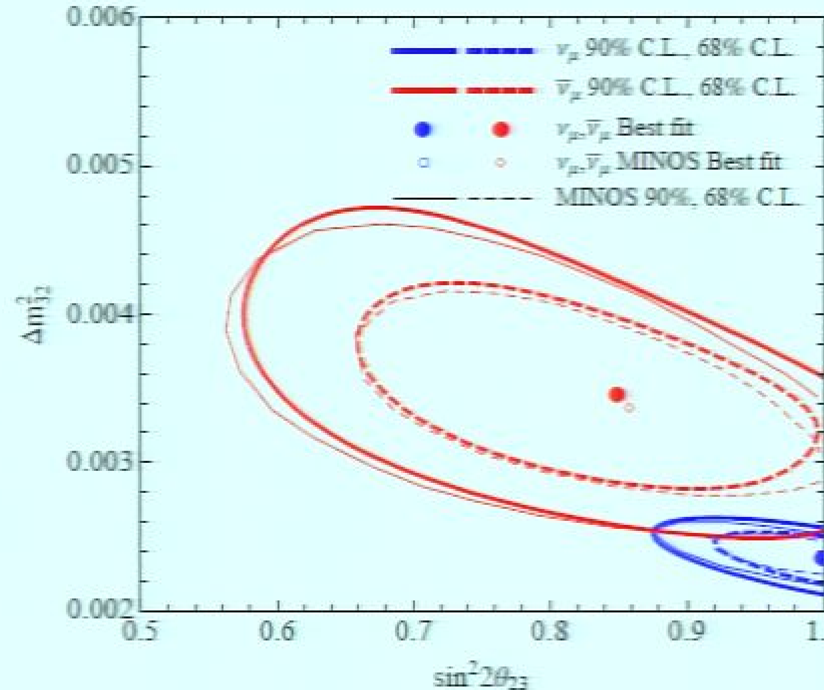
This result first presented by P. Vahle at Neutrino 2010, see also arXiv:1104.0344

MINOS oscillation fit

MINOS fit



Comparison to our fit



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- Two-flavor fits: $P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$
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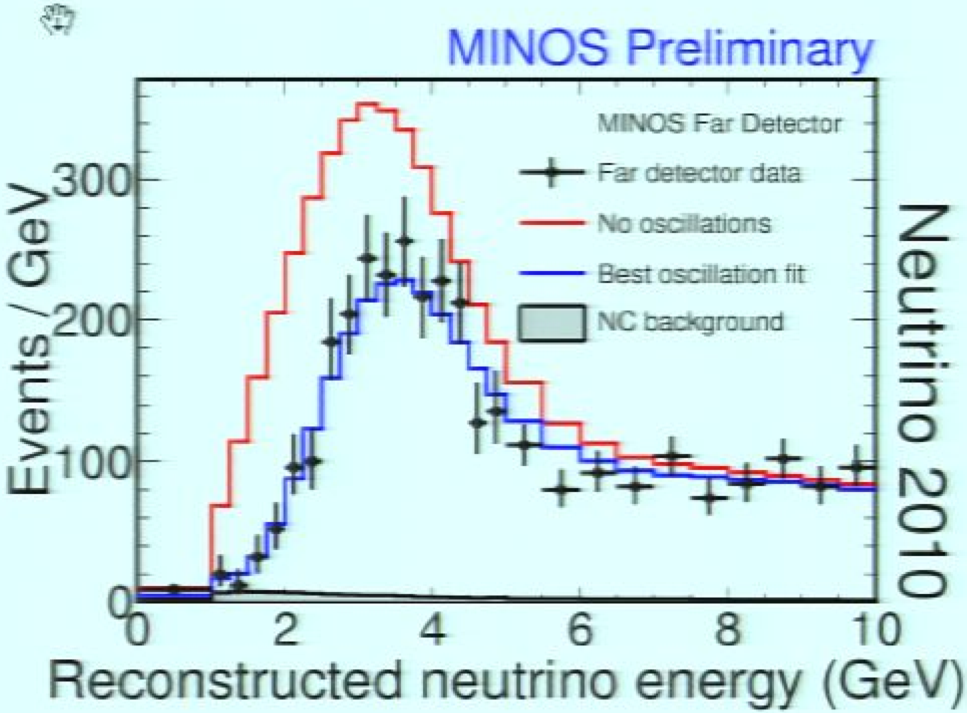

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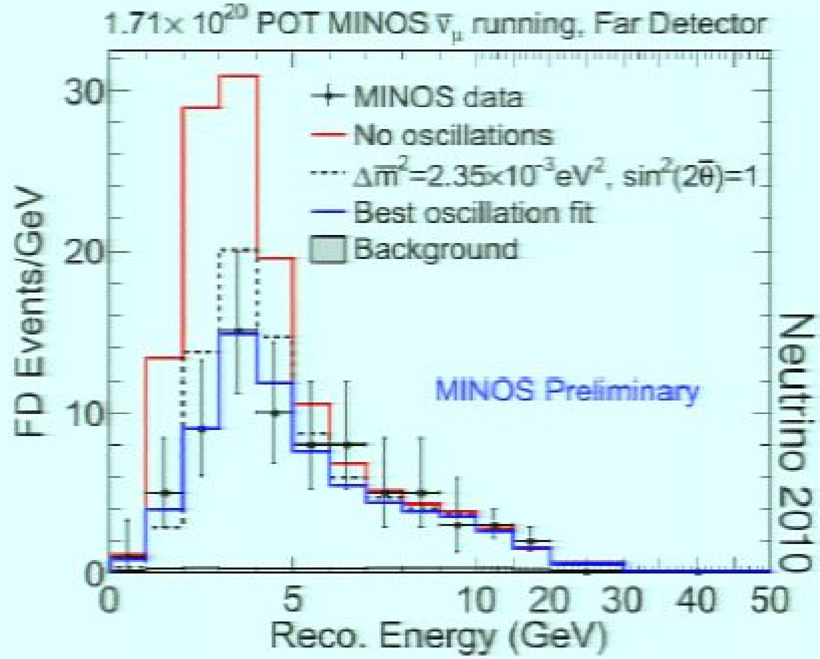

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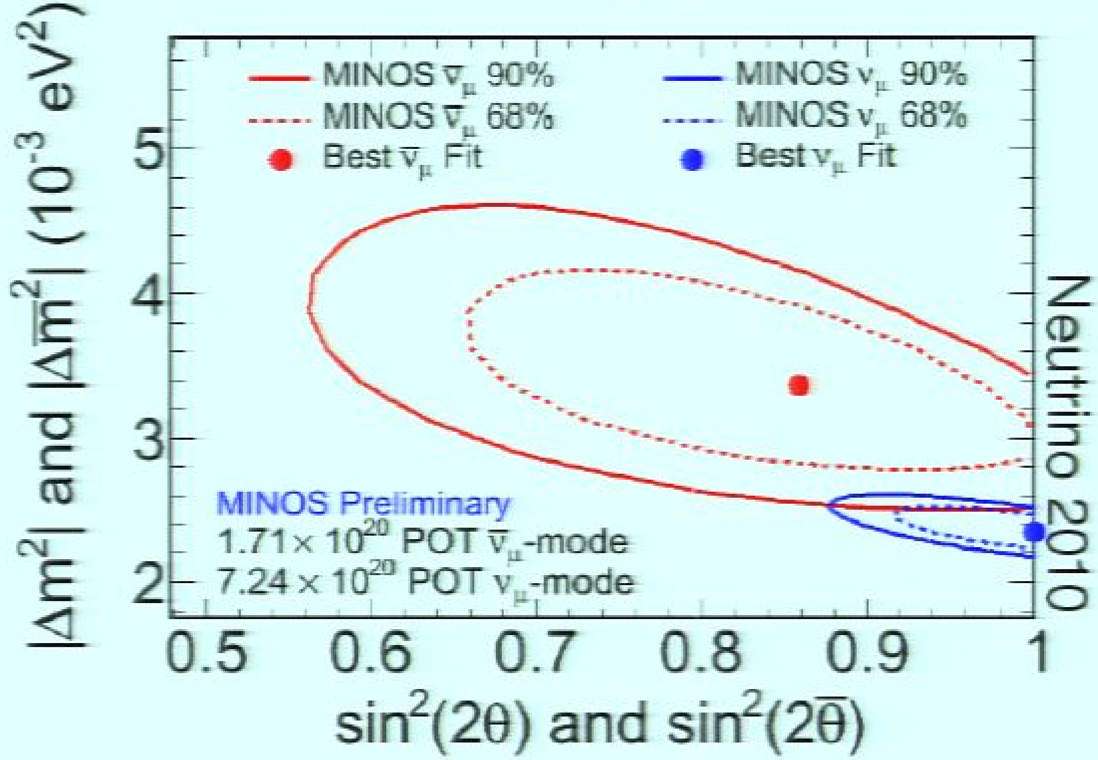

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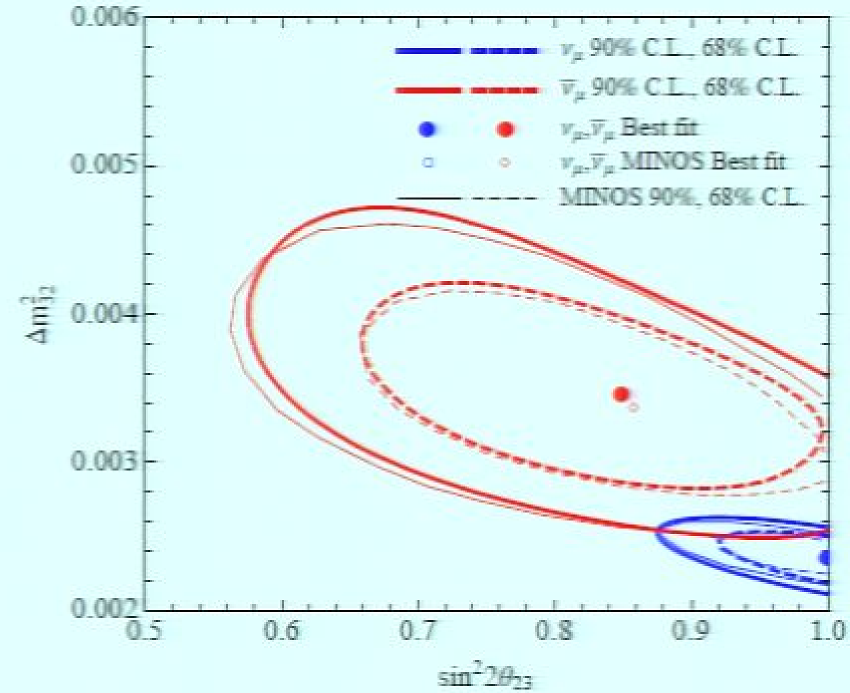

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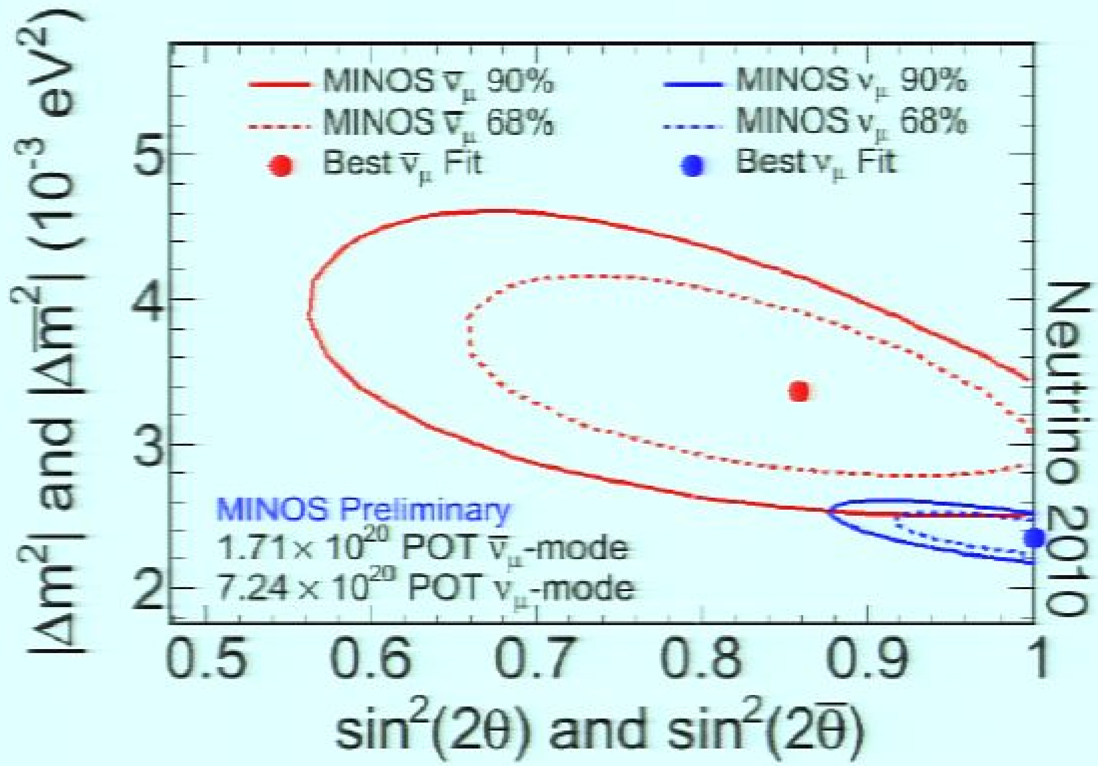

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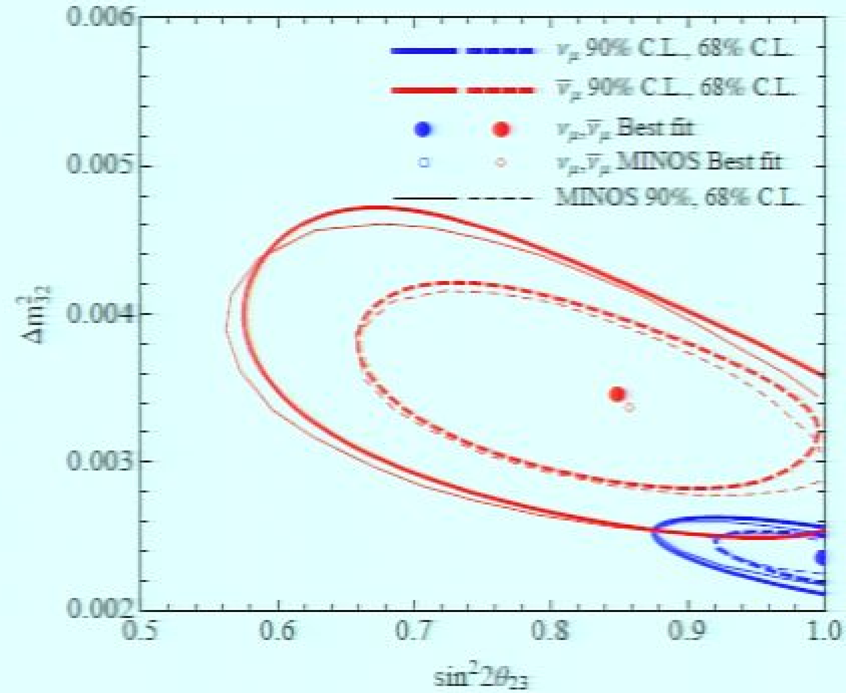

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Non-standard matter effects in the μ–τ sector

- $\Delta m^2_{\rm eff} = [(\Delta m^2_{32}\cos 2\theta_{23} + (\epsilon_{\tau\tau} - \epsilon_{\mu\mu})A)^2 + |\Delta m^2_{32}\sin 2\theta_{23} + 2\epsilon_{\mu\tau}A|^2]$

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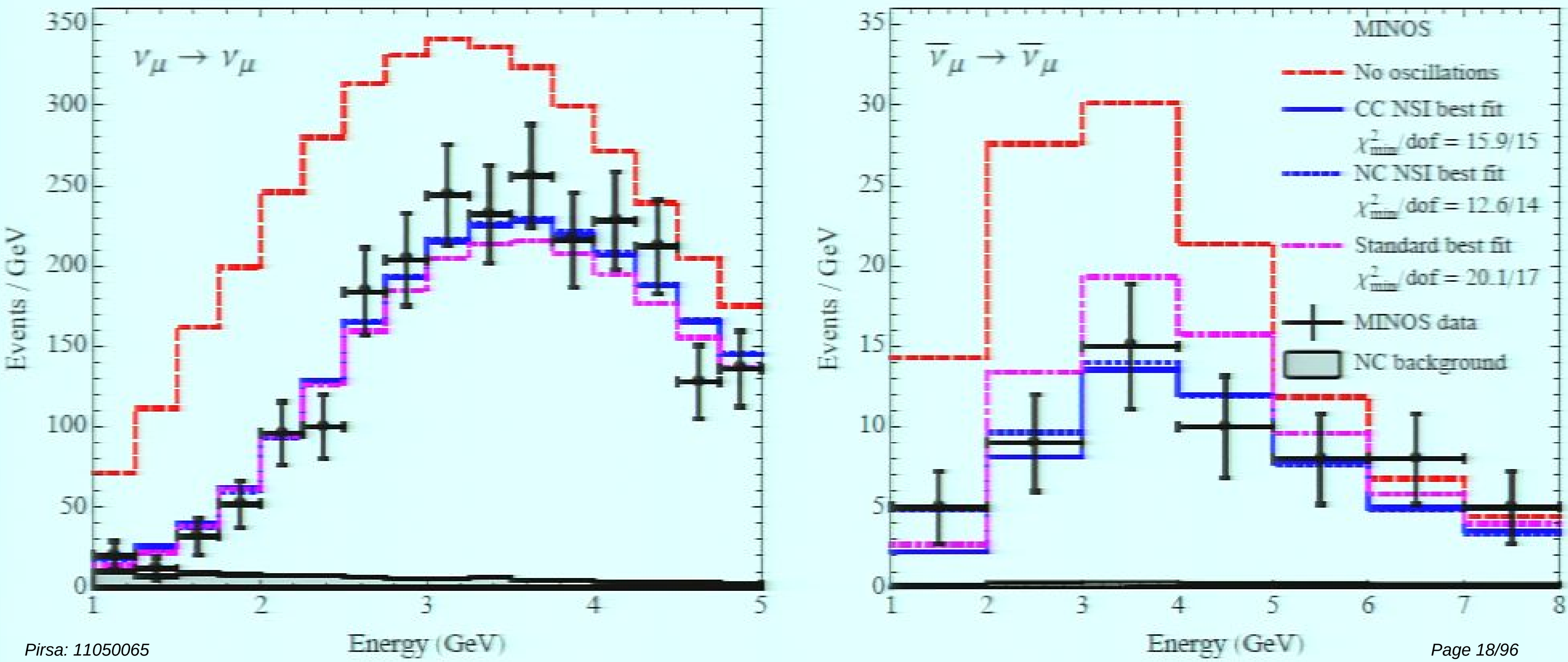

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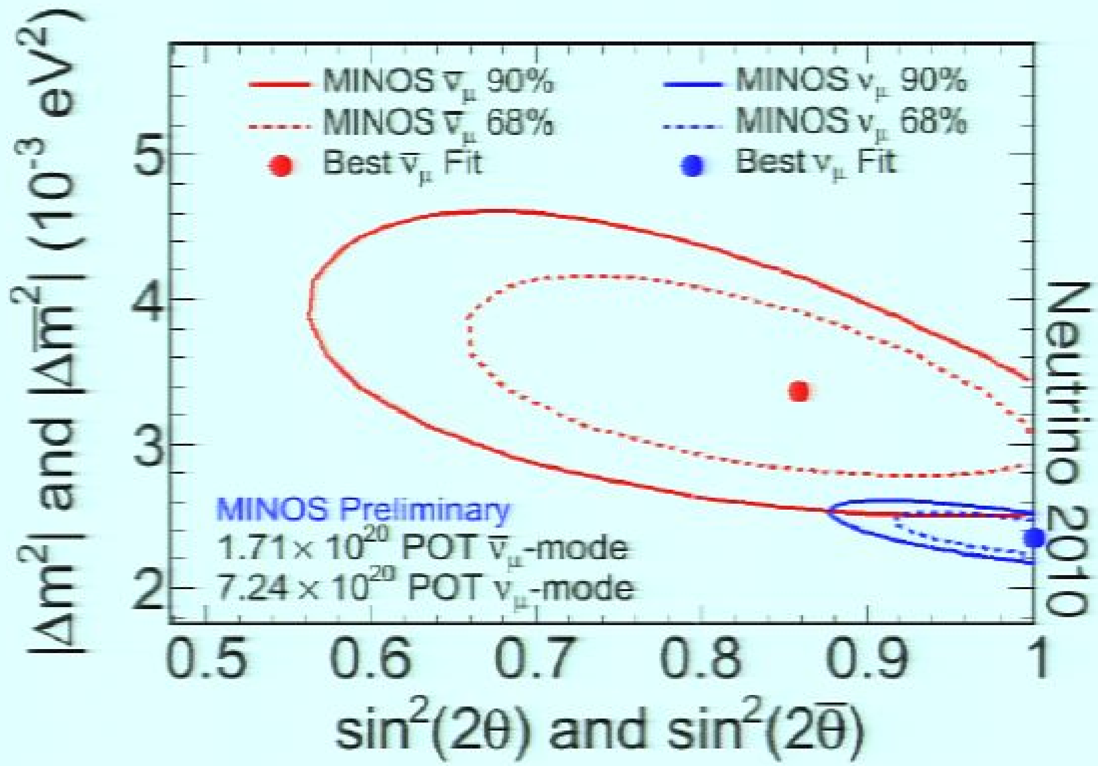

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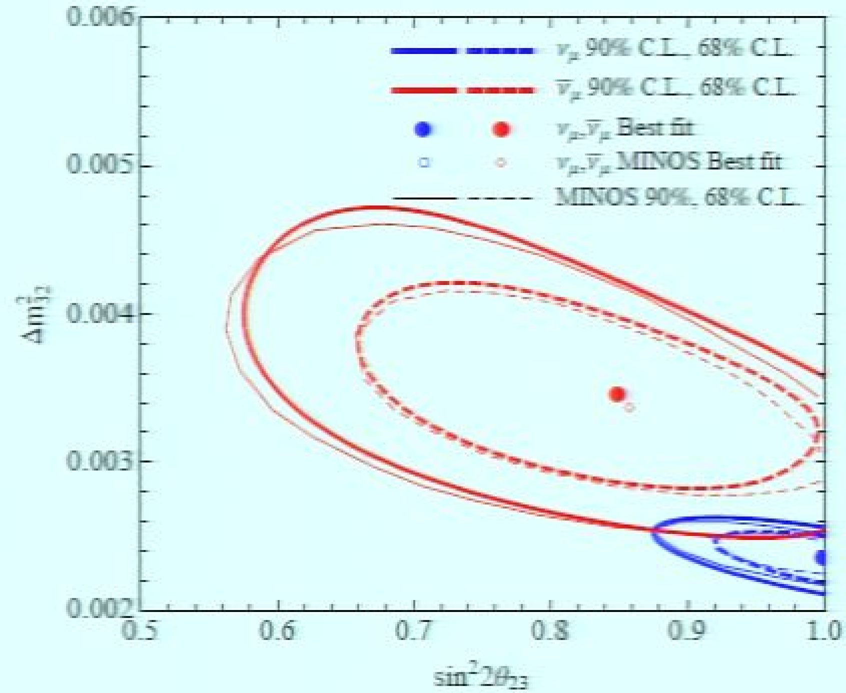

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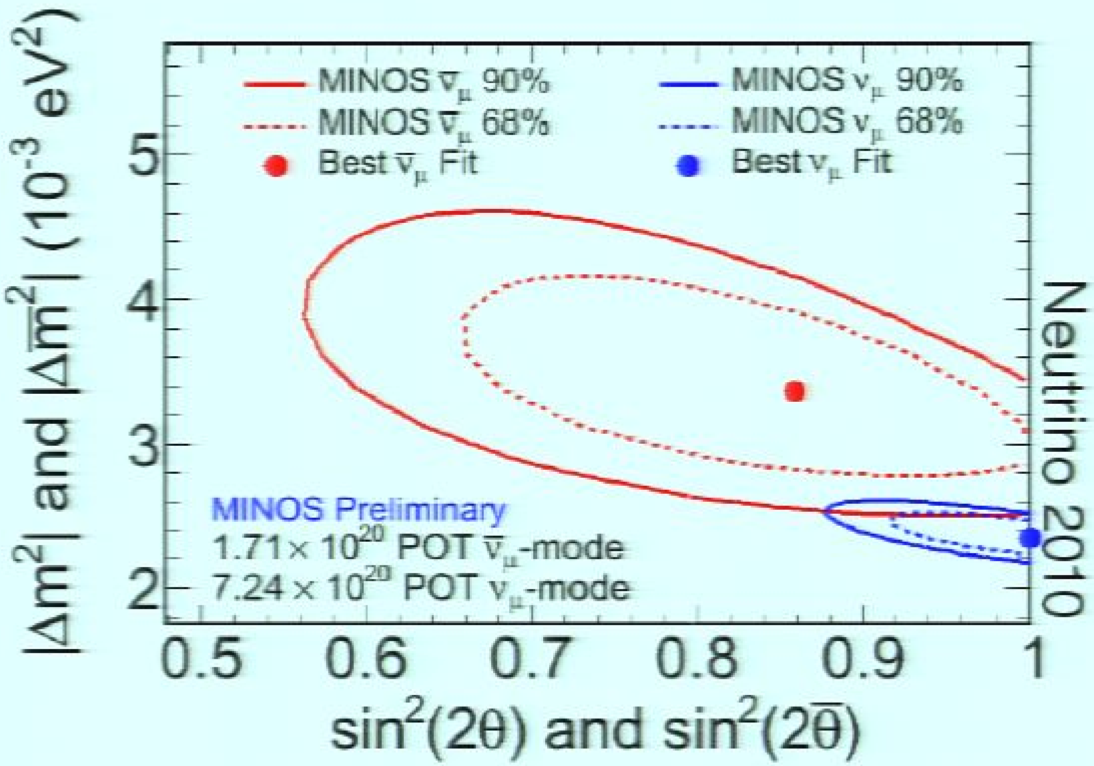

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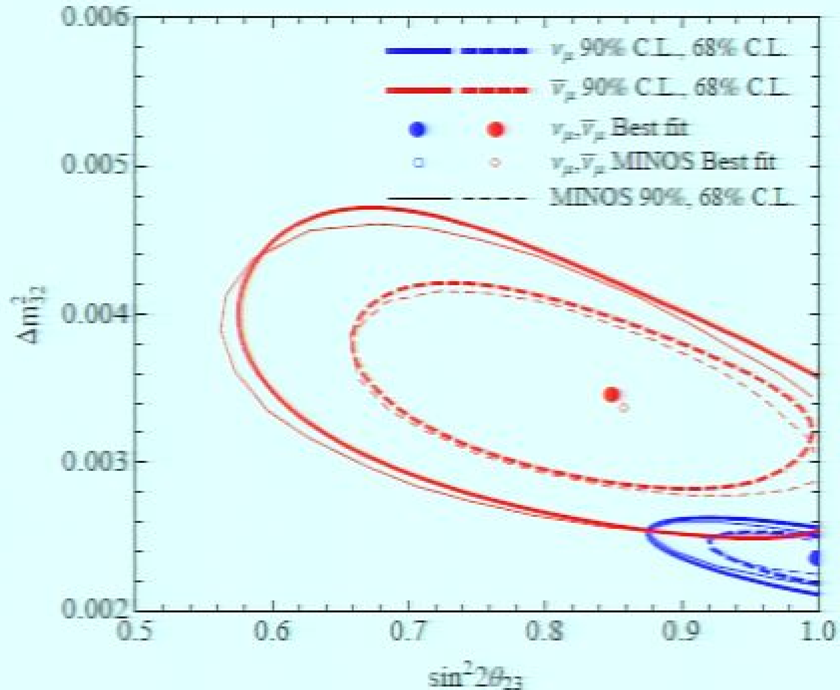

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CPT violation?

Why not just *CP* violation?

- $\nu_\mu \to \nu_\mu$ is a *T*-invariant process
- By virtue of *CPT*, it must conserve *CP*.
- Note: *CP* violation in interactions is a possibility—see later

Phenomenological parameterizations

- Assume mixing matrices for ν and $\bar{\nu}$ to be completely independent and perform global fit

Barenboim Lykken arXiv:0908.2993

- Introduce Lorentz- and *CPT*-violating operators like $A_\mu \bar{\psi} \gamma^\mu \psi$ (with A_μ a constant 4-vector)

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A model of spontaneous *CPT* violation

Mukohyama Park arXiv:1009.1251

- Ghost condensation ($\langle \partial_0 \phi \rangle \neq 0$) on a distant brane in 5D.
  $\Rightarrow$ preferred frame
- Right-handed neutrinos propagating in the bulk couple to $\partial_\mu \phi$ and to ν_L.
- After ghost-condensation, Lorentz-violating neutrino mass terms are generated.

Effective *CPT* violation: Neutrino matter effects

In the Standard Model:

$$\mathcal{L}_{\text{eff}} \sim -2\sqrt{2}G_F\left[\bar{e}\gamma^\mu P_L\nu_e\right]\left[\bar{\nu}_e\gamma_\mu P_L e\right]$$
$$\sim -2\sqrt{2}G_F\left[\bar{e}\gamma^\mu P_L e\right]\left[\bar{\nu}_e\gamma_\mu P_L\nu_e\right]$$

In ordinary matter

$$\langle\bar{e}\gamma^0 e\rangle = n_e \qquad \langle\bar{e}\vec{\gamma}e\rangle \sim \langle\vec{v}_e\rangle = 0$$
$$\langle\bar{e}\gamma^0\gamma^5 e\rangle \sim \langle\vec{\sigma}_e\vec{p}_e/E_e\rangle = 0 \qquad \langle\bar{e}\vec{\gamma}\gamma^5 e\rangle \sim \langle\vec{\sigma}_e\rangle = 0$$

Potential felt by electron neutrinos in ordinary matter:

$$V = \sqrt{2}G_F n_e$$

Sign changes for $\nu_\mu \leftrightarrow \bar{\nu}_\mu$
$\Rightarrow$ Effective *CPT* violation due to *CPT*-asymmetric background matter

In the SM, these effects are far too small to explain MINOS ν_μ disappearance data since they are suppressed by θ_{13}, $\Delta m^2_{21}/\Delta m^2_{31}$

Non-standard matter effects

Many previous works on NSI in MINOS, but mostly focussing on the $\nu_\mu \to \nu_e$ appearance channel.

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Two modes of searching for new neutrino interactions at MINOS
hep-ph/0606101

Kitazawa Sugiyama Yasuda
Will MINOS see new physics?
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Consider a neutral current (NC) non-standard interaction (NSI) of the form

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leading to off-diagonal (flavor-violating) and/or non-universal matter potential. In the flavor basis,

$$V = \sqrt{2}G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} .$$

The oscillation probability is

$$P(\nu_\alpha \to \nu_\beta) = \left|\langle\nu_\beta|e^{-iHt}|\nu_\alpha\rangle\right|^2, \quad H = \frac{1}{2E}U\begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix}U^\dagger + V \,.$$

For $\bar{\nu}$: $U \to U^*, V \to -V$

$\Rightarrow$ Effective CPT violation

Non-standard matter effects in the μ–τ sector

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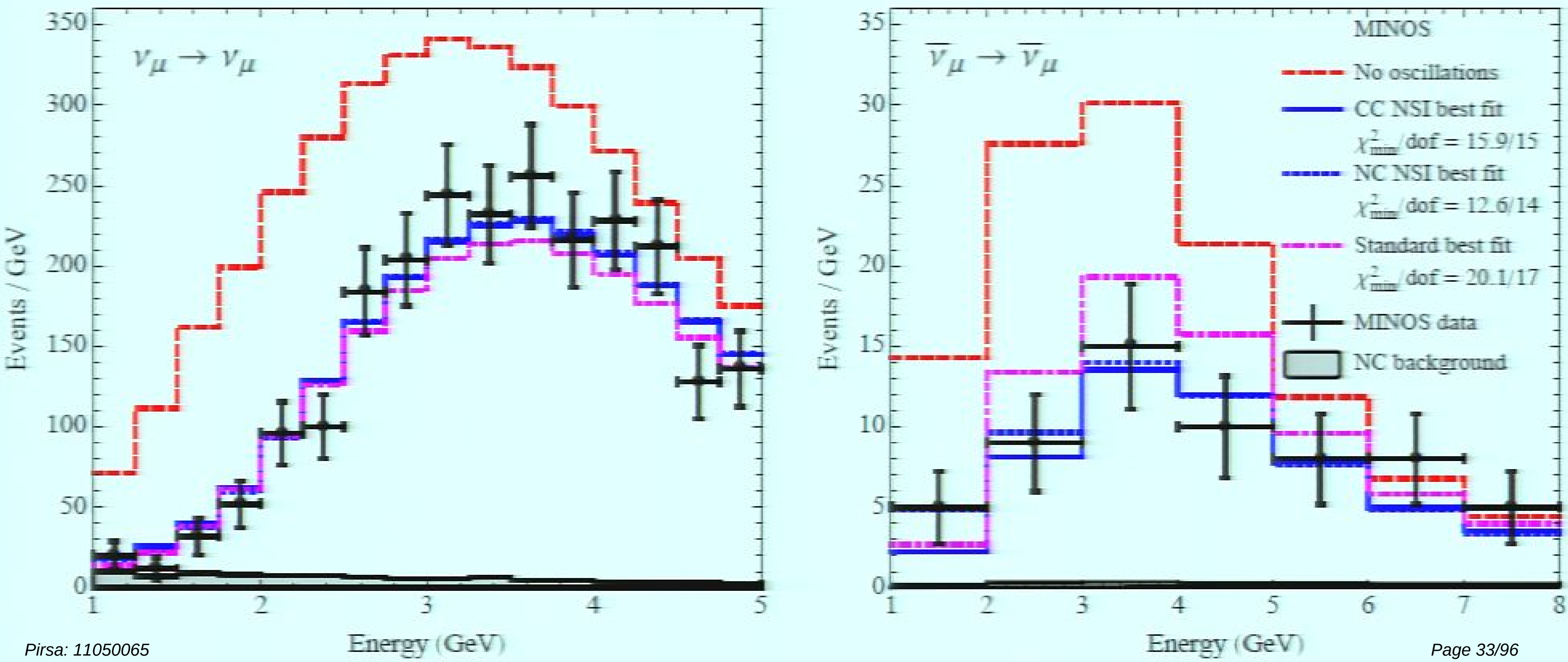

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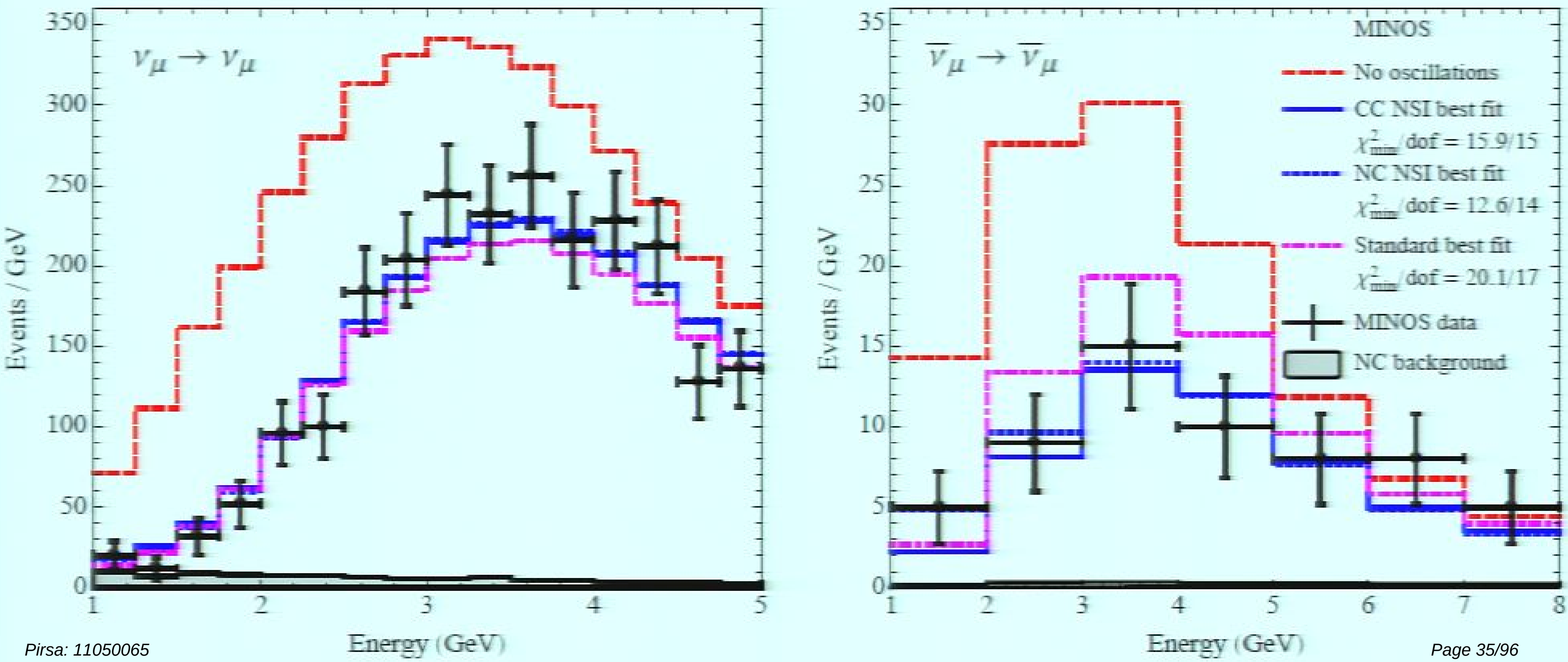

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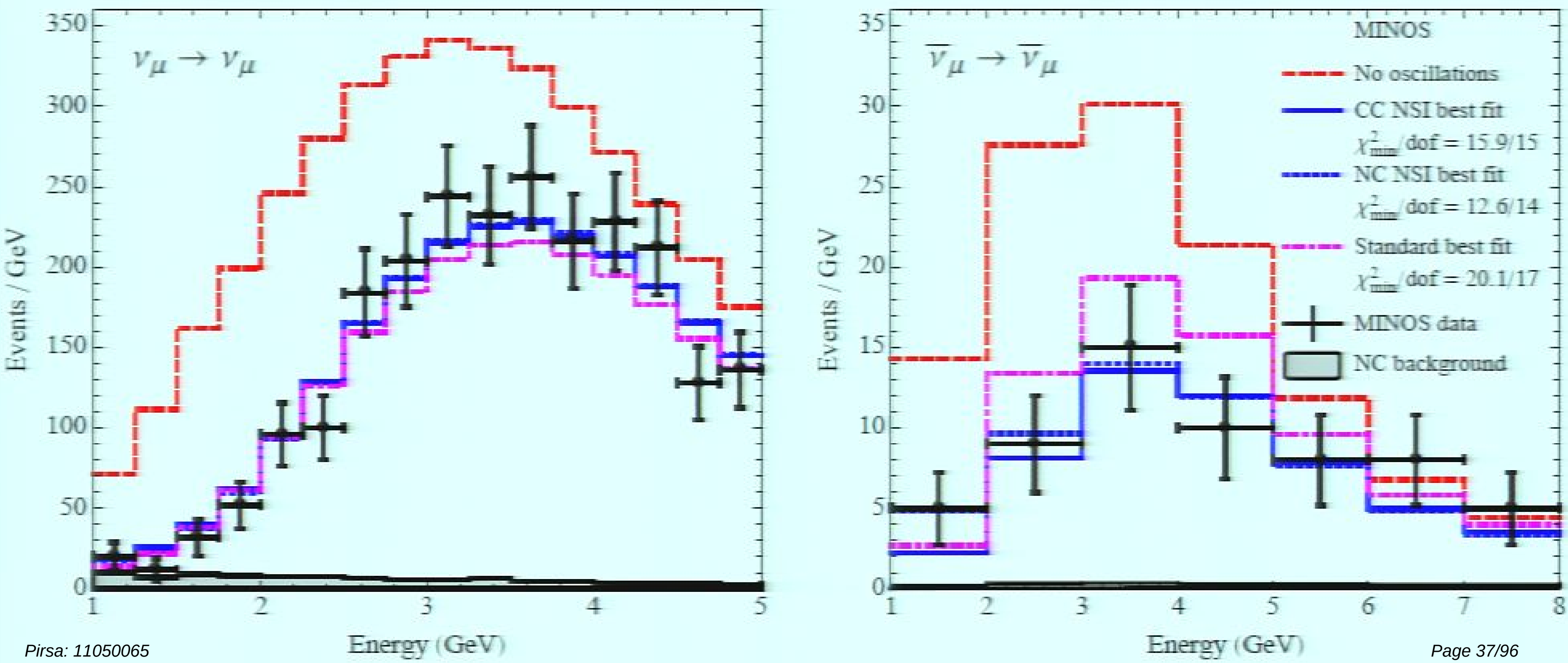
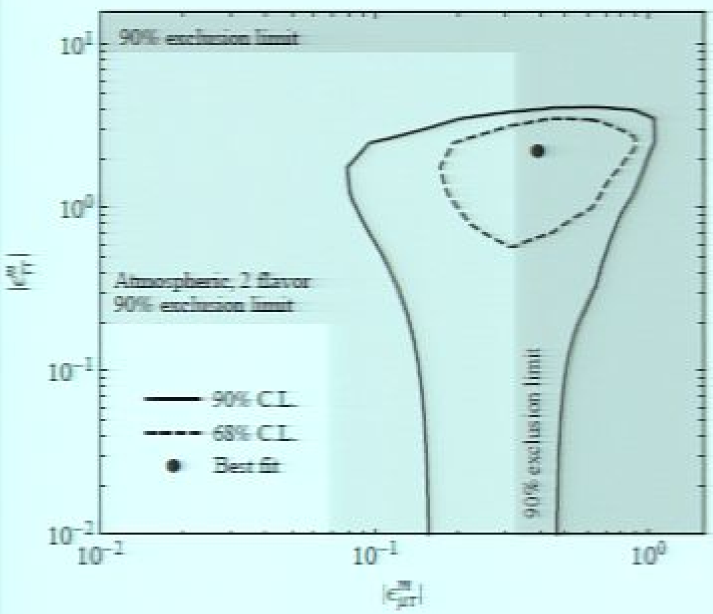
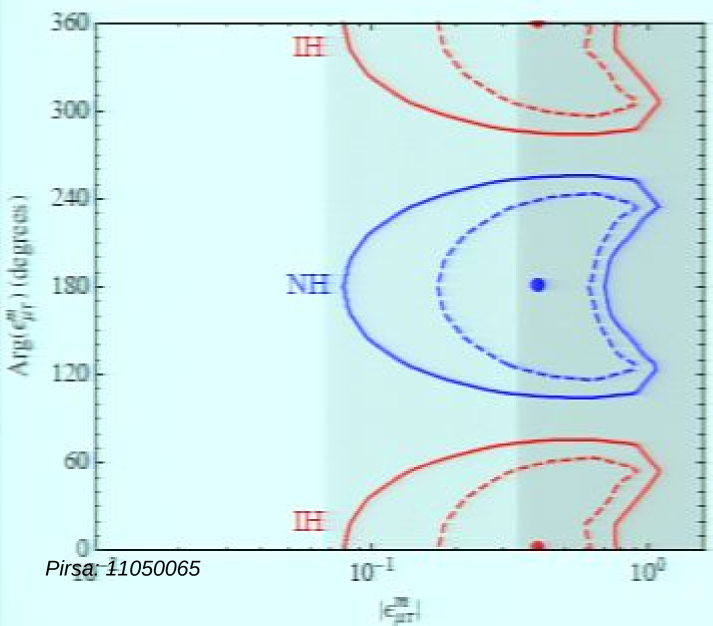
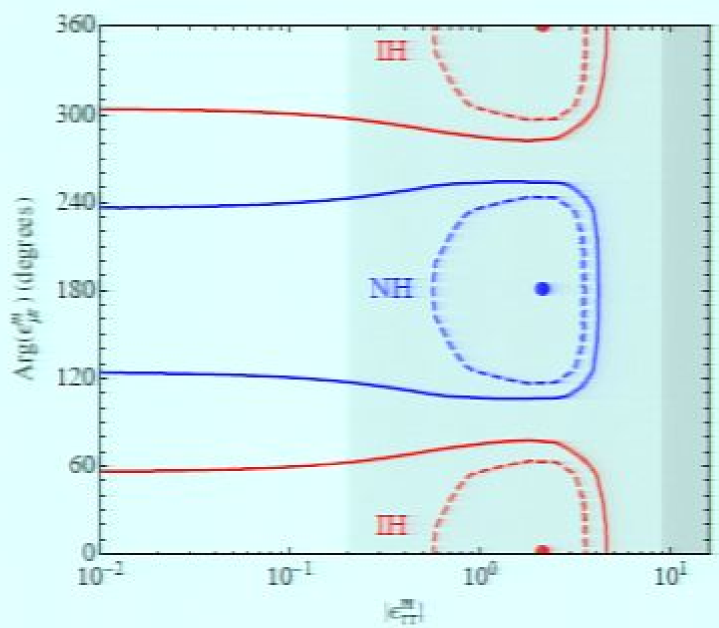


Non-standard matter effects in the μ–τ sector (2)



- $|\epsilon| \gtrsim 0.1$ required (almost as strong as SM weak interactions)
- Consistent with constraints on $\epsilon_{\mu\tau}$ from CHARM ($\nu_\mu e \to \nu e$) and NuTeV ($\nu_\mu q \to \nu q$)
- Consistent with constraints on $\epsilon_{\tau\tau}$ from $\Gamma_{\text{inv}}^{Z^0}$
- Disfavored by atmospheric neutrinos (These are 2-flavor limits, may not be robust)
- Model-dependent constraints: See later





Similar analysis performed by Mann Cherdack Musial Kafka arXiv:1006.5720

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Non-standard matter effects

Consider a neutral current (NC) non-standard interaction (NSI) of the form

$$\mathcal{L}_{\rm NSI} \sim -2\sqrt{2} G_F \epsilon^f_{\alpha\beta} \left[\bar{f}\gamma^\mu f\right]\left[\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta\right] \qquad\qquad f = e, \mu, \tau \,,$$

leading to off-diagonal (flavor-violating) and/or non-universal matter potential. In the flavor basis,

$$V = \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} .$$

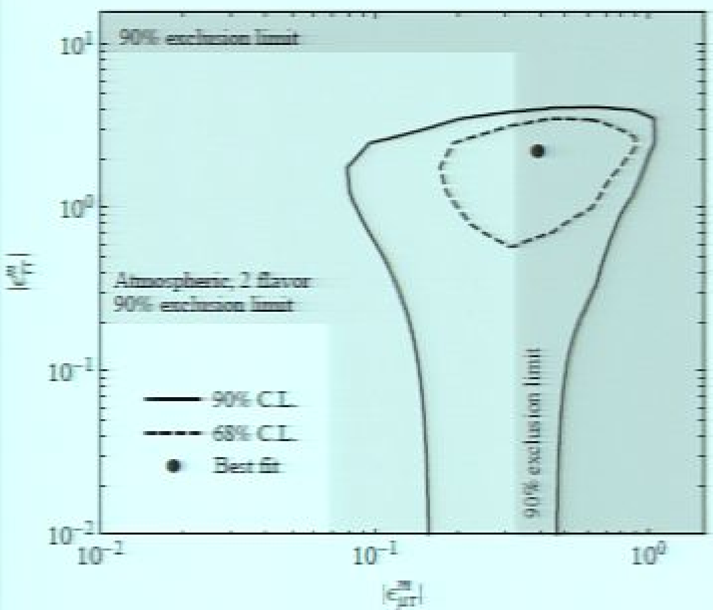
The oscillation probability is

$$P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | e^{-iHt} | \nu_\alpha \rangle\right|^2, \quad H = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger + V \,.$$

For $\bar{\nu}$: $U \to U^*, V \to -V$

$\Rightarrow$ Effective CPT violation

Non-standard matter effects in the μ–τ sector (2)



- $|\epsilon| \gtrsim 0.1$ required (almost as strong as SM weak interactions)
- Consistent with constraints on $\epsilon_{\mu\tau}$ from CHARM ($\nu_\mu e \to \nu e$) and NuTeV ($\nu_\mu q \to \nu q$)
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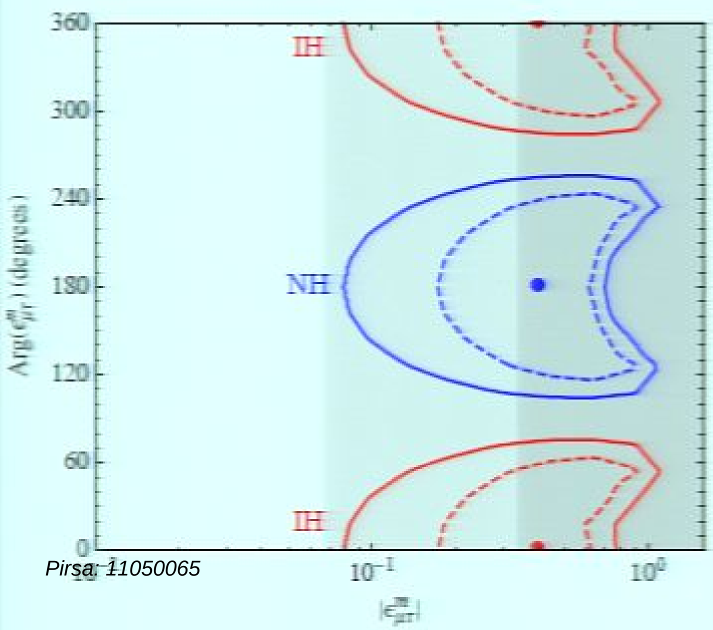

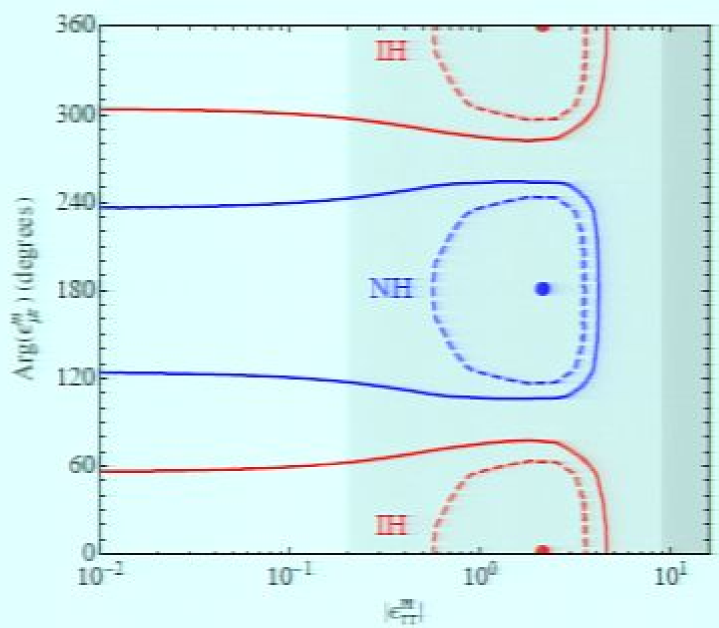

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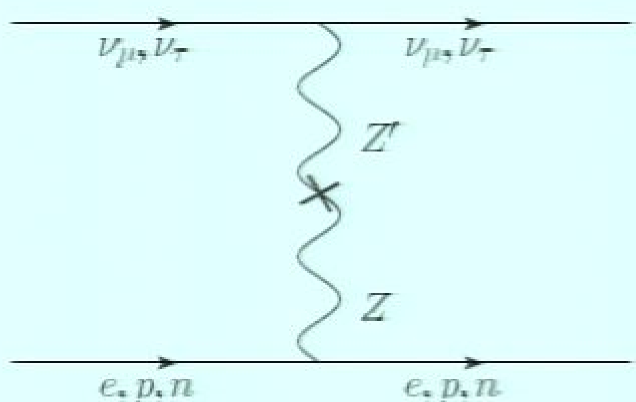
A new long-range force?

Heeck Rodejohann arXiv:1007.2655
Davoudiasl Lee Marciano arXiv:1102.5352

- A very light $L_\mu - L_\tau$ or $B - L_e - 2L_\tau$ gauge boson Z' ($m_{Z'} \lesssim 10^{-18}$ eV ~ 1 a.u.$^{-1}$)
- Very weak couplings ($\alpha \lesssim 10^{-50}$)
- Mixing with the SM Z



- ν_μ, ν_τ feel potential generated by the Sun (contribution from the Earth is ~ 3 times smaller)
- Since the Sun contains no anti-matter, and since ν and $\bar{\nu}$ have opposite $L_\mu - L_\tau$ and $B - L_e - 2L_\tau$ charges), this leads to effective CPT violation.
- Phenomenologically equivalent to $\epsilon_{\mu\mu}$, $\epsilon_{\tau\tau}$.

A CP-violating charged current interaction?

- Remeber: $\nu_\mu \to \nu_\mu$ is CP-invariant
- But: π(source) $\to ??? \to \mu$(detector) does not have to be.
- Two possibilities
  - Modified ν_μ flux at far detector, but not at near detector.
    ν_τ contamination in the NuMI beam?
    $\Rightarrow$ Ruled out by NOMAD.
  - A new interaction of the form

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    e.g.

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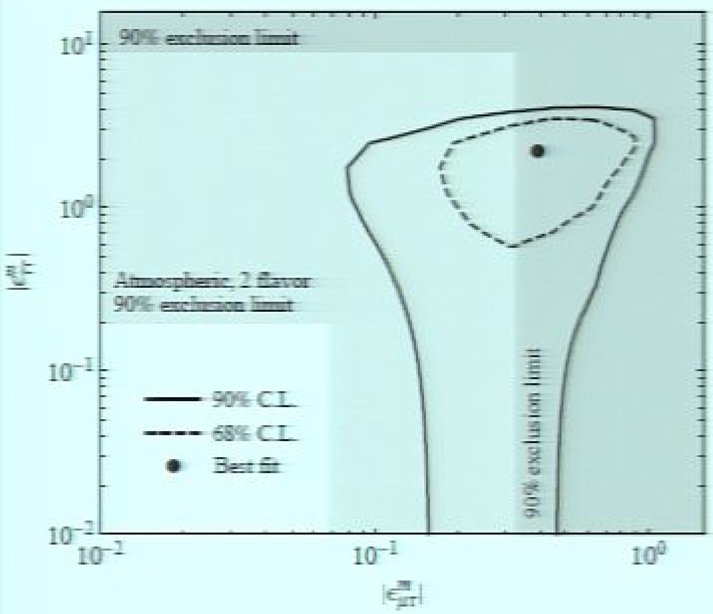

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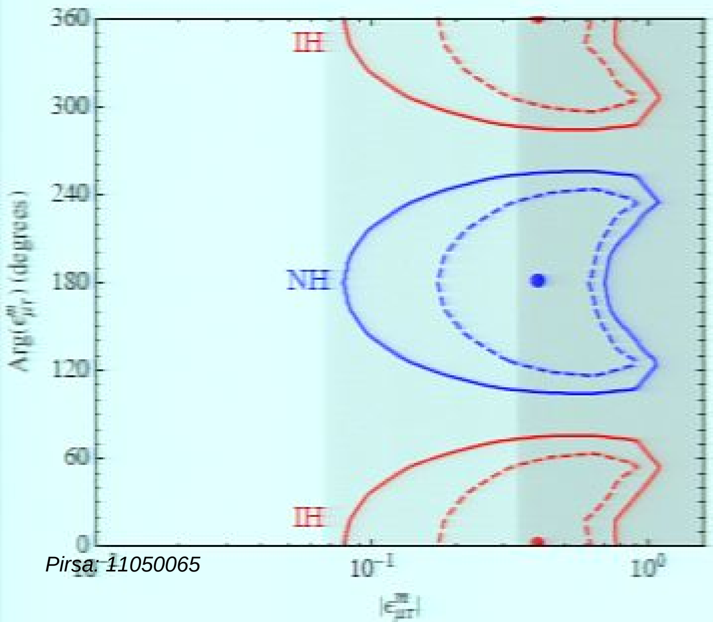

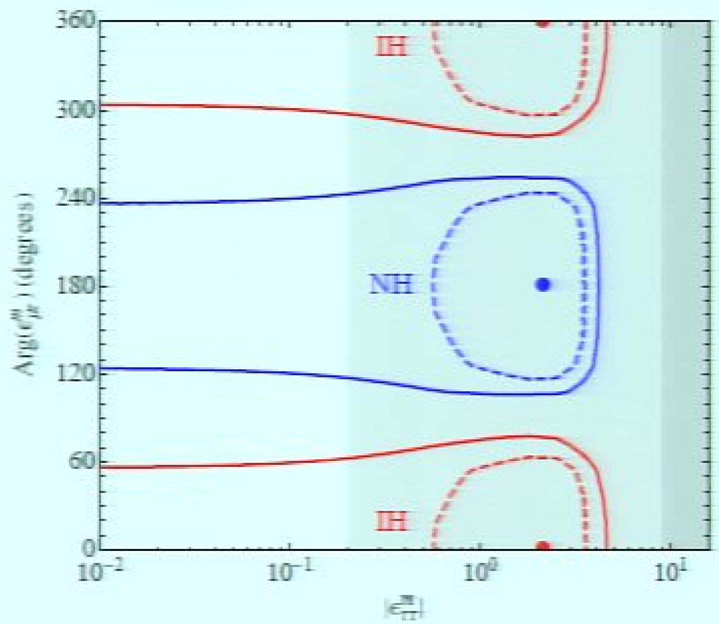

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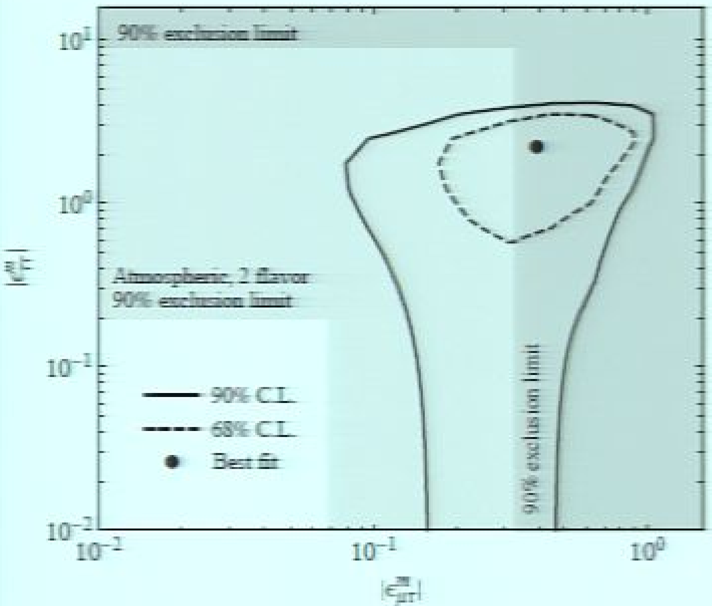

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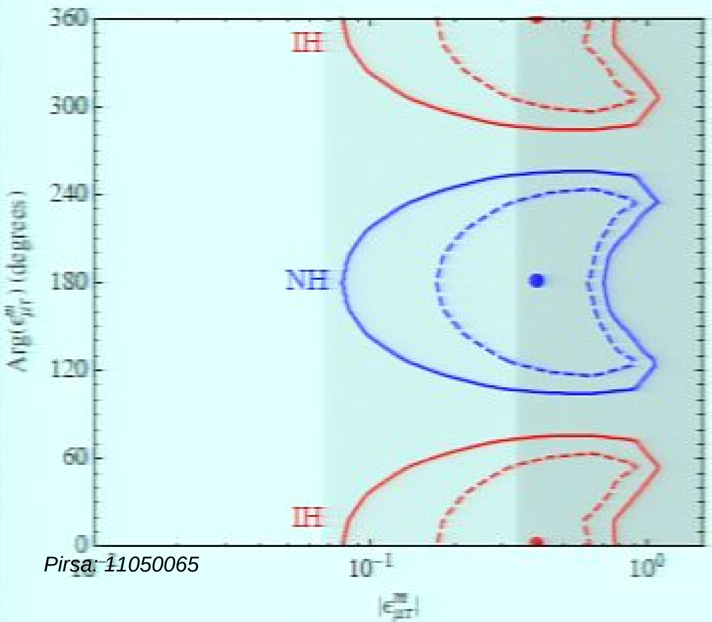

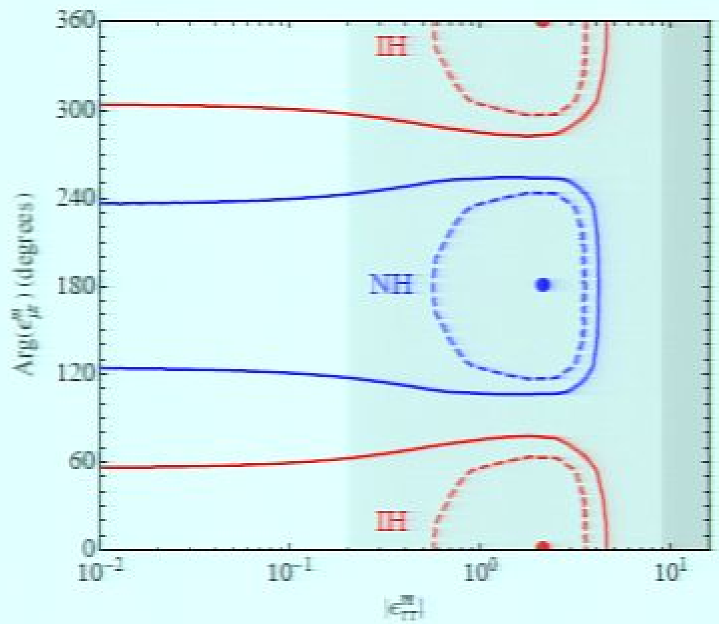

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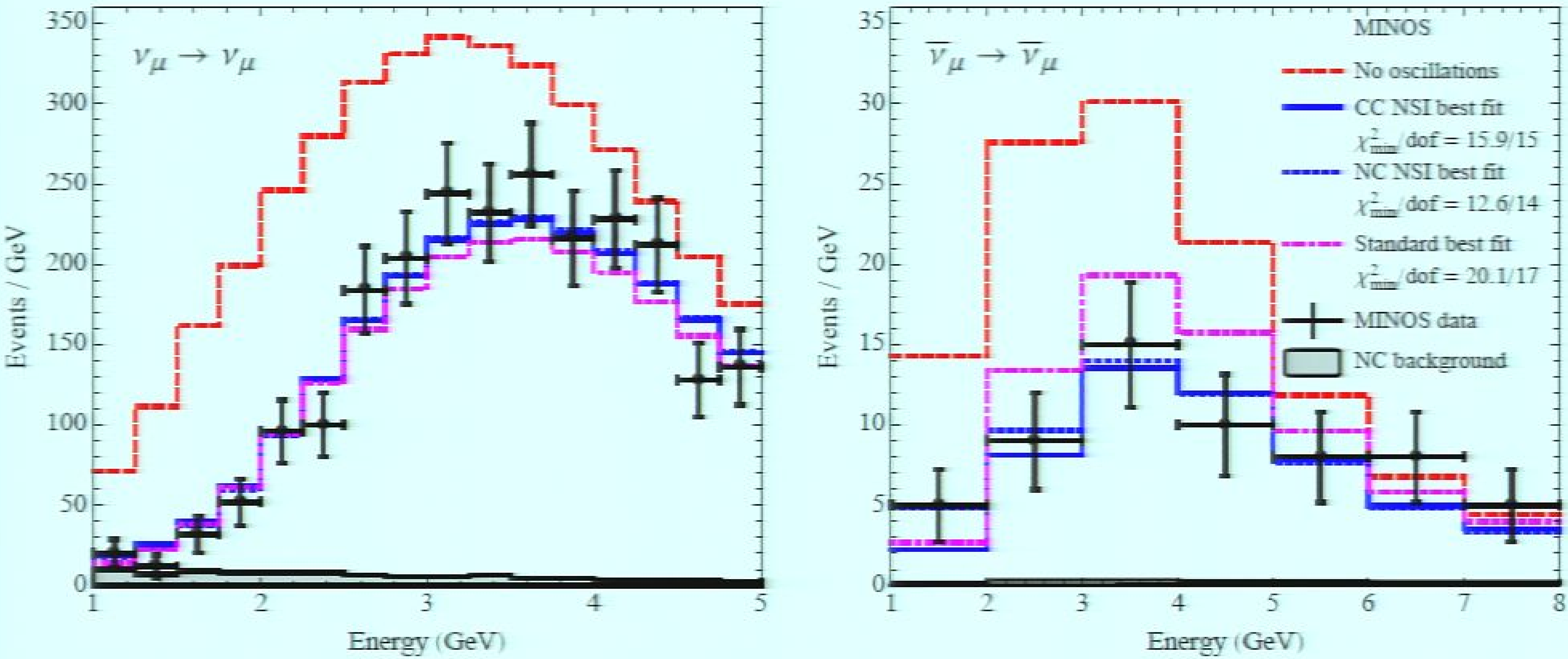

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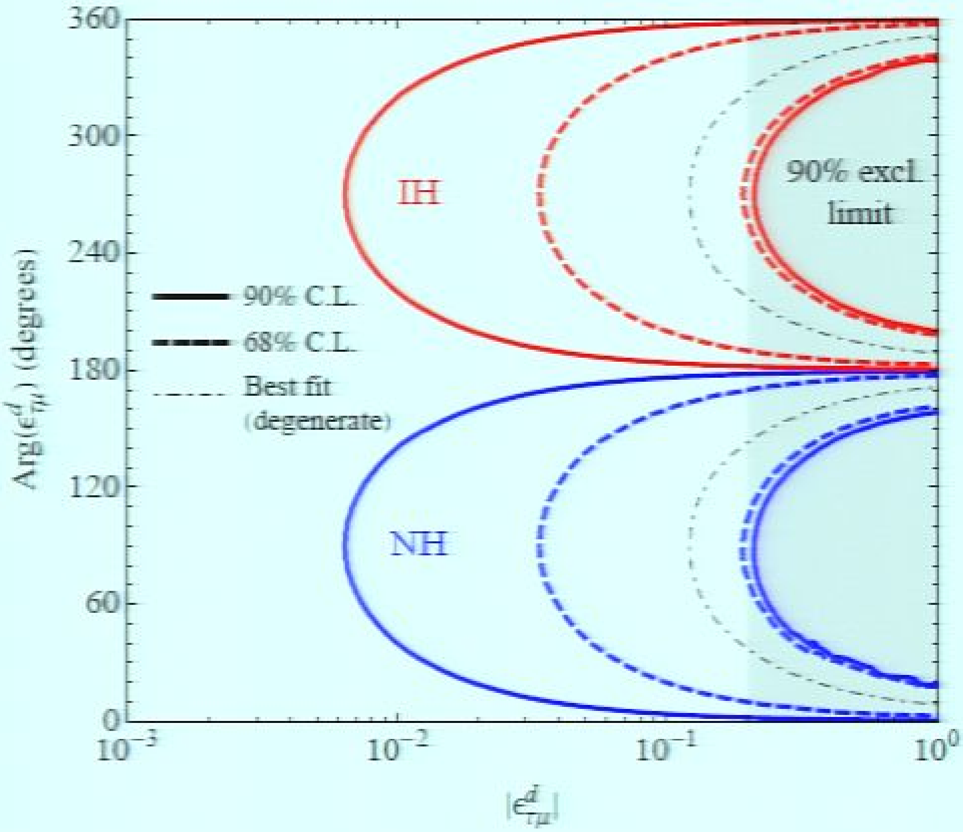

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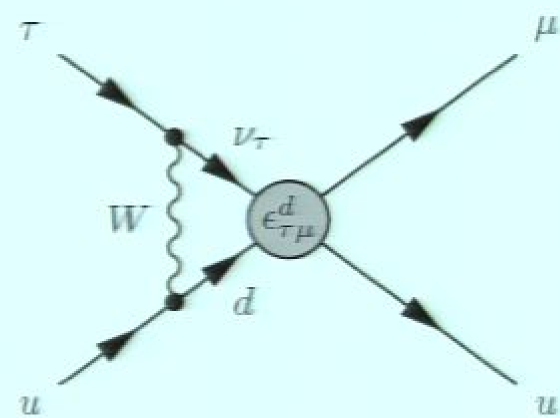

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- $SU(2)$ invariant operators for neutrino NSI are usually accompanied by charged lepton NSI, which are heavily constrained.
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see e.g. Antusch Baumann Fernández-Martínez arXiv:0807.1003
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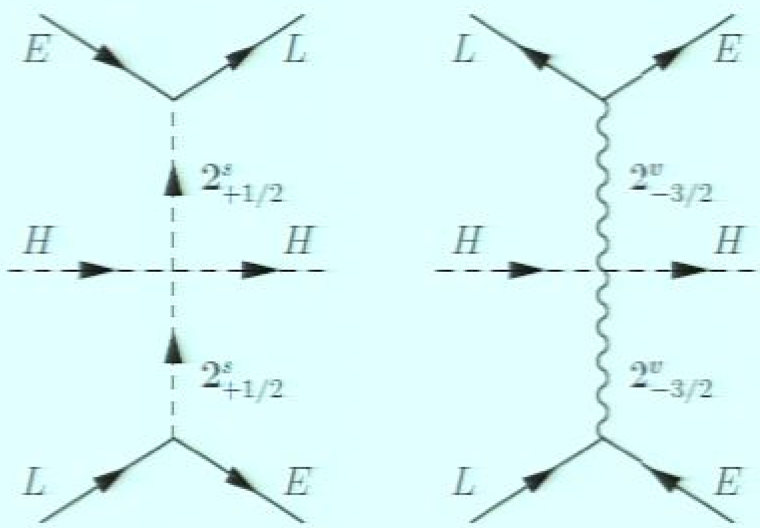

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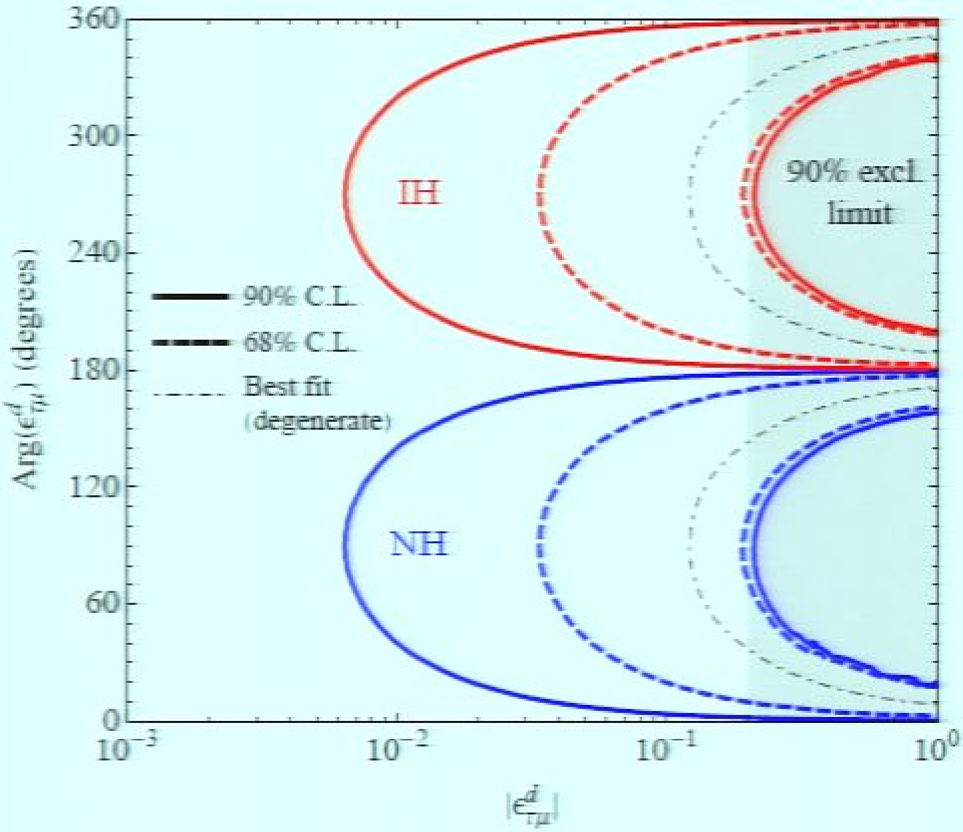

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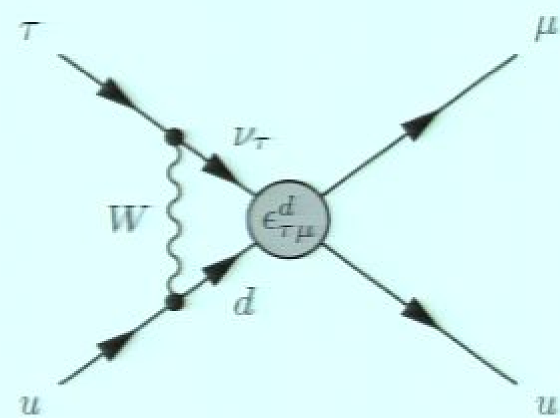

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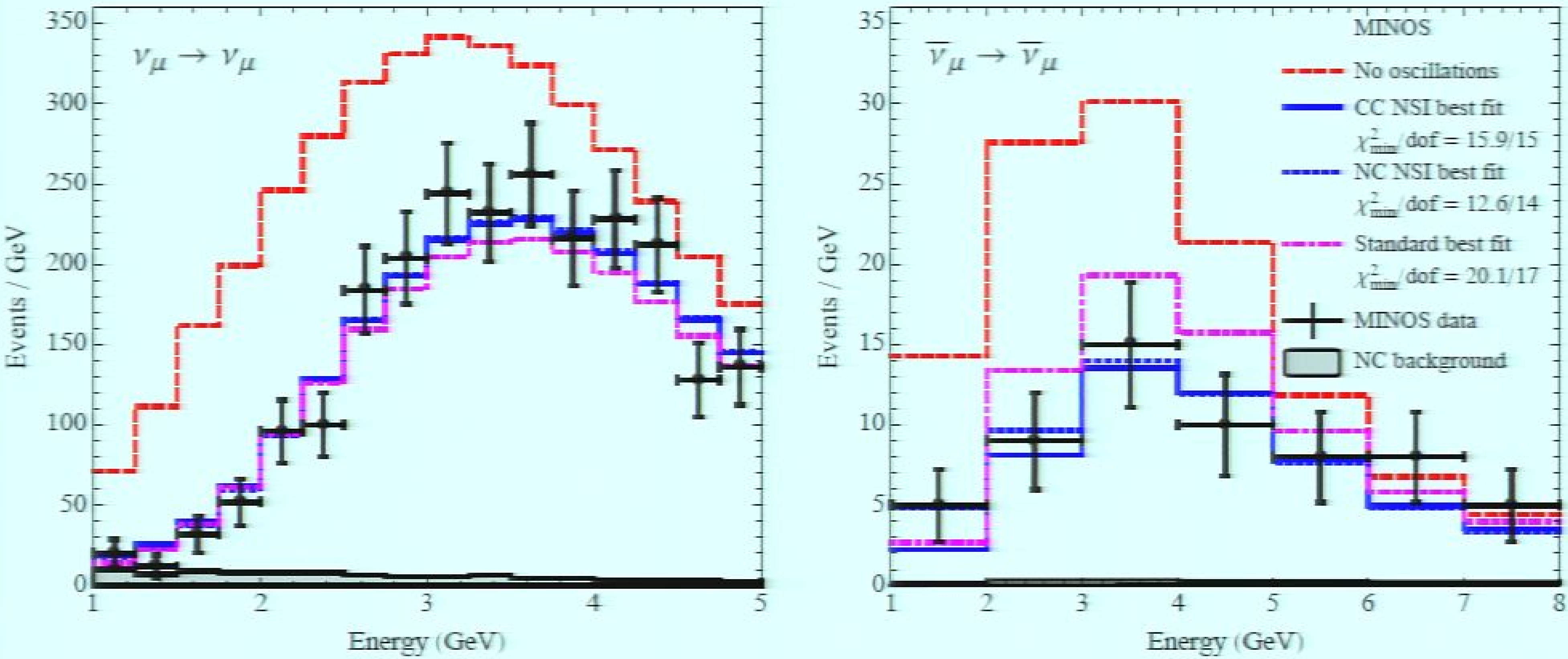

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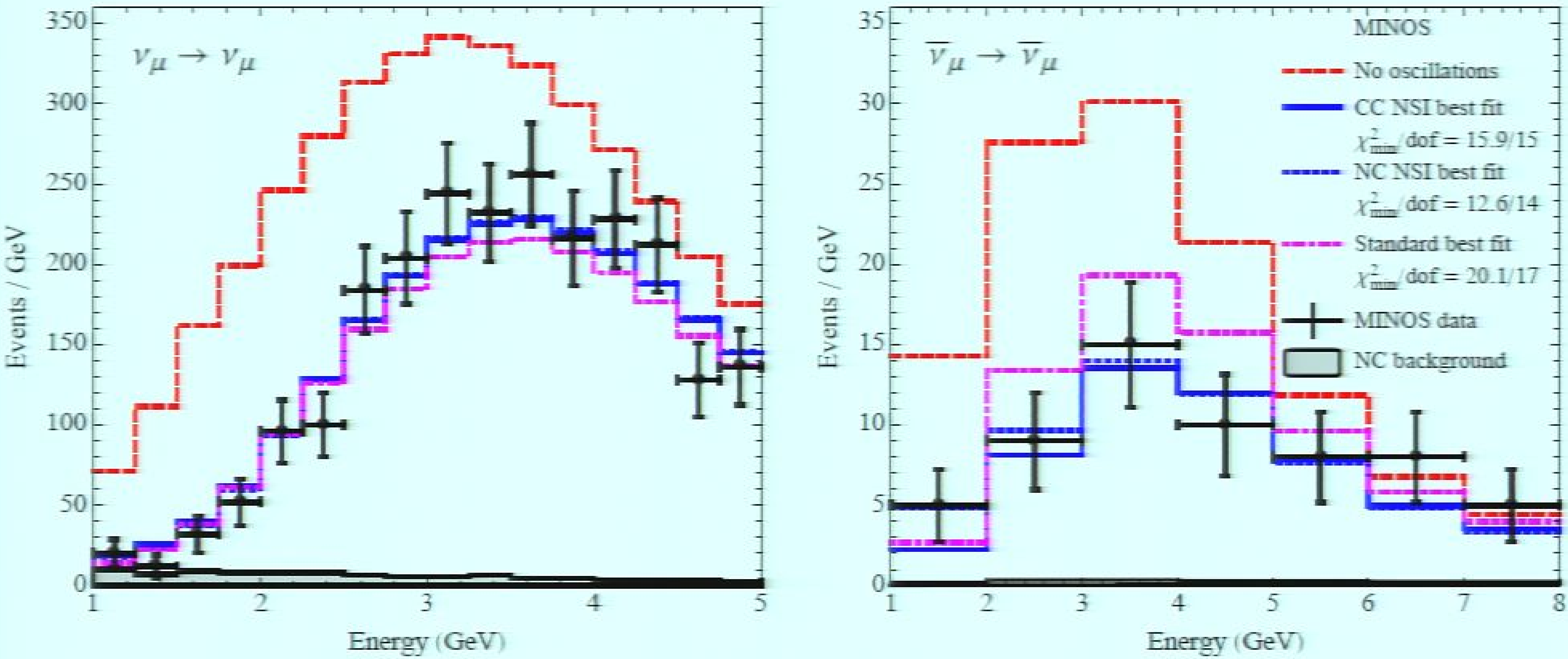

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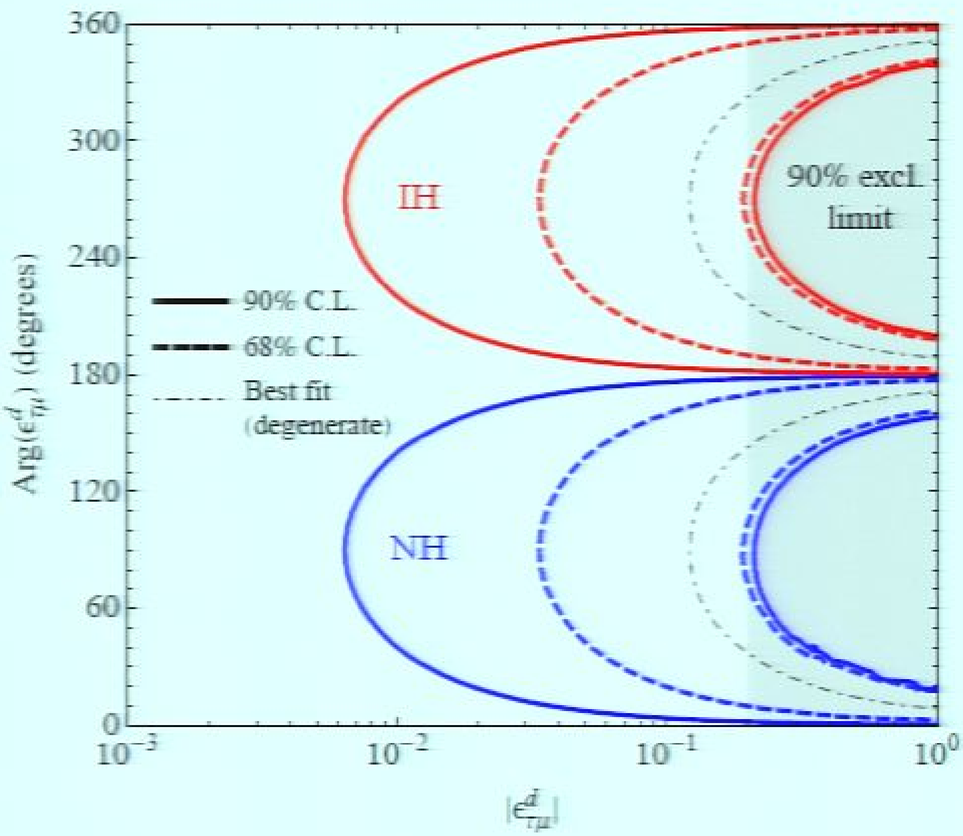

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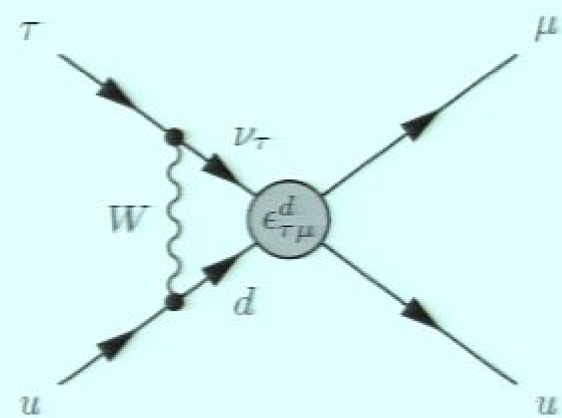

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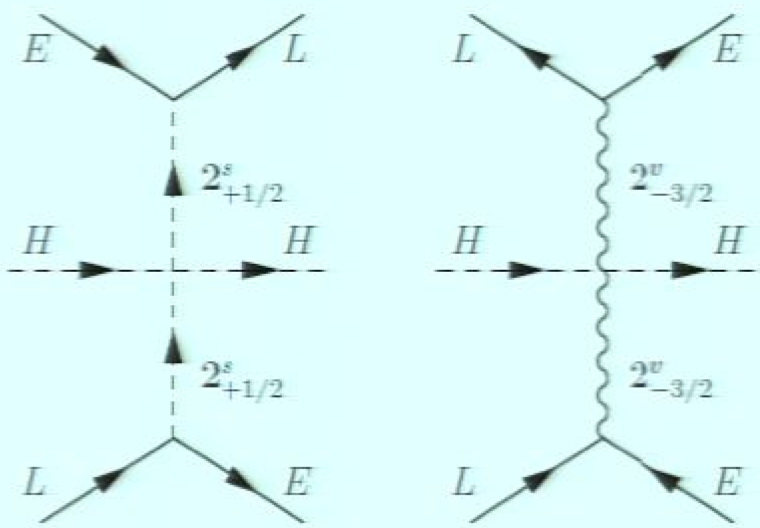

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- Many constraints on NSI come from high-energy ($\gtrsim \mathcal{O}(\text{GeV})$) processes.
- On the other hand, assume new mediator(s) with very small masses m and with extremely weak coupling g

Nelson Walsh arXiv:0711.1363; Engelhardt Nelson Walsh arXiv:1002.4452

  - high-energy cross sections/rates suppressed by g^4
  - Coherent forward scattering ($q^2 = 0$) only suppressed by $(g^2 \sin^2\theta_w / e^2)(M_W^2/m^2)$ compared to SM weak interactions
  - . . . can be relatively large

- Light new physics also motivated by Dark Matter (Sommerfeld enhancement)
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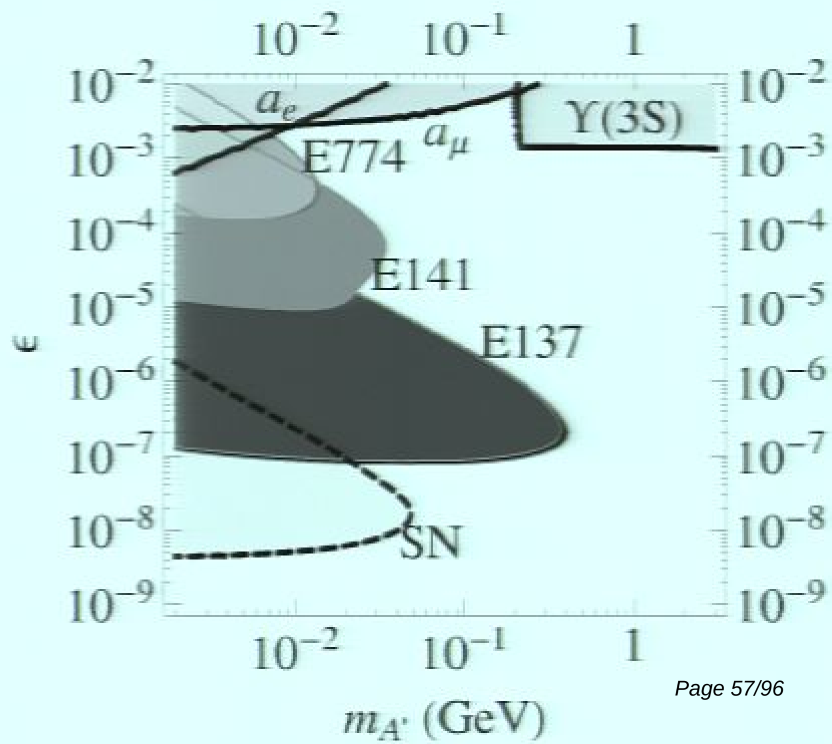
Pospelov 1103.3261, Harnik JK Machado, in progress (ASK ME!)



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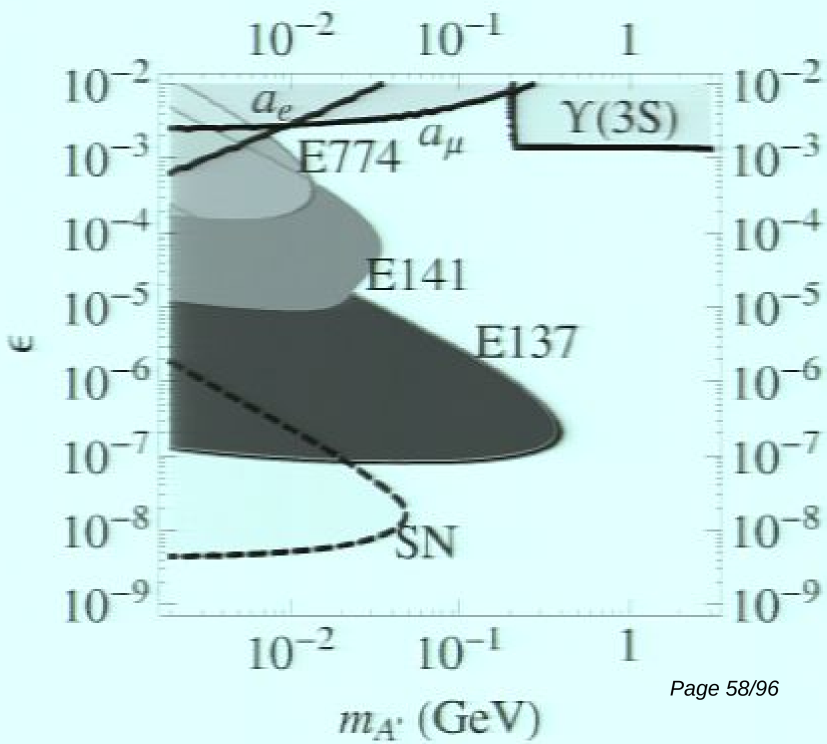


Outline

1. The MINOS experiment and its results—a hint for CPT violation?
   - The MINOS experiments and (some of) its results
   - Explanation attempts
2. MiniBooNE and the reactor anti-neutrino anomaly—sterile neutrinos?
   - The reactor anti-neutrino anomaly
   - LSND and MiniBooNE
   - The Gallium anomaly
   - Global fit

The reactor anti-neutrino anomaly

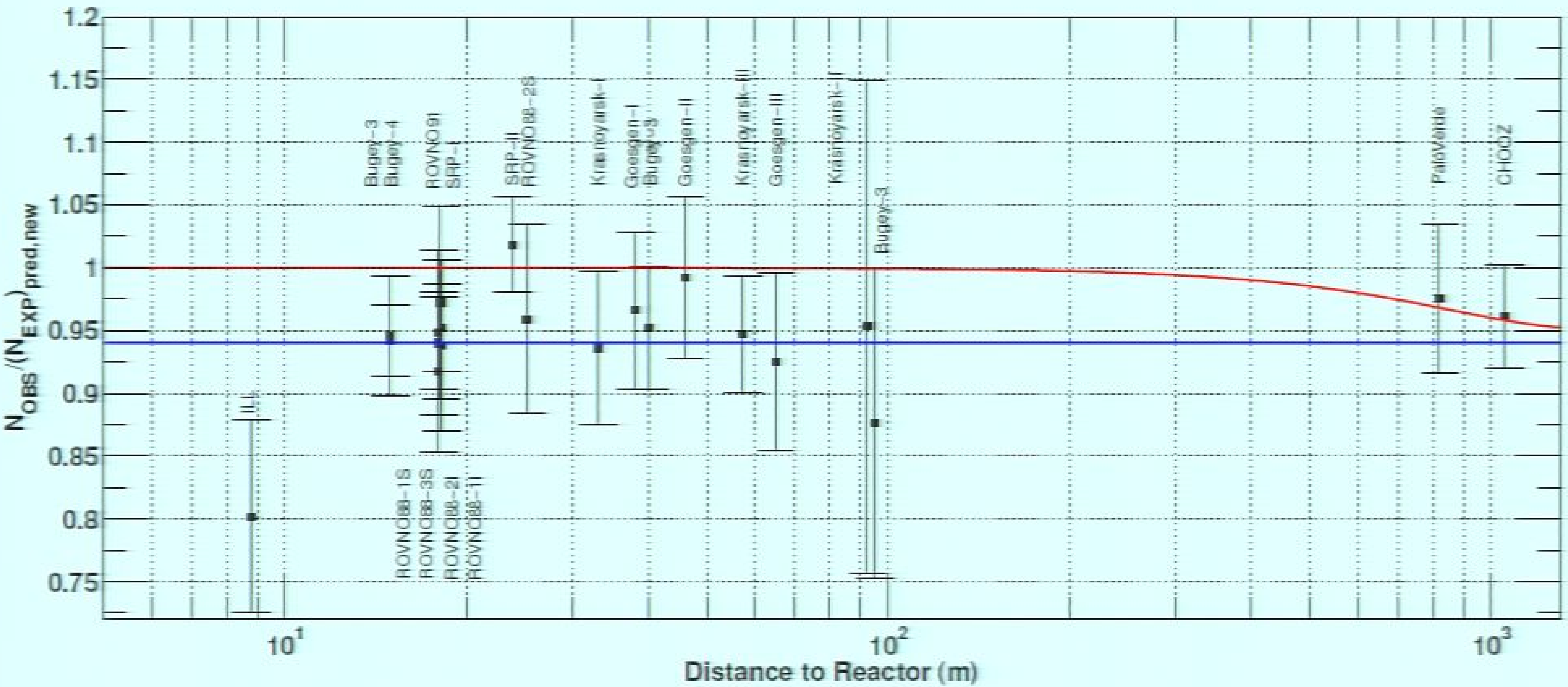
- Recent reevaluation of expected reactor $\bar{\nu}_e$ flux is $\sim 3.5\%$ higher than previous prediction Mueller et al. arXiv:1101.2663 vs. Schreckenbach 1985
- Method: Use measured β-spectra from ^{238}U, ^{235}U, ^{241}Pu fission at ILL and convert to $\bar{\nu}_e$ spectrum
- Problem: Requires knowledge of Q-values for all contributing decays.

Old method Schreckenbach 1985	New method Mueller et al. arXiv:1101.2663
30 effective branches	Uses nuclear databases (90% of $\bar{\nu}_e$ flux)
	5 effective branches (remaining 10%)
	Error propagation, correlation matrix
	Off-equilibrium corrections (short irradiation time at ILL $\rightarrow$ not all β-branches in equilibrium

- Cross check:
  - Simulate "true" e^- spectra using set of few well-known β-branches ($\rightarrow \bar{\nu}_e$ spectrum known)
  - Reconstruct $\bar{\nu}_e$ spectrum using old method: Result is 3% too low
  - Reconstruct $\bar{\nu}_e$ spectrum using new method: Result is exact.

The reactor anti-neutrino anomaly (2)

- Have short-baseline reactor experiments observed a deficit?



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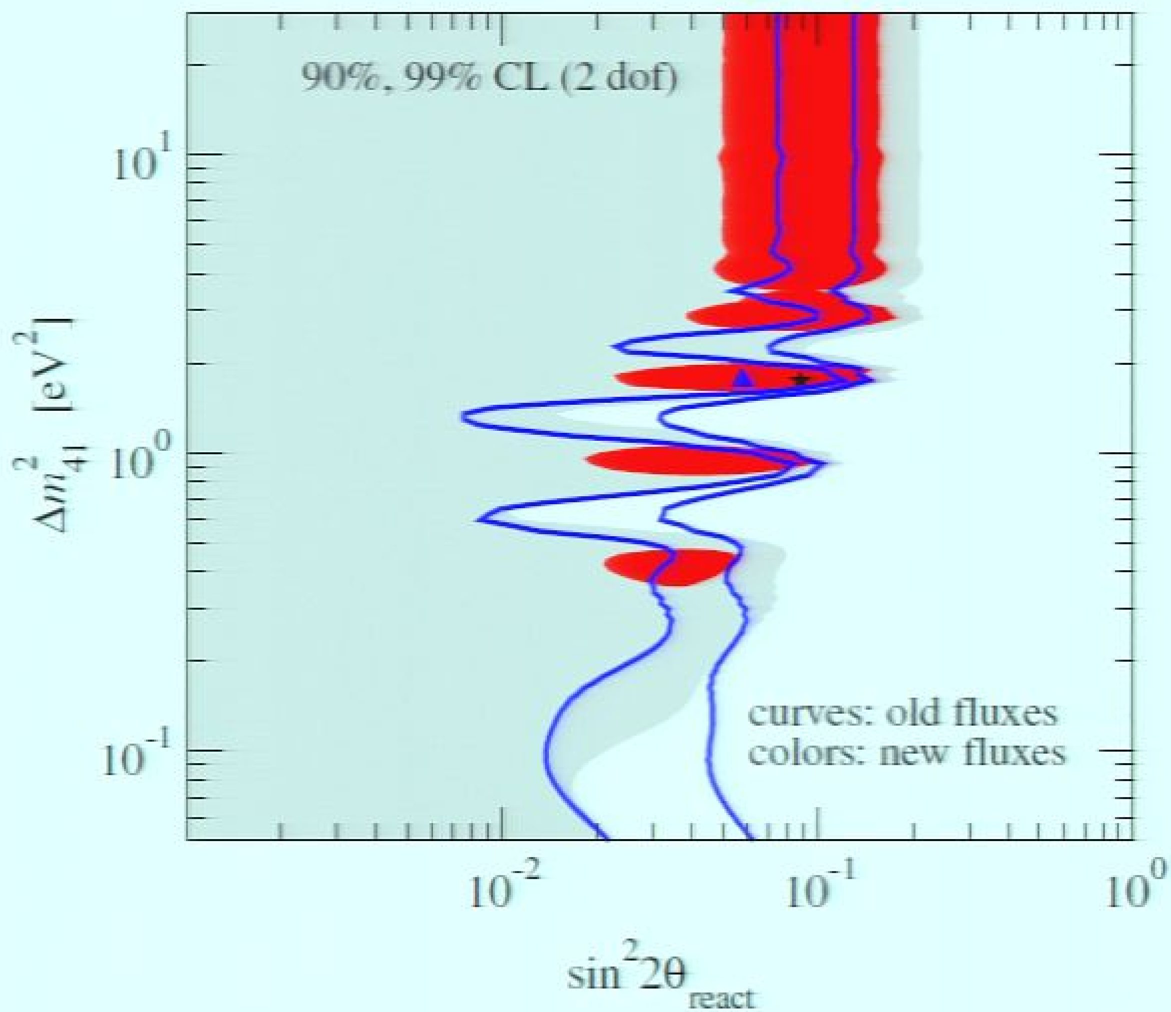
Global fit to reactor anti-neutrino data



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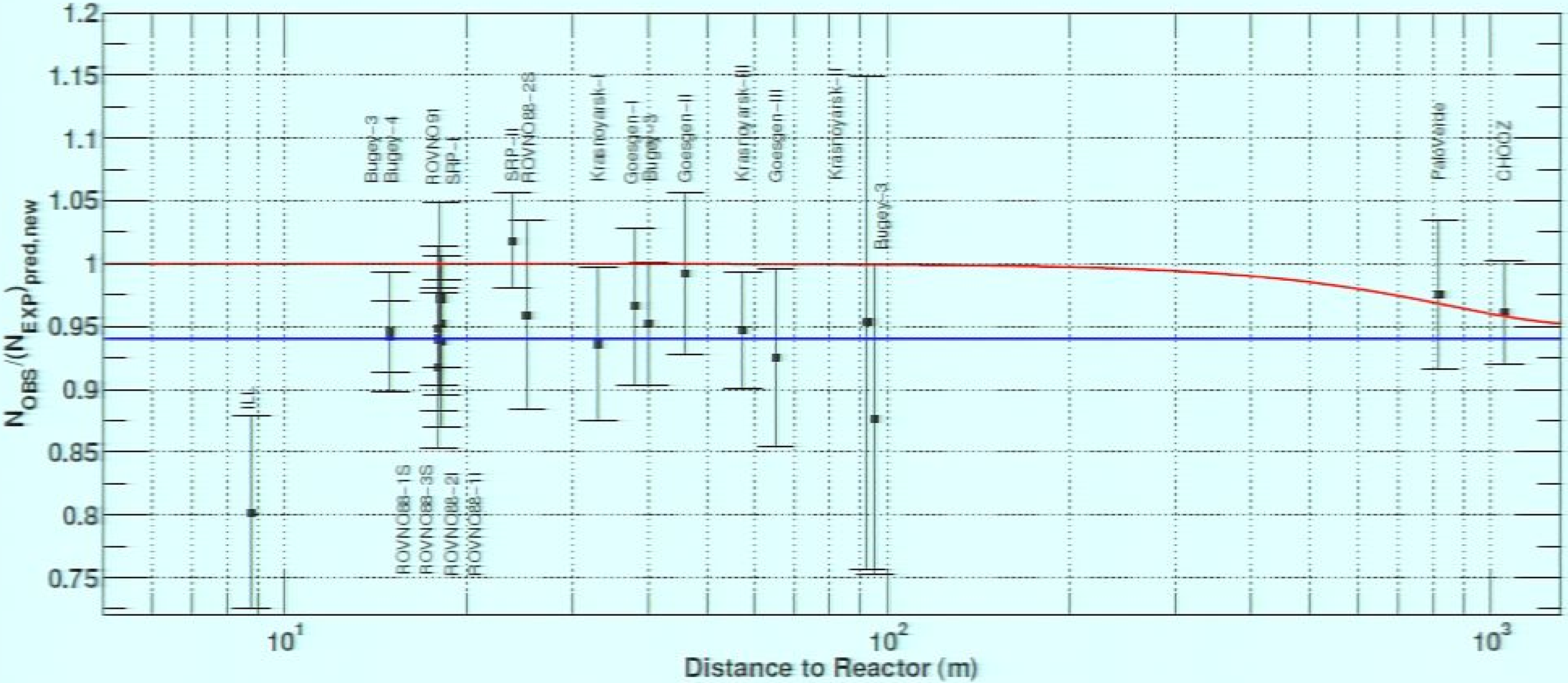

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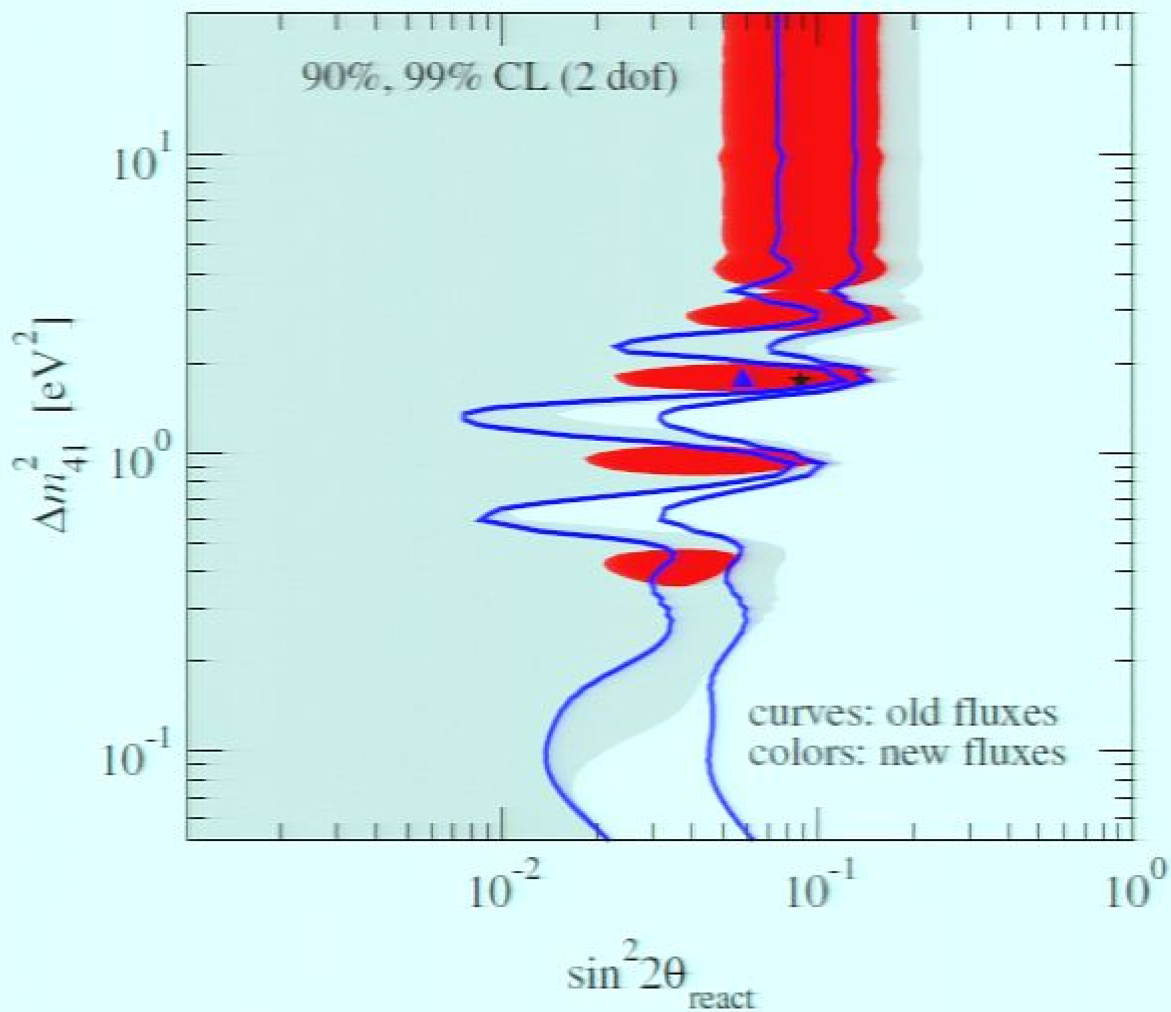

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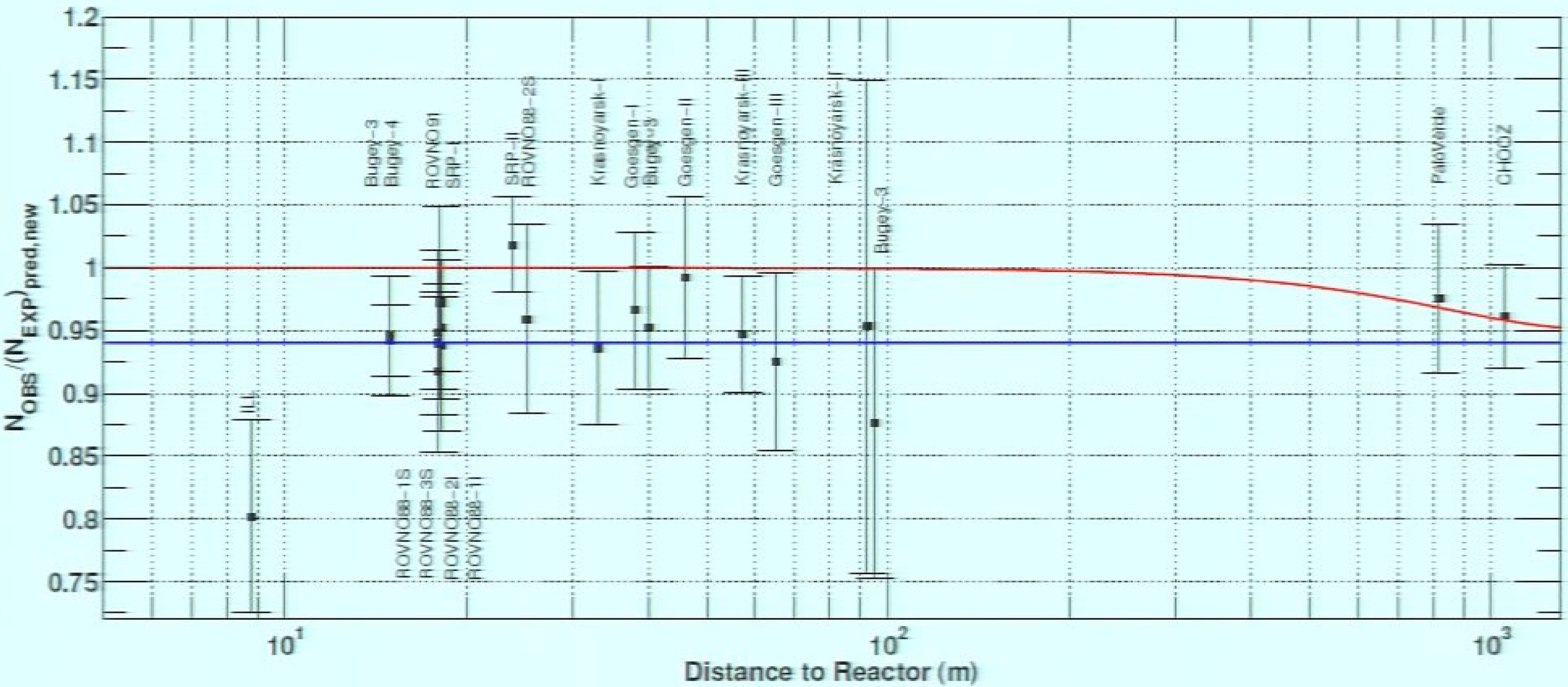

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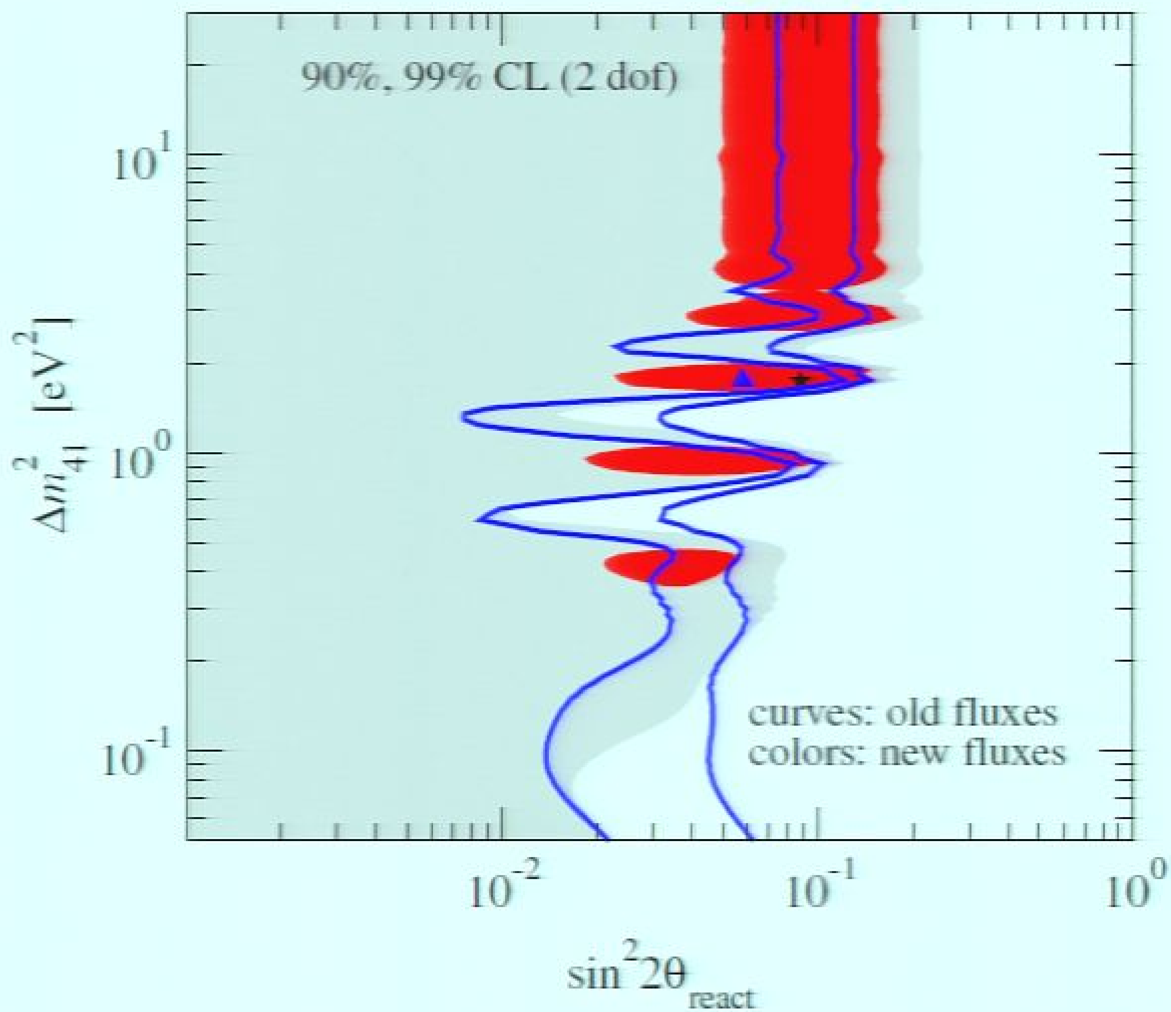

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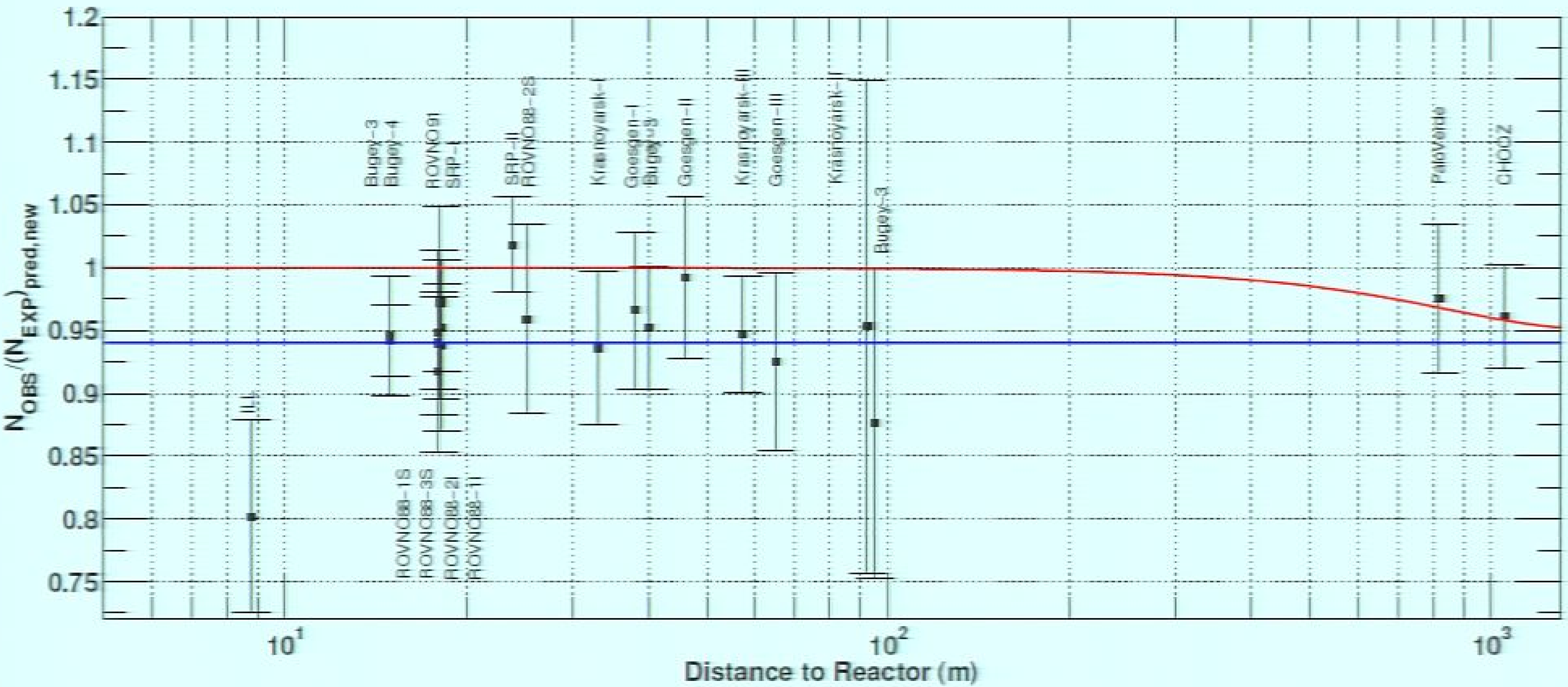

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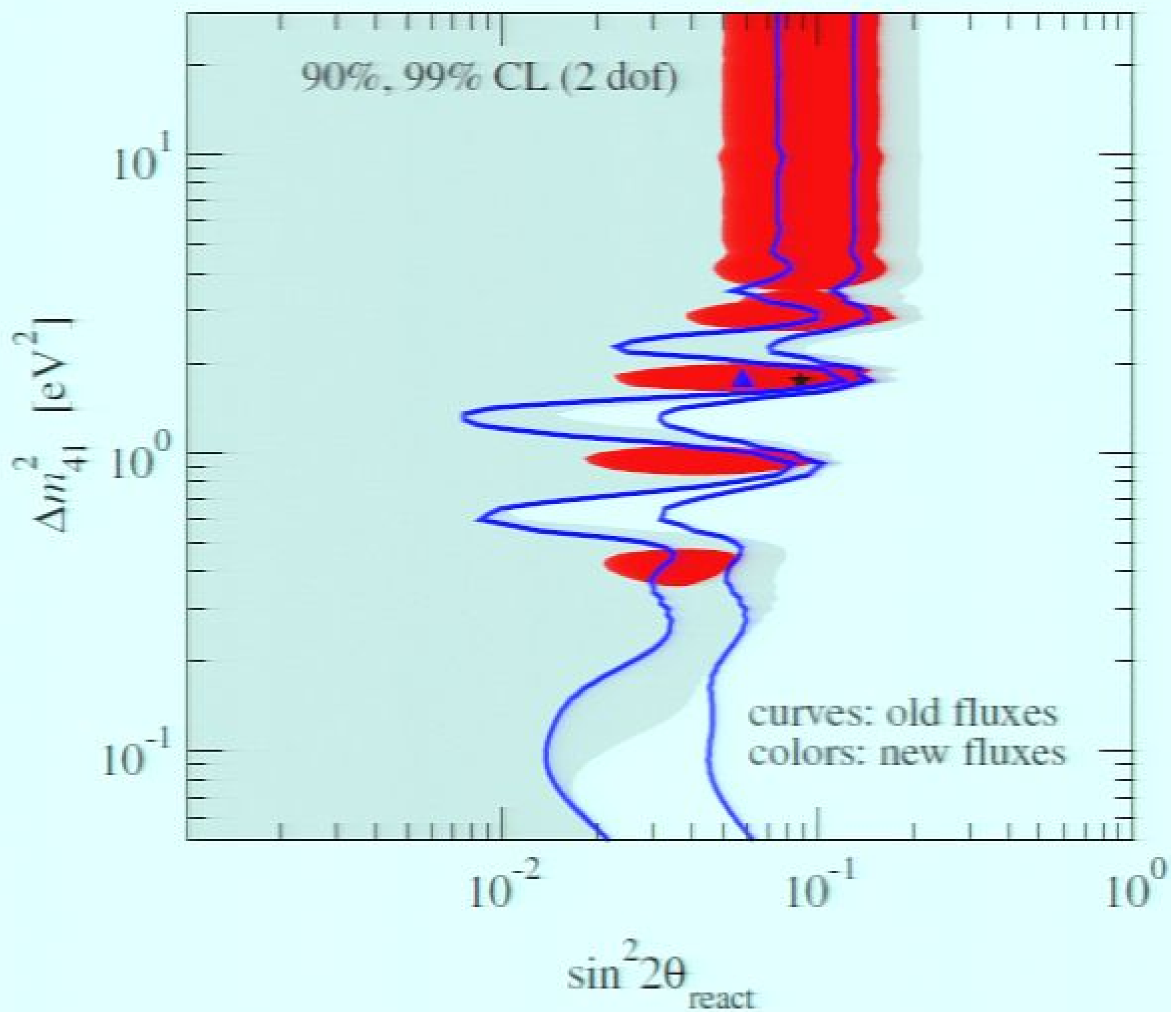
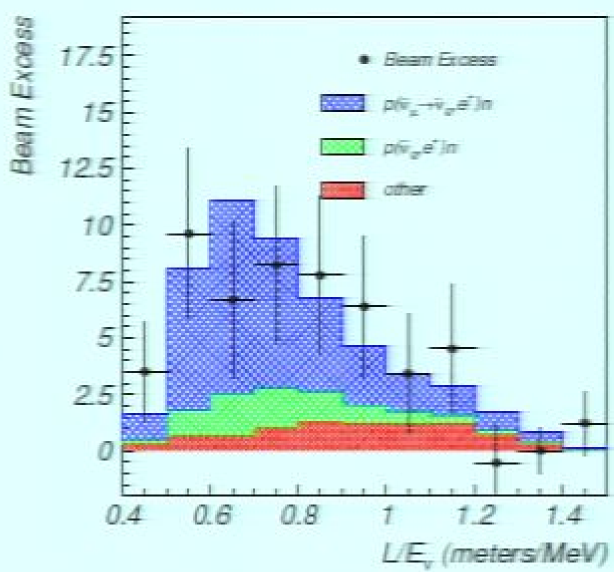
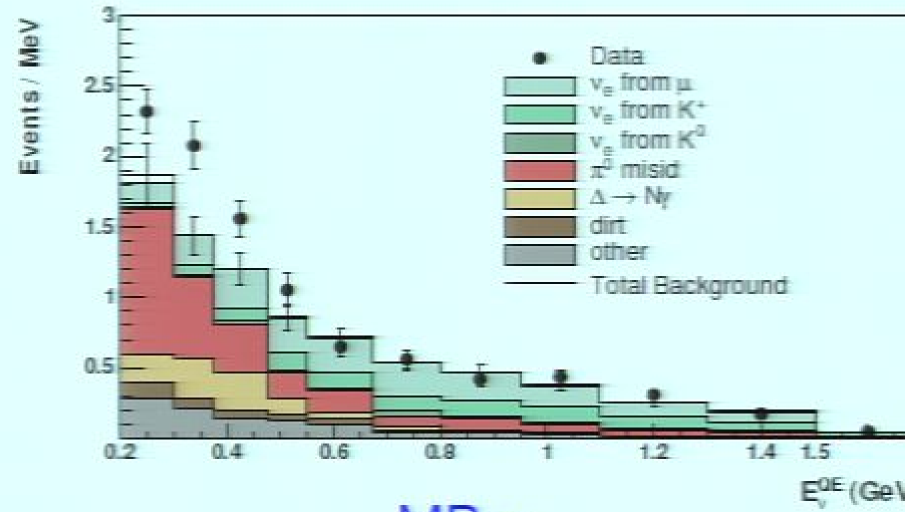


LSND, KARMEN, MiniBooNE

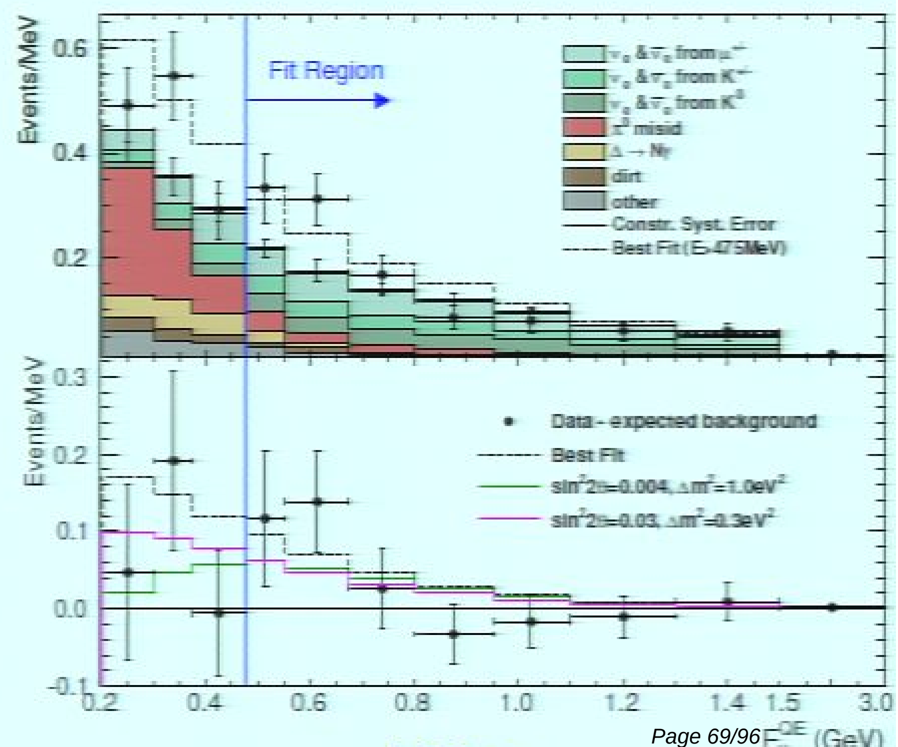
- LSND:
  - $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam from stopped pion source
- MiniBooNE:
  - $\bar{\nu}_e$ appearance in accelerated $\bar{\nu}_\mu$ beam
  - No ν_e appearance in interesting energy region → CP violation?
- KARMEN:
  - Very similar to LSND, but no excess



LSND $\bar{\nu}_e$



MB ν_e



MB $\bar{\nu}_e$

SBL appearance vs. disappearance experiments

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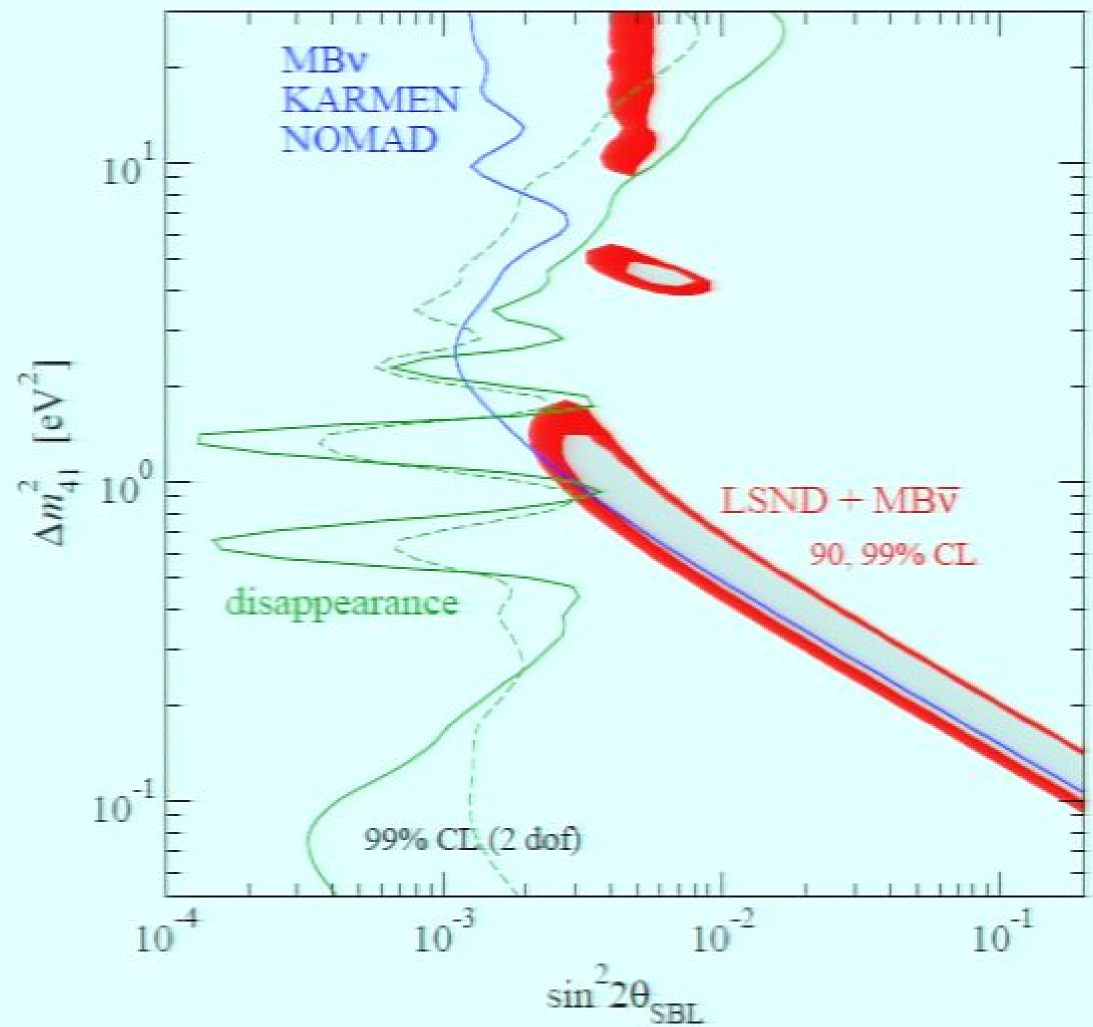
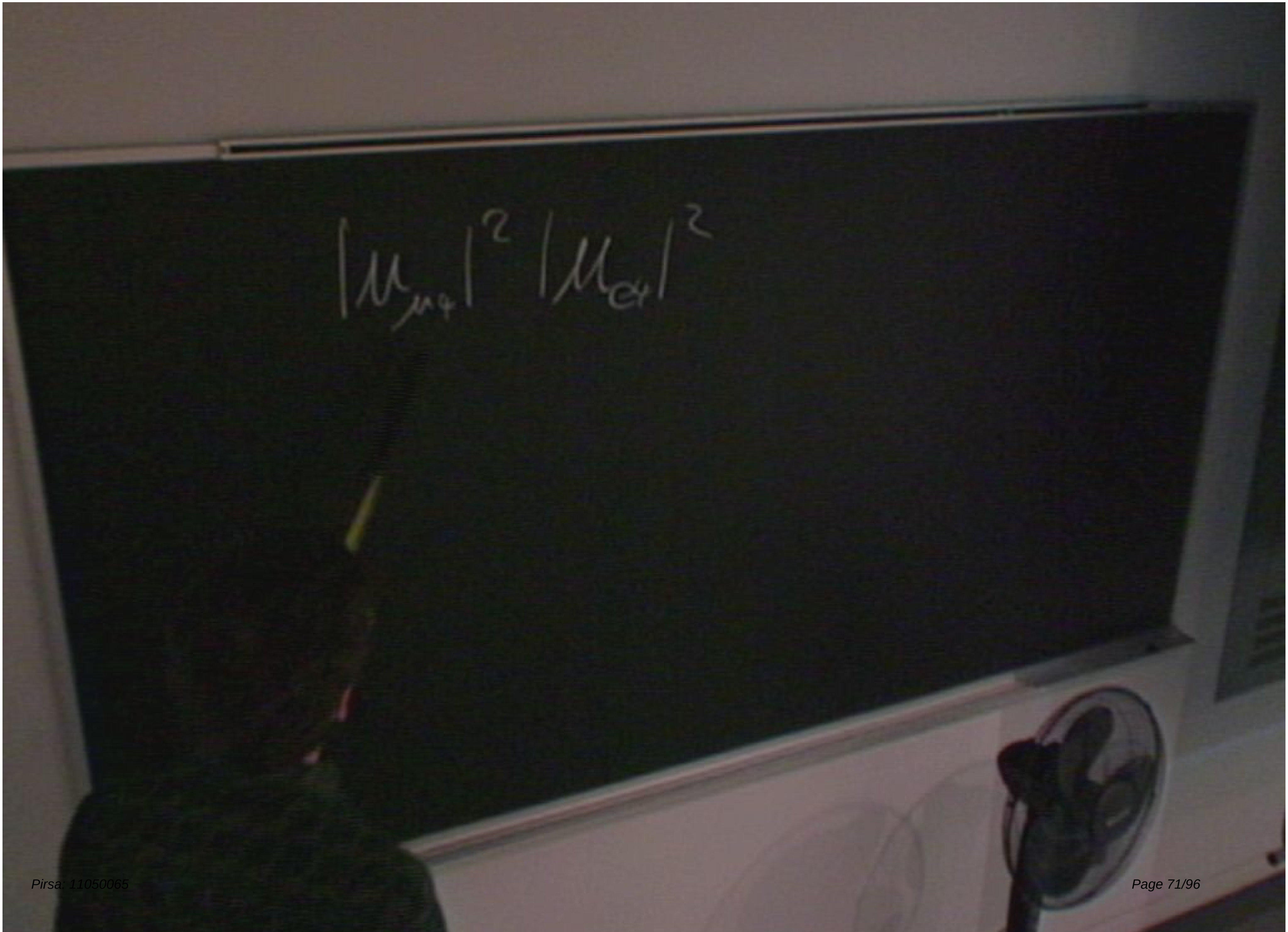
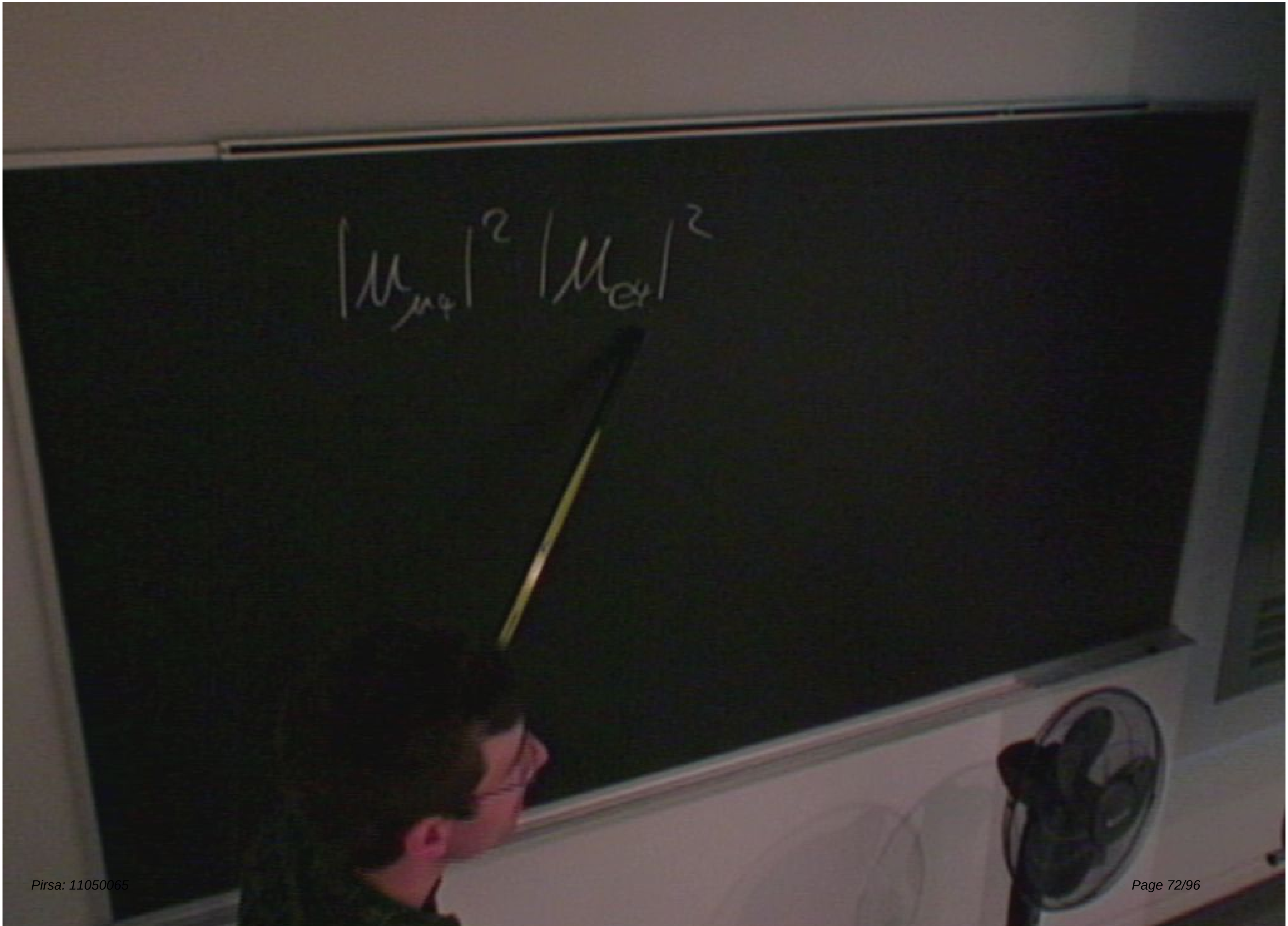



$|U_{\mu 4}|^2 |U_{e4}|^2$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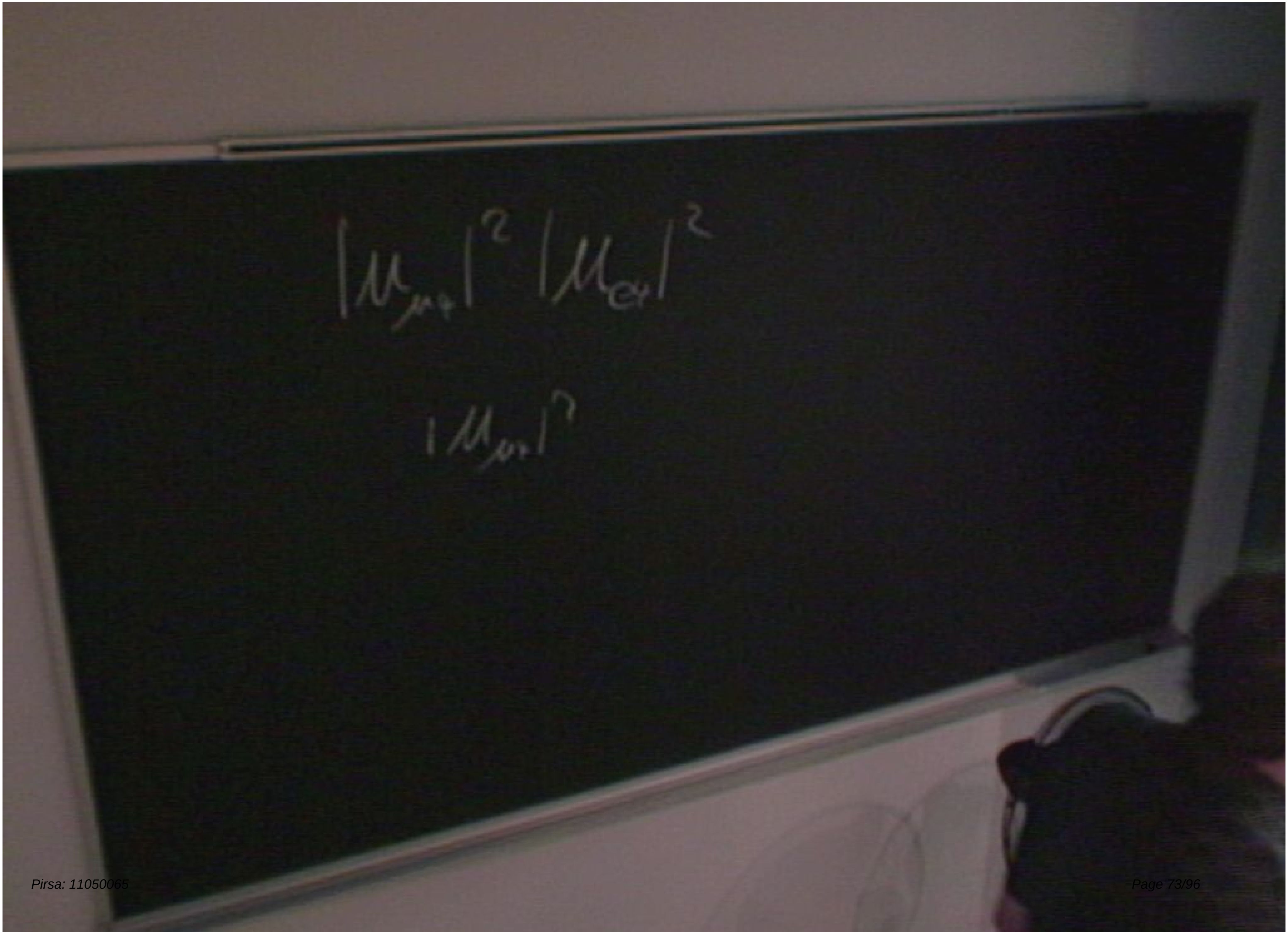

$|M_{\mu\phi}|^2 \; |M_{e\phi}|^2$
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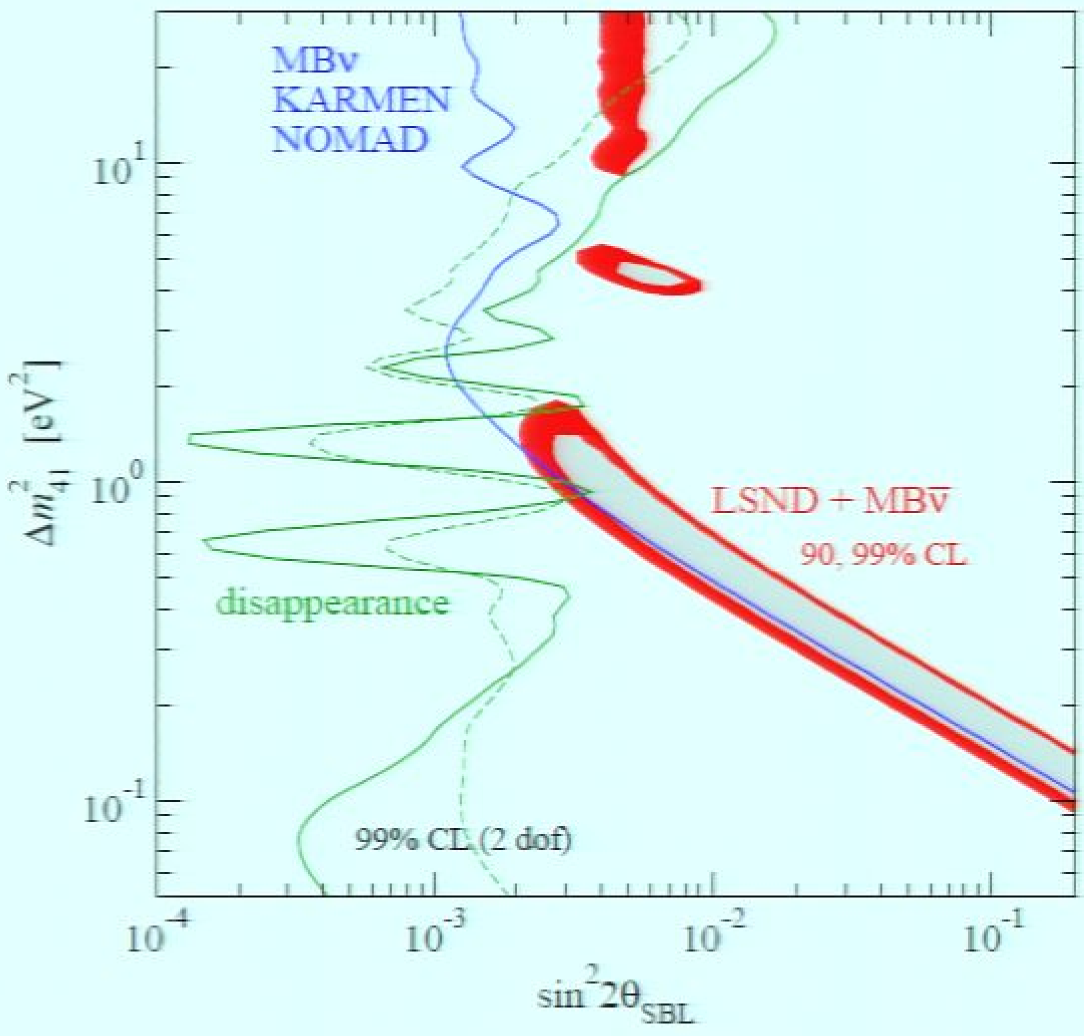

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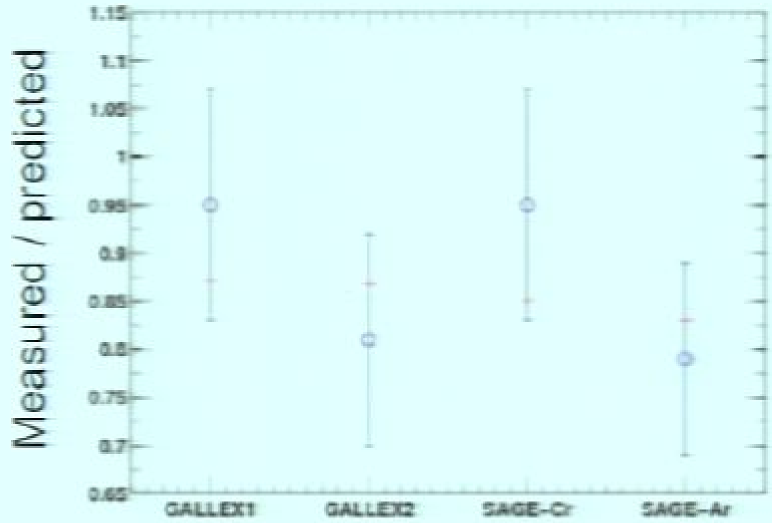

Giunti Laveder arXiv:1005.4599, arXiv:1006.3244
Mention et al. Moriond 2011 talk

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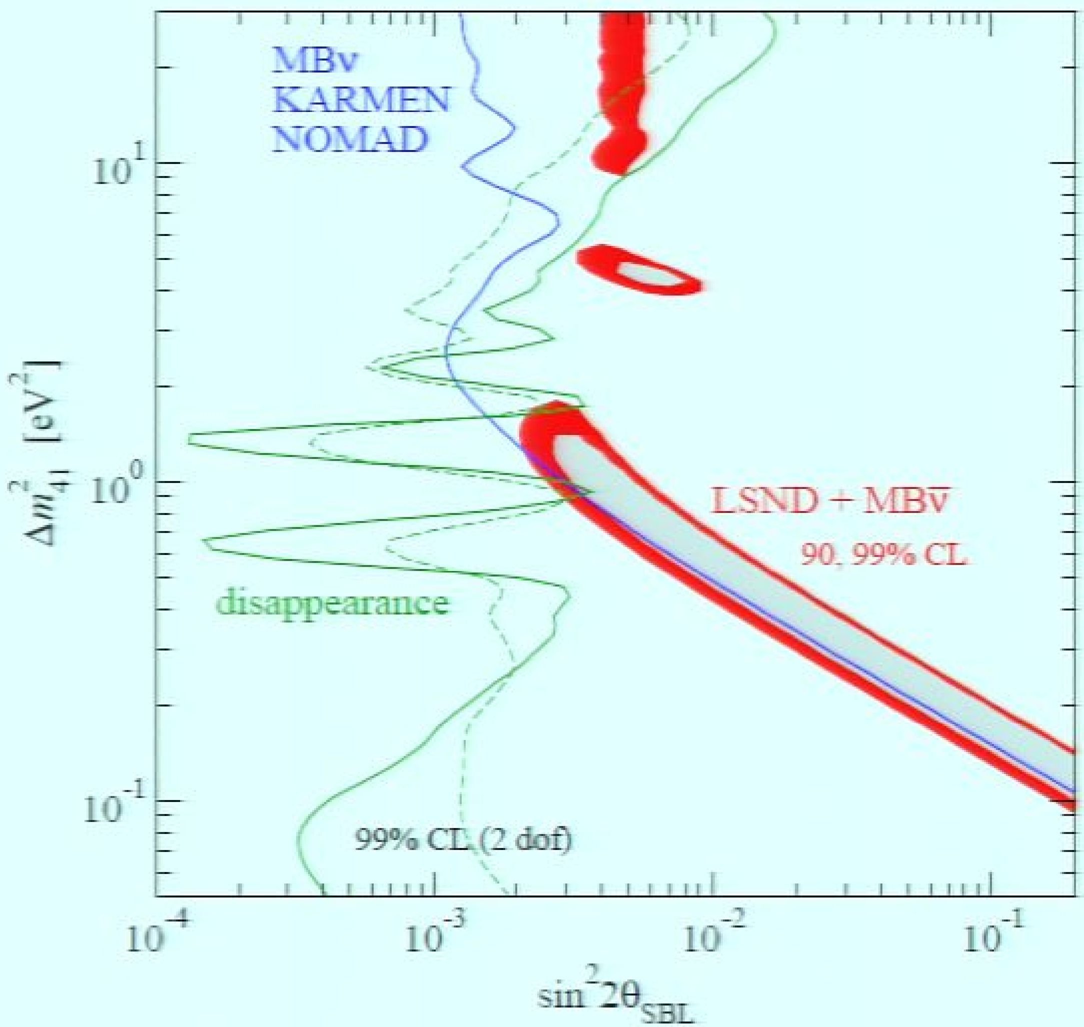

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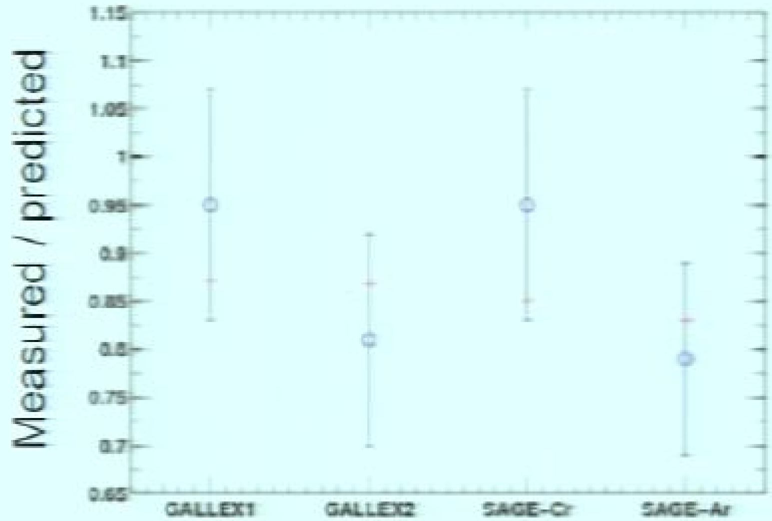

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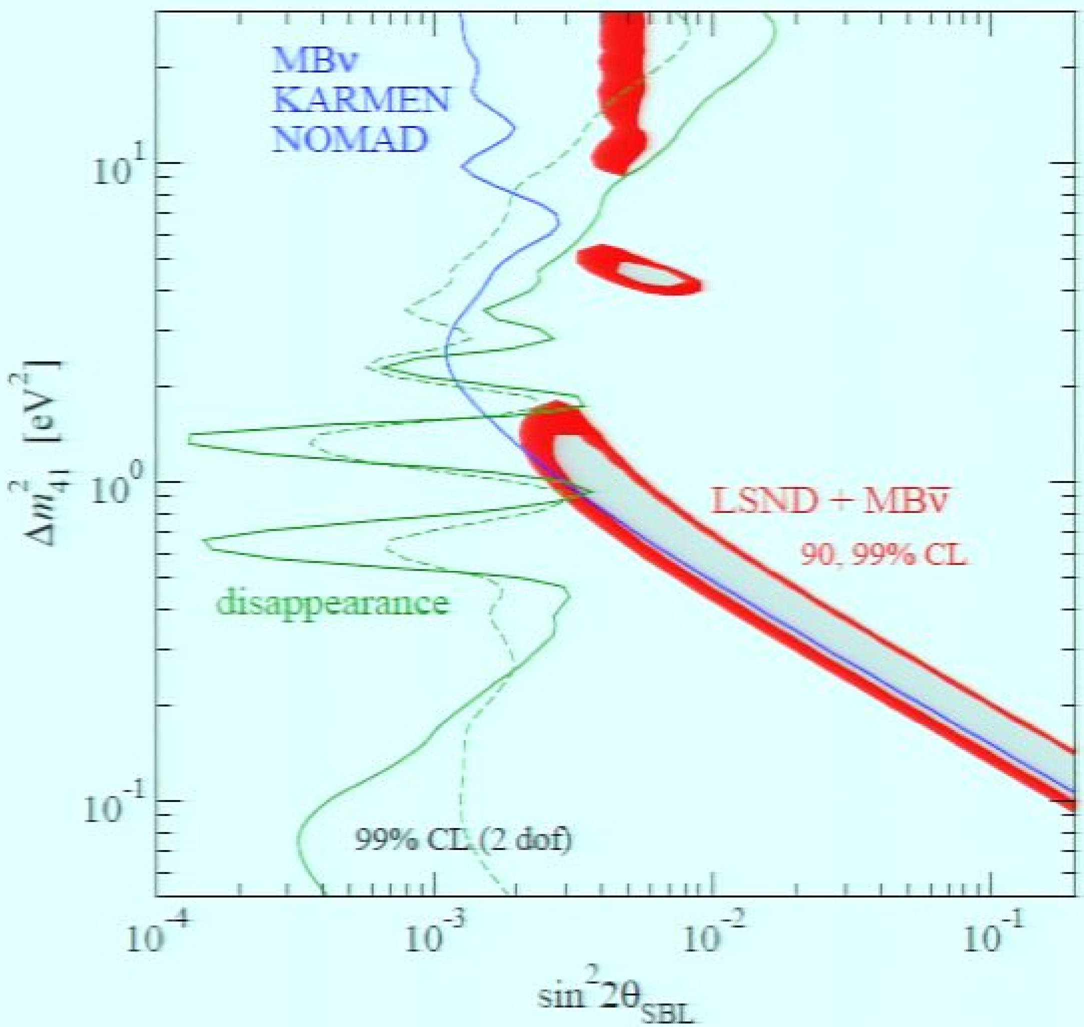

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Global fit in a 5-flavor scheme

Why 5 flavors?

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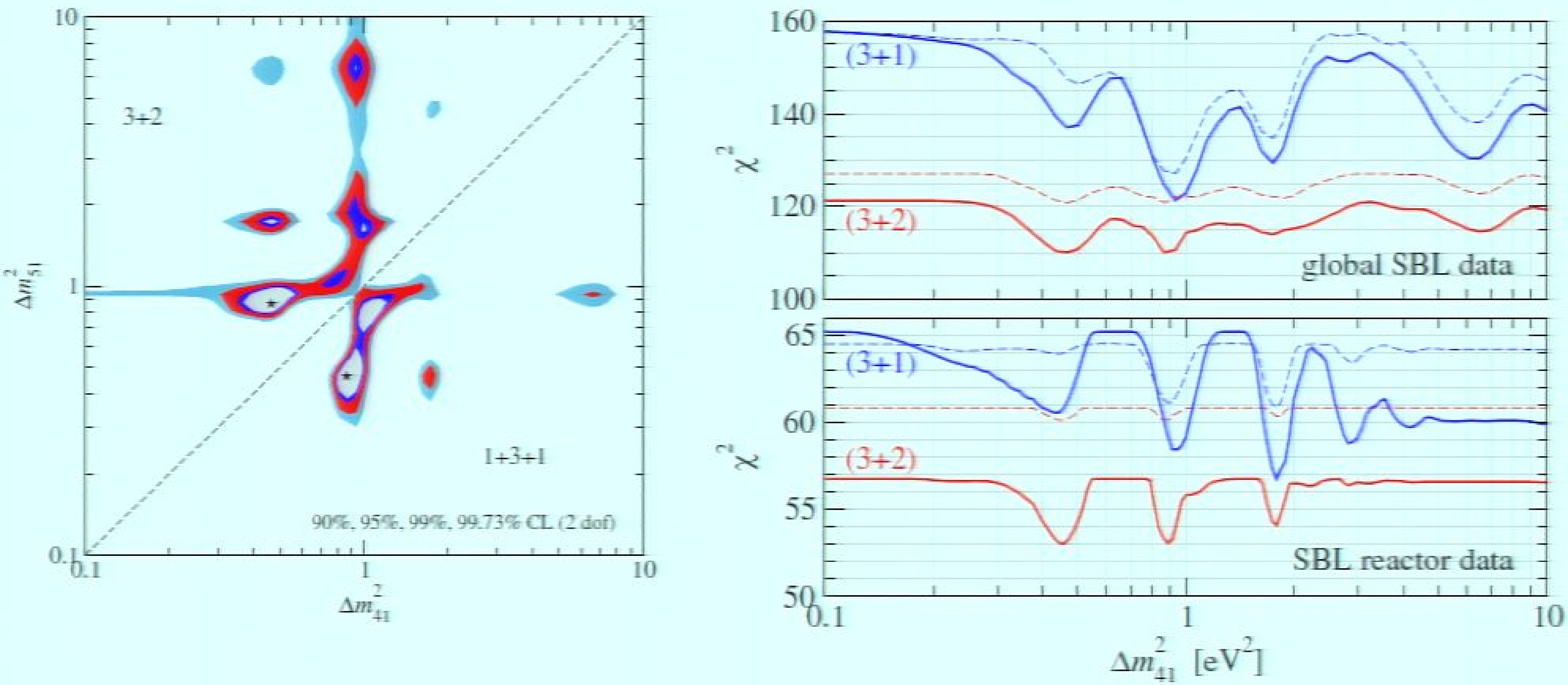

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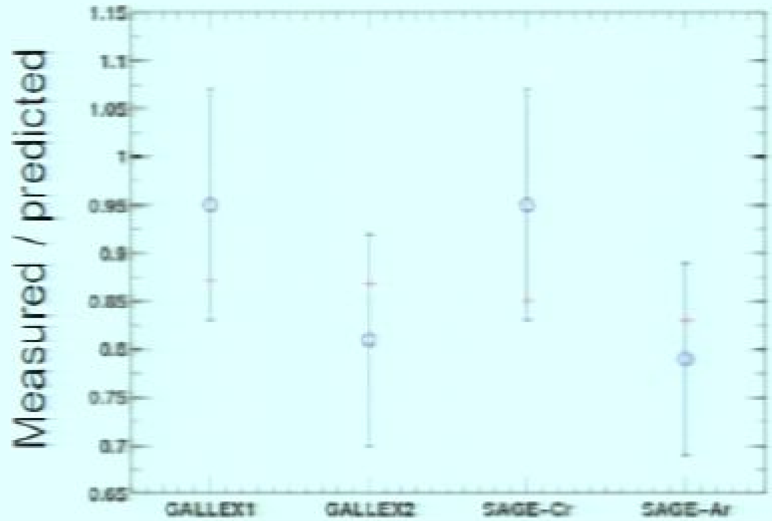

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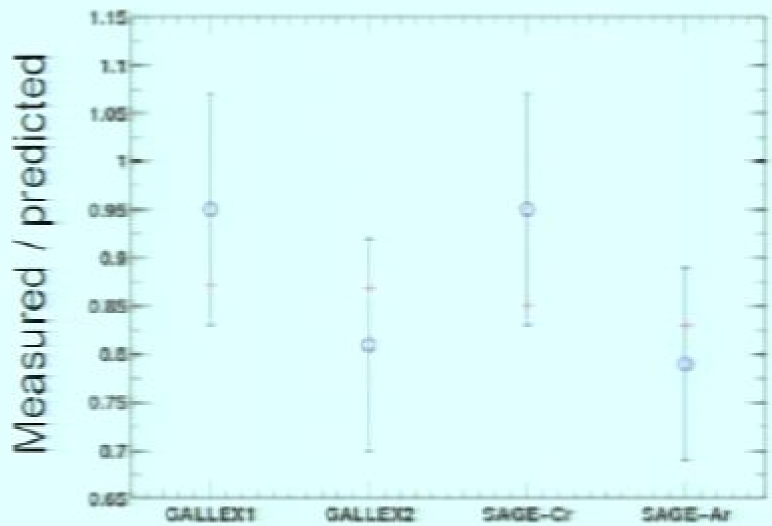

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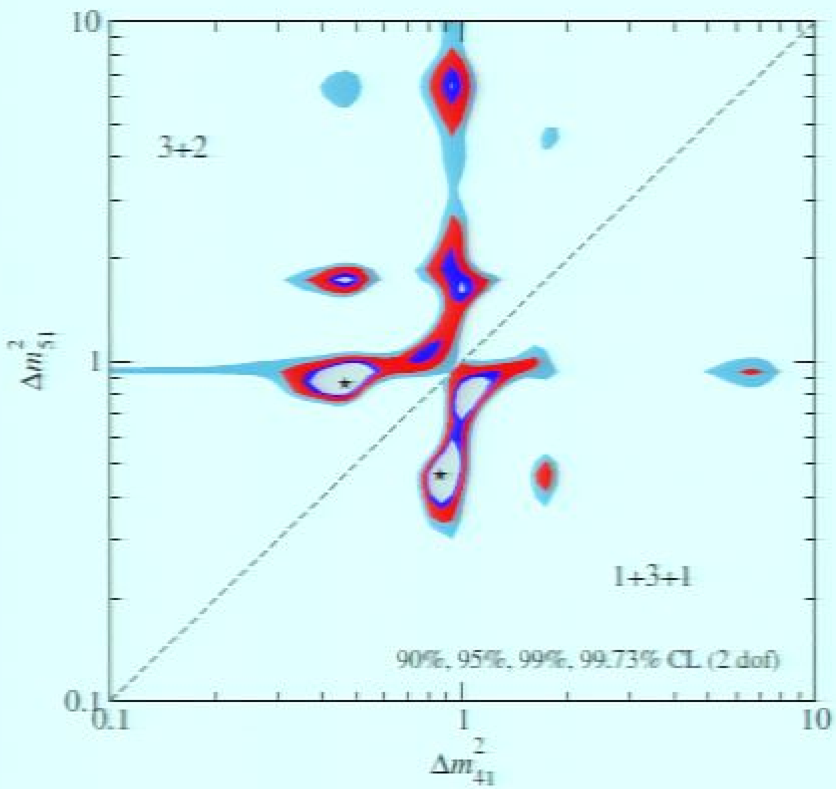

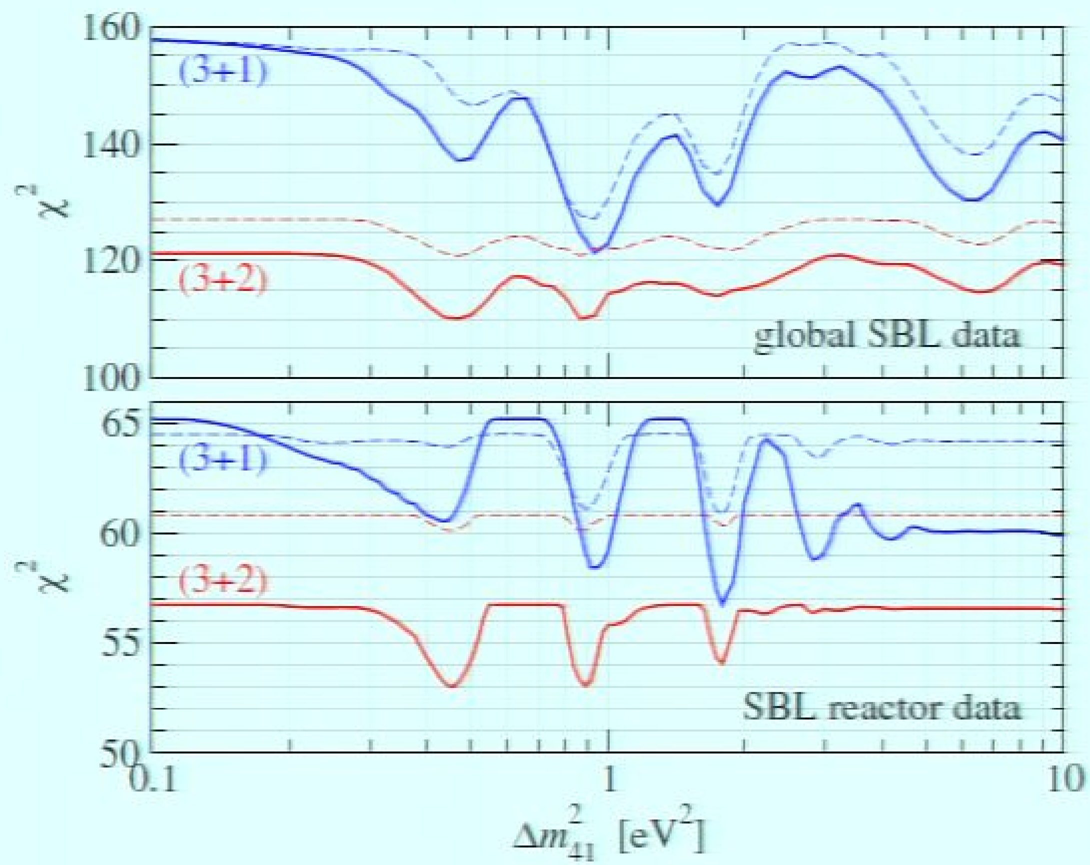

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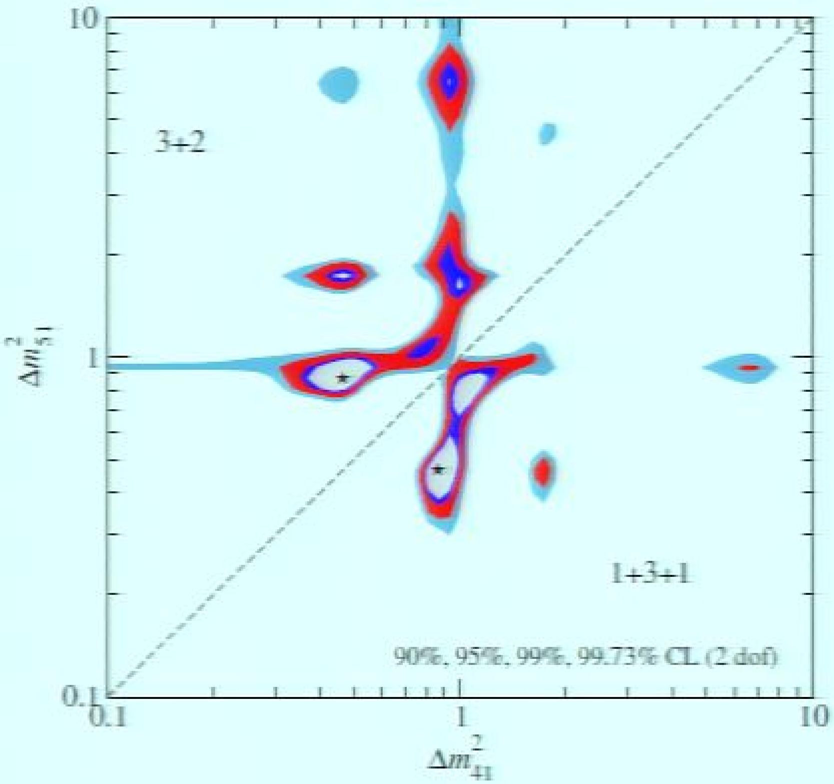

	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130
1+3+1	0.47	0.129	0.154	0.87	0.142	0.163	0.35	106.1/130

Best fit point

	LSND+MB($\bar{\nu}$) vs rest		appearance vs disapp.	
	old	new	old	new
$\chi^2_{\mathrm{PG},3+2}$/dof	25.1/5	19.9/5	19.9/4	14.7/4
PG_{3+2}	10^{-4}	0.13%	5×10^{-4}	0.53%
$\chi^2_{\mathrm{PG},1+3+1}$/dof	19.6/5	16.0/5	14.4/4	10.6/4
PG_{1+3+1}	0.14%	0.7%	0.6%	3%

Parameter goodness of fit test

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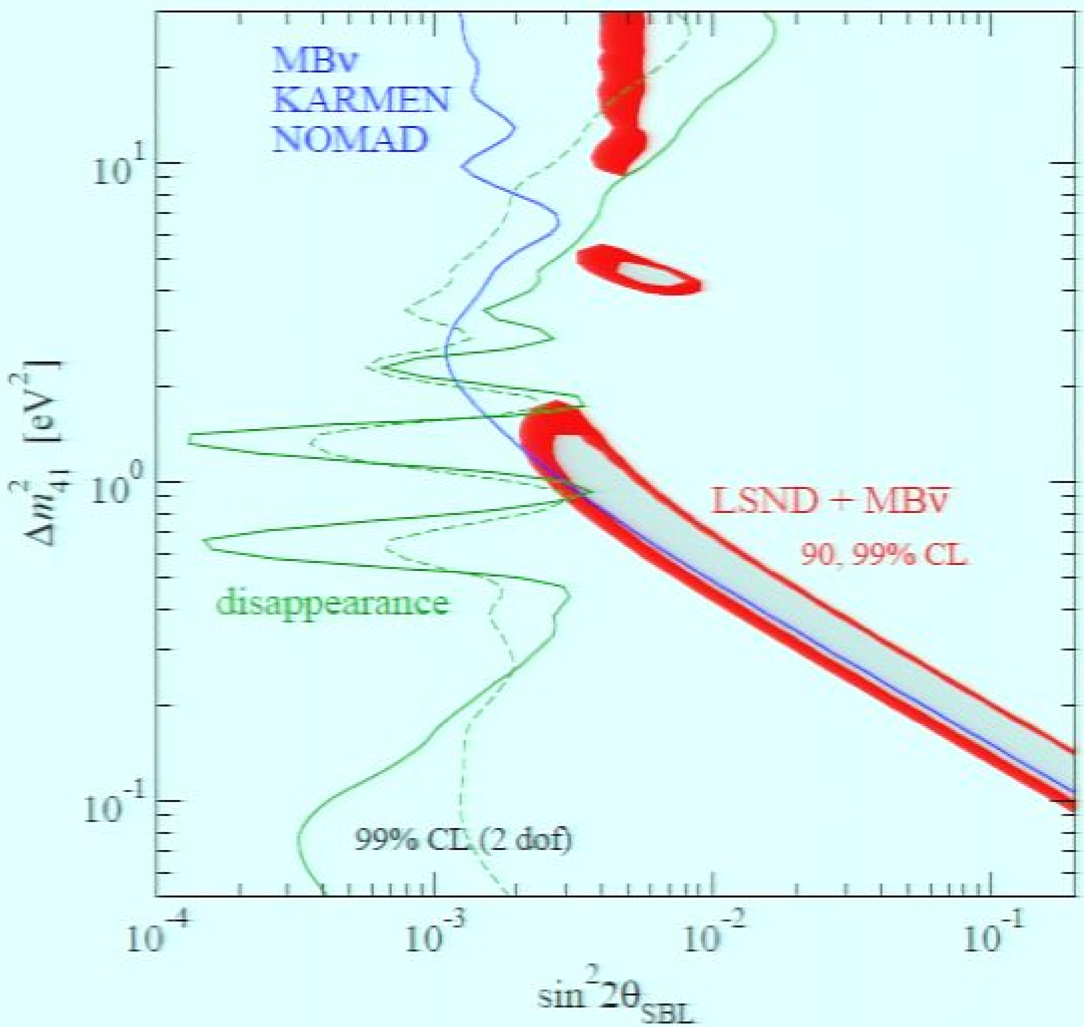

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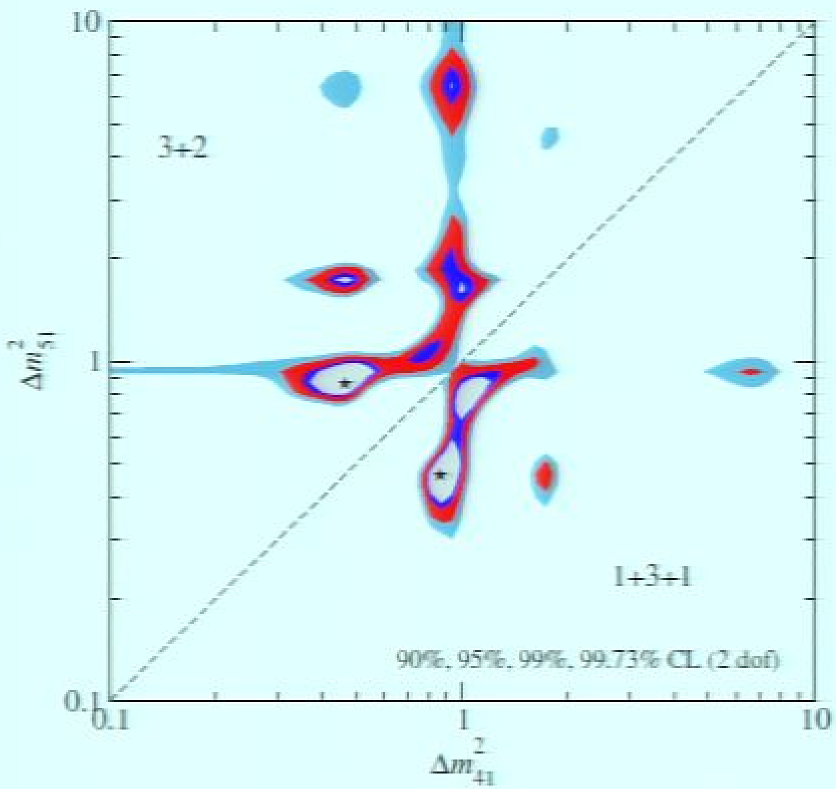

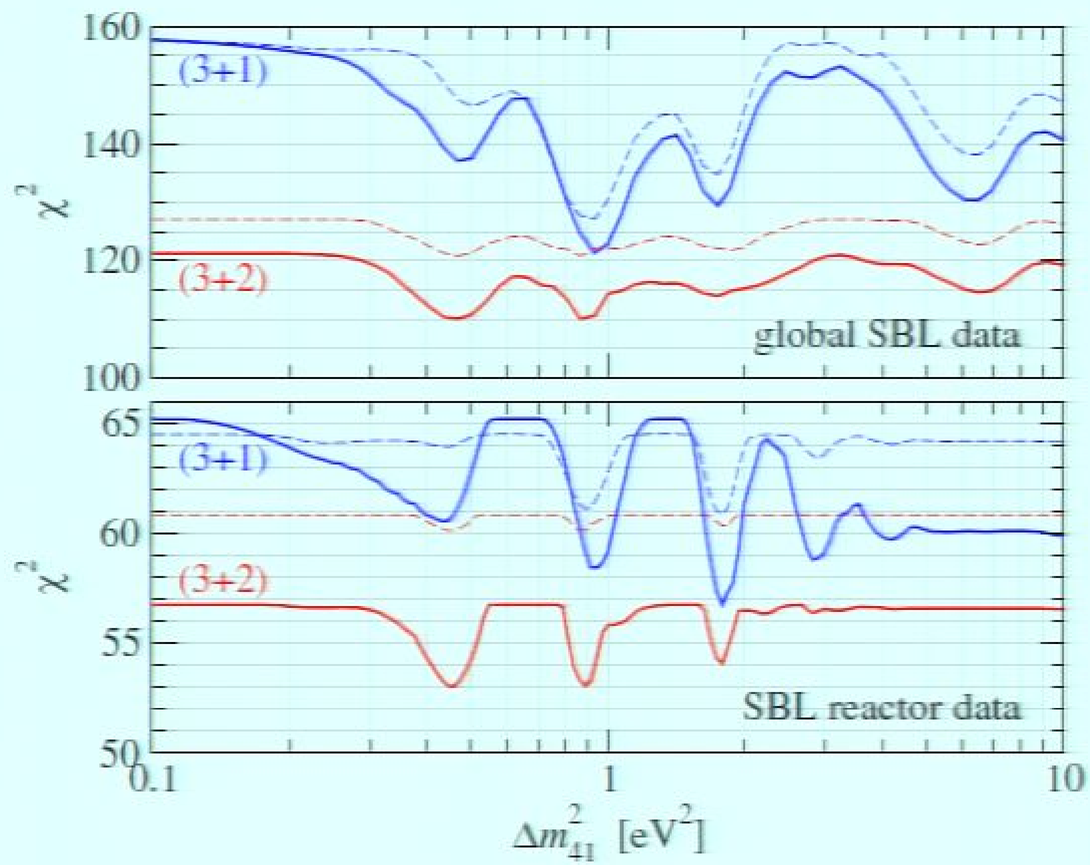

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A common explanation for MINOS and SBL results?

- If SBL anomalies are due to sterile neutrinos ...
  - Any CPT-conserving oscillation phenomenon will affect ν_μ and $\bar{\nu}_\mu$ in MINOS in the same way
- If SBL anomalies are due to some new type of neutrino interaction
  - The only conceivable new interaction that explains MINOS seems to be one involving ν_τ
  - No ν_τ at short baseline $\rightarrow$ need several new interactions to explain everything
  - Hard to reconcile with constraints from charged leptons
- More exotic ideas
  - Sterile neutrinos *and* new interactions
    $\rightarrow$ Many parameters, loss of predicitivity
    $\rightarrow$ One sterile neutrino probably still not sufficient

Conclusions

- Accumulation of interesting anomalies in neutrino physics
- MINOS
  - Tension between fits to ν_μ and $\bar{\nu}_\mu$ disappearance data
  - Statistical or systematical uncertainty?
  - CPT violation?
  - Non-standard matter effects or new long-range force . . . difficult to reconcile with atmospheric neutrinos
  - Modified charged current interactions . . . difficult for model-building
- LSND, MiniBooNE and the reactor anomaly
  - Three independent results pointing to the existence of sterile neutrinos
  - $3+1$ model does not work (need CP violation to reconcile MiniBooNE ν_e and $\bar{\nu}_e$ results)
  - $3+2$ models work much better, but tension remains
  - Interesting consequences for $\mathcal{O}$(TeV) atmospheric neutrinos $\Rightarrow$ IceCube!

Razzaque Smirnov arXiv:1104.1390

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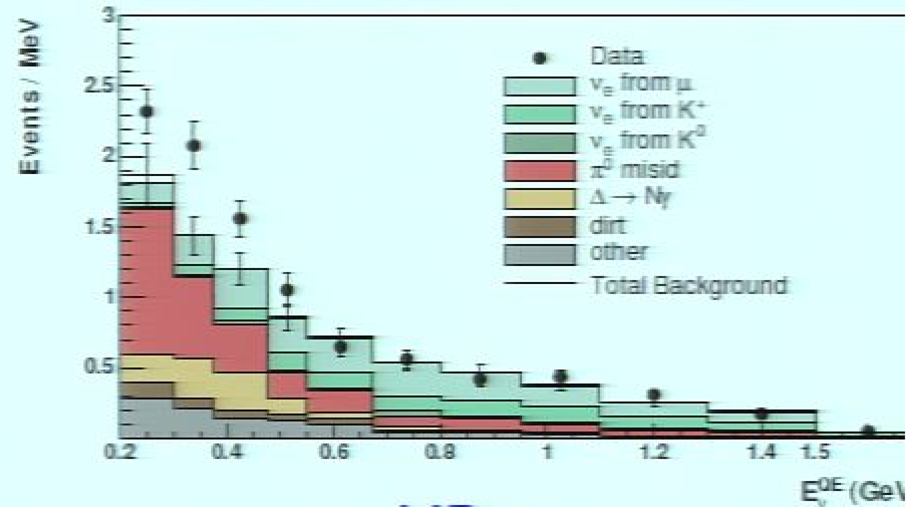
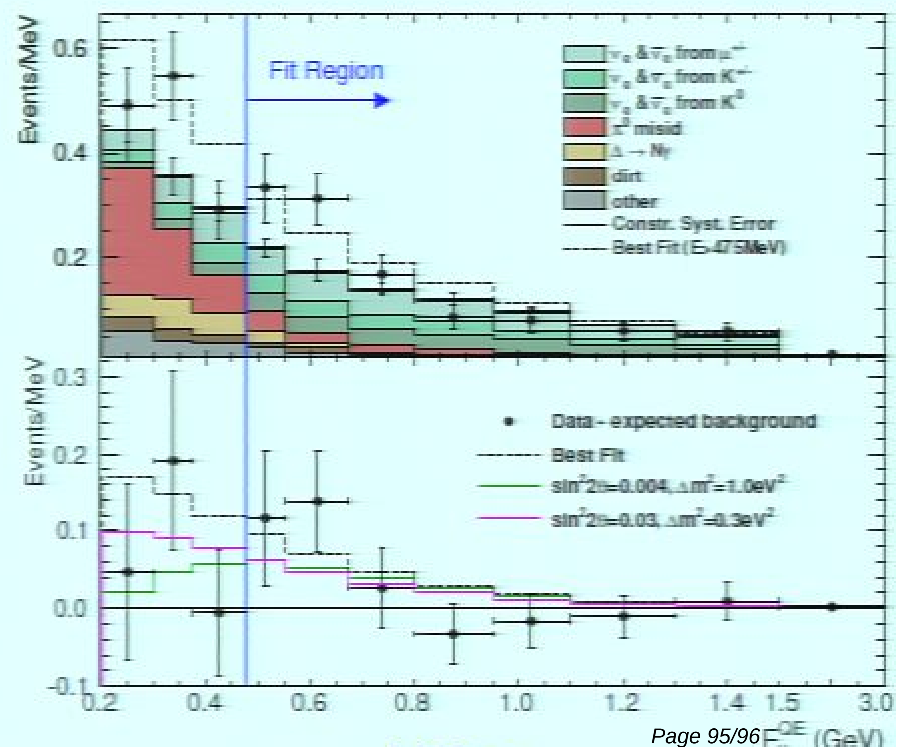
Thank you!

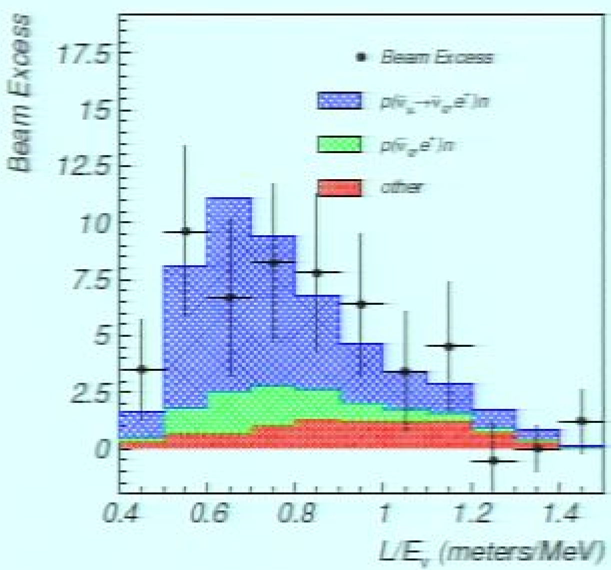
LSND, KARMEN, MiniBooNE

- LSND:
  - $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam from stopped pion source
- MiniBooNE:
  - $\bar{\nu}_e$ appearance in accelerated $\bar{\nu}_\mu$ beam
  - No ν_e appearance in interesting energy region $\rightarrow$ CP violation?
- KARMEN:
  - Very similar to LSND, but no excess



MB ν_e





LSND $\bar{\nu}_e$

MB $\bar{\nu}_e$

The reactor anti-neutrino anomaly

- Recent reevaluation of expected reactor $\bar{\nu}_e$ flux is $\sim 3.5\%$ higher than previous prediction Mueller et al. arXiv:1101.2663 vs. Schreckenbach 1985
- Method: Use measured β-spectra from ^{238}U, ^{235}U, ^{241}Pu fission at ILL and convert to $\bar{\nu}_e$ spectrum
- Problem: Requires knowledge of Q-values for all contributing decays.

Old method Schreckenbach 1985	New method Mueller et al. arXiv:1101.2663
30 effective branches	Uses nuclear databases (90% of $\bar{\nu}_e$ flux) 5 effective branches (remaining 10%) Error propagation, correlation matrix Off-equilibrium corrections (short irradiation time at ILL $\rightarrow$ not all β-branches in equilibrium

- Cross check:
  - Simulate "true" e^- spectra using set of few well-known β-branches ($\rightarrow \bar{\nu}_e$ spectrum known)
  - Reconstruct $\bar{\nu}_e$ spectrum using old method: Result is 3% too low
  - Reconstruct $\bar{\nu}_e$ spectrum using new method: Result is exact.