Interpretations of recent MINOS results

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Short Baseline Neutrino Workshop, May 13, 2011

Fermilab

Outline

1. The MINOS experiments and (some of) its results
2. Explanation attempts
   - Low statistics?
   - A systematic error?
   - “Real” *CPT* violation?
   - Effective *CPT* violation: Neutrino matter effects?
   - A *CP*-violating charged current interaction?
   - Non-standard neutrino interactions in renormalizable models
3. A common explanation for MINOS and SBL results?
4. Conclusions

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

Abstract

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.

Outline

Disclaimer

I'm not a member of the MINOS collaboration
I take the full blame for this talk.

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:

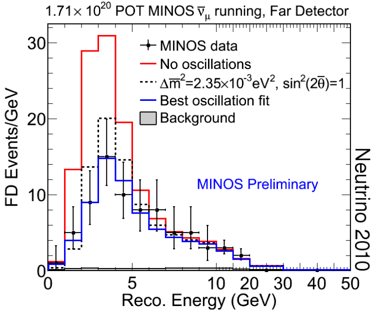
- 5.4 kt magnetized iron / solid scintillator

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



$\bar{\nu}_\mu$ data

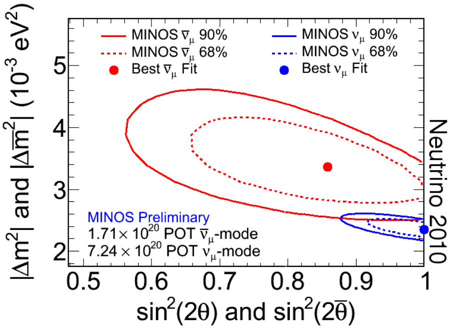


Image credit: MINOS collaboration, http://www-numi.fnal.gov/
This result first presented by P. Vahle at Neutrino 2010, see also arXiv:1104.0344

- Two-flavor fits: $P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$
- Separate fits for neutrinos and anti-neutrinos differ at 98% confidence level.

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Explanation attempts

- Low statistics?
  $\bar{\nu}_\mu$ sample is about 20 times smaller than ν_μ sample.
  $\Rightarrow$ Effect might go away with more statistics

Explanation attempts

- Systematic effect?
  I can only speculate . . .

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)

  Dighe Ray arXiv:0802.0121

A model of spontaneous *CPT* violation

- 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.

Mukohyama Park arXiv:1009.1251

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

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

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

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

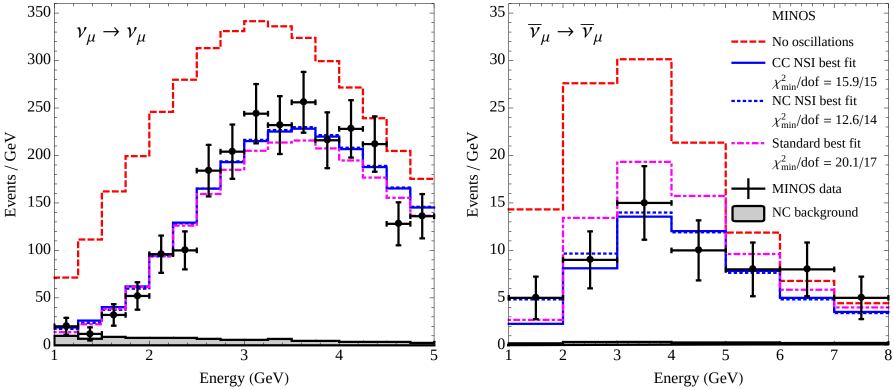
$\Rightarrow$ Effective CPT violation

Non-standard matter effects in the μ–τ sector

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

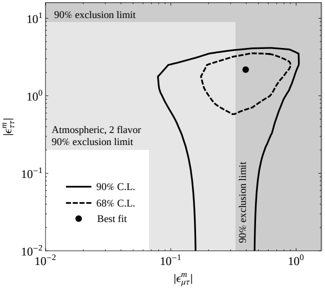
$$\sin^2 2\theta_{\text{eff}} = |\Delta m^2_{32}\sin 2\theta_{23} + 2\epsilon_{\mu\tau}A|^2/\Delta m^4_N\,,$$

(with $A = A = 2\sqrt{2}G_F n_e E$)

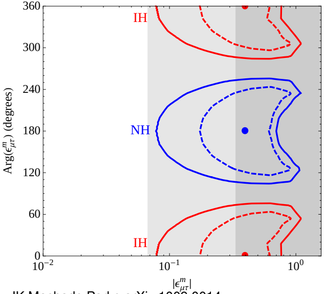


JK Machado Parke arXiv:1009.0014

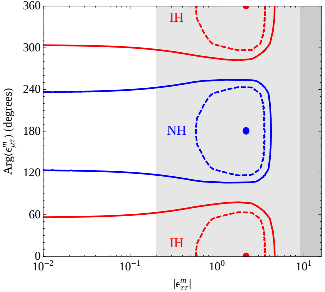
Non-standard matter effects in the μ–τ sector (2)



- $|\epsilon| \gtrsim 0.1$ 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 $\Gamma^{Z^0}_{\text{inv}}$
- Disfavored by atmospheric neutrinos (These are 2-flavor limits, may not be robust)
- Model-dependent constraints: See later



JK Machado Parke arXiv:1009.0014



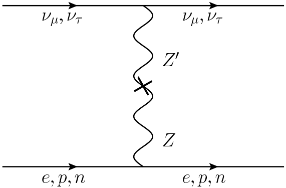
Similar analysis performed by Mann Cherdack Musial Kafka arXiv:1006.5720

Note: We included only the low-energy part of the MINOS spectrum. As shown in 1103.4365 the high-E part is important and makes the fit worse.

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) $\to$??? $\to$ μ(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

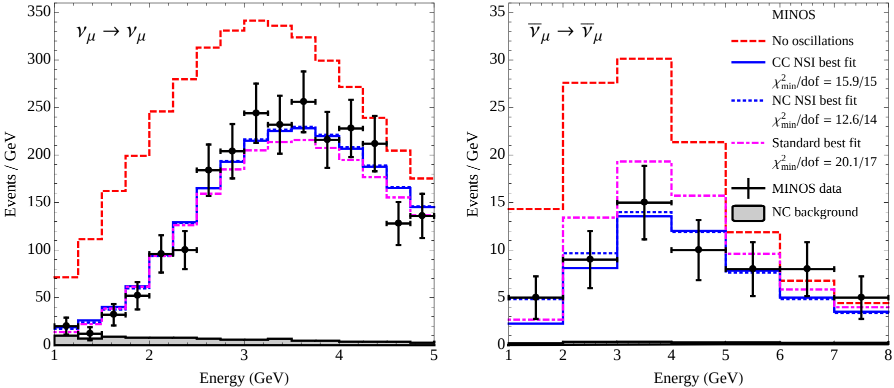
    $$\nu_\tau + N \to X + \mu\,,$$

    e.g.

    $$\mathcal{L}_{\rm NSI} \supset -2\sqrt{2} G_F \epsilon^d_{\tau\mu} V_{ud}\, [\bar{u}\gamma^\rho d]\, [\bar{\mu}\gamma_\rho P_L \nu_\tau] + h.c.$$

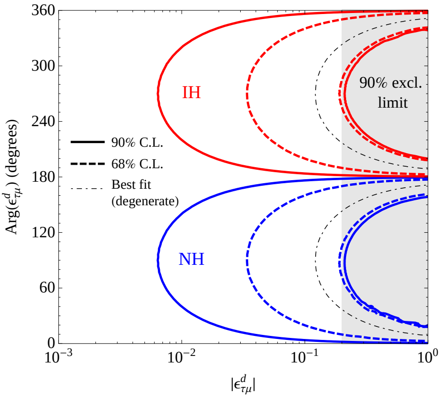
- If the new interaction is vector-like, it will not contribute to $\pi \to \mu\nu_\tau$, which is constrained by NOMAD.

A *CP*-violating charged current interaction? (2)



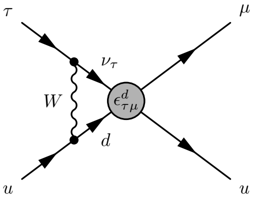
JK Machado Parke arXiv:1009.0014

A *CP*-violating charged current interaction? (3)



JK Machado Parke arXiv:1009.0014

- $|\epsilon| \gtrsim 0.1$ required (almost as strong as SM weak interactions)
- Consistent with model-independent constraint from $\tau \to \mu +$ hadrons



(Model-independent = consider only log-divergent part)

- Hard to embed in a renormalizable model

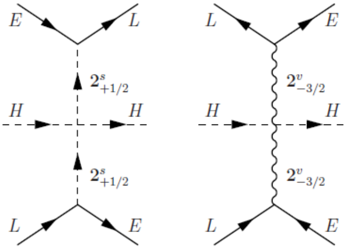
Non-standard interactions from heavy new physics

Aim: Relate NSI operators to renormalizable model

- $SU(2)$ invariant operators for neutrino NSI are usually accompanied by charged lepton NSI, which are heavily constrained.
  (Exception: NC $[\bar{\nu}_\tau \nu_\tau][\bar{f} f]$ couplings)

see e.g. Antusch Baumann Fernández-Martínez arXiv:0807.1003
Gavela Hernandez Ota Winter arXiv:0809.3451

- One way out: Dimension 8 operators, e.g. $[\overline{E^c}_\gamma \gamma^\rho L_\alpha][\bar{L}^\beta \gamma_\rho E^{c\,\delta}]$



  - Requires new mediators
  - Requires cancellation between couplings to avoid large dim-6 effects.

Non-standard interactions from light new physics

- Many constraints on NSI come from high-energy ($\gtrsim \mathcal{O}$(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)
- ...and can potentially explain DAMA, CoGeNT, CRESST signals

Pospelov 1103.3261, Harnik JK Machado, in progress (ASK ME!)

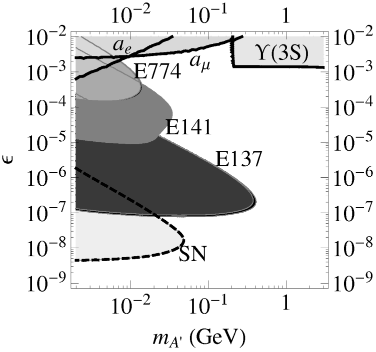


figure from Bjorken Essig Schuster Toro arXiv:

Outline

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

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Conclusions

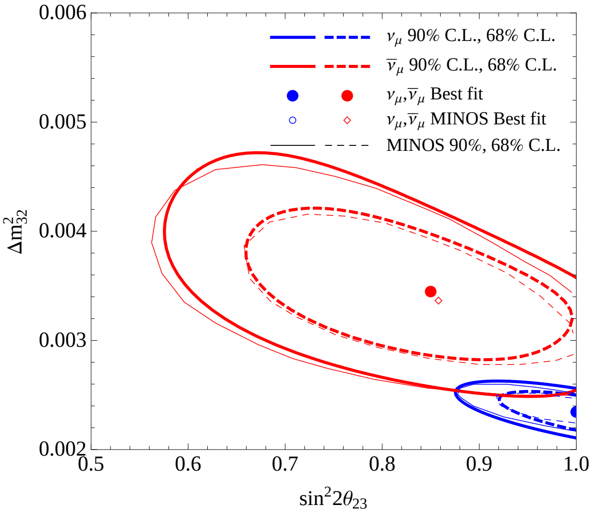
- MINOS sees interesting, but not yet conclusive, discrepancy between neutrino and anti-neutrino oscillations
- Explanation attempts
  - Low statistics
  - Systematic uncertainty?
  - CPT violation (can be spontaneous)?
  - Non-standard matter effects or new long-range force
    ...difficult to reconcile with atmospheric neutrinos
  - Modified charged current interactions
    ...difficult for model-building
- Possible sources of new physics in neutrino oscillations
  - Only flavor-non-universal or flavor-violating effects detectable
  - Heavy new physics: Small effects, usually easier to see in charged leptons
  - Light new physics: Well motivated, and neutrino matter effects are an interesting discovery channel
- The MINOS anomaly and the short-baseline anomalies seem to be independent effects so far

The future

- New experiments will hopefully confirm or refute the anomalies
- A reanalysis of older experimental data is desirable:
  - The considerable tension in the global fit indicates that some results are probably wrong.
- Theorists have to understand the origin of the anomalies if they persist

Thank you!

Verification of our simulation



Non-standard matter effects in the μ–τ sector

Two-flavor calculation leads to

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_N \sin^2\left(\frac{\Delta m_N^2 L}{4E}\right)$$

with

$$\Delta m_N^2 = \Big[(\Delta m_{32}^2 \cos 2\theta_{23} + \epsilon_{\tau\tau} A)^2 + |\Delta m_{32}^2 \sin 2\theta_{23} + 2\epsilon_{\mu\tau} A|^2\Big]$$

$$\sin^2 2\theta_N = |\Delta m_{32}^2 \sin 2\theta_{23} + 2\epsilon_{\mu\tau} A|^2 / \Delta m_N^4 ,$$

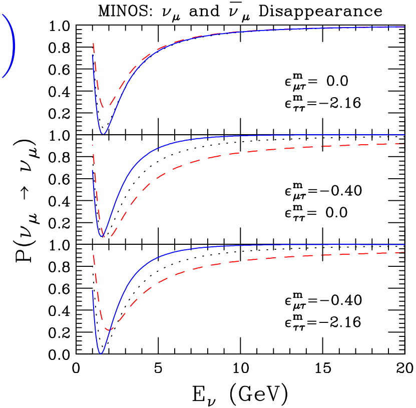
and $A = A = 2\sqrt{2} G_F n_e E$. (we set $\epsilon_{\mu\mu} = 0$ since flavor-universal terms can be subtracted from V)

Note the following symmetries:

$$\arg(\epsilon_{\mu\tau}) \to 2\pi n - \arg(\epsilon_{\mu\tau})$$

$$\epsilon_{\mu\tau} \to -\epsilon_{\mu\tau} , \qquad \epsilon_{\tau\tau} \to -\epsilon_{\tau\tau} , \qquad \Delta m_{32}^2 \to -\Delta m_{32}^2 ,$$

$$\epsilon_{\tau\tau} \to -\epsilon_{\tau\tau} , \qquad \theta_{23} \to \frac{\pi}{2} - \theta_{23} .$$



Non-standard charged current interactions

"Apparent" oscillation probability:

$$\tilde{P}(\nu_\mu \to \nu_\mu) =$$

$$1 - \left[1 + 2\,|\epsilon^d_{\tau\mu}|\cot 2\theta_{23}\cos\left[\arg(\epsilon^d_{\tau\mu})\right] - |\epsilon^d_{\tau\mu}|^2\right]\sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

$$+\,2\,|\epsilon^d_{\tau\mu}|\sin 2\theta_{23}\sin\left[\arg(\epsilon^d_{\tau\mu})\right]\sin\left(\frac{\Delta m^2_{32}L}{4E}\right)\cos\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

For anti-neutrinos:

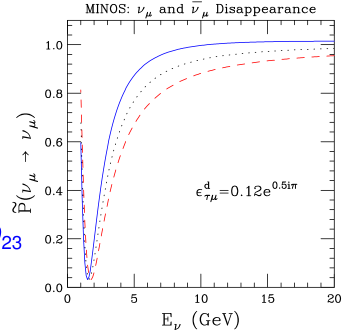
$$\arg(\epsilon^d_{\tau\mu}) \to -\arg(\epsilon^d_{\tau\mu})$$

Symmetries:

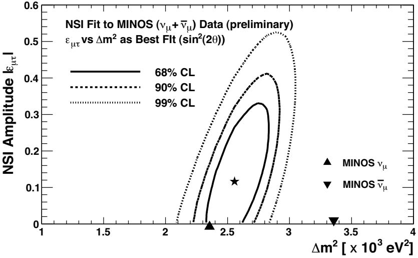
$$\arg(\epsilon^d_{\tau\mu}) \to 2\pi n - \arg(\epsilon^d_{\tau\mu})\,, \quad \Delta m^2_{32} \to -\Delta m^2_{32}$$

$$\arg(\epsilon^d_{\tau\mu}) \to (2n+1)\pi - \arg(\epsilon^d_{\tau\mu})\,, \quad \theta_{23} \to \frac{\pi}{2} - \theta_{23}$$

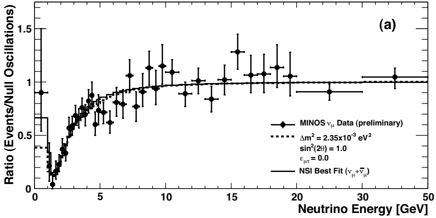
(The second of these can be generalized to a continuous symmetry.)

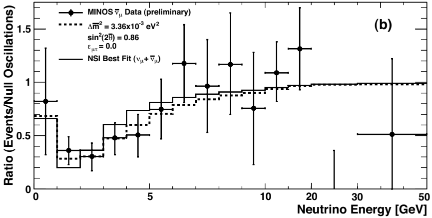


A similar analysis of NSI in the μ–τ sector



- Assume only $\epsilon_{\mu\tau} \neq 0$
- Fit to extracted oscillation probability rather than spectrum.
- Results agree with ours qualitatively, but not quantitatively.
- Possible reason: Fit to probability cannot fully include effect of experimental energy resolution





Mann Cherdack Musial Kafka arXiv:1006.5720