Interpretations of recent MINOS results

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Los Alamos National Laboratory, October 21st, 2010

Fermilab

partly based on work done collaboration with
Pedro A. N Machado and Stephen J. Parke (arXiv:1009.0014)

Outline

1. The MINOS experiment and its results—a hint for CPT violation?

2. Explanation attempts
   - Low statistics?
   - A systematic error?
   - "Real" *CPT* violation?
   - Effective *CPT* violation: Non-standard neutrino matter effects
   - A new long range force?
   - A *CP*-violating charged current interaction?

3. Non-standard neutrino interactions in renormalizable models

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.

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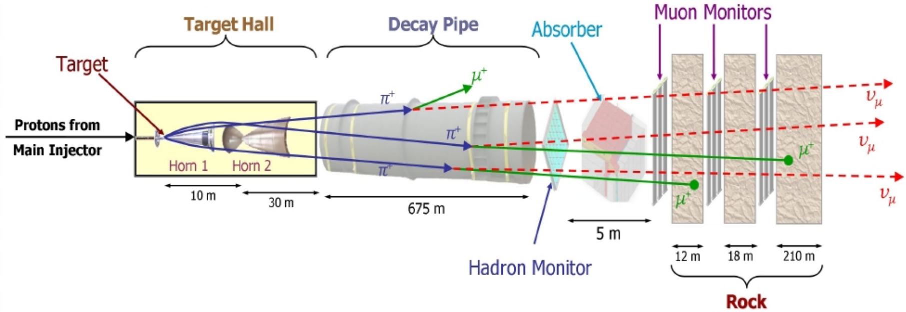
Disclaimer

I'm not a member of the MINOS collaboration,
and what I'm going to say in this talk
is entirely my own responsibility.

The NuMI beam



- ν_μ from decay in flight of focused π^+ + K^+ beam
- Intrinsic backgrounds: $\bar{\nu}_\mu$, ν_e from subdominant π^+, K^+ decays (e.g. $K^+ \to \pi^0 e^+ \nu_e$) and from muon decays
- Polarity of focussing system can be inverted to obtain $\bar{\nu}_\mu$ beam.

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

The MINOS experiment

Far detector:

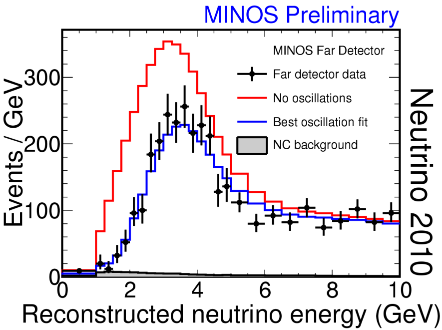
- 5.4 kt magnetized iron, interleaved with solid scintillator plates to record tracks

Near detector:

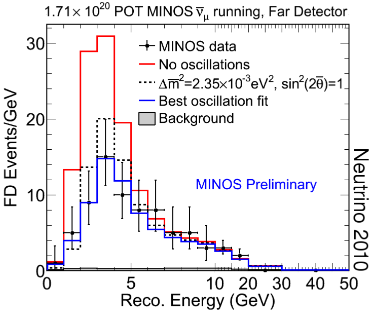
- Similar to the far detector but smaller
- Measures unoscillated neutrino flux
  $\Rightarrow$ reduction of systematic uncertainties

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

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



ν_μ

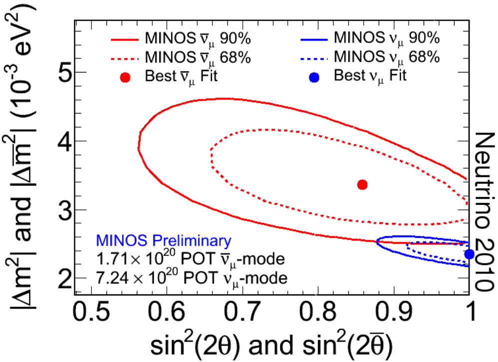


$\bar{\nu}_\mu$

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

MINOS oscillation fit

MINOS fit



Comparison to our fit

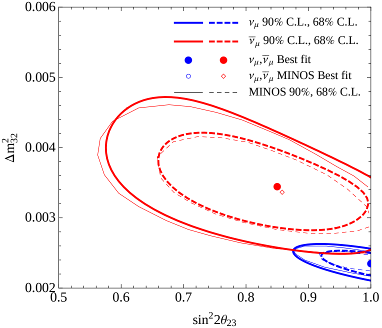


Image credit: MINOS collaboration, http://www-numi.fnal.gov/
This result first presented by P. Vahle at Neutrino 2010

- 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 $\sim 2\sigma$ confidence level.

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Low statistics?

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

A systematic error?

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 parameterization

Barenboim Lykken arXiv:0908.2993

- Assume mixing matrices for ν and $\bar{\nu}$ to be completely independent.
- Fit to MINOS (older dataset), Super-K, KamLAND, CHOOZ yields

	ν	$\bar{\nu}_\mu$
Δm^2_{31} [eV^2]	0.0025	0.02
$\sin^2 2\theta_{23}$	1.0	0.55

CPT violation?

Another parameterization:

- Introduce Lorentz- and *CPT*-violating operators like $A_\mu \bar{\psi} \gamma^\mu \psi$ (with A_μ a constant 4-vector)
- Studied in detail in Dighe Ray arXiv:0802.0121 (but not in the context of MINOS)

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.

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

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

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.

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

Kitazawa Sugiyama Yasuda
Will MINOS see new physics?
hep-ph/0606013

Blennow Ohlsson Skrotzki
Effects on non-standard interactions in the MINOS experiment
hep-ph/0702059

Non-standard matter effects

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

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

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

Two-flavor calculation leads to

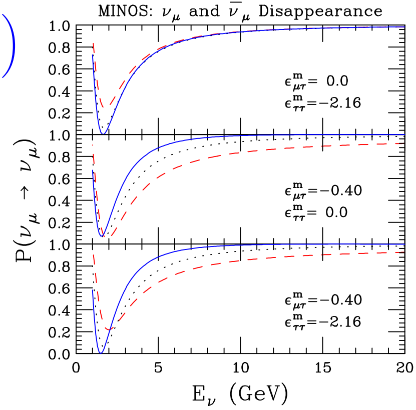
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_N \sin^2 \left(\frac{\Delta m_N^2 L}{4E} \right)$$

with

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

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

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)



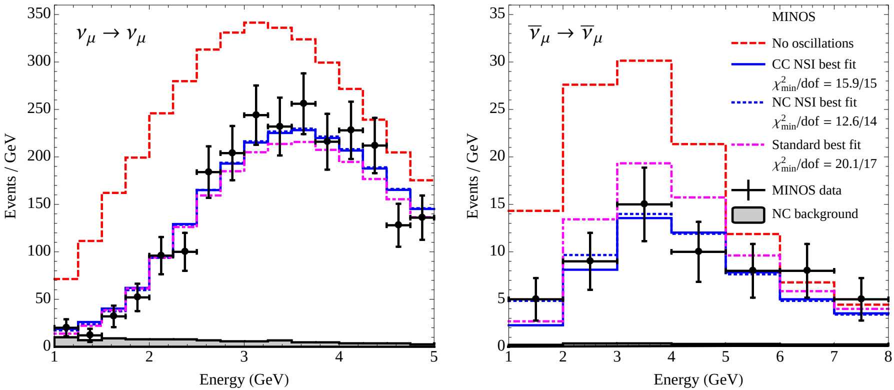
Note the following symmetries:

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

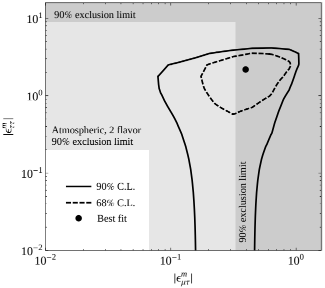
$$\epsilon_{\mu\tau} \to -\epsilon_{\mu\tau} , \qquad \epsilon_{\tau\tau} \to -\epsilon_{\tau\tau} , \qquad \Delta m_{32}^2 \to -\Delta m_{32}^2 ,$$

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

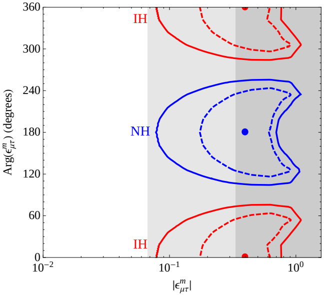
Non-standard matter effects in MINOS?

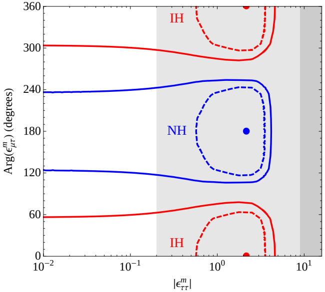


Non-standard matter effects in MINOS? (2)

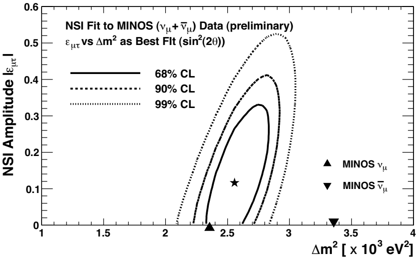


- $|\epsilon| \gtrsim 0.1$ required (almost as strong as SM weak interactions)
- Consistent with constraints on $\epsilon_{\mu\tau}$ from CHARM ($\nu_\mu e \to \nu e$) and NuTeV ($\nu_\mu q \to \nu q$)
- Consistent with constraints on $\epsilon_{\tau\tau}$ from $\Gamma^{Z^0}_{\text{inv}}$
- Disfavored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

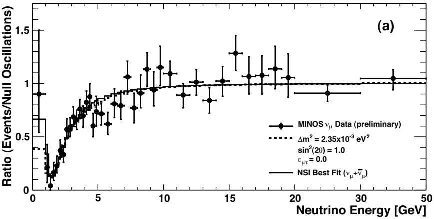


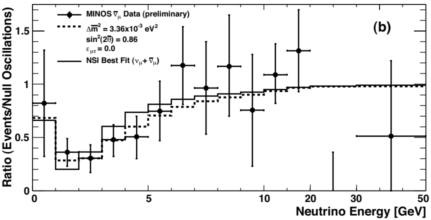


A similar analysis



- 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



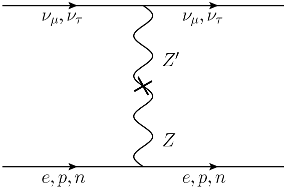


Mann Cherdack Musial Kafka arXiv:1006.5720

A new long-range force?

Heeck Rodejohann arXiv:1007.2655

- A very light $L_\mu - L_\tau$ 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 $L_\mu - L_\tau$ charges), this leads to effective CPT violation.
- Phenomenologically equivalent to $\epsilon_{\mu\mu}$, $\epsilon_{\tau\tau}$.

Non-standard charged current interactions

- 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.

Non-standard charged current interactions (2)

"Apparent" oscillation probability:

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

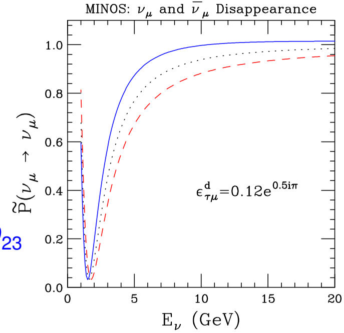
For anti-neutrinos:

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

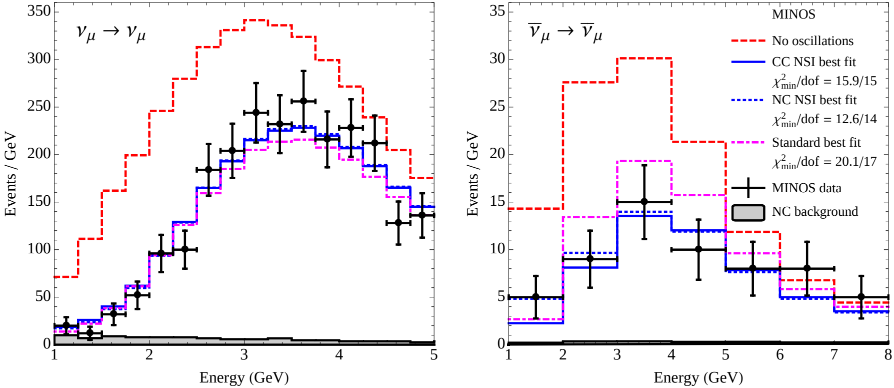
Symmetries:

$$\arg(\epsilon^d_{\tau\mu}) \to 2\pi n - \arg(\epsilon^d_{\tau\mu}), \quad \Delta m^2_{32} \to -\Delta m^2_{32}$$
$$\arg(\epsilon^d_{\tau\mu}) \to (2n+1)\pi - \arg(\epsilon^d_{\tau\mu}), \quad \theta_{23} \to \frac{\pi}{2} - \theta_{23}$$

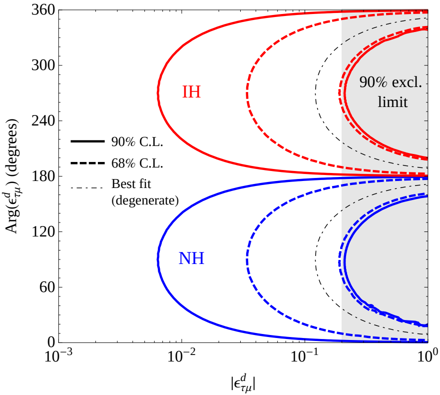
(The second of these can be generalized to a continuous symmetry.)



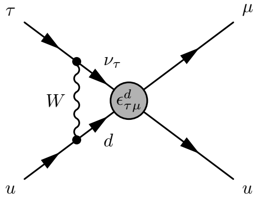
CC NSI in MINOS?



CC NSI in MINOS? (2)



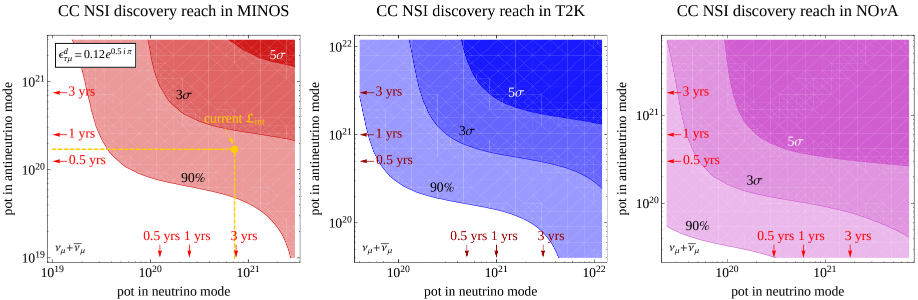
- $|\epsilon| \gtrsim 0.1$ required (almost as strong as SM weak interactions)
- Consistent with model-independent constraint from $\tau \to \mu +$ hadrons



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

- Hard to embed in a renormalizable model

Future tests



- Ideally, slightly more time spent on $\bar{\nu}$ running
  $\Rightarrow$ Similar statistics in ν and $\bar{\nu}$ in spite of lower $\bar{\nu}$ cross section
- At this time: More $\bar{\nu}$ running in MINOS desirable

Outline

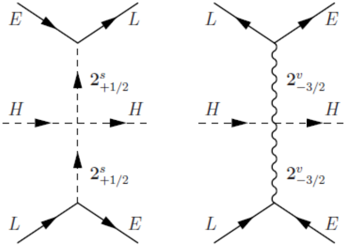
Neutrino NSI from new physics at high scales

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 lar dim-6 effects.

Neutrino NSI from light new physics

- Many constraints on NSI come from high-energy ($\mathcal{O}$(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 $(g^2 \sin^2\theta_w/e^2)(M_W^2/m^2)$
  - …can be relatively large

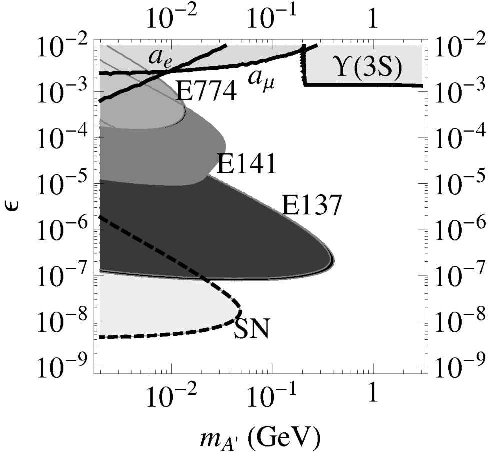
- Light new physics also motivated by Dark Matter (Sommerfeld enhancement)

Constraints on light new physics

Constraints on new kinetically mixed $U(1)$ gauge boson from

- Fixed target (beam dump) experiments
- Supernova cooling
- Electron/Muon $g-2$
- BaBar search for $\Upsilon(3S) \to \gamma Z' \to \gamma\mu^+\mu^-$

Note: For flavor-violating couplings, some constraints may become weaker



Bjorken Essig Schuster Toro arXiv:0906.0580

Outline

Conclusions

- MINOS observes interesting $\sim 2\sigma$ discrepancy between ν_μ and $\bar{\nu}_\mu$ oscillations.
- Possible explanations:
  - Low $\bar{\nu}_\mu$ statistics
  - Systematic effect
  - *CPT* violation
  - Non-standard neutrino matter effects (NC NSI)
  - A long-range force from the Sun
  - A *CP*-violating CC interaction (CC NSI)
- All these effects are not generic in extensions of the Standard model, but can be accomodated.
- In the future
  - MINOS will collect more $\bar{\nu}$ statistics
  - T2K and NOνA can confirm or refute the effect, provided they are operated also in $\bar{\nu}$ mode.

Thank you!