New interactions in the ν sector

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Fermilab

Outline

1. Effective field theory approach to new physics
2. Non-standard matter effects in long baseline experiments
3. New physics in low-energy neutrino scattering
4. Conclusions

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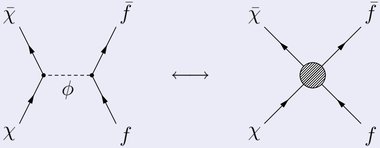
Effective field theory approach to new physics

Our approach to new physics in the ν sector here:

Effective field theory: Integrating out heavy new particles



$$(\bar{\chi}\chi)\frac{i}{q^2 - m_\phi^2}(\bar{f}f) \quad \rightarrow \quad \frac{i}{m_\phi^2}(\bar{\chi}\chi)(\bar{f}f)$$

Very successful in the past:

- Fermi theory of weak interactions
- Tests of new physics in the quark flavor sector
- Dark matter direct detection
- . . .

Neutrino matter effects in the Standard Model

In the Standard Model: Effective theory of weak interactions

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

In ordinary matter

$$\left\langle\bar{e}\gamma^0 e\right\rangle = n_e \qquad\qquad \left\langle\bar{e}\vec{\gamma}e\right\rangle \sim \left\langle\vec{v}_e\right\rangle = 0$$

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

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 suppressed by θ_{13}, $\Delta m^2_{21}/\Delta m^2_{31}$

New interactions in the neutrino sector

- "New physics" often leaves low-energy fingerprints in the form of effective, non-standard 4-fermion interactions (*NSI*).
  ⇒ Modification of weak interaction Lagrangian
- NSI can affect neutrino production (CC), propagation (NC), and detection (CC)

Grossman PL **B359** (1995) 141

Wolfenstein PR **D17** (1978) 2369, Valle PL **B199** (1987) 432, Guzzo Masiero Petcov PL **B260** (1991) 154, Roulet PR **D44** (1991) R935, etc.

- Lagrangian:

$$\mathcal{L}_{\text{NSI}} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\epsilon}^{s,f,f'}_{\alpha\beta} \left[\bar{\nu}_\beta \gamma^\rho (1-\gamma^5) \ell_\alpha\right] \left[\bar{f}' \gamma_\rho (1-\gamma^5) f\right] + \frac{G_F}{\sqrt{2}} \sum_{f} \tilde{\epsilon}^{m,f}_{\alpha\beta} \left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5) \nu_\beta\right] \left[\bar{f} \gamma_\rho (1-\gamma^5) f\right] + \text{h.c.},$$

- Lorentz structures different from $(V-A)(V-A)$ are possible.

Constraints on new interactions in the ν sector

- $SU(2)$ 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

Is there any room left for detectable new physics in the ν sector?

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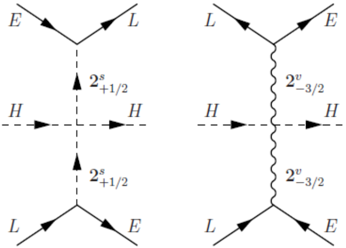
Is there any room left for detectable new physics in the ν sector?

- One possible scenario: Dim 8 operators, e.g. $[\overline{E^c}_\gamma \gamma^\rho L_\alpha][\bar{L}^\beta \gamma_\rho E^{c\,\delta}](H^\dagger H)$



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

Neutrino NSI from light new physics

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- Note that 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 0711.1363; Engelhardt Nelson Walsh 1002.4452
  - high-energy cross sections/rates suppressed by $g^4/(q^2)^2$
  - Low-E processes such as
    - ★ coherent forward scattering ($q^2 = 0$)
    - ★ coherent ν–N scattering
    - ★ low- ν–e scattering

    only suppressed by $(g^4/(q^2 - m^2)^2$
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- Light new mediators must be electrically neutral
- Light new force mediators also interesting in many other contexts:
  - Dark Matter (Sommerfeld enhancement) Arkani-Hamed Finkbeiner Slatyer Weiner 2009 + many others
  - Explaining dark matter anomalies through modified interactions of solar neutrinos Pospelov 2011, Harnik JK Machado 2012, Pospelov Pradler 2012
  - Residual $U(1)$'s from string compactifications
  - The APEX experiment
  - Fifth force searches (Eöt-Wash, …)
  - …and they are not ruled out experimentally

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Non-standard matter effects from NC NSI

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

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

leads to off-diagonal (flavor-violating) and/or non-universal terms in the MSW 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

Example: NC NSI in the μ–τ sector

Two-flavor calculation leads to

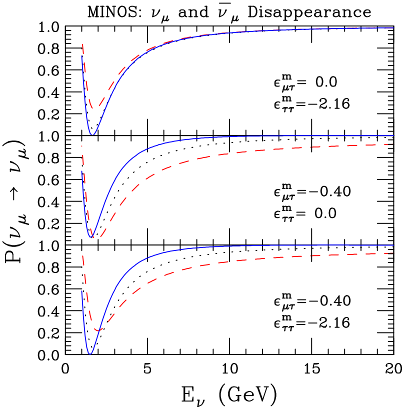
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_N \sin^2\left(\frac{\Delta m_N^2 L}{4E}\right)$$

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)

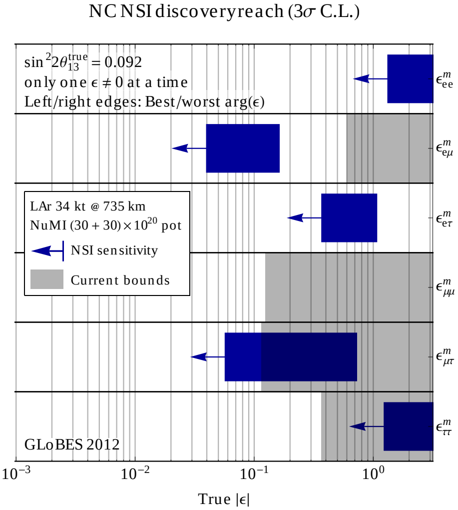


JK Machado Parke 2010

Small matter effects most visible at high energy

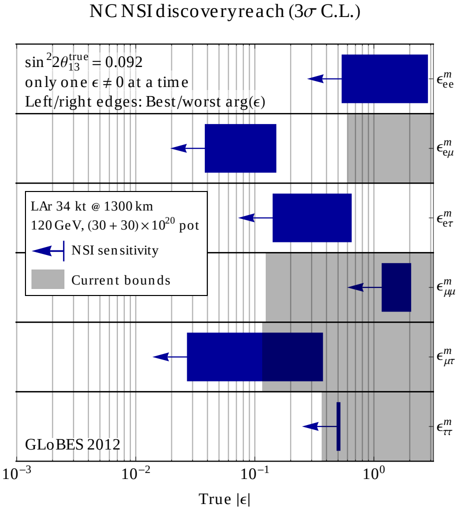
→ Most interesting for long-baseline superbeam or neutrino factory

Discovery reach in super-MINOS vs. LBNE



super-MINOS

(34 kt LAr @ 735 km, NuMI beam)

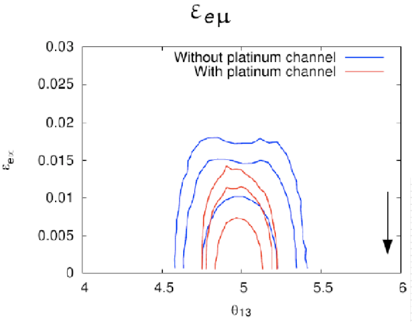


full LBNE

(34 kt LAr @ 1300 km, LBNE beam)

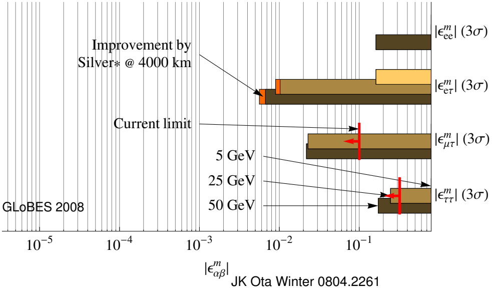
Discovery reach at a neutrino factory

low-E ν-fact



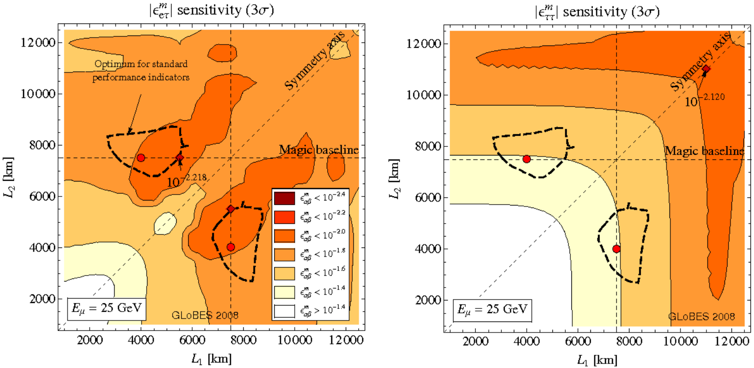
Li et al., in preparation

high-E ν-fact



JK Ota Winter 0804.2261

Baseline dependence of discovery reach at a HENF



JK Ota Winter, 0804.2261

- Long baseline generally a good thing for NSI searches
- Note: These plots are for the HENF, but qualitatively similar conclusions are expected for the LENF.

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Enhanced neutrino scattering at low energy

Remember:

New interactions mediated by a light new particle are strongest at low-q^2/low energy

In the following:

- Low-energy neutrino scattering
- Low-treshold detectors (dark matter technology)
- Will show plots for solar neutrinos, but man-made (Project X-based?) low-E neutrino sources are equally interesting

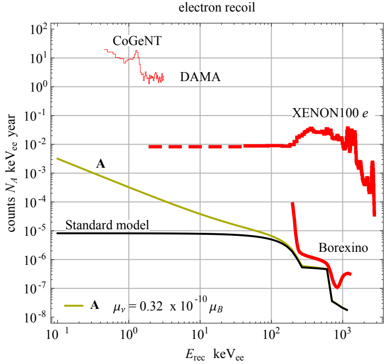
Example 1: Neutrino magnetic moments

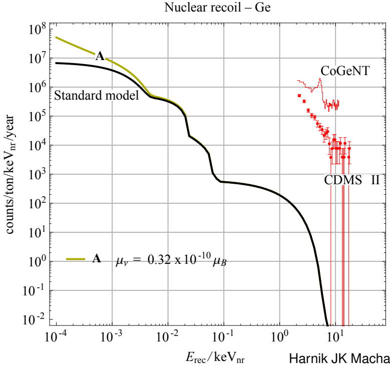
Assume neutrinos carry an enhanced magnetic moment

$$\mathcal{L}_{\mu_\nu} \supset \mu_\nu \, \bar{\nu} \sigma^{\alpha\beta} \partial_\beta A_\alpha \nu \,, \qquad \mu_\nu \gg \mu_{\nu,\text{SM}} = 3.2 \times 10^{-19} \mu_B$$

Here, the light mediator is just the photon.
Cross section large at low energies due to photon propagator $\propto q^{-2}$

$$\frac{d\sigma_\mu(\nu e \to \nu e)}{dE_r} = \mu_\nu^2 \alpha \left(\frac{1}{E_r} - \frac{1}{E_\nu} \right) ,$$





Harnik JK Machado 1202.6073

Example 2: Z'-enhanced ν scattering at low E

Consider a new Z' gauge boson coupling to neutrinos as well as charged SM particles

$$\frac{d\sigma_{Z'}(\nu e \to \nu e)}{dE_r} = \frac{g^2_{Z'e} g_{Z'\nu} m_e}{4\pi p_\nu^2 (M^2_{Z'} + 2E_r m_e)^2} \left[2E_\nu^2 + E_r^2 - 2E_r E_\nu - E_r m_e - m_\nu^2\right]$$

$$\frac{d\sigma_{Z'}(\nu N \to \nu N)}{dE_r} = \frac{g^2_{Z'N} g_{Z'\nu} m_N F^2(E_r)}{4\pi p_\nu^2 (M^2_{Z'} + 2E_r m_N)^2} \left[2E_\nu^2 + E_r^2 - 2E_r E_\nu - E_r m_N - m_\nu^2\right]$$

"ν" can be a conventional active neutrino, or a new sterile neutrino (light or heavy)

$M_{Z'}$	Z' mass
$g_{Z'e}$, $g_{Z'N}$	Z' couplings to electrons, nucei
E_r	electron/nuclear recoil energy
m_e, m_N	mass of electron, nucleus
E_ν, p_ν, m_ν	energy, momentum, mass of neutrino
$F(E_r)$	Nuclear form factor

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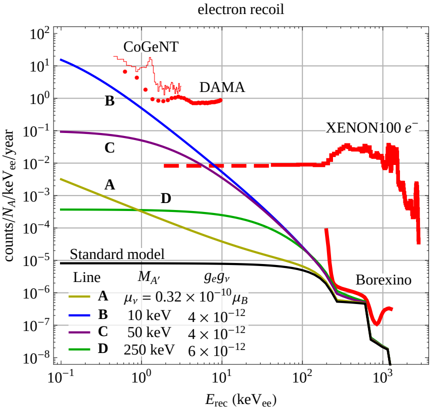

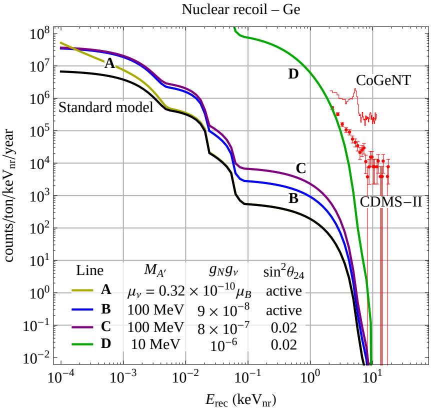

A: ν magnetic moment
B, C, D: kinetically mixed A' + sterile ν_s

A: ν magnetic moment
B: $U(1)_{B-L}$ boson
C: kinetically mixed $U(1)'$ + sterile ν_s
D: $U(1)_B$ + sterile ν_s charged under $U(1)_B$

- Enhanced scattering at low E_r for light A'
- Negligible compared to SM scattering ($\sim g^4 m_T / M_W^4$) at energies probed in conventional neutrino experiments

Pospelov 1103.3261, Harnik JK Machado 1202.6073, Pospelov Pradler 1203.0545

Outline

Summary

- Low-mass new particles with ultra-weak couplings are theoretically well-motivated
- MSW-type matter effects are a zero momentum transfer process and are therefore very sensitive to light new physics
    - In effective theory language: “Non-standard neutrino interactions”
    - Can be probed in oscillation experiments if the flavor-structure is non-trivial
    - Typically long baseline and high energy favorable
- Low-energy neutrino scattering is another sensitive probe of light new force mediators
    - Coherent neutrino–nucleus scattering
    - Dark matter detectors
    - Especially interesting if there are sterile neutrinos which can couple more strongly to the new force than the active ones
    - In this case, low-E scattering can be enhanced by several orders of magnitude

FROM FERMILAB AND DOE THE MAKERS OF

THE TEVATRON

PROJECT X

coming to your lab in 20XX

THE PARTY YOU'VE ONLY
DREAMED ABOUT