# New physics from neutrino experiments

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# Outline

# Non-standard neutrino interactions (NSI)

Low-energy fingerprint of new physics often has the form of effective 4-fermion interactions.

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## Neutrino oscillations including NSI

$$P_{\nu_\alpha^s \to \nu_\beta^d} = |\langle \nu_\beta^d | e^{-i(H + V_{\mathrm{NSI}})L} | \nu_\alpha^s \rangle|^2 = |\langle \nu_\beta | (1 + \varepsilon^d) e^{-i(H + V_{\mathrm{NSI}})L} (1 + \varepsilon^s) | \nu_\alpha \rangle|^2$$

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## Neutrino oscillations including NSI

$$P_{\nu^s_\alpha \to \nu^d_\beta} = |\langle \nu^d_\beta | e^{-i(H + V_{\text{NSI}})L} | \nu^s_\alpha \rangle|^2 = |\langle \nu_\beta | (1 + \varepsilon^d) e^{-i(H + V_{\text{NSI}})L} (1 + \varepsilon^s) | \nu_\alpha \rangle|^2$$

- CC type NSI: Flavour mixture at source and detector (Grossman PL **B359** (1995) 141)

$$|\nu^s_\alpha\rangle = |\nu_\alpha\rangle + \sum_{\beta = e,\mu,\tau} \varepsilon^s_{\alpha\beta} |\nu_\beta\rangle, \qquad \text{e.g. } \pi^+ \xrightarrow{\varepsilon^s_{\mu e}} \mu^+ \nu_e$$

$$\langle\nu^d_\beta| = \langle\nu_\beta| + \sum_{\alpha = e,\mu,\tau} \varepsilon^d_{\alpha\beta} \langle\nu_\alpha| \qquad \text{e.g. } \nu_\tau N \xrightarrow{\varepsilon^d_{\tau e}} e^- X$$

- NC type NSI: Extra matter effects in propagation

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

$$(V_{\text{NSI}})_{\alpha\beta} = \sqrt{2} G_F N_e \varepsilon^m_{\alpha\beta}$$

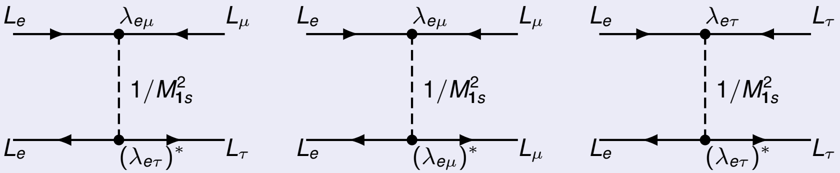
# Non-standard neutrino interactions (NSI)

- Generic expectation: $|\varepsilon| \sim M_W^2/M_{NSI}^2 \lesssim 10^{-2}$
- Current model-independent bounds: Typically $\mathcal{O}(10^{-2} - 10^{-1})$
- Bounds are usually stronger in concrete models.

# NSI in models

How large can NSI be in concrete models?

## dim = 6 operators



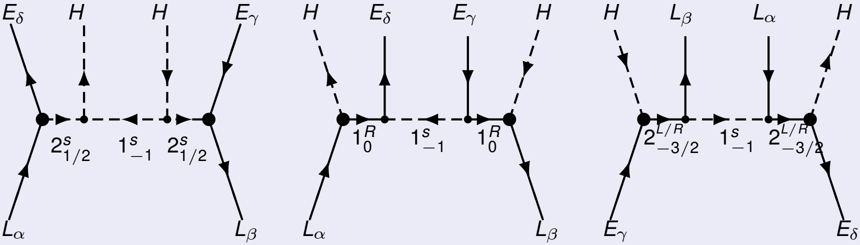

- Gauge invariance: NSI accompanied by charged lepton flavor violation $\rightarrow$ generically, strong bounds apply
- Exception: $ee\nu_\tau\nu_\tau$ coupling: $\varepsilon^m_{\tau\tau} \sim 0.1$ allowed.
- Not all $\varepsilon^{s,d,m}_{\alpha\beta}$ are independent

Gavela Hernandez Ota Winter arXiv:0809.3451

# NSI in models

How large can NSI be in concrete models?

## dim $=$ 8 operators




- More freedom to suppress charged LFV
- But have to cancel accompanying dim $=$ 6 operators ($\rightarrow$ symmetries, fine-tuning)
- Suppressed by $M_W^2 v^2 / M_{NSI}^4$ $\rightarrow$ smaller than dim $=$ 6 effects
- Not all $\varepsilon^{s,d,m}_{\alpha\beta}$ are independent

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# Non-unitary lepton mixing

## A special type of non-standard interactions

General idea: Lepton mixing matrix $U$ replaced by non-unitary matrix $N = (1 + \varepsilon)U$ with $\varepsilon = \varepsilon^\dagger$.

Current model-independent bounds (from $W$ and $Z$ decays, universality tests, LFV):

$$|\varepsilon| \approx \begin{pmatrix} < 2.0 \cdot 10^{-3} & < 3.5 \cdot 10^{-5} & < 8.0 \cdot 10^{-3} \\ < 3.5 \cdot 10^{-5} & < 8.0 \cdot 10^{-4} & < 5.1 \cdot 10^{-3} \\ < 8.0 \cdot 10^{-3} & < 5.1 \cdot 10^{-3} & < 2.7 \cdot 10^{-3} \end{pmatrix} \qquad \text{(90\% C.L.)}$$

Antusch Blennow Fernandez-Martinez arXiv:0903.3986 and references therein

Bounds are usually stronger in concrete models.

# Non-unitarity in inverse seesaw models

Introduce 3 right handed neutrinos $N_i$ + 3 extra singlet fermions $S_i$
$N_i$ and $S_i$ form pseudo-Dirac multiplets.

Complete $9 \times 9$ mass matrix:

$$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M^T \\ 0 & M & \mu \end{pmatrix} \qquad m_D \sim \mathcal{O}(100 \text{ GeV})\,,\ \mu \sim \mathcal{O}(1 \text{ keV})\,,\ M \sim \mathcal{O}(10^4 \text{ GeV})$$

Effective light neutrino mass matrix:

$$m_\nu = m_D^T\,(M^T)^{-1}\,\mu\,M^{-1}\,m_D \sim \mathcal{O}(1 \text{ eV})$$

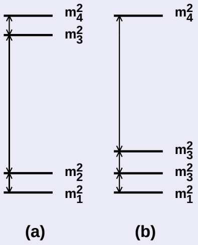
Light neutrinos mix with heavy states at the level of $m_D\,M^{-1} \sim 10^{-2}$
$\rightarrow$ Unitarity violation at the per cent level

# Sterile neutrinos

## A special type of non-unitarity

### Example: One extra sterile neutrino Donini Fuki López-Pavó Meloni Yasuda arXiv:0812.3703

Two possible schemes:




2+2 3+1

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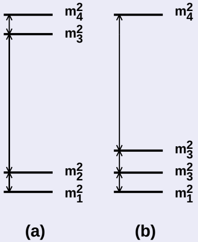


2+2 3+1

- 2+2 ruled out
  3+1 OK if LSND is ignored
- For large $\Delta m^2_{41}$, coherent production is impossible $\rightarrow$ effective three-flavour situation. Condition:

$$\sigma_{m^2} = \sqrt{(2E\sigma_E)^2 + (2p\sigma_p)^2} > \Delta m^2_{41}$$

Kayser 1981

- Mixing matrix is now $4 \times 4$.
- Upper left $3 \times 3$ submatrix is non-unitary.
  $\Rightarrow$ Experiment sees apparent unitarity violation.
- Note: $N_{\nu,\mathrm{light}} \geq 4$ disfavoured by BBN.

Barger Kneller Lee Marfatia Steigmann hep-ph/0305075

# NSI discovery potential of near detectors

Look for anomalous CC couplings ($\mathcal{O}(\varepsilon^2)$ effects):

$\nu_\mu + N \to e + X, \quad \nu_e + N \to \mu + X$

- Limited by uncertainties in primary fluxes
- Different spectrum helps a little
- Sensitivity to $\varepsilon^s_{\alpha\beta}$, $\varepsilon^d_{\alpha\beta}$ is $\mathcal{O}(10^{-1} - 10^{-2})$
- Much easier to see with neutrinos from muon beam
- NSI can spoil calibration of far detector oscillation analysis!

# NSI discovery potential of near detectors

Look for anomalous CC couplings ($\mathcal{O}(\varepsilon^2)$ effects):

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

Detector technology: Emulsion Cloud Chamber (ECC)

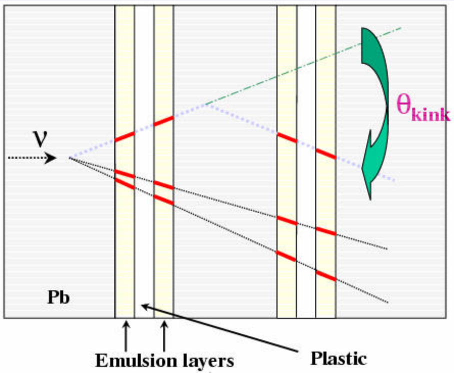


Image: OPERA

- $2m \times 2m$ acceptance feasible @ $5M\$$.
- Full scanning of last plane feasible.
- Extremely good background suppression $\rightarrow$ Sensitivity to $\mathcal{O}(10^{-6})$ effects
- Translates into $\varepsilon \sim 10^{-3}$

Adam Para is the expert!

# Discovery potential of far detectors

Advantages of far detectors for new physics search:

- Sensitivity to non-standard matter effects
- Sensitivity to larger number of channels by interference of standard and non-standard amplitudes

  e.g. $\pi \xrightarrow{\text{NSI}} \nu_\tau \xrightarrow{\text{osc.}} \nu_\mu$

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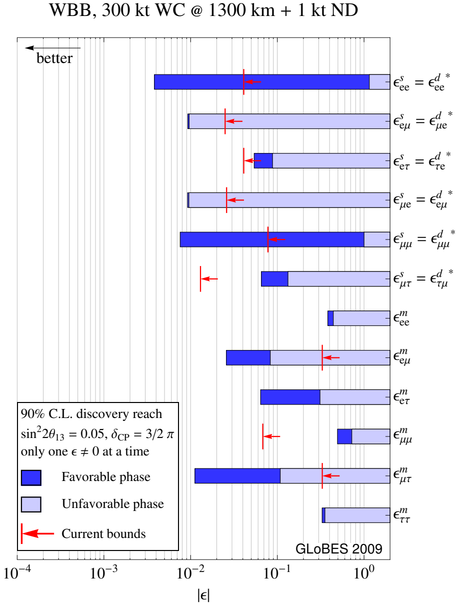
Disadvantages of far detectors for new physics search:

- Low event rate
- Disentangling different contributions is hard
  (parameter correlations, degeneracies)

$\Rightarrow$ Fortunately, future experiments will have near and far detectors.

# NSI sensitivity of FNAL-DUSEL wide band beam




## GLoBES simulation:

- $\nu + \bar{\nu}$ running
  $3 \times 10^{21}$ $p^+$ on target each
- Far detector: 300 kt (fiducial)
  water Čerenkov @ 1 300 km
- Includes hypothetical 1 kt
  water Čerenkov near detector
- Includes 3-flavor treatment, systematical uncertainties, detector response function, parameter correlations, ...

GLoBES experiment description based on work by Mary Bishai, Mark Dierckxsens, Milind Diwan, Christine Lewis, Patrick Huber
Current bounds from Biggio Blennow Fernandez-Martinez arXiv:0907.0097

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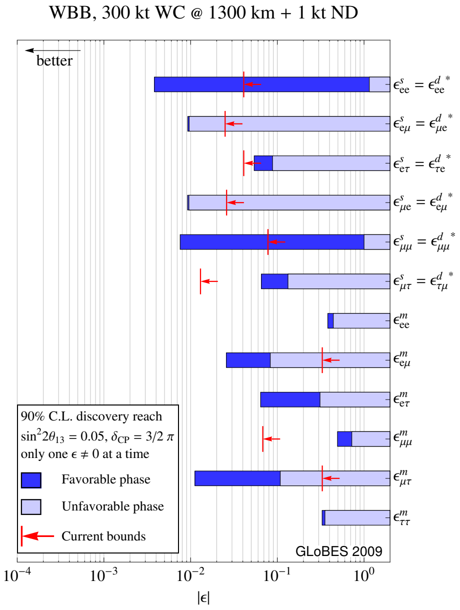


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## Result:

Bounds can be improved by up to one order of magnitude, but not to the level that is interesting from a model builder's point of view.

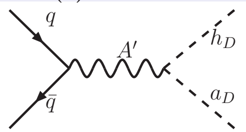
# Light long-lived hidden sector particles

Light hidden sectors motivated by recent results on Dark Matter

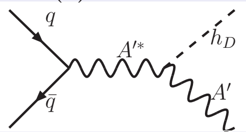
## Hidden $U(1)'$ + hidden Higgs boson $h_D$

- $h_D$ produced in beam dump experiment

(a)




(b)




- Long-lived because $A'$-mediated decay to SM particles is suppressed
- Possible signature: Decay into $\ell^+\ell^-$ pair behind shielding.

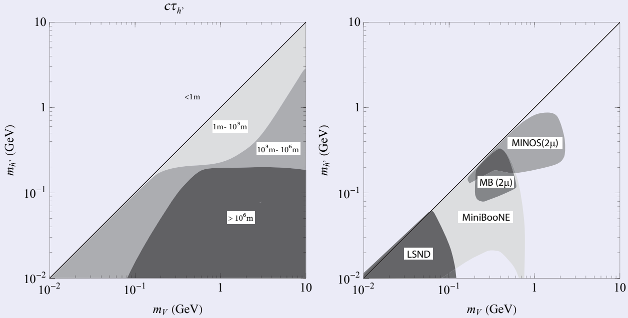
Batell Pospelov Ritz arXiv:0906.5614, Schuster Tori Yavin arXiv:0910.1602

# Light long-lived hidden sector particles

## Hidden $U(1)'$ + hidden Higgs boson $h_D$

- Sensitivity of different experiments to $e^+e^-$ and $\mu^+\mu^-$ final states:

  Right plot: Shaded regions indicate $\geq 10$ expected events for $A'$ kinetic mixing near upper bound




Batell Pospelov Ritz arXiv:0906.5614

- Improvements can be achieved with
  - More luminosity ($\rightarrow$ Project X)
  - Larger detectors
  - Sensitivity to new $h_D$ decay channels ($\tau^+\tau^-$)
    however, $\tau$ detector would need to have size comparable to MINOS ND

# Conclusions

- Possible signals of new physics in the neutrino sector:
  - Non-standard interactions
  - Non-unitary mixing
  - Mixing with sterile neutrinos
- High-intensity neutrino beams can significantly improve bounds, but discoveries still require very large new physics effects
- Another use of future neutrino detectors:
  Search for light, long-lived hidden sector particles ($\rightarrow$ Dark Matter?)
- An interesting near-future possibility: Emulsion Cloud Chamber ($\nu_\tau$ detector) in the NuMI beam
  - Sensitive to non-standard decay $\pi \rightarrow \nu_\tau$ (down to $\mathrm{BR} < 10^{-6}$)
  - $\nu_\tau$ detection desirable for optimum coverage of flavor space

# The game of the name

| | |
|---|---|
| Proton RIFLE | Protons for Research at the Intensity Frontier at Low Energy |
| PANDAS | Proton Accelerator for the Next Decade of Advancements in Science<br>Alternatively:<br>Proton Accelerator with No Decent Acronym So far |

Thank you!