Neutrino factory optimization for non-standard interactions

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J. Kopp, TO, and W. Winter
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Preface

Within the current precision — Leading Order (LO)

Oscillation probabilities for $\nu_\mu \to \nu_\alpha$ (@atmospheric region $\Delta m^2_{31} L/E \sim 1$)

$$\underbrace{P_{\nu_\mu \to \nu_e}}_{0} + P_{\nu_\mu \to \nu_\mu} + \underbrace{P_{\nu_\mu \to \nu_\tau}}_{1 - P_{\nu_\mu \to \nu_\mu}} = 1 \qquad \text{(unitarity)}$$

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Future experiments are sensitive to the Next LO

$$P_{\nu_\mu \to \nu_e} = 0 \qquad \boxed{\text{Leading Order}}$$

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$$\begin{aligned} P_{\nu_\mu \to \nu_e} = \; & 0 && \boxed{\text{Leading Order}} \\ & + \mathcal{O}(s_{13}^2) && \boxed{\text{Mass-Texture, LFV Prediction...}} \\ & + \mathcal{O}(s_{13} \Delta m_{21}^2 / \Delta m_{31}^2) && \boxed{\text{CP violation (Leptogenesis)...}} \end{aligned}$$

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Outline

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1. Introduction

2. NSI search in a neutrino factory
   - Neutrino factory for standard oscillation parameters
   - Neutrino factory for NSI
     - Correlations between NSIs
     - Silver detector for NSI
     - Optimization of Golden detector baselines

3. Model building for large NSI [short comment]

4. Summary

Introduction — NSI in oscillation

- NSI — Exotic interactions with neutrinos which are parametrized as four-Fermi interactions:

Standard oscillation

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu_\beta | \mathrm{e}^{-\mathrm{i}HL} | \nu_\alpha \rangle \right|^2$$

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With NSI in source and detection

$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu_\beta^d | \mathrm{e}^{-\mathrm{i}HL} | \nu_\alpha^s \rangle \right|^2$$

- CC type NSI — flavour mixture states at source and detection

Grossman PL**B359** (1995) 141.

$$|\nu_\alpha^s\rangle = |\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon_{\alpha\gamma}^s |\nu_\gamma\rangle, \qquad \text{e.g., } \pi^+ \xrightarrow{\epsilon_{\mu e}^s} \mu^+ \nu_e$$

$$\langle\nu_\alpha^d| = \langle\nu_\alpha| + \sum_{\gamma=e,\mu,\tau} \epsilon_{\gamma\alpha}^d \langle\nu_\gamma|, \qquad \text{e.g., } \nu_\tau N \xrightarrow{\epsilon_{\tau e}^d} e^- X$$

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$$P_{\nu_\alpha \to \nu_\beta} = \left| \langle \nu_\beta | \mathrm{e}^{-\mathrm{i}HL} | \nu_\alpha \rangle \right|^2$$

With NSI in propagation

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

- NC type NSI — extra matter effect in propagation

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

$$(V_{\mathrm{NSI}})_{\beta\alpha} = \sqrt{2} G_F N_e \begin{pmatrix} \epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^{m*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^{m*}_{e\tau} & \epsilon^{m*}_{\mu\tau} & \epsilon^m_{\tau\tau} \end{pmatrix},$$

e.g., $\nu_e \xrightarrow{\epsilon^m_{e\tau}} \nu_\tau$ in propagation

- We will focus on NSI in the propagation in this talk.

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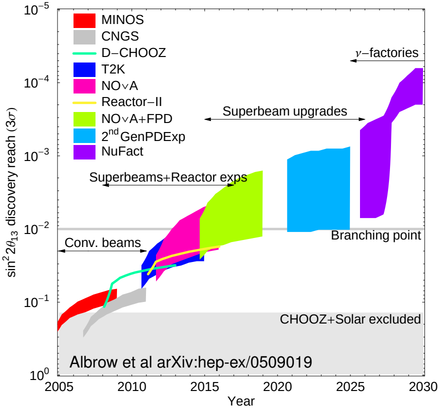
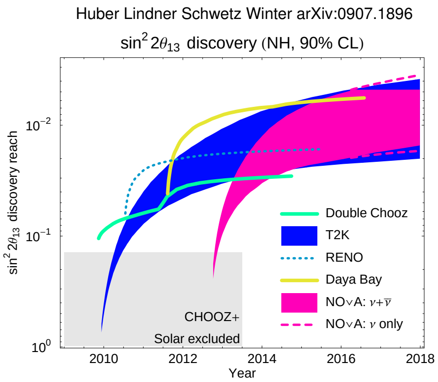
Oscillation experiments in next generation



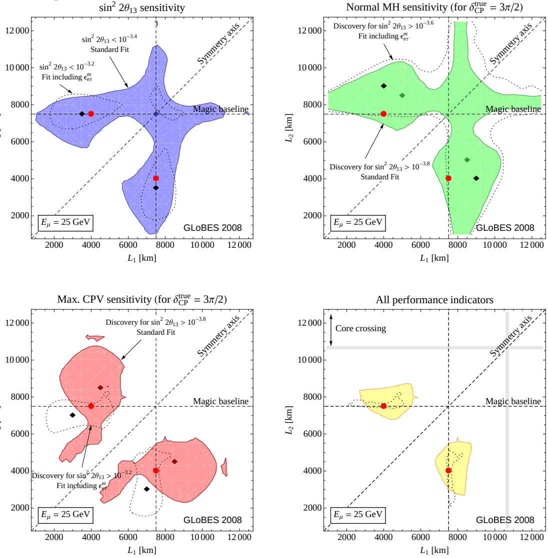


Central theme of this talk

What is the optimal setup (E_μ, L, and type of detectors) for measuring θ_{13}, $\delta_{\rm CP}$, sign[Δm^2_{31}], and NSI parameters $\epsilon^m_{\alpha\beta}$?

Kopp O Winter

Optimization for standard oscillation parameters



For θ_{13}, $\delta_{\rm CP}$, and sign$[\Delta m^2_{31}]$

Optimum at 4000+7500 km
Optimization does not change in presence of NSI

- The qualitatively different observations (matter osc. max and magic baseline) help resolve the parameter degeneracies.
- If we have two Golden dets at 4000km+7500km, Silver det (included in IDS-NF) does not contribute improving sensitivities.

Relevant NSI in a neutrino factory experiment

Relevant NSI in each channel

e.g., Kikuchi Minakata Uchinami JHEP**0903** (2009) 114, Kopp Lindner O Sato PR**D77** (2008) 013007

- Appearance channel: $\epsilon^m_{e\mu}$ and $\epsilon^m_{e\tau}$

On bounds on ϵ: Biggio Blennow Fernandez-Martinez JHEP**0903** (2009) 139 and arXiv:0907.0097

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MIND (Golden) det

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→ MIND (Golden) det

- Silver channel: $\epsilon^m_{e\tau}$ and $\epsilon^m_{e\mu}$ — ECC (Silver) det

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Tau-associated NSI $\epsilon^m_{e\tau}$ $\epsilon^m_{\mu\tau}$, and $\epsilon^m_{\tau\tau}$

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Appearance and disapp. channels — MIND (Golden) det

Silver channel — ECC (Silver) det

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Central questions for NSI search

- Correlation between NSIs and its resolution

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(Appearance and Disapp. channels) — MIND (Golden) det

(Silver channel) — ECC (Silver) det

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- Necessity of Silver channel

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Central questions for NSI search

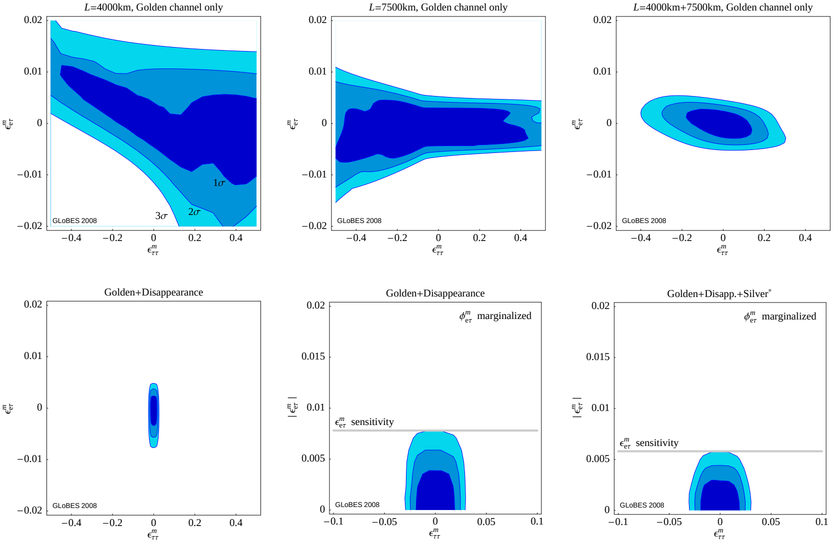
- Correlation between NSIs and its resolution
- Necessity of Silver channel

We address them with full simulations powered by GLoBES

GLoBES Website: http://www.mpi-hd.mpg.de/lin/globes/

Ribeiro Minakata Nunokawa Uchinami Zukanovich-Funchal JHEP **0712** (2007) 002. Kopp O Winter

Correlation between $\epsilon^m_{e\tau}$ and $\epsilon^m_{\tau\tau}$



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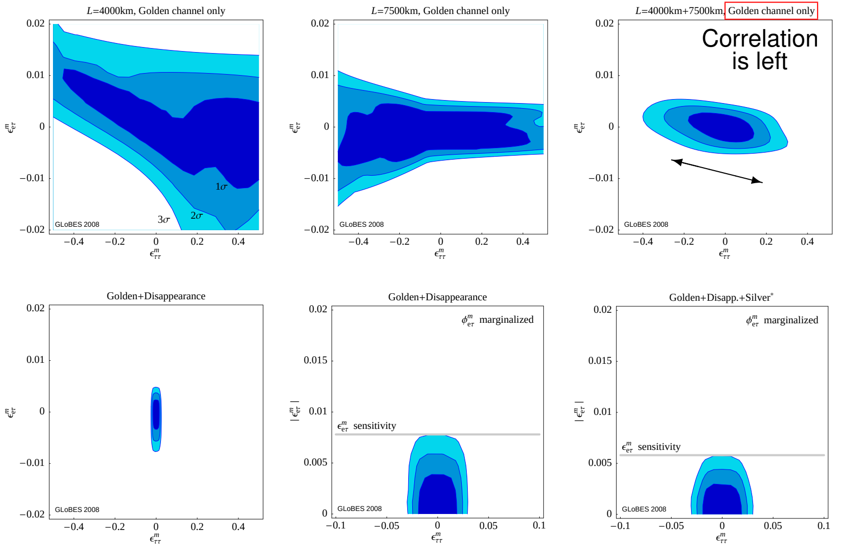

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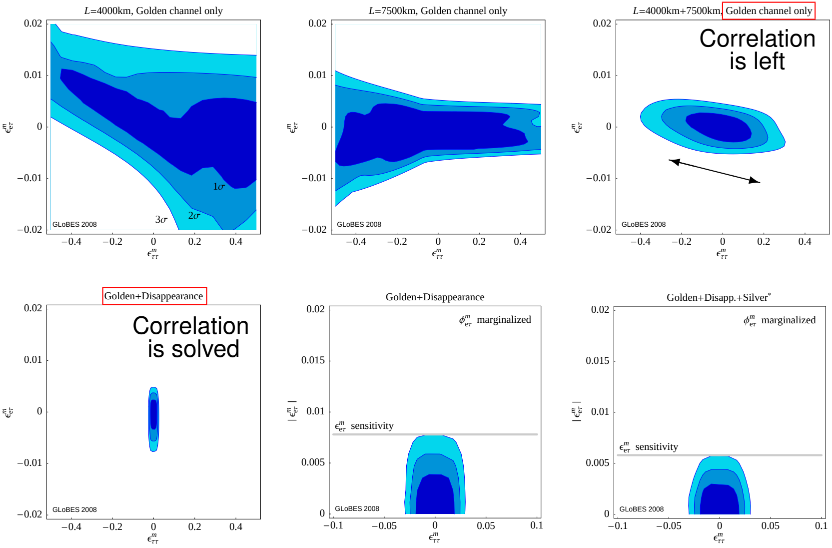

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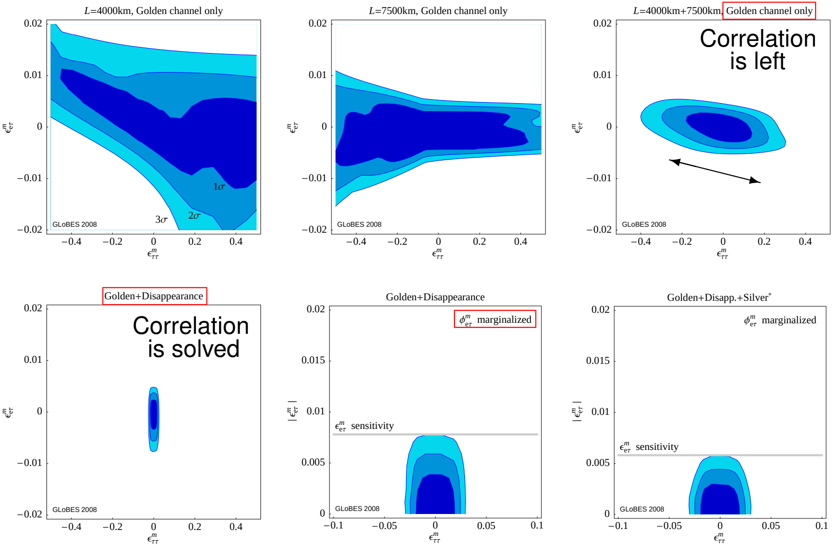

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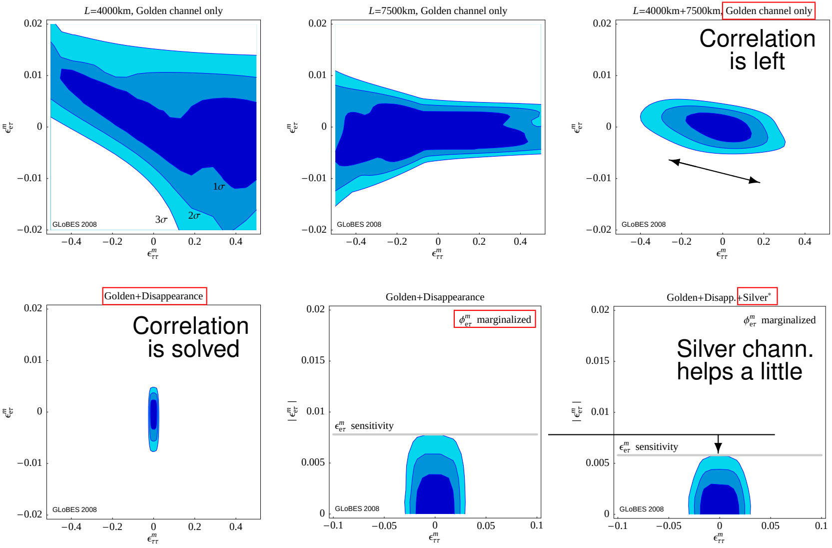
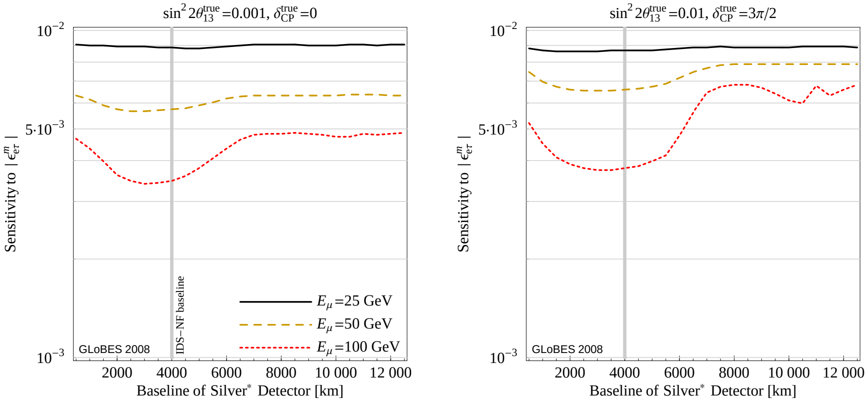
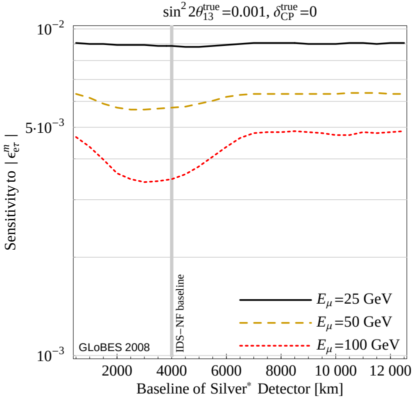


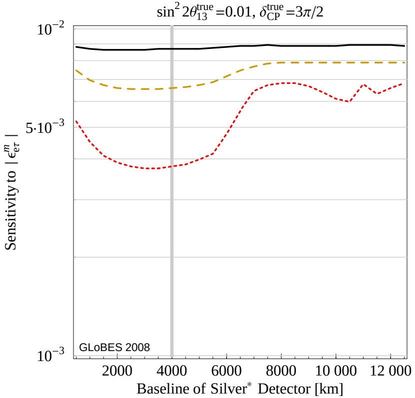
Optimization of silver detector baseline



- Fix two Golden dets at $L = 4000 + 7500$ km.

Optimization of silver detector baseline





- Fix two Golden dets at $L = 4000 + 7500$ km.
- Silver detector only relevant $L \sim 4000$ km and $E_\mu \gg 25$ GeV.
  $\rightarrow$ Fix Silver det at $L = 4000$ km ...

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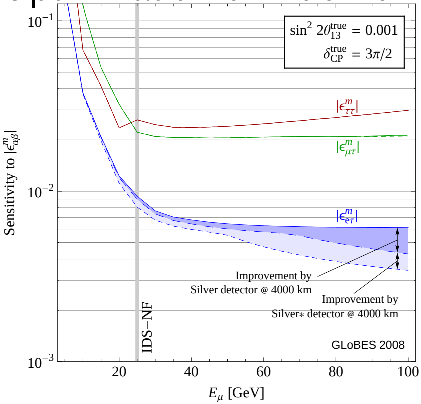
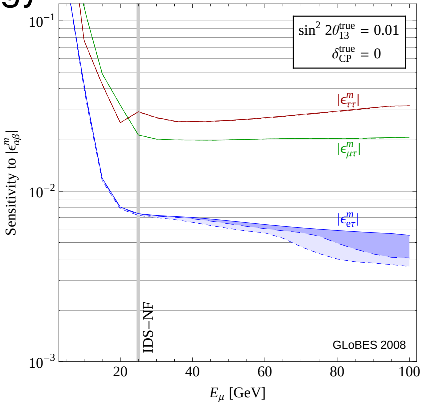
Optimization of muon energy





- Fix Goldens at $L = 4000 + 7500$ km and Silver at $L = 4000$ km

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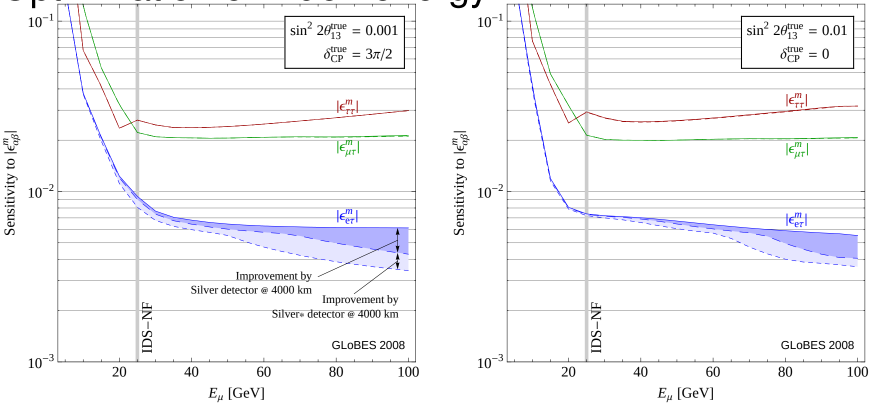

- Fix Goldens at $L = 4000 + 7500$ km and Silver at $L = 4000$ km
- Silver detector only useful at $E_\mu \gg 50$ GeV.
  $\rightarrow$ Fix $E_\mu = 25$ GeV (IDS-NF baseline), omit Silver detector...

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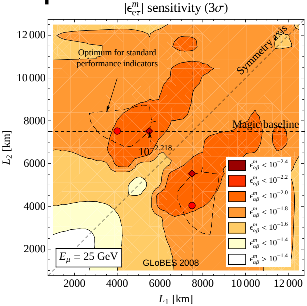
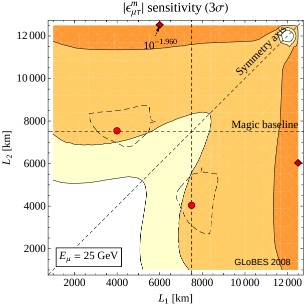
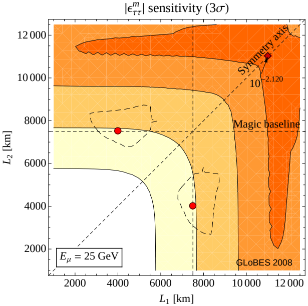
Optimization of Golden detector baselines







- For $\epsilon^m_{e\tau}$: $L =$4000km+7500km is almost optimal.
- For $\epsilon^m_{\mu\tau}$ and $\epsilon^m_{\tau\tau}$: longer baseline is preferred.
  Sensitivity is dominated by the longer baseline, and it is simply proportional to the baseline length.

Note For NSI search, higher E_μ (and longer L) is preferred.

Outline

NSI from Dim.6 and Dim.8

Dim.6 op — 4-Fermi

$\nu_\alpha \xrightarrow{\epsilon^m_{\alpha\beta}} \nu_\beta$ is parametrized as 4-Fermi interaction

$$\frac{1}{\Lambda^2}[\bar{\nu}_\beta \gamma^\rho \mathrm{P}_L \nu_\alpha][\bar{f}\gamma_\rho \mathrm{P}_L f]$$

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$$\frac{1}{\Lambda^2}[\bar{L}_\beta \gamma^\rho L_\alpha][\bar{f}\gamma_\rho \mathrm{P}_L f]$$

$$= \frac{1}{\Lambda^2}\left[[\bar{\nu}_\beta \gamma^\rho \mathrm{P}_L \nu_\alpha] + [\bar{\ell}_\beta \gamma^\rho \mathrm{P}_L \ell_\alpha]\right][\bar{f}\gamma_\rho \mathrm{P}_L f]$$

includes also SU(2) counter process Exception $[\overline{L^c}L][\overline{L^c}L]$

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includes also SU(2) counter process Exception $[\overline{L^c}L][\overline{L^c}L]$

Dim.8 op — 4-Fermi and 2-Higgs

SM gauge invariant form

$$\frac{1}{\Lambda^4}[(\bar{L}_\beta H)\gamma^\rho (H^\dagger L_\alpha)][\bar{f}\gamma_\rho \mathrm{P}_L f]$$

NSI from Dim.6 and Dim.8

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Dim.8 op — 4-Fermi and 2-Higgs

SM gauge invariant form and after EWSB

$$\frac{1}{\Lambda^4}[(\bar{L}_\beta H)\gamma^\rho (H^\dagger L_\alpha)][\bar{f}\gamma_\rho \mathrm{P}_L f]$$

$$=\frac{v^2}{2\Lambda^4}[\bar{\nu}_\beta \gamma^\rho \nu_\alpha][\bar{f}\gamma_\rho \mathrm{P}_L f] + \text{(Higgs ints.)}$$

$SU(2)$ relation is broken with Higgs vev.

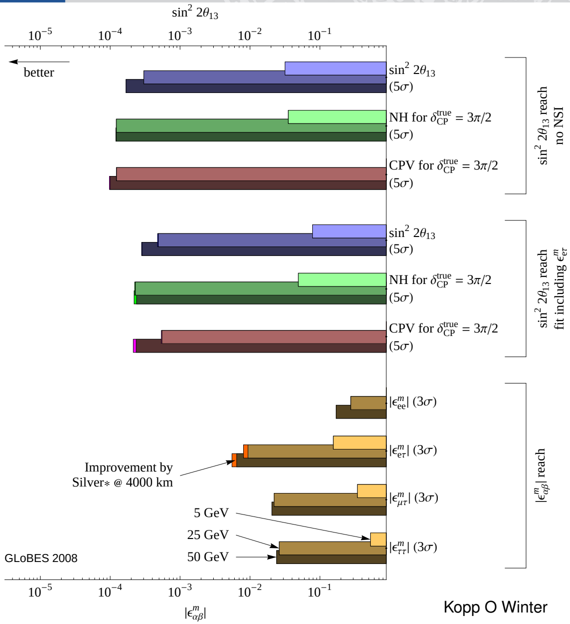
Gavela Hernandez O Winter

NSI from Dim.8

- NSI from Dim.6 (4-Fermi) are strongly constrained
  No $SU(2)$ violation
  Bergmann Grossman Pierce PR**D61** (2000) 053005
- NSI from Dim.8 (4-Fermi+2Higgs) have some chance
  $SU(2)$ relation is broken with Higgs vev
  Berezhiani Rossi PL**B535** (2002) 207, Davidson Pena-Garay Rius Santamaria JHEP**0303** (2003) 011, Biggio Blennow Fernandez-Martinez JHEP**0903** (2009) 139 and arXiv:0907.0097
- NSI from a Dim.8 diagram is always constrained
  Antusch Baumann Fernandez-Martinez NP**B810** (2009) 369
- Combination of diagrams can help to obtain large NSI avoiding constraints.

#	Dim. eight operator	$\mathcal{C}^1_{LEH}$	$\mathcal{C}^3_{LEH}$	$\mathcal{O}_{\rm NSI}$?	Mediators
Combination $\bar{L}L$					
1	$(\bar{L}\gamma^\rho L)(\bar{E}\gamma_\rho E)(H^\dagger H)$	1			$\mathbf{1}^v_0$
2	$(\bar{L}\gamma^\rho L)(\bar{E}H^\dagger)(\gamma_\rho)(HE)$	1			$\mathbf{1}^v_0 + 2^{L/R}_{-3/2}$
3	$(\bar{L}\gamma^\rho L)(\bar{E}H^T)(\gamma_\rho)(H^* E)$	1			$\mathbf{1}^v_0 + 2^{L/R}_{-1/2}$
4	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}\gamma_\rho E)(H^\dagger \vec{\tau} H)$		1		$\mathbf{3}^v_0 + \mathbf{1}^v_0$
5	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}H^\dagger)(\gamma_\rho \vec{\tau})(HE)$		1		$\mathbf{3}^v_0 + 2^{L/R}_{-3/2}$
6	$(\bar{L}\gamma^\rho \vec{\tau} L)(\bar{E}H^T)(\gamma_\rho \vec{\tau})(H^* E)$		1		$\mathbf{3}^v_0 + 2^{L/R}_{-1/2}$
Combination $\bar{E}L$					
7	$(\bar{L}E)(\bar{E}L)(H^\dagger H)$	$-1/2$			$\mathbf{2}^s_{+1/2}$
8	$(\bar{L}E)(\vec{\tau})(\bar{E}L)(H^\dagger \vec{\tau} H)$		$-1/2$		$\mathbf{2}^s_{+1/2}$
9	$(\bar{L}H)(H^\dagger E)(\bar{E}L)$	$-1/4$	$-1/4$	✓	$\mathbf{2}^s_{+1/2} + 1^R_0 + 2^{L/R}_{-1/2}$
10	$(\bar{L}\vec{\tau}H)(H^\dagger E)(\vec{\tau})(\bar{E}L)$	$-3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + 3^{L/R}_0 + 2^{L/R}_{-1/2}$
11	$(\bar{L}\mathrm{i}\tau^2 H^*)(H^T E)(\mathrm{i}\tau^2)(\bar{E}L)$	$1/4$	$-1/4$		$\mathbf{2}^s_{+1/2} + 1^{L/R}_{-1} + 2^{L/R}_{-3/2}$
12	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2 H^*)(H^T E)(\mathrm{i}\tau^2\vec{\tau})(\bar{E}L)$	$3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + 3^{L/R}_{-1} + 2^{L/R}_{-3/2}$
Combination $\overline{E^c}L$					
13	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}\gamma_\rho L)(H^\dagger H)$	-1			$\mathbf{2}^v_{-3/2}$
14	$(\bar{L}\gamma^\rho E^c)(\vec{\tau})(\overline{E^c}\gamma_\rho L)(H^\dagger \vec{\tau} H)$		-1		$\mathbf{2}^v_{-3/2}$
15	$(\bar{L}H)(\gamma^\rho)(H^\dagger E^c)(\overline{E^c}\gamma_\rho L)$	$-1/2$	$-1/2$	✓	$\mathbf{2}^v_{-3/2} + 1^R_0 + 2^{L/R}_{+3/2}$
16	$(\bar{L}\vec{\tau}H)(\gamma^\rho)(H^\dagger E^c)(\vec{\tau})(\overline{E^c}\gamma_\rho L)$	$-3/2$	$1/2$		$\mathbf{2}^v_{-3/2} + 3^{L/R}_0 + 2^{L/R}_{+3/2}$
17	$(\bar{L}\mathrm{i}\tau^2 H^*)(\gamma^\rho)(H^T E^c)(\mathrm{i}\tau^2)(\overline{E^c}\gamma_\rho L)$	$-1/2$	$1/2$		$\mathbf{2}^v_{-3/2} + 1^{L/R}_{-1} + 2^{L/R}_{+1/2}$
18	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2 H^*)(\gamma^\rho)(H^T E^c)(\mathrm{i}\tau^2\vec{\tau})(\overline{E^c}\gamma_\rho L)$	$-3/2$	$-1/2$		$\mathbf{2}^v_{-3/2} + 3^{L/R}_{-1} + 2^{L/R}_{+1/2}$
Combination $H^\dagger L$					
19	$(\bar{L}E)(\bar{E}H)(H^\dagger L)$	$-1/4$	$-1/4$	✓	$\mathbf{2}^s_{+1/2} + 1^R_0 + 2^{L/R}_{-1/2}$
20	$(\bar{L}E)(\vec{\tau})(\bar{E}H)(H^\dagger \vec{\tau} L)$	$-3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + 3^{L/R}_0 + 2^{L/R}_{-1/2}$
21	$(\bar{L}H)(\gamma^\rho)(H^\dagger L)(\bar{E}\gamma_\rho E)$	$1/2$	$1/2$	✓	$\mathbf{1}^v_0 + 1^R_0$
22	$(\bar{L}\vec{\tau}H)(\gamma^\rho)(H^\dagger \vec{\tau} L)(\bar{E}\gamma_\rho E)$	$3/2$	$-1/2$		$\mathbf{1}^v_0 + 3^{L/R}_0$
23	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}H)(\gamma^\rho)(H^\dagger L)$	$-1/2$	$-1/2$	✓	$\mathbf{2}^v_{-3/2} + 1^R_0 + 2^{L/R}_{+3/2}$
24	$(\bar{L}\gamma^\rho E^c)(\overline{E^c}H)(\gamma^\rho)(H^\dagger L)$	$-3/2$	$1/2$		$\mathbf{2}^v_{-3/2} + 3^{L/R}_0 + 2^{L/R}_{+3/2}$
Combination HL					
25	$(\bar{L}E)(\mathrm{i}\tau^2)(\bar{E}H^*)(H^T\mathrm{i}\tau^2 L)$	$1/4$	$-1/4$		$\mathbf{2}^s_{+1/2} + 1^{L/R}_{-1} + 2^{L/R}_{-3/2}$
26	$(\bar{L}E)(\vec{\tau}\mathrm{i}\tau^2)(\bar{E}H^*)(H^T\mathrm{i}\tau^2\vec{\tau}L)$	$3/4$	$1/4$		$\mathbf{2}^s_{+1/2} + 3^{L/R}_{-1} + 2^{L/R}_{-3/2}$
27	$(\bar{L}\mathrm{i}\tau^2 H^*)(\gamma^\rho)(H^T\mathrm{i}\tau^2 L)(\bar{E}\gamma_\rho E)$	$-1/2$	$1/2$		$\mathbf{1}^v_0 + 1^{L/R}_{-1}$
28	$(\bar{L}\vec{\tau}\mathrm{i}\tau^2 H^*)(\gamma^\rho)(H^T\mathrm{i}\tau^2\vec{\tau}L)(\bar{E}\gamma_\rho E)$	$-3/2$	$-1/2$		$\mathbf{1}^v_0 + 3^{L/R}_{-1}$
29	$(\bar{L}\gamma^\rho E^c)(\mathrm{i}\tau^2)(\overline{E^c}H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2 L)$	$1/2$	$-1/2$		$\mathbf{2}^v_{-3/2} + 1^{L/R}_{-1} + 2^{L/R}_{+1/2}$
30	$(\bar{L}\gamma^\rho E^c)(\vec{\tau}\mathrm{i}\tau^2)(\overline{E^c}H^*)(\gamma_\rho)(H^T\mathrm{i}\tau^2\vec{\tau}L)$	$3/2$	$1/2$		$\mathbf{2}^v_{-3/2} + 3^{L/R}_{-1} + 2^{L/R}_{+1/2}$

Outline



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Optimal Nufact setup for NSI

$E_\mu = 25$ GeV OK
L =4000km+7500km OK

Same for the standard oscillation parameters.

- Silver channel ($\nu_e \to \nu_\tau$) does not help much.
- Combination of Golden and Disapp. channels, and also combination of two baselines help to resolve parameter correlations.

Backup: Experimental setup

Our setup is based on IDS-NF baseline:

- 50 kton Magnetized Iron Detector (MIND) for Golden and Disapp. channels.
- 10 kton emulsion cloud chamber for Silver channel
- Silver* = signal$\times 5$ and background$\times 3$.
- $2.5 \cdot 10^{21}$ useful muon decays per baseline and polarity
- Charge ID in Golden and Silver channels,
  but not in Disapp.
  We can count out charge missID background.
  Huber Lindner Rolinec Winter PR**D74** (2006) 073003.

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Backup: higher muon energy $E_\mu = 50$ GeV