Open Issues in ν Physics:
(flavour-changing) Non-Standard-Interactions (and LFV)

Sacha Davidson , (M Gorbahn + J Hackett)
IN2P3/CNRS, France

1. Some thoughts about New/ν Physics

2. Non Standard (newtrino) Interactions
   - what are they?
   - what do we know now?

3. flavour-changing NSI vs (charged) Lepton Flavour Violation
   - how can NSI avoid inducing tree-level LFV?
   - build models that do that?
   - Do NSI induce LFV via loops?

4. Summary

Some thoughts about New ν Physics

1. ν leave no tracks $\Rightarrow$ exptal detection/facilities different from charged leptons+quarks

2. a few decades ago: discovered small m_ν, large leptonic mixing angles
   $\Rightarrow$ exptal programme to measure...
   $\Rightarrow$ What other New/ν Physics could one look for?

   (a) more than 3 ν mass eigenstates?
   (b) non-electroweak interactions of ν with SM ($(g-2)_\nu$,**NSI**,...)?
   (c) ...

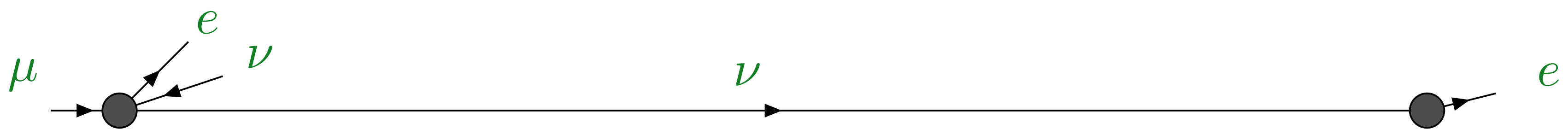
Wolfenstein, Valle, GuzzoMasieroPetcov

What are Non-Standard Interactions

$$\mathbf{NSI}: \ \delta\mathcal{L} = -2\sqrt{2} G_F \varepsilon_f^{\rho\sigma} (\overline{\nu}_\rho \gamma_\alpha P_L \nu_\sigma)(\overline{f}\gamma^\alpha f) \quad , \quad f \in \{e, d, u\} \ \ \varepsilon \text{ matrix}$$

(sometimes $(\overline{f}\gamma^\alpha f) \to (\overline{f}\gamma^\alpha P_X f)$). QED×QCD invariant.

= BSM to find in ν oscillations: induces $\Delta m^2_{eff}/E \sim \sqrt{2} G_F \varepsilon_f^{\rho\sigma} n_f$ in matter



source, CC,messy | clean, quantum, NC | detector, CC, messy

probe (little known) ν propagator

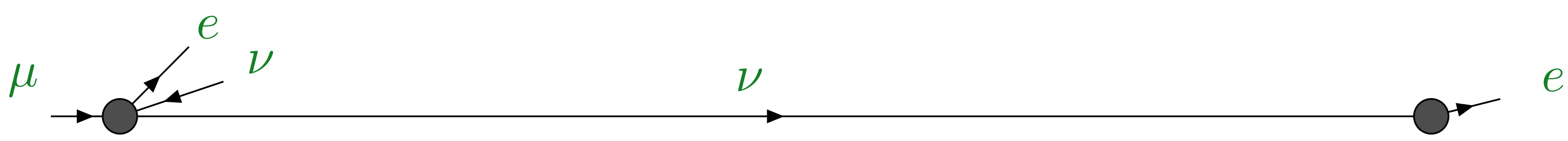
Wolfenstein, Valle, GuzzoMasieroPetcov

What are Non-Standard Interactions

$$\mathbf{NSI}: \ \delta\mathcal{L} = -2\sqrt{2} G_F \varepsilon_f^{\rho\sigma} (\overline{\nu}_\rho \gamma_\alpha P_L \nu_\sigma)(\overline{f}\gamma^\alpha f) \quad , \quad f \in \{e, d, u\} \ \ \varepsilon \text{ matrix}$$

(sometimes $(\overline{f}\gamma^\alpha f) \to (\overline{f}\gamma^\alpha P_X f)$). QED×QCD invariant.

= BSM to find in ν oscillations: induces $\Delta m^2_{eff}/E \sim \sqrt{2} G_F \varepsilon_f^{\rho\sigma} n_f$ in matter



source, CC,messy — clean, quantum, NC probe (little known) ν propagator — detector, CC, messy

"**Generalised Neutrino Interactions**": $2\nu 2f$ four-fermion interactions, ν light, can be sterile $\simeq \nu_R$, $f \in \{e, d, u\}$

... AristizabalSierradeRomeriRojas AltmannshoferTammaroZupan FalkowskiGonzalezAlonsoTabrizi

$$(\overline{\nu}_\rho \gamma P_L \nu_\sigma)(\overline{f}\gamma P_X f) \quad , \quad (\overline{\nu}_\rho P_L \nu_\sigma)(\overline{f} P_X f) \quad , \quad (\overline{\nu}_\rho \sigma P_L \nu_\sigma)(\overline{f}\sigma P_L f)$$

interest: COHERENT measured Coherent Elastic ν-Nucleus Scattering (CEνNS: $\sigma(\nu A \to \nu A)$ at $q^2 \sim 50$ MeV). *Not* forward scattering, sensitive to more operators, in different combo from high-E σ.

This talk: stick to NSI...

What do we know now: from oscillation data + COHERENT

Add NSI to low-E $\mathcal{L}_\nu$ (no new CC), suppose $\varepsilon_f^{\alpha\beta} = \varepsilon^{\alpha\beta}\varepsilon_f$.

$-.008 < \varepsilon_u^{ee} < .62$ $-.01 < \varepsilon_d^{ee} < .56$ $-.01 < \varepsilon_e^{ee} < 2.0$	$-.06 < \varepsilon_u^{e\mu} < .05$ $-.06 < \varepsilon_d^{e\mu} < .05$ $-.18 < \varepsilon_e^{e\mu} < .15$	$-.25 < \varepsilon_u^{e\tau} < .11$ $-.21 < \varepsilon_d^{e\tau} < .11$ $-.86 < \varepsilon_e^{e\tau} < .35$
	$-.11 < \varepsilon_u^{\mu\mu} < .40$ $-.10 < \varepsilon_d^{\mu\mu} < .36$ $-.36 < \varepsilon_e^{\mu\mu} < 1.3$	$-.012 < \varepsilon_u^{\mu\tau} < .009$ $-.011 < \varepsilon_d^{\mu\tau} < .009$ $-.035 < \varepsilon_e^{\mu\tau} < .35$
		$-.11 < \varepsilon_u^{\tau\tau} < .40$ $-.10 < \varepsilon_d^{\tau\tau} < .36$ $-.35 < \varepsilon_e^{\tau\tau} < 1.40$

$\approx$ *constraints* = bigger is incompatible with data.

(as opposed to *sensitivities* = one-op-at-a-time bounds, which say smaller is unobservable).

Oscillations only sensitive to $\varepsilon^{\alpha\alpha} - \varepsilon^{\beta\beta}$, but COHERENT lifts degeneracy

?separately constrain $\varepsilon_u^{\alpha\beta}$ and $\varepsilon_d^{\alpha\beta}$ because sun made of protons? (in earth, $n_e = n_p \approx n_n$)

neglected solutions where $\{\theta_{ij}\}$ disconnected from bestfit values (LMA-Dark solution)

$\varepsilon_e^{\alpha\alpha} \sim 1$ allowed because flips sign of SM $(\bar\nu\gamma P_L\nu)(\bar f\gamma P_L f)$ (osc. sensitive to signs of flavour diffs...)

(Energy scales: $q^2 \to 0$ in matter effect, ~ 50 MeV in COHERENT)

BerezhianiRossi
DavidsonPenaGaraySantamariaRius

Neutral Current ν interactions

chiral ε ($g_L^f \neq g_R^f$ in SM), $\approx$ sensitivities

$-1, -.4 < \varepsilon^{ee}_{u,L,R} < .3, .7$	$-.5 < \varepsilon^{e\mu}_{u,L,R} < .5$	$-.5 < \varepsilon^{e\tau}_{u,L,R} < .5$
$-.3, -.6 < \varepsilon^{ee}_{d,L,R} < .3, .5$	$-.5 < \varepsilon^{e\mu}_{d,L,R} < .5$	$-.5 < \varepsilon^{e\tau}_{d,L,R} < .5$
$-1, -.07 < \varepsilon^{ee}_{e} < .11, .5$	$-.18 < \varepsilon^{e\mu}_{e} < .15$	$-.7, -.4 < \varepsilon^{e\tau}_{e} < .4, .7$
	$-.008, -.003 < \varepsilon^{\mu\mu}_{u,L,R} < .003, .003$	$-.05 < \varepsilon^{\mu\tau}_{u,L,R} < .05$
	$-.008, -.003 < \varepsilon^{\mu\mu}_{d,L,R} < .003, .015$	$-.05 < \varepsilon^{\mu\tau}_{d,L,R} < .05$
	$-.03 < \varepsilon^{\mu\mu}_{e,L,R} < .03$	$-.1 < \varepsilon^{\mu\tau}_{e,L,R} < .1$
		$< \varepsilon^{\tau\tau}_{u,L,R} <$
		$< \varepsilon^{\tau\tau}_{d,L,R} <$
		$-.6, -.4 < \varepsilon^{\tau\tau}_{e,L,R} < .4, .6$

$$L_{min}, R_{min} < \varepsilon^{ee}_{u} < L_{max}, R_{max} \text{ means } L_{min} < \varepsilon^{ee}_{u,L} < L_{max},\ R_{min} < \varepsilon^{ee}_{u,R} < R_{max}$$

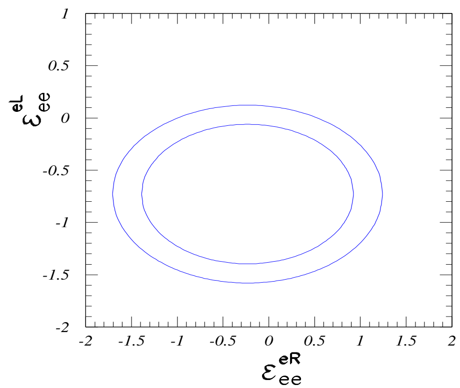
LSND: $\nu_e e \to \nu e$

CHARM: $\nu_e q \to \nu q$

CHARMII: $\nu_\mu e \to \nu e$

NuTeV: $\nu_\mu q \to \nu q$

LEP-1: $Z \to \nu\nu\gamma$



But Standard Model neutrinos are in a doublet $\ell_\rho = \begin{pmatrix} \nu_\rho \\ e_\rho \end{pmatrix}$...LFV?

New Physics must respect SM gauge symmetries: given bounds on (charged) Lepton Flavour Violation, can NSI be detectably large?

But Standard Model neutrinos are in a doublet $\ell_\rho = \begin{pmatrix} \nu_\rho \\ e_\rho \end{pmatrix}$...LFV?

New Physics must respect SM gauge symmetries: given bounds on (charged) Lepton Flavour Violation, can NSI be detectably large?

- ex: SU(2) invariant dimension 6 operators that induce $\nu_\tau \to \nu_\mu$ NSI on e

$$\varepsilon^{\tau\mu}_{(3)\ell\ell}(\overline{\ell}_\tau \gamma_\alpha \tau^a \ell_\mu)(\overline{\ell}_e \gamma^\alpha \tau^a \ell_e) \quad , \quad \varepsilon^{\tau\mu}_{\ell\ell}(\overline{\ell}_\tau \gamma_\alpha \ell_\mu)(\overline{\ell}_e \gamma^\alpha \ell_e) \quad , \quad \varepsilon^{\tau\mu}_{ee}(\overline{\ell}_\tau \gamma^\alpha \ell_\mu)(\overline{e}_e \gamma_\mu e_e)$$

NSI $\propto \varepsilon^{\tau\mu}_{(3)\ell\ell} + \varepsilon^{\tau\mu}_{\ell\ell}$, $\varepsilon^{\tau\mu}_{ee}$
$\widetilde{BR}(\tau \to 3l) \simeq |\varepsilon^{\tau\mu}_{(3)\ell\ell} - \varepsilon^{\tau\mu}_{\ell\ell}|^2 + |\varepsilon^{\tau\mu}_{ee}|^2 \lesssim 10^{-7}$ ...
$\Rightarrow$ LFV constraints, applied at tree level, exclude several (combinations of) dim 6 operators from inducing observable NSI.

But Standard Model neutrinos are in a doublet $\ell_\rho = \begin{pmatrix} \nu_\rho \\ e_\rho \end{pmatrix}$...LFV?

New Physics must respect SM gauge symmetries: given bounds on (charged) Lepton Flavour Violation, can NSI be detectably large?

- ex: SU(2) invariant dimension 6 operators that induce $\nu_\tau \to \nu_\mu$ NSI on e

$$\varepsilon^{\tau\mu}_{(3)\ell\ell}(\overline{\ell}_\tau \gamma_\alpha \tau^a \ell_\mu)(\overline{\ell}_e \gamma^\alpha \tau^a \ell_e) \quad , \quad \varepsilon^{\tau\mu}_{\ell\ell}(\overline{\ell}_\tau \gamma_\alpha \ell_\mu)(\overline{\ell}_e \gamma^\alpha \ell_e) \quad , \quad \varepsilon^{\tau\mu}_{ee}(\overline{\ell}_\tau \gamma^\alpha \ell_\mu)(\overline{e}_e \gamma_\mu e_e)$$

NSI $\propto \varepsilon^{\tau\mu}_{(3)\ell\ell} + \varepsilon^{\tau\mu}_{\ell\ell}$, $\varepsilon^{\tau\mu}_{ee}$

$\widetilde{BR}(\tau \to 3l) \simeq |\varepsilon^{\tau\mu}_{(3)\ell\ell} - \varepsilon^{\tau\mu}_{\ell\ell}|^2 + |\varepsilon^{\tau\mu}_{ee}|^2 \lesssim 10^{-7}$ ...

$\Rightarrow$ LFV constraints, applied at tree level, exclude several (combinations of) dim 6 operators from inducing observable NSI.

- To avoid LFV constraints, build NSI at dimension 8 $f \in \{e, u, d, q_1, \ell_e\}$:

$$\frac{C^{\rho\sigma}_f}{\Lambda^4}(\overline{\ell}_\rho \epsilon H^*)\gamma_\alpha (H \epsilon \ell_\sigma)(\overline{f}\gamma^\alpha f) \xrightarrow{H \to v} \frac{C^{\rho\sigma}_f v^2}{\Lambda^4}(\overline{\nu}_\rho \gamma_\alpha \nu_\sigma)(\overline{f}\gamma^\alpha f) \quad , \quad \varepsilon^{\rho\sigma}_f = \frac{C^{\rho\sigma}_f v^4}{\Lambda^4}$$

$\varepsilon^{\rho\sigma}_f \gtrsim 10^{-2} \Leftrightarrow \Lambda \lesssim .3 \to 1$ TeV $\Rightarrow$ *is there a model?*

Is there a model?

1. $10^{-2} \lesssim \varepsilon \lesssim 1$ suggests feebly-coupled mediator, $m \ll m_W$?

   - $\sim$10 MeV Z', flav.diag. coupling $g' \sim 10^{-4}$ to $\ell_\mu, \ell_\tau, q_{L,1}, u_R, d_R$. Farzan
   - light Z' feebly coupled to quarks and $\nu_{sterile}$, small $m\nu_s\nu_{SM}$. PospelovPradler

   avoid some ν scattering bounds if $m^2_{mediator} \ll \langle q^2 \rangle$
   avoid inducing LFV by chosing couplings...

Is there a model?

1. $10^{-2} \lesssim \varepsilon \lesssim 1$ suggests feebly-coupled mediator, $m \ll m_W$?

   - $\sim$10 MeV Z', flav.diag. coupling $g' \sim 10^{-4}$ to $\ell_\mu, \ell_\tau, q_{L,1}, u_R, d_R$. Farzan
   - light Z' feebly coupled to quarks and $\nu_{sterile}$, small $m\nu_s\nu_{SM}$. PospelovPradler

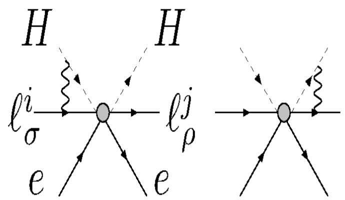
   avoid some ν scattering bounds if $m^2_{mediator} \ll \langle q^2 \rangle$
   avoid inducing LFV by chosing couplings...

2. heavy New Physics, $m_{mediator} \gtrsim m_W$ recipe to build: GavelaHernandezOtaWinter
   tune NP masses/cplgs such that LFV coefficients vanish at tree(dim 6 and 8):
   eg on e at dimension 6, need

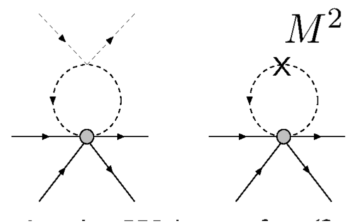
$$\varepsilon^{\tau\mu}_{(3)\ell\ell} - \varepsilon^{\tau\mu}_{\ell\ell} = \varepsilon^{\tau\mu}_{ee} = 0$$

   ex: scalar + vector leptoquark with tuned masses/couplings.
   or scalar bilepton S, with $L=2, Q_{em}=1$, $S\ell^\alpha_i \epsilon^{ij} \ell^\beta_j$, induces only $2e2\nu$ interactns

$\star$can do EFT = make generic statements that apply to many models*



If heavy NP: what about loop-induced LFV?



Suppose flavour-changing NSI at dimension 8, induced by $M \gtrsim m_W$ New Physics. No tree-level LFV at dimension 6 or 8. Focus on flavour-changing NSI on electrons:

$$(\overline{\nu}_\tau \gamma_\alpha \nu_\mu)(\overline{e}\gamma^\alpha P_R e) \leftrightarrow (\overline{\ell}_\tau \epsilon H^*)\gamma_\alpha (H\epsilon \ell_\mu)(\overline{e}\gamma^\alpha P_R e) \equiv \mathcal{O}^{\tau\mu}_{NSI}$$

If decorate with W, H loops, does one obtain LFV operators:

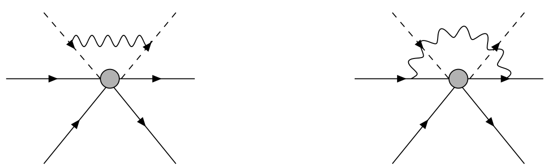
$$(\overline{\tau}\gamma_\alpha \mu)(\overline{e}\gamma^\alpha P_R e) \leftrightarrow (\overline{\ell}_\tau H \gamma_\alpha H^\dagger \ell_\mu)(\overline{e}\gamma^\alpha P_R e) \equiv \mathcal{O}_{H2} \quad , \quad M^2(\overline{\ell}_\tau \gamma_\alpha \ell_\mu)(\overline{e}\gamma^\alpha P_R e) \equiv \mathcal{O}_{M2}$$

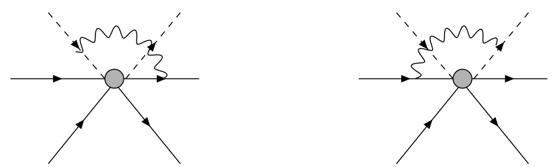
Yes! get (both) operators ☺

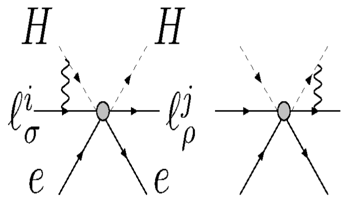
but, ☹ at $\mathcal{O}(\log/16\pi^2)$, sum $\to 0$ at min. of Higgs pot. : $\lambda \mathcal{O}_{H2} - \mathcal{O}_{M2} = 0$

BiggioBlennowFernandezMartinez

$\Rightarrow$ What about higher order?

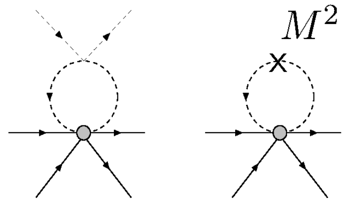






technical details

to calculate divergent part of diagrams



1. restrict to dim8 NSI with SU(2)-singlet first generation fermions $f \in \{e_R, u_R, d_R\}$

$$\delta\mathcal{L} = \frac{C}{\Lambda^4_{NP}}\mathcal{O}^{\tau\mu}_{NSI} \equiv \frac{C}{\Lambda^4_{NP}}(\overline{\ell}_\tau \epsilon H^*)\gamma_\alpha(H\epsilon\ell_\mu)(\overline{e}\gamma^\alpha P_R e) \leftrightarrow 2\sqrt{2}G_F\varepsilon(\overline{\nu}_\tau\gamma_\alpha\nu_\mu)(\overline{e}\gamma^\alpha P_R e)$$

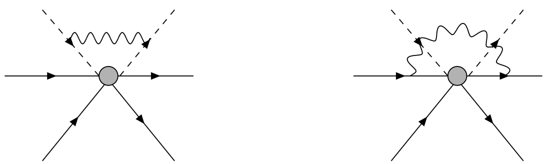
2. calculate, in unbroken SU(2): $\mathcal{O}_{NSI} \to \mathcal{O}_{H2}$, $\mathcal{O}_{M2}$

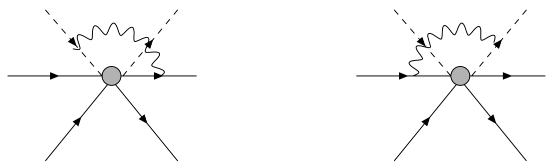
$$\mathcal{O}^{\tau\mu}_{H2} \equiv (\overline{\ell}_\tau H\gamma_\alpha H^\dagger\ell_\mu)(\overline{e}\gamma^\alpha P_R e) \ , \ \mathcal{O}^{\tau\mu}_{M2} \equiv M^2(\overline{\ell}_\tau\gamma_\alpha\ell_\mu)(\overline{e}\gamma^\alpha P_R e) \leftrightarrow (\overline{\tau}\gamma_\alpha\mu)(\overline{e}\gamma^\alpha P_R e)$$

3. project onto LFV operator in "broken" theory, where $\lambda v^2/2 - M^2 = 0$:

$$\mathcal{O}_{vanish} = \lambda\mathcal{O}_{H2} - \mathcal{O}_{M2} \quad , \quad \mathcal{O}_{LFV} = \mathcal{O}_{H2} + \lambda\mathcal{O}_{M2}$$

4. 1-loop divergences determine all $\mathcal{O}(\log/16\pi^2)^n$ terms in the NSI contribution to LFV operators.
   Only retain $\log(\Lambda_{NP}/m_W)$s (not because are big) because can compute reliably in EFT
   (=independent of operator renormalisation scheme)





Results ((loop$\times$log)^n contributions of NSI to LFV)

1. W $(+B)$ loops renormalise $\mathcal{O}_{NSI,f}$ $(f \in \{e,d,u\})$, $\mathcal{O}_{H2,f}$ $\mathcal{O}_{M2,f}$ (... no mixing)
2. Higgs loops mix $\mathcal{O}_{NSI,f} \to \mathcal{O}_{H2,f}$, $\mathcal{O}_{NSI,f} \to \mathcal{O}_{M2,f}$
Neglect running of SM couplings$\Rightarrow$write loop$\times$log contributions([γ^T] anom.dim. matrix):

$$\begin{pmatrix} C_{NSI} \\ C_{vanis} \\ C_{LFV} \end{pmatrix}(m_W) = \left([1] - \frac{\log \frac{\Lambda}{m_W}}{16\pi^2} \begin{bmatrix} .. & .. & .. \\ .. & .. & .. \\ 0 & .. & .. \end{bmatrix} + \frac{[\gamma^T \gamma^T]}{2(16\pi^2)^2} \log^2 \frac{\Lambda}{m_W} \right) \begin{pmatrix} C_{NSI} \\ 0 \\ 0 \end{pmatrix}(\Lambda)$$

Results

1. W $(+B)$ loops renormalise $\mathcal{O}_{NSI,f}$ $(f \in \{e,d,u\})$, $\mathcal{O}_{H2,f}$ $\mathcal{O}_{M2,f}$ (... no mixing)
2. Higgs loops mix $\mathcal{O}_{NSI,f} \to \mathcal{O}_{H2,f}$, $\mathcal{O}_{NSI,f} \to \mathcal{O}_{M2,f}$
Neglect running of SM couplings$\Rightarrow$ write loop$\times$log contributions($[\gamma^T]$ anom.dim. matrix):

$$\begin{pmatrix} C_{NSI} \\ C_{vanis} \\ C_{LFV} \end{pmatrix}(m_W) = \left([1] - \frac{\log \frac{\Lambda}{m_W}}{16\pi^2} \begin{bmatrix} .. & .. & .. \\ .. & .. & .. \\ 0 & .. & .. \end{bmatrix} + \frac{\log^2(\frac{\Lambda}{m_W})}{2(16\pi^2)^2} \begin{bmatrix} .. & .. & .. \\ .. & .. & .. \\ \frac{-4.5\lambda g^2 - 2\lambda^2}{\lambda^2+1} & .. & .. \end{bmatrix} \right) \begin{pmatrix} C_{NSI} \\ 0 \\ 0 \end{pmatrix}(\Lambda)$$

3. SM loop corrections to $\mathcal{O}_{NSI}$ generate $\mathcal{O}_{LFV}$ suppressed by (loop$\times \log)^2$

$$\varepsilon_{LFV} \sim \frac{\varepsilon_{NSI}}{(16\pi^2)^2} \sim 4 \times 10^{-5} \varepsilon_{NSI}$$

(uses tree minimisation of Higgs pot)

4. Suppose could see $\varepsilon^{\rho\sigma}_{NSI} \gtrsim 10^{-2} \to 10^{-3}$, can LFV processes see $\varepsilon^{\rho\sigma}_{LFV} \lesssim 4 \times 10^{-7} \to 10^{-8}$?

	current	soon	
$\mu \to e\bar{e}e$	$\varepsilon^{\mu eee}_{V,LR} < 10^{-6}$	$\varepsilon^{\mu eee}_{V,LR} < 10^{-8}$	(Mu3e)
$\mu - e$ conv.	$\varepsilon^{\mu euu}_{V} + \varepsilon^{\mu edd}_{V} < 10^{-7}$	$\varepsilon^{\mu euu}_{V} + \varepsilon^{\mu edd}_{V} < 10^{-9}$	(COMET,Mu2e)
τs	$\varepsilon \lesssim ...\times 10^{-4}$	$\varepsilon \lesssim ...\times 10^{-5}$ ☹	

Summary

NSI are low-energy NC vector interactions of neutrinos, induced by New Physics:

$$2\sqrt{2}\varepsilon_f^{\rho\sigma} G_F(\overline{\nu}_\rho \gamma_\alpha P_L \nu_\sigma)(\overline{f}\gamma^\alpha f) \quad , \quad f \in \{e, d, u\}$$

Could be observed in oscillations and ν scattering expts; current sensitivity to $1 \gtrsim \varepsilon \gtrsim 10^{-2}$.

ν share a doublet with charged leptons — whose BSM interactions are better constrained. What does this allow to conclude?

- lepton flavour changing NSI:

if NP is heavy:

$\mu \to e$ bounds probably exclude $\nu_\mu - \nu_e$ NSI.

$\nu_\tau \to \nu_l$ NSI compatible with LFV ? ☹

if NP is light:

? (in progress)

- lepton flavour conserving NSI:

?relation to EW precision? maybe talk by M Gonzalez-Alonso?

BackUp

Sensitivities to diagonal NSI, Tortola-Farzan review

	90% C.L. range	origin	Ref.
		NSI with quarks	
ϵ_{ee}^{dL}	$[-0.3, 0.3]$	CHARM	[128]
ϵ_{ee}^{dR}	$[-0.6, 0.5]$	CHARM	[128]
$\epsilon_{\mu\mu}^{dV}$	$[-0.042, 0.042]$	atmospheric + accelerator	[165]
$\epsilon_{\mu\mu}^{uV}$	$[-0.044, 0.044]$	atmospheric + accelerator	[165]
$\epsilon_{\mu\mu}^{dA}$	$[-0.072, 0.057]$	atmospheric + accelerator	[165]
$\epsilon_{\mu\mu}^{uA}$	$[-0.094, 0.14]$	atmospheric + accelerator	[165]
$\epsilon_{\tau\tau}^{dV}$	$[-0.075, 0.33]$	oscillation data + COHERENT	[127]
$\epsilon_{\tau\tau}^{uV}$	$[-0.09, 0.38]$	oscillation data + COHERENT	[127]
$\epsilon_{\tau\tau}^{qV}$	$[-0.037, 0.037]$	atmospheric	[140] [a]
		NSI with electrons	
ϵ_{ee}^{eL}	$[-0.021, 0.052]$	solar + KamLAND	[131]
ϵ_{ee}^{eR}	$[-0.07, 0.08]$	TEXONO	[163]
$\epsilon_{\mu\mu}^{eL}$, $\epsilon_{\mu\mu}^{eR}$	$[-0.03, 0.03]$	reactor + accelerator	[128, 162]
$\epsilon_{\tau\tau}^{eL}$	$[-0.12, 0.06]$	solar + KamLAND	[131]
$\epsilon_{\tau\tau}^{eR}$	$[-0.98, 0.23]$ [-0.25, 0.43]	solar + KamLAND and Borexino reactor + accelerator	[131, 133] [162]
$\epsilon_{\tau\tau}^{eV}$	$[-0.11, 0.11]$	atmospheric	[140]

[a] Bound adapted from $\epsilon_{\tau\tau}^{eV}$.

Cancellations among coefficients in EFT

scalar and tensor operators run with QCD...can cancel to $\lesssim$ one sig. figG against each other vector coefficients?

Within each subset of operatorswith same QCD running, coeffs have different QED anomalous dimensions... coefficients that cancel at the high scale, could differ by $\mathcal{O}(\frac{\alpha}{4\pi}\log)$ at low energy $\Leftrightarrow$ cancellations "natural" to 3 sig. figs?

$\Rightarrow$ If NSI gives LFV coeff at $\mathcal{O}(\log/16\pi^2)^2$, could it cancel against other $\mathcal{O}(\log/16\pi^2)^2$ operators?

Not against S or T. And no other vectors (?if our basis complete?)