ν and Beyond-the-Standard-Model

after lunch : (ν in the Early U)

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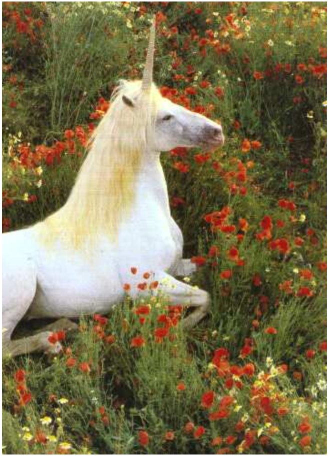
1. ν in the SM
2. why BSM
3. to build a ν mass model
4. how to know which model ?
   — $0\nu2\beta$
   — Lepton Flavour Violation
5. Non-Standard ν Interactions
6. (new light νs ?)

ν :Standard Member of particle bestiary. Invisible.

Magical property of demonstrating BSM in the lab



I use Dirac spinors, with 4 degrees of freedom(dof) labelled by $\{\pm E, \pm s\}$, in *chiral* decomposition

$$\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \quad , \; \{\gamma^\alpha\} = \left\{ \begin{bmatrix} 0 & I \\ I & 0 \end{bmatrix}, \begin{bmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{bmatrix} \right\}$$

$$\{\sigma_i\} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}, \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

$$\psi_L = \; P_L\,\psi \quad \text{avec} \quad P_L = \frac{(1-\gamma_5)}{2} \quad , \; \psi_R = \; P_R\,\psi$$

chirality is *not* an observable ($\rightarrow$ helicity $= \pm\hat{s}\cdot\hat{k} = \pm 1/2$ in relativistic limit), but $P_{L,R}$ simple to calculate with :)

notation : $\overline{(\psi_R)} = (P_R\psi)^\dagger\gamma_0 = \psi^\dagger P_R\gamma_0 = \psi^\dagger\gamma_0 P_L = (\overline{\psi})_L$

$(\psi^c)_L = P_L(-i\gamma_0\gamma_2\gamma_0\psi^*) = -i\gamma_0\gamma_2\gamma_0\psi_R^*$

Summary : leptons in the Standard Model

- 3 generations of lepton doublets, and charged singlets :

$$\ell_{\alpha L} \in \left\{ \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} , \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} , \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix} \right\} \qquad e_{\alpha R} \in \{ e_R, \ \mu_R, \ \tau_R \}$$

in charged lepton mass basis (greek index, eg α).

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- No ν_R in SM because
  1. data did not require m_ν when SM was defined (ν are shy in the lab...)
  2. ν_R an SU(2) singlet $\Leftrightarrow$ no gauge interactions
     $\Rightarrow$ not need ν_R for anomaly cancellation
     $\Rightarrow$ if its there, its hard to see
- most general, renormalisable, $SU(2) \times U(1)$-invariant $\mathcal{L}$ for those particles gives :

Charged Current ν production
no lepton flavour change
Universal Z cpling to 3 ν (Γ_{inv} says 2.994 ± 0.012)

Neutrinos have gravitational interactions

1. expected from equivalence principle : carry 4-momentum
2. Big Bang Nucleosynthesis ($\tau_U \sim$ few minutes) :
   - $T \sim$MeV, baryons in n, p, combine into light nuclei
   - light element abundances depend on $\tau_U \leftrightarrow$ expansion rate $\leftrightarrow \rho_{rad} \leftrightarrow N_\nu = \#$ light ν in equilibrium
   - observed abundances today confirm $N_\nu \lesssim 4$
3. Cosmic Microwave Background : (is a fit to a multi-parameter model), and U is mat-dim at recombination. But sensitivity for similar reasons to # of relativistic species present... Lesgourgues reviews

Why Beyond the Standard Models (of part phys+ cosmo) ?

The SM (of particle phys + cosmo) does not explain :

1. Dark Matter
2. the origin of low-multipole $\Delta T/T$ in the CMB
3. the Baryon Asymmetry of the U
4. **ν masses**
   but 'tis Pandoras box ! What about adding/looking for :
   - new short-range interactions for neutrinos/leptons(new heavy particles)
   - new long-range interactions for neutrinos/leptons (new light particles)
   - more light neutrinos

stay focussed : how to include m_ν ?

To write a neutrino mass

At low energy, only restriction on m_ν is Lorentz invariance.
Mass term for a four-component fermion ψ :

$$m\overline{\psi}\,\psi \;=\; m\overline{\psi_L}\,\psi_R \;+ m\overline{\psi_R}\,\psi_L$$

1. Dirac mass term : introduce ≥ 2 new chiral gauge singlets ν_R
Construct fermion number conserving mass term like for other SM fermions :

$$m\overline{\nu_L}\,\nu_R \; + m\overline{\nu_R}\,\nu_L$$

In full SM : $\lambda(\overline{\nu_L}, \overline{e_L}) \begin{pmatrix} H_0 \\ H_- \end{pmatrix} \nu_R \equiv \lambda(\bar{\ell} H)\nu_R \rightarrow \; m = \lambda \langle H_0 \rangle$

added new light particles...add more and have ν_s ?

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2. Majorana mass term : $(\nu_L)^c$ is right-handed !

$\Rightarrow$ write a mass term with ν_L ; *no new fields*, but lepton number violating mass :

$$\begin{aligned}\frac{m}{2}[\overline{\nu_L}(\nu_L)^c + \overline{(\nu_L)^c}\nu_L] &= \frac{m}{2}[(\nu_L)^\dagger\gamma_0(\nu_L)^c + ((\nu_L)^c)^\dagger\gamma_0\nu_L] \\ &= -i\frac{m}{2}[\nu_L^\dagger\sigma_2\nu_L^* + \nu_L^T\sigma_2\nu_L] \equiv \frac{m}{2}\nu_L\nu_L + h.c.\end{aligned}$$

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(2nd line = 2 comp notn) *Non*-renormalisable in full SM :

$$\mathcal{L} = ... + \frac{K}{2M}(\ell H)(\ell H) + h.c. \rightarrow \frac{m}{2}\nu_L\nu_L + h.c. \quad , \quad m = \frac{K}{M}\langle H_0 \rangle^2$$

$\Rightarrow$ *requires New Heavy Particles*

Mechanisms/Models

to obtain small Majorana masses

1. suppress by small scale ratio m/M
   seesaw type 1
   inverse seesaw
2. suppress by loops/small couplings
   leptoquark model

neglect Dirac mass because phenomenologically boring, and we don't understand Yukawas = whether they can be so small.

(Theory parenthesis : why replace non-renorm. operator with renormalisable model of heavy particles ?)

renormalisable theories allow to calculate *every* observable to *arbitrary* precision as a function of a *finite* number of input parameters
$\Leftrightarrow$ predictive

But : there are maany models, they have lots of parameters, and we only need to calculate observables to the accuracy at which they can be measured.

expectation (Wilson) that all particles have renormalisable interactions at energies above their mass scale.

Tree-level Majorana mass models (*minimal*)

Heavy new particles (mass M) induce dimension 5 operator in $\mathcal{L}$:

$$\frac{K}{2M}[\ell H][\ell H] \to \nu\nu \frac{K\langle H_0\rangle^2}{2M}$$

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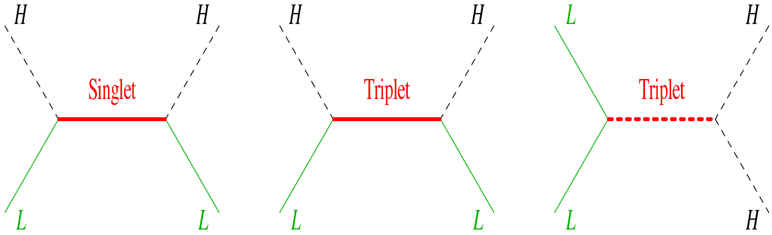
Three possibilities at tree level :

SU(2) singlet fermions	triplet fermions	triplet scalars
Type I	Type III	Type II



Add to SM a singlet $N(\equiv \nu_R)$ with all renorm. interactions :

$$\mathcal{L}_{lep}^{Yuk} = h_e(\overline{\nu_L}, \overline{e_L}) \begin{pmatrix} -H^+ \\ H^{0*} \end{pmatrix} e_R + \lambda(\overline{\nu_L}, \overline{e_L}) \begin{pmatrix} H^0 \\ H^- \end{pmatrix} N + \frac{M}{2} \overline{N^c} N + h.c.$$

$$m_e \overline{e_L} e_R \qquad + m_D \overline{\nu_L} N \qquad + \frac{M}{2} \overline{N^c} N + h.c.$$

$\Rightarrow$ neutrino mass matrix :

$$\begin{pmatrix} \overline{\nu_L} & \overline{N^c} \end{pmatrix} \begin{bmatrix} 0 & m_D \\ m_D & M \end{bmatrix} \begin{pmatrix} \nu_L^c \\ N \end{pmatrix} \qquad (\nu_L^c \equiv (\nu_L)^c)$$

$\Rightarrow$ eigenvectors $\simeq$: ν_L with $m_\nu \sim \frac{m_D^2}{M}$, N with mass $\sim M$

The type I seesaw, 3 generations

Minkowski, Yanagida
Gell-Mann Ramond Slansky

- add 3 singlet N to the SM in charged lepton and N mass bases :

$$\mathcal{L} = \mathcal{L}_{SM} + \boldsymbol{\lambda}_{\alpha J} \overline{N}_J \ell_\alpha \cdot H - \frac{1}{2} \overline{N_J} M_J N_J^c$$

add 18 parameters :
M_1, M_2, M_3

18 - 3 (ℓ phases) in λ

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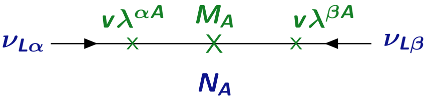
- at low scale, for $M \gg m_D = \lambda v$, light ν mass diagram



9 parameters :
m_1, m_2, m_3
6 in U_{MNS}

$$[m_\nu] \quad = \quad \boldsymbol{\lambda} M^{-1} \boldsymbol{\lambda}^T v^2$$

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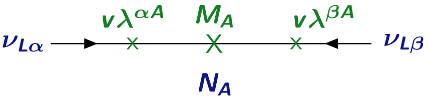

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$$[m_\nu] \quad = \quad \boldsymbol{\lambda} M^{-1} \boldsymbol{\lambda}^T v^2$$

$$\text{for} \quad \begin{matrix} \lambda \sim h_t \;, & M \sim 10^{15}\ \text{GeV} \\ \lambda \sim 10^{-6}, & M \sim\ \text{TeV} \end{matrix} \qquad \sim \quad .05\ \text{eV}$$

"natural" $m_\nu \ll m_f$, but N hard to detect ?

The type I seesaw + Higgs mass

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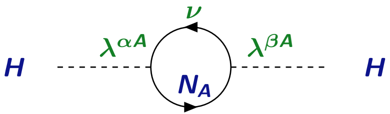

$$\delta m_H^2 \simeq -\sum_I \frac{[\boldsymbol{\lambda}^\dagger \boldsymbol{\lambda}]_{II}}{8\pi^2} M_I^2 \sim \frac{m_\nu M_I^3}{8\pi^2 v^4} v^2$$

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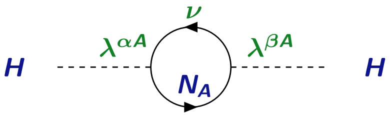

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for $M \gtrsim 10^7$ GeV $\quad > \quad v^2 \quad$ tuning problem

(? adding particles to cancel 1 loop ? Need symmetry to cancel $\geq$ 2 loop ?)
$\Rightarrow$ do seesaw with $M_I \lesssim 10^8$ GeV ?

• add two singlets N, S per generation to the SM : Valle

$$\mathcal{L} = \mathcal{L}_{SM} + \boldsymbol{\lambda}\overline{N}\ell \cdot H - \overline{N}MS - \frac{1}{2}\overline{S}\mu S^c$$

...

Dirac mass between N and S, small Majorana mass for S.

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Dirac mass between N and S, small Majorana mass for S.
For $\mu = 0$, lepton number conserved, L=1 for ℓ, N, S, and $m_\nu = 0$ To check in 1-gen : mass matrix is

$$\left(\begin{array}{ccc} \overline{\nu_L} & \overline{N^c} & \overline{S} \end{array} \right) \left[\begin{array}{ccc} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & 0 \end{array} \right] \left(\begin{array}{c} \nu_L^c \\ N \\ S^c \end{array} \right)$$

determinant vanishes.

- add two singlets N, S per generation to the SM :

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Dirac mass between N and S, small Majorana mass for S.
For $\mu \neq 0 \ll m_D \lesssim M$,

$$\left(\begin{array}{ccc} \overline{\nu_L} & \overline{N^c} & \overline{S} \end{array} \right) \left[\begin{array}{ccc} 0 & m_D & 0 \\ m_D & 0 & M \\ 0 & M & \mu \end{array} \right] \left(\begin{array}{c} \nu_L^c \\ N \\ S^c \end{array} \right)$$

determinant = $\mu m_D^2 \Rightarrow$ masses $M, M, m_D^2\mu/M^2$

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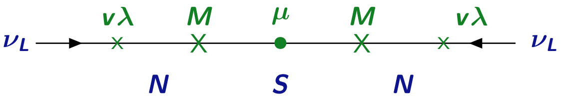
- at low scale, light ν mass matrix



$$[m_\nu] \quad = \quad \boldsymbol{\lambda} M^{-1}\mu M^{-1}\boldsymbol{\lambda}^T v^2 \sim .05 \text{ eV}$$

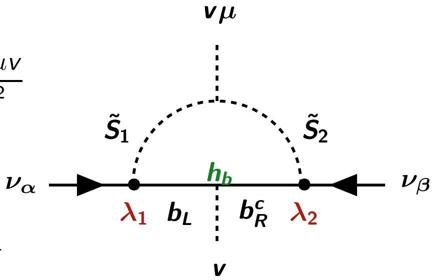
for $\lambda \sim 0.01$, $M \sim$ TeV, $\Rightarrow \mu \sim 10$ keV

Naturally small m_ν, and N @ TeV with $\mathcal{O}(1)$ yukawas.

Consider SU(2)-doublet and singlet leptoquarks (squarks) $\tilde{S}_2$ and $\tilde{S}_1$, with lepton number violating interactions :

$$\lambda_{2,b\alpha}(\overline{\ell}_\alpha \tilde{S}_2) b_R + \lambda_{1,b\alpha} \tilde{S}_1 (\overline{q^c_L} \ell_\alpha) + \mu (H^\dagger \tilde{S}_2) \tilde{S}_1^\dagger + \tilde{m}_1^2 \tilde{S}_1^\dagger \tilde{S}_1 + \tilde{m}_2^2 \tilde{S}_2^\dagger \tilde{S}_2$$

$$[m_\nu]_{\alpha\beta} \simeq \frac{3\lambda_{1,b\alpha}\lambda^*_{2,b\beta}}{16\pi^2} \frac{m_b \mu v}{\tilde{m}^2}$$



$m_\nu \sim .1$ eV for $\tilde{m}_i, \mu \gtrsim$ TeV, $\lambda \sim 10^{-4}$

$\tilde{S}_i$ coloured, pair produce in strong interactions at the LHC

(This (?baroque ?) construction is RPV SUSY...)

How to know which model ?

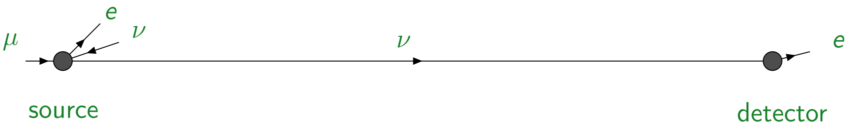
Other observables :
discover new particles at LHC ?
(charged)Lepton Flavour Violation
$0\nu2\beta$
...

What is Lepton Flavour Violation ?

- three lepton flavours in the Standard Model : $\boldsymbol{e}, \boldsymbol{\mu}, \tau$

(flavour $\equiv$ mass eigenstate)

- LFV $\equiv$ charged lepton flavour change, at a point $= \nu$ oscillations don't count.



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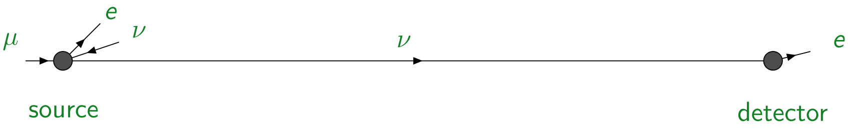


- Lepton Flavour Change is interesting :
  - — none in the Standard Model with $m_\nu = 0$
  - — occurs with m_ν and mixing matrix U

  m_ν renormalisable Dirac : LFV amplitudes GIM-suppressed (like quarks)

$$\mathcal{A} \propto \frac{m_\nu^2}{m_W^2} \Rightarrow BR \lesssim 10^{-48}$$

$\Rightarrow$ if see LFV, lepton flavour sector different from quarks !

LFV good place to look for footprints of Majorana Mass

What do we know about LFV :exptal bounds

some processes	current constraints on BR	future sensitivities
$\mu \to e\gamma$	$< 4.2 \times 10^{-13}$	6×10^{-14} (MEG)
$\mu \to e\bar{e}e$	$< 1.0 \times 10^{-12}$(SINDRUM)	10^{-16} (2021, Mu3e)
$\mu A \to eA$	$< 7 \times 10^{-13}$ Au, (SINDRUM)	$10^{-(16\to?)}$ (Mu2e,COMET)
		10^{-18} (PRISM/PRIME)
$\overline{K_L^0} \to \mu\bar{e}$	$< 4.7 \times 10^{-12}$ (BNL)	
$K^+ \to \pi^+\bar{\mu}e$	$< 1.3 \times 10^{-11}$ (E865)	10^{-12} (NA62)
$\tau \to \ell\gamma$	$< 3.3, 4.4 \times 10^{-8}$	few$\times 10^{-9}$ (Belle-II)
$\tau \to 3\ell$	$< 1.5 - 2.7 \times 10^{-8}$	few$\times 10^{-9}$ (Belle-II, LHCb ?
$\tau \to e\phi$	$< 3.1 \times 10^{-8}$	few$\times 10^{-9}$ (Belle-II)
$h \to \tau^\pm e^\mp$	$< 6.9 \times 10^{-3}$	
$Z \to e^\pm\mu^\mp$	$< 7.5 \times 10^{-7}$	

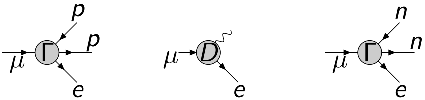
BR $\equiv$ Branching Ratio : (rate for process)/(total decay rate)
$\mu A \to eA \equiv \mu$ in $1s$ state of nucleus A converts to e

(What is ($\mu A \to eA$) $\equiv$ $\mu \to e$ conversion ?)

- μ^- captured by *Al* nucleus, tumbles down to 1*s*. ($r \sim Z\alpha/m_\mu \gtrsim r_{Al}$)
- in SM : muon capture $\mu + p \to \nu + n$

(What is $(\mu A \to eA) \equiv \mu \to e$ conversion ?)

- μ^- captured by *Al* nucleus, tumbles down to 1*s*. $(r \sim Z\alpha/m_\mu \gtrsim r_{Al})$
- in SM : muon capture $\mu + p \to \nu + n$
- bound μ interacts with nucleus, converts to e $(E_e \approx m_\mu)$



$\approx$ WIMP scattering on nuclei

1) "Spin Independent" rate $\propto A^2$ (amplitude $\propto \sum_N \propto A$)

2)"Spin Dependent" rate $\sim \Gamma_{SI}/A^2$ (sum over nucleons $\propto$ spin of only unpaired nucleon)

Are those bounds restrictive? What does $BR < 10^{-12}$ mean?

LFV Branching Ratios normalised to μ *weak* decay, $\tau_\mu \sim 2 \times 10^{-6}$sec

$$BR(\mu \to e\bar{e}e) \equiv \frac{\Gamma(\mu \to e\bar{e}e)}{\Gamma(\mu \to e\bar{\nu}\nu)} \quad , \quad \Gamma(\mu \to e\bar{\nu}\nu) = \frac{G_F^2 m_\mu^5}{192\pi^3} = \frac{m_\mu^5}{1536\pi^3 v^4}$$

so if

$m_\mu = .105$ GeV
$v = 174$ GeV

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$$\Gamma(\mu \to e\bar{e}e) \simeq \frac{m_\mu^5}{1536\pi^3 \Lambda_{LFV}^4} \Rightarrow BR \lesssim \begin{cases} 10^{-12} \Rightarrow \Lambda_{LFV} \sim 10^3 v \simeq 200 \text{ TeV} \\ 10^{-16} \Rightarrow \Lambda_{LFV} \sim 10^3 v \simeq 2000 \text{ TeV} \end{cases}$$

NB : $\Lambda_{LFV} = (16\pi^2)^n M_{LFV}$/couplings ; *not* the mass scale of new particles M_{LFV}

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$v = 174$ GeV

$$\Gamma(\mu \to e\bar{e}e) \simeq \frac{m_\mu^5}{1536\pi^3 \Lambda_{LFV}^4} \Rightarrow BR \lesssim \begin{cases} 10^{-12} \Rightarrow \Lambda_{LFV} \sim 10^3 v \simeq 200 \text{ TeV} \\ 10^{-16} \Rightarrow \Lambda_{LFV} \sim 10^3 v \simeq 2000 \text{ TeV} \end{cases}$$

NB : $\Lambda_{LFV} = (16\pi^2)^n M_{LFV}/$couplings ; *not* the mass scale of new particles M_{LFV}

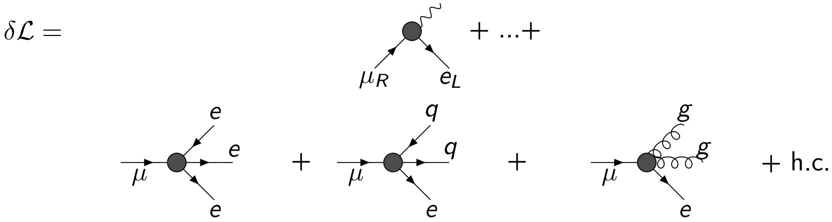
Compare to $\frac{(g-2)_\mu}{2} \equiv a \simeq \alpha_{em}/\pi$ (electromagnetic *amplitude*) :
torque $\vec{\tau} = \vec{\mu} \times \vec{B}$; $\vec{\mu} = g \frac{e}{2m} \vec{S}$

$$\Delta a \equiv a^{SM} - a^{exp} \simeq 3 \times 10^{-9}$$
$$\sim \frac{m_\mu^2}{16\pi^2 \Lambda_{NP}^2}$$

$\Rightarrow \Lambda_{NP} \sim m_t$.

To parametrise all those LFV processes

... add to $\mathcal{L}$: three- and four-point LFV contact interactions. Called "operators", should respect relevant gauge symmetries (QED*QCD), and can be classified by dimension.



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$$\delta\mathcal{L} \;=\; \sum_{n=1}^{3} \frac{1}{v^n} \sum_{X,\zeta} c_X^\zeta \mathcal{O}_X^\zeta + h.c.$$

$v \approx m_t$, $2\sqrt{2}G_F = 1/v^2$
$\{\mathcal{O}_X^\zeta\}$ = QED*QCD invar operators with 3 or 4 legs
X = Lorentz structure, ζ = flavour labels.
$\{c_X^\zeta\}$ dimless coefficients, calculable in models, input to calculate LFV rates

82 operators to parametrise $\mu \to e$ processes below m_W :

Want all three and four-point interactions involving e and μ, and 1 or 2 gauge fields, or 2(same-flavour) fermions $f \in u, d, s, c, b, \tau$. or $l \in \{e, \mu\}$. $X \neq Y \in \{L, R\}$. $QED * QCD$ invariant. :

$$em_\mu(\overline{e}\sigma^{\alpha\beta}P_Y\mu)F_{\alpha\beta} \qquad \textit{dim } 5$$

$$(\overline{e}\gamma^\alpha P_Y\mu)(\overline{l}\gamma_\alpha P_Y l) \qquad (\overline{e}\gamma^\alpha P_Y\mu)(\overline{l}\gamma_\alpha P_X l)$$

$$(\overline{e}P_Y\mu)(\overline{l}P_Y) \qquad \textit{dim } 6$$

$$(\overline{e}\gamma^\alpha P_Y\mu)(\overline{f}\gamma_\alpha f) \qquad (\overline{e}\gamma^\alpha P_Y\mu)(\overline{f}\gamma_\alpha\gamma_5 f)$$

$$(\overline{e}P_Y\mu)(\overline{f}f) \qquad (\overline{e}P_Y\mu)(\overline{f}\gamma_5 fl)$$

$$(\overline{e}\sigma P_Y\mu)(\overline{f}\sigma f)$$

$$\frac{1}{m_t}(\overline{e}P_Y\mu)G_{\alpha\beta}G^{\alpha\beta} \qquad \frac{1}{m_t}(\overline{e}P_Y\mu)\tilde{G}_{\alpha\beta}\tilde{G}^{\alpha\beta} \qquad \textit{dim } 7$$

$$\frac{1}{m_t}(\overline{e}P_Y\mu)F_{\alpha\beta}F^{\alpha\beta} \qquad \frac{1}{m_t}(\overline{e}P_Y\mu)\tilde{F}_{\alpha\beta}\tilde{F}^{\alpha\beta}$$

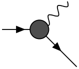
...zzz...

(*plus* quark flavour-changing...$P_X, P_Y = (1 \pm \gamma_5)/2$.

$\mu \to e\gamma$, $\mu \to e\bar{e}e$, and $\mu - e$ conv. sensitive to coefficients of most of these operators

Sensitivity to New Physics in loops

Two dipole operators contribute to $\mu \to e\gamma$:



$$\delta\mathcal{L}_{meg} = -\frac{4G_F}{\sqrt{2}} m_\mu \left(C_R^D \overline{\mu_R} \sigma^{\alpha\beta} e_L F_{\alpha\beta} + C_L^D \overline{\mu_L} \sigma^{\alpha\beta} e_R F_{\alpha\beta} \right)$$

$$BR(\mu \to e\gamma) = 384\pi^2(|C_R^D|^2 + |C_L^D|^2) < 4.2 \times 10^{-13}$$

$$\Rightarrow |C_X^D| \lesssim 10^{-8}$$

MEG expt, PSI

How big does one expect C to be ?

			$n = 1$	$n = 2$
$C\frac{m_\mu}{v^2} \sim \frac{ev}{(16\pi^2)^n \Lambda^2}$	$\Rightarrow$ probes	$\Lambda \lesssim$	3000 TeV	300 TeV
$C\frac{m_\mu}{v^2} \sim \frac{em_\mu}{(16\pi^2)^n \Lambda^2}$	$\Rightarrow$ probes	$\Lambda \lesssim$	100 TeV	10 TeV

2-loop sensitivity to New Particles that are beyond the reach of the LHC...

But QED loops are $\mathcal{O}(\alpha/4\pi)$... surely negligeable correction to tree?

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Work top-down = suppose a model that gives only tensor operator at m_W :

$$2\sqrt{2}G_F \; C_T(\overline{u}\sigma u)(\overline{e}\sigma P_Y \mu)$$

1 : forget RGEs Match to nucleons $N \in \{n, p\}$ as
$\widetilde{C}_T^{NN} = \langle N|\bar{u}\sigma u|N\rangle C_T^{uu} \lesssim \frac{3}{4} C_T^{uu}$

nuclear matrix elements : EngelRTO, KlosMGS

$$\Rightarrow \boldsymbol{BR \approx BR_{SD} \approx \frac{1}{2}|C_T|^2}$$

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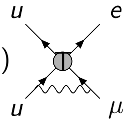
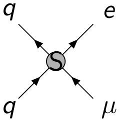


$+ \ldots \quad \Rightarrow$



$64\frac{\alpha_e}{4\pi} \log \frac{m_W}{m_\tau} \; C_T^{uu} \; (\overline{u}u)(\overline{e}P_Y \mu)$

$\Delta C_S^{uu}(m_\tau) \sim \frac{1}{7} C_T^{uu}(m_W)$

Then match to nucleons : $\widetilde{C}_S^{NN} = \langle N|\bar{u}u|N\rangle \Delta C_S^{uu} \sim C_T^{uu}$ so $\widetilde{C}_S^{pp} \gtrsim \widetilde{C}_T^{pp}$,

$$\boldsymbol{BR \approx BR_{SI} \sim Z^2|2C_T^{uu}|^2 \sim 8Z^2 BR_{SD}}$$

$\Rightarrow$ loop effects mix tensor to scalar.. change $BR(\mu A \to eA)$ by $\mathcal{O}(10^3)$

What do we know about ν mass mechanism from LFV ?

contribution of light,active neutrino masses is negligeable :

1. renormalisable Dirac masses :
$\mathcal{A}_{LFV} \propto m_\nu^2/m_W^2 =$ unobservable
(like $0\nu2\beta$)

2.majorana masses : *calculable* contribution
of dim5 operator to $\mathcal{A}_{LFV} \propto m_\nu^2 \log$ DavidsonGorbahnLeak
(unlike $0\nu2\beta$)

3. ...

$\Rightarrow$ LFV an orthogonal probe of leptonic New Physics models, but what constraints mean is non-trivial....

So what to do ?

Georgi, EFT, ARNPP 43(93) 209
(one of my all-time
favourite papers)

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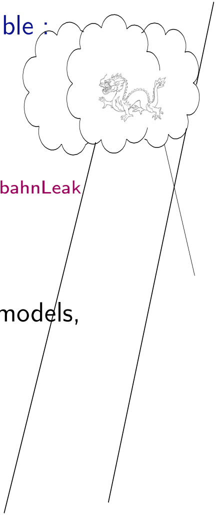

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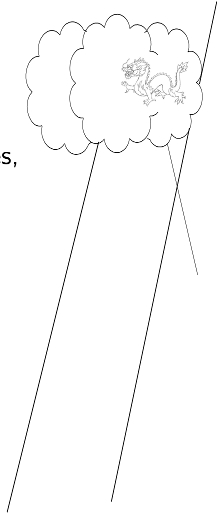
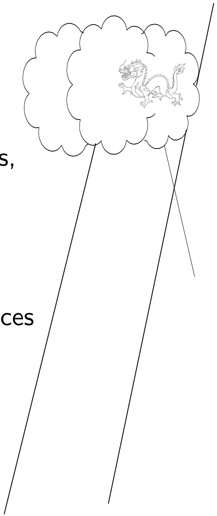
So what to do ?

data

1. pick motivated, natural+ beautiful model,
perform difficult multi-loop calculation of all LFV rates,
extract constraints on model parameters





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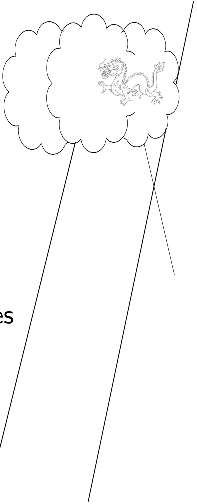
Then build the high scale model to satisfy constraints.



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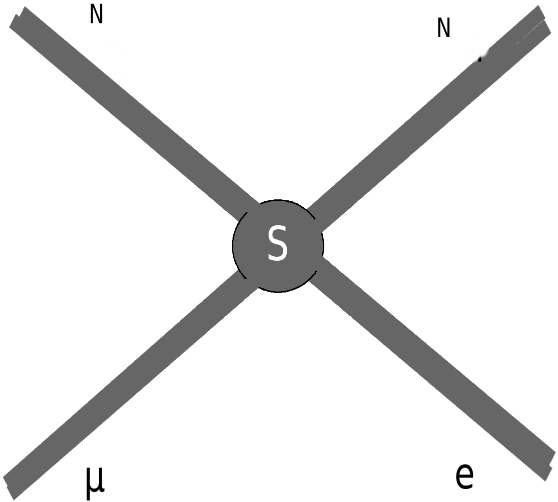
Why : the SM loop calns are hard, so
do once, carefully, in EFT (where its easier).
There are very many models... easier to identify dragon
at the top, than through SM haze from the bottom.
Calculate same diagrams in both cases :
In model, start at short distances and add loop corrections (caln exact to fixed order),

In EFT start at long distance and subtract (caln at leading log, NLL, etc).

data

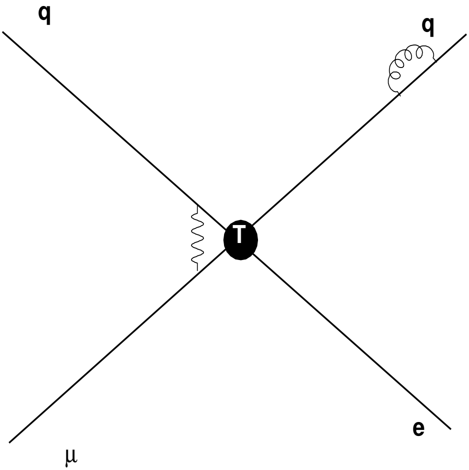
Peeling off SM loop corrections — at exptal scale

expt measures operator coefficient $\widetilde{C}(\mu_{exp})$, at exptal energy scale $\sim m_\mu \to m_\tau$, among external legs at same scale...



Peeling off SM loop corrections

But if I look on shorter distance scale ($\sim 1/m_W$) I might see



In practise...consider $\mu \leftrightarrow e$ processes :

1. exptal bds on $BR(\mu \to e\gamma)$,$BR(\mu \to e\bar{e}e)$ and $BR(\mu - e \text{ conv.})$.
2. give stringent bounds on $12 \to 20$ operator coefficients *eg*

   $$BR(\mu \to e\gamma) = 384\pi^2(C_{D,L}^2 + C_{D,R}^2) \leq 4.2\times10^{-13} \Rightarrow |C_{D,X}| \leq 1.05\times10^{-8}$$

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$$\begin{aligned}
10^{-8} \quad \gtrsim \quad & \Bigg| C_{D,X}\left(1 - 16\frac{\alpha_e}{4\pi}\ln\frac{m_W}{m_\mu}\right) \\
& - \frac{\alpha_e}{4\pi e}\ln\frac{m_W}{m_\mu}\left(-8\frac{m_\tau}{m_\mu}C_{T,XX}^{\tau\tau} + C_{S,XX}^{\mu\mu} + C_{2loop}\right) + 16\frac{\alpha_e^2}{2e(4\pi)^2}\ln^2\frac{m_W}{m_\mu}\left(\frac{m_\tau}{m_\mu}C_{S,XX}^{\tau\tau}\right) \\
& - 8\lambda^{aT}\frac{\alpha_e}{4\pi e}\ln\frac{m_W}{2\text{ GeV}}\left(-\frac{m_s}{m_\mu}C_{T,XX}^{ss} + 2\frac{m_c}{m_\mu}C_{T,XX}^{cc} - \frac{m_b}{m_\mu}C_{T,XX}^{bb}\right) f_{TD} \\
& + 16\frac{\alpha_e^2}{3e(4\pi)^2}\ln^2\frac{m_W}{2\text{ GeV}}\left(\sum_{u,c}4\frac{m_q}{m_\mu}C_{S,XX}^{qq} + \sum_{d,s,b}\frac{m_q}{m_\mu}C_{S,XX}^{qq}\right)\Bigg|
\end{aligned}$$

these C at scale m_W (part way up mountain)

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4. ...can make a table of "sensitivities", eg $C_{T,XX}^{cc}(m_W) \leq \ldots$ CrivellinEtal
   If your model, at tree level, gives C smaller than the sensitivity, then agrees with data. If it gives C bigger, then you need a cancellation against some other term in the sum to satisfy bound...

$0\nu 2\beta$

Neutrinoless double beta decay : looking for lepton *number* violation

Single β decay kinematically forbidden for some nuclei
(eg ${}^{76}_{32}Ge$ lighter than ${}^{76}_{33}As$, so ${}^{76}_{32}Ge \rightarrow^{76}_{34} Se + ee\bar{\nu}_e\bar{\nu}_e$. $\tau \sim 10^{21}$ yrs)

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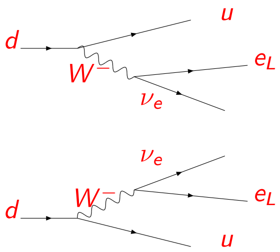

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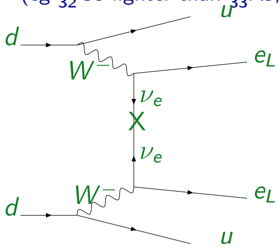
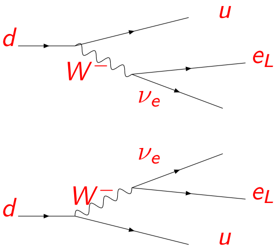
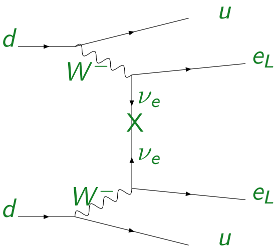
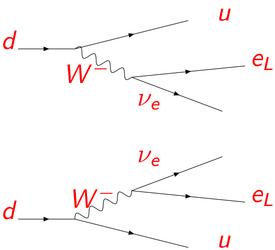


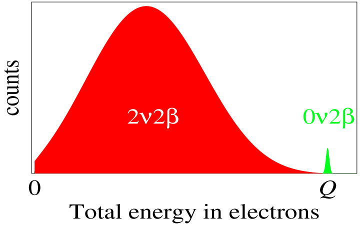


for majorana neutrinos, or other LNV, but not Dirac neutrinos.

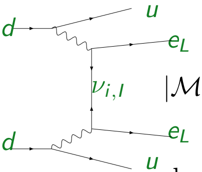
Detecting $0\nu2\beta$







$0\nu2\beta$—to calculate ?



$$|\mathcal{M}|^2 \sim \left| \begin{array}{c} \text{nuclear} \\ \text{matrix} \\ \text{element} \end{array} \right|^2 \times \left| \sum_i U_{ei}^2 \frac{m_i}{Q^2} + \sum_I U_{eI}^2 \frac{1}{M_I} + \text{other} \right|^2$$

where

$$\frac{\not{Q} + m_\nu}{Q^2 - m_\nu^2} \to \left\{ \begin{array}{ll} m_i/Q^2 & m_i \ll Q \sim 100 \text{ MeV} \\ 1/M_I & M_I \gg Q \sim 100 \text{ MeV} \end{array} \right.$$

If neglect heavy neutrino + other heavy contributions

$$|\mathcal{M}|^2 \propto \left| c_{13}^2 c_{12}^2 e^{-i2\phi} m_1 + c_{13}^2 s_{12}^2 e^{-i2\phi'} m_2 + s_{13}^2 e^{-i2\delta} m_3 \right|^2$$

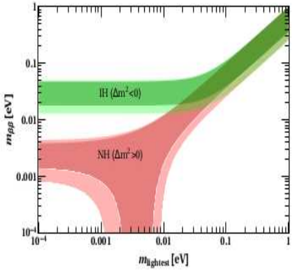
... appearance of the majorana phases !
but : $\propto m_\nu^2$, and ± 3 ? from nuclear matrix element

What can we learn/confirm ?

$$
\begin{aligned}
|\mathcal{M}|^2 &\propto |\frac{3}{4}e^{-i2\phi}m_1 + \frac{1}{4}e^{-i2\phi'}m_2 + s_{13}^2 e^{-i2\delta}m_3|^2 \\
&\to |\frac{3}{4}e^{-i2\phi}m_1 + \frac{1}{4}e^{-i2\phi'}m_{sol} + (.15)^2 e^{-i3\pi}m_{atm}|^2 \\
&\simeq m_{sol}^2|\frac{3m_1}{m_{sol}} + e^{-i2(\phi-\phi')}|^2 \\
&\to m_{atm}^2|3 + e^{-i2(\phi'-\phi)}|^2
\end{aligned}
$$

• Inverse hierarchy ($m_1 \sim m_2 > m_3$) :
observe at $|m_{ee}| \sim m_{atm}$,
OR neutrinos are Dirac

• Hierarchical ($m_1 < m_2 < m_3$) :
observe at $|m_{ee}| \sim m_{sol}$, if m_1 negligeable,
BUT can vanish for $m_1 \sim m_{sol}/3$



NSI

BSM to find in ν oscillations

(not neccessarily BSM where to learn about mass mechanism)

Non-Standard Interactions

Wolfenstein, Valle, GuzzoMasieroPetcov

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

QED×QCD invariant.

Wolfenstein, Valle, GuzzoMasieroPetcov

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QED×QCD invariant. At finite density

$$\langle \text{medium}|\overline{\hat{f}}\gamma_\alpha\hat{f}(x)|\text{medium}\rangle \to \delta_{\alpha 0}n_f \ ,$$

contributes to forward scattering amplitude ⇔ "effective $\Delta m^2/E \sim \sqrt{2}G_F n_e$" to oscillation Hamiltonian

Non-Standard Interactions

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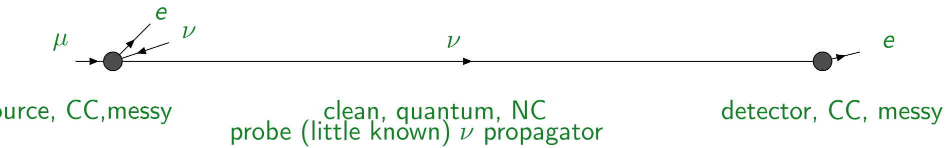

interest : ν oscillations= quantum mechanics on macroscopic scales = *very* sensitive window to probe poorly known ν propagator ($\Leftrightarrow m_\nu$ + NC ν interactions)

("Generalised Neutrino Interactions") ...

AristizabalSierradeRomeriRojas
AltmannshoferTammaroZupan
FalkowskiGonzalezAlonsoTabrizi

$2\nu 2f$ four-fermion interactions, ν light, can be sterile $\simeq \nu_R$, $f \in \{e, d, u\}$

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

interest : COHERENT measured Coherent Elastic ν-Nucleus Scattering [CEνNS : $\sigma(\nu A \to \nu A)$, $q^2 \sim 50$ MeV so $\mathcal{M}(\nu A \to \nu A) \propto A \mathcal{M}(\nu n \to)$]
CEνNS *not* forward scattering, sensitive to more operators, in different combo from (incoherent) high-E σ.

NSI : coherent, some flavour combos interfere with SM
scalar GNI : coherent, not interfere SM (outgoing ν_R)
axial/pseudoscalar/tensor : f current $\to$ nucleon spin, incoherent on unpolaised target...

Lets stick to NSI...

Current constraints on NSI from oscillation data + COHERENT

EstebanGonzalezGarciaMaltoniEtal

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

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

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

Comments...

- ?oscillations (maybe) have separate sensitivity to NSI on u and d because the sun is made of protons ?
- Oscillations only sensitive to $\varepsilon^{\alpha\alpha} - \varepsilon^{\beta\beta}$, but COHERENT lifts degeneracy (NC scattering, sensitive to $\varepsilon^{\sigma\rho}$)
- ranges *neglect* other solutions where SM parameters disconnected from bestfit values (LMA-Dark solution) !
- $\varepsilon_e^{\alpha\alpha} \sim 1$ allowed because flips sign of SM $(\bar{\nu}\gamma P_L \nu)(\bar{f}\gamma P_L f)$ (oscillations sensitive to signs, but only of flavour differences...)
- not matched onto SMEFT, so not accounting for potential contribution to flav-diagonal "SM" inputs by CC or charged-lepton components of the SMEFT operator.
- Energy scales : $q^2 \to 0$ in matter effect, 30-70 MeV at COHERENT.

Neutral Current ν scattering (high energy)

BerezhianiRossi
DavidsonPenaGaraySantamariaRius

chiral ε ($g_L^f \neq g_R^f$ in SM), weaker bd to fit on slide

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

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 ?

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

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

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

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

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

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

$\varepsilon^{\rho\sigma}_f \gtrsim 10^{-2} \Leftrightarrow \Lambda \lesssim .3 \to 1$ 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 $\ell_\mu, \ell_\tau, q_{L,1}, u_R, d_R$.
   - light Z' feebly coupled to quarks and $\nu_{sterile}$, small $m\nu_s\nu_{SM}$. Farzan

   PospelovPradler

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

2.

3. heavy New Physics, $m_{mediator} \gtrsim m_W$ recipe :GavelaHernandezOtaWinter
   tune NP masses/cplgs so tree LFV coefficients vanish(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 $L=2, Q_{em}=1$, $S\ell_i^\alpha \epsilon^{ij} \ell_j^\beta$, induces only $2e2\nu$

   $\star$can do EFT = results that apply to many models

Summary of this lecture

1. neutrinos are magical particles : masses imply that there is BSM
2. many models reproduce observed neutrino masses and mixing angles, so other observables to discriminate among models are welcome.
   2.1 (discover new particles involved in ν mass mechanism ?)
   2.2 ($0\nu2\beta$?)
   2.3 LFV has to exist — measure it ?
   2.4 ...

   easy to say, but what to do as a theorist ? There are maaanny models... how to know which model, with which parameters, is true ?
   - you have a favourite model : calculate
   - you lack such illumination : for heavy BSM, EFT could clarify constraints on models$\Leftrightarrow$ which ones work
3. since we found some BSM in neutrinos, can look for more : NSI !