Phenomenology, leptons and the LHC

some parts of sections 2 and 3 of the lepton chapter

for refs:
see draft

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1. Attraction of the lepton sector: $m_\nu \Rightarrow$ BSM Physics
   - But what is it?
   - parametrise via effective Lagrangian

2. What can current (lepton) data tell us about what we see at the LHC?
   - tables of bounds on operator coefficients

3. What can the LHC tell us about neutrino mass generation mechanism?
   - no pheno answer (that I know of, at the moment) $\Rightarrow$ models
   - intro to the seesaw, parametrisations thereof (see A Rossi for predictions)
   - leptogenesizzzzzzzzz

4. A question for authors of chapter 3

The Standard Model Lagrangian for Leptons

$$\mathcal{L}_{\rm lep} \;=\; \sum_{\alpha=e,\mu,\tau} i\,\overline{\ell_L^\alpha}^T \gamma^\mu \mathbf{D}_\mu \,\ell_L^\alpha + \sum_{\alpha=e,\mu,\tau} i\overline{e_R^\alpha}\,\gamma^\mu D_\mu \,e_R^\alpha - \sum_{\alpha=e,\mu,\tau} \{\; Y_e^\alpha \;(\overline{l_L^\alpha}\,H_d) e_R^\alpha + \text{h.c.}\}$$

Three generations of doublets, and charged singlets

$$\ell^\alpha = \left\{ \begin{pmatrix} \nu_L^e \\ e_L \end{pmatrix} \;, \begin{pmatrix} \nu_L^\mu \\ \mu_L \end{pmatrix} \;, \begin{pmatrix} \nu_L^\tau \\ \tau_L \end{pmatrix} \right\} \qquad e_R^\alpha = \{e_R \;\;, \mu_R \;\;, \tau_R\}$$

Yukawa matrix $[Y_e]$ diagonal in charged lepton mass basis

...no m_ν, three conserved flavours.

lepton flavour violation in neutrino oscillations $\Rightarrow$ New Physics

Two directions in which can extend SM to give neutrinos mass:

1. add new light singlet fermions and renormalisable interactions

2. add non-renormalisable effective operator (heavy new physics)

...neither "indicates" new physics at the TeV-scale ...but... there is a multitude of models crowding between these two cases, many of them predict NP @ LHC...

neutrino oscillations ⇒ New Physics, not neccessarily at LHC

Two directions in which can extend SM to give neutrinos mass:

1. add new light singlet fermions and renormalisable interactions
   $e.g.$ at least two "right-handed" neutrinos N^J and neutrino Yukawa matrix Y_ν

   $$\Delta\mathcal{L} = -[Y_\nu]^*_{\alpha J}(\overline{\ell^\alpha} H_d) N^J + h.c.$$

   ¿conventions?

   gives lepton number conserving ("Dirac") neutrino mass matrix $[m_D]_{\alpha J} = [Y_\nu]^*_{\alpha J}\langle H_d\rangle$.
   Y_ν eigenvalues $\lesssim 10^{-13}$ (could also add small majorana masses $\mu\overline{N^c}N + h.c.$)
2. add non-renormalisable effective operator (heavy new physics).

neutrino oscillations ⇒ New Physics, not neccessarily at LHC

Two directions in which can extend SM to give neutrinos mass:

1. add new light singlet fermions and renormalisable interactions

2. add non-renormalisable effective operator (heavy new physics). Such as

$$\Delta\mathcal{L} = \frac{1}{2}\kappa_{\alpha\beta}(\overline{\ell^{c\alpha}}H_u)(\ell^\beta H_u) + h.c.$$

gives lepton number violating ("Majorana") neutrino mass matrix $[m]_{\alpha\beta} = [\kappa]_{\alpha\beta}\langle H_u\rangle^2$. If

$$\kappa \sim \frac{\lambda^2}{M} \qquad \lambda \sim 1 \Rightarrow M \sim 10^{14}\text{GeV} \gg \text{TeV}$$

...but... there is a multitude of models crowding between these two cases, many of them predict NP @ LHC. Useful way to parametrise effects of unknown new physics: effective Lagrangian

Effective Lagrangians

Can parametrise effects of new physics, in leptons sector, by adding to $\mathcal{L}_{SM}$ the effective Lagrangian

$$\begin{aligned}
\Delta\mathcal{L}_{eff}^{leptons} &= \sum_{d\geq 5}\frac{1}{m_{NP}^{d-4}}\sum_{n} C_n O_n(H,\ell^\alpha,e_R^\alpha,...) + h.c. \\
&= \frac{1}{2}\kappa_{\alpha\beta}H_u\ell^\alpha H_u\ell^\beta + h.c. \\
&\quad +4\frac{G_F}{\sqrt{2}}\sum_n \epsilon_n[\text{four lepton operators}] + \text{other dim 6} + h.c \\
&\quad +[\nu \text{ mag mos and other dim 7}] + ...
\end{aligned}$$

Two questions:

1. what can current constraints on coefficients C_n tell us about new particles to be discovered at the LHC?

$$\Rightarrow \text{ tables}$$

2. can we determine the neutrino mass generation mechanism from the C_n and LHC data? ??

$$\Rightarrow \text{ models...}e.g. \text{ seesaw}$$

Tables: bounds on coefficients

1) Consider, for simplicity, 4-lepton operators:

$$(\overline{\ell}_i \gamma^\mu \ell_j)(\overline{\ell}_k \gamma_\mu \ell_l) + h.c. \qquad (\overline{\ell}_i \tau^I \gamma^\mu \ell_j)(\overline{\ell}_k \tau^I \gamma_\mu \ell_l) + h.c.$$

$$(\overline{e}_i \gamma^\mu P_R e_j)(\overline{e}_k \gamma_\mu P_R e_l) + h.c \qquad (\overline{\ell}_i \gamma^\mu P_L \ell_l)(\overline{e}_k \gamma_\mu P_R e_j) + h.c.$$

(all have 4-charged lepton component) and also dipole moment operators

$$\overline{\ell}_i \sigma^{\mu\nu} e_j H B_{\mu\nu} + h.c. \qquad \overline{\ell}_i \sigma^{\mu\nu} \tau^I e_j H W^I_{\mu\nu} + h.c.$$

2) Suppose (four-lepton) operators appear one at a time in the Lagrangian, $e.g.$

$$\Delta\mathcal{L} = \epsilon_{ijkl} \frac{4G_F}{\sqrt{2}} (\overline{\nu}_i \gamma^\mu P_L \nu_j + \overline{e}_i \gamma^\mu P_L e_j)(\overline{\nu}_k \gamma_\mu P_L \nu_l + \overline{e}_k \gamma_\mu P_L e_l) + h.c.$$

for some choice of i, j, k, l. ϵ_{ijkl} dim-less.

3) Calculate contribution of $(\overline{e}_i \gamma^\mu P_L e_j)(\overline{e}_k \gamma_\mu P_L e_l)$ to FCNC, Z width....
Best bounds from 4-charged-lepton legs, except for τs $\Rightarrow$ use G_τ.

Table 1: Bounds on coefficients of flavour conserving 4-lepton operators. The number is the upper bound on the dimensionless operator coefficient ϵ^{ijkl}, arising from the measurement in the last colomn. The bound applies also to ϵ^{klij}, ϵ^{jilk} and ϵ^{ilkj}, except in the cases labelled by $*$. The constraints in [brackets] apply to the 2-charged-lepton-2-neutrino operator of the same flavour structure.

$(ijkl)$	$(\overline{e}\gamma^\mu P_L e)(\overline{e}\gamma_\mu P_L e)$	$(\overline{e}\gamma^\mu P_R e)(\overline{e}\gamma_\mu P_R e)$	$(\overline{e}\gamma^\mu P_R e)(\overline{e}\gamma_\mu P_L e)$	expt, limit
$\overline{e}e\overline{e}e$	$(-1.8 \to 2.8) \cdot 10^{-3}$	$(-1.8 \to 2.8) \cdot 10^{-3}$	$(-4.7 \to 9.8) \cdot 10^{-3}$	Λ@ LEP2
$\overline{e}e\overline{\mu}\mu$	$(-3.6 \to 2.9) \cdot 10^{-3}$	$(-3.9 \to 3.2) \cdot 10^{-3}$	$(-1.9 \to 1.9) \cdot 10^{-2}$	Λ@LEP2
$\overline{e}e\overline{\tau}\tau$	$(-3.7 \to 8.0) \cdot 10^{-3}$	$(-4.0 \to 8.6) \cdot 10^{-3}$	$(-2.3 \to 3.6) \cdot 10^{-2}$	Λ@LEP2
$\overline{\mu}\mu\overline{\mu}\mu$	~ 1	~ 1	~ 1	$BR(Z \to \mu$
$\overline{\mu}\mu\overline{\tau}\tau$	$\sim 1[0.001]$	~ 1	$\sim 1[0.1]\ *$	$BR(Z \to \mu$
$\overline{\tau}\tau\overline{\tau}\tau$	~ 1	~ 1	~ 1	$BR(Z \to \tau$

what are tables for?:
If see some excess of events at the LHC, maybe can use "low energy " data to constrain (flavour structure) of new particle interactions

:(since LHC is a pp collider, $(\overline{\ell}\gamma\ell)(\overline{q}\gamma q)$ operators would have been useful :(

caveats

1. constraints calculated on one operator at a time are unrealistic: BSM will induce many operators.

2. such constraints are dangerous: maybe a symmetry in New Physics causes $\epsilon_1 = \epsilon_2$. If an observable constrains $\epsilon_1 - \epsilon_2$, "one-operator-at-a-time" gives a bound that does not exist.

3. incomplete set of operators ? (scalars, covar derivatives and leptons ?)

4. ¿dim > 6? If effective operators are induced by TeV mass particles, is it safe to neglect dimension 7,8 operators? $e.g$

$$\frac{1}{m_{NP}^4} H H \bar{\psi}\psi\bar{\psi}\psi \simeq \frac{1}{m_{NP}^2}\frac{v^2}{m_{NP}^2}\bar{\psi}\psi\bar{\psi}\psi$$

Question 2: Can the LHC tell us about the ν mass generation mechanism?

The Type 1 Seesaw, in the usual top-down presentation

Add 3 (or 2) singlet "right-handed" neutrinos with Majorana masses $M_I \gtrsim$ or $\gg$ TeV, and a Yukawa coupling. In the charged lepton ("flavour") and $N (= \nu_R)$ mass bases, at large energy scale $\gg M_i$:

21 parameters chez les leptons:
$m_e, m_\mu, m_\tau, M_1, M_2, M_3$
18 - 3 (ℓ phases) in Y_ν

$$\mathcal{L}_{lep} \quad = \quad (\overline{\ell_L}\, H_d^*)\mathbf{Y}_\mathbf{e}^* e_R - (\overline{\ell} H_u^*)\mathbf{Y}_\nu{}^* N - \frac{1}{2}\overline{N^c}\mathbf{M}N + \text{h.c.}$$

after EWSB, $[m_D] = Y_\nu \langle H_u \rangle$, the 6×6 neutrino mass matrix is

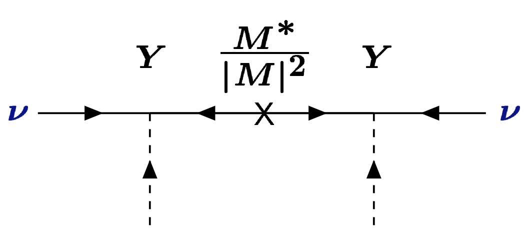
$$\left(\begin{array}{cc} 0 & m_D \\ m_D^T & M \end{array} \right) = V^* \mathcal{D} V^\dagger \qquad v_u = \langle H_u^0 \rangle$$

$$\text{where } \mathcal{D} \quad = \quad \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3}, M_{N_1}, M_{N_2}, M_{N_3}) \qquad V = \left(\begin{array}{cc} U & G \\ S & T \end{array} \right)$$

For $m_D \ll M$, this is equivalent to "integrating out" the N_J, to get dimension 5 operator $(H_u \ell) Y_\nu M^{-1} Y_\nu^T (H_u \ell)$ (conventions: index order LR, cc à la superpotential, see diagram)

$$-U^\dagger m_D M^{-1} m_D{}^T U^* \quad \equiv \quad U^\dagger [m_\nu] U^* = \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$$

$$\sim \quad \frac{m_t^2}{10^{14} GeV} \sim .1 eV$$



The Seesaw(s)—parametrisations of

1. **top-down**: (in your favourite texture model...)
   input the eigenvalues of $\mathbf{Y}_e\mathbf{Y}_e^\dagger$ and $\mathbf{M}$, and $[\mathbf{Y}_\nu] = \mathbf{V}_L^\dagger \mathbf{D}_{Y_\nu} \mathbf{V}_R$

   $$\Rightarrow \text{ calculate } \mathbf{U}\mathbf{D}_m\mathbf{U}^T = [\mathbf{m}_\nu] = \mathbf{V}_L^\dagger \mathbf{D}_{Y_\nu} \mathbf{V_R} \mathbf{D}_M^{-1} \mathbf{V}_R^T \mathbf{D}_{\mathbf{Y}_\nu} \mathbf{V_L}^* v_u^2$$

   :(calculate measured quantites in terms of inputs
2. **left-handed/bottom-up**: observables ($e.g.$ m$_\nu$, $\mathbf{U}_{PMNS}$) amoung inputs
   input $\mathbf{Y_e Y_e}^\dagger$ eigenvalues ($=$ charged lepton masses), m_{ν_i}, U_{PMNS}, V_L and D_{Y_ν}

   $$\Rightarrow \text{ calculate } [\mathbf{M}]^{-1} = \mathbf{D}_{Y_\nu}^{-1} \mathbf{V}_L \mathbf{U} \mathbf{D}_m \mathbf{U}^T \mathbf{V}_L^T \mathbf{D}_{Y_\nu}^{-1}$$

   :) useful for hand-waving in MSUGRA: $V_L^\dagger D_Y^2 V_L$ appears in slepton RGEs
3. **Casas-Ibarra**: maybe prefer observables *and* M_J ?
   Can parametrise seesaw with $\mathbf{Y_e Y_e}^\dagger$ eigenvalues, m_{ν_i}, U_{PMNS}, the three M_J, and a *complex* orthogonal matrix R, such that (in $\mathbf{Y_e Y_e}^\dagger$, M eigenbases):

   $$\begin{aligned} Y_\nu &\equiv U D_m^{1/2} R D_M^{1/2} v_u^{-1} \\ \mathcal{I} &= (D_m^{-1/2} U^\dagger Y_\nu D_M^{-1/2})(D_M^{-1/2} Y_\nu^T U^* D_m^{-1/2}) v_u^2 = RR^T \end{aligned}$$

   caveat 1) $2\cos(\rho + i\eta) = \cos\rho\cosh\eta - i\sin\rho\sinh\eta$. So phases in **R** $\Rightarrow$ $C\!\!\!/P$, and exponential scaling of real parameters
   caveat 2) measure on parameter space ?

Additions to, Variations on, and tree-level Alternatives to the Seesaw

Type 1: put 3 N because there are three generations. Most general renormalisable $\mathcal{L}$ contains neutrino Yukawa Y_ν and masses M for the Ns.

1. supersymmetrise—same parametrisations work for Type I.
2. Type II seesaw: add an SU(2) scalar triplet $\vec{T}$

$$\Delta\mathcal{L} \sim t_{\alpha\beta}\ell_\alpha\tau\cdot\vec{T}\ell_\beta + \mu H\tau\cdot\vec{T}H$$

   T_0 gets a small vev after EWSB. This generates *additional* contribution to light neutrino mass matrix $\propto t_{\alpha\beta}$. Motivated in GUTS, more unknown parameters.
3. Suppose the(heavy) triplet and no N:

$$[m_\nu]_{\alpha\beta} \propto t_{\alpha\beta}$$

   12 (?) parameters, more predictive that Seesaw1 for SUSY LFV (A Rossi), leptogen?
4. more singlet neutrinos. For instance, N and ν_R per generation, with " large" Dirac mass $M\overline{N}\nu_R$ and $\ll$ Majorana mass $\mu\nu_R\nu_R \Rightarrow$ light masses

$$m_\nu \sim m_D M^{-1}\mu M^{-1T} m_D^T$$

5. ...

Leptogenesis ... many scenarios

1. produce (thermal production, inflaton decay...) some number density of Ns
2. generate lepton asymmetry of flavour α in the $C\not{P}$, out-of-thermal-equilibrium N_1 interactions, $e.g\ N \to H\ell_\alpha$.
3. non-perturbative SM processes (sphalerons): lepton asymmetry $\to$ baryon asymmetry

Interesting because, if the baryon asymmetry was produced by leptogenesis, and one assumes a production mechanism, then this gives one more observation to constrain the 21 - 7 unknown seesaw parameters.

comment on flavour:

it has little interesting effect on the envelope of parameter space where leptogenesis *can* work. It changes significantly the value of the asymmetry produced at a particular point.

Question instead of Summary (for authors of chapter 3)

What do (scatter) plots of one (not-yet measured) observable as a function of another (not-yet-measured) observable mean?

$e.g.$ a plot of $\Gamma(\mu \to e\gamma)$ vs the $0\nu2\beta$ rate, in the MSUGRA Seesaw, with unspecified scan over unknown parameters.

Two clear cases

1. a (texture) model gives an expected range for all parameters, so a measure on the space of unknown parameters.
   The point density in the scatter plot represents probable predictions of the model
2. one observable is sensitive to the other. Ex: EW precision observables were sensitive to the top mass $\Rightarrow m_t$ from LEP..