New ways to TeV scale leptogenesis

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Outline

1. Motivation
2. The Models
3. Leptogenesis at TeV scale
4. Collider Signatures
5. Summary

Outline

Motivation

'Simplest' way to give neutrino masses: introducing a gauge singlet fermion N

[Minkowski(1977),Yanagida(1979), Gell-Mann et al. (1979), Glashow (1980), Mohapatra and Senjanovic (1981)]

$$\text{Type-I seesaw:} \quad m_\nu \simeq -\lambda M^{-1} \lambda^T \langle H \rangle^2$$

For free: baryogenesis through leptogenesis [Fukugita and Yanagida (1986)]

Conventional type-I leptogenesis requires $M \gtrsim 10^9$ GeV $\implies \lambda \sim 10^{-3}$

[Davidson and Ibarra (2002)]

- Too heavy for production in the collider!

Resonant type-I leptogenesis with $M \sim 10^3$ GeV $\implies \lambda \sim 10^{-6}$ [Pilaftsis (1997)]

- Neutrino Yukawa coupling too small for production in the collider!

Consider a scenario which fulfills:

(i) type-I seesaw at the TeV scale

(ii) leptogenesis at $T \sim O(\text{TeV})$

(iii) testable at the LHC via direct production of N and of *the new scalars*

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The Models

Type-I seesaw

$$-\mathcal{L}_{\text{seesaw}} = \frac{1}{2} M_i \overline{N_i^c} N_i + \epsilon_{ab} \lambda_{\alpha i} \overline{\ell_\alpha^a} N_i \, H^{b*} \; + \; \text{h.c.}$$

2012 would mark the beginning of the discovery of fundamental scalars in nature

+ new scalar $\tilde{\psi}$

$$-\mathcal{L}_{\tilde{\psi}} = \frac{1}{2} M_{\tilde{\psi}}^2 \tilde{\psi}^\dagger \tilde{\psi} + \overline{\psi}_L \cdot \eta \cdot N \, \tilde{\psi} + \sum_{\psi' \, \psi''} \overline{\psi_L'} \cdot y \cdot \psi_R'' \, \tilde{\psi} \; + \; \text{h.c.}$$

Scalar field $\tilde{\psi}$	y-type couplings	B	L	ΔB	ΔL
$\tilde{\ell}$	$\bar{\ell} e \, (\epsilon \tilde{\ell}^*), \;\; \bar{Q} d \, (\epsilon \tilde{\ell}^*), \;\; \bar{Q} u \, \tilde{\ell}$	0	0	0	-1
$\tilde{e}$	$\bar{\ell} (\epsilon \ell^c) \, \tilde{e}$	0	+2	0	$+1$
$\tilde{Q}$	$\bar{\ell} d \, (\epsilon \tilde{Q}^*)$	$+1/3$	-1	0	-1
$\tilde{u}$	$\overline{d^c} d \, \tilde{u}$	$-2/3$	0	-1	0
$\tilde{d}$	$\bar{\ell} (\epsilon Q^c) \, \tilde{d}, \; \overline{Q^c} (\epsilon Q) \, \tilde{d}, \; \bar{u} e^c \, \tilde{d}, \; \overline{u^c} d \, \tilde{d}$	–	–	–	–

Convention: $L(N) = 0$

The Models

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Scalar field $\tilde{\psi}$	y-type couplings	B	L	ΔB	ΔL
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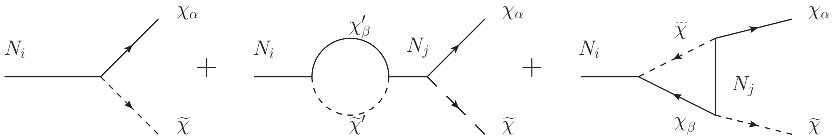
How does a new scalar help?

1. The production of RH neutrino through $\tilde{\psi}$ exchange which, being gauge non-singlets, have sizable couplings to the SM gauge bosons.
2. The new decay channel $N \to \bar{\psi}\tilde{\psi}$ with associated CP violating asymmetry contributions from self energy loops (λ and η), and from vertex corrections (λ).
3. They contribute via new self energy diagrams (λ) to the CP asymmetries in $N \to \bar{\ell}H$ decays.

Since the couplings η are not related to light neutrino masses, they can be sufficiently large to allow for N production with observable rates and for large enhancements of the CP asymmetries.



$\chi^{(\prime)} = \ell_\alpha,\ (\psi_m)$ and $\tilde{\chi}^{(\prime)} = H,\ (\tilde{\psi})$

The Models with $\tilde{\ell}$, $\tilde{u}$ and $\tilde{d}$

1. $\tilde{\ell}$ is a second Higgs. At TeV scale can induce dangerous FCNC at the tree level [Georgi (1979)]. Experimental limits then imply that either $M_{\tilde{\ell}}$ very large, or that its couplings sufficiently small [Branco (2012)] $\Longrightarrow$ a TeV-scale $\tilde{\ell}$ is not favorable.
2. The scalar $\tilde{u}$ can couple to SM fermions in a B and L conserving way with $L(\tilde{u}) = 0$ and $B(\tilde{u}) = -2/3$. The only L-violating term is still $\lambda\,\bar{\ell}NH$ violate L $\Longrightarrow$ doesn't help with leptogenesis. Moreover, $\bar{u}N^c\tilde{u}$ violates B by one unit and gives rise (after EWSB) to dimension 6 operator that induces $p, n \to \pi\nu$: $\frac{1}{M_{\tilde{u}}^2}\sqrt{\frac{m_\nu}{M_N}}\left(\bar{d}^c d\right)\,(\bar{\nu}u)$.

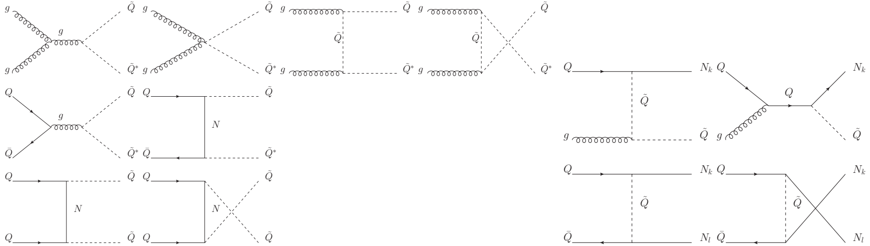
   Taking $m_\nu \sim 10^{-2}$ eV and $M_{\tilde{u}} \sim M_N \sim 1$ TeV we have

   $$\tau_{N\to\pi\nu} \sim 10^{32}\left(\frac{10^{-19}}{y_{dd\tilde{u}}\,\eta_{Nu\tilde{u}}}\right)^2 \text{yrs.}\,.$$

   To satisfy the experimental limits [Beringer (2012)] $\tau_{p,n\to\pi\nu} \lesssim 10^{32}$ yrs. requires extreme suppression of the couplings y and η $\Longrightarrow$ we won't consider this possibility.
3. The scalar $\tilde{d}$ can be coupled in a gauge invariant way both to quark-quark and to quark-leptons bilinears, and thus there is no possible assignment that conserves B and L. Hence it can mediate proton decay via unsuppressed dimension 6 operators $\Longrightarrow$ a TeV scale $\tilde{d}$ must be excluded.

The Models with $\tilde{e}$ and $\tilde{Q}$

1. $\tilde{e}$ is a lepton with $L = +2$
   - No B violation, safe from nucleon decays
   - $\overline{e}_L \cdot \eta \cdot \tilde{e}$ violates L, suitable to enhance the CP asymmetries for leptogenesis
   - Can be produced at the LHC via $q\bar{q} \to \tilde{e}\tilde{e}^*$
   - if $M_{\tilde{e}} > M_1$, can have $\tilde{e} \to e\, N_1$
2. $\tilde{Q}$ is a leptoquark with $L = -1$ and $B = +1/3$
   - No B violation, safe from nucleon decays
   - $\overline{Q}_L \cdot \eta \cdot \tilde{Q}$ violates L, suitable to enhance the CP asymmetries for leptogenesis
   - Can be produced via $gg \to \tilde{Q}\tilde{Q}^*$ and $q\bar{q} \to \tilde{Q}\tilde{Q}^*$ (also $qq \to \tilde{Q}\tilde{Q}$)
   - Can bridge RH neutrino production at the observable level if its η couplings are sufficiently large



TeV-scale $\tilde{Q}$ and $\tilde{e}$ are good candidates.

Outline

Leptogenesis at TeV scale: Sakhavrov's conditions

Sakharov's conditions [Sakharov (1967)]: (i) L violation (ii) C & CP violation (iii) *Out of equilibrium* N_1 *dynamics*: $N_1 \to \ell H, \psi\tilde{\psi}^*$

$$\begin{aligned} \Gamma_1 &\lesssim H(T) \\ \frac{M_1}{16\pi}\left(\kappa_\ell(\lambda^\dagger\lambda)_{11} + \kappa_\psi(\eta^\dagger\eta)_{11}\right) &\lesssim 17\,\frac{T^2}{M_p} \end{aligned}$$

which, at temperatures $T \sim M_1 \sim 1$ TeV, gives

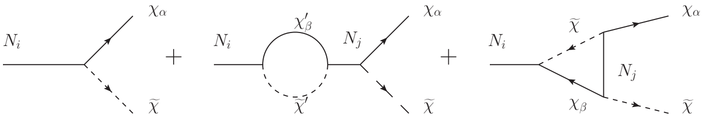
$$\kappa_L(\lambda^\dagger\lambda)_{11} + \kappa_\psi(\eta^\dagger\eta)_{11} \lesssim 7 \cdot 10^{-14}$$

$\longrightarrow$ excludes direct production of N_1 at colliders*

$\longrightarrow$ but direct production of $N_{2,3}$ would be possible with $\eta_{\alpha(2,3)} \gg \eta_{\alpha 1}$

**if* $M_{\tilde{\psi}} > M_1$, *we can have* $\tilde{\psi} \to \psi N_1$

Leptogenesis at TeV scale: CP asymmetry & washout



Assuming $M_j > M_1 > M_{\tilde{\psi}}$, the CP asymmetries in $N_1 \to \psi\tilde{\psi}^*$ decay is

$$\epsilon \sim -\sum_j \frac{\kappa}{16\pi(\eta^\dagger\eta)_{11}} \left|(\eta^\dagger\eta)^2_{1j}\right| (\sin\phi)\frac{M_1}{M_j}, \qquad (\kappa = 7 \text{ for } \tilde{Q} \text{ and } 2 \text{ for } \tilde{e})$$

For example the s-channel washout processes:

$$\mathcal{O}\left(|\eta_{\beta j}|^2 \cdot |\lambda_{\alpha j}|^2\right): \qquad \bar{\psi}_\beta\tilde{\psi} \leftrightarrow \ell_\alpha H\,(\ell_\alpha H)$$

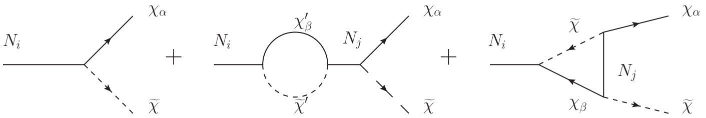
$$\mathcal{O}\left(|\eta_{\alpha j}|^2 \cdot |\eta_{\beta j}|^2\right): \qquad \bar{\psi}_\alpha\tilde{\psi} \leftrightarrow \psi_\beta\tilde{\psi}^*$$

The condition of out of equilibrium reads:

$$\frac{1}{\pi^3}\frac{T^3}{M_j^2}|\xi_{\alpha j}|^2 \cdot |\xi'_{\beta j}|^2 \lesssim 17\frac{T^2}{M_p} \implies |\xi_{\alpha j}| \cdot |\xi'_{\beta j}| \lesssim 1.6 \cdot 10^{-7}\,\frac{M_j}{M_1}\left(\frac{M_1}{1\,\mathrm{TeV}}\right)^{1/2}$$

where ξ and ξ' denote either λ or η.

Leptogenesis at TeV scale: CP asymmetry & washout



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Can we still have $\eta_{\alpha 2(3)}$ large?

Leptogenesis at TeV scale: Subtleties

In fact, $\bar{\psi}_\alpha \tilde{\psi} \leftrightarrow \psi_\beta \tilde{\psi}^*$ in equilibrium $\Longrightarrow \mu_{\tilde{\psi}} = \mu_\psi \Longrightarrow$ No washout!
The reason being $\mu_\psi - \mu_{\tilde{\psi}}$ is precisely the number densities factor that weights the washout rates from the inverse decays $\psi + \tilde{\psi}^* \to N_1$ and $\bar{\psi} + \tilde{\psi} \to N_1$.

However *null* washout is a **killer** for leptogenesis (with vanishing initial N_1 abundance). The reason being the asymmetry generated when $\psi\tilde{\psi}^* \to N_1$ exactly cancels the opposite sign asymmetry when $N_1 \to \psi\tilde{\psi}^*$.

This is easily understood by writing the Boltzmann equations with no washout term:

$$\begin{aligned} \dot{Y}_N &= -(y_N - 1)\,\gamma_{N\psi\tilde{\psi}} \\ \dot{Y}_{\Delta_{B-L}} &= -\epsilon_{\tilde{\psi}}\,(y_N - 1)\,\gamma_{N\psi\tilde{\psi}} \\ &= \epsilon_{\tilde{\psi}}\dot{Y}_N \end{aligned}$$

where $\dot{Y} = (sHz)\,dY/dz$, with s the entropy density and $z = M/T$. After integrating, we obtain at the final time $z_f \gg 1$:

$$Y_{\Delta_{B-L}}(z_f) = \epsilon_{\tilde{\psi}}\,Y_N(z_i)$$

where we have used $Y_N(z_f) = 0$ and assuming no initial asymmetries $Y_{\Delta B-L}(z_i) = 0$.

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\dot{Y}_{\Delta_{B-L}} &= -\epsilon_{\tilde{\psi}}\,(y_N - 1)\,\gamma_{N\psi\tilde{\psi}} + \frac{1}{2} y_{\Delta_{B-L}} \gamma_{N\ell H} \\
&= \epsilon_{\tilde{\psi}} \dot{Y}_N + \frac{1}{2} y_{\Delta_{B-L}} \gamma_{N\ell H}
\end{aligned}$$

where $\dot{Y} = (sHz)\, dY/dz$, with s the entropy density and $z = M/T$. After integrating, we obtain at the final time $z_f \gg 1$:

$$Y_{\Delta_{B-L}}(z_f) = \epsilon_{\tilde{\psi}} \int_{z_i}^{z_f} dz' \, \frac{dY_N}{dz'} \, exp\left[\int_{z'}^{z_f} dz'' g(z'')\,\gamma_{N\ell H}(z'')\right]$$

where we have used $Y_N(z_f) = 0$ and assuming no initial asymmetries $Y_{\Delta B-L}(z_i) = 0$.

But we do have washout from neutrino Yukawa interaction $N_1 \to \ell H$!

Leptogenesis at TeV scale: Summary I

For $M_{\tilde{\psi}} < M_1 < M_{2,3}$, leptogenesis can proceed through

1. $N_1 \to Q\tilde{Q}^*$ creating $Y_{\Delta\tilde{Q}}$ then transfer to $Y_{\Delta\ell}$ through $\tilde{Q}^* \to \ell\bar{d}$
2. $N_1 \to e\tilde{e}^*$ creating $Y_{\Delta\tilde{e}}$ then transfer to $Y_{\Delta\ell}$ through $\tilde{e} \to \ell\ell$

With $\eta_{\alpha 1}, y, \lambda_{\alpha 1} \lesssim 10^{-7}$, $\lambda_{\alpha 2(3)} \lesssim 10^{-6}$, $\eta_{\alpha 2(3)} \sim 0.1$ and $M_1/M_2 = 0.5$, we have

$$\epsilon_{\tilde{Q}} \sim 7 \times 10^{-4}, \qquad \epsilon_{\tilde{e}} \sim 2 \times 10^{-4}$$

$$Y_{\Delta B} \sim 9 \times 10^{-7} \eta_{\rm eff}^{\tilde{Q}}, \qquad Y_{\Delta B} \sim 3 \times 10^{-7} \eta_{\rm eff}^{\tilde{e}}$$

From CMB, we have $Y_{\Delta B}^{\rm CMB} = 8.8 \times 10^{-11}$ [Komatsu et al. (2011)]

$$\Longrightarrow \quad \eta_{\rm eff}^{\tilde{Q}} \gtrsim 9 \times 10^{-5}, \qquad \eta_{\rm eff}^{\tilde{e}} \gtrsim 3 \times 10^{-4}$$

Leptogenesis at TeV scale: Summary II

For $M_1 < M_{\tilde{\psi}} < M_{2,3}$, leptogenesis can proceed through

1. $N_2 \to Q\tilde{Q}^*$ creating $Y_{\Delta\tilde{Q}}$ then transfer to $Y_{\Delta\ell}$ through $\tilde{Q}^* \to \ell\bar{d}$
2. $N_2 \to e\tilde{e}^*$ creating $Y_{\Delta\tilde{e}}$ then transfer to $Y_{\Delta\ell}$ through $\tilde{e} \to \ell\ell$

With $\eta_{\alpha 1(2)}, y, \lambda_{\alpha 1(2)} \lesssim 10^{-7}$, $\lambda_{\alpha 3} \lesssim 10^{-6}$, $\eta_{\alpha 2(3)} \sim 0.1$ and $M_2/M_3 = 0.5$, we have

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$$Y_{\Delta B} \sim 9 \times 10^{-7} \eta_{\rm eff}^{\tilde{Q}} \times {\rm BR}(\tilde{Q}^* \to \ell\bar{d}), \qquad Y_{\Delta B} \sim 3 \times 10^{-7} \eta_{\rm eff}^{\tilde{e}} \times {\rm BR}(\tilde{e} \to \ell\ell)$$

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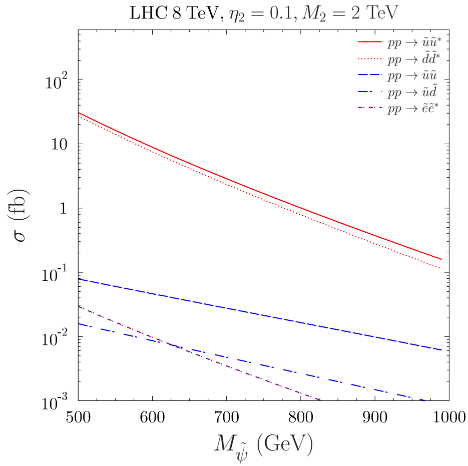
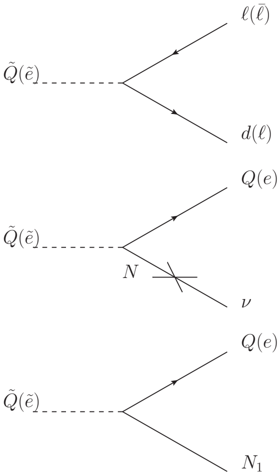
In this case, after $\tilde{Q}$ and $\tilde{e}$ are produced at LHC, we can have $\tilde{Q} \to Q\, N_1$ and $\tilde{e} \to e\, N_1$

Outline

Collider Signatures





Exclude $M_{\tilde{Q}} < 1070(785)$ GeV at 95 % CL at $\sqrt{s} = 8$ TeV and 19.6 fb^{-1} assuming BR$(\tilde{Q} \to \bar{\ell}_\mu d) = 1.0(0.5)$ [CMS collaboration (2013)]

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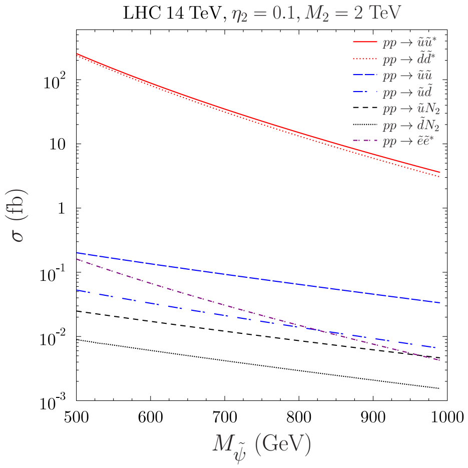

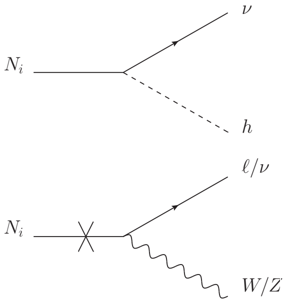

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Summary

Type-I seesaw with the addition of new scalars $\tilde{Q}(3, 2, 1/6)$ and/or $\tilde{e}(1, 1, -1)$ at the TeV scale, we can

- Generate neutrino masses at the TeV scale
- Realize a new way of TeV scale leptogenesis
- Testable at the collider with the production of new scalars and right-handed neutrinos
- Fulfill phenomenological constraints (nucleon decays)

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Thanks for your attention.