New ways to TeV leptogenesis

Eduardo Peinado

INFN – Laboratori Nazionali di Frascati

In collaboration with:
Chee Sheng Fong, M.C. Gonzalez-Garcia and E. Nardi.

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Plan of the talk

1) Motivations

2) Present the possible models

3) How can help to LG

4) Discuss the two viable models

5) Possible signatures in colliders

6) Summary

Motivation

The simplest way to neutrino masses: Type I see-saw

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

$$-\mathcal{L}_{\rm seesaw} = \frac{1}{2} M_i \overline{N}_i N_i^c + \lambda_{\alpha i} \overline{\ell}_\alpha N_i \, \epsilon H^*$$

$$m_\nu \simeq -\lambda M^{-1} \lambda^T \langle H \rangle^2$$

We get for **free**: baryogenesis through leptogenesis [Fukugita and Yanagida (1986)]

Conventional Type-I leptogenesis requires

$$M \gtrsim 10^9 \text{ GeV} \implies \lambda \sim 10^{-3}$$

[Davidson and Ibarra (2002)]

Resonant leptogenesis

$$M \sim 10^3 \text{ GeV} \implies \lambda \sim 10^{-6}$$

[Pilaftsis (1997)]

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*

Possible models

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New scalar that couple to **RH neutrino** and SM fermions $\tilde{\psi}$

$$-\mathcal{L}_{\tilde{\psi}} = \eta_{mi} \bar{\psi}_{Lm} N_i \, \tilde{\psi}$$

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$\psi_L, \, \psi'_L$ (LH) fermion fields $\ell, \, e^c, \, Q, \, d^c, \, u^c$

ψ''_R RH fields $\ell^c, \, e, \, Q^c, \, d, \, u$

Possible models

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$$\tilde{\psi} = \tilde{\ell} \, , \, \tilde{e}, \, \tilde{Q}, \, \tilde{d}, \, \tilde{u}$$

To match the gauge qn of ψ_L

Possible models

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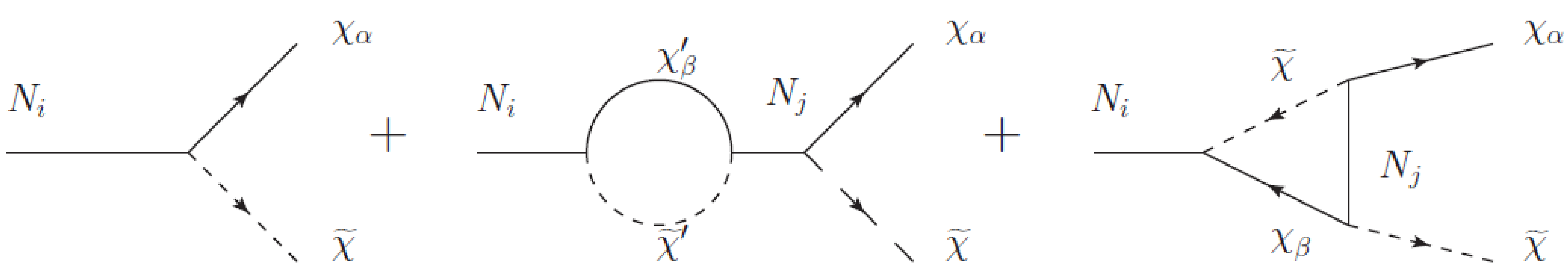
ARE NOT SUPERPARTNERS !!!!!!!

How does it works?

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 $N \to \bar{\tilde{\psi}}\tilde{\psi}$ 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 $\tilde{\chi}^{(\prime)} = H,\ (\tilde{\psi})$

Possible models

$$L(N) = 0$$

Scalar field	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	$+1$
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Like another Higgs

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This two cases are the interesting one (I'll come back later)

Possible models

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$$L(\tilde{u}) = 0 \text{ and } B(\tilde{u}) = -2/3$$

$\bar{u} N^c \tilde{u}$ $\quad$ L conserving

$\lambda\,\bar{\ell} N H$ violate L $\quad$ $\lambda \to 0$ $\quad$ L conserving

$$\frac{1}{M_{\tilde{u}}^2} \sqrt{\frac{m_\nu}{M_N}}\,(\bar{d}^c d)\ (\bar{\nu} u) \qquad \tau_{N \to \pi \nu} \sim 10^{32} \left(\frac{10^{-19}}{y_{dd\tilde{u}}\,\eta_{Nu\tilde{u}}} \right)^2 \text{yrs}$$

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Fast proton decay

Viable TeV leptogenesis

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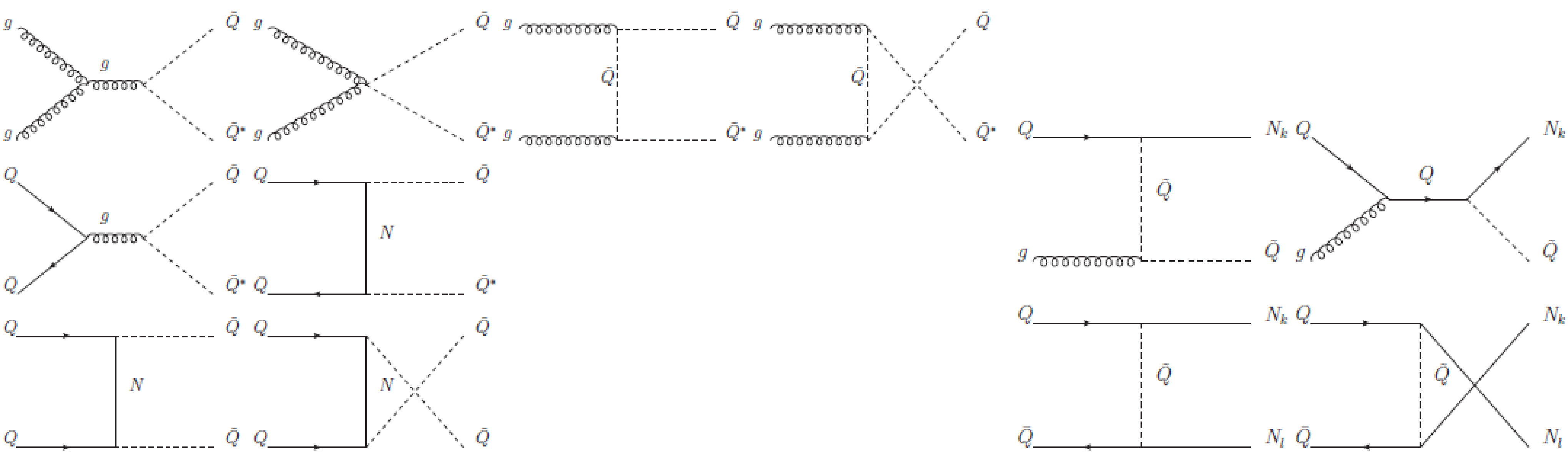

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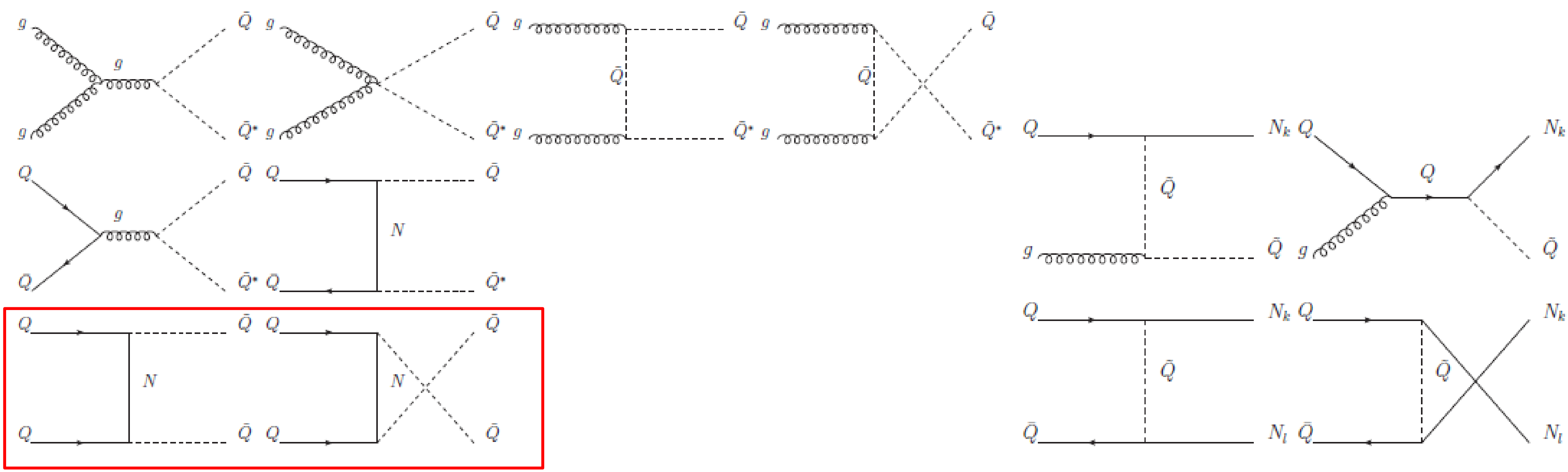


TeV leptogenesis: Sakharov conditions

Sakharov's conditions [Sakharov (1967)]: (i) L violation (ii) C & CP violation

TeV leptogenesis: Sakharov conditions

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

$$\Gamma_1 \lesssim H(T)$$

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

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

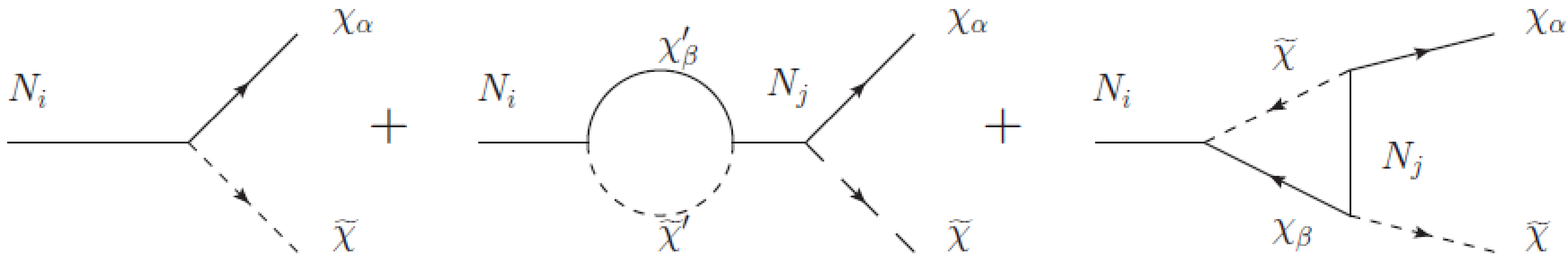
$$\kappa_L(\lambda^\dagger\lambda)_{11} + \kappa_\psi(\eta^\dagger\eta)_{11} \lesssim 7 \cdot 10^{-14}$$

excludes direct production of N_1 at colliders

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* $\tilde{\psi} \to \psi N_1$

TeV leptogenesis: CP asymmetry



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

$$\epsilon^S_{1\chi} = \frac{\kappa_\chi}{16\pi D_1} \sum_{j\neq 1} \sum_{\chi'} \kappa_{\chi'} \,\mathrm{Im}\left[\left(\xi^\dagger_{\chi'}\xi_{\chi'}\right)_{1j}\left(\xi^\dagger_{\chi}\xi_{\chi}\right)_{1j}\right] f^S\left(\frac{M_j^2}{M_1^2}\right),$$

$$\epsilon^V_{1\chi} = \frac{\kappa_\chi}{8\pi D_1} \sum_{j\neq 1} \mathrm{Im}\left[\xi^\dagger_{\chi}\xi_{\chi}\right]^2_{1j} f^V\left(\frac{M_j^2}{M_1^2}\right),$$

$$\chi, \chi' = \{\ell, \psi\}$$

$$\xi_\chi, \xi_{\chi'} = \{\lambda, \eta\}$$

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.

The order of magnitude of couplings

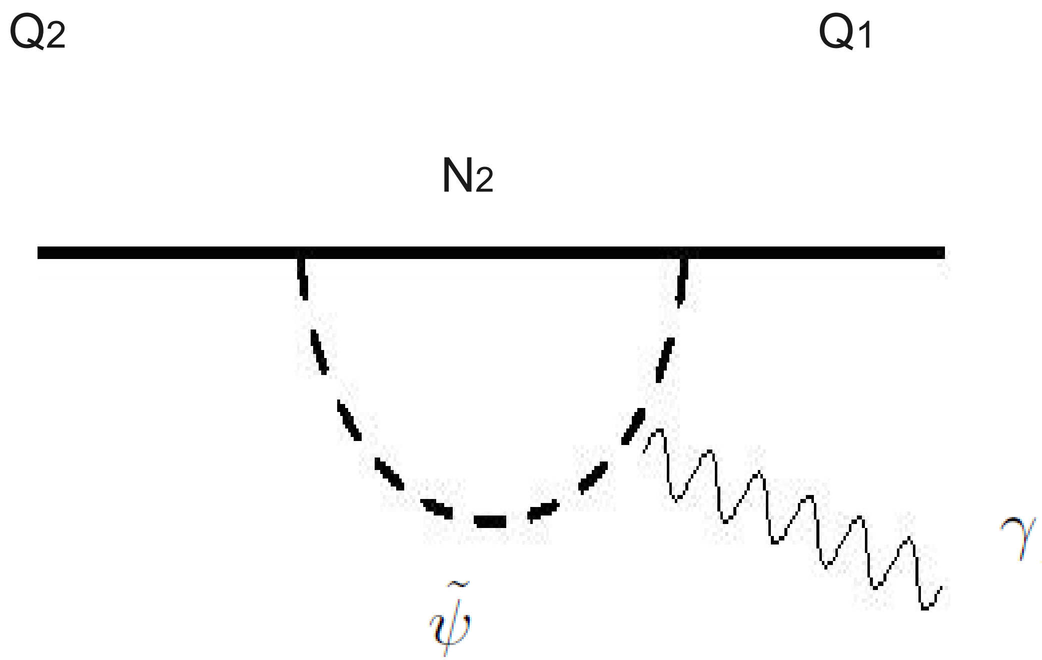
$$\lambda_{\alpha i}\bar{\ell}_\alpha N_i \,\epsilon H^* \qquad \eta_{mi}\bar{\psi}_{Lm}N_i\,\tilde{\psi} \qquad y_{mn}\bar{\psi}'_{Lm}\psi''_{Rn}\,\tilde{\psi}$$

$$|\lambda_{\alpha 1}|,\ |\eta_{m1}|,\ |y| \lesssim 10^{-7}$$

$$|\lambda_{\alpha 2}|,\ |\lambda_{\alpha 3}| \lesssim 10^{-6}$$

$$|\eta_{m2}|,\ |\eta_{m3}| \sim 10^{-1}$$

FCNC constraints



$$s \to d\gamma$$

$$\mu \to e\gamma$$

$$|\eta_{m2}|,\ |\eta_{m3}| \sim 10^{-1}$$

FCNC constraints

1. $\tilde{\psi} = \tilde{Q}$: Through a loop involving N and $\tilde{Q}$

$$s \to d\gamma$$

$$\mathrm{Br}(K^+ \to \pi^+\gamma) = \tau_K \frac{\alpha|\eta_{2j}\eta^*_{1j}|^2}{(8\pi)^4} \frac{m_K^5}{M_{\tilde{Q}}^4} f\left(\frac{M_j^2}{M_{\tilde{Q}}^2}\right) \sim 4.3 \times 10^{-7} \, |\eta_{2j}\eta^*_{1j}|^2$$

$\mathrm{Br}(K^+ \to \pi^+\gamma) < 2.9 \times 10^{-9}$ $\qquad$ $\sqrt{|\eta_{2j}\eta^*_{1j}|} \lesssim 0.29$

2. $\tilde{\psi} = \tilde{e}$ $\qquad$ $\mathrm{Br}(\mu^+ \to e^+\gamma) = \tau_\mu \frac{\alpha|\eta_{2j}\eta^*_{1j}|^2}{(8\pi)^4} \frac{m_\mu^5}{M_{\tilde{e}}^4} f\left(\frac{M_j^2}{M_{\tilde{e}}^2}\right) \sim 2.5 \times 10^{-8} \, |\eta_{2j}\eta^*_{1j}|^2$

$\mathrm{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ $\qquad$ $\sqrt{|\eta_{2j}\eta^*_{1j}|} \lesssim 0.07$

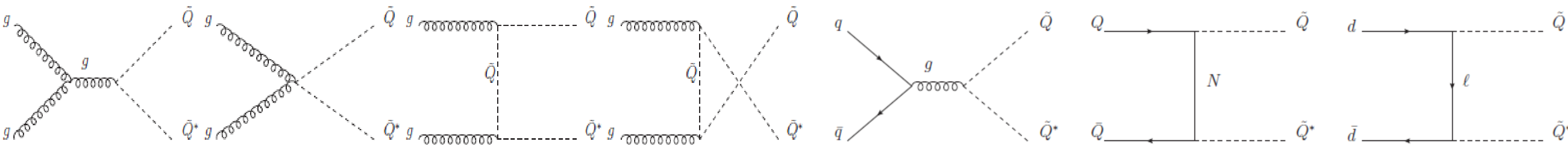
Production

$pp \to \tilde{e}\tilde{e}^*$ mediated by a photon or a Z boson

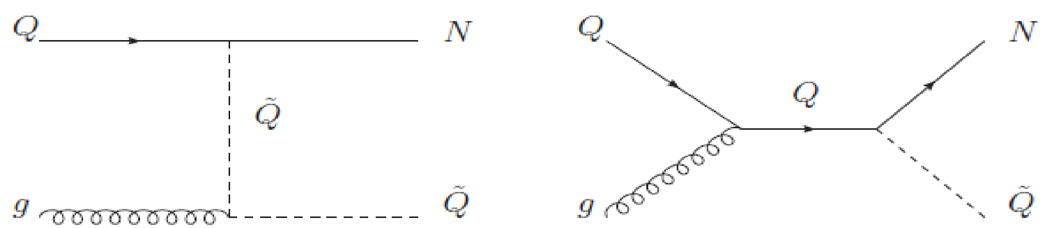
Production

The scalar leptoquark $\tilde{Q}$

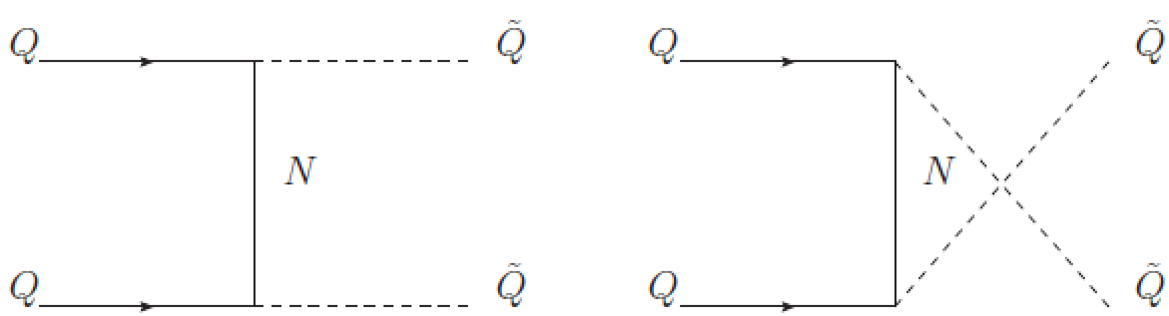
$pp \to \tilde{Q}\tilde{Q}$



single N production via quark-gluon coannihilation



L-violating production $QQ \to \tilde{Q}\tilde{Q}$



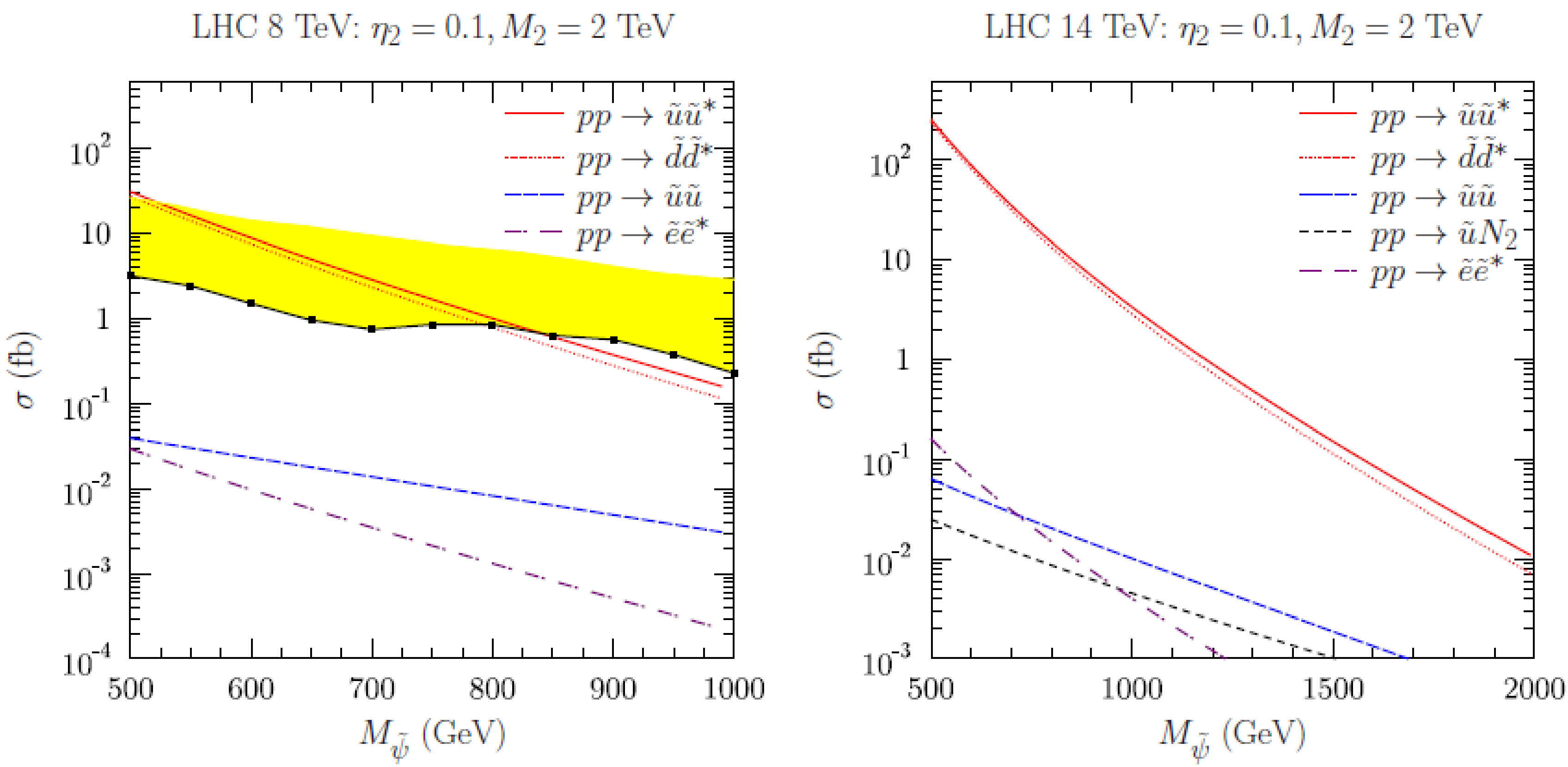


Figure 6. Production cross section for leptoquarks and scalar leptons at LHC8 (left) and LHC14(right). The line with black squares in the left panel gives the CMS 95% CL exclusion limits (with 19.6 fb^{-1} [41]) for leptoquark searches through the process $pp \to \tilde{Q}\tilde{Q}^* \to \mu\mu jj$ assuming leptoquarks decay with 100% branching fraction to muon+jet. The yellow band shows our estimated sensitivity for leptoquarks decaying 100% into third generation fermions $pp \to \tilde{Q}\tilde{Q}^* \to \tau\tau bb$

Summary

- Type I see-saw with new scalars

$$\tilde{Q}(3, 2, 1/6) \quad \text{and/or} \quad \tilde{e}(1, 1, -1)$$

- Generate neutrino masses
- Realize a new way to TeV scale Leptogenesis
- Possibility to detect at colliders*

Thanks for your attention

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 $Y_{\Delta B-L}(z_i) = 0$.

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