New processes at LHC and n-$\bar{\mathrm{n}}$ Oscillations

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The goal is to generate n-$\bar{\mathrm{n}}$ oscillation operator

$$\mathbf{u^c\, d^c\, d^c\, u^c\, d^c\, d^c}$$

integration out TeV scale vector like particles.

d=5 proton decay operators

$$\mathbf{qq q}\ell,\ \mathbf{u^c d^c u^c e^c}$$

Symmetry to forbid $\Delta B = 1$ nucleon decay operators

$$\mathbf{qu^cH_u + qd^cH_d + \ell e^cH_d + \ell\nu^cH_u + \mu H_uH_d + M_p\left(\frac{S}{M_p}\right)^m \nu^c\nu^c}$$

Since there are 9 fields and 6 terms, there are 3 independent U(1) symmetries in the superpotential. The three symmetries correspond to the hypercharge U(1)$_Y$, baryon and lepton number symmetries. The S field carries lepton number $\mathbf{2/m}$.

Suppose that we allow a non-renormalizable term $\mathbf{S^n(u^cd^cd^c)^2}$.

	q	u^c	d^c	ℓ	e^c	ν^c	h_u	h_d	S
$-(\mathbf{n}B+\mathbf{m}L)/2$	$-\frac{n}{6}$	$\frac{n}{6}$	$\frac{n}{6}$	$-\frac{m}{2}$	$\frac{m}{2}$	$\frac{m}{2}$	0	0	-1

With $\mathbf{n}$ odd and $\mathbf{m}$ even, all $\Delta B = \pm 1$ operators are forbidden. $\mathbf{n = -1}$ and $\mathbf{m = 1}$ corresponds to the $B - L$ symmetry .

Vector-like matter and $\Delta B = 2$ operators

The operator $u^c\, d^c\, d^c\, u^c\, d^c\, d^c$ induces $\Delta B = \pm 2$, $\Delta L = 0$ transitions and contributes to $\mathrm{n} - \overline{\mathrm{n}}$ oscillations.The coupling strength scales as $G_{\Delta B = 2} \sim \frac{1}{M_*^5}$.

From the perturbativity and unification condition we have:
(I) **up to 4 pairs of $(\mathbf{5} + \bar{\mathbf{5}})$'s,**
(II) **one pair of $(\mathbf{10} + \overline{\mathbf{10}})$**
(III) **the combination, $(\mathbf{5} + \bar{\mathbf{5}} + \mathbf{10} + \overline{\mathbf{10}})$.**

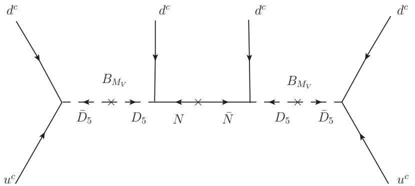
MSSM $+ 5 + \overline{5}$ and $\mathrm{n} - \overline{\mathrm{n}}$ Oscillation

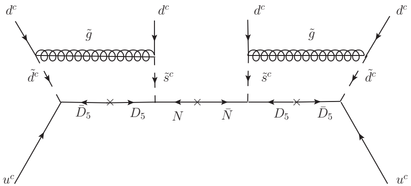
$$\mathbf{5}+\overline{\mathbf{5}} = L_5\left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)+\overline{L}_5\left(\mathbf{1}, \mathbf{2}, \frac{1}{2}\right)+\overline{D}_5\left(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3}\right)+D_5\left(\mathbf{3}, \mathbf{1}, -\frac{1}{3}\right).$$

To generate the effective $\mathrm{n} - \overline{\mathrm{n}}$ oscillation operator we need have to an additional MSSM singlet field (N, $\overline{N}$)

$$\begin{aligned} \mathbf{W} &= \kappa_1 qqD_5 + \kappa_2 u^c d^c \overline{D}_5 + \kappa_3 D_5 d^c N + \kappa_4 D_5 d^c \overline{N} \\ &+ \frac{1}{2} M_N NN + M_V \left(\overline{D}_5 D_5 + \overline{L}_5 L_5 + N\overline{N}\right), \end{aligned}$$

Note that the couplings $\mathbf{D_5 d^c \nu^c}$, $\mathbf{D_5 u^c e^c}$, and $\mathbf{\overline{D}_5 q \ell}$ are forbidden when $\mathbf{n + m}$ is odd by the $-(\mathbf{nB + mL})/2$ symmetry, while $\mathbf{u^c d^c \overline{D}_5}$, $\mathbf{qqD_5}$ couplings are allowed.





The contribution to the $\mathbf{n}-\overline{\mathbf{n}}$ oscillations are:

$$G_{\mathbf{n}-\overline{\mathbf{n}}} \sim \frac{\kappa^4}{M_V}\left(\frac{B_{M_V}}{(M_V^2+m_0^2)^2 - B_{M_V}^2}\right)^2$$

$$G_{\mathbf{n}-\overline{\mathbf{n}}} \sim (\alpha_s/4\pi)^2\kappa^4/(m_{SUSY}^2 M_V^3)$$

$$\tau_{n-\bar{n}} \geqslant 0.86 \times 10^8 s \quad \Rightarrow \quad G_{\mathbf{n}-\overline{\mathbf{n}}} \leqslant 3 \times 10^{-28} \ \textbf{GeV}^{-5}$$

$$M_V^5 G_{\mathbf{n}-\overline{\mathbf{n}}} \leqslant \left(\frac{M_V}{1 \ \mathrm{TeV}}\right)^5 \times 3 \times 10^{-13} \quad \Rightarrow \quad \kappa_i \sim 10^{-3} - 10^{-4}$$

We can understand the strengths of these couplings through the Froggatt–Nielsen mechanism.

$\Delta B = \Delta L = 2$ operators

The $\Delta B = \Delta L = 2$ operators (typically $(qqq\ell)^2$) are responsible for $\mathrm{H} - \overline{\mathrm{H}}$ (hydrogen-anti hydrogen) oscillations, and double nucleon decays (e.g. $pp \to e^+e^+$) $\tau_{pp} \gtrsim 10^{30}$ years. This is interpreted as $\tau_{\mathbf{H}-\overline{\mathbf{H}}} > 10^{17}$ years.

If there are vector-like matter fields $\mathbf{5} + \overline{\mathbf{5}} + \mathbf{10} + \overline{\mathbf{10}}$, it is possible to generate $\Delta B = \Delta L = 2$ operators.

Anomalous $U(1)_A$ Flavor Symmetry and $\mathrm{n}-\overline{\mathrm{n}}$ Oscillations

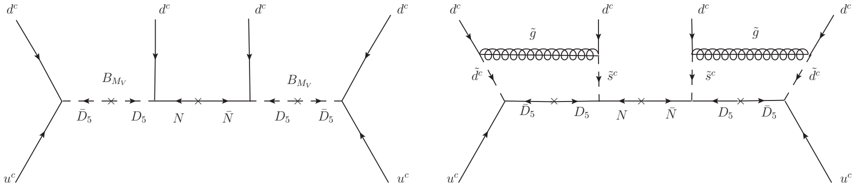
q_i	u_i^c	d_i^c	ℓ_i	e_i^c	ν_i^c	h_u	h_d
$-\frac{n}{6}+n_i^q$	$\frac{n}{6}+n_i^u$	$\frac{n}{6}+n_i^d$	$-\frac{m}{2}+n_i^\ell$	$\frac{m}{2}+n_i^e$	$\frac{m}{2}+n_i^\nu$	**0**	**0**

$$n_i^q=(4-\alpha,2,0),\ n_i^u=(4-\alpha,2,0),\ n_i^d=(2,1,1),$$
$$n_i^\ell=(2,1,1),\ n_i^e=(4-\alpha,2,0),\ n_i^\nu=(\gamma+1,\gamma,\gamma),$$

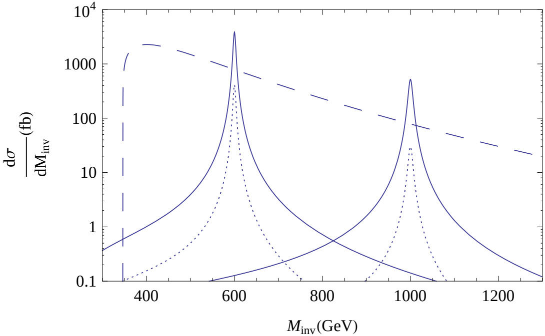
where α is 0 or 1.

$$\frac{1}{M_V^5}\left(\frac{S}{M_{st}}\right)^{n+16-2\alpha} u^c d^c d^c u^c d^c d^c$$

Implications for LHC

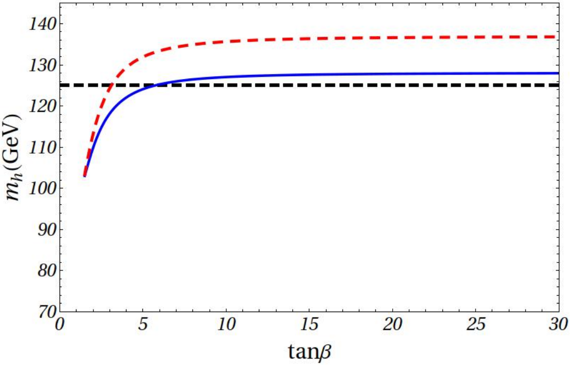


$$W = \left(\frac{S}{M_{st}}\right)^{n_i^q + n_j^q + \frac{X_D}{2}} D_5 q_i q_j + \left(\frac{S}{M_{st}}\right)^{n_i^u + n_j^d - \frac{X_D}{2}} \overline{D}_5 u_i^c d_j^c.$$



The differential cross sections for tb (solid line), $\bar{t}\bar{b}$ (dotted line) production versus the invariant mass of the final states. The left peak corresponds to $M_D = 600$ GeV and the right one to $M_D = 1$ TeV. The dashed line is the standard model $t\bar{t}$ background. Here $\kappa = 0.3$

Higgs mass and low scale vector like matter



Blue line - the MSSM with $M_S = 2$ TeV and $A_t = \sqrt{6}M_S$ and red line corresponds – MSSM + $(10 + \overline{10})$ with $M_S = 200$ GeV and M_V=1 TeV

see, K. S. Babu, I.G., M. U. Rehman, Q. Shafi, Phys. Rev. D78, 055017 (2008)

Summary

- We explore extensions of the MSSM in which TeV scale vector-like multiplets can mediate observable $\mathrm{n} - \overline{\mathrm{n}}$ oscillations.
- In this scenario we can have vector-like diquark with mass around a TeV scale.
- For plausible values of the diquark-quark-quark couplings can be produced at the LHC and detected through its decay into a top quark and a jet.