Leptoquarks, Baryon number violation and Pati Salam symmetry

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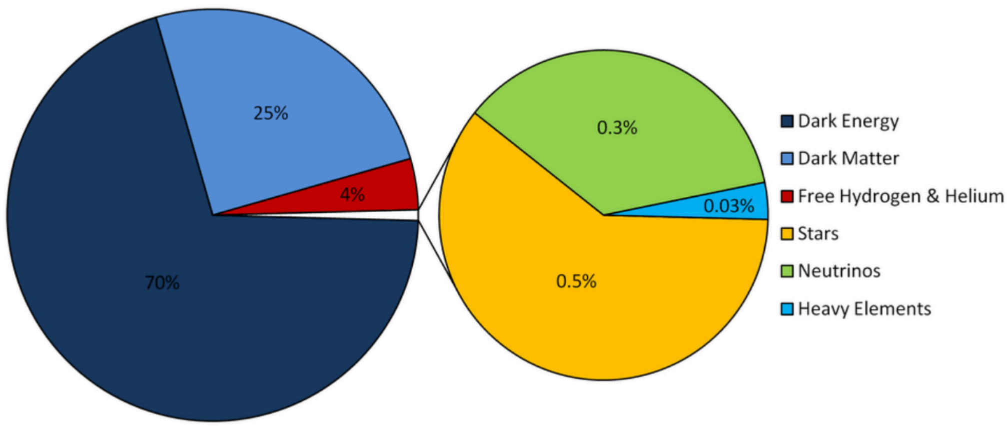
The Standard Model

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Lorentz
$Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \end{pmatrix}$	3	2	1/6	(1/2,0)
u_R^i	3	1	2/3	(0,1/2)
d_R^i	3	1	-1/3	(0, 1/2)
$L_L^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$	1	2	-1/2	(1/2,0)
e_R^i	1	1	-1	(0,1/2)
$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$	1	2	1/2	(0,0)

SM effective theory Neutrino Masses

$$\frac{(L\epsilon H)(L\epsilon H)}{\Lambda} \qquad m_\nu \sim \frac{v_H^2}{\Lambda} \qquad m_\nu \sim 10^{-1}\mathrm{ev}, \quad \Lambda \sim 10^{14}\mathrm{GeV}$$



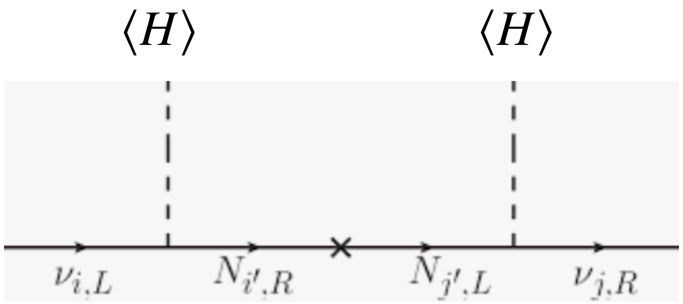
SM no dark matter candidate

Baryon number violation in SM effective theory

$$\frac{\epsilon_{\alpha\beta\gamma}(u_{\alpha R}\epsilon d_{\beta R})(u_{R\gamma}\epsilon e_R)}{\Lambda^2}, \ldots \qquad p \to e^+\pi^0 \qquad \tau_p > 10^{33} yr \qquad \Lambda > 10^{15}\mathrm{GeV}$$

SM effective theory provides an explanation of conservation of baryon number provided no new physics up to scale Λ

Type I See Saw



$$m_\nu \sim Y_\nu^2 \frac{v_H^2}{m_N}$$

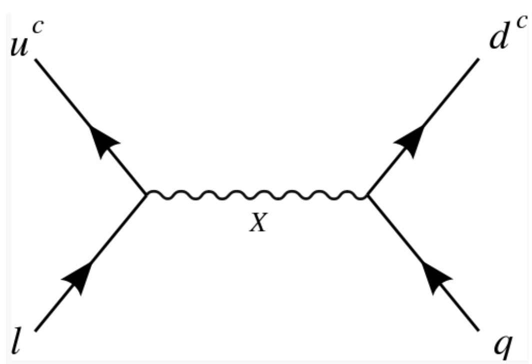
SU(5) of Georgi and Glashow

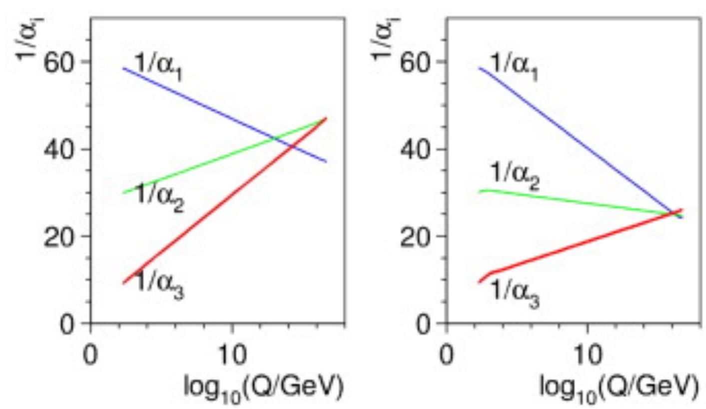
$$\bar{5}_\alpha \sim (\bar{3},1,1/3)_{SM},\ \bar{5}_j \sim (1,2,-1/2)_{SM}$$

$$\bar{\mathbf{5}}_F = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e \\ -\nu \end{pmatrix} \qquad \mathbf{10}_F = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e_R \\ -d_1 & -d_2 & -d_3 & -e_R & 0 \end{pmatrix}$$

$$10_{\alpha\beta} \sim (\bar{3},1,-2/3) \quad 10_{\alpha j} \sim (3,2,1/6)_{SM}$$

$$10_{ij} \sim (1,1,1)_{SM} \quad \text{(Note in figure replace } e_R \to e^c\text{)}$$





$$R_{K^{(*)}} = \frac{Br(B \to K^{(*)}\mu\mu)}{Br(B \to K^{(*)}ee)}$$ =1 in SM. Measured less than 1. Significance ~ 3-4 sigma

Introduction

Pati Salam gauge theory, color SU(3) goes to SU(4).

Theory that unifies quarks and leptons, lepton number is the fourth color.

Beautiful idea.

Not as attractive as SU(5) grand unification but nature may choose it.

Minimal gauge group SU(4)XSU(2)XU(1) contains leptoquarks scalar and vectors

Discuss baryon number violation in Pati Salam gauge theory treating it as an effective theory.

In Standard model (SM) effective theory leptoquark scalars give rise to unacceptably large baryon number violation by dimension 4 and/or 5 operators.

Not necessarily in Pati Salam extension of SM.

Talk motivated somewhat by B decay anomaly:

$$R_{K^{(*)}} = \frac{Br(B \to K^{(*)}\mu\mu)}{Br(B \to K^{(*)}ee)}$$

Some References

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Complete list of references in paper with Clara Murgui

Leptoquarks in the SM effective field theory

$(\mathrm{SU}(3), \mathrm{SU}(2)_L, \mathrm{U}(1)_Y)_{SM}$	Renormalizable interactions	Type	B violation
$(3,3,-1/3)_{SM}$	$X_A^\alpha(Q_L^\beta \tau^A Q_L^\gamma)\epsilon_{\alpha\beta\gamma}(\mathrm{A})$, $X_A^\alpha((Q_L^\dagger)_\alpha \tau^A L_L^\dagger)$	M	dim 4
$(3,1,-4/3)_{SM}$	$X^\alpha((d_R^\dagger)_\alpha e_R^\dagger)$, $X^\alpha(u_R^\beta u_R^\gamma)\epsilon_{\alpha\beta\gamma}$ (A)	M	dim 4
$(3,1,-1/3)_{SM}$	$X^\alpha(Q_L^\beta Q_L^\gamma)\epsilon_{\alpha\beta\gamma}(\mathrm{S})$, $X^\alpha((Q_L^\dagger)_\alpha L_L^\dagger)$, $X^\alpha(u_R^\beta d_R^\gamma)\epsilon_{\alpha\beta\gamma}$, $X^\alpha((u_R^\dagger)_\alpha e_R^\dagger)$	M	dim 4
$(3,2,7/6)_{SM}$	$X^\alpha((Q_L^\dagger)_\alpha e_R)$, $X^\alpha(L_L(u_R^\dagger)_\alpha)$	LQ	dim 5
$(3,2,1/6)_{SM}$	$X^\alpha(L_L(d_R^\dagger)_\alpha)$	LQ	dim 5
$(3,1,2/3)_{SM}$	$X^\alpha(d_R^\beta d_R^\gamma)\epsilon_{\alpha\beta\gamma}(\mathrm{A})$	DQ	dim 5
$(\bar{6},3,-1/3)_{SM}$	$X_{\alpha\beta}^A(Q_L^\alpha \tau_A Q_L^\beta)$ (S)	DQ	dim 5
$(\bar{6},1,-1/3)_{SM}$	$X_{\alpha\beta}(u_R^\alpha d_R^\beta)$, $X_{\alpha\beta}(Q_L^\alpha Q_L^\beta)$ (A)	DQ	dim 5
$(\bar{6},1,2/3)_{SM}$	$X_{\alpha\beta}(d_R^\alpha d_R^\beta)$ (S)	DQ	dim 5
$(\bar{6},1,-4/3)_{SM}$	$X_{\alpha\beta}(u_R^\alpha u_R^\beta)$ (S)	DQ	$>$ dim 6

Flavor indices and epsilon's contracting SU(2) and Lorentz indices are suppressed above

Mixed scalars violate baryon number at tree level at dim 4 from couplings above

Pure leptoquarks dim 4 couplings above don't violate baryon number.   But at dimension 5

$$\Phi_3 \sim (\bar{3},2,-1/6)_{SM}, \Phi_4 \sim (3,2,7/6)_{SM}$$

$$\frac{\epsilon_{\alpha\beta\gamma}}{\Lambda}(d_R^\alpha u_R^\beta)(\Phi_3^\dagger)^\gamma H^\dagger, \quad \frac{\epsilon_{\alpha\beta\gamma}}{\Lambda}(Q_L^\alpha Q_L^\beta)(\Phi_3^\dagger)^\gamma H^\dagger, \quad \frac{\epsilon_{\alpha\beta\gamma}}{\Lambda}(d_R^\alpha d_R^\beta)(\Phi_3^\dagger)^\gamma H, \quad \frac{\epsilon_{\alpha\beta\gamma}}{\Lambda}(d_R^\alpha d_R^\beta)\Phi_4^\gamma H^\dagger$$

No renormalizable baryon number from Φ_3 scalar $\epsilon_{\alpha\beta\gamma}\epsilon_{ij}\Phi_3^{\dagger\alpha i}\Phi_3^{\dagger\beta j}\Phi_3^{\dagger\gamma k}H_k^\dagger = 0$

Expanding contractions at least two Φ_3 with same

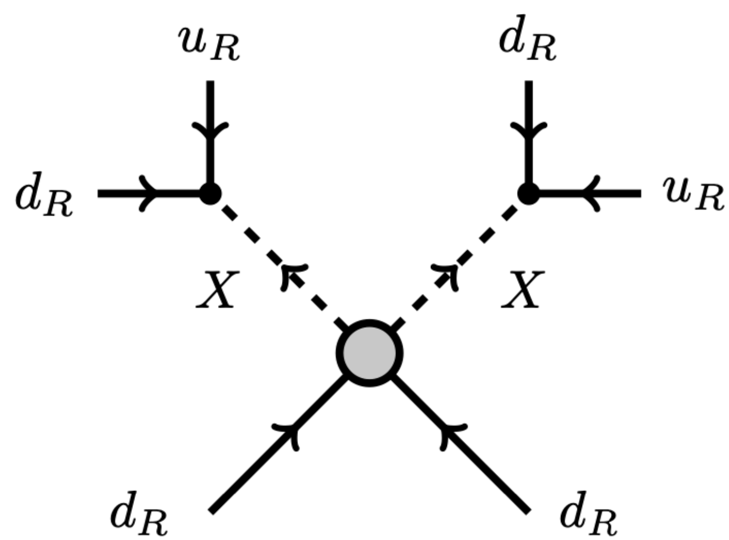
SU(2) indices and then zero because of antisymmetry on color indices.

Lets briefly consider one of the diquarks that is a color six $X \sim (\bar{6},1,-1/3)_{SM}$

From previous slide renormalizable tree level diquark couplings $X_{\alpha\beta}(u_R^\alpha d_R^\beta)$, $X_{\alpha\beta}(Q_L^\alpha Q_L^\beta)$

Get baryon number violation by combining with dim 5 operator

$$\frac{1}{\Lambda}(X^\dagger)^{\alpha\alpha'}(X^\dagger)^{\beta\beta'}(d_R^\gamma d_R^{\gamma'})\epsilon_{\alpha\beta\gamma}\epsilon_{\alpha'\beta'\gamma'}$$



$$\Delta B = 2$$

Experimental limit from neutron anti neutron oscillations implies that

$$M_X > 300\text{GeV}\left(\frac{M_{PL}}{\Lambda}\right)^{(1/4)}$$

Pati Salam

Gauge group $SU(4) \times SU(2) \times U(1)_R$

Fermions in representations $F_d = (d_R^1, d_R^2, d_R^3, e_R) \sim (4,1,-1/2)_{PS}$ $F_u = (u_R^1, u_R^2, u_R^3, \nu_R) \sim (4,1,1/2)_{PS}$

$F_{QL} = (Q_L^1, Q_L^2, Q_L^3, L_L) \sim (4,2,0)_{PS}$ **Just SM fermions plus right handed neutrinos**

Discuss two ways to break $SU(4) \times U(1)_R \to SU(3) \times U(1)_Y$

VeV of $\chi \sim (4,1,1/2)_{PS}$ $\langle \chi^A \rangle = \delta^{A4} v_\chi / \sqrt{2}$ **VeV of** $\Delta \sim (\overline{10},1,-1)_{PS}$ $\langle \Delta_{AB} \rangle = \delta_{A4}\delta_{B4} v_\Delta / \sqrt{2}$

SM Hypercharge $Y = R + \frac{\sqrt{6}}{3} T_4,$ $\frac{\sqrt{6}}{3} T_4 = \mathrm{diag}(1/6,1/6,1/6,-1/2)$

Two more scalar representations to give mass to Fermions and break SM gauge group

$H \sim (1,2,1/2)_{PS}$ $\Phi_{15} = \begin{pmatrix} \Phi_8 & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + H_2 T_4 \sim (15,2,1/2)_{PS}$

$\langle H^j \rangle = \delta^{j2} v_H / \sqrt{2}$ $\langle H_2^j \rangle = \delta^{j2} v_\Phi / \sqrt{2}$

$\Phi_8 \sim (8,2,1/2)_{SM},$ $\Phi_3 \sim (\bar{3},2,-1/6)_{SM}$ $\Phi_4 \sim (3,2,7/6)_{SM}$

$1/2 = 1/2 + 0,$ $-1/6 = 1/2 - 1/6 - 1/2,$ $7/6 = 1/2 + 1/6 + 1/2$

$$-\mathcal{L} = Y_1 H (F_{QL}^A (F_u^\dagger)_A) + Y_2 (\Phi_{15})_A^B (F_{QL}^A (F_u^\dagger)_B) + Y_3 H^\dagger (F_{QL}^A (F_d^\dagger)_A) + Y_4 (\Phi_{15}^\dagger)_A^B (F_{QL}^A (F_d^\dagger)_B)$$

$$M_u = Y_1 \frac{v_H}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_2 \frac{v_\Phi}{\sqrt{2}}, \qquad M_d = Y_3 \frac{v_H}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_4 \frac{v_\Phi}{\sqrt{2}};$$

$$M_\nu^{\text{Dirac}} = Y_1 \frac{v_H}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_2 \frac{v_\Phi}{\sqrt{2}}, \qquad M_e = Y_3 \frac{v_H}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_4 \frac{v_\Phi}{\sqrt{2}};$$

Treat Pati Salam as an effective theory.
As in SM dimension six sermonic operators that cause proton decay

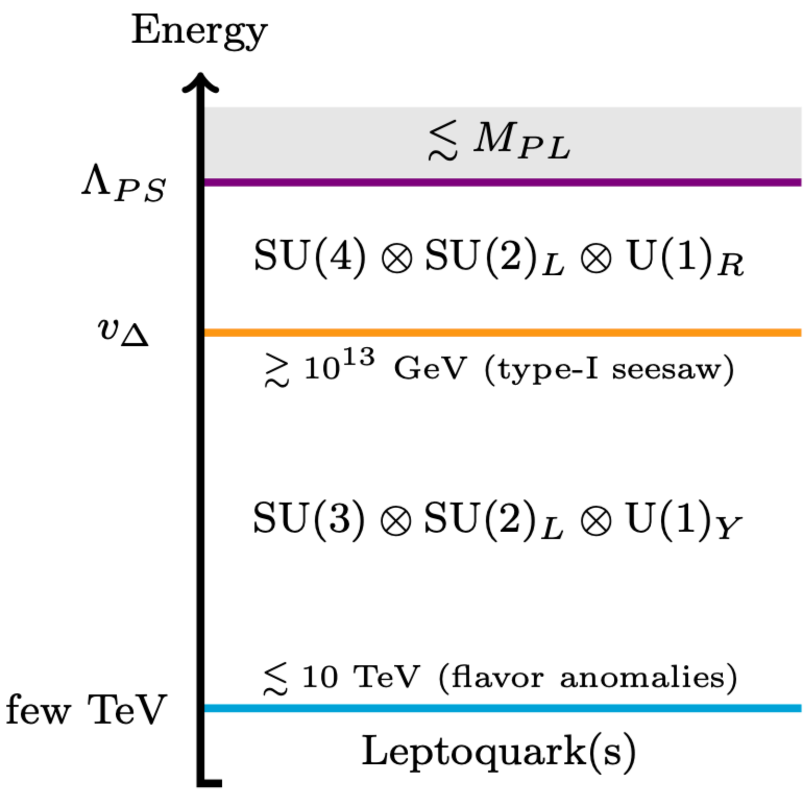
$$\frac{1}{\Lambda_{PS}^2} \epsilon_{ABCD} (F_{QL}^A F_{QL}^B)(F_{QL}^C F_{QL}^D), \quad \frac{1}{\Lambda_{PS}^2} \epsilon_{ABCD} (F_u^A F_d^B)(F_u^C F_d^D) + \ldots,$$

$$\Lambda_{PS} > 10^{15} \text{GeV}$$

What about the leptoquarks

$$-\mathcal{L} \supset Y_2 (Q_L^\alpha \nu_R^\dagger) \Phi_{3\alpha} + Y_2 (L_L (u_R^\dagger)_\alpha) \Phi_4^\alpha + Y_4 (Q_L^\alpha e_R^\dagger)(\Phi_4^\dagger)_\alpha + Y_4 (L_L (d_R^\dagger)_\alpha)(\Phi_3^\dagger)^\alpha + \text{h.c.}$$

High-scale Pati-Salam breaking (Δ)



$$Y_\nu F_u^A F_u^B \Delta_{AB} \to Y_\nu \nu_R \nu_R v_\Delta / \sqrt{2}$$

What about dimension 5 SM baryon number violation.
Comes from dimension 6. For example,

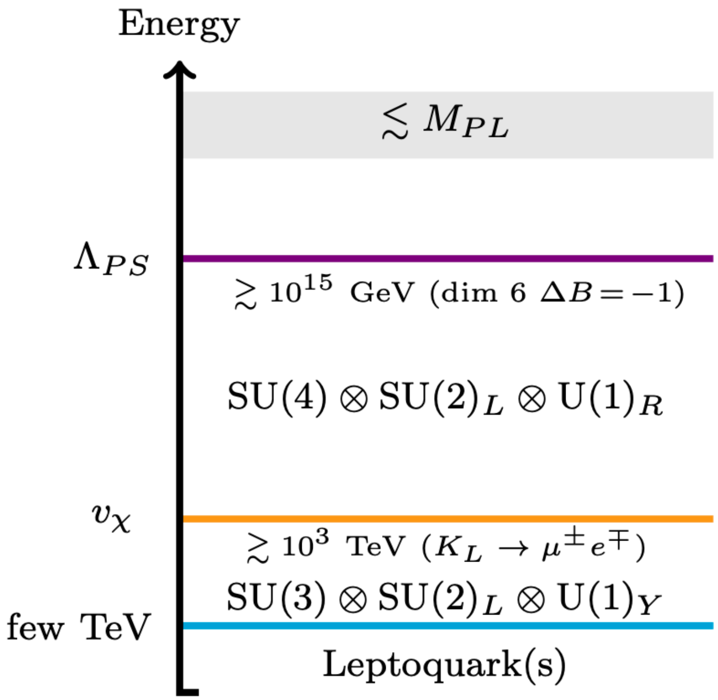
$$\frac{1}{\Lambda_{PS}^2}(F_u^A F_d^B)(\Phi_{15}^\dagger)_E^C \; H^\dagger (\Delta^\dagger)^{ED} \epsilon_{ABCD} \quad \overset{\langle\Delta\rangle}{\to} \quad \frac{v_\Delta}{\sqrt{2}\Lambda_{PS}^2}(u_R^\alpha d_R^\beta)(\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}$$

$$\frac{1}{\Lambda_{PS}^2}(F_u^E F_d^B)(\Phi_{15}^\dagger)_E^A (\Phi_{15}^\dagger)_F^C (\Delta^\dagger)^{FD} \epsilon_{ABCD} \quad \overset{\langle\Delta\rangle}{\to} \quad \frac{v_\Delta}{\sqrt{2}\Lambda_{PS}^2}(u_R^\alpha d_R^\beta)(\Phi_3^\dagger)^\gamma H_2^\dagger \epsilon_{\alpha\beta\gamma}.$$

Not a disaster
because leptoquark
has a small coupling to light quarks

$$v_\Delta \lesssim 1 \times 10^{15} \text{ GeV} \left(\frac{M_{\Phi_3}}{2 \text{ TeV}}\right)^2 \left(\frac{\Lambda_{PS}}{M_{PL}}\right)^2$$

Low-scale Pati-Salam breaking (χ)



Inverse see saw for neutrino masses

What about dimension 5 SM baryon number violation

Comes from dimension 7 PS operators

$$\frac{1}{\Lambda_{PS}^3}(F_u^A F_d^B)(\Phi_{15}^\dagger \chi)^C \chi^D H^\dagger \epsilon_{ABCD} \quad \xrightarrow{\langle\chi\rangle} \quad \frac{v_\chi^2}{\Lambda_{PS}^3}(d_R^\alpha u_R^\beta)(\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma},$$

$$\frac{1}{\Lambda_{PS}^3}(F_{QL}^A F_{QL}^B)(\Phi_{15}^\dagger \chi)^C \chi^D H^\dagger \epsilon_{ABCD} \quad \xrightarrow{\langle\chi\rangle} \quad \frac{v_\chi^2}{\Lambda_{PS}^3}(Q_L^\alpha Q_L^\beta)(\Phi_3^\dagger)^\gamma H^\dagger \epsilon_{\alpha\beta\gamma},$$

$$\frac{1}{\Lambda_{PS}^3}(F_d^A F_d^B)(\Phi_{15}^\dagger \chi)^C \chi^D H \epsilon_{ABCD} \quad \xrightarrow{\langle\chi\rangle} \quad \frac{v_\chi^2}{\Lambda_{PS}^3}(d_R^\alpha d_R^\beta)(\Phi_3^\dagger)^\gamma H \epsilon_{\alpha\beta\gamma},$$

$$\frac{1}{\Lambda_{PS}^3}(F_d^A F_d^B)(\Phi_{15} \chi)^C \chi^D H^\dagger \epsilon_{ABCD} \quad \xrightarrow{\langle\chi\rangle} \quad \frac{v_\chi^2}{\Lambda_{PS}^3}(d_R^\alpha d_R^\beta)\Phi_4^\gamma H^\dagger \epsilon_{\alpha\beta\gamma}.$$

Results depend on light field content! Well known that there can be unacceptably large baryon number violation in Pati Salam models

For example add scalar representation

$$\Phi_6 = \begin{pmatrix} \epsilon^{\alpha\beta\gamma}(\phi_{\rm DQ})_\gamma & \phi^\alpha_{\rm LQ} \\ -\phi^\alpha_{\rm LQ} & 0 \end{pmatrix} \sim (6,1,0)_{PS}$$

$\phi_{DQ} \sim (\bar{3},1,1,1/3) \quad \phi_{LQ} \sim (3,1,-1/3)$ are mixed scalars

$$\begin{aligned} -\mathcal{L} &= Y_6\, F_u^A F_d^B (\Phi_6^\dagger)_{AB} + Y_6'\, \epsilon_{ABCD} F_u^A F_d^B \Phi_6^{CD} \\ &\quad + Y_6'' F_{QL}^A F_{QL}^B (\Phi_6^\dagger)_{AB} + Y_6''' \epsilon_{ABCD} F_{QL}^A F_{QL}^B \Phi_6^{CD} + \text{h.c.} \\ &= Y_6 \epsilon_{\alpha\beta\gamma} u_R^\alpha d_R^\beta (\phi^\dagger_{\rm DQ})^\gamma + 2Y_6' u_R^\alpha e_R\, \phi_{DQ\alpha} + \cdots + \text{h.c.}\ . \end{aligned}$$

Tree level exchange of mixed scalar gives proton decay

Inverse See Saw For Low Scale Breaking

$$M_u = Y_1 \frac{v_H}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_2 \frac{v_\Phi}{\sqrt{2}}$$
$$M_\nu^{\rm Dirac} = Y_1 \frac{v_H}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_2 \frac{v_\Phi}{\sqrt{2}}$$

To avoid tuning of parameters add three Pati Salam singlet fermions N_L

Simplify discussion, one generation. Add to Lagrangian $Y_5 F_u \chi N_L^\dagger + \frac{\mu}{2} N_L^\dagger N_L^\dagger + h.c.$

Define $M_\chi^D = Y_5 v_\chi / \sqrt{2}$ For small μ one heavy Dirac neutrino with mass $\sqrt{(M_\chi^D)^2 + (M_\nu^D)^2}$

$\nu_{hL} = \frac{M_\chi^D N_L + M_\nu^D \nu_L}{\sqrt{(M_\chi^D)^2 + (M_\nu^D)^2}}$ paired with $\nu_{hR} = \nu_R$

Orthogonal linear combination light $\nu_l = \frac{-M_\nu^D N_L + M_\chi^D \nu_L}{\sqrt{(M_\chi^D)^2 + (M_\nu^D)^2}}$

Massless in limit $\mu \to 0$

$\mu << M_\nu^D << M_\chi^D$ $\quad m_{\nu_l} = \mu (M_\nu^D)^2 / (M_\chi^D)^2$

Conclusions

Treating the SM as an effective theory if all you use is dimensional analysis mixed and leptoquark scalars give rise to unacceptable baryon number violation

Minimal Pati Salam (PS) based on gauge group SU(4)XSU(2)U(1) contains scalar leptoquarks

Discussion motivated in part by some of the flavor anomalies in B decays.