Pheno 2019

7 May 2:45 PM

Minimal $SU(4)$ models & B-meson anomalies

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Minimal *SU*(4) models & B-meson anomalies

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Stavanger, Norway

Lepton Flavor group

Lepton Flavor group

Sensu lato: $U(3)_{L_L} \times U(3)_{e_R}$

$$L \to \mathcal{U} \bullet L$$
$$e_R \to \mathcal{U}' \bullet e_R$$

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$\mathcal{L}^{\rm SM}_{\rm Y-lept} = \bar{L} Y_l e_R \Phi$

$Y_l \stackrel{!}{=} 0$

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~~SM~~

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$$\cap \quad \mathcal{U}' = \mathcal{U}$$

Sensu mezzostricto: $U(3)_{\rm LF}$

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$\mathcal{U} = {\rm diag}(e^{i\alpha}, e^{i\beta}, e^{i\gamma})$

Sensu stricto:

$$U(1)_e \times U(1)_\mu \times U(1)_\tau$$

✓ SM

~~ν oscillations~~

✓ all other experiments

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Lepton number: $U(1)_{\rm L}$

✓ SM

✓ SM $\oplus$ Dirac ν_R

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$\det \mathcal{U} = 1$

Lepton Flavor Universality:

$SU(3)_{\rm LFU}$

$Y_l \stackrel{!}{=} \mathbb{1} y$

$m_e \stackrel{!}{=} m_\mu \stackrel{!}{=} m_\tau$

~~SM~~

✓ SM @ $E \gg \Delta m_l$

~~B-meson decays~~

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~~B-meson decays~~

LFUV in *B*-meson decays

(Cf. today morning talks for details)

Charged current anomaly

Neutral current anomaly

Support from various b-s-μ-μ probes

LFUV in *B*-meson decays

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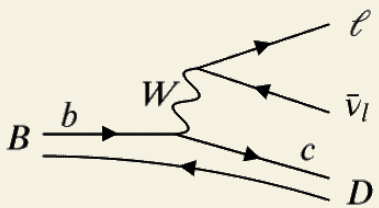
Charged current anomaly

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\bar{\nu})}{\mathrm{BR}(B \to D^{(*)}l\bar{\nu})}$$

$$R^{\mathrm{exp}}_{D^{(*)}} > R^{\mathrm{exp2019}}_{D^{(*)}} \gtrsim R^{\mathrm{SM}}_{D^{(*)}}$$



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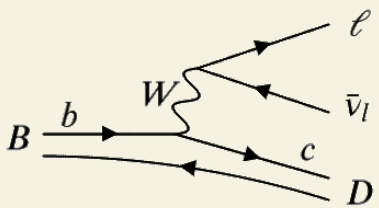
$$R^{\mathrm{SM}}_{D} = 0.299 \pm 0.003$$

$$R^{\mathrm{SM}}_{D^*} = 0.258 \pm 0.005$$



Pre-Moriond2019 average:

$$R_D = 0.407 \pm 0.039 \pm 0.024$$

$$R_{D^*} = 0.306 \pm 0.013 \pm 0.007$$

LHCb: [1904.08794]

$$R_D = 0.307 \pm 0.037 \pm 0.016$$

$$R_{D^*} = 0.283 \pm 0.018 \pm 0.014$$

Gone?

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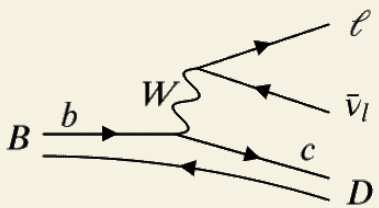

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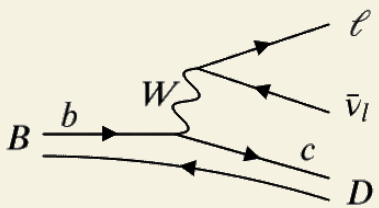

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$$R^{\mathrm{exp}}_{K} = 0.745^{+0.090}_{-0,074} \pm 0.036$$

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LHCb: [1903.09252]

$$R_K = 0.846\,^{+\,0.060\,+\,0.016}_{-\,0.054\,-\,0.014}$$

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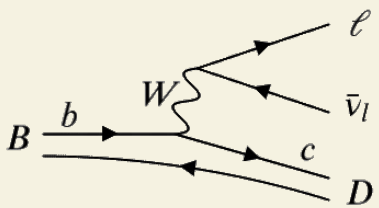

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Support from various b-s-μ-μ probes

- angular obs. in B → K*μμ (P_5')
- $B_s \to \mu\mu$

LF[U]V in LeptoQuark interactions

$$\mathcal{L}_{\mathrm{LQ-int}} = \begin{pmatrix} \bar{d} & \bar{s} & \bar{b} \end{pmatrix} \begin{pmatrix} y_{de} & y_{d\mu} & y_{d\tau} \\ y_{se} & y_{s\mu} & y_{s\tau} \\ y_{be} & y_{b\mu} & y_{b\tau} \end{pmatrix} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} LQ^{+2/3}$$

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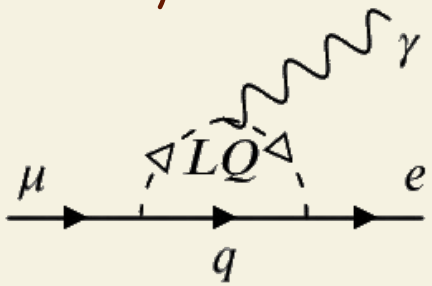
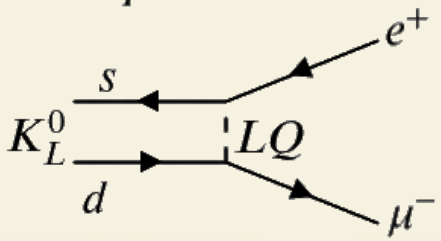
Lepton Flavor violation

⇕

(At least) two nonzero columns



$$\begin{pmatrix} 0 & 0 & 0 \\ \bullet & \bullet & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



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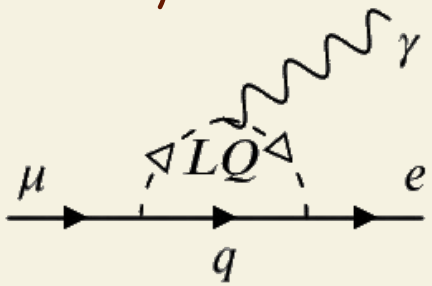

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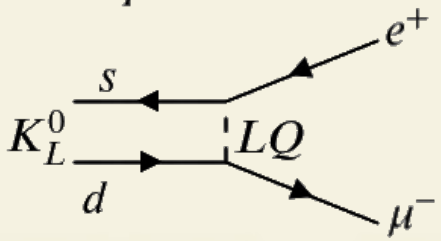

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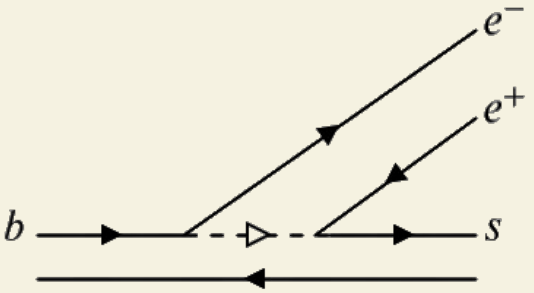
Lepton Flavor Universality violation

⇕

Two (or more) columns differ



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Minimal *SU(4)* model(s)

A. D. Smirnov (et al.)

- The Minimal quark - lepton symmetry model and the limit on Z' mass
  Phys. Lett. B346 (1995) 297-302 arXiv: hep-ph/9503239
- Phys. Lett. B431 (1998) 119-126 arXiv: hep-ph/9805339
- Mod. Phys. Lett. A20 (2005) 3003-3012 arXiv: 0511149
- Mod. Phys. Lett. A23 (2008) 2907-2913 arXiv: 0807.4486
- Mod. Phys. Lett. A24 (2009) 1199-1207 arXiv: 0902.2931
- Mod. Phys. Lett. A31 (2016) 39, 1650224 arXiv: 1610.08409
- Vector leptoquark mass limits and branching ratios of K_L^0, B^0, $B_s \to l_i^+ l_j^-$ decays with account of fermion mixing...
  Mod. Phys. Lett. A33 (2018) 1850019 arXiv: 1801.02895

vanilla version

P. Fileviez Pérez, M. B. Wise

- Low-scale quark-lepton unification
  Phys. Rev. D88 (2013) 057703 arXiv: 1307.6213

inverse seesaw

T. Faber, W. Porod, M. Hudec, M. Malinský, H. Kolešová, F. Staub

- A unified LQ model confronted with lepton non-universality in B-meson decays
  Phys. Lett. B 787 (2018) 159-166 arXiv: 1808.05511
- Collider phenomenology of a unified LQ model arXiv: 1812.07592

Minimal *SU(4)* model(s)

- $SU(4)_C \times SU(2)_L \times U(1)_R$
- No extra charged fermions
- Minimal scalar sector

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  Quark-Lepton unification

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  mandatory: ν_R

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$$F_{(4,2,0)} = \begin{pmatrix} Q \\ L \end{pmatrix}$$

$$f^c_{u\,(4,1,+1/2)} = \begin{pmatrix} {u_R}^c & {\nu_R}^c \end{pmatrix}$$

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$$N_{(1,1,0)}$$

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  Cascade SSB

  Independent fermion masses

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  Independent fermion masses

$$\chi_{\,(4,1,+1/2)} = \begin{pmatrix} \bar{S}^\dagger_{1\,(3,1,+2/3)} \\ \chi^0_{\,(1,1,0)} \end{pmatrix}$$

$$H_{(1,2,+1/2)}$$

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$$\Phi_{\,(15,2,+1/2)} = \begin{pmatrix} G_{\,(8,2,+1/2)} + \frac{H_2}{\sqrt{12}} & R_{2\,(3,2,+7/6)} \\ \tilde{R}^\dagger_{2\,(\bar{3},2,-1/6)} & \frac{-3}{\sqrt{12}} H_{2\,(1,2,+1/2)} \end{pmatrix}$$

Minimal *SU(4)* model(s)

- $SU(4)_C \times SU(2)_L \times U(1)_R$

$$A_\mu^{SU(4)} = \begin{pmatrix} G_\mu + \frac{\mathbb{1}}{\sqrt{12}} A_\mu^{15} & U_{1\mu} \\ U_{1\mu}^\dagger & \frac{-3}{\sqrt{12}} A_\mu^{15} \end{pmatrix}$$

Quark-Lepton unification

natural LeptoQuark environment

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$$H_{(1,2,+1/2)}$$

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The R_2 LeptoQuark & R(K$^{(*)}$) anomaly

$$R_2 = \begin{bmatrix} R^{5/3} \\ R^{2/3} \end{bmatrix} \sim \left(3, 2, +\frac{7}{6}\right)$$

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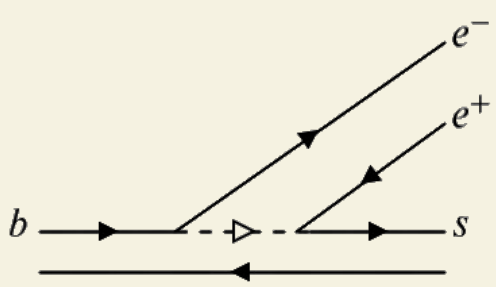
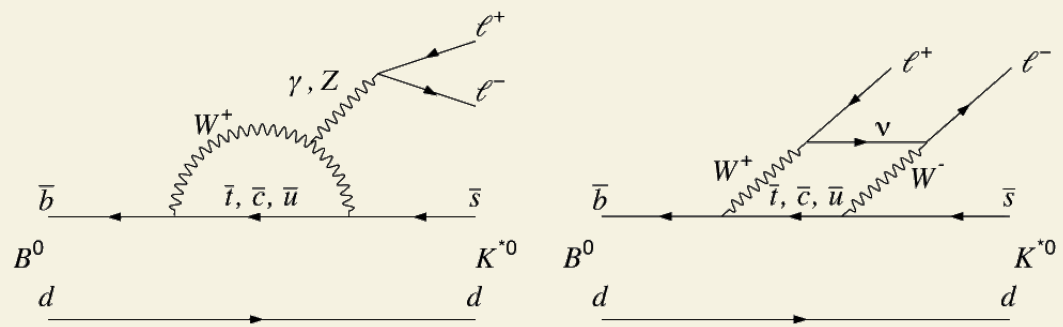
Different chiralities than weak interactions

→ sums incoherently with SM contributions

→ can improve R(K) iff coupling to electrons



$$C_9^{\mathrm{NP}} = C_{10}^{\mathrm{NP}}$$



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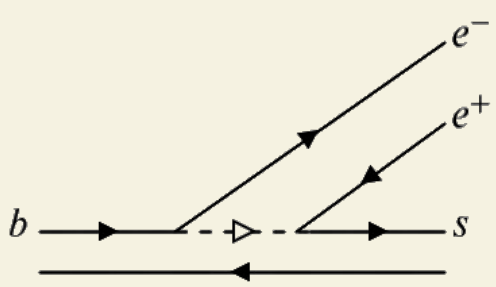

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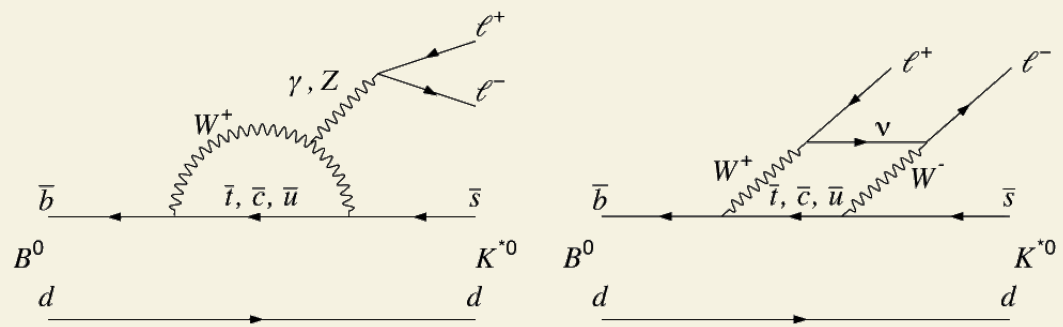

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Ideal case: $Y_4 = \begin{pmatrix} 0 & 0 & 0 \\ \bullet & 0 & 0 \\ \bullet & 0 & 0 \end{pmatrix} \longrightarrow R_K \approx \dfrac{|C^{\mathrm{SM}}|^2}{|C^{\mathrm{SM}}|^2 + |C_{ee}^{\mathrm{NP}}|^2}$

Constraints on the R_2 LQ interaction from extended gauge symmetry

The relevant Yukawa matrix must satisfy

$$Y_4 = \frac{U\hat{M}_d - \hat{M}_l V}{\sqrt{2/3}\, v_{\rm ew} \cos\beta} \propto \begin{array}{c} \\ d_L \\ s_L \\ b_L \end{array} \begin{array}{c} \begin{array}{ccc} e_R & \mu_R & \tau_R \end{array} \\ \begin{pmatrix} u_{de}m_d - v_{de}m_e & u_{d\mu}m_d - v_{d\mu}m_\mu & u_{d\tau}m_d - v_{d\tau}m_\tau \\ u_{se}m_s - v_{se}m_e & u_{s\mu}m_s - v_{s\mu}m_\mu & u_{s\tau}m_s - v_{s\tau}m_\tau \\ u_{be}m_b - v_{be}m_e & u_{b\mu}m_b - v_{b\mu}m_\mu & u_{b\tau}m_b - v_{b\tau}m_\tau \end{pmatrix} \end{array}$$

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LFV inevitable

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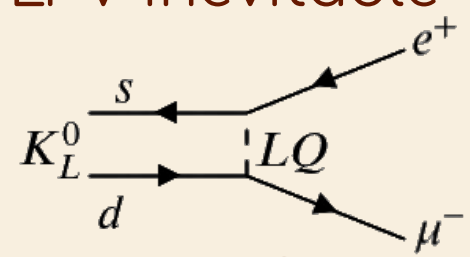

model with R_K = 0.8 EXCLUDED

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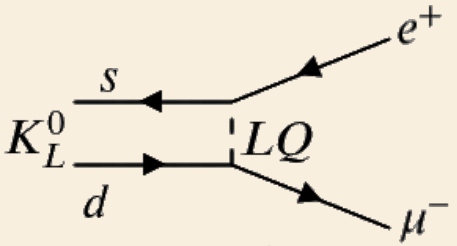

model with R_K = 0.8 EXCLUDED

Only working scenario:

$$Y_4 = \sqrt{\frac{3}{2}} \frac{1}{v_{\rm ew}\cos\beta} \begin{pmatrix} 0 & 0 & m_\tau \sin\phi \\ m_s/\sqrt{2} & 0 & m_\tau \cos\phi \\ m_b/\sqrt{2} & 0 & -m_b/\sqrt{2} \end{pmatrix}$$

NO muon flavor violation

Summary of Results

	Vanilla minimal model	Minimal model + inverse seesaw - SO(10)	Minimal model + inverse seesaw
$R(D^{(*)})$	✗	✗	✗
$R(K^{(*)})$	✗	✗	✓ • $1 \times 10^{-8} < \tau \to e\gamma < 3 \times 10^{-8}$ discovery@BelleII • $\tau \to eee$, $\tau \to e\mu\mu$ @BelleII • $\tau \to e\pi\pi$ possible @BelleII • 2/3 LQ decaying to $be^+ : b\tau^+ : j\tau^+ = 1 : 1 : 1.17$ @pp-colliders
b-s-μ-μ	✗	✗	✗

Thank you

Matěj Hudec

Scalar potential

$$
\begin{aligned}
V = {} & \mu_H^2|H|^2 + \mu_\chi^2|\chi|^2 + \mu_\Phi^2 \mathrm{Tr}(|\Phi|^2) + \lambda_1|H|^2|\chi|^2 + \lambda_2|H|^2\mathrm{Tr}(|\Phi|^2) + \lambda_3|\chi|^2\mathrm{Tr}(|\Phi|^2) \\
& + (\lambda_4 H_i^\dagger \chi^\dagger \Phi^i \chi + \mathrm{h.c.}) + \lambda_5 H_i^\dagger \mathrm{Tr}(\Phi_j^\dagger \Phi^i) H^j + \lambda_6 \chi^\dagger \Phi^i \Phi_i^\dagger \chi + \lambda_7 |H|^4 + \lambda_8 |\chi|^4 + \lambda_9 \mathrm{Tr}(|\Phi|^4) \\
& + \lambda_{10}(\mathrm{Tr}|\Phi|^2)^2 + \Big(\lambda_{11} H_i^\dagger\ \mathrm{Tr}(\Phi^i\,\Phi^j) H_j^\dagger + \lambda_{12} H_i^\dagger\ \mathrm{Tr}(\Phi^i\,\Phi^j\,\Phi_j^\dagger) + \lambda_{13} H_i^\dagger\ \mathrm{Tr}(\Phi^i\,\Phi_j^\dagger\,\Phi^j) + \mathrm{h.c.}\Big) \\
& + \lambda_{14}\chi^\dagger|\Phi|^2\chi + \lambda_{15}\mathrm{Tr}(\Phi_i^\dagger\,\Phi^j\,\Phi_j^\dagger\,\Phi^i) + \lambda_{16}\mathrm{Tr}(\Phi_i^\dagger\,\Phi^j)\,\mathrm{Tr}(\Phi_j^\dagger\,\Phi^i) + \lambda_{17}\mathrm{Tr}(\Phi_i^\dagger\,\Phi_j^\dagger)\,\mathrm{Tr}(\Phi^i\,\Phi^j) \\
& + \lambda_{18}\mathrm{Tr}(\Phi_i^\dagger\,\Phi_j^\dagger\,\Phi^i\,\Phi^j) + \lambda_{19}\mathrm{Tr}(\Phi_i^\dagger\,\Phi_j^\dagger\,\Phi^j\,\Phi^i)
\end{aligned}
$$

$$\Downarrow$$

$$
\begin{aligned}
m_G^2 &= \left(\frac{\sqrt{3}\lambda_4}{4}\tan\beta - \frac{3}{8}\left(\lambda_6 + \lambda_{14}\right)\right) v_\chi^2\,, \\
m_{R_2}^2 &= \left(\frac{\sqrt{3}\lambda_4}{4}\tan\beta + \frac{\lambda_{14} - 3\lambda_6}{8}\right) v_\chi^2\,, \\
m_{\tilde{R}_2}^2 &= \left(\frac{\sqrt{3}\lambda_4}{4}\tan\beta + \frac{\lambda_6 - 3\lambda_{14}}{8}\right) v_\chi^2\,, \\
m_{\hat{H}}^2 &= \frac{\sqrt{3}\lambda_4}{2\sin(2\beta)} v_\chi^2\,,
\end{aligned}
$$

$$\Downarrow$$

$$m_G^2 + 2m_{\hat{H}}^2 \sin^2\beta = \frac{3}{2}(m_{R_2}^2 + m_{\tilde{R}_2}^2)$$

Some more eqns

Fermions	**Scalars**
$F_{(4,2,0)} = \begin{pmatrix} Q \\ L \end{pmatrix}$	$\chi_{(4,1,+1/2)} = \begin{pmatrix} \bar{S}^{\dagger}_{1\,(3,1,+2/3)} \\ \chi^{0}_{\;(1,1,0)} \end{pmatrix}$
$f^c_{u\,(\bar{4},1,-1/2)} = \begin{pmatrix} u^c & \nu^c \end{pmatrix}$	$H_{(1,2,+1/2)}$
$f^c_{d\,(\bar{4},1,+1/2)} = \begin{pmatrix} d^c & e^c \end{pmatrix}$	$\Phi_{(15,2,+1/2)} = \begin{pmatrix} G_{(8,2,+1/2)} + \frac{\mathbb{1}}{\sqrt{12}} H_2 & R_{2\,(3,2,+7/6)} \\ \tilde{R}^{\dagger}_{2\,(\bar{3},2,-1/6)} & \frac{-3}{\sqrt{12}} H_{2\,(1,2,+1/2)} \end{pmatrix}$
$N_{(1,1,0)}$	

$$-\mathcal{L}_Y = f^c_u Y_1 H F + f^c_u Y_2 \Phi F + f^c_d Y_3 H^{\dagger} F + f^c_d Y_4 \Phi^{\dagger} F + f^c_u Y_5 \chi N + \frac{1}{2} N \mu N + \text{h.c.}$$

Scalar extensions of SM

$\Psi(Y)^{3B}_{L}$	$\overline{\nu_R}\,(0)^{0}_{-1}$	$\overline{e_R}\,(-1)^{0}_{-1}$	$L^j\,(-\frac{1}{2})^{0}_{1}$	$\overline{d_{R\beta}}\,(\frac{1}{3})^{-1}_{0}$	$\overline{u_{R\beta}}\,(-\frac{2}{3})^{-1}_{0}$	$Q^{j\beta}\,(\frac{1}{6})^{1}_{0}$
$Q^{i\alpha}\,(\frac{1}{6})^{1}_{0}$	$\tilde{R}^{\dagger}_{2\alpha i}\,(-\frac{1}{6})$	$R^{\dagger}_{2\alpha i}\,(-\frac{7}{6})$	$S_{1\alpha}\varepsilon_{ij}$ $S_{3\,\alpha ij}$ $(\frac{1}{3})$	$H^{\dagger}_{i}\delta^{\beta}_{\alpha}$ $G^{\dagger\,\beta}_{\alpha j}$ $(-\frac{1}{2})$	$H^{j}\varepsilon_{ij}\delta^{\beta}_{\alpha}$ $X^{j\beta}_{\alpha}\varepsilon_{ij}$ $(\frac{1}{2})$	$S^{\dagger\,\gamma}_{1}\varepsilon_{\alpha\beta\gamma}\,\varepsilon_{ij}$ $\chi_{\alpha\beta}\,\varepsilon_{ij}$ $S^{\dagger\,\gamma}_{3\,ij}\,\varepsilon_{\alpha\beta\gamma}$ $X_{\alpha\beta ij}$ $(-\frac{1}{3})$
$\overline{u_{R\alpha}}\,(-\frac{2}{3})^{-1}_{0}$	$\bar{S}^{\dagger\,\alpha}_{1}\,(\frac{2}{3})$	$S^{\dagger\,\alpha}_{1}(-\frac{1}{3})$	$R_{2}{}^{\alpha i}\,\varepsilon_{ij}\,(\frac{7}{6})$	$S_{1\gamma}\,\varepsilon^{\alpha\beta\gamma}$ $\chi^{\dagger\alpha\beta}$ $(\frac{1}{3})$	$\tilde{S}_{1\gamma}\,\varepsilon^{\alpha\beta\gamma}$ $\chi^{\dagger\alpha\beta}$ $(\frac{4}{3})$	
$\overline{d_{R\alpha}}\,(\frac{1}{3})^{-1}_{0}$	$S^{\dagger\,\alpha}_{1}(-\frac{1}{3})$	$\tilde{S}^{\dagger}_{1}(-\frac{4}{3})$	$\tilde{R}_{2}{}^{\alpha i}\,\varepsilon_{ij}(\frac{1}{6})$	$\chi^{\dagger}_{\gamma}\,\varepsilon^{\alpha\beta\gamma}$ $\chi^{\dagger\alpha\beta}$ $(-\frac{2}{3})$		
$L^{i}(-\frac{1}{2})^{0}_{1}$	$H^{j}\,\varepsilon_{ij}\,(\frac{1}{2})$	$H^{\dagger}_{i}\,(-\frac{1}{2})$	$\varphi\,\varepsilon_{ij}$ Δ_{ij} (1)			
$\overline{e_R}\,(-1)^{0}_{-1}$	$\varphi^{\dagger}\,(-1)$	$\varphi^{\dagger}\,(-2)$				
$\overline{\nu_R}\,(0)^{0}_{-1}$	$\varphi\,(0)$					

Baryon & lepton numbers

	G	$G_{\rm SM}$	$G_{\rm vac}$	$[B-L]$	F	M	B	L, L'
Fermions								
$F_L = \begin{pmatrix} Q \\ L \end{pmatrix}$	$(4,2,0)$	$Q \quad (3,2,{}^1\!/_6)$ $L \quad (1,2,{}^-\!{}^1\!/_2)$	$u \quad (3,{}^2\!/_3)$ $d \quad (3,{}^-\!{}^1\!/_3)$ $\nu \quad (1,0)$ $e \quad (1,-1)$	$\begin{pmatrix} +{}^1\!/_3 \\ -1 \end{pmatrix}$	$+1$	$+1$	$\begin{pmatrix} +{}^1\!/_3 \\ 0 \end{pmatrix}$	$\begin{pmatrix} 0 \\ +1 \end{pmatrix}$
$f_u^c = \begin{pmatrix} u^c & \nu^c \end{pmatrix}$	$(\overline{4},1,{}^-\!{}^1\!/_2)$	$u^c \quad (\overline{3},1,{}^-\!{}^2\!/_3)$ $\nu^c \quad (1,1,0)$	$(\overline{3},{}^-\!{}^2\!/_3)$ $(1,0)$	$\begin{pmatrix} -{}^1\!/_3 & 1 \end{pmatrix}$	-1	-1	$\begin{pmatrix} -{}^1\!/_3 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \end{pmatrix}$
$f_d^c = \begin{pmatrix} d^c & e^c \end{pmatrix}$	$(\overline{4},1,{}^1\!/_2)$	$d^c \quad (\overline{3},1,{}^1\!/_3)$ $e^c \quad (1,1,1)$	$(\overline{3},{}^1\!/_3)$ $(1,1)$	$\begin{pmatrix} -{}^1\!/_3 & 1 \end{pmatrix}$	-1	-1	$\begin{pmatrix} -{}^1\!/_3 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \end{pmatrix}$
N	$(1,1,0)$	$(1,1,0)$	$(1,0)$	0	$+1$	0	0	$0,+1$
Scalars								
$\chi = \begin{pmatrix} \bar{S}_1^\dagger \\ \chi^0 \end{pmatrix}$	$(4,1,{}^1\!/_2)$	$\bar{S}_1^\dagger \quad (3,1,{}^2\!/_3)$ $\chi^0 \quad (1,1,0)$	$(3,{}^2\!/_3)$ $(1,0)$	$\begin{pmatrix} +{}^1\!/_3 \\ -1 \end{pmatrix}$	0	$+1$	$\begin{pmatrix} +{}^1\!/_3 \\ 0 \end{pmatrix}$	$\begin{pmatrix} 0 \\ +1 \end{pmatrix}, \begin{pmatrix} -1 \\ 0 \end{pmatrix}$
H	$(1,2,{}^1\!/_2)$	$(1,2,{}^1\!/_2)$	$H_1^+ \quad (1,1)$ $H_1^0 \quad (1,0)$	0	0	0	0	0
$\Phi = \begin{pmatrix} G & R_2 \\ \tilde{R}_2^\dagger & 0 \end{pmatrix}$ $+\sqrt{2}\,T^{15} H_2$	$(15,2,{}^1\!/_2)$	$R_2 \quad (3,2,{}^7\!/_6)$ $\tilde{R}_2^\dagger \quad (\overline{3},2,{}^-\!{}^1\!/_6)$ $G \quad (8,2,{}^1\!/_2)$ $H_2 \quad (1,2,{}^1\!/_2)$	$R_2^{5/3} \quad (3,{}^5\!/_3)$ $R_2^{2/3} \quad (3,{}^2\!/_3)$ $\tilde{R}_2^{-1/3\,\dagger} \quad (\overline{3},{}^1\!/_3)$ $\tilde{R}_2^{2/3\,\dagger} \quad (\overline{3},{}^-\!{}^2\!/_3)$ $G^+ \quad (8,1)$ $G^0 \quad (8,0)$ $H_2^+ \quad (1,1)$ $H_2^0 \quad (1,0)$	$\begin{pmatrix} 0 & +{}^4\!/_3 \\ -{}^4\!/_3 & 0 \end{pmatrix}$	0	0	$\begin{pmatrix} 0 & +{}^1\!/_3 \\ -{}^1\!/_3 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \\ +1 & 0 \end{pmatrix}$
Gauge Bosons								
$A_\mu = \begin{pmatrix} G_\mu & X_\mu \\ X_\mu^* & 0 \end{pmatrix}$ $+T^{15} B'_\mu$	$(15,1,0)$	$G_\mu \quad (8,1,0)$ $X_\mu \quad (3,1,{}^2\!/_3)$ $B'_\mu \quad (1,1,0)$	$(8,0)$ $(3,{}^2\!/_3)$ $(1,0)$	$\begin{pmatrix} 0 & +{}^4\!/_3 \\ -{}^4\!/_3 & 0 \end{pmatrix}$	0	0	$\begin{pmatrix} 0 & +{}^1\!/_3 \\ -{}^1\!/_3 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & -1 \\ +1 & 0 \end{pmatrix}$
W_μ	$(1,3,0)$	$(1,3,0)$	$W_\mu^\pm \quad (1,\pm 1)$ $W_\mu^3 \quad (1,0)$	0	0	0	0	0
B_μ	$(1,1,0)$	$(1,1,0)$	$(1,0)$	0	0	0	0	0

$$M = (\#\,\text{upper } SU(4) \text{ indices}) - (\#\,\text{lower } SU(4) \text{ indices})$$