Unified Framework for Flavor Anomalies, Muon g-2 and Neutrino Masses

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KIAS HEP Semiar
June 22, 2021

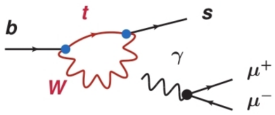
Outline

- Lightning review of anomalies:
  - R_K, R_{K^*}: Neutral current decays of $\boldsymbol{B}$ mesons
  - $\boldsymbol{R_D}$, $\boldsymbol{R_{D^*}}$: Charged current decays of $\boldsymbol{B}$ mesons
  - Muon (g-2) anomaly
  - Neutrino masses and oscillations
- Unified description in terms of leptoquarks R_2 and S_3
  K. S. Babu, P. S. B. Dev, S. Jana, A. Thapa, JHEP **03**, 179 (2021)
- Collider constraints and tests
- Muon (g-2) and neutrino magnetic moment
  K. S. Babu, S. Jana, M. Lindner, Vishnu P. K, [arXiv:2104.03291 [hep-ph]]

Neutral Current B Decay Anomalies

- Lepton flavor universality apparently broken in $B \to K^{(*)}\ell^+\ell^-$
- Characterized by two "clean" ratios:

$$R_K = \frac{\Gamma\left(\bar{B} \to \bar{K}\mu^+\mu^-\right)}{\Gamma\left(\bar{B} \to \bar{K}e^+e^-\right)}, \quad R_{K^*} = \frac{\Gamma\left(\bar{B} \to \bar{K}^*\mu^+\mu^-\right)}{\Gamma\left(\bar{B} \to \bar{K}^*e^+e^-\right)}$$

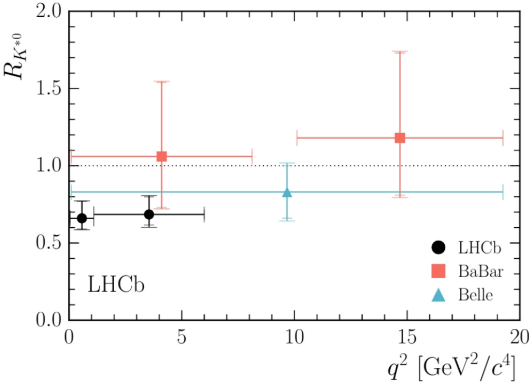


$R_K = 0.846^{+0.042+0.013}_{-0.031-0.012}, 1.1\,\mathrm{GeV}^2 \le q^2 \le 6\,\mathrm{GeV}^2$ LHCb (2021)

$$R_K^{\mathrm{SM}} = 1.0003 \pm 0.0001$$

(3.1 sigma deviation)

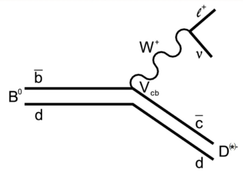
R_{K^*} Anomaly



$$R_{K^*}^{\rm SM} = 1.00 \pm 0.01$$

Charged Current B Decay Anomaly

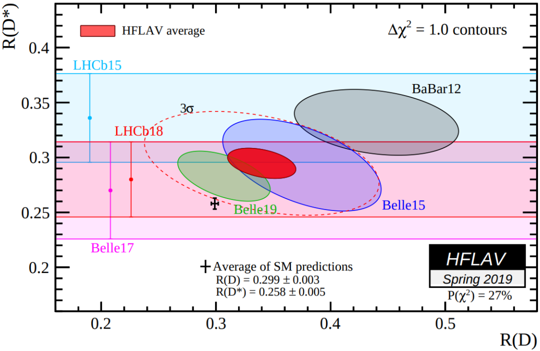
$$R_D = \frac{\Gamma(\bar{B} \to D\tau\nu)}{\Gamma(\bar{B} \to D\ell\nu)}, \quad R_{D^*} = \frac{\Gamma\left(\bar{B} \to D^*\tau\nu\right)}{\Gamma\left(\bar{B} \to D^*\ell\nu\right)}, \quad \ell = e, \mu$$



$$R_D^{SM} = 0.299 \pm 0.003$$
$$R_{D^*}^{SM} = 0.258 \pm 0.005$$

$$R_D^{exp} = 0.340 \pm 0.027 \pm 0.013$$
$$R_{D^*}^{exp} = 0.295 \pm 0.011 \pm 0.008$$

$\sim$ 3 sigma discrepancy



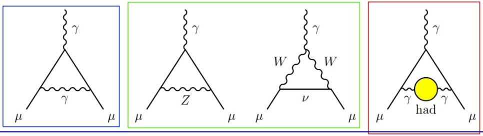
Muon (g-2) Anomaly

- Anomalous magnetic moment of muon a_μ:

$$H = -\vec{\mu} \cdot \vec{B}, \quad \vec{\mu} = g \frac{e}{2m} \vec{s}$$

- $a_\mu \equiv (g_\mu - 2)/2$, is precisely computed in QFT
  J. Schwinger (1948); R. Kusch and H. M. Foley (1948)
- The Standard Model contribution to the lepton $g-2$:

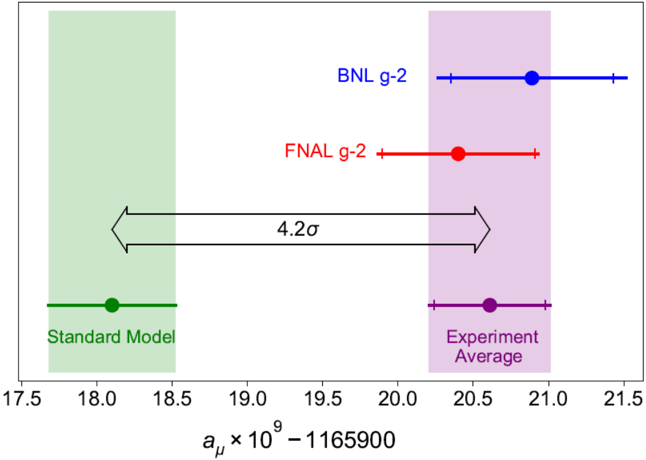
$$a_\ell = a_\ell(\mathrm{QED}) + a_\ell(\text{ weak }) + a_\ell(\text{ hadron })$$



$$\Delta a_\mu \equiv a_\mu^{\exp} - a_\mu^{\mathrm{SM}} = (251 \pm 59) \times 10^{-11}. \qquad 4.2\sigma$$

Brookhaven (2006); Fermilab (2021)

Muon (g-2) Anomaly



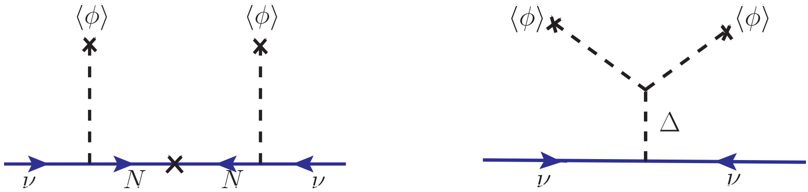
Neutrino Masses and Mixings

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

I. Estaban, M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, A. Zhou (2020)

Seesaw Paradigm for Neutrino Masses

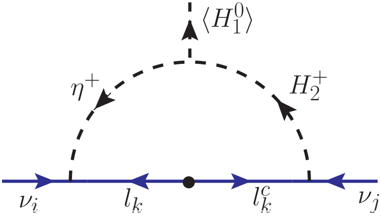
- Neutrino mass induced via Weingberg's dimension-5 operator, $LL\phi\phi$, suppressed by a large mass scale
- Different realizations (Type-I, II, III):



- The scale of new physics can be rather high $\sim 10^{14}$ GeV

Radiative Neutrino Mass Generation

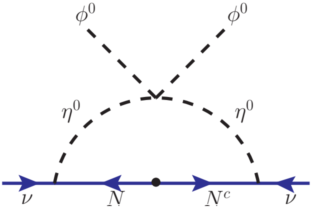
- Neutrino masses are zero at tree level: ν_R may be absent
- Small, finite masses are generated as quantum corrections
- Typically involves exchange of two scalars leading to lepton number violation
- Simple realization is the Zee Model, which has a second Higgs doublet and a charged singlet



- Smallness of neutrino mass is explained via loop and chiral suppression.
- New physics in this framework may lie at the TeV scale.

Radiative Neutrino Masses

- Obtained from effective d = 7, 9, 11... operators with $\Delta L = 2$ selection rule
- If the loop diagram has at least one Standard Model particle, this can be cut to generate such effective operators
- Not true when all particles inside loop are BSM, such as in scotogenic models



- Neutrino mass has no chiral suppression; new scale can be large
- Other considerations (dark matter) may require TeV scale new physics   Ma (2006)

Unified Framework for Anomalies and m_ν

- A pair of leptoquark scalars (R_2 and S_3) can generate neutrino masses radiatively
- LQ R_2 explains $R_{D^{(*)}}$, S_3 explains $R_{K^{(*)}}$
- The same R_2 LQ also induces muon (g-2)
- Flavor structure to achieve these is very constrained
- Framework can be tested at LHC as well as in processes such as $\tau \to \mu\gamma$

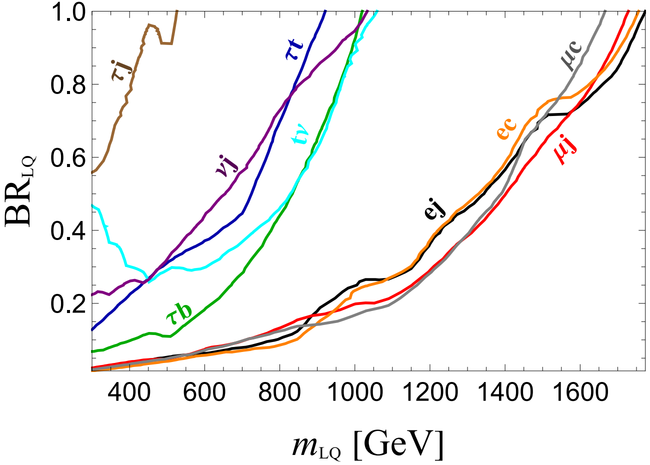
Constraints on LQ Models

- Direct limits from LHC on the masses of LQs
- $pp \to \ell^+\ell^-$ mediated by LQs limit their couplings to light quarks
- Single LQ solution to $R_{D^{(*)}}$ and $R_{K^{(*)}}$ not viable with these constraints

A. Angelescu et. al., [arXiv:2103.12504 [hep-ph]].

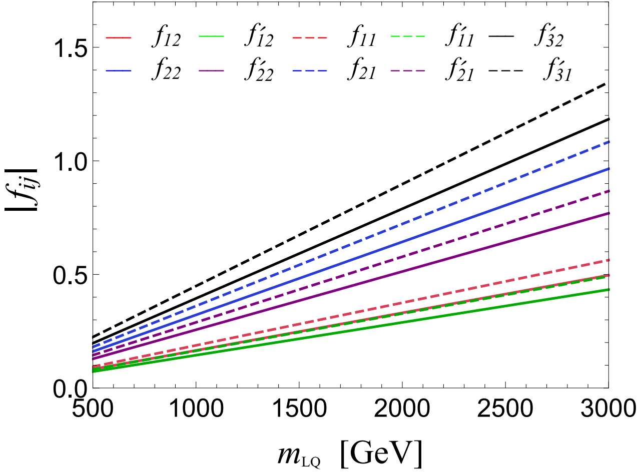
Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_3 $(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	✓	✗	✗
S_1 $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	✗	✓	✗
R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$	✗	✓	✗
U_1 $(\mathbf{3}, \mathbf{1}, 2/3)$	✓	✓	✓
U_3 $(\mathbf{3}, \mathbf{3}, 2/3)$	✓	✗	✗

Constraints LQs from LHC



Babu, Dev, Jana, Thapa (2020)

Bounds from $pp \to \ell_i^+ \ell_j^-$



Babu, Dev, Jana, Thapa (2020)

A Unified Model

- The model is based on SM gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$, with an extended scalar sector.

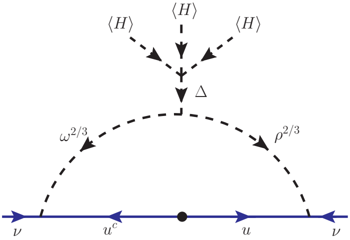
$$R_2 = \begin{pmatrix} \omega^{5/3} \\ \omega^{2/3} \end{pmatrix} \sim (3, 2, 7/6) \qquad S_3 = \begin{pmatrix} \rho^{4/3} \\ \rho^{1/3} \\ \rho^{-2/3} \end{pmatrix} \sim (\bar{3}, 3, 1/3)$$

$$\Delta = \left(\Delta^{+++},\ \Delta^{++},\ \Delta^{+},\ \Delta^{0}\right)^T \sim (1, 4, 3/2)$$

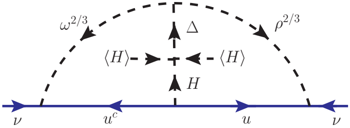
- The Yukawa couplings are given by

$$\mathcal{L}'_{Yuk} = f_{ab} u^c_a \psi^i_b R^j_2 \epsilon^{ij} - f'_{ab} Q^i_a e^c_b \widetilde{R}^j_2 \epsilon^{ij} + y_{ab} Q_a \tau_\alpha \psi_b S_{3\alpha} + \mathrm{H.c}$$

Neutrino Mass Generation



$\mathcal{O}_{\rm eff}^{d=7} = \psi\psi HHH^\dagger H$



$\mathcal{O}_{\rm eff}^{d=5} = \psi\psi HH$

- Neutrino mass matrix:

$$M_\nu = (\kappa_1 + \kappa_2)(f^T M_u V^* y + y^T V^\dagger M_u f)$$

$$\kappa_1 = \frac{1}{16\pi^2} \sin 2\varphi \log\left(\frac{M_2^2}{M_1^2}\right) \qquad \kappa_2 \approx \frac{1}{(16\pi^2)^2} \frac{\lambda_5 v \mu}{M_{1,2}^2}$$

Yukawa Textures

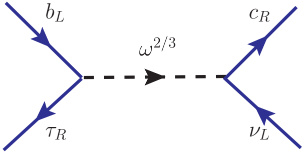
$$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f'_{32} & f'_{33} \end{pmatrix}, \; f = \begin{pmatrix} 0 & 0 & 0 \\ 0 & f_{22} & f_{23} \\ 0 & f_{32} & f_{33} \end{pmatrix}, \; y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & y_{23} \\ y_{31} & y_{32} & 0 \end{pmatrix}$$

f_{ab} ($a \rightarrow$ quark flavor, $b \rightarrow$ lepton flavor)

- $f'_{32} f_{32}$: $(g-2)_\mu$
- $f'_{33} f_{23} + f'_{33} f_{22}$: $R_D - R_{D^*}$
- f_{33} : `fine-tunning`
- $y_{22} y_{32}$: $R_K - R_{K^*}$
- y_{31}, y_{23} : ν `fit` $(\Delta m^2_{21}, \Delta m^2_{31}, \sin^2\theta_{13}, \sin^2\theta_{23}, \sin^2\theta_{12}, \delta_{CP})$

Charged Current Anomaly: R_D, R_{D^*}

- Assume the NP contributes to the transisiton $b \to c\ell\bar{\nu}$ is negligible to the electron and muon modes.



$R_2 \sim (3, 2, 7/6)$

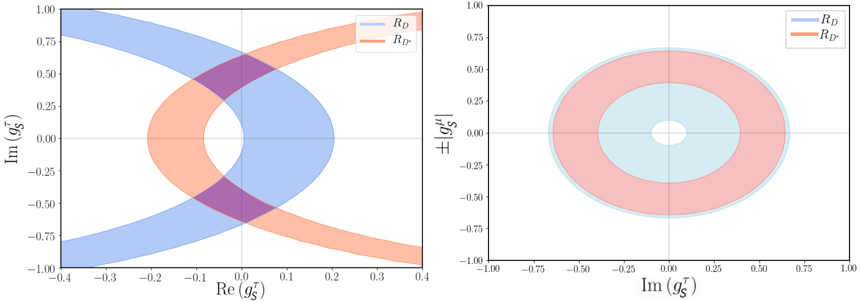
$R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1+g_V)(\bar{\tau}_L \gamma^\mu \nu_L)(\bar{c}_L \gamma_\mu b_L) + g_S(\mu)(\bar{\tau}_R \nu_L)(\bar{c}_R b_L) + g_T(\mu)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L)(\bar{c}_R \sigma_{\mu\nu} b_L) \right] + \text{H.c.}$$

- Taking $g_V > 0$ corresponds to an overall rescaling of the SM. The allowed 1σ range is (0.072, 0.11).

$R_D, \ R_{D^*}$

- Scalar LQ exchange leads to $g_s = \pm 4 g_T$ at scale $\mu = m_{LQ}$, which is of the order 1 TeV.



R_D, R_{D^*} (cont.)

$$g_S\left(\mu = m_{R_2}\right) = 4 g_T\left(\mu = m_{R_2}\right) = \frac{f_{2\alpha} f'^*_{33}}{4\sqrt{2} m^2_{R_2} G_F V_{cb}}$$

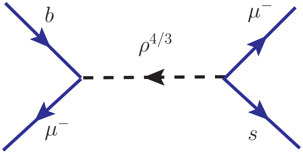
$$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & f'_{33} \end{pmatrix}, \; f = \begin{pmatrix} 0 & 0 & 0 \\ f_{21} & f_{22} & f_{23} \\ 0 & 0 & 0 \end{pmatrix}$$

- What about $S_3 \sim (\bar{3}, 3, 1/3)$ via $\rho^{1/3}$?

  It gives negative contribution to g_V, at odds with $R^{\text{exp}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}}$; also constrained by $D^0 - \bar{D}^0$ and $B \to K \nu \bar{\nu}$.

Neutral Current Anomaly R_K, R_{K^*}

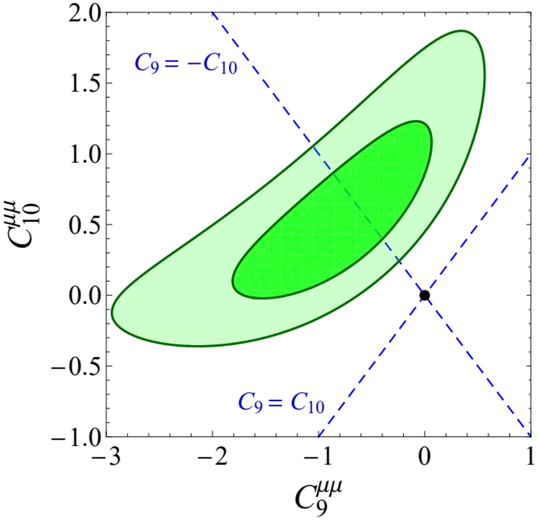
- Assume NP couplings to electron is negligible.



$S_3 \sim (\bar{3}, 3, 1/3)$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{(4\pi)^2} \left\{ C_9^{\mu\mu} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu P_L \mu) + C_{10}^{\mu\mu} (\bar{s}\gamma_\mu b)(\bar{\mu}\gamma^\mu \gamma^5 \mu) \right\}$$

$C_9 = -C_{10}$ preferred



Fitting $R_{K^{(*)}}$

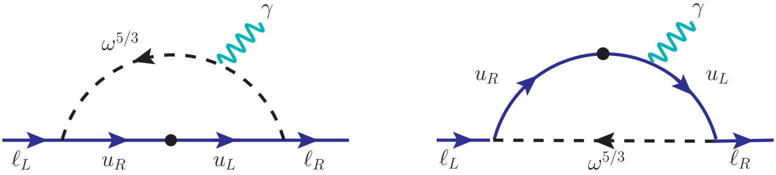
$$C_9 = -C_{10} = \frac{\pi v^2}{V_{tb} V_{ts}^* \alpha_{\rm em}} \frac{y_{22} y_{32}^*}{m_{S_3}^2}$$

$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{22} & 0 \\ 0 & y_{32} & 0 \end{pmatrix}$$

- What about $R_2 \sim (3, 2, 7/6)$ via $\omega^{2/3}$?

It would lead to $C_9 = C_{10}$ at tree-level, and leads to $R_{K^{(\star)}}^{\rm exp} > R_{K^{(\star)}}^{\rm SM}$, in conflict with experiment

Anomalous magnetic moment of Muon



$$\mathcal{L}_{\omega^{5/3}} = \bar{u}(fP_L + f'P_R)e\omega^{5/3} + \text{H.c.}$$

$$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f'_{32} & 0 \end{pmatrix}, \; f = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & f_{32} & 0 \end{pmatrix}$$

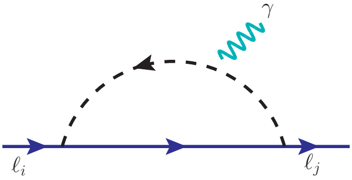
- For 1 TeV LQ mass, the required product of Yukawa is

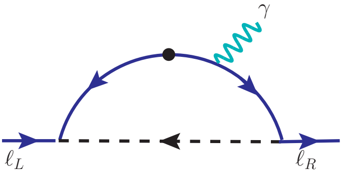
$$(g-2)_\mu : \qquad f_{32} f'_{32} = -0.0019$$

Experimental Constraints

- $\ell_i \to \ell_j \gamma$
- $\mu - e$ conversion
- $Z \to \tau\tau$ decay
- Rare D-meson Decay
- $D^0 - \bar{D}^0$ mixing
- Bounds from kaons
- Collider constraints

$\ell_i \to \ell_j \gamma$





$$\Gamma(\ell_\alpha \to \ell_\beta \gamma) = \frac{9 m_\alpha^5 \alpha}{16(16\pi^2)^2}\left[\frac{|f_{q\beta} f_{q\alpha}^*|^2}{4 m_{R_2}^4} + \frac{|y_{q\beta} y_{q\alpha}^*|^2}{9 m_{S_3}^4}\right]$$

$$\Gamma(\ell_\alpha \to \ell_\beta \gamma) = \frac{9\alpha}{144}\frac{|f'_{q\alpha} f_{q\beta}^* + f_{q\alpha} f'^*_{q\beta}|^2}{(16\pi^2)^2}\frac{m_\alpha^3}{m_{R_2}^4} m_q^2 \left(1 + 4\log\frac{m_q^2}{m_{R_2}^2}\right)^2$$

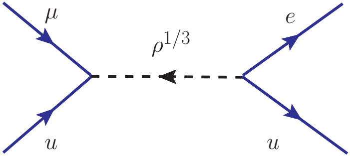
$\ell_i \to \ell_j \gamma$

Process	Exp. limit	Constraints	
		f	$f\hat{f}'$
$\mu \to e\gamma$	$Br < 4.2 \times 10^{-13}$	$\lvert f_{qe} f^*_{q\mu}\rvert < 4.82 \times 10^{-4} \left(\frac{m_R}{\text{TeV}}\right)^2$	$\lvert f_{t\mu} \hat{f}'^*_{te} + \hat{f}'_{t\mu} f^*_{te}\rvert < 3.49 \times 10^{-8} \left(\frac{m_R}{\text{TeV}}\right)^2$ $\lvert f_{c\mu} \hat{f}'^*_{ce} + \hat{f}'_{c\mu} f^*_{ce}\rvert < 1.15 \times 10^{-6} \left(\frac{m_R}{\text{TeV}}\right)^2$
$\tau \to e\gamma$	$Br < 3.3 \times 10^{-8}$	$\lvert f_{qe} f^*_{q\tau}\rvert < 0.32 \left(\frac{m_R}{\text{TeV}}\right)^2$	$\lvert f_{t\tau} \hat{f}'^*_{te} + \hat{f}'_{t\tau} f^*_{te}\rvert < 3.91 \times 10^{-4} \left(\frac{m_R}{\text{TeV}}\right)^2$ $\lvert f_{c\tau} \hat{f}'^*_{ce} + \hat{f}'_{c\tau} f^*_{ce}\rvert < 1.28 \times 10^{-2} \left(\frac{m_R}{\text{TeV}}\right)^2$
$\tau \to \mu\gamma$	$Br < 4.4 \times 10^{-8}$	$\lvert f_{q\mu} f^*_{q\tau}\rvert < 0.37 \left(\frac{m_R}{\text{TeV}}\right)^2$	$\lvert f_{t\tau} \hat{f}'^*_{t\mu} + \hat{f}'_{t\tau} f^*_{t\mu}\rvert < 4.51 \times 10^{-4} \left(\frac{m_R}{\text{TeV}}\right)^2$ $\lvert f_{c\tau} \hat{f}'^*_{c\mu} + \hat{f}'_{c\tau} f^*_{t\mu}\rvert < 1.48 \times 10^{-2} \left(\frac{m_R}{\text{TeV}}\right)^2$

- Constraints on Yukawa coupling y $(V^* y)$ of LQ S_3 arising from $\bar{d}^c_L e_L \rho^{4/3}$ $(\bar{u}^c_L e_L \rho^{1/3})$ are weaker by factor of 3/2 (18) in comparison to f Yukawa coupling.

$\mu - e$ conversion

- LQs S_3, via CKM rotation, are subjected to cLFV process from coherent $\mu - e$ conversion in the nuclei.

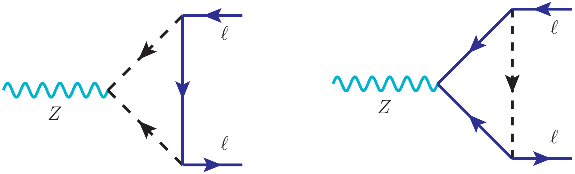


- The experimental limt for gold nuclei provides most stringent bound of $BR < 7.0 \times 10^{-13}$ providing constraint on the Yukawa as follows

$$\left|(V^\star y)_{11}(y^\star V)_{12}\right| < 8.58 \times 10^{-6} \left(\frac{m_{S_3}}{\text{TeV}}\right)^2$$

$Z \to \tau\tau$ decay

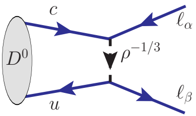
- $Z-$boson decay to pair of leptons via one-loop radiative diagrams mediated by LQs put yet another important constraints on the Yukawa couplings

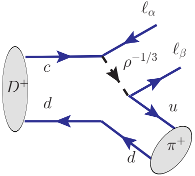


$$\mathcal{L} = \bar{u}(V^* f') P_R e \omega^{5/3} + \bar{d} f' P_R e \omega^{2/3} + \text{H.c.}$$

$$\boxed{|f'_{33}| \leq 0.854\,(1.22)}$$

Rare D Meson decays





$$\mathcal{L}_Y \supset u^T \left(V^* y\right) e \frac{\rho^{1/3}}{\sqrt{2}} + \text{H.c.}$$

$$\Gamma_{D^0\to\mu\mu} = \frac{|y_{22}|^4\,|V_{us}V_{cs}^*|^2}{128\pi}\frac{m_\mu^2 f_D^2 m_D}{m_{S_3}^4}\left(1-\frac{4m_\mu^2}{m_D^2}\right)^{1/2} \Longrightarrow |y_{22}| < 0.797\left(\frac{M_{S_3}}{\text{TeV}}\right)$$

$$\Gamma_{D^+\to\pi^+\mu\mu} = \left[\frac{|y_{22}|^2}{4m_{R_2}^2}\frac{f_D}{f_\pi}g_{D^*D\pi}|V_{us}V_{cs}^*|\right]^2\frac{1}{64\pi^3 m_D}\mathcal{F} \Longrightarrow |y_{22}| < 0.414\left(\frac{m_{R_2}}{\text{TeV}}\right)$$

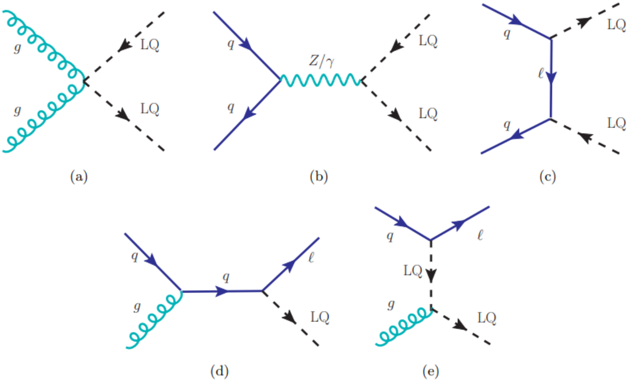
Other Constraints

- $D^0 - \bar{D}^0$ mixing :

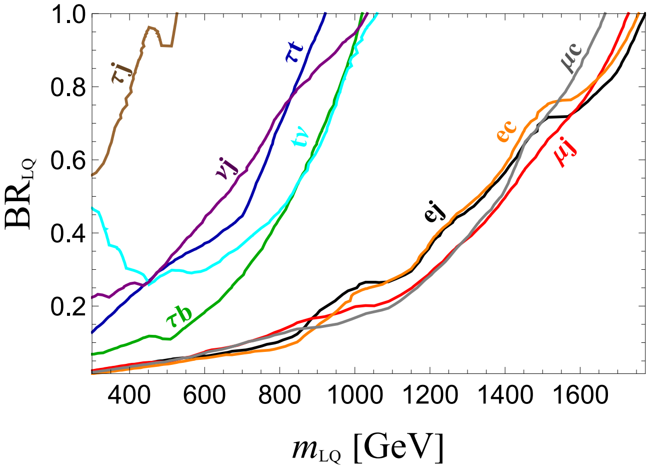
$$|f_{2\alpha} f_{1\beta}| < 0.0137 \left(\frac{m_{R_2}}{\text{TeV}}\right)^2, \qquad |y_{1\alpha}|, |y_{2\alpha}| < 0.250 \left(\frac{m_{S_3}}{\text{TeV}}\right)$$

- Bounds from Kaon
  - $K_L \to ee \Longrightarrow |f'_{21}| < 0.096 \left(\frac{M_{R_2}}{\text{TeV}}\right)$
  - $K_L \to \mu\mu \Longrightarrow |f'_{32}| < 0.38 \left(\frac{M_{R_2}}{\text{TeV}}\right)$
  - $K_L \to e^\pm \mu^\mp \Longrightarrow |f'_{21} f'_{32}| < 1.11 \times 10^{-3} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$
  - $K^+ \to \pi^+ \mu^+ e^- \Longrightarrow |f'_{21} f'_{32}| < 2.3 \times 10^{-2} \left(\frac{M_{R_2}}{\text{TeV}}\right)^2$

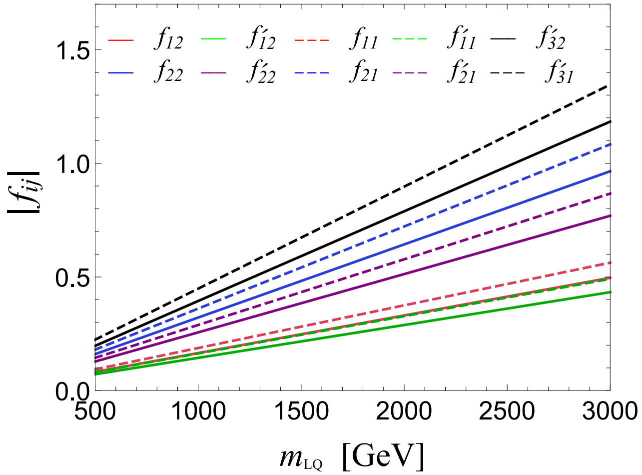
LQ Pair production at LHC



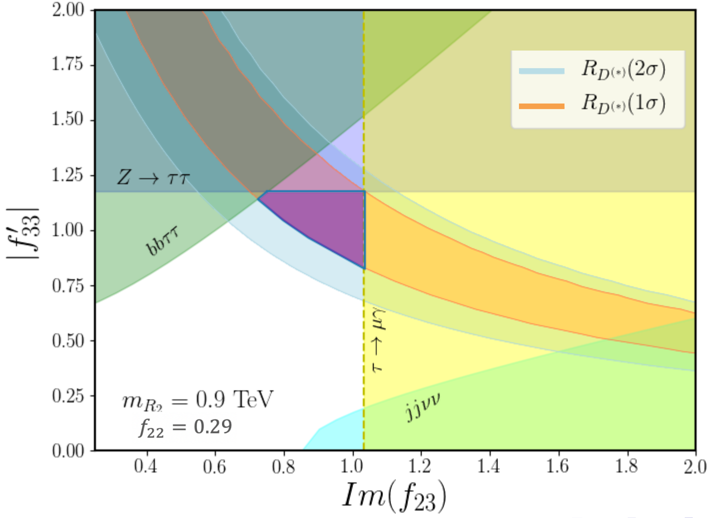
LHC Limits on LQ Mass



Bounds from $pp \to \ell_i^+ \ell_j^-$



Fit to $R_{D(*)}$



$R_{D^{(*)}}(2\sigma)$
$R_{D^{(*)}}(1\sigma)$
$Z \to \tau\tau$
$bb\tau\tau$
$\tau \to \mu\gamma$
$jj\nu\nu$
$m_{R_2} = 0.9$ TeV
$f_{22} = 0.29$
$|f'_{33}|$
$Im(f_{23})$
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

Numerical Fit

$M_{R_2} = 0.9\,\mathrm{TeV}, \;\; M_{S_3} = 2.0\,\mathrm{TeV}$

- $$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -0.29 & 1.06 \end{pmatrix} \qquad f = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.29 & 0.886i \\ 0 & 0.0059 & 0.0226 \end{pmatrix}$$

$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.124 & 0.064 \\ -0.016 & 0.028 & 0 \end{pmatrix} \qquad (\mathtt{TX-I})$$

- $$f' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -0.29 & 1.06 \end{pmatrix} \qquad f = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.29 & 0.887i \\ 0 & 0.0061 & 0.0215 \end{pmatrix}$$

$$y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.22 & 0 \\ 0.026 & 0.0155 & -0.035 \end{pmatrix} \qquad (\mathtt{TX-II})$$

Neutrino oscillation fit

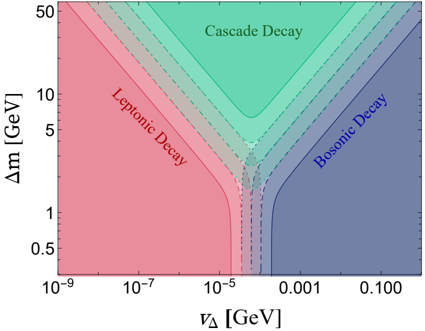
Oscillation parameters	3 σ allowed range from NuFit4.1	Model `Fit I`	Model `Fit II`
$\sin^2\theta_{12}$	0.275 - 0.350	0.290	0.324
$\sin^2\theta_{13}$	0.02046 - 0.02440	0.0235	0.0210
$\sin^2\theta_{23}$	0.427 - 0.609	0.472	0.430
Δm^2_{21} $(10^{-5} eV^2)$	6.79 - 8.01	7.39	7.45
Δm^2_{23} $(10^{-3} eV^2)$	2.432 - 2.618	2.54	2.49
δ	$[-3.41, -0.03]$	-0.53	-0.65
Observable	1σ **range**		
R_D	$0.303 - 0.365$	0.34	0.34
$R_{D\star}$	$0.282 - 0.312$	0.282	0.282
$C_9 = -C_{10}$	$[-0.61, -0.45]$	-0.52	-0.51
$(g-2)_\mu$ (10^{-9})	2.97 ± 0.73	2.97	3.44

Collider Implications, Higgs quadruplet Δ

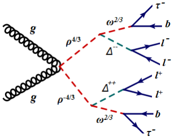
- Doubly charged scalar can decay into $W^{\pm}W^{\mp}$ and into pair of leptons.

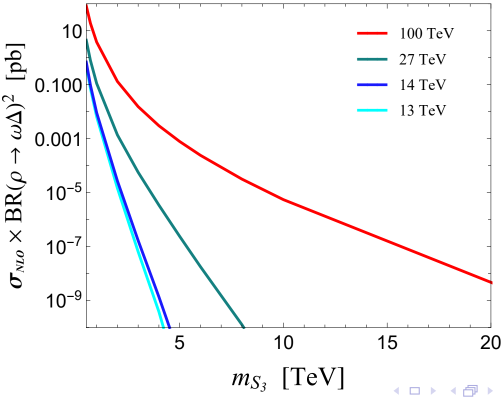
$$\Gamma\left(\Delta^{\pm\pm} \to l_i^{\pm} l_j^{\pm}\right) \sim \frac{m_\nu}{v_\Delta}.$$

- If the mass splitting between quadruplet members are non-zero $\longrightarrow$ leads to cascade decay via $\Delta^{\pm}X^{\pm}$or $\Delta^{\pm\pm\pm}X^{\mp}$ (where $X = \pi, W^*$).



Higgs quadruplet Δ





Neutrino Magnetic Moment and Muon g-2

- Neutrino magnetic moment of order $2 \times 10^{-11} \mu_B$ can explain the excess in electron recoil observed by XENON1T in $(1 - 7)$ keV energy range
- Such a large neutrino magnetic moment generally will lead to neutrino mass of order 0.1 MeV
- One way to decouple neutrino mass from its magnetic moment is to use an SU(2) symmetry that transforms ν_e into ν_μ Voloshin (1988); Babu, Mohapatra (1989)
- An $SU(2)_H$ symmetric neutrino magnetic moment model has been proposed to explain XENON1T Babu, Jana, Lindner (2020)
- This model gives the right magnitude and sign for muon g-2 as well Babu, Jand, Lindner, Vishnu (2021)

$SU(2)_H$ Model for Neutrino mag. mom.

- $SU(2)_L \times U(1)_Y \times SU(2)_H$ as an approximate symmetry:

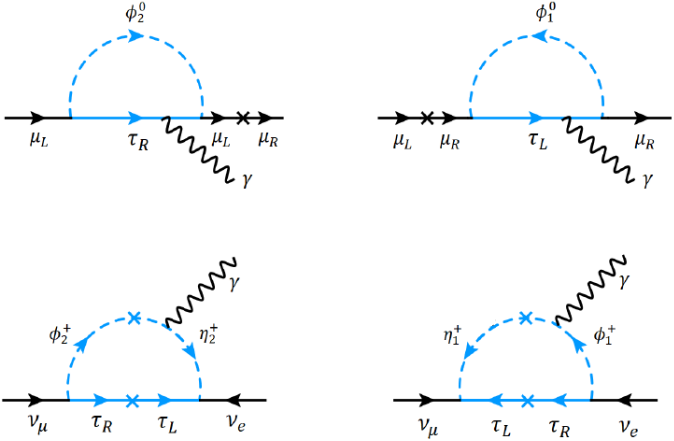
$$\psi_L = \begin{pmatrix} \nu_e & \nu_\mu \\ e & \mu \end{pmatrix}_L \sim (2, -\frac{1}{2})(2), \quad \psi_R = (e \quad \mu)_R \sim (1, -1)(2)$$

$$\psi_{3L} = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \sim (2, -\frac{1}{2})(1), \quad \tau_R \sim (1, -1)(1)$$

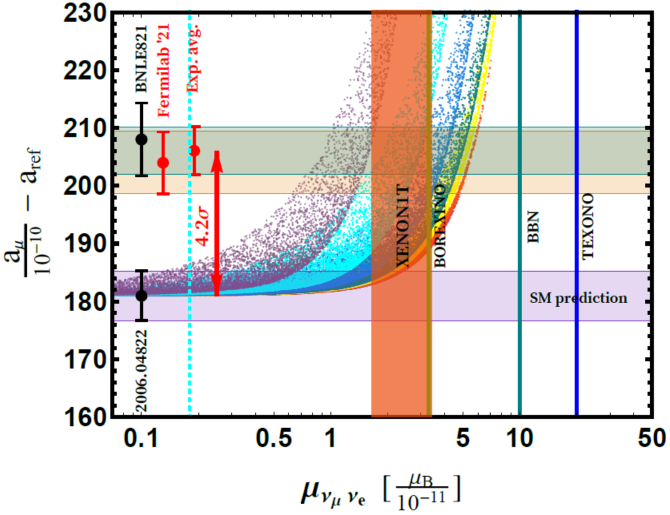
- Higgs fields:

$$\phi_S = \begin{pmatrix} \phi_S^+ \\ \phi_S^0 \end{pmatrix} \sim (2, \frac{1}{2})(1), \quad \Phi = \begin{pmatrix} \phi_1^+ & \phi_2^+ \\ \phi_1^0 & \phi_2^0 \end{pmatrix} \sim (2, \frac{1}{2})(2), \quad \eta = (\eta_1^+ \quad \eta_2^+) \sim (1, 1)(2).$$

$SU(2)_H$ Model for Neutrino mag. mom.



Muon g-2 and neutrino magnetic moment



Conclusions

- Simple one loop neutrino mass model utilizes TeV scale LQ and explains B- anomalies
- Same model simultaneously explains the muon $g-2$ anomaly
- The model also utilizes Higgs quadruplet Δ, which provides interesting new collider signals
- The model is in consistent with observed neutrino oscillation data
- A new model that explains naturally large neutrino magnetic moment predicts muon g-2 of the correct sign and magnitude

Thank You