Institut "Jožef Stefan", Ljubljana, Slovenija

University of Ljubljana
Faculty of Mathematics and Physics

Anomalies in B meson decays

Nejc Košnik

Getting to Grips with QCD, Primošten, Sep. 21 2018

Outline

- Standard model and lepton flavor universality
- ``Ordinary'' decay $B \to D^{(*)} \tau\nu$
- Rare decay $B \to K^{(*)}\mu^+\mu^-$
- New Physics solution with two leptoquarks

Flavors in the Standard model

- Standard model contains 3 identical copies of fermionic matter

$$\mathcal{L} = \mathcal{L}_{\text{kin.}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

- Flavor symmetry of gauge interactions

$$U(3)^5 \sim U(3)_Q \otimes U(3)_L \otimes U(3)_u \otimes U(3)_d \otimes U(3)_e$$

$$\mathcal{L}_{\text{kin.}} = \sum_{i=1}^{3} \sum_{f\in\{Q,u,d,L,e\}} \bar{f}_i i \not{D} f_i + \cdots$$

an example of flavor transform: $Q_i \to e^{i\alpha_0}[\exp(i\lambda_a \alpha_a)]_{ij} Q_j$

- Yukawa couplings break the flavor symmetry. Only Higgs knows the leptons and quarks by flavor.

$$\mathcal{L}_{\text{Yukawa}} = -y_{ij}^{(u)} \bar{Q}_i \tilde{H} u_j - y_{ij}^{(d)} \bar{Q}_i H d_j - y_{ij}^{(e)} \bar{L}_i H e_j \qquad U(1)_B \otimes U(1)_e \otimes U(1)_\mu \otimes U(1)_\tau$$

diagonalization of Yukawa matrices reveals physical masses

- The SM flavor puzzle: — huge hierarchies in the fermion masses
  — structure of the CKM matrix
  — neutrino sector?

Lepton flavor universality

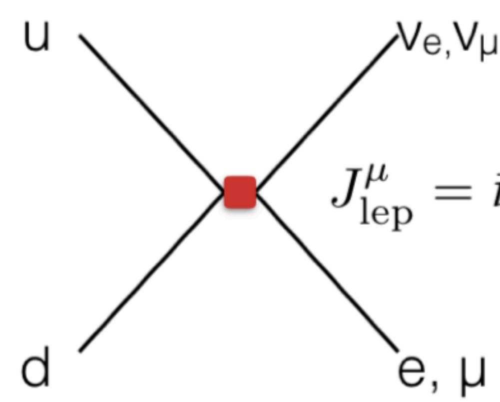
- Weak interactions are lepton flavor universal (contrary to the CKM mixing of quarks). The only distinguishing property between lepton generations are masses

$$\mathcal{L}_{\rm kin} = -\frac{g}{\sqrt{2}}\left(\bar{\nu}_e\gamma^\mu\frac{1-\gamma^5}{2}e + \bar{\nu}_\mu\gamma^\mu\frac{1-\gamma^5}{2}\mu + \bar{\nu}_\tau\gamma^\mu\frac{1-\gamma^5}{2}\tau\right)W^+_\mu + \cdots$$

- Lepton flavor universality (LFU) first observed within the Fermi theory

$$G_F^e \approx G_F^\mu$$

$$J^\mu_{\rm quark} = \bar{n}\gamma^\mu(1-a\gamma_5)p$$



$$J^\mu_{\rm lep} = \bar{\nu}_e\gamma^\mu(1-\gamma_5)e + \bar{\nu}_\mu\gamma^\mu(1-\gamma_5)\mu$$

$$\frac{G_F}{\sqrt{2}}J_{{\rm lep},\mu}J^\mu_{\rm had}$$

- LFU tested in many observables

High energy probe at LEP: Z → ee, $\mu\mu$, $\tau\tau$

$$\Gamma_{ll}^{SM} = \frac{GM_Z^3}{6\sqrt{2}\pi}\left((C_V^f)^2 + (C_A^f)^2\right) = 83.42\text{MeV}$$

$$C_V^\ell = -1$$

$$C_A^\ell = -1 + 4\sin^2\theta_W$$

$$\Gamma_{ee} = (83.94 \pm 0.14)\text{MeV}$$

$$\Gamma_{\mu\mu} = (83.84 \pm 0.20)\text{MeV}$$

$$\Gamma_{\tau\tau} = (83.68 \pm 0.24)\text{MeV}$$

Tests of LFU

- LFU ratios largely cancel out non-perturbative effects of QCD

$$\Gamma_{P\to\ell\nu} \sim G_F^2 |V_{ij}|^2 f_P^2 m_P {m_\ell}^2 \underbrace{\left(1-\frac{{m_\ell}^2}{m_P^2}\right)}_{\text{chiral SM interaction}} \underbrace{\left(1-\frac{{m_\ell}^2}{m_P^2}\right)}_{\text{phase space}}$$

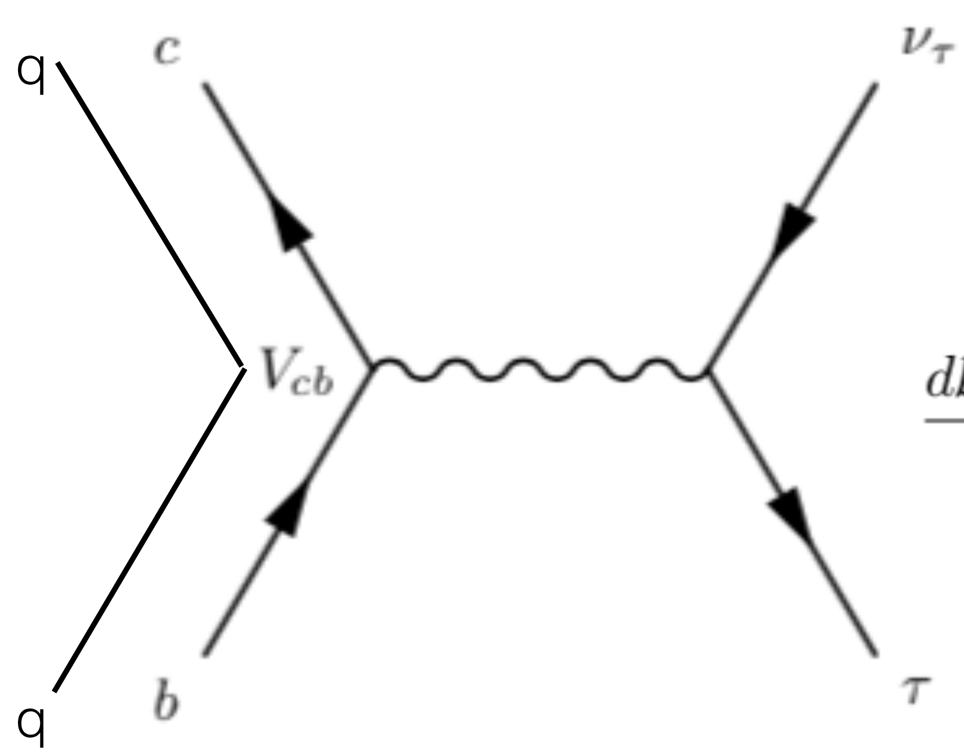
f_P = meson decay constant

- Tested to per-mille level in the first two generations

	SM	exp. value
$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi\to e\bar\nu)}{\Gamma(\pi\to\mu\bar\nu)}$	$(1.2352 \pm 0.0001)\times 10^{-4}$	$(1.2327 \pm 0.0023)\times 10^{-4}$
$R^{K}_{e/\mu} = \frac{\Gamma(K\to e\bar\nu)}{\Gamma(K\to\mu\bar\nu)}$	$(2.477 \pm 0.001)\times 10^{-5}$	$(2.488 \pm 0.010)\times 10^{-5}$
$R^{K}_{\tau/\mu} = \frac{\Gamma(\tau\to K\bar\nu)}{\Gamma(K\to\mu\bar\nu)}$	$(1.1162 \pm 0.00026)\times 10^{-2}$	$(1.101 \pm 0.016)\times 10^{-2}$
$R^{B}_{\tau/\mu} = \frac{\Gamma(B\to\tau\nu)}{\Gamma(B\to\mu\bar\nu)}$	223	$\gtrsim 100$

The LFU ratio $R_{D^{(*)}}$

LFU in b → cℓν



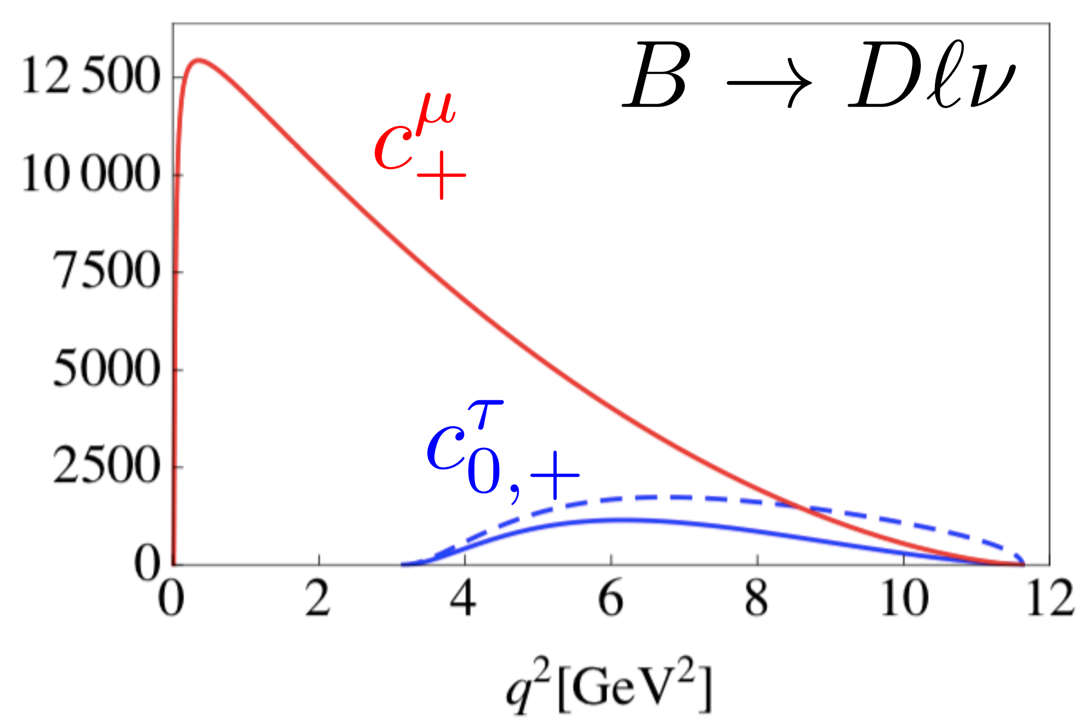
$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{cb}\,(\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell)$$

$$\frac{d\mathcal{B}(\bar{B}\to D\ell\bar{\nu}_\ell)}{dq^2} = \tau_{B^0}\frac{G_F^2|V_{cb}|^2}{192\pi^3 m_B^3}\left[c_+^\ell(q^2)|F_+(q^2)|^2 + c_0^\ell(q^2)|F_0(q^2)|^2\right]$$

B^+ DECAY MODES		Fraction (Γ_i/Γ)	Scal Confide
		Semileptonic and leptonic modes	
$\ell^+\nu_\ell$ anything	[a]	(10.99 ± 0.28) %	
$e^+\nu_e X_c$		(10.8 ± 0.4) %	
$D\,\ell^+\nu_\ell$ anything		(8.4 ± 0.5) %	
$\overline{D}^0\ell^+\nu_\ell$	[a]	(2.20 ± 0.10) %	
$\overline{D}^0\tau^+\nu_\tau$		(7.7 ± 2.5) $\times 10^{-3}$	

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

LFU is badly broken as $m_\mu < m_\tau \sim m_B$



b → cℓν universality, exp. Vs. SM

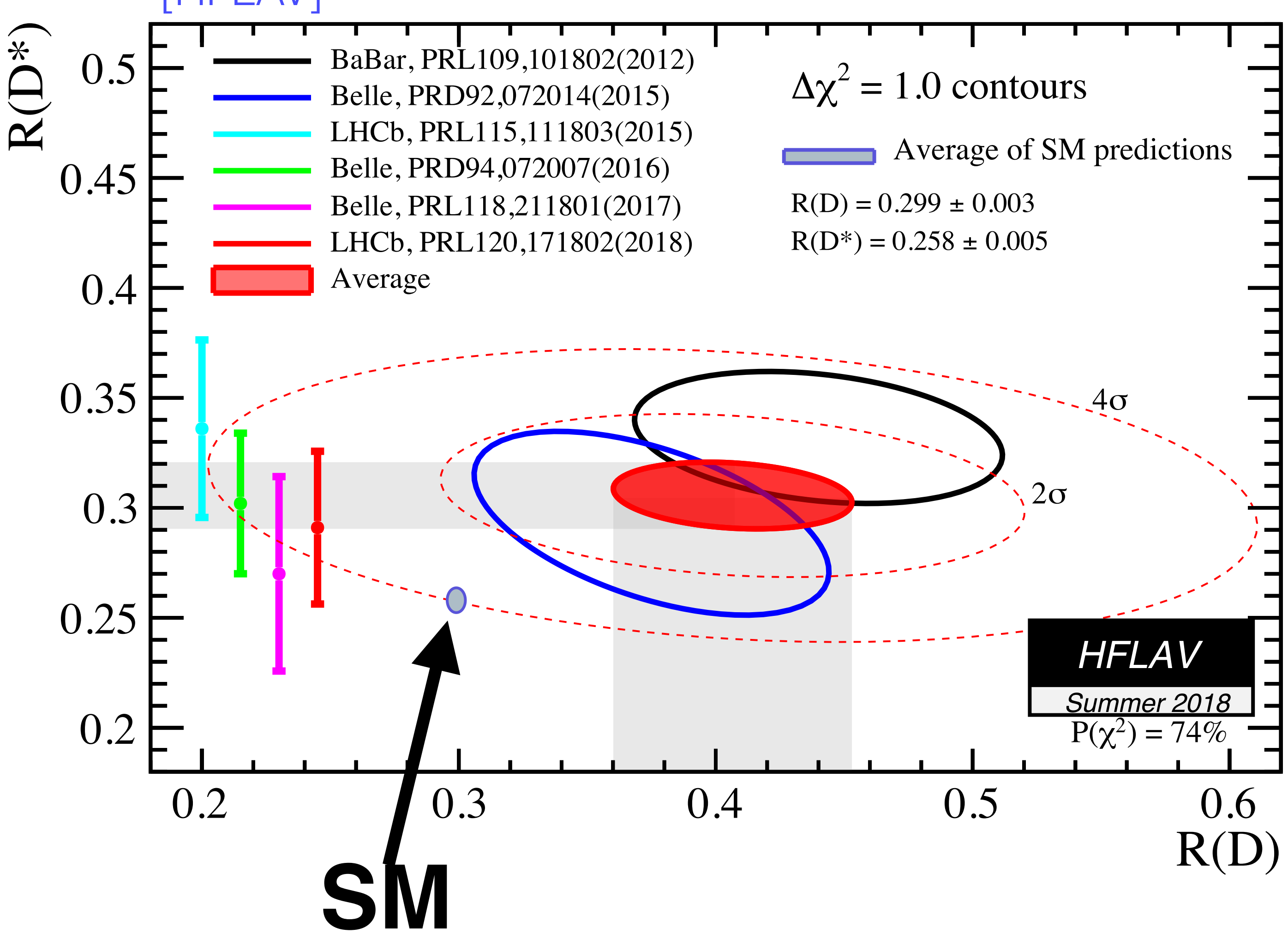
QCD nonperturbative effects cancel partially

$$R_D^{\rm SM} = 0.29(1)$$ ← lattice form factors of MILC and HPQCD

$$R_{D^*}^{\rm SM} = 0.257(3)$$ ← heavy quark symmetry + power + α_s corrections fitted to measured Belle spectra of ℓ=e, μ

[Bernlochner et al, 1703.05330]

[HFLAV]



+ angular observables in B → D*$\tau\nu$

+Similar trend in

$$R_{J/\psi}^{\rm SM} < 0.71(17)(18)$$

[Cohen et al, '18, LHCb]

See the afternoon talks by Andrey, Damir, Elena

World average excludes the SM point at 4σ

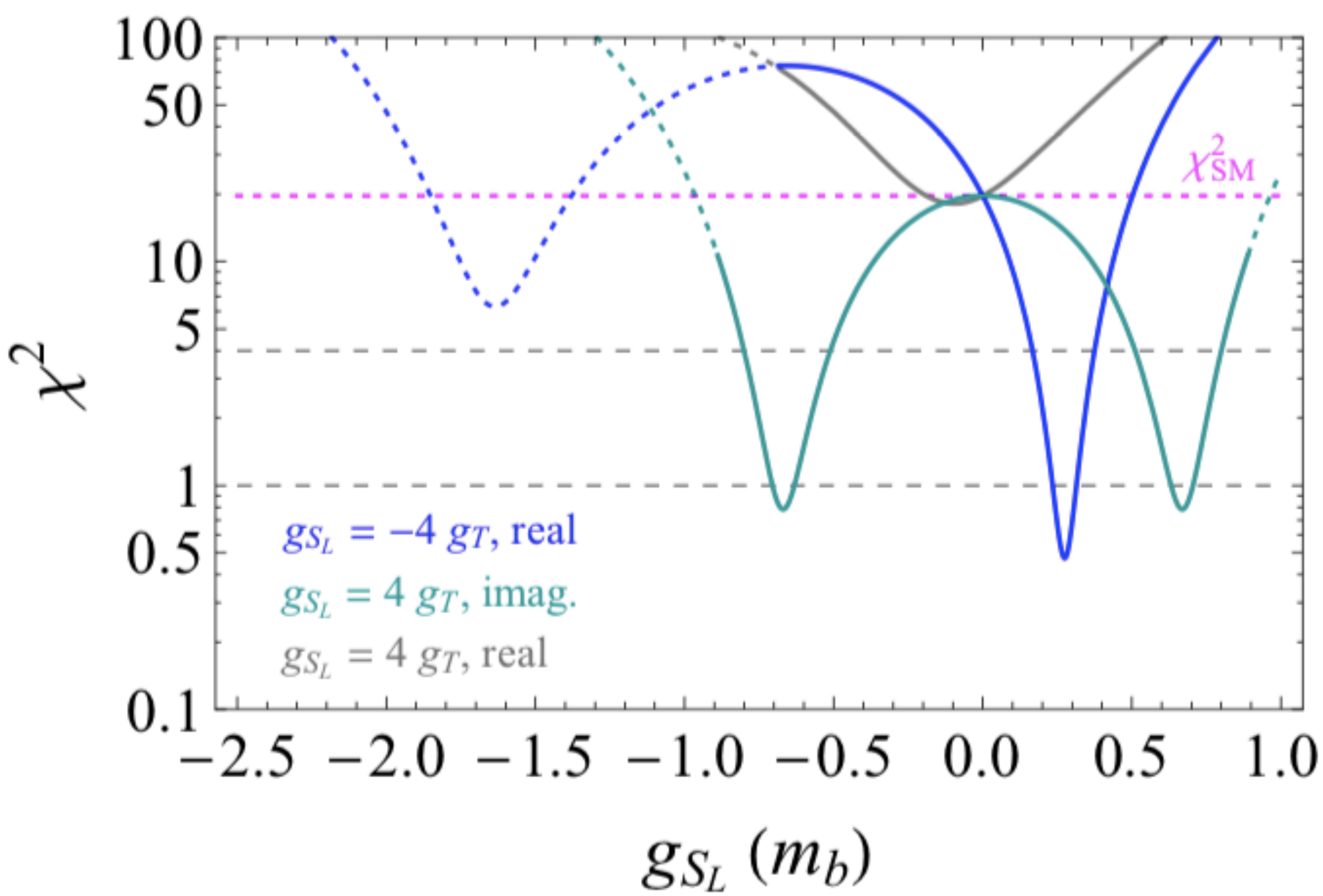
b → cℓν universality, heavy NP

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cb} \big[(1 + g_{V_L})(\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma_\mu P_L \nu_\tau) + g_{S_L}(\bar{c} P_L b)(\bar{\tau} P_L \nu_\tau) + g_{S_R}(\bar{c} P_R b)(\bar{\tau} P_L \nu_\tau) + g_T(\bar{c}\sigma_{\mu\nu} P_L b)(\bar{\tau}\sigma^{\mu\nu} P_L \nu_\tau) \big]$$

Assuming negligible contribution of NP to $b \to ce\nu$, $c\mu\nu$, motivated by $R_{D^{(*)}}^{\mu/e} \approx 1$

Particular choice of NP direction, implemented in the scalar LQ scenarios.

Indication of complex effective couplings in $g_S = 4\, g_T$

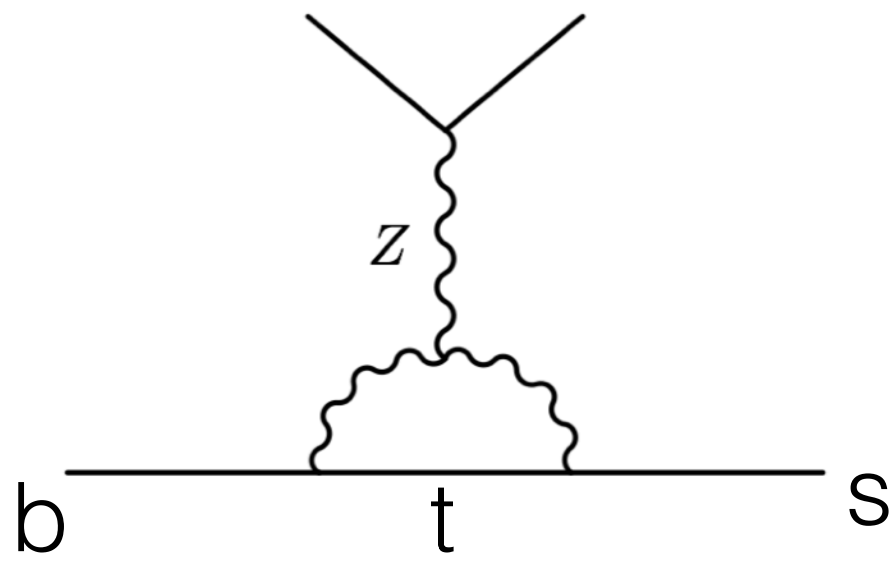


[Angelescu, Becirevic, Faroughy, Sumensari, 1808.08179]

The LFU ratio $R_{K^{(*)}}$ and related anomalies

LFU in B→K(*)ℓ+ℓ-

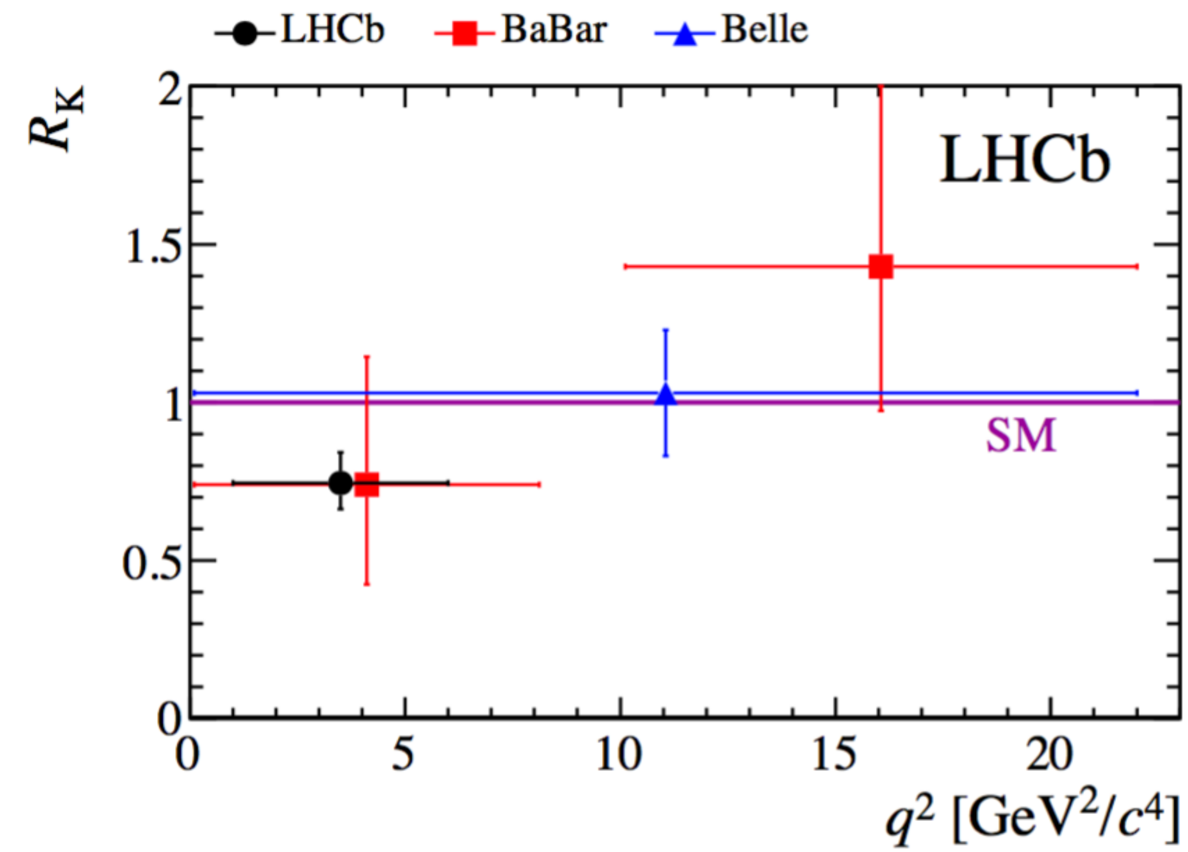
GIM suppressed, Br(B→Kℓℓ) ~ 4x10-7
Sensitive to New Physics

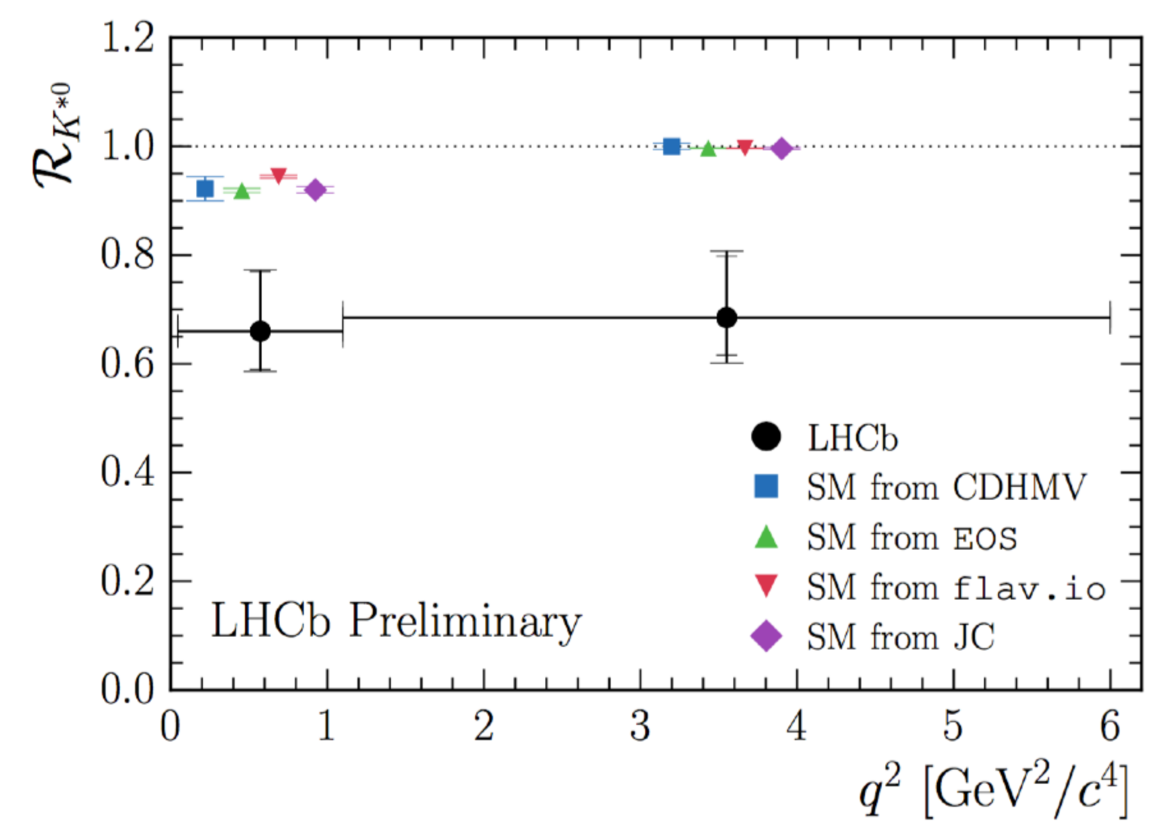


$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

Hadronic uncertainties cancel out effectively:

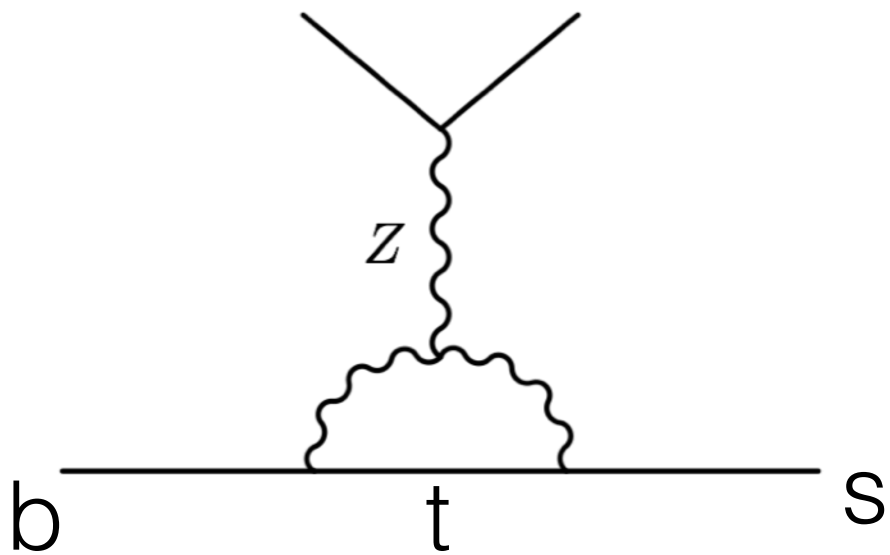
	LHCb	SM	dev.
R_K	0.745(97)	1.00(1)	2.6σ
$R_{K^*\mathrm{low}}$	0.660(113)	0.906(28)	2.1σ
R_{K^*}	0.685(122)	1.00(1)	2.6σ
			$\sim \mathbf{4\sigma}$





[Kruger, Hiller '03]
[LHCb '14, '16]
[Bordone, Isidori, Pattori '16]

$B \to K^{(*)} \ell^+ \ell^-$



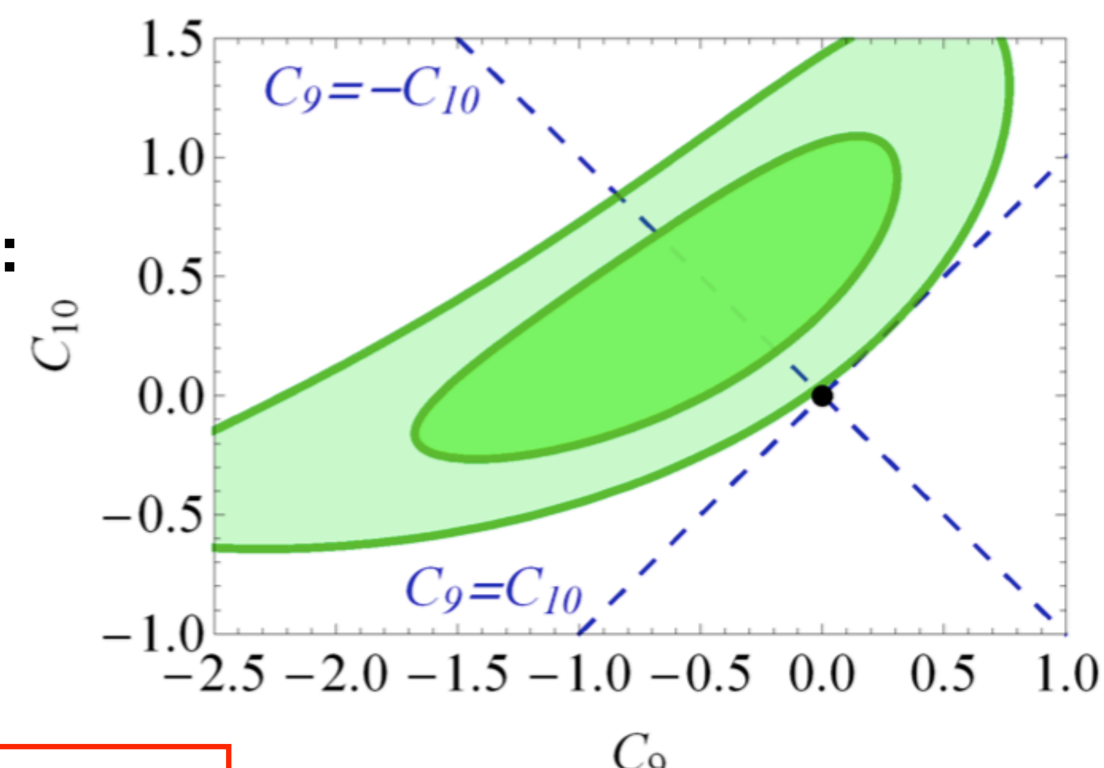
$$\mathcal{H}_{\text{eff}}^{b\to sll} = -\frac{4G_F\lambda_t}{\sqrt{2}} \sum_{i=7,9,10} C_i(\mu)\mathcal{O}_i(\mu)$$

$$\mathcal{O}_{9(10)} = \frac{e^2}{(4\pi)^2}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{l}\gamma^\mu(\gamma^5)l\right) \quad \text{vector(axial)}$$

$$\mathcal{O}_7 = \frac{em_b}{(4\pi)^2}\left(\bar{s}_L\sigma_{\mu\nu}F^{\mu\nu}b_R\right) \quad \text{dipole}$$

Assume that NP modifies $C_{9,10}$ of muons

Consider theoretically reliable observables:
R_K, R_{K^*},
$B_s \to \mu\mu$,
$B \to K\mu\mu$
partial width at $q^2 > 15$ GeV^2



Anomaly in R_K, R_{K^*} is consistent with measurements of branching fractions in the $\mu\mu$ channel

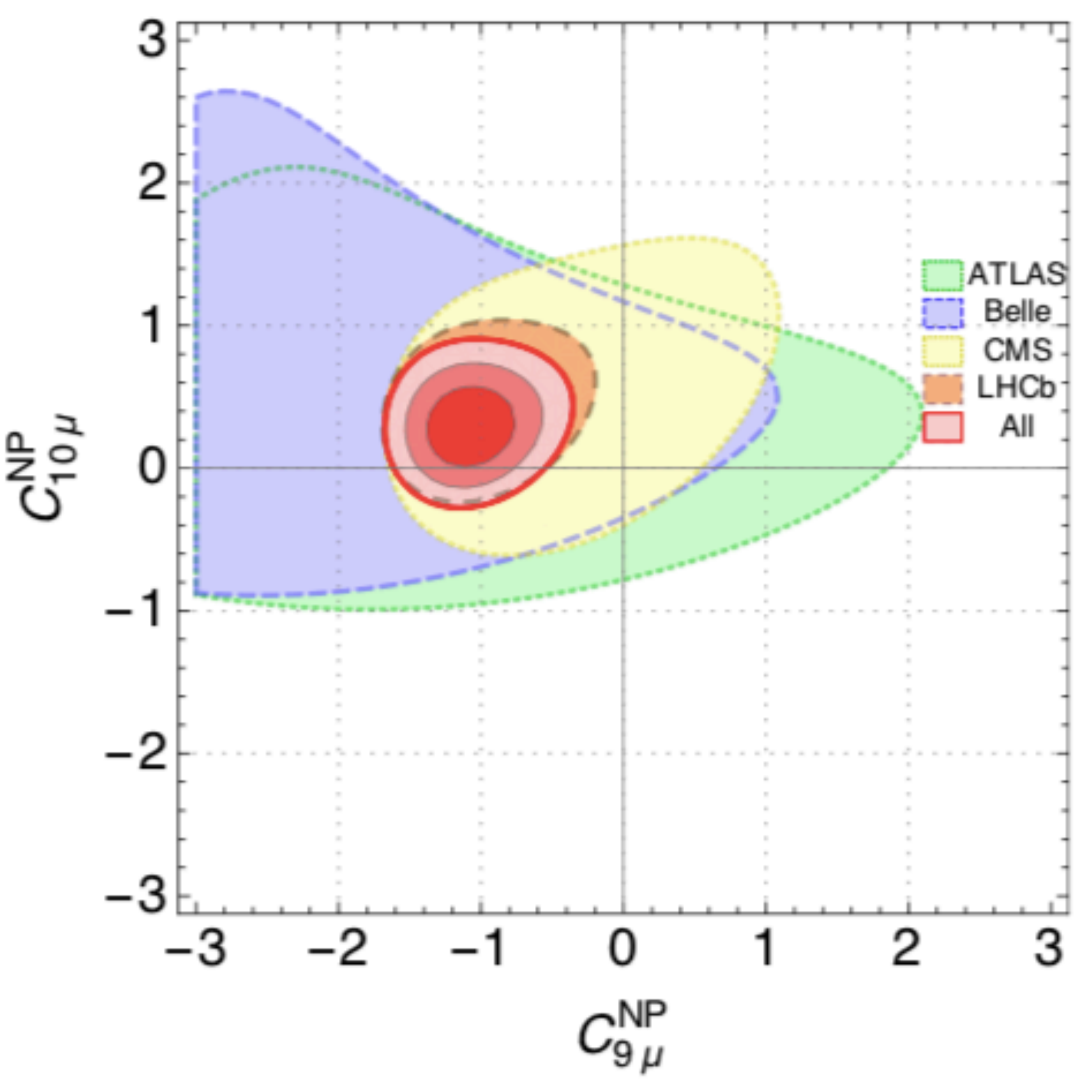
$b \to s \ell^+ \ell^-$ global fits

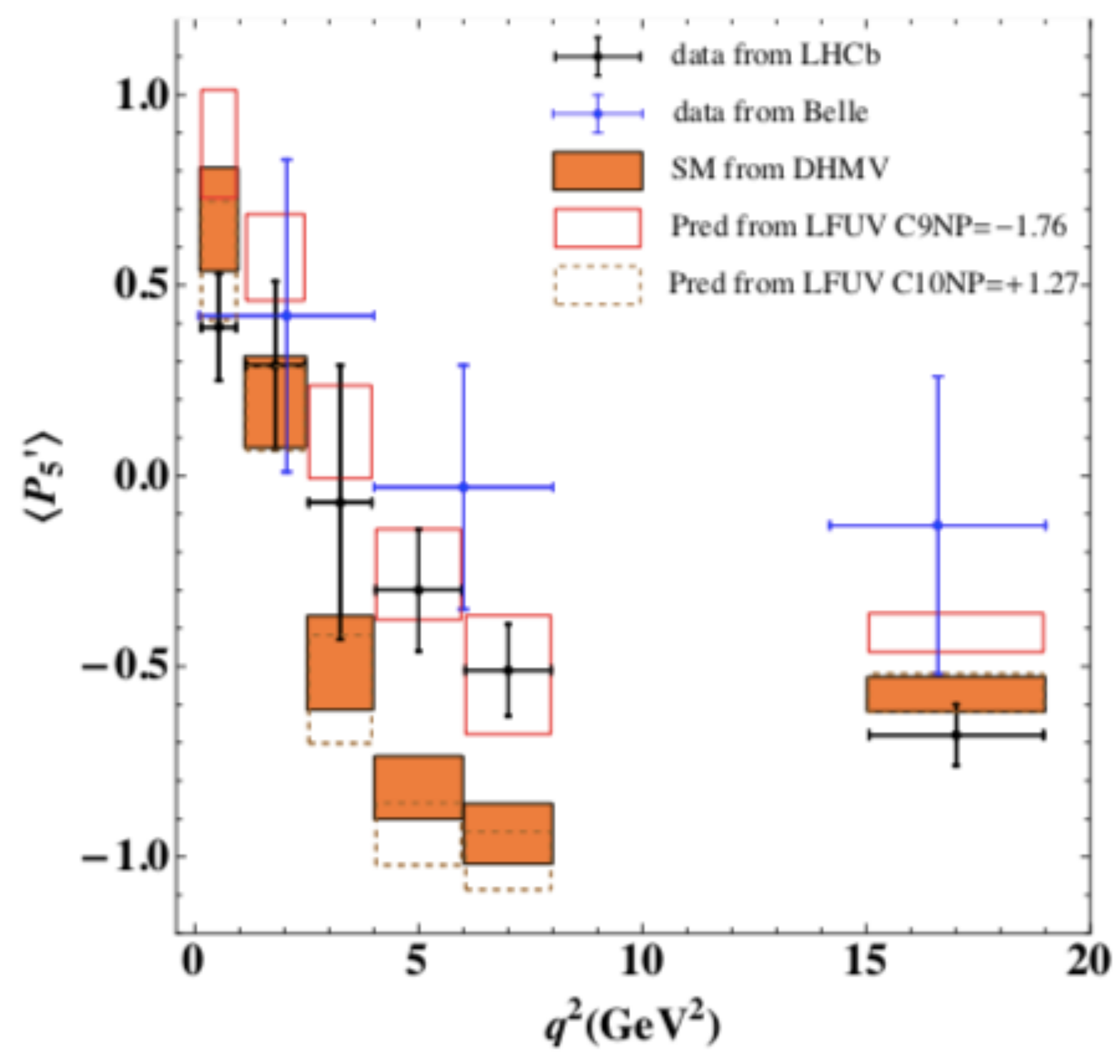
Theoretically less reliable observables also show deviations which are consistent with the expectation from LFU anomaly

-spectra

-angular distributions

-e+e- data are included





[Capdevilla et al '17]

Model with two scalar leptoquarks from GUT

Implications for New Physics

- $R_{K^{(*)}} \sim 10\%$ modification of the 1-loop GIM-suppressed amplitude
- $R_{D^{(*)}} \sim 10\%$ effect on the tree-level W exchange V_{cb}.
- *Can the two effects have common NP origin?*

$\rightarrow$ What are typical mass scales of NP addressing the two LFUV phenomena? (Assume NP contributes to the SM operator with coupling 1)

$R_{K^{(*)}}$ $(b \to s\mu\mu)$

- SM: $\approx \frac{G_F V_{ts} V_{tb} \alpha}{(4\pi)} (\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu \mu)$

$\Rightarrow$ 1-loop NP: $\frac{1}{(4\pi)^2 \Lambda^2} \Rightarrow \Lambda \approx 3\ \mathrm{TeV}$

$\Rightarrow$ Tree-level NP: $C_9 \sim \frac{1}{\Lambda^2} \Rightarrow \Lambda \approx 30\ \mathrm{TeV}$

$R_{D^{(*)}}$ $(b \to c\tau\nu)$

- SM: $\frac{G_F V_{cb}}{\sqrt{2}} (\bar{c}b)_{V-A} (\bar{\ell}\nu)_{V-A}$

$\Rightarrow$ Tree-level NP: $\frac{1}{\Lambda^2} \Rightarrow \Lambda \approx 3\ \mathrm{TeV}$

How to explain different sizes of the effects?

1. Different scales of NP for $R_{K^{(*)}}$ and $R_{D^{(*)}}$
2. Loop ($R_{K^{(*)}}$) Vs. tree ($R_{D^{(*)}}$)
3. Suppression of NP couplings in $R_{K^{(*)}}$ compared to $R_{D^{(*)}}$

Identifying a viable model

- Effective theory analysis focused on left-handed current operators

$$\frac{C_1}{\Lambda^2}(\bar{Q}_3\gamma^\mu Q_3)(\bar{L}_3\gamma_\mu L_3) + \frac{C_3}{\Lambda^2}(\bar{Q}_3\boldsymbol{\sigma}\gamma^\mu Q_3)\cdot(\bar{L}_3\boldsymbol{\sigma}\gamma_\mu L_3)$$

[Buttazzo et al '17, Bhattacharya et al '14, Feruglio et al '16]

- As a single mediator particle, vector leptoquark $U_1(3,1,2/3)$ is singled out [Buttazzo et al '17]
- UV complete setting needed (Pati-Salam, 4321 model) [Assad et al '17, Bordone et al '17,18, Greljo et al '18, Di Luzio et al '17, Blanke, Crivellin et al '18, Calibbi et al '17]

- Scalar LQs are not UV sensitive, however single LQ does not work
- Two scalar LQs can generate left-handed operators and solve the B-anomalies [Crivellin '17]
- Two scalar LQs can also contribute to alternative Lorentz structures, no UV complete model available

Two light scalar LQ model

- SM + 2 leptoquarks at 1 TeV, guided by $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

$$R_2(3,2,7/6): \quad Y_R^{ij}\bar{Q}_i'\ell_{Rj}'R_2 + Y_L^{ij}\bar{u}_{Ri}'\widetilde{R}_2^\dagger L_j'$$

$$\text{mass basis} \rightarrow (VY_RE_R^\dagger)^{ij}\bar{u}_{Li}\ell_{Rj}R_2^{\frac{5}{3}} + (Y_RE_R^\dagger)^{ij}\bar{d}_{Li}\ell_{Rj}R_2^{\frac{2}{3}} + (U_RY_L)^{ij}\bar{u}_{Ri}\nu_{Lj}R_2^{\frac{2}{3}} - (U_RY_L)^{ij}\bar{u}_{Ri}\ell_{Lj}R_2^{\frac{5}{3}}$$

$$\text{Assumption:} \quad Y_RE_R^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \quad U_RY_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

$$S_3(\bar{3},3,1/3): \quad Y^{ij}\bar{Q}_i'^C i\tau_2(\tau_k S_3^k)L_j'$$

$$\text{mass basis} \rightarrow -(Y)^{ij}\bar{d}_{Li}^C\nu_{Lj}S_3^{\frac{1}{3}} + \sqrt{2}(V^*Y)^{ij}\bar{u}_{Li}^C\nu_{Lj}S_3^{-\frac{2}{3}} \sqrt{2}Y^{ij}\bar{d}_{Li}^C\ell_{Lj}S_3^{\frac{4}{3}} - (V^*Y)^{ij}\bar{u}_{Li}^C\ell_{Lj}S_3^{\frac{1}{3}}$$

$$\text{GUT relation}: \quad Y = -Y_L = -\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

[0] Free parameters: m_{R_2}, m_{S_3}, complex $y_R^{b\tau}$, $y_L^{c\mu}$, $y_L^{c\tau}$, θ

GUT framework for R_2 and S_3

- $SU(5)$ unified gauge group
- fermions

$$\bar{\mathbf{5}}_i = (L, \bar{d}_R)_i, \qquad \mathbf{10}_i = (\bar{e}_R, \bar{u}_R, Q)_i$$

- At unification scale $M_{\rm GUT}$ gauge bosons of $SU(5)$ (vector leptoquarks) couple leptons and quarks
- Scalar representations contain scalar leptoquarks:
  - **24** breaks $SU(5)$, $M_{X,Y} \sim g_{\rm GUT} M_{\rm GUT}$
  - **45** contains R_2 and S_3
  - **50** contains R_2'
- Yukawa couplings

$$a^{ij}\mathbf{10}_i\bar{\mathbf{5}}_j\,\mathbf{45} \qquad b^{ij}\mathbf{10}_i\mathbf{10}_j\,\mathbf{50} \qquad (b = b^T,\ \text{symmetric in flavor space})$$

- R_2 and R_2' mix via $\mu\mathbf{45}\,\overline{\mathbf{50}}\,\mathbf{24}$ into light R_2 and heavy R_{2H}.

GUT framework for R_2 and S_3

- Matching onto effective theory results in the couplings considered in flavor and LHC

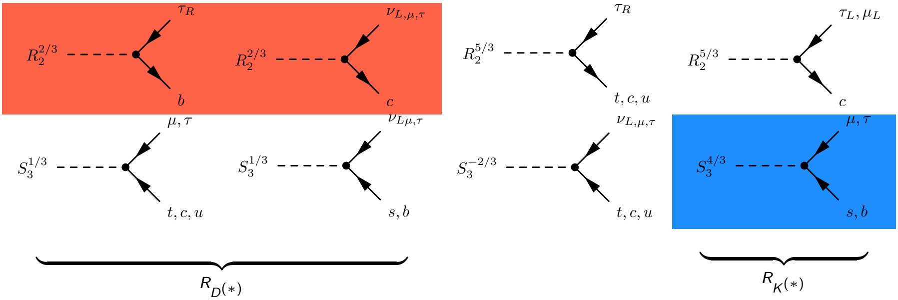
$$Y_R^{ij}\bar{Q}'_i \ell'_{Rj} R_2 + Y_L^{ij}\bar{u}'_{Ri}\widetilde{R}_2^{\dagger} L'_j + Y^{ij}\bar{Q}_i'^{C} i\tau_2(\tau_k S_3^k)L'_j$$

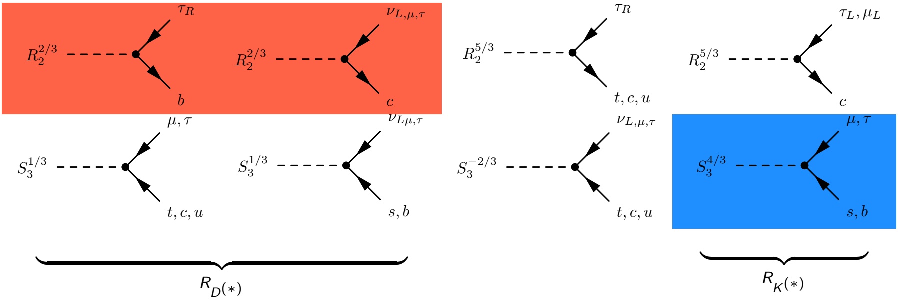
where

$$Y_L = a\cos\phi \qquad Y_R = b\sin\phi, \qquad Y = -\frac{a}{\sqrt{2}}$$

- Assume $\phi = \pi/2$ (assumption is not crucial to further analysis)
- Proton destabilizing diquark interactions $\bar{Q}\bar{Q}S_3$ ($\mathbf{10}_i\mathbf{10}_j\mathbf{45}$) can be forbidden.[Doršner et al, 2017]

Charged currents





$R_{D^{(*)}}$

Dominant contribution by R_2 via scalar and tensor interactions

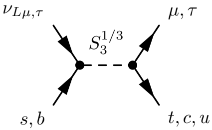
$$\mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[g_{S_L} (\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + g_T (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right]$$

$$g_{S_L} = 4 g_T = \frac{y_L^{c\nu}\, y_R^{b\tau\,*}}{4\sqrt{2}\, m_{R_2}^2\, G_F V_{cb}} \qquad (g_{S_L}(m_b) \approx 7 g_T(m_b))$$

- Scalar and tensor $B \to D$ form factors from lattice QCD [HPQCD '15, MILC '15]
- $B \to D^*$ FFs extracted from exp. spectra using the heavy quark symm. [Bernlochner et al'18, HFLAV]

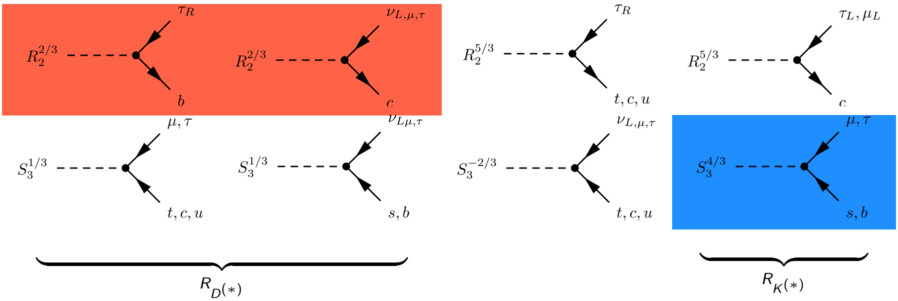
Charged currents constraints

- $b \to c\tau\nu$ is the *only* charged-current affected by R_2
  - $B_c \to \tau\nu$ taken into account
- Leptoquark state S_3 affects many charged currents via charge 1/3 component:



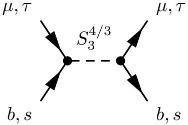
We consider the most relevant constraints:
  - $R_{D^{(*)}}^{\mu/e} = \mathcal{B}(B \to D^{(*)}\mu\bar{\nu})/\mathcal{B}(B \to D^{(*)}e\bar{\nu})$
  - $B \to \tau\nu$
  - $\mathcal{B}(K \to e\nu)/\mathcal{B}(K \to \mu\nu)$
  - $\mathcal{B}(\tau \to K\nu)/\mathcal{B}(K \to e\nu)$

- Explained by the $S_3^{4/3}$ charge eigenstate



$R_{K^{(*)}}$ and neutral currents

- $S_3^{4/3}$ couples to left-handed fermions



- Left-handed current operators with μ and τ

$$\mathcal{H}_{\rm eff}^{b\to sll} = -\frac{4G_F\lambda_t}{\sqrt{2}} \sum_{i=7,9,10} C_i(\mu)\mathcal{O}_i(\mu)$$

$$\mathcal{O}_{9(10)} = \frac{e^2}{(4\pi)^2}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{l}\gamma^\mu(\gamma^5)l\right)$$

$$\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu} = \frac{\pi v^2}{\lambda_t\alpha_{\rm em}}\frac{y^{b\mu}\left(y^{s\mu}\right)^*}{m_{S_3}^2} = \frac{\pi v^2}{\lambda_t\alpha_{\rm em}}\frac{\sin 2\theta\,(y_L^{c\mu})^2}{2m_{S_3}^2}$$

- $\sin 2\theta$ and large mass supresses the S_3 effect in $R_{K^{(*)}}$
- Use constraint on $\delta C_9 = -\delta C_{10}$ determined from clean observables: $R_{K^{(*)}}$, $B_s \to \mu^+\mu^-$

$$\delta C_9^{\mu\mu} \in (-0.85, -0.50)^1$$

[1] In agreement with global analyses of $b \to s\mu\mu$ observables. [Capdevilla et al '17, ...]

Neutral current constraints

- $B_s - \bar{B}_s$, Δm_s constraint, suppressed by θ [S_3]

$$\Delta m_s^{\mathrm{S}_3} \sim \sin^2 2\theta \left[(y_L^{c\mu})^2 + (y_L^{c\tau})^2 \right]^2 / m_{S_3}^2$$

- $\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$ [S_3 and R_2]
- $Z \to \ell\ell$ constraints at LEP [S_3 and R_2]

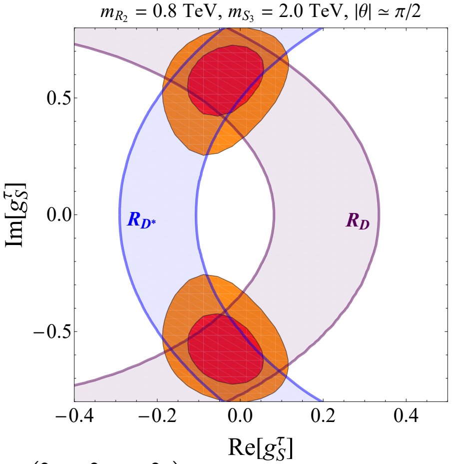
$$\frac{g_V^\tau}{g_V^e} = 0.959(29), \qquad \frac{g_A^\tau}{g_A^e} = 1.0019(15), \qquad \frac{g_V^\mu}{g_V^e} = 0.961(61), \qquad \frac{g_A^\mu}{g_A^e} = 1.0001(13)$$

- $\mathcal{B}(\tau \to \mu\phi) \sim \cos^4\theta (y_L^{c\mu} y_L^{c\tau})^2 / m_{S_3}^4 < 8.4 \times 10^{-8}$, resolves $\theta = 0, \pi$ degeneracy [S_3]
- Small effect in $(g-2)_\mu$

- We *predict* the S_3 contribution to $R_{\nu\nu}^{(*)} = \mathcal{B}(B \to K^{(*)}\nu\nu)/\mathcal{B}(B \to K^{(*)}\nu\nu)_{\mathrm{SM}}$ and compare it with $R_{\nu\nu}^{(*)} < 2.7$ [Belle '17]

Flavor coupling analysis

- Perform a fit with fixed $m_{R_2} = 0.8$ TeV, $m_{S_3} = 2$ TeV, variables $y_L^{c\mu}$,$y_L^{c\tau}$, $\mathrm{Re}\, y_R^{b\tau}$, $\mathrm{Im}\, y_R^{b\tau}$, mixing angle θ
- Larger mass m_{S_3} and small $\sin 2\theta$ suppress the effects in neutral currents relative to $R_{D^{(*)}}$

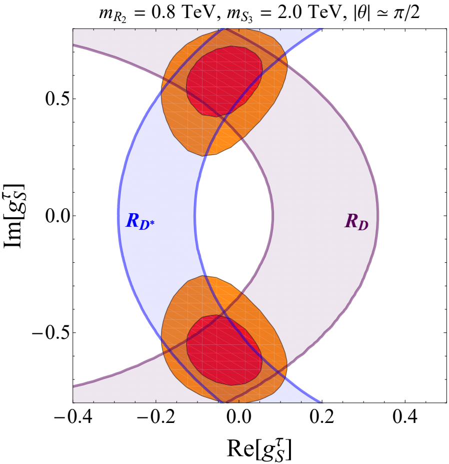


- Degeneracy of minima with $\theta \approx 0, \pi/2$ is broken by $\tau \to \mu\phi$ which selects $\theta \approx \pi/2$. $\Rightarrow$ S_3 couplings to s-quark are suppressed

$$Y_{d\ell} \approx -\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 1\\ 0 & -1 & 0\end{pmatrix}\begin{pmatrix}0 & 0 & 0\\ 0 & y_L^{c\mu} & y_L^{c\tau}\\ 0 & 0 & 0\end{pmatrix} \approx \begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & y_L^{c\mu} & y_L^{c\tau}\end{pmatrix}$$

Flavor coupling analysis

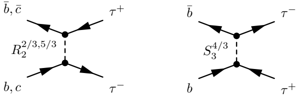
- Complex g_S^τ needed in order to reconcile R_D and R_{D^*}. Imaginary g_S^τ has strictly positive effect on $R_{D^{(*)}}$.
- SM point is excluded at 3.8σ (5 degrees of freedom)
- Both $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies are reduced to $< 1\sigma$ level



[Becirevic, Dorsner, Fajfer, Faroughy, NK, Sumensari, 1806.05689]

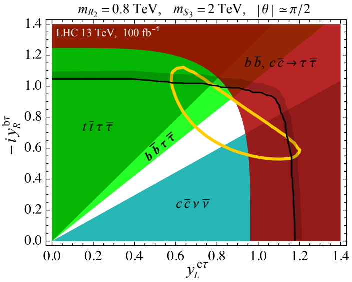
LHC constraints

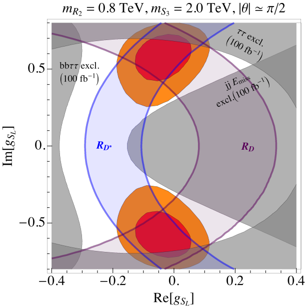
- t-channel $pp \to \tau^+\tau^-$. Dominated by R_2, S_3 only from b-quarks



- Require Yukawa couplings of the two LQs to remain perturbative to the unification scale 5×10^{15} GeV
- Constrained by searches for heavy $\tau\tau$ resonance [ATLAS, JHEP 1801, 055]

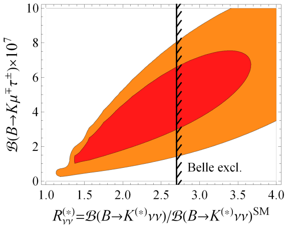
- Leptoquark pair production bounds the R_2 mass





Future tests

- LFV and 2ν modes in reach of future high-intensity experiments
- Correlation between LFV observables



- $\mathcal{B}(B \to K\nu\bar\nu) \gtrsim 1.5 \times \mathcal{B}(B \to K\nu\bar\nu)_{\rm SM}$, genuine prediction.
- LFV decays
  - $\mathcal{B}(\tau \to \mu\gamma) > 1.5 \times 10^{-8}$
  - $\mathcal{B}(B \to K^*\tau\mu) \approx 1.9 \times \mathcal{B}(B \to K\mu\tau)$
  - $\mathcal{B}(B_s \to \tau\mu) \approx 0.9 \times \mathcal{B}(B \to K\mu\tau)$
  - All LFV limits will be improved by LHCb and Belle 2

Conclusion

- Presented model with two light leptoquarks, $R_2(3, 2, 7/6)$ and $S_3(\bar{3}, 3, 1/3)$
  - R_2 accommodates $R_{D^{(*)}}$ via complex Scalar and Tensor couplings
  - S_3 accommodates $R_{K^{(*)}}$ via real $C_9 = -C_{10}$
- $SU(5)$ GUT framework connects the couplings of R_2 and S_3

- Flavor fit
  - Light $m_{R_2} = 0.8\ \mathrm{TeV}$, requires complex coupling $y_R^{b\tau}$
  - Heavier $S_3 = 2.0\ \mathrm{TeV}$
- Complete resolution of $R_{K^{(*)}}$ and $R_{D^{(*)}}$

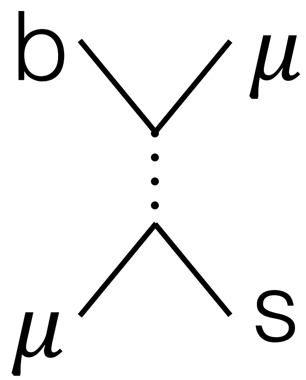
- Well-defined GUT completion, perturbative couplings to high scales
- Model consistent with LHC constraints, preferred region can be probed at HL-LHC

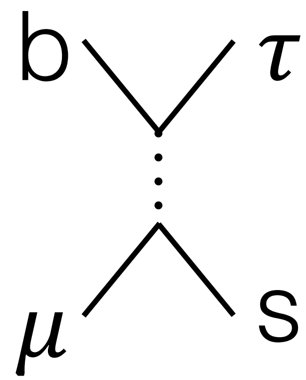
- Predicted enhanced LFV signals in $\tau\mu$ sector as well as enhanced $b \to s\nu\bar{\nu}$ modes
- Interesting target for future Belle 2 and LHCb searches

Backup

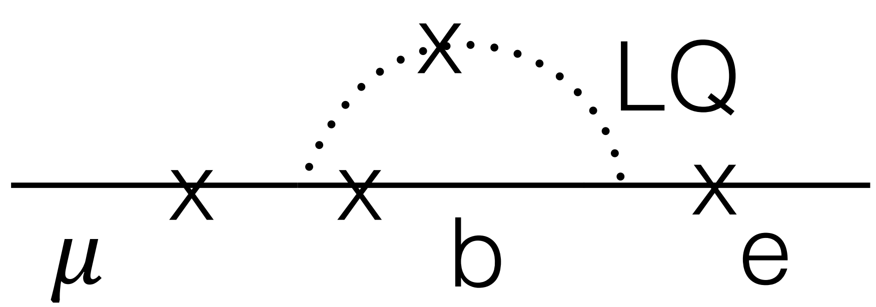
LQs effects at low energies - overview

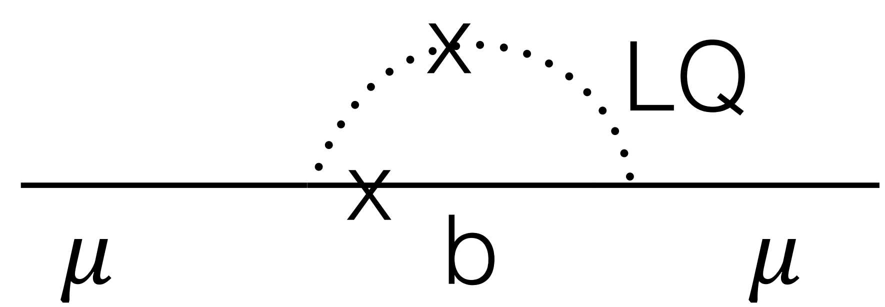
- Tree-level contributions: LL QQ operators





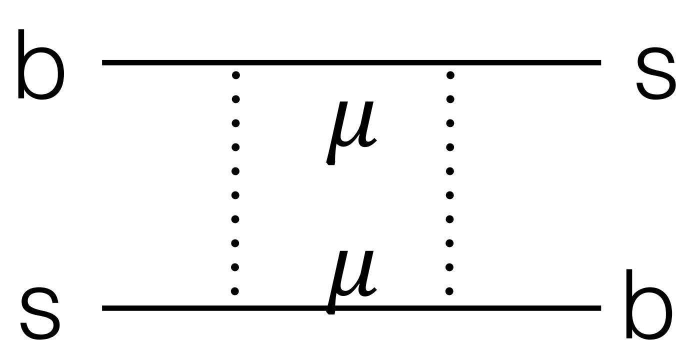
- Penguin-type: radiative processes, electro-magnetic moments

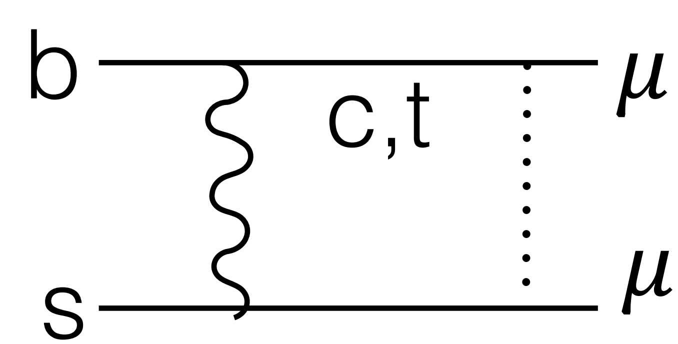




magnetic
and electric moments

- Box-type: neutral meson mixing, $\tau \to 3\mu$, LL QQ operators





novel mechanism
to generate R_K

- For generic flavour pattern LFU and LFV is expected.

Theoretical motivation: Unification of quarks and leptons

- At unification scale M_{GUT} gauge bosons of SU(5) X and Y couple to quarks and leptons - they are called leptoquark gauge bosons - **vector leptoquarks**

- Scalar representations contain **scalar leptoquarks**. In order to break SU(5) to SU(3)xSU(2)xU(1) the Higgs mechanism is involved: **24**-dim scalar develops a VEV

$$M_{X,Y} \sim g M_{\rm GUT}$$

- EW breaking is achieved with additional **5**-dim scalar

doublet-triplet splitting

$$\mathbf{5} = \underbrace{(1,2,1/2)}_{H} \oplus \underbrace{(3,1,-1/3)}_{S_1^*}$$

Higgs is a proof of existence of light scalar particles

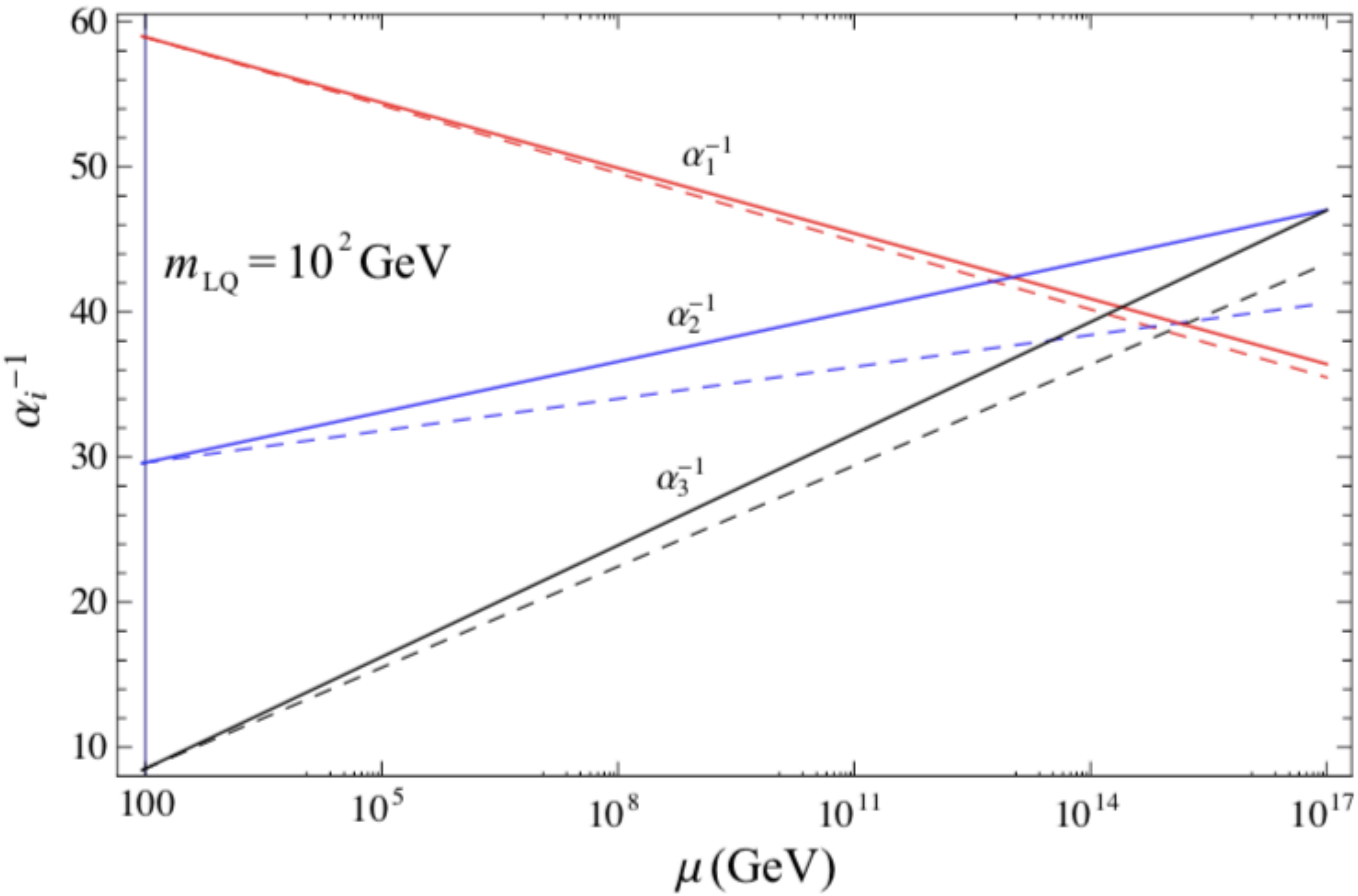
- To reproduce realistic Yukawa couplings require additional scalar, e.g.,

$$\mathbf{45} = (8,2,1/2) \oplus (\bar{6},1,-1/3) \oplus \underbrace{(3,3,-1/3)}_{S_3} \oplus \underbrace{(\bar{3},2,-7/6)}_{R_2} \oplus (3,1,-1/3) \oplus (\bar{3},1,4/3) \oplus \underbrace{(1,2,1/2)}_{H}$$

$$\mathbf{50} = \underbrace{(3,2,7/6)}_{R_2} \oplus \cdots$$

- We know the SM Higgs is light, also other scalar LQs can be light. (Beware of proton decay!)

Theoretical motivation: Unification of quarks and leptons



[Dorsner et al, 1603.04993]

Full: SM

Dashed: SM + 3 scalars at 100 GeV:

(1,2,1/2) + (3,2,1/6) + (3,2,1/6)

Higgs-like leptoquark leptoquark

[Murayama, Yanagida `92]

$$\alpha_3(m_Z) = 0.1176$$
$$\alpha_{em}^{-1}(m_Z) = 127.906$$
$$\sin^2\theta_W(m_Z) = 0.23122$$

Low energy perspective (EW scale)

- Above the weak scale, extend the SM spectrum with LQ fields. Respect SU(3)xSU(2)xU(1)

- Leptoquark (LQ) is a scalar or vector particle Φ with quantum numbers (3,T,Y), with T and Y such that dim-4 couplings of Φ L Q are allowed

- "Discover" leptoquarks by writing all possible LQ bilinears of SM fields (easy exercise). Gauge + Lorentz symmetry

$$
\begin{aligned}
&\bar{L}\gamma^\mu Q \sim (3,1,-1/3) \to U_1^\mu \\
&\bar{e}_R\gamma^\mu u_R \sim (3,1,-1/3) \to U_1^\mu \\
&\bar{L}\boldsymbol{\sigma}\gamma^\mu Q \sim (3,3,-1/3) \to U_3^\mu \\
&\bar{L}^c(i\sigma^2)\boldsymbol{\sigma}Q \sim (3,3,2/3) \to S_3 \\
&\bar{L}u_R \sim (3,2,7/6) \to R_2 \\
&\bar{e}_R Q \sim (3,2,7/6) \to R_2 \\
&\vdots
\end{aligned}
$$

$Q = Y + T_3$

- Vector LQs in general need a UV completion (Higgs mechanism). Some quantities may still be computed without the full theory. [Crivellin et al.1807.02068]

Baryon and lepton number

- In general, LQs exchange quarks for leptons and violate both B and L. Use freedom to consistently choose B and L numbers of a LQ field.

$$\bar{L}\gamma^\mu Q \sim (3,1,-1/3) \to U_1^\mu$$
$$\bar{e}_R\gamma^\mu u_R \sim (3,1,-1/3) \to U_1^\mu$$
$$\bar{L}\boldsymbol{\sigma}\gamma^\mu Q \sim (3,3,-1/3) \to U_3^\mu$$
$$\bar{L}^c(i\sigma^2)\boldsymbol{\sigma}\gamma^\mu Q \sim (3,3,2/3) \to S_3 \qquad \leftarrow \text{ but also } \bar{Q}\boldsymbol{\sigma}i\sigma^2 Q^c$$
$$\bar{L}u_R \sim (3,2,7/6) \to R_2$$
$$\bar{e}_R Q \sim (3,2,7/6) \to R_2$$
$$\vdots$$

Double nature of S_3 l:eptoquark and diquark!

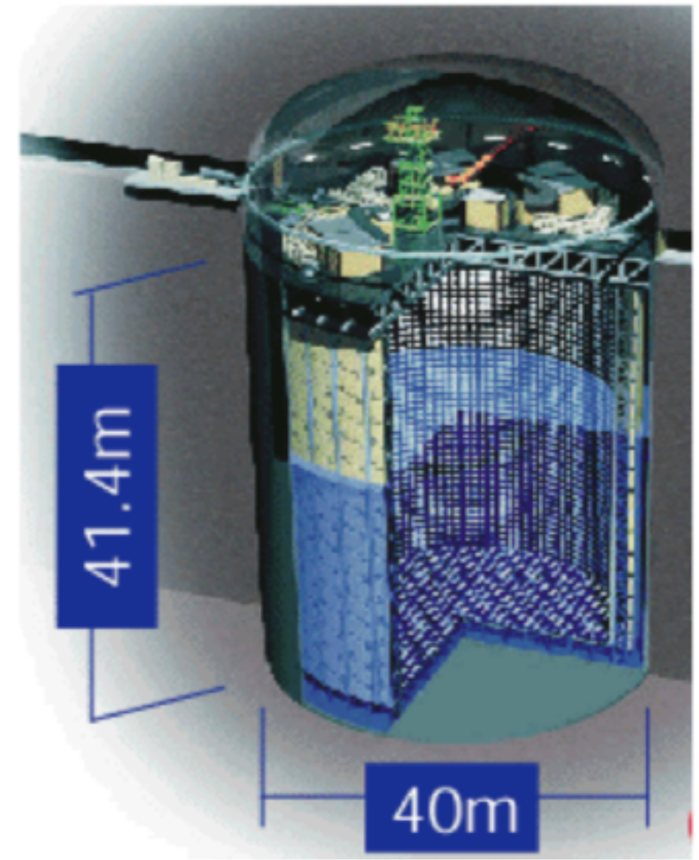
- F=3B+L fermion number
  - F=0 LQs have well defined **B = 1/3, L = -1** (*genuine leptoquarks)*
  - LQs which have diquark nature have |F|=2, not possible to assign B and L consistently: B_{lq} = 1/3, L_{lq} = 1
    B_{qq} = -2/3, L_{qq} = 0
  - B-L is still conserved

Baryon and lepton number

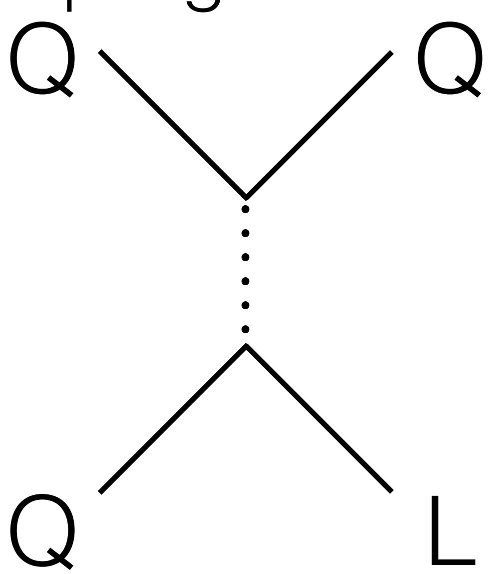
- Proton lifetime from Super Kamiokande

$$\tau(p \to e^+\pi^0) > 1.6 \times 10^{34}\,\text{years}$$
$$\tau(p \to \mu^+\pi^0) > 7.7 \times 10^{33}\,\text{years}$$

ΔB = ΔL = -1



- Light LQs cannot have large **lq** and **qq** couplings

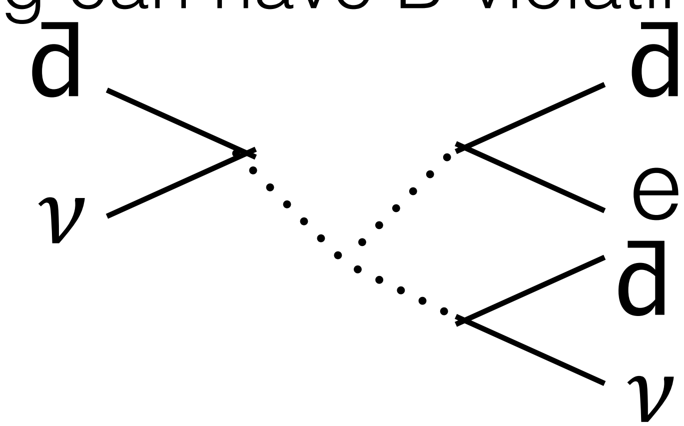


$$\sim \frac{y_{LQ} z_{QQ}}{M_{S_3}^2} (\bar{Q}^c i\sigma^2 \boldsymbol{\sigma} Q)(\bar{L} \boldsymbol{\sigma} i\tau^2 Q)$$

- Even LQs that appear B-conserving can have B-violating terms in the potential. e.g., ~R2 (3,2,1/6)

$$\lambda H^* \tilde{R}_2 \tilde{R}_2 \tilde{R}_2$$

B = 1, L = -3



$$p \to \pi^+\pi^+ e^- \nu\nu$$

(ex.: work out in isospin and color space)

[Weinberg, PRD22,7]

Catalogue

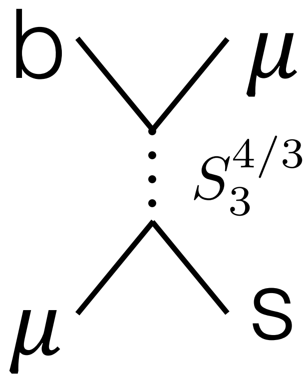
	$(SU(3), SU(2), U(1))$	Spin	Symbol	Type	F
	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3	$LL\,(S_1^L)$	-2
	$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2	$RL\,(S_{1/2}^L)$, $LR\,(S_{1/2}^R)$	0
	$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L)$, $\overline{LR}\,(\tilde{S}_{1/2}^{\bar{L}})$	0
	$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S_0^L)$, $RR\,(S_0^R)$, $\overline{RR}\,(S_0^{\bar{R}})$	-2
ν_R	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	$\overline{RR}\,(\bar{S}_0^{\bar{R}})$	-2
	$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3	$LL\,(V_1^L)$	0
	$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2	$RL\,(V_{1/2}^L)$, $LR\,(V_{1/2}^R)$	-2
	$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}_{1/2}^L)$, $\overline{LR}\,(\tilde{V}_{1/2}^{\bar{R}})$	-2
	$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$	$RR\,(\tilde{V}_0^R)$	0
	$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1	$LL\,(V_0^L)$, $RR\,(V_0^R)$, $\overline{RR}\,(V_0^{\bar{R}})$	0
ν_R	$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$	$\overline{RR}\,(\bar{V}_0^{\bar{R}})$	0

Singlet fermions ν_R included, indicated by $\overline{}$

[Dorsner et al, 1603.04993]
[Buchmueller et al, PLB 177; PLB 191]

Transition to mass basis

- Consider $b \to s\mu\mu$ process in the presence of S_3 (3*,3,1/3)



Lagrangian in the interaction basis

$$
\begin{aligned}
&Y^{ij}\bar{Q}_i'^{C} i\tau_2(\tau_k S_3^k)L_j' \\
&\to -(Y)^{ij}\bar{d}_{Li}^{C}\nu_{Lj}S_3^{\frac{1}{3}} + \sqrt{2}(V^*Y)^{ij}\bar{u}_{Li}^{C}\nu_{Lj}S_3^{-\frac{2}{3}} \\
&+ \sqrt{2}Y^{ij}\bar{d}_{Li}^{C}\ell_{Lj}S_3^{\frac{4}{3}} - (V^*Y)^{ij}\bar{u}_{Li}^{C}\ell_{Lj}S_3^{\frac{1}{3}}
\end{aligned}
$$

(neutrinos in the flavour basis)

Transition to the mass eigenstate of fermions is achieved by unitary rotations

$$
\begin{aligned}
\mathcal{L}_{\text{upYukawa}} &= -y_{(u)}^{ij}\bar{Q}'^{i}\tilde{H}u_R'^{j} \\
&\to -\bar{u}_L'\left(\frac{y_{(u)}v}{\sqrt{2}}\right)u_R' \\
&\to -\bar{u}_L\underbrace{\left(U_L y_{(u)} U_R^\dagger\right)}_{\text{diag}(y_u,y_c,y_t)}(v/\sqrt{2})u_R
\end{aligned}
$$

$$u_{L,R} = U_{L,R}u'_{L,R}$$

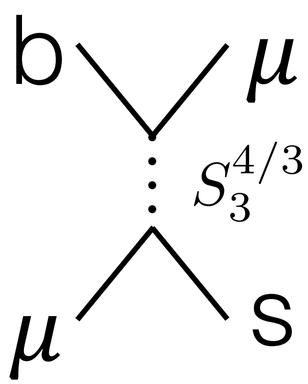
$$V = U_L D_L^\dagger$$

- LQs interacting with Q doublets have relative CKM rotation between u_L and d_L couplings, e.g.

$$
Y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & Y_{s\mu} & 0 \\ 0 & Y_{b\mu} & 0 \end{pmatrix} \quad \Rightarrow \quad V^*Y = \begin{pmatrix} 0 & V_{us}^*Y_{s\mu} + V_{ub}^*Y_{s\mu} & 0 \\ 0 & V_{cs}^*Y_{s\mu} + V_{cb}^*Y_{s\mu} & 0 \\ 0 & V_{ts}^*Y_{s\mu} + V_{tb}^*Y_{s\mu} & 0 \end{pmatrix}
$$

Operator basis

- Consider b→s$\mu\mu$ process in the presence of S_3 (3*,3,1/3)



Tree-level matching results in the Fierzed basis

$$\mathcal{A} = \frac{2i Y^{b\mu} Y^{s\mu *}}{m_{S_3}^2} (\bar{b}_L^C \mu_L)(\bar{\mu}_L s_L^C) \quad \Rightarrow \quad \mathcal{L}_{\text{eff}} = \frac{2 Y^{b\mu} Y^{s\mu *}}{m_{S_3}^2} (\bar{b}_L^C \mu_L)(\bar{\mu}_L s_L^C)$$

$$= -\frac{Y^{b\mu} Y^{s\mu *}}{m_{S_3}^2} (\bar{b}_L^C \gamma^\mu s_L^C)(\bar{\mu}_L \gamma_\mu \mu_L)$$

$$= \frac{Y^{b\mu} Y^{s\mu *}}{m_{S_3}^2} (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$$

n.b.

1. Fierz identites for fields
2. Bilinear transpose to get rid of C operators

$$\psi^c \equiv C\bar{\psi}^T, \qquad \overline{\psi^c} = -\psi^T C^\dagger$$

$$C^\dagger = C^{-1}, \qquad C^T = -C$$

$$\gamma^{\mu T} = -C^\dagger \gamma^\mu C$$

- Effective Hamiltonian for b→s$\mu\mu$

$$\mathcal{H}_{\text{eff}}^{b\to sll} = -\frac{4 G_F \lambda_t}{\sqrt{2}} \sum_{i=7,9,10} C_i(\mu) \mathcal{O}_i(\mu)$$

$$\mathcal{O}_{9(10)} = \frac{e^2}{(4\pi)^2} \left(\bar{s}_L \gamma_\mu b_L\right) \left(\bar{l} \gamma^\mu (\gamma^5) l\right)$$

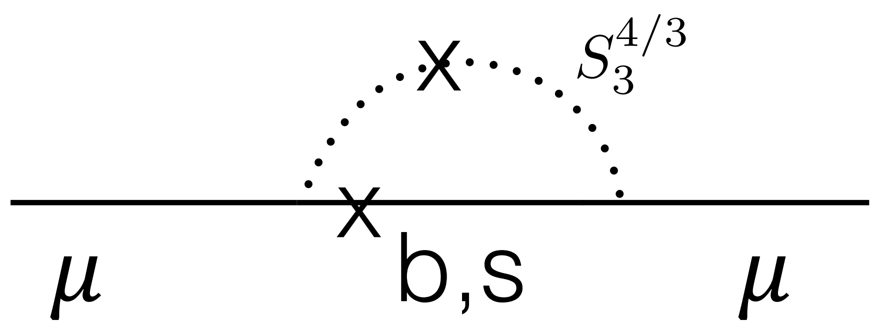
$$\delta C_9^{\mu\mu} = -\delta C_{10}^{\mu\mu} = \frac{\pi v^2}{\lambda_t \alpha_{\text{em}}} \frac{Y^{b\mu} Y^{s\mu *}}{m_{S_3}^2}$$

Simplest V-A tree-level attempt to solve R_K

Many related flavor violating processes depend on the combination of Y's

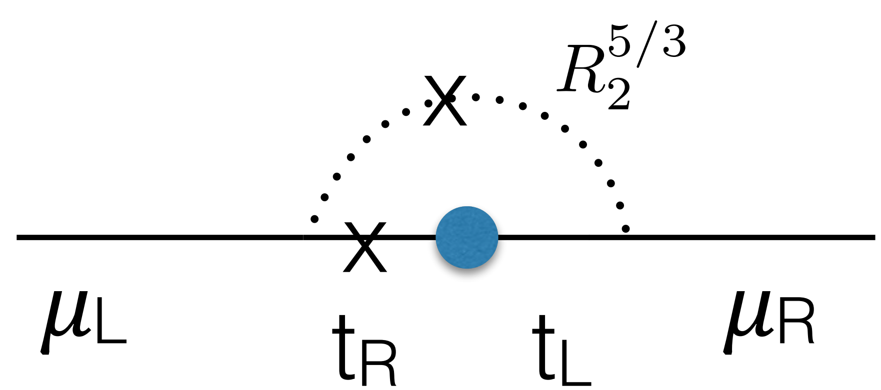
g-2 in simple S_3 model

- Penguin diagram with same couplings



$$\delta a_\mu = -\frac{3m_\mu^2}{32\pi^2 m_{S_3}^2}\left(|Y^{s\mu}|^2 + |Y^{b\mu}|^2\right)$$

- Wrong sign contribution! Constrains individual Yukawas
- Chiral LQs contributons are mass suppressed ($\overline{\mu}_R\, \sigma^{\mu\nu}\, q_\nu\, \mu_L$) and with fixed sign
- Non-chiral LQs allow for freedom in sign and enhancement with quark mass! E.g. R_2



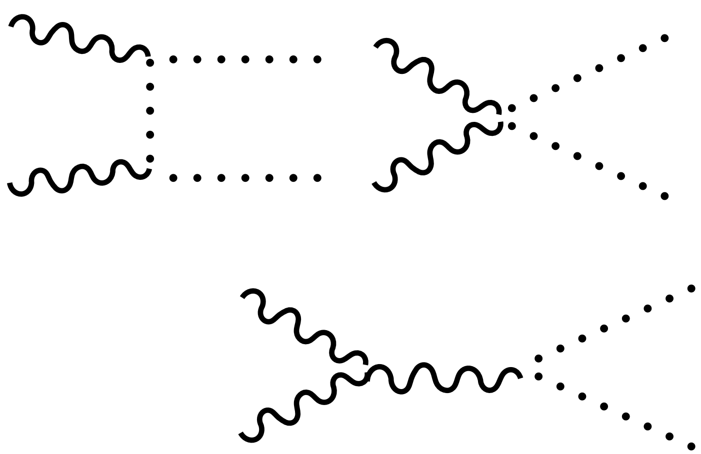
recall!

$\bar{L} u_R \sim (3, 2, 7/6) \to R_2$

$\bar{e}_R Q \sim (3, 2, 7/6) \to R_2$

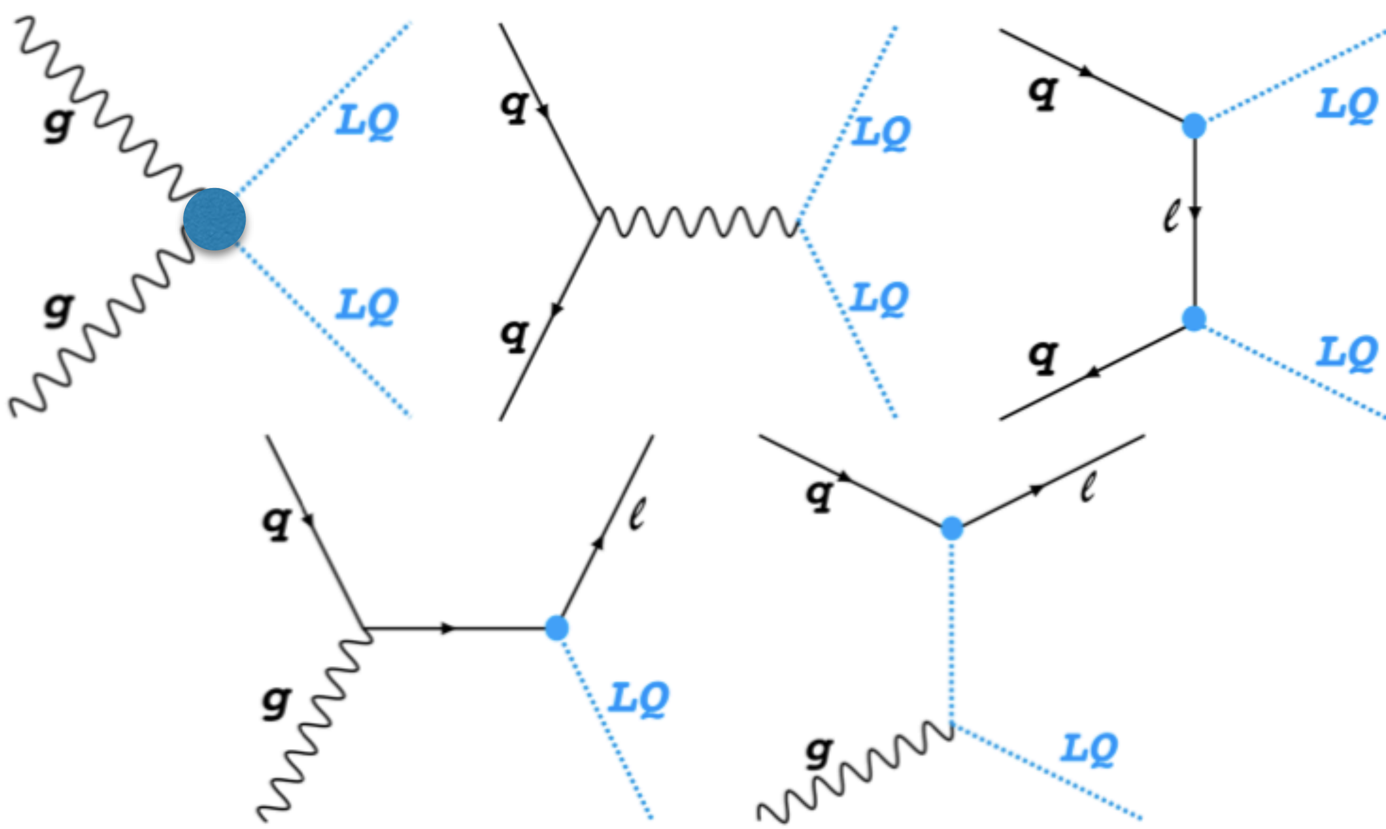
Direct searches at the LHC

- LQs are color triplet states - model independent production cross section



$$\hat{\sigma}[g\,g \to \mathrm{LQ}\,\overline{\mathrm{LQ}}] = \frac{\alpha_3^2 \pi}{96 \hat{s}} \left[\beta(41 - 31\beta^2) + (18\beta^2 - \beta^4 - 17) \log \frac{1+\beta}{1-\beta} \right]$$

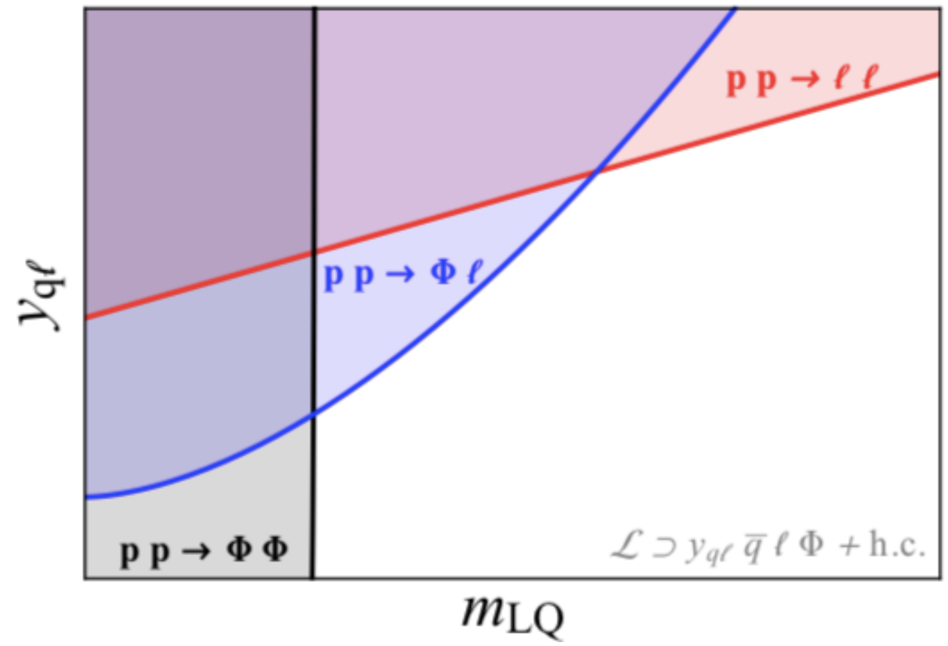
- Need large energies to produce a heavy pair of LQs
- With large Yukawa couplings also single LQ can be produced



[Dorsner, Greljo,1801.07641]

Direct searches at the LHC

- LQs produced decay to jets+leptons or jets+neutrinos



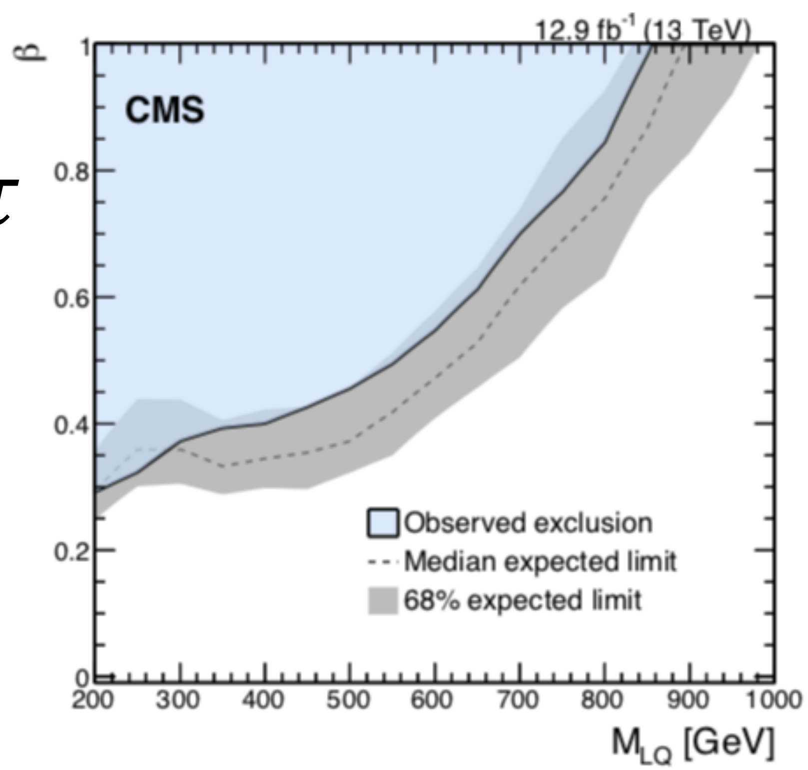
[Dorsner, Greljo,1801.07641]

$$\Gamma_S = \frac{|y|^2}{16\pi} m_{LQ}$$

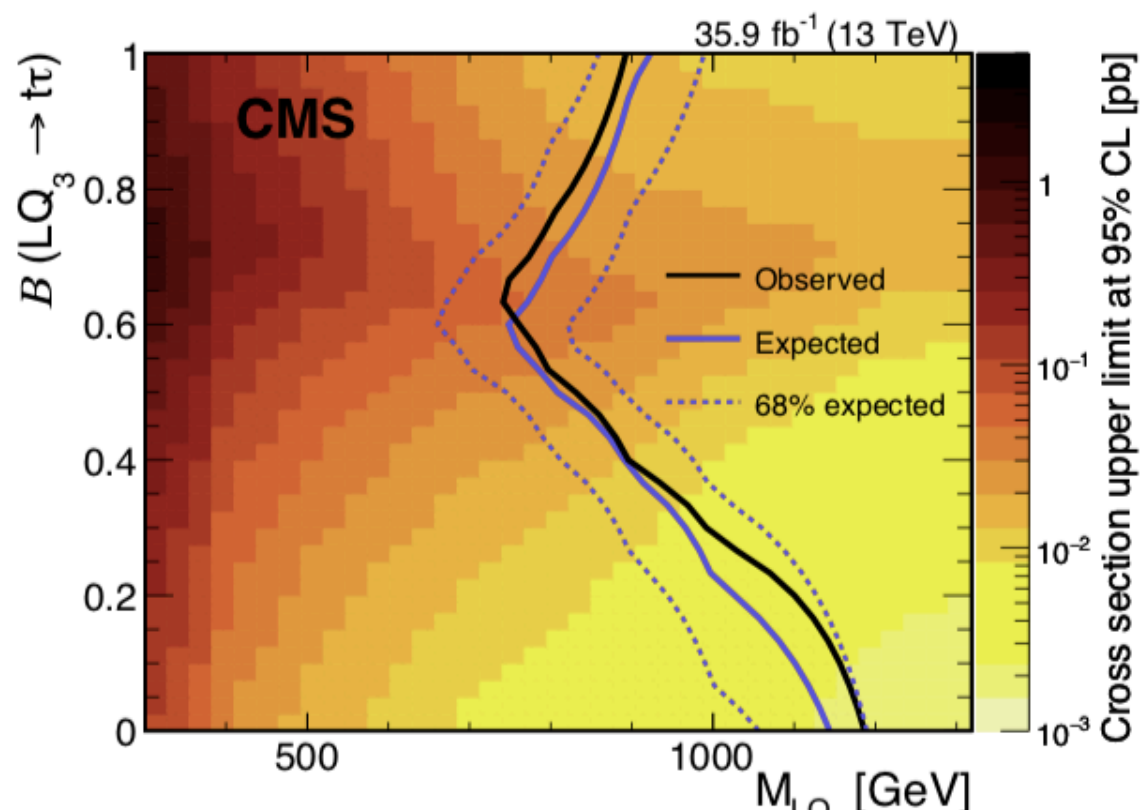
(assume prompt decay)

- Current bounds from pair-production (3rd gen. LQ), M_{LQ} > 1 TeV

$b\tau$



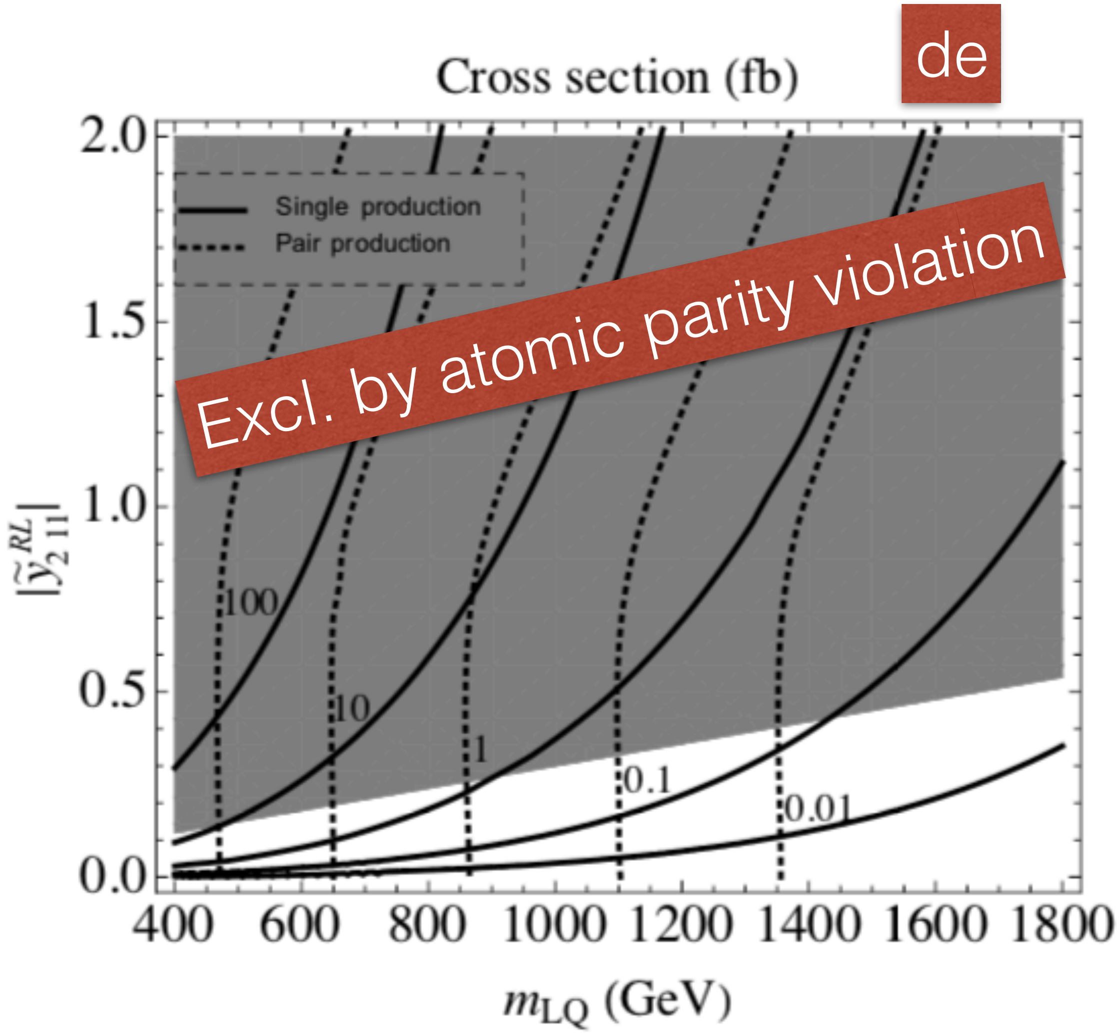
[CMS 1703.03995]

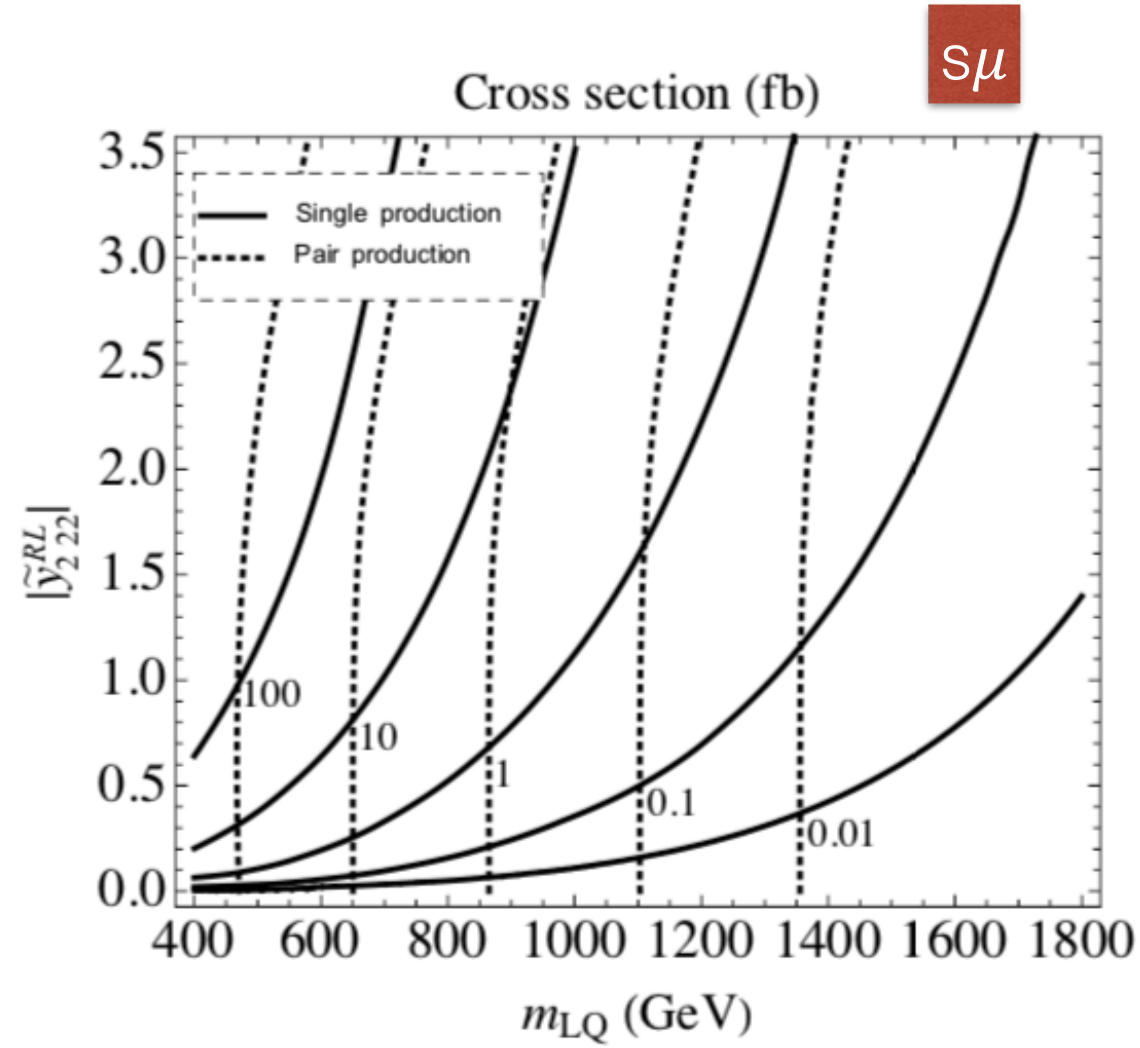


[CMS 1803.02864]

Interplay of low and high energy processes

$$\sigma_{\text{pair}}(y_i, m_{\text{LQ}}) = a_0(m_{\text{LQ}}) + a_2(m_{\text{LQ}})|y_i|^2 + a_4(m_{\text{LQ}})|y_i|^4,$$
$$\sigma_{\text{single}}(y_i, m_{\text{LQ}}) = a(m_{\text{LQ}})|y_i|^2,$$





$$-\bar{d}_R \tilde{y}_2^{RL} \tilde{R}_2^T i\sigma^2 L$$

$\sqrt{s} = 8\,\text{TeV}$

leading order σ

·······	pair production
———	single LQ production

APV and LFV in light generations

Atomic parity violation (in ^{133}Cs)

$$\mathcal{L}_{PV} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \bar{e}\gamma^\mu\gamma^5 e\ (\delta C_{1u}\bar{u}\gamma_\mu u + \delta C_{1d}\bar{d}\gamma_\mu d) \qquad \delta C_{1q} = c^{LL}_{qq;ee} - c^{LR}_{qq;ee} + c^{RL}_{qq;ee} - c^{RR}_{qq;ee}$$

Experimentally:

$$\delta Q_W(Z,N) = -2(2Z+N)\delta C_{1u} - 2(Z+2N)\delta C_{1d}$$

$$Q_W - Q_W^{SM} \equiv \delta Q_W = 0.65(43)$$

$$\Rightarrow\ |\delta C_{1u(d)}| \lesssim 10^{-3}$$

LQ	$d_j \to d_i \ell^- \ell'^+$ decays	$u_j \to u_i \ell^- \ell'^+$ decays
S_3	$c^{LL} = -\frac{v^2}{2m^2_{\rm LQ}} y^{LL}_{3\,j\ell'} y^{LL*}_{3\,i\ell}$	$c^{LL} = -\frac{v^2}{2m^2_{\rm LQ}} (V^T y_3^{LL})_{j\ell'} (V^T y_3^{LL})^*_{i\ell}$
R_2	$c^{LR} = \frac{v^2}{4m^2_{\rm LQ}} y^{LR}_{2\,\ell j} y^{LR*}_{2\,\ell' i}$	$c^{LR} = \frac{v^2}{4m^2_{\rm LQ}} (y_2^{LR} V^\dagger)_{\ell j} (y_2^{LR} V^\dagger)^*_{\ell' i}$ $c^{RL} = \frac{v^2}{4m^2_{\rm LQ}} y^{RL}_{2\,i\ell'} y^{RL*}_{2\,j\ell}$ $g^{LL} = 4h^{LL} = -\frac{v^2}{4m^2_{\rm LQ}} y^{RL*}_{2\,j\ell} (y_2^{LR} V^\dagger)^*_{\ell' i}$ $g^{RR} = 4h^{RR} = -\frac{v^2}{4m^2_{\rm LQ}} y^{RL}_{2\,i\ell'} (y_2^{LR} V^\dagger)_{\ell j}$
$\tilde{R}_2$	$c^{RL} = \frac{v^2}{4m^2_{\rm LQ}} \tilde{y}^{RL}_{2\,i\ell'} \tilde{y}^{RL*}_{2\,j\ell}$	
$\tilde{S}_1$	$c^{RR} = -\frac{v^2}{4m^2_{\rm LQ}} \tilde{y}^{RR}_{1\,j\ell'} \tilde{y}^{RR*}_{1\,i\ell}$	
S_1		$c^{LL} = -\frac{v^2}{4m^2_{\rm LQ}} (V^T y_1^{LL})_{j\ell'} (V^T y_1^{LL})^*_{i\ell}$ $c^{RR} = -\frac{v^2}{4m^2_{\rm LQ}} y^{RR}_{1\,j\ell'} y^{RR*}_{1\,i\ell}$ $g^{LL} = -4h^{LL} = \frac{v^2}{4m^2_{\rm LQ}} y^{RR}_{1\,j\ell'} (V^T y_1^{LL})^*_{i\ell}$ $g^{RR} = -4h^{RR} = \frac{v^2}{4m^2_{\rm LQ}} (V^T y_1^{LL})_{j\ell'} y^{RR*}_{1\,i\ell}$

[Dorsner et al, 1603.04993]

APV and LFV in light generations

μ-e conversion in nuclei (Au, Ti)

$$\Gamma_{\rm conversion} = 2G_F^2 \left| A_R^* D + (2g_{LV}^{(u)} + g_{LV}^{(d)})V^{(p)} + (g_{LV}^{(u)} + 2g_{LV}^{(d)})V^{(n)} + (G_S^{(u,p)} g_{LS}^{(u)} + G_S^{(d,p)} g_{LS}^{(d)} + G_S^{(s,p)} g_{LS}^{(s)})S^{(p)} + (G_S^{(u,n)} g_{LS}^{(u)} + G_S^{(d,n)} g_{LS}^{(d)} + G_S^{(s,n)} g_{LS}^{(s)})S^{(n)} \right|^2 + (L \leftrightarrow R)\,,$$

nuclear matrix elements

[Kitano et al, hep-ph/0203110]

LQ	$d_j \to d_i \ell^- \ell'^+$ decays	$u_j \to u_i \ell^- \ell'^+$ decays
S_3	$c^{LL} = -\frac{v^2}{2m_{\rm LQ}^2} y_{3\,j\ell'}^{LL} y_{3\,i\ell}^{LL*}$	$c^{LL} = -\frac{v^2}{2m_{\rm LQ}^2} (V^T y_3^{LL})_{j\ell'} (V^T y_3^{LL})_{i\ell}^*$
R_2	$c^{LR} = \frac{v^2}{4m_{\rm LQ}^2} y_{2\,\ell j}^{LR} y_{2\,\ell' i}^{LR*}$	$c^{LR} = \frac{v^2}{4m_{\rm LQ}^2} (y_2^{LR} V^\dagger)_{\ell j} (y_2^{LR} V^\dagger)_{\ell' i}^*$ $c^{RL} = \frac{v^2}{4m_{\rm LQ}^2} y_{2\,i\ell'}^{RL} y_{2\,j\ell}^{RL*}$ $g^{LL} = 4h^{LL} = -\frac{v^2}{4m_{\rm LQ}^2} y_{2\,j\ell}^{RL*} (y_2^{LR} V^\dagger)_{\ell' i}^*$ $g^{RR} = 4h^{RR} = -\frac{v^2}{4m_{\rm LQ}^2} y_{2\,i\ell'}^{RL} (y_2^{LR} V^\dagger)_{\ell j}$
$\tilde{R}_2$	$c^{RL} = \frac{v^2}{4m_{\rm LQ}^2} \tilde{y}_{2\,i\ell'}^{RL} \tilde{y}_{2\,j\ell}^{RL*}$	
$\tilde{S}_1$	$c^{RR} = -\frac{v^2}{4m_{\rm LQ}^2} \tilde{y}_{1\,j\ell'}^{RR} \tilde{y}_{1\,i\ell}^{RR*}$	
S_1		$c^{LL} = -\frac{v^2}{4m_{\rm LQ}^2} (V^T y_1^{LL})_{j\ell'} (V^T y_1^{LL})_{i\ell}^*$ $c^{RR} = -\frac{v^2}{4m_{\rm LQ}^2} y_{1\,j\ell'}^{RR} y_{1\,i\ell}^{RR*}$ $g^{LL} = -4h^{LL} = \frac{v^2}{4m_{\rm LQ}^2} y_{1\,j\ell'}^{RR} (V^T y_1^{LL})_{i\ell}^*$ $g^{RR} = -4h^{RR} = \frac{v^2}{4m_{\rm LQ}^2} (V^T y_1^{LL})_{j\ell'} y_{1\,i\ell}^{RR*}$

[Dorsner et al, 1603.04993]

$$\mathrm{BR}_{\mu e}^{(\mathrm{Ti})} < 4.3 \times 10^{-12}$$

$$\mathrm{BR}_{\mu e}^{(\mathrm{Au})} < 7 \times 10^{-13}$$

[SINDRUM]

⇓

$$c_{qq,e\mu}^{XY} \lesssim 10^{-8}$$

+ Br($\mu \to e\gamma$) < 4.2 10^{-13} [MEG]
+ Z → ee [LEP]
+ EWPO

⇓

LQs in e, d, u are extremely well constrained