Gauged flavour symmetries and Z' for $b \to sll$

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Based on work with Rodrigo Alonso, Chengcheng Han, Tsutomu Yanagida

(arXiv:1704.08158, arXiv:1705.03858)

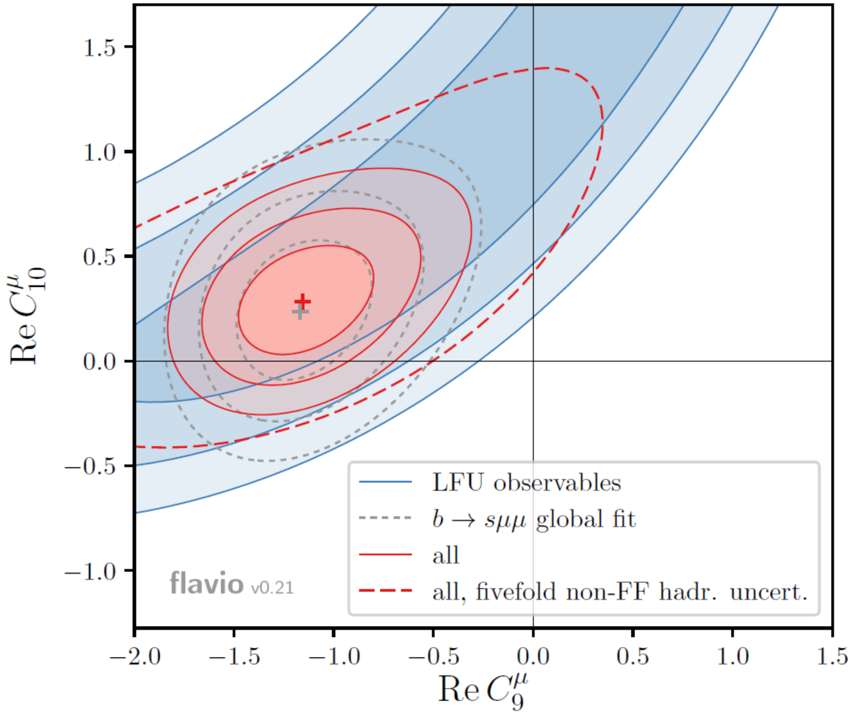
Anomalies in $b \to sll$

- Fits to the $b \to sll$ data suggest new physics contributions in C_9^μ and C_{10}^μ

$$\mathcal{O}_9^l = \frac{\alpha}{4\pi} \left(\bar{s}\gamma_\mu b_L\right)\left(\bar{l}\gamma_\mu l\right)$$

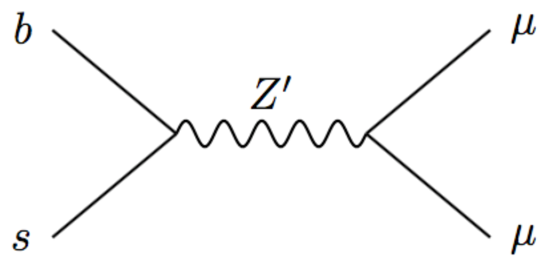
$$\mathcal{O}_{10}^l = \frac{\alpha}{4\pi} \left(\bar{s}\gamma_\mu b_L\right)\left(\bar{l}\gamma_\mu \gamma^5 l\right)$$

Altmannshofer et al. 1704.05435



$b \to sll$ with a Z'

- One of the simple, tree-level choices to UV complete the effective operators is a Z'



$$\mathcal{O}_9^l = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu b_L) (\bar{l}\gamma_\mu l)$$
$$\mathcal{O}_{10}^l = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu b_L) (\bar{l}\gamma_\mu \gamma^5 l)$$

Necessary ingredients:

- Symmetry that involves both quarks and leptons
- Non-trivial structure in flavour space

Models must also be self-consistent (e.g. anomalies cancel)

What is the underlying motivation / flavour structure?

Gauged flavour symmetries

- An obvious way forward is gauged horizontal/flavour symmetries

$$G_{SM} \times G'$$

- Take a minimal approach and assume only chiral fermions are SM+3ν_R

What is the largest, anomaly-free local symmetry?

Gauged flavour symmetries

- An obvious way forward is gauged horizontal/flavour symmetries

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What is the largest*, anomaly-free local symmetry?

$$SU(3)_Q \times SU(3)_L \times U(1)_{B-L}$$

*largest does *not* mean it contains them all

Connecting quarks and leptons

- $SU(3)_Q \times SU(3)_L \times U(1)_{B-L}$ doesn't directly connect quarks and leptons in flavor space

- A natural starting point is the diagonal subgroup:

$$SU(3)_H \times U(1)_{B-L}$$

- Fits nicely with Pati-Salam quark-lepton unification

$$SU(4) \times SU(2)_L \times SU(2)_R \times SU(3)_H$$

$SU(3)_H \times U(1)_{B-L} \longrightarrow U(1)_h$

- Breaking pattern is realised by two triplets: $\phi_1, \phi_2 \sim$ (3,-1)

$$\langle\phi_1\rangle = (v_H, 0, 0) \qquad \langle\phi_2\rangle = v'_H(c_\alpha, s_\alpha, 0)$$

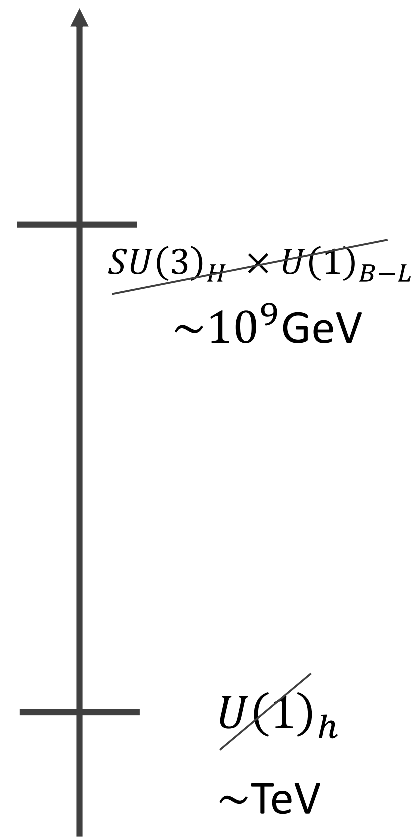
- Can also generate Majorana masses for two RH neutrinos

$$\bar{\nu}_R^c \lambda_{ij} \phi_i^* \phi_j^\dagger \nu_R$$

- $U(1)_h$: $\quad T_h = T_H^8 + \frac{1}{2\sqrt{3}} T_{B-L}$

$$T_Q^h = \frac{1}{2\sqrt{3}} \begin{pmatrix} \frac{4}{3} & & \\ & \frac{4}{3} & \\ & & -\frac{5}{3} \end{pmatrix} \qquad T_L^h = \frac{1}{2\sqrt{3}} \begin{pmatrix} 0 & & \\ & 0 & \\ & & -3 \end{pmatrix}$$

quarks leptons



Rotation to mass basis: $f_{L(R)} \to U_{L(R)} f_{L(R)}$

- Chiral rotation to mass basis after $U(1)_h$ and EW breaking
- Potentially have many new mixing angles involving 3rd generation

- For simplicity, assume the minimal scenario:

$$U_{d_L} = V_{CKM} \qquad U_{e_L} = R^{23}(-\theta_l)$$

$$U_{u_L} = \mathbb{1} \qquad U_{\nu_L} = R^{23}(\theta_{23} - \theta_l) R^{13}(\theta_{13}) R^{12}(\theta_{12})$$

(no rotation of RH fermions)

$$J_\mu = \sum_f \bar{f} U_f^\dagger T^f U_f \gamma_\mu f$$

- Off-diagonal couplings in down sector have an MFV structure:

$$\bar{d}^i \gamma_\mu V_{ti}^* V_{tj} d_j$$

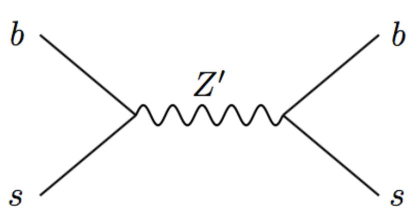
$U(1)_h$ phenomenology

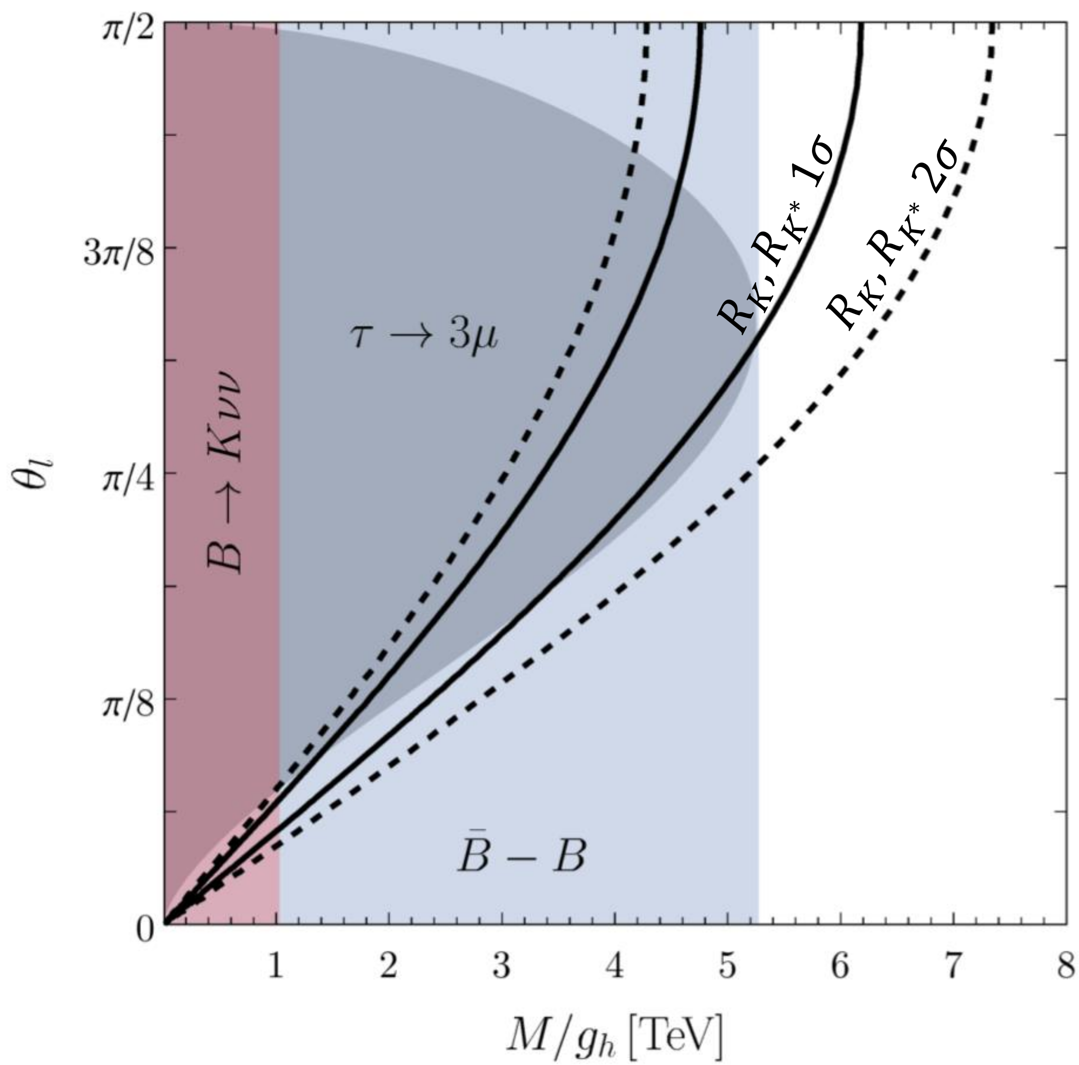
$T_Q \sim \left(\frac{4}{3}, \frac{4}{3}, -\frac{5}{3}\right)$, $T_L \sim (0, 0, -3)$

$$\delta C_9^\mu = -\delta C_{10}^\mu = -\frac{\pi}{\alpha\sqrt{2}G_F}\frac{3}{4}\frac{g_h^2}{M^2}s_{\theta_l}^2$$

Leading constraints:

- $B_{(s)} - \bar{B}_{(s)}$ mixing
- $\tau - \mu$ cLFV

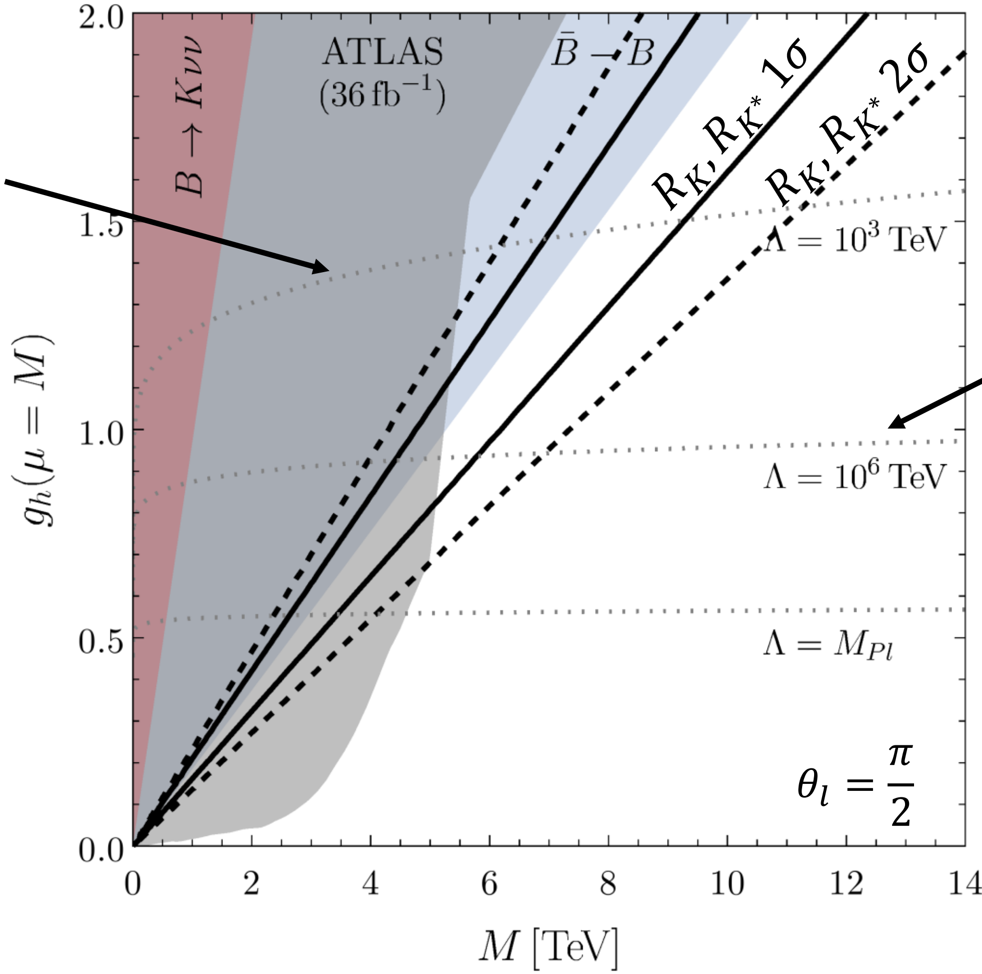




$U(1)_h$ phenomenology

$T_Q \sim \left(\frac{4}{3}, \frac{4}{3}, -\frac{5}{3}\right)$, $T_L \sim (0,0,-3)$

Strong limit from Z' searches at LHC (resonant *and* high-pT)



Upper limit on $SU(3)_H \times U(1)_{B-L}$ breaking scale from perturbativity

Remaining parameter space should be covered by high-pT searches at HL-LHC

[talk by A. Greljo]

What other symmetries could we have?

Recall, the largest local symmetry is

$$SU(3)_Q \times SU(3)_L \times U(1)_{B-L}$$

- What other breaking patterns could we have?
- Many possible U(1) subgroups to consider

Can reduce the number of possibilities by imposing some 'phenomenological' constraints…

Reducing the possibilities

In quark sector, need to avoid dangerous FCNC mediated by Z'
i.e. $K - \overline{K}$ and $D^0 - \overline{D}^0$ mixing

1) Assume same charges for 1st & 2nd generation

$$Q_q = (a, a, b)$$

Potentially have more freedom in lepton sector

2) Impose requirement that two RH neutrinos can obtain large Majorana masses, motivated by see-saw and leptogenesis

$$Q_l = (0, 1, -1) \qquad Q_l = (0, 0, -1)$$

Two classes of U(1)

- With a few assumptions, narrowed down to just two classes of U(1) at low-energy!

$$Q_q = (a, a, -2a), \qquad Q_l = (0, 1, -1)$$

$L_\mu - L_\tau$

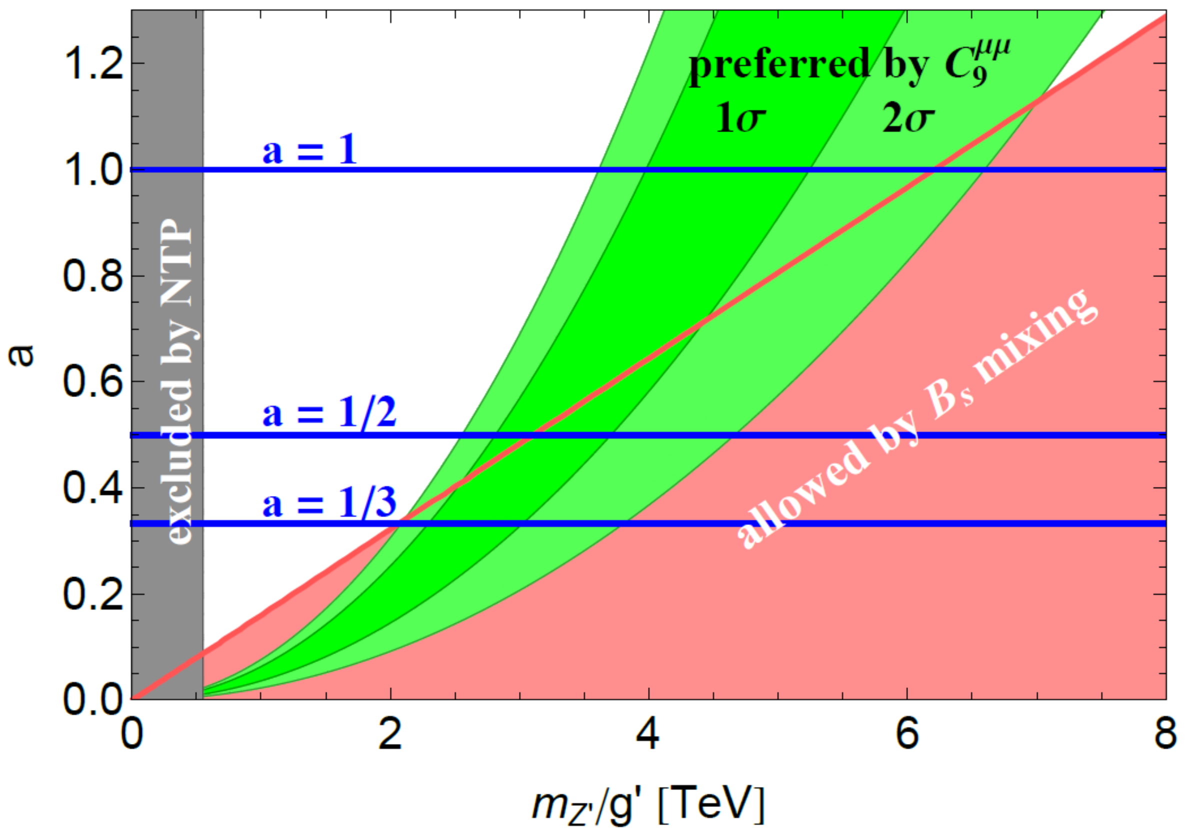
[see Crivellin, D'Ambrosio, Heeck 1503.03477]

$$Q_q = \left(a, a, \frac{1}{3} - 2a\right), \quad Q_l = (0, 0, -1)$$

$SU(3)_H$ model is $a = 4/9$

Two classes of U(1)

$$Q_q = (-a, -a, 2a), \qquad Q_l = (0, 1, -1)$$



[Crivellin, D'Ambrosio, Heeck 1503.03477]

Flavoured B-L

$$Q_q = \left(a, a, \frac{1}{3} - 2a\right), \quad Q_l = (0, 0, -1)$$

Interesting special case $a = 0$ ⟶ flavoured B-L symmetry

- B-L doesn't need to be universal
  anomalies cancel *within* each generation (like SM)

- From point of view of $b \to sll$, flavoured B-L is likely to be the *least* constrained possibility
  (lack of 1st and 2nd generation couplings means it can evade direct searches)

Rotation to mass basis: $f_{L(R)} \to U_{L(R)} f_{L(R)}$

- In this case, assuming only CKM angles in the quark sector gives the wrong sign contribution to C_9^{μ}

- Take a minimal approach and introduce two new angles

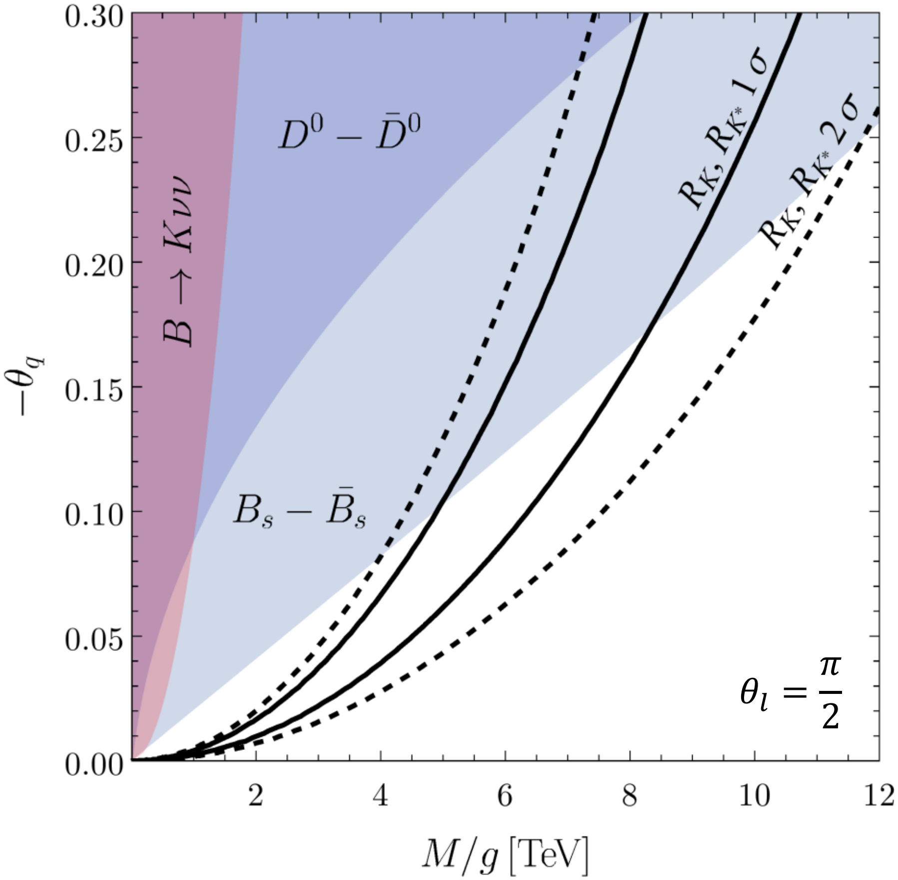
$$U_{d_L} = R^{23}(\theta_q), \qquad U_{e_L} = R^{23}(\theta_l)$$

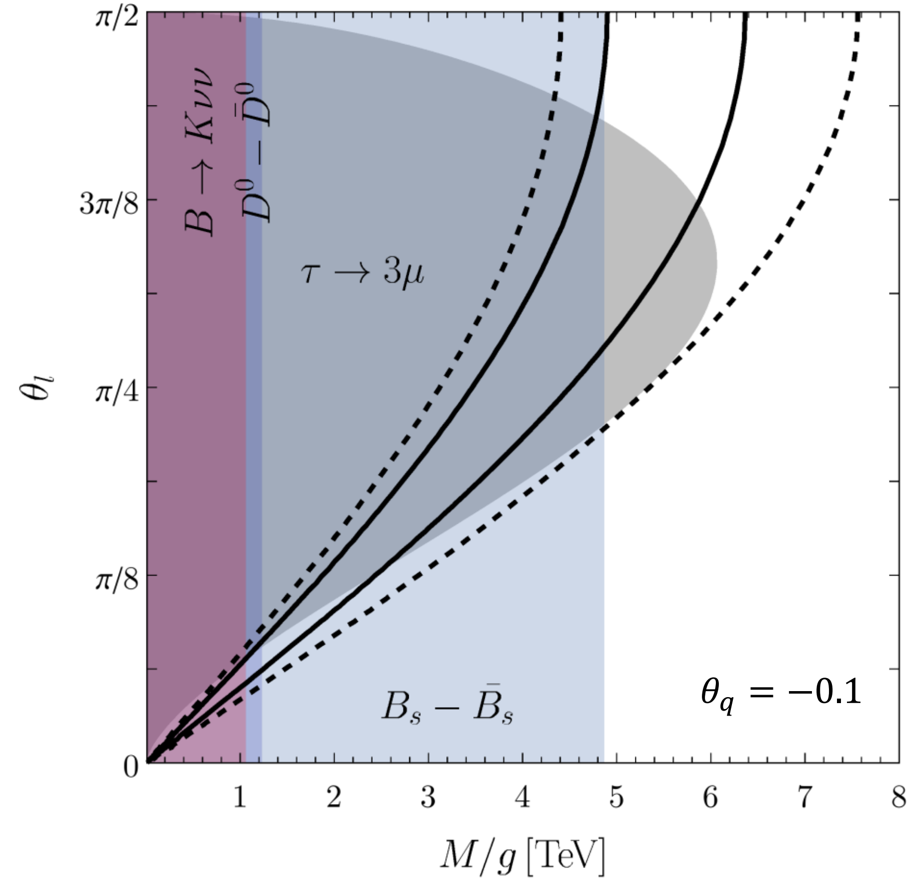
$$U_{u_L} = R^{23}(\theta_q)V_{CKM}^{\dagger}, \qquad U_{\nu_L} = R^{23}(\theta_l)U_{PMNS},$$

(no rotation of RH fermions)

$$\delta C_9^{\mu} = -\delta C_{10}^{\mu} = -\frac{\pi}{\alpha\sqrt{2}G_F V_{tb}V_{ts}^*}\frac{g^2 s_{\theta_q} c_{\theta_q} s_{\theta_l}^2}{3M^2}$$

$U(1)_{(B-L)_3}$ phenomenology



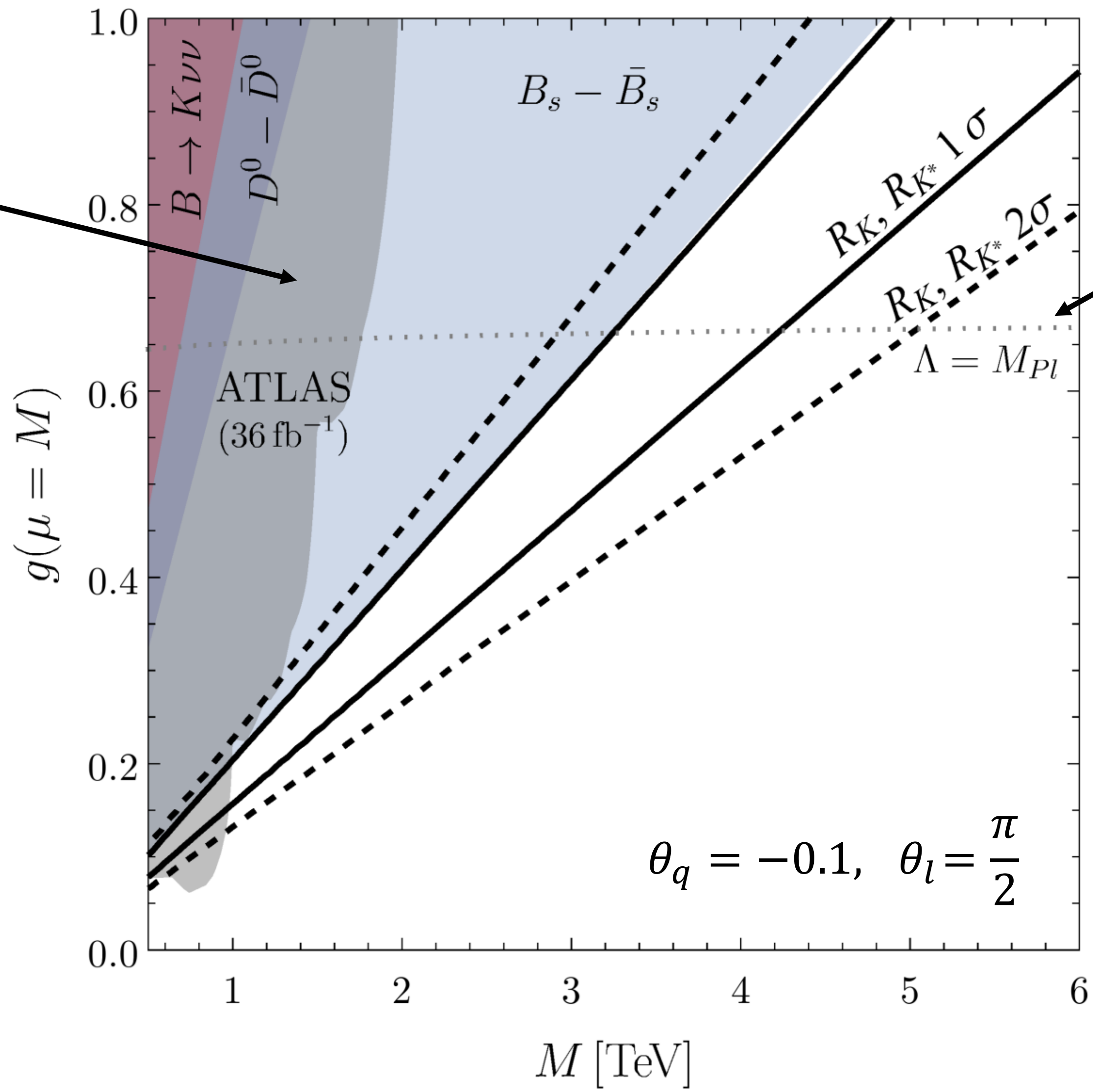


$\bar{B}_s - B_s \Rightarrow |\theta_q| \lesssim 0.15$

$\tau \to \mu\mu\mu$ disfavours maximal mixing

$U(1)_{(B-L)_3}$ phenomenology

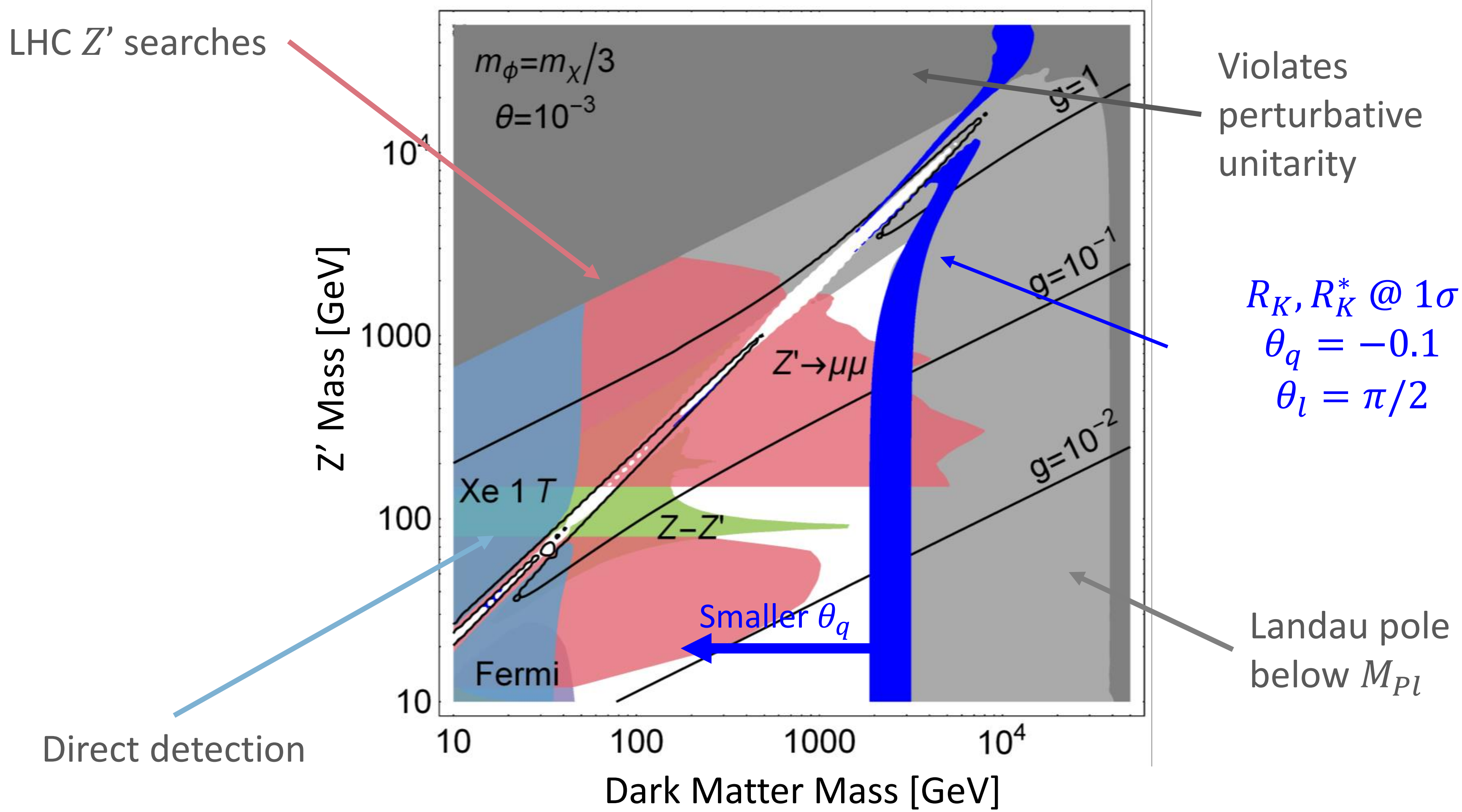
Weaker limit from LHC Z' searches



Perturbativity up to M_{Pl}

Connection with dark matter

ν_R^3 is charged under $U(1)_{(B-L)_3}$ and remains light → DM candidate?
→ Yes! but already strong constraints from Z' searches



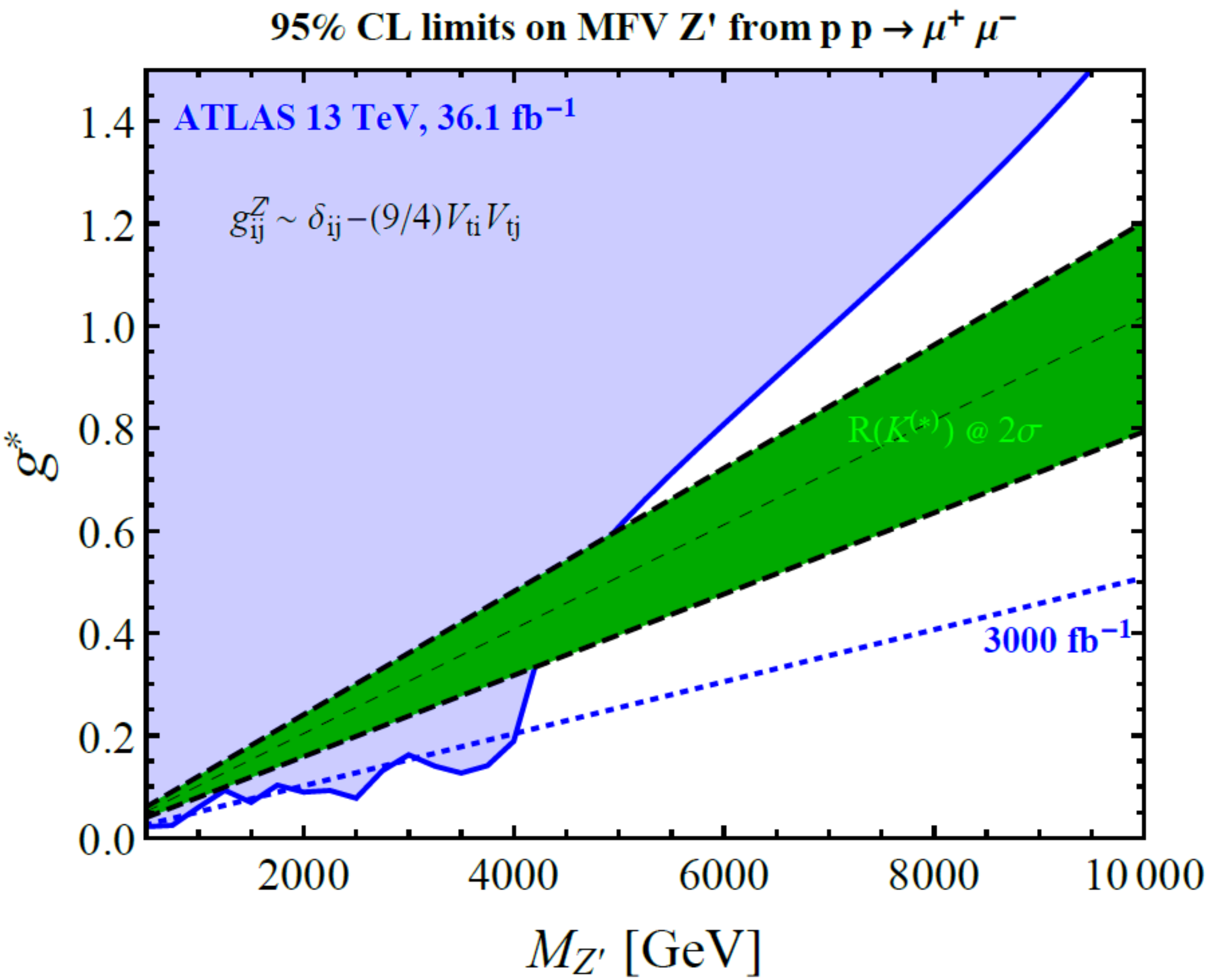
Summary

- Z' provides a simple, tree-level explanation of the $b \to sll$ anomalies
- Starting from $SU(3)_Q \times SU(3)_L \times U(1)_{B-L}$, two interesting classes of U(1) to consider
- One possibility is $SU(3)_H \times U(1)_{B-L} \longrightarrow U(1)_h$
  $\to$ can fit the data currently, but strong constraints from LHC searches
- Flavoured B-L can evade direct searches and remain valid to high scale
- In general, additional complexity needed in the Yukawa sector to generate mixing with 3rd generation after U(1) breaking

Backup

High-pT projections for $U(1)_h$

Courtesy of Admir Greljo



Yukawa Structure

- Off-diagonal Yukawa couplings involving 3rd generation forbidden by new gauge symmetry

$$Y_d = \begin{pmatrix} \hat{Y}_d^{2\times 2} & 0 \\ 0 & Y_b \end{pmatrix}$$

→ Require a mechanism to generate these upon $U(1)'$ breaking

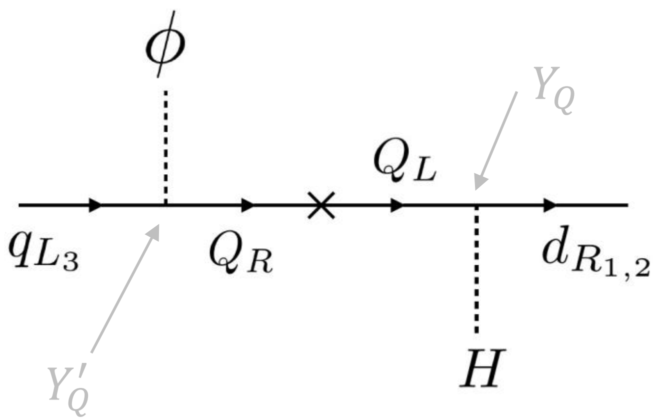
Two general possibilities:

- Additional Higgs doublets charged under $U(1)'$
- New vector-like fermions

Yukawa Structure for $U(1)_{(B-L)_3}$

To generate general 3x3 Yukawa couplings, introduce:

- $U(1)_{(B-L)_3}$ neutral *V-L* fermions: $Q_{L,R}, U_{L,R}, D_{L,R}, L_{L,R}, E_{L,R}, N_{L,R}$
- SM singlet scalars ($U(1)'$ *breaking*): $\phi_l(+1), \phi_q(+\frac{1}{3})$



$$\begin{pmatrix} \bar{q}_{L_{1,2}} & \bar{q}^3_L \end{pmatrix} H \begin{pmatrix} \hat{Y}_d^{2\times 2} & -\frac{Y'_D \phi_q^*}{M_D} Y_D \\ -\frac{Y'_Q \phi_q}{M_Q} Y_Q^T & Y_b \end{pmatrix} \begin{pmatrix} d_{R_{1,2}} \\ b_R \end{pmatrix}$$

Rotation Matrices for $U(1)_{(B-L)_3}$

$$U_{d_L} = \begin{pmatrix} \mathbf{V}_L^d & -\frac{Y_D' \phi_q^*}{M_D Y_b} Y_D \\ \frac{Y_D'^* \phi_q}{M_D^* Y_b^*} Y_D^\dagger \mathbf{V}_L^d & 1 \end{pmatrix} + \mathcal{O}(\epsilon^2)$$

$$U_{d_R} = \begin{pmatrix} \mathbf{V}_R^d & -\frac{Y_Q'^* \phi_q^*}{M_Q^* Y_b^*} Y_Q^* \\ \frac{Y_Q' \phi_q}{M_Q Y_b} Y_Q^T \mathbf{V}_R^d & 1 \end{pmatrix} + \mathcal{O}(\epsilon^2)$$

- V-L fermions can be relatively heavy and still easily generate CKM-sized mixing angles

- RH rotations can be naturally suppressed by decoupling M_Q

Connection with dark matter?

- One RH neutrino is charged under $U(1)_{(B-L)_3}$ and remains light
  → DM candidate?

- Spontaneous breaking by $\Phi(+2)$, can generate Majorana mass for ν_R^3

$$\mathcal{L} = \frac{i}{2}\bar{\chi}\partial\!\!\!/\chi + \frac{g}{2}Z'_\mu\bar{\chi}\gamma^5\gamma^\mu\chi - (\frac{y}{2}\bar{\chi}\Phi P_R\chi + h.c.) \qquad \chi = (-\varepsilon\nu_R^{3*},\, \nu_R^3)^T$$

- Stability can be guaranteed by $\mathbb{Z}_2$

- Relic abundance from freeze-out via $U(1)_{(B-L)_3}$ gauge interactions