# New Physics explanations of neutral current *B*-anomalies

Joe Davighi, DAMTP, University of Cambridge

Beyond the flavour anomalies, IPPP, Durham (April 2020)

# Plan for this talk

- Focus on two general features of the *B*-anomaly measurements:
  - Third family alignment
  - Preservation of SM accidental symmetries
- Will discuss three model-building frameworks that are guided by these two features, and look at their broad implications e.g. for future measurements
- Will focus on models for the neutral current *B*-anomalies (even though the two features above are shared by the charged current anomalies)

# “Four” categories of anomaly

### Neutral current BRs

- BRs:

  $B \to K^{(*)}\mu\mu,\, B_s \to (\varphi)\mu\mu$

### Neutral current angular

- $P_5'$ $(B \to K^*\mu\mu)$ etc.

  (n.b. 2020 LHCb update)

### Neutral current LFUV

- $R_K,\, R_{K^*}$

### Charged current LFUV

- $R_D,\, R_{D^*}$

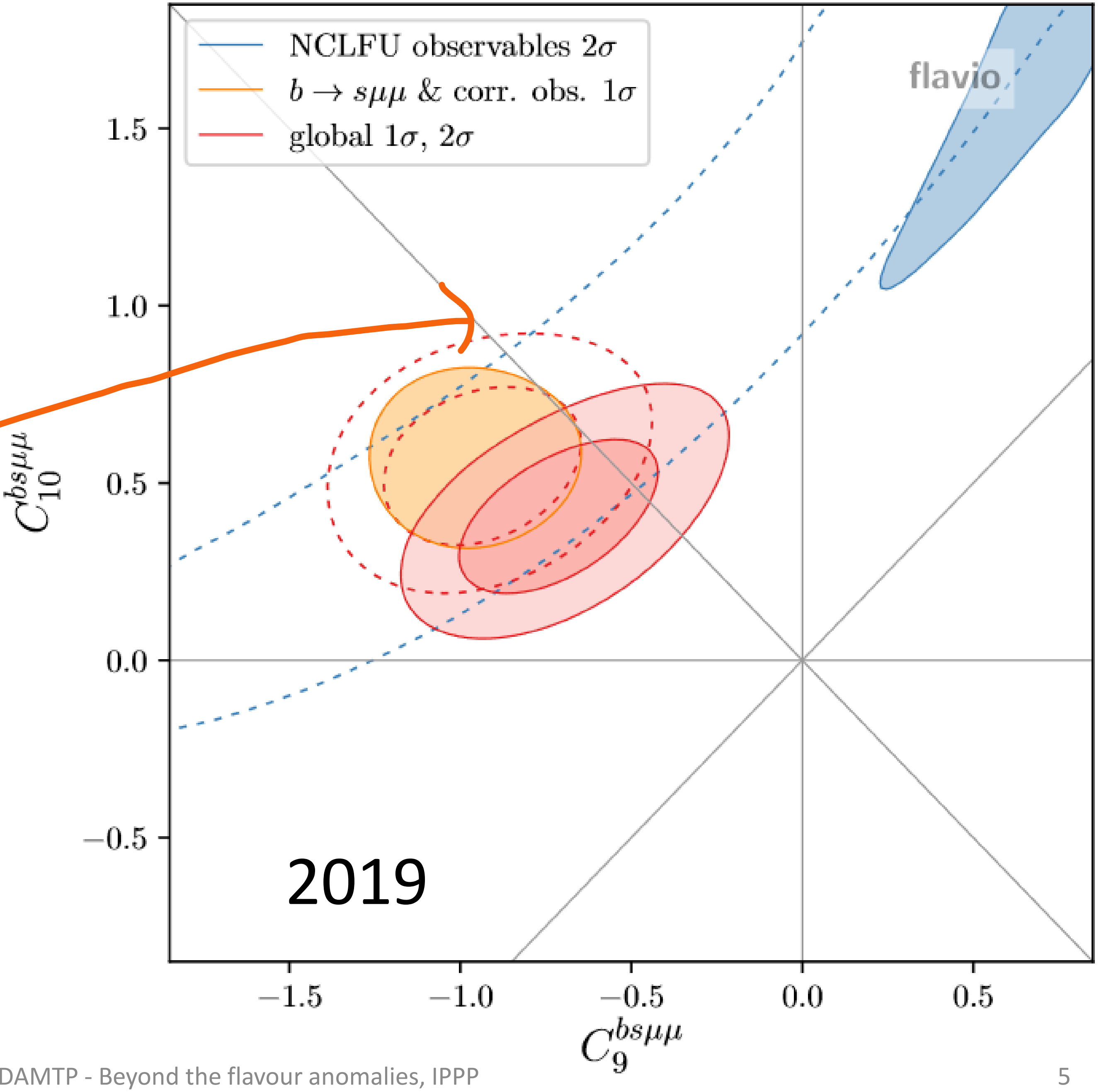
We focus on $b \to sll$ system

For models that address all four categories, see Gino's talk

# Global fits to WET coefficients

$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

E.g. $C_9 = -C_{10}$ fits data better than SM, pull of $6.6\sigma$




- 2019 global fits driven by $b \to s\mu\mu$, not $R_{K^{(*)}}$
- Perhaps even an internal tension → $C_9^U \neq 0$

Aebischer, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub, 2019

# Global fits to WET coefficients

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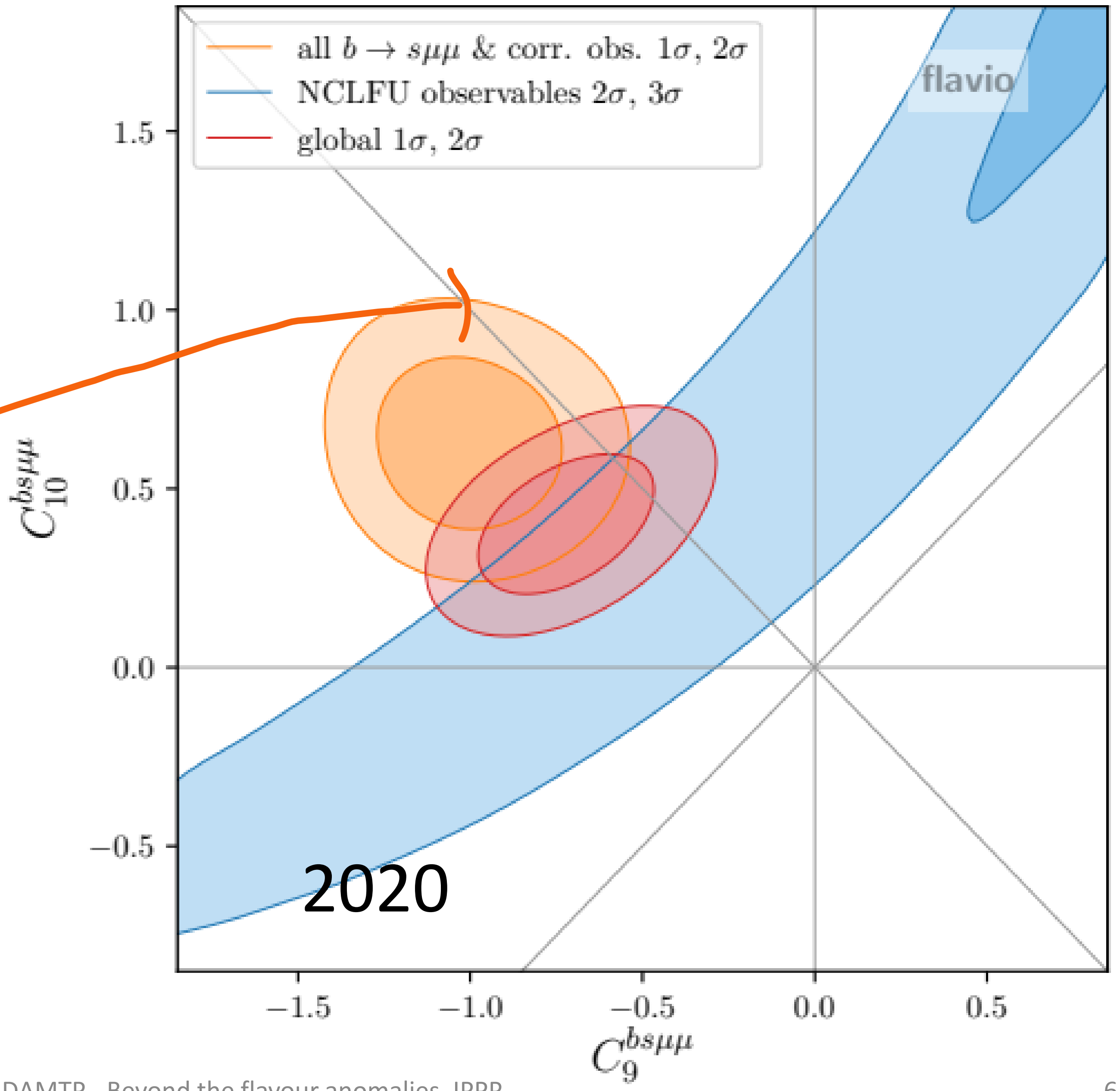
E.g. $C_9 = -C_{10}$ fits data better than SM, pull of **6.9$\sigma$**

- 2020 global fits driven by $b \to s\mu\mu$, not $R_{K^{(*)}}$, internal tension remains
- Similar overall picture



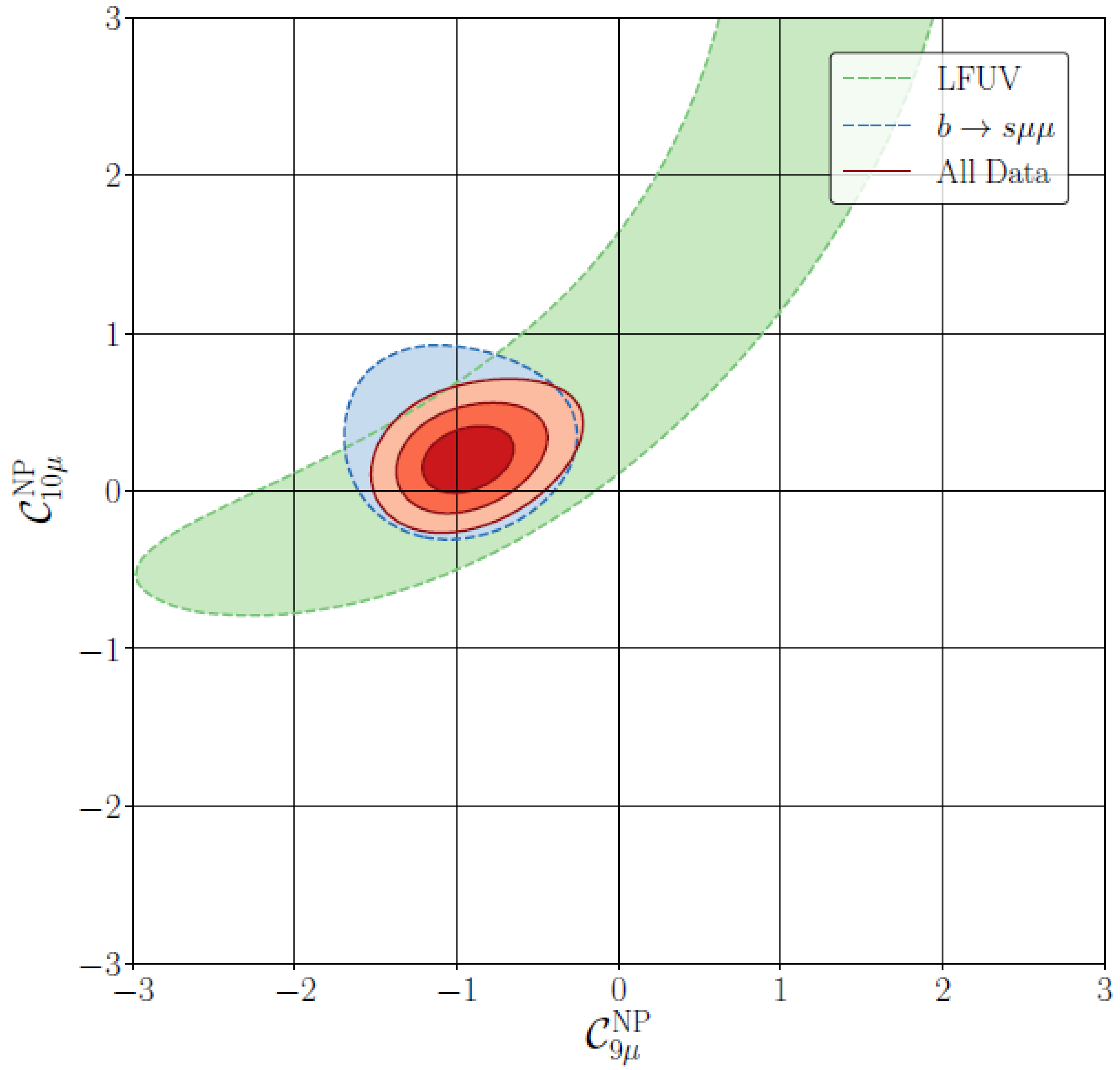

See Peter and Sébastien's talk

# Global fits to WET coefficients

- Again including $b \to s\mu\mu$ locates elliptical fit region, and drives $C_9 < 0$

- Here LFUV internally consistent with $b \to s\mu\mu$

Alguero, Capdevila, Crivellin, Descotes-Genon, Masjuan, Matias, Virto 2019

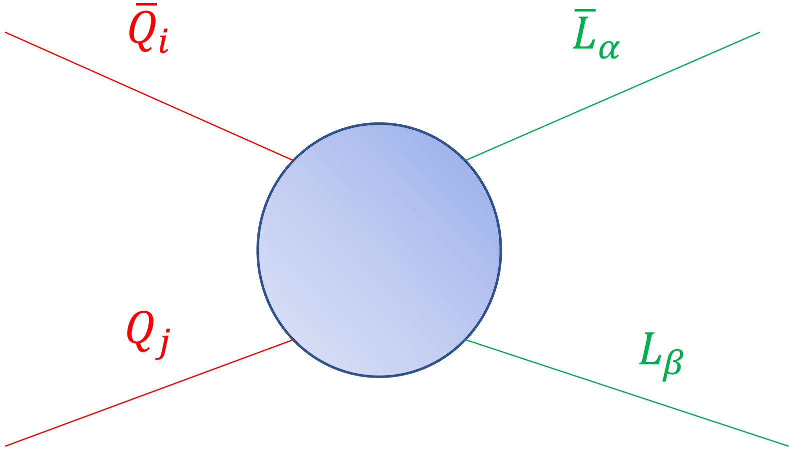


# WET → SMEFT → Models

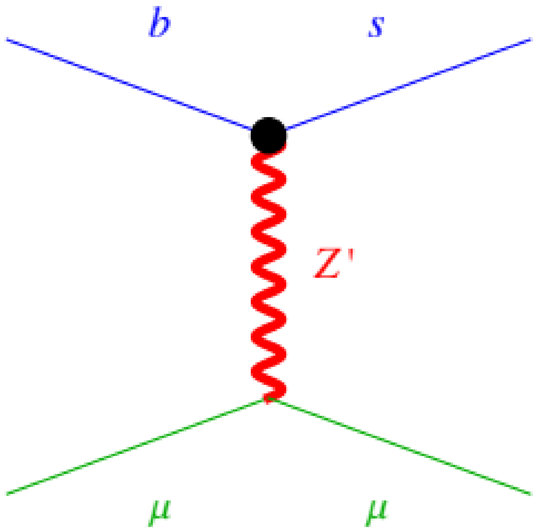
Good fit for $C_9 = -C_{10}$, i.e. $LL$ chirality operator. Match to SMEFT operators,

$$(\bar{Q}_i \gamma^\mu Q_j)(\bar{L}_\alpha \gamma_\mu L_\beta), \qquad (\bar{Q}_i \gamma^\mu \sigma^a Q_j)(\bar{L}_\alpha \gamma_\mu \sigma^a L_\beta)$$

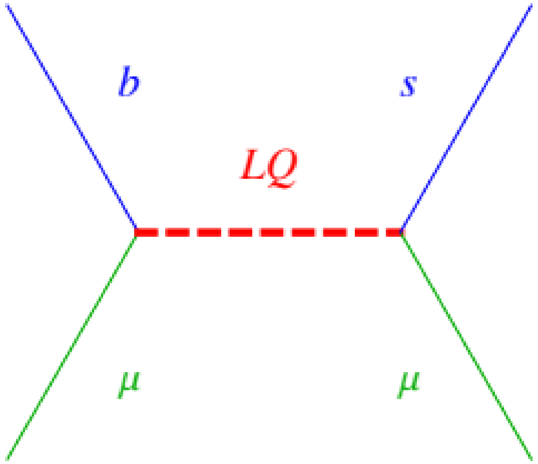
These 4-fermi operators could arise from integrating out a heavy particle



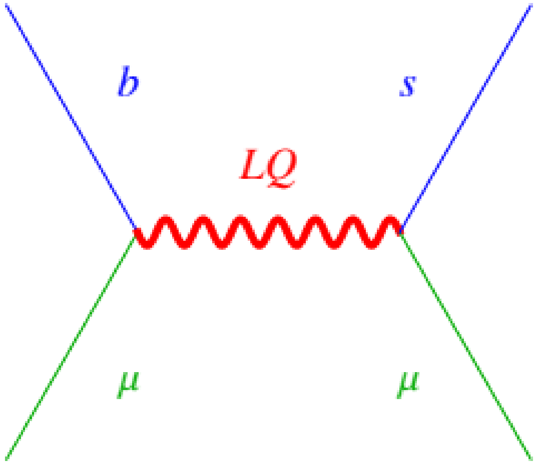
# Tree-level mediators: Mass/g ~3 TeV/0.1




$Z'$



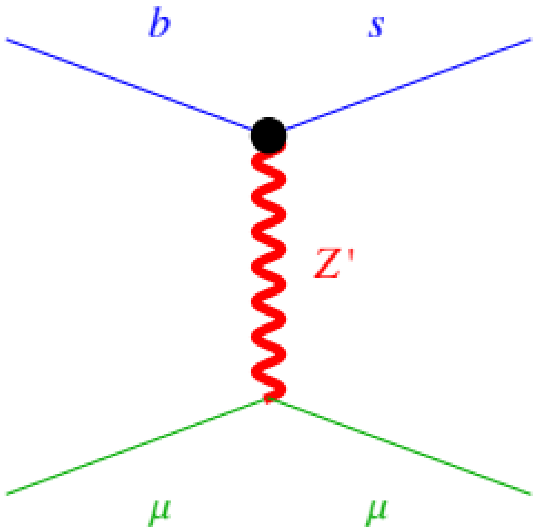

$S_3$




$U_1$, $U_3$

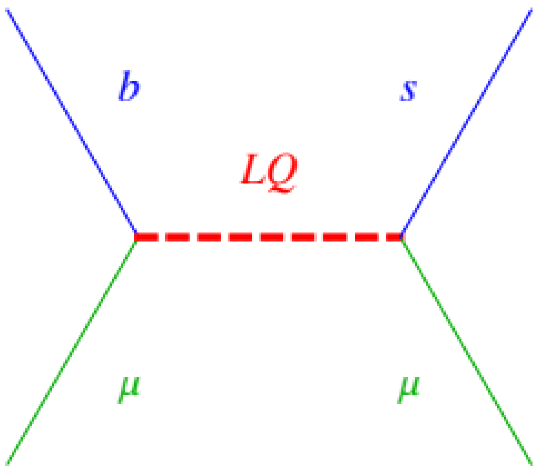
The only single mediator that can also explain CC anomalies

# Tree-level mediators: Mass/g ~3 TeV/0.1



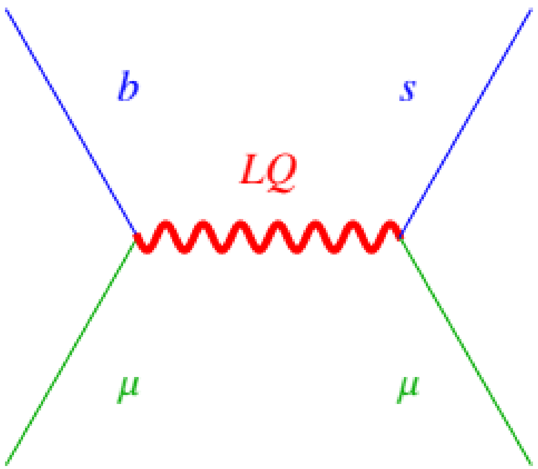

$Z'$

E.g. spontaneously-broken $U(1)$. Anomaly-free?




$S_3$

Light scalar - how? Why no proton decay due to $\overline{Q^c}S_3Q$ ?




$U_1, \ U_3$

Non-renormalizable; UV completions? E.g. PS-based models, "4321",...

[… or new physics in **Loops** - push down mass of BSM mediator to as low as O(100 GeV) scale … ]

# Guiding principles

## A. Third family (quark) alignment

- No anomalies (NC or CC) in kaon/ pion/ charm physics – only in bottom physics
- Indirect evidence: absence of NP in high-$p_T$ searches suggests couples weakly to valence quarks
- **Symmetry** reason for alignment?

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Bordone, Cornella, Fuentes-Martin, Isidori, 2018

?

The flavour problem

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## B. Anomalies respect the SM accidental symmetries

- **Why LFUV but no LFV?** Very stringent bounds on e.g. $l \to l'\gamma$, $Z \to ll'$, $l \to l'l'l'$, …
- Also risk of baryon number violation e.g. in LQ models

Inspired by principles A. and B., will discuss three frameworks:

A.

1. Rank One Flavour Violation
2. Third family Z' models

B.

3. Gauging accidental SM symmetries

[n.b. none of these "frameworks" are based on flavour structures of the kind discussed by Claudia and Gino e.g. $U(2)^5$]

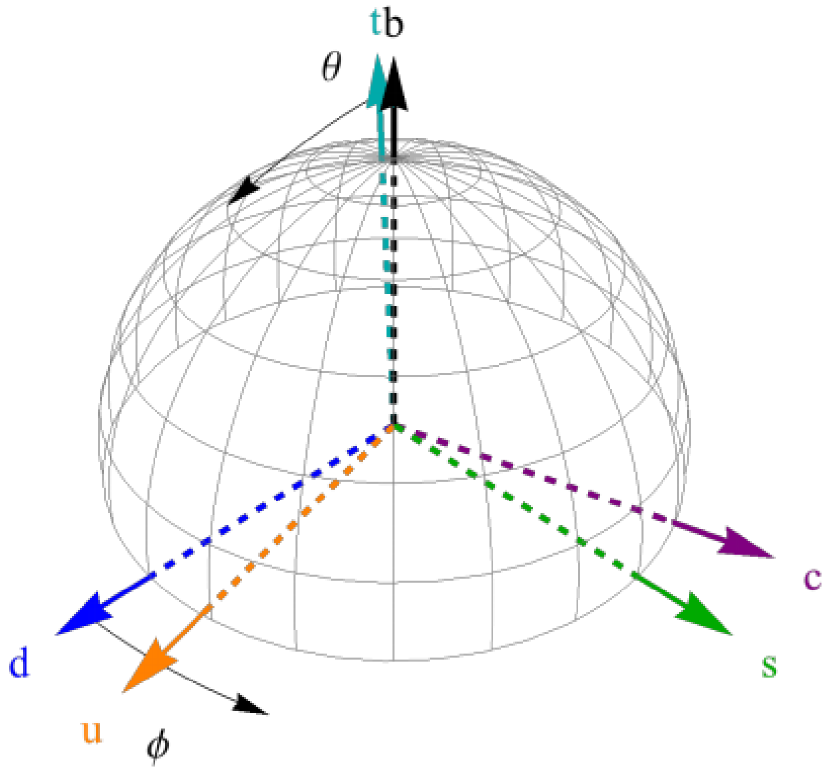
# 1. Rank One Flavour Violation

A systematic parametrization of how much NP can depart from third family alignment, assuming NP is of the form:

$$C_S^{ij}(\bar{Q}_i\gamma^\mu Q_j)(\bar{L}_2\gamma_\mu L_2) + C_T^{ij}(\bar{Q}_i\gamma^\mu\sigma^a Q_j)(\bar{L}_2\gamma_\mu\sigma^a L_2) + C_R^{ij}(\bar{Q}_i\gamma^\mu Q_j)(\bar{e}_2\gamma_\mu e_2),$$

where $C_{S,T,R}^{ij} = C_{S,T,R}\hat{n}^i\hat{n}^{j*}$

$$\hat{n} = \begin{pmatrix} \sin\theta\cos\phi\, e^{i\alpha_{bd}} \\ \sin\theta\sin\phi\, e^{i\alpha_{bs}} \\ \cos\theta \end{pmatrix}$$




Gherardi, Marzocca, Nardecchia, Romanino, 2019

# 1. Rank One Flavour Violation

This "model-independent" framework is *not* an assumption about flavour structure, but rather an assumption about underlying dynamics that includes many popular models:

- All single leptoquark models
- Some $Z'$ models e.g. gauged $L_\mu - L_\tau$ — Altmannshofer, Gori, Pospelov, Yavin, 2014
- Loop models in which flavour violation is linear in quark fields — Gripaios, Nardecchia, Renner, 2016

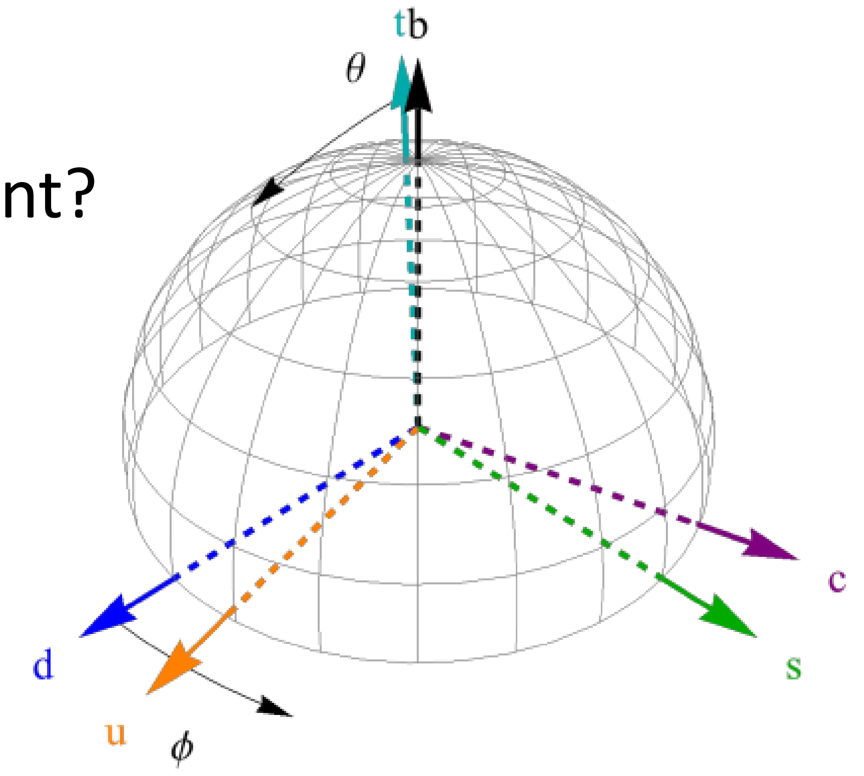
| Simplified model | Spin | SM irrep | $(c_S, c_T, c_R)$ |
|---|---|---|---|
| $S_3$ | 0 | $(\bar{3}, 3, 1/3)$ | $(3/4, 1/4, 0)$ |
| $U_1$ | 1 | $(3, 1, 2/3)$ | $(1/2, 1/2, 0)$ |
| $U_3$ | 1 | $(3, 3, 2/3)$ | $(3/2, -1/2, 0)$ |
| $V'$ | 1 | $(1, 3, 0)$ | $(0, 1, 0)$ |
| $Z'$ | 1 | $(1, 1, 0)$ | $(1, 0, c_R)$ |

# 1. Rank One Flavour Violation

The idea is to constrain the possible directions $\hat{n}$ by using other precision flavour observables, which are necessarily "disturbed" from their SM predictions

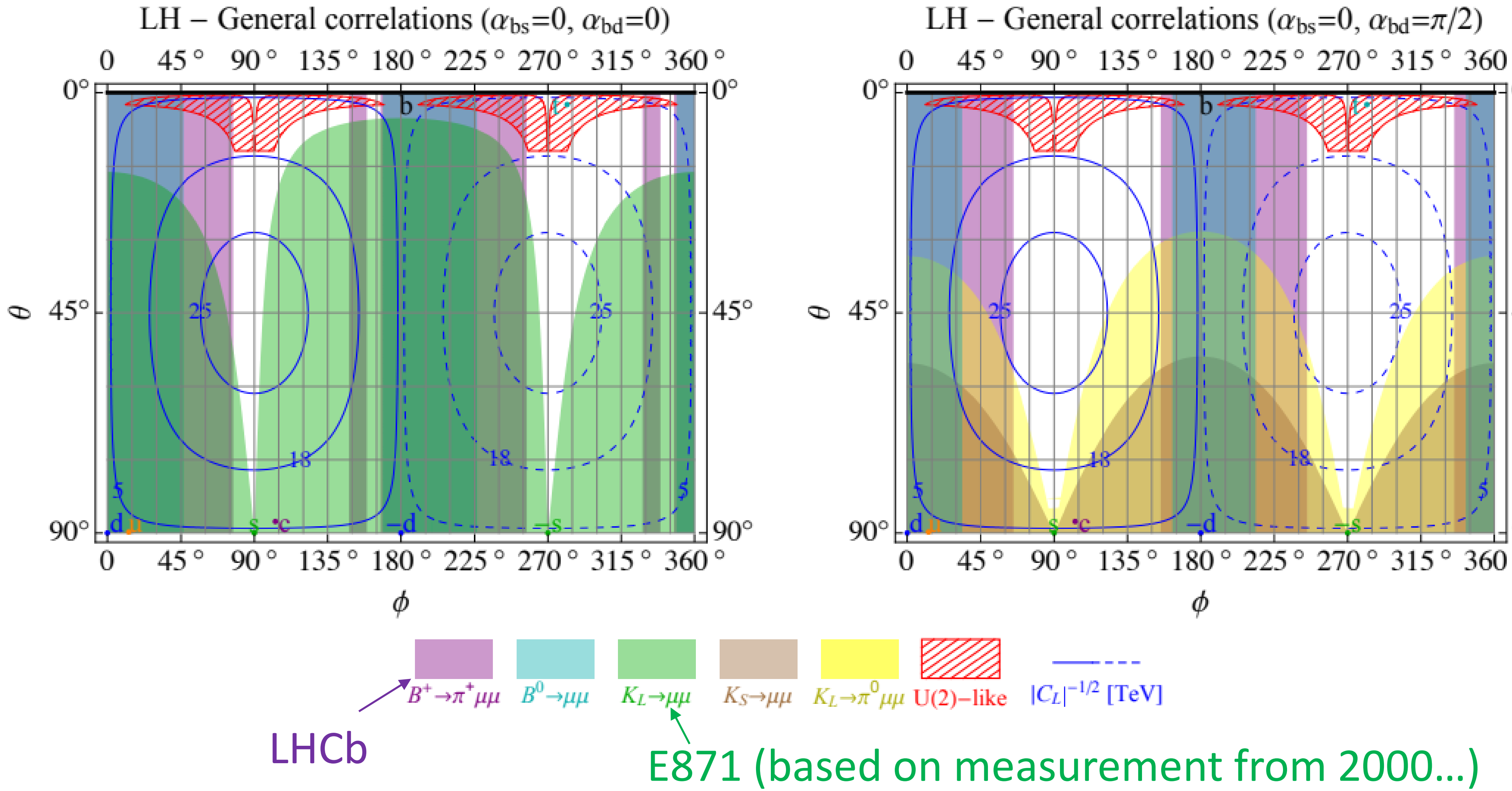
How far can we deviate from TF alignment?

$$\hat{n} = \begin{pmatrix} \sin\theta \cos\phi \, e^{i\alpha_{bd}} \\ \sin\theta \sin\phi \, e^{i\alpha_{bs}} \\ \cos\theta \end{pmatrix}$$



E.g. for $C_R = 0$, constraints from $d_i \to d_j \mu^+ \mu^-$ only:

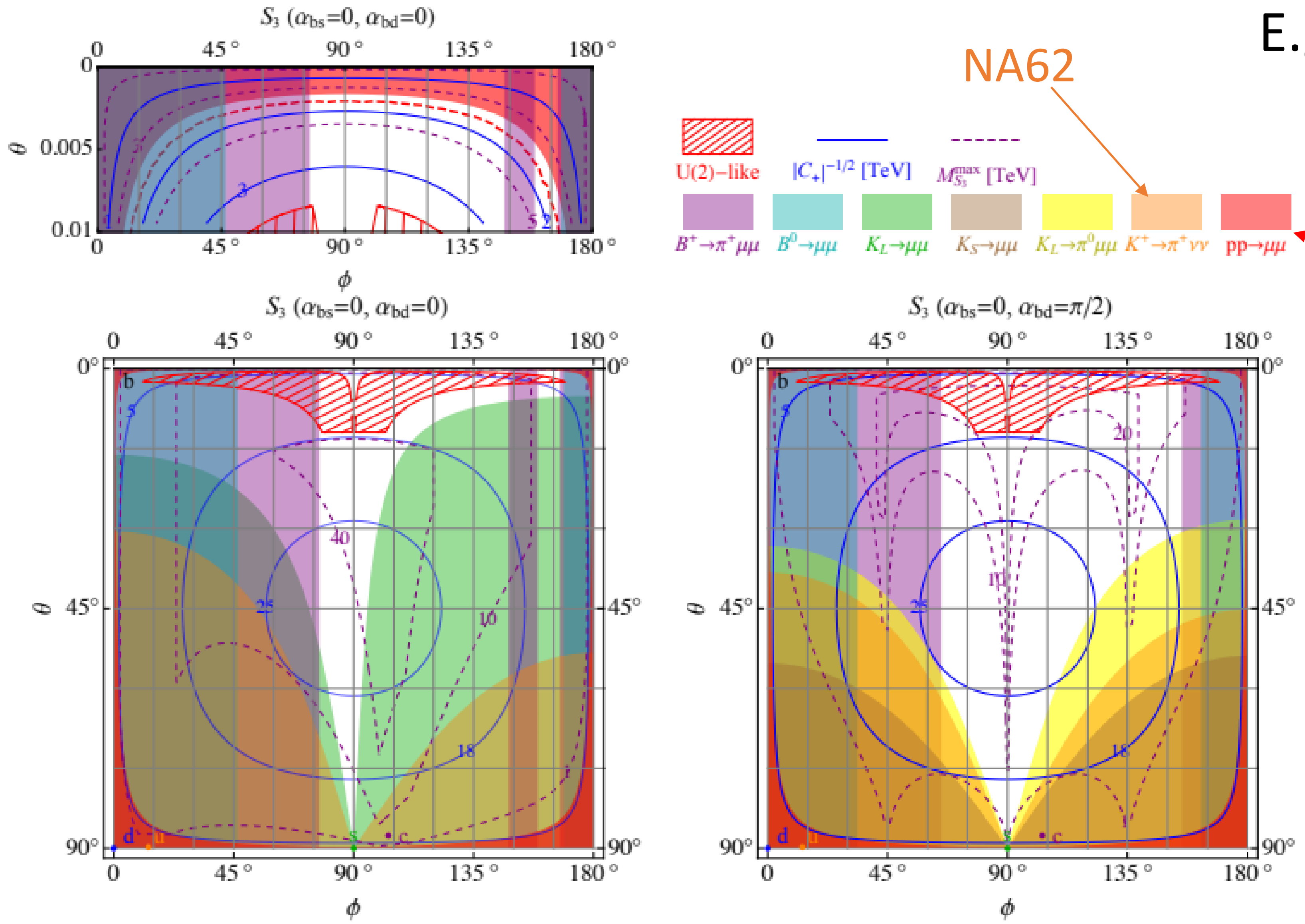
($bs$ coupling is everywhere fitted to $B$-anomalies)



Bring in further constraints by $SU(2)_L$ invariance, i.e. up-type quark transitions and muon neutrino processes – but model dependent.

E.g. for $S_3$ leptoquark

NA62




LHC

One message from ROFV:

*you cannot deviate too much from third-family alignment without being squeezed by other precision flavour bounds*

We will discuss three frameworks:

1. Rank One Flavour Violation
2. Third family Z’ models
3. Gauging accidental SM symmetries

# 2. Third Family $Z'$ models – Part I

Let's start very simple:

- Suppose there is a *Z'* coupled only to third family in weak eigenbasis
- Cancelling gauge anomalies then fixes charges uniquely

$$\boxed{\begin{array}{cccc} F_{Q_i'} = 0 & F_{u_{Ri}'} = 0 & F_{d_{Ri}'} = 0 & F_{L_i'} = 0 \\ F_{e_{Ri}'} = 0 & F_H = -1/2 & F_{Q_3'} = 1/6 & F_{u'_{R3}} = 2/3 \\ F_{d'_{R3}} = -1/3 & F_{L_3'} = -1/2 & F_{e'_{R3}} = -1 & F_\theta \neq 0 \end{array}}$$

… this is just third family hypercharge

Allanach & JD, 2018

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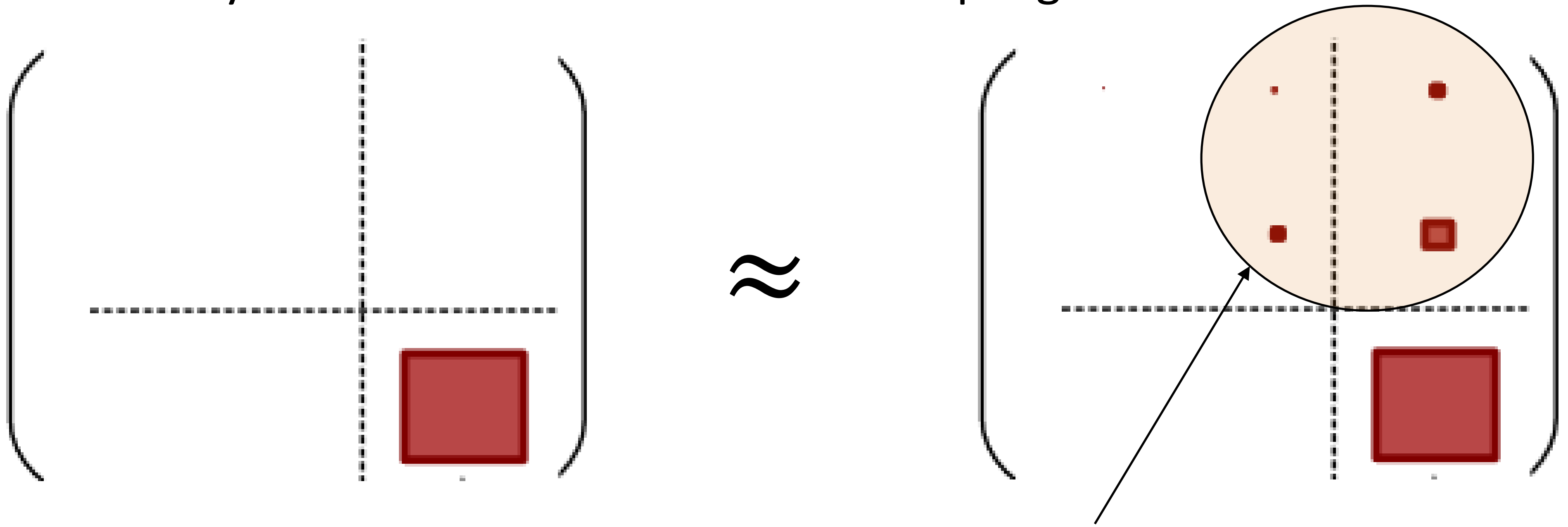
Allanach & JD, 2018

# Simple connection to flavour problem?

Only third family have renormalizable Yukawa couplings



Generated by higher-dim operators
($Z'$ model itself a low-energy EFT)

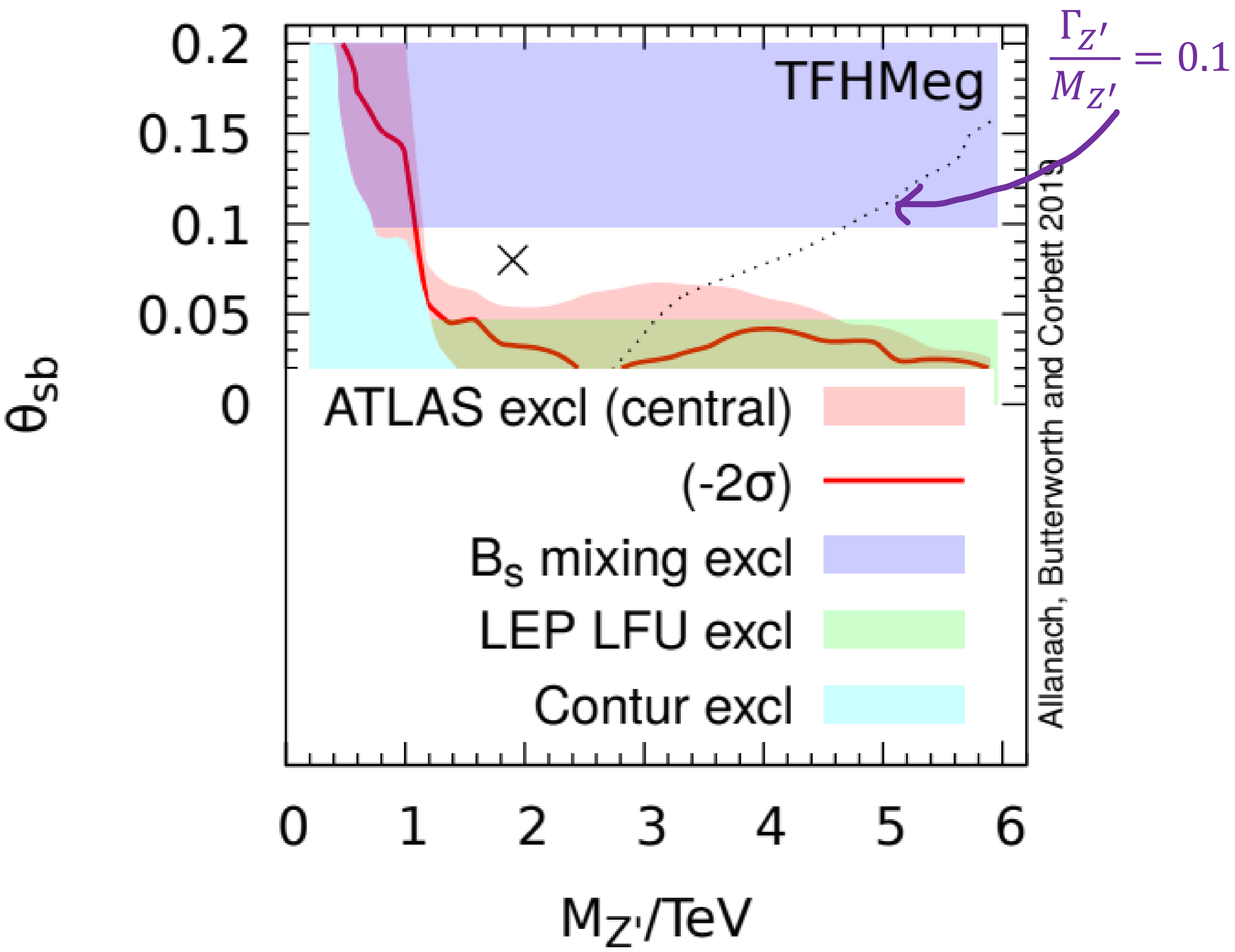
- Expect third family hierarchically heavy
- Expect 1-3 and 2-3 quark mixing angles small

[ If only an EFT, why bother with anomaly cancellation?

- Don’t need to include Wess-Zumino-Witten terms in low-energy theory
- Can build a UV completion by adding only vector-like fermions, for which we can easily write down mass terms
- If the $Z'$ theory were anomalous, would need massive chiral fermions to cancel anomalies in UV – difficult not to break $SU(2)_L$ prematurely

]

# Phenomenology




<u>Example case couplings:</u>

$$V_{e_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{sb} & -\sin\theta_{sb} \\ 0 & \sin\theta_{sb} & \cos\theta_{sb} \end{pmatrix}$$

$g_X$ is everywhere fit to *B*-anomalies

White region allowed (95% C.L.); parameter space for $M_{Z'} > 1.2$ TeV

Allanach & JD, 2018
Allanach, Butterworth, Corbett, 2019
King, Lenz, Rauh, 2019

# Third Family $Z'$ models – Part II

- Also charge 2nd family leptons under $U(1)_X$, to **avoid large $\mu/\tau$ mixing (LFV)**
- Linear anomaly cancellation equations fix:

$$F_{Q_3} = 1, \;\; F_{u_3} = 4, \;\; F_{d_3} = -2, \;\; F_{L_2} + F_{L_3} = -3, \;\; F_{e_2} + F_{e_3} = -6$$

- The quadratic anomaly equation becomes*

$$\left(F_{e_2} - F_{e_3}\right)^2 - \left(F_{L_2} - F_{L_3}\right)^2 = 27$$

- which has a **unique** non-trivial solution in the integers:

$$14^2 - 13^2 = 27$$

Allanach & JD, 2019

*cubic anomaly equation is automatically satisfied

# Third Family $Z'$ models – Part II

- "Deformed TFHM" charge assignment:

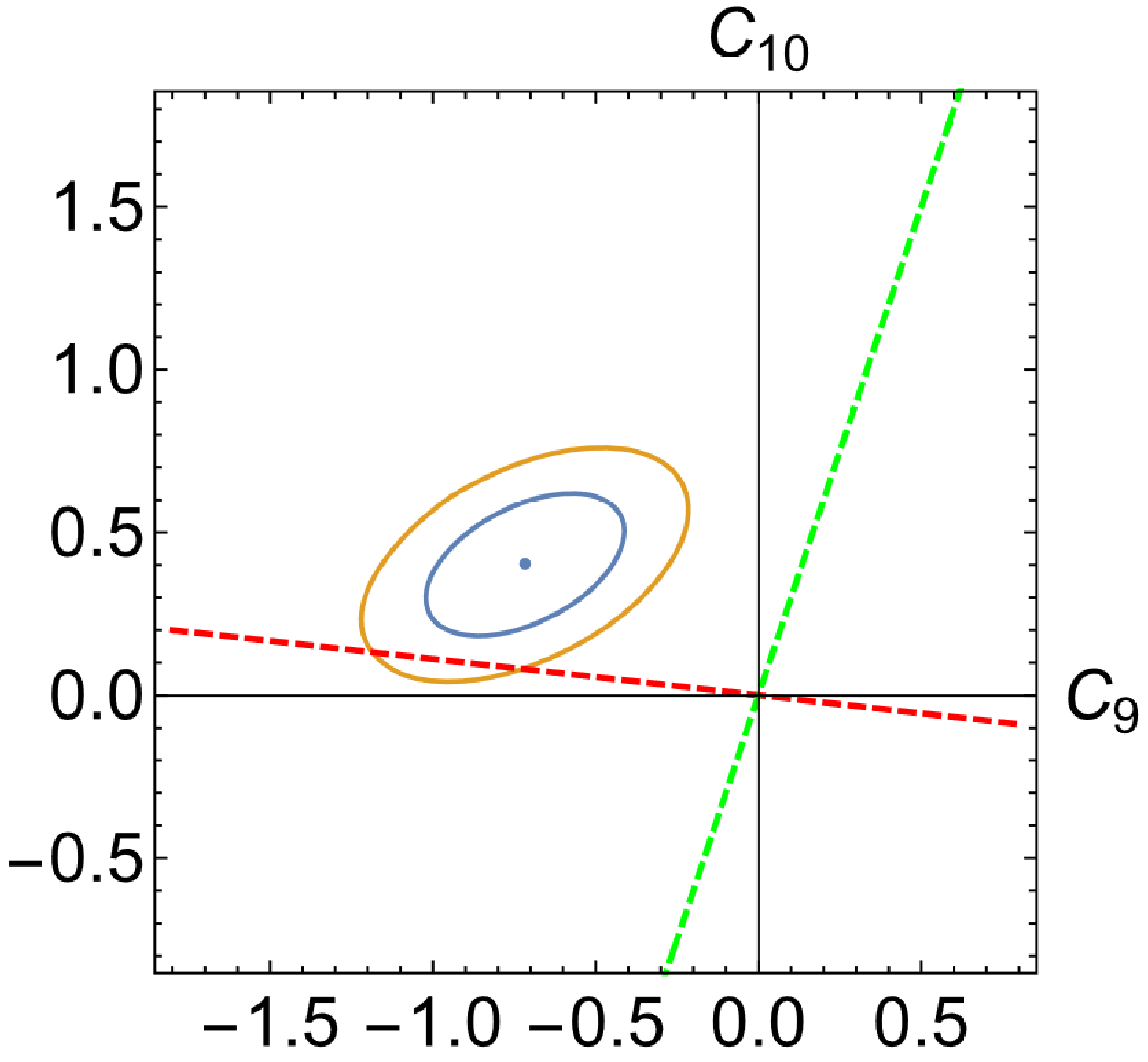
$$
\begin{aligned}
F_{Q'_1} &= 0 & F_{u_{R'_1}} &= 0 & F_{d_{R'_1}} &= 0 \\
F_{Q'_2} &= 0 & F_{u_{R'_2}} &= 0 & F_{d_{R'_2}} &= 0 \\
F_{Q'_3} &= 1/6 & F_{u'_{R3}} &= 2/3 & F_{d'_{R3}} &= -1/3 \\
F_{L'_1} &= 0 & F_{e_{R'_1}} &= 0 & F_H &= -1/2 \\
F_{L'_2} &= 5/6 & F_{e_{R'_2}} &= 2/3 & F_\theta & \\
F_{L'_3} &= -4/3 & F_{e'_{R3}} &= -5/3 & &
\end{aligned}
$$

$\rightarrow C_9 = -9C_{10}$

- No longer allows any charged lepton Yukawas → all non-renormalizable

This model probes a novel combination of Wilson coefficients,

$C_9 = -9C_{10}$ [fixed uniquely by anomaly cancellation]




Using contours from Straub et al'19, we find point on the red-line that minimizes $\chi^2$ - pull of $5.9\sigma$ w.r.t. SM

- Slightly worse fit than for LH coupling
- Better fit than for vector coupling

# Phenomenology

White region allowed (95% C.L.); valid parameter space for

$M_{Z'} > 0.8$ TeV

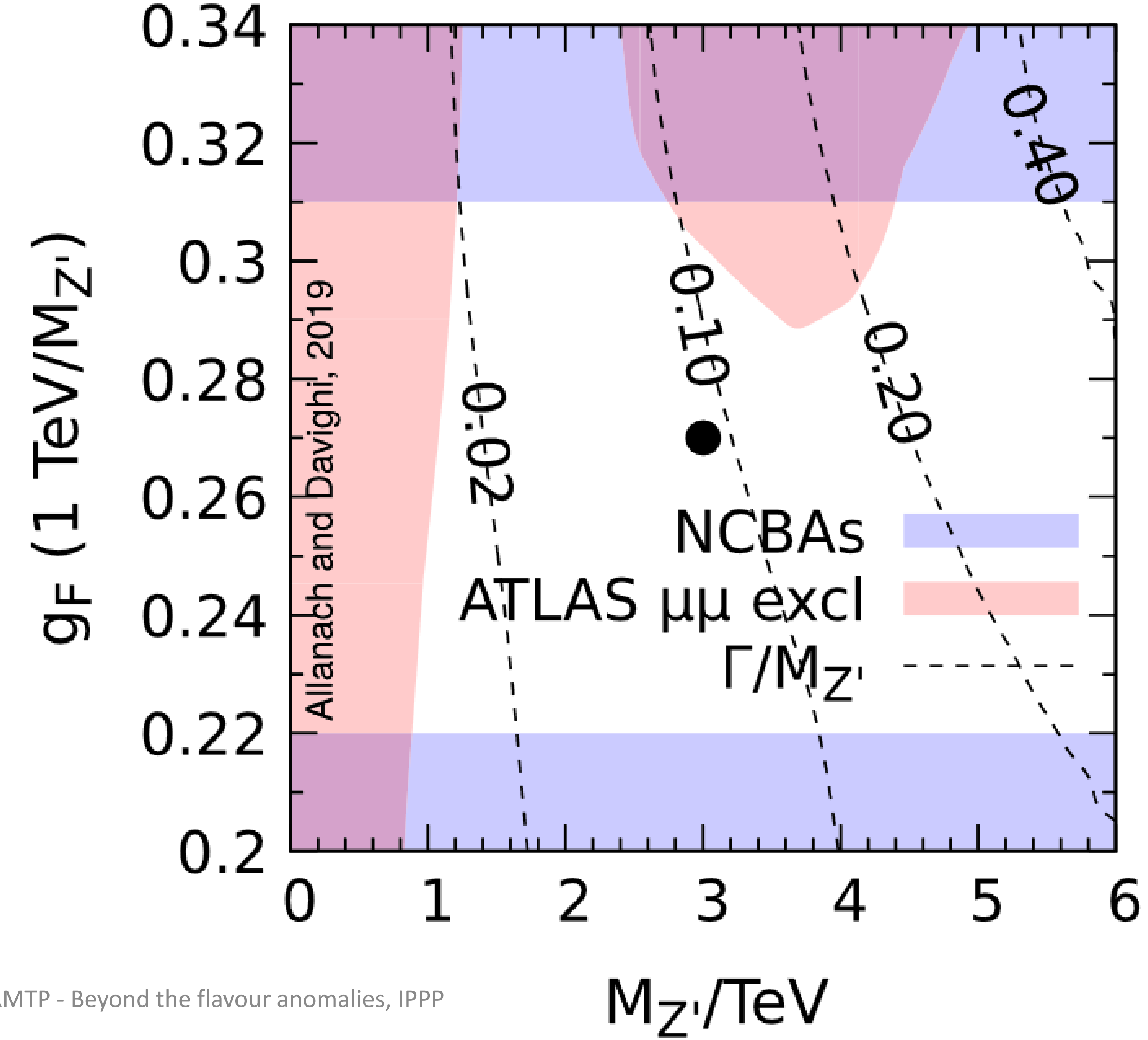
<u>Example case couplings:</u>

$V_{d_L}$ = CKM

$V_{\nu_L}$ = (PMNS)*

Other mixing matrices = 1

Allanach & JD, 2019



# Third Family $Z'$ model predictions

## High $p_T$

$Z'$ decays mainly to third generation fermions. Branching ratios:

1. TFHM: $t\bar{t}$ (42%), $\tau^+\tau^-$ (30%), $b\bar{b}$ (12%), $\mu^+\mu^-$ (8%), neutrinos (8%)
2. DTFHM: $\tau^+\tau^-$ (46%), neutrinos (25%), $t\bar{t}$ (14%), $\mu^+\mu^-$ (11%), $b\bar{b}$ (4%),

As well as dimuon, important decays to tops and tauons

LFUV of $Z$ couplings to $e$ vs. $\mu$; FCC-ee would close parameter space with huge lumi $Z$ production

## Low $p_T$

New physics in tau

e.g. BSM contributions to

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

[a challenging direct measurement at LHCb, but see Claudia/Sam's talk for 3 ways to constrain it going forward]

Different patterns for angular observables

esp. from $C_9 = -9C_{10}$ combination

We will discuss three frameworks:

1. Rank One Flavour Violation
2. Third family Z’ models
3. Gauging accidental SM symmetries

Recall our second "guiding principle":

## B. Anomalies respect the SM accidental symmetries

- $U(1)_B, U(1)_e, U(1)_\mu, U(1)_\tau$ extremely well-tested symmetries of Nature*
- **Why LFUV but no LFV?** Very stringent bounds on e.g. $l \to l'\gamma, Z \to ll', l \to l'l'l', \ldots$
- Also risk of baryon number violation e.g. in LQ models

*Ignoring neutrino oscillations… (and matter-antimatter asymmetry…)

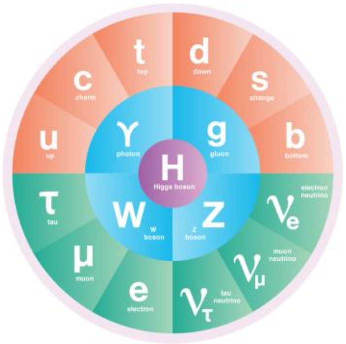
# 3. Gauging the accidental symmetries of the SM

- The idea: $U(1)_B, U(1)_e, U(1)_\mu, U(1)_\tau$ remain accidental symmetries of BSM theory.
- Want to ban all renormalizable terms in $\mathcal{L}$ that would violate any of these $U(1)$s.

$\Lambda_{LFV} \sim 10^5$ TeV — *Dark stuff responsible for B-violation and LFV (neutrino oscillations)*

$\Lambda_{LFUV} \sim 1$ TeV — *New physics that explains B-anomalies*

$v \sim 246$ GeV




Altmannshofer, JD, Nardecchia 2019

# 3. Gauging the accidental symmetries of the SM

- Simplest way to do this is by gauging a linear combination of these accidental symmetries.
- In particular, gauge $U(1)_X$, where

$$T_X = a_e T_{L_e} + a_\mu T_{L_\mu} + a_\tau T_{L_\tau} - \left(\frac{a_e + a_\mu + a_\tau}{3}\right) a_B + a_Y T_Y,$$

4 rational parameters $\{a_e, a_\mu, a_\tau, a_Y\}$

- This can always be made anomaly-free if allow up to three SM singlet chiral fermions (e.g. RH neutrinos) to soak up gravity & $[U(1)_X]^3$ anomalies:

$$A_{\text{grav}} = a_e + a_\mu + a_\tau - \sum_{i=1}^{3} \hat{Q}_{\nu^i} \qquad A_{\text{cubic}} = a_e^3 + a_\mu^3 + a_\tau^3 - \sum_{i=1}^{3} \hat{Q}_{\nu^i}^3$$

See also Salvioni, Strumia, Villadoro, Zwirner, 2010

# LFUV without LFV

Yukawas allowed by this gauge symmetry (assuming $a_e, a_\mu, a_\tau$ all different):

$$Y_{U,D} = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}, \qquad Y_E = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix},$$

$U(1)_X$ is **most general** anomaly-free choice that allows these Yukawa textures at renormalizable level

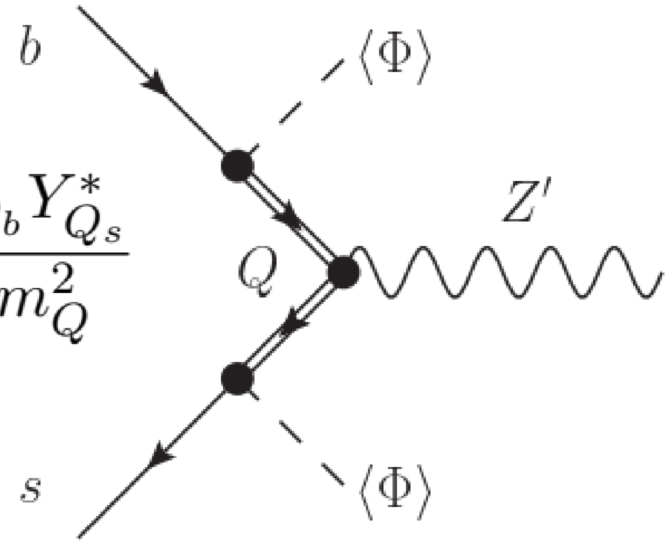
Mass eigenbasis = Weak eigenbasis,
∴ no LFV from $Z'$ couplings
(as expected, because $U(1)_X$ protects individual lepton numbers)

# Explaining the *B*-anomalies

$Z'$ couplings to $bs$ generated by coupling through heavy vector-like quarks

$$\mathcal{L}_{\text{mix}} = -m_Q \overline{Q} Q + \left( Y_{Qi}\, \overline{q}^{i}_{L} Q_R \Phi + \text{h.c} \right)$$

$$g_{sb} = -g_X v_\Phi^2 \frac{Y_{Q_b} Y^*_{Q_s}}{2 m_Q^2}$$




LFUV

$$C_9^\alpha = -\frac{Y_{Qb} Y^*_{Qs}}{2 m_Q^2} \left( a_\alpha - \frac{3}{4} a_Y \right),$$

$$C_{10}^\alpha = \frac{Y_{Qb} Y^*_{Qs}}{8 m_Q^2} a_Y .$$

$$T_X = a_Y T_Y + a_e T_{L_e} + a_\mu T_{L_\mu} + a_\tau T_{L_\tau} - \left(\frac{a_e + a_\mu + a_\tau}{3}\right) a_B$$

*This framework leads to a particular structure for the anomalies:*

$$C_9^\alpha = -\frac{Y_{Qb} Y_{Qs}^*}{2m_Q^2} \left(a_\alpha - \frac{3}{4} a_Y\right),$$

$$C_{10}^\alpha = \frac{Y_{Qb} Y_{Qs}^*}{8m_Q^2} a_Y.$$

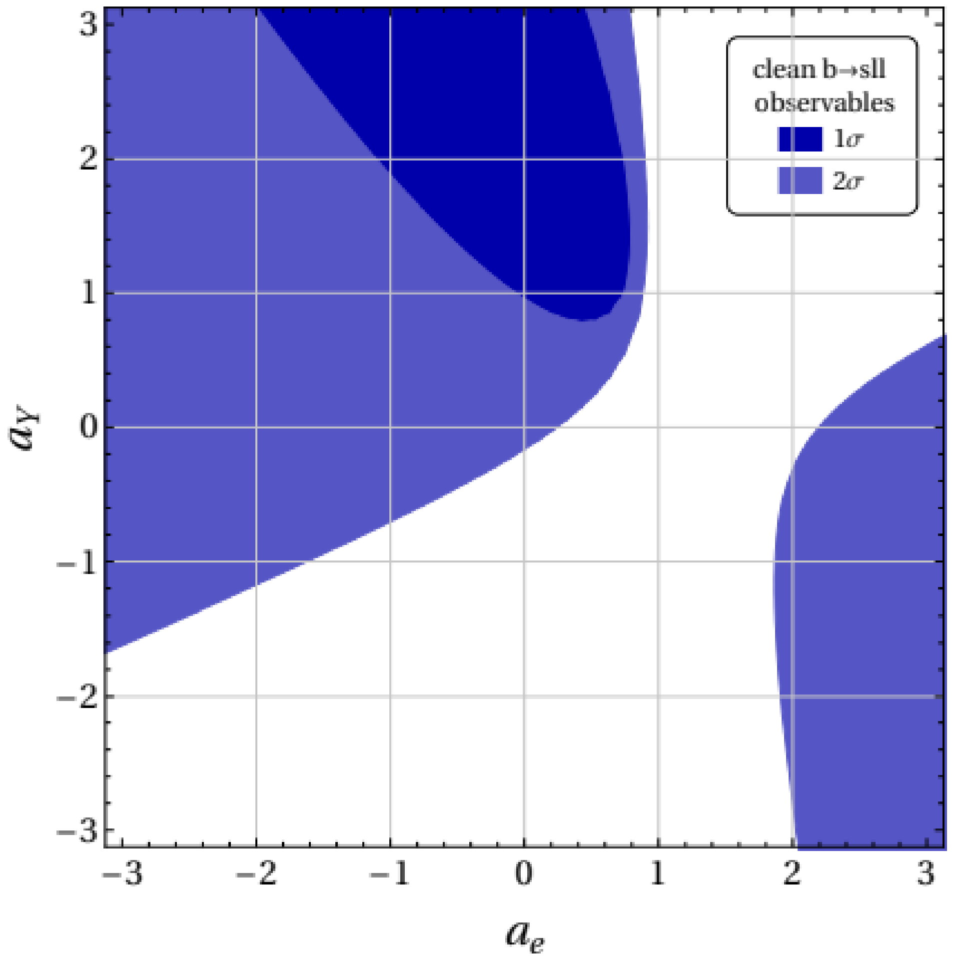
1. The LFUV must come entirely from the vector current

2. An axial contribution must be lepton flavour universal, and requires $a_Y \neq 0$; hence $Z'$ coupling to Higgs. Immediate consequences:

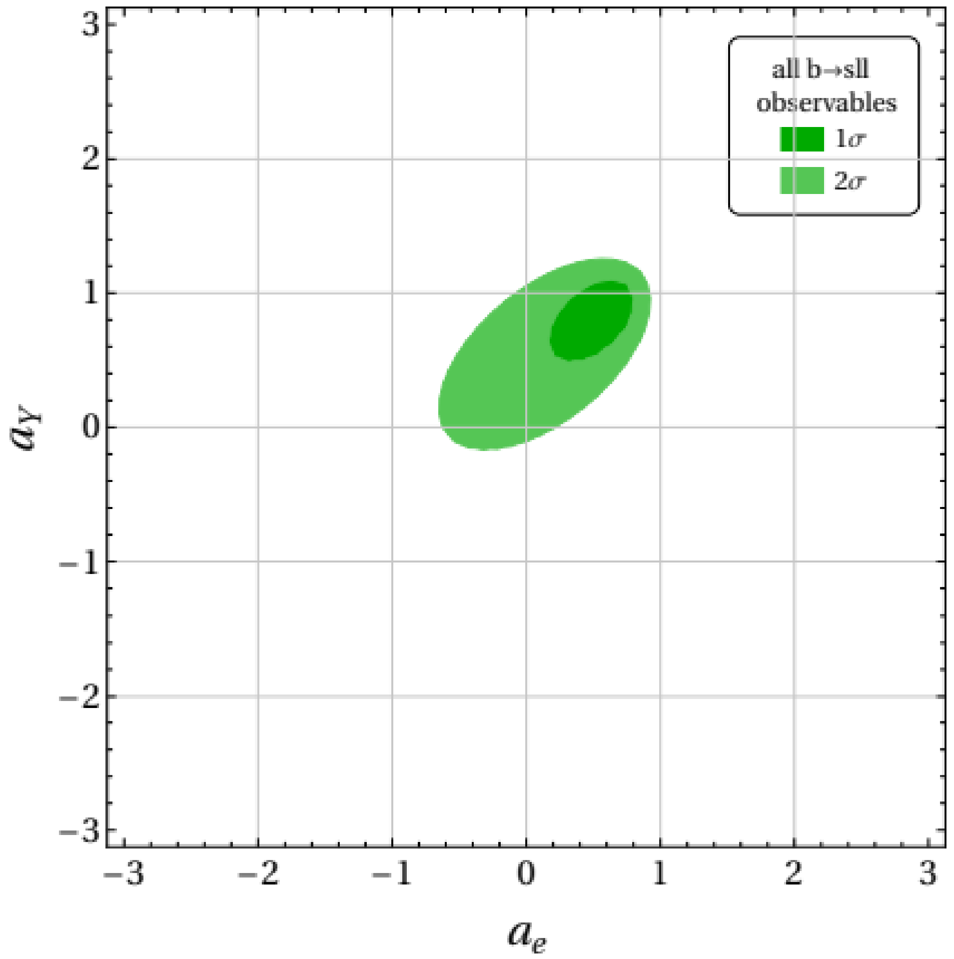
- $Z$-$Z'$ mixing, hence LEP constraints on $Z$ boson LFUV
- $Z'$ couples to valence quarks, hence enhanced $pp$ production at LHC

# Phenomenology

We fit to the $B$-anomaly data in flavio, with $a_\mu = 1$ and $a_\tau = 0$. Recall $T_X = a_Y T_Y + a_e T_{L_e} + a_\mu T_{L_\mu} + a_\tau T_{L_\tau} - \left(\frac{a_e + a_\mu + a_\tau}{3}\right) a_B$



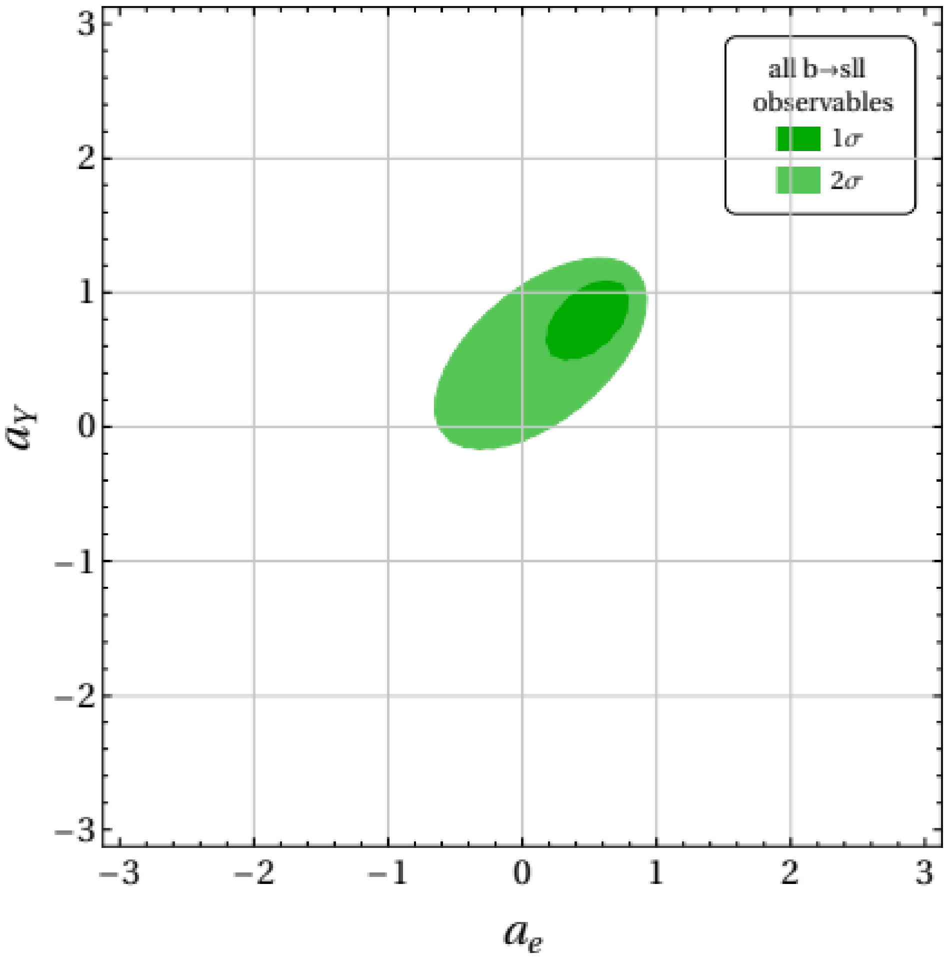

Fit includes: $R_{K^{(*)}}$ (LHCb & Belle), BR $B_s \to \mu\mu$ (LHCb, ATLAS, CMS), inclusive BRs $B \to X_s ll$ (BaBar, Belle)




Fit **also** includes: BRs $B^0 \to K^{0(*)}\mu\mu$, $B^\pm \to K^{\pm(*)}\mu\mu$, $B_s \to \varphi\mu\mu$, $\Lambda_b \to \Lambda\mu\mu$, and angular observables (LHCb, ATLAS, CMS).

# Phenomenology

$a_\mu = 1$ and $a_\tau = 0$




At best-fit point, passes bounds from:

- LHC searches
- $B_s$ mixing
- EW precision
- Neutrino trident

- Strong push to include a **flavour-universal axial component** $a_Y \neq 0$, $a_Y \approx a_\mu$ (probably to push muon coupling closer to LH given 2019 data)
- This unavoidably leads to tight constraints from direct search & EW precision, e.g. $\rho$-parameter
- Favour some **NP in electron** ($a_e \neq 0$ also)

# Conclusions

Two obvious but intriguing features in the $B$-anomaly data:

A. Third family alignment

B. Respect SM accidental symmetries

**Welcome any measurements that refine this hypothesis e.g. $B \to K\tau\mu$, $B \to K\mu e$**

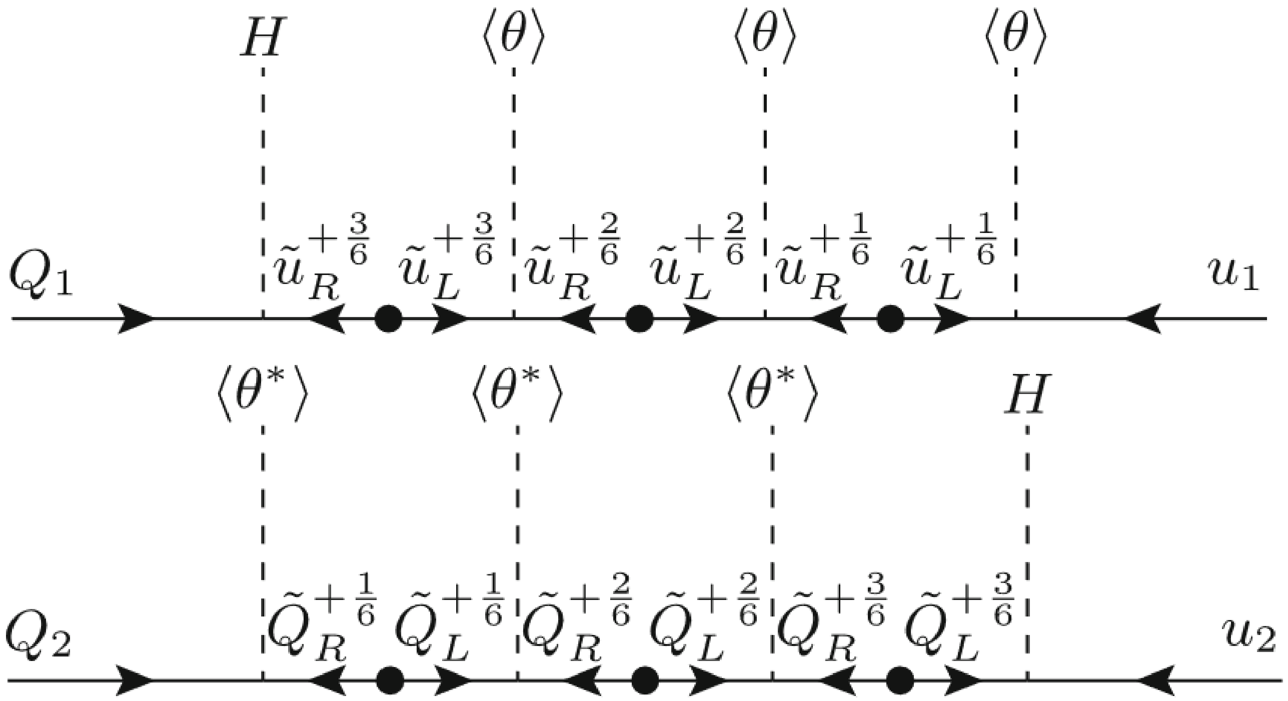
Explore the consequences of these features using simple frameworks

→ find general patterns of experimental signatures:

1. Rank-one flavour violation → *precision flavour constraints*
2. Third Family $Z'$ models → *third family decays*
3. Gauging SM accidental symmetries → *electroweak precision constraints*

# Backup

# Example case mixing matrices from a Froggatt-Nielsen-type mechanism




Eg: how to achieve $V_{u_L} = V_{u_R} = 1$?
Clearly breaks $U(2)_Q \times U(2)_U$

1. $M_{\tilde{u}} \sim \frac{1}{10} M_{\tilde{Q}} \to m_u \sim \frac{1}{1000} m_c$

2. If no fundamental interactions $\overline{u_1} H \tilde{Q}_L^{+\frac{3}{6}}$ or $\tilde{u}_R^{+\frac{3}{6}} H Q_2$ present, then off-diagonal Yukawas $\sim 0$.

Froggatt & Nielsen, 1979
Allanach & JD, 2019