Connecting $R_{K(*)}$ with the Heaviness of the Third Family

Joe Davighi, DAMTP, University of Cambridge

CERN-TH Institute, 31st October 2018

Work with Ben Allanach

Outline of Talk

1. Introduction
2. Connecting $R_{K^{(*)}}$ and fermion masses: Third Family Hypercharge (TFHM)

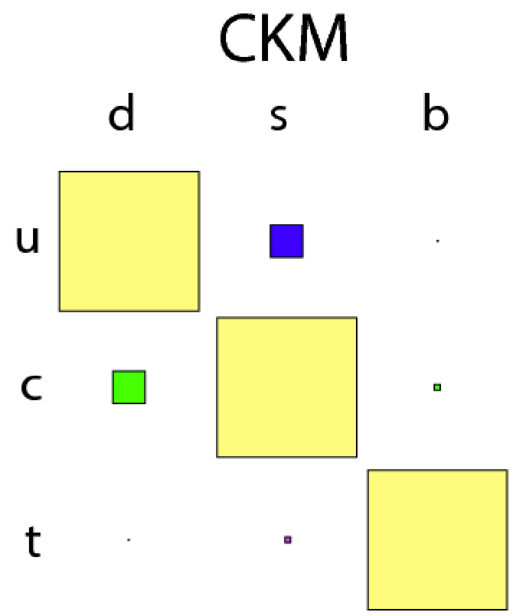
   Allanach, JD, 1809.01158
3. Experimental Bounds on TFHM
4. Predictions of TFHM
5. Outlook: going beyond Third Family Hypercharge

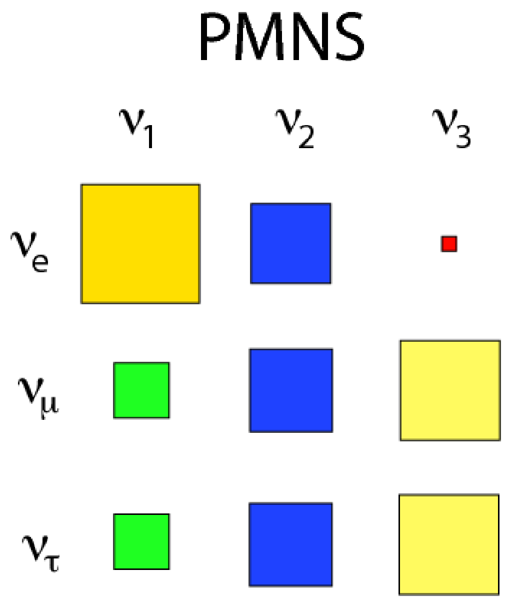
1. Introduction: The Flavour Problem

Huge hierarchies in fermion masses:

$y_{up} \sim 10^{-5}, \quad y_{top} \sim 1$ etc

… why?





Hierarchy vs Anarchy

… why?

Are the Yukawas the only source of flavour-symmetry breaking, as in SM?

i.e. are the third family really just “heavy copies”?

Possible answer: forget about naturalness

Perhaps we accept that fermion masses and mixing angles (CKM, PMNS) are ***arbitrary input parameters*** with no deeper explanation behind their structure

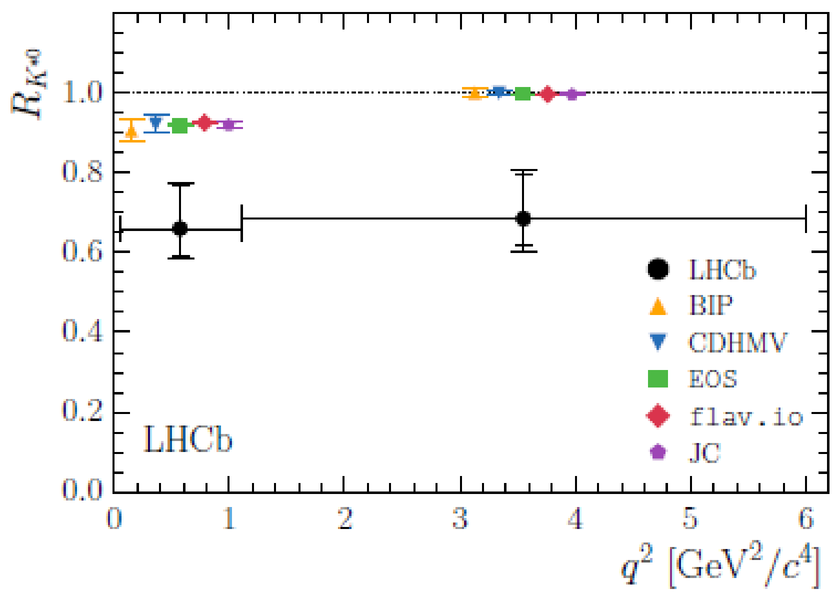
At least they are technically natural (i.e. radiatively stable unlike m_H)

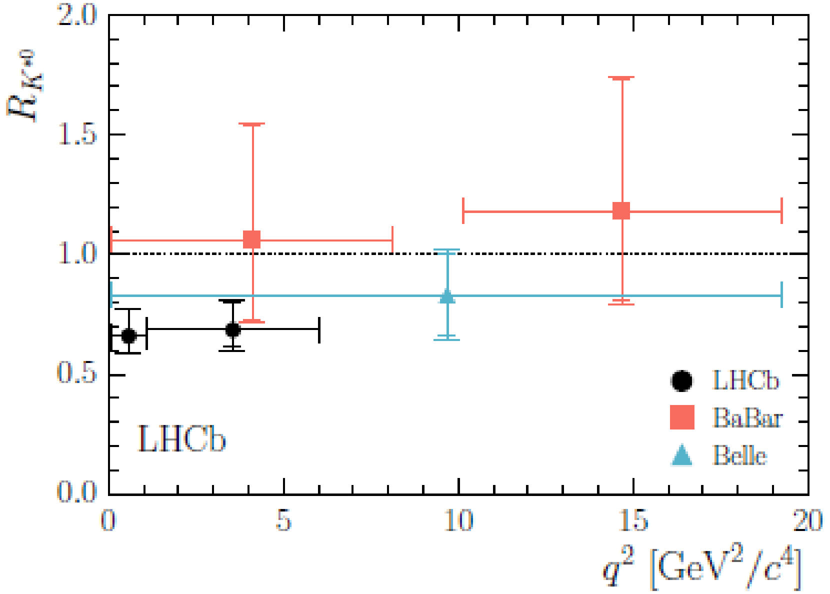
Enter LHCb


813 members
16 countries
59 institutes
(July 1, 2012)
Countries member of the LHCb Collaboration

LFUV in neutral currents

$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}, \qquad R_{K^*} = \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^*e^+e^-)}.$$

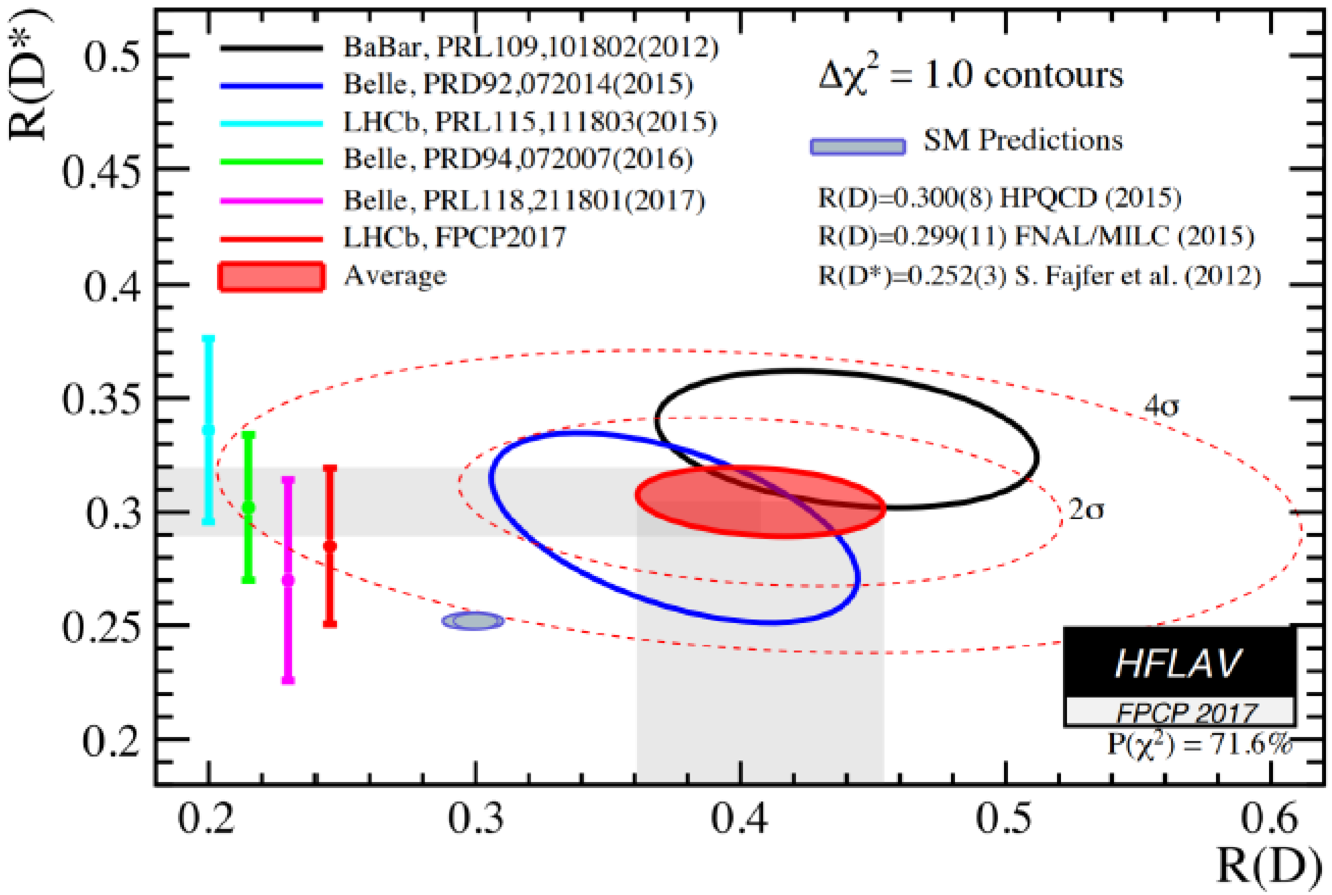




- Suggests muon not “just a heavy electron”
- Scale of NP: about 32 TeV

LFUV in charged currents

$$R_{D^{(*)}} = BR(B^- \to D^{(*)}\tau\nu)/BR(B^- \to D^{(*)}\mu\nu)$$



- Suggests tauon not just a heavy muon
- Scale of NP: about 2.5 TeV (!!)

Will not try to explain $R_{D(*)}$ here (or muon g-2 anomaly). Sorry.

B anomalies suggest different generations have

different (gauge) interactions as well as different Yukawa structures

… a coincidence? Or a consequence of the same New Physics that breaks flavour symmetry?

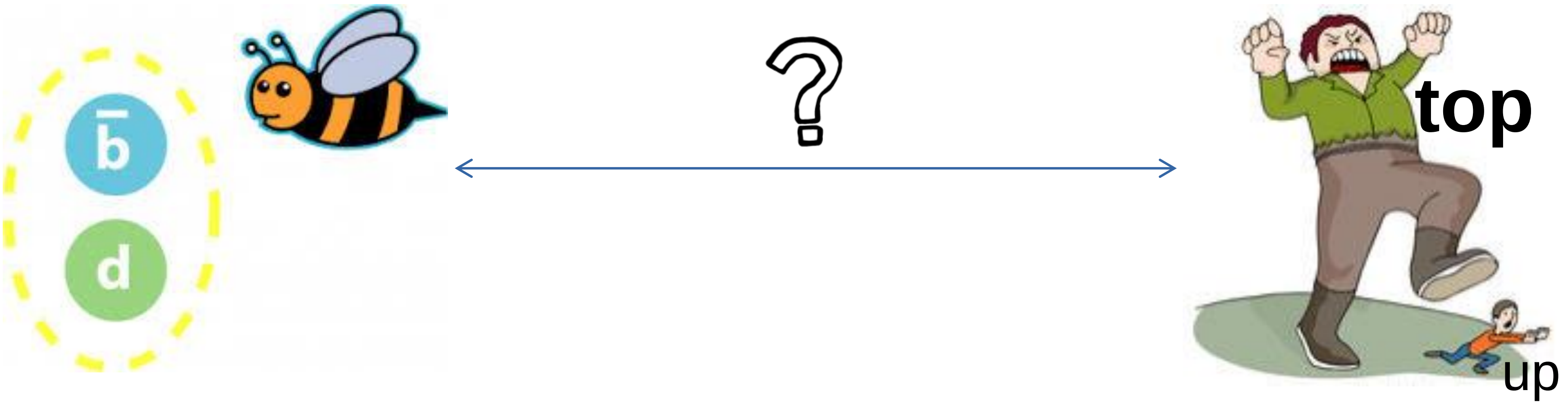
An important clue

No evidence for LFUV in e.g. kaon/ pion decays (i.e. with light quarks) or charm decays. NP in light generations is tightly constrained.

Want **new physics coupling mainly to third generation**

See J. Kamenik’s and G. Isidori’s summary talks

2. *Z'* model for $R_{K(*)}$ and fermion masses



Can fit $R_{K(*)}$ with a single higher dimension operator in the SMEFT:

$$\mathcal{O} \propto [\bar{s}\gamma_\mu P_L b][\bar{\mu}\gamma^\mu P_X \mu]$$

with e.g. $P_X = 1$ or $P_X = P_L$

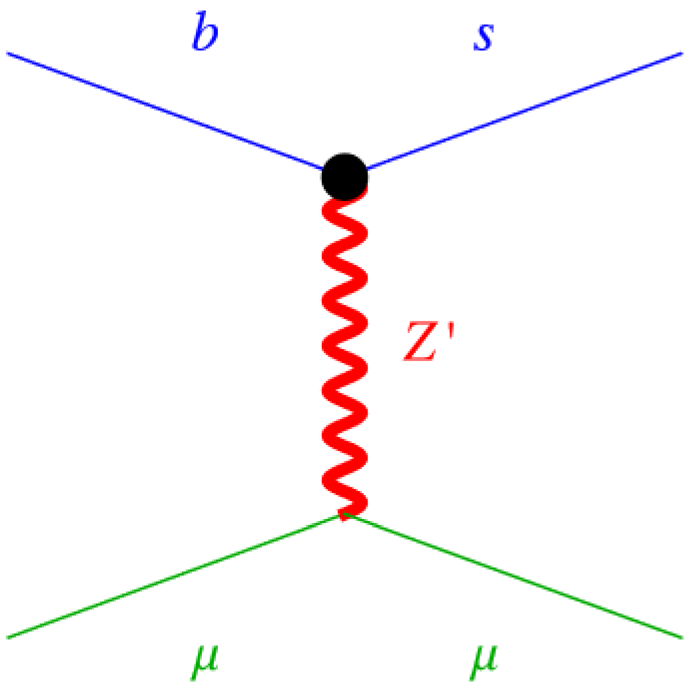
D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano, 1704.05438

Z' models for $R_{K(*)}$

Need at least

$$\mathcal{L}_{Z'}^{\text{min.}} \supset \left(g_L^{sb} Z'_\rho \bar{s}\gamma^\rho P_L b + \text{h.c.}\right) + g_L^{\mu\mu} Z'_\rho \bar{\mu}\gamma^\rho P_L \mu \,,$$

Can "mix in" couplings to $\bar{b}_L s_L$ and $\mu_L \mu_L$ from the third family – perhaps we can couple the Z' only to third family?



Wishlist for a (UV) complete and simple Z' model

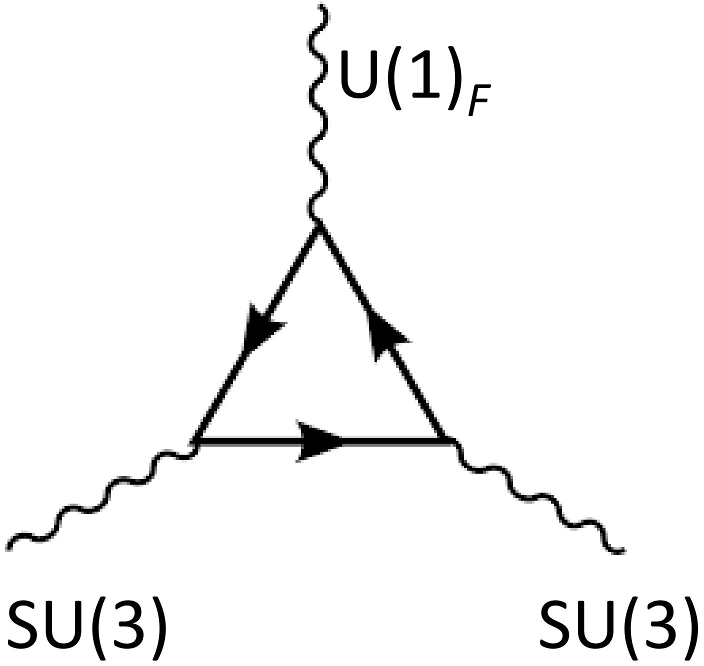
Suppose Z' is massive gauge boson for a flavoured $U(1)_F$ gauge symmetry, spontaneously-broken by flavon vev $\langle\theta\rangle \neq 0$. We desire:

1. Respects SM symmetries - in particular $SU(2)_L$
2. Anomaly-free
3. No BSM fermions needed
4. Correct Wilson coefficients e.g. C_L to fit $R_{K(*)}$
5. Consistent with low-p_T flavour constraints e.g. $B_s - \overline{B_s}$ mixing, kaon sector
6. Consistent with high-p_T LHC searches e.g. dimuon
7. Bonus: shed light on the flavour problem?

Intermezzo: gauge anomalies

No gauge-invariant way of regulating loop divergences e.g. in triangle diagrams. Means the gauge theory is inconsistent*

Anomalies can cancel for specific sets of fermion reps under G, as in the SM



*or, at least, incomplete

Anomaly cancellation in Z' model building

Anomaly-cancellation not essential since heavy chiral fermions could have been integrated out (can cancel any anomaly in an EFT with a Wess-Zumino term)

Preskill 1991

… but is a sure-fire way to define a UV complete(able) theory (modulo Landau poles)

Therefore anomaly-cancellation is a useful guide for model-building

For a $U(1)_F$ factor in G, anomaly cancellation gives a set of nonlinear constraints on the $U(1)_F$ charges

Anomaly cancellation in Z' model building

1. $SU(3)_C^2 \times U(1)' \implies \sum_{i=1}^3 (2F_{Q_i} - F_{u_i} - F_{d_i}) = 0,$
2. $SU(2)_L^2 \times U(1)' \implies \sum_{i=1}^3 (3F_{Q_i} + F_{L_i}) = 0,$
3. $U(1)_Y^2 \times U(1)' \implies \sum_{i=1}^3 (F_{Q_i} + 3F_{L_i} - 8F_{u_i} - 2F_{d_i} - 6F_{e_i}) = 0,$
4. Gauge-gravity $\implies \sum_{i=1}^3 (6F_{Q_i} + 2F_{L_i} - 3F_{u_i} - 3F_{d_i} - F_{e_i}) = 0,$

Linear

---

5. $U(1)_Y \times U(1)'^2 \implies \sum_{i=1}^3 \left(F_{Q_i}^2 - F_{L_i}^2 - 2F_{u_i}^2 + F_{d_i}^2 + F_{e_i}^2\right) = 0,$
6. $U(1)'^3 \implies \sum_{i=1}^3 \left(6F_{Q_i}^3 + 2F_{L_i}^3 - 3F_{u_i}^3 - 3F_{d_i}^3 - F_{e_i}^3\right) = 0,$

Non-linear

Anomaly cancellation in Z' model building

Huge number of solutions including $L_\mu - L_\tau$, $B_1 + B_2 - 2B_3$, $B_3 - L_3$ if include $3\nu_R$

See W. Altmannshofer's talk

Need some phenomenological input to cut-down possibilities

See also P. Cox's talk

E.g. 1: Ellis et al. impose strong assumptions which knock out *all* the solutions. Somewhat by accident…

J. Ellis, M. Fairbairn, P. Tunney, arXiv:1705.03447

E.g. 2: if insist only on charges in one generation, we cut-down the possibilities to …

… a unique solution

(End of intermezzo)

Suppose $U(1)_F$ couples only to third family

There is a unique anomaly-free set of third family U(1) charges

This is just third family hypercharge

$$F_{Q'_i} = 0 \quad F_{u_{R'_i}} = 0 \quad F_{d_{R'_i}} = 0 \quad F_{L'_i} = 0 \quad F_{e_{R'_i}} = 0 \qquad i=1,2$$
$$F_{Q'_3} = 1/6 \quad F_{u'_{R3}} = 2/3 \quad F_{d'_{R3}} = -1/3 \quad F_{L'_3} = -1/2 \quad F_{e'_{R3}} = -1$$

n.b. provides a basis-independent definition of third family – the states that couple to $U(1)_F$

Suppose $U(1)_F$ couples only to third family

… at this point *Z'*-ers typically introduce additional Higgs doublets to write down enough Yukawa couplings – but this is missing an opportunity!

Just SM Higgs, & assign

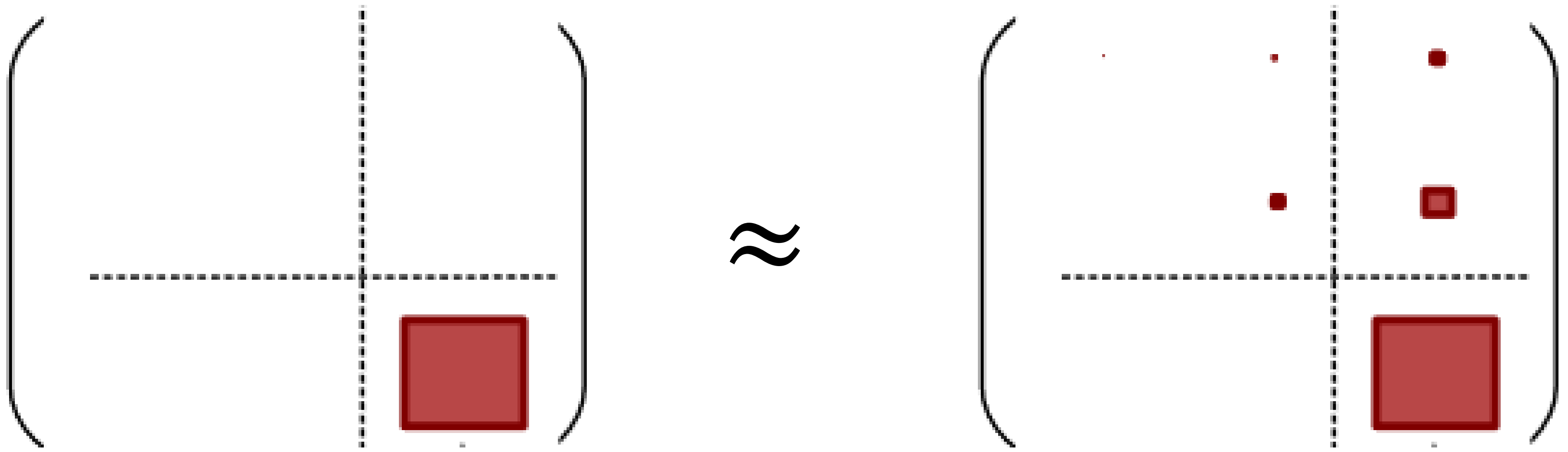
$$F_H = -1/2$$

n.b. qualitative similarity with PS^3

and then the only renormalizable Yukawas you can write down are

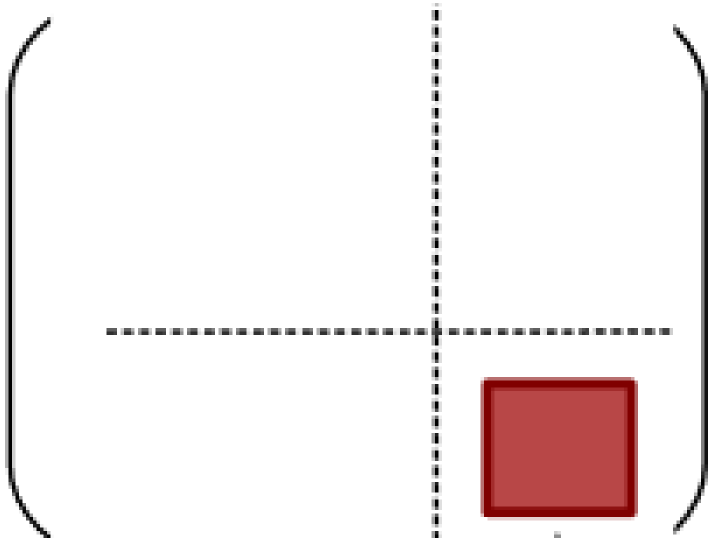
$$\mathcal{L} = Y_t \overline{Q_3'}_L H t_R' + Y_b \overline{Q_3'}_L H^c b_R' + Y_\tau \overline{L_3'}_L H^c \tau_R' + H.c.,$$

…which is what we observe to leading order



Assume other entries in Yukawa matrix come from higher dimension operators → suppressed by mass scale of heavy NP

- First two families light (albeit degenerate – unbroken SU(2))
- Expect 1-3 and 2-3 quark mixing small (almost diagonal)
- Lepton mixing not necessarily small (depends on neutrino mass mechanism)

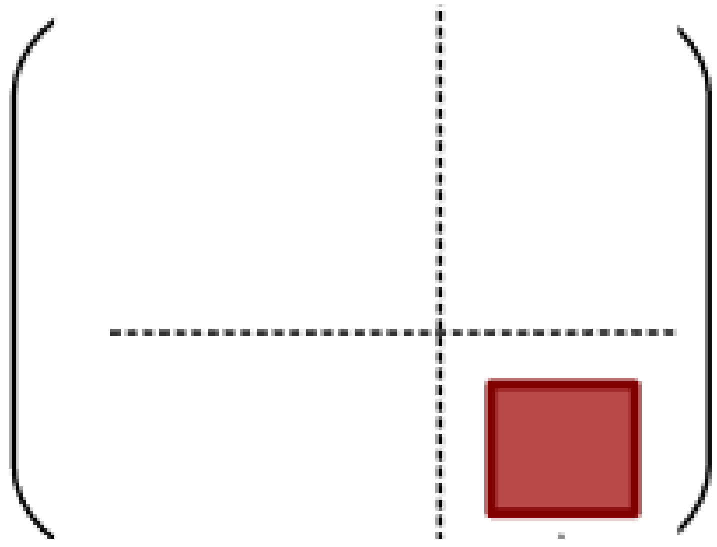


What higher dimension operators?

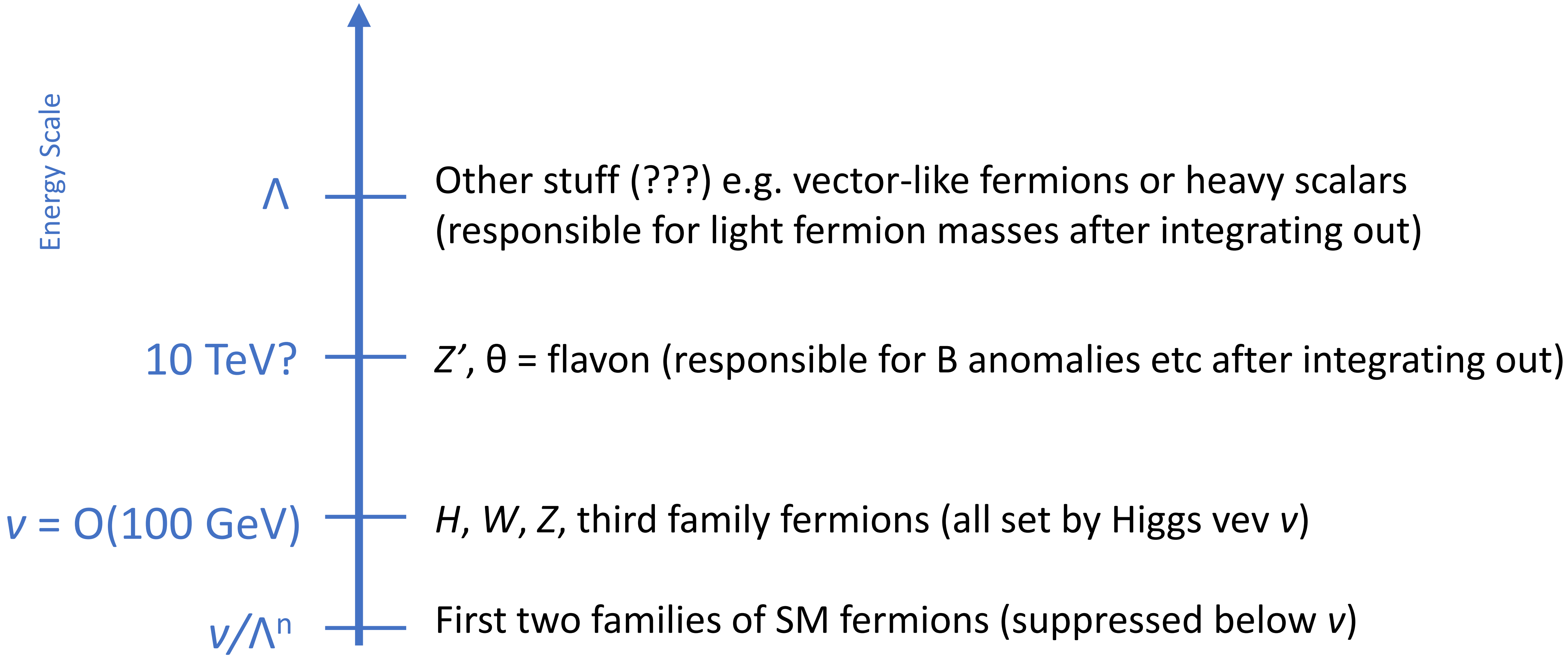
- e.g. from Froggatt-Nielsen
- or something else…

requires more detailed model building

we remain agnostic for now



Froggatt, Nielsen, NPB147 (1979) 277


Energy Scale
Λ
Other stuff (???) e.g. vector-like fermions or heavy scalars (responsible for light fermion masses after integrating out)
10 TeV?
Z′, θ = flavon (responsible for B anomalies etc after integrating out)
v = O(100 GeV)
H, W, Z, third family fermions (all set by Higgs vev v)
v/Λ^n
First two families of SM fermions (suppressed below v)

Energy Scale

Λ — Other … s (respo … t)

10 TeV? — Z', θ = flavon (responsible for B anomalies etc after integrating out)

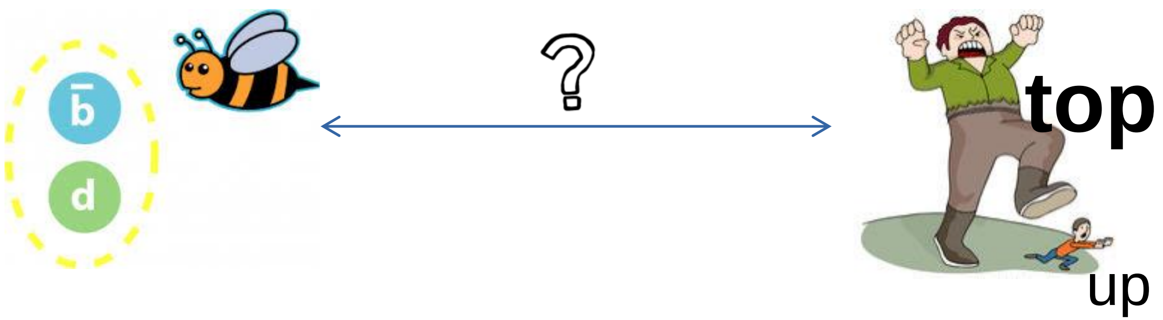
$v = O(100 \text{ GeV})$ — *H*, *W*, *Z*, third family fermions (all set by Higgs vev v)

v/Λ^n — First two families of SM fermions (suppressed below v)

This is bottom-up model building!

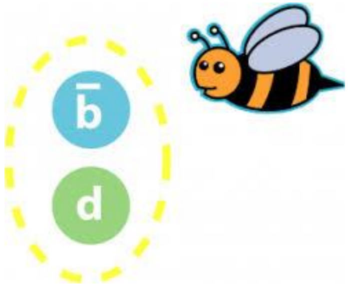
Third Family Hypercharge Model

Main idea: ban the light Yukawas (at the renormalizable level) with the same $U(1)_F$ spontaneously-broken, flavoured gauge symmetry whose Z’ gauge boson explains $R_{K(*)}$



Third Family Hypercharge Model

Ticks all the boxes for a UV complete (and simple) Z' model for the B data: anomaly-free; only SM fermion content; fits $R_{K(*)}$ and other data



Only renormalizable Yukawa couplings are

$$\mathcal{L} = Y_t \overline{Q_3{}'_L} H t'_R + Y_b \overline{Q'_{3L}} H^c b'_R + Y_\tau \overline{L_3{}'_L} H^c \tau'_R + H.c.,$$

Lighter masses will come from higher dimension operators. Explains coarsest features of fermion masses, i.e. heaviness of third family & smallness of quark mixing

The price to pay

$$F_H \neq 0$$

leads to *Z*-*Z'* mixing → strong constraints e.g. from LEP precision measurements

Z-Z' mixing

See also S. Fajfer's talk

Mass matrix for neutral gauge bosons:

$$\mathcal{M}_N^2 = \frac{v^2}{4}\begin{pmatrix} g'^2 & -gg' & g'g_F \\ -gg' & g^2 & -gg_F \\ g'g_F & -gg_F & g_F^2(1+4F_\theta^2 r^2) \end{pmatrix} \begin{matrix} -B_\mu \\ -W_\mu^3 \\ -X_\mu \end{matrix}$$

U(1)$_F$ gauge coupling — flavon charge

$r \equiv v_F/v \gg 1$

from expanding scalar kinetic terms around vevs v and $v_F = \langle\theta\rangle$

Diagonalize → physical gauge bosons (and masses)

Z-Z' mixing

$$\mathcal{M}_N^2 = \frac{v^2}{4}\begin{pmatrix} g'^2 & -gg' & g'g_F \\ -gg' & g^2 & -gg_F \\ g'g_F & -gg_F & g_F^2(1+4F_\theta^2 r^2) \end{pmatrix} \begin{matrix} -B_\mu \\ -W_\mu^3 \\ -X_\mu \end{matrix}$$

2nd and 3rd eigenstates mix

heavy 3rd eigenvalue

$r \equiv v_F/v \gg 1$

Physical *Z* contains small admixture of the *X*:

$$Z_\mu = \cos\alpha_z\left(-\sin\theta_w B_\mu + \cos\theta_w W_\mu^3\right) + \sin\alpha_z X_\mu.$$

where mixing angle is:

$$\sin\alpha_z \approx \frac{g_F}{\sqrt{g^2+g'^2}}\left(\frac{M_Z}{M_Z'}\right)^2 .$$

Z' couplings to fermions

In weak eigenbasis, Z' couples only to third family:

$$\mathcal{L}_{X\psi} = g_F \left(\frac{1}{6}\overline{Q'_{3L}}\gamma^\rho Q'_{3L} - \frac{1}{2}\overline{L'_{3L}}\gamma^\rho L'_{3L} - \overline{e'_{3R}}\gamma^\rho e'_{3R} + \frac{2}{3}\overline{u'_{3R}}\gamma^\rho u'_{3R} - \frac{1}{3}\overline{d'_{3R}}\gamma^\rho d'_{3R} \right) X_\rho,$$

Rotation to mass basis induces couplings to lighter families, including to $\overline{b}_L s_L$ and $\mu_L \mu_L$

Z' couplings to fermions

In mass basis:

$$\mathcal{L}_{X\psi} = g_F \left(\frac{1}{6}\overline{\mathbf{u_L}}\Lambda^{(u_L)}\gamma^\rho \mathbf{u_L} + \frac{1}{6}\overline{\mathbf{d_L}}\Lambda^{(d_L)}\gamma^\rho \mathbf{d_L} - \frac{1}{2}\overline{\mathbf{n_L}}\Lambda^{(n_L)}\gamma^\rho \mathbf{n_L} - \frac{1}{2}\overline{\mathbf{e_L}}\Lambda^{(e_L)}\gamma^\rho \mathbf{e_L} + \frac{2}{3}\overline{\mathbf{u_R}}\Lambda^{(u_R)}\gamma^\rho \mathbf{u_R} - \frac{1}{3}\overline{\mathbf{d_R}}\Lambda^{(d_R)}\gamma^\rho \mathbf{d_R} - \overline{\mathbf{e_R}}\Lambda^{(e_R)}\gamma^\rho \mathbf{e_R} \right) Z'_\rho,$$

$$\Lambda^{(I)} \equiv V_I^\dagger \xi V_I, \qquad \xi = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$I \in \{u_L, d_L, e_L, \nu_L, u_R, d_R, e_R\}$$

The model does not yet predict the mixing matrices V_I (because have not specified where the higher dim eff Yukawa ops come from)

Rather, the V_I matrices are inputs which must be consistent with CKM (V) and PMNS (U)

$$V = V_{u_L}^\dagger V_{d_L}, \qquad U = V_{\nu_L}^\dagger V_{e_L}.$$

To compare with experiment, we must make a specific choice

(Some) other models for B data and fermion masses

Z' models:

A. Falkowski, M. Nardecchia, R. Ziegler, 1509.01249

From a U(2) model

- More detailed model than ours — see Ziegler's talk
- *Z'* strongly coupled to light generations (Higgs uncharged). Strong $pp \to \mu\mu$ constraints
- Froggatt-Nielsen framework not anomaly-free

With a fourth vector-like family — S.F. King, 1806.06780

- Two Higgs doublets
- SM fermions uncharged; couple to *Z'* through additional fields
- Our solution is "more minimal"

(Some) other models for B data and fermion masses

Leptoquark models:

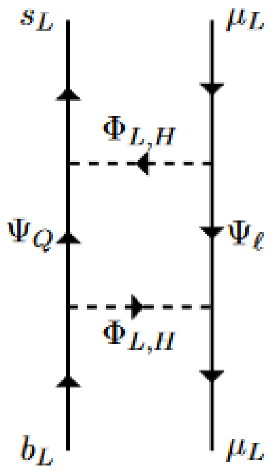
e.g. F. F. Deppisch, S. Kulkarni, H. Ps and E. Schumacher, 1603.07672

- Global $U(1)_F$ symmetry with fermion masses from Froggatt-Nielsen
- Leptoquarks separately assigned charges which explain B data
- Fermion masses and B data problems effectively "decouple"

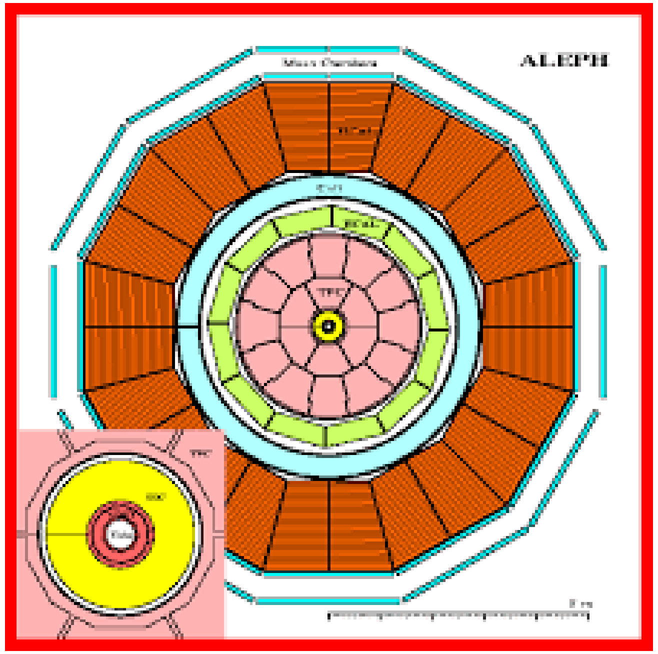
Loop model:

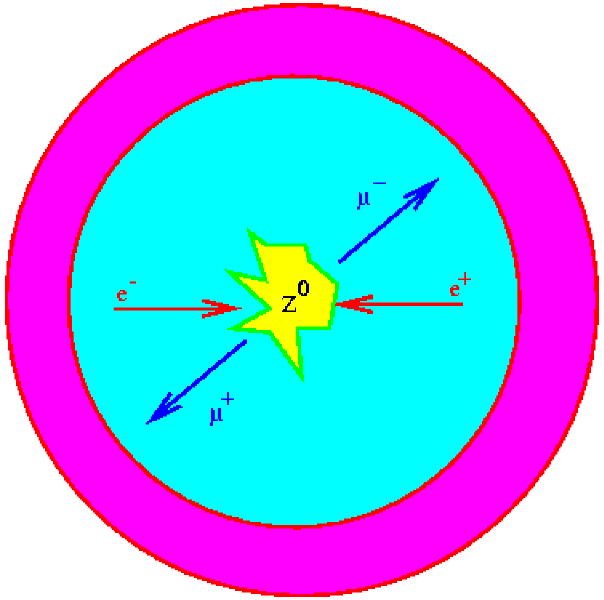
B. Grinstein, S. Pokorski, G.G. Ross, arXiv:1809.01766

- Froggatt-Nielsen setup for Yukawa structure
- $R_{K(*)}$ anomaly from heavy vector-like FN fermions in loops
- Stabilize flavon with Z_2 – DM candidate
- Anomalous g-2 of muon



3. Experimental bounds on Third Family Hypercharge Model





Example Case

A straightforward limiting case:

$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{sb} & -\sin\theta_{sb} \\ 0 & \sin\theta_{sb} & \cos\theta_{sb} \end{pmatrix} \quad \text{and} \quad V_{e_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$$V_{u_L} = V_{d_L} V^\dagger \qquad V_{d_R} = 1 \qquad V_{u_R} = 1 \qquad V_{\nu_L} = V_{e_L} U^\dagger \qquad V_{e_R} = 1$$

A one-parameter ($\theta_{sb} > 0$) family of example cases

Example Case

$$V_{d_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{sb} & -\sin\theta_{sb} \\ 0 & \sin\theta_{sb} & \cos\theta_{sb} \end{pmatrix} \quad \text{and} \quad V_{e_L} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$V_{u_L} = V_{d_L} V^\dagger$ $\quad V_{d_R} = 1$ $\quad V_{u_R} = 1$ $\quad V_{\nu_L} = V_{e_L} U^\dagger$ $\quad V_{e_R} = 1$

$$\mathcal{L}_{X\psi} = g_F \left(\frac{1}{6} \overline{\mathbf{u_L}} \Lambda^{(u_L)} \gamma^\rho \mathbf{u_L} + \frac{1}{6} \overline{\mathbf{d_L}} \Lambda^{(d_L)} \gamma^\rho \mathbf{d_L} - \frac{1}{2} \overline{\mathbf{n_L}} \Lambda^{(n_L)} \gamma^\rho \mathbf{n_L} - \frac{1}{2} \overline{\mu_L} \gamma^\rho \mu_L \right.$$
$$\left. + \frac{2}{3} \overline{t_R} \gamma^\rho t_R - \frac{1}{3} \overline{b_R} \gamma^\rho b_R - \overline{\tau_R} \gamma^\rho \tau_R \right) Z'_\rho,$$

where $\Lambda^{(u_L)} = V V^\dagger_{d_L} \xi V_{d_L} V^\dagger$, $\Lambda^{(n_L)} = U V^\dagger_{e_L} \xi V_{e_L} U^\dagger$, and

$$\Lambda^{(d_L)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2\theta_{sb} & \frac{1}{2}\sin 2\theta_{sb} \\ 0 & \frac{1}{2}\sin 2\theta_{sb} & \cos^2\theta_{sb} \end{pmatrix}.$$

Bound 1: Fit to $R_{K(*)}$

Recall good fit to $R_{K(*)}$ from EFT operator $\mathcal{O} = C\,[\bar{s}\gamma_\mu P_L b]\,[\bar{\mu}\gamma^\mu P_L \mu]$

$$\mathcal{L}_{X\psi} = \left(\frac{g_F}{12}\sin 2\theta_{sb}\bar{s}\gamma^\rho P_L b - \frac{g_F}{2}\bar{\mu}\gamma^\rho P_L \mu + H.c.\right) Z'_\rho + \dots$$

integrate out Z' to obtain Wilson coefficient $C = -\frac{g_F^2 \sin^2 2\theta_{sb}}{24 M_{Z'}^2}$

→ constraint on $g_F/M_{Z'}$ (95% CL):

$$\frac{M_{Z'}}{2.53\ \text{TeV}}\sqrt{\frac{0.04}{\frac{1}{2}\sin 2\theta_{sb}}} < g_F < \frac{M_{Z'}}{1.46\ \text{TeV}}\sqrt{\frac{0.04}{\frac{1}{2}\sin 2\theta_{sb}}}$$

D'Amico, Nardecchia, Panci, Sannino, Strumia, Torre, Urbano, 1704.05438

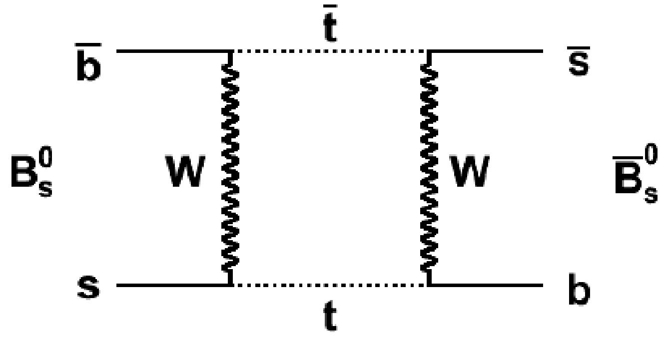
Bound 1: Fit to $R_{K(*)}$

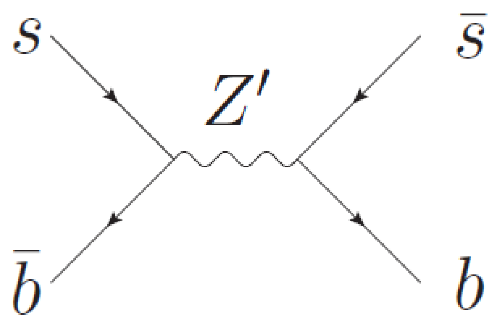
n.b. there is now a contribution to $R_{K(*)}$ from Z exchange, due to Z-Z' mixing

- but subleading ✓

Bound 2: neutral meson mixing

Loop-suppressed in SM, but tree-level in *Z’* model:



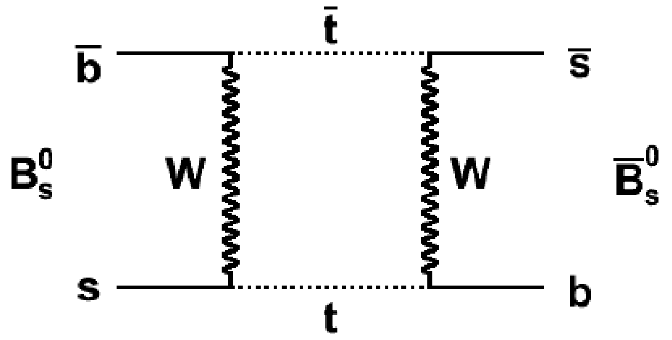


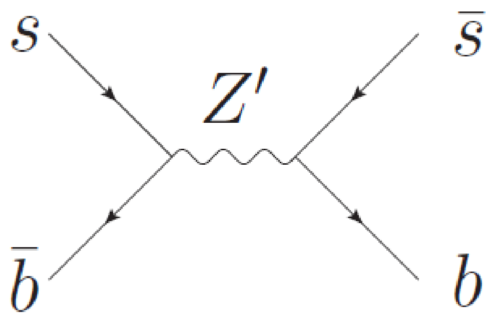
Gives a constraint on the *Z’* coupling to $\bar{b}_L s_L$

$$\frac{g_F}{12}\sin 2\theta_{sb} < \frac{M_{Z'}}{148\ \text{TeV}}$$

Bound 2: neutral meson mixing

Loop-suppressed in SM, but tree-level in Z' model:





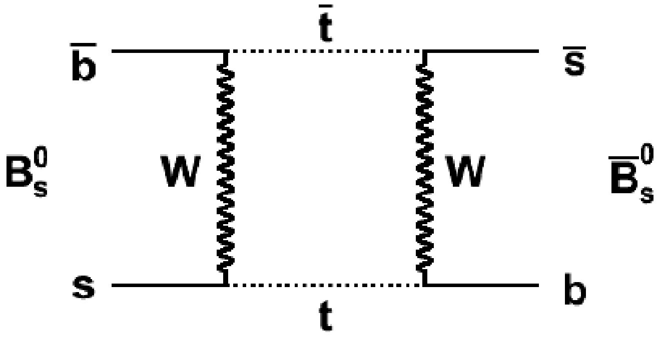
Gives a constraint on the Z' coupling to $\bar{b}_L s_L$

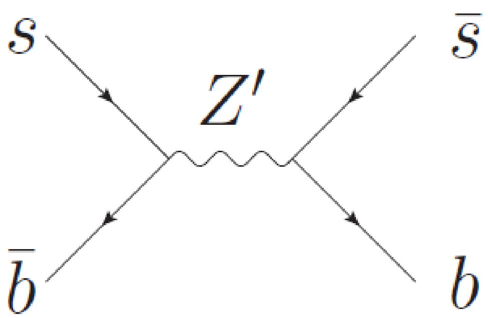
$$\frac{g_F}{12}\sin 2\theta_{sb} < \frac{M_{Z'}}{148\ \text{TeV}}$$

Using 2σ 2016 FLAG averages for bag parameter B_{B_s} and hadronic form factor f_{B_s}, NOT the recent Fermilab/MILC result

Bound 2: neutral meson mixing

Loop-suppressed in SM, but tree-level in Z' model:





Gives a constraint on the Z' coupling to $\bar{b}_L s_L$

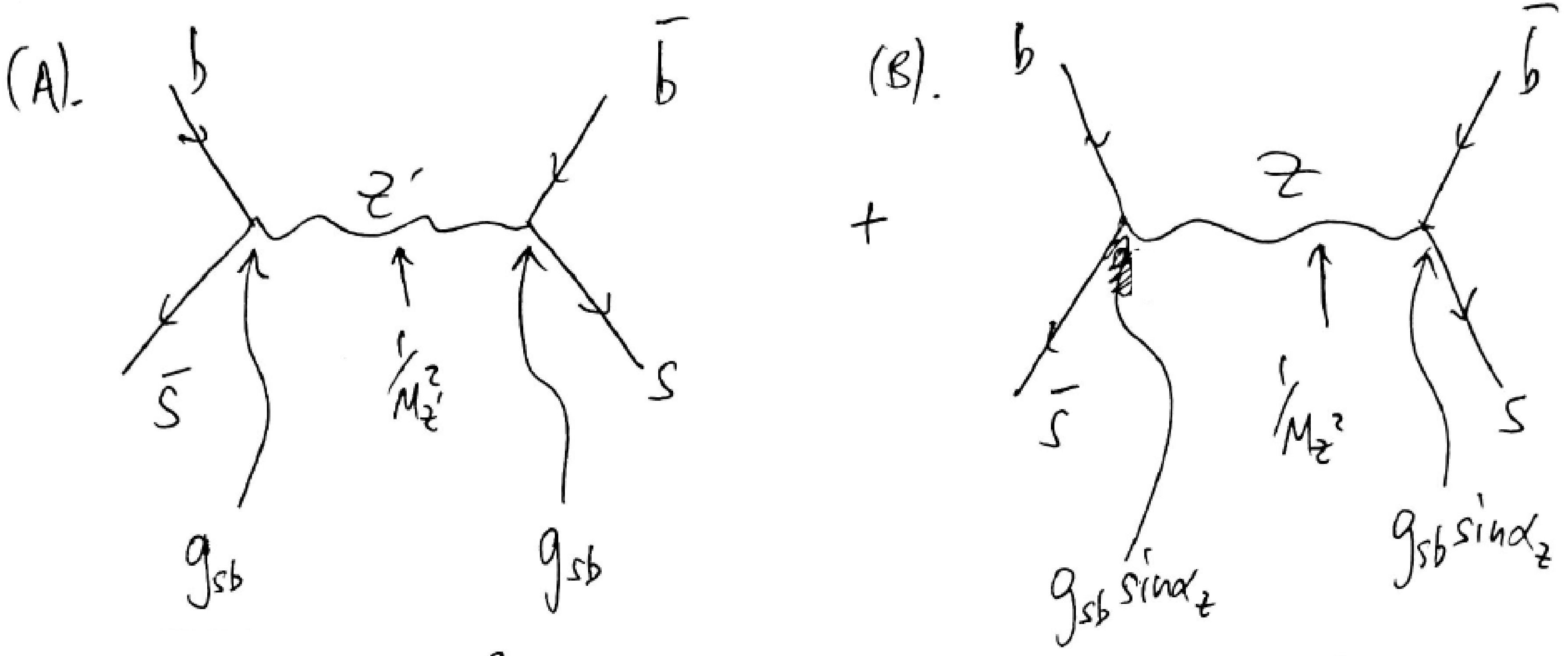
$$\frac{g_F}{12}\sin 2\theta_{sb} < \frac{M_{Z'}}{148\ \text{TeV}}$$

$$\Lambda^{(d_L)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sin^2\theta_{sb} & \frac{1}{2}\sin 2\theta_{sb} \\ 0 & \frac{1}{2}\sin 2\theta_{sb} & \cos^2\theta_{sb} \end{pmatrix}$$

Recall, no Z' coupling to $\bar{b}_L d_L$ or $\bar{s}_L d_L$, so no constraints from kaon or B_d mixing

Bound 2: neutral meson mixing

We also have a BSM tree-level contribution from *Z* exchange



$$\sim -\frac{g_{sb}^2}{2M_{Z'}^2}$$

$$\sim -\frac{(g_{sb}\sin\alpha_z)^2}{2M_Z^2} = -\frac{g_{sb}^2}{2M_{Z'}^2}\cdot\left[\left(\frac{g_F^2}{g^2+g'^2}\right)\left(\frac{M_Z}{M_{Z'}}\right)^2\right]$$

suppressed w.r.t. *Z'* contribution

Bound 3: LFU of the Z boson

Z boson now couples differently to muons and electrons; need to be consistent with LEP measurement:

$$R_{\rm LEP} = 0.999 \pm 0.003, \qquad R \equiv \frac{\Gamma(Z \to e^+e^-)}{\Gamma(Z \to \mu^+\mu^-)}.$$

In Third Family Hypercharge Model,

$$R_{\rm model} = \frac{|g_Z^{e_L e_L}|^2 + |g_Z^{e_R e_R}|^2}{|g_Z^{\mu_L \mu_L}|^2 + |g_Z^{\mu_R \mu_R}|^2},$$

Modified in TFHM due to tree-level *Z-Z'* mixing

Bound 3: LFU of the Z boson

In Third Family Hypercharge Model, have *X* couplings to leptons:

$$\mathcal{L}_{lZ'} = \overline{e_L}\left(-\frac{1}{2}g\not{W}^3 - \frac{1}{2}g'\not{B}\right)e_L + \overline{\mu_L}\left(-\frac{1}{2}g\not{W}^3 - \frac{1}{2}g'\not{B} - \frac{1}{2}g_F\not{X}\right)\mu_L + \overline{\tau_L}\left(-\frac{1}{2}g\not{W}^3 - \frac{1}{2}g'\not{B}\right)\tau_L + \overline{\mathbf{e_R}}\left(-g'\not{B}\right)\mathbf{e_R} + \overline{\tau_R}\left(-g_F\not{X}\right)\tau_R,$$

rotate to gauge boson mass basis → *Z* coupling to $\mu_L\mu_L$

$$R_{\rm model} = \frac{|g_Z^{e_L e_L}|^2 + |g_Z^{e_R e_R}|^2}{|g_Z^{\mu_L \mu_L}|^2 + |g_Z^{\mu_R \mu_R}|^2},$$

$$g_Z^{\mu_L \mu_L} = -\frac{1}{2}g\cos\theta_w + \frac{1}{2}g'\sin\theta_w - \frac{1}{2}g_F\sin\alpha_z$$

Bound 3: LFU of the Z boson

Taylor expand R_{model} in $\sin\alpha_z$:

$$R_{\rm model} = 1 - \frac{2g_F(g\cos\theta_w - g'\sin\theta_w)\sin\alpha_z}{(g\cos\theta_w - g'\sin\theta_w)^2 + 4g'^2\sin^2\theta_w} = 1 - 4.2g_F^2\left(\frac{M_Z}{M_{Z'}}\right)^2$$

Comparison to LEP LFU yields constraint:

$$g_F^2\left(\frac{M_Z}{M_{Z'}}\right)^2 < 0.0017 \Rightarrow g_F < \frac{M_{Z'}}{2.2\ \text{TeV}}$$

Bound 4: top decays

Have terms in lagrangian coupling *Z'* to up-type quarks:

$$\mathcal{L}_{Xtq} = \frac{g_F}{6}\left(\Lambda_{23}^{(u_L)}\bar{c}\gamma^\rho P_L t + \Lambda_{13}^{(u_L)}\bar{u}\gamma^\rho P_L t + H.c.\right) X_\rho$$

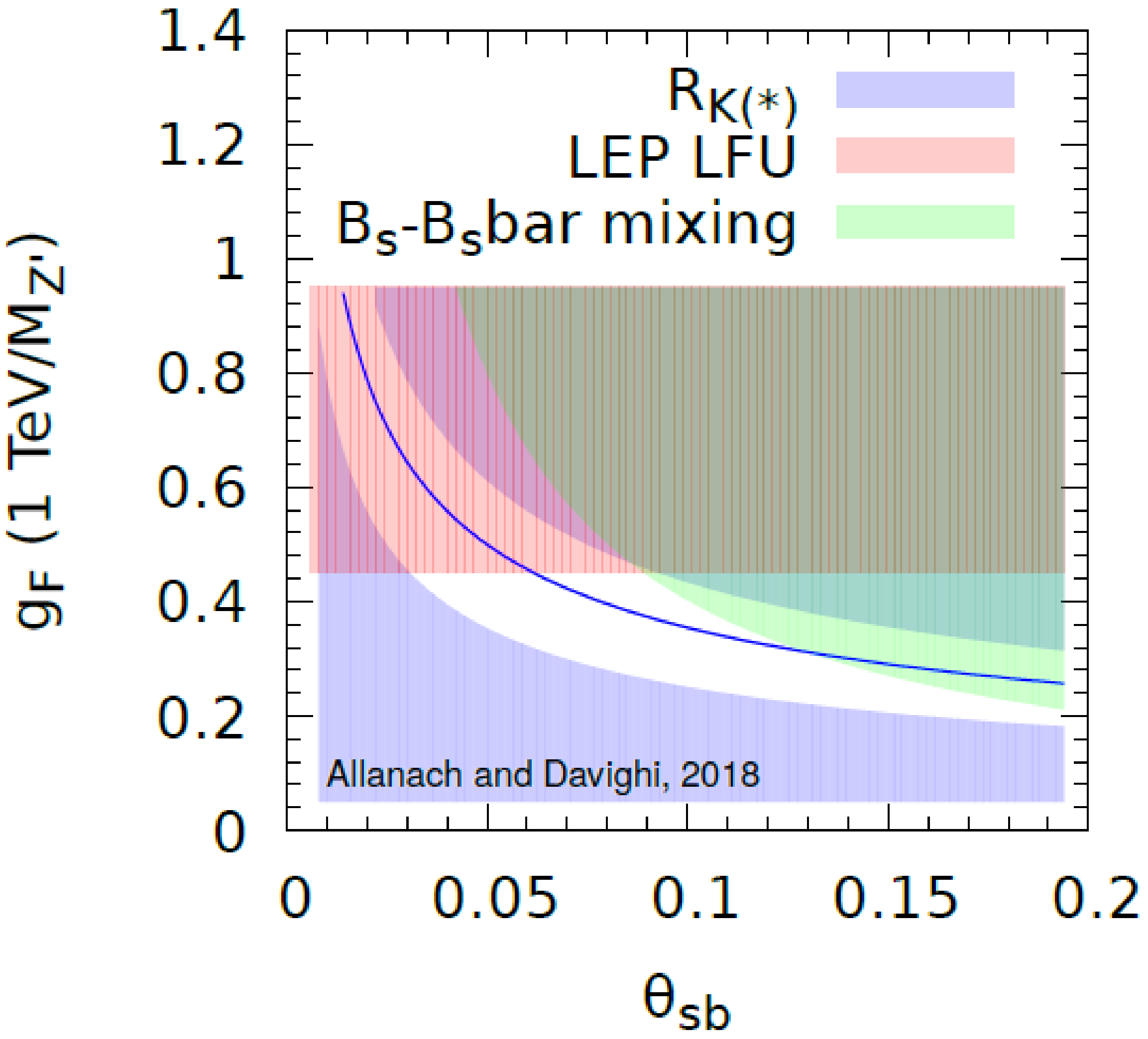
which yield (given *Z-Z'* mixing) new top decays to *Zq*, where *q* = *u*, *c*

But couplings small,

→ constraints very weak

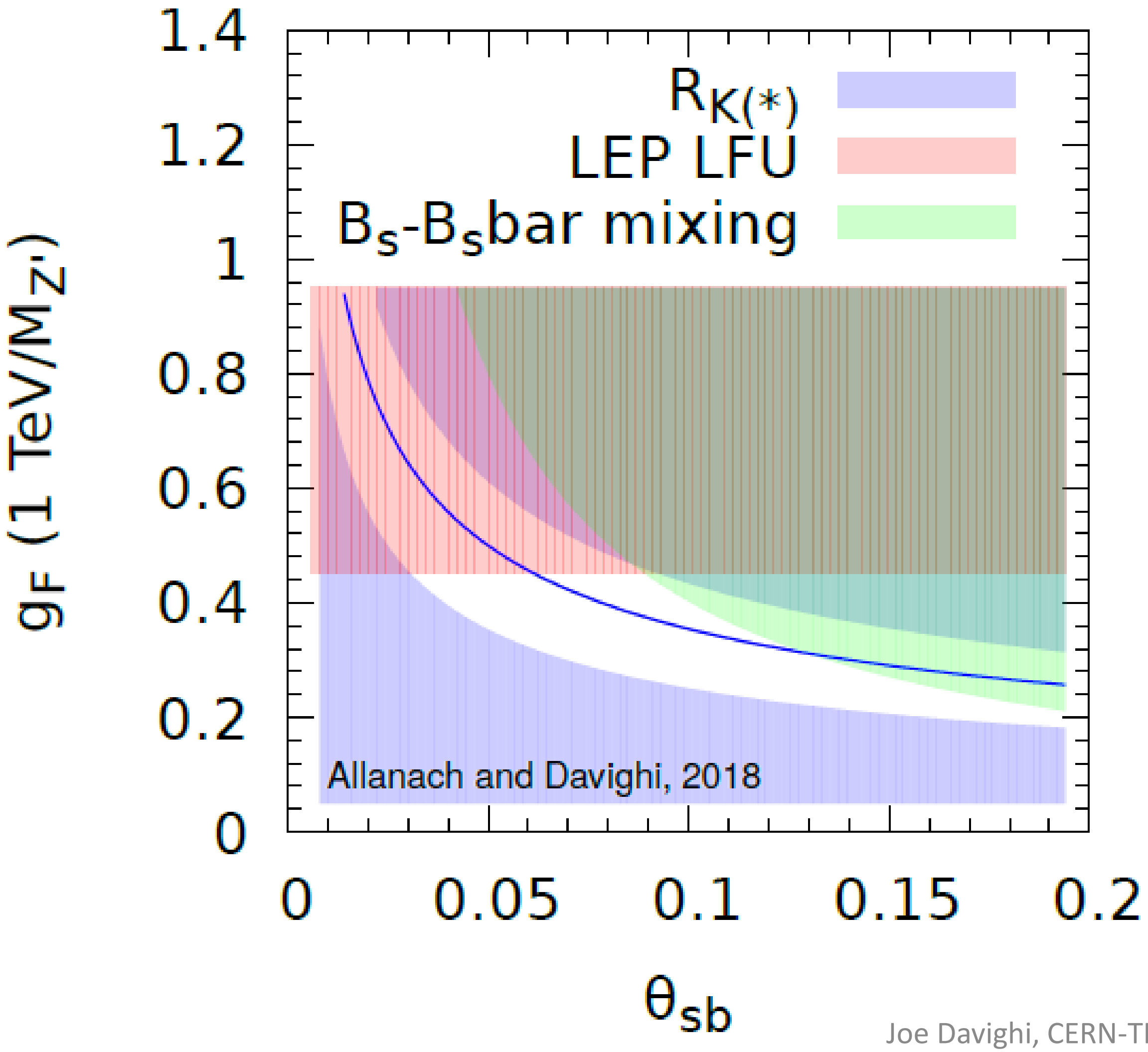
$$\Lambda^{(u_L)} = \begin{pmatrix} 0.0002 & 0.001 & 0.012 \\ 0.001 & 0.006 & 0.079 \\ 0.012 & 0.079 & 0.995 \end{pmatrix}$$

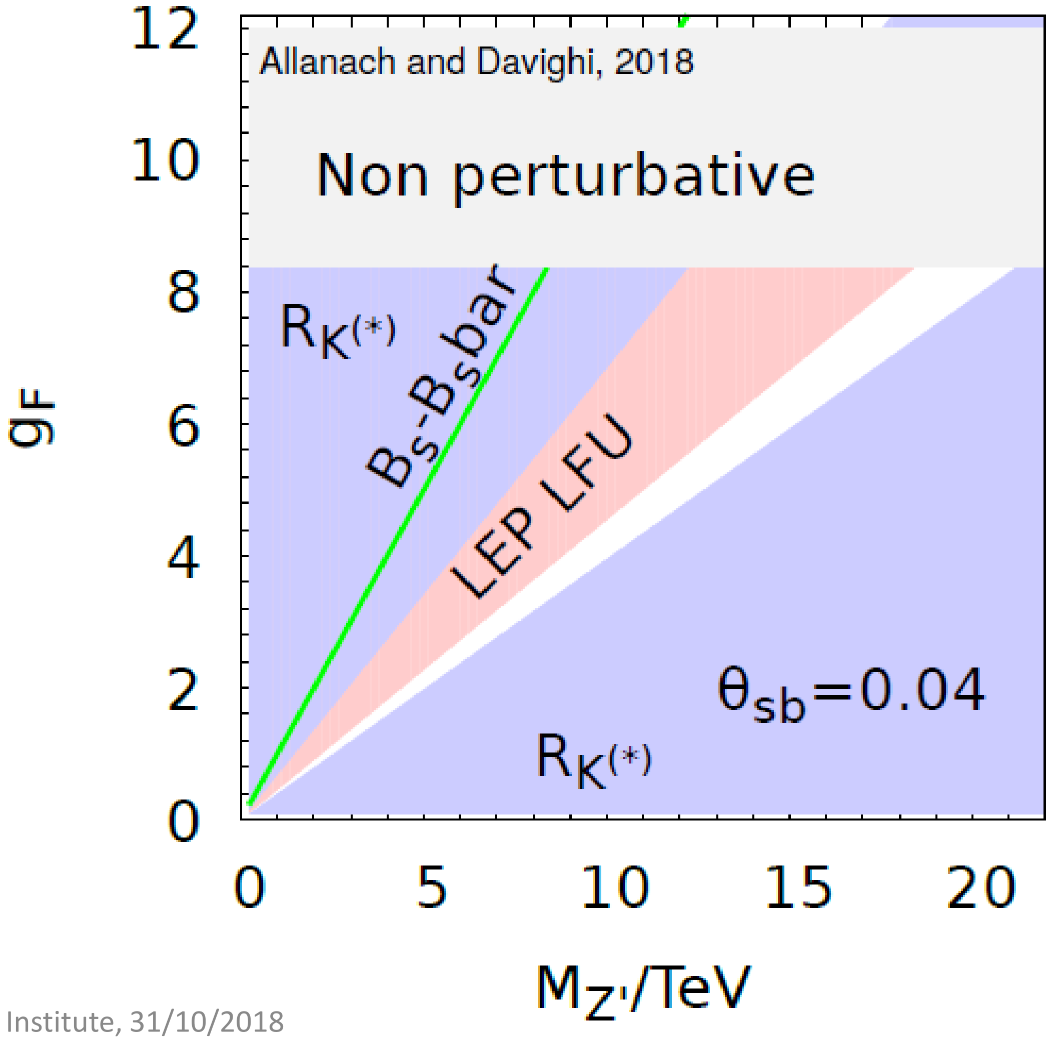
Combination of constraints



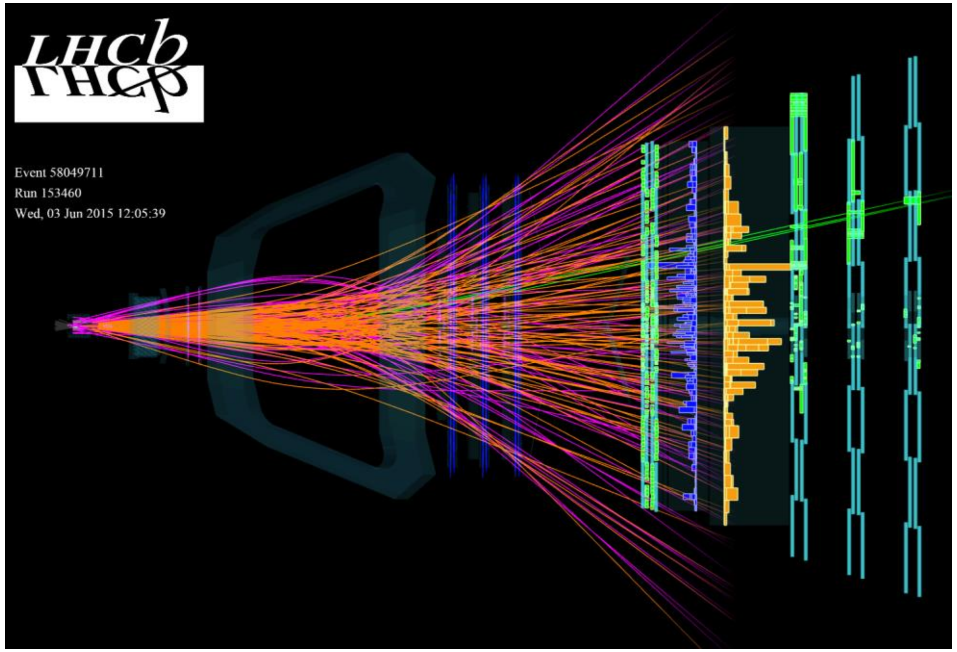
White region is allowed at 95% CL

Combination of constraints





4. Predictions of the Third Family Hypercharge Model



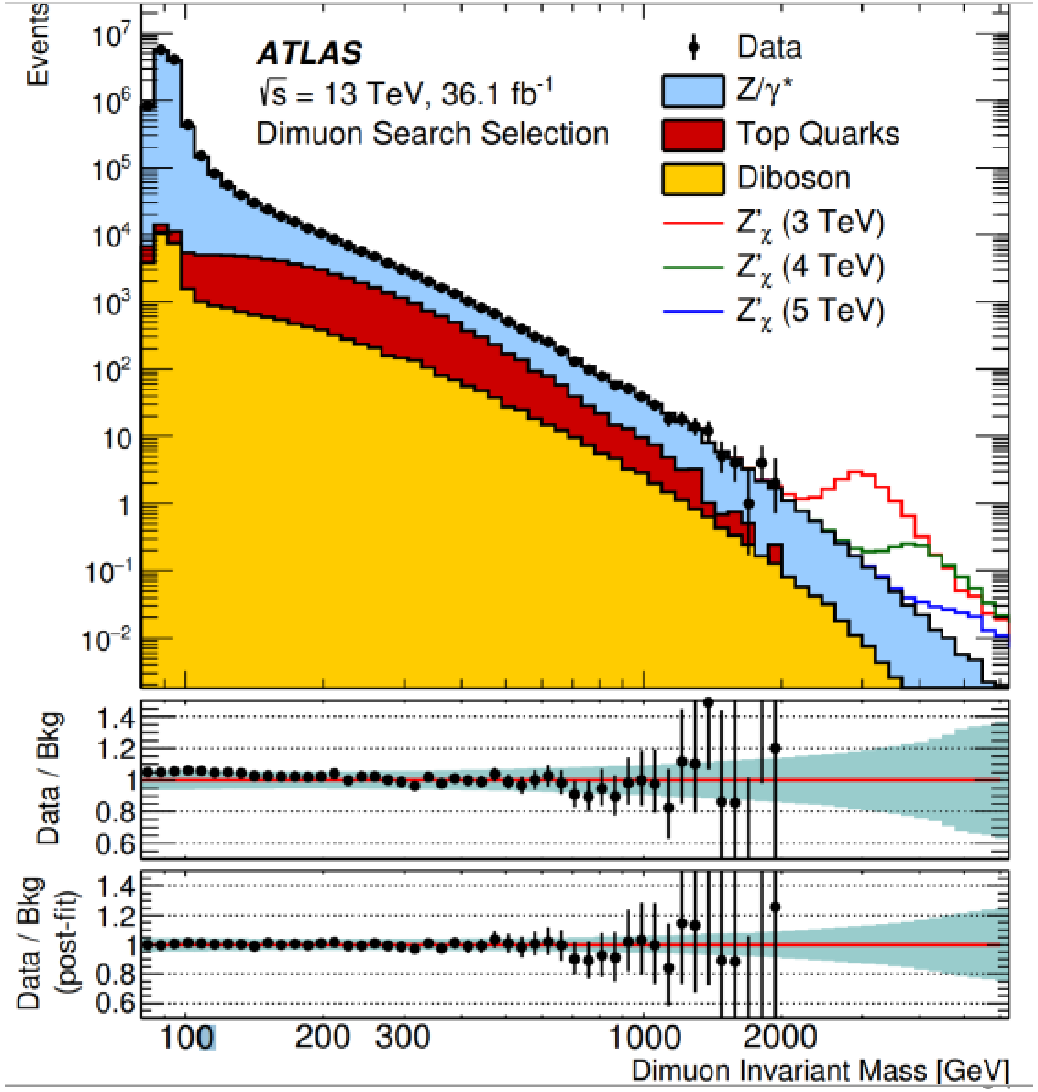
See A. Greljo's talk

High p_T: collider searches

ATLAS Collab., 1707.02424

No Z primes at LHC yet:

- $M_{Z'} < 4.5$ TeV excluded, assuming Z' couples as SM Z
- Need to recast bounds for TFHM (Z' has tiny couplings to valence quarks)



HL LHC projection?

HE LHC?

FCC?

Allanach, Gripaios, You, 1710.06363
Allanach, Corbett, Dolan, You, 1810.02166

High p_T: collider searches

Example Case *Z'* branching ratios:

Mode	BR	Mode	BR	Mode	BR
$t\bar{t}$	0.42	$b\bar{b}$	0.12	$\nu\bar{\nu}'$	0.08
$\mu^+\mu^-$	0.08	$\tau^+\tau^-$	0.30	other $f_i f_j$	$\sim \mathcal{O}(10^{-4})$

Decays mainly to **third generation** fermions

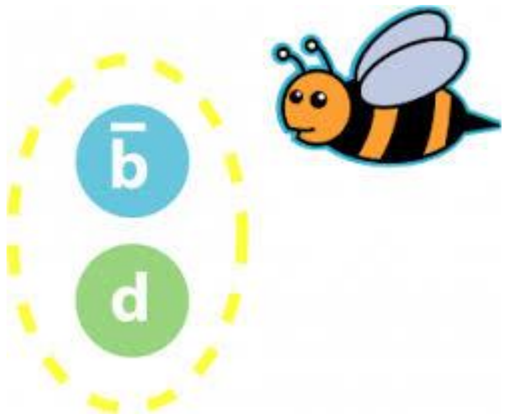
Dominant decays to top pairs and tauon pairs; challenging signatures for direct search

High p_T: HI-LUMI searches

E.g. for rare top decays like

$$t \to Zu, \qquad t \to Zc$$

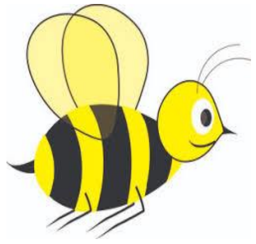
Low p_T: more rare decays



BSM contribution (deficit, right-handed) to $BR(B \to K^{(*)}\tau^+\tau^-)$

… and many others, predictions depending on the example case

5. Outlook



Beyond Third Family Hypercharge

Pheno of TFHM:

- Explore experimental constraints beyond our Example Case
- Effect of flavon-Higgs mixing on Higgs couplings esp to tau, top, bottom
- Recast collider bounds for TFHM, and explore low-p_T predictions
- Neutrino trident constraint? Probably weaker than LEP LFU (large $M_{Z'}$)

Further model-building:

- TFHM is really a bare-bones model. Would like to extend to explain:
  1. Neutrino masses
  2. CKM mixing hierarchy, PMNS mixing "anarchy"
  3. Mass hierarchies between all three families - need to break $SU(2)_F$

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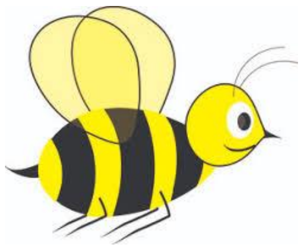
connected… (1 ↔ 2)

Summary

We have constructed a complete and (perhaps too) simple *Z'* model for the neutral current B anomaly measurements, which moreover explains the heaviness of the third family fermions

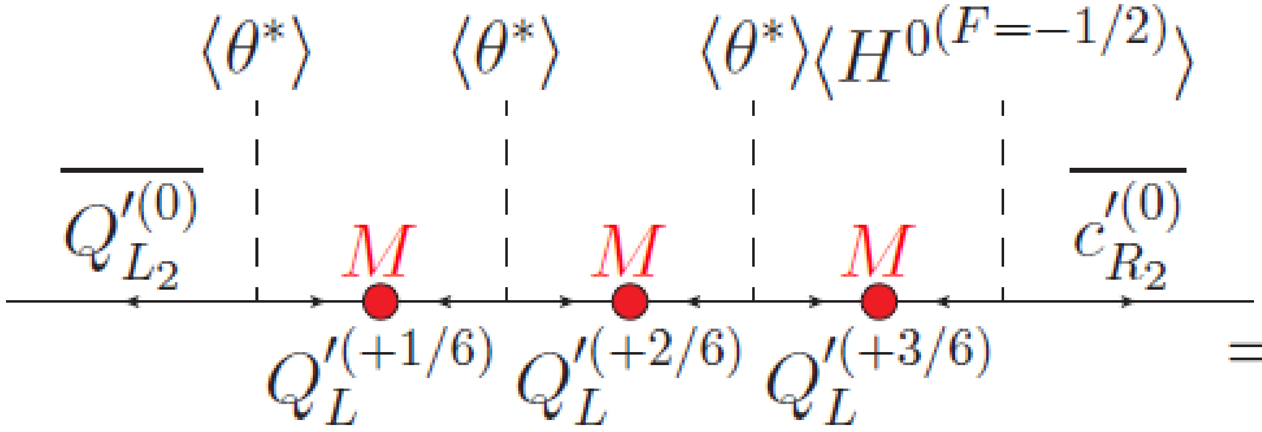
The plan: incrementally build towards a model of flavour physics, led by B data



Backup Slides

Light quark masses from the Froggatt-Nielsen mechanism

$$Y_c \overline{Q'_{L2}}^{(F=0)} H^{(F=-1/2)} c_R'^{(F=0)} \sim \mathcal{O}\left[\left(\frac{\langle\theta\rangle}{M}\right)^3 \overline{Q'_{L2}} H c'_R\right]$$



eg $\left(\frac{\langle\theta\rangle}{M}\right) \sim 0.2$

$\Rightarrow Y_c/Y_t \sim 1/100$

Froggatt, Nielsen, NPB147 (1979) 277

Details of the model: *Z*-*Z'* mixing

Masses in limit $M_Z/M_{Z'} \ll 1$:

$$M_Z \approx \frac{M_W}{\cos\theta_w} = M_W \frac{\sqrt{g^2+g'^2}}{g}, \qquad M_{Z'} \approx M_W \frac{g_F\sqrt{1+4F_\theta^2 r^2}}{g},$$

Mixing angle:

$$\sin\alpha_z \approx \frac{g_F}{\sqrt{g^2+g'^2}}\left(\frac{M_Z}{M_Z'}\right)^2 .$$

Z boson contains small admixture of the *X* field:

$$Z_\mu = \cos\alpha_z\left(-\sin\theta_w B_\mu + \cos\theta_w W_\mu^3\right) + \sin\alpha_z X_\mu,$$

Caveat: charged leptons in the example case

Want large coupling of Z' to muons, but do not want Z' coupling to $\tau\mu$ – strong constraint from $\tau \to 3\mu$

This bound motivates extreme example ca

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

which really implies

$$Y_E = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & Y_\tau \\ 0 & x & 0 \end{pmatrix}$$

suppose suppressed by some UV mechanism/ symmetry…

so example case doesn't explain heavy tauon (… but tauon not *that* heavy anyway…)