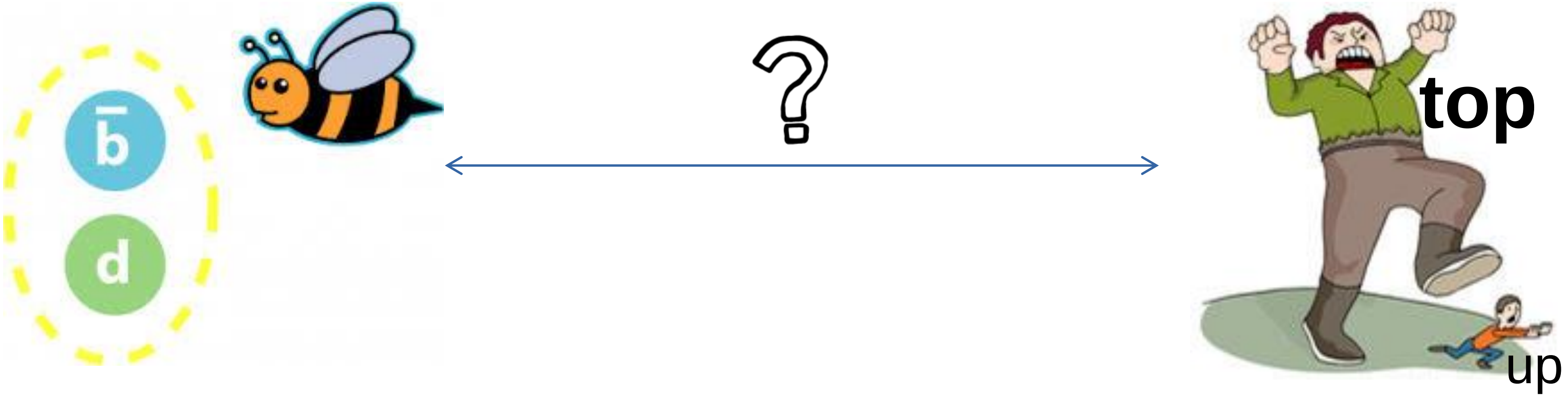
Simple *Z'* models for *B*-anomalies and fermion masses



Joe Davighi, DAMTP, University of Cambridge
Work done with Ben Allanach

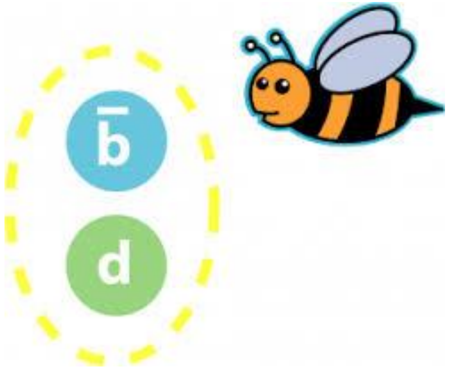
LHCbUK 2020, Huddersfield

Outline

1. Motivation - neutral current *B* anomalies
2. Third Family Hypercharge Model (TFHM) B. Allanach, JD, *JHEP 12 (2018) 075*
3. Deformed TFHM B. Allanach, JD, *EPJC 79 (2019) no.11, 908*
4. What to look for next

Motivation = neutral current B anomalies

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



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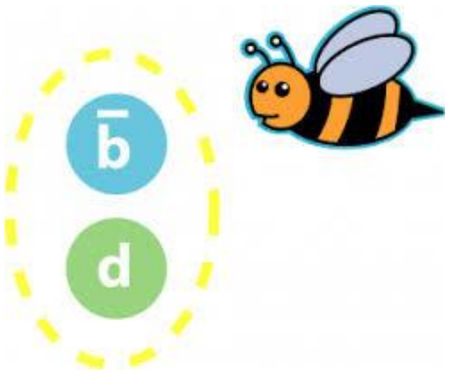


LHCb measurements (all below SM predictions):

q^2/GeV²			Deviation from SM
[0.045,1.1]	R_{K^*}	$0.66^{+0.11}_{-0.07} \pm 0.03$	$\sim 2.5\sigma$
[1.1,6.0]	R_{K^*}	$0.69^{+0.11}_{-0.07} \pm 0.05$	$\sim 2.5\sigma$
[1.1,6.0]	R_K	$0.846^{+0.06+0.016}_{-0.05-0.014}$	$\sim 2.5\sigma$

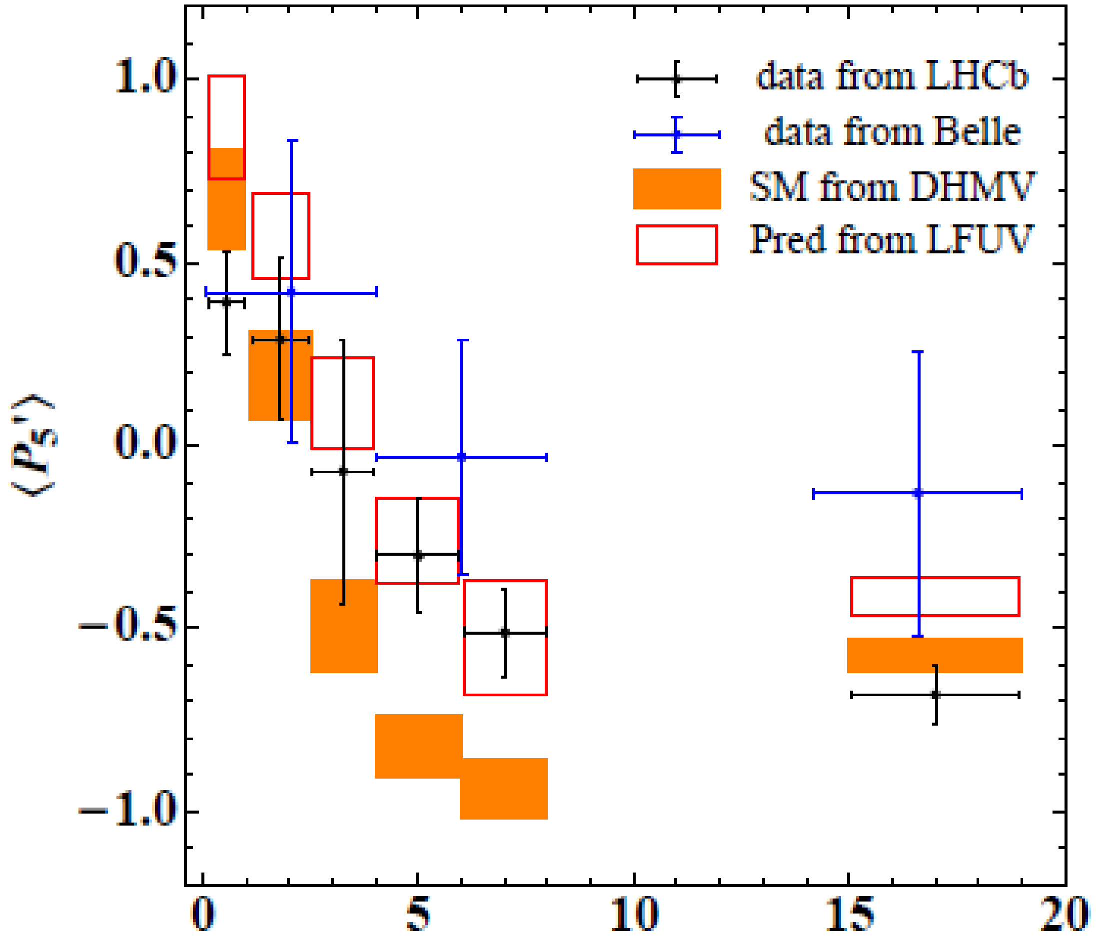
Motivation = neutral current B anomalies

<u>Other observables:</u>

LHCb
- $BR(B \to K\mu\mu)$
- $BR(B \to K^*\mu\mu)$
- $BR(B_s \to \varphi\mu\mu)$

LHCb +ATLAS +CMS
- $BR(B_s \to \mu\mu)$; about 2σ below SM

LHCb +Belle
- Angular distribution in $B \to K^*\mu\mu$



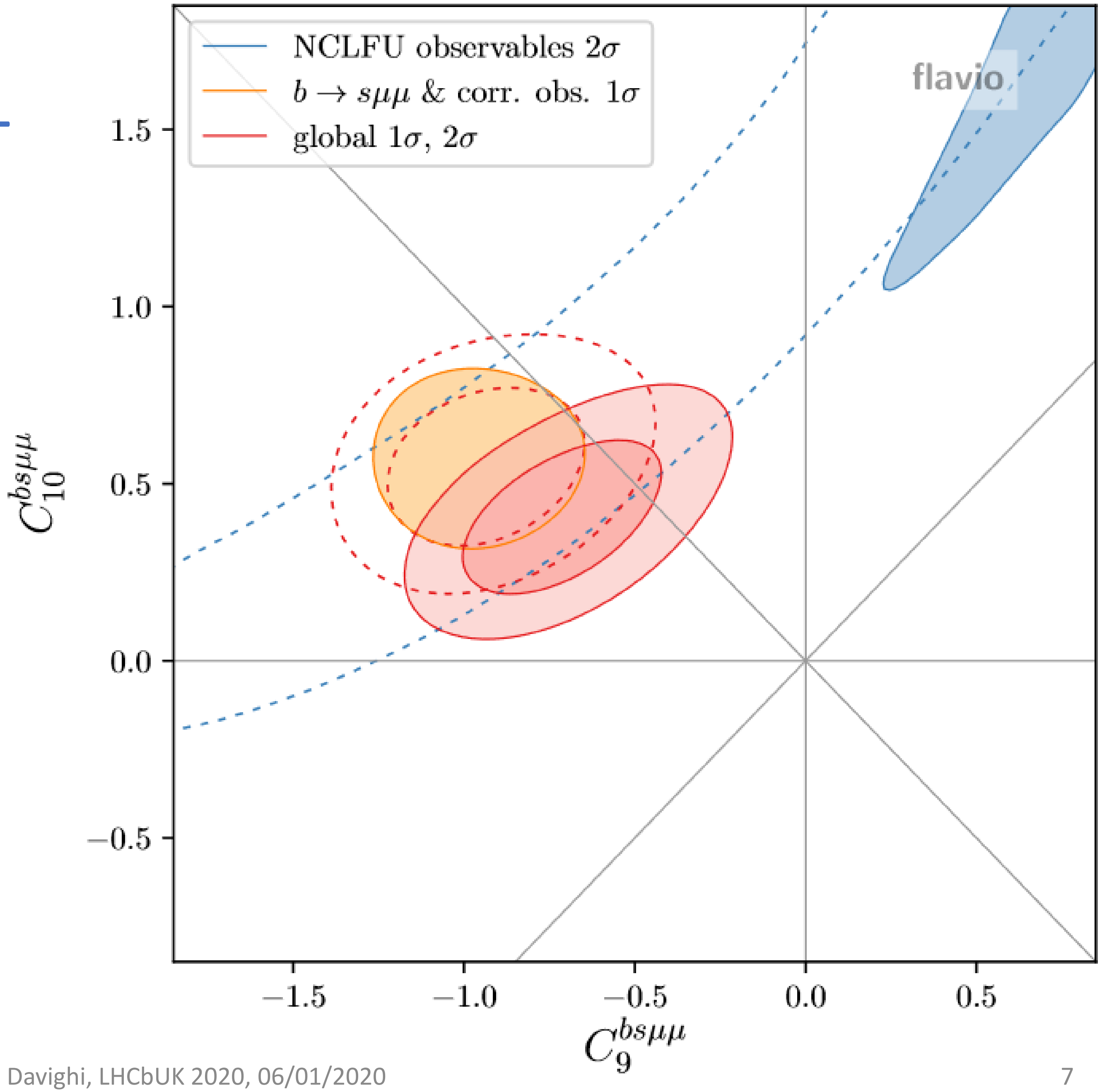
Could these discrepancies with the SM be due to New Physics?

Global fit to SMEFT coefficients

Data can be well-fitted assuming NP in two muonic operators:

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

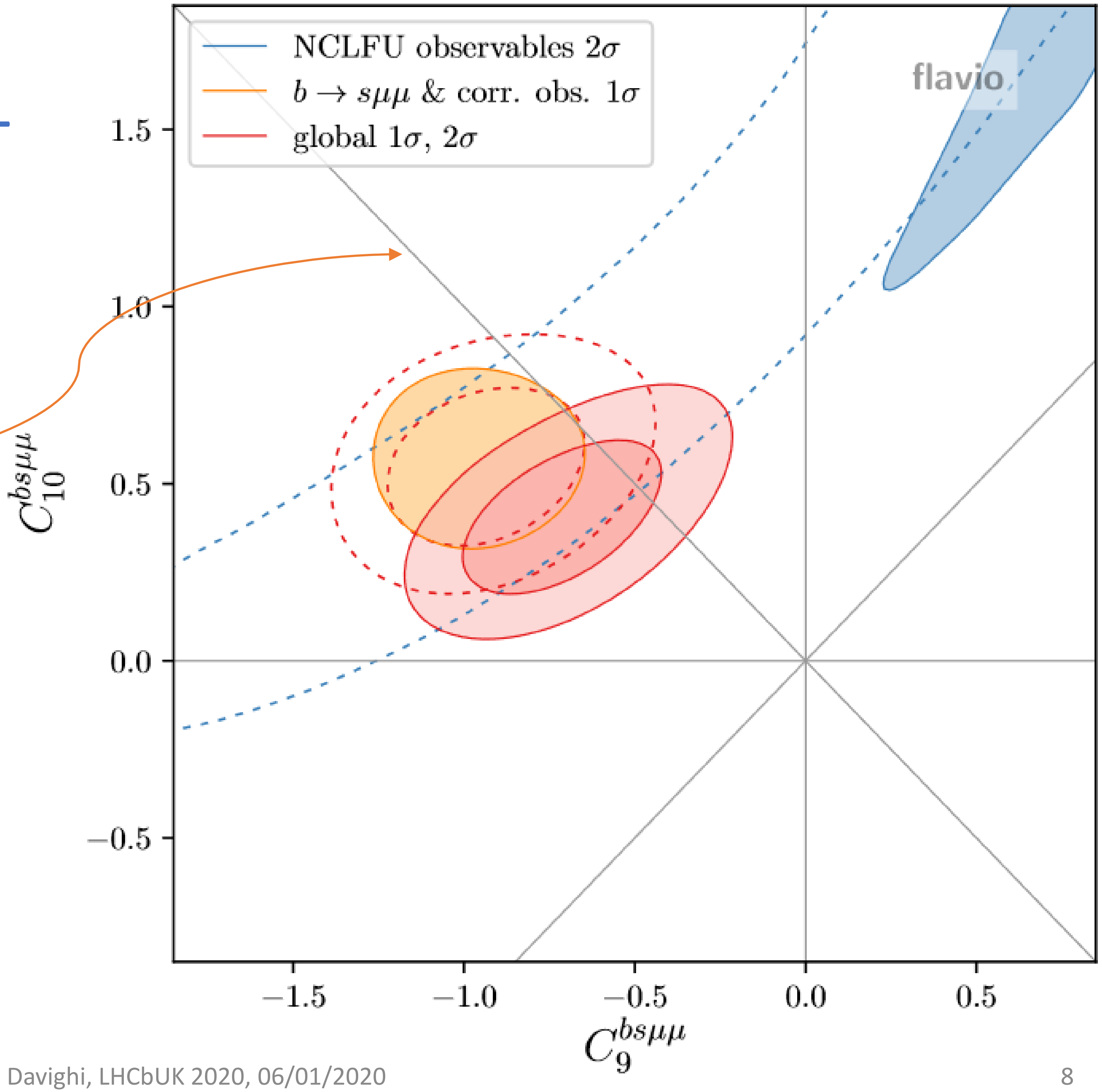
Aebischer, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub, 1903.10434



Global fit to SMEFT coefficients

LH muon current ($C_9 = -C_{10}$) fits data better than SM with a pull of 6.6σ

(preferred over C_9 only after Moriond 2019)



Aebischer, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub, 1903.10434

What do the (NC) *B* anomalies tell us?

1. Lepton flavour universality violation (**LFUV**) between e and μ

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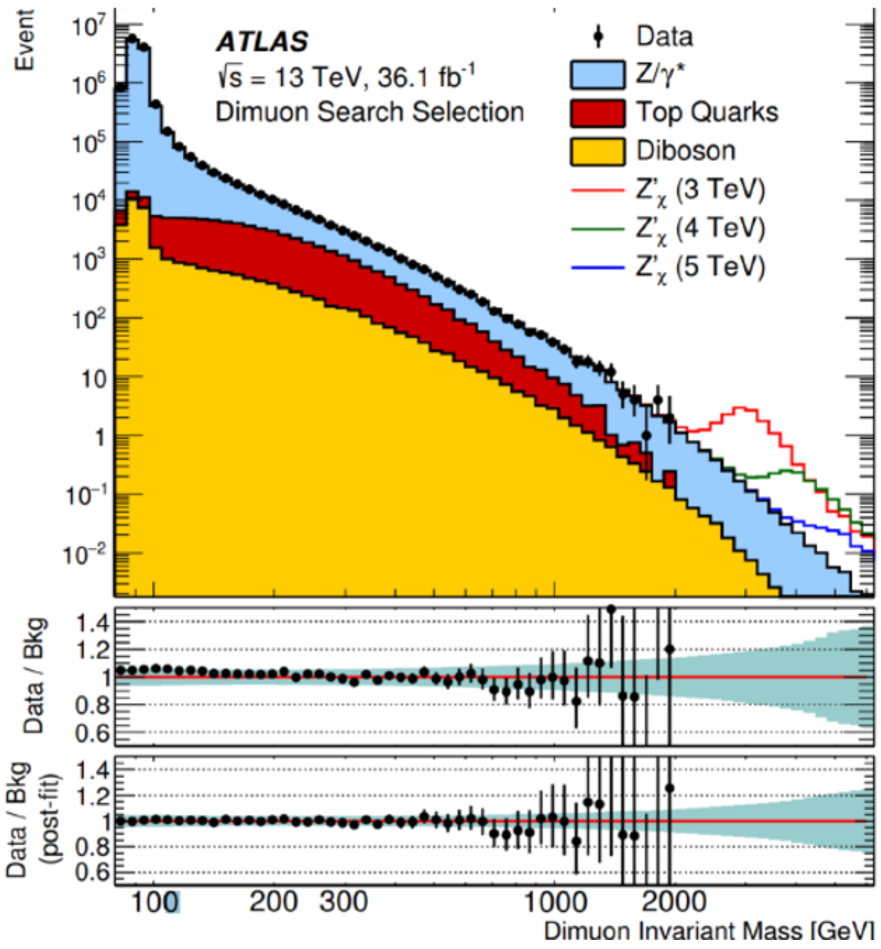
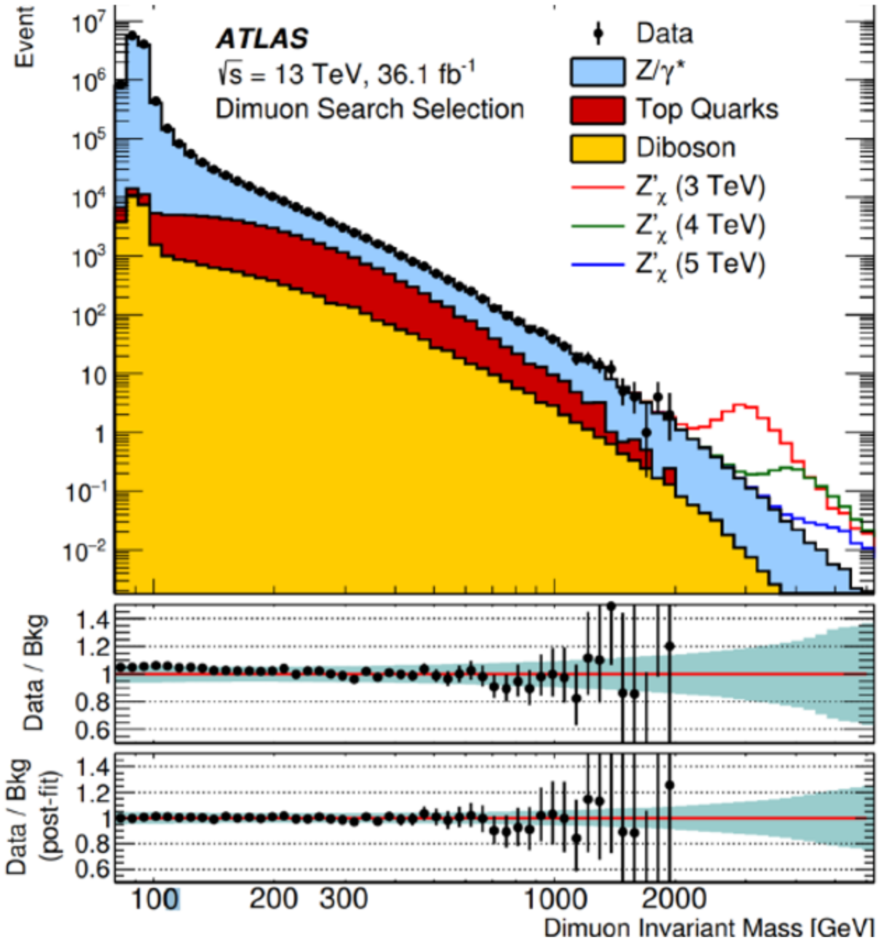


What do the (NC) *B* anomalies tell us?

2. Hints that new physics "aligned" with third family (quarks)

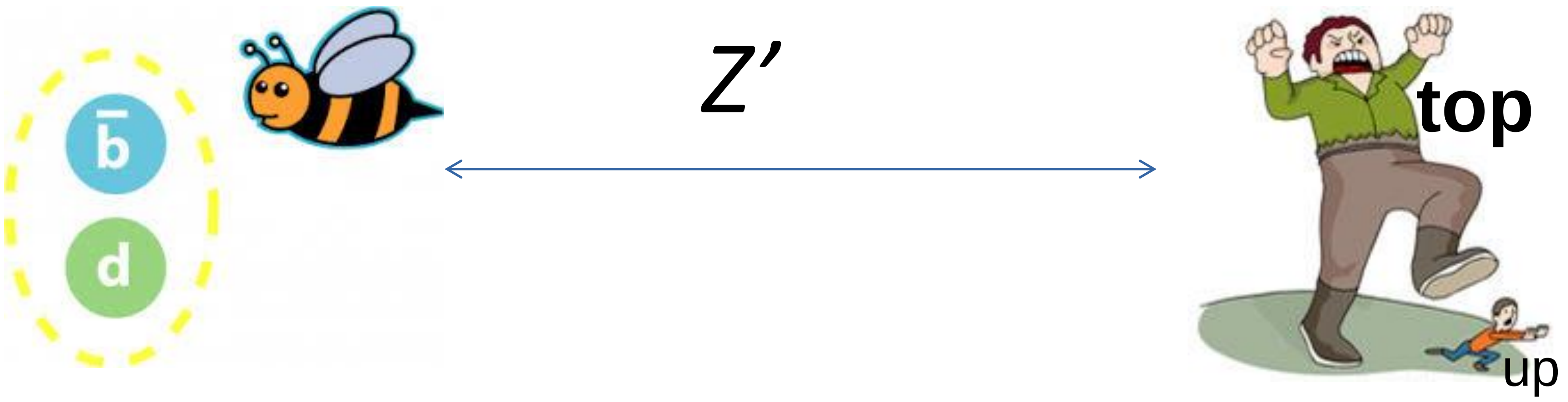
- All discrepancies involve bottom
- No LFUV in kaon/ pion/ charm physics
- Absence of NP in high-p_T searches
- Also charged current anomalies (though will not discuss this here)



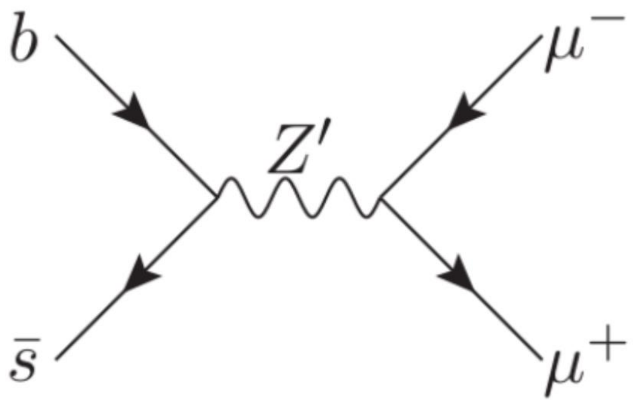
Third family alignment → connections to flavour problem?

up charm top

Third Family Hypercharge Model (TFHM)



Z' models



Suppose Z' is heavy gauge boson for a spontaneously-broken U(1)

$$G_{SM} \times U(1) \xrightarrow{\langle\theta\rangle \sim \text{TeV}} G_{SM}$$

Assume only SM fermion content for simplicity

- Let's assume Z' coupled only to third family in weak eigenbasis

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- Cancellation of gauge anomalies then fixes charges uniquely

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

… this is just third family hypercharge

- Let's assume Z' coupled only to third family in weak eigenbasis
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$$\begin{array}{cccc} F_{Q'_i} = 0 & F_{u_{R_i}'} = 0 & F_{d_{R_i}'} = 0 & F_{L'_i} = 0 \\ F_{e_{R_i}'} = 0 & F_H = -1/2 & F_{Q'_3} = 1/6 & F_{u'_{R3}} = 2/3 \\ F_{d'_{R3}} = -1/3 & F_{L'_3} = -1/2 & F_{e'_{R3}} = -1 & F_\theta \neq 0 \end{array}$$

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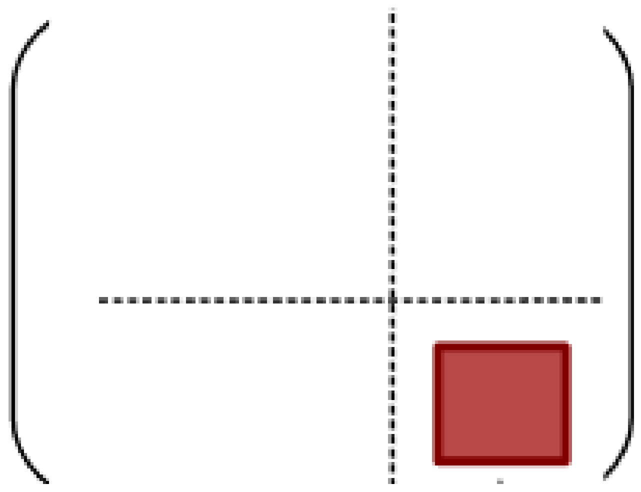
Connection with the flavour problem

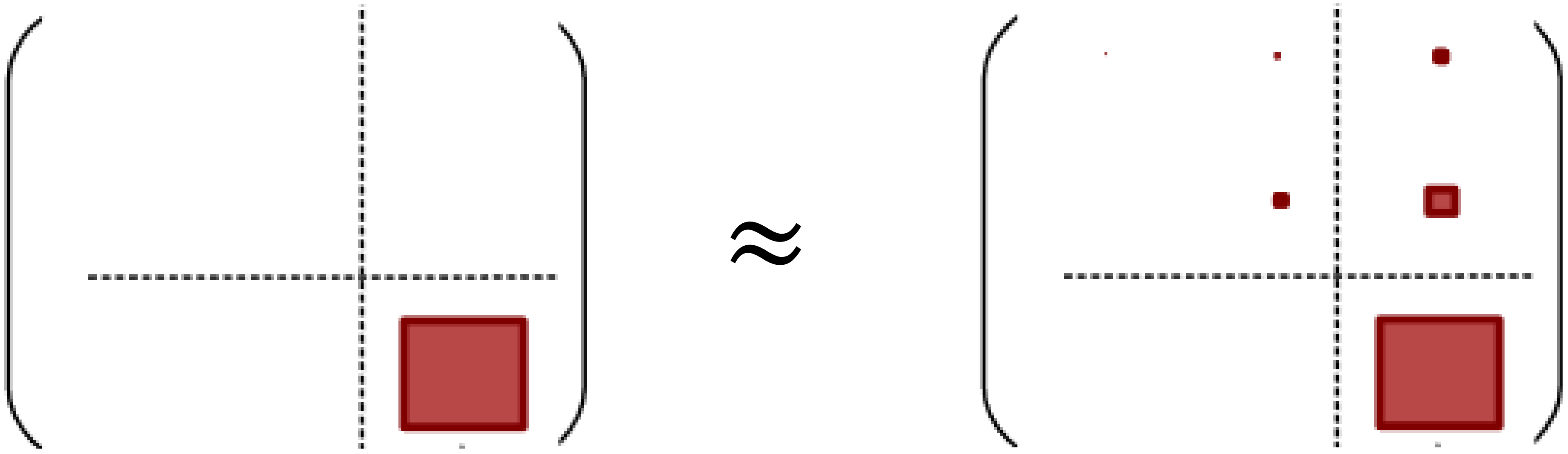
- Third family have masses:

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

- First two families massless at renormalizable level



…which is what we observe to leading order



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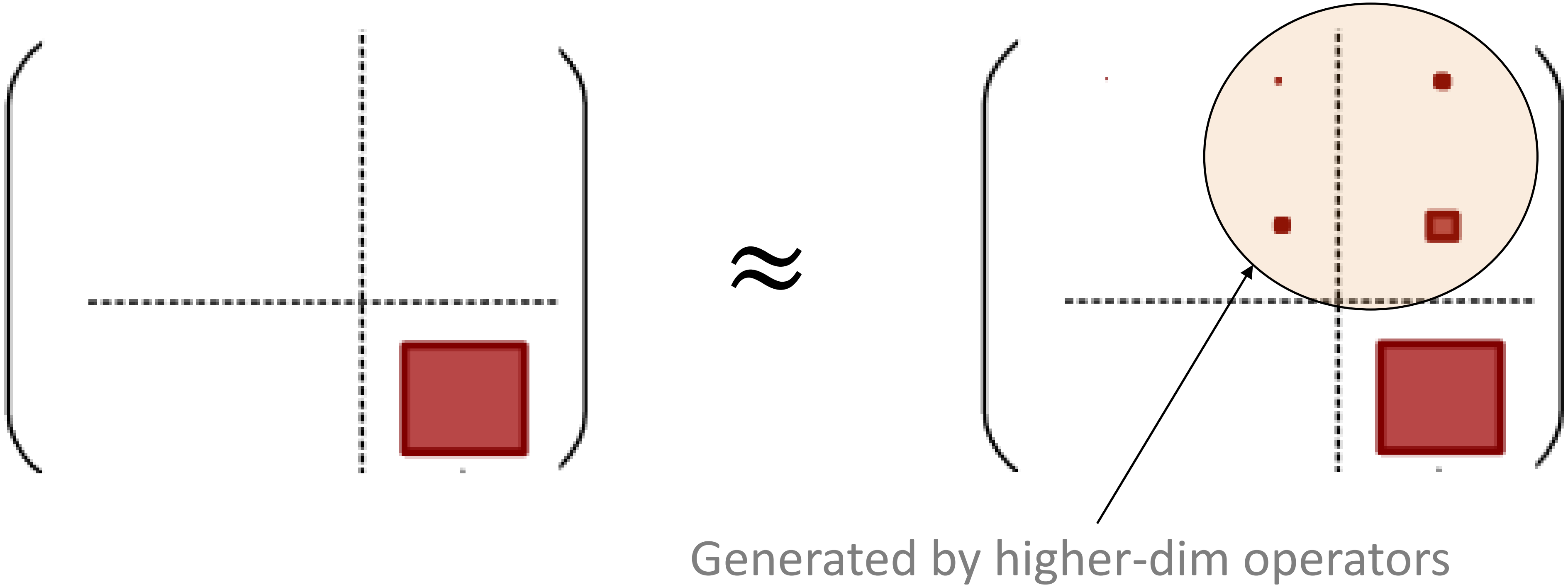

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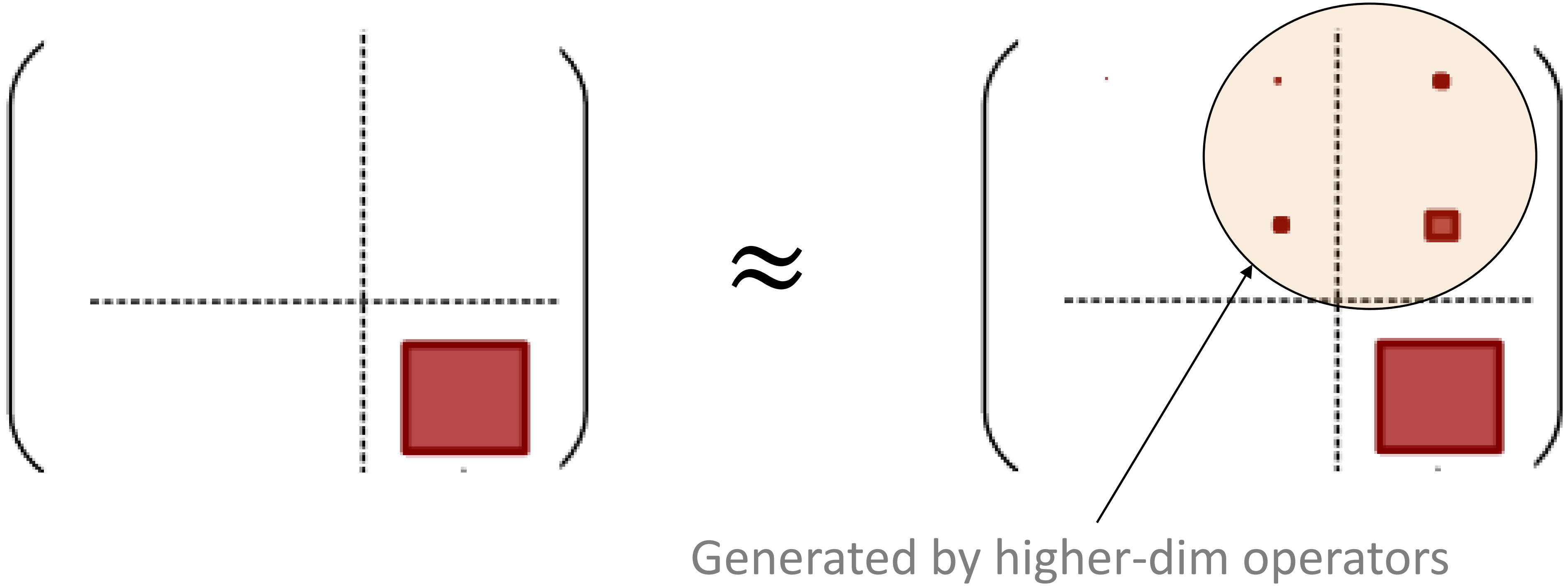


Sheds light on coarse features of flavour problem:

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

Z-Z' mixing

Higgs charged under both EW and $U(1)$ → *Z-Z'* mixing:

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

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

Gives LFUV contributions to *Z* boson couplings

→ strong constraints e.g. from LEP

Z' couplings to fermions

In weak eigenbasis only couplings to third family

Rotation to mass basis induces couplings to lighter families

- The rotation matrices are inputs which must be consistent with observed CKM and PMNS

A simple example case

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

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

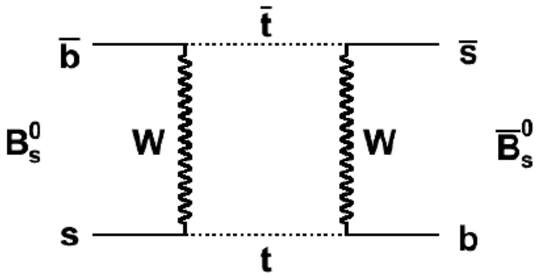
Gives NP in $C_9 = -C_{10}$ direction due to

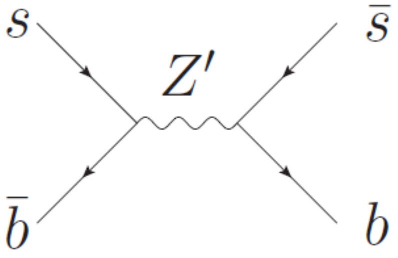
$$\mathcal{L}_{X\psi} = \left(\frac{g_F}{12} \sin 2\theta_{sb} \bar{s} \gamma^\rho P_L b - \frac{g_F}{2} \bar{\mu} \gamma^\rho P_L \mu + \text{H.c.} \right) Z'_\rho + \ldots$$

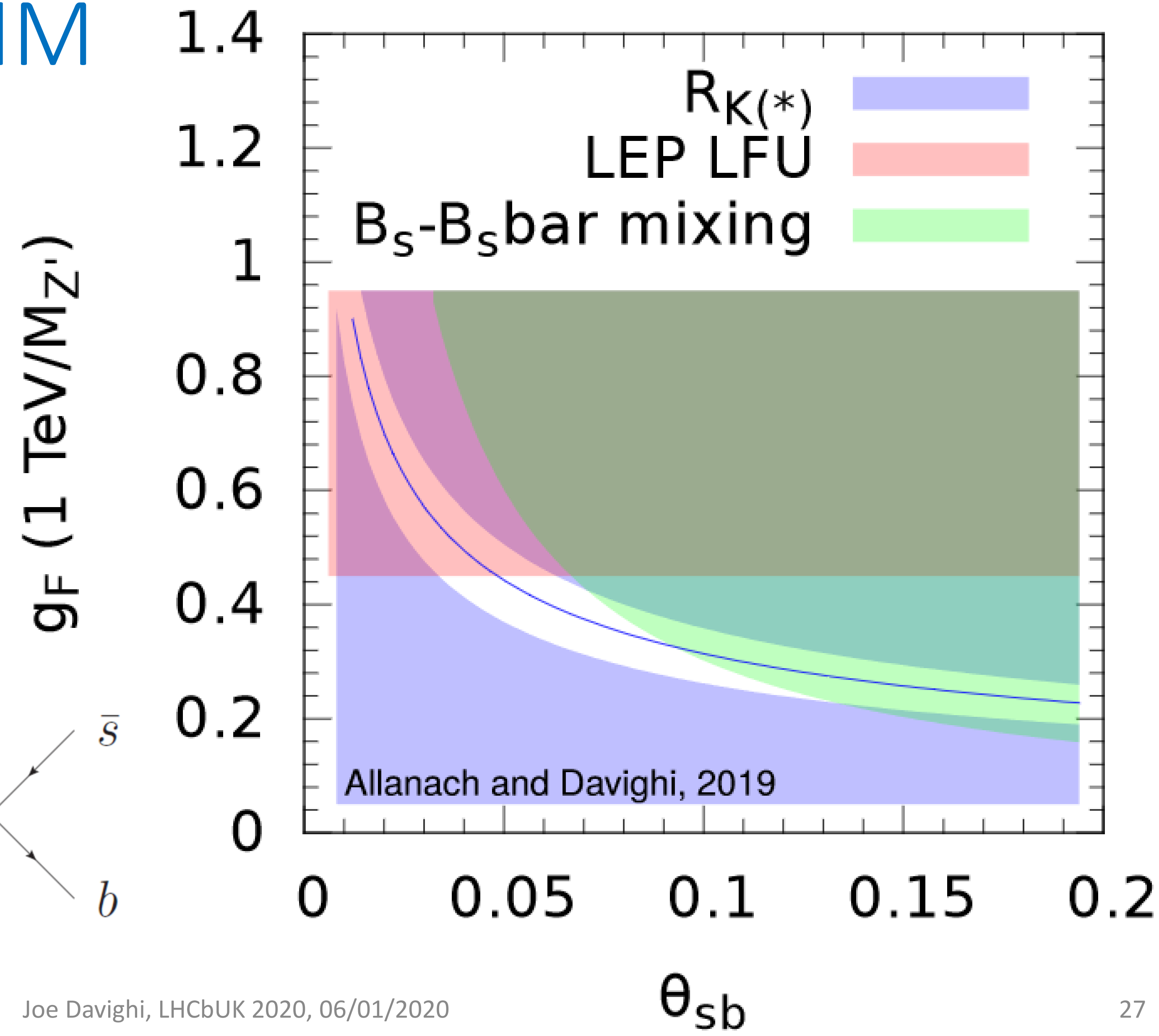
Constraints on TFHM

White region is allowed at 95% CL

B_s mixing constraint from Lenz et al arXiv:1904.00940

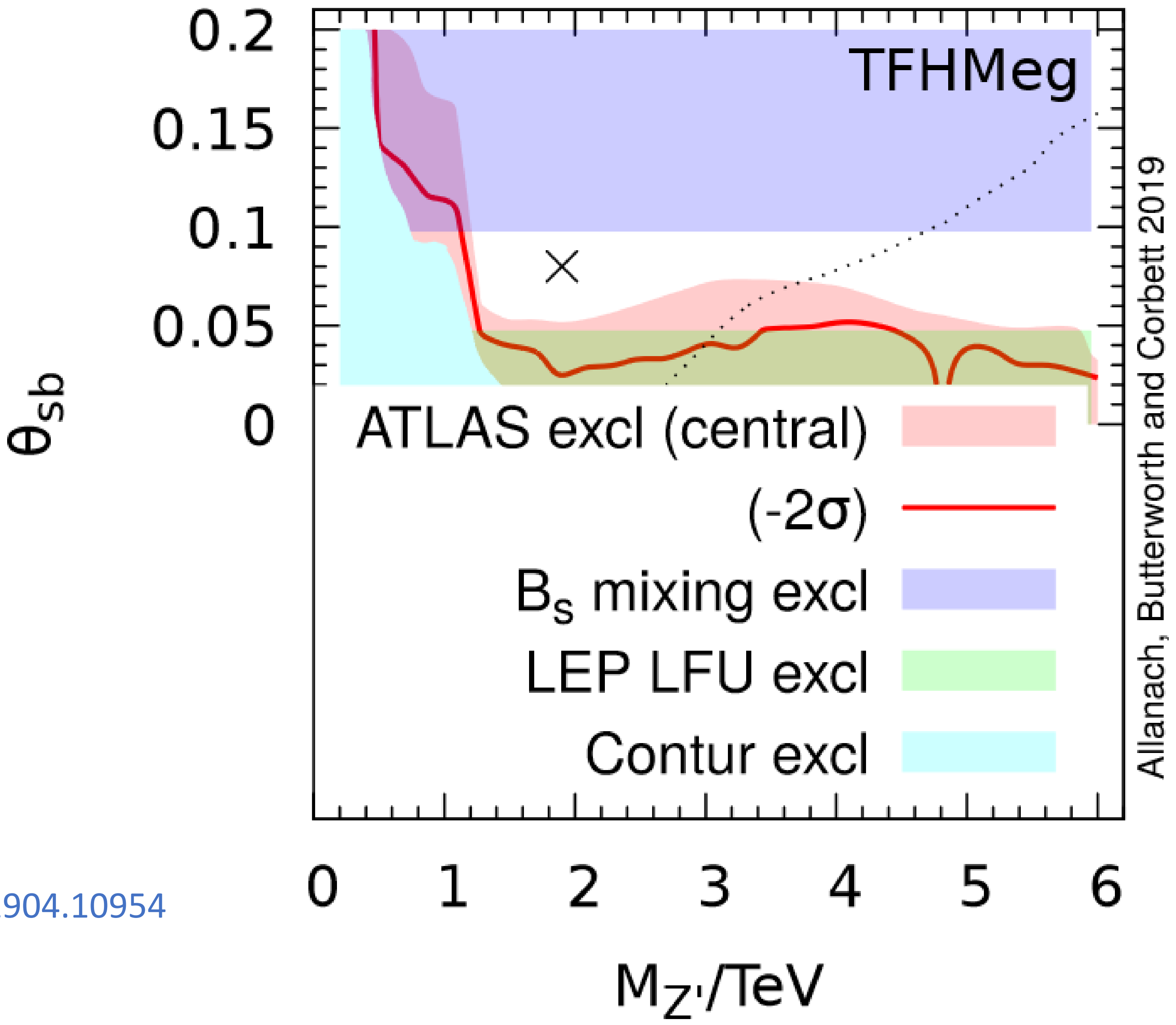






Including direct search constraints

- Recast ATLAS direct search for $Z' \to \mu\mu$ (Run II 139 fb^{-1}, 13 TeV)
- Coupling g_F is everywhere fitted to NCBAs (best-fit point)
- Valid parameter space for $M_{Z'} > 1.2$ TeV



Allanach, Butterworth, Corbett, arXiv:1904.10954

The Deformed TFHM

The "problem" with a third family Z'

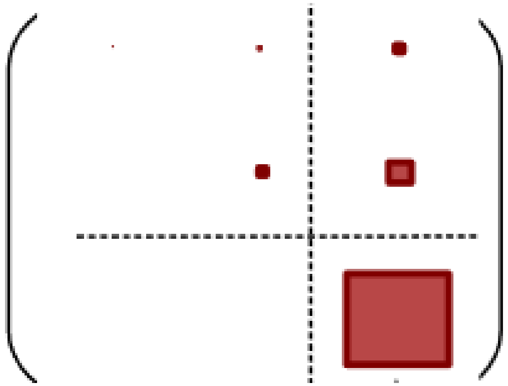
- Need to transfer Z' coupling from τ_L to μ_L to explain B anomalies.
- Large 2-3 mixing in V_{e_L} induces LFV ($\tau \rightarrow \mu\mu\mu$)

The "problem" with a third family Z′

- Need to transfer Z′ coupling from τ_L to μ_L to explain *B* anomalies.
- Large 2-3 mixing in V_{e_L} induces LFV ($\tau \to \mu\mu\mu$)
- We evaded with a mixing angle $\approx 90°$

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

- But $V_{e_{L/R}}$ diagonalize Y_e; implies $(Y_e)_{33} \ll (Y_e)_{23}$.



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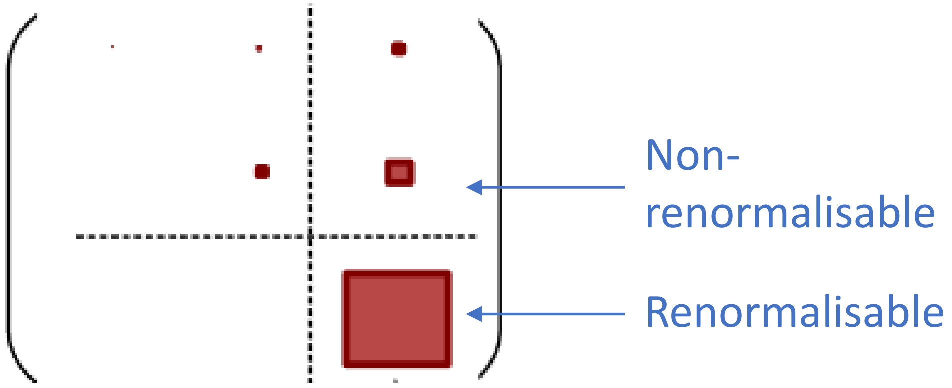
- A naturalness problem.



Deforming the TFHM

- Allow direct Z' couplings to second family leptons (but still only third family quarks)
- Non-zero $U(1)$ charges for $Q_3, u_3, d_3, L_2, L_3, e_2, e_3, H$
- Fix these charges using anomaly cancellation

Anomaly cancellation

- The linear anomaly equations fix

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

- 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) integer solution:

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

---

*The cubic anomaly equation is trivially satisfied here

- "Deformed TFHM" charge assignment:

$$F_{Q'_1} = 0 \quad F_{u_{R'_1}} = 0 \quad F_{d_{R'_1}} = 0$$

$$F_{Q'_2} = 0 \quad F_{u_{R'_2}} = 0 \quad F_{d_{R'_2}} = 0$$

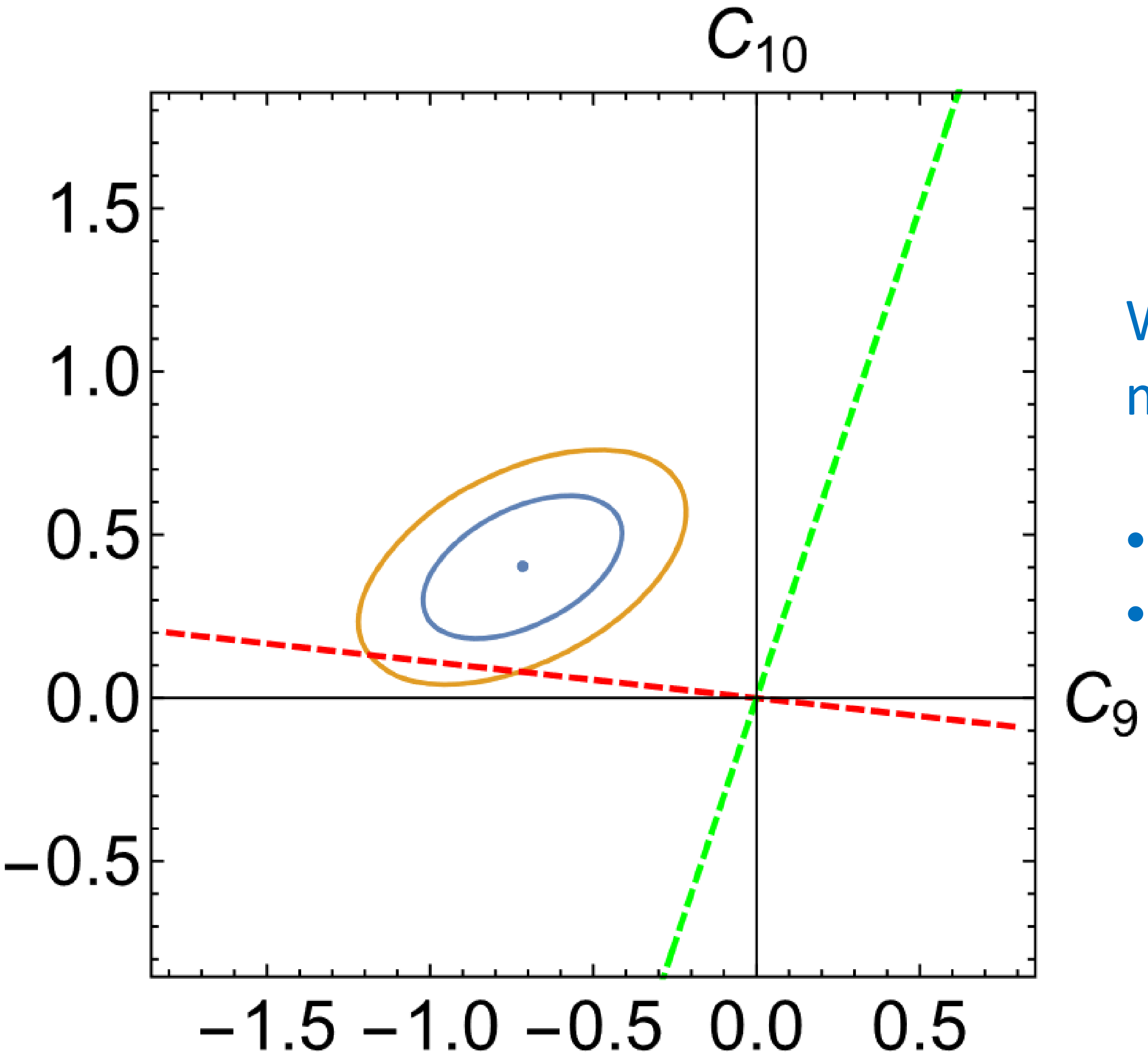
$$F_{Q'_3} = 1/6 \quad F_{u'_{R3}} = 2/3 \quad F_{d'_{R3}} = -1/3$$

$$F_{L'_1} = 0 \quad F_{e_{R'_1}} = 0 \quad F_H = -1/2$$

$$F_{L'_2} = 5/6 \quad F_{e_{R'_2}} = 2/3 \quad F_\theta$$

$$F_{L'_3} = -4/3 \quad F_{e'_{R3}} = -5/3$$

This model probes a novel combination of Wilson coefficients, $C_9 = -9C_{10}$



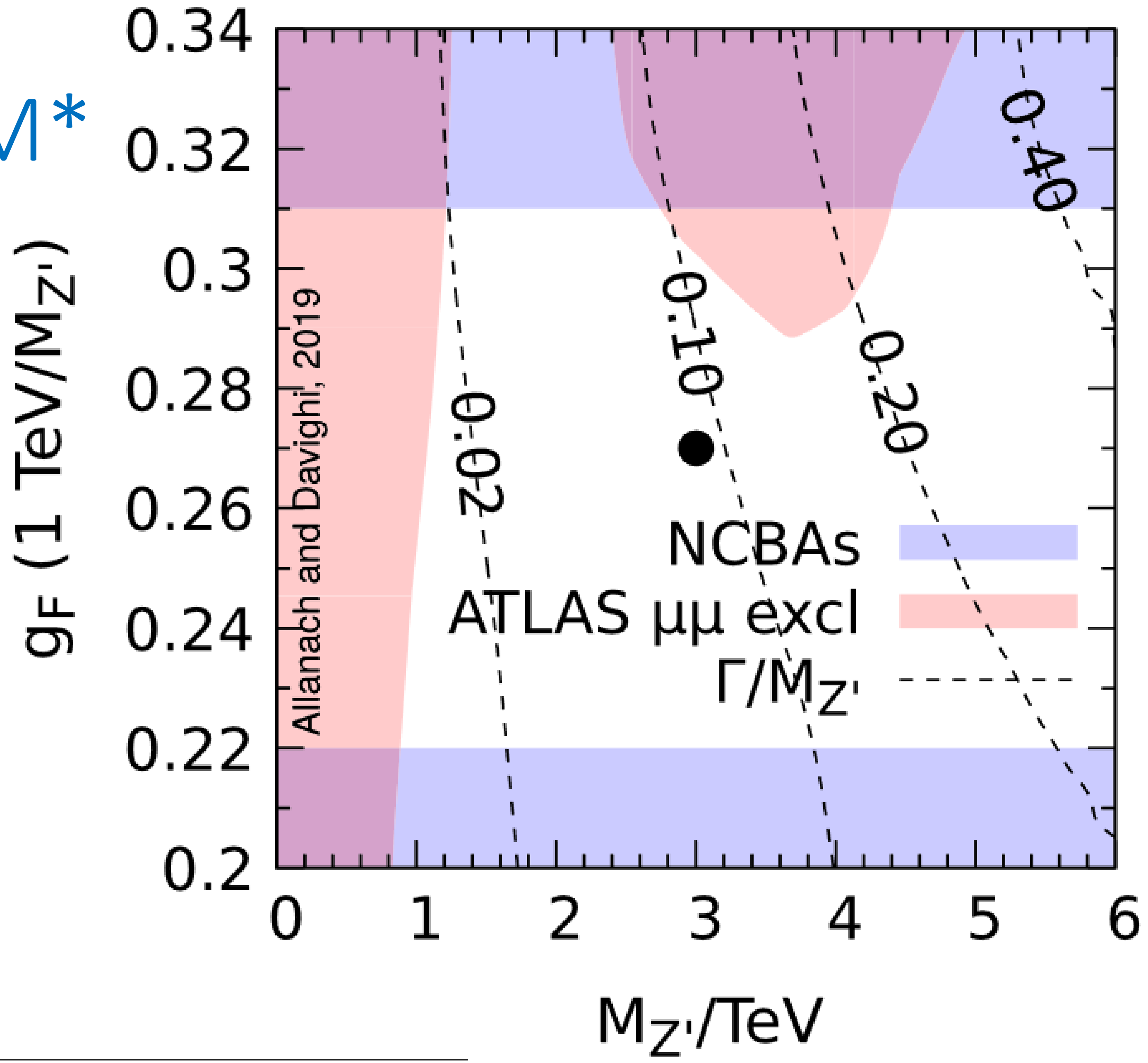
We find point on the red-line that minimizes χ^2 - pull of 5.9σ w.r.t. SM

- Worse fit than for LH coupling
- Better fit than for vector coupling

Constraints on DTFHM*

- Recast ATLAS direct search for $Z' \to \mu\mu$ (Run II 139 fb^{-1})
- Dominant production is $bb \to Z'$
- Constraints from B_s mixing and Z LFU much weaker than before (outside range of plot)

- Valid parameter space for $M_{Z'} > 0.8$ TeV



*Again this is a specific example case. For details see backup slides and arXiv:1905.10327

What to look for next

These simple *Z′* models make some generic predictions.

High p_T predictions

The *Z'* in both models decays mainly to third generation fermions

Z' 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

Low p_T predictions

Notable prediction is new physics in tau

e.g. BSM contributions to $BR(B \to K^{(*)}\tau^+\tau^-)$
[deficits in both models; RH for TFHM; almost vector-like for DTHFM]

so measurements of LFUV ratios involving τ are well-motivated

Conclusions

- Flavour anomalies might be linked to an explanation of fermion mass hierarchy
- Can explain with simple family-dependent Z' models, with charges fixed uniquely by anomaly cancellation
- Reasons to expect new physics associated with third family

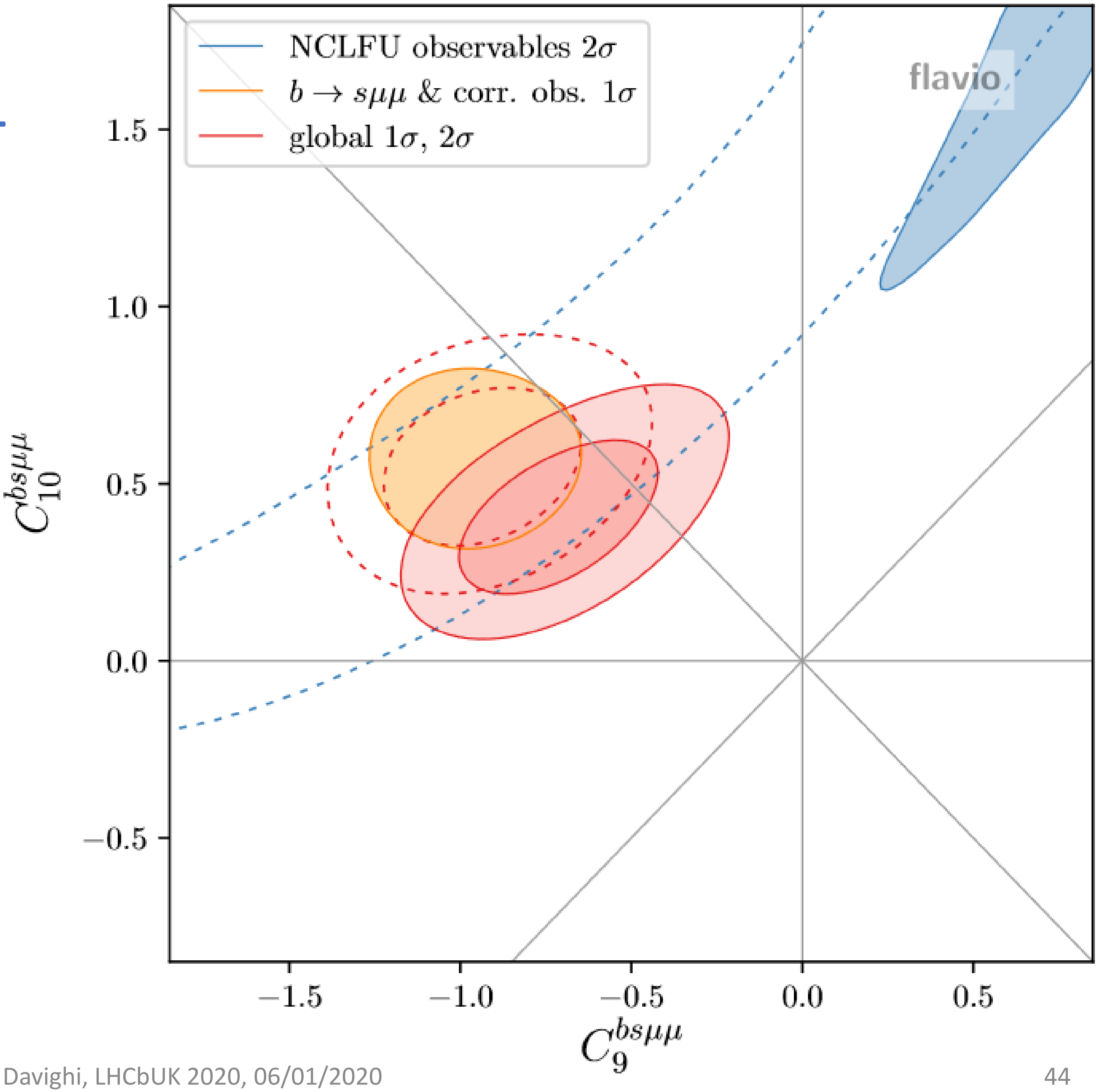
Backup

Global fit to SMEFT coefficients

- Recent global fits (post Moriond 2019) seemingly driven by $b \to s\mu\mu$, not LFUV ratios

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

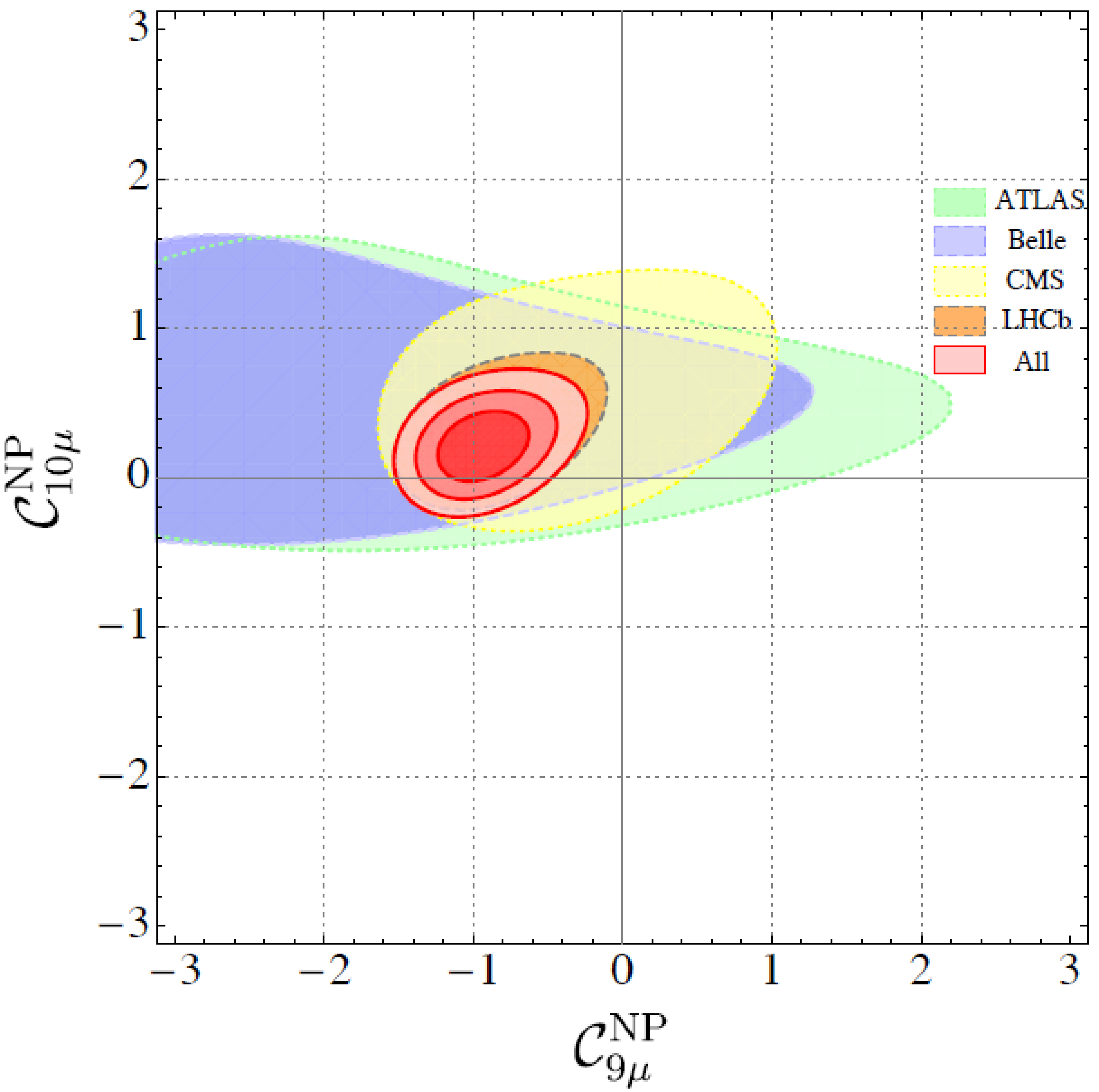
Aebischer, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub, 1903.10434

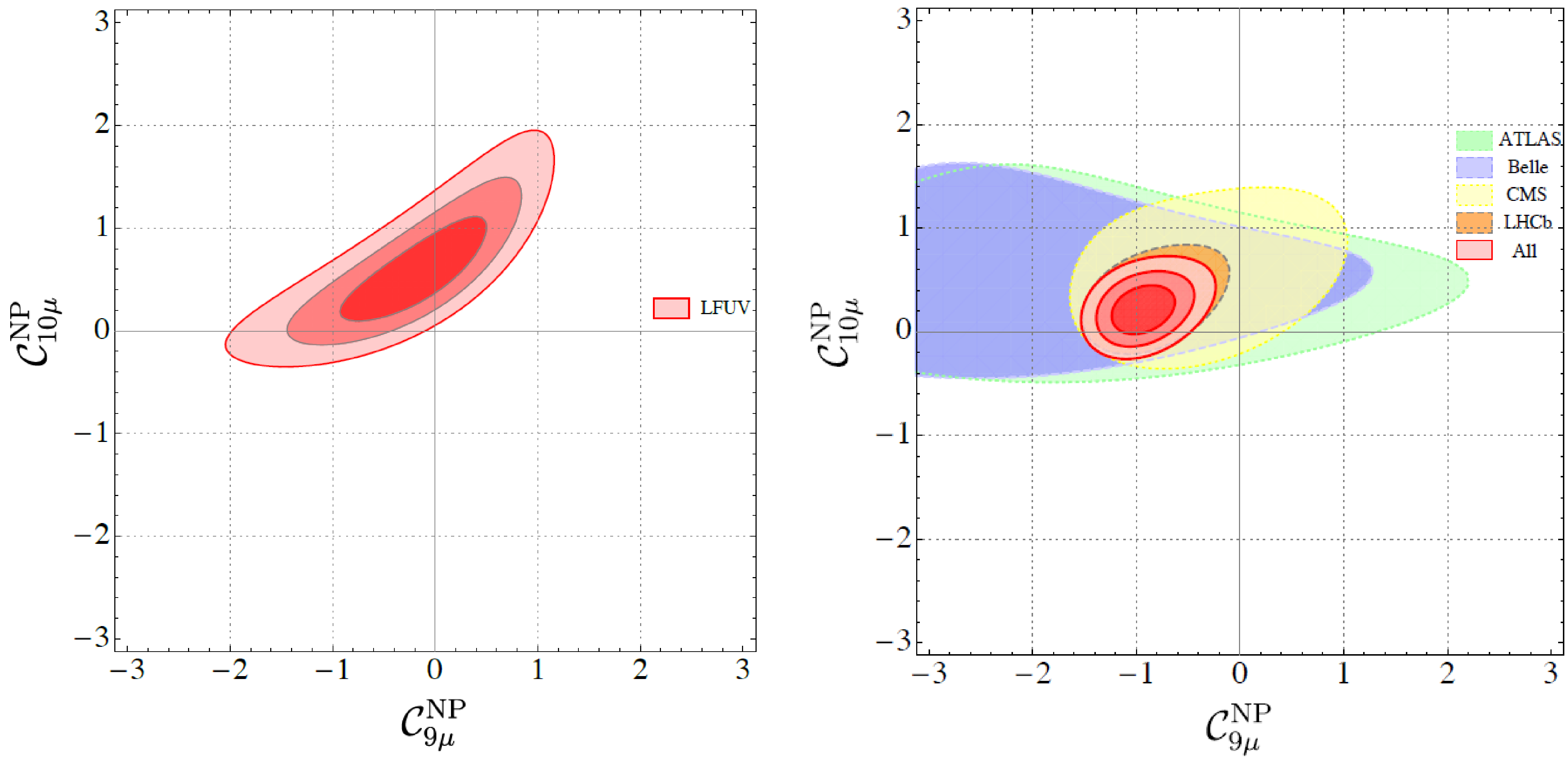


Global fit to SMEFT coefficients

- Similar best-fit ellipse (with $C_9 < 0$) from other global fitting methodologies
- LHCb measurements are driving the best fit region

Alguero, Capdevila, Crivellin, Descotes-Genon, Masjuan, Matias, Virto, arXiv:1903.09578



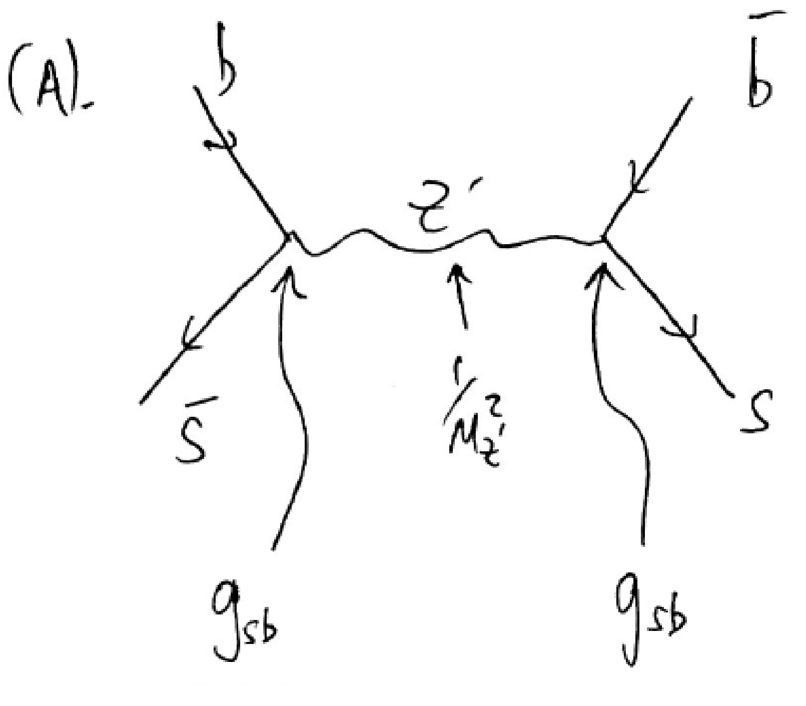


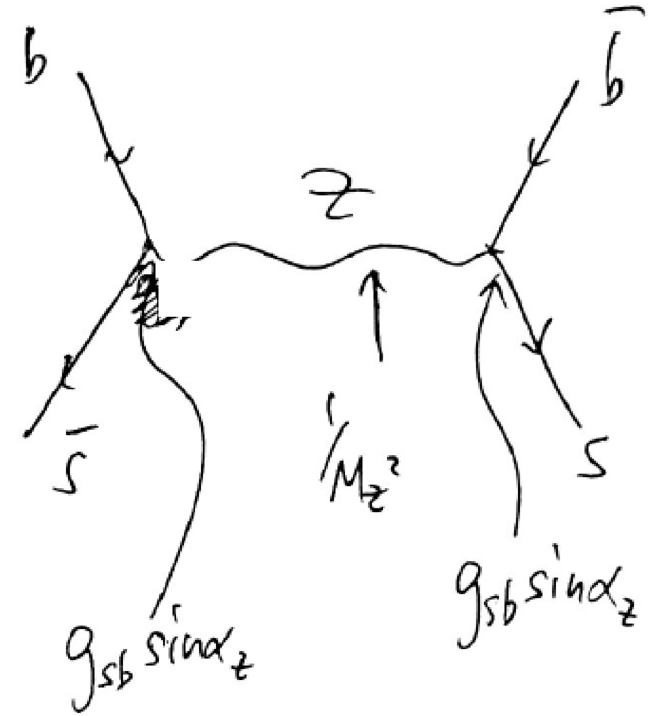
Note that LFUV observable fit has better overlap here than in fits of Straub et al.

Alguero, Capdevila, Crivellin, Descotes-Genon, Masjuan, Matias, Virto, arXiv:1903.09578

More on $B_s - \overline{B_s}$ mixing constraint

also a BSM contribution from *Z* boson exchange due to *Z*-*Z*′ mixing:





+

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

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

suppressed w.r.t. *Z*′ contribution

LFU of Z boson constraint

Z boson couples differently to muons and electrons due to *Z-Z'* mixing; need to be consistent with LEP measurement:

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

In TFHM:

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

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

Constraint from top decays

In TFHM example case we have couplings

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

$$\Lambda^{(u_L)}_{23} \approx V_{cb}V^*_{tb} + \tfrac{1}{2}\sin 2\theta_{sb} V_{cs} V^*_{tb} \qquad \Lambda^{(u_L)}_{13} \approx V_{ub}V^*_{tb} + \tfrac{1}{2}\sin 2\theta_{sb} V_{us} V^*_{tb}$$

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

$$\begin{aligned} BR(t\to Zc) &= \frac{g_F^2 \Lambda^{(u_L)2}_{23} f(M_Z, M_W, M_t)\sin^2\alpha_z}{18 g^2 |V_{tb}|^2} BR(t \to Wb) \\ &= 1.1\times 10^{-3} g_F^4 \left(\frac{M_Z}{M_{Z'}}\right)^4 \left(\frac{|V_{cb}V^*_{tb} + \frac{1}{2}\sin 2\theta_{sb} V_{cs}V^*_{tb}|^2}{0.0062}\right) \end{aligned}$$

→ v. weak constraint from current bounds

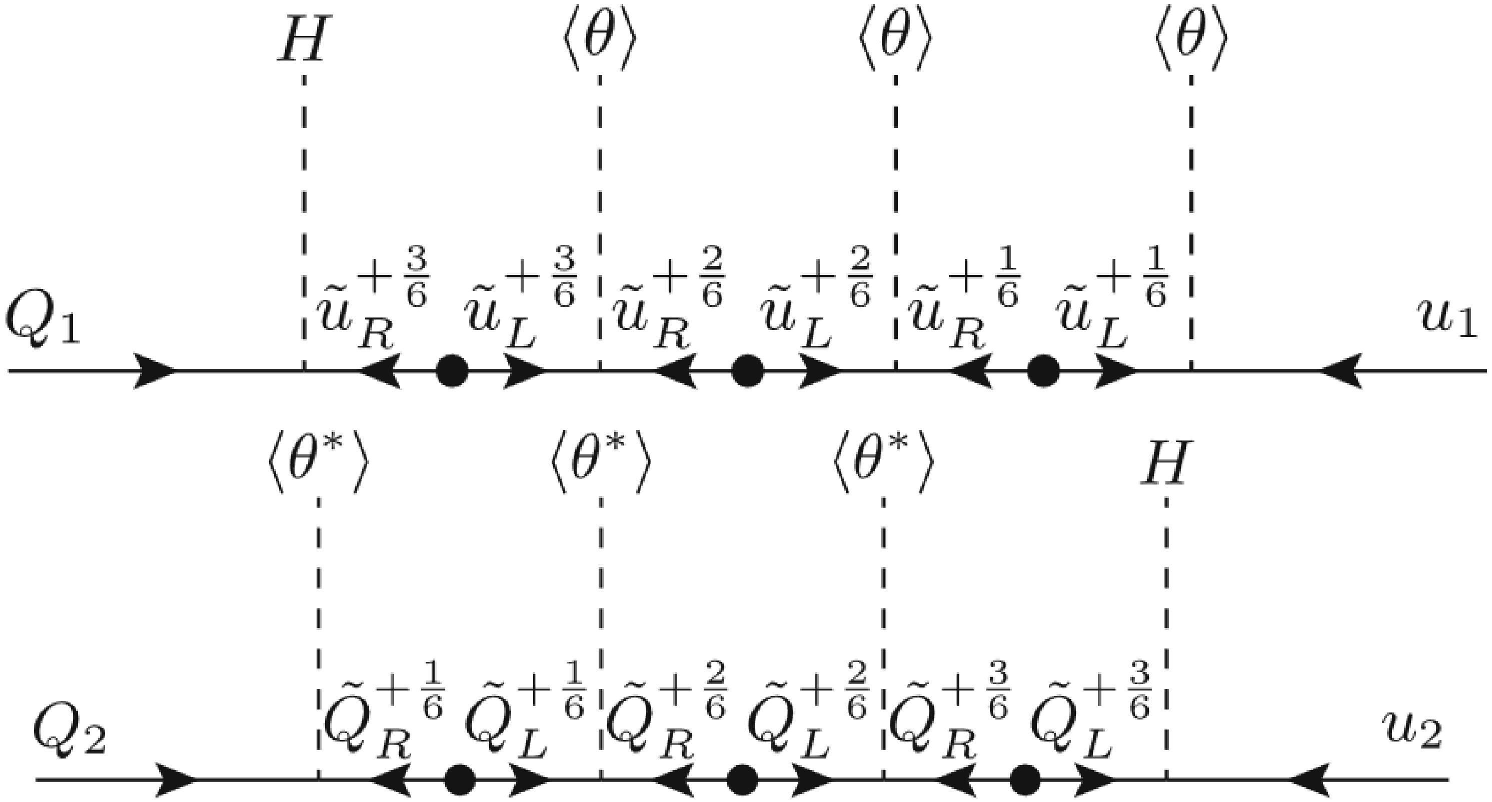
DTFHM: a simple example case

- Down-type quark mixing = CKM matrix
- Neutrino mixing = PMNS matrix (no need for charged lepton mixing)

<u>Other nice phenomenological features:</u>

  - Large lepton charges makes B_s mixing bound far weaker
  - Relative signs give big cancellations in LFUV of Z boson couplings

Light quark masses from a Froggatt-Nielsen-type mechanism



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

2. Off-diagonal Yukawas suppressed

Froggatt, Nielsen, NPB147 (1979) 277

B. Allanach, JD, arXiv:1905.10327