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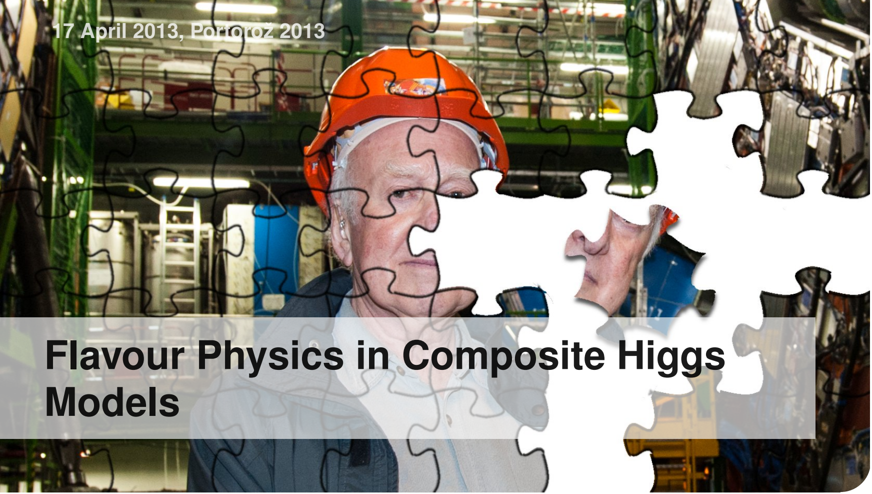

# Flavour Physics in Composite Higgs Models

**David M. Straub** | Johannes Gutenberg University Mainz

JG|U

# Outline

1. **Setup**: partial compositeness & EWPT
2. **Flavour**: anarchy vs. symmetry
3. Flavour-changing **Z couplings** and rare decays

# Composite Higgs & partial compositeness

Solving the hierarchy problem without SUSY: the **Higgs is composite**

- bound state of a new strong interaction which breaks EW symmetry

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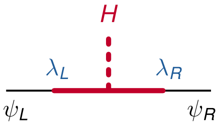
How to accomodate **fermion masses**?

- Composite fermions excluded by LEP ↯
- TC-like bilinear coupling $\lambda \psi_L \psi_R \mathcal{O}$ disfavoured by FCNC ↯
- **Linear coupling** $\lambda_L \bar{\psi}_L \mathcal{O}_R + \lambda_R \bar{\psi}_R \mathcal{O}_L$ ✓

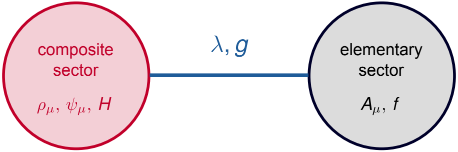



**Partial compositeness**

# The two-site picture

[Contino et al. hep-ph/0612180]

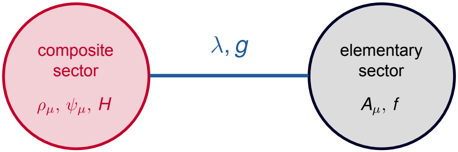
A simple 4D theory realizing the partial compositeness paradigm




$$\mathcal{L}_s = -\bar{Q}_L\, m_Q\, Q_R - \bar{U}_L\, m_U\, U_R - \bar{D}_L\, m_D\, D_R$$
$$+\bar{Q}_L \mathcal{H}\, Y_U\, U_R + \bar{Q}_L \mathcal{H}\, Y_D\, D_R + \text{h.c}$$
$$\mathcal{L}_{\text{mix}} = \lambda_L\, \bar{q}_L Q_R + \lambda_{Ru}\, \bar{U}_L u_R + \lambda_{Rd}\, \bar{D}_L d_R$$

$$q^{\text{phys}} = c_L\, q + s_L\, Q \qquad \frac{s_L}{c_L} = \frac{\lambda_L}{m_Q} \qquad m_{q^{\text{phys}}} = \frac{v}{\sqrt{2}} Y\, s_L\, s_R \qquad \text{etc.}$$

# Similarly for spin-1



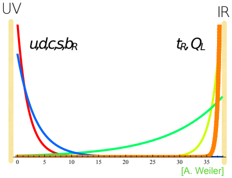

$$\mathcal{L}_{\text{el}} = -\frac{1}{4g^2} A_{\mu\nu} A^{\mu\nu}$$

$$\mathcal{L}_{\text{co}} = -\frac{1}{4g_\rho^2} \rho_{\mu\nu} \rho^{\mu\nu}$$

$$\mathcal{L}_{\text{mix}} = \frac{f^2}{2} (A_\mu - \rho_\mu)^2$$

# Relation to similar models

- AdS/CFT: 2-site model $\sim$ truncated KK theory of 5D model
  - RS with brane Higgs: degree of compositeness $\sim$ wavefunction overlap



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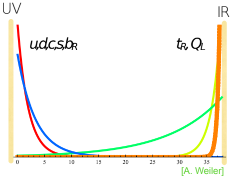
  - RS with brane Higgs: degree of compositeness ∼ wavefunction overlap

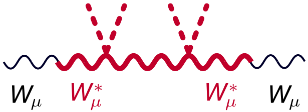



- PNGB Higgs (∼ 5D Gauge-Higgs unifcation)
  - additional structure in the Higgs sector

**Tree-level effects** in flavour physics are **well described** by the two-site Lagrangian in all cases

# Electroweak precision tests: $T$

Dangerous tree-level contributions to the ***T* parameter**

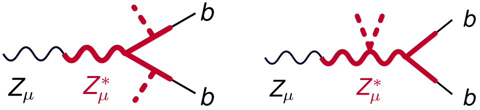



- The strong sector has to respect custodial symmetry

$$SU(2)_L \times SU(2)_R \times U(1)_X \qquad Y = T_{3R} + X$$

# Electroweak precision tests: $R_b$

Dangerous tree-level contributions to the $Z \longrightarrow b_L \bar{b}_L$ coupling




- Quark mixing has to respect a discrete $P_{LR}$ symmetry (restricts the choice of fermion representations)

[Agashe et al. hep-ph/0605341]

# Choices for composite fermion representations

$SU(2)_L \times SU(2)_R$ rep.s allowed by the requirement of cust. symm. & $P_{LR}$

| $Q_u$ | $Q_d$ | $U$ | $D$ | |
|---|---|---|---|---|
| $(2, \mathbf{2})$ | | $(1, \mathbf{3})$ | | triplet model, MCHM10 |
| $(2, \mathbf{2})$ | $(2, \mathbf{2})$ | $(1, \mathbf{1})$ | $(1, \mathbf{1})$ | bidoublet model, MCHM5, MCHM14 |

$$\lambda_{Lu}\, \bar{q}\, Q_u + \lambda_{Ld}\, \bar{q}\, Q_d + \lambda_{Ru}\, \bar{u}\, U + \lambda_{Rd}\, \bar{d}\, D$$

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| $(2,\mathbf{2})$ | | $(1,\mathbf{3})$ | | triplet model, MCHM10 |
| $(2,\mathbf{2})$ | | $(1,\mathbf{1})$ | $(1,\mathbf{3})$ | RS with custodial protection [Blanke et al.] |
| $(2,\mathbf{2})$ | $(2,\mathbf{2})$ | $(1,\mathbf{1})$ | $(1,\mathbf{1})$ | bidoublet model, MCHM5, MCHM14 |
| $\dots$ | $\dots$ | | | |

$$\lambda_{Lu}\,\bar{q}\,Q_u + \lambda_{Ld}\,\bar{q}\,Q_d + \lambda_{Ru}\,\bar{u}\,U + \lambda_{Rd}\,\bar{d}\,D$$

# Outline

1. **Setup**: partial compositeness & EWPT
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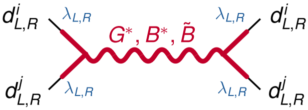
# Flavour anarchy

Assumption: the strong sector is flavour anarchic. Hierarchies in quark masses, mixings arise from hierarchical composite-elementary mixing




FCNCs protected by small degree of compositeness of light generations, e.g. LR operator

$$s_{Li}^2 s_{Rj}^2 \sim y_{di} y_{dj}$$

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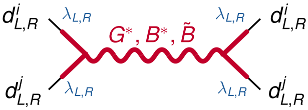



FCNCs protected by small degree of compositeness of light generations, e.g. LR operator

$$s^2_{Li} s^2_{Rj} \sim y_{di} y_{dj}$$

But not sufficient for $\epsilon_K$: $Y f > 14$ TeV

Some (approximate) flavour symmetry needed!

# $U(3)^3$ left-handed compositeness

[Cacciapaglia et al. 0709.1714, Redi and Weiler 1106.6357]

- the strong sector is flavour blind
- the right-handed composite-elementary mixings are the only spurions breaking $U(3)^3$

$$\mathcal{L}_{\text{mix}} = m_Q^i \lambda_L^{ij} \bar{q}_L^i Q_R^j + m_R^i \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + m_R^i \lambda_{Rd}^{ij} \bar{D}_L^i d_R^j$$

$$\lambda_L \propto \mathbb{1} \qquad \lambda_{Ru} \propto V_{\text{CKM}}^\dagger Y_u \qquad \lambda_{Rd} \propto Y_d$$

- Virtue: no tree-level FCNCs $\Rightarrow$ no flavour problem
- Problem: large contributions to EW precision observables from composite 1st/2nd gen. LH quarks

# $U(3)^3$ right-handed compositeness [Redi and Weiler 1106.6357]

- the right-handed composite-elementary mixings are the only spurions breaking $U(3)^3$

$$\mathcal{L}_{\text{mix}} = m_{Q_u} \lambda_{Lu}^{ij} \bar{q}_L^i Q_{Ru}^j + m_U \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + (U, u \to D, d)$$

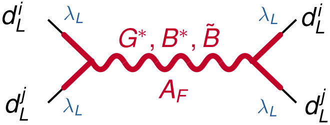
$$\lambda_{Lu} \propto V_{\text{CKM}}^\dagger Y_u \qquad \lambda_{Ld} \propto Y_d \qquad \lambda_{Ru,d} \propto \mathbb{1}$$

- tree-level FCNCs present, but MFV
- EWPT ok
- Potential problem: dijet constraints

# $U(3)^3_{\mathrm{RC}}$ FCNCs vs. dijets

[Barbieri et al. 1211.5085]

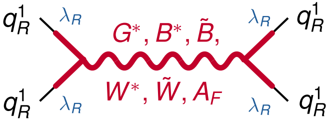
**$\Delta F = 2$ LL operator**




$\Rightarrow f\,Y \gtrsim 3.7$ TeV $x_t$

$(x_t \equiv s_{Lt}/s_{Rt})$

**1st gen. RR operator**




Modifies the angular distribution of $pp \to jj$ @LHC

$\Rightarrow f\,Y \gtrsim 3.0$ TeV $/\, x_t$

# $U(2)^3$

[Barbieri et al. 1203.4218, Barbieri et al. 1211.5085]

Separate the 3rd from the 1st/2nd generations:

- strong sector is invariant under $U(2)$ (3rd generation transforms as singlet)
- LH *or* RH comp.-el. mixings are the only spurions breaking $U(2)^3 = U(2)_q \times U(2)_u \times U(2)_d$

$$U(2)^3_{\text{LC(RC)}} : \lambda_{L(R)} \propto \begin{pmatrix} \epsilon & & \\ & \epsilon & \\ & & 1 \end{pmatrix}$$

- $U(3)^3$ problems (EW, dijets) cured!

# Outline

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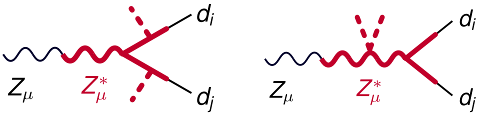
# Flavour-changing $Z$ couplings

Partial compositeness induces tree-level FC $Z$ couplings




$$\delta g^{ij}_{L,R} = \underbrace{\frac{v^2}{f^2}}_{\equiv \xi} \left[ a \underbrace{\left(\frac{Y f}{m_\psi}\right)^2}_{O(1)} + b \underbrace{\left(\frac{g_\rho f}{m_\rho}\right)^2}_{O(1)} \right] s^i_{L,R}\, s^j_{L,R}$$

$P_{LR}$ symmetry protecting $Z \to b\bar{b}$ also acts on FC couplings!

[Agashe et al. hep-ph/0605341, Blanke et al. 0812.3803]

# Pattern of flavour-changing *Z* couplings

- triplet model: $P_{LR}$ forbids $g_L^{ij}$
- bidoublet model: $P_C$ forbids $g_R^{ij}$
- $U(2)^3$ forbids $g_R^{ij}$

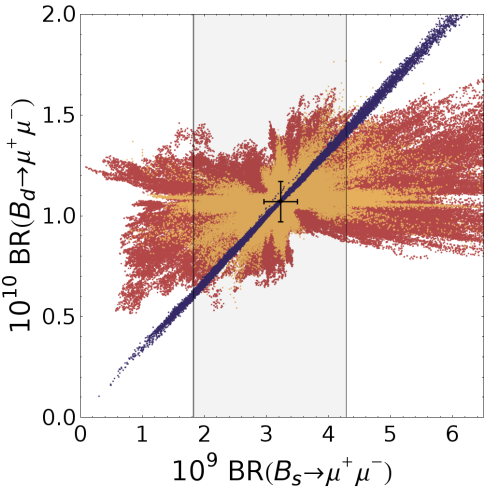
| | | $K$ | | $B_{d,s}$ | | $D$ | |
|---|---|---|---|---|---|---|---|
| | | $L$ | $R$ | $L$ | $R$ | $L$ | $R$ |
| Ⓐ | triplet | | $\mathbb{C}$ | | $\mathbb{C}$ | $\mathbb{C}$ | |
| | bidoublet | $\mathbb{C}$ | | $\mathbb{C}$ | | $\mathbb{C}$ | |
| $U(2)^3_{\mathrm{LC}}$ | triplet | | | | | $\mathbb{R}$ | |
| | bidoublet | $\mathbb{R}$ | | $\mathbb{C}$ | | $\mathbb{R}$ | |

# The $Z$ coupling precision era has begun!

| $s \to d$ | $b \to d$ | $b \to s$ |
|---|---|---|
| $K_L \to \mu^+\mu^-$ | $B_d \to \mu^+\mu^-$ | $B_s \to \mu^+\mu^-$ |
| $K \to \pi\ell\ell$ | $B \to \pi\mu^+\mu^-$ | $B \to K^*\mu^+\mu^-$ |
| | $\dots$ | $B \to K\mu^+\mu^-$ |
| $K^+ \to \pi^+\nu\bar{\nu}$ | | $B \to K\nu\bar{\nu}$ |
| $K_L \to \pi^0\nu\bar{\nu}$ | | $\dots$ |
| $\dots$ | | |

How large can the effects in rare $B$ and $K$ decays become in anarchy & $U(2)^3$?

# $B_s \to \mu\mu$ vs. $B_d \to \mu\mu$




triplet + anarchy

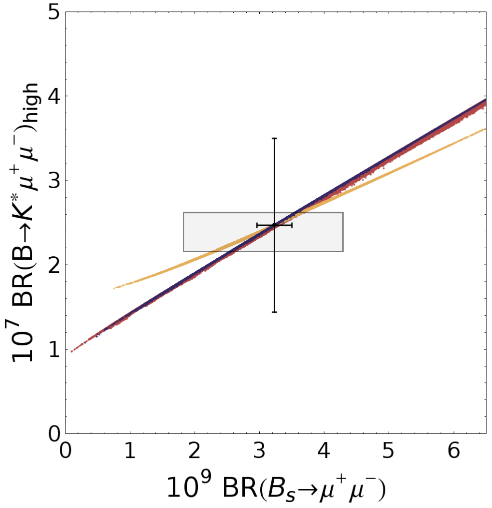
bidoublet + anarchy

bidoublet + $U(2)^3$

- LHCb **starts** to probe the models
- MFV-like $B_d \leftrightarrow B_s$ correlation in $U(2)^3$

[Straub 1302.4651]

# $B_s \to \mu\mu$ vs. $B \to K^*\mu\mu$




triplet + anarchy

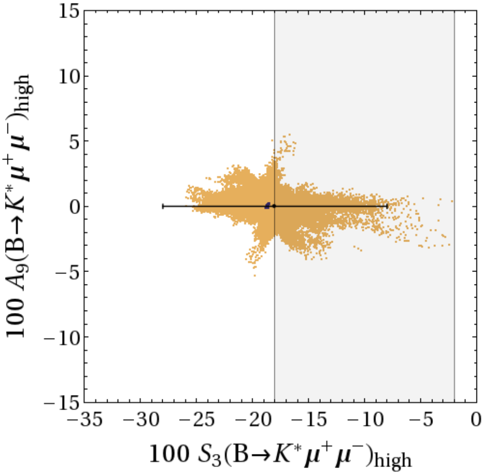
bidoublet + anarchy

bidoublet + $U(2)^3$

- Correlation due to protection of LH *or* RH coupling

[Straub 1302.4651]

# $B \to K^* \mu\mu$ angular observables

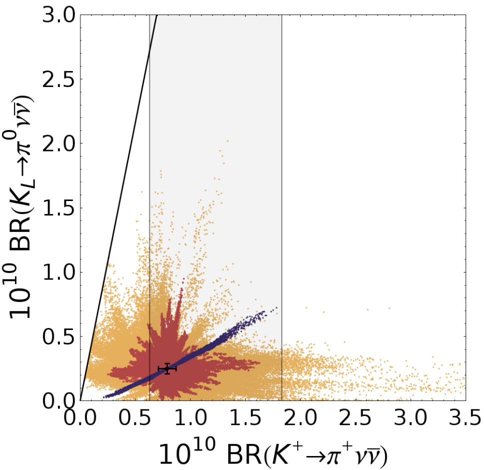



triplet + anarchy
bidoublet + anarchy
bidoublet + $U(2)^3$

- $S_3$, $A_9$ probe RH currents: effects only in triplet model
- only small effects

[Straub 1302.4651]

# $K^+ \to \pi^+ \nu\bar{\nu}$ vs. $K_L \to \pi^0 \nu\bar{\nu}$

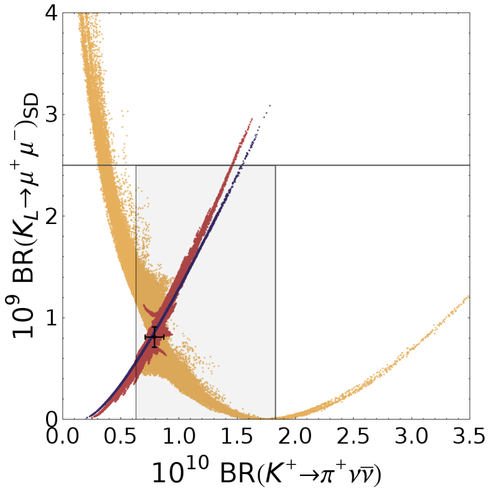



triplet + anarchy
bidoublet + anarchy
bidoublet + $U(2)^3$

- Visible effects in both modes
- $U(2)^3$: aligned in phase with the SM

[Straub 1302.4651]

# $K^+ \to \pi^+ \nu\bar{\nu}$ vs. $K_L \to \mu^+\mu^-$




triplet + anarchy

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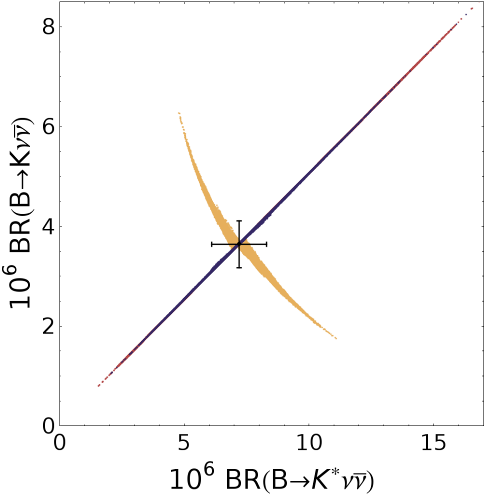
bidoublet + $U(2)^3$

- triplet: RH coupling
- bidoublet: LH coupling

[Straub 1302.4651]

cf. [Blanke et al. 0812.3803]

# $B \to K\nu\bar{\nu}$ vs. $B \to K^*\nu\bar{\nu}$




triplet + anarchy

bidoublet + anarchy

bidoublet + $U(2)^3$

- triplet: RH coupling
- bidoublet: LH coupling

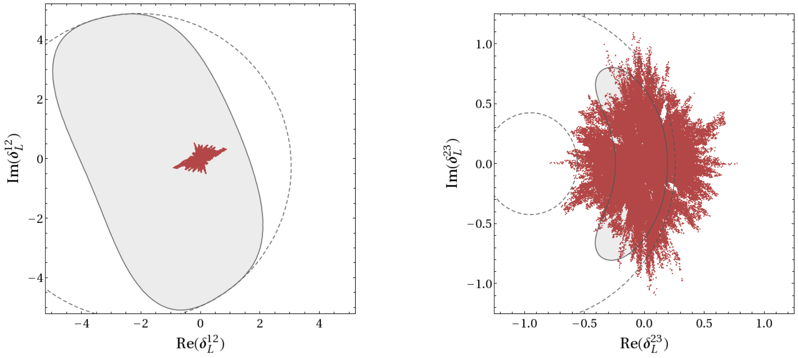
[Straub 1302.4651]

# Conclusions

1. CHM with partial compositeness are an attractive **alternative to SUSY**
2. They predict flavour-changing $Z$ couplings that can lead to **visible effects** in rare $B$ and $K$ decays like $B_{s,d} \to \mu\mu$, $K \to \pi\nu\bar{\nu}$, ...
3. Custodial protection (necessary due to EWPT) forbids LH **or** RH couplings $\Rightarrow$ characteristic pattern of effects in rare decays can **distentangle the models**
4. $U(2)^3$ flavour symmetry **solves** the $\epsilon_K$ problem and predicts correlations in rare decays

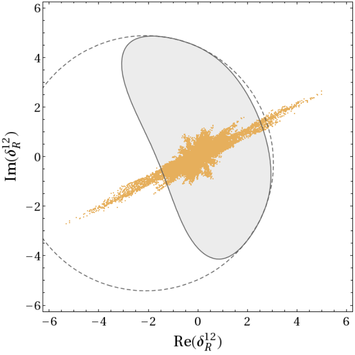
# Backup

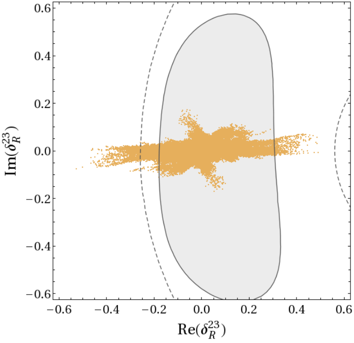
# Anarchic bidoublet model: $Z$ couplings




[Straub 1302.4651]

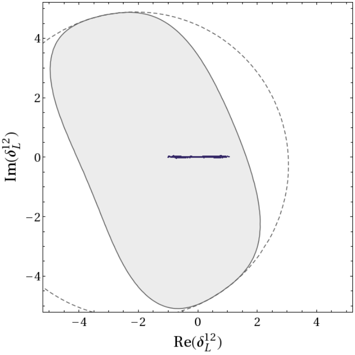
# Anarchic triplet model: *Z* couplings

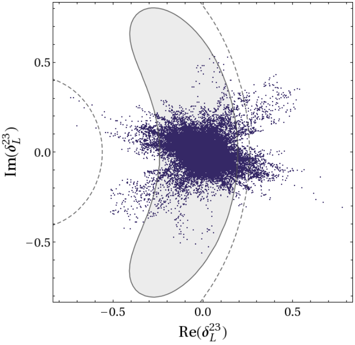



[Straub 1302.4651]

# $U(2)^3$ bidoublet model: $Z$ couplings




[Straub 1302.4651]

# Setup: the triplet model

| | $SU(3)_c$ | $SU(2)_L$ | $SU(2)_R$ | $U(1)_X$ |
|---|---|---|---|---|
| $L = (Q \;\; Q')$ | **3** | **2** | **2** | $\frac{2}{3}$ |
| $R = (X \;\; U \;\; D)^T$ | **3** | **1** | **3** | $\frac{2}{3}$ |
| $R'$ | **3** | **3** | **1** | $\frac{2}{3}$ |

$$\mathcal{L}_s^{\text{triplet}} = -\text{tr}[\bar{L}^i m_L^i L^i] - \text{tr}[\bar{R}^i m_R^i R^i] + \left( Y^{ij} \text{tr}[\bar{L}_L^i \mathcal{H} R_R^j] + \text{h.c} \right)$$

$$\mathcal{L}_{\text{mix}}^{\text{triplet}} = m_L^j \lambda_L^{ij} \bar{q}_L^i Q_R^j + m_R^i \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + m_R^i \lambda_{Rd}^{ij} \bar{D}_L^i d_R^j$$

# Setup: the bidoublet model

| | $SU(3)_c$ | $SU(2)_L$ | $SU(2)_R$ | $U(1)_X$ |
|---|---|---|---|---|
| $L_U = (Q_u \;\; Q'_u)$ | **3** | **2** | **2** | $\frac{2}{3}$ |
| $L_D = (Q'_d \;\; Q_d)$ | **3** | **2** | **2** | $-\frac{1}{3}$ |
| $U$ | **3** | **1** | **1** | $\frac{2}{3}$ |
| $D$ | **3** | **1** | **1** | $-\frac{1}{3}$ |

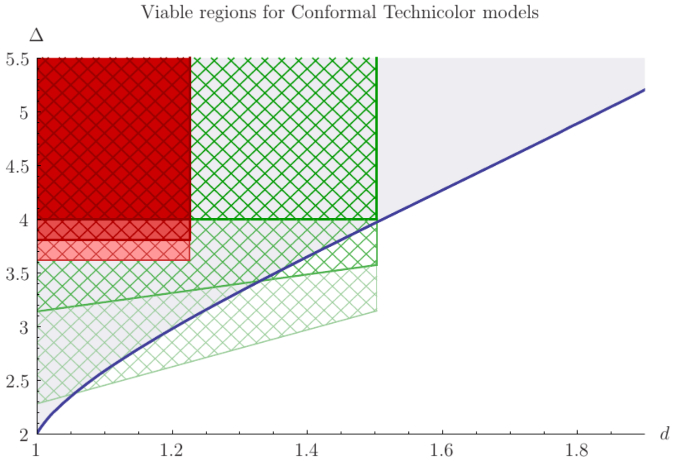
$$\mathcal{L}_s^{\text{bidoublet}} = -\text{tr}[\bar{L}_U^i m_{Q_u}^i L_U^i] - \bar{U}^i m_U^i U^i + \left( Y_U^{ij} \text{tr}[\bar{L}_U^i \mathcal{H}]_L U_R^j] + \text{h.c} \right)$$
$$+(U, u \to D, d)$$
$$\mathcal{L}_{\text{mix}}^{\text{bidoublet}} = m_{Q_u} \lambda_{Lu}^{ij} \bar{q}_L^i Q_{Ru}^j + m_U \lambda_{Ru}^{ij} \bar{U}_L^i u_R^j + (U, u \to D, d) \,,$$

# Anarchic $\Delta F = 2$ bounds

| | doublet | triplet | bidoublet |
|---|---|---|---|
| $\epsilon_K\ (Q_S^{LR})$ | 14 | 14 | 14 $z$ |
| $\epsilon_K\ (Q_V^{LL})$ | 2.7 $x_t$ | 3.9 $x_t$ | 3.9 $x_t$ |
| $B$-$\bar{B}$ | 2.3 $x_t$ | 3.4 $x_t$ | 3.4 $x_t$ |
| $B_s$-$\bar{B}_s$ | 2.3 $x_t$ | 3.4 $x_t$ | 3.4 $x_t$ |
| $D$-$\bar{D}\ (Q_S^{LR})$ | 0.5 | 0.5 | 0.5 |
| $D$-$\bar{D}\ (Q_V^{LL})$ | 0.4 $x_t$ | 0.6 $x_t$ | 0.6 $x_t$ |

using bounds in [Isidori et al. 1111.4987, Calibbi et al. 1204.1275]

# Technicolour vs. flavour




[Poland et al. 1109.5176]