Global view on flavour anomalies

Sebastian Jäger (University of Sussex)

Flavour physics & CP violation 2019

University of Victoria, 9 May 2019

Coverage

1) Flavour: anomalies
2) Accessing BSM through RGE
3) Flavour: non-anomalies
4) Implications for BSM models

Much more has been said on this in excellent dedicated presentations at this conference, to which I refer you.

Summary of (quark) flavour anomalies

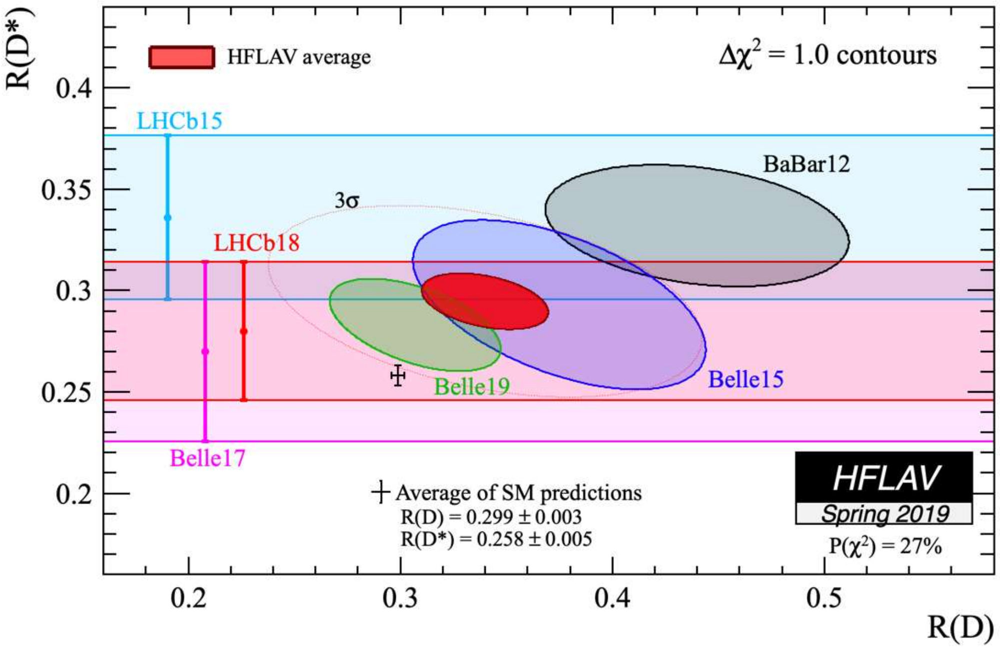
observable	Anomaly	Significance (sigma)
BR($B \to \{K,K^*,\phi\}\ \mu\mu$) at low dilepton mass q^2	Lowish w.r.t expectation	1-2 ?
$B \to K^*\mu\mu$ angular distribution (low q^2)	P_5' off for some q^2	2-3 ?
$R_{D(*)}$ = BR($B \to D(*)\tau\nu$)/ BR($B \to D(*)l\nu$)	Enhanced w.r.t. SM	3-4
Lepton-universality ratios (R_K, R_{K*})	Suppressed w.r.t. SM	3-4 (3 observables combined)
ε'/ε (direct CPV in $K_L \to \pi\pi$)	Below SM	3 ?

LHCb: rapidly increasing dataset

$R_{K(*)}$, $R_{D(*)}$: theoretical errors neglibible. Large statistics. Focus on these.

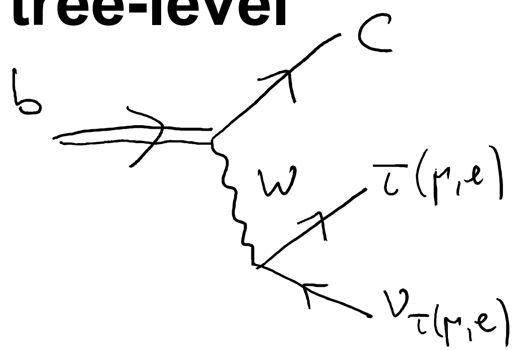
Non-rare semileptonic decays

see talks by D Robinson, D London, M Moscati (Wednesday)



$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\ell\nu_\ell)}$$

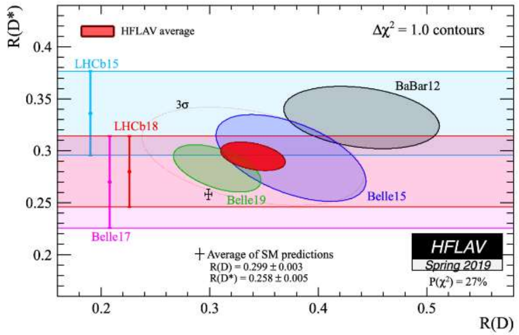
SM **tree-level**



large effect; theory error still (almost) negligible

How significant is this deviation?

HFLAV quote a 3.1σ discrepancy with SM



This is a statement that, within a model where (R_D, R_{D^*}) are free parameters, the SM values are excluded at 3.1σ.

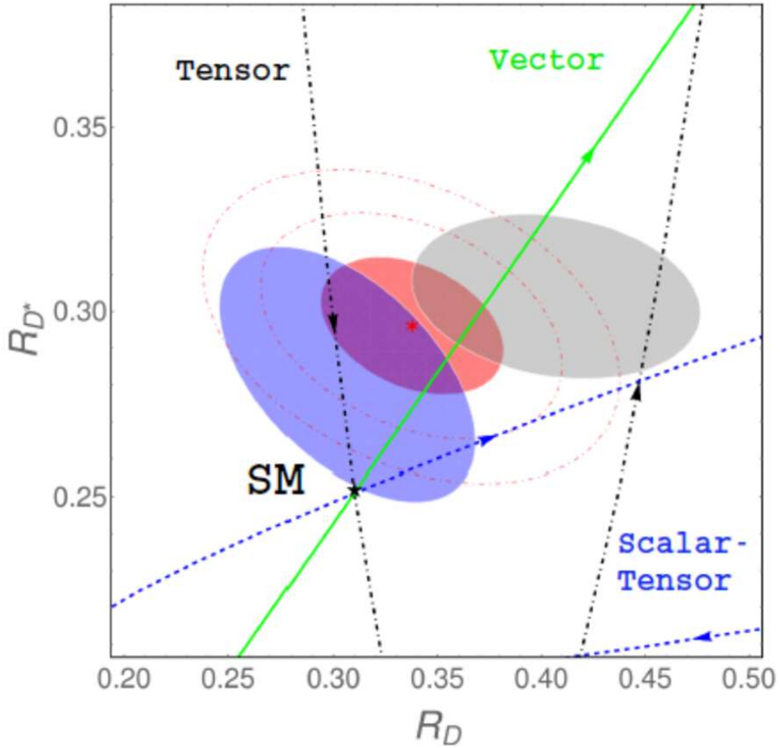
By contrast, evaluating the p-value of the SM (where R_D and R_{D^*} have definite values!) from χ^2_{min} would give an exclusion of the SM at about 4.4 σ (neglecting the small theory error), **slightly** down from 4.5 σ in 2018.

However, may be problematic because the measurements are not counting experiments (use same data to disentangle signal + background)

Possible BSM

ε_R^l flavour-universal by SU(2) x U(1) invariance (no dim-6 SMEFT operator)

$$\mathcal{L}_{\rm eff}^{\rm LE} \supset -\frac{4G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^\tau)(\bar\tau\gamma_\mu p_L\nu_\tau)(\bar c\gamma^\mu P_L b) + \epsilon_R^\tau(\bar\tau\gamma_\mu P_L\nu_\tau)(\bar c\gamma^\mu P_L b)$$
$$+\epsilon_{S_L}^\tau(\bar\tau P_L\nu_\tau)(\bar c P_L b) + \epsilon_{S_R}^\tau(\bar\tau P_L\nu_\tau)(\bar c P_R b) + \epsilon_T^\tau(\bar\tau\sigma_{\mu\nu}P_L\nu_\tau)(\bar c\sigma^{\mu\nu}P_L b)] + \text{H.c.},$$



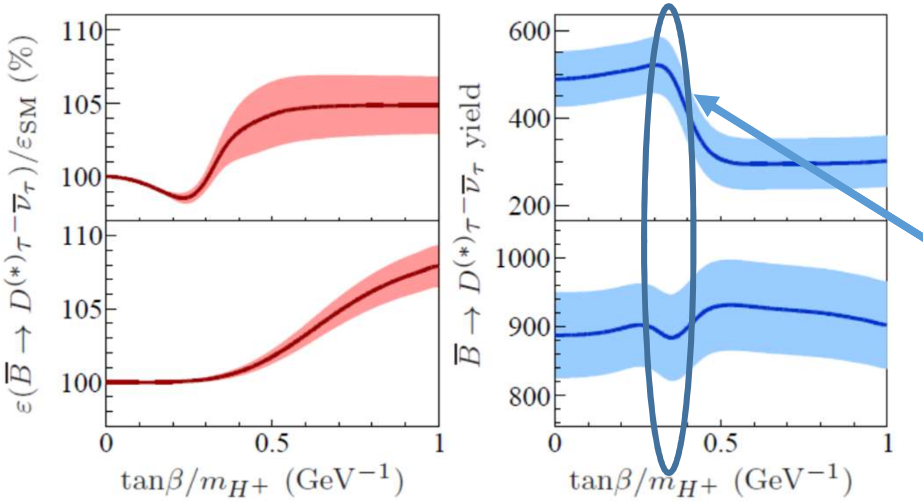
Best fit value moved **substantially** closer to SM with Belle 2019 update

Different BSM operators imply different correlations between shifts to RD, RD*

Caveat

$$\mathcal{L}_{\rm eff}^{\rm LE} \supset -\frac{4G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^\tau)(\bar\tau\gamma_\mu p_L\nu_\tau)(\bar c\gamma^\mu P_L b) + \epsilon_R^\tau(\bar\tau\gamma_\mu P_L\nu_\tau)(\bar c\gamma^\mu P_L b)$$
$$+\epsilon_{S_L}^\tau(\bar\tau P_L\nu_\tau)(\bar c P_L b) + \epsilon_{S_R}^\tau(\bar\tau P_L\nu_\tau)(\bar c P_R b) + \epsilon_T^\tau(\bar\tau\sigma_{\mu\nu}P_L\nu_\tau)(\bar c\sigma^{\mu\nu}P_L b)] + \text{H.c.},$$

BSM affects signal shape, hence fitted value of R_D, R_{D^*} through signal efficiencies and fitted background components



Babar 1303.0571
2HDMII (= ε_{SR}^τ model)

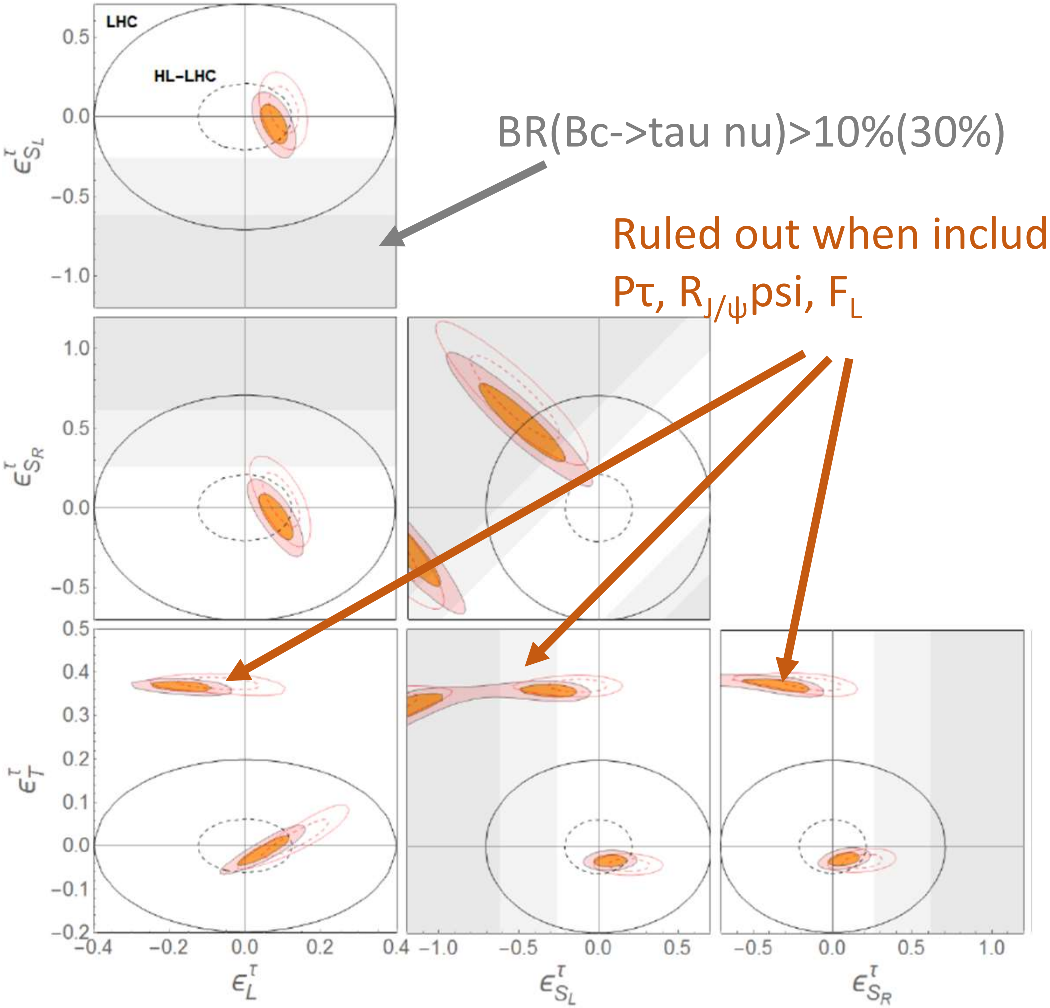
BSM starts to dominate
ε_{SR}^τ ~ 1 here !

For BSM << SM, the modifications are small.
Ultimately addressed through Wilson coefficient fits by the experiments (Hammer) **see talk by D Robinson (Wednesday)**

BSM Wilson coefficient fit results

Shi, Geng, Grinstein, SJ, Martin Camalich soon

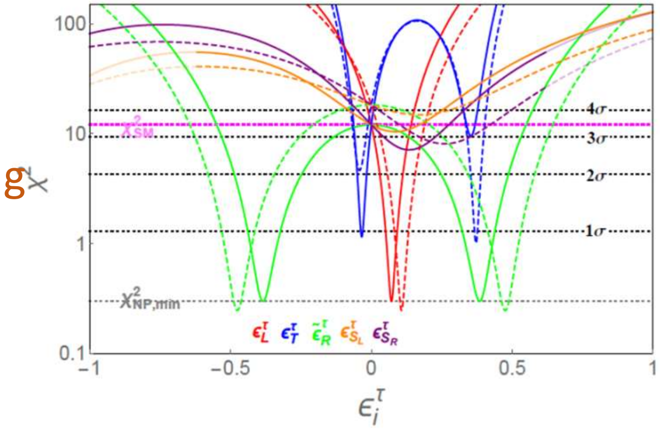
2 coefficient simultaneous fits



BR(Bc->tau nu)>10%(30%)

Ruled out when including
Pτ, $R_{J/\psi}$psi, F_L

1-coefficient fits



	Best fit	p-value	1σ range
ϵ^τ_L	0.07	0.58	(0.05, 0.09)
ϵ^τ_T	−0.03	0.28	(−0.04, −0.02)
$\epsilon^\tau_{S_L}$	0.09	1.23×10^{-3}	(0.02, 0.15)
$\epsilon^\tau_{S_R}$	0.13	7.54×10^{-3}	(0.07, 0.20)
$\tilde{\epsilon}^\tau_R$	0.38	0.58	(0.32, 0.44)
$\epsilon^\tau_{S_L} = -4\epsilon^\tau_T$	0.09	0.06	(0.06, 0.12)

Rare B-decay: observables

Branching ratios

leptonic (differential in dilepton mass)
$B_s \to \mu\mu$, $B_d \to \mu\mu$,

Nonperturbative QCD fully controlled (decay constant from lattice)

semileptonic (differential in dilepton mass)
$B \to K^{(*)}\mu\mu$, $B \to K^{(*)}ee$, $B_s \to \phi\mu\mu$

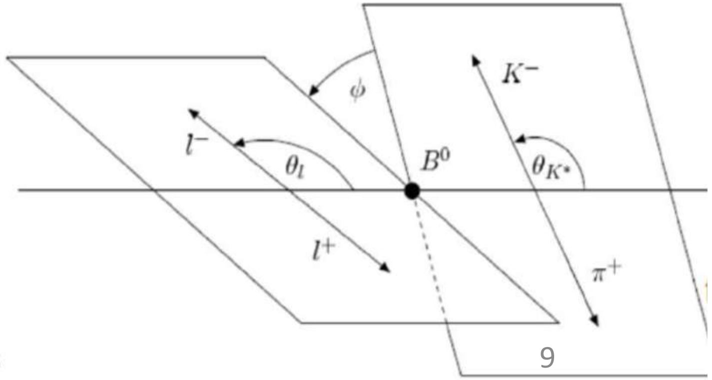
Lepton universality ratios

$$R_{K^{(*)}}[a,b] = \frac{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}\mu^+\mu^-)dq^2}{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}e^+e^-)dq^2}$$

Form factors, 4-quark operator contributions, QED radiation cancel out to ~% level (relative to LHCb treatment)

eg Bordone,Isidori,Pattori arXiv:1605.07633

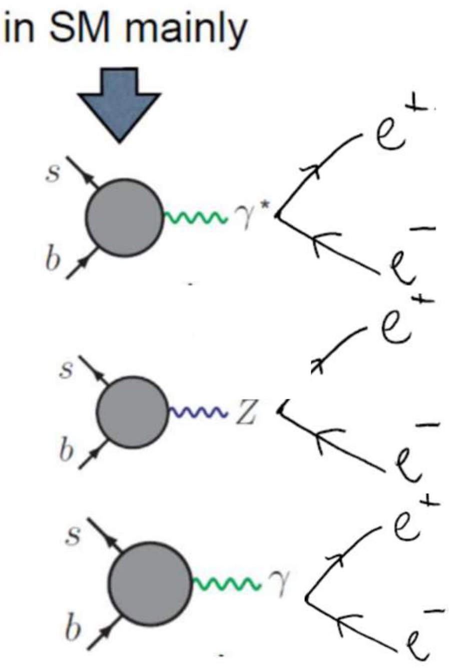
differential angular distribution for B->Vll
3 angles, dilepton mass q^2



7 angular differential observables:
(A_{FB}, P_5', etc)

Operators mediating rare B-decay

BSM (and SM weak interactions) enter flavour physics through effective contact interactions (SMEFT/H_{weak})



C_9: dilepton from vector current

$$(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$$

C_{10}: dilepton from axial current

$$(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma^5 l)$$

C_7: dilepton from dipole

$$(\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu}$$

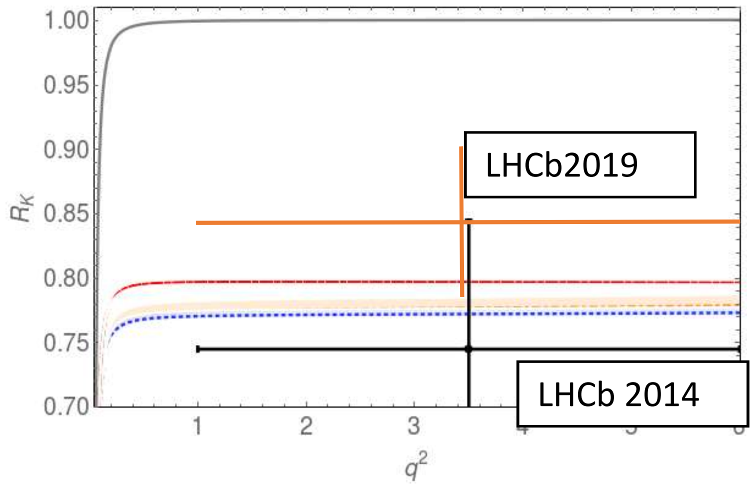
+parity conjugate "right-handed currents (suppressed in SM)
Alternative basis with chiral leptons l_L, l_R

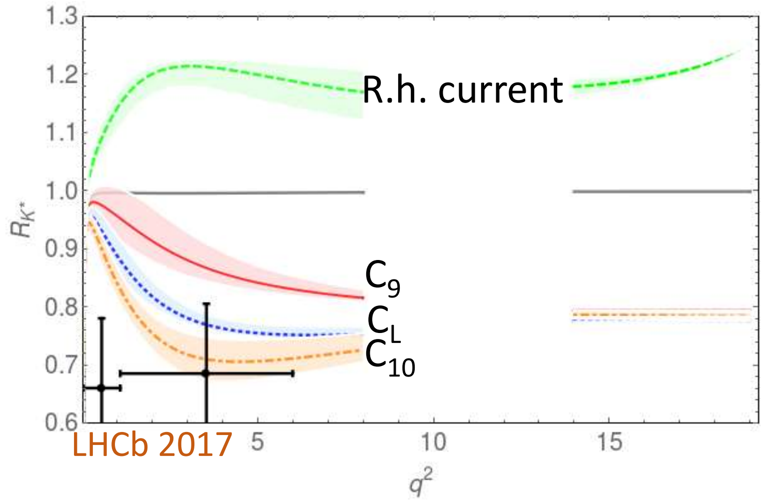
$C_L = (C_9 - C_{10})/2$ $\qquad$ $C_R = (C_9 + C_{10})/2$

Lepton-flavour ratios

$$R_{K^{(*)}}[a,b] = \frac{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}\mu^+\mu^-)dq^2}{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}e^+e^-)dq^2}$$

Fig. from Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446





Theory uncertainties negligible relative to experiment.
p(SM) ≈ 2 x 10^{-4} (3.7σ), slightly reduced with LHCb update

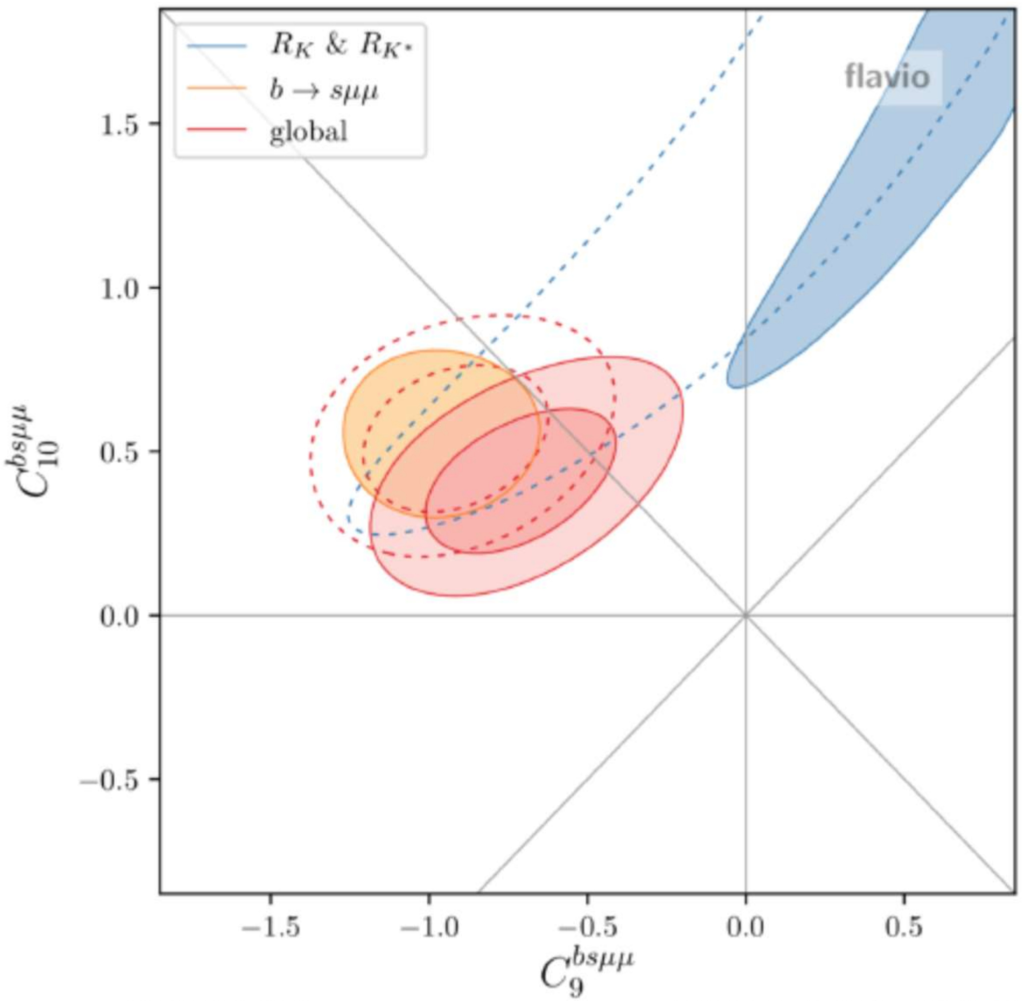
coloured lines: scenarios with NP in muonic operators

Slight indication for a C_{10}^{BSM} effect – as opposed to pure C_9

Global fit: FCNC B decays

see talks by R Alonso (Monday), D Kumar, J Kumar (Tuesday)

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



Assuming effect to be muon-specific:

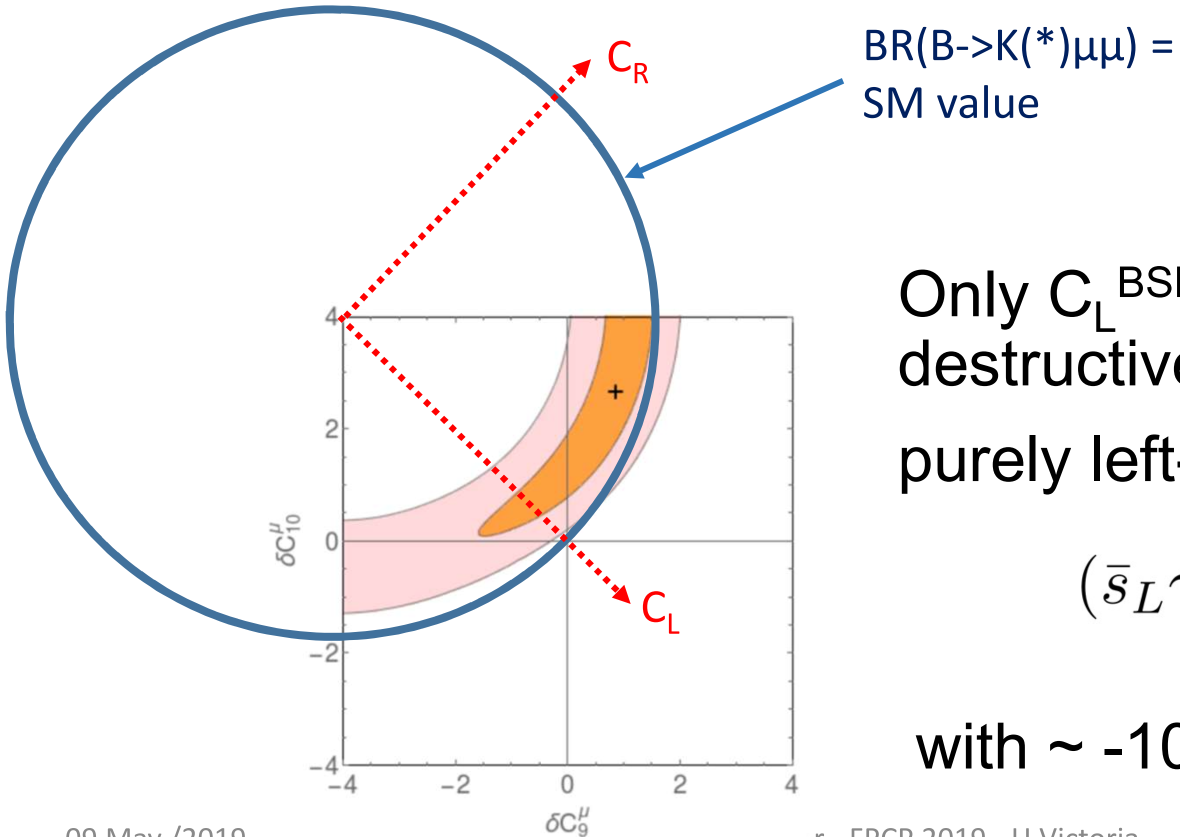
R_K and R_{K^*} on their own suggest a nonzero C_L value (displacement from SM along diagonal)

Including angular analysis data pins down both C_L and C_R (or C_9 and C_{10})

$R_K^{(*)}$ and C_L

Assume here that the BSM effect is in the muonic mode, and no right-handed currents.

Because in the SM, $|C_R|, |C_7| << |C_L|$,
$BR \approx$ const $|C_L^{SM} + C_L^{BSM}|^2 + \ldots \approx$ const $|4 + C_L^{BSM}|^2$ +positive



Only C_L^{BSM} can interfere destructively: $R_K^{(*)}$ point to purely left-handed coupling

$$(\bar{s}_L \gamma^\mu b_L)\,(\bar{\mu}_L \gamma_\mu \mu_L)$$

with ~ -10% of SM value

Flavour: the dogs that did not bark

From AC Doyle, “The Adventure of Silver Blaze” [with thanks to J Ellis]

Gregory (Scotland Yard detective): "Is there any other point to which you would wish to draw my attention?"
Holmes: "To the curious incident of the dog in the night-time."
Gregory: "The dog did nothing in the night-time."
Holmes: "That was the curious incident."

Quote and S Paget’s illustration via Wikipedia

Every child knows that science proceeds by falsification of hypotheses. Absence of an effect in a BSM-sensitive observable can be as important a clue as an anomaly.

Null results

Clean null tests of SM from (mainly) B → K*ɣ and B→ K*μμ

$$P_1 \equiv \frac{I_3 + \bar{I}_3}{2(I_{2s} + \bar{I}_{2s})} = \frac{-2\,\mathrm{Re}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} \approx 0$$

$$P_3^{CP} \equiv -\frac{I_9 - \bar{I}_9}{4(I_{2s} + \bar{I}_{2s})} = -\frac{\mathrm{Im}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} \approx 0$$

(Melikhov 1998)
Krueger, Matias 2002
Lunghi, Matias 2006
Becirevic, Schneider 2011
Becirevic, Kou, et al 2012
SJ, Martin Camalich 2012

Generated in the present of right-handed currents. No effect seen in data.
'Pseudo-observables:' Wilson coefficients from global fit

$$C'_{7\gamma} = 0.018 \pm 0.037$$ Aebischer et al arXiv:1903.10434

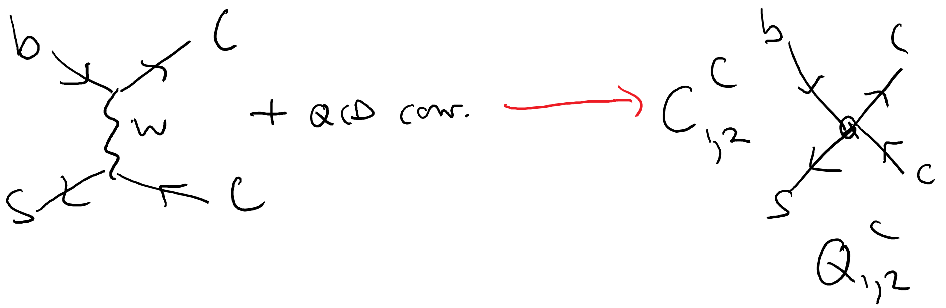
$$C'_{9V} = 0.09 \pm 0.15$$ Paul & Straub arXiv:1608.02556

ΔF=2: Neutral meson mixing also stringent constraints

Accessing BSM through RGE

Impact of 4-quark operator on rare decay

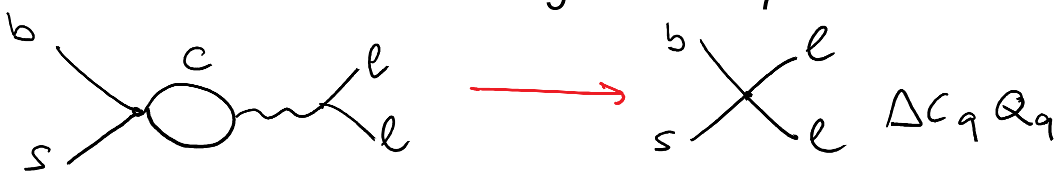
Also **purely hadronic** operators enter, in SM primarily:



$$Q_1^c = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i)$$

$$Q_2^c = (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j)$$

RG mixes these into C_9 and C_7



$$C_7^{\text{eff}}(4.6\text{GeV}) = 0.02\, C_1(M_W) - 0.19\, C_2(M_W)$$

$$C_9(4.6\text{GeV}) = 8.48\, C_1(M_W) + 1.96\, C_2(M_W)$$

SM: O(50%) of total in both cases!

At μ=m_b: C_7^{eff} ~ -0.3 , C_L ~ 4 , $C_R \approx 0$

SM contribution is accidentally almost purely left-chiral

Charming BSM scenario

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

As long as NP mass scale M is >(>) mb, most general BSM in $b \to c\bar{c}s$ **model-independently** captured by an effective Hamiltonian with 20 operators/Wilson coefficients (including SM)

$$
\begin{aligned}
Q_1^c &= (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i), & Q_2^c &= (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j), \\
Q_3^c &= (\bar{c}_R^i b_L^j)(\bar{s}_L^j c_R^i), & Q_4^c &= (\bar{c}_R^i b_L^i)(\bar{s}_L^j c_R^j), \\
Q_5^c &= (\bar{c}_R^i \gamma_\mu b_R^j)(\bar{s}_L^j \gamma^\mu c_L^i), & Q_6^c &= (\bar{c}_R^i \gamma_\mu b_R^i)(\bar{s}_L^j \gamma^\mu c_L^j), \\
Q_7^c &= (\bar{c}_L^i b_R^j)(\bar{s}_L^j c_R^i), & Q_8^c &= (\bar{c}_L^i b_R^i)(\bar{s}_L^j c_R^j), \\
Q_9^c &= (\bar{c}_L^i \sigma_{\mu\nu} b_R^j)(\bar{s}_L^j \sigma^{\mu\nu} c_R^i), & Q_{10}^c &= (\bar{c}_L^i \sigma_{\mu\nu} b_R^i)(\bar{s}_L^j \sigma^{\mu\nu} c_R^j),
\end{aligned}
$$

+ parity conjugates

RG evolution - numerical

SJ, Kirk, Lenz, Leslie arxiv:1701.09183 and to appear

Some elements first arise at two loops – still give important constraints.

$$
\begin{pmatrix} C_1(\mu_b) \\ C_2(\mu_b) \\ C_3(\mu_b) \\ C_4(\mu_b) \\ C_5(\mu_b) \\ C_6(\mu_b) \\ C_7(\mu_b) \\ C_8(\mu_b) \\ C_9(\mu_b) \\ C_{10}(\mu_b) \\ C_{7\gamma}^{\rm eff}(\mu_b) \\ C_{9V}(\mu_b) \end{pmatrix}
=
\begin{pmatrix}
1.1 & -0.27 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-0.27 & 1.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.92 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.33 & 1.9 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1.9 & 0.33 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.92 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1.0 & 0.05 & 2.70 & 1.70 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.37 & 2.0 & 2.30 & -0.55 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.07 & 0.07 & 1.80 & 0.04 \\
0 & 0 & 0 & 0 & 0 & 0 & 0.01 & -0.02 & -0.29 & 0.82 \\
0.02 & -0.19 & -0.015 & -0.13 & 0.56 & 0.17 & -1.0 & -0.47 & 4.00 & 0.70 \\
8.50 & 2.10 & -4.30 & -2.00 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix} C_1(M_W) \\ C_2(M_W) \\ C_3(M_W) \\ C_4(M_W) \\ C_5(M_W) \\ C_6(M_W) \\ C_7(M_W) \\ C_8(M_W) \\ C_9(M_W) \\ C_{10}(M_W) \\ C_{7\gamma}^{\rm eff}(M_W) \\ C_{9V}(M_W) \end{pmatrix}
$$

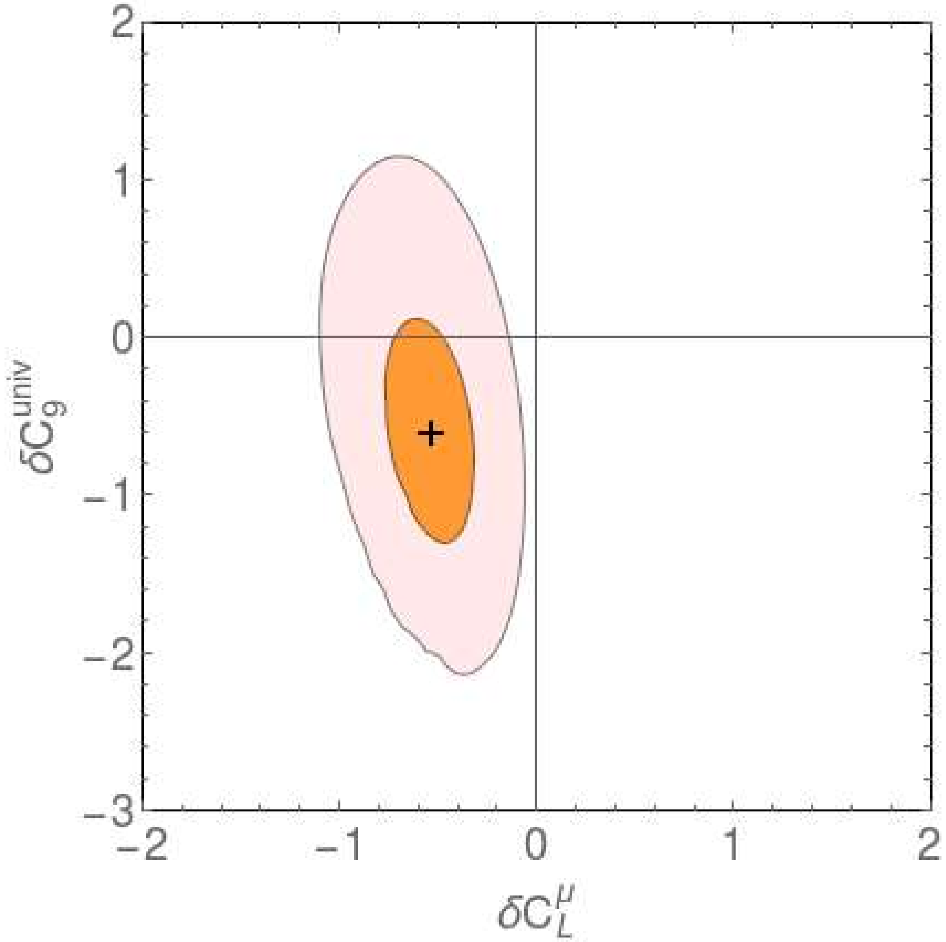
Enormous RG effects - can accommodate P_5'. **But lepton-universal**

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

RH(primed) 4-quark ops constrained by both C_7' and C_9'

Must C_9 violate lepton flavour?

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446



(also Alguero et al arXiv:1809.08447; post 2019 Moriond fits)

Modified C_{10} needed to suppress R_K* (both bins)

A model with (for example) nonzero $C_L{}^{\mu}$ and in addition an ordinary, **lepton-flavour-universal, C_9**, could describe the data as well or better

may be **radiatively generated**

$$(\bar{s}\gamma^{\mu} P_L b)(\bar{c}\gamma_{\mu} P_L c)$$

('charming BSM' scenario)

SJ, Kirk, Lenz, Leslie arXiv:1701.09183

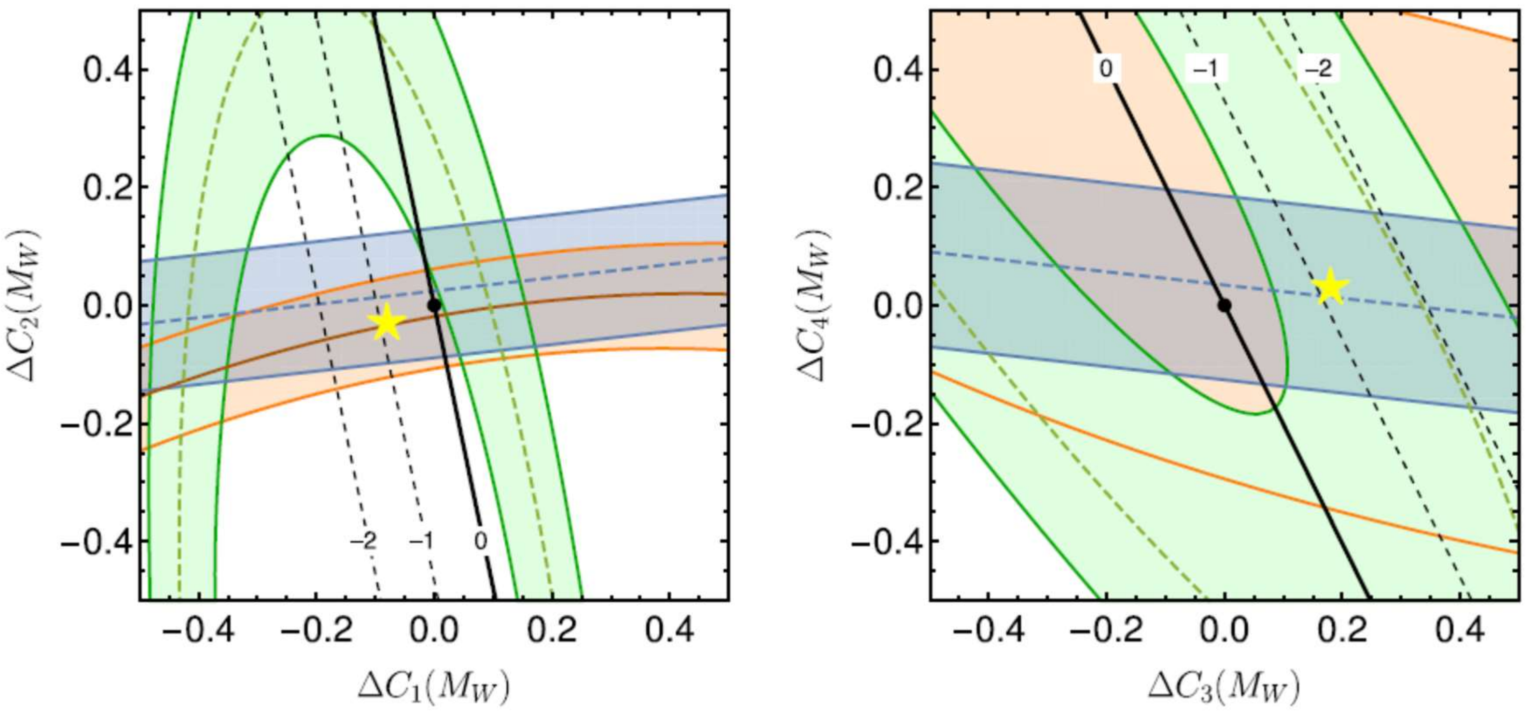
or $(\bar{s}\gamma^{\mu} P_L b)(\bar{\tau}\gamma_{\mu} P_L \tau)$

Bobeth & Haisch 1109.1826, Crivellin et al arXiv:1807.02068

Global analysis

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

'LH currents' – strong mixing into C_9



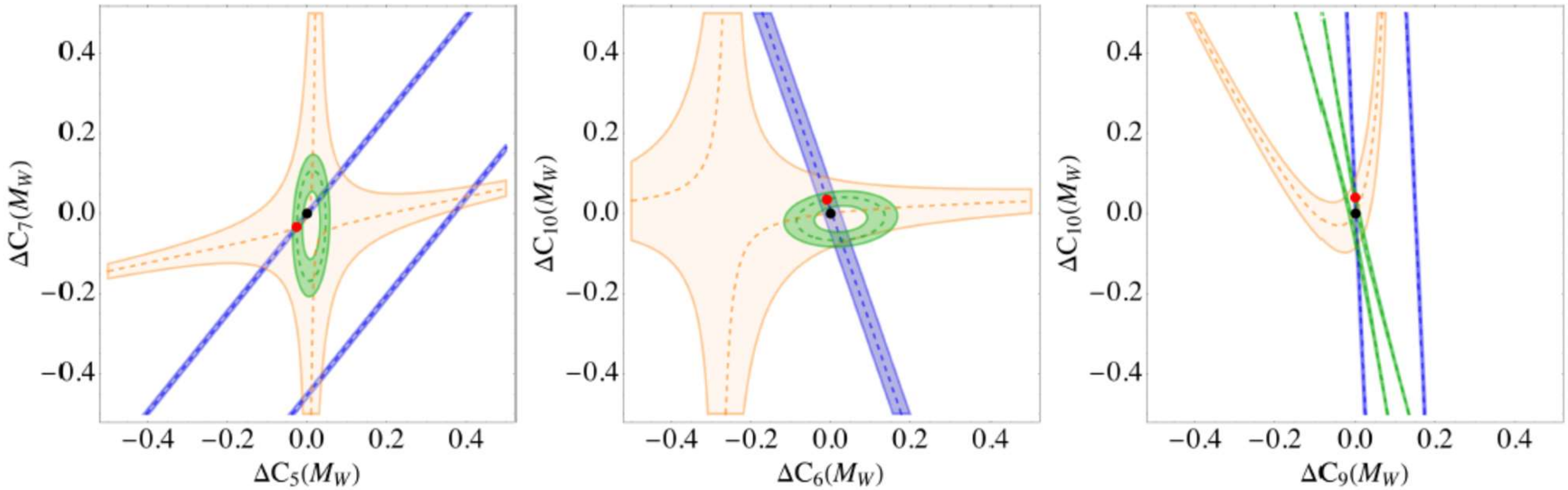
Blue – radiative decay, green – lifetime ratio, brown – lifetime difference

Dashed/solid black: C9(BSM)

Global analysis

SJ, Kirk, Lenz, Leslie   to appear

‘LH currents’ – strong mixing into dipole

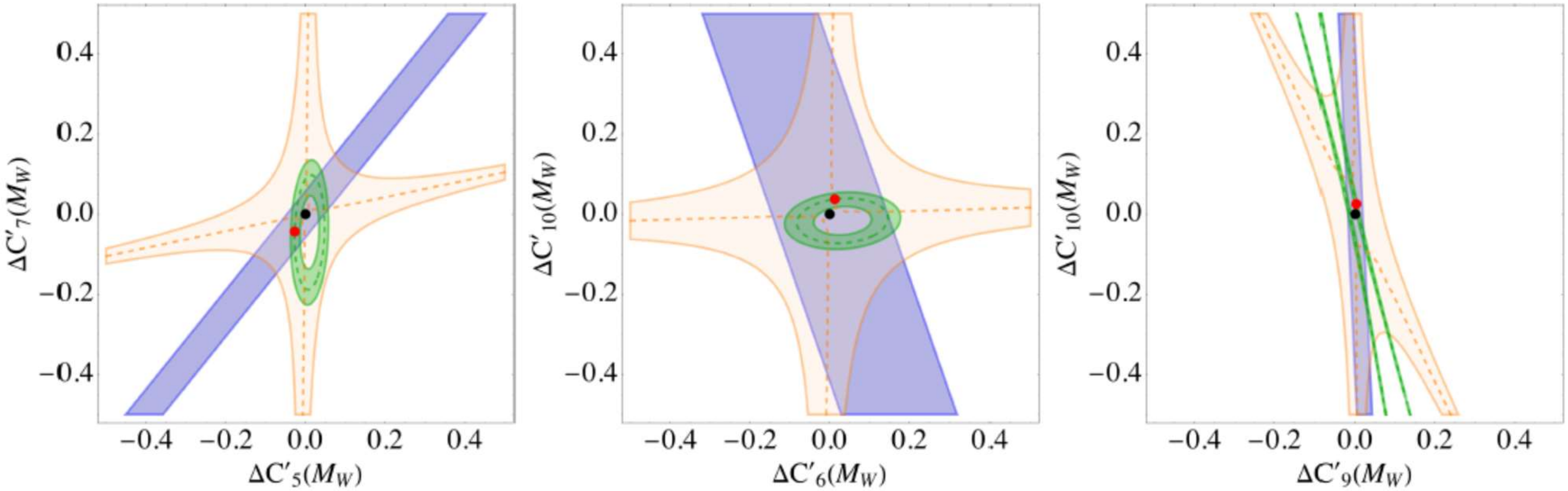


Blue – radiative decay, green – lifetime ratio, brown – lifetime difference

Global analysis

SJ, Kirk, Lenz, Leslie   to appear

‘RH currents’ – strong mixing into dipole



Blue – radiative decay, green – lifetime ratio, brown – lifetime difference

Lower bounds on NP scale

SJ, Kirk, Lenz, Leslie, to appear

Delta C<0

Delta C>0

Coeff.	$\Delta\chi^2 \leq 1$	Λ_-(TeV)	Λ_+(TeV)
ΔC_5	$[-0.01, 0.01]$	9.7	10.5
ΔC_6	$[-0.02, 0.02]$	5.6	5.8
ΔC_7	$[-0.01, 0.01]$	8.8	9.7
ΔC_8	$[-0.02, 0.02]$	6.2	6.9
ΔC_9	$[-0.001, 0.005]$	22.3	12.6
ΔC_{10}	$[0.01, 0.05]$	-	3.8
$\Delta C'_1$	$[-0.01, 0.02]$	11.9	5.5
$\Delta C'_2$	$[-0.04, 0.09]$	4.5	2.8
$\Delta C'_3$	$[-0.04, 0.02]$	4.5	7.0
$\Delta C'_4$	$[-0.07, 0.03]$	3.2	5.1
$\Delta C'_5$	$[-0.02, 0.03]$	5.9	4.8
$\Delta C'_6$	$[-0.07, 0.10]$	3.3	2.8
$\Delta C'_7$	$[-0.03, 0.02]$	5.2	6.6
$\Delta C'_8$	$[-0.05, 0.04]$	3.7	4.3
$\Delta C'_9$	$[0.002, 0.010]$	-	8.6
$\Delta C'_{10}$	$[-0.08, -0.06], [0.02, 0.05]$	7.1	3.5

C_9 from BSM $(\bar{s}b)(\bar{\tau}\tau)$ operators

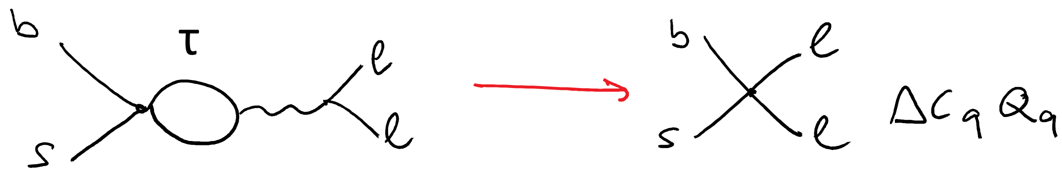
Bobeth, Haisch arXiv:1109.1826
Crivellin et al arXiv:1807.02068

Similarly strong RG mixing into C_9 as in charming BSM case

- This operator is automatically present for "left-handed" $R_{D(*)}$ explanations via $(\bar{c}_L \gamma^\mu b_L)(\bar{\nu}_\tau \gamma_\mu \tau_L)$

  This is a consequence of $SU(2)_W$ symmetry and the experimental bound on $B \to K^*\nu\nu$ Buras et al arXiv:1409.4557

- Radiatively generated C_9 is again O(1) and negative (and lepton-universal)



BSM implications

$SU(2)_W$ & model-independent constraints

Two purely left-handed SU(2) invariants once doublet structure of fermions considered (for each choice of generation indices)

$$O_S = (\bar{L}\gamma_\mu \bar{L})(\bar{Q}\gamma^\mu Q) \qquad O_T = (\bar{L}\gamma_\mu \sigma^I \bar{L})(\bar{Q}\gamma^\mu \sigma^I Q)$$

Both operators contribute to further processes that are experimentally constrained, in particular:

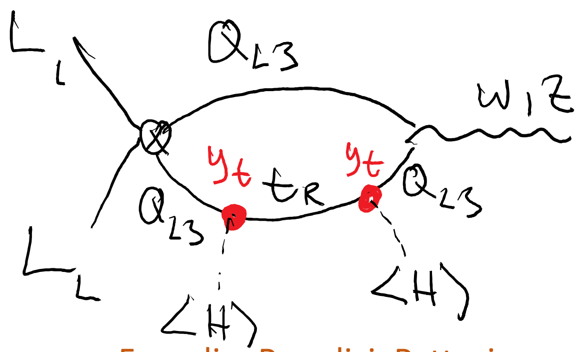
$B \to K^* \nu\nu \quad \to \quad C_{T,3323} \approx C_{S,3323}$

at one loop:

$Z \to \tau\tau$, $Z \to \nu\nu$

$\tau \to Z^*\mu$, $W^*\nu$ ($\to$ 3 leptons)

Problematic for very low Λ



Feruglio, Paradisi, Pattori
arXiv:1606.00524, arXiv:1705.00929

Tree-level mediators: leptoquarks

Scalar or vector leptoquarks can generate interactions

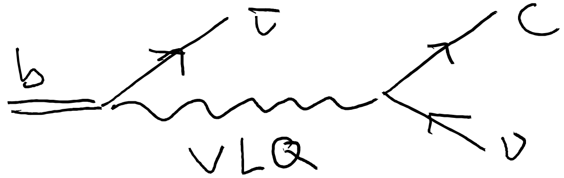
Eg Gripaios, Nardecchia, Renner, …
(Hiller, Nisandzic 2017)

$$\frac{1}{\Lambda^2}\,(\bar{c}_L \gamma^\mu b_L)\,(\bar{\nu}_\tau \gamma_\mu \tau_L)$$

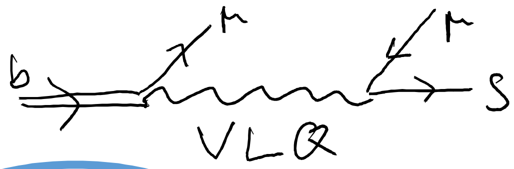
$$\frac{1}{\Lambda^2}\,(\bar{s}_L \gamma^\mu b_L)\,(\bar{\mu}_L \gamma_\mu \mu_L)$$

$(3,1,-1/3)$ or $(3,3,2/3)$

$(3,3,-1/3)$



$(3,1,2/3)$ or $(3,3,2/3)$

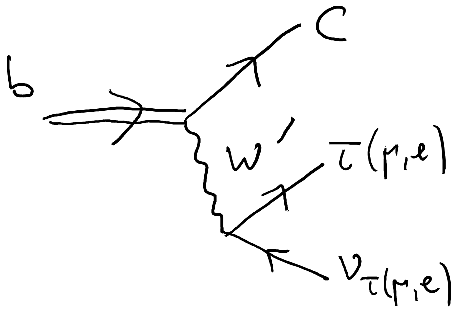


$(3,1,2/3)$ or $(3,3,2/3)$

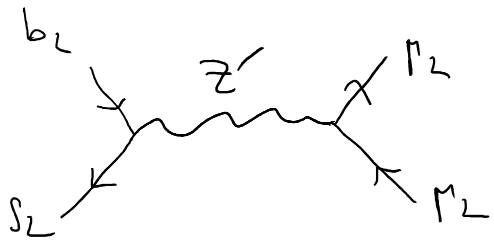
(more possibilities at loop level Eg Bauer,Neubert; Becirevic et al)

Tree-level mediators: W', Z'

$$\frac{1}{\Lambda^2}\left(\bar{c}_L\gamma^\mu b_L\right)\left(\bar{\nu}_\tau\gamma_\mu\tau_L\right) \qquad \frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\mu}_L\gamma_\mu\mu_L\right)$$



$(0,3,0)$



$(0,3,0)$ or $(0,1,0)$

- appear as resonances in composite models (KK excitations in RS, vectors coupling to symmetry currents in 4D composite models)

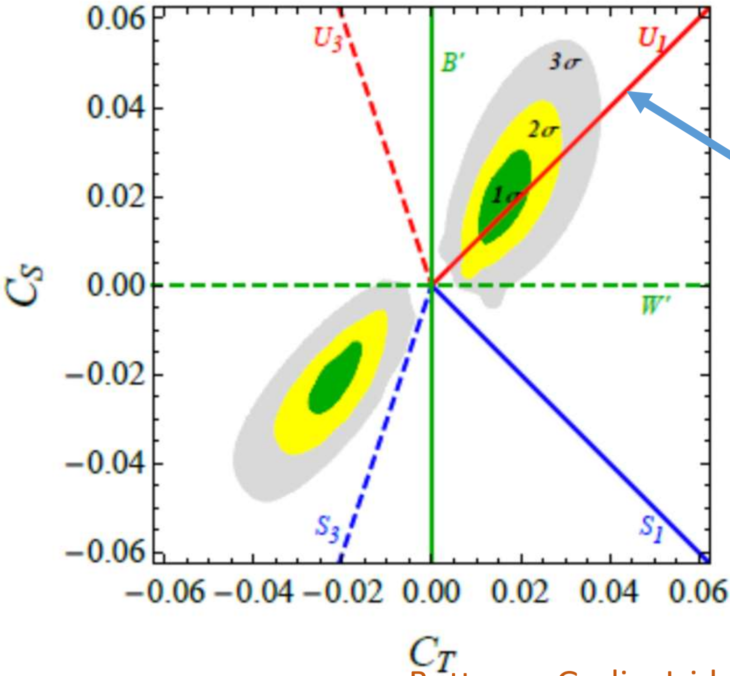
- Z' exchange contributes to B_s mixing at tree-level. Leptoquarks do not!

Isidori et al, Quiros et al, Ligeti et al, Becirevic et al, Crivellin et al, …

Global fit & single mediators

- Global fit to anomalies, previously mentioned constraints, and the coefficients of the two purely left-handed operators
- Compare to pattern predicted by a single mediator

(Axis scales depend on flavour structure of mediator couplings, fitted simultaneously.)



$(3, 1, 2/3)$

vector leptoquark

Buttazzo, Greljo, Isidori, Marzoca arXiv:1706.07808

Partial compositeness

SM fermions are mixtures of elementary and composite particles, eg

$$|t_L^{\rm phys}\rangle \approx \cos\phi_{t_L}|t_L\rangle + \sin\phi_{t_L}|T_L\rangle$$

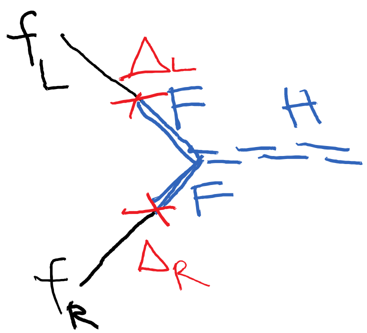
by virtue of

$$\mathcal{L}_{\rm mix} \supset -\lambda_{tL}\bar{t}_L T_L \qquad\qquad (\sin\phi_{t_L} = \lambda_{t_L}/(1+\lambda_{t_L}^2))$$

where T_L is a CFT spin ½ operator with dimension ~ 5/2 and $|T_L\rangle$ its lightest excitation (a Dirac fermion)

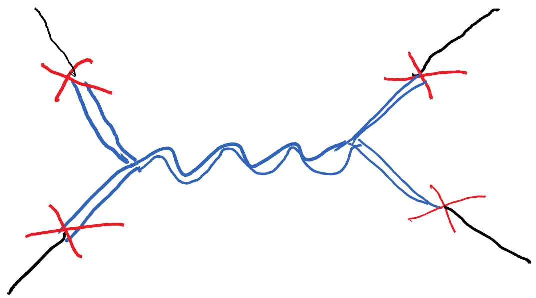
Can generate a pNGB (natural) Higgs potential & cause EWSB

can generate flavour hierarchies



$$Y_{ij} = (\Delta_L^\dagger M_L^{-1}\hat{Y}M_R^{-1}\Delta_R)_{ij}$$

leading BSM effects:



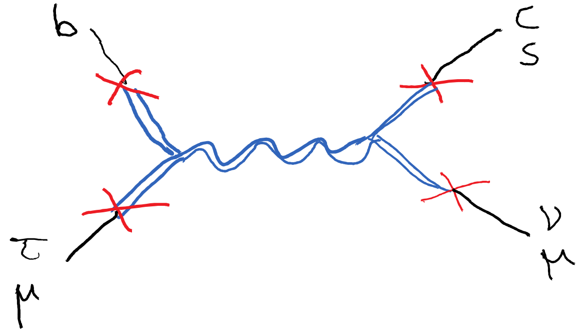
$$\sim \frac{g_*^2\Delta^4}{M^6}(\bar{f}\Gamma f)(\bar{f}\Gamma f)$$

Composite leptoquark

Minimal G is $SU(3)_C x SU(2)_L x SU(2)_R x U(1)_X$ [hypercharge & EWPT]

$Y = T_{3R} + X$

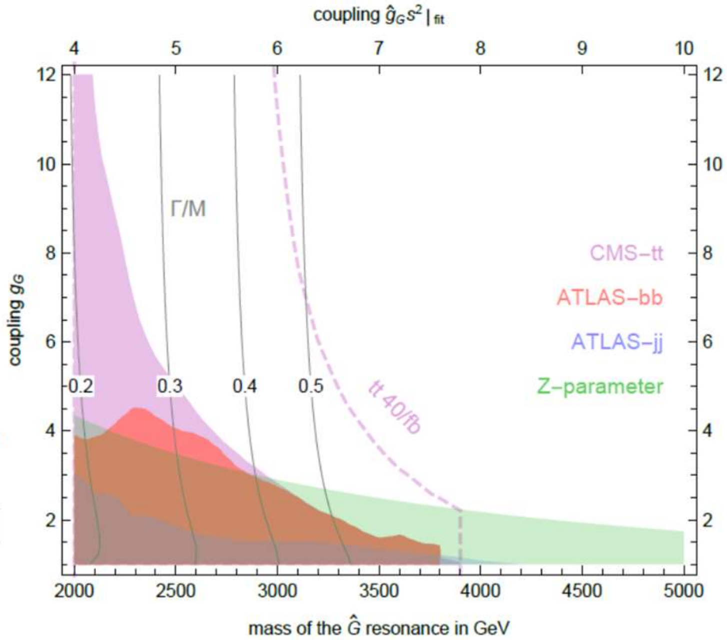
Increasing the SU(3) to SU(4) get **symmetry currents in** $(3, 1, 2/3)$ **of SM & vector leptoquarks** Barbieri, Murphy, Senia arXiv:1611.04930



Extend to [SU(4)xSO(5)xU(1)]/[SU(4)xSO(4)xU(1)] NGB Higgs model Barbieri, Tesi arXiv:1712.06844

Flavour structure based on approximate $U(2)^3$ symmetry Barbieri, Isidori, Pattori, Senia 1512.0156

Stringent LHC constraints, strong coupling



Conclusions

Flavour anomalies persist. Simple and consistent BSM explanation in terms of purely left-handed 4-fermion operators

RG mixing implies stringent constraints on 4-quark operators! Could also expain P5’ (but not, on its own, RK(*))

Reconciling the anomalies with naturalness most plausibly involves partial compositeness and new spin-1 states including leptoquarks. Important target for LHC searches.

BACKUP

A Z’ model for $R_{K(*)}$

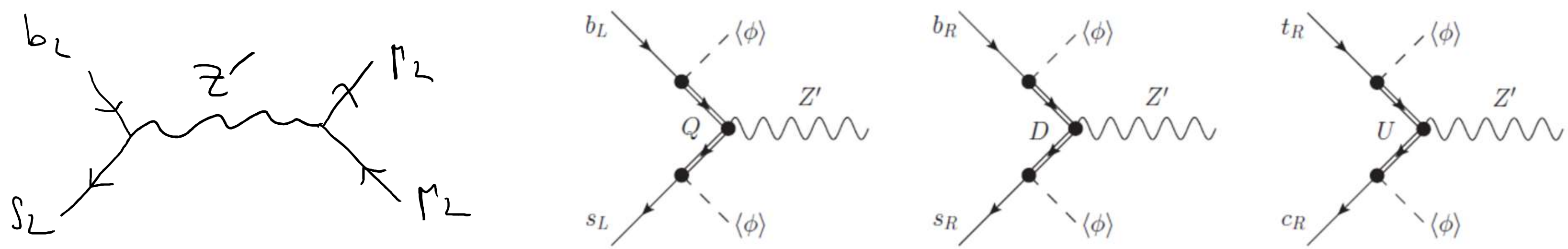
Accommodating *all* b->s l l anomalies *requires* a muon-specific C_L – type interaction

$$\frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\mu}_L\gamma_\mu\mu_L\right)$$

with $\Lambda \sim 30$ TeV

However, C_R is weakly constrained and can also be present.

Anomaly-free Z’ model with gauged L_μ - L_τ , nonminimal (dim-6) coupling to quarks, can eg come from heavy vectorlike quarks:



The small coupling to quarks suppresses contributions to Bs mixing

Also Crivellin et al, …

Scale of new physics & no-lose theorem

Di Luzio, Nardecchia 2017

The B-decay anomalies point to (at least) the interactions

$$\frac{1}{\Lambda^2}(\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L) \qquad \frac{1}{\Lambda^2}(\bar{c}_L\gamma^\mu b_L)(\bar{\nu}_\tau\gamma_\mu\tau_L)$$

numerically $\Lambda \sim 30$ TeV and $\Lambda \sim 3$ TeV, respectively

- Recall in the case of the Fermi theory, $G_F \sim g^2/M_W^2$

- Redoing the calculation here, $M_{NP} = g_{NP}\,\Lambda \leq 4\pi\,\Lambda$.
For the rare decay anomalies, at most 300-400 TeV.

Partial-wave unitarity: maximal NP scale below 100 TeV.

If the NP is less than maximally flavour-violating, or the NP is weakly coupled, the scale will be 1-2 orders of magnitudes lower.

While the bounds are (so far) high, the fact that there are any at all should be encouraging, further refinements may be possible.

Implications for model building

Background: inadequacies of the SM (naturalness, dark matter, flavor puzzle)

I can think of 3 different meanings of "model":

	SMEFT	Simplified model	UV-complete model/theory
+	Minimal consistent description of low-energy phenomena	Describes limited set of on-shell signals Guidance for UV model building	Description of a 'closed set' of phenomena valid to high energies, in terms of a limited number of building blocks (symmetries, fields, equations, …) (cf SM)
-	Low cutoff (for B-anomalies) No on-shell BSM signals Only falsifiable by discovering real NP states	Typically low cutoff (close to resonance mass) Tacit assumptions (BRs, …) - unsystematic	Equations may be difficult to discover and/or express (cf QCD, strings) Solving them may be even harder (cf QCD)

Naturalness

In SM extensions small ratios involving scalar masses, eg

m_H/M_{GUT} , m_H/M_{planck} , $m_H/M_{\nu R}$

receive O(1) quantum corrections (in absolute terms!)

- **correctly** reflected in the SM with a cutoff by **quadratic cutoff dependence** of the small $(\text{masses})^2$

(NB it is **not** correctly reflected with dimensional regularisation.)

For $\Lambda \gg m_W$ (UV completeness) tuning becomes implausible

Known exceptions:

NGB scalar (but then no potential)

supersymmetry (potential does not renormalize)

composite scalars (binding energy replaces cutoff)

relaxion, clockwork

Natural models for the anomalies

Low-scale SUSY: {N/U/E6/…}MSSM: natural & calculable.
Does not seem to accommodate the B-physics anomalies

Numerous renormalizable, calculable models with new scalars exist. (But either low cutoff or unnatural.)

Bordone, Cornella, Fuentes-Martin, Isidori arXiv:1712.01368, arXiv:1805.09328,
Di Luzio, Greljo, Nardecchia arXiv:1708.08450, …

Composite Higgs with partially composite fermions can accommodate the anomalies.

- Partial compositeness can relieve flavour puzzle & may also explain flavour hierarchies
- Generally requires strong coupling; loss of/limits to calculability. **But that's not a problem with the physics**

(DM candidates often available or addable in these setups.)

Composite Higgs

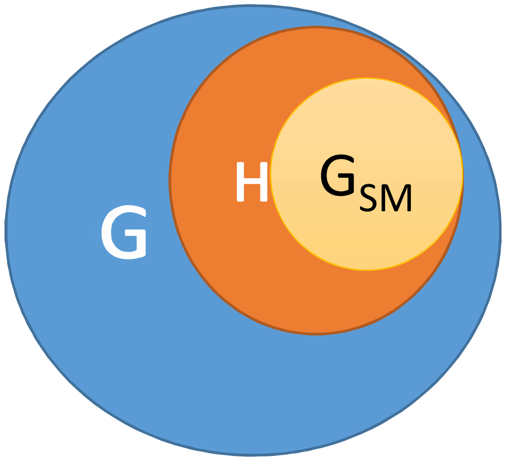
Higgs = bound state of some near-conformal new sector

(Relevant perturbations of) CFT's are **precisely** the UV-complete quantum field theory models (limit $\Lambda \to \infty$ exists)

Weak coupling, eg SM: CFT = free theory; global symmetry $\Pi_i\ U(N_i)$

Strong coupling: little known about possible symmetries

Symmetry of CFT must include G_{SM} = SU(3) x SU(2) x U(1)



conformal symmetry broken & $G \to H$

at scale M ~ few TeV <<Λ

Higgs may be NGB (preferable for little hierarchy)

weak gauging of G_{SM} explicitly breaks G,

generates Higgs potential (but no EWSB)