Perspectives on new physics from the $b \to s l^+ l^-$ anomalies

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Workshop on high-energy implications of flavour anomalies

CERN, 22 October 2018

Coverage

1) Anomalies
2) Scales & mediators
3) A bit on naturalness and models

This is not a full review talk – in particular referencing is incomplete. See the specialist talks on BSM models.

Summary of flavour anomalies

observable	Anomaly	Significance (sigma)
BR(B →{K,K*,ϕ} μμ) at low dilepton mass q^2	Lowish w.r.t expectation	1-2 ?
B→K*μμ angular distribution (low q^2)	P_5' off for some q^2	2-3 ?
$R_{D(*)}$ = BR(B→D(*)τν)/ BR(B→D(*)lν)	Enhanced w.r.t. SM	4.1
Lepton-universality ratios (R_K, R_{K*})	Suppressed w.r.t. SM	3.7 (3 observables combined)
ε'/ε (direct CPV in K_L->ππ)	Below SM	2.9

LHCb: rapidly increasing dataset

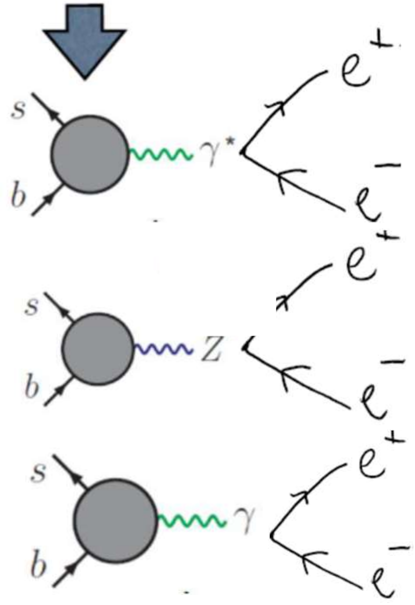
$R_{K(*)}$, $R_{D(*)}$: theoretical errors neglibible. Large statistical significance.

Systematic effect or BSM signal?

Operators mediating rare B-decay

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

in SM mainly



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

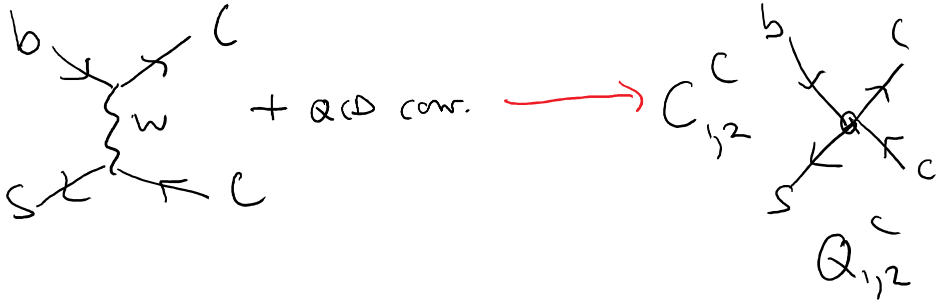
$$(\bar{s}\sigma^{\mu\nu} P_R b)F_{\mu\nu}$$

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

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

Impact of 4-quark operators

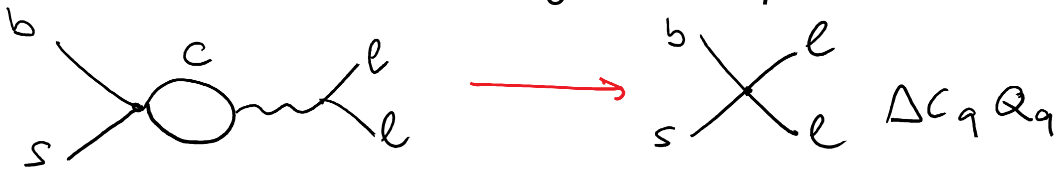
Also **purely hadronic** operators enter, in SM primarily:



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

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

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

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

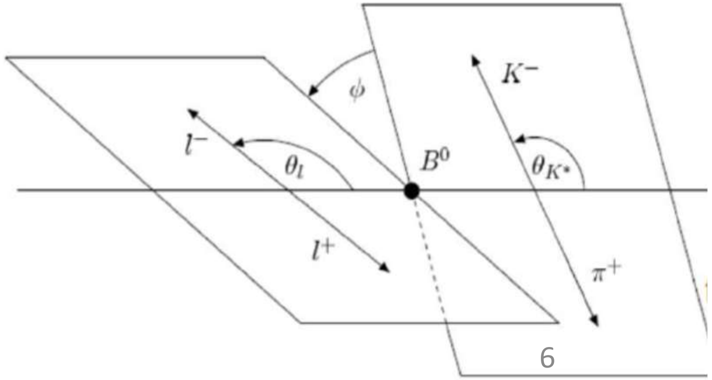
Lepton universality ratios

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

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

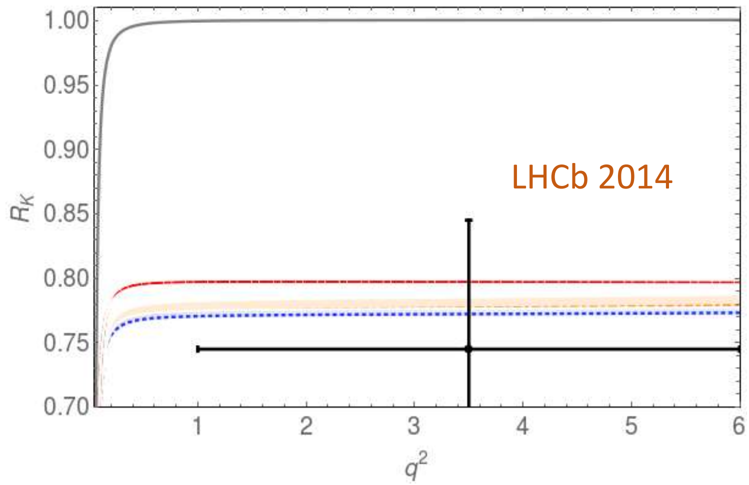


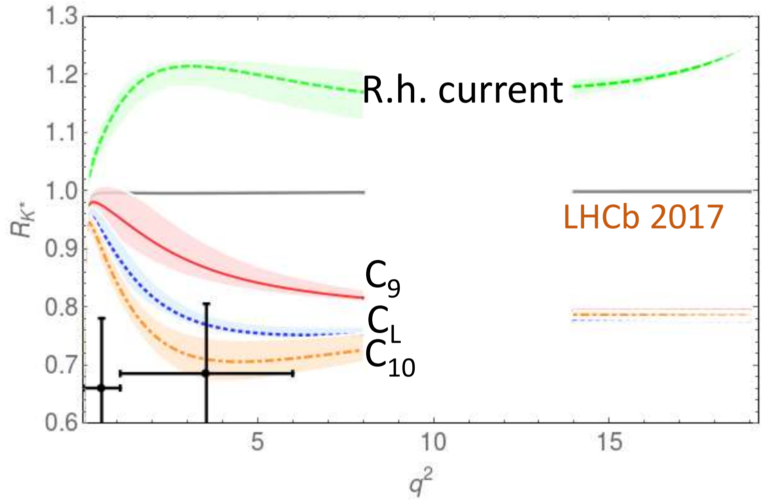
7 angular differential observables:
(A_{FB}, P_5', etc)

Lepton-flavour ratios at LHCb

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

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





Theory uncertainties negligible relative to experiment.
p(SM) = 2.1 x 10^{-4} (3.7σ)

coloured lines: scenarios with NP in muonic operators

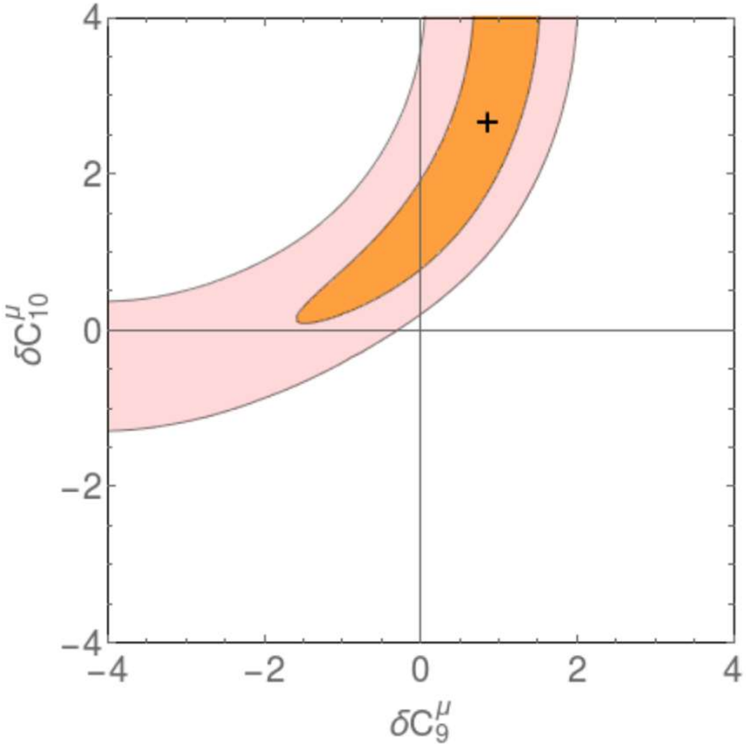
Slight indication for a C_{10}^{BSM} effect – as opposed to pure C_9

Fit to new physics: LUV only

Assume here that the BSM effect is in the muonic mode

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446
Also Capdevila et al, Ciuchini et al, Altmannshofer et al, D'Amico et al, Hiller & Nisandzic

Obs.	Expt.	SM	$\delta C_L^\mu = -0.5$	$\delta C_9^\mu = -1$	$\delta C_{10}^\mu = 1$	$\delta C_9'^\mu = -1$
R_K [1, 6] GeV^2	0.745 ± 0.090	$1.0004^{+0.0008}_{-0.0007}$	$0.773^{+0.003}_{-0.003}$	$0.797^{+0.002}_{-0.002}$	$0.778^{+0.007}_{-0.007}$	$0.796^{+0.002}_{-0.002}$
R_{K^*} [0.045, 1.1] GeV^2	0.66 ± 0.12	$0.920^{+0.007}_{-0.006}$	$0.88^{+0.01}_{-0.02}$	$0.91^{+0.01}_{-0.02}$	$0.862^{+0.016}_{-0.011}$	$0.98^{+0.03}_{-0.03}$
R_{K^*} [1.1, 6] GeV^2	0.685 ± 0.120	$0.996^{+0.002}_{-0.002}$	$0.78^{+0.02}_{-0.01}$	$0.87^{+0.04}_{-0.03}$	$0.73^{+0.03}_{-0.04}$	$1.20^{+0.02}_{-0.03}$
R_{K^*} [15, 19] GeV^2	–	$0.998^{+0.001}_{-0.001}$	$0.776^{+0.002}_{-0.002}$	$0.793^{+0.001}_{-0.001}$	$0.787^{+0.004}_{-0.004}$	$1.204^{+0.007}_{-0.008}$



Theory uncertainties negligible.

1σ and 3σ confidence regions

$C_{10}^{BSM} > 0$ favoured

$p(C_9 \,\&\, C_{10}) = 0.158$

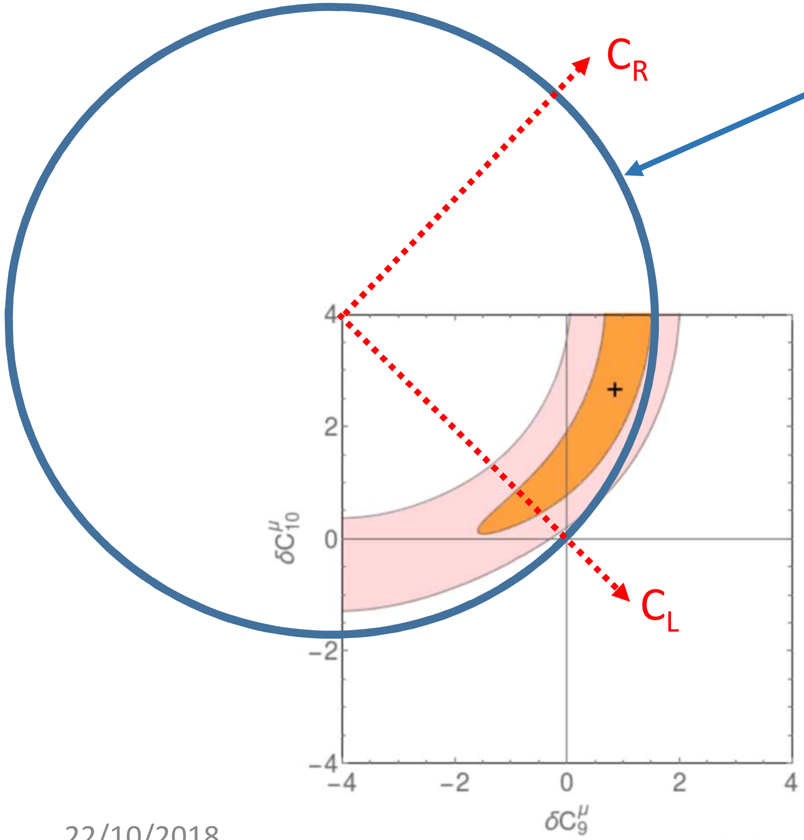
SM point excluded at 3.78 σ

Considerable degeneracy (flat direction in χ^2)

$R_K^{(*)}$ 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 ≈ const $|C_L^{SM} + C_L^{BSM}|^2$ + … ≈ const $|4 + C_L^{BSM}|^2$ +positive



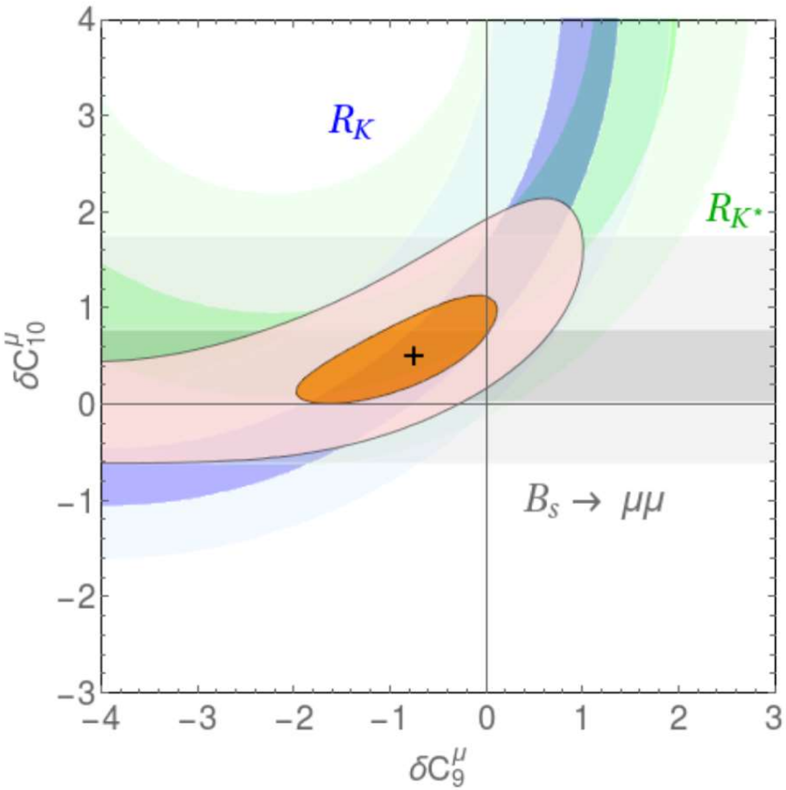
BR(B->K(*)μμ) = SM value

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

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

with ~ -(10-15)% of SM value

Adding $B_s \to \mu\mu$



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

Selective probe of C_{10} (and C_{10}')

Theory error negligible relative to exp (will hold till the end of HL-LHC !)

Considerably narrows the allowed fit region

p= 0.191

SM point excl. at 3.76 σ

Fit prefers nonzero BSM effect $C_L = (C_9-C_{10})/2$

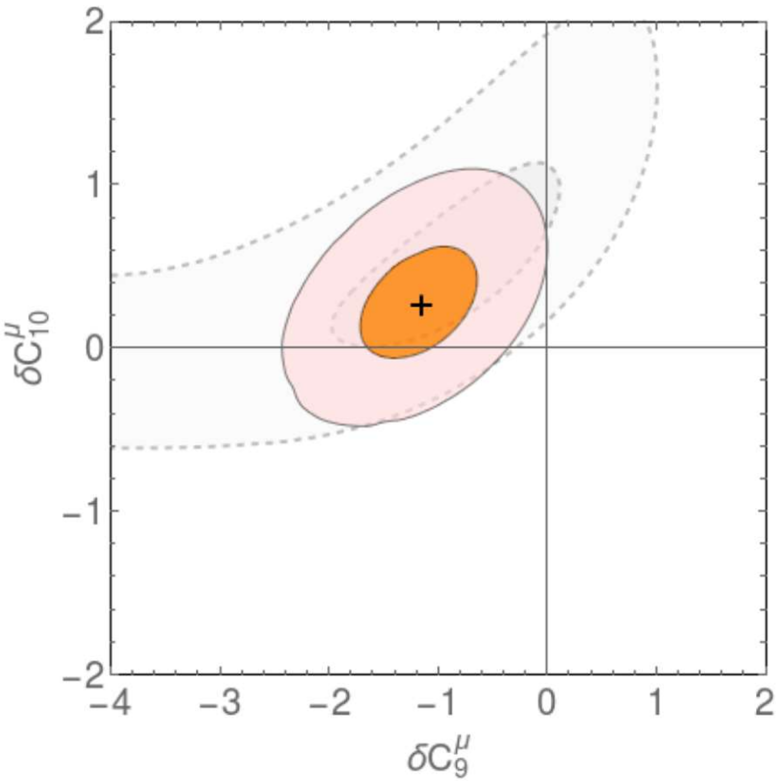
$C_R = (C_9+C_{10})/2$ not well constrained and consistent with zero

1-parameter C_L fit: best fit -0.61. 1σ [-0.78, -0.46], p = 0.339

SM point (origin) excluded at 4.16 sigma

Adding B→K*μμ,ee angular data

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



Serves to determine best-fit region even better.

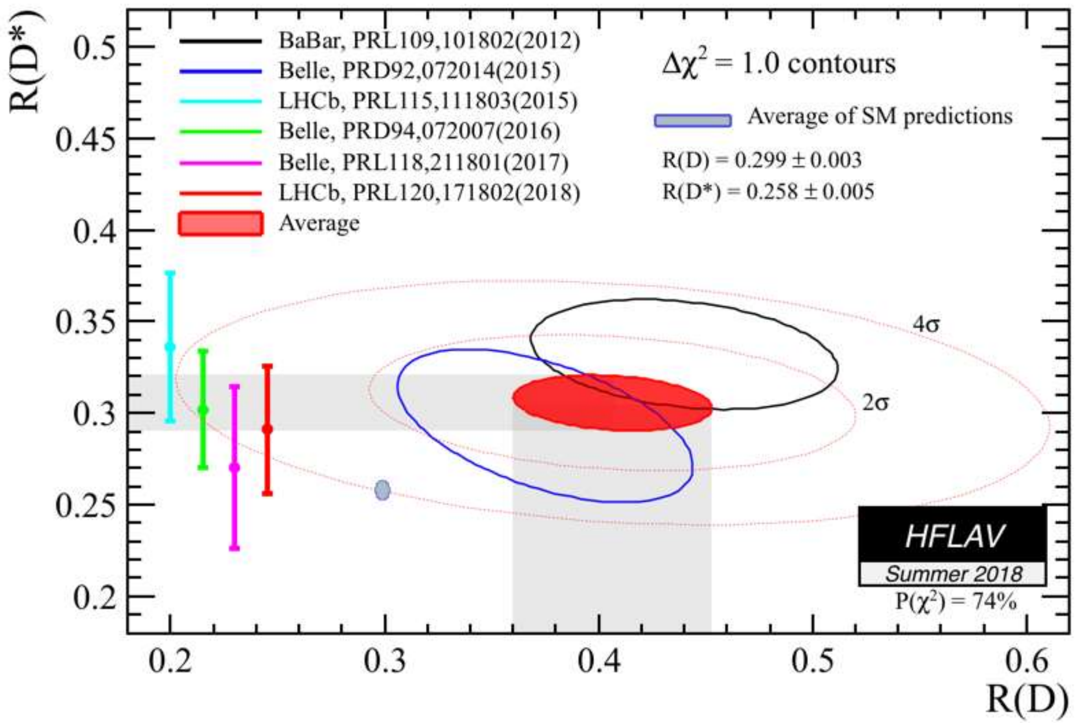
SM pull 4.17 σ

p = 0.572 [63 dof]

(but p(SM) now up to to 0.086)

Wilson coefficient value C_L=0 again excluded at high confidence.

Non-rare semileptonic decays



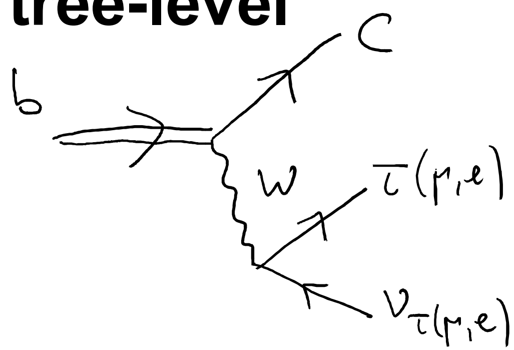
see Tuesday's sessions

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

3.8σ effect

~20% deviation

SM **tree-level**



large effect; theory error negligible

~10% enhancement of SM operator $(\bar{c}_L \gamma^\mu b_L)\,(\bar{\nu}_\tau \gamma_\mu \tau_L)$ favoured (benefit from SM interference; bound on $B_c \to \tau\nu$; differential distribution)

Eg Ligeti et al 2015,16, Freytsis et al 2015, Celise et al 2016, Lie et al, Alonso et al 2016, Akeroyd & Chen 2017

Operators and operator mixing

The B-decay anomalies suggest (at least) the interactions

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

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

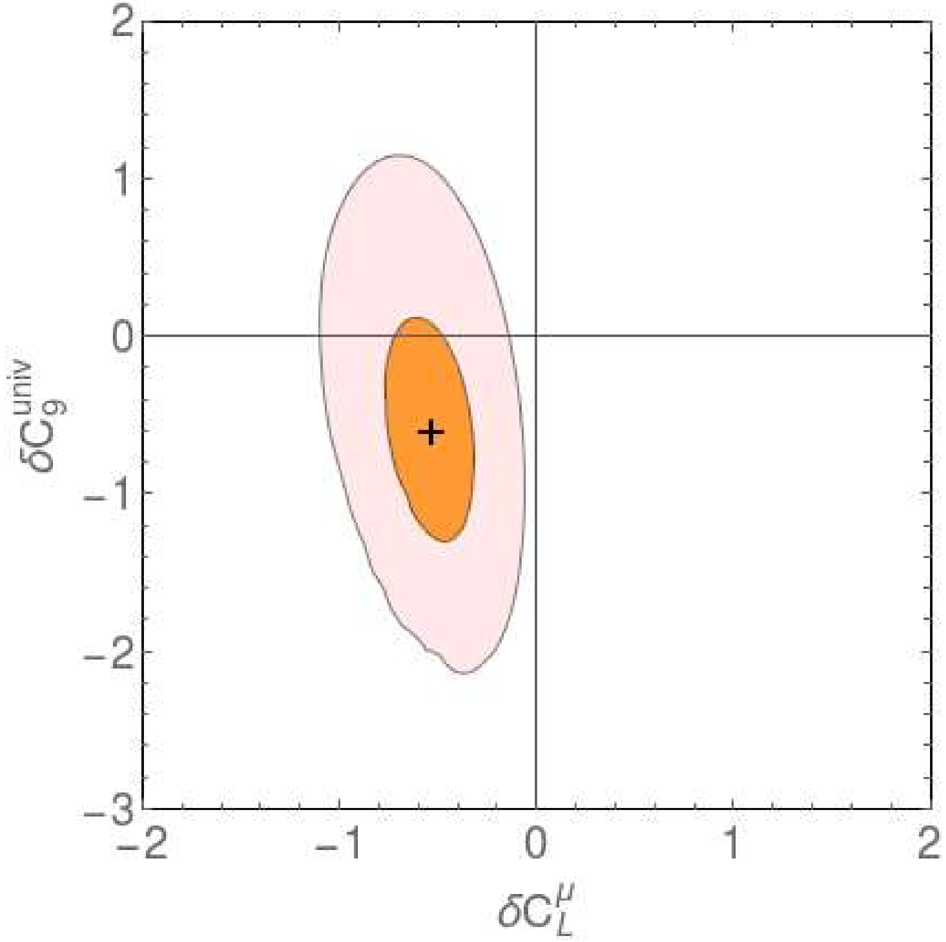
Will focus on these, even though other possibilities (especially when operators with electrons are invoked for $R_{K(*)}$)

- Rare B-decay ‘signal’ factor 10^2 smaller than $R_{D(*)}$
- Small enough to be a loop effect even BSM (as it is in SM!), particularly when large logs $\ln(\Lambda/M_W)$ present: RGE

Must C_9 violate lepton flavour?

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

(also Alguero et al arXiv:1809.08447)



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)

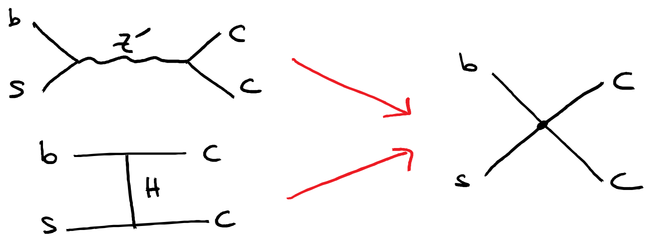
SJ, Kirk, Lenz, Leslie arXiv:1701.09183

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

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

SJ, Kirk, Lenz, Leslie arxiv:1701.09183
SJ, Kirk, Lenz, Leslie w.i.p.



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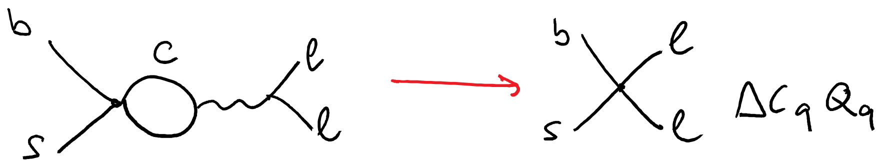


Evolution from M_W to 4.6 GeV: [$Q_{3,4} \sim (\bar{s}_L \gamma^\mu b_L)(\bar{c}_R \gamma_\mu c_R)$]

$$\Delta C_7^{\text{eff}} = 0.02 \Delta C_1 - 0.19 \Delta C_2 - 0.01 \Delta C_3 - 0.13 \Delta C_4$$
$$\Delta C_9^{\text{eff}} = 8.48 \Delta C_1 + 1.96 \Delta C_2 - 4.24 \Delta C_3 - 1.91 \Delta C_4$$

- Setting Delta C_2 to 1 and rest to zero, reproduce the (large) SM charm contribution to C_9(4.6 GeV).

But C_1 and C_3 are even more effective in generating C_9!

- C_2 and C_4 feed strongly into C_7^{eff}, hence $B \to X_s \gamma$

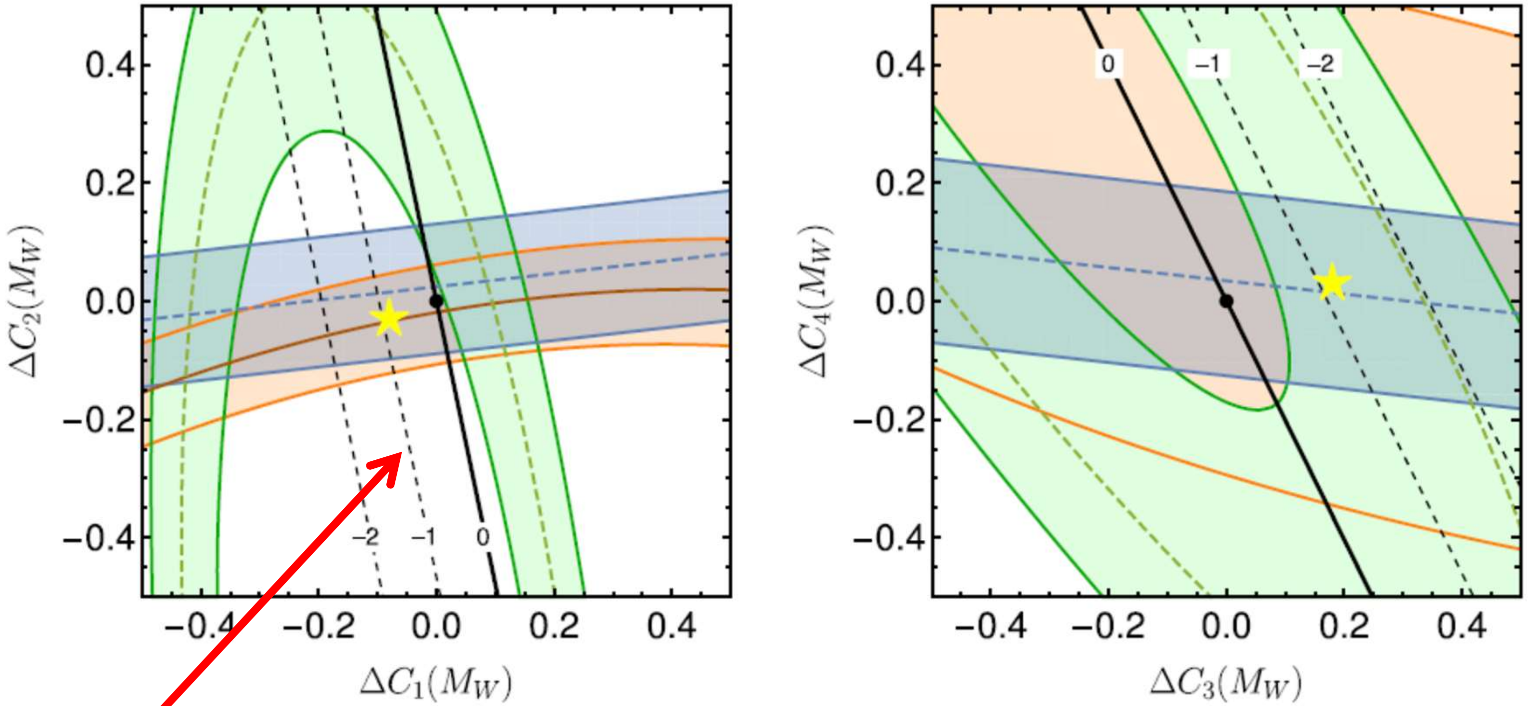
But C_1 and C_3 are practically irrelevant for radiative decay!

Interesting interconnections between rare decays and B-lifetime (difference) observables

Rare decay vs lifetime observables

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

Blue – $B \to X_s \gamma$, green – B_d/B_s lifetime ratio, brown – B_s lifetime difference



$C_9 \sim -1$ from small BSM C_1 or C_3 (however lepton-universal)

(more combinations in paper)

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

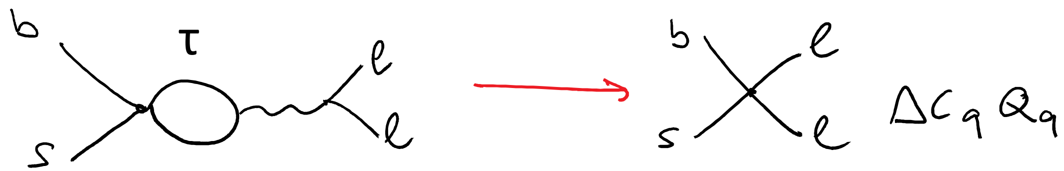
Bobeth, Haisch arXiv:1109.1826
Crivellin et al arXiv:1807.02068

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)



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:

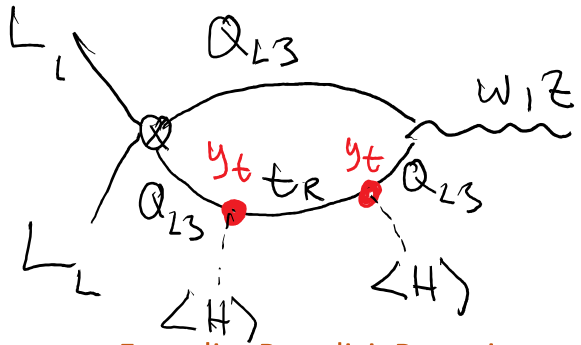
B → K* νν → $C_{T,3323} \approx C_{S,3323}$

at one loop:

Z → ττ , Z→νν

τ →Z*μ, W* ν (→ 3 leptons)

Problematic for very low Λ



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

Tree-level mediators: leptoquarks

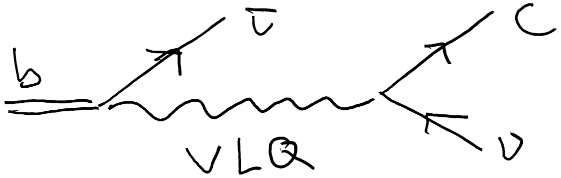
Scalar or vector leptoquarks can generate interactions

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

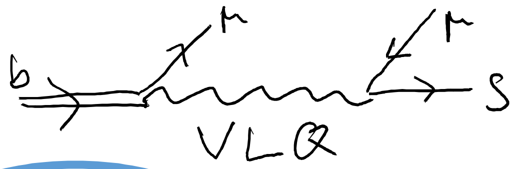
$$\frac{1}{\Lambda^2}\,(\bar{c}_L\gamma^\mu b_L)\,(\bar{\nu}_\tau\gamma_\mu\tau_L) \qquad\qquad \frac{1}{\Lambda^2}\,(\bar{s}_L\gamma^\mu b_L)\,(\bar{\mu}_L\gamma_\mu\mu_L)$$

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

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



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

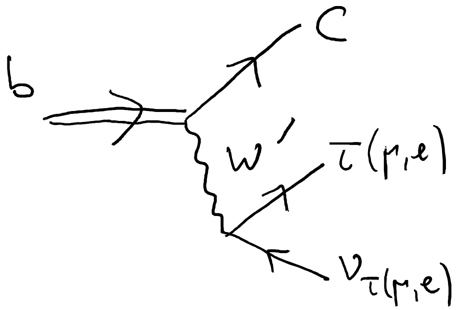


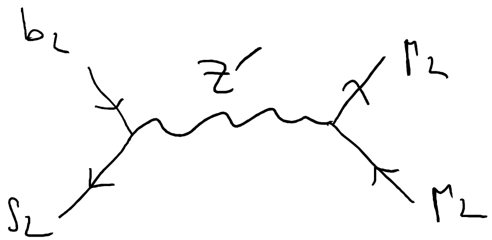
$(3,1,2/3)$ or $(3,3,2/3)$

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

Tree-level mediators: W', Z'

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





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

- appear as resonances in composite models (KK excitations in RS)

- Z' exchange contributes to B_s mixing at tree-level (unlike leptoquarks)

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

A Z' model for $R_{K(*)}$

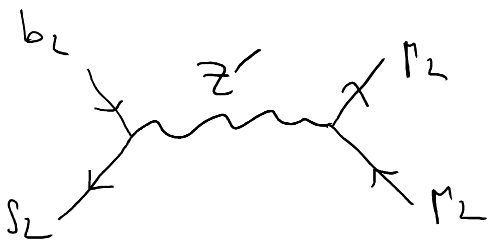
Accommodating *all* b->s l l anomalies *requires* a muon-specific C_L – type interaction

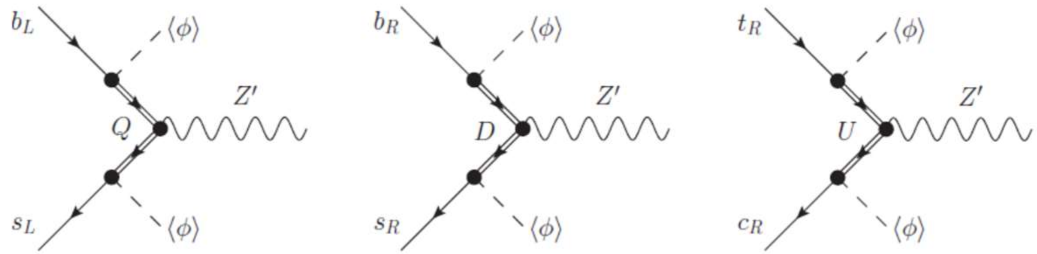
$$\frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\mu}_L\gamma_\mu\mu_L\right)$$

with Λ ~ 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:





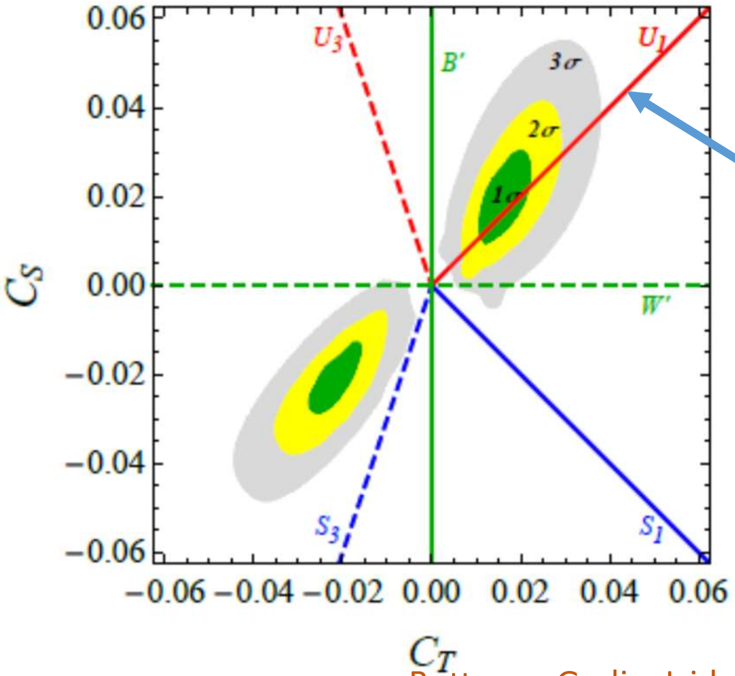
The small coupling to quarks suppresses contributions to Bs mixing

Also Crivellin et al, …

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

Scale of new physics & no-lose theorem

Di Luzio, Nardecchia 2017

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

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

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.

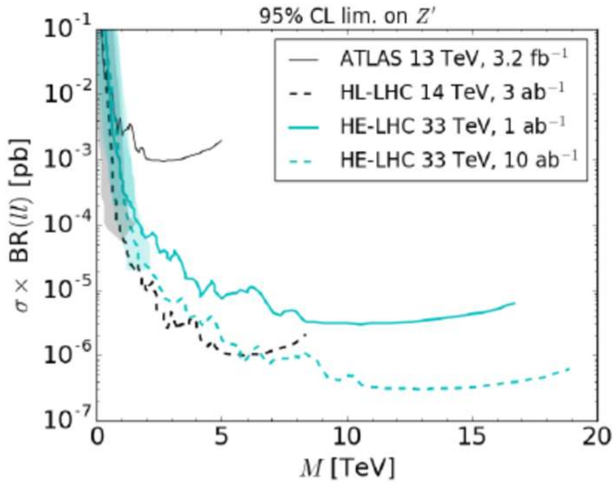
If the NP is less than maximally flavour-violating, or the NP is weakly coupled, the scale will be 1-2 orders of magnitudes lower.

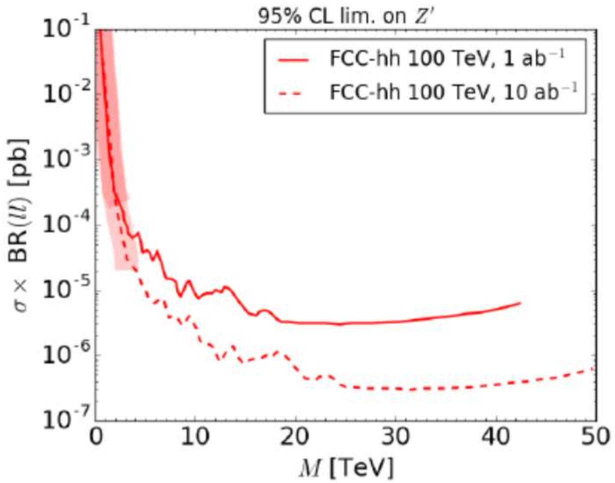
While the bounds are (so far) high, the fact that there are any at all should be encouraging, further refinements may be possible.

Future collider direct searches

Allanach, Gripaios, You arXiv:1710.06363

- Consider simplified Z' and LQ models of $R_{K^{(*)}}$





FCC-hh 100 TeV 1 ab^{-1} covers all of viable Z' parameter space, 33 TeV LHC "most",

Leptoquark coverage slightly less perfect

Implications for model building

"The main focus [of the workshop] will be on the models of new physics that can explain the anomalies, but could also address some of the other 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

see Gripaios's talk

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.) see Di Luzio's talk

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

see Gripaios's talk

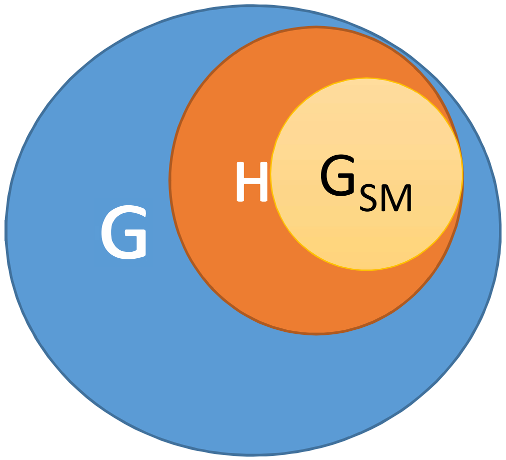
Higgs = bound state of some near-conformal new sector

(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 $\ll \Lambda$

Higgs may be NGB (preferable for little hierarchy)

weak gauging of G_{SM} explicitly breaks G,

generates Higgs potential (but no EWSB)

Partial compositeness

see Gripaios's talk

SM fermions are mixtures of elementary and composite particles, eg

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

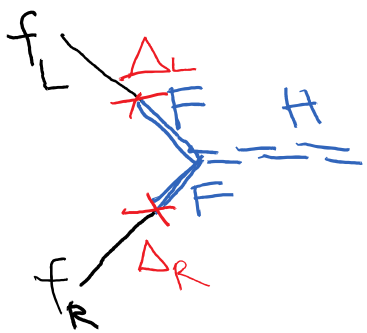
by virtue of

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

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

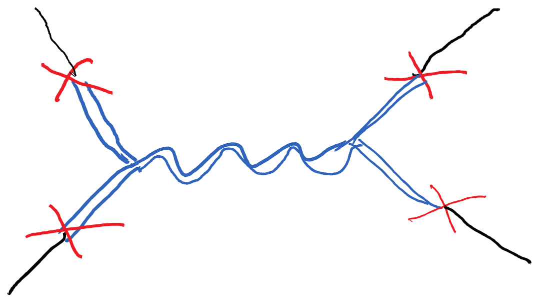
Can destabilize a pNGB Higgs potential & cause EWSB

can generate flavour hierarchies



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

leading BSM effects:



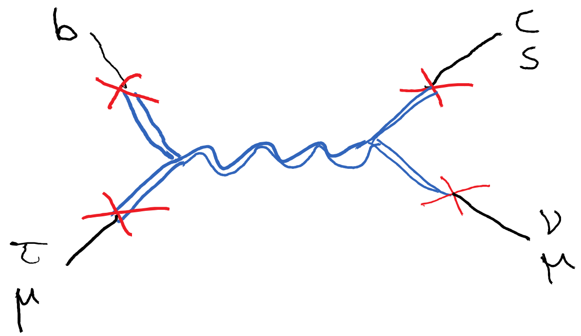
$$\sim \frac{g_*^2\Delta^4}{M^6}(\bar{f}\Gamma f)(\bar{f}\Gamma f)$$

Composite leptoquark

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

$Y = T_{3R} + X$

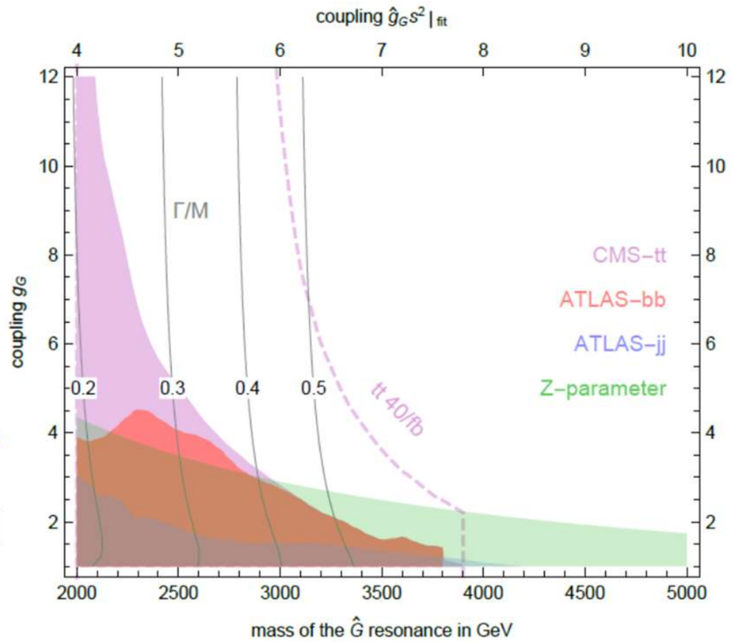
Increasing the SU(3) to SU(4) get **symmetry currents in** $(3, 1, 2/3)$ **of SM & vector leptoquarks** Barbieri, Murphy, Senia arXiv:1611.04930



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 in B-decays abound, including a few theoretically immaculate ones. Data point to very specific contact interactions.

Rare B-decay anomalies do receive important loop contributions (though these are lepton-universal). Possible interplay with hadronic observables such as B-meson lifetimes

Rare B-decay mediators may be out of LHC (& HL-LHC) reach but good coverage with 100TeV. ($R_{D(*)}$ important target for LHC)

Reconciling the anomalies with naturalness most plausibly involves partial compositeness.

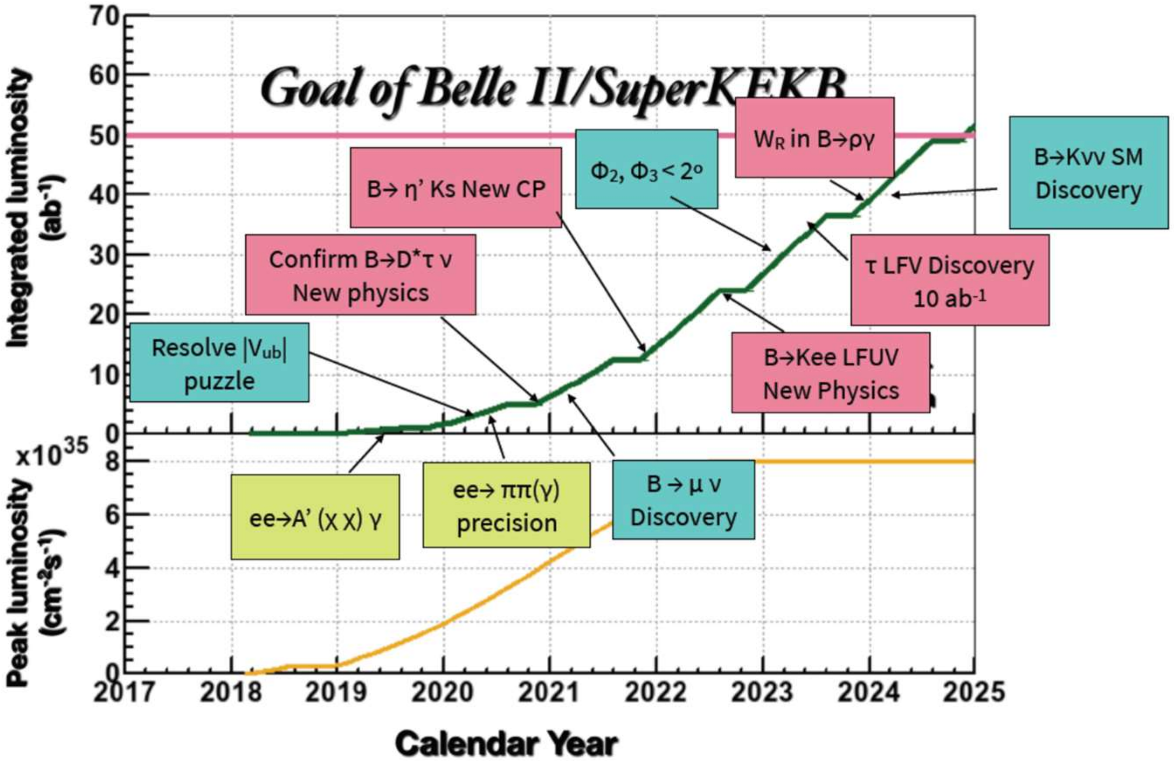
BACKUP

Belle 2

Belle 2: an experiment with very different systematics

Statistics disadvantage relative to LHC, but better idenfication of electrons in final states

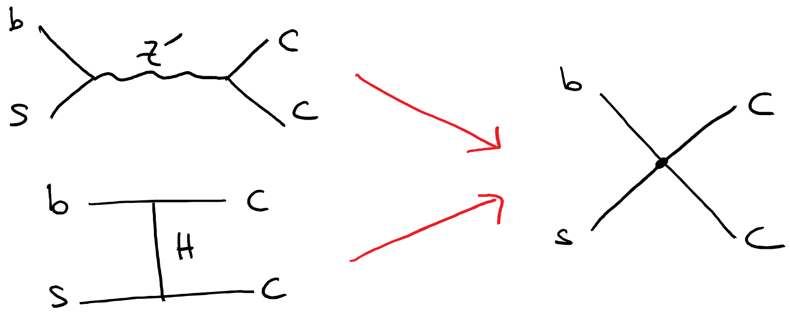
Unofficial Belle 2 “road map” (P Urquiqjo, Rare b decay workshop Munich 2018)



Charming BSM scenario

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

e.g. 1)



2)

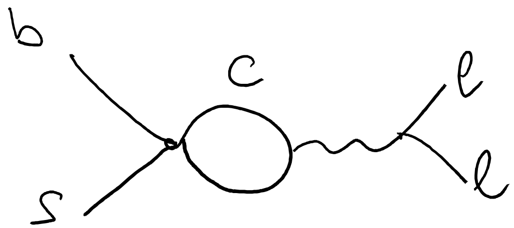
very efficient way to generate C9(NP) = O(1)

$$C_7^{\rm eff}(4.6{\rm GeV}) = 0.02\, C_1(M_W) - 0.19\, C_2(M_W)$$
$$C_9(4.6{\rm GeV}) = 8.48\, C_1(M_W) + 1.96\, C_2(M_W)$$

(In SM, O(50%) of total in both cases)

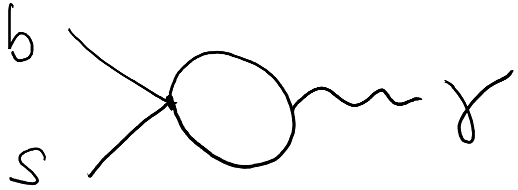
Observables

SJ, Kirk, Lenz, Leslie arxiv:1701.09183



$$\Delta C_9^{\rm eff}(q^2) = \left(C_{1,2}^c - \frac{C_{3,4}^c}{2} \right) h(q^2, m_c, \mu) - \frac{2}{9} C_{3,4}^c$$

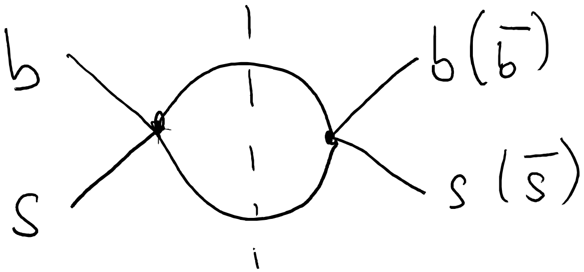
$$C_{x,y}^c = 3\Delta C_x + \Delta C_y$$



$$\Delta C_7^{\rm eff}(q^2) = \frac{m_c}{m_b} \left[(4C_{9,10}^c - C_{7,8}^c) y(q^2, m_c, \mu) + \frac{4\,C_{5,6}^c - C_{7,8}^c}{6} \right]$$

note that h and y are q2-dependent

At one loop, radiative decay constrains C5..C10, but not C1..C4.
Focus on the latter. Then consider lifetime (mixing) observables



$\Delta\Gamma_s$ and τ_{B_s}/τ_{B_d} calculable in OPE
for general C1 .. C4

High NP scale – global analysis

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

Blue – $B \to X_s\gamma$, green – lifetime ration, brown –lifetime difference