$b \to s l^+ l^-$ anomalies & ATLAS B physics

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ATLAS B-physics meeting

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ATLAS analyses

Analysis	Expected/plausible BSM scale	theory	current BSM significance
B(s,d) -> mu mu	(few) TeV (nat'lness)	excellent	2-3 σ
RK(*)	(few) TeV (nat'lness)	excellent	3-4 σ
B->K*mu mu (ee?) angular	(few) TeV (nat'lness)	good (P5') to excellent (rh current)	unclear
Tau->3 mu	GUT scale or below	excellent	none
B->J/psi phi etc	(few) TeV	depends	none
B lifetimes	(few) TeV	depends	none
4 muons searches	}		
Bc/Bc(2S)	}	Outside scope of what I can discuss in this talk	
Pentaquark/Zc	}		
CPV in b from ttbar	}		

Outline

In the following I will focus about two topics which I have worked on

1) The b->s l l anomalies, with emphasis on theoretically controlled obervables
2) A possible connection with lifetime/mixing observables

SM(EFT) theory

Rare B-decay: short-distance

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

C_9: dilepton from vector current

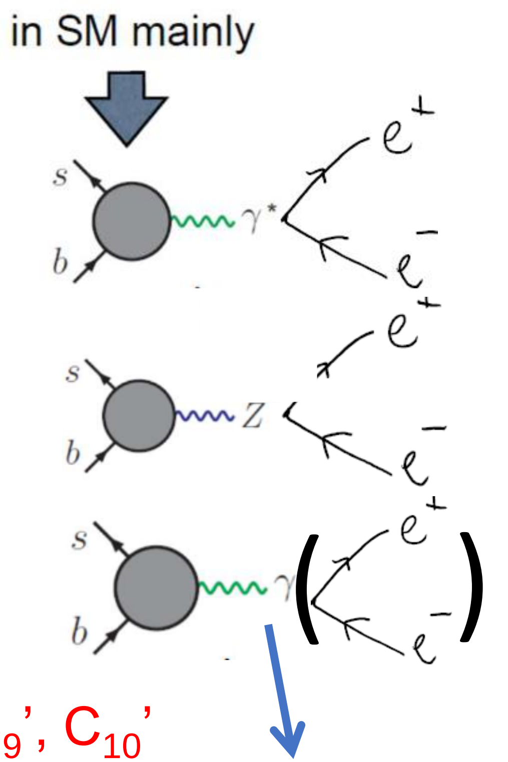
$$(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$$

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

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



Can also have real photon

+parity conjugate "right-handed currents" - C_7', C_9', C_{10}' suppressed by m_s/m_b in SM

Alternative basis with chiral leptons l_L, l_R

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

Importance of virtual charm

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

+ dipole

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

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

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: accidentally almost left-chiral muon interactions
- Long-distance virtual charm important theory uncertainty

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

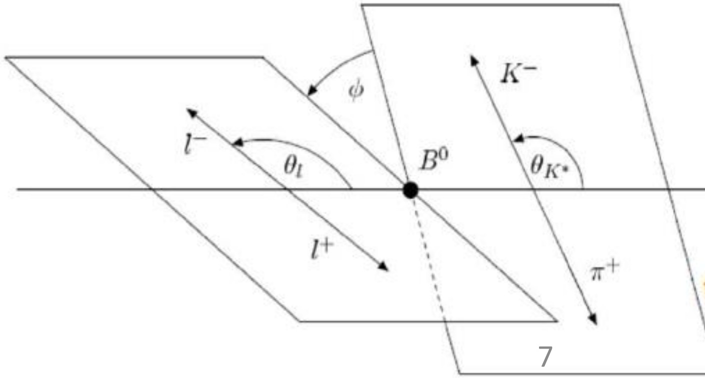
Lepton universality ratios

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

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

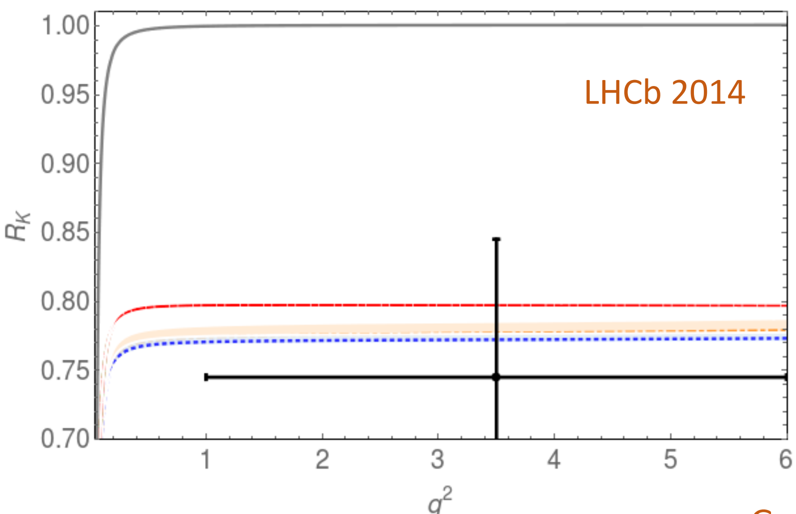
$$R_{K^{(*)}}[a,b] = \frac{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}\mu^+\mu^-)dq^2}{\int_a^b \frac{d\Gamma}{dq^2}(B \to K^{(*)}e^+e^-)dq^2}$$

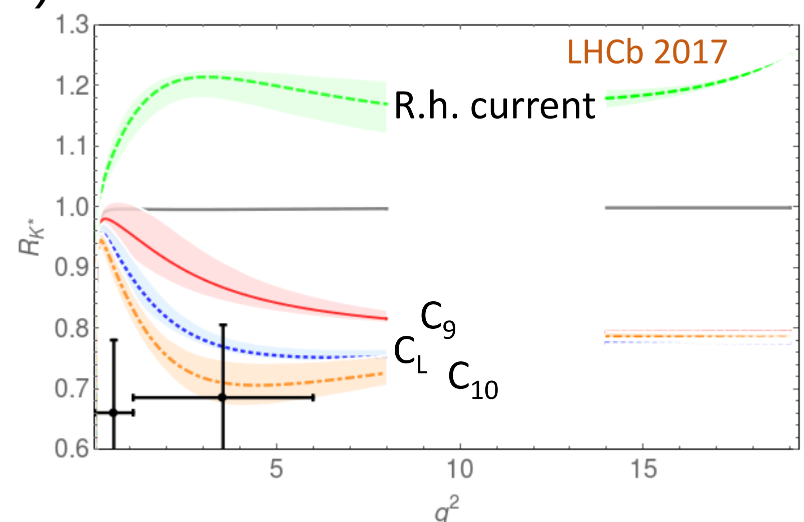
Theory uncertainties largely cancel out, negligible relative to experiment.

leading is QED: net effect <1% after experimental corrections

Bordone, Isidori, Pattori 2016; Isidori, Nabeebaccus, Zwicky 2020

Situation in 2017 (first RK* measurement):





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

BSM fit

Observables in the fit

Basic idea: use only observables which are sensitive to b->s l l but independent of hadronic form factors, long-distance charm etc.

I.e. $R_{K(*)}$ and B_s -> mu mu.

This is a well-defined set of observables, first employed in 2017, with several data updates since then. No “look-elsewhere effect” to take into account.

In the following I describe the fit in arXiv:2103.12738 (Geng, Grinstein, SJ, Li, Martin Camalich, Shi); see also work by Altmannshofer & Stangl

A note on the $B_s \to \mu\mu$ input

Together with the R_{K^*} update, LHCb presented a significant update to $BR(B_s \to \mu\mu)$

ATLAS and CMS have also measured this

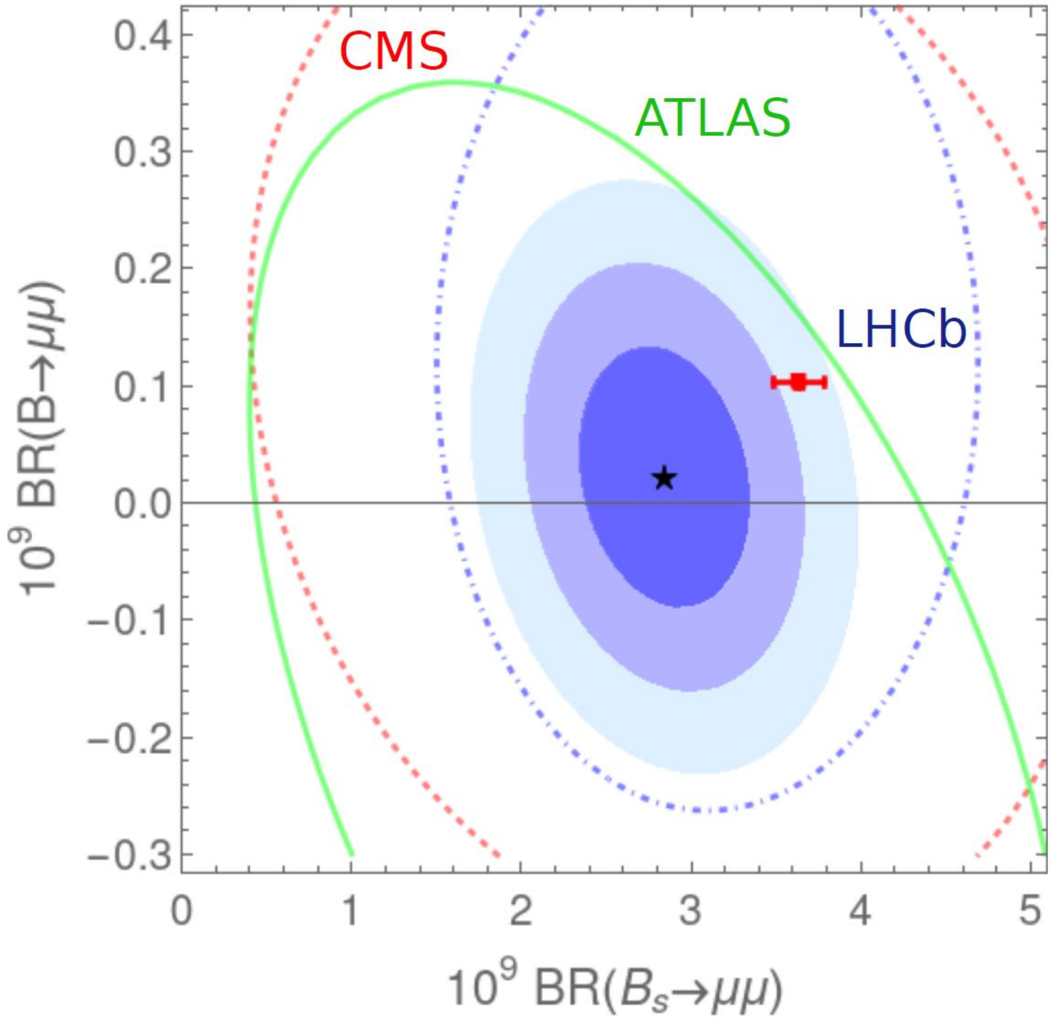
Measurements show non-negligible correlations with $BR(B_d \to \mu\mu)$ (biggest in ATLAS).

Hence to obtain a $BR(B_s \to \mu\mu)$ average first combine the 3x2 measurements.

Then profile over $BR(B_d \to \mu\mu)$.

$B_q \to \mu\mu$ world combination

Geng, Grinstein, SJ, Li, Martin Camalich, Shi arXiv:2103.12738



From this:

$BR(B_s \to \mu\mu) = (2.8 \pm 0.3) 10^{-9}$

$\chi^2_{min} = 3.75$ (5 d.o.f.)

Input data

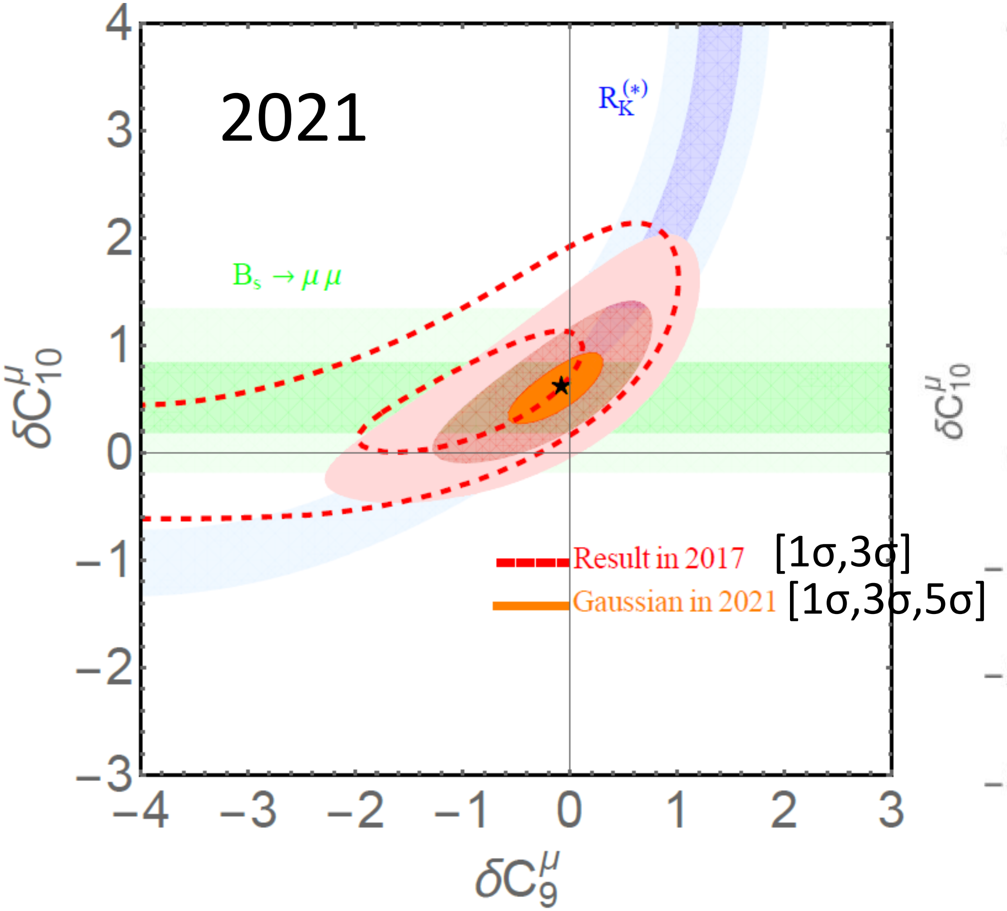
Observable	Value	Source	Reference
$BR(B_s \to \mu^+\mu^-)$	$(2.8^{+0.8}_{-0.7}) \times 10^{-9}$	ATLAS	[11]
	$(2.9 \pm 0.7 \pm 0.2) \times 10^{-9}$	CMS	[12]
	$(3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$	LHCb update	[10]
	$(2.842 \pm 0.333) \times 10^{-9}$	our average	this work
	$(3.63 \pm 0.13) \times 10^{-9}$	SM prediction	[13]
$R_K[1.1, 6]$	0.846 ± 0.044	LHCb	[6]
$R_K[1, 6]$	1.03 ± 0.28	Belle	[14]
$R_{K^*}[0.045, 1.1]$	0.660 ± 0.113	LHCb	[15]
$R_{K^*}[1.1, 6]$	0.685 ± 0.122	LHCb	[15]
$R_{K^*}[0.045, 1.1]$	0.52 ± 0.365	Belle	[16]
$R_{K^*}[1.1, 6]$	0.96 ± 0.463	Belle	[16]

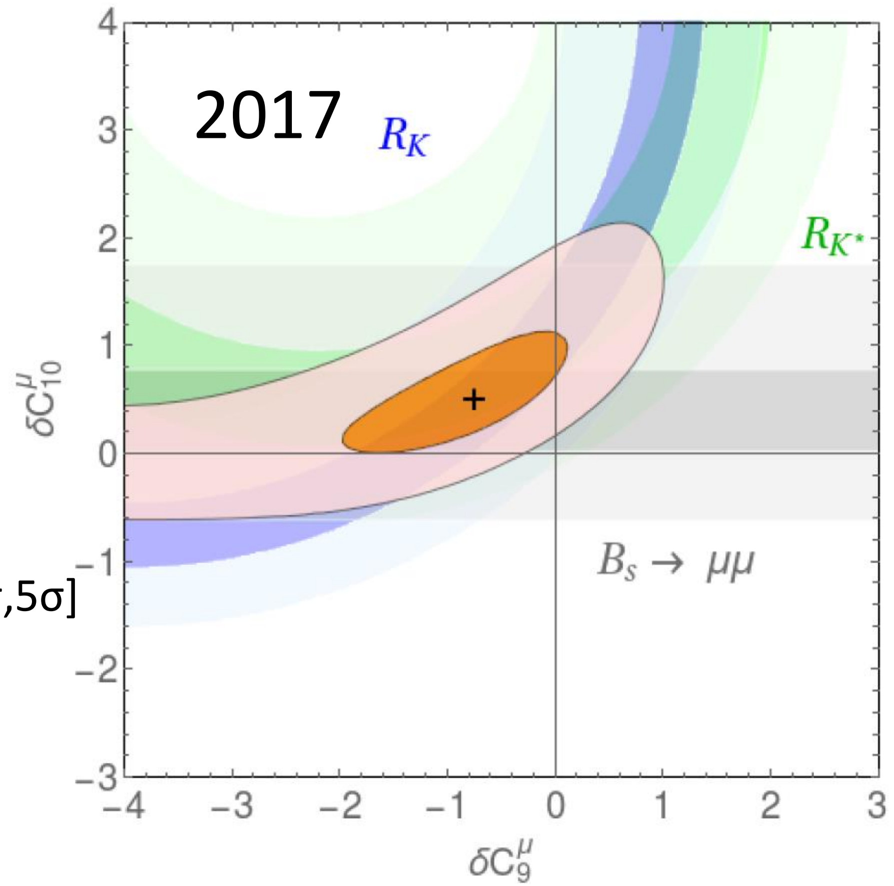
Self-consistency of dataset: χ^2_{min}= 4.61 (8 d.o.f.) / p = 0.80 (counting 6 BR($B_q \to \mu\mu$) measurements)

SM p-value is 5.4 x 10^{-5} (4.0σ) [counting BR($B_s \to \mu\mu$) average] reduces to 3.5σ when counting the 6 BR($B_q \to \mu\mu$) measurements separately

Clean fit: results: 2-parameter BSM fit

Geng, Grinstein, SJ, Li, Martin Camalich, Shi arXiv:2103.12738





Clean fits: numerical results

Geng, Grinstein, SJ, Li, Martin Camalich, Shi arXiv:2103.12738

Fit three 1-parameter scenario (vectorial, axial, left-handed coupling to muons)

TABLE II. Best fit values, $\chi^2_{\rm min}$, p-value, $\text{Pull}_{\rm SM}$ and confidence intervals of the Wilson coefficients in the fits of the R_K, R_{K^*}, $B_s \to \mu\mu$ da only using Gaussian form $\chi^2_{\rm th}$. For the cases of single Wilson-coefficient fits, we show the 1σ and 3σ confidence intervals. In the $(\delta C_9^\mu, \delta C_1$ case, the 1σ interval of each Wilson coefficient is obtained by profiling over the other one to take into account their correlation.

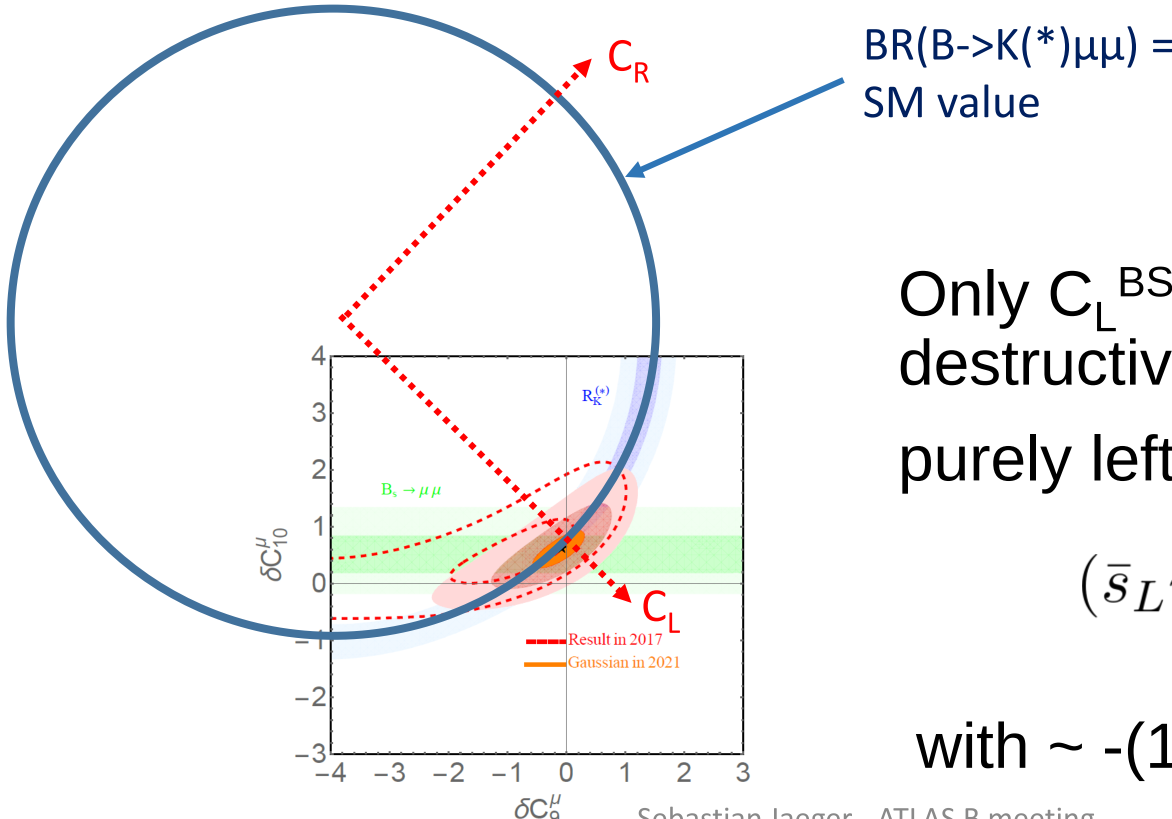
Coeff.	best fit	$\chi^2_{\rm min}$	p-value	$\text{Pull}_{\rm SM}$	1σ range	3σ range	ρ
δC_9^μ	-0.82	14.70 [6 dof]	0.02	4.08	$[-1.06, -0.60]$	$[-1.60, -0.20]$	–
δC_{10}^μ	0.65	6.52 [6 dof]	0.37	4.98	$[0.52, 0.80]$	$[0.25, 1.11]$	–
δC_L^μ	-0.40	7.36 [6 dof]	0.29	4.89	$[-0.48, -0.31]$	$[-0.66, -0.15]$	–
$(\delta C_9^\mu, \delta C_{10}^\mu)$	$(-0.11, 0.59)$	6.38 [5 dof]	0.27	4.62	$\delta C_9^\mu \in [-0.41, 0.17]$	$\delta C_{10}^\mu \in [0.38, 0.81]$	0.762
$(\delta C_L^\mu, \delta C_R^\mu)$	$(-0.35, 0.25)$				$\delta C_L^\mu \in [-0.45, -0.26]$	$\delta C_R^\mu \in [0.00, 0.48]$	0.406

Note that C_L is well-determined in both the left-handed and the two-parameter scenario, with consistent values. Not true for C_9. Pure C_9 model also much worse fit (p=1/50).

$R_K^{(*)}$ 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



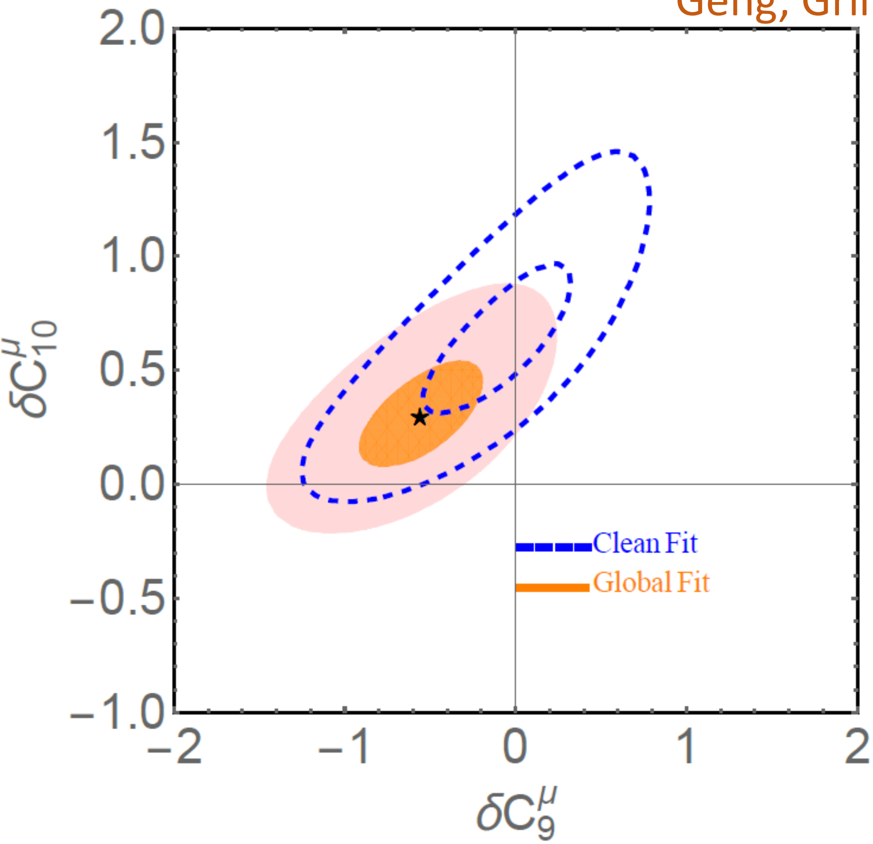
Only C_L^{BSM} can interfere destructively: $R_K^{(*)}$ point to purely left-handed coupling

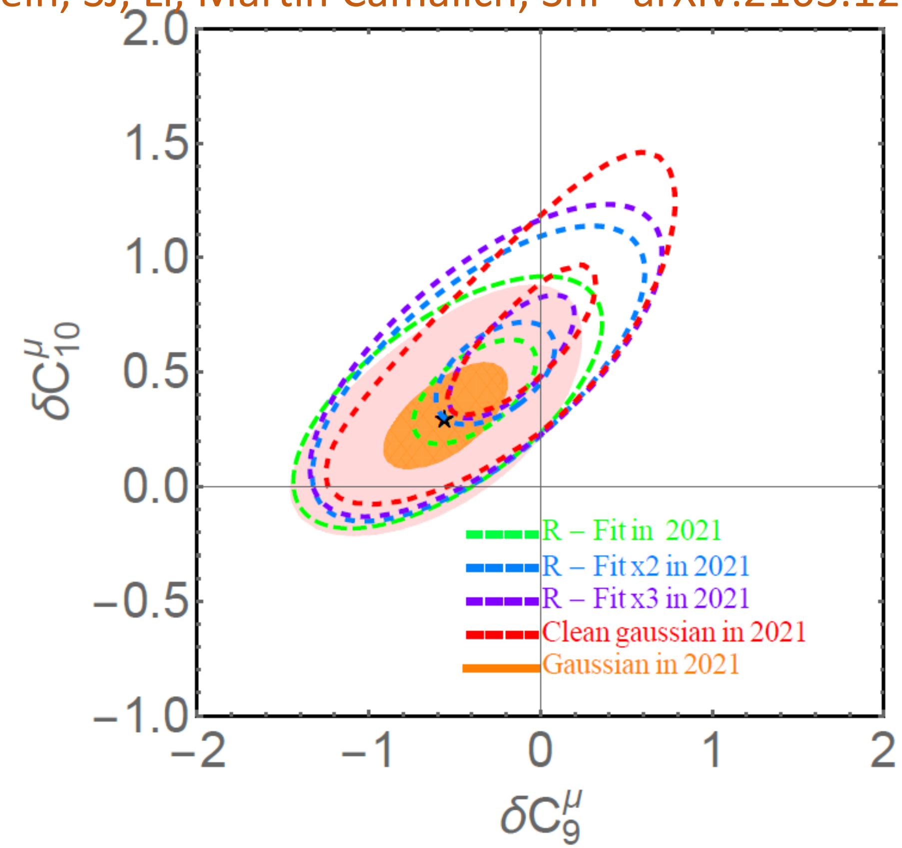
$$(\bar{s}_L \gamma^\mu b_L)\,(\bar{\mu}_L \gamma_\mu \mu_L)$$

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

Adding B→K*μμ angular data

Geng, Grinstein, SJ, Li, Martin Camalich, Shi   arXiv:2103.12738





Left plot: extra data pulls fit approx. along the C_R direction.
C_L=0 remains excluded at high confidence.
p(SM) up at 0.02
Right plot: effect of increasing hadronic uncertainties

Minimal contact interaction

In summary, the B-decay anomalies suggest at a minimum the interaction

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

numerically $\Lambda \sim 40$ TeV

Small enough to be a loop effect even BSM (as it is in SM!)

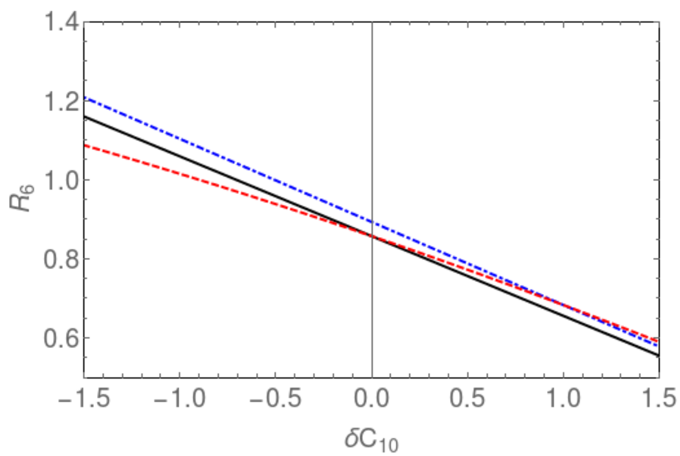
Determining CR (break C9/C10 degeneracy)

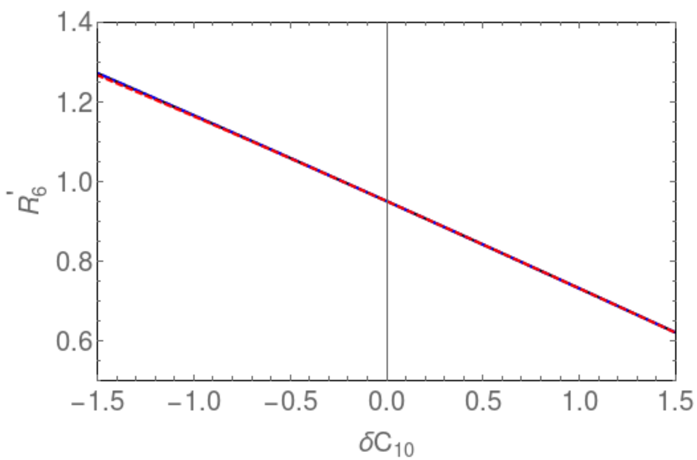
Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446

Propose to measure observable

$$R_6[a,b] = \frac{\int_a^b \Sigma_6^\mu dq^2}{\int_a^b \Sigma_6^e dq^2} \approx \frac{C_{10}^\mu}{C_{10}^e} \times \frac{\int_a^b |\vec{k}| q^2 \beta_\mu^2 \, \mathrm{Re}[H_{V-}^{(\mu)}(q^2)] V_-(q^2)}{\int_a^b |\vec{k}| q^2 \, \mathrm{Re}[H_{V-}^{(e)}(q^2)] V_-(q^2)}$$

and/or $R_6' = \langle P_2^{(\mu)} \rangle / \langle P_2^{(e)} \rangle$



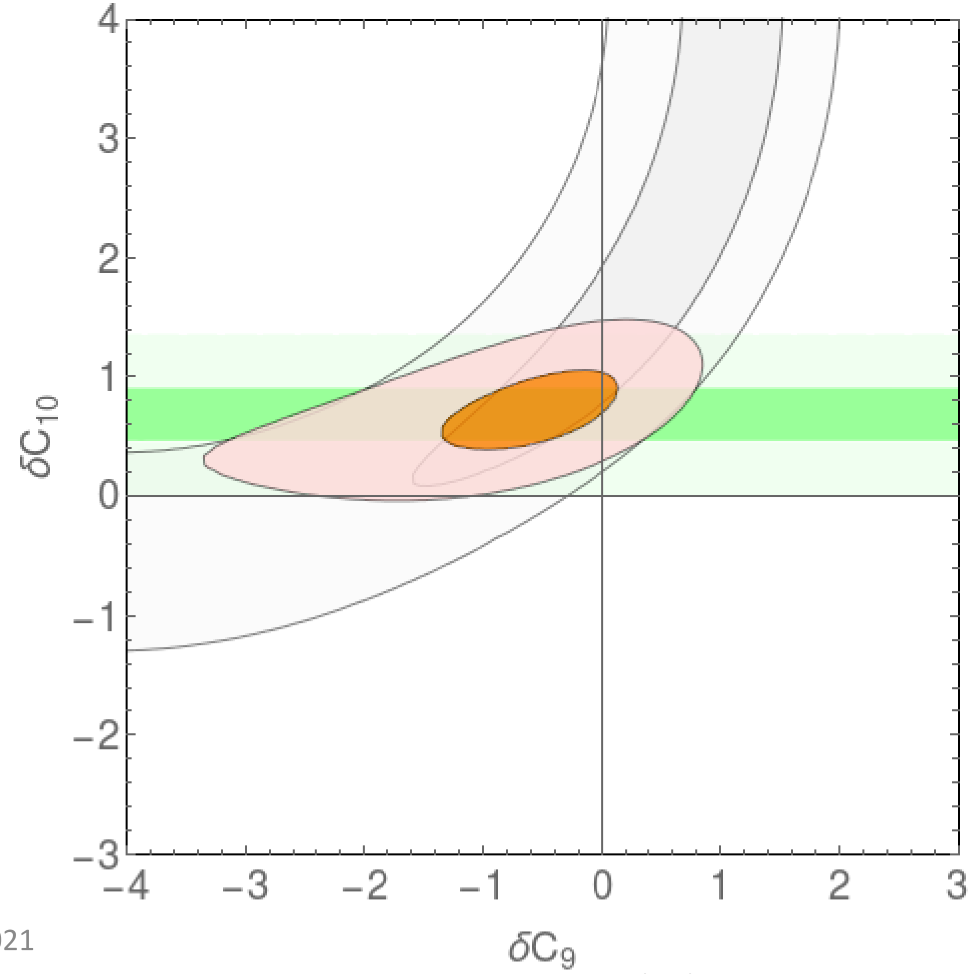


Remains very clean in presence of new physics.
Probes a LUV C10 precisely, irrespective of values of C9e, C9mu

Prospective fit with LUV obs. only

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

Consider a hypothetical experimental result R6' = 0.80(5) [other data from 2017 – not updated!]



Charming new B-physics

Charm and new physics

Postulated to explain non-observation of $K_L \to \mu^+\mu^-$ (GIM)

Discovery key to establishing SM

In B physics, charm appears in leading decays through a partonic $b \to c\bar{c}s$ transition. Large CKM factor.

Usually one assumes BSM corrections to be negligible.

Is this assumption well grounded in data (or theory)?

Observables

rare semileptonic (P5' etc)

radiative ($B \to X_s \gamma$)

width/lifetime differences

$$\Delta\Gamma_s \quad \tau_{B_s}/\tau_{B_d}$$

All calculable in heavy-quark expansion (1/mb)

exclusive charmful: BR, A_{CP}, S_{CP} precisely measured

- not calculable (HQE is $1/(m_c\ \mathrm{alpha}_s)$))

will show a data-driven method

Rare & radiative decays

Standard Model: tree-level W exchange

$$Q_1^c = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i)$$
$$Q_2^c = (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j)$$

RG evolution:

$$Q_9 \propto (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$$

$$Q_7 \propto (\bar{s}\sigma_{\mu\nu} P_R b)F^{\mu\nu}$$

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

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

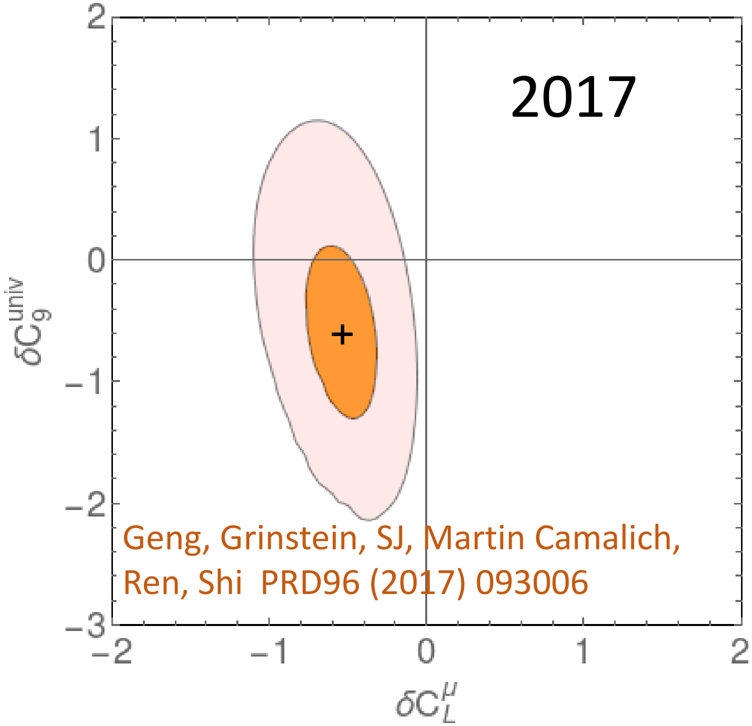
In SM: O(50%) in both cases comes from virtual charm

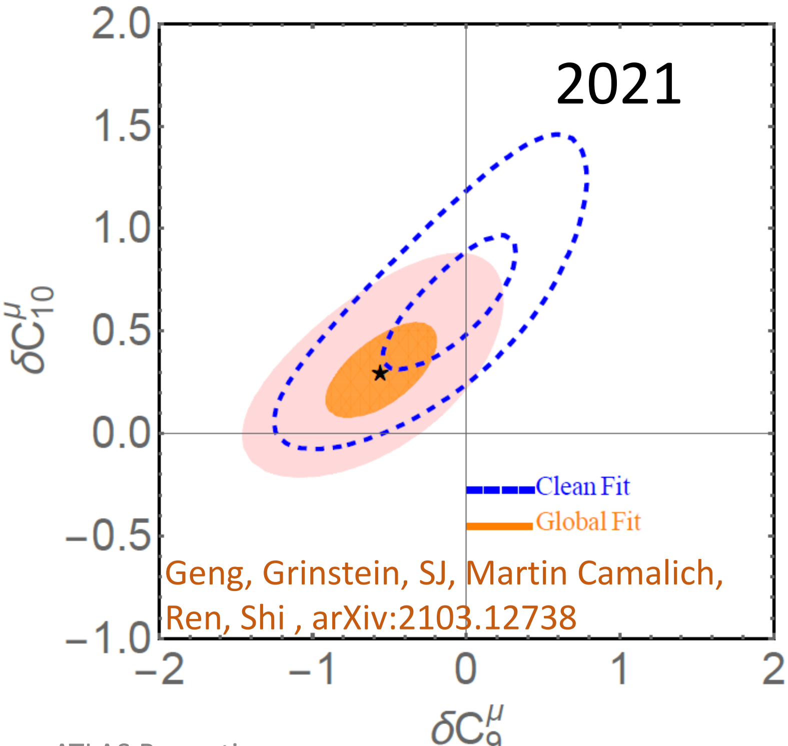
Rare & radiative decays: experiment

Rare B-decay data shows tensions with SM

1) Lepton-universality breaking - needs lepton-flavour specific effect
2) $B_s \to \mu\mu$
3) angular distribution (P_5') - could be lepton-universal C_9-type effect

[2) could be either, but not via C_9]





A UV model may well give both.

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)

$$Q_1^c = (\bar{c}_L^i \gamma_\mu b_L^j)(\bar{s}_L^j \gamma^\mu c_L^i), \qquad Q_2^c = (\bar{c}_L^i \gamma_\mu b_L^i)(\bar{s}_L^j \gamma^\mu c_L^j),$$

$$Q_3^c = (\bar{c}_R^i b_L^j)(\bar{s}_L^j c_R^i), \qquad Q_4^c = (\bar{c}_R^i b_L^i)(\bar{s}_L^j c_R^j),$$

$$Q_5^c = (\bar{c}_R^i \gamma_\mu b_R^j)(\bar{s}_L^j \gamma^\mu c_L^i), \qquad Q_6^c = (\bar{c}_R^i \gamma_\mu b_R^i)(\bar{s}_L^j \gamma^\mu c_L^j),$$

$$Q_7^c = (\bar{c}_L^i b_R^j)(\bar{s}_L^j c_R^i), \qquad Q_8^c = (\bar{c}_L^i b_R^i)(\bar{s}_L^j c_R^j),$$

$$Q_9^c = (\bar{c}_L^i \sigma_{\mu\nu} b_R^j)(\bar{s}_L^j \sigma^{\mu\nu} c_R^i), \qquad Q_{10}^c = (\bar{c}_L^i \sigma_{\mu\nu} b_R^i)(\bar{s}_L^j \sigma^{\mu\nu} c_R^j),$$

+ parity conjugates

RG evolution - numerical

SJ, Kirk, Lenz, Leslie, arxiv:1701.09183 and arXiv:1910.12924,

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

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

Enormous RG effects - can accommodate P_5'

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

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

Observables/constraints

Lifetime ratio $\frac{\tau(B_s)}{\tau(B_d)} = 0.9994 \pm 0.0025$

Width difference $\Delta\Gamma_s^{\rm exp} = 0.088 \pm 0.006\,{\rm ps}^{-1}$

Inclusive radiative decay $\mathcal{B}(\bar{B} \to X_s\gamma)^{\rm exp} = (3.32 \pm 0.15) \times 10^{-4}$

'Pseudo-observables:' fitted Wilson coefficients from (mainly) exclusive radiative and semileptonic decay

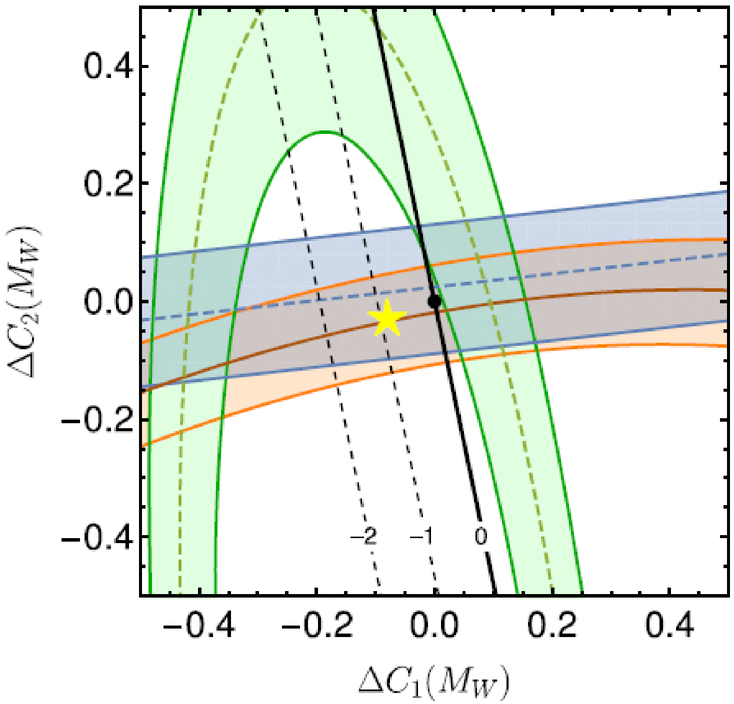
$C'_{7\gamma} = 0.018 \pm 0.037$ Aebischer et al arXiv:1903.10434

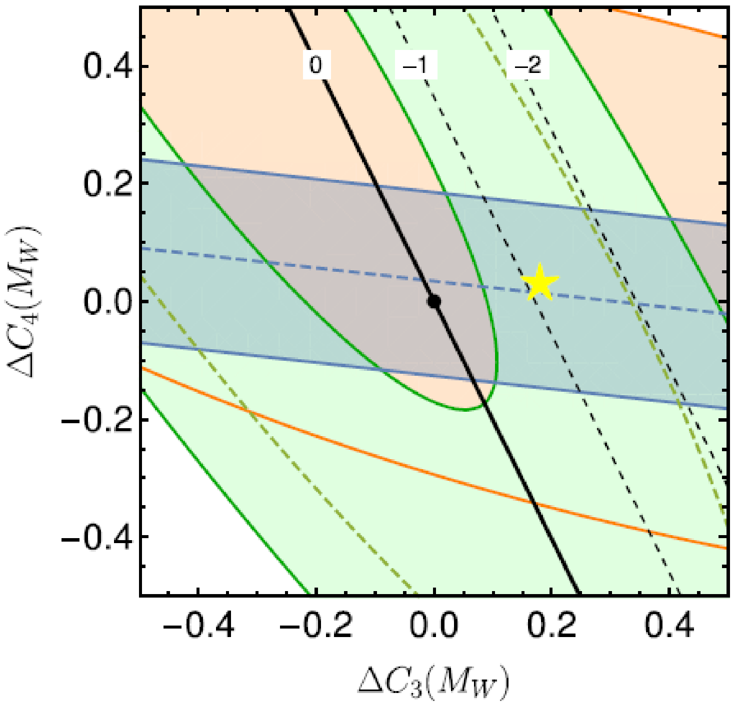
$C'_{9V} = 0.09 \pm 0.15$ Paul & Straub arXiv:1608.02556

Global analysis

SJ, Kirk, Lenz, Leslie, arXiv:1910.12924

‘LH currents’ – strong mixing into C_9





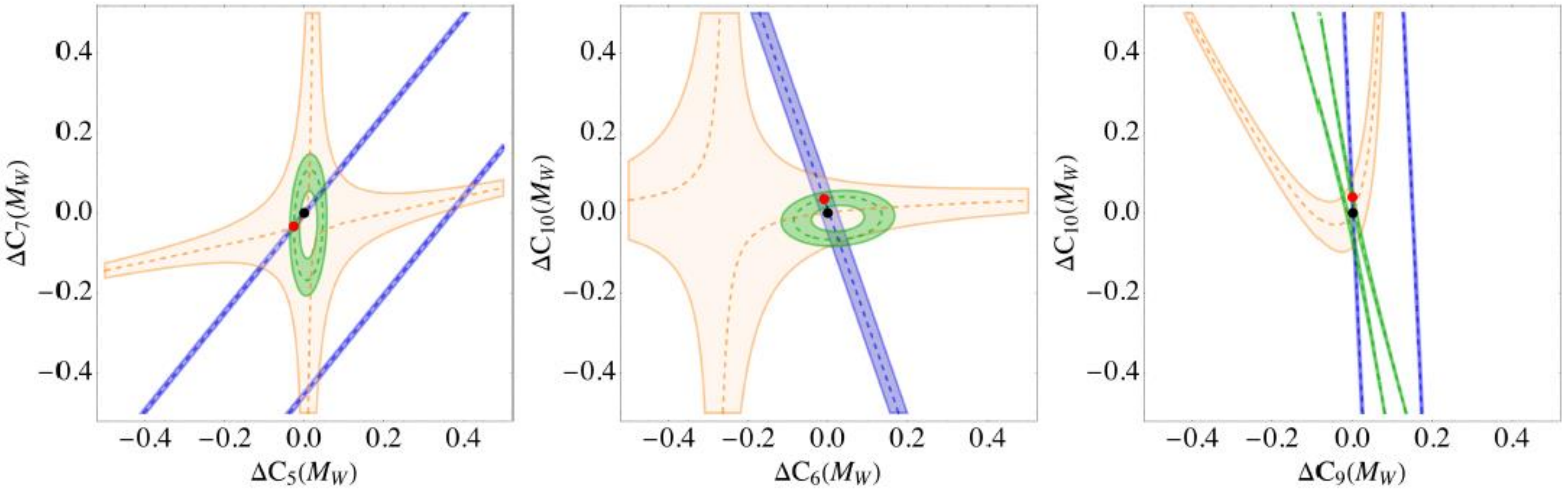
Blue – radiative decay, green – lifetime ratio, brown – width difference

Dashed/solid black: C9(BSM)

Global analysis

SJ, Kirk, Lenz, Leslie, arXiv:1910.12924

‘LH currents’ – strong mixing into dipole



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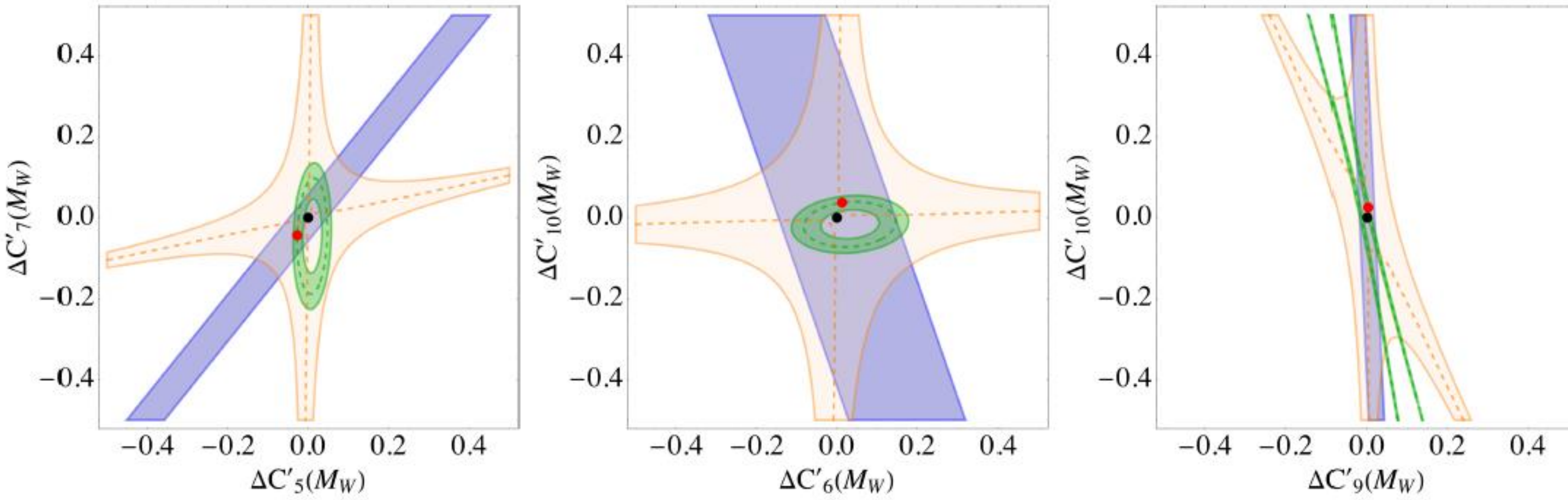
Global analysis

SJ, Kirk, Lenz, Leslie, arXiv:1910.12924

‘RH currents’ – strong mixing into dipole



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

Lower bounds on NP scale

SJ, Kirk, Lenz, Leslie, arXiv:1910.12924

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

B→J/ψ K_S & CP violation

If new physics in $b \to c\bar{c}s$ is CP-violating, it will impact on the precisely measured exclusive B→J/ψ K_S decays.

Three precisely observables:

$$S_{J/\psi K_S} = 0.699 \pm 0.017$$

$$C_{J/\psi K_S} = -0.005 \pm 0.015$$

$$\mathcal{B}(B_d \to J/\psi K_S) = (8.73 \pm 0.32) \times 10^{-4}$$

Note: The impact on the semileptonic asymmetry turns out to be comparably small (will show).

Exclusive B-decay

Exclusive charmful hadronic B-decays suffer from large hadronic uncertainties

e.g data suggests corrections to (calculable) naïve factorisation O(100%)

Weak sensitivity to BSM contributions, especially if CP-conserving

B→J/ψ K_S : theory

Problem: hadronic matrix elements $\langle J/\psi K_S | Q_i | B \rangle$

Heavy-quark expansion uncontrolled

expansion parameter is $\Lambda_{\rm QCD}/(\alpha_s m_c)$

But $\langle J/\psi K_S | Q_1 | B \rangle = \frac{M_B p_c}{2} f_{J/\psi} F^{B\to K} \left(1 + \frac{1}{N_c^2}\right)$

factorizes naively, up to colour-suppressed corrections.

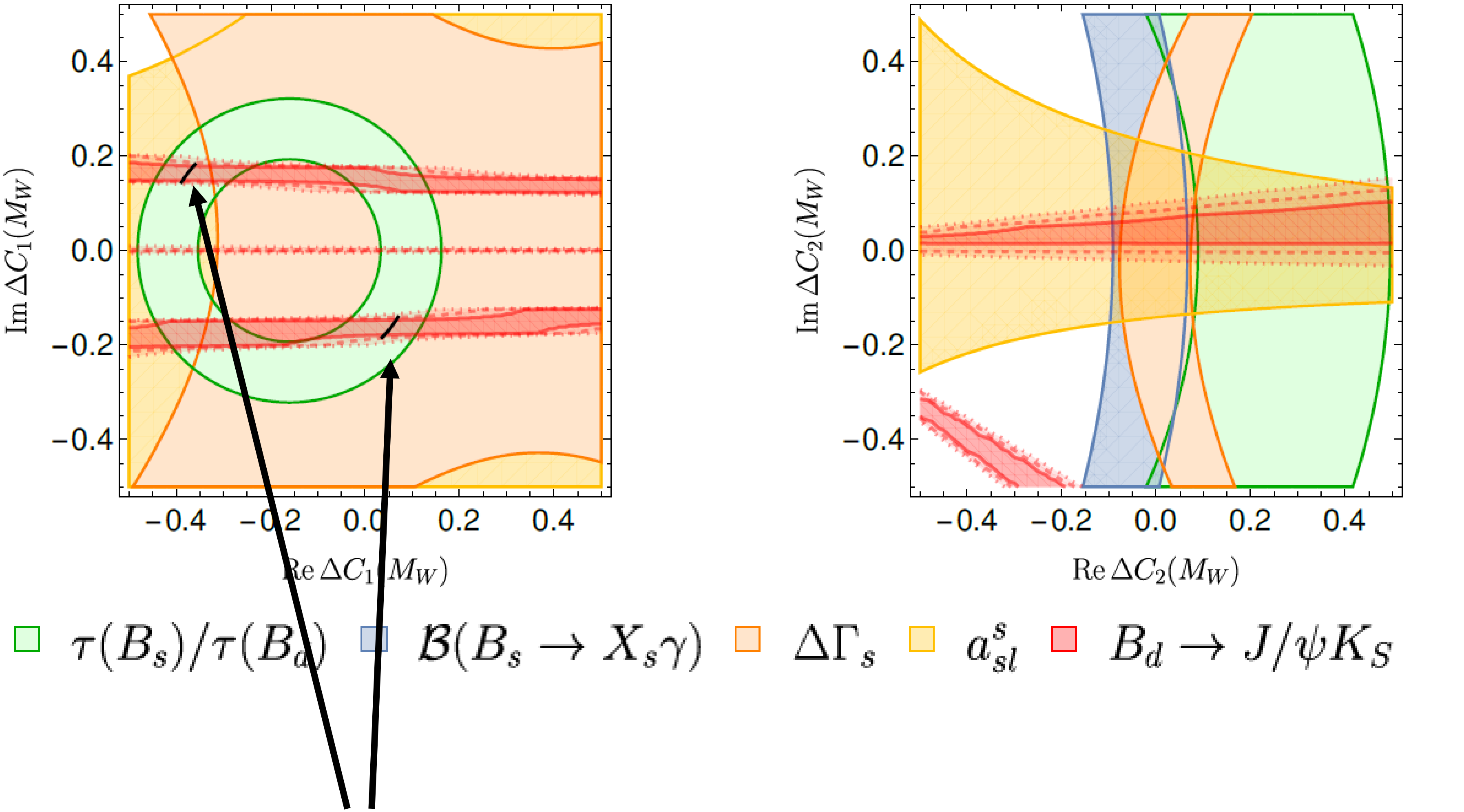
If new physics only affects C_1 or C_2, the incalculable hadronic dynamics is largely contained in a single complex ratio $r_{21} = \langle Q_2 \rangle / \langle Q_1 \rangle$

e.g. $\lambda_{J/\psi K_S} = \frac{q}{p}\frac{\bar{A}}{A} \propto \frac{C_1^* + r_{21} C_2^*}{C_1 + r_{21} C_2}$

4 unknowns (Re C, Im C, Re r_{21}, Im r_{21}) : fit to data !

Global analysis: CP-violating case

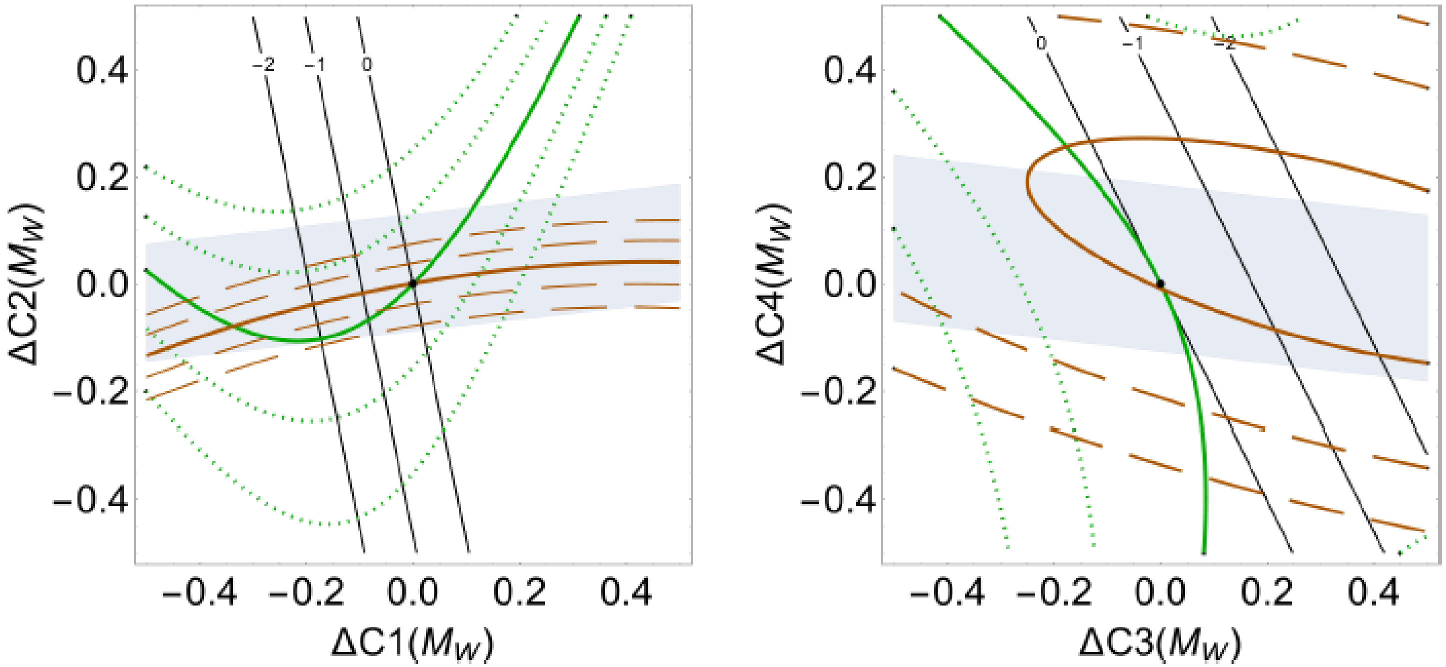
SJ, Kirk, Lenz, Leslie, arXiv:1910.12924



Fitted r_{21} agrees with naïve (!) factorisation

Future prospects for mixing

SJ, Kirk, Lenz, Leslie arxiv:1701.09183



Brown – width difference, green -- lifetime ratio

solid – SM central value

spacing of contours – projected half-width of a 1-σ band

Grey – current BR($B \to X_s \gamma$)

Assumptions: 5% combined (th/exp) error on width difference

0.001 combined error on lifetime ratio

Conclusions

The LHCb updates on R_{K*} and on BR($B_s \rightarrow \mu\mu$) have increased the tension with the SM to 4.0σ. ATLAS contribution is and will be important.

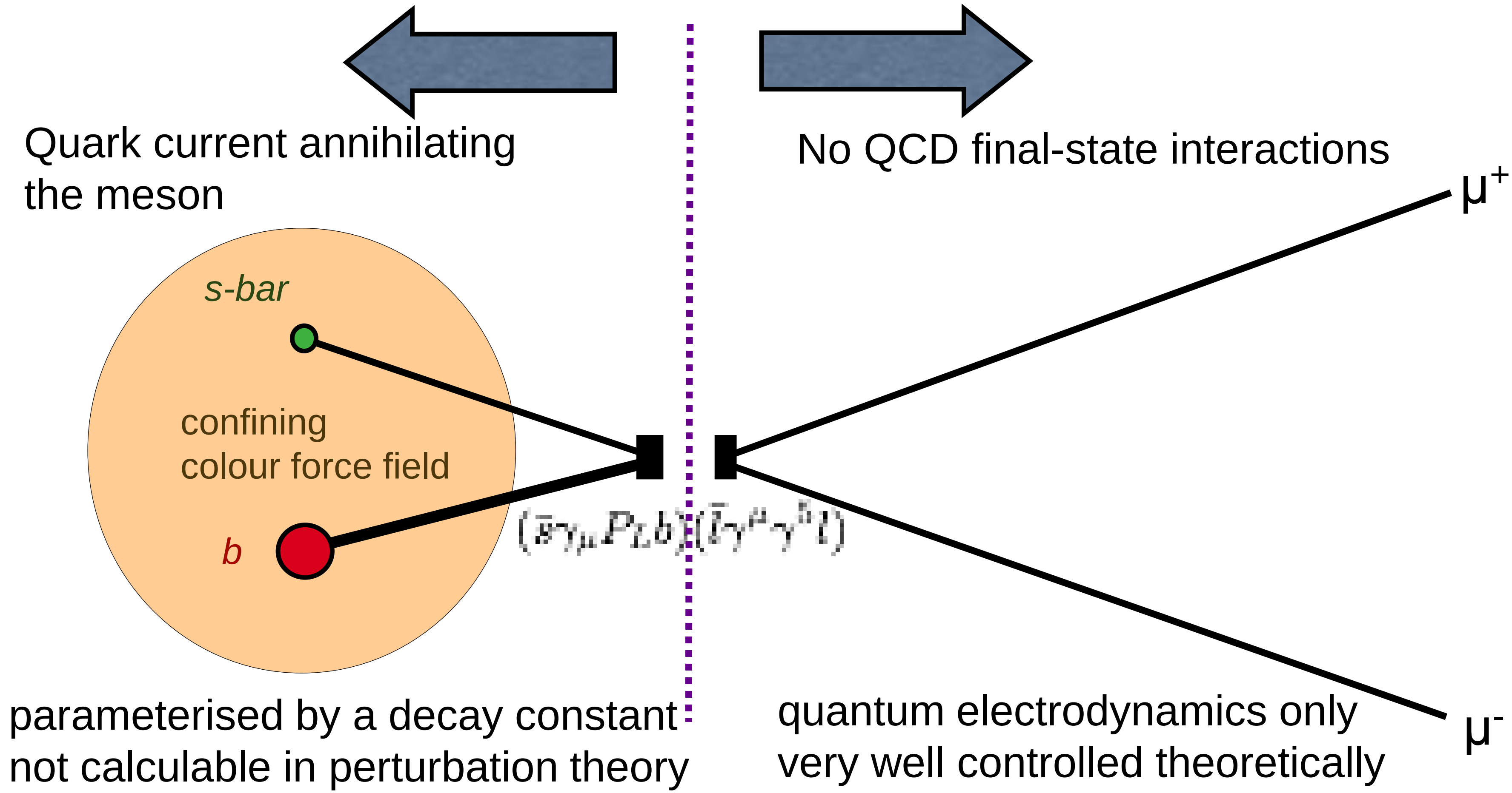
The leptonic decay itself is more than 2σ off and plays an important role in pinning down a region in the 2-parameter BSM fit [always assuming left-handed quark interactions]

In my opinion, this is unlikely to be a statistical fluctuation and very unlikely to be a theoretical issue.

BSM involving charm quarks may contribute to P5’ anomaly (not RK(*)) and provide connection with theoretically controlled hadronic observables (lifetime differences/ratios, CPV in B->J/psi K etc).

BACKUP

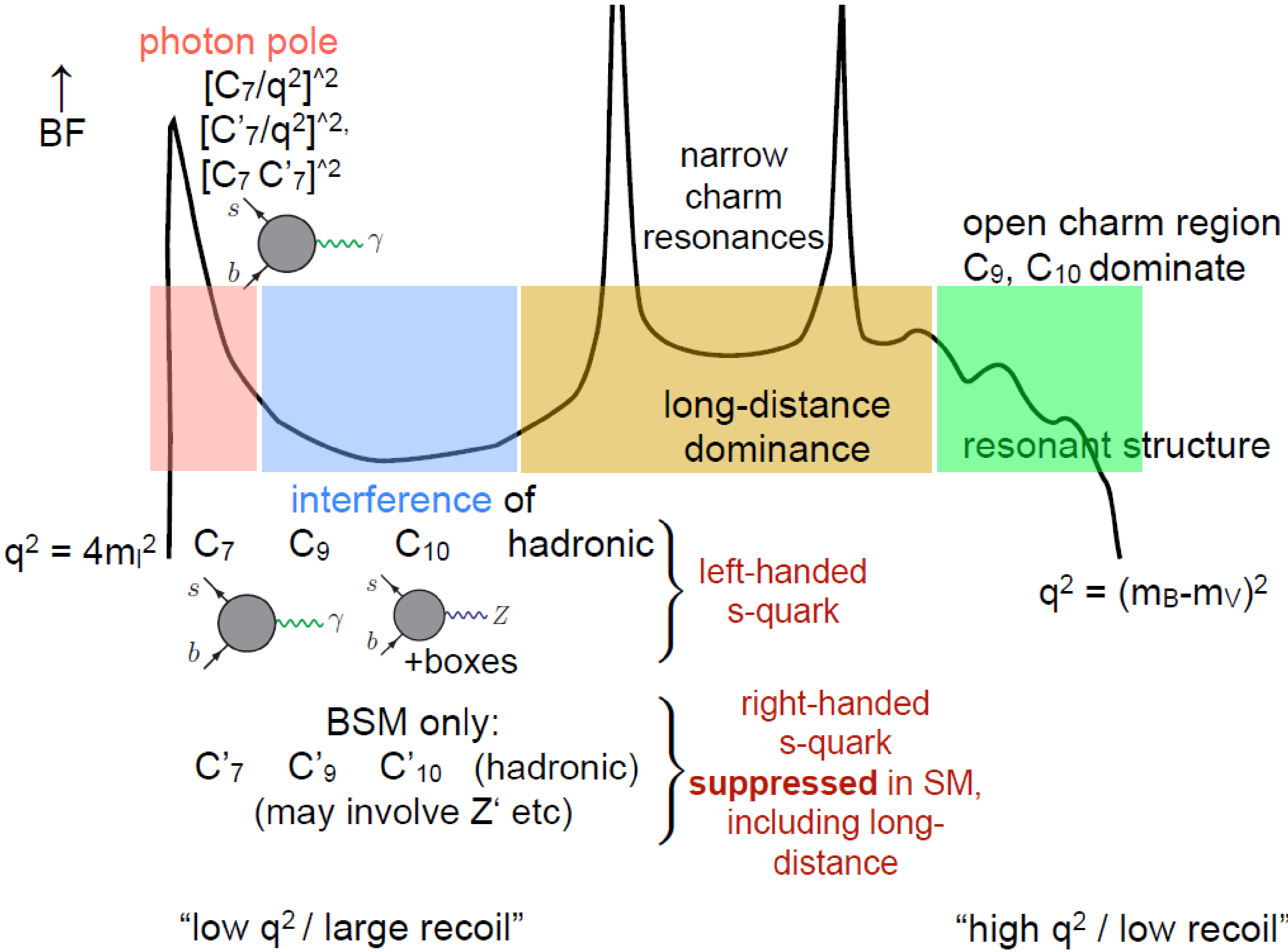
Leptonic decay



Very small long-distance QED corrections Beneke, Bobeth, Szafron 2019

leading theory uncertainty are CKM parameters & decay constant

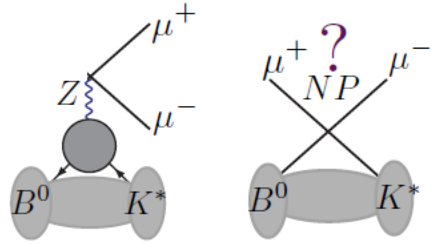
B->V l l: rate (schematic)



Decay amplitude structure

Two mechanisms to produce dilepton in & beyond SM

- via axial lepton current (in SM: Z, boxes) C10

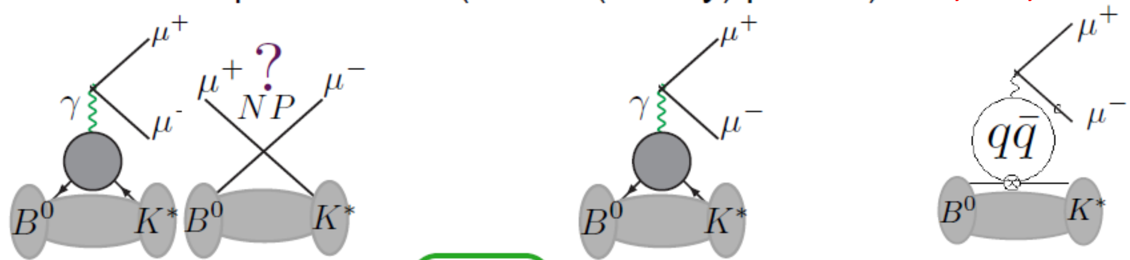


K* helicity

$$H_A(\lambda) \propto \tilde{V}_\lambda(q^2) C_{10} - V_{-\lambda}(q^2) C'_{10}$$

one form factor (nonperturbative) per helicity
amplitudes factorize naively
[nb - one more amplitude if not neglecting lepton mass]

- via vector lepton current (in SM: (mainly) photon) C7, C9, hadronic hamiltonian



$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2) C_9 - V_{-\lambda}(q^2) C'_9 + \frac{2\, m_b m_B}{q^2}\left(\tilde{T}_\lambda(q^2) C_7 - \tilde{T}_{-\lambda}(q^2) C'_7\right) - \frac{16\,\pi^2 m_B^2}{q^2} h_\lambda(q^2)$$

photon pole at $q^2=0$

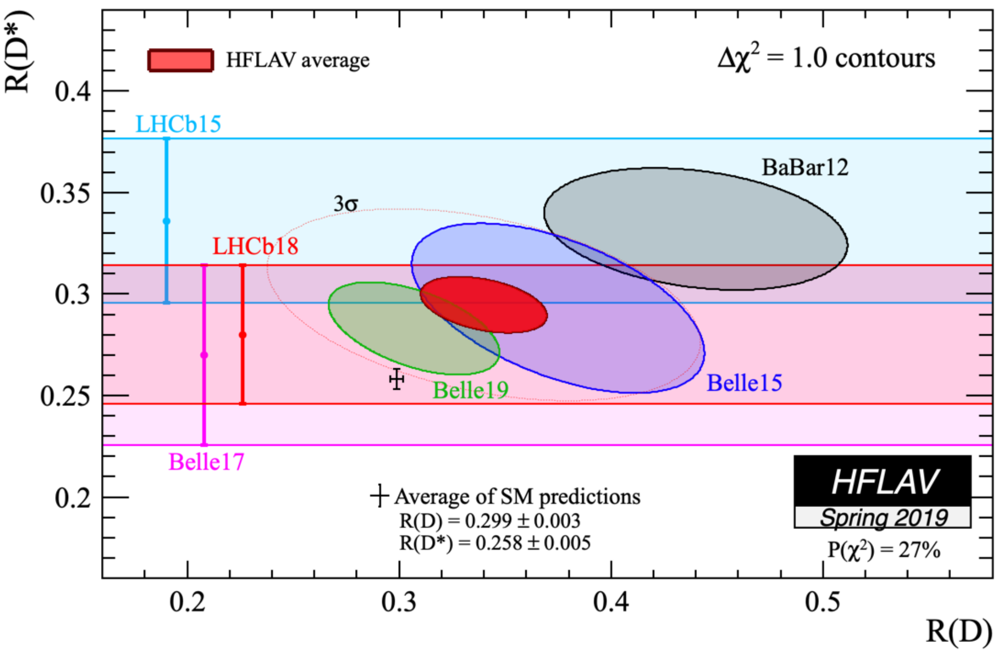
two form factors interfere for each helicity

nonlocal “quark loops”
do **not** factorize naively

Natural, systematic discussion in terms of helicity amplitudes SJ, Martin Camalich 2012, 2014

Photon pole absent for helicity-0 (form factor rescaling)

Non-rare semileptonic decays



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

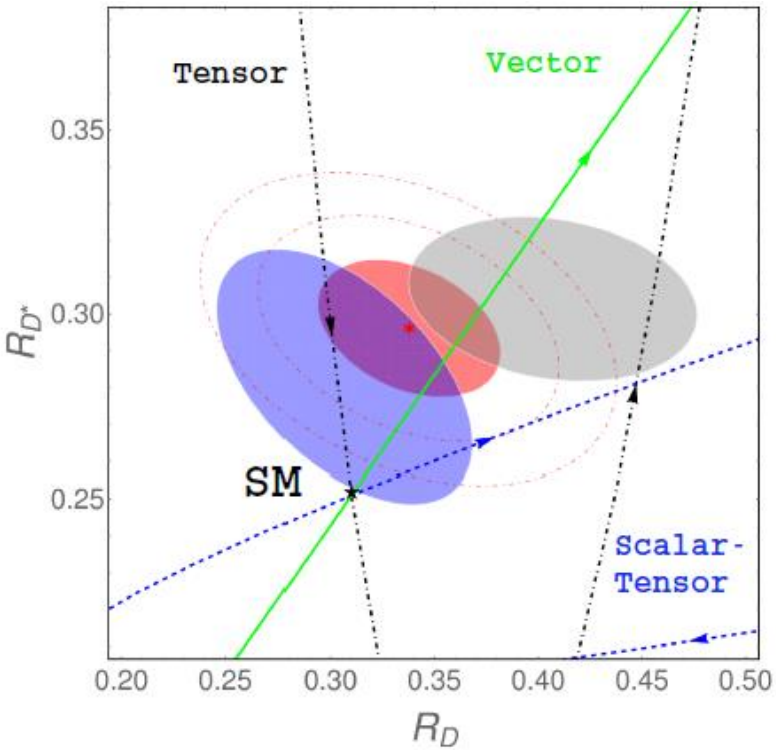
SM **tree-level**

large effect; theory error still (almost) negligible

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*

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 Λ ~ 30 TeV and Λ ~ 3 TeV, respectively
(The latter operator is suggested by the $R_{D^{(*)}}$ anomalies, which I did not discuss.)

- 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.

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)

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

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

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

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

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

$(0,3,0)$

$(0,3,0)$ 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

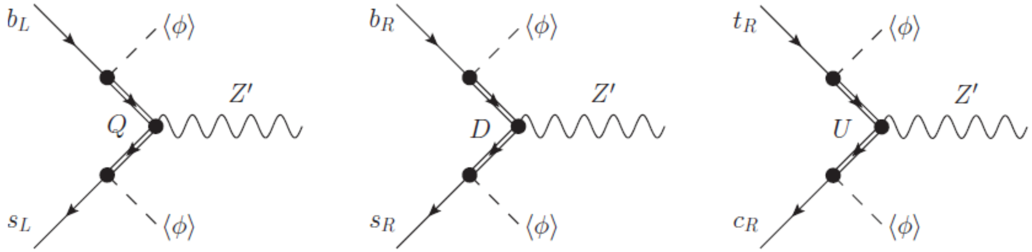
$$\frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\mu}_L\gamma_\mu\mu_L\right)$$

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:

Altmannshofer et al 2014



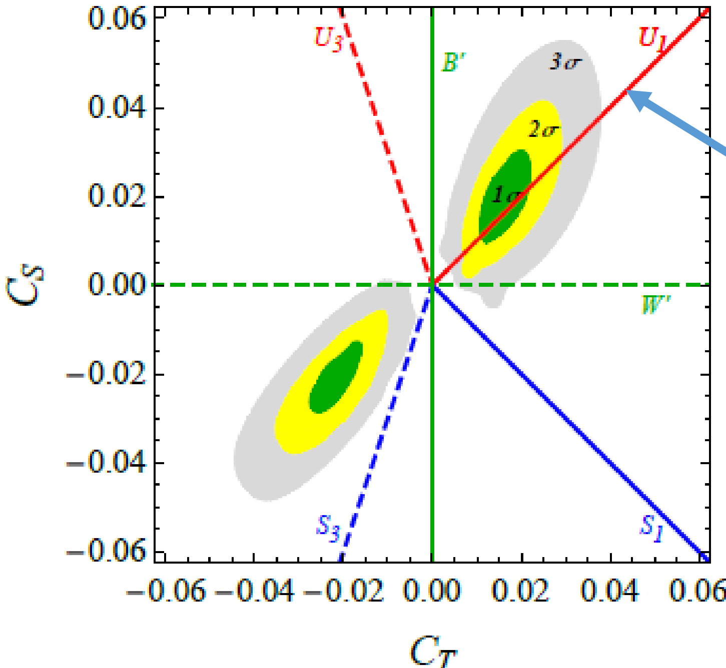
The small coupling to quarks suppresses contributions to Bs mixing

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.)



$(3, 1, 2/3)$

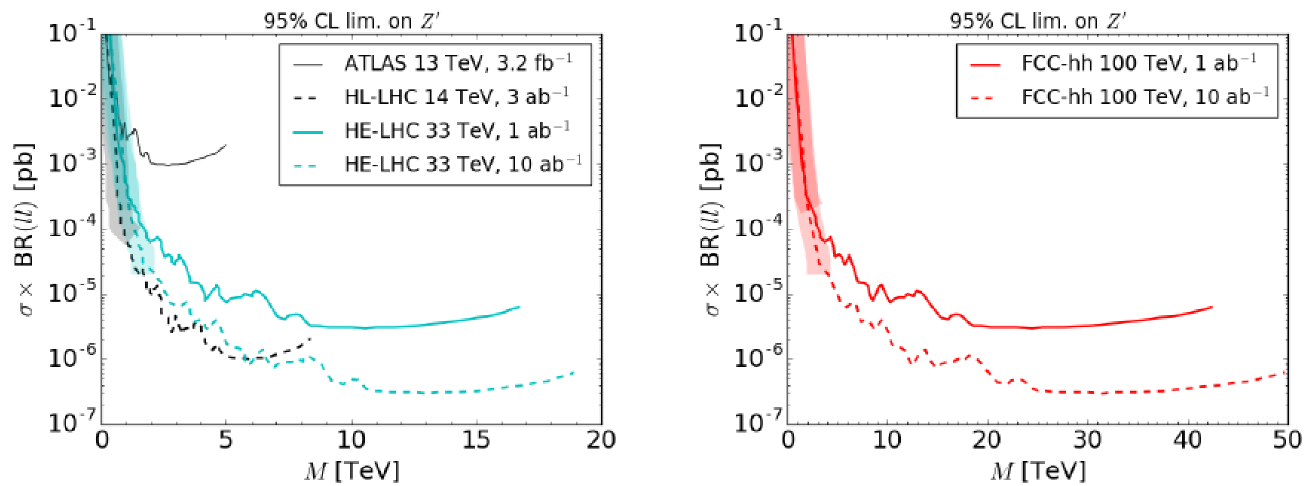
vector leptoquark

Buttazzo, Greljo, Isidori, Marzoca arXiv:1706.07808

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

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.

&

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

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

- 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 $C_7^{\rm eff}$, 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

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 → K*vv Buras et al arXiv:1409.4557

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

τ