Thoughts on B-physics Anomalies

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NExT Meeting

Sussex, 10 May 2017

Largely based on
- arXiv:1701.09183 (w/ M Kirk, A Lenz, K Leslie)
- arXiv:1704.05446 (w/ L-S Geng, B Grinstein, J Martin Camalich, X-L Ren, R-X Shi

Outline

Why BSM flavour?

RD and RD* (lepton-universality tests)

Brief recap on B->K* l l angular distribution

RK and RK* (lepton-universality tests): Interpretation as lepton-universality-violation in semileptonic Wilson coefficients

Next steps: angular observables to pin down chirality structure

Semi-universal BSM Wilson coefficients, ‘charming BSM scenario’ and connection with lifetime observables

What we know

(Ordered by elegance)

spin 1

electromagnetism U(1)

weak interactions SU(2)

strong interactions SU(3)

spin 1/2

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R d_R	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	c_R s_R	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	t_R b_R	$Q = +2/3$ $Q = -1/3$
$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$-$ e_R	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$-$ μ_R	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	$-$ τ_R	$Q = 0$ $Q = -1$

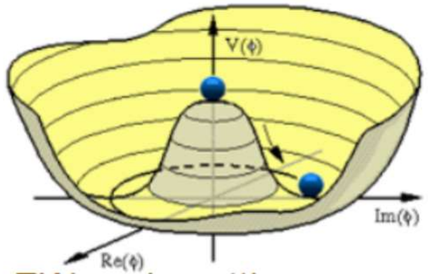
NEW **spin 0**

Higgs - sets mass scale of entire Standard Model

But: naturalness? Dark matter? Point to TeV BSM physics

Dynamics

The discovery of a Higgs scalar and apparent absence of other particles implies the following approximate Lagrangian at length scales between an attometre and a fermi

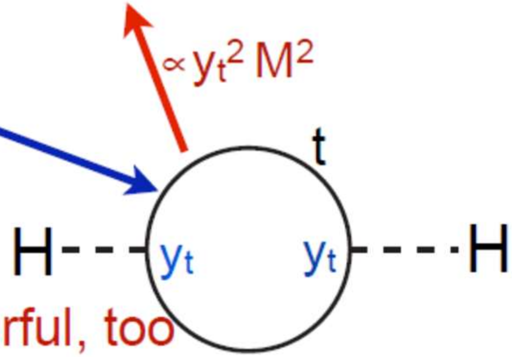


SU(3)^5 flavour symmetric kinetic/gauge terms

EW scale setting

$$\mathcal{L}_{\rm SM} \sum_f \bar{\psi}_f \gamma^\mu D_\mu \psi_f - \sum_{i,a} \frac{1}{4} g_i F^{ia}_{\mu\nu} F^{ia\mu\nu}$$
$$-\bar{u}_R Y_U \phi^{c\dagger} Q_L - \bar{d}_R Y_D \phi^\dagger D_L - \bar{e}_R Y_E \phi^\dagger E_L + \mu^2 \phi^\dagger \phi - \frac{\lambda}{2}(\phi^\dagger \phi)^2$$

flavour-breaking fermion masses and Higgs couplings



NB: naturalness problem is (mostly) caused by top Yukawa, a flavour-breaking term

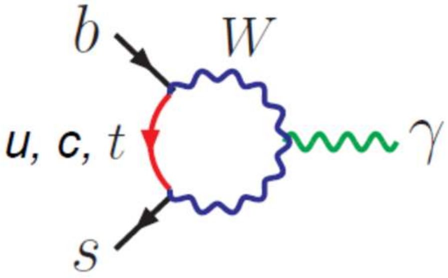
Physics addressing naturalness should be flavourful, too

This happens in supersymmetry, extra dim/composite Higgs, ...

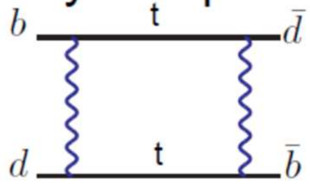
Rare decays

SM: Loop + CKM suppression of FCNC (GIM)

y_t main source of GIM breaking: enhanced sensitivity to top

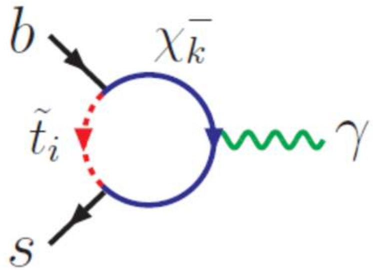


e.g. B-Bbar oscillations first indication of a heavy top (Argus 1987)



Charm contribution sometimes sizable/uncertain due to large logarithms and/or nonperturbative QCD effects. Often leading source of uncertainty

BSM: Can compete even in weakly coupled case (MSSM)



MSSM: sensitive to stops and their couplings
Stringent constraints on 1st-2nd generation mixing

In more general cases can have tree-level contributions (Z')

In strongly coupled models may lose loop suppression, flavour most stringent generic constraint absent flavour protection (RS)

Effective contact interactions

Heavy physics with mass scale M described by local effective Lagrangian at energies below M (many incarnations)

Effective Lagrangian dimension-5,6 terms describes **all** BSM physics to O(E^2/M^2) accuracy. **Systematic & simple**. E.g.

Buchmuller, Wyler 1986
Grzadkowski, Misiak, Iskrzynski, Rosiek 2010

Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

operators (vertices) are catalogued for arbitrary (heavy) new physics

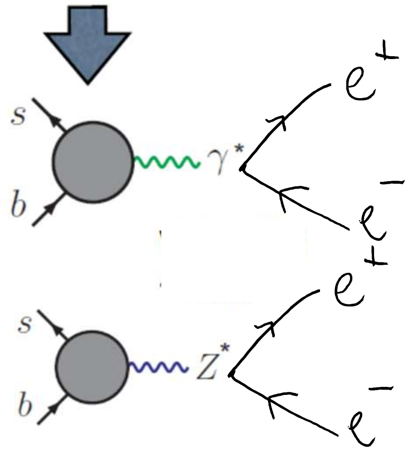
Only trace of BSM physics is in their (Wilson) coefficients

Much slower decoupling with M than in high-pT physics.

Possibility to probe well beyond energy frontier.

Effective Hamiltonian: rare (semileptonic) decays

in SM mainly



C_9 : dilepton from vector current (L=1)

$$Q_{9V} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$$

C_{10} : dilepton from axial current (L=1 or 0)

$$Q_{10A} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu\gamma^5 l)_A$$

- both can be obtained from Z' exchanges
- or leptoquarks

Descotes-Genon et al; Altmannshofer et a
Crivellin et al; Gauld et al; ...

Alonso-Grinstein-Martin Camalich; Hiller-Schmaltz; Allanach et al; Gripajos et al; ...

C_7 : dilepton produced through photon (virtuality q^2, pole at q^2=0)

$$Q_{7\gamma} = \frac{e}{16\pi^2} m_b\, (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}$$

- strongly constrained from inclusive b->s decay

BSM: also parity-transformed operators (C_9', C_{10}', C_7')

C_9, C_{10} can depend on the lepton flavour.

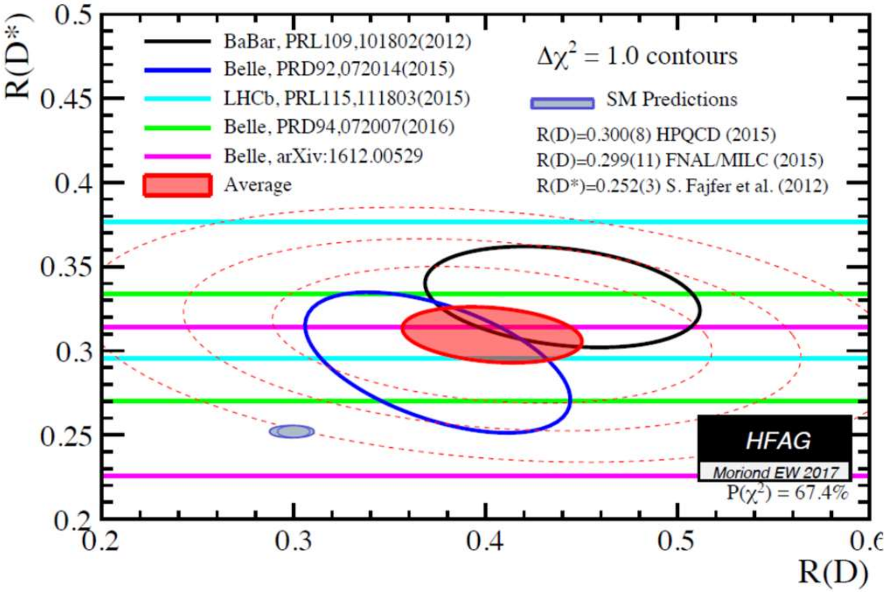
Universal BSM effects in C_9 mimicked by a range of SM effects

C10 effects or lepton-specific effects distinguishable from SM effects

Anomaly I: b→c τ ν(τ)

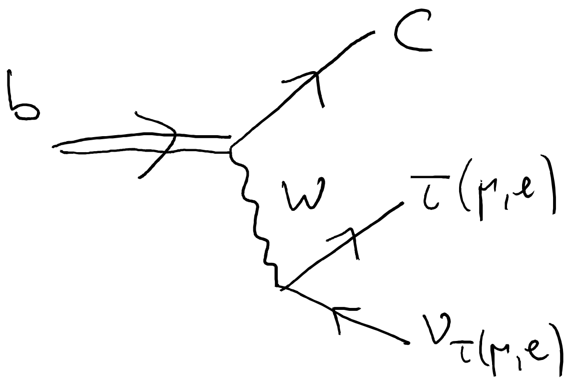
For some time B-factories and LHCb have consistently shown semileptonic B ->D (D*) τν decay rates larger than expected

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



3.9 sigma effect

SM **tree-level** effect



Theory error negligible relative to experiment

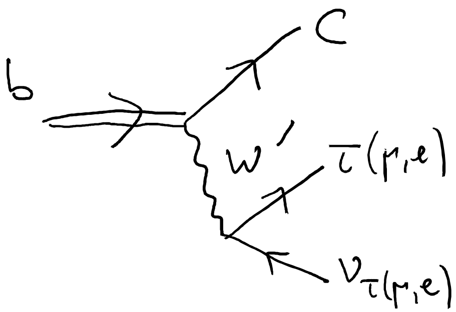
Anomaly I: $b \to c\, \tau\, \nu(\tau)$

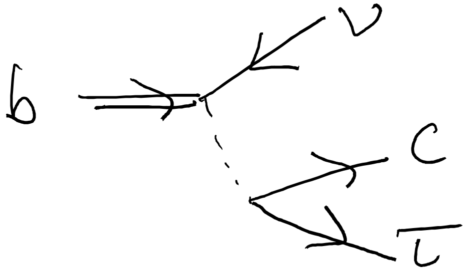
Can be interpreted as BSM effect

Including differential decay distribution, data favour modification of SM effective coupling (operator with all fermions left-handed)

Eg Ligeti et al 2015,16

Possible mediation by W' or leptoquarks,





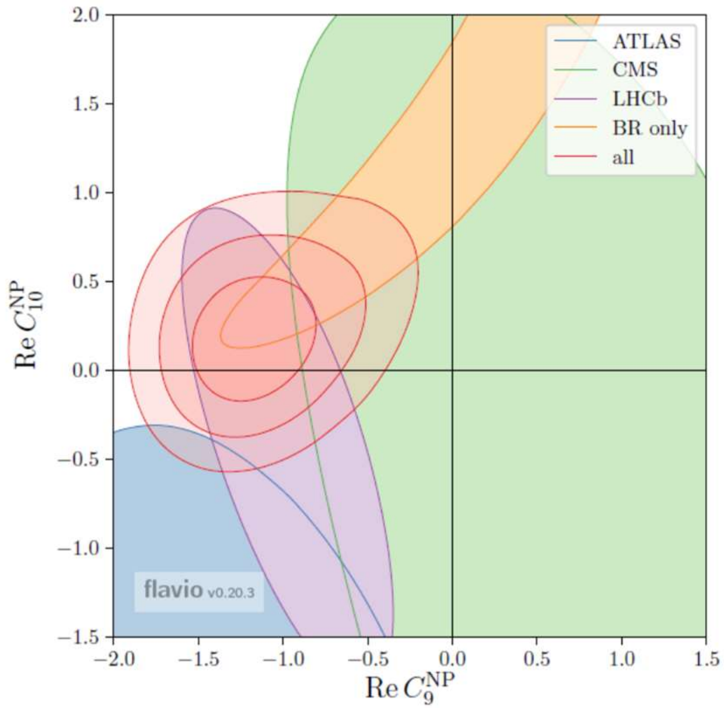
Isidori et al, Ligeti et al, Becirevic et al, Crivellin et al, …

In principle R(D(*)) could also be affected by suppressing the couplings to light leptons; disvafoured by B-factory data

Anomaly II: b->sll angular distribution

=the P5' saga

The B->K* mu mu angular distribution (32 measurements at small dilepton mass by LHCb; several more at large dilepton mass, and by ATLAS, CMS, and Belle) may point to modified C9 and/or C10 couplings



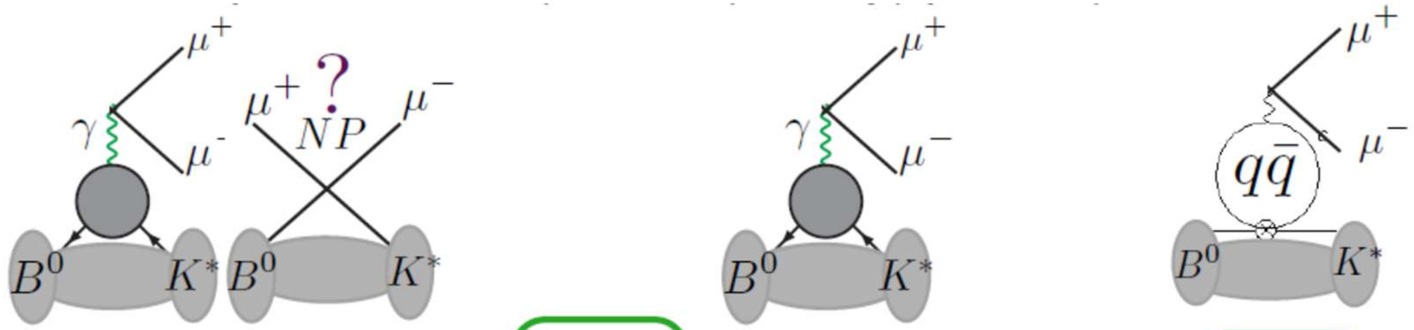
Eg Altmannshofer et al 2017

Several branching ratios seem low but theory normalisation uncertain

Preference for C9 shift from angular analysis (specifically S5 / P5' term) unfortunately also depends on assumptions about form factors

Anomaly II: theory bug-bears

C9 enters through the vector helicity amplitudes



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

photon pole at $q^2=0$

Main problem: C9 effects are degenerate with form factor uncertainties and virtual-charm effects

Both constrained by heavy-quark limit; power corrections?

SJ, Martin Camalich 2012, 2014

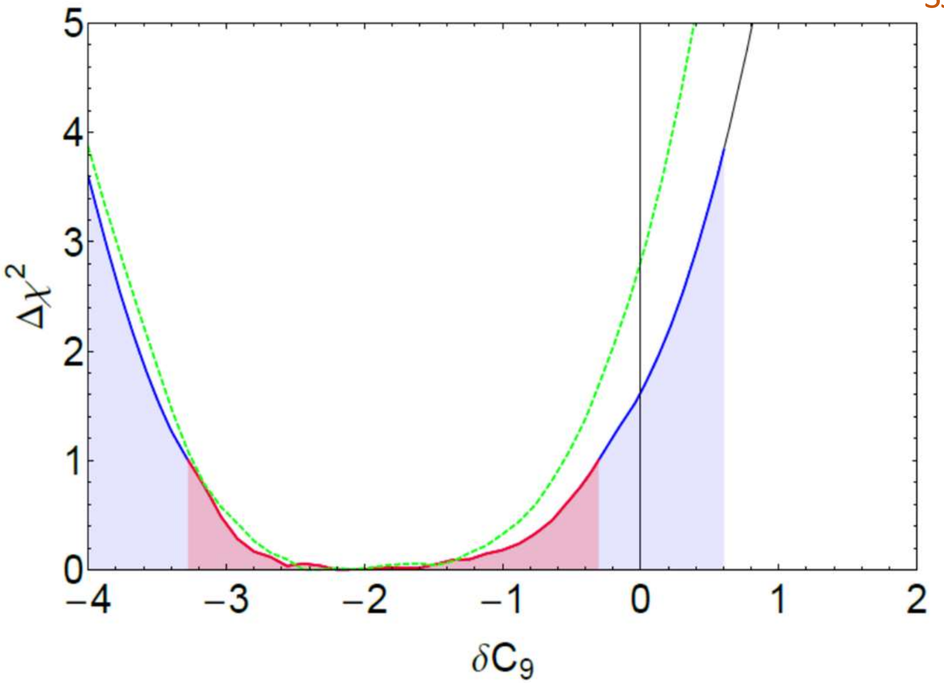
Purported BSM effect O(20%); two relevant form factor ratios; need ~10% accuracy.
Analyses **crucially** rely in one way or another on light-cone sum rule estimate quoting few-% errors

Ball&Braun; Ball& Zwicky; Bharucha,Straub,Zwicky 2015

C9 sensitivity w/o light-cone sum rules

Most general parameterisation of power correction to the heavy-quark limit; varying each parameter at 10% of ‘natural’ leading-power effect; profile likelihood

SJ, Martin Camalich 2012, 2014



from SJ, Martin Camalich 1412.3183 (angular obs. with 1 fb^-1 LHCb data)

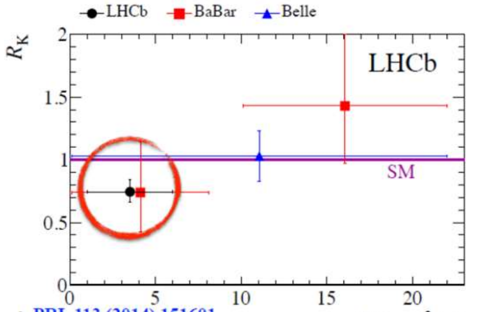
two paramerterisation

schemes (green, blue)

Preference for C9<C9SM, with modest significance

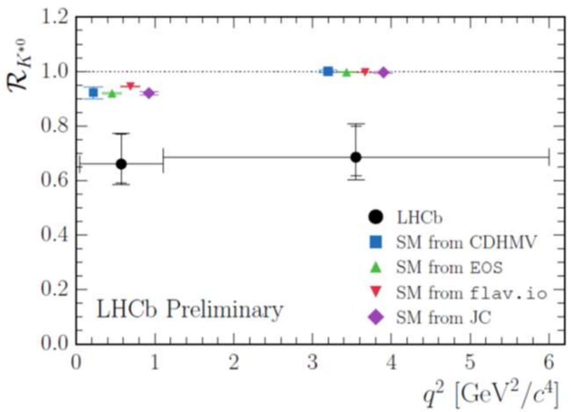
Anomaly III: b->sll lepton-universality violation (LUV)

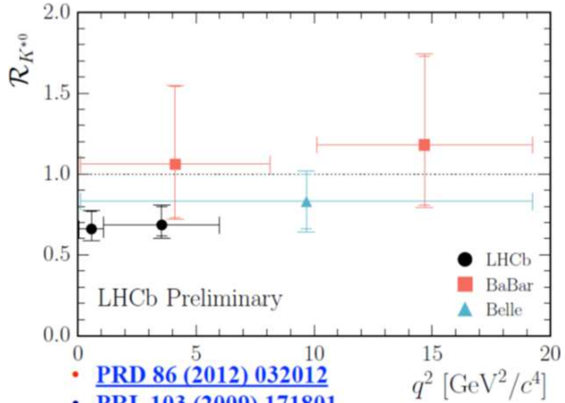
In 2014 LHCb reported R(K) = BR(B->Kmumu)/BR(B->Kee) < 1
(in a bin where the lepton mass should be irrelevant)



- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

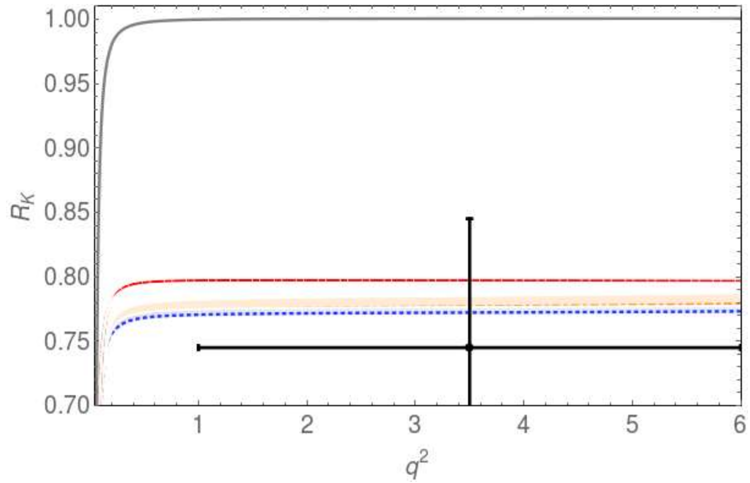
On 18 April 2017 LHCb reported on a much-anticipated measurement of R(K*) = BR(B->K*mu mu)/BR(B->K*ee) in two bins

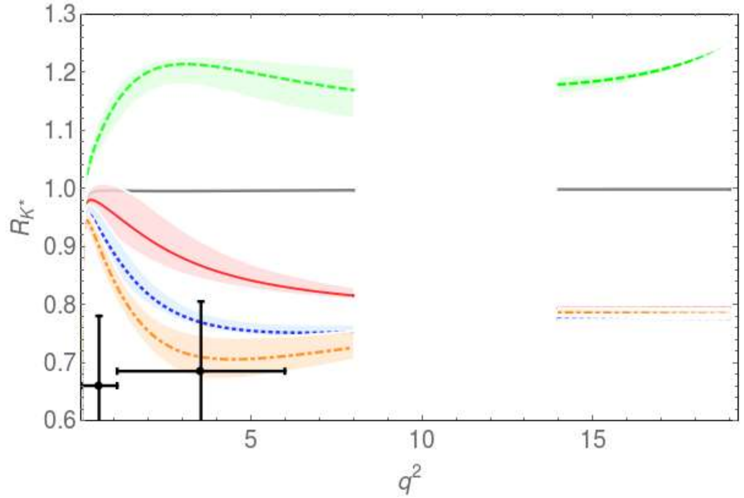




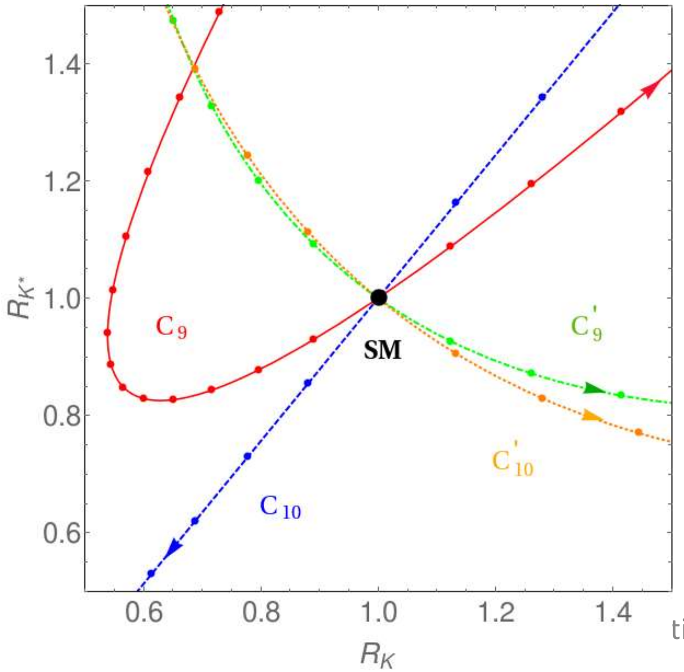
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

LUV measurements vs theory





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



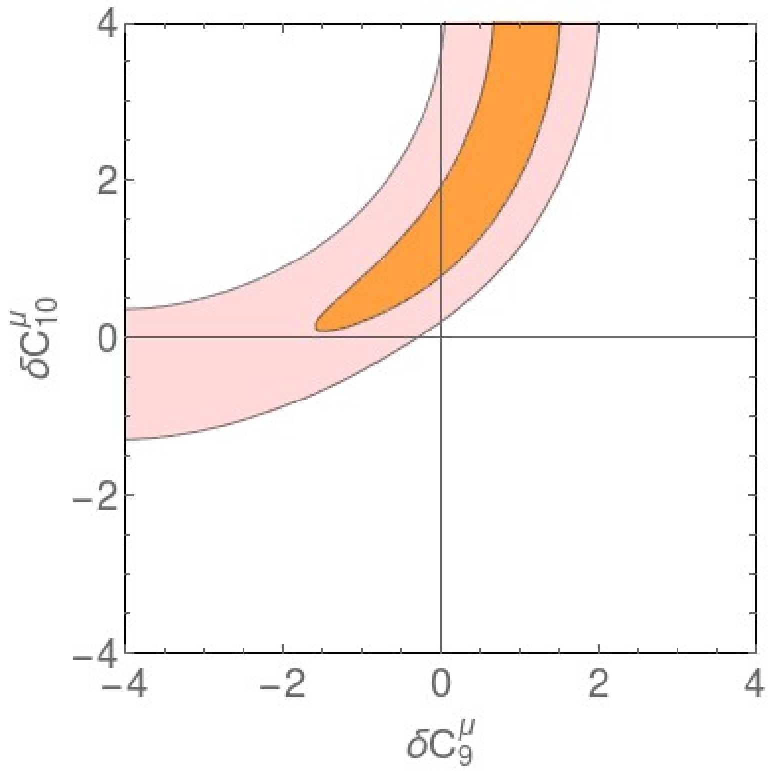
p(SM) = 2.1 x 10^-4 (3.7)

Suggests nonzero C10(BSM)

Pure LUV fit

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.

1sigma and 3sigma confidence regions

C10(BSM)>0 favoured

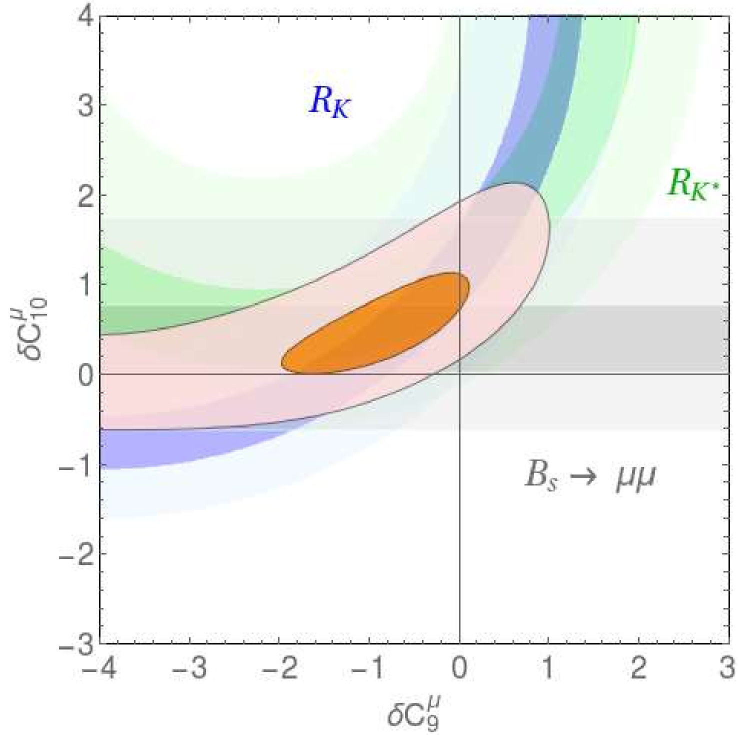
p = 0.158

SM pull 3.78 sigma

Considerable degeneracy (flat direction in chi2)

Adding Bs->mu mu

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



Selective probe of C10 (and C10')

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

Considerably narrows the allowed fit region

p = 0.191

SM pull 3.76 sigma

Fit prefers nonzero CL = (C9-C10)/2

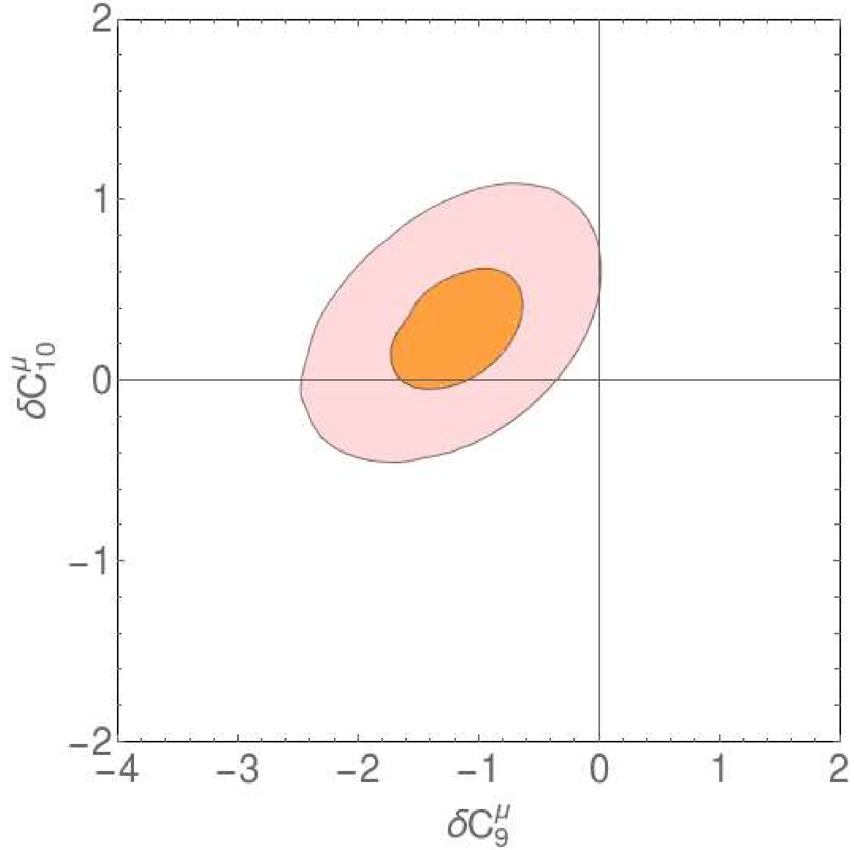
CR = (C9+C10)/2 not well constrained and consistent with zero

1-parameter CL fit: besf fit -0.61. 1sigma [-0.78, -0.41], p = 0.339

SM point (origin) excluded at 4.16 sigma

Adding B->K*mu mu angular

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



Serves to determine best-fit region even better.

SM pull 4.17 sigma

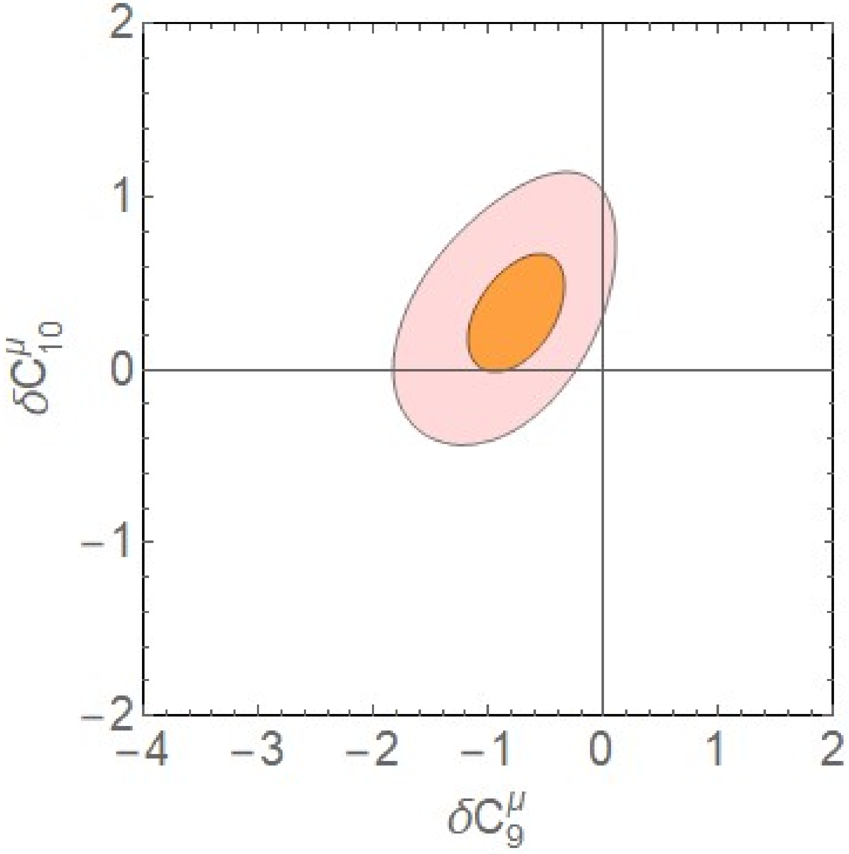
p = 0.572

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

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

Adding B->K*e e BR & angular

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



(preliminary)

Serves to determine best-fit region even better.

Similar significance and pull as before

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

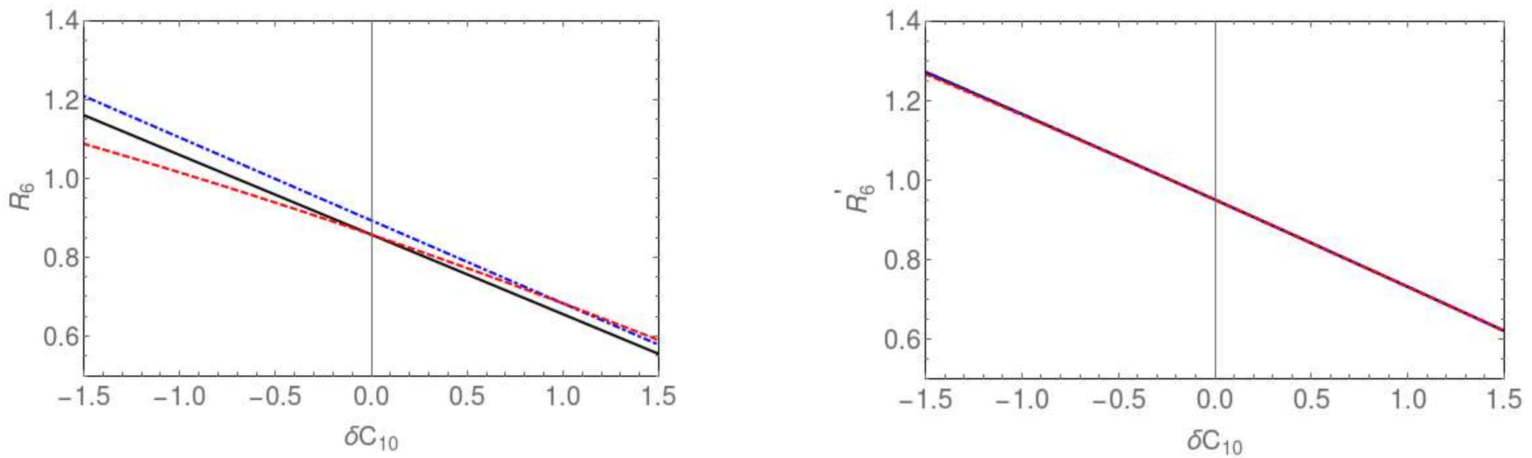
Determining CR (break C9/C10 degeneracy)

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

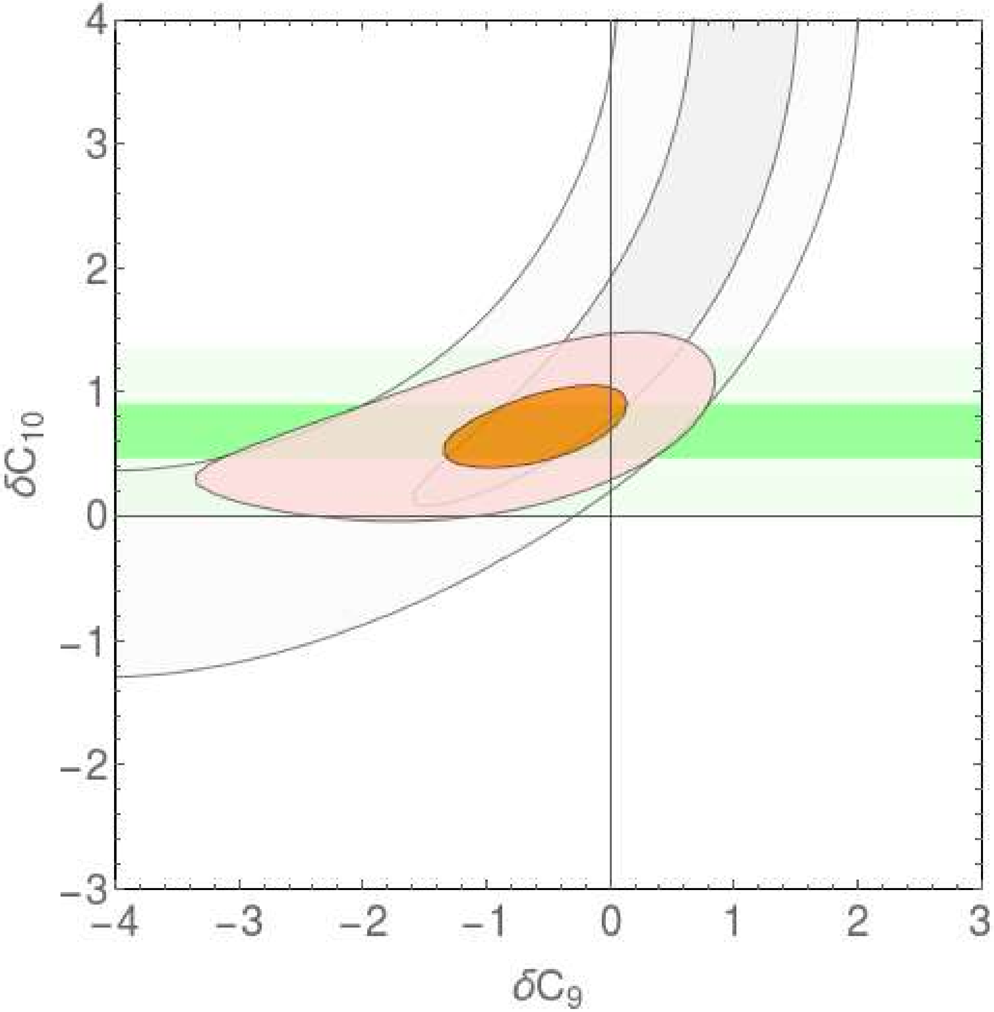


Remains very clean in presence of new physics.
Probes a LUV C10 precisely, irrespective of values of C9e, C9mu

Prospective fit with LUV obs. only

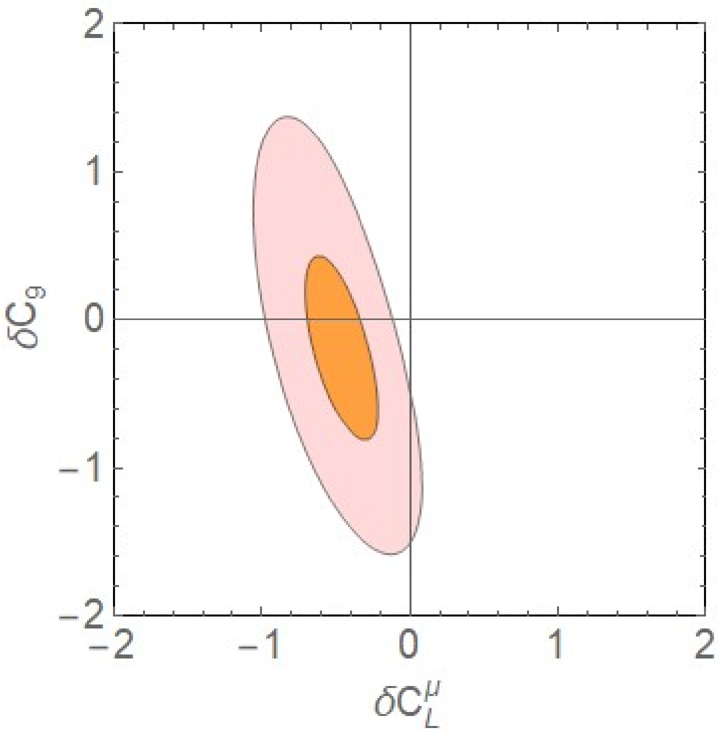
Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446

Consider a hypothetical experimental result R6' = 0.80(5)



Must C9 show LUV ?

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



Modified C10 needed to suppress RK* (both bins)

Preference for modified C9 (over C10) is due to angular observables in B->K* mu mu

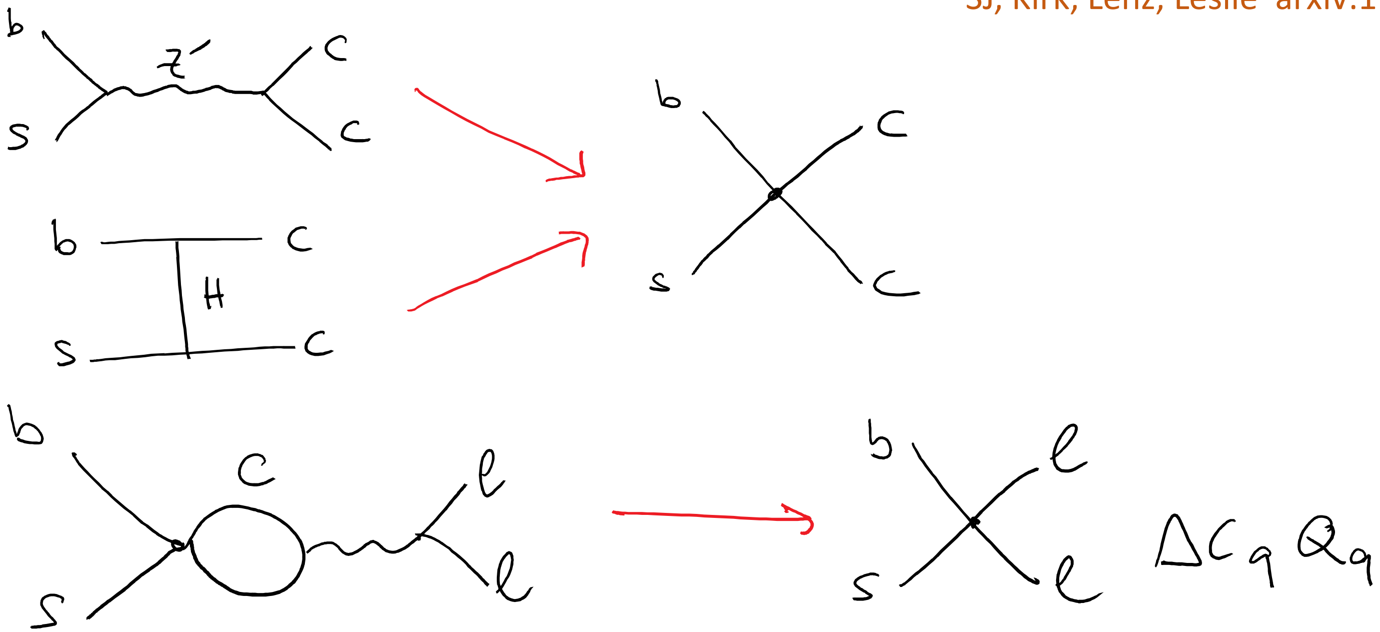
This means a model with (for example) nonzero CLmu and in addition an ordinary, **lepton-flavour-universal, C9**, can describe the data similarly well or better

[preliminary plot]

Can generate from 4-quark operators

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

e.g.



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

"Charming BSM scenario"

I have (...) heard on good authority that I was dead. (…) The report of my death was an exaggeration.

As we just saw, LUV does allow such a scenario, and may even favour it. We will see that it remains alive in light of other data.

Charming BSM scenario

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

As long as NP mass scale M is >(>) mb, **model-independently** captured by an effective Hamiltonian with 20 operators/Wilson coefficients (including C1, C2 of SM)

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

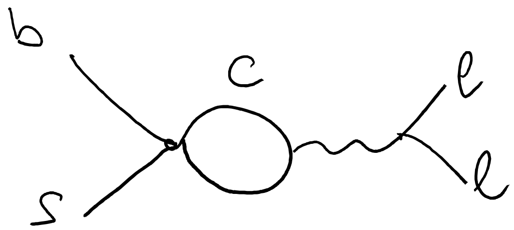
+ parity conjugates

virtual-charm BSM previously considered by

He, Tandean, Valencia (2009) (in a model; did not consider semilept/radiative decays)
Lyon&Zwicky (2014) (as a possible origin of the observed resonance structure in the open-charm region in B->Kmumu)

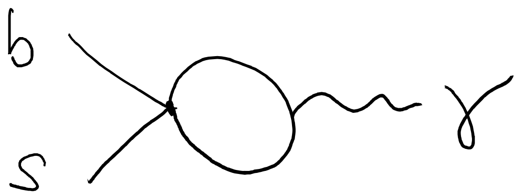
Observables

SJ, Kirk, Lenz, Leslie arxiv:1701.09183



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

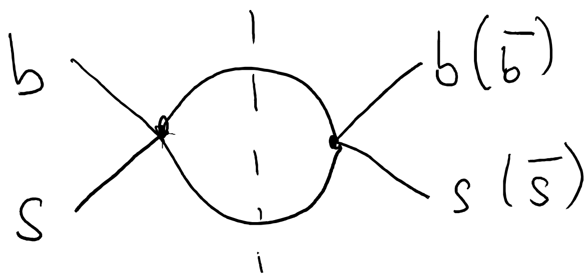
$$C_{x,y}^c = 3\Delta C_x + \Delta C_y$$



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

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

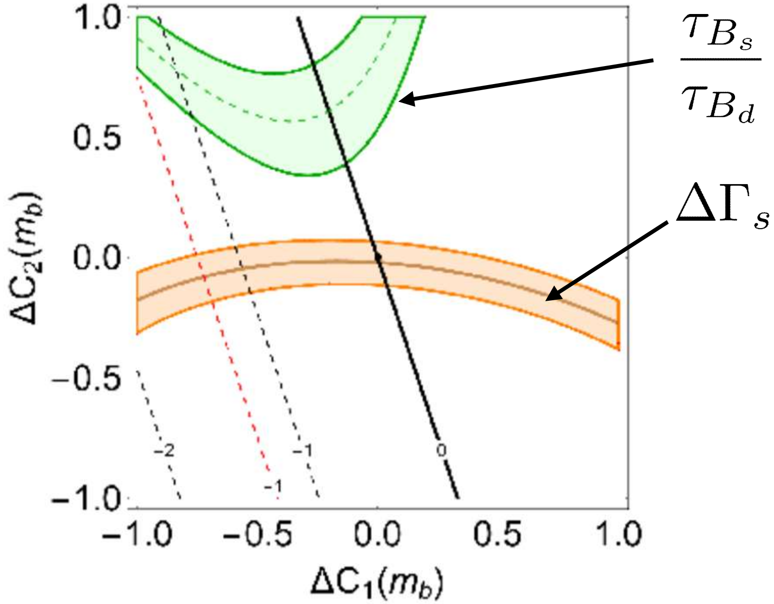


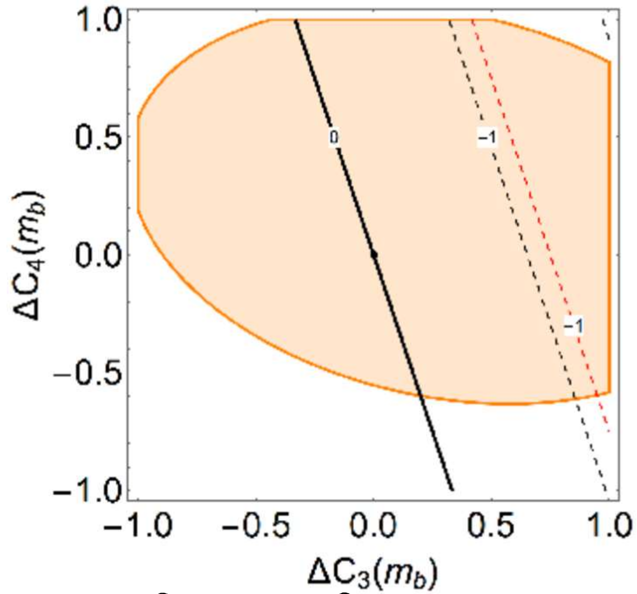
$\Delta\Gamma_s$ and τ_{B_s}/τ_{B_d} calculable in OPE
for general C1 .. C4

Phenomenology – low NP scale

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

If ln(M/m_B) not large, higher-order corrections (including RGE effects) small.
Can set $\mu \sim m_B, m_b$ (we choose mu = 4.6 GeV).





Straight lines: $\Delta C_9(q^2)$ contours. Red dotted: q^2=2 GeV^2, black: 5 GeV^2.

Can easily accommodate P5' anomaly while satisfying width difference.

Note that the lifetime ratio is not well consistent with the SM. Could reconcile with CBSM physics, but never consistent with width difference.

High new physics scale

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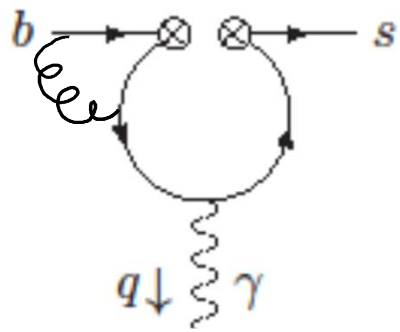
If ln(M/m_B) >> 1 then should resum to all orders.

Technically, RG-evolve the Wilson coefficients from μ ~M to μ~ m_B
q2 dependence now a *subleading* (NLL) effect.

For C1 .. C4, leading order is
2-loop for b->s gamma (C7eff)

Technically nontrivial
(spurious IR divergences, scheme dependence of diagrams, spurious gauge-noninvariant terms, etc).



Follow method of Chetyrkin, Misiak, Muenz NPB 518 (1998) 473, hep-ph/9711266

End result gauge- and scheme-independent if expressed in terms of the scheme-independent coefficient $C_7^{\rm eff}$ (which enters observables).

RGE evolution - numerical

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For evolution from MW to 4.6 GeV: (l.h.s. at 4.6 GeV, r.h.s. at MW)

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

Setting Delta C2 to 1 and rest to zero, reproduce the (large) SM charm contribution to C9(4.6 GeV).

But C1 and C3 are even (much) more effective in generating C9!

C2 and C4 feed strongly into C7eff, hence $B \to X_s \gamma$.

But C1 and C3 are practically irrelevant for radiative decay!

One can also have a 'pure C2-C4' scenario, where both contributions to C7eff cancel.

The four-quark Wilson coefficients also evolve, but comparatively mildly (see paper).

High NP scale – global analysis

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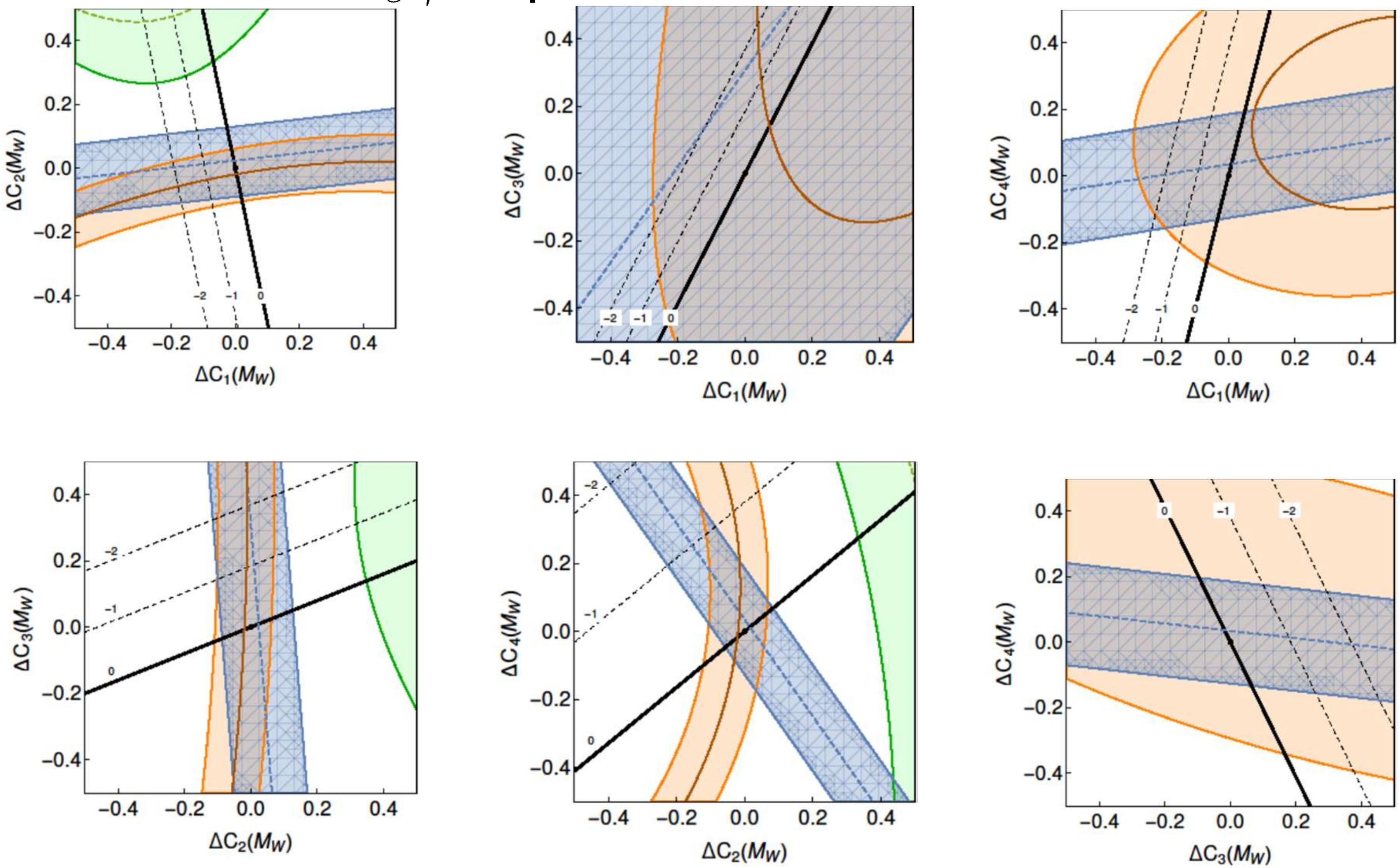
Blue – $B \to X_s\gamma$ experiment



Prospects

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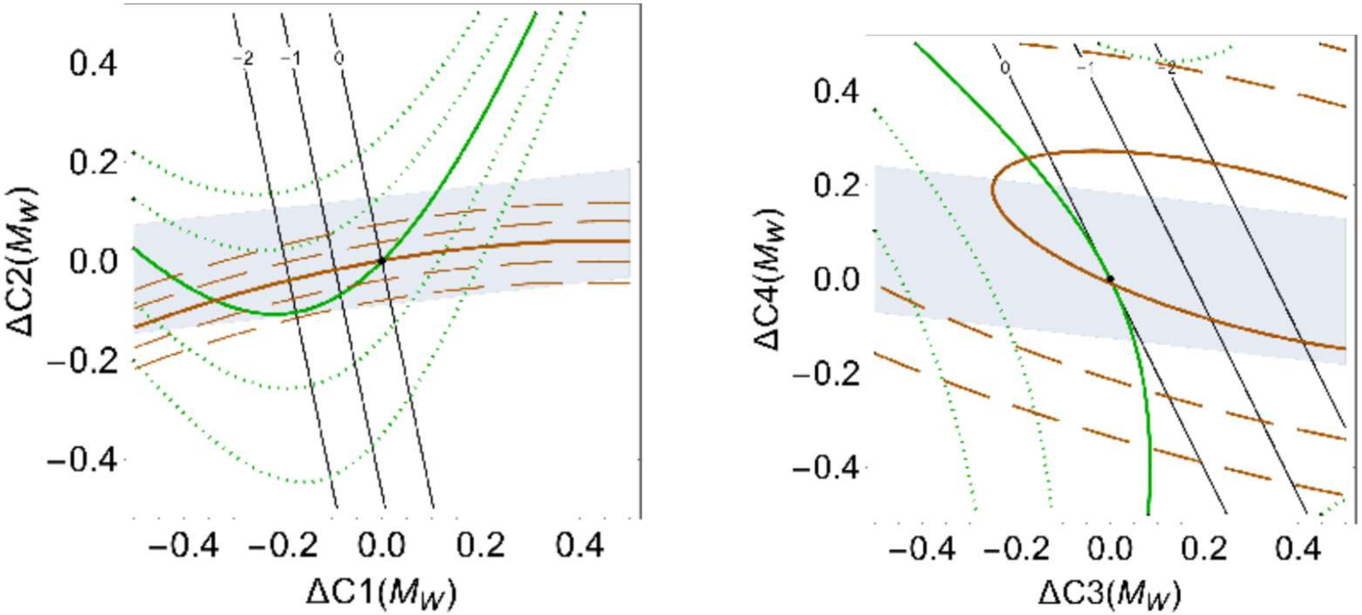
Width difference, lifetime ratio, and $B \to X_s\gamma$ will all be measured with increased precision at LHCb and Belle2.
May allow to pin down allowed region in CBSM parameter space quite precisely:



Bands between width difference/lifetime contours = projected furture 1-sigma experimental error. According theory progress required.

Conclusions

Flavour physics probes fundamental mass scales (and symmetries). I focused on three conspicuous, apparent discrepancies between theory and data.

For some time, semileptonic b->c l nu measurements have shown a discrepancy with the SM (about 4 sigma).

Global fits to recently measured, theoretically extremely clean lepton-universality-violating ratios indicate a lepton-specific, BSM contribution to the combination CL = ½(C9-C10),

In addition, angular observables/allow prefer an extra effect in C9, but this does not need to be LUV for a consistent picture. Can be generated through BSM charm penguins. Potential to connect rare decays and lifetime observables.