Flavour theory

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Workshop ‘Pushing the boundaries of the energy and intensity frontiers – the HL-LHC and beyond’

Durham, 19 April 2018

Outline

1) Intensity frontier and new physics

2) Anomalies and effective contact interactions

3) UV models and future prospects

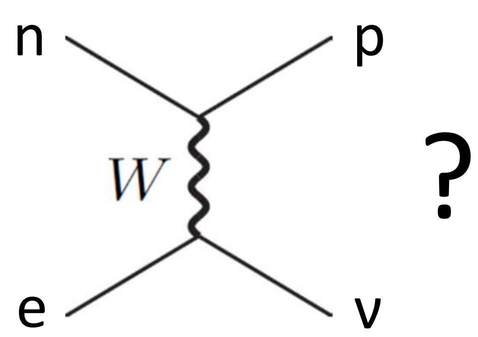
History: Beyond QED

Fermi's original description of beta decay (1934) (in modernised notation):

$$H_W \sim G_F\,(\bar{p}\gamma^\mu n)\,(\bar{e}\gamma_\mu \nu)$$

In modern language: nonrenormalizable, dim-6 operator.

The current-current structure (resembling a QED 2→2 scattering amplitude) is suggestive of a massive vector-boson mediator



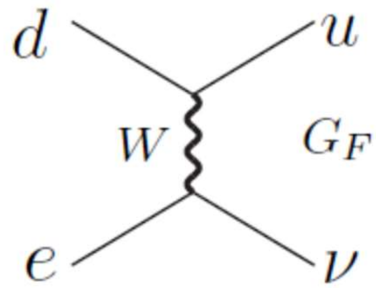
The precision frontier

After several further discoveries and insights, including

- parity violation — Lee, Yang 1956; Wu et al, Goldhaber et al 1957
- V-A structure of weak interactions — Feynman, Gell-Mann 1957; Shudarshan, Marshak 1957
- universality of weak decays — Gell-Mann, Levy 1960
- CP violation — Christenson et al 1964
- electroweak symmetry breaking — BEHGHK, Glashow, Salam, Weinberg
- charm to explain $K_L \to \mu\mu$ suppression — Glashow, Iliopoulos, Maiani 1970
- third generation to explain CPV — Kobayashi, Maskawa 1972

the SM was complete.

Neutral currents, charm, W,Z,H,
3rd generation later discovered.



$$G_F = \frac{g^2}{4\sqrt{2}M_W^2}$$

The SM

spin 1

electromagnetism U(1)

weak interactions SU(2)

strong interactions SU(3)

universal couplings — 3 generations

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	$Q = 0$ $Q = -1$

spin 0

Higgs - sets mass scale of entire Standard Model

Renormalizable: may have cut-off >> M_W

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

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.

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

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

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.

Where to look

Observables with suppressed and/or controlled SM contribution

- flavour-changing neutral currents, eg

  $b \to s\mu^+\mu^-$ and $b \to s\gamma$

  $B \to K^{(*)} \mu^+\mu^-$, $B \to K^{(*)} e^+e^-$, $B_s \to \phi\mu^+\mu^-$
  $B \to K^{(*)} \gamma$ — Babar, Belle; LHCb, ATLAS, CMS; Belle2

  $B \to X_s \mu^+\mu^-$, $B \to X_s \gamma$ — Babar, Belle, Belle2

  $s \to d\nu\nu$

  $K^+ \to \pi^+ \nu \nu$ — NA62 (CERN)

- lepton-flavour ratios, eg

  $BR(B \to K^{(*)} \mu^+\mu^-)/BR(B \to K^{(*)} e^+e^-) - 1$
  $BR(B \to D^{(*)} \tau\nu)/BR(B \to D^{(*)} l\nu) - (SM)$ — Babar, Belle, LHCb; Belle2

- CP violation, eg

  $K_L \to \pi\, \pi$ $(\varepsilon_K, \varepsilon'_K)$ — …, NA48, KTeV

  $K_L \to \pi^0 \nu \nu$ — KOTO

Summary: flavour anomalies

observable	Anomaly	Significance (sigma)
BR(B ->{K,K*,phi} mu mu) at low dilepton mass q2	Lowish w.r.t expectation	1-2 ?
B->K*mu mu angular distribution (low q2)	P5' off for some q2	2-3 ?
RD(*) = BR(B->D(*)tau nu)/BR(B->D(*)l nu)	Enhanced w.r.t. SM	4.1
Lepton-universality ratios (RK, RK*)	Below SM	3.7 (3 observables combined)
ε'/ε (direct CPV in KL->ππ)	Below SM	2.9

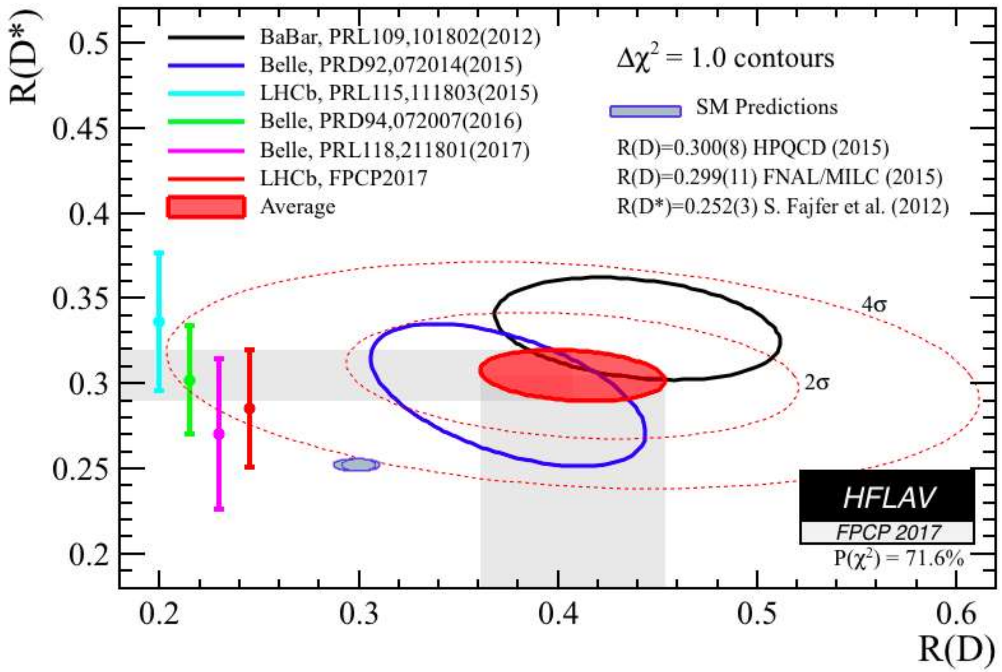
LHCb: rapidly increasing dataset

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

Systematic effects or BSM signal?

Anomaly I: semileptonic decays

For some time B-factories and LHCb have consistently shown semileptonic B ->D (D*) τν decay rates larger than expected (relative to the rate for light leptons).

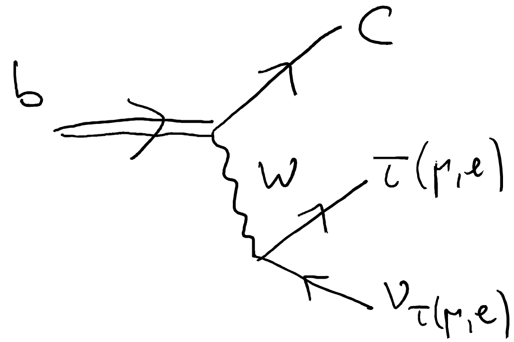


$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\ell\nu_\ell)}$$

4.1 sigma effect

ca 20% deviation

SM **tree-level**



A **large** effect; theory error negligible

What operators?

Several possible contact interactions

$$(\bar{c}\Gamma b)(\bar{\nu}_\tau \Gamma' \tau)$$

with different spin (Dirac) structure.

Several further clues:

- measured shape of differential decay distribution

Eg Ligeti et al 2015,16

- avoiding excessive contributions to B_c decay

Grinstein et al 2016, …

- interference with SM amplitude to enhance effect

favour a purely left-handed coupling $(\bar{c}_L \gamma^\mu b_L)\,(\bar{\nu}_\tau \gamma_\mu \tau_L)$
with coefficient ~ 10% of SM value

Rare semileptonic B-decay

many results from Babar, Belle, LHCb, ATLAS, CMS

Sensitive to several contact interactions:

C9: dilepton from vector current

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

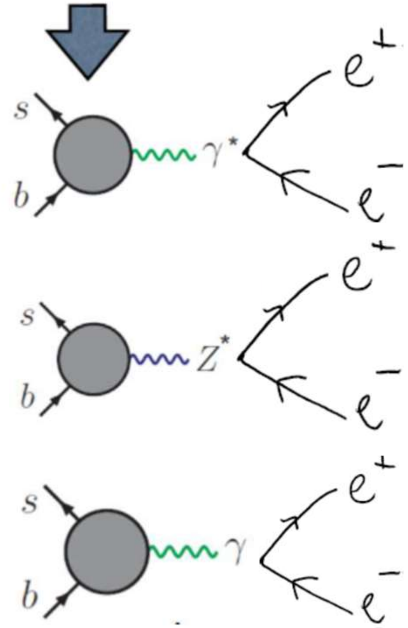
C10: dilepton from axial current

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

C7: dilepton from dipole

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

in SM mainly

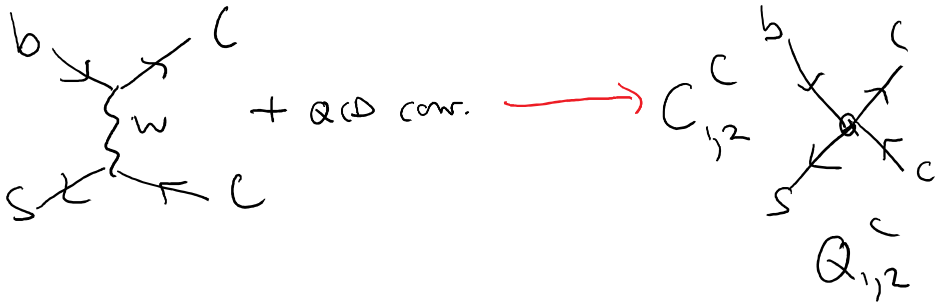


Alternative basis with chiral leptons

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

Impact of 4-quark operators

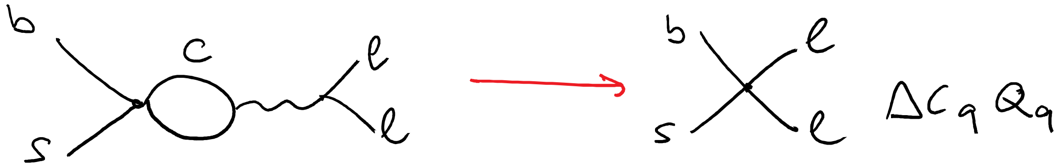
Also **purely hadronic** operators are important, primarily:



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

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

RG mixes these into C9 and C7



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

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

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

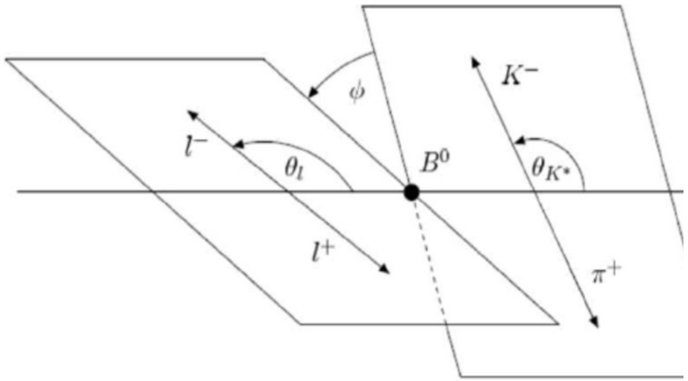
Branching ratios (differential in dilepton mass):

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

Lepton universality ratios

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

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

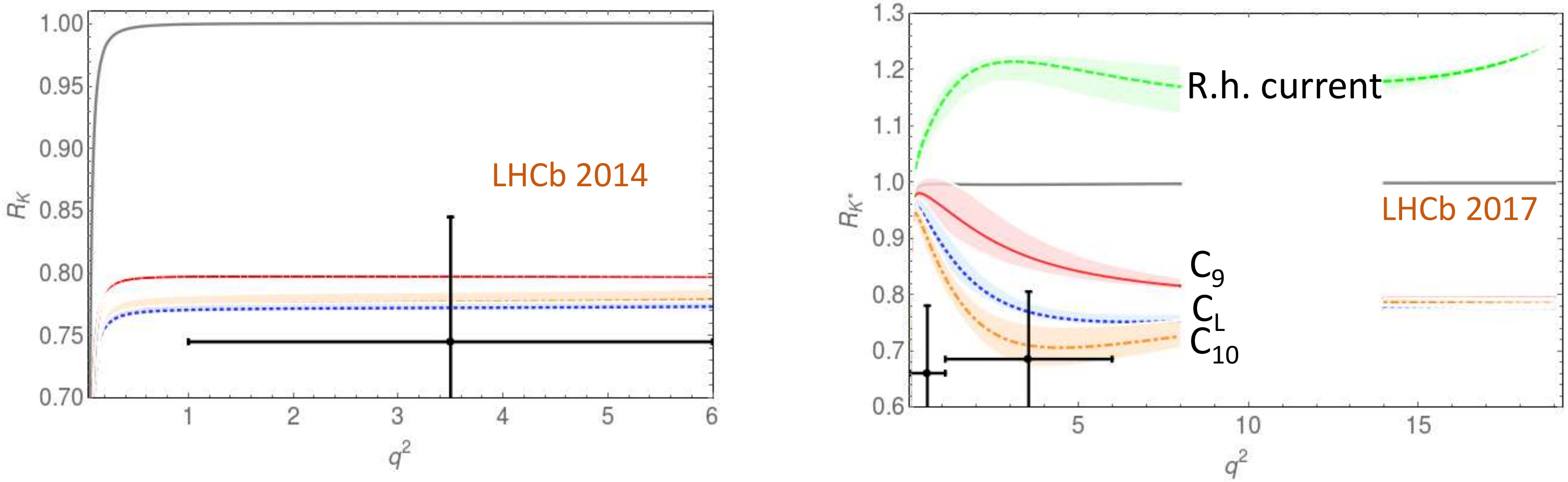


7 angular differential observables:
(A_{FB}, P_5', etc)

Anomaly II: 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)

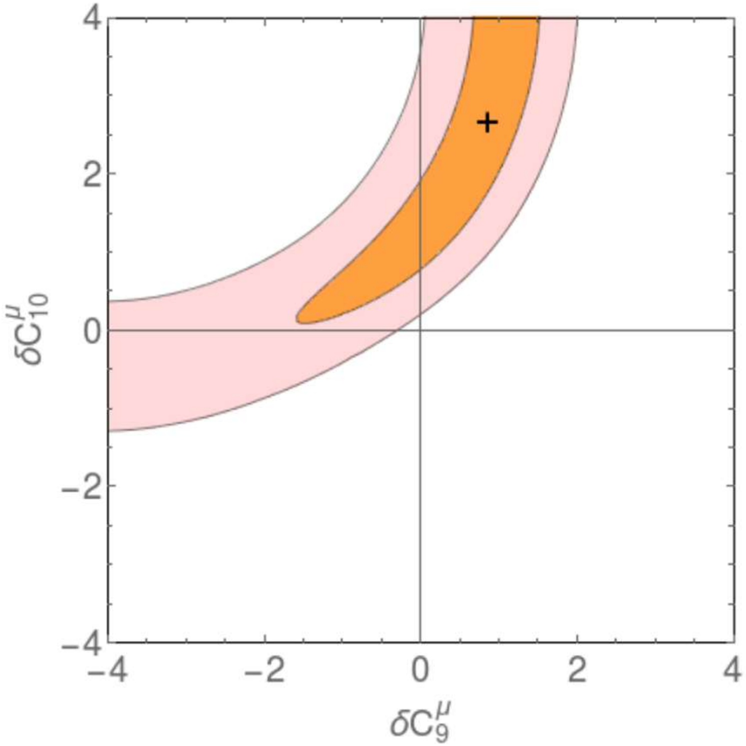
Suggests nonzero, muon-specific C_{10}^{BSM} - not pure C_9

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

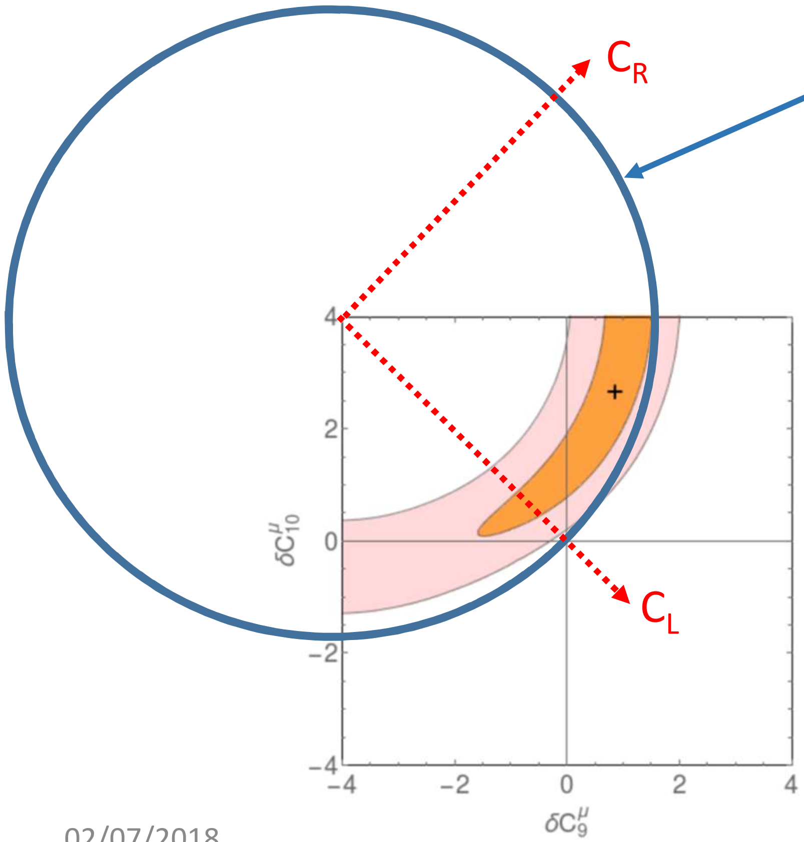
Considerable degeneracy (flat direction in χ^2)

$R_K^{(*)}$ 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

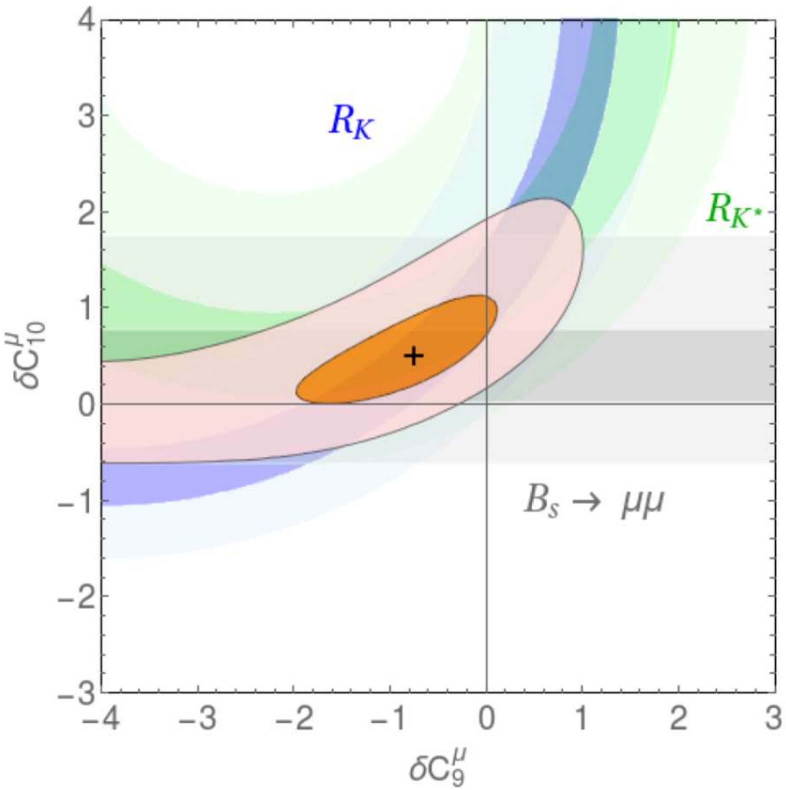


Only C_L^{BSM} can interfere destructively: $R_K^{(*)}$ point to purely left-handed coupling

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

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 $C_L = (C_9-C_{10})/2$

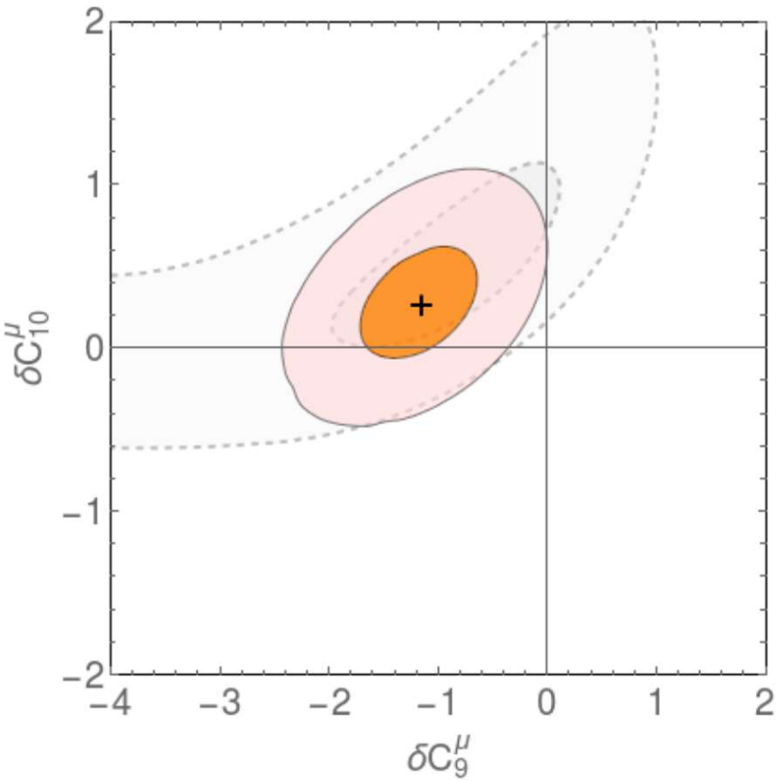
$C_R = (C_9+C_{10})/2$ not well constrained and consistent with zero

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)

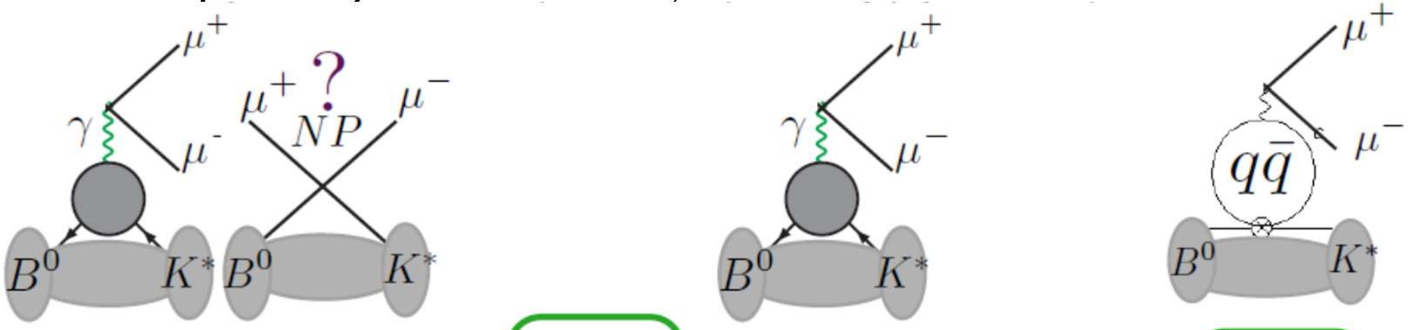
Wilson coefficient value C_L=0 again excluded at high confidence.

Questions

1) How to corroborate the anomalies ?
2) Scale of new physics ?
3) Dynamical models (UV completion of the EFT) ?
4) Prospects for LHC discoveries ?

Rare decays: amplitude anatomy

C_9 enters multiplied by a form factor, and with additive corrections:



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

photon pole at q^2=0

C_i degenerate with form factor uncertainties and virtual charm

SJ, Martin Camalich 2012, 2014

Cancel out in lepton-flavour ratios $R_{K(*)}$, $R_{D(*)}$ (to <~ 1%): no issue

Relevant for rates and angular observables (P_5')

controlled computation (so far) only for B->K form factors

recent conceptual advances in lattice QCD (B -> V form factors)

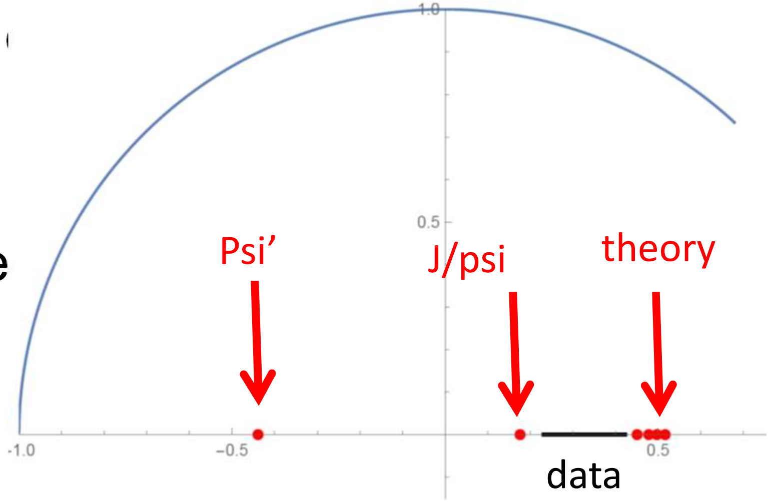
heavy-quark relations and and light-cone sum rules

Fits of hadronic parameters to data?

Bobeth, Chrzaszcz, Van Dyk, Virto 2017

Basic idea: reduce theory dependence of long-distance virtual charm by using data & analyticity

- use/assume analyticity of the virtual-charm dilepton mass
- Use theory input only at q2 <~ 0
- Data to fix/constrain the residues at the pole
- Conformal mapping to increase separation of the input data from the cut; polynomial fit



k	0	1	2
$\mathrm{Re}[\alpha_k^{(\perp)}]$	-0.06 ± 0.21	-6.77 ± 0.27	18.96 ± 0.59
$\mathrm{Re}[\alpha_k^{(\parallel)}]$	-0.35 ± 0.62	-3.13 ± 0.41	12.20 ± 1.34
$\mathrm{Re}[\alpha_k^{(0)}]$	0.05 ± 1.52	17.26 ± 1.64	–
$\mathrm{Im}[\alpha_k^{(\perp)}]$	-0.21 ± 2.25	1.17 ± 3.58	-0.08 ± 2.24
$\mathrm{Im}[\alpha_k^{(\parallel)}]$	-0.04 ± 3.67	-2.14 ± 2.46	6.03 ± 2.50
$\mathrm{Im}[\alpha_k^{(0)}]$	-0.05 ± 4.99	4.29 ± 3.14	–

Results disfavour attributing effects to virtual-charm

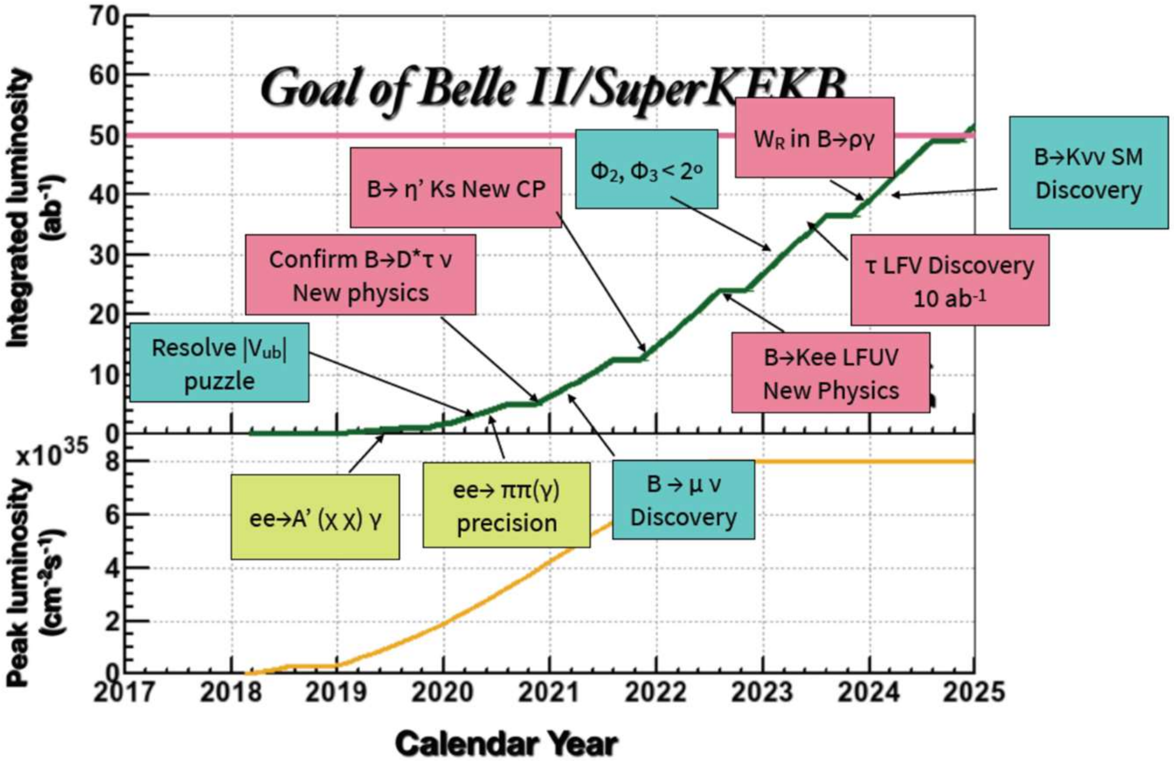
No new information on form factors (but see LHCb’s fit to B→Kμμ)

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)



Scale of new physics & no-lose theorem

Di Luzio, Nardecchia 2017

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

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

numerically $\Lambda \sim 3$ TeV and $\Lambda \sim 30$ TeV.

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.

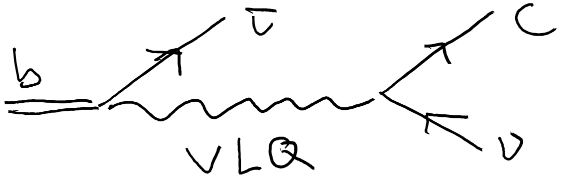
Tree-level mediators: leptoquarks

Scalar or vector leptoquarks can generate interactions

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

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

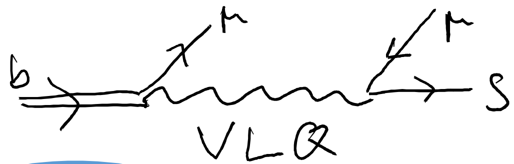
$(3, 1, -1/3)$ or $(3, 3, 2/3)$



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

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

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

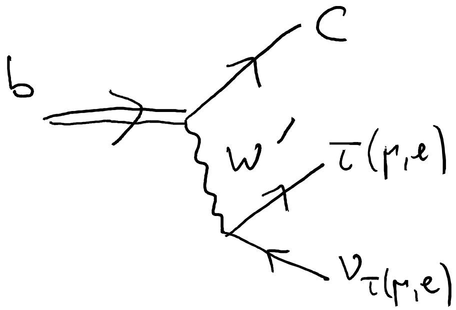


$(3, 1, 2/3)$ or $(3, 3, 2/3)$

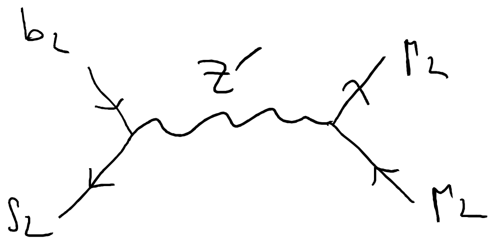
(more possibilities at loop level Eg Bauer,Neubert; Becirevic et al)

Possible 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)

- Z' exchange contributes to Bs 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 $R_{K(*)}$

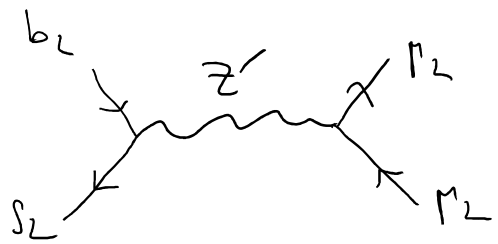
Accommodating *all* b->s l l anomalies *requires* a muon-specific C_L – type interaction

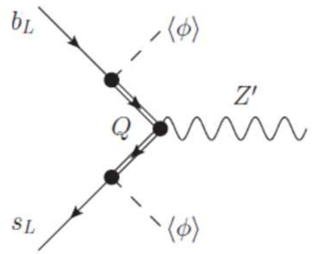
$$\frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\mu}_L\gamma_\mu\mu_L\right)$$

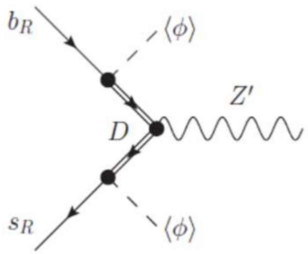
with Λ ~ 30 TeV

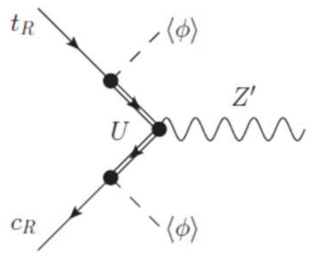
However, C_R is weakly constrained and can also be present.

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, …

SU(2) structure & global picture

Two SU(2) invariants (O_T / O_S) for each operator once doublet structure of fermions considered

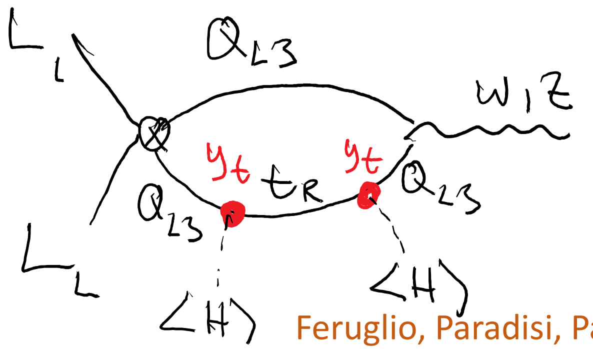
Both operators contribute to further processes that are experimentally constraints, in particular:

$B \to K^* \nu\nu$

at one loop:

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

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



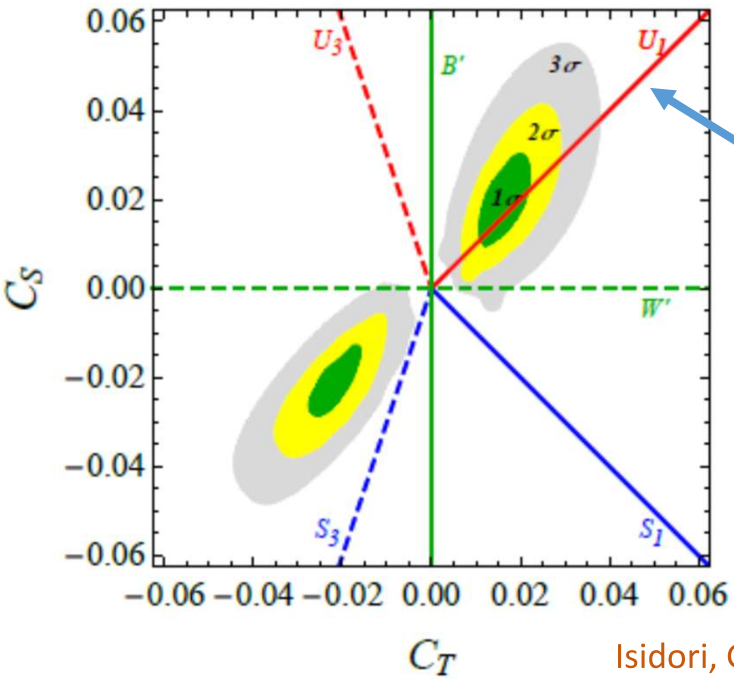
Feruglio, Paradisi, Pattori
arXiv:1606.00524, arXiv:1705.00929

In a given model there may be further correlations (eg to mixing)

Global fit & single mediators

Two SU(2) invariants (O_T / O_S) for each operator once doublet structure of fermions considered

(Axis scales depend on flavour structure of mediator couplings)



$(3, 1, 2/3)$
vector
leptoquark

Isidori, Greljo arXiv:1706.07808

Multi-mediator and (for $R_{K(*)}$) loop-level scenarios possible!

Composite leptoquark?

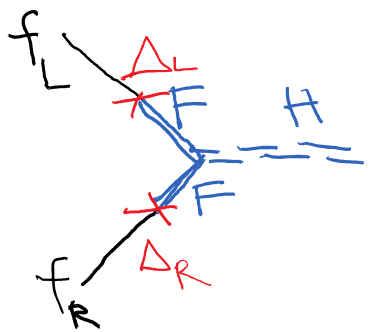
Basic idea of composite Higgs models:

1) Higgs = bound state of a new strong sector (with TeV-ish confinement/conformal symmetry breaking scale)

at least $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X$ symmetry [partly gauged]

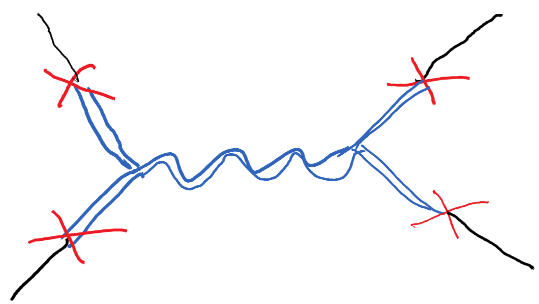
2) SM fermions are mixtures of elementary and composite particles

can generate flavour hierarchies



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

leading BSM effects:

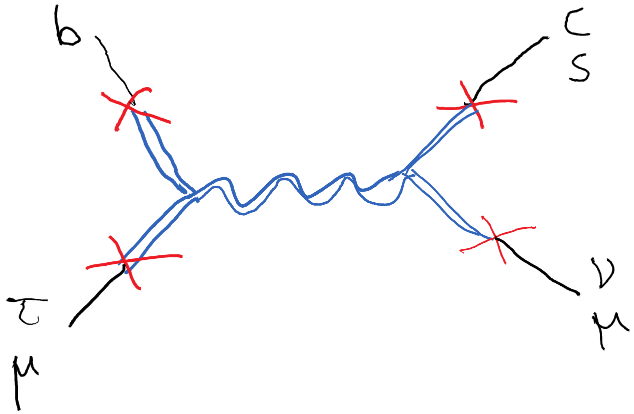


$$\sim \frac{g_*^2 \Delta^4}{M^6} (\bar{f}\Gamma f)(\bar{f}\Gamma f)$$

Composite leptoquark?

The SM representation $(3, 1, 2/3)$ appears in the restriction of the Pati-Salam (SU(4) x SU(2) x SU(2)) adjoint to the SM gauge group.

Increasing SU(3)xSU(2)xSU(2)xU(1) to SU(4)xSU(2)xSU(2)xU(1), get **spin-1 vector leptoquark states with precisely these quantum numbers**.



Some recent models:

3-site SU(4) x SU(2) x SU(2) gauge model

Bordone, Cornella, Fuentes-Martin, Isidori arXiv:1712.01368, arXiv:1805.09328

[SU(4) x SO(5) x U(1)] / [SU(4) x SO(4) x U(1)] Nambu-Goldstone Higgs model Barbieri, Tesi arXiv:1712.06844

SU(4) x SU(2) x SU(2) Randall-Sundrum (warped ED) model (elementary Higgs, but partially composite matter)

Blanke, Crivellin arXiv:1801.07256

Prospects for LHC direct searches

(see also talk by A Cerri)

Mediator of $R_{D(*)}$ may be in LHC reach. The partially composite models predict TeV-scale leptoquark, colour octet, and Z' particles, predominantly coupled to 3rd generation particles

Some relevant search modes:

tau pair production (t-channel VLQ, s-channel Z')
leptoquark pair production

dijet (colour-octet-mediated)

Also composite fermions & scalars: more model-dependent

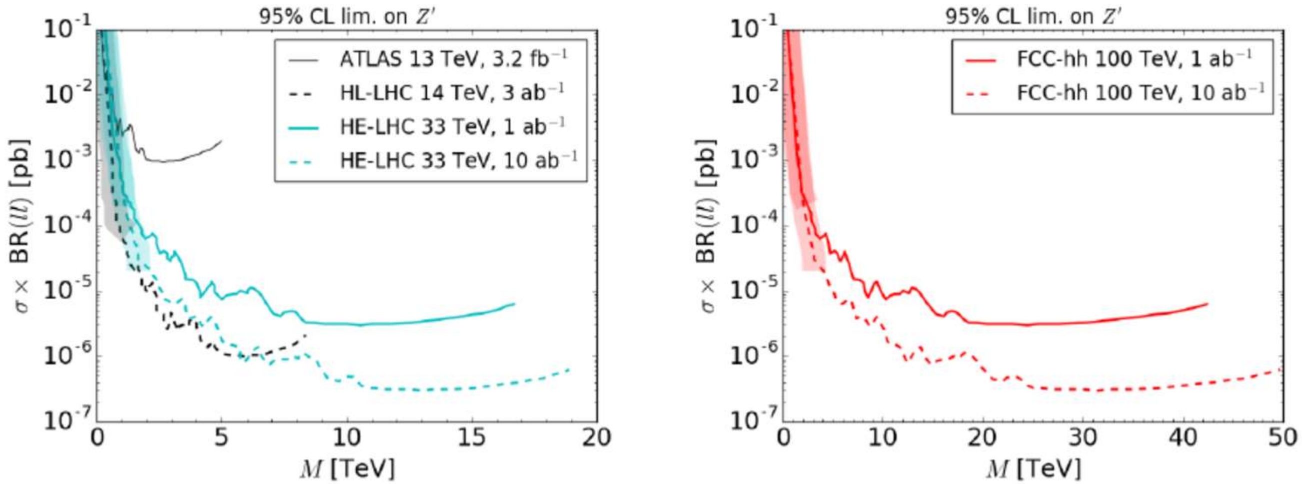
For tree-level $R_{K(*)}$ origin, mediator typically out of LHC reach (naïve scale ~ 30 TeV), though model-dependent

Future collider direct searches

Recall partial-wave unitarity bounds (conservative)
of ~100 from RK(*) / 10 TeV from RD(*)

- Consider simplified Z' and LQ models of RK(*)

Allanach, Gripaios, You arXiv:1710.06363



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

Leptoquark coverage slightly less perfect

Other flavour frontiers

K->pi nu nu

epsilon'

Delta M_K as a precision constraint

Conclusions

Precision frontier has a good track record and the potential to probe beyond the energy frontier

Several theoretically robust anomalies, and further ones which give a consistent picture.
Different systematics at upcoming Belle2 experiment.
LHC experiments will retain statistics edge

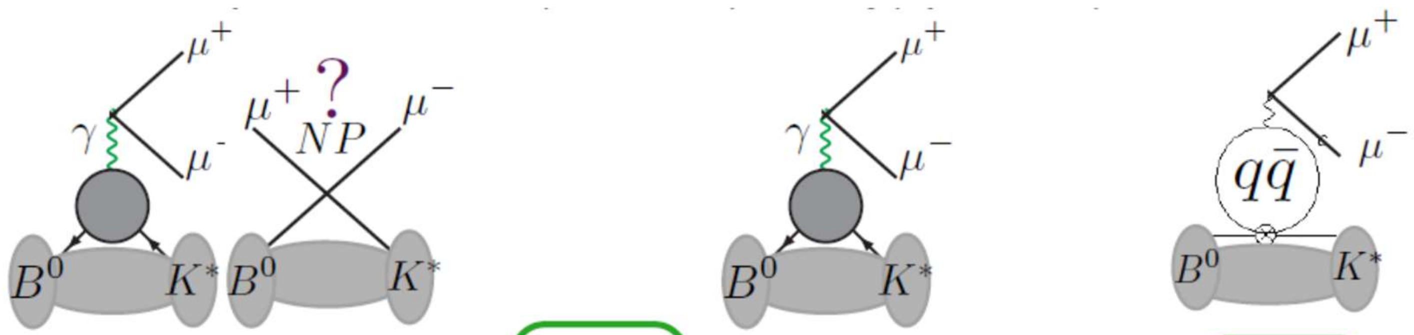
Recent increase in model-building; specifically composite leptoquark and Z' models

If anomalies confirmed, imply upper bounds on NP scale

BACKUP

Rare decays: amplitude anatomy

C_9 enters multiplied by a form factor, and with additive corrections:



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

photon pole at $q^2=0$

shifts of C_i degenerate with form factor uncertainties and virtual-charm effects. Cancels out only in lepton-flavour ratios (to <~ 1%)

Form factor *ratios* relevant to angular observables; constrained by heavy-quark limit; power corrections? SJ, Martin Camalich 2012, 2014

No controlled computation of most form factor in most of parameter space; typically light-cone sum rules. Ball&Braun; Ball& Zwicky; Bharucha et al 2015

Anomaly III: several low branching ratios

Schematically for B→Kμμ   (neglecting small imaginary parts)

$$H_V = C_7 T + C_9 V + h \qquad\qquad H_A = C_{10} V$$

$$BR \propto (|H_V|^2 + |H_A|^2) = \frac{1}{2}(C_7 T + h_0 + 2C_R V)^2 + \frac{1}{2}(C_7 T + h_0 + 2C_L V)^2$$

C_7, h_0, and C_R are small in the SM

BR essentially is determined by the product $C_L \cdot V$ of a Wilson coefficient and a form factor (V cancelled out for R_K)

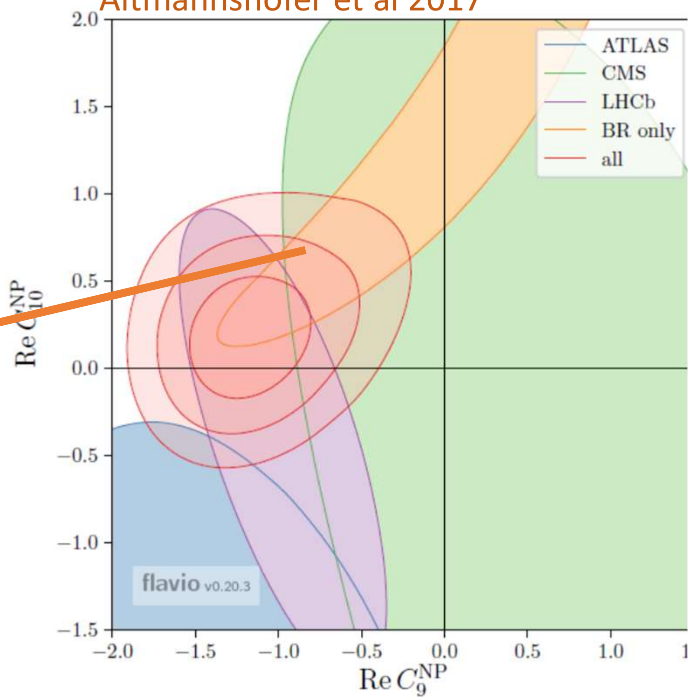
suggests 10-15% reduction of C_L

But perfectly degenerate with form factor V !

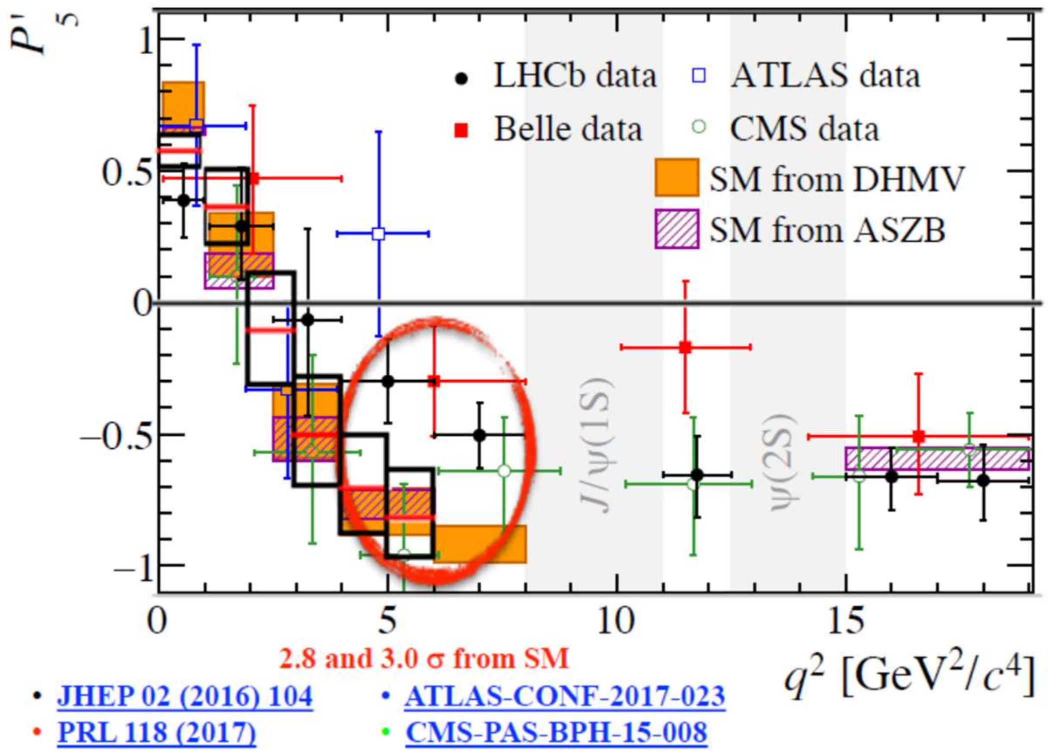
However, consistent global picture.

Global fit to b->s l l data

Altmannshofer et al 2017



Anomaly IV: The (in)famous P5'



Simone Bifani, seminar at CERN (overlaid predictions from SJ&Martin Camalich 2014)

Modest discrepancy around 4-6 GeV, suggesting reduced C_9

SM theory is subtle – form factors, long-distance virtual-charm somewhat uncertain

Angular observables

Numerous independent observables. Each a distribution in dilepton mass.

$$I_2^c = -F\,\frac{\beta^2}{2}\left(|H_V^0|^2 + |H_A^0|^2\right),$$

$$I_2^s = F\,\frac{\beta^2}{8}\left(|H_V^+|^2 + |H_V^-|^2\right) + (V \to A)$$

"longitudinal" rate (sim. to scalar BR)

"transverse" rate

Usually reported as BR and FL

$$I_6^s = F\beta\,\mathrm{Re}\left[H_V^-(H_A^-)^* - H_V^+(H_A^+)^*\right]$$

Lepton forward-backward rate asymmetry

Usually reported as AFB or P2

$$I_4 = F\,\frac{\beta^2}{4}\mathrm{Re}\left[\left(H_V^- + H_V^+\right)\left(H_V^0\right)^*\right] + (V \to A).$$

$$I_5 = F\Big\{\frac{\beta}{2}\mathrm{Re}\left[\left(H_V^- - H_V^+\right)\left(H_A^0\right)^*\right] + (V \leftrightarrow A)$$

Often discuss P4' and P5' instead

$$I_3 = -\frac{F}{2}\mathrm{Re}\left[H_V^+(H_V^-)^*\right] + (V \to A)$$

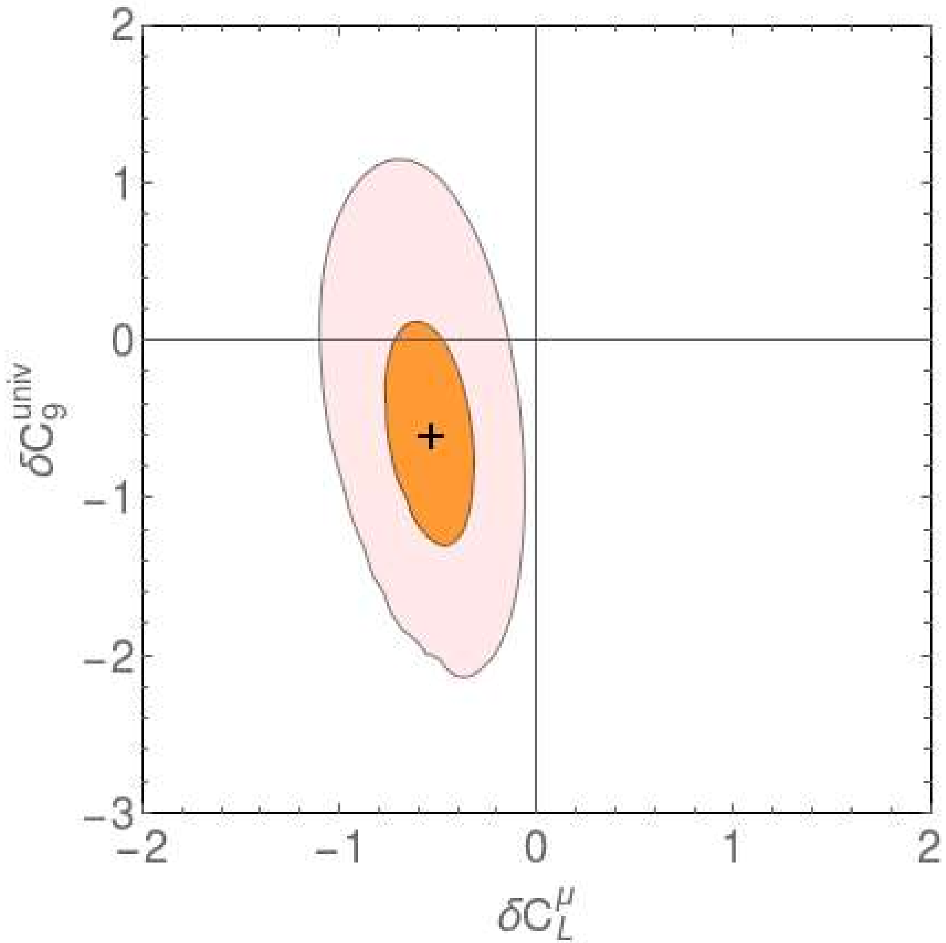
$$I_9 = F\,\frac{\beta^2}{2}\mathrm{Im}\left[H_V^+(H_V^-)^*\right] + (V \to A)$$

Require presence of "wrong-helicity" amplitudes (suppressed in SM)

Probe right-handed currents

Must C_9 violate lepton flavour?

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



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

Modest preference for modified C_9 (over C_{10}) is due to angular observables in $B \to K^*$ μμ

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

Eg. 'charming BSM' scenario

SJ, Kirk, Lenz, Leslie arXiv:1701.09183

Anomaly V: direct CP violation in Kaons

Precisely known experimentally for a decade

$$(\varepsilon'/\varepsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$$

average of NA48 (CERN) and KTeV

$$\left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 \simeq 1 - 6\,\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

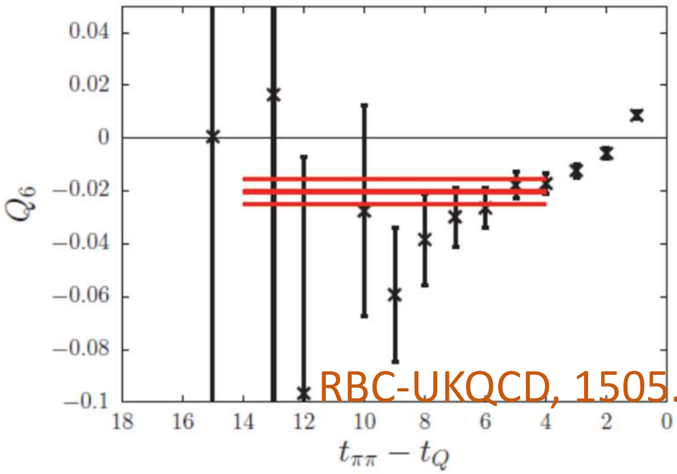
defines Re(ε'/ε) experimentally
left-hand side is measured

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}, \qquad \eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}$$

(magnitudes directly measurable from decay rates)

Major progress in lattice QCD computations of nonperturbative matrix elements allows controlled errors for the first time

Good near-term prospects



RBC-UKQCD, 1505.07863v4

State of phenomenology (NLO)

$$(\varepsilon'/\varepsilon)_{\rm SM} = (1.9 \pm 4.5) \times 10^{-4}$$ Buras, Gorbahn, SJ, Jamin arXiv:1507.06345

$$(\varepsilon'/\varepsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$$ 2.9σ discrepancy

(see also Kitahara, Nierste, Tremper 1607.06727)
(see also Kitahara, Nierste, Tremper 1607.06727)

parameterise hadronic matrix elements
values from RBC-UKQCD 2015

quantity	error on ε'/ε	quantity	error on ε'/ε
$B_6^{(1/2)}$	4.1	$m_d(m_c)$	0.2
NNLO	1.6	q	0.2
$\hat{\Omega}_{\rm eff}$	0.7	$B_8^{(1/2)}$	0.1
p_3	0.6	${\rm Im}\lambda_t$	0.1
$B_8^{(3/2)}$	0.5	p_{72}	0.1
p_5	0.4	p_{70}	0.1
$m_s(m_c)$	0.3	$\alpha_s(M_Z)$	0.1
$m_t(m_t)$	0.3		

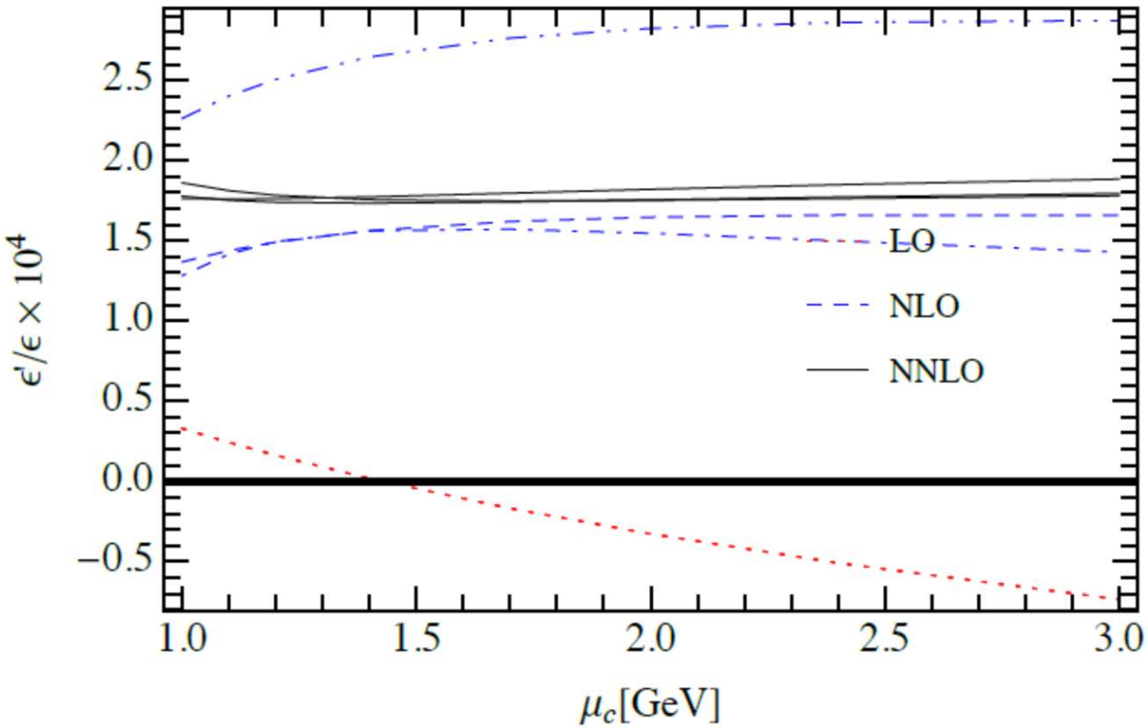
all in units of 10^-4

(still) completely dominated by $\langle Q_6 \rangle_0 \propto B_6^{1/2}$

next are NNLO and isospin breaking

NNLO computation (partial)

Cerda-Sevilla, Gorbahn, SJ, Kokulu, wip



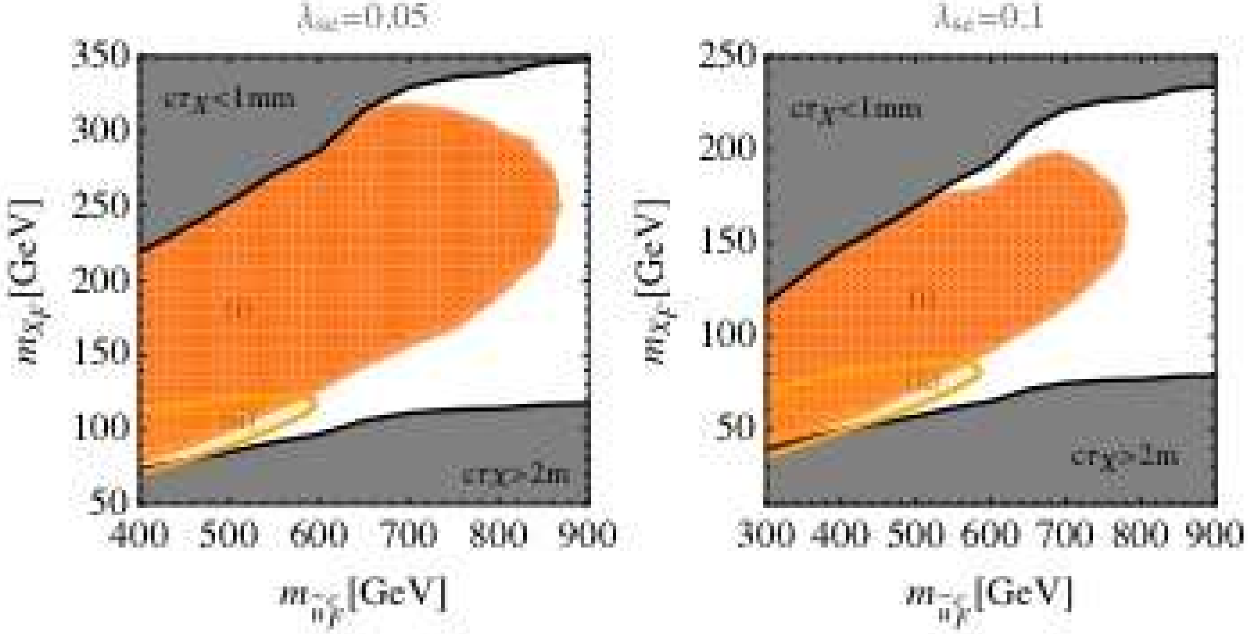
NNLO QCD-penguin corrections tiny; excellent behaviour of perturbation theory; cuts residual perturbative error in half – this is not the reason for the apparent tension!

Natural scalar leptoquark explanations?

The representations under the SM gauge group that work seem ‘unusual’ – not present in MSSM, not easy in composite models

To explain only the theoretically robust lepton-universality ratios in rare decays, one can also ***enhance the electron decay rate***. This does not require interference with the SM, so various chiralities work.

- Eg hyperfolded SUSY with SU(2) singlet “stop” of charge 4/3 can generate $b_R \to s_R\, e_R^+\, e_R^-$ Interesting interplay with collider searches.

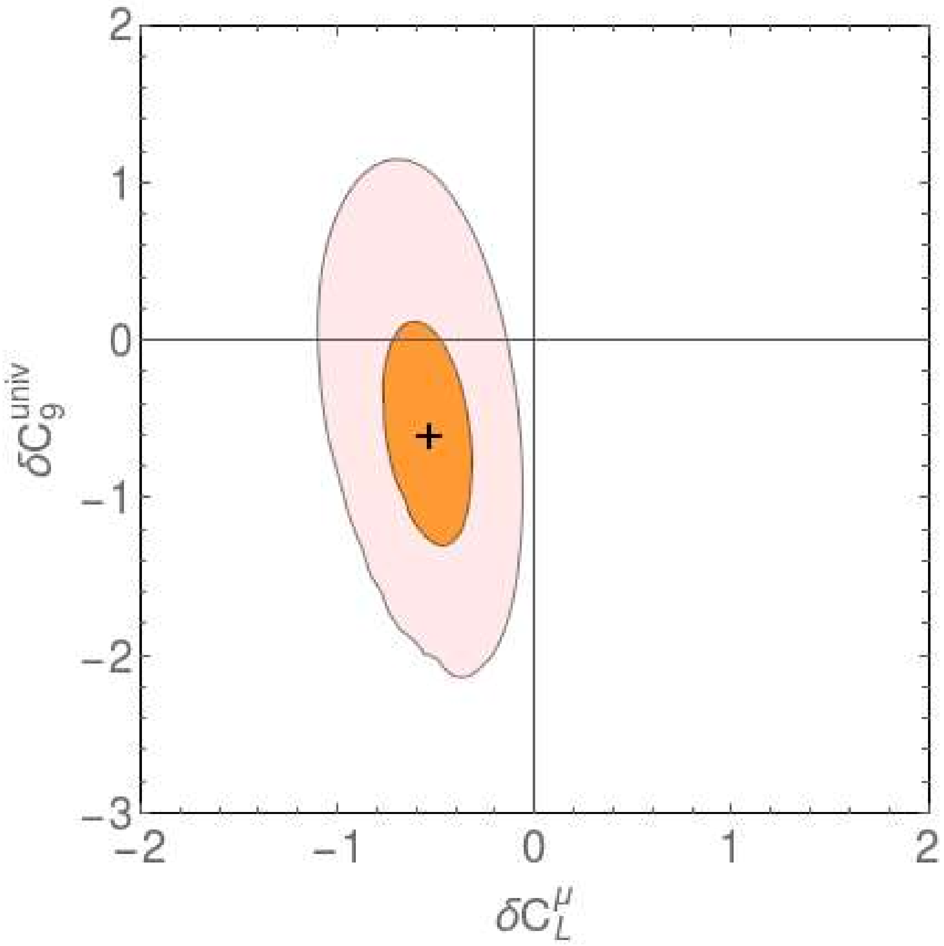


Faroughy, SJ, Kamenik, Perez, Sato, Zupan w.i.p.

- composite right-handed electron scenario Carmona, Goertz arXiv:1712.02536

Must C9 show LUV ?

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



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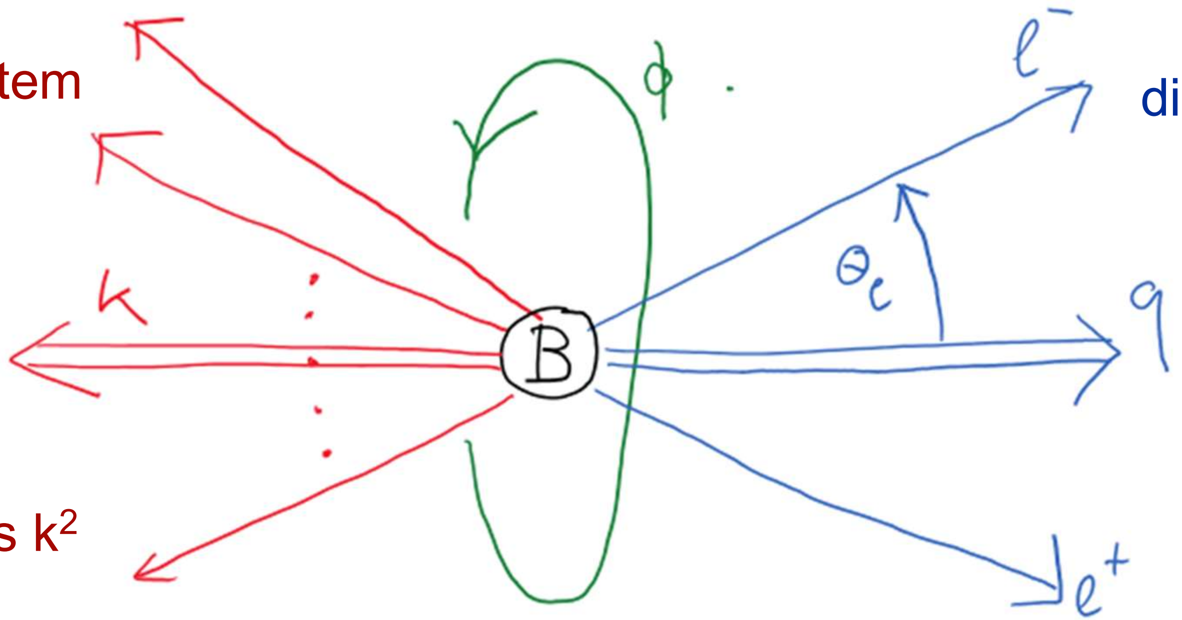
This means a model with (for example) nonzero C_L^{μ} and in addition an ordinary, **lepton-flavour-universal, C_9**, can describe the data similarly well or better

Eg. 'charming BSM' scenario

SJ, Kirk, Lenz, Leslie arXiv:1701.09183

Semileptonic decays

hadronic system



dilepton

hadronic mass k^2

dilepton mass q^2

hadronic angles & energies
equivalently:
  angular momentum L'
  helicity λ'
  (+ more if >2 hadrons)

one hadronic/leptonic relative angle Φ if >1 hadron

leptonic angle
equivalently:
  angular momentum L
  helicity λ

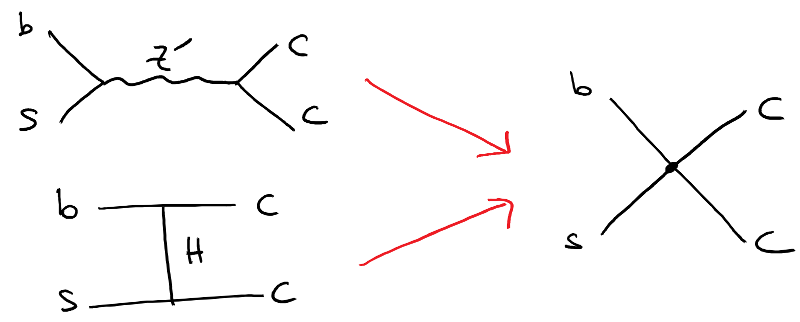
B has spin zero => $\lambda = \lambda'$

Observing Φ requires interference $A(\lambda_1) A(\lambda_2)^*$ $\exp(i\,(\lambda_1 - \lambda_2)\Phi)$

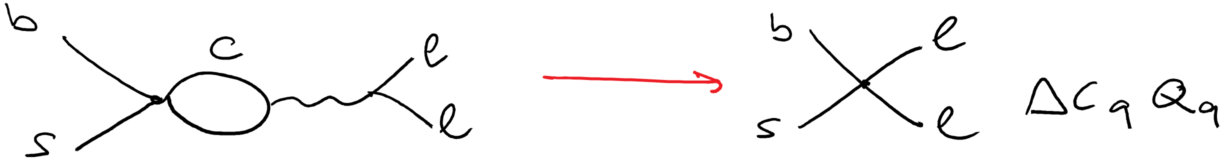
Charming BSM scenario

SJ, Kirk, Lenz, Leslie arxiv:1701.09183

e.g. 1)



2)



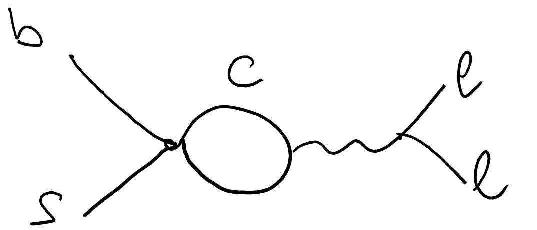
very efficient way to generate C9(NP) = O(1)

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

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

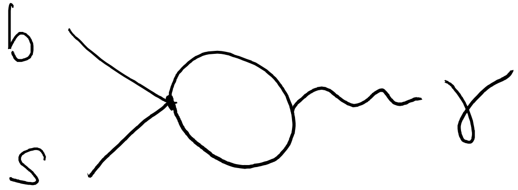
Observables

SJ, Kirk, Lenz, Leslie arxiv:1701.09183



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

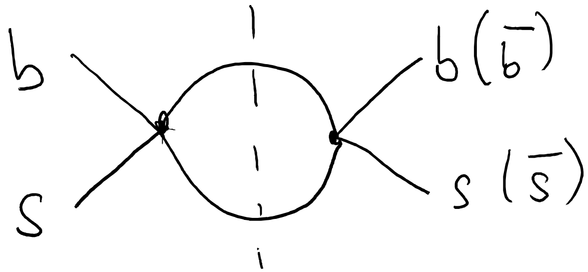
$$C_{x,y}^c = 3\Delta C_x + \Delta C_y$$



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

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