Flavour: Theory perspective

Sebastian Jäger (University of Sussex)

PPAP meeting on UK input to the European Strategy Update
Birmingham, 21 September 2018

From the ‘bullet point document’

“1) Complimentary [sic] to energy frontier collider physics. Provides an indirect probe [of] higher mass scales. Should be pursued.

a. May provide insights and guidance for decision on future energy and intensity frontier machines.”

I agree but I would add:

- Might provide sufficient clues to determine part or all of the underlying theory. Historical precedent: the SM
- Has multiple evidence-level tensions with the SM (‘anomalies’)
- Poses particular requirements on theory (precision) and computing (lattice QCD simulations)

Disclaimer

In the following I will be selective, talking mostly about B-physics.

This should not be misunderstood as a ‘prioritization’ – from a theory perspective, whether new physics is more pronounced in (for example) B-physics or K-physics is a **very model-dependent question.** Similarly for g-2, which is reasonably considered within flavour physics.

I will not talk about beam dumps or SHIP, this is simply for lack of time and competence. Other theorists will be more qualified.

Outline

1) Fundamental physics and the intensity frontier
2) Anomalies and interpretations
3) Energy scales
4) Corroboration and complementarity
5) Precision and Computing
6) Conclusions and opinions

Some ‘big’ questions

1) Is there a unified theory of:
different forces / matter & forces / quarks & leptons / “everything” ?

2) What underlies the pattern of generations, masses, mixing angles (CKM, PMNS) ?

3) What is the origin of the huge hierarchy between the electroweak and gravitational physics ?

4) What is the origin of the matter-antimatter asymmetry in the universe?

Flavour physics may be relevant to all of them.

ν

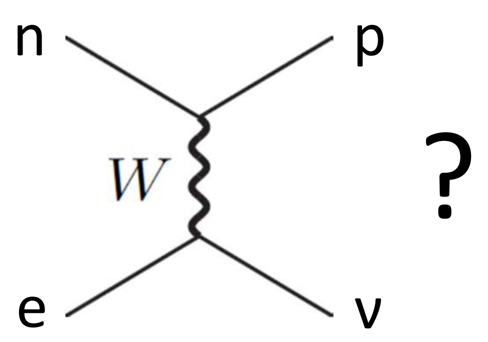
History: Beyond QED

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

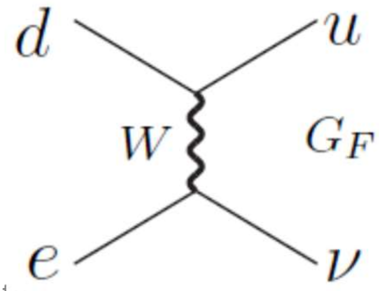


The precision frontier: track record

various "indirect" 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

exhibited the **full (!)** structure of the SM



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

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

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(E²/M²) 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.

Some flavour physics observables

Observables with suppressed and/or controlled SM contribution

- flavour-changing neutral currents, eg

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

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

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

- CP violation, eg

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

  $K_L \to \pi^0 \nu \nu$ — KOTO

Summary of 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 negligible. Large statistical significance.

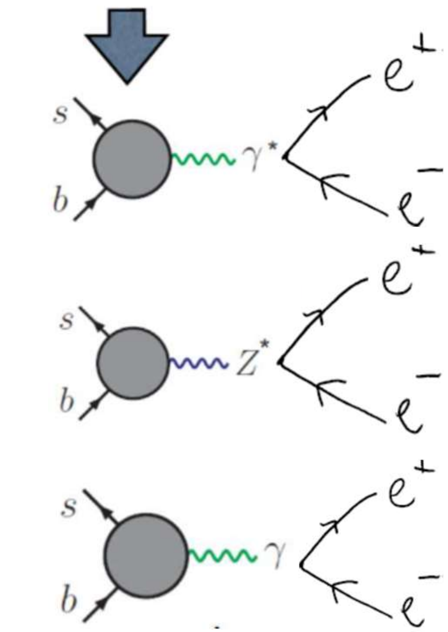
Systematic effects or BSM signal?

Rare semileptonic B-decay

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

Sensitive to several contact interactions:

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

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

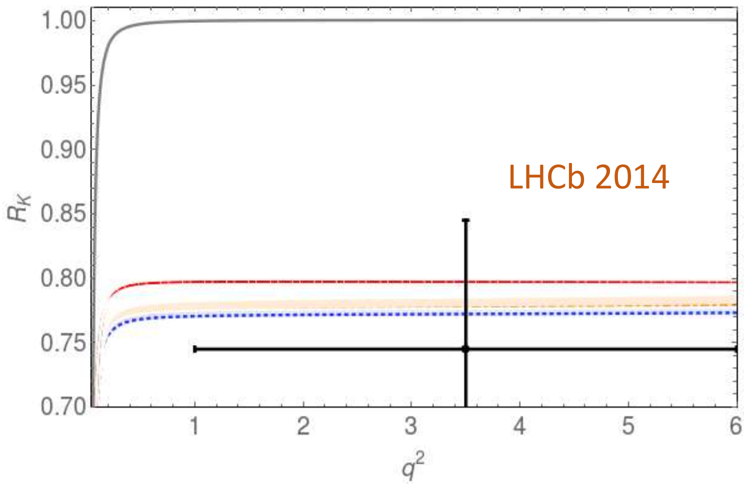
Alternative basis with chiral leptons

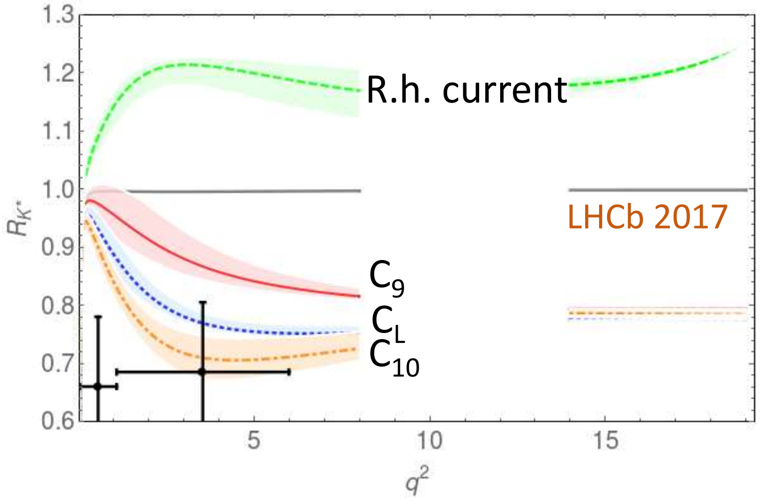
$C_L = (C_9 - C_{10})/2$, $C_R = (C_9 + C_{10})/2$, SM: $C_R \sim 0$

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) = 2.1×10^{-4} (3.7σ)

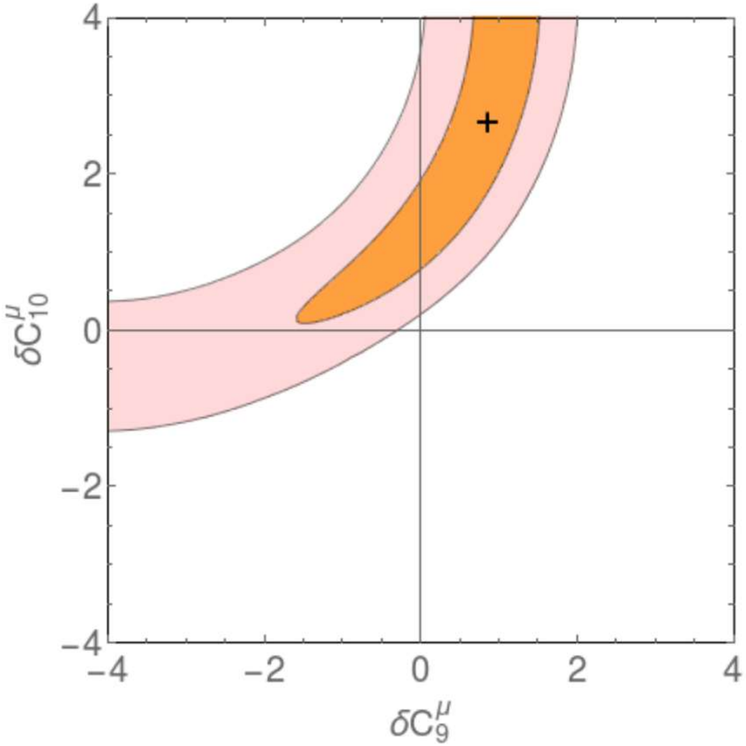
Suggests nonzero, muon-specific C_{10}^{BSM} - not pure C_9

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

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

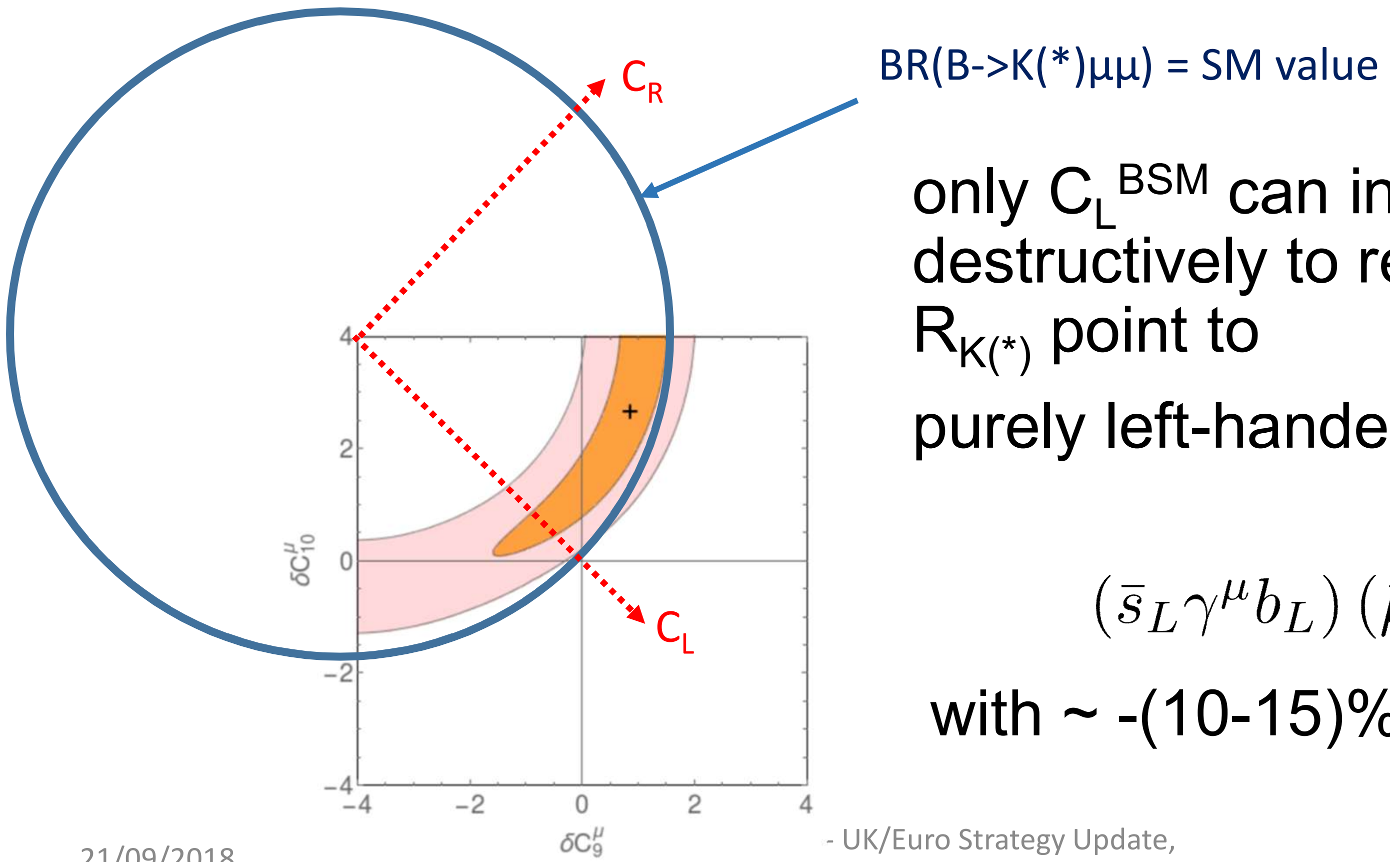
SM point excluded at 3.78 σ

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, $|C_R|$, $|C_7| << |C_L|$, when R_K and R_{K^*} are jointly considered,



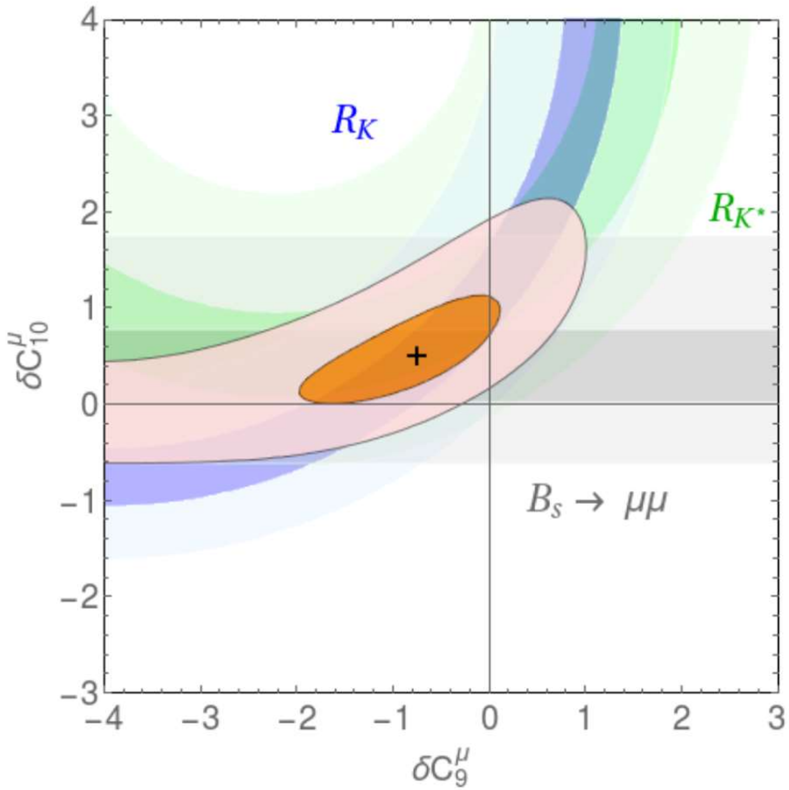
only C_L^{BSM} can interfere destructively to reduce both: $R_{K(*)}$ point to

purely left-handed coupling

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

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

The role of $B_s \to \mu\mu$



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

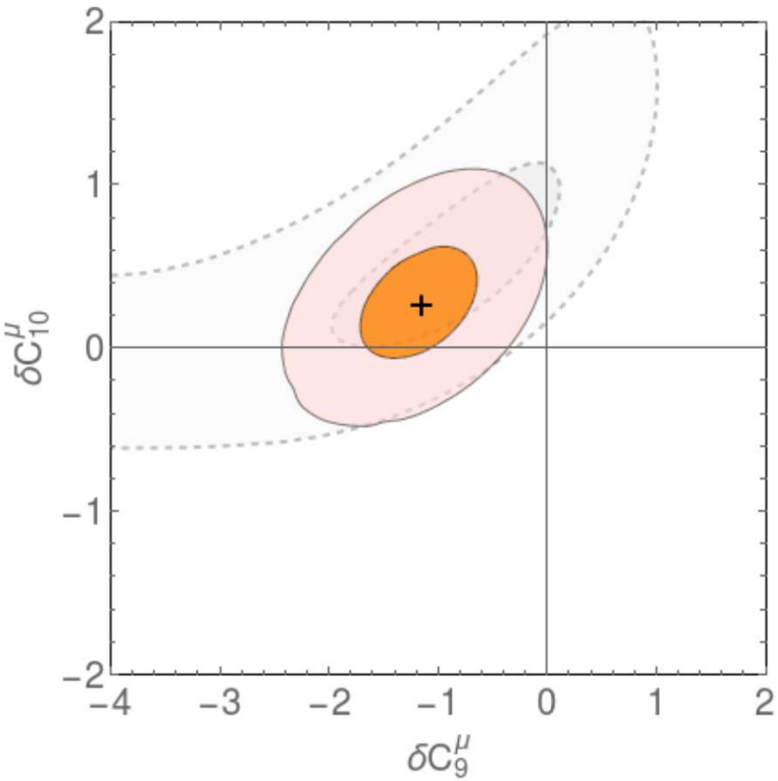
SM point excl. at 3.76 σ

Potential to break degeneracy

Statistics limited: domain of LHCb, CMS, ATLAS. Belle 2 won't be able to compete.

B→K*μμ,ee global fit

Including angular distributions



Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446
Also Capdevila et al; Altmannshofer & Straub; …

SM pull 4.17 σ

p = 0.572 [63 dof]

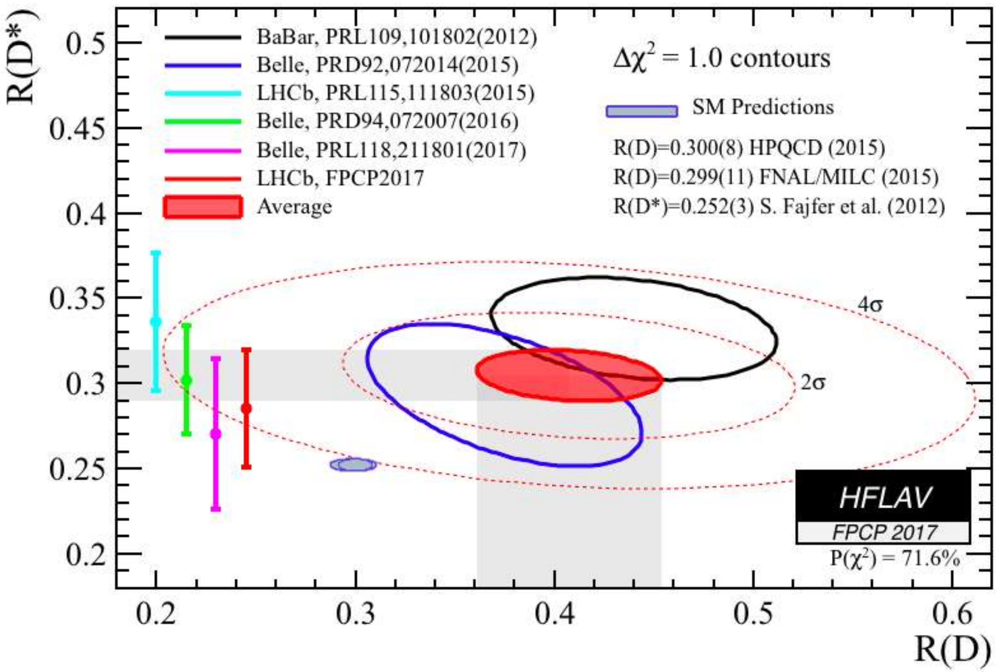
(but p(SM) now up to to 0.086)

Angular observables (P5' etc): good model discrimination.

Much more challenging theoretically (SM predictions)

Semileptonic decays: $R_{D(*)}$

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).

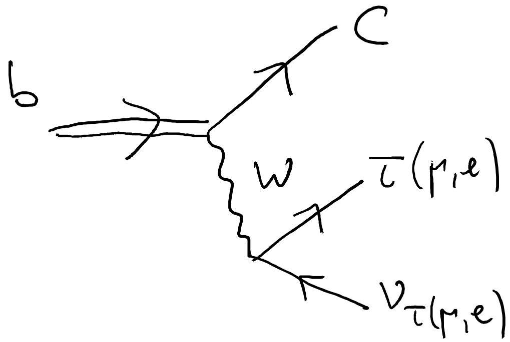


$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\ell\nu_\ell)}$$

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

Tree-level mediators: leptoquarks

Scalar or vector leptoquarks can generate interactions

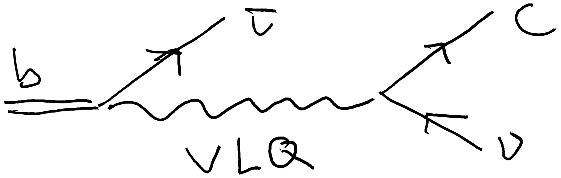
Eg Gripaios, Nardecchia, Renner, …
(Hiller, Nisandzic 2017)

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

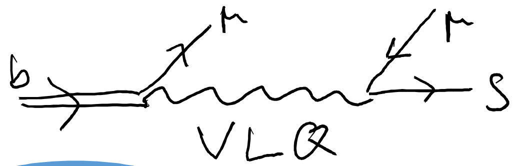
$$\frac{1}{\Lambda^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\mu}_L\gamma_\mu\mu_L\right)$$

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

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



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



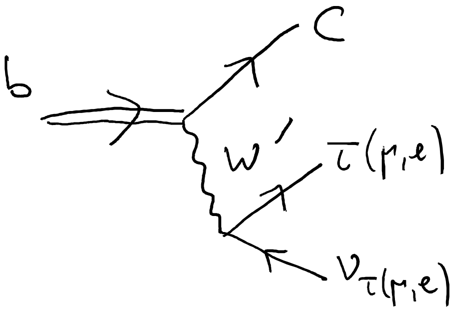
$(3,1,2/3)$ or $(3,3,2/3)$

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

Possible mediators: W', Z'

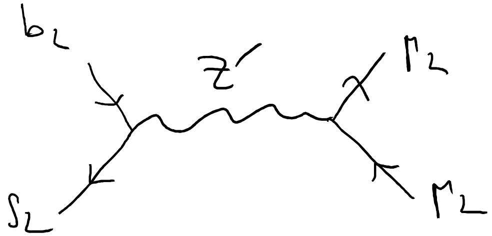
Isidori et al, Quiros et al, Ligeti et al, Becirevic et al, Crivellin et al, …

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



$(0,3,0)$

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



$(0,3,0)$ 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)

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

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

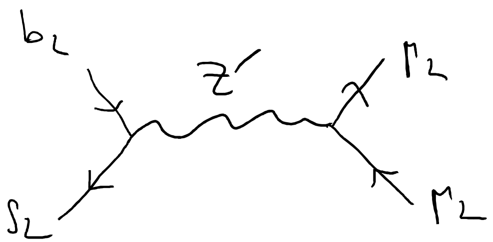
$$\frac{1}{\Lambda^2}\left(\bar{s}_L \gamma^\mu b_L\right)\left(\bar{\mu}_L \gamma_\mu \mu_L\right)$$

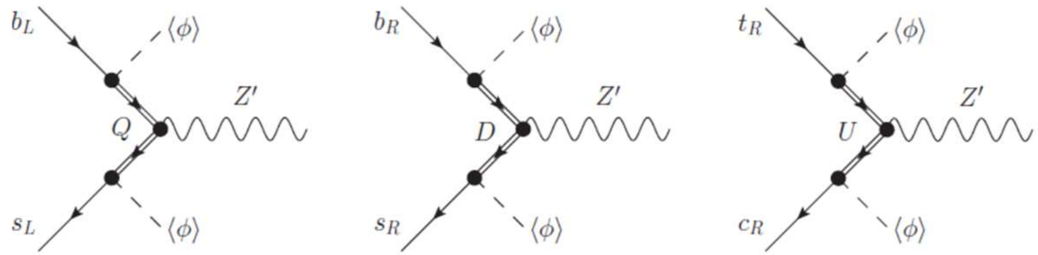
with Λ ~ 30 TeV

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





The small coupling to quarks suppresses contributions to B_s 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

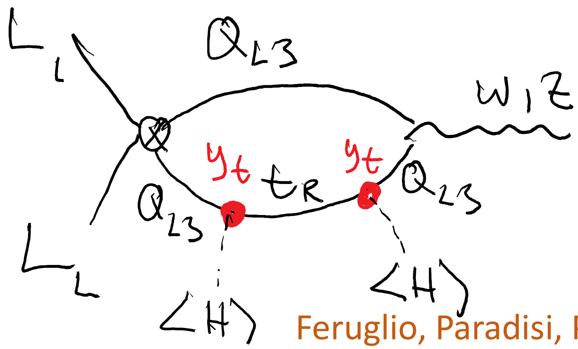
Both operators contribute to further processes that are experimentally constraints, in particular:

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

at one loop:

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

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



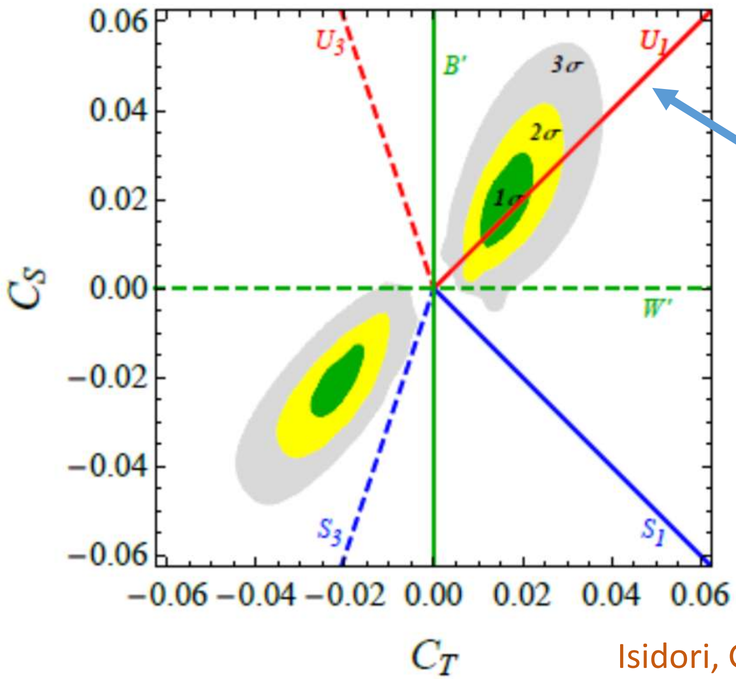
Feruglio, Paradisi, Pattori
arXiv:1606.00524, arXiv:1705.00929

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?

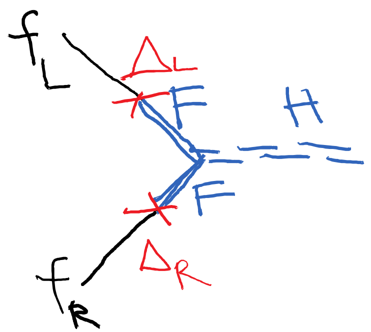
Basic idea of composite Higgs models (major BSM paradigm!)

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]

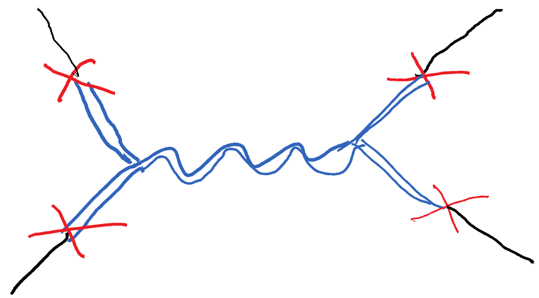
2) SM fermions are mixtures of elementary and composite particles

can generate flavour hierarchies



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

leading BSM effects:

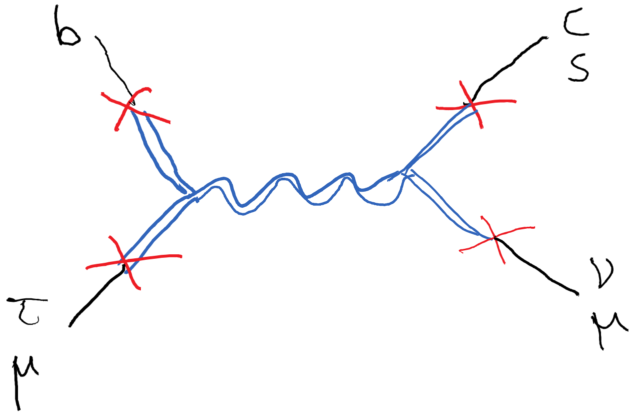


$$\sim \frac{g_*^2 \Delta^4}{M^6} (\bar{f} \Gamma f)(\bar{f} \Gamma f)$$

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

Scale of new physics & no-lose theorem

Di Luzio, Nardecchia 2017

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

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

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.

Prospects for LHC direct searches

Mediator of $R_{D(*)}$ may be in LHC reach, very likely in HE-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

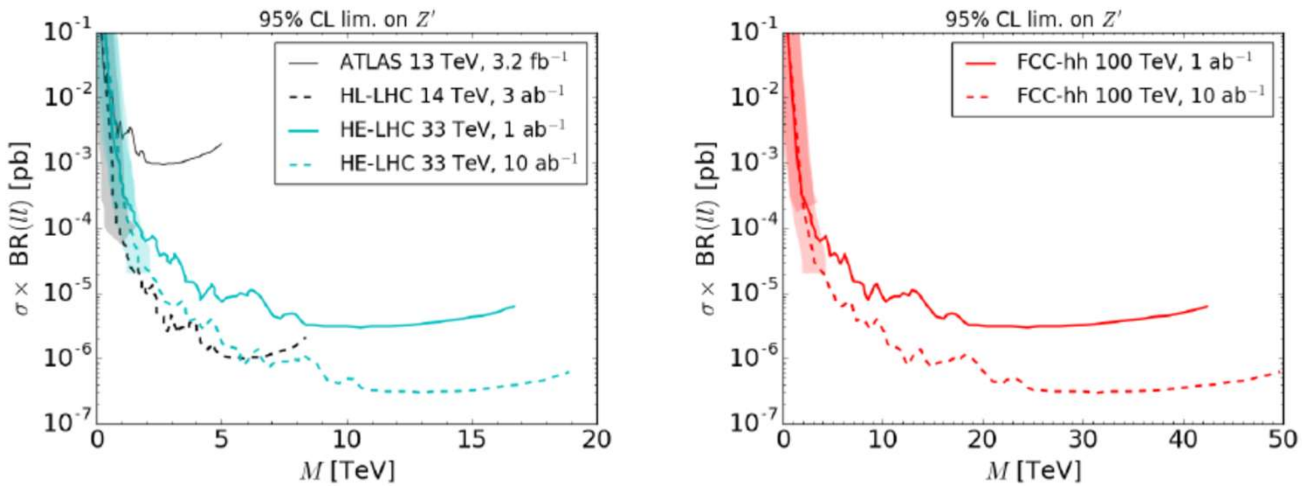
For tree-level $R_{K(*)}$ origin, mediator typically out of LHC reach (naïve scale ~ 30 TeV), though model-dependent

Future collider direct searches

Recall partial-wave unitarity bounds (conservative) of ~100 from $R_{K(*)}$ / 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

Corroboration and complementarity

Given the potential significance of the anomalies, both in their own right and for guiding future efforts, how can they be corroborated ?

R_{K^*}: theory beyond doubt - this is either real, a large statistical fluctuation, or an underestimated LHCb systematic. Belle2 should be able to verify this.

R_{D^*} : theory no issue. World average includes measurements from several experiments, but measurements tend to be systematics limited. Again, Belle2 will have sensitivity

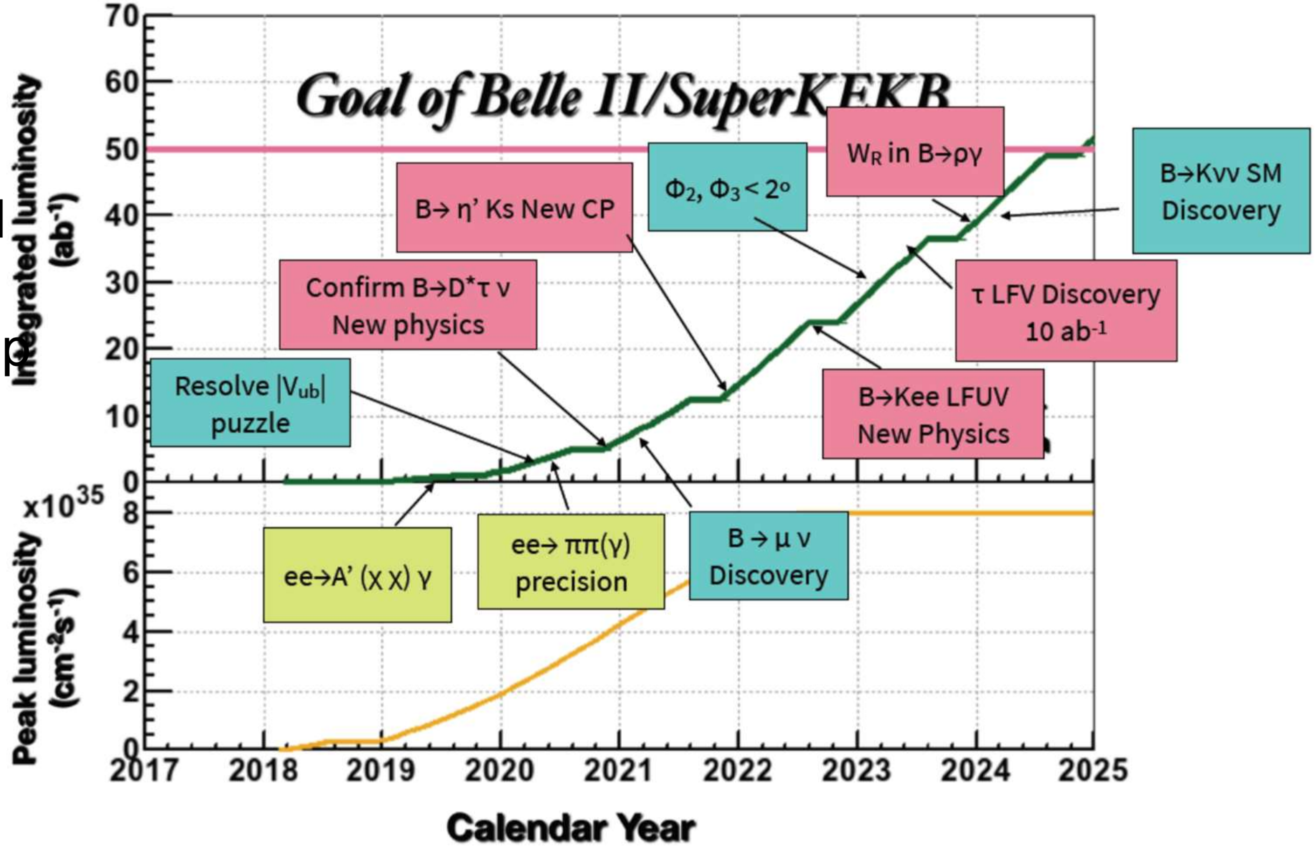
P_5’: theory is at its present limit, LHCb statistics will dominate over Belle2. Progress will eventually come from lattice QCD; possibly data-driven approaches

Belle 2

Belle 2: B-factory lepton collider, very different systematics

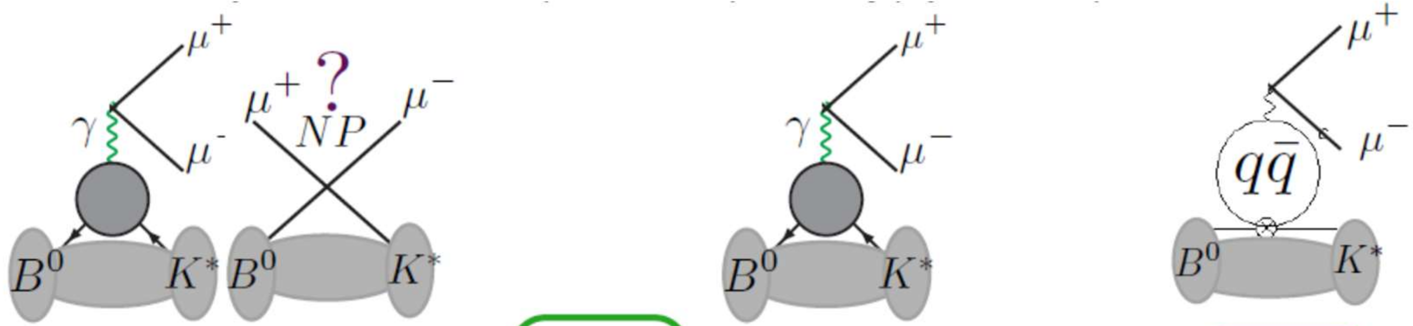
Statistics disadvantage relative to LHC, but better identification of electrons in final states

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



Rare decays: theory issues

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 (lattice)
- recent conceptual advances in lattice QCD (B -> V form factors)
- heavy-quark relations and and light-cone sum rules

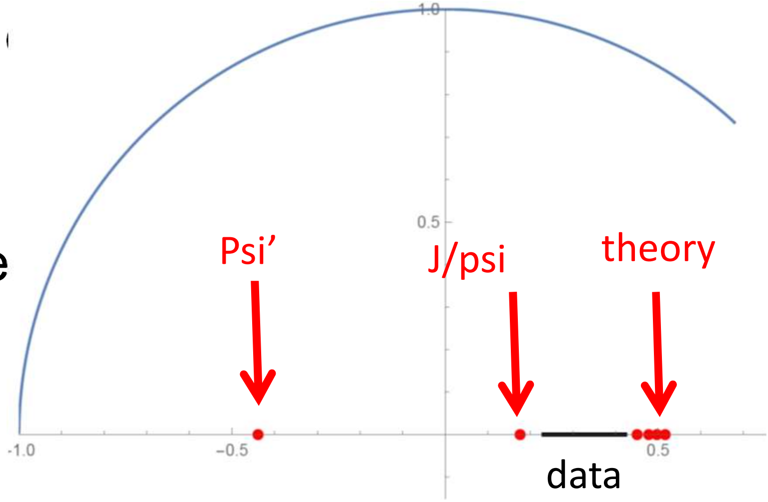
Ball&Braun; Ball& Zwicky; Bharucha et al 2015

Determining form factors from data?

Bobeth, Chrzaszcz, Van Dyk, Virto 2017

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

- use/assume analyticity of the virtual-charm dilepton mass dependence
- 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



Results *disfavour* attributing effects to virtual-charm

No (?) new information on form factors (but see LHCb's fit to $B \to K\mu\mu$)

Recent feasibility claim for a joint determination of virtual charm and C_9 from unbinned HL-LHC data on $B \to K^*\mu\mu$ Chrzaszcz et al 2018

Precision and computing

Theory uncertainty is often a limiting factor. [$R_{K(*)}$ and $R_{D(*)}$ exceptions]. E.g:

rare B decays

require heavy-light form factors B->K, B->K pi

+ amenable to lattice QCD calculations;
  - currently only for low Kaon energies;
  - more complicated for K pi (“K*”) final state

B meson lifetimes and mixings:

require hadronic matrix elements of increasing dimension
- currently mix of lattice QCD and QCD sum rule computations

CP violation in K->pi pi (similar for rare K decays)

Numerous hadronic matrix elements required; pioneered by RBC&UKQCD
perturbative QCD computations (Wilson coefficients, ADMs)

Direct CP violation in Kaons: another anomaly?

Precisely known experimentally for a decade

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

average of NA48 (CERN) and KTeV

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

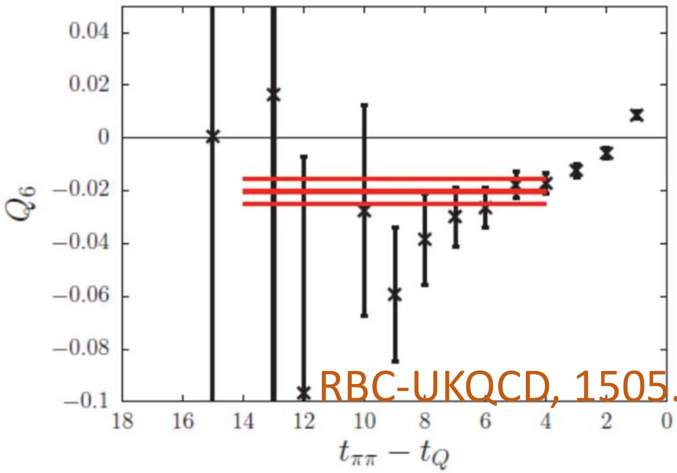
defines Re(ε'/ε) experimentally
left-hand side is measured

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

(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)

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		

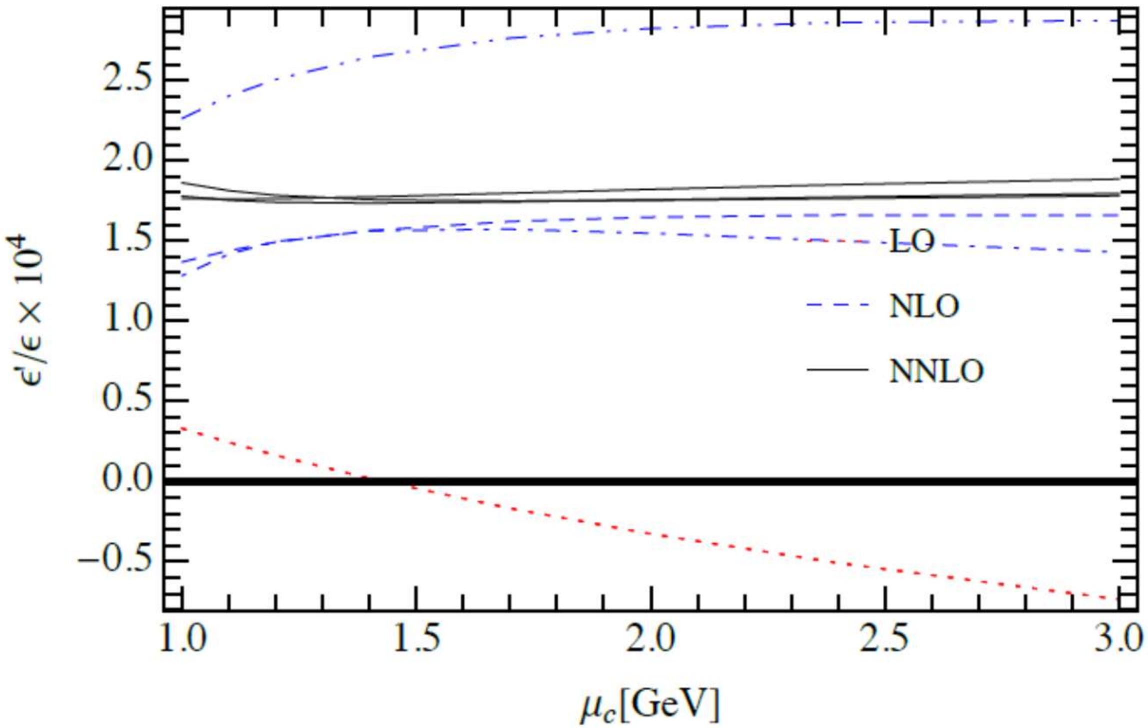
all in units of 10^-4

(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!

Computing & lattice

Bulk of computing requirements relate to lattice QCD

- crucial for controlled theory predictions
- requirements set by precision (and complexity)

Large UK activity and leadership (UKQCD, HPQCD)

Important goals for flavour phenomenology include:

- heavy-light form factors for semileptonic B decay (including rare); small q^2 requires fine lattices and high statistics
- long-distance effects in rare K decays (such as for K^+ ->pi nu nubar measured at NA62)
- vacuum polarisation, light-by-light in g-2

Some further flavour frontiers

current:

K->pi nu nu (NA62, KOTO)
(probe naïve BSM scales of several 100 TeV !)

with anticipated lattice QCD progress:

Delta M_K as a precision constraint
(sensitive to CP-conserving new physics)

Conclusions and opinions

Belle2 crucial in corroborating and complementing B-physics anomalies. **Maximize involvement**, there's a real chance to miss out on major discoveries, particularly for the UK.

B-physics anomalies help pinpointing the NP scale.

Confirmation of $R_{D(*)}$ would provide **strong evidence for new physics within direct reach of HE-LHC**. Otherwise, a new hadron machine should probably **maximize the energy reach – $\mathbf{R_{K(*)}}$** energy scale may be order 100 TeV but no higher

More generally, ensure a **diverse** flavour physics programme. **Kaons** (NA62 etc) probe the highest scales of all (quark) flavour transitions. Note that B-anomalies are **not** in the a priori expected places (like B-Bbar mixing). Lepton flavour, beam dump, SHIP etc [from a theory perspective these tend to probe different physics]

Conclusions and opinions

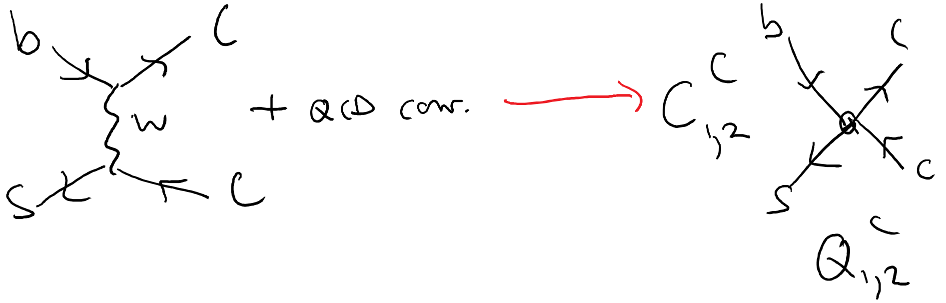
Accuracy of SM predictions is limiting factor in many case – e.g. P_5', epsilon'. Appropriate **computing resources for lattice QCD calculations**

Human resources: Flavour (and theory more generally) needs suitable funding, eg a project grant scheme (funding eg postdocs). Currently badly under-resourced in several European countries, particularly so in the UK

BACKUP

Impact of 4-quark operators

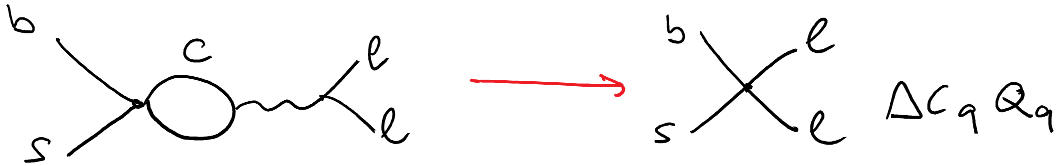
Also **purely hadronic** operators are important, primarily:



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

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

RG mixes these into C9 and C7



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

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

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

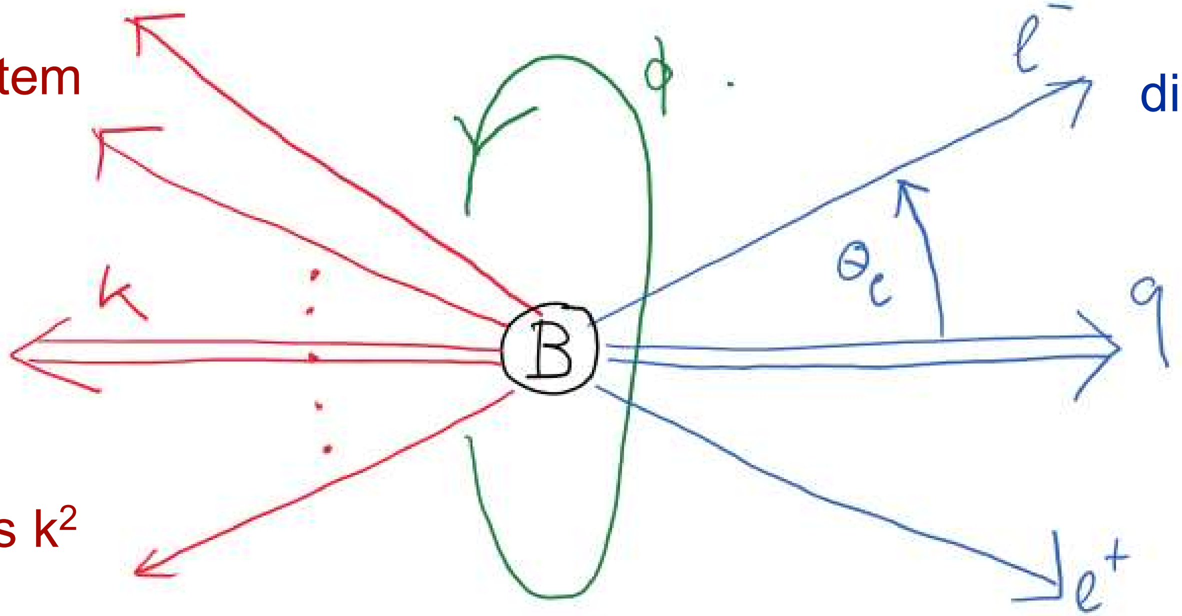
At μ=m_b: C_7^{eff} ~ -0.3 , C_L ~ 4 , $C_R \approx 0$

SM contribution is accidentally almost purely left-chiral

Semileptonic decays

hadronic system

dilepton



hadronic mass k^2

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

dilepton mass q^2

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 $A(\lambda_1)\, A(\lambda_2)^* \exp(i\,(\lambda_1 - \lambda_2)\Phi)$

Rare B-decay: observables

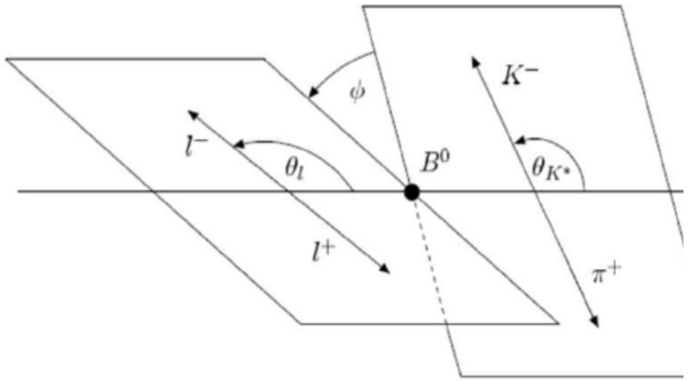
Branching ratios (differential in dilepton mass):

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

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)

Low branching ratios

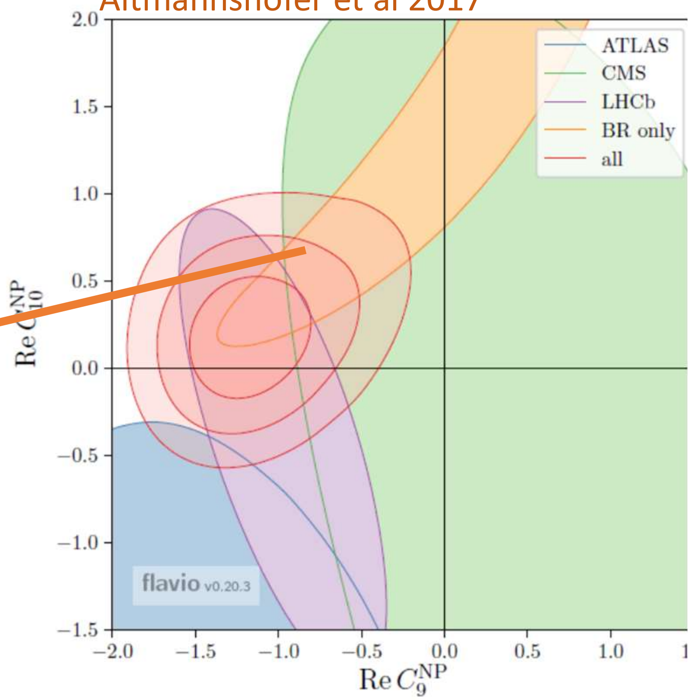
Schematically for B→Kμμ (neglecting small imaginary parts)

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

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

Global fit to b->s l l data

Altmannshofer et al 2017



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.

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

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

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

Often discuss P4' and P5' instead

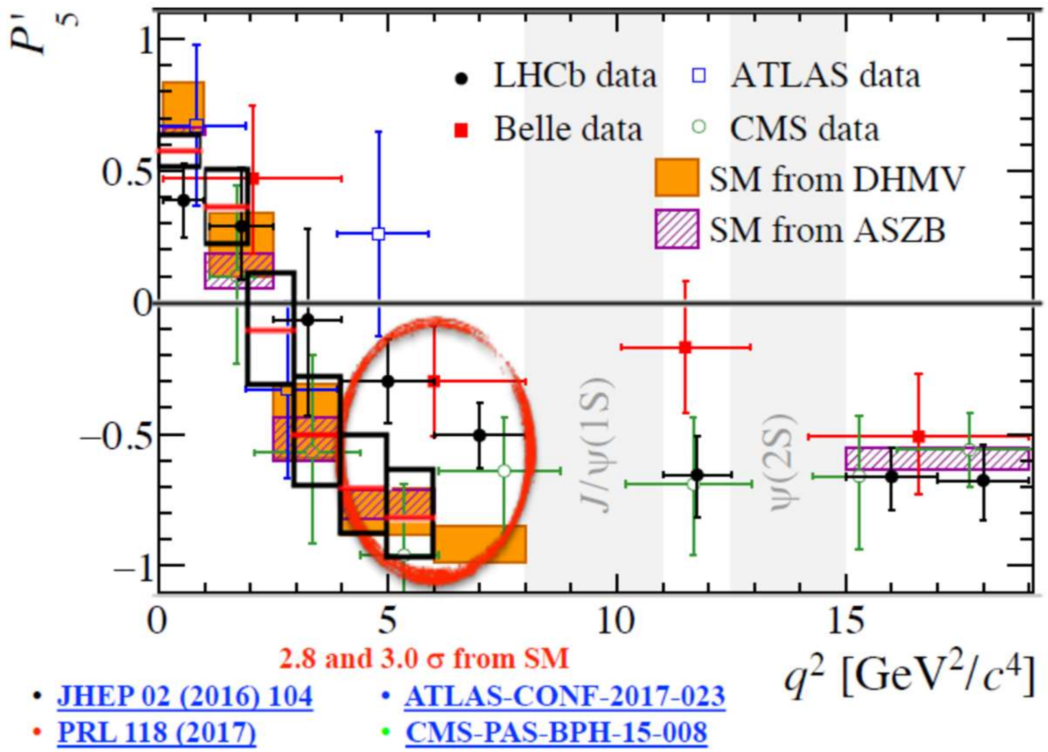
$$I_3 = -\frac{F}{2}\mathrm{Re}\left[H_V^+(H_V^-)^*\right] + (V \to A)$$

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

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

Probe right-handed currents

The (in)famous P5’



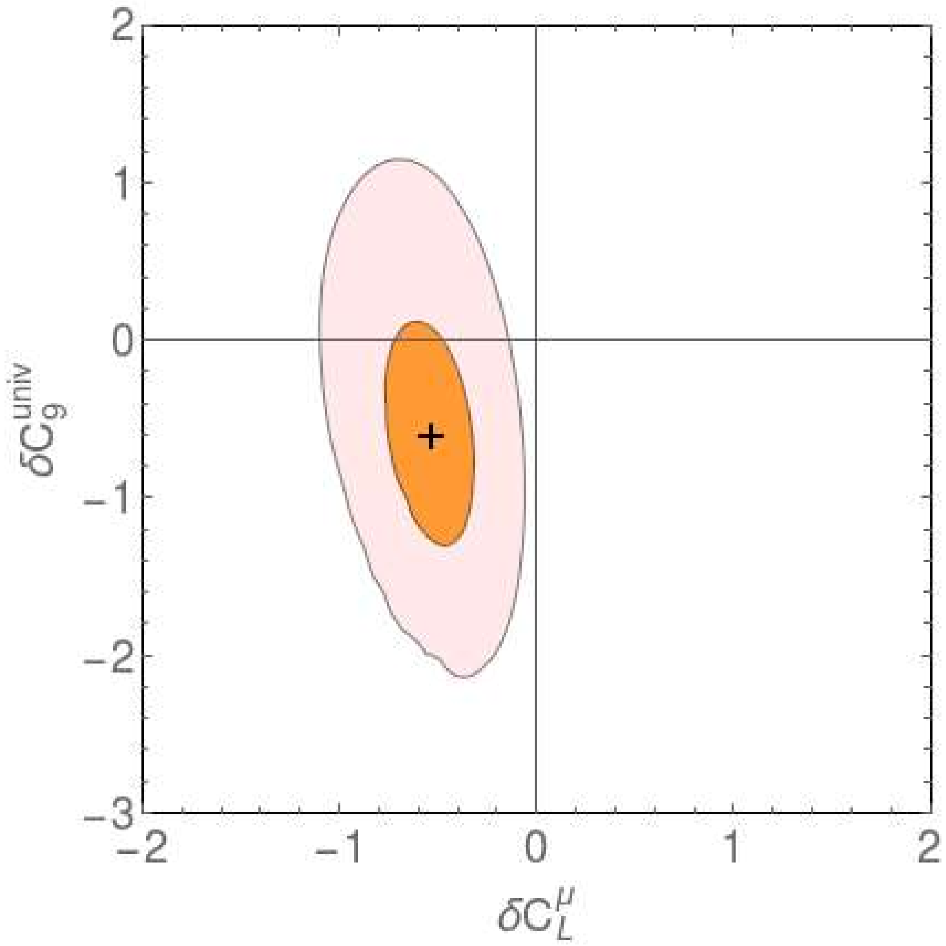
Simone Bifani, seminar at CERN (overlaid predictions from SJ&Martin Camalich 2014)

Modest discrepancy around 4-6 GeV, suggesting reduced C_9

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

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 $B \to K^* \mu\mu$

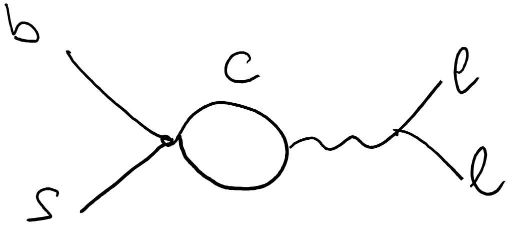
A model with (for example) nonzero C_L^{μ} and in addition an ordinary, **lepton-flavour-universal, C_9**, could describe the data similarly well or better

Eg. 'charming BSM' scenario

SJ, Kirk, Lenz, Leslie arXiv:1701.09183

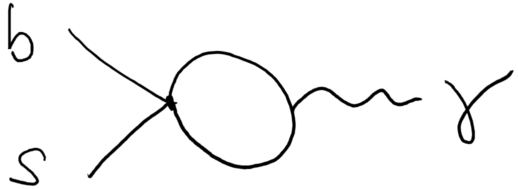
NP in b->c cbar s

SJ, Kirk, Lenz, Leslie arxiv:1701.09183



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

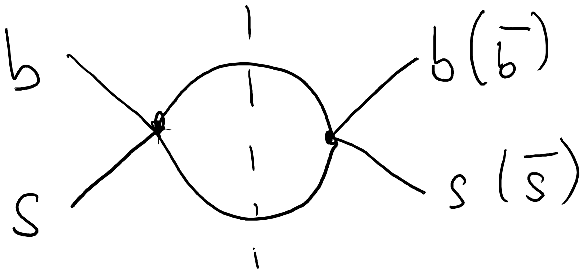
$$C_{x,y}^c = 3\Delta C_x + \Delta C_y$$



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

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