New Physics with (Mostly Heavy) Flavours

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Outline

Case for new physics with flavour

B-physics and anomalies

Implications: NP scales and mediators

A little bit on Kaons

Summary
History: Beyond Electrodynamics

The garbage of the past often becomes the treasure of the present (and vice versa).

A Polyakov

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
- V-A structure of weak interactions
- universality of weak decays
- CP violation
- electroweak symmetry breaking
- charm to explain $K_L \rightarrow \mu\mu$ suppression
- third generation to explain CPV

the SM was complete.

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

**Spin 1**
- Electromagnetism $U(1)$
- Weak interactions $SU(2)$
- Strong interactions $SU(3)$

**Spin 1/2**

<table>
<thead>
<tr>
<th></th>
<th>$u_L$</th>
<th>$u_R$</th>
<th>$c_L$</th>
<th>$c_R$</th>
<th>$t_L$</th>
<th>$t_R$</th>
<th>$Q = +2/3$</th>
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<tbody>
<tr>
<td>$d_L$</td>
<td>$d_R$</td>
<td>$s_L$</td>
<td>$s_R$</td>
<td>$b_L$</td>
<td>$b_R$</td>
<td>$Q = -1/3$</td>
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<tr>
<td>$\nu_{eL}$</td>
<td>$\nu_{\mu L}$</td>
<td>$\nu_{\tau L}$</td>
<td>$\nu_{e R}$</td>
<td>$\nu_{\mu R}$</td>
<td>$\nu_{\tau R}$</td>
<td>$Q = 0$</td>
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</tr>
<tr>
<td>$e_L$</td>
<td>$e_R$</td>
<td>$\mu_L$</td>
<td>$\mu_R$</td>
<td>$\tau_L$</td>
<td>$\tau_R$</td>
<td>$Q = -1$</td>
<td></td>
</tr>
</tbody>
</table>

**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.

\[
\begin{align*}
Q_{ll} & : (\bar{t}_p \gamma_\mu t_r)(\bar{t}_s \gamma^\mu t_t) \\
Q^{(1)}_{qq} & : (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t) \\
Q^{(3)}_{qq} & : (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma_\mu q_r q_t) \\
Q^{(1)}_{lq} & : (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t) \\
Q^{(3)}_{lq} & : (\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma_\mu q_r q_t)
\end{align*}
\]

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 \( b \to s \gamma \)
  \( B \to K(*) \mu^+ \mu-, \ B \to K(*)e^+e^- \), \( B_s \to \phi \mu^+ \mu^- \)
  \( B \to K(*) \gamma \)
  \( B \to X_s \mu^+ \mu-, \ B \to X_s \gamma \)

\( s \to d \nu \nu \)

- lepton-flavour ratios, eg
  \( \text{BR}(B \to K(*) \mu^+ \mu^-)/\text{BR}(B \to K(*)e^+e^-) - 1 \)
  \( \text{BR}(B \to D(*) \tau \nu)/\text{BR}(B \to D(*)l \nu) - \text{(SM)} \)
- CP violation, eg
  \( K_L \to \pi \pi \quad (\epsilon_K, \epsilon'_K) \)
  \( K_L \to \pi^0 \nu \nu \)

Babar, Belle
LHCb, ATLAS, CMS
Belle2
Babar, Belle, Belle2

NA62 (CERN)

Babar, Belle, LHCb
Belle2

..., NA48, KTeV

KOTO
Anomaly I: semileptonic decays

For some time B-factories and LHCb have consistently shown semileptonic $B \rightarrow D (D^*) \tau \nu$ decay rates larger than expected (relative to the rate for light leptons).

\[ R(D^*) = \frac{BR(B \rightarrow D^{(*)}\tau\nu)}{BR(B \rightarrow D^{(*)}\ell\nu_\ell)} \]

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 $\sim 10\%$ 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

\[ (\bar{s}_u \gamma_\mu P_L b)(\bar{\ell}_l \gamma^{\mu} l) \]

C10: dilepton from axial current

\[ (\bar{s}_u \gamma_\mu P_L b)(\bar{\ell}_l \gamma^{\mu} \gamma^5 l) \]

C7: dilepton from dipole

\[ (\bar{s}_u \sigma^{\mu\nu} P_R b) F_{\mu\nu} \]

Alternative basis with chiral leptons

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

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Impact of 4-quark operators

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

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

RG mixes these into C9 and C7

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

At \( \mu=m_b \):
\[ C_7^{\text{eff}} \sim -0.3, \quad C_L \sim 4, \quad C_R \approx 0 \]

SM contribution is accidentally almost purely left-chiral
Rare B-decay: observables

Branching ratios (differential in dilepton mass):

\[ B \to K^{(*)}\mu\mu, \quad B \to K^{(*)}ee, \quad B_s \to \phi\mu\mu \]

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 \( B \to V\ell \ell \):
3 angles, dilepton mass \( q^2 \)

7 angular differential observables:
(\( A_{FB}, P_5', \) etc)
Anomaly II: Lepton-flavour ratios at LHCb

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

Theory uncertainties negligible relative to experiment.

\[ p(\text{SM}) = 2.1 \times 10^{-4} \ (3.7\sigma) \]

Suggests nonzero, muon-specific \( C_{10}^{\text{BSM}} \) - not pure \( C_9 \)

Geng, Grinstein, SJ, Martin Camalich, Ren, Shi arxiv:1704.05446
Assume here that the BSM effect is in the muonic mode

<table>
<thead>
<tr>
<th>Obs.</th>
<th>Expt.</th>
<th>SM</th>
<th>$\delta C_{10}^\mu = -0.5$</th>
<th>$\delta C_{9}^\mu = -1$</th>
<th>$\delta C_{10}^\mu = 1$</th>
<th>$\delta C_{9}^\mu = -1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_K$ [1, 6] GeV$^2$</td>
<td>0.745 ± 0.090</td>
<td>1.0004$^{+0.0008}_{-0.0007}$</td>
<td>0.773$^{+0.0003}_{-0.0003}$</td>
<td>0.797$^{+0.0002}_{-0.0002}$</td>
<td>0.778$^{+0.0007}_{-0.0007}$</td>
<td>0.796$^{+0.0002}_{-0.0002}$</td>
</tr>
<tr>
<td>$R_{K^*}$ [0.045, 1.1] GeV$^2$</td>
<td>0.66 ± 0.12</td>
<td>0.920$^{+0.007}_{-0.006}$</td>
<td>0.88$^{+0.01}_{-0.02}$</td>
<td>0.91$^{+0.01}_{-0.02}$</td>
<td>0.862$^{+0.016}_{-0.011}$</td>
<td>0.98$^{+0.03}_{-0.03}$</td>
</tr>
<tr>
<td>$R_{K^*}$ [1.1, 6] GeV$^2$</td>
<td>0.685 ± 0.120</td>
<td>0.996$^{+0.002}_{-0.002}$</td>
<td>0.78$^{+0.02}_{-0.01}$</td>
<td>0.87$^{+0.04}_{-0.03}$</td>
<td>0.73$^{+0.03}_{-0.04}$</td>
<td>1.20$^{+0.03}_{-0.03}$</td>
</tr>
<tr>
<td>$R_{K^*}$ [15, 19] GeV$^2$</td>
<td>–</td>
<td>0.998$^{+0.001}_{-0.001}$</td>
<td>0.776$^{+0.002}_{-0.002}$</td>
<td>0.793$^{+0.001}_{-0.001}$</td>
<td>0.787$^{+0.004}_{-0.004}$</td>
<td>1.204$^{+0.007}_{-0.008}$</td>
</tr>
</tbody>
</table>

Theory uncertainties negligible.

1σ and 3σ confidence regions

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

$p(C_{9} \& C_{10}) = 0.158$

SM point excluded at 3.78 σ

Considerable degeneracy (flat direction in $\chi^2$)
Because in the SM, $|C_R|, |C_7| \ll |C_L|$, 
$BR \approx \text{const } |C_L^{SM} + C_L^{BSM}|^2 + \ldots \approx \text{const } |4 + C_L^{BSM}|^2 + \text{positive}$

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

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

with $\sim -(10-15)\%$ of SM value
Adding $B_s \rightarrow \mu\mu$

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 $\sigma$

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 $-0.61$. 1$\sigma$ $[-0.78, -0.46]$, $p = 0.339$

SM point (origin) excluded at 4.16 sigma
Rare decays: amplitude anatomy

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

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

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

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 $B \rightarrow K \mu \mu$ (neglecting small imaginary parts)

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

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

$C_7$, $h_0$, 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.
Anomaly IV: The (in)famous P5’

Modest discrepancy around 4-6 GeV, suggesting reduced $C_9$

SM theory is subtle – form factors, long-distance virtual-charm somewhat uncertain
Adding $B \to K^* \mu\mu, e\bar{e}$ angular data

Serves to determine best-fit region even better.

SM pull 4.17 $\sigma$

$p = 0.572$ [63 dof]

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

Wilson coefficient value $C_L = 0$ again excluded at high confidence.
Must $C_9$ violate lepton flavour?

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 $C_L^\mu$ and in addition an ordinary, lepton-flavour-universal, $C_9$, could describe the data similarly well or better

Eg. ‘charming BSM’ scenario

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

SJ, Kirk, Lenz, Leslie arXiv:1701.09183
Fits of hadronic parameters to data?

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 q^2 \ll 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→Kμμ)
## B-anomalies: summary & prospects

<table>
<thead>
<tr>
<th>observable</th>
<th>Anomaly</th>
<th>Significance (sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{BR}(B \to {K,K^*,\phi} \mu \mu) ) at low dilepton mass ( q_2 )</td>
<td>Lowish w.r.t expectation</td>
<td>1-2 ?</td>
</tr>
<tr>
<td>( B\to K^* \mu \mu ) angular distribution (low ( q_2 ))</td>
<td>( P5' ) off for some ( q_2 )</td>
<td>2-3 ?</td>
</tr>
<tr>
<td>( \text{RD}(<em>) = \frac{\text{BR}(B \to D(</em>)\tau \nu)}{\text{BR}(B \to D(*)l \nu)} )</td>
<td>Enhanced w.r.t. SM</td>
<td>4.1</td>
</tr>
<tr>
<td>Lepton-universality ratios (( RK, RK^* ))</td>
<td>Below SM</td>
<td>3.7 (3 observables combined)</td>
</tr>
</tbody>
</table>

### LHCb: rapidly increasing dataset

All will be measured at Belle 2 in the next few years (lower luminosity, but different systematics and excellent control over the electronic final state)
Implications: scale of new physics

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

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

numerically \( \Lambda \sim 3 \) TeV and \( \Lambda \sim 30 \) TeV.

Uncertainties below factor 2 (if anomalies are genuine).

Recall in the case of the Fermi theory, \( G_F \sim \frac{g^2}{M_W^2} \)

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 of 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.
Possible mediators: $b \rightarrow c \tau \nu(\tau)$

Recall favoured BSM effective interaction

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

numerically $\Lambda \sim 3$ TeV

Less if new physics has flavour suppression

Possible mediation by $W'$ (could be composite) or leptoquarks,

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

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

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Possible mediators for $b \to s \mu \mu$: $Z'$

Accommodating all $b \to s \ell \ell$ 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 $\Lambda \sim 30$ TeV

However, $C_R$ is weakly constrained and can also be present. So for example a pure $C_9$ effect is possible (P5' may prefer this).

Anomaly-free $Z'$ model with gauged $L_\mu - L_\tau$, nonminimal (dim-6) coupling to quarks, can eg come from heavy vectorlike quarks:

The small coupling to quarks suppresses contributions to $B_s$ mixing
Leptoquark-mediated rare decay

Scalar or vector leptoquarks exchange can also generate a $C_L$ effect.

Tree-level exchange viable for

- scalar in SM gauge representation $(\bar{3}, 3, 1/3)$

- vector in SM gauge representation $(\bar{3}, 1, 2/3)$ or $(\bar{3}, 3, -2/3)$

Contributions to $B_s$ mixing absent at tree level.

More possibilities at loop level, can try to employ the same leptoquark to mediate RD and RK$^*$.
Combined explanations

Isidori, Greljo arXiv:1706.07808
Natural vector leptoquark?

The SM representation \((\bar{3}, 1, 2/3)\) appears in the restriction of the Pati-Salam (SU(4) x SU(2) x SU(2)) adjoint to the SM.

The associated conserved current can create spin-1 vector leptoquark states with these quantum numbers. Several partially-composite models of this type have recently appeared.

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


[SU(4) x SO(5) x U(1)] / [SU(4) x SO(4) x U(1)] pNGB Higgs model

Barbieri, Tesi arXiv:1712.06844

SU(4) x SU(2) x SU(2) Randall-Sundrum (warped ED) model

Blanke, Crivellin arXiv:1801.07256
Must $C_9$ show LUV?

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 $B \rightarrow K^* \mu \mu$

This means a model with (for example) nonzero $C_L^\mu$ 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
Theory progress & anomaly V: CPV in $K_L \rightarrow \pi\pi$

Precisely known experimentally for a decade

$$\frac{\epsilon' / \epsilon}_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}$$

average of NA48 (CERN) and KTeV

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

defines $\text{Re}(\epsilon'/\epsilon)$ experimentally left-hand side is measured

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

(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)

\[(\varepsilon'/\varepsilon)_{\text{SM}} = (1.9 \pm 4.5) \times 10^{-4}\]
\[(\varepsilon'/\varepsilon)_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}\]

2.9\sigma discrepancy
(see also Kitahara, Nierste, Tremper 1607.06727)
(see also Kitahara, Nierste, Tremper 1607.06727)

<table>
<thead>
<tr>
<th>quantity</th>
<th>error on ( \varepsilon'/\varepsilon )</th>
<th>quantity</th>
<th>error on ( \varepsilon'/\varepsilon )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_6^{(1/2)} )</td>
<td>4.1</td>
<td>( m_d(m_c) )</td>
<td>0.2</td>
</tr>
<tr>
<td>NNLO</td>
<td>1.6</td>
<td>( q )</td>
<td>0.2</td>
</tr>
<tr>
<td>( \hat{\Omega}_{\text{eff}} )</td>
<td>0.7</td>
<td>( B_8^{(1/2)} )</td>
<td>0.1</td>
</tr>
<tr>
<td>( p_3 )</td>
<td>0.6</td>
<td>( \text{Im}\lambda_t )</td>
<td>0.1</td>
</tr>
<tr>
<td>( B_8^{(3/2)} )</td>
<td>0.5</td>
<td>( p_{72} )</td>
<td>0.1</td>
</tr>
<tr>
<td>( p_5 )</td>
<td>0.4</td>
<td>( p_{70} )</td>
<td>0.1</td>
</tr>
<tr>
<td>( m_s(m_c) )</td>
<td>0.3</td>
<td>( \alpha_s(M_Z) )</td>
<td>0.1</td>
</tr>
<tr>
<td>( m_t(m_t) )</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(all in units of \(10^{-4}\))

parameterise hadronic matrix elements
values from RBC-UKQCD 2015

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

next are NNLO and isospin breaking
NNLO computation (partial)

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!
Conclusions

Physics with heavy (and not so heavy) flavours provides many search channels that can probe contact interactions with scales beyond the energy frontier.

A variety of intriguing signs for departure from the SM, with good prospects for the significance.

A genuine effect will provide an upper bound on the mass scale of new physics.

May point to leptoquark and/or Z’ mediators, generally within the reach of future colliders. Possible connections with naturalness only recently explored.
BACKUP
Semileptonic decays

hadronic system

hadronic mass $k^2$

hadronic angles & energies equivalently:
- angular momentum $L'$
- helicity $\lambda'$
  (+ more if >2 hadrons)

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

Observing $\Phi$ requires interference $A(\lambda_1)A(\lambda_2)^* \exp(i(\lambda_1 - \lambda_2)\Phi)$
Charming BSM scenario

very efficient way to generate $C_9(NP) = O(1)$

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

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

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

At one loop, radiative decay constrains $C_{5..10}$, but not $C_{1..4}$. Focus on the latter. Then consider lifetime (mixing) observables

$$\Delta C_{9}^{\text{eff}}(q^2) = \left( C_{1,2}^c - \frac{C_{3,4}^c}{2} \right) h(q^2, m_c, \mu) - \frac{2}{9} C_{3,4}^c \quad C_{x,y}^c = 3\Delta C_x + \Delta C_y$$

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

Note that $h$ and $y$ are $q^2$-dependent.

$\Delta \Gamma_s$ and $\tau_{B_s}/\tau_{B_d}$ calculable in OPE for general $C_{1..4}$
High NP scale – global analysis

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

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