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Anomalies in B meson decays: Present Status and Future Colliders Prospects

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Based on **JA**, J. Guasch, S. Peñaranda:
Eur.Phys.J.C 79 (2019) 7, 588 1805.03636 & 2012.14799.
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Outline

1. Introduction
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   - Effective Field Theory and SMEFT.
2. Our results.
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   - Weak Effective Theory and RGE running.
   - B-meson observables in EFT.
   - Global fits.
   - Observables after the fit.
3. Prospects from e^+e^- linear colliders.
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   - Probing Wilson coefficients.
   - Electroweak precission tests.
4. Conclusions.

Anomalies in B meson decays

Flavour-Changing Neutral decays proceed through $b \to s\ell^+\ell^-$ $(\ell = e,\ \mu)$.

- Anomalies first observed in $B \to K^{(*)}\mu^+\mu^-$.
- Present in theoretically clean ratios

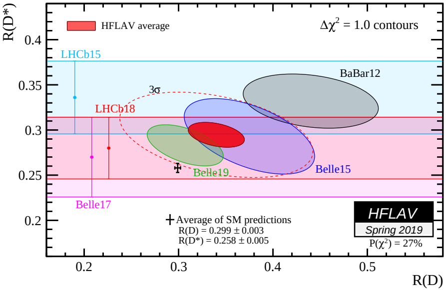
$$R_{K^{(*)}} = \frac{\mathrm{BR}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{BR}(B \to K^{(*)}e^+e^-)},$$

  $R^{\mathrm{SM}}_{K^{(*)}} = 1.000(1) \Longrightarrow$ Lepton Flavour Universality,

- ...but the experimental measurements at low and mid q^2 are 2.5σ below:
  $R_{K^+}^{[1.1,\,6]} = 0.846^{+0.060+0.016}_{-0.054-0.014}$ LHCb, PRL**122** (2019) 19, 191801. arXiv:1903.09252
  $R_{K^{*\,0}}^{[0.045,\,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$ LHCb, JHEP**08** (2017), 055. arXiv:1705.05802
  $R_{K^{*\,0}}^{[1.1,\,6]} = 0.685^{+0.113}_{-0.069} \pm 0.047$
- Also in the clean angular observable P_5'.

Anomalies in B meson decays

Flavour-Changing Charged decays proceed through $b \to c\ell\nu$ ($\ell = e,\ \mu,\ \tau$).



HFLAV, 1909.12524 [hep-ex]

- In the $R_{D^{(*)}}$ ratios

$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)}.$$

When combined, a 3σ excess with respect to SM.

- Also an excess in $R_{J/\psi}$.

Effective Field Theory and SMEFT

- EFT "integrates out" heavy degrees of freedom above energy scale Λ, resulting in operators with dim > 4. The short-distance physics is encoded in the Wilson coefficient that multiplies each operator.

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum C^{(5)}\mathcal{O}^{(5)} + \frac{1}{\Lambda^2}\sum C^{(6)}\mathcal{O}^{(6)} + \cdots$$

- In particular, SMEFT integrates out NP degrees of freedom.
  - Model-independent description.
  - 2499 dimension-6 operators ($\Delta B = \Delta L = 0$).
  - Warsaw basis is the most common choice.

    B. Grzadkowski *et al.*, JHEP 10 (2010) 085. arXiv:1008.4884 [hep-ph]

SMEFT for the B anomalies

- We consider the following effective Lagrangian

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2} \sum_{i=e,\mu,\tau} (C^i_{\ell q(1)} \mathcal{O}^i_{\ell q(1)} + C^i_{\ell q(3)} \mathcal{O}^i_{\ell q(3)})$$

at the scale $\Lambda = 1$ TeV, using the SMEFT operators:

$$\mathcal{O}^i_{\ell q(1)} = (\bar{\ell}_i \gamma_\mu \ell_i)(\bar{q}_3 \gamma^\mu q_3),$$
$$\mathcal{O}^i_{\ell q(3)} = (\bar{\ell}_i \gamma_\mu \tau^I \ell_i)(\bar{q}_3 \gamma^\mu \tau^I q_3),$$

where ℓ and q are the $SU(2)_L$ doublets.

- We perform a global fit using `flavio`, including B-physics and electroweak observables. D. M. Straub, arXiv:1810.08132 [hep-ph]
- Constrains from $\mathrm{BR}(B \to K^{(*)} \nu \bar{\nu})$ impose

$$C^i_{\ell q(1)} = C^i_{\ell q(3)} \equiv C^i_{\ell q}.$$

F. Feruglio *et al.*, JHEP 09 (2017) 061. arXiv:1705.00929 [hep-ph]

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Γ_Z, M_W, A_e, A_μ, A_τ, A_b, A_c, R_e, R_μ, R_τ, R_b, R_c, A^{FB}, σ_0^{had}

$R_{K^{(*)}}$ and differential observables, $R_{D^{(*)}}$, $B_{(s)} \to \mu^+\mu^-$, $B \to K^{(*)}\nu\bar{\nu}$

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Weak Effective Theory and RGE running

- The scale of B decays is $\mu \approx m_b$. We need to integrate out t, H, W and Z.
- The Weak Effective Lagrangian is given by

$$\mathcal{L}_{\text{WET}} = \mathcal{L}_{\text{SM}} - \frac{4G_F}{\sqrt{2}} V_{cb} \sum_{\ell=e,\mu,\tau} (1+C^\ell_{VL})\mathcal{O}^\ell_{VL} + \frac{4G_F}{\sqrt{2}} V_{tb}V^*_{ts} \frac{e^2}{16\pi^2} \sum_{\ell=e,\mu} (C^\ell_9 \mathcal{O}^\ell_9 + C^\ell_{10}\mathcal{O}^\ell_{10}) \,,$$

$$\mathcal{O}^\ell_{VL} = (\bar{c}_L \gamma_\alpha b_L)(\bar{\ell}_L \gamma^\alpha \nu_\ell) \,,$$

$$\mathcal{O}^\ell_9 = (\bar{s}_L \gamma_\alpha b_L)(\bar{\ell}\gamma^\alpha \ell) \,, \qquad \mathcal{O}^\ell_{10} = (\bar{s}_L \gamma_\alpha b_L)(\bar{\ell}\gamma^\alpha \gamma_5 \ell) \,.$$

- We obtained the running from the SMEFT operators at $\Lambda = 1$ TeV down to $\mu = m_b$ using the RGE:

$$C_9^{\text{NP}\ e,\mu} = -0.583\, C^{e,\mu}_{\ell q(1)} - 0.596\, C^{e,\mu}_{\ell q(3)} \,, \qquad C_{10}^{\text{NP}\ e,\mu} = 0.588\, C^{e,\mu}_{\ell q(1)} + 0.591\, C^{e,\mu}_{\ell q(3)} \,,$$

$$C^{e,\mu}_{VL} = 0.0012\, C^{e,\mu}_{\ell q(1)} - 0.0644\, C^{e,\mu}_{\ell q(3)} \,, \qquad C^{\tau}_{VL} = -0.0598\, C^{\tau}_{\ell q(3)} \,.$$

JA et al. arXiv:2012.14799 [hep-ph]

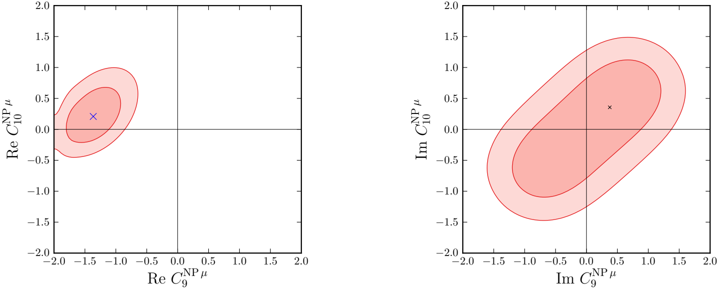
B-meson Observables in EFT

JA, J. Guasch, S. Peñaranda: Some Results on Lepton Flavour Universality Violation. Eur.Phys.J.C 79 (2019) 7, 588. 1805.03636

We obtained the analytical expression for the $R_{K^{(*)}}$ observables defined at $\mu = m_b$ as

$$R_{K^*}^{[1.1,6]} \simeq \frac{0.9875 + 0.1759\,\mathrm{Re}\,C_9^\mu - 0.2954\,\mathrm{Re}\,C_{10}^\mu + 0.0212|C_9^\mu|^2 + 0.0350|C_{10}^\mu|^2}{1 \qquad + 0.1760\,\mathrm{Re}\,C_9^e - 0.3013\,\mathrm{Re}\,C_{10}^e + 0.0212|C_9^e|^2 + 0.0357|C_{10}^e|^2}\ .$$

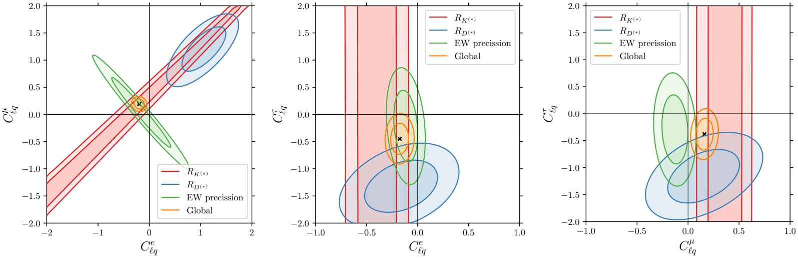
We performed a fit to the WET operators



Global fits

J. Alda, J. Guasch and S. Peñaranda, *Anomalies in B decays: A phenomenological approach*. 2012.14799 [hep-ph]

We performed a global fit (B-physics + EW) to the SMEFT operators



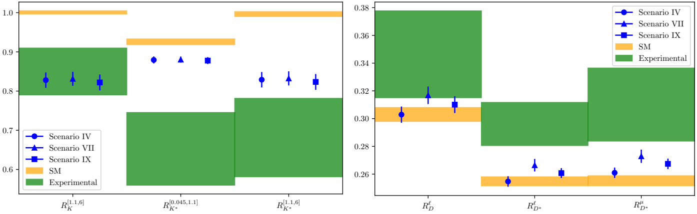
- $\mathcal{O}^{\mu}_{\ell q} - \mathcal{O}^{e}_{\ell q}$ describes violations of lepton universality, fit dominated by $R_{K^{(*)}}$ and $R_{D^{(*)}}$ observables. Large deviations from SM.
- $\mathcal{O}^{\mu}_{\ell q} + \mathcal{O}^{e}_{\ell q}$ describes flavour-universal contributions, fit dominated by EW observables. Compatible with SM.
- $\mathcal{O}^{\tau}_{\ell q}$ uncorrelated with the other operators. Compatible with SM (but large uncertainties).

Observables after the fit

J. Alda, J. Guasch and S. Peñaranda, *Anomalies in B decays: A phenomenological approach*. 2012.14799 [hep-ph]

We consider different scenarios for the SMEFT coefficients. The most relevant are:

- Scenario IV: Fit to $C_{\ell q}^{e}$, $C_{\ell q}^{\mu}$.
- Scenario VII: Fit to $C_{\ell q}^{e}$, $C_{\ell q}^{\mu}$, $C_{\ell q}^{\tau}$.
- Scenario IX: Fit to $C_{\ell q}^{e} = C_{\ell q}^{\tau} = -C_{\ell q}^{\mu}$.



- $C_{\ell q}^{e} \approx -C_{\ell q}^{\mu}$ improves the prediction for $R_{K^{(*)}}$.
- $C_{\ell q}^{\tau}$ needed for $R_{D^{(*)}}$.

Electron colliders and Flavour Physics

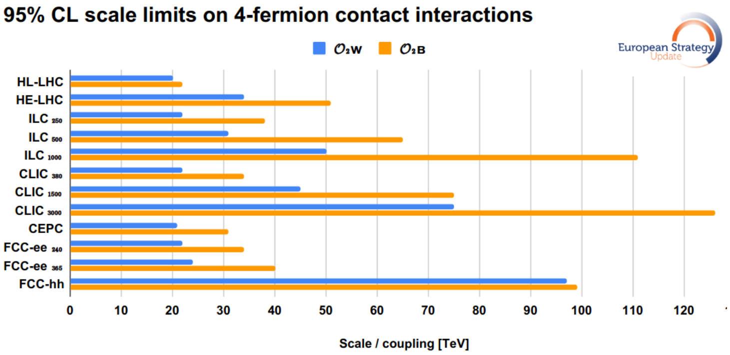
Electron colliders are powerful tools in testing neutral currents:

- Clean signatures.
- Small uncertainties.
- Detailed differential analyses in di-fermion final states.
- Different longitudinal polarisation of the beams.
- Experimental sensitivity increases with $\sqrt{s}$,

$$\mathcal{A}_{\text{dim6}} \sim C \frac{E^2}{\Lambda^2}.$$

Probing Wilson coefficients

- ILC at $\sqrt{s} = 250\mathrm{GeV}$ has better sensitivity than HL-LHC.
- ILC at $\sqrt{s} = 1000\mathrm{GeV}$ can probe up to $\Lambda \sim 100\mathrm{TeV}$.

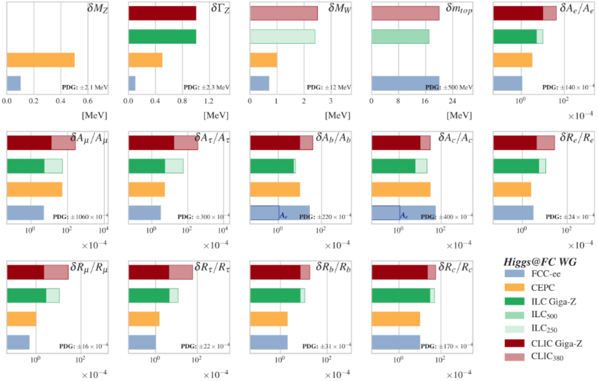


R. K. Ellis *et al.* arXiv:1910.11775 [hep-ex]

$$\mathrm{EOM}\begin{cases}\mathcal{O}_{2W} \Leftrightarrow \mathcal{O}_{\ell q(3)} \\ \mathcal{O}_{2B} \Leftrightarrow \mathcal{O}_{\ell q(1)}\end{cases}$$

Electroweak precission tests

ILC can improve the precission of EW observables that enter in the global fit, both in Giga-Z configuration and at $\sqrt{s} = 250\text{GeV}$.



R. K. Ellis *et al.* arXiv:1910.11775 [hep-ex]

The improved precission in EW observables will further restrict our global fits (work in progress).

Conclusions

- Hints of violations of Lepton Flavour Universality in $b \to s\ell^+\ell^-$ and $b \to c\ell\nu$ decays.

- We have studied the anomalies using dim-6 four-fermion operators:
  - We have performed a global fit to B-physics and EW observables in the SMEFT.
  - Our fit improves the prediction for the anomalies.
  - Our fit can be interpreted in terms of specific leptoquark/Z' models.

- Linear e^+e^- colliders will clear the picture...
  - ... by probing Wilson coefficients,
  - ... by constraining the global fits through Electroweak precission tests,
  - ... by searching for New Physics particles (LQs, Z').

Backup slides

New Physics models

- The most promising candidate is the vector leptoquark U_1:
  - Charged under the SM gauge groups as $(\mathbf{3}, \mathbf{1}, 2/3)$.
  - Contributes to both $b \to s\ell\ell$ and $b \to c\tau\nu$.
  - Generates the SMEFT operators

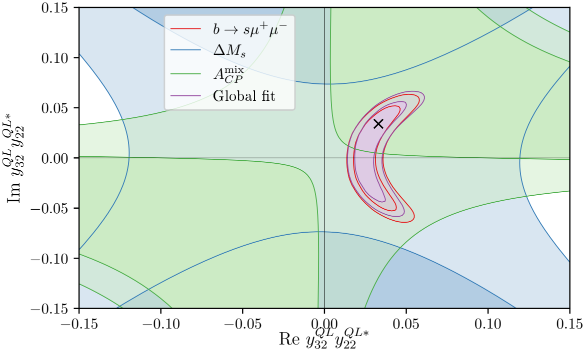
$$C^i_{\ell q(1)} = C^i_{\ell q(3)}.$$

  - Needs UV completion.

- Other options:
  - Scalar leptoquarks $S_1 \equiv (\bar{\mathbf{3}}, \mathbf{1}, -1/3) + S_3 \equiv (\bar{\mathbf{3}}, \mathbf{3}, -1/3)$.
  - New gauge bosons W' and Z'.

Fits to leptoquarks

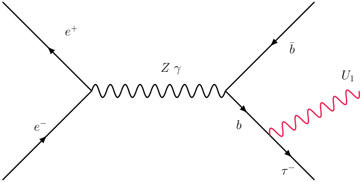
JA, J. Guasch, S. Peñaranda: Some Results on Lepton Flavour Universality Violation. Eur.Phys.J.C 79 (2019) 7, 588. 1805.03636



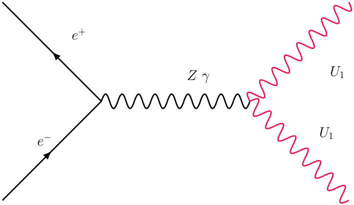
Leptoquark direct searches

Production of leptoquarks in e^+e^- colliders.

Single LQ:



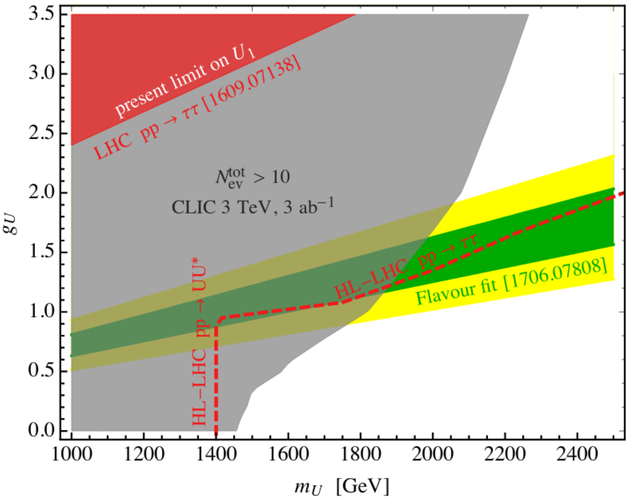
Two LQs:



In both cases, the final state is $b\bar{b}\tau^+\tau^-$.

Leptoquark direct searches

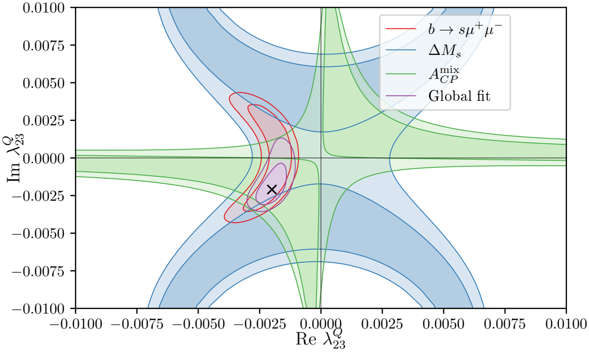
CLIC at $\sqrt{s} = 3\text{TeV}$ and HL-LHC reach similar exclusion limits.



J. de Blas *et al.* CERN Yellow Report **3** (2018). arXiv:1812.02093 [hep-ph]

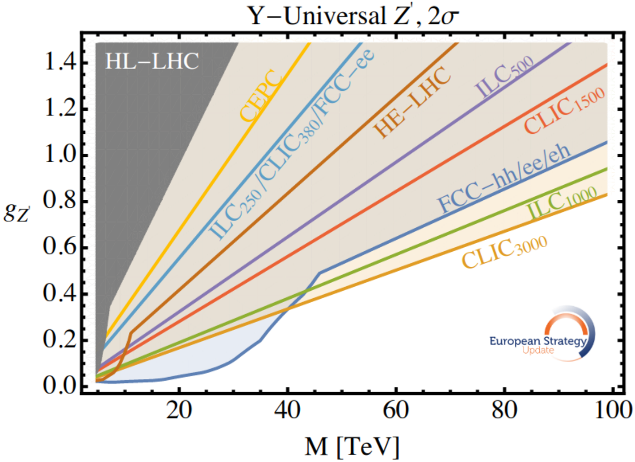
Fits to Z'

JA, J. Guasch, S. Peñaranda: Some Results on Lepton Flavour Universality Violation. Eur.Phys.J.C 79 (2019) 7, 588. 1805.03636



Z' indirect searches

Great sensitivity in e^+e^- colliders due to higher energies available.



R. K. Ellis *et al.* arXiv:1910.11775 [hep-ex]