The flavour anomalies:

the impact on future experiments

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Introduction

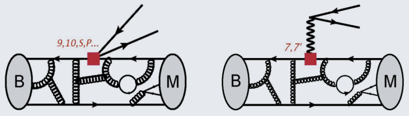
- Several anomalies in B physics semi-leptonic $b \to s$ and $b \to c$ channels,
- Been around for almost a decade; while central values haven't stayed constant, significance has not gone away !
- One of only signs of BSM physics at the moment, need to be taken into consideration in designing future experiments.
- In this talk I want to answer the following questions :
  1. What is the status of the anomalies?
  2. What are the experimental and theoretical prospects?
  3. What role could the FCC play ?

Introduction to the anomalies

Calculations in $b \to s\ell\ell$

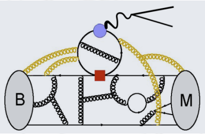
Wilson Coeff.	Operator
Photon penguin $\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$,
Gluon penguin $\mathcal{C}_8^{(\prime)}$	$\frac{1}{g_s} m_b (\bar{s}\sigma_{\mu\nu} T^a P_{R(L)} b) G^{\mu\nu\, a}$,
EW penguin (V) $\mathcal{O}_9^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$,
EW penguin (A) $\mathcal{O}_{10}^{(\prime)}$	$\frac{e^2}{g^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$,

[Meril Reboud 2022]



- Write amplitude: $\mathcal{A}_{\mathcal{B}\to\mathcal{M}\ell^+\ell^-} = \langle \ell^+\ell^-\mathcal{M}|\mathcal{H}_{\rm eff}|\mathcal{B}\rangle = \frac{4G_F}{\sqrt{2}}\lambda \sum_i \langle \ell^+\ell^-\mathcal{M}|C_i\mathcal{O}_i|\mathcal{B}\rangle$.
  where
  $$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}}\lambda_t \left(C_1\mathcal{O}_1^c + C_2\mathcal{O}_2^c + \sum_{i=3}^{6} C_i\mathcal{O}_i + \sum_{i=7,8,9,10,P,S} (C_i\mathcal{O}_i + C_i'\mathcal{O}_i'), \right)$$
- Cannot write $\mathcal{O} \sim j_\ell\, j_q$, due to contributions from photonic and gluonic penguins and four quark operators
- Schematically $\mathcal{A}_{\mathcal{B}\to\mathcal{M}\ell^+\ell^-} \sim \mathcal{N}\left(C\mathcal{F}^V(q^2) + \frac{1}{q^2}\left(C\mathcal{F}^T(q^2) - \mathcal{H}(q^2) \right)\right) \langle \ell^+\ell^-|j_\ell|0\rangle$,

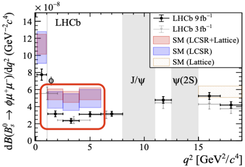
Dominant uncertainty from $\mathcal{H}(q^2) \Rightarrow$ non-local hadronic matrix element of four-quark operators, $\mathcal{H}^\mu(q^2) \equiv$
$i\int d^4x e^{iqx} \langle \mathcal{M}(k)|T\{j_\mu^{\rm em}(x), (C_1\mathcal{O}_1 + C_1\mathcal{O}_2)(0)\}|\mathcal{B}(q+k)\rangle$
where $j_\mu^{\rm em} = \sum_q Q_q \bar{q}\gamma_\mu q$



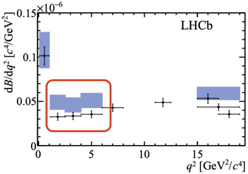
[Meril Reboud 2022]

Branching ratios from C. Langenbruch, Implications 2022

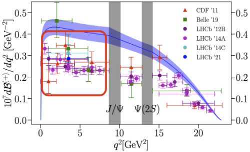
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [PRL 127 (2021) 151801]



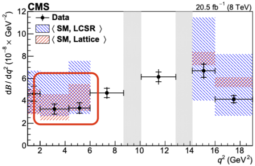
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



Lattice $B^+ \to K^+\mu^+\mu^-$ [arXiv:2207.13371]



CMS $B^0 \to K^{*0}\mu^+\mu^-$ [PLB 753 (2016) 424]



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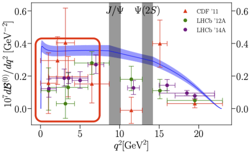
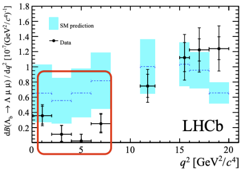


LHCb $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



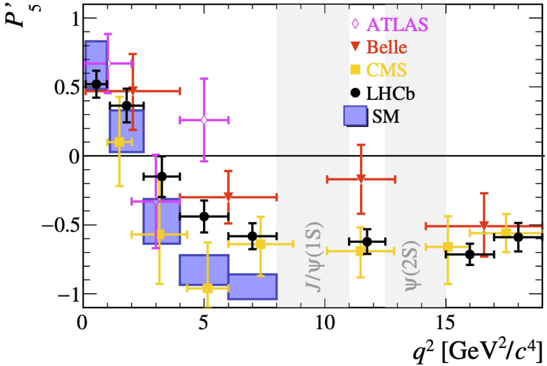
- New results from Lattice QCD [HPQCD 2022] shown for $B^0 \to K^0$ and $B^+ \to K^+$
- Especially at low q^2 data lies consistently below theory ($\sim$ 1-3 σ)

Angular observables

a.k.a. the infamous P_5'

In q^2 bins [4.0, 6.0] and [6.0, 8.0] GeV^2 local tensions of 2.5 and 2.9 σ, global analysis finds tension $\sim 3.3\sigma$ [LHCb 2020], consistent with [Belle 2017, CMS 2018,ATLAS 2018]

[PIPNP 120 (2021) 103885]

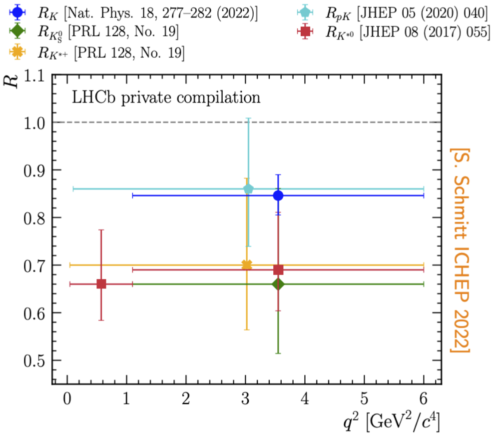


- Recent LHCb measurement for B^+ decay using Run 1+2 data [LHCb 2021], consistent with neutral channel. see also [CMS 2021]
- LHCb update coming soon, and unbinned analysis ongoing

Lepton Universality Ratios

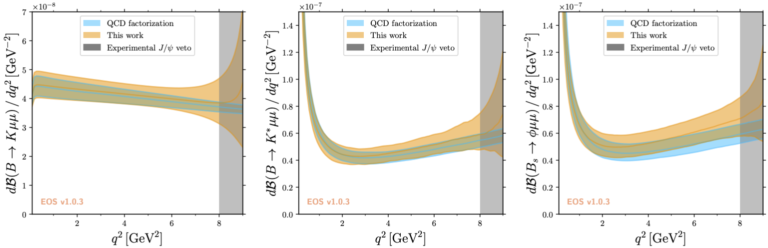
Updates in 2022:

observable	tension
R_K,	3.1σ
$R_{K_S^0}$	1.5σ
$R_{K^{*+}}$	1.4σ



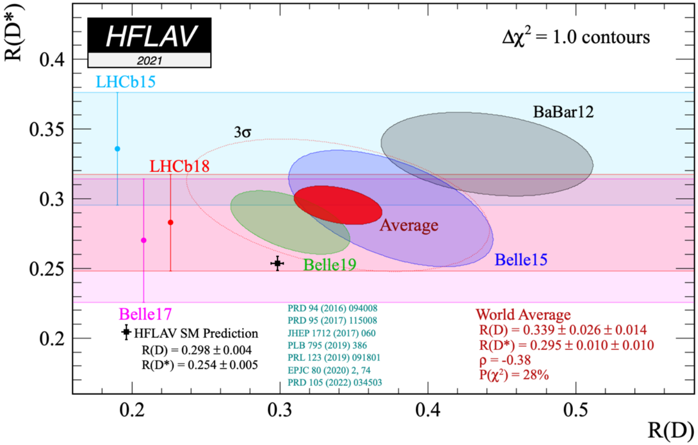
- LHCb working on unified R_K and R_{K^*} analysis, where a "deeper understanding of the LFU measurements" will apparently "be reflected in results"!
- R_{pK}, R_ϕ, and $R_{K\pi\pi}$ ... all ongoing!

Recent theory advances



- Non-resonant background for K^*, form factors for $B \to K\pi$ [Descotes-Genon et al 2019] (effect goes in wrong direction to explain the anomaly)
- Charm contribution, recent analysis shows cannot explain anomaly [Gubernari et al 2021, 2022]
- Form factors for alternative channels, e.g. baryons, see LQCD [Meinel et al 2021]
- Possible explanations for the deviation from the SM of $R_{K^{(*)}}$ in terms of QED corrections have been ruled out [Bordone et al 2016, Isidori et al 2020], for the branching ratios and angular observables it would be interesting to see extensions of [Beneke 2018] (for $B_s \to \ell^+\ell^-$)

HFLAV latest results for $R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$



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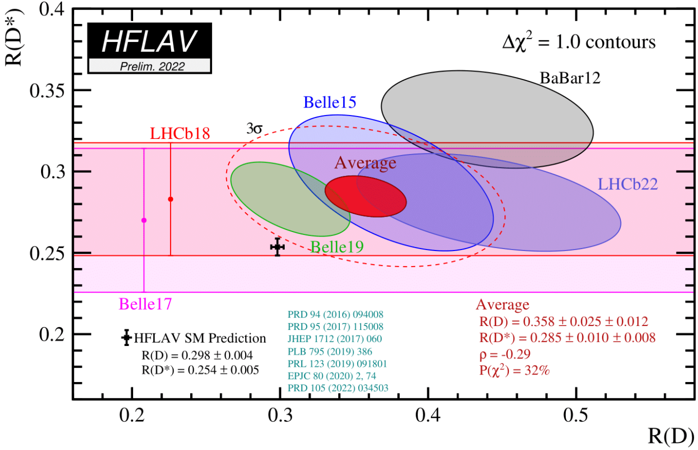
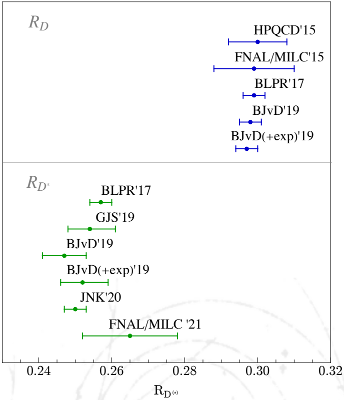


Lepton Universality Ratios

- For ratios involving the charged current, $b \to c\ell\nu$, the SM prediction deviates significantly from unity due to the large τ mass.
- More dependence on form factors than neutral channel. Calculations in Lattice/sum rules/HQET. Latest theory predictions compared here (Bernlochner et al=BLPR, Bordone et al=BJvD, Gambino et al=GJS, Jaiswal et al=JNK).
- Perform fits of data to theory as function of q^2 ($\ell\nu$ momentum squared) using theoretically motivated parameterization, BGL preferred [Boyd et al 1996]
- R_D good agreement: Lattice QCD at non-zero recoil [HPQCD 2015, FNAL/MILC 2015]+data+HQET are consistent, tension$\sim 1.4\,\sigma$

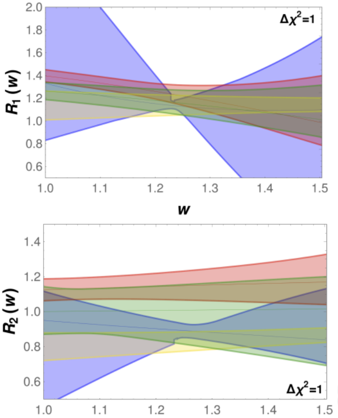


[AB 2022]

Comparing the slope for R_{D^*}

Recent results

- For the R_{D^*} result, agreement not perfect following 2017/2018 Belle results: 1) need more FF shape information 2) Prefer BGL to CLN parameterization as less assumptions about HQET corrections, or go to higher orders
- This was achieved: 1) recent results at non-zero recoil [FNAL/MILC 2021], 2) Calculation of HQET corrections@$1/m_c^2$ [Jung et al 2020]
- Test compatibility via plots of FF slopes [Jung 2022]: FNAL/MILC 2021, HQE@$1/m_c^2$, Exp (BGL), JLQCD prel.
- While $R_1(w)$ agrees, in $R_2(w)$ there are deviations between FNAL/MILC 2021, previous FFs and experiment
- preliminary JLQCD results don't give decisive answer. Waiting for further Lattice results and further measurements!



[Jung 2022]

What about the FCC? [Monteil 2021]

Anomalies will be further investigated at Belle 2 and high-lumi LHC, by the time FCC is built we will know if they are confirmed or not

- How does the FCC compare to Belle II and LHCb? [Monteil and Wilkinson 2021]
- Productions of B-mesons at FCC-ee are $\sim$ 20 times more than those at Belle II, while the $B_s \sim 10^3$ more, plus highly boosted so reconstruction highly efficient [Lu and Liu 2020]

Attribute	$\Upsilon(4S)$ (Belle II)	pp (LHC)	Z^0 (FCC-ee)
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Channel	Belle II	LHCb	Giga-Z	Tera-Z	10×Tera-Z (FCC-ee)
B^0, $\bar{B}^0$	5.3×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^{8}	1.2×10^{11}	1.2×10^{12}
$B^\pm$	5.6×10^{10}	$\sim 6 \times 10^{13}$	1.2×10^{8}	1.2×10^{11}	1.2×10^{12}
B_s, $\bar{B}_s$	5.7×10^{8}	$\sim 2 \times 10^{13}$	3.2×10^{7}	3.2×10^{10}	3.2×10^{11}
$B_c^\pm$	-	$\sim 4 \times 10^{11}$	2.2×10^{5}	2.2×10^{8}	2.2×10^{9}
Λ_b, $\bar{\Lambda}_b$	-	$\sim 2 \times 10^{13}$	1.0×10^{7}	1.0×10^{10}	1.0×10^{11}

For the anomalies, the FCC-ee is unique in that:

- τ-modes are key to testing models explaining anomalies, and only experiment where the SM values can be reached is the FCC-ee, Exploratory work $b \to s\tau\tau$ promising, [Kamenik et al 2017, Lu and Liu 2020]
- LFV decay modes of b quarks are important to test BSM models if anomalies confirmed
- Possibilty to study $B_c \to \tau\nu$ for the first time again exploratory work promising [Amhis et al 2021] (also measurement of V_{cb} by running at the WW threshold)

Summary

and Outlook

Anomalies in $b \to s$ and $b \to c$ transitions

- Anomalies in $b \to s\ell\ell$ still standing, waiting for update from LHCb on R_{K^*} Belle II will measure R_X to a few percent with 50 ab^{-1}
- For $b \to c\ell\nu$ looking forward to the updated unfolded spectrum from Belle II, Lattice collaborations to clarify situation with R_{D^*}
- Anomalies should be clarified by the LHC and Belle II

FCC prospects:

- High production rates, highly boosted, high reconstruction efficiency, all hadron species: very promising
- Sensitivity to decays with τ final states, e.g. $b \to s\tau\tau$, $B_c \to \tau\nu$, precise measurement ofLFV decays of b hadrons and more
- High sensitivity to τ decays, vibrant τ physics program

Theory for the future:

- Lattice QCD for heavier baryons (Λ_b advanced state, B_c ongoing)
- Such precise measurements, QED effects will need to be studied more thoroughly

Thanks for listening![1]

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[1] and to Martin Jung, Stephane Monteil, Christoph Langenbruch, Francesco Polci, Lukas Allwicher, Meril Reboud for their slides

Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\left(\lambda_t \mathcal{H}^{(t)}_{\text{eff}} + \lambda_u \mathcal{H}^{(u)}_{\text{eff}}\right) \tag{1}$$

where G_F is the Fermi constant, $\lambda_q = V_{qb}V^*_{qs}$ and

$$\begin{aligned}
\mathcal{H}^{(t)}_{\text{eff}} &= C_1\mathcal{O}^c_1 + C_2\mathcal{O}^c_2 + \sum_{i=3}^{6} C_i\mathcal{O}_i + \sum_{i=7,8,9,10,P,S} (C_i\mathcal{O}_i + C'_i\mathcal{O}'_i)\,, \\
\mathcal{H}^{(u)}_{\text{eff}} &= C_1(\mathcal{O}^c_1 - \mathcal{O}^u_1) + C_2(\mathcal{O}^c_2 - \mathcal{O}^u_2)\,.
\end{aligned}$$

The operators $\mathcal{O}_{i\leq 6}$ are given by the P_i given in [**?**], while the remaining ones are given by

$$\mathcal{O}_7 = \frac{e}{g^2} m_b(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \qquad \mathcal{O}'_7 = \frac{e}{g^2} m_b(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}, \tag{2}$$

$$\mathcal{O}_8 = \frac{1}{g_s} m_b(\bar{s}\sigma_{\mu\nu}T^a P_R b)G^{\mu\nu\,a}, \qquad \mathcal{O}'_8 = \frac{1}{g_s} m_b(\bar{s}\sigma_{\mu\nu}T^a P_L b)G^{\mu\nu\,a}, \tag{3}$$

$$\mathcal{O}_9 = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\mu), \qquad \mathcal{O}'_9 = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu\mu), \tag{4}$$

$$\mathcal{O}_{10} = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\gamma_5\mu), \qquad \mathcal{O}'_{10} = \frac{e^2}{g^2}(\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu\gamma_5\mu), \tag{5}$$

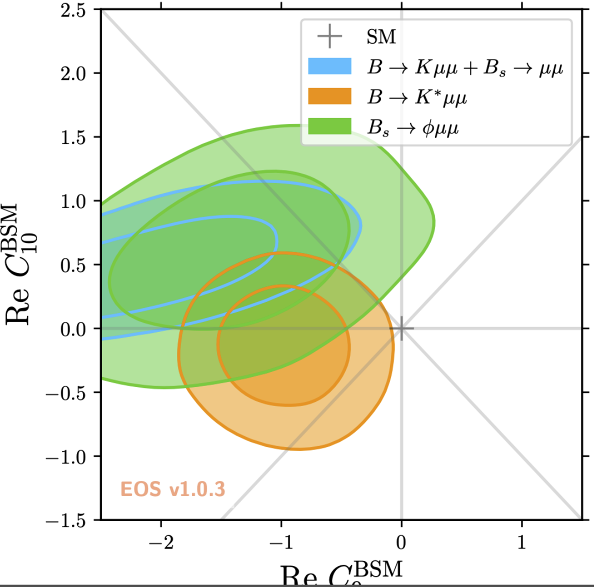
$$\mathcal{O}_S = \frac{e^2}{16\pi^2} m_b(\bar{s}P_R b)(\bar{\mu}\mu), \qquad \mathcal{O}'_S = \frac{e^2}{16\pi^2} m_b(\bar{s}P_L b)(\bar{\mu}\mu), \tag{6}$$

$$\mathcal{O}_P = \frac{e^2}{16\pi^2} m_b(\bar{s}P_R b)(\bar{\mu}\gamma_5\mu), \qquad \mathcal{O}'_P = \frac{e^2}{16\pi^2} m_b(\bar{s}P_L b)(\bar{\mu}\gamma_5\mu), \tag{7}$$

where g_s is the strong coupling constant, the left, right projectors are defined via $P_{L,R} = (1 \mp \gamma_5)/2$ and m_b is b

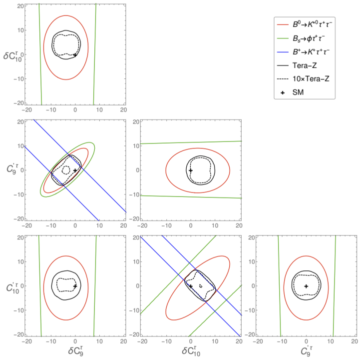
Global Analyses

An example from [Gubernari et al 2022]



$b \to s\tau\tau$ [Kamenik et al 2017, Lu and Liu 2020]

- FCC-ee can access the SM values ($10^{-7} - 10^{-6}$) of $B \to K^*\tau\tau$, $B^+ \to K^+\tau\tau$, $B_s \to \phi\tau\tau$ and $B_s \to \tau\tau$, [Lu and Liu 2020]
- Could pinpoint possible BSM contributions to C_9 and C_{10} for τ leptons.
- Access to τ polarization, theoretically clean observables suggested in the form of single- and double-τ polarization in [Kamenik et al 2017]



τ-lepton decay sensitivities [Dam 2018]

- Z factory very well suited for precision τ-physics measurements (LEP measurements still stand unchallenged. despite B factories), 5 orders of magnitude more events at FCC-ee than LEP
- More than one order of magnitude improvements are expected in the lifetime and branching fraction measurements. This will enable tests of lepton universality down to a precision at the 0.01% level. (to improve further need better precision on τ mass. at e.g. next generation τ factory)
- In general about an order of magnitude improvements can be ultimately expected from the full LHC samples for LFV Z decays.
- Charged lepton flavour violation in τ to be further improved at Belle II, FCC-ee will perform competitive measurements

Decay	Present bound	FCC-ee sensitivity
$Z \to \mu e$	0.75×10^{-6}	10^{-10}–10^{-8}
$Z \to \tau\mu$	12×10^{-6}	10^{-9}
$Z \to \tau e$	9.8×10^{-6}	10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2.1×10^{-8}	10^{-10}