B Physics: From Present to Future Colliders

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P3H
Particle Physics Phenomenology after the Higgs Discovery

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New Physics, where are you?

Despite convincing motivations for NP at the TeV scale,
we are still lacking a discovery!

Where is everyone?

too heavy to be probed by direct searches, EWPT & Higgs physics

too weakly coupled to leave a visible imprint on these observables

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Needed: indirect probes of new particles and interactions that are sensitive even to very small NP effects

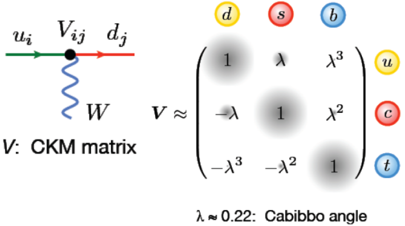
➢ **flavour physics!**

also $(g-2)$, EDMs...

The flavour of the Standard Model

SM flavour structure

- generated by quark & lepton Yukawa couplings $Y_{U,D}, Y_L$
- very hierarchical pattern
- misalignment between Y_U and Y_D parametrised by CKM matrix that enters charged current interactions



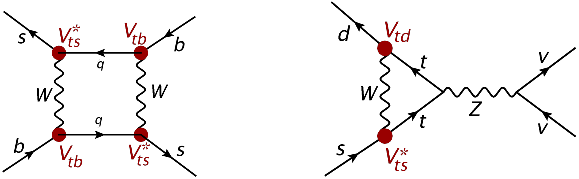
- CKM unitarity ➢ no tree-level flavour-changing neutral currents (FCNCs)

Flavour changing neutral current processes

FCNCs are strongly suppressed in the SM

- loop factor
- CKM hierarchy
- chiral structure of weak interactions
- GIM mechanism (CKM unitarity)

➢ **unique sensitivity to NP** contributions – probing scales far beyond the TeV range

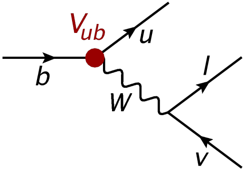


Crucial:

high precision in ➢ measurements of flavour violating decays
➢ predictions of the SM contribution

Precision determination of CKM elements

Tree level decays: flavour changing charged current interactions



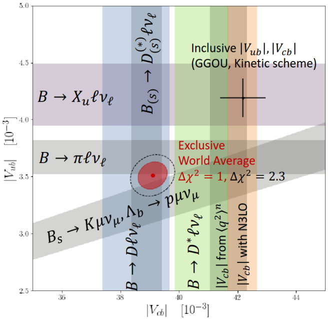
➢

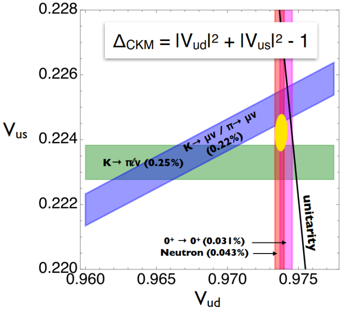
$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

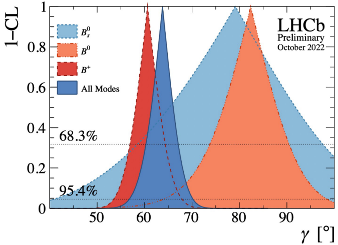
- direct sensitivity to relevant CKM element
- small impact of NP contributions expected
- four independent measurements needed to fully determine CKM matrix

➢ model-independent determination of CKM matrix as a **standard candle** of the SM

Precise CKM determination from tree-level decays?







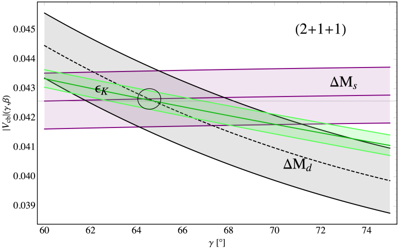
- tensions in $|V_{ub}|$, $|V_{cb}|$ and $|V_{us}|$ determinations ➢ theory description? measurement?
- determination of CP-violating angle γ statistics-limited, but theoretically very clean

➢ current lack of precision impacts ability to **constrain/discover New Physics**

Alternative strategy: CKM from meson mixing data

Alternative strategy

- use precisely known meson mixing observables to (over)constrain CKM matrix



➢ perfect consistency and high precision!

Buras, Venturini (2022)

see also MB, Buras (2018); MB @LP2019; global fits

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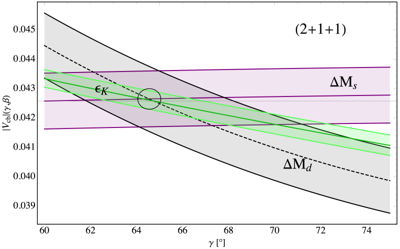

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- *assuming* no New Physics in meson mixings, make precise predictions for rare decays
- confront with available data: clean opportunity to identify first hints at New Physics

➢ some appealing **discrepancies in B meson decays**, but higher precision (th+exp) needed to draw definite conclusions

Buras (2022)

Persisting flavour anomalies

1. 3.2σ tension in semi-tauonic B decays
   exhibiting **lepton flavour universality violation**
2. set of **consistent** anomalies in $b \to s\mu^+\mu^-$ transitions
   ~~including lepton flavour universality violation~~

In addition & possibly related?

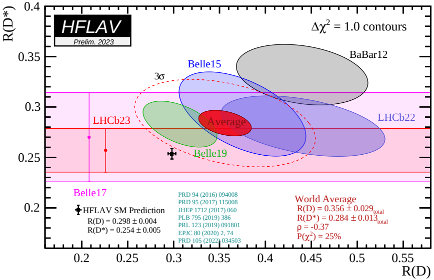
3. discrepancies in tree-level CKM determinations:
   $|V_{ub}|$ and $|V_{cb}|$ problems, Cabibbo angle anomaly (1st row unitarity)
4. muon anomalous magnetic moment $(g-2)_\mu$

The $\mathcal{R}(D^{(*)})$ anomaly

Test of lepton flavour universality in semi-leptonic B decays

$$\mathcal{R}(D^{(*)}) = \frac{\text{BR}(B \to D^{(*)}\tau\nu)}{\text{BR}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$

➢ persisting tension between SM prediction and data for > 10 years!



- theoretically clean, as hadronic and $|V_{cb}|$ uncertainties largely cancel in ratio
- measurements by BaBar, Belle, and LHCb in decent agreement with each other
- LHCb found $\mathcal{R}(J/\psi)$ to be larger than expected in SM

➢ **3.2σ anomaly**

$\mathcal{R}(\Lambda_c)$ – a sum rule challenging the anomaly?

Approximate sum rule relating $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(\Lambda_c)$

MB, Crivellin et al. (2018), (2019)
Fedele, MB et al. (2022)

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} \simeq 0.280\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.720\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)}$$

$$\left[\mathcal{R}(\Lambda_c) = \frac{\text{BR}(\Lambda_b \to \Lambda_c \tau\nu)}{\text{BR}(\Lambda_b \to \Lambda_c \ell\nu)}\right]$$

- enhancement of $\mathcal{R}(D^{(*)})$ implies $\mathcal{R}(\Lambda_c) > \mathcal{R}_{\rm SM}(\Lambda_c) = 0.33 \pm 0.01$
- consistent with expectation from heavy-quark symmetry
- model-independent – holds for NP in τ and/or light lepton channels

Model-independent prediction: $\mathcal{R}(\Lambda_c) = 0.380 \pm 0.012_{\mathcal{R}(D^{(*)})} \pm 0.005_{\text{form factors}}$

LHCb 2022: $\mathcal{R}(\Lambda_c^+) = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$

➢ **more precise data needed!**

Effective Hamiltonian for $b \to c\tau\nu$

New Physics above B meson scale described model-independently[1] by

$$\mathcal{H}_{\text{eff}} = 2\sqrt{2}G_F V_{cb}\Big[(1 + C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\Big]$$

with $O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau)$, $O_S^{R/L} = \left(\bar{c}P_{R/L}b\right)\left(\bar{\tau}P_L\nu_\tau\right)$, $O_T = (\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau)$

Possible BSM scenarios (tree level!)

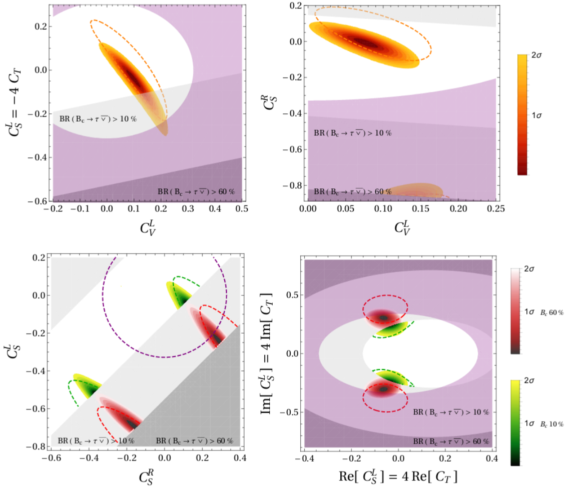
- charged Higgs contributions ➢ $C_S^{L,R} \neq 0$ — Kalinowski (1990); Hou (1993) Crivellin, Kokulu, Greub (2013)...
- charged vector boson W' ➢ $C_V^L \neq 0$ — He, Valencia (2012); Greljo, Isidori, Marzocca (2015)...
- (scalar or vector) leptoquark ➢ various $C_j \neq 0$ (depending on model)

see e. g. Tanaka, Watanabe (2012); Deshpande, Menon (2012); Kosnik (2012); Freytsis et al (2015) Alonso et al (2015); Calibbi et al (2015); Fajfer, Kosnik (2015); Becirevic et al (2016),(2018)

[1] assuming no light ν_R and no NP in e/μ channel

Single particle scenarios – current status

MB, Crivellin, Kitahara, Moscati, Nierste, Nišandžić (2019)
see also Murgui et al (2019); Shi et al (2019)
Iguro, Kitahara, Watanabe (2022)

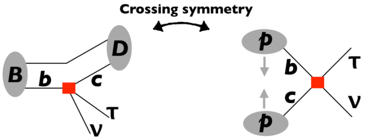


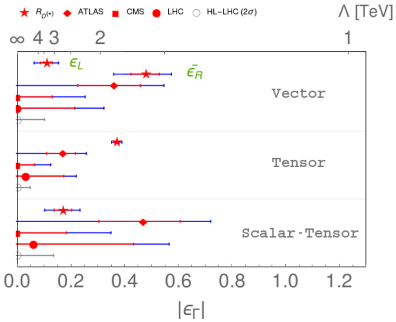
- W' solution disfavoured by LHC direct searches and EWP constraints
  Faroughy, Greljo, Kamenik (2016)
  Farruglio, Paradisi, Pattori (2017)
- significant improvement possible with various leptoquark (LQ) scenarios
- charged Higgs scenario predicts large $\mathrm{BR}(B_c \to \tau\nu)$ ➢ not excluded!
  see Alonso, Grinstein, Martin Camalich (2016)
  Akeroyd, Chen (2017); MB et al (2018)
  Aebischer, Grinstein (2021)
- constraints from LHC mono-τ constraints
  Greljo, Martin Camalich, Ruiz-Alvarez (2018)

More on LHC mono-τ searches

Greljo, Martin Camalich, Ruiz-Alvarez (2018)

- crossing symmetry relates $b \to c\tau\nu$ to $pp \to X\tau\nu$
- mono-$\tau + \not{E}_T$ signature probes NP models for $\mathcal{R}(D^{(*)})$ anomaly





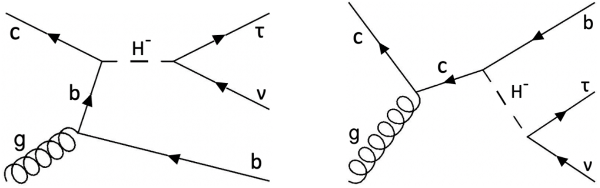
➢ **LHC has become competitive in testing the $\mathcal{R}(D^{(*)})$ anomaly**

- charged Higgs ruled out for $m_{H^-} > 400$ GeV

  Iguro, Omura, Takeuchi (2018)
- leptoquark models less pressured
- HL-LHC should be able to *probe all possible NP models* solving anomaly

What about a light charged Higgs?

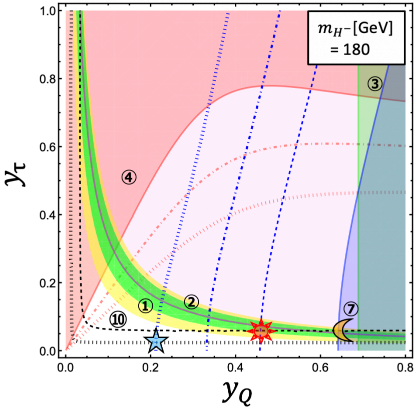
- light charged Higgs ($m_{H^-} < 400\,\text{GeV}$) not excluded by mono-$\tau$ data due to huge $W \to \tau\nu$ background
- efficient background suppression by requiring additional b-tagged jet



➢ **Is this sufficient to exclude the charged Higgs solution to the $\mathcal{R}(D^{(*)})$ anomaly?**

MB, Iguro, Zhang (2022)

Reach of the $b\tau\nu$ signature



Minimal coupling scenario MB, Iguro, Zhang (2022)

(additional couplings do not alter conclusions)

$$\mathcal{L}_{\text{int}} = +y_Q H^-(\bar{b}P_R c) - y_\tau H^-(\bar{\tau}P_L\nu_\tau)$$

- H^- close to top threshold most difficult to test
- relevant constraints from SUSY stau and (flavoured) dijet searches at the LHC Iguro (2022)
- performing (flavoured) dijet and **proposed $b\tau\nu$ search** with Run 2 data would *almost* exclude charged Higgs solution for $\mathcal{R}(D^{(*)})$
- **final verdict** from future (HL-)LHC runs

Remaining option: leptoquarks

- "exotic"? – present in *any* theory unifying quarks and leptons
- favoured solution for the "B anomalies"
- popular scenario: $\boldsymbol{SU(2)}$**-singlet vector leptoquark** $\boldsymbol{U_1 \equiv \Delta}$

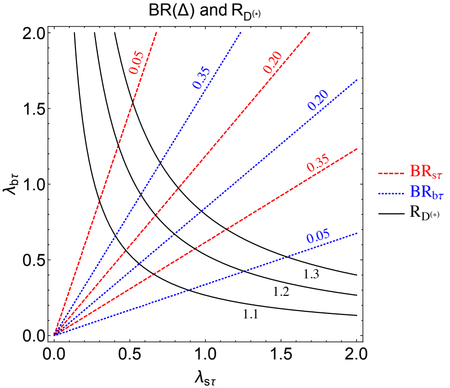
  - ➢ compatible with other flavour constraints (B_s mixing, $B \to K\nu\bar{\nu}\ldots$)
  - ➢ can also solve $b \to s\mu\mu$ anomalies (see later)
  - ➢ no proton decay induced
  - ➢ **attractive for model-building** *(main challenge: flavour structure!)*
    contained in Pati-Salam gauge group $SU(4)_c \times SU(2)_L \times SU(2)_R$
    unifying quarks and leptons   PATI, SALAM (1974)

What can we learn from direct leptoquark searches?

Bernigaud, MB, de Medeiros, Talbert, Zurita (2021)

Example: $SU(2)$-singlet vector leptoquark

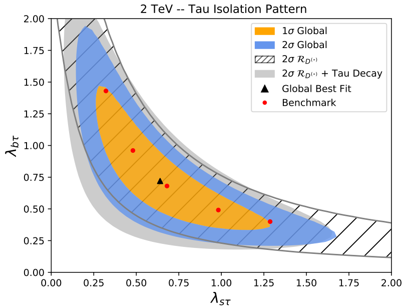
- $\mathcal{R}(D^{(*)})$ constrain $\quad \dfrac{\lambda_{b\tau}\lambda_{c\nu}}{M^2} \simeq \dfrac{\lambda_{b\tau}\lambda_{s\tau}}{M^2}$
- LQ mass M can be measured at LHC from pair-production cross-section and invariant mass
- branching ratios $\text{BR}_{b\tau} \simeq \text{BR}_{t\nu}$, $\text{BR}_{s\tau} \simeq \text{BR}_{c/u\nu}$ determine ratio of couplings $\lambda_{b\tau}/\lambda_{s\tau}$



➢ synergy between flavour and collider data **fully determines leptoquark parameters**

Leptoquark branching ratios: pair production

Bernigaud, MB, de Medeiros, Talbert, Zurita (2021)



BR($\Delta\Delta \to$ QLQL) [%]

	$b\tau b\tau$	$t\nu t\nu$	$b\tau t\nu$	$b\tau s\tau$	$b\tau c\nu$	$t\nu s\tau$	$t\nu c\nu$	$s\tau s\tau$	$s\tau c\nu$	$c\nu c\nu$
BP_1	0.2	0.1	0.3	4.0	3.9	3.0	3.0	20.8	40.5	19.7
BP_2	1.0	0.7	1.7	8.0	7.9	6.7	6.6	16.0	31.6	15.6
BP_3	6.3	5.2	11.5	12.6	12.9	11.5	11.8	6.3	12.9	6.6
BP_4	16.1	14.5	30.6	8.1	8.9	7.7	8.5	1.0	2.2	1.2
BP_5	22.9	21.5	44.4	2.3	3.1	2.3	3.0	0.1	0.2	0.1

Constraints from $b\tau\, t\nu$ – and jets+$\not{E}_T$

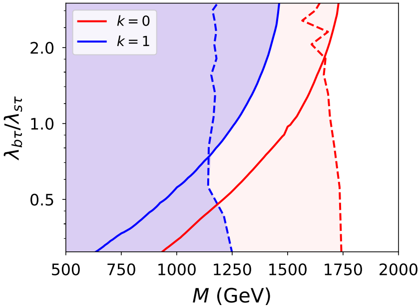
Bernigaud, MB, de Medeiros, Talbert, Zurita (2021)

Mixed channel $\Delta\Delta \to b\tau\, t\nu$ — ATLAS, CMS (2021)

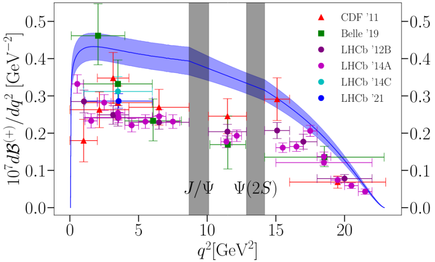
- reinterpretation of existing experimental analysis
  see also Belanger et al. (2021)
- strong sensitivity to coupling ratio $\lambda_{b\tau}/\lambda_{s\tau}$

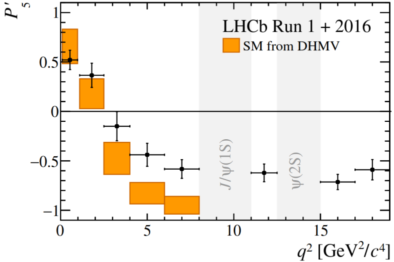
Jets+$\not{E}_T$ from final-state neutrinos — ATLAS (2020)

- most stringent constraint identified in CheckMATE analysis
- less sensitive to leptoquark coupling structure
- complementary to $b\tau\, t\nu$



Anomalies in $b \to s\mu^+\mu^-$ transitions





Significant tensions with SM predictions

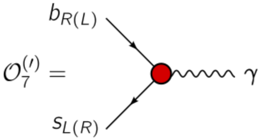
- branching ratios of $b \to s\mu\mu$ transitions e. g. BR$(B \to K\mu^+\mu^-)$, BR$(B_s \to \phi\mu^+\mu^-)$
- theoretically cleaner angular distribution of $B \to K^*\mu^+\mu^-$ (P_5' and friends)

New Physics in $b \to s\ell^+\ell^-$

Effective $b \to s\ell^+\ell^-$ Hamiltonian:

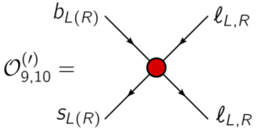
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{e^2}{16\pi^2} \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i') + h.c.$$

with the operators most sensitive to New Physics



electromagnetic dipole operators $O_7^{(\prime)}$

- govern inclusive and exclusive $b \to s\gamma$ transitions
- enhanced contribution to $B \to K^* \ell^+\ell^-$ in low q^2 region

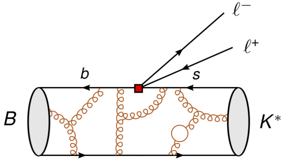


semileptonic four-fermion operators $O_9^{(\prime)}, O_{10}^{(\prime)}$

- loop-suppressed in the SM, but potentially tree level in the presence of NP

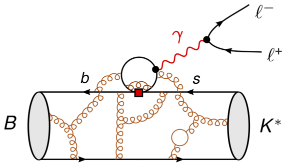
Hadronic uncertainties in $B \to K^*\mu^+\mu^-$ (and similar)

$B \to K^*$ form factors



- from lattice QCD and light-cone sume rules
- systematic improvements possible

non-factorisable corrections



- "charm loops" at low q^2, broad $c\bar{c}$ resonances
- dominant uncertainty, no systematic theory description

➢ **construct observables in which these uncertainties cancel**

Clean(er) observables

Optimised observables P_i, P_i' MATIAS ET AL. (2012)

- describe angular distribution in $B \to K^*\mu^+\mu^-$
- designed to be form-factor-free at leading order
- still susceptible to non-factorisable corrections

Lepton flavour universality (LFU) ratios HILLER, KRÜGER (2003)

$$\mathcal{R}(K^{(*)}) = \frac{\text{BR}(B \to K^{(*)}\mu^+\mu^-)}{\text{BR}(B \to K^{(*)}e^+e^-)}$$

- theoretically extremely clean test of SM
  ➢ deviation from $\mathcal{R}(K^{(*)}) \simeq 1$ would signal NP

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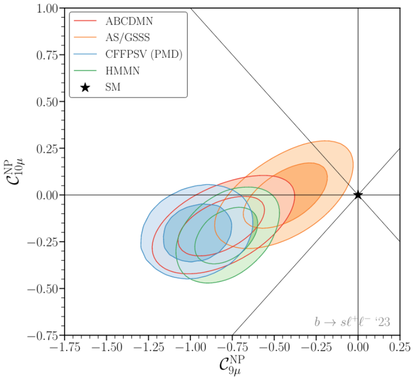
  - ➢ latest LHCb result SM-like

Current status & recent development



Capdevila @ Beyond Flavour Anomalies Workshop 2023

- good agreement between various fits, despite differing th & exp inputs
- pull towards large negative $C_{9\mu}^{\text{NP}}$ in the ballpark of 4σ – could be mimicked by charm loops?
- SM-like $\text{BR}(B_s \to \mu^+\mu^-)$ implies $C_{10\mu}^{\text{NP}}$ consistent with zero
- recent LHCb finding $\mathcal{R}(K^{(*)}) \sim 1$ requires NP in $b \to s\mu\mu$ and $b \to see$ to be lepton-flavour universal

The quest for future colliders

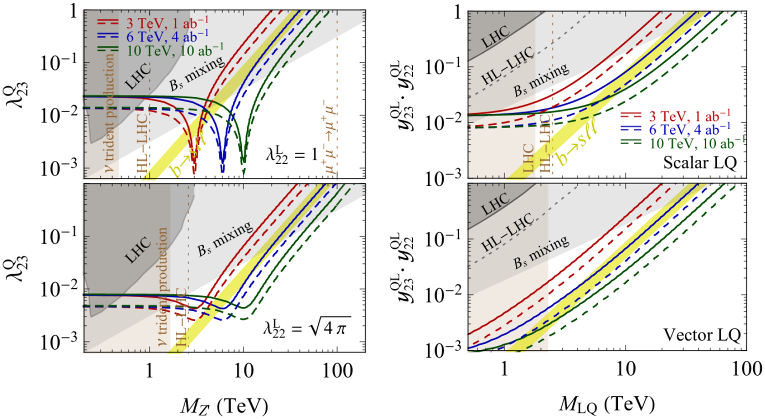
Generic $b \to s\mu\mu$ NP scale

$$\frac{1}{(40\ \text{TeV})^2}(\bar{Q}_3 Q_2)(\bar{L}_2 L_2)$$

- nightmare for (HL-)LHC
- improved reach with 100 TeV pp collider
- promising physics case for high-energy muon collider

$$\mu^+\mu^- \to bs$$

(also motivated by $(g-2)_\mu$)



Huang, Jana, Queiroz, Rodejohann (2021)
see also Azatov et al. (2022)

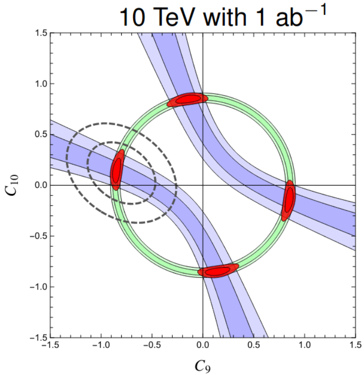
➢ **What about e^+e^- colliders?** Emergy and lumi needed?

Beyond discovery

$\mu^+\mu^- \to bs$ at 10 TeV muon collider

- cross-section measurement determines overall size of NP contribution
  ➢ circle in $C_9^{\rm NP} - C_{10}^{\rm NP}$ plane
- forward-backward asymmetry distinguishes between vector and axial muon current
- *advantage:* no issue with long-distance QCD effects!

➢ **complementary to B decay measurements**



Altmannshofer, Gadam, Profumo (2022)
Altmannshofer @ Beyond Flavour Anomalies Workshop 2023

What NP could it be?

Generic EFT arguments hint to tree-level NP scale $\lesssim 40\,\text{TeV}$

$$\frac{1}{(40\text{ TeV})^2}(\bar{Q}_3 Q_2)(\bar{L}_{1,2} L_{1,2})$$

but potentially lower, depending on flavour structure!

Possible tree-level models

1. flavour-changing Z' boson
   - *stringent constraints* from $B_s - \bar{B}_s$ mixing data ➢ large coupling to muons
   - lepton universality implies Z' coupling also to electrons
     ➢ tight LEP bounds on $e^+e^- \to \mu^+\mu^-/e^+e^-$
2. scalar or vector leptoquark
   - less restricted by $B_s - \bar{B}_s$ mixing
   - μ-e universality requires *second* leptoquark to avoid lepton flavour violation

Alternative: Loop contributions

NP in $b \to s\mu\mu$ could also contribute at the one-loop level

- NP scale lower by (at least) one order of magnitude: $\lesssim$ few TeV
- much more easily accessible at collider experiments!

➢ **intriguing possiblity: link $b \to s\mu\mu$ anomaly to NP in $\mathcal{R}(D^{(*)})$**

- vector leptoquark mediating $b \to c\tau\nu$ can generate C_9^{NP} via τ-loop
  ➢ large NP effects in $b \to s\tau\bar{\tau}$ predicted

  Bobeth, Haisch (2011)
  Crivellin, Greub, Müller, Saturnino (2018)
  Aebischer, Isidori, Pesut, Stefanek, Wilsch (2022)

- $H^{\pm}$ contributing to $\mathcal{R}(D^{(*)})$ can enter $b \to s\mu\mu$ through penguins and boxes
  ➢ can be tested in $t\tau\bar{\tau}$ final state at the LHC — Kumar (2022); Iguro 2023

Summary. . .

Flavour anomalies among strongest hints for BSM physics

$\mathcal{R}(D^{(*)})$ anomaly

persists, but scrutinised by

- related flavour observables
  - ➢ $\mathcal{R}(\Lambda_c)$ sum rule
- complementary (HL-)LHC searches
  - ➢ $(b+)\tau\nu$, leptoquark searches etc.

$b \to s\mu^+\mu^-$ anomalies

- consistently solved by global NP fit
- recent data points to μ-e universality
- generic NP scale beyond (HL-)LHC reach
- . . . or TeV-scale NP in loops?

Are they linked to the same underlying NP?

. . . and outlook

To move forward on these (or future) B anomalies, here's what we need

from experiment

- (even more) *precise measurements* of relevant B meson decays
- better data on related *decays of heavier b hadrons*, e. g. Λ_b, B_c
- *complementary information* from NP searches and precision tests at high-energy hadron and lepton colliders

from theory

- better understanding of *non-perturbative QCD effects* in form factors and beyond
- guidance for the experimental community on *promising observables*
- *open mind* regarding the nature of the anomalies!


Ευχαριστώ!
Thank you!