Karlsruher Institut für Technologie

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Institut für Theoretische Teilchenphysik (KIT)

Flavour anomalies, leptoquarks, renormalisation group fixed-points, and collider physics

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Leptoquarks and semileptonic decays

Scalar leptoquarks are a popular explanation of flavour anomalies.

S_1 or R_2 for

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

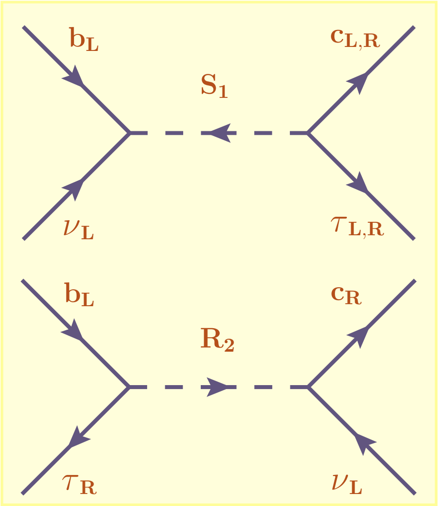
S_3 for low-q^2 deficit in several

$$b \to s\ell^+\ell^-, \qquad \ell = e, \mu,$$

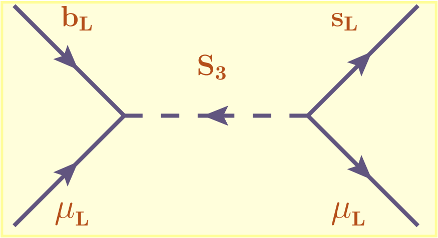
decay distributions.

Spin 0,
SU(2) singlet

Spin 0,
SU(2) doublet



Spin 0,
SU(2) triplet



BSM mass reach

Flavour physics probes virtual effects of new heavy particles coupling to quarks, with a mass reach of

a few TeV in the case of S_1 or R_2 for $b \to c\tau\bar{\nu}$ and

a few tens of TeV in the case of S_3 for $b \to s\ell^+\ell^-$.

⇒ The firm establishment of a flavour anomaly helps for the design of a future hadron collider and could establish a “no-lose” situation for FCC-hh.

FCC-hh fans ♥ flavour physics

flavour physicists ♥ FCC-ee: 10^{13} Z bosons are a perfect b factory!

Outline

- Status of new physics in $b \to c\tau\nu$
- Status of new physics in $b \to s\ell^+\ell^-$
- Renormalisation group analysis of leptoquark solutions
- Leptoquarks at colliders
- Summary and outlook

Status of new physics in $b \to c\tau\nu$

$b \to c\tau\nu$

b-flavoured hadron $H_b = B_d, B^+, \Lambda_b$:

$$R(H_c) \equiv \frac{B(H_b \to H_c\tau\nu)}{B(H_b \to H_c\ell\nu)} \text{ with } \ell = e, \mu$$

Predictions involve form factors like $\langle D(\vec{p}_D)\,|\,\gamma^\mu\,|\,B(\vec{p}_B)\rangle$ or $\langle D^*(\vec{p}_D, \epsilon)\,|\,\gamma^\mu\gamma_5\,|\,B(\vec{p}_B)\rangle$.

Lattice gauge theory calculates form factors for $\vec{p}_D = \vec{p}_B = 0$ and a few points with small $D^{(*)}$ velocity.

$b \to c\tau\nu$: Developments since *Quirks 2022*

$$R(H_c) \equiv \frac{B(H_b \to H_c\tau\nu)}{B(H_b \to H_c\ell\nu)}$$

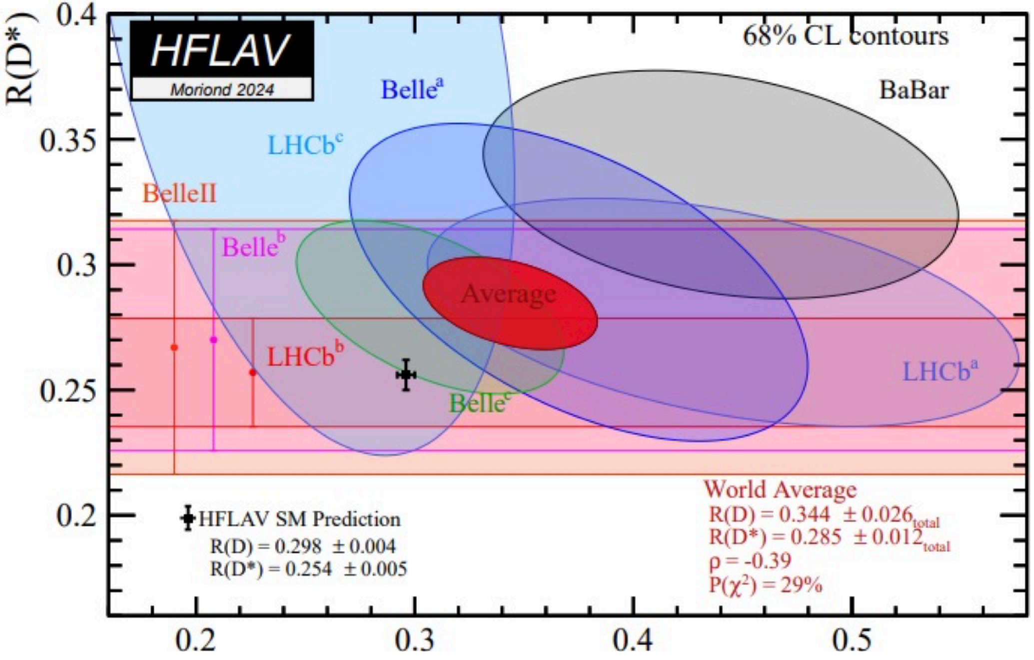
New LHCb $R(D^+)$ measurement:
Significance of deviation from SM down:

3.3σ → 3.1.σ,

for the form factors used by HFLAV.

Different measurements (from four experiments) agree within normal statistical fluctuations.

After $R(D^+)$



$B \to D^*$ form factors

Compare

BGL (Boyd, Grinstein, Lebed 1995):

global fit by Gambino, Jung, Schacht in 2019 to all available calculations and data in $B \to D^* \ell \nu$ with light leptons $\ell = e, \mu$. Phys. Lett. B 795 (2019) 386

HQET (using expansions in $\Lambda_{\mathrm{QCD}}/m_{c,b}$):

global fit by Iguro, Kitahara and Watanabe in 2022 to all available calculations and data (including q^2 shapes) in $B \to D^* \ell \nu$ with light leptons $\ell = e, \mu$. arXiv:2210.10751

Fermilab/MILC (2021):

first lattice calculation employing $q^2 \neq q^2_{\mathrm{max}}$.

Eur. Phys. J. C 82 (2022) 1141, Eur.Phys.J.C 83, 21 (2023).

$B \to D^*$ form factors

DM (Dispersive Matrix approach, Rome lattice group):

uses Fermilab/MILC data and Rome calculation of susceptibility χ,

employs analyticity and unitarity constraints to derive two-sided bounds on form factors.

G. Martinelli, S. Simula, and L. Vittorio, Phys. Rev. D 104 (2021) 094512,
Eur. Phys. J. C 82 (2022) 1083, JHEP 08 (2022) 022.
G. Martinelli, M. Naviglio, S. Simula, and L. Vittorio, Phys. Rev. D 106 (2022) 093002.

With DM method find $R(D^*)$ compatible with Standard Model prediction and furthermore $|V_{cb}|$ from $B \to D^* \ell \nu$ consistent with $|V_{cb}|$ from inclusive $B \to X_c \ell \nu$ decays.

$B \to D^*$ form factors vs new physics

Next slides: confront all four form factor predictions with new data on

the fraction $F_L^{D^*,\mathrm{light}}$ of longitudinally polarized D^* in $B \to D^*\ell\nu$

and

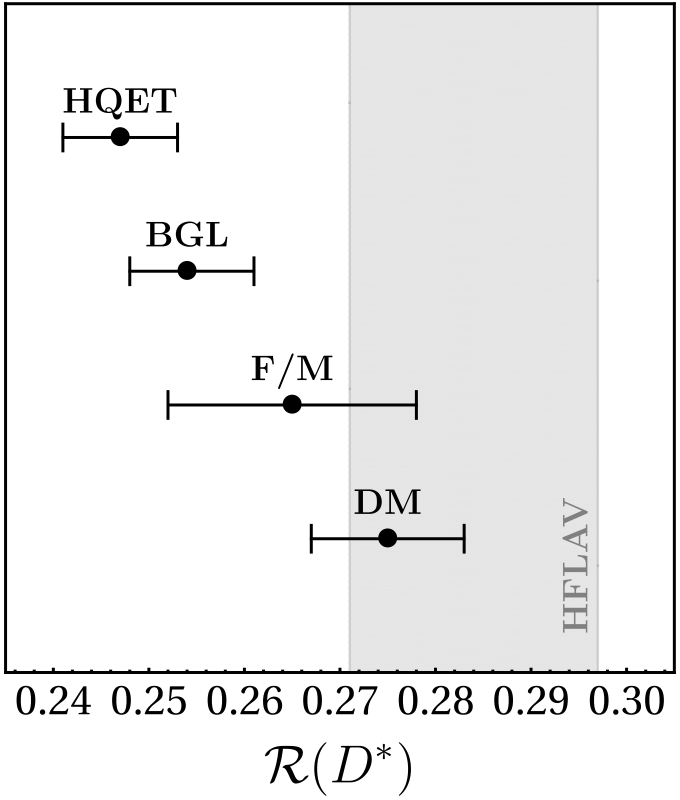
the forward-backward asymmetries A_{FB}^{e} and A_{FB}^{μ}

Belle, 2301.07529; Belle II, talk by Chaoyi Lyu at ALPS, March 2023

Discriminating $B \to D^*\ell\nu$ form factors via polarization observables and asymmetries

Fedele,Blanke,Crivellin,Iguro,UN,Simula,Vittorio, arXiv:2305.15457.

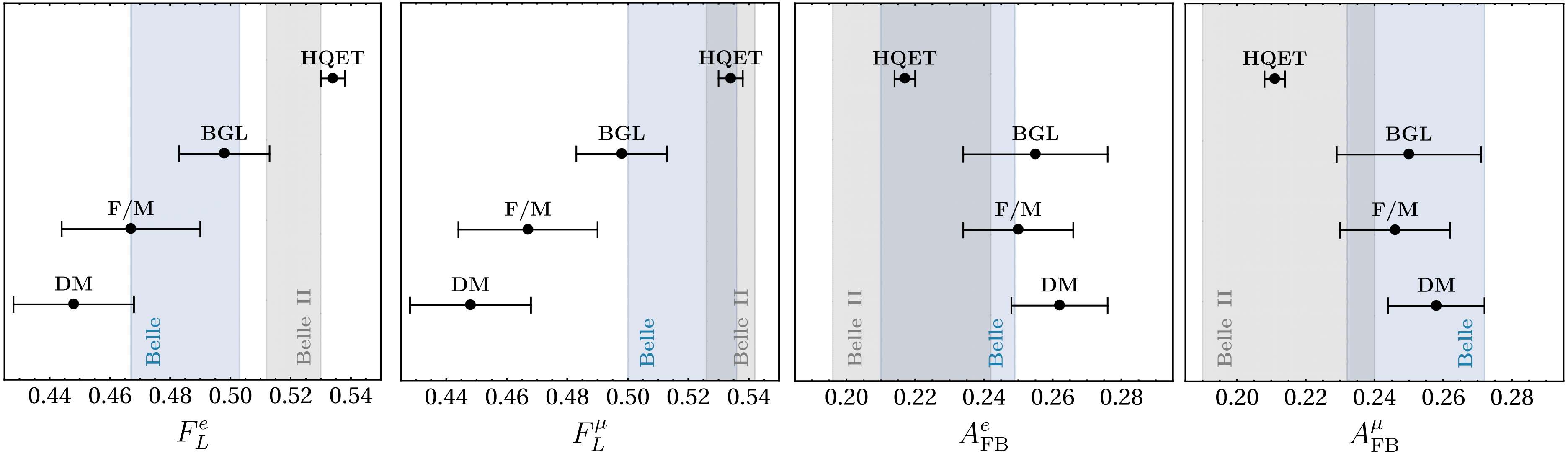
$B \to D^*$ form factors vs new physics



compatible with Standard Model

with DM method one finds the same $R(D)$
as with other methods, arXiv:2205.13952

Predictions for $F_L^{D^*,\mathrm{light}}$ and $A_{\mathrm{FB}}^{e,\mu}$



SM predictions with $\left\{ \begin{array}{l} \text{HQET or BGL} \\ \text{F/M or DM} \end{array} \right\}$ describe $\left\{ \begin{array}{l} B \to D^* \ell \nu \\ R(D^*) \end{array} \right\}$ data.

Effective BSM operators

Nice: We can describe all types of new physics in terms of effective four-quark operators:

$$O_V^L = \bar{c}_L \gamma^\mu b_L \, \bar{\tau}_L \gamma_\mu \nu_{\tau L} \,,$$
$$O_S^R = \bar{c}_L b_R \, \bar{\tau}_R \nu_{\tau L} \,,$$
$$O_S^L = \bar{c}_R b_L \, \bar{\tau}_R \nu_{\tau L} \,,$$
$$O_T = \bar{c}_R \sigma^{\mu\nu} b_L \, \bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L} \,.$$

Fit the corresponding coefficients $C_V^L, C_S^{R,L}, C_T$ to data.

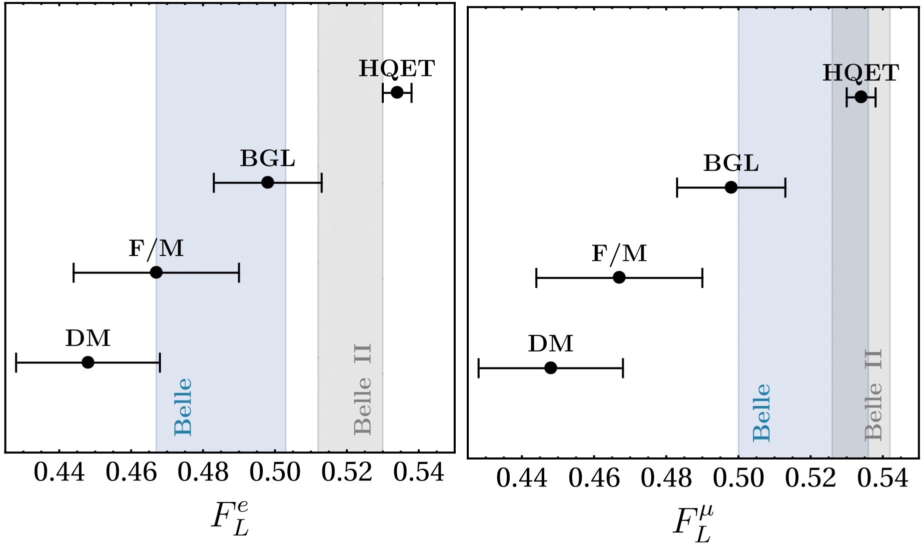
Blanke,Crivellin,de Boer,UN,Nisandzic,Kitahara, *Phys.Rev.D* 100(2019) 3, 035035

Iguro, Kitahara,Watanabe, arXiv:2210:10751, arXiv:2405:06062

$F_L^{D^*,\mathrm{light}}$ as a form factor filter

No BSM scenario has a measurable impact on $F_L^{D^*,\mathrm{light}}$!

Fedele,Blanke,Crivellin,UN,Iguro,Simula,Vittorio, *Phys.Rev.D 108 (2023) 5, 5*

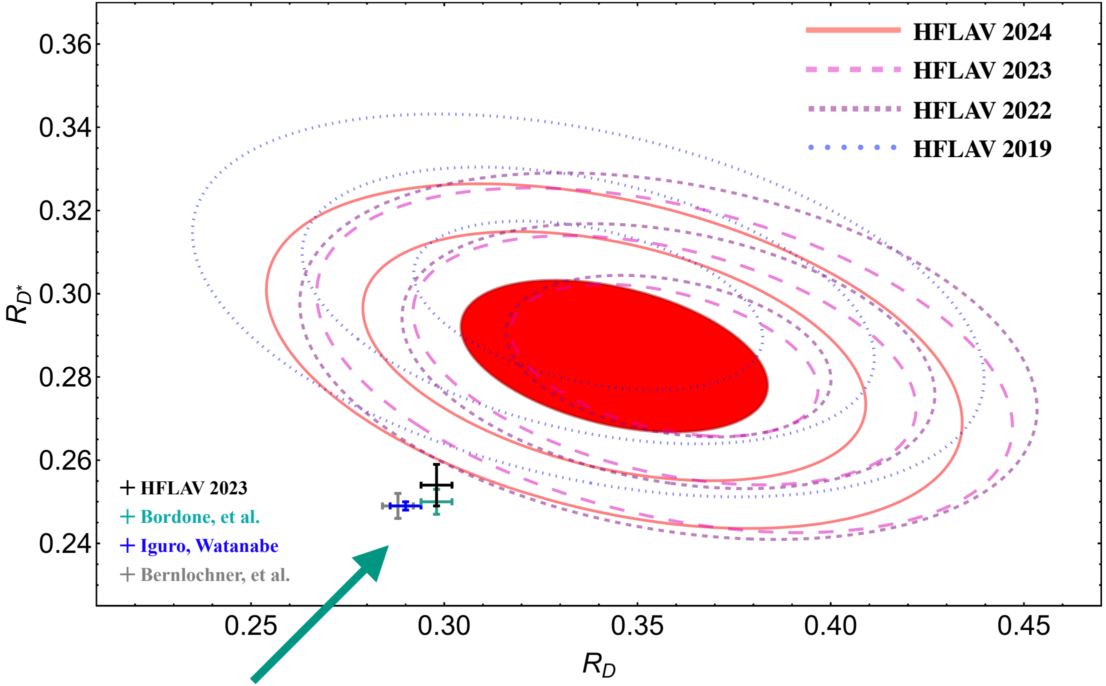


} good form factors

} too steep form factors

"HQET" form factors of Watanabe et al. use Belle(-II) data

$R(D^{(*)})$ with best form factors



difference in HFLAV and HQET form factors matters!

Deviation from SM prediction:

4.3σ

using also new Belle/LHCb average

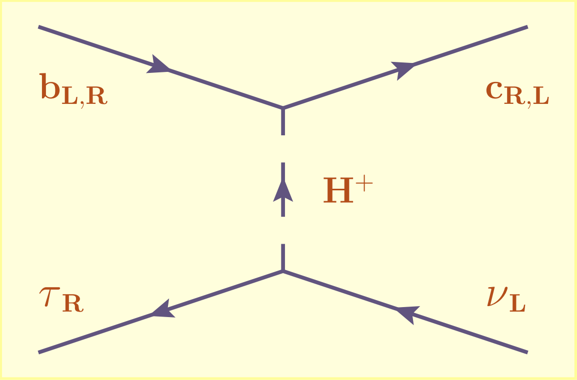
$$F_L^{D^*,\tau} = 0.49 \pm 0.05$$

Good fits (pulls $\geq 4.0\sigma$) for all tree-level BSM scenarios, including charged-Higgs exchange.

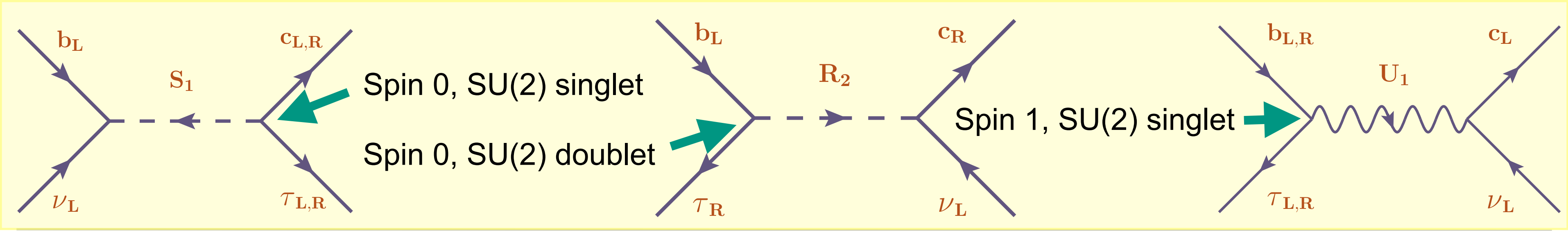
Iguro, Kitahara, Watanabe, arXiv:2405.06062

BSM explanations of $b \to c\tau\bar{\nu}$ data

- Charged Higgs boson:
  was known to be sensitive to effects of a hypothetical charged Higgs boson since 1992.
  Grzadkowski,Hou, Phys. Lett. B **283** (1992) 427

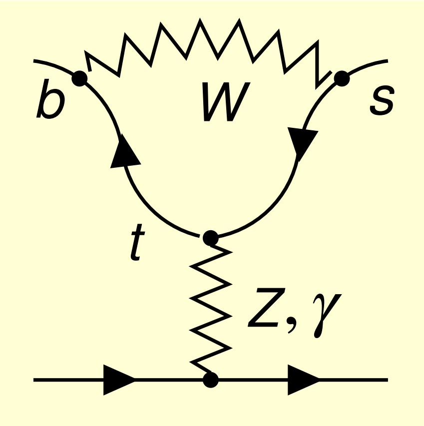


- Leptoquarks:
  - bosons with quark-lepton coupling
  - appear in SU(4) gauge theories, where lepton number is the fourth colour



Status of new physics in $b \to s\ell^+\ell^-$

$b \to s\ell^+\ell^-$ and $b \to s\nu\bar{\nu}$: Developments since Quirks 2022



Belle II has measured $B(B \to K\nu\bar{\nu})$ 2.7σ above the SM prediction.

arXiv:2311.14647

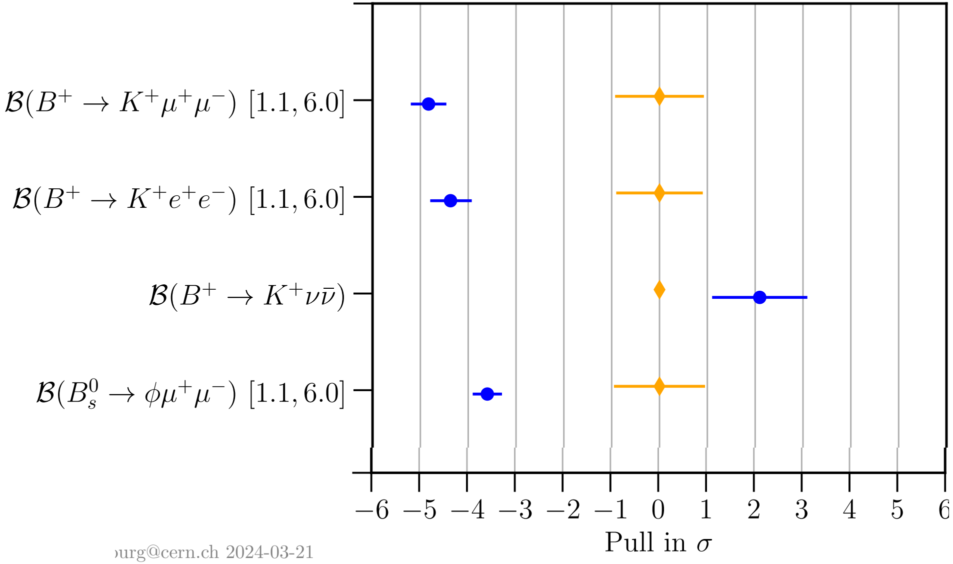
persists since 2013

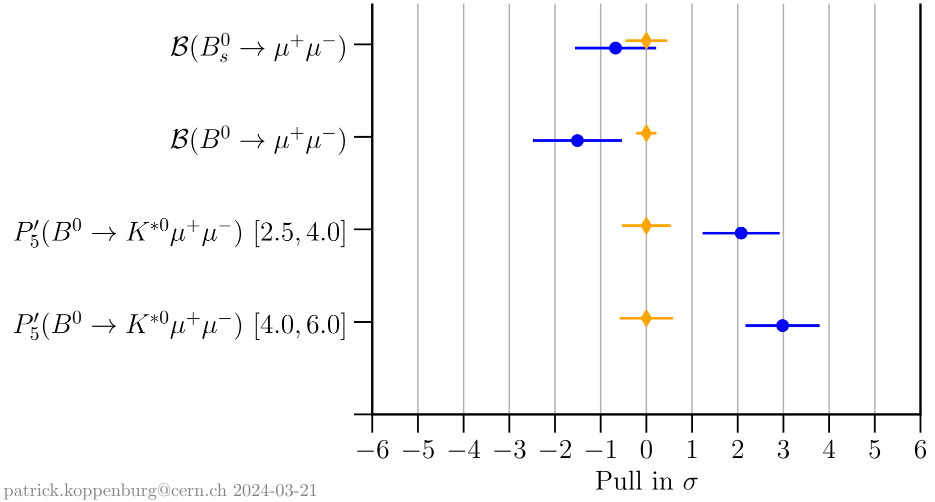
$B(B \to K^{(*)}\ell^+\ell^-)$, $B(B_s \to \phi\mu^+\mu^-)$ lower than SM predictions for $1.1\,\text{GeV}^2 \leq q^2 \leq 8\,\text{GeV}^2$.

ν_ℓ and ℓ form an SU(2) doublet $L = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}$.

$\Rightarrow$ potential connection between the two anomalies.

$b \to s$ flavour anomalies overview





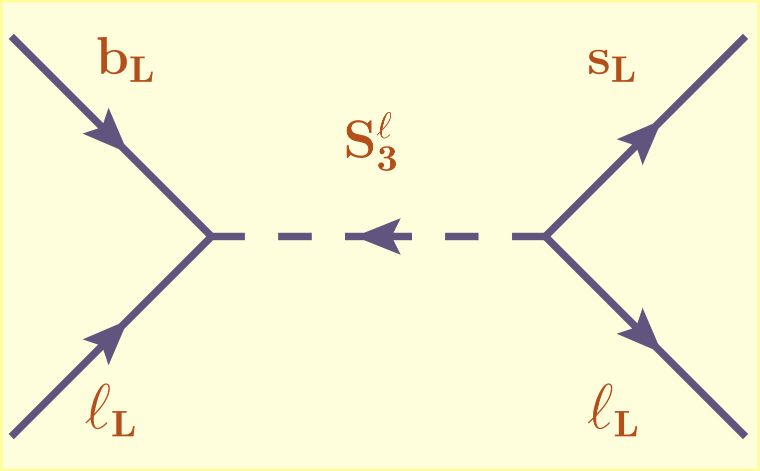
from Patrick Koppenburg's web page https://www.nikhef.nl/~pkoppenb/anomalies.html

$b \to s\ell^+\ell^-$: Developments since Quirks 2022

Hints of $B(B \to K^{(*)}e^+e^-) \neq B(B \to K^{(*)}\mu^+\mu^-)$ were not confirmed after 2022 reanalysis of LHCb data.

$\Rightarrow$ New-physics contributions must affect **both** $b \to s\mu^+\mu^-$ and $b \to se^+e^-$.

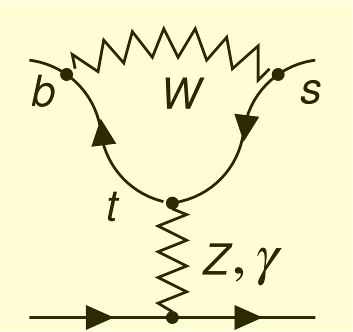
Leptoquarks: To avoid excessive contributions to $\mu \to e$ conversion, need different copies of S_3^ℓ, with S_3^e coupling to electrons and S_3^μ coupling to muons.



LHCb data are compatible with lepton flavour universality (LFU)

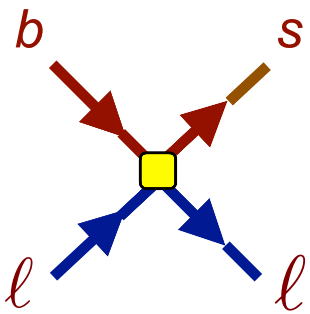
Effective hamiltonian

$$H \propto \sum_{\ell=e,\mu,\tau} C_9^\ell Q_9^\ell + C_{10}^\ell Q_{10}^\ell$$

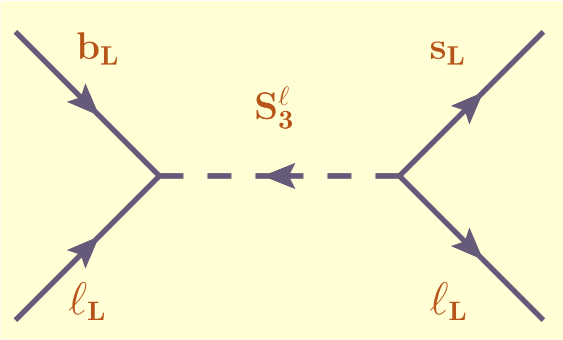


with

$$Q_9^\ell = \frac{\alpha}{4\pi}\bar{s}_L\gamma_\mu b_L\,\ell\gamma^\mu\ell \quad \text{and} \quad Q_{10}^\ell = \frac{\alpha}{4\pi}\bar{s}_L\gamma_\mu b_L\,\ell\gamma^\mu\gamma_5\ell$$



Leptoquark explanation



SU(3) triplet leptoquark.
Mass < 35 TeV for couplings $< \mathcal{O}(1)$.

Contributes to both $C_9^{\ell\ell}$ and $C_{10}^{\ell\ell}$. Effects in $C_{10}^{\mu\mu}$ will affect $B(B_s \to \mu^+\mu^-)$ as well. O.k. with LHCb data, less so with CMS data.

To avoid unacceptably large $\mu \to e$ conversion postulate one leptoquark S_3^ℓ per flavour $\ell = e, \mu, \tau$.
But observed approximate lepton flavour universality requires $M_{S_3^e} \sim M_{S_3^\mu}$ and also similar couplings of S_3^e and S_3^μ.

Renormalisation group analysis of leptoquark solutions

Mass gap

Flavour anomalies are usually explained by postulating a new particle with mass in the TeV range *ad-hoc*. The other particles of a reasonable UV completion are heavier.

Leptoquarks: Motivation in models with quark-lepton unification, such as $SU(4)_c$ models à la Pati-Salam. Heavy gluons (which are vector-like leptoquarks) must have masses above 1000 TeV to comply with bounds on $B(K_L \to \mu e)$.

Mass gap between the LQ masses as and the scale of the UV completion:

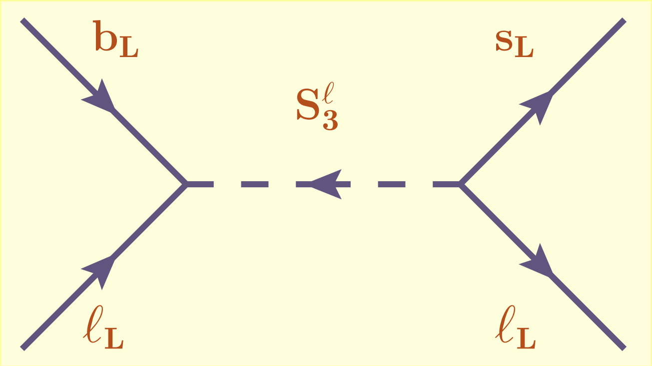
$\Rightarrow$ study low-energy properties of LQ couplings without knowing details of the UV model with renormalisation group (RG) equations.

Prototype example: Probing SM gauge unification at GUT scale only involves SM RG equations. GUT masses only enter next-to-leading order corrections.

Leptoquark-quark-lepton couplings

Couplings of several SU(2) triplet leptoquarks S_3^a:

$$\mathscr{L}_{S_3} = y^a_{3\,ij}\,\bar{Q}^{C,\,l}_{L,\,i}\epsilon^{lm}(\tau^k S_3^{a,\,k})^{mn} L^n_{L,\,j} + \text{h.c.}$$



a: labels the LQ
i: quark generation index
j: lepton generation index

$$\epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Pauli matrices

Consider lepton number conservation $y^a_{3\,ij} \propto \delta_{aj}$ to suppress LFV processes like $\mu \to e$ conversion.

Infrared fixed-point

RG beta functions are known for generic BSM theories.

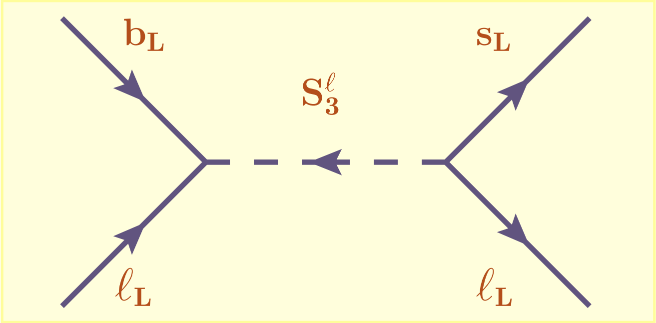
Machacek, Vaughn, 1983, 1984

At fixed points of the RG equations the beta functions are zero.
Quasi-fixed point: The beta functions of the LQ couplings $y^{a}_{3\,ij}$ are zero, while the beta function of the SM couplings are not.

Infrared fixed point: $y^{a}_{3\,ij}$ at the low scale as probed in flavour or collider experiments is predicted.

Infrared fixed-point for S_3^ℓ scenario

Result for S_3^ℓ leptoquarks: Fedele, UN, Wüst, JHEP 11 (2023) 131, Bachelor thesis F.Wüst



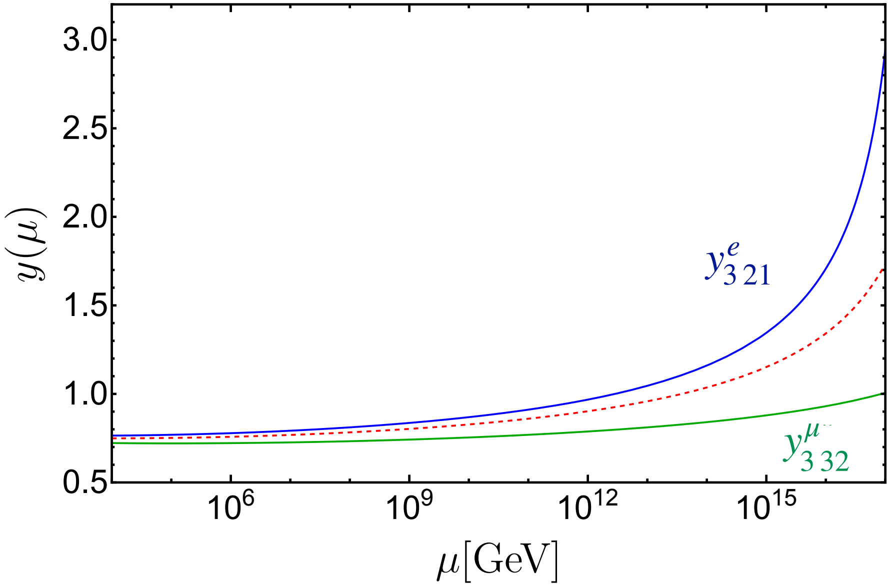
- Infrared fixed-point solutions:

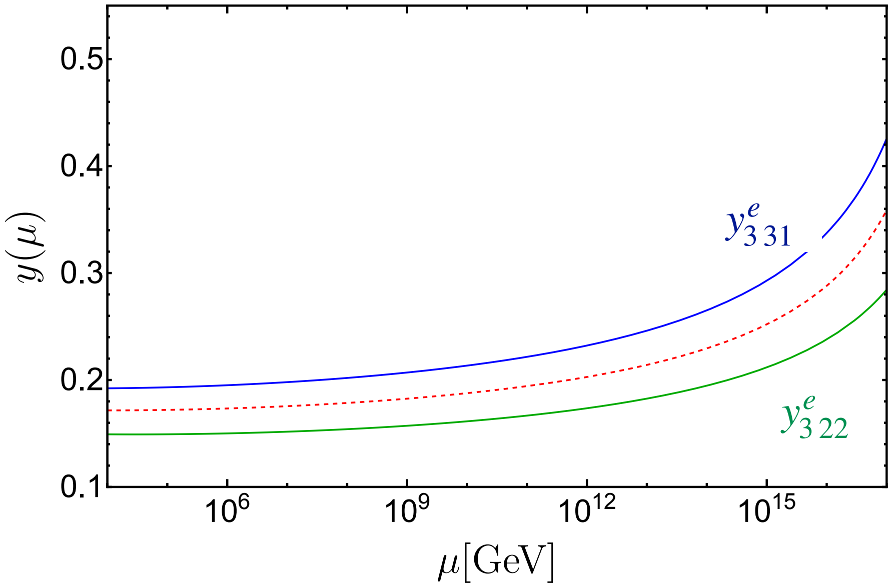
$y^e_{3\,21}$	$y^e_{3\,31}$	$y^\mu_{3\,22}$	$y^\mu_{3\,32}$	$y^\tau_{3\,23}$	$y^\tau_{3\,33}$
0.760	0.189	0.191	0.759	0.639	-0.452
0.189	0.760	0.759	0.191	0.639	-0.452

and two more pairs found from permutations of (e, μ, τ).
Partial lepton-flavour universality (LFU) as an emerging feature! The third generation comes with opposite sign for $C_{9,10}^{\ell\ell}$. Prediction for $b \to s\tau^+\tau^-$!

- LFU needs three copies of S_3^ℓ, with just two S_3^ℓ find opposite signs.

Infrared fixed-point for (S_1^ℓ, S_3^ℓ) scenario



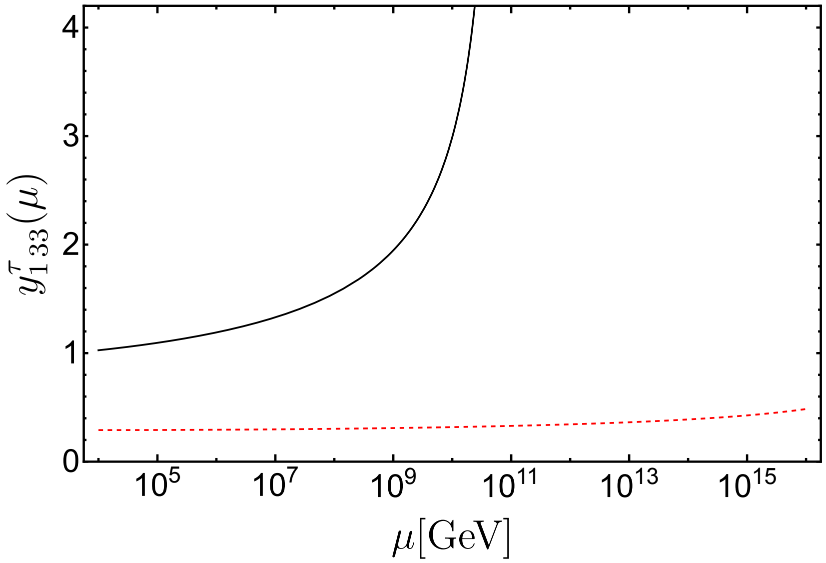


Bizarre: *s*-*e* coupling converges to *b*-μ coupling and *b*-*e* coupling converges to s-μ coupling!

Infrared fixed-point (S_1^ℓ, S_3^ℓ) scenario

The infrared fixed point for the S_1^τ coupling is smaller that the coupling inferred from $b \to c\tau\bar{\nu}$ data (for S_1^τ masses allowed by collider searches).

Landau pole:



$\Rightarrow$ upper bound on scale of quark-lepton unification:

$$M_{\mathrm{QLU}} \lesssim 10^{11}\ \text{GeV}$$

Prediction for $B \to K^{(*)}\nu\bar{\nu}$

For the fixed-point solution for the S_3^ℓ couplings and the S_1^ℓ coupling fixed from the $b \to c\tau\nu$ anomaly we find a 10% enhancement of $B(B \to K\nu\bar{\nu})$ and $B(B \to K^*\nu\bar{\nu})$ from the S_1^ℓ contribution, detectable by Belle II.

Leptoquarks at colliders

Radiative corrections…

…to collider processes with leptoquarks (LQ):

- QCD corrections to pair production at Tevatron and LHC:

  M. Krämer, T. Plehn, M. Spira, P.M. Zerwas, Phys. Rev. Lett. 79, 341 (1997), Phys.Rev.D 71 (2005) 057503;

- QCD and QED corrections to resonant production:

  A. Greljo, N. Selimovic, JHEP 03 (2021) 279.

- NNLO resummation of soft gluon radiation in pair production

  C. Borschensky, B. Fuks, A. Kulesza, D. Schwartländer, JHEP 02 (2022) 157.

But if we invoke $\mathcal{O}(1)$ quark-lepton-LQ couplings to explain B anomalies, radiative corrections with these might be sizeable as well.

Radiative corrections…

…linking low-energy to collider observables.

Innes Bigaran, Rodolfo Capdevilla, UN

Focus: universal radiative corrections linking couplings

y_{njk}^{XY} with $X, Y = L, R$,

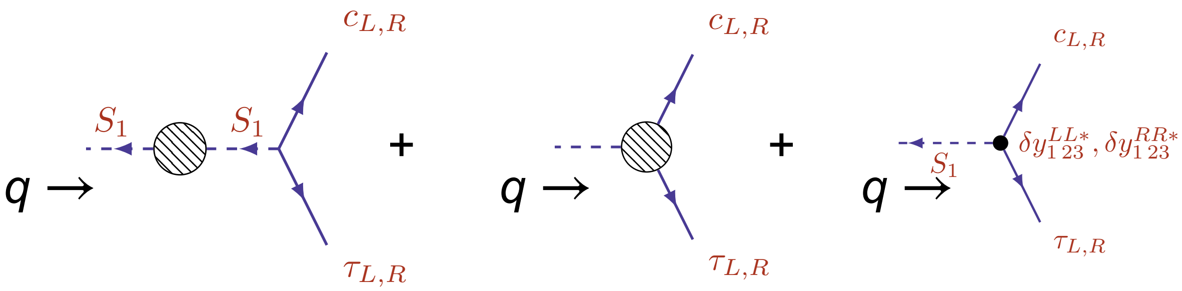
probed at low and high energy to each other.

Define two renormalisation schemes with couplings $y_{njk}^{XY,\mathrm{low}}$ and $y_{njk}^{XY,\mathrm{high}}$,

defined such that radiative corrections vanish for zero LQ momentum q or for on-shell LQ, $q^2 = M_{\mathrm{LQ}}^2$.

Coupling renormalisation

Example: coupling of LQ S_1 to charm and tau, $y_{1\,23}^{LL,RR}$.



+ fermion wave f. ren. $\overset{!}{=} 0$

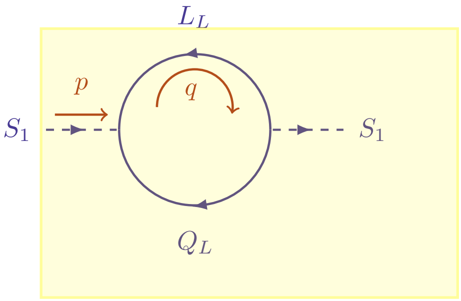
For $y_{1\,23}^{LL,RR,\,\mathrm{low}}$ this condition on the counterterm is imposed for $q=0$. $b \to c\tau\bar{\nu}$ data constrain $y_{1\,23}^{LL,RR,\,\mathrm{low}} \times y_{1\,33*}^{LL,RR,\,\mathrm{low}}$ as a function of M_{S_1}.

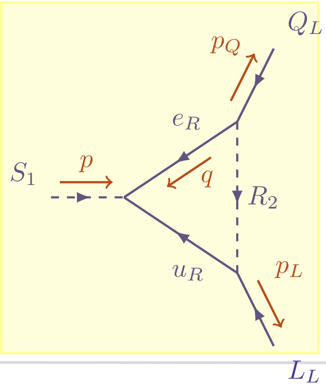
Likewise $y_{1\,23}^{LL,RR,\,\mathrm{high}}$ is defined by imposing this for $q^2 = M_{S_1}^2$.

Couplings at low and high energy

$\kappa^{LL}_{1\,jk} \equiv \dfrac{y^{LL,\mathrm{high}}_{1\,jk}}{y^{LL,\mathrm{low}}_{1\,jk}}$ captures the process-independent part of the radiative corrections entering collider-physics observables of S_1 , if $y^{LL\,\mathrm{low}}_{1\,jk}$ is taken from flavour data.

If only one LQ species is present, there are no vertex corrections. For these need both S_1 and R_2:





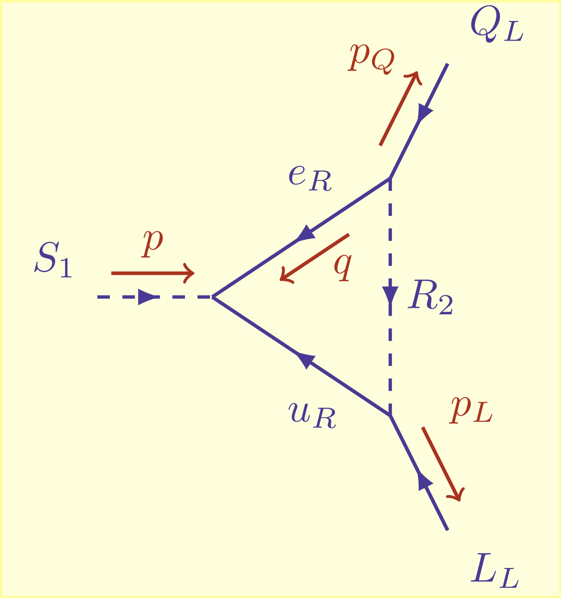
If only one LQ species is present, only the LQ self-energy contributes to $\kappa^{LL}_{1\,jk}$.

Couplings at low and high energy

- The $\kappa_{n\,jk}^{XY}$ factors are close to one, if all $y_{n\,jk}^{XY}$ are $\leq \mathcal{O}(1)$. In these cases one can use the $y_{n\,jk}^{XY}$ inferred from the flavour anomalies for collider searches.
- Perturbation theory seems to work for $y_{n\,jk}^{XY} = \mathcal{O}(5)$. Collider searches first exclude the parameter region with small LQ mass and large couplings, thus for this the $\kappa_{n\,jk}^{XY}$ factors matter. If such a scenario shall explain flavour anomalies (with not-too-heavy LQ), the couplings must be hierarchical, e.g. $|y_{1\,23}^{LL,RR}| \gg |y_{1\,33}^{LL,RR}|$ or $|y_{1\,23}^{LL,RR}| \ll |y_{1\,33}^{LL,RR}|$.
- $\kappa_{n\,jk}^{XY} < 1 \;\Rightarrow$ couplings in collider processes weaker than in flavour physics

Vertex corrections

- The vertex correction in scenarios with both S_1 and R_2 involves different couplings than the tree-level coupling, e.g.



$S_1 - Q_L - L_L$ coupling $\propto y_{1\,jk}^{RR} \times y_{2\,jl}^{RL} \times y_{2\,mk}^{LR*}$

can be important if $y_{1\,ml}^{LL}$ is small.

The vertex loop function is smaller than expected.

Summary

Summary

- Current flavour anomalies probe BSM physics with particle masses in the multi-TeV range.

  $\Rightarrow$ instrumental to justify and design future hadron colliders

- $b \to c\tau\bar{\nu}$:
  - Form factors better known thanks to new polarisation measurements in $b \to c\ell\bar{\nu}$ polarisation data.
  - Charged-Higgs and various leptoquark scenarios have pulls of 4.0σ compared to SM.
  - Future: D^* and τ polarisation data

Summary

- $b \to s\ell^+\ell^-$:
  - Data show approximate LFU between e and μ. Popular S_3 leptoquark needs several copies with lepton number conservation
- Leptoquark models:
  - embedding into theory of quark-lepton unification requires a mass gap, opportunity to use RG methods
  - $S_3^{\ell\ell}$ couplings have IR fixed point with equal contributions to two of the three $C_{9,10}^{\ell\ell}$ coefficients, while the third one has opposite sign.

    $\Rightarrow$ Two-generation LFU emerges dynamically.

Summary

- Radiative corrections with virtual leptoquarks involve small loop functions.
  - Does perturbation theory permit largish quark-lepton-LQ couplings? Will this permit us to explain $b \to c\tau\bar{\nu}$ anomalies with large LQ masses evading collider search bounds?
  - For $\mathcal{O}(1)$ couplings our radiative corrections are very small.
  - Since collider exclusion bounds probe the large-coupling region most efficiently, the κ_{njk}^{XY} factors should be included when deriving bounds on the couplings y_{njk}^{XY}.

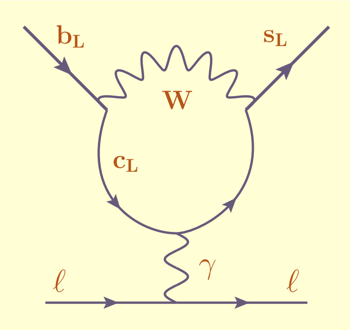
Backup slides

$b \to s\ell^+\ell^-$

A BSM explanation of $b \to s\ell^+\ell^-$ data require contribution to $C_9^{\mu\mu} \sim C_9^{ee}$ of order $-0.25 \cdot C_9^{SM}$.

Claim: enhancement of charm loop could fake BSM signal.

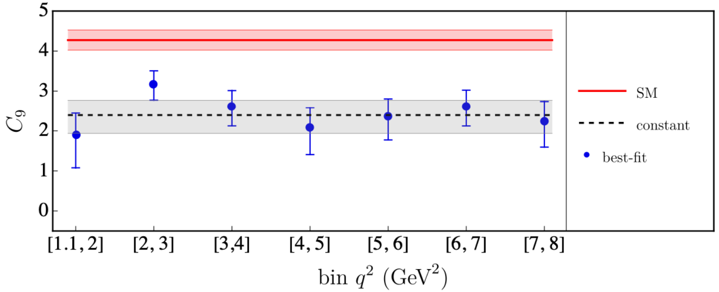
Test this by fitting for q^2 -dependence of C_9^{BSM}:



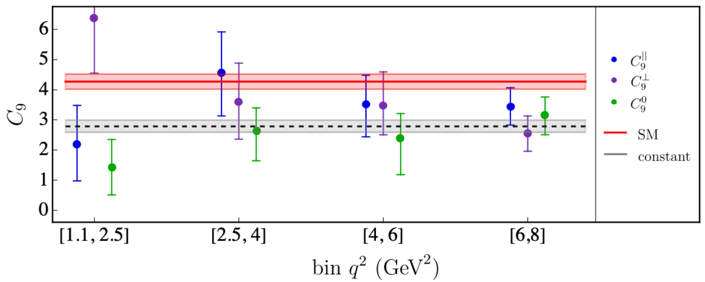
Compatible with LHCb analysis!

$B \to K\bar{\ell}\ell$

Low q^2



$B \to K^*\bar{\ell}\ell$



Bordone,Isidori,Mächler,Tinari, arXiv:2401.18007