Karlsruher Institut für Technologie

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Institut für Theoretische Teilchenphysik (KIT)

Leptoquarks: emerging lepton flavour universality from RG evolution and flavour-collider connection

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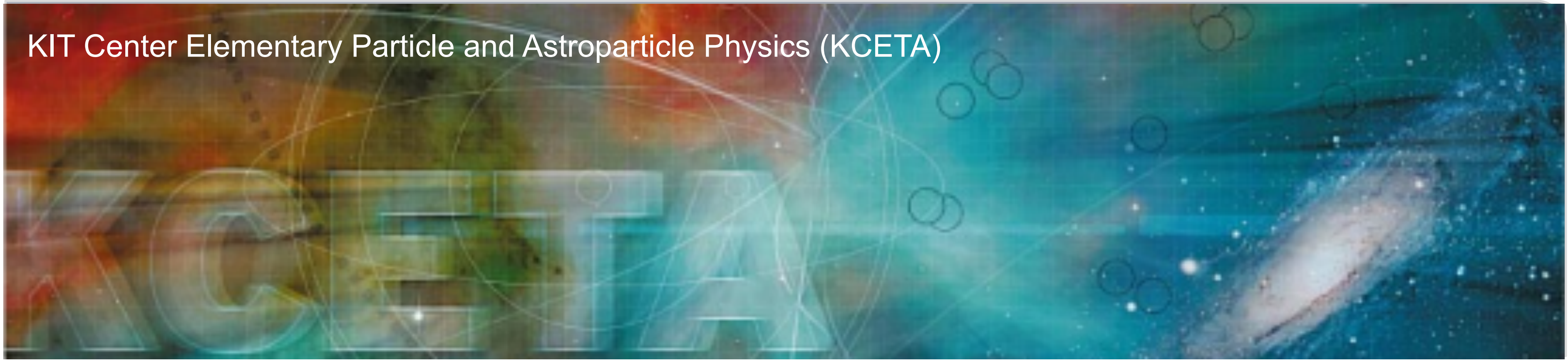
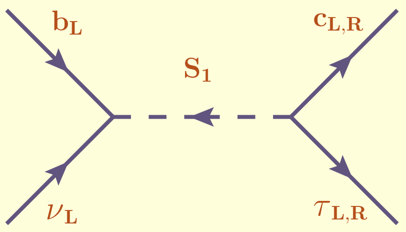
Institute for Theoretical Particle Physics (TTP)



Leptoquarks and semileptonic decays

Scalar leptoquarks are a popular explanation of flavour anomalies.

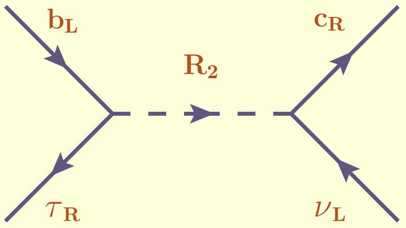
Spin 0,
SU(2) singlet



S_1 or R_2 for

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

Spin 0,
SU(2) doublet

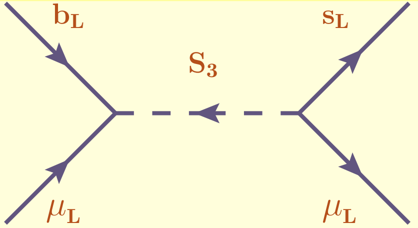


S_3 for low-q^2 deficit in several

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

decay distributions.

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

- New developments in $b \to c\tau\nu$
- Renormalisation group analysis of leptoquark solutions
- Leptoquarks at colliders
- Summary and outlook

New developments in $b \to c\tau\nu$

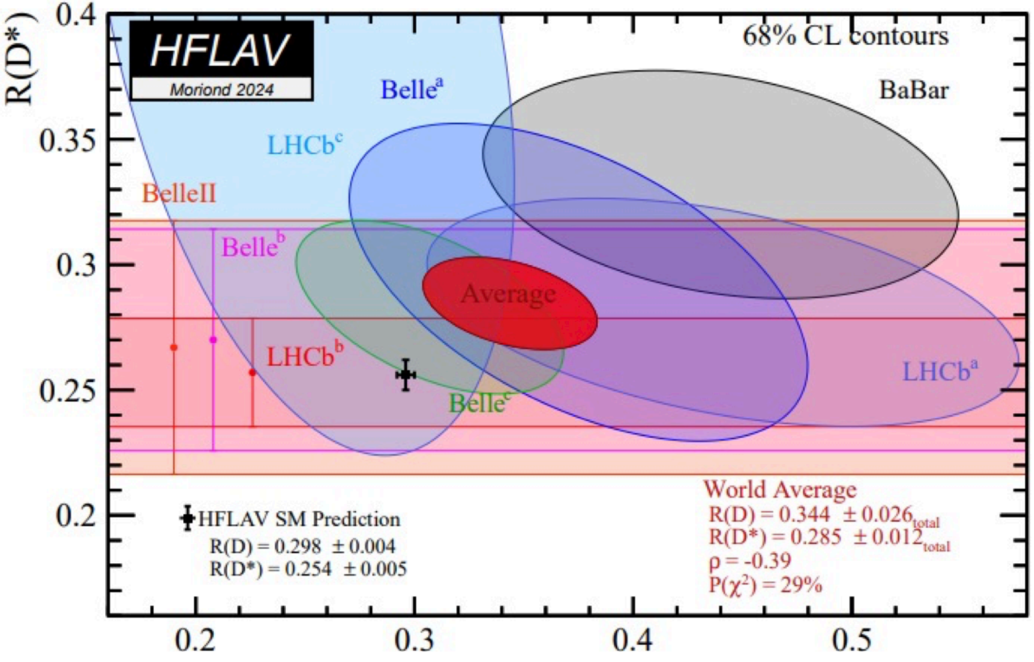
New developments in $b \to c\tau\nu$

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

Spring 2024:
Significance of deviation from SM:
3.1.σ,
for the form factors used by HFLAV.

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

With 2024 LHCb measurement of $R(D^+)$:



$B \to D^*$ form factors

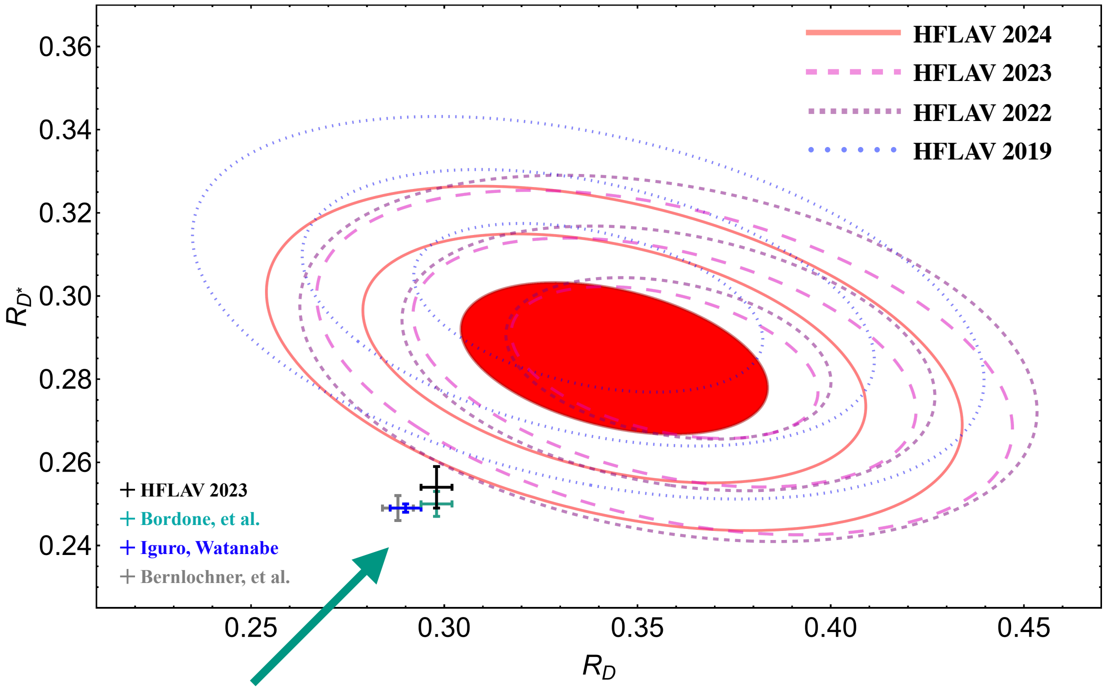
2022: Iguro, Kitahara and Watanabe employed Heavy Quark Effective Theory (HQET) and a systematic expansion of form factors in $1/m_b$ and performed a fit to all available data (including q^2 shapes) in $B \to D^* \ell \nu$ with light leptons $\ell = e, \mu$. arXiv:2210.10751

2023: new data on the fraction $F_L^{D^*,\text{light}}$ 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

The HQET form factors excellently describe these data, while other form factor calculations do not. Fedele,Blanke,Crivellin,Iguro,UN,Simula,Vittorio, arXiv:2305.15457

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



difference in HFLAV and HQET form factors matters!

2024 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, 2405.06062

From Iguro, Kitahara, Watanabe, 2405.06062:

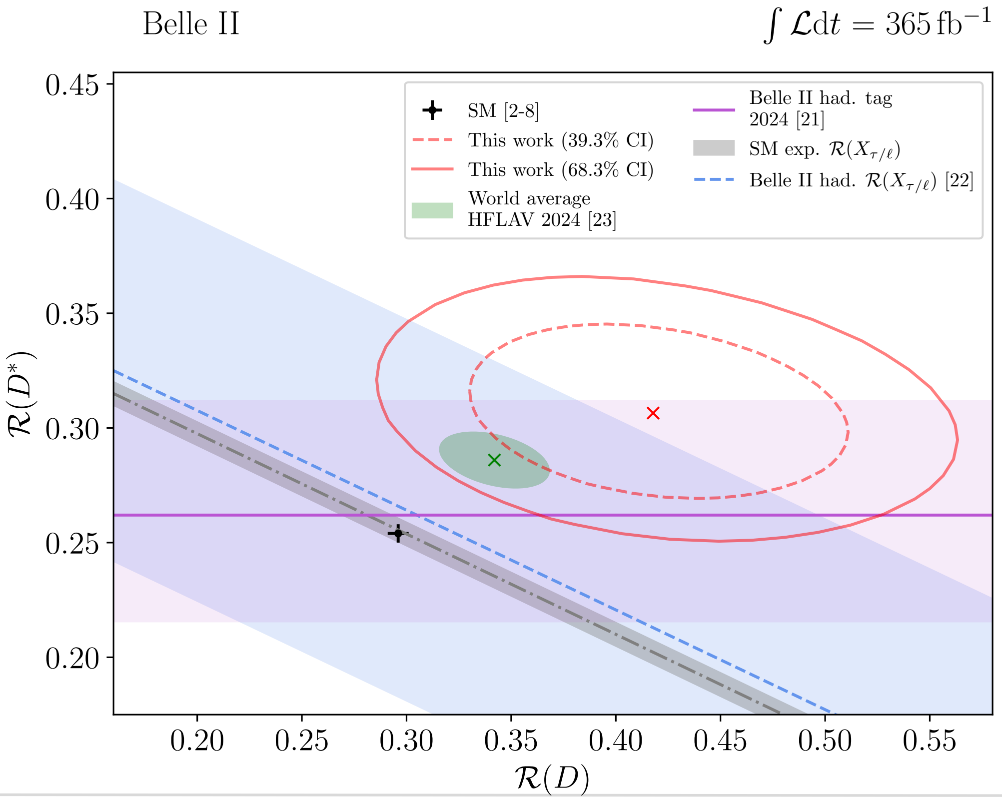
Reference	R_D	R_{D^*}	P_τ^D	$-P_\tau^{D^*}$	$F_L^{D^*}$	$R_{J/\psi}$	R_{Λ_c}	$R_{\Upsilon(3S)}$
Bernlochner, *et al.* [29]	0.288(4)	0.249(3)	–	–	–	–	–	–
Iguro, Watanabe [30]	0.290(3)	0.248(1)	0.331(4)	0.497(7)	0.464(3)	–	–	–
Bordone, *et al.* [31,32]	0.298(3)	0.250(3)	0.321(3)	0.492(13)	0.467(9)	–	–	–
? → HFLAV2024 [14]	0.298(4)	0.254(5)	–	–	–	–	–	–
Refs. [33–35]	–	–	–	–	–	0.258(4)	0.324(4)	0.9948
Data	0.342(26)	0.287(12)	–	$0.38^{+0.53}_{-0.55}$	0.49(5)	0.61(18)	0.271(72)	0.968(16)

! ?

$R(D^{(*)})$ from Belle II in 2025

- 2025 Belle II, semileptonic tag: slight increase of the global significance

  Belle II coll., 2504.11220

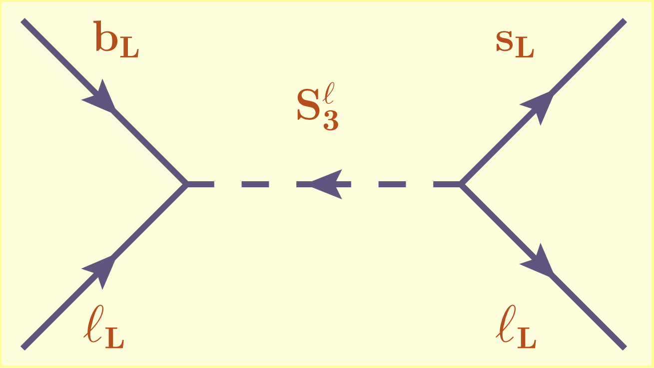


Renormalisation group analysis of leptoquark solutions

Leptoquark-quark-lepton couplings

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

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



$\ell = e, \mu, \tau$ labels the LQ
i: quark generation index
j: lepton generation index

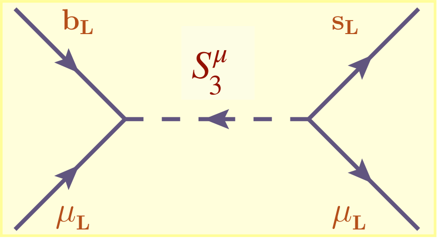
$$\epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

Pauli matrices

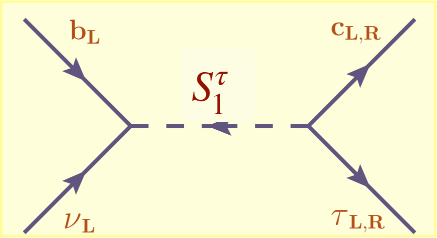
Consider lepton number conservation $y^{\ell}_{3\,ij} \propto \delta_{\ell j}$ to suppress LFV processes like $\mu \to e$ conversion.

Leptoquark solutions to flavour anomalies

- The deficit in $b \to s\ell^+\ell^-$ for low q^2 can be cured with three copies S_3^e, S_3^μ, S_3^τ of SU(2) triplet leptoquarks with masses below $\mathcal{O}(50)$ TeV.



- The enhancement of $b \to c\tau\nu$ can be explained with an SU(2) singlet leptoquark S_1^τ with mass below $\mathcal{O}(5)$ TeV. We consider three copies S_1^e, S_1^μ, S_1^τ.



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.

Infrared fixed-point

RG beta functions are known for generic BSM theories.

Machacek, Vaughn, 1983, 1984

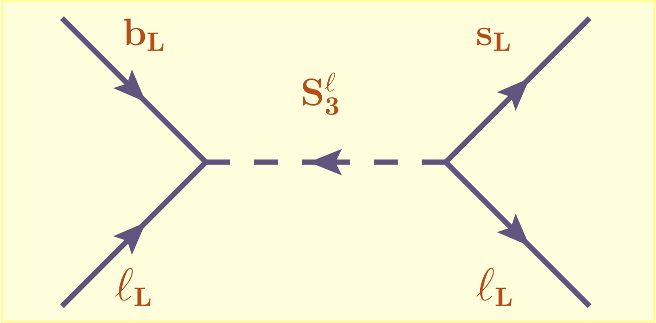
At fixed points of the RG equations the beta functions are zero.
Quasi-fixed point: The beta functions of the LQ couplings $y^a_{3\,ij}$ are zero, while the beta function of the SM couplings are not.

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:

Marco Fedele, UN, Felix Wüst, JHEP 11 (2023) 131.



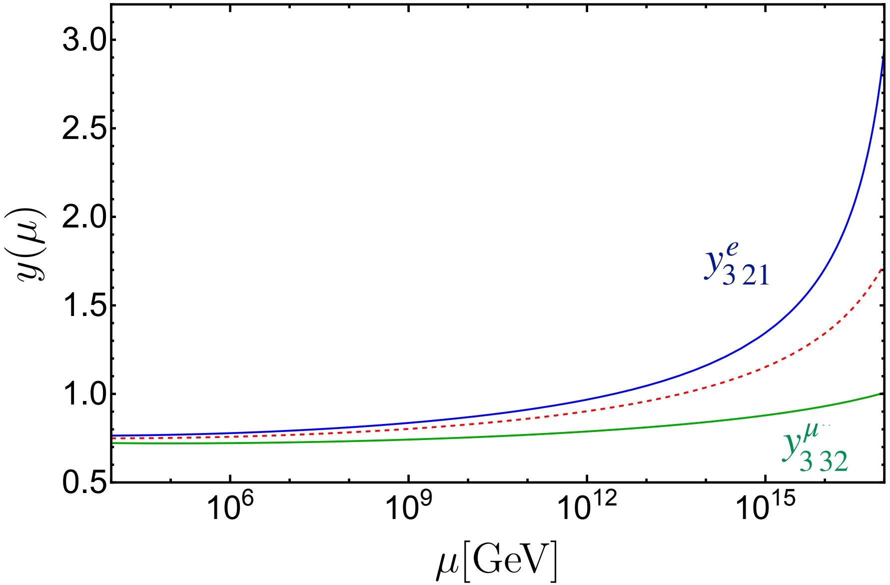
- Infrared fixed-point solutions:

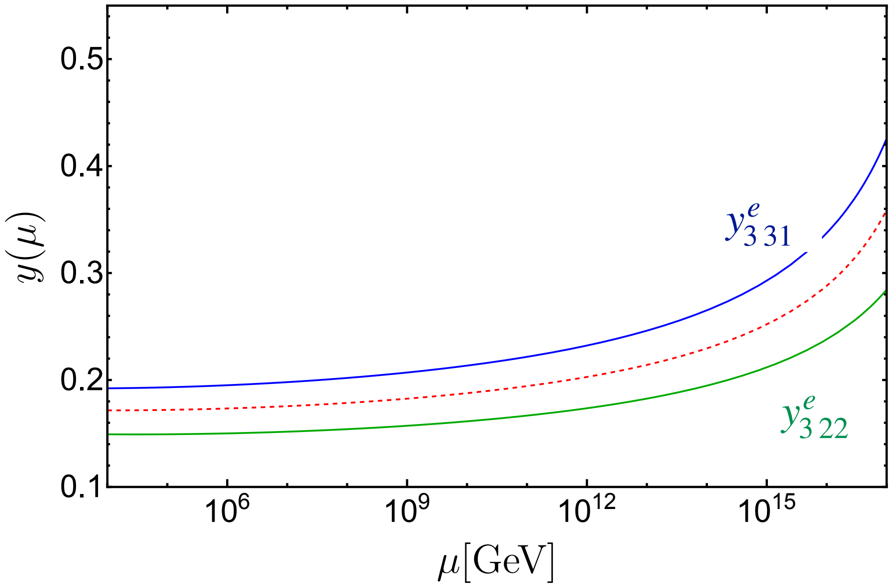
$y^e_{3\,21}$	$y^e_{3\,31}$	$y^\mu_{3\,22}$	$y^\mu_{3\,32}$	$y^\tau_{3\,23}$	$y^\tau_{3\,33}$
0.760	0.189	0.191	0.759	0.639	−0.452
0.189	0.760	0.759	0.191	0.639	−0.452

and two more pairs found by 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



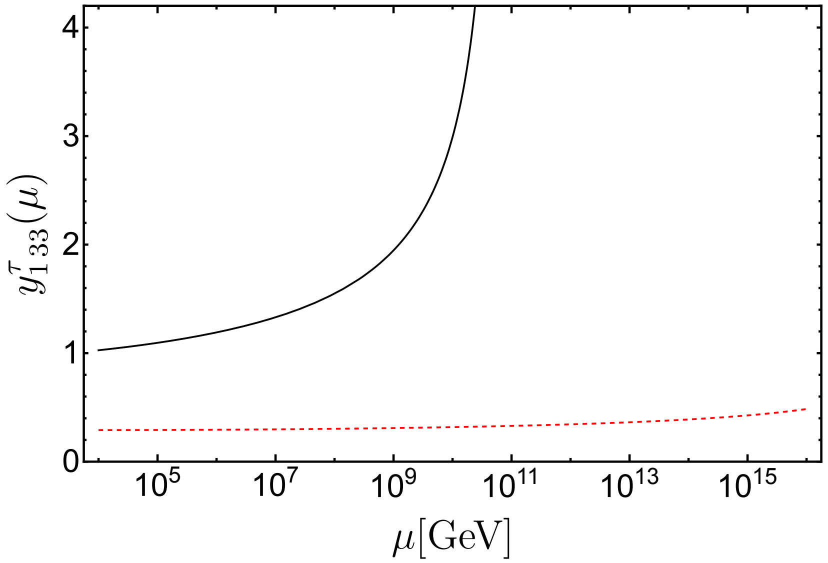


Bizarre: *s-e* coupling converges to *b-μ* coupling and *b-e* coupling converges to s-μ coupling!

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:



⇒ upper bound on scale of quark-lepton unification:

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

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 couplings might be sizeable as well.

Radiative corrections…

…linking low-energy to collider observables.

Innes Bigaran, Rodolfo Capdevilla, UN, 2408.06501

Focus: universal radiative corrections linking couplings

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

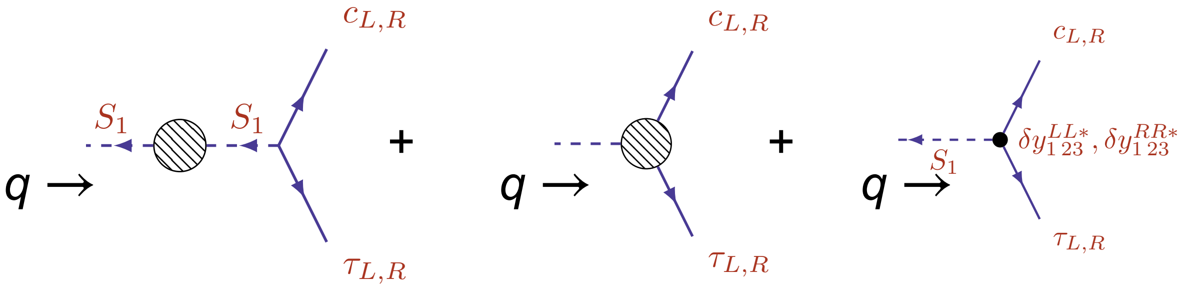
probed at low and high energy to each other.

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}.

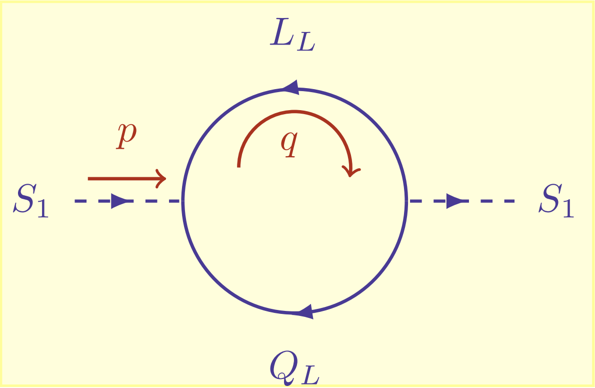
Likewise $y_{1\,23}^{LL,RR,\,\mathrm{high}}$ is defined by imposing this for $q^2 = M_{S_1}^2$.

Couplings at low and high energy

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



Couplings at low and high energy

- The $\kappa_{n\,jk}^{XY}$ factors are close to one, if all $y_{n\,jk}^{XY}$ are $\leq \mathcal{O}(1)$. Example for S_1 LQ with mass 2 TeV and with couplings $(y_{1\,23}^{RR}, y_{1\,33}^{LL}) = (2.6, -0.41)$:

$$\kappa_{1\,jk}^{LL} = \kappa_{1\,jk}^{RR} = 0.98.$$

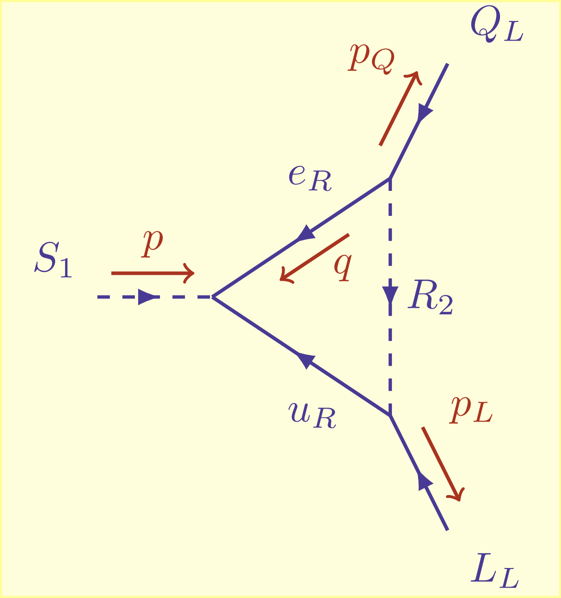
- Perturbation theory seems to work for $y_{n\,jk}^{XY} = \mathcal{O}(5)$. Collider searches first exclude the parameter region with small LQ mass and large couplings. Example for a 2 TeV R_2 LQ with couplings $(y_{2\,33}^{LR}, y_{2\,23}^{RL}) \approx (0.5, -0.82 \pm 6.86\,i)$:

$$\kappa_{2\,jk}^{LR} = \kappa_{2\,jk}^{RL} = 0.85.$$

- $\kappa_{n\,jk}^{XY} < 1 \quad \Rightarrow$ 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 $\propto y^{RR}_{1\,jk} \times y^{RL}_{2\,jl} \times y^{LR*}_{2\,mk}$ can be important if $y^{LL}_{1\,ml}$ is small.

The vertex loop function with real part

$$f_\kappa(x) = \frac{1}{x}\left[\mathrm{Li}_2(-x) + \ln x\,\left[\ln(1+x) - x\right] + x\right]$$

is smaller than expected:

$-1.17 \le f_\kappa \le 0.23,$ where $x = M^2_{S_1}/M^2_{R_2}$.

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
- Leptoquarks (LQs) with $\mathcal{O}$(TeV) masses can give imprints on low-energy observables (e.g. in B physics) and are searched for at LHC.
  - embedding LQs into a theory of quark-lepton unification requires a mass gap. RG evolution for triplet LQ $S_3^{\ell\ell}$ reveals infrared fixed-points for two out of three coefficients $C_9^{\ell\ell}$, e.g. $C_9^{ee} = C_9^{\mu\mu}$.

    $\Rightarrow$ Two-generation lepton-flavour universality emerges dynamically.
  - Collider bounds probe LQ couplings at high momentum transfer differing from low-energy couplings by a scaling factor $\kappa_{njk}^{XY} < 1$.

Backup slides

$B \to D^*$ 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 $\Lambda_{\rm QCD}/m_{c,b}$):

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 $q^2 \neq q^2_{\rm max}$.

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):

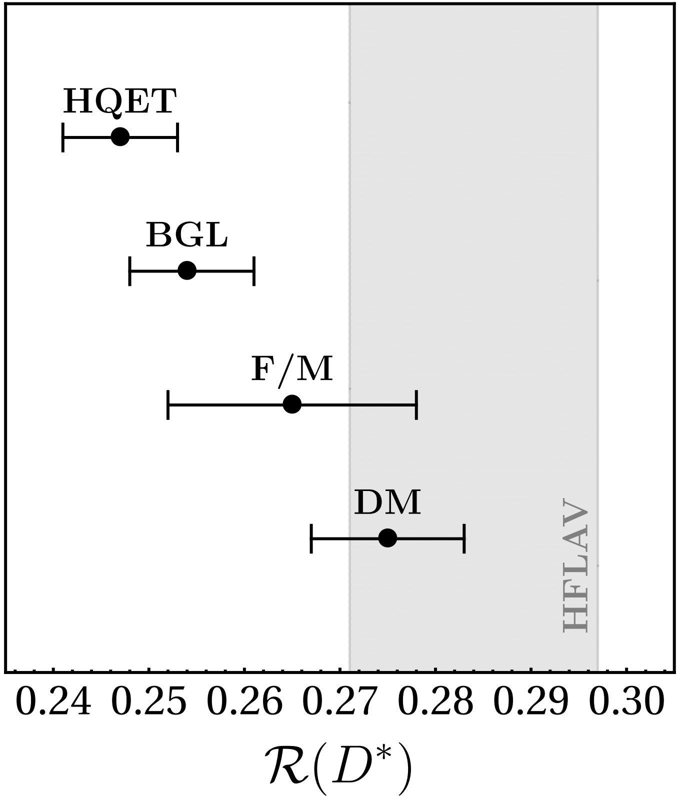
uses Fermilab/MILC data and Rome calculation of susceptibility χ,

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.

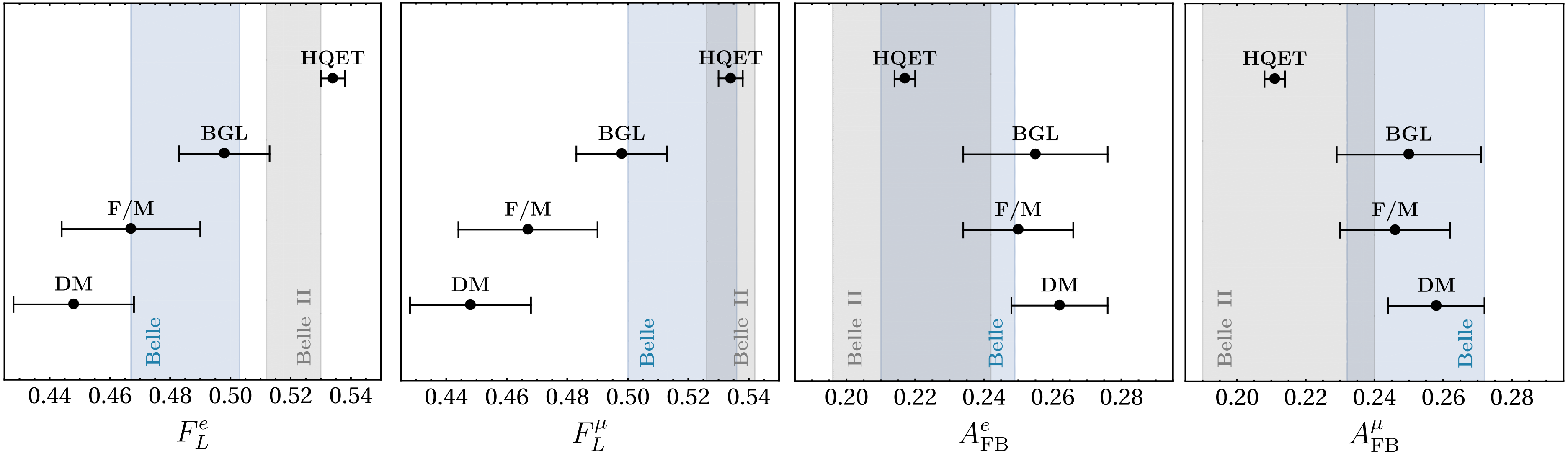
$B \to D^*$ form factors vs new physics



} compatible with Standard Model

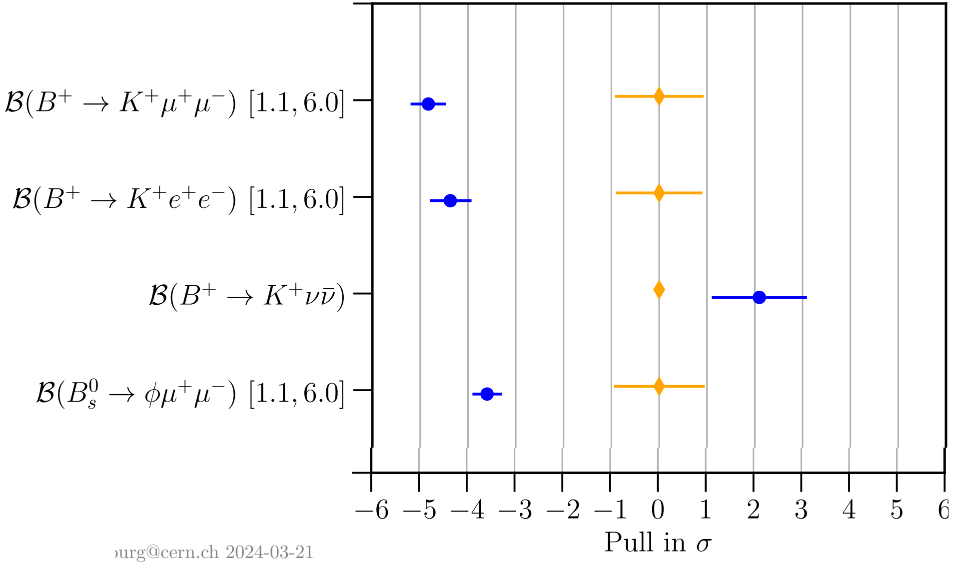
with DM method one finds the same $R(D)$ as with other methods, arXiv:2205.13952

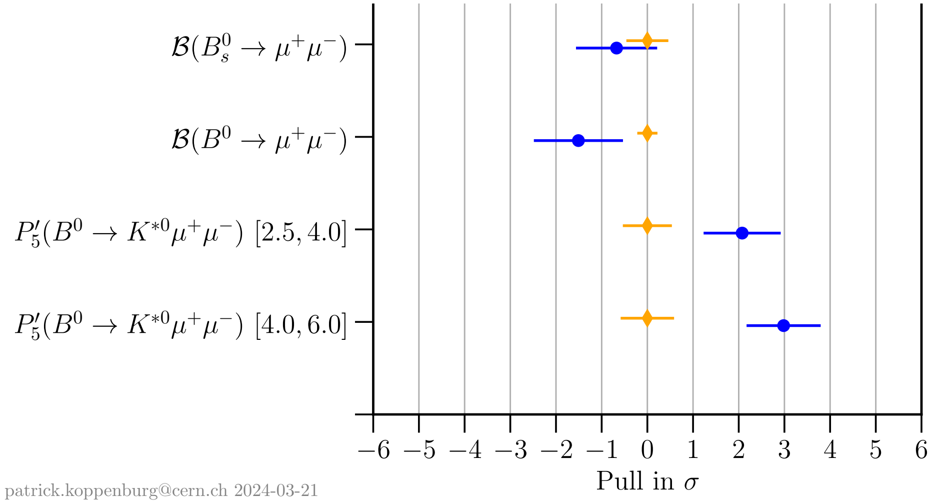
Predictions for $F_L^{D^*,\text{light}}$ and $A_{\text{FB}}^{e,\mu}$



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.

$b \to s$ flavour anomalies overview





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