Karlsruher Institut für Technologie

Collaborative Research Center TRR 257

Particle Physics Phenomenology after the Higgs Discovery

Institut für Theoretische Teilchenphysik (KIT)

Flavour anomalies and new physics

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Heinrich Hertz

1886: discovery of electromagnetic waves

1889: Karlsruhe → Bonn

Flavour physics

studies transitions between fermions of different generations.

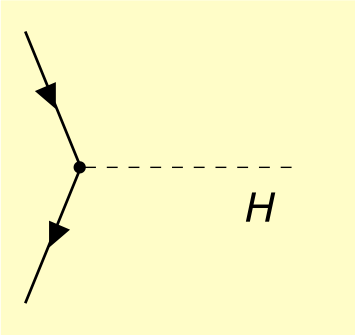
Gauge eigenstates: SU(2) doublets $(u_{jL}, d_{jL})^T$ with

$(d_1, d_2, d_3) \equiv (d', s', b')$ for down, strange, and bottom quark

$(u_1, u_2, u_3) \equiv (u', c', t')$ for up, charm, and top quark

Quark Yukawa lagrangian of the Standard Model:

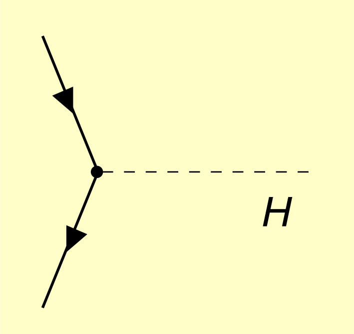
$$-L_Y = Y^d_{jk}\, \bar{d}^j_L\, d^k_R \frac{h}{\sqrt{2}} + Y^u_{jk}\, \bar{u}^j_L\, u^k_R \frac{h}{\sqrt{2}} + \mathrm{h.c.}$$



with two complex 3×3 matrices Y^d and Y^u.

Quark Yukawa lagrangian

$$-L_Y = Y^d_{jk}\, \bar{d}^j_L\, d^k_R\, \frac{h}{\sqrt{2}} + Y^u_{jk}\, \bar{u}^j_L\, u^k_R\, \frac{h}{\sqrt{2}} + \text{h.c.}$$



Replace $h \to \sqrt{2}v$ with the vacuum expectation value v:

→ Two mass matrices $M^d = Y^d v$ and $M^u = Y^u v$!

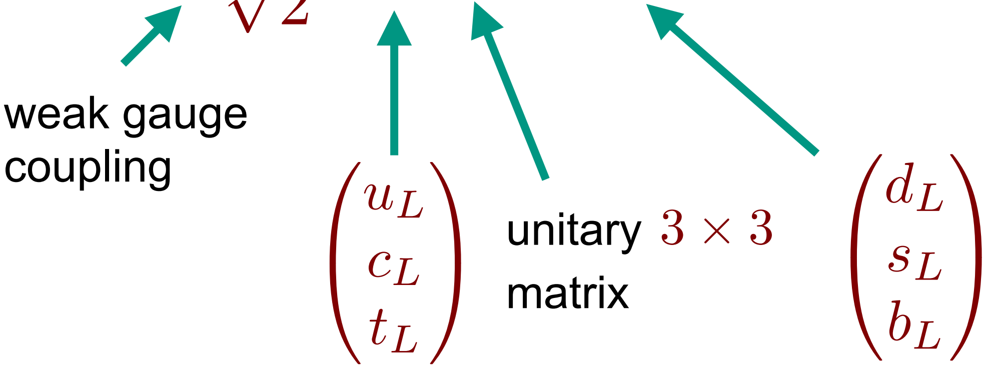
Four unitary rotations of $\begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix}$ and $\begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix}$ (for both L and R) diagonalise M^d

and M^u and yield the physical quark fields d,s,b and u,c,t.

CKM matrix

The unitary rotations diagonalising $M^d = Y^d v$ and $M^u = Y^u v$ drop out everywhere except in the coupling of the W boson:

$$L_W = \frac{g_2}{\sqrt{2}} \left[\bar{u}_L V \gamma^\mu d_L W_\mu^+ + \bar{d}_L V^\dagger \gamma^\mu u_L W_\mu^- \right]$$



weak gauge coupling

$$\begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix}$$

unitary 3×3 matrix

$$\begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

V is the unitary Cabibbo-Kobayashi-Maskawa matrix or quark mixing matrix.

In the SM V is the only source of transitions between quarks of different fermion generations.

Cabibbo-Kobayashi-Maskawa matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 0.97 & 0.22 & 0.037\, e^{-i\gamma} \\ -0.23 & 0.97 & 0.042 \\ 0.0086\, e^{-i\beta} & -0.042\, e^{i\beta_s} & 0.999 \end{pmatrix}$$

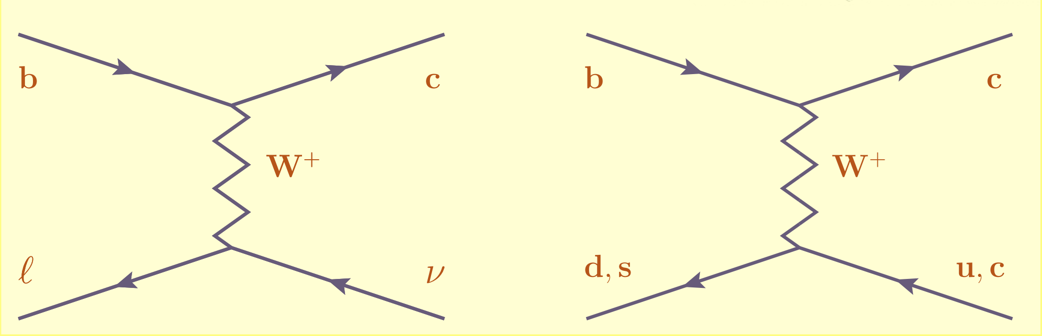
with $\gamma = 66^\circ,\ \beta = 23^\circ, \beta_s = 1.1^\circ$.

The SM quark Yukawa sector involves 10 parameters:

- 6 quark masses ⇒ flavour-diagonal Yukawa couplings $y_q = m_q/v$
- 4 parameters in the unitary CKM matrix V:
  - 3 angles
  - 1 phase

$\}\{$ express by e.g. V_{us}, V_{cb}, $|V_{ub}|$, γ.

b physics



b-flavoured hadrons:

$B_d \sim \bar{b}d,\ B^+ \sim \bar{b}u,\ B_s \sim \bar{b}s,$
$B_c^+ \sim \bar{b}c,\ \Lambda_b \sim bud,$ …

Dominant b decay rates $\propto |V_{cb}|^2 = 1.7 \cdot 10^{-3}$ $\Rightarrow$ total rate $\Gamma_{\rm tot}$ suppressed

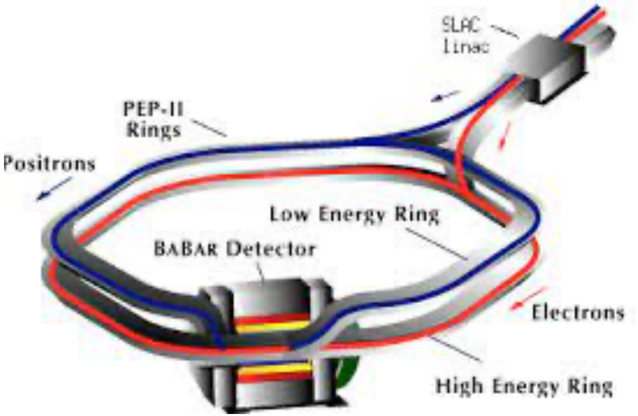
$\Rightarrow$

- enhanced branching ratios $B(B \to X) = \Gamma(B \to X)/\Gamma_{\rm tot}$, sensitivity to rare decays $B \to X$ $\Rightarrow$ probe small couplings or large masses of virtual particles
- large lifetimes, e.g. $\tau(B_d) \simeq \tau(B_s) = 1.5\,{\rm ps}^{-1}$, permitting time-dependent studies $\Rightarrow$ mixing-induced CP asymmetries $\Rightarrow$ probe phases of couplings

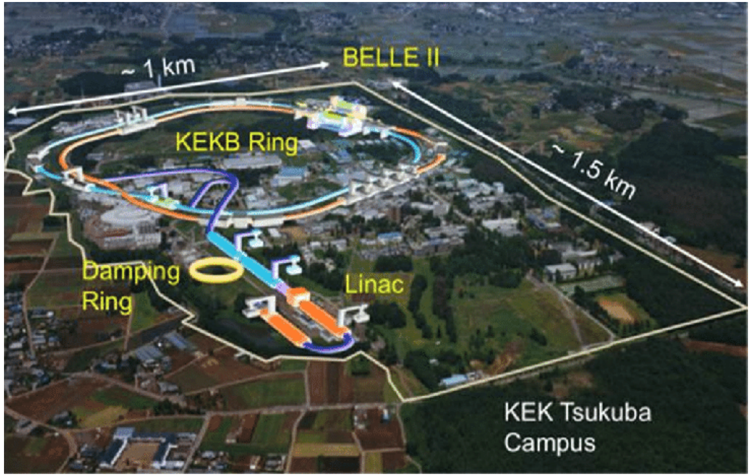
Experiments

Asymmetric B factories: $e^+ - e^-$ colliders with different energies of the e^+ and e^- beams (3.1 GeV vs. 9 GeV). Center-of-mass energy: $\sqrt{s} = M_{\Upsilon(4S)} = 10.58$ GeV

Only $B_d \bar{B}_d$ and $B^+ B^-$ pairs produced!



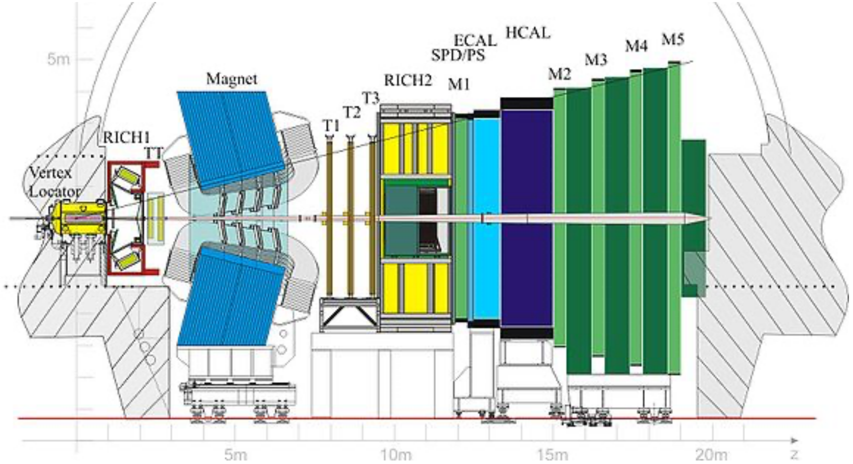
PEP-II collider with BaBar experiment
SLAC,USA, 1999-2008



Super-KEKB collider with Belle experiment
KEK, Tsukuba, Japan, 1999-2010,
Belle II since 2018

Experiments

LHCb at CERN, Geneva, Switzerland, since 2010: *pp* collisions



All b-flavoured hadrons are produced: $B_d, \bar{B}_d, B^\pm, B_c^\pm, \Lambda_b$, and other baryons.

Outline

- Flavour anomalies and Beyond-Standard Model (BSM) physics
- $b \to c\tau\nu$: charged Higgs or leptoquark?
- $b \to s\ell^+\ell^-$: leptoquark or miscalculated QCD?
- Renormalisation group analysis of leptoquark solutions
- Summary and outlook

Flavour anomalies and Beyond-Standard Model (BSM) physics

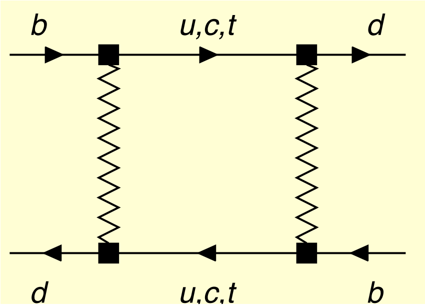
Flavour anomalies

Flavour anomalies = deviations between data and SM predictions

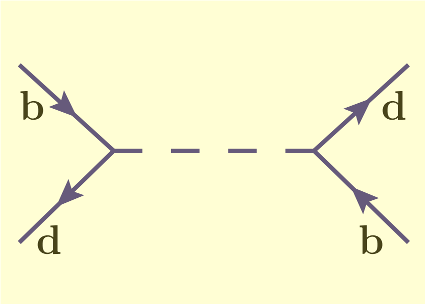
BSM mass reach of a given observable:
Assume a particle of mass M mediating the considered transition at tree level with coupling constants equal to 1.
Calculate the largest value of M for which the BSM contribution is larger than the theoretical and experimental uncertainties of the quantity.

Example: $B_d - \bar{B}_d$ oscillation frequency ΔM_d:

SM:

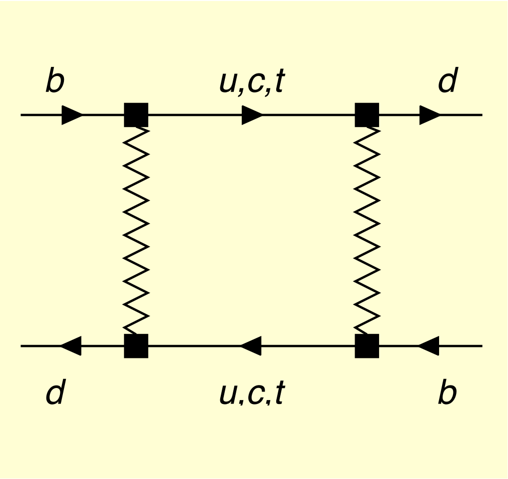


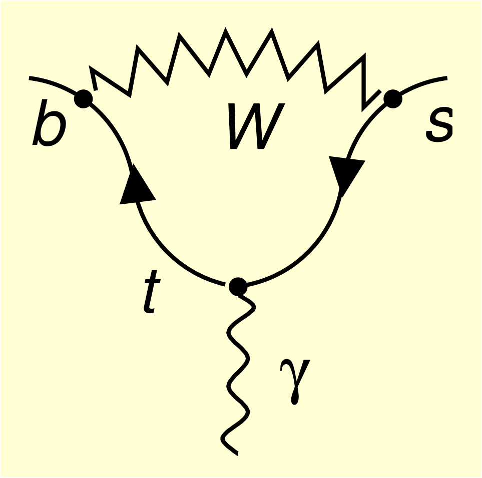
BSM:

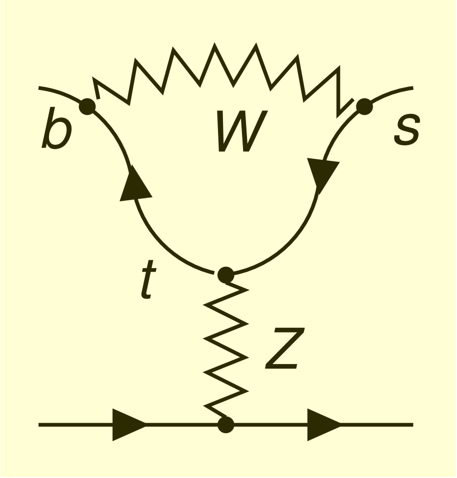


BSM reach

Most sensitive:
Flavour-changing neutral current (FCNC) processes.







BSM mass reach

- Meson-antimeson mixing, $K \to \pi\nu\bar{\nu}$: 1000 TeV
- FCNC B decays: 50 TeV
- $b \to c\tau\nu$: 4 TeV

$\Rightarrow$ 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.

BSM mass reach

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⇒ 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!

Flavour anomalies in 2024

- $R(D) = \dfrac{B(B \to D\tau\nu)}{B(B \to D\ell\nu)}$, $R(D^*) = \dfrac{B(B \to D^*\tau\nu)}{B(B \to D^*\ell\nu)}$, where $\ell = e, \mu$; deviation to SM prediction between 3.1σ and 4.3σ.
- Too small $B(B \to K^{(*)}\ell^+\ell^-)$, $B(B_s \to \phi\mu^+\mu^-)$ for low values of q^2, the dilepton invariant mass^2.
- Belle II: $B(B \to K\nu\bar{\nu})$ exceeds SM prediction by 2.7σ.
- LHCb: $A_{CP}(D \to \pi^+\pi^-)$ exceeds SM expectation by a factor of six.
- $B(B_d \to K^*\bar{K}^*)/B(B_s \to K^*\bar{K}^*)$ exceeds SM prediction by a factor of three.
- Cabibbo anomaly: V_{us} from $K \to \pi\ell\nu$ inconsistent with both $K^+ \to \ell^+\nu$ and $|V_{us}|^2 = 1 - |V_{ud}|^2$ with 3σ.

Flavour anomalies in 2024

Obstacles to relate these anomalies to BSM physics:

- SM predictions involve hadronic matrix elements, which are calculated with non-perturbative methods and might have underestimated uncertainties.
  Still: In all presented flavour anomalies the hadronic uncertainties are sub-leading in some small paramemeter such as Λ_{QCD}/m_b, m_τ/m_b, $m_s/\Lambda_{\text{QCD}}, \ldots$
- SM predictions depend on CKM elements which are found from fits to data assuming no BSM contamination of the data.
  Moreover: Discrepancy with different methods to measure V_{cb} and $|V_{ub}|$.
  - ⇒ The correct way would be to fit the CKM elements together with BSM parameters.

$b \to c\tau\nu$: charged Higgs or leptoquark?

$b \to c\tau\nu$

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

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

Predictions involve form factors like $\langle D(\vec{p}_D) \,|\, \gamma^\mu \,|\, B(\vec{p}_B) \rangle$ or $\langle D^*(\vec{p}_D, \epsilon) \,|\, \gamma^\mu \gamma_5 \,|\, B(\vec{p}_B) \rangle$. The dominant form factor drops out in the ratio, remaining form factor ratio suppressed by m_τ / m_b.

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

$b \to c\tau\nu$

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

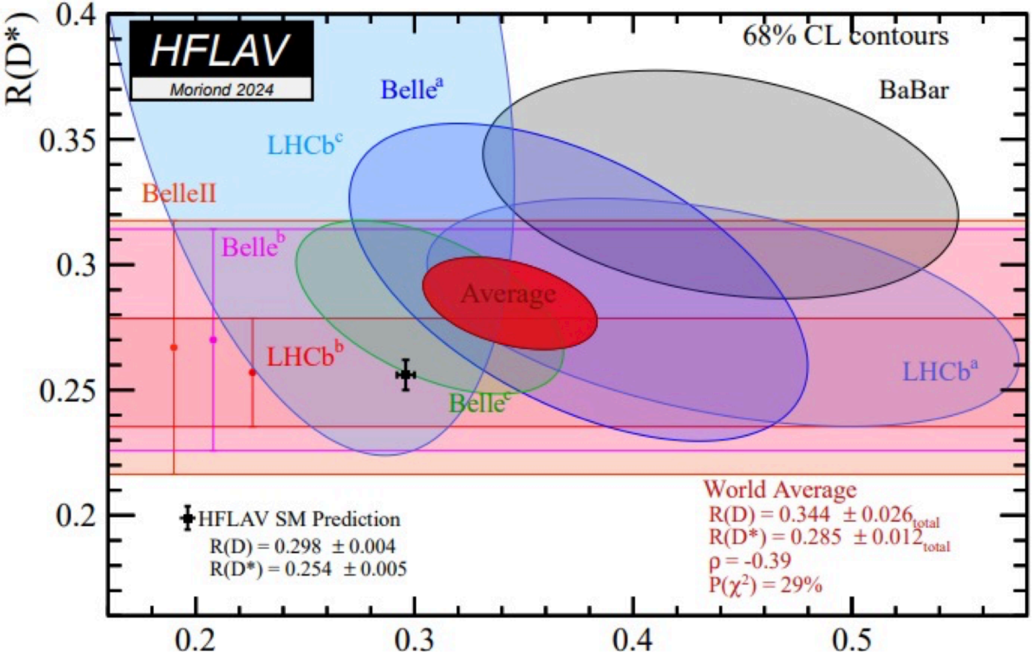
New LHCb $R(D^+)$ measurement:
Significance of deviation from SM down:

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

and

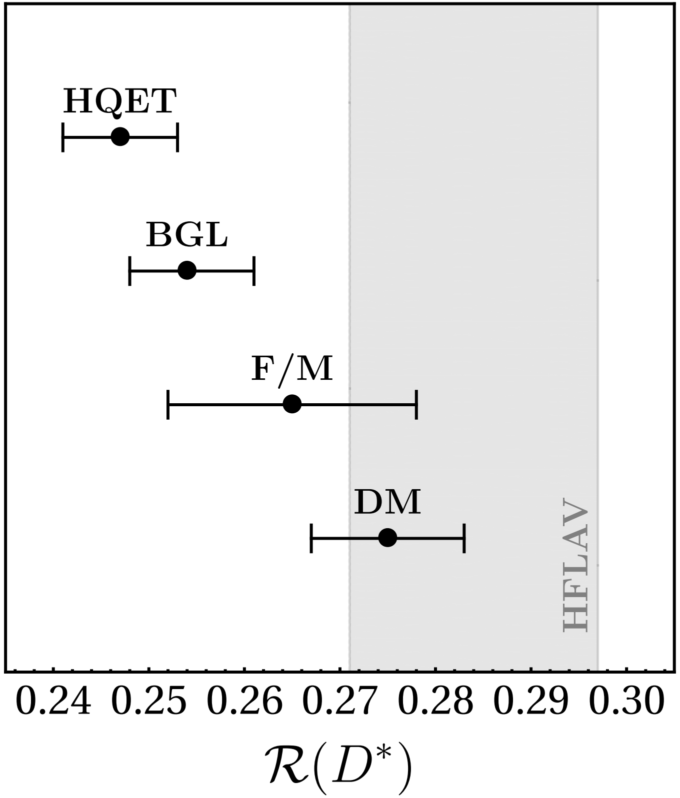
the forward-backward asymmetries A_{FB}^{e} and A_{FB}^{μ}

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

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

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

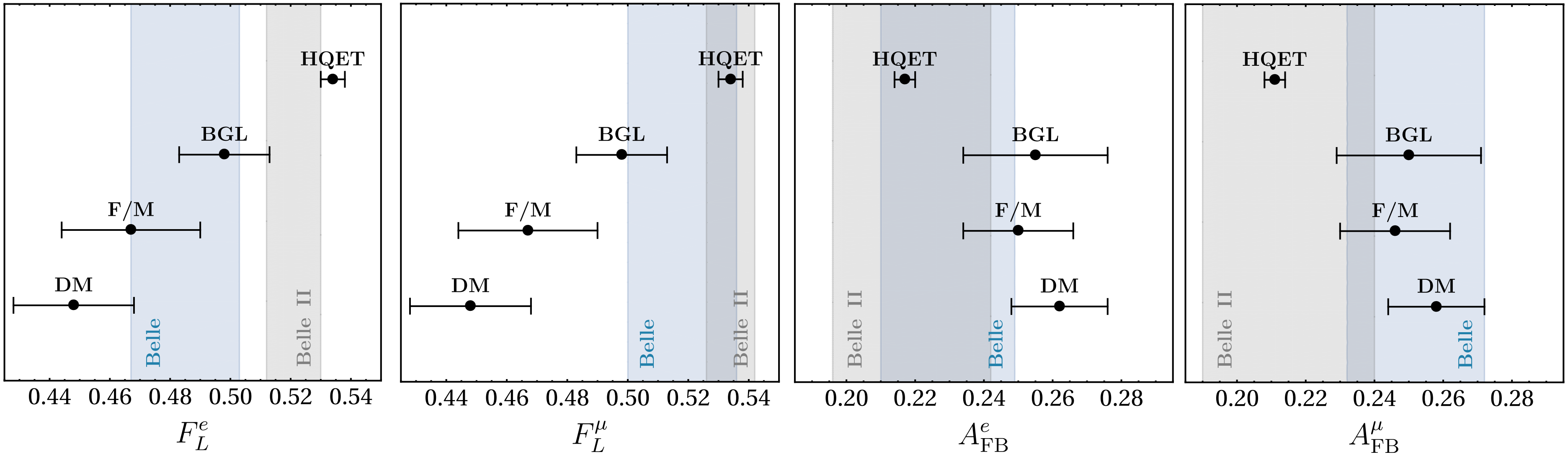
$B \to D^*$ form factors vs new physics



} compatible with Standard Model

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

Predictions for $F_L^{D^*,\text{light}}$ 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.

Effective BSM operators

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

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

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

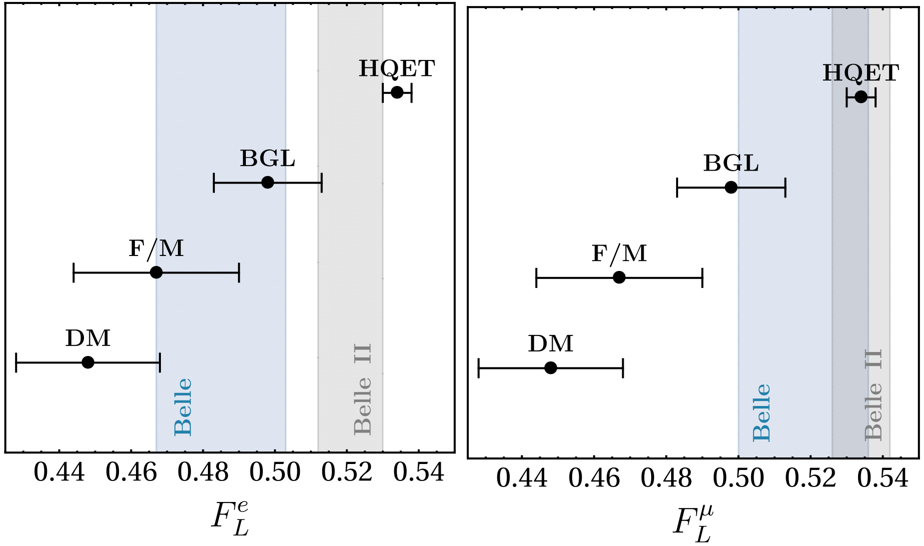
Blanke,Crivellin,de Boer,UN,Nisandzic,Kitahara, *Phys.Rev.D* 100(2019) 3, 035035

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

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

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

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

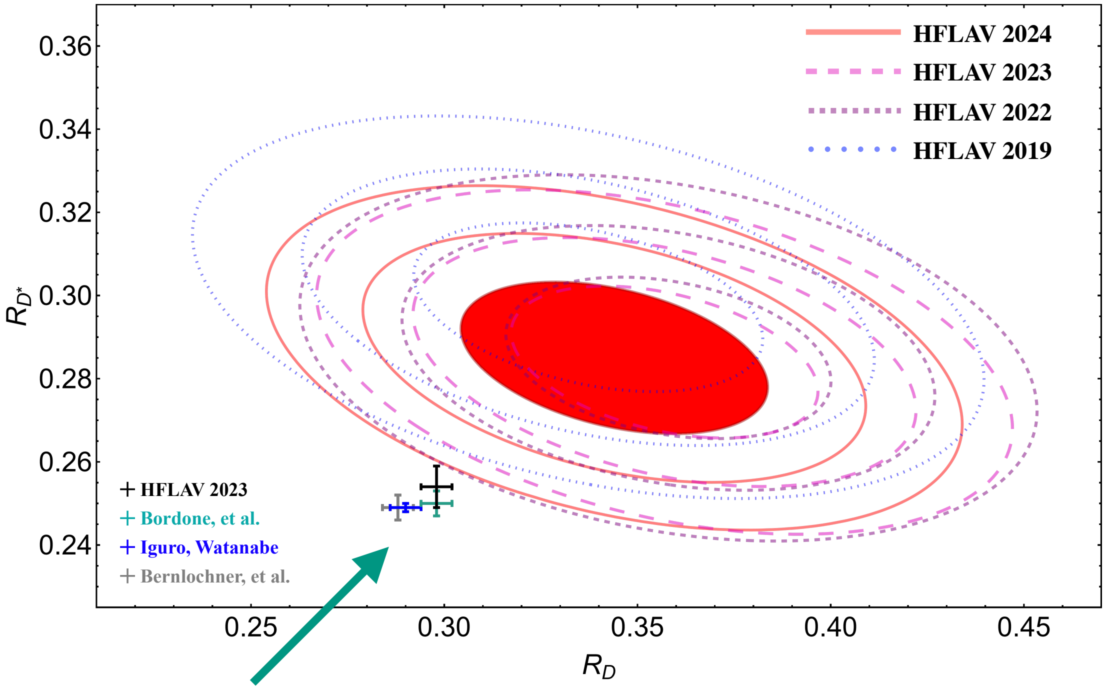


} good form factors

} 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

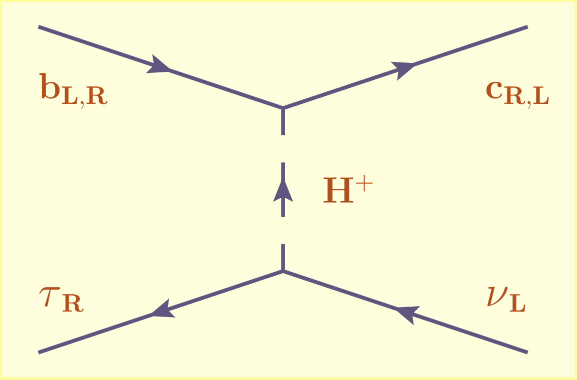
$$F_L^{D^*,\tau} = 0.49 \pm 0.05$$

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

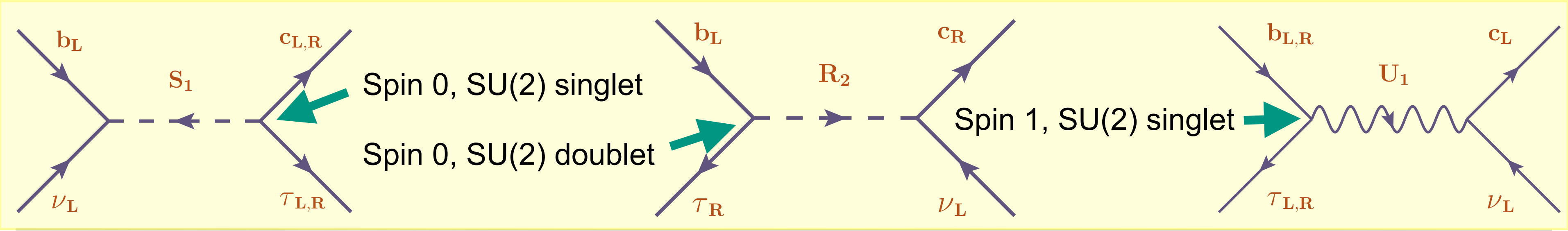
Iguro, Kitahara, Watanabe, arXiv:2405.06062

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



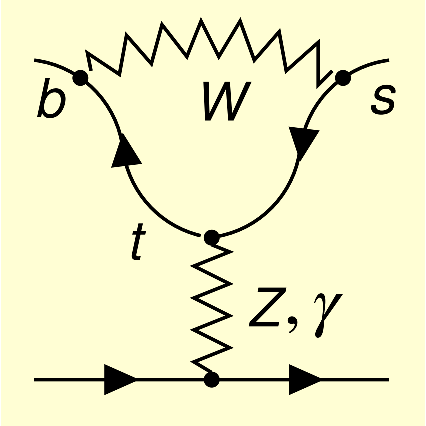
Spin 0, SU(2) singlet

Spin 0, SU(2) doublet

Spin 1, SU(2) singlet

$b \to s\ell^+\ell^-$: leptoquark or miscalculated QCD?

$b \to s\ell^+\ell^-$ and $b \to s\nu\bar{\nu}$



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

arXiv:2311.14647

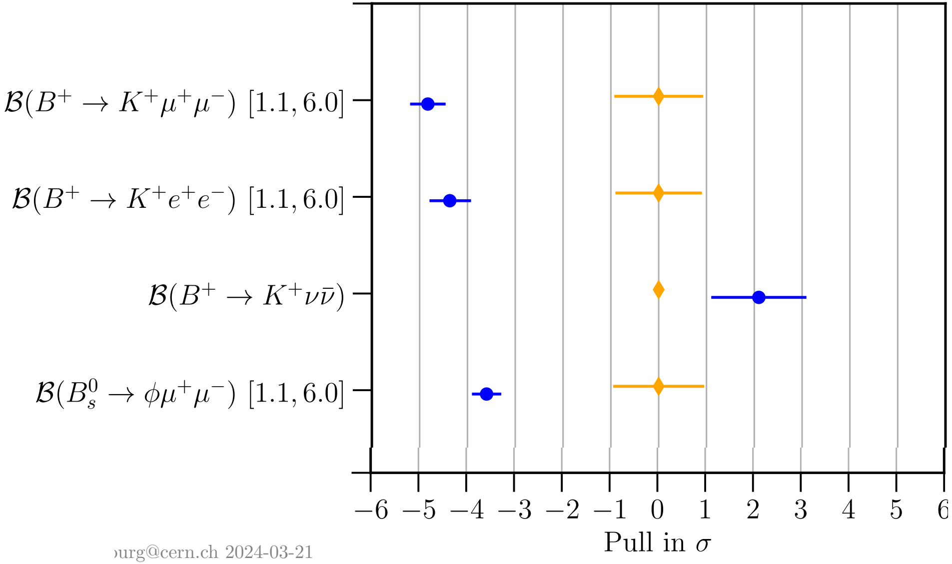
persist since 2013

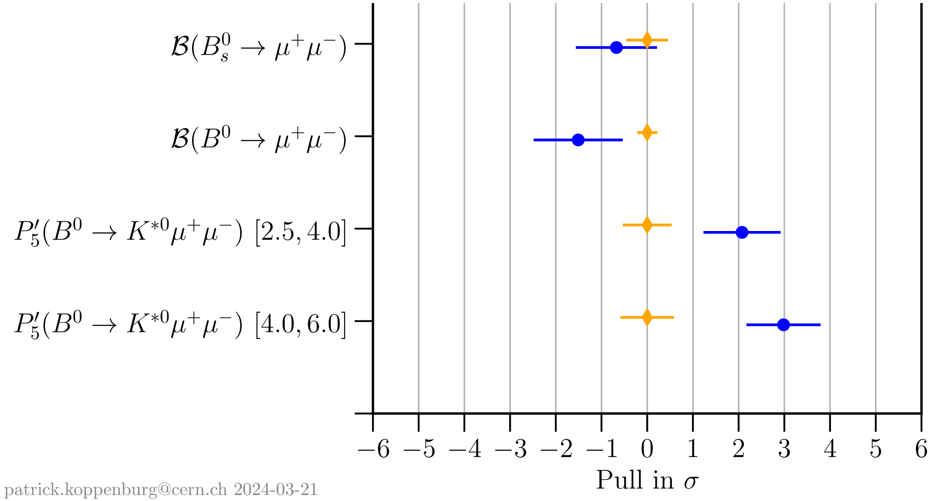
$B(B \to K^{(*)}\ell^+\ell^-)$,
$B(B_s \to \phi\mu^+\mu^-)$ lower than SM predictions for 1.1 GeV $\leq q^2 \leq 8$ GeV.

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

$\Rightarrow$ Connection between the two anomalies.

$b \to s$ flavour anomalies overview





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

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

Effective hamiltonian

At the energy scale of a B decay, $m_b \sim 5\,\text{GeV}$, interactions mediated by much heavier particles appear point-like.

Concept: Derive an effective hamiltonian with four-fermion operators:

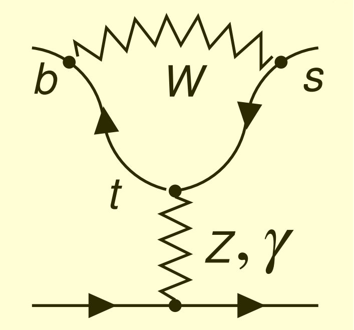
$$H = -\frac{4G_F V_{tb} V_{ts}^*}{\sqrt{2}} \sum_{\ell,\ell'=e,\mu,\tau} \left[C_9^{\ell\ell'} O_9^{\ell\ell'} + C_{10}^{\ell\ell'} O_{10}^{\ell\ell'} \right] + \dots$$

The couplings of the effective operators are called Wilson coefficients and are calculated from the Feynman diagrams.

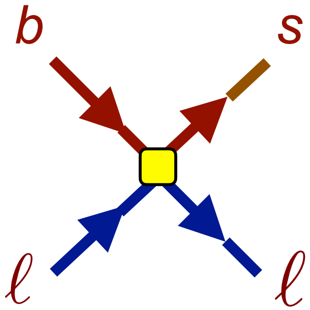
We are interested in

$$O_9^{\ell\ell'} = \frac{\alpha}{4\pi} [\bar{s}_L \gamma^\mu b_L]\, [\bar{\ell} \gamma_\mu \ell'], \qquad O_{10}^{\ell\ell'} = \frac{\alpha}{4\pi} [\bar{s}_L \gamma^\mu b_L]\, [\bar{\ell} \gamma_\mu \gamma^5 \ell']$$

α is the QED coupling (Sommerfeld constant).



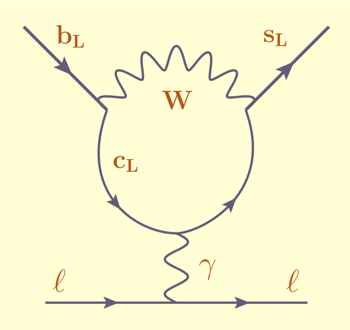
Four-fermion interaction as in Fermi theory of beta decay:



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

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

Claim: enhancement of charm loop could fake BSM signal.

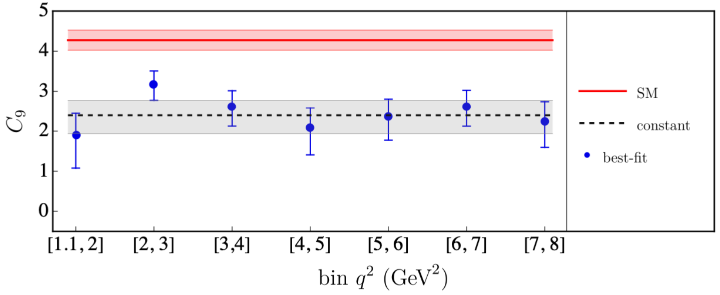


Test this by fitting for q^2 -dependence of C_9^{BSM}:

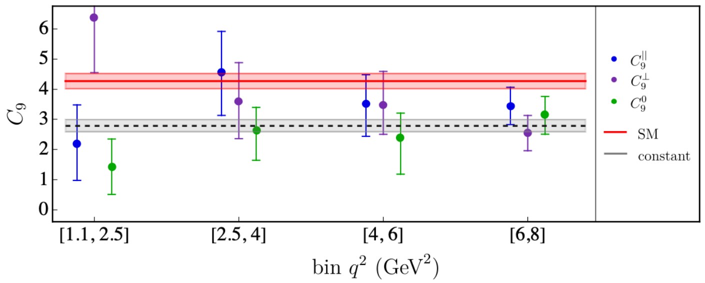
Compatible with LHCb analysis!

Low q^2

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

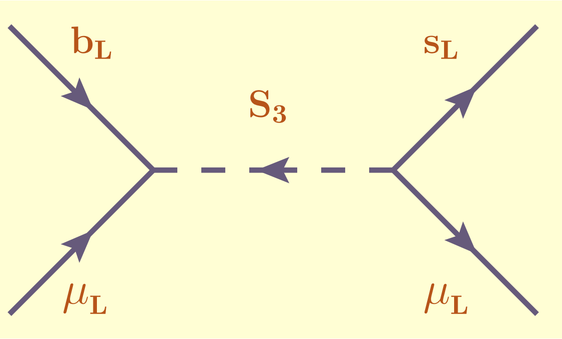


$B \to K^*\bar{\ell}\ell$



Bordone,Isidori,Mächler,Tinari, arXiv:2401.18007

Leptoquark explanation



SU(3) triplet leptoquark.
Mass < 35 GeV 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.

One cannot use the same leptoquark for $b \to s e^+ e^-$ and $b \to s \mu^+ \mu^-$, because this leads to unacceptably large $\mu \to e$ conversion.

$\Rightarrow$ 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:

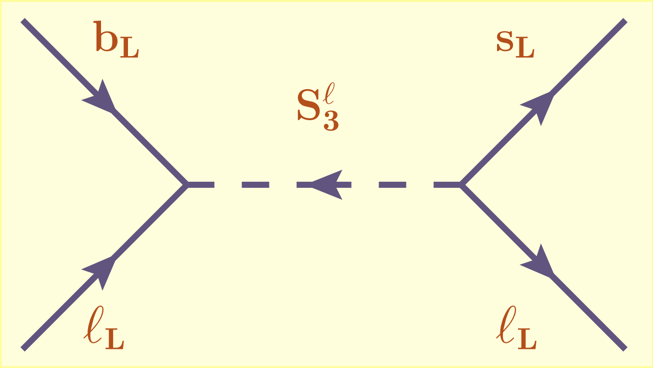
$\Rightarrow$ study low-energy properties of LQ couplings without knowing details of the UV model with renormalisation group (RG) equations.

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.

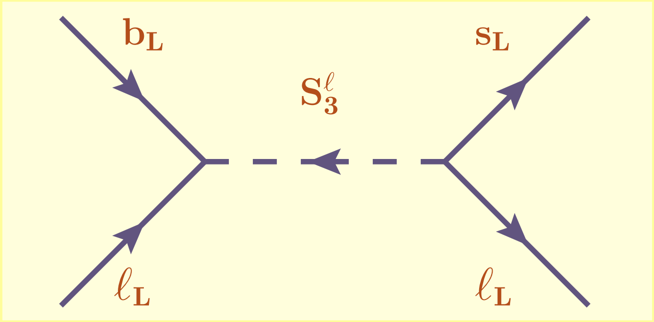
Machacek, Vaughn, 1983, 1984

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

Infrared fixed point: $y_{3\,ij}^{a}$ at the low scale 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



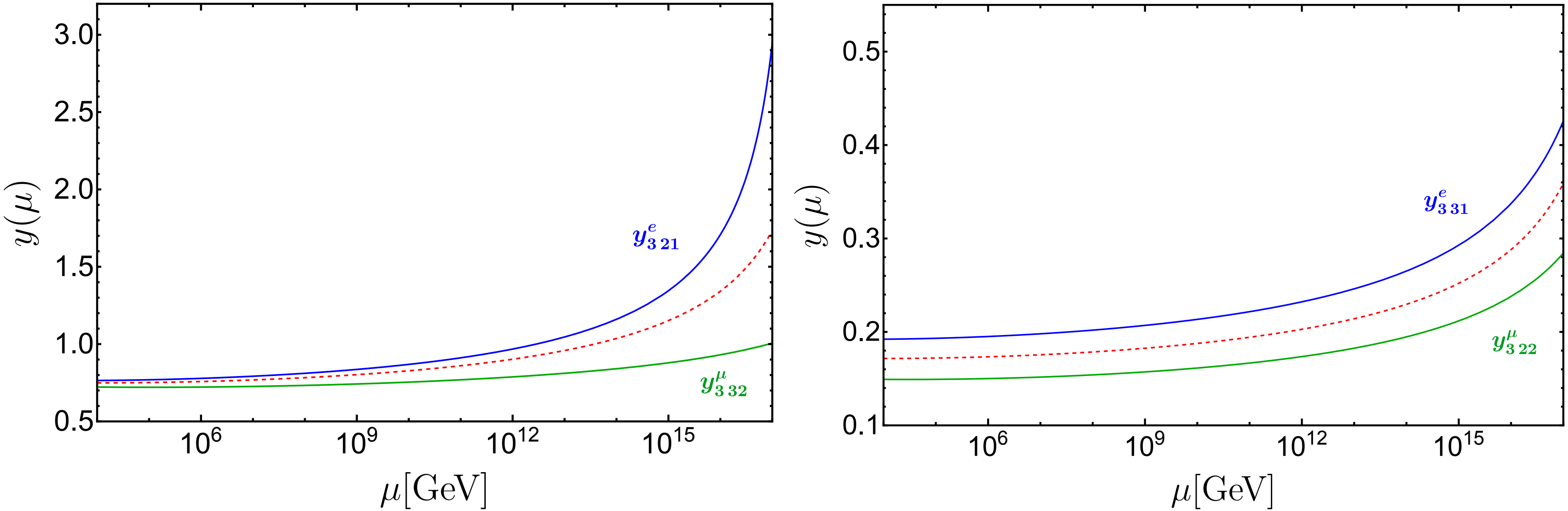
- Infrared fixed point:

$y^e_{3\,21}$	$y^e_{3\,31}$	$y^\mu_{3\,22}$	$y^\mu_{3\,32}$	$y^\tau_{3\,23}$	$y^\tau_{3\,33}$
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 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

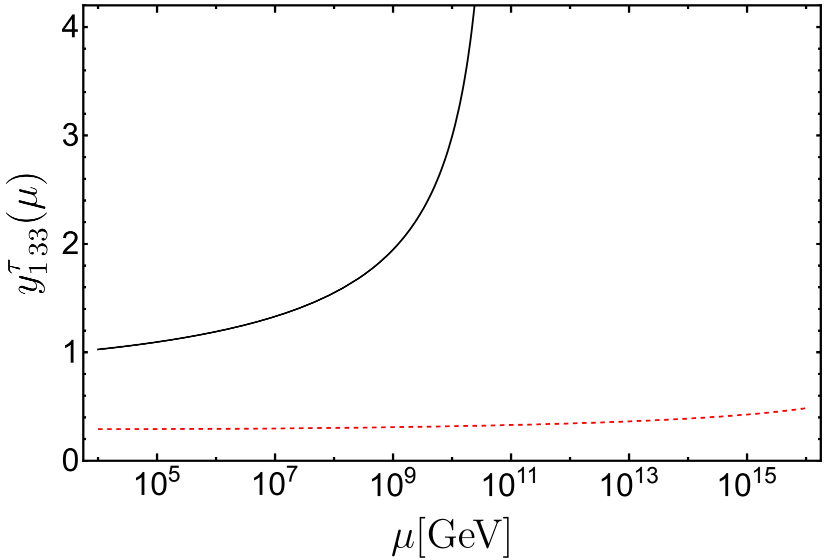


Bizarre: *s-e* coupling converges to *b*-μ coupling and *b-e* coupling converges to s-μ coupling!

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.

Summary and outlook

Summary and outlook

- Quark flavour physics: # data points $\gg$ # of theorists
- Current flavour anomalies probe BSM physics with particle masses in the multi-TeV range.
  $\Rightarrow$ instrumental to justify and design future hadron colliders
- No clear direction, different flavour anomalies require different virtual particles.
- $b \to c\tau\bar{\nu}$:
  - 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 and outlook

- $b \to s\ell^+\ell^-$:
  - Data show no evidence for a miscalculated charm contribution.
  - Data show approximate LFU between e and μ. Popular S_3 leptoquark needs several copies with lepton number conservation
  - Future: CP asymmetries, free of hadronic uncertainties
- 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.