Scalar Leptoquarks in Flavour Physics

Svjetlana Fajfer
Institute J. Stefan, Ljubljana and
Physics Department, University of Ljubljana, Slovenia

19 June 2024

Outline

SMEFT

Flavour puzzles

Leptoquarks

LFU tests

Testable Predictions

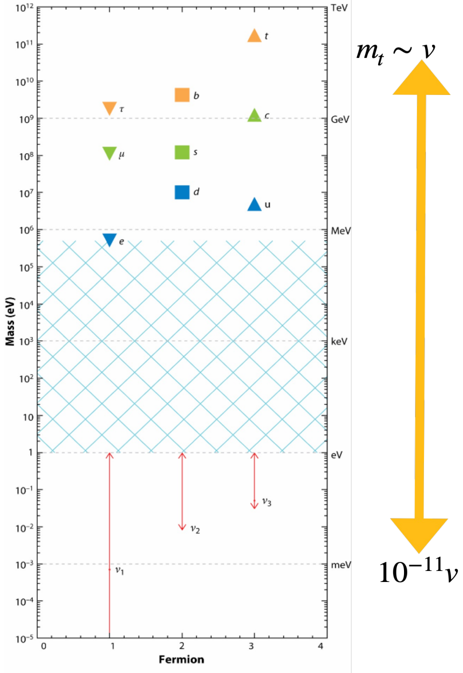
What SM cannot explain?

- Neutrino masses and mixings
- The presence of non-baryonic, cold dark matter
- Dark matter is neutral, colourless, non-baryonic, and massive. The only such particles in the SM are neutrinos, (these are too light, warm dark matter)
- The observed abundance of matter over anti-matter

> "I would rather have questions that can't be answered than answers that can't be questioned."
> — Richard Feynman

Unexplained features of the SM

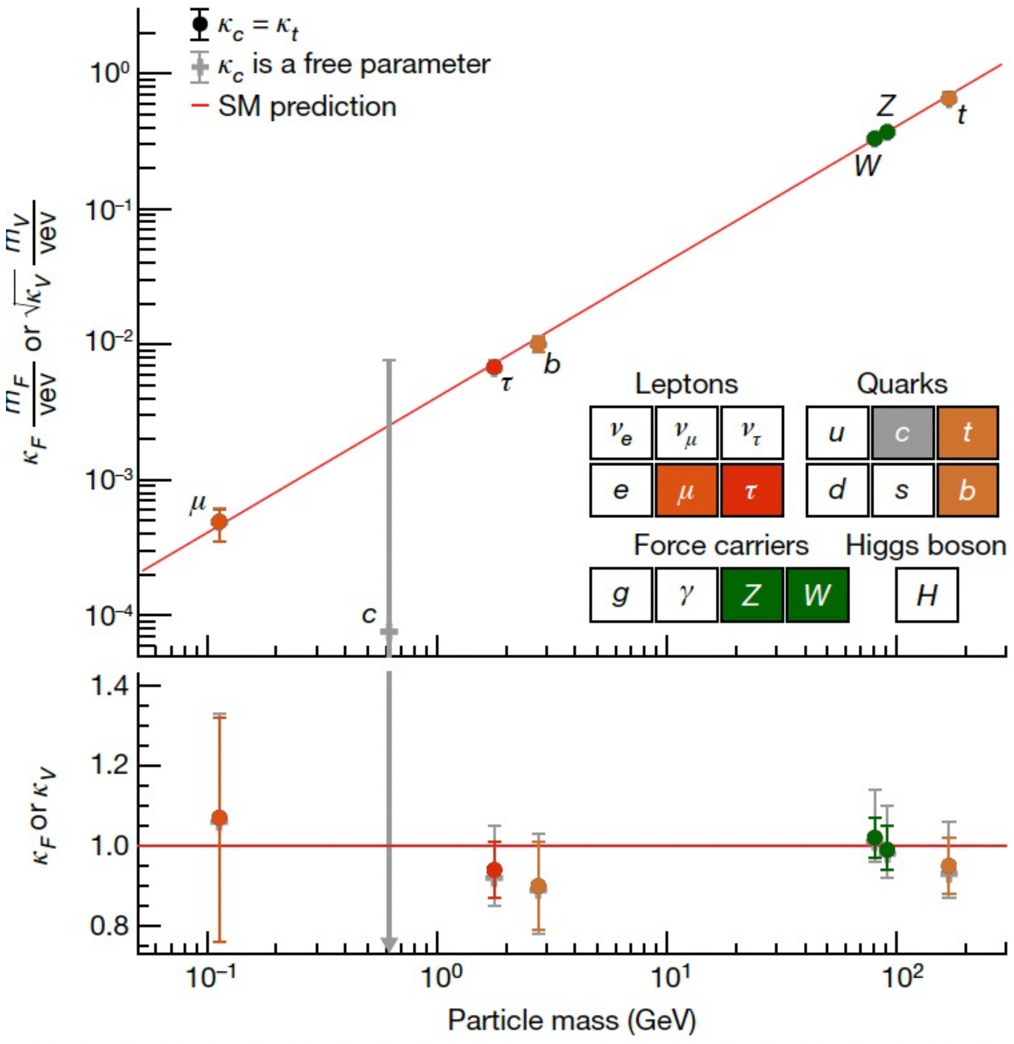
- The inability to describe physics at Plankian scale
- The structure of fermion masses and mixing
- The smallness of measured electric dipole moments
- The comparable size of 3 gauge couplings
- The quantization of electric charge
- The number of fermion families



de Gouvêa A. 2016.
Annu. Rev. Nucl. Part. Sci. 66:197–217

Do we understand this mass range?

ATLAS, Nature, 607, 52–59 (2022)



A great test of the SM

This linear dependence tells us that masses of SM fermions (no neutrinos) originate from SM vev.

Evidence that the Higgs mechanism is responsible for the masses of weak bosons and the third generation of fermions!

"The progress of science has been largely a matter of discovering what questions should be asked."

– **Steven Weinberg, To Explain the World: The Discovery of Modern Science**

Standard model effective field theory (SMEFT)

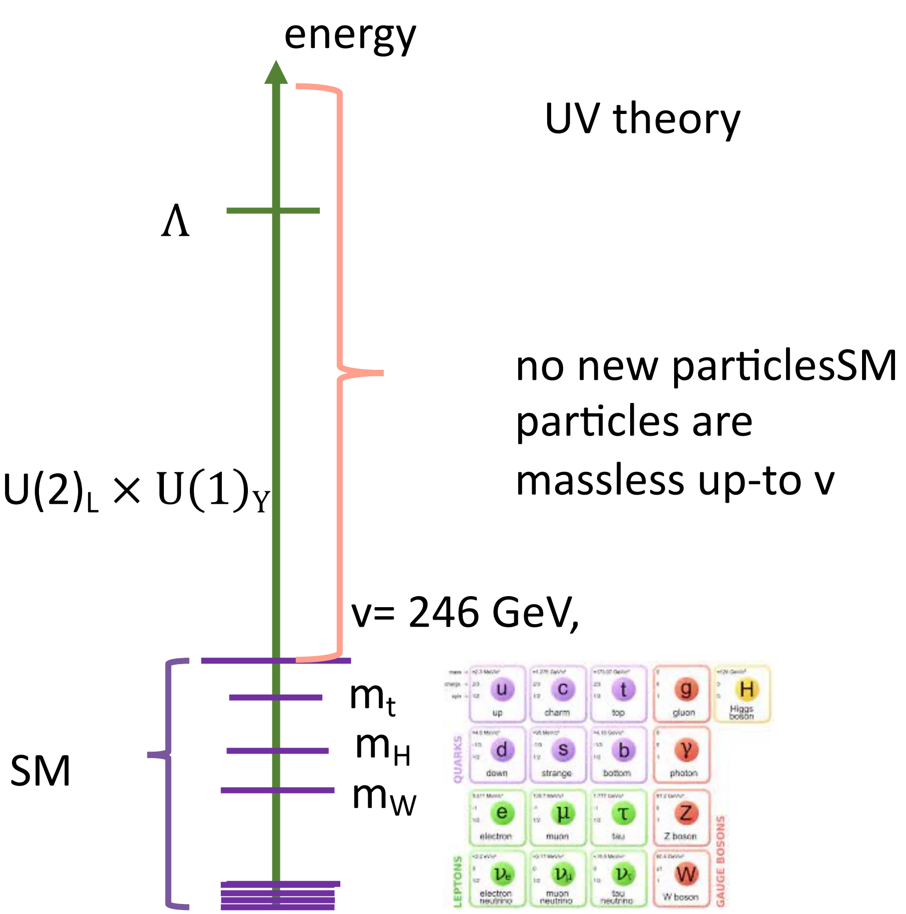
Weak interactions before SM

$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} J^{\dagger}_{\mu} J^{\mu}$$

However, we know that at low energies

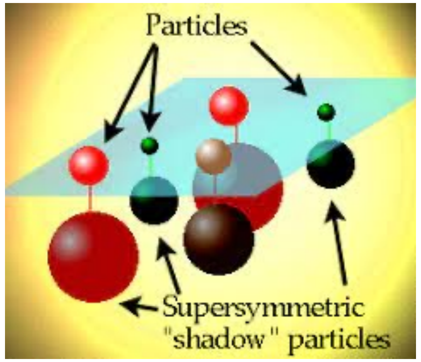
$$\frac{g_2^2}{8\, m_W^2} = \frac{G_F}{\sqrt{2}} = \frac{1}{2\, v^2}$$

Energy scale of $SU(2)_L \times U(1)_Y$

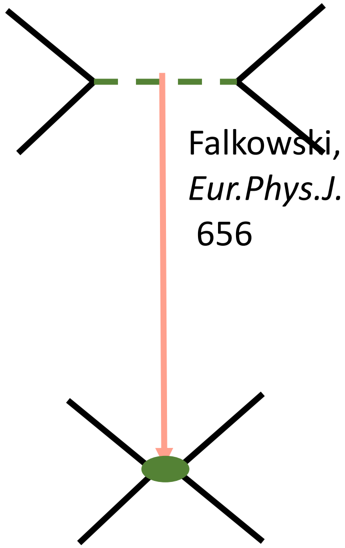


- Expectation: NP appears at high energy scale Λ;
- No new degrees of freedom bellow this scale;
- New NP mediators create operators of dimension d$\geq$ 5;
- Integrating out heavy degrees of freedom we create new operators not present in the SM

SMEFT role towards a theory of NP



new heavy particle



Falkowski, *Eur.Phys.J.C* 83 (2023) 7, 656

integrate out heavy field

There are many ways in which higher-dimensional operators can affect observables.

- **New vertices:** interaction vertices in the SMEFT Lagrangian that do not occur in the SM Lagrangian, due to symmetries or accidental reasons.
- **New Lorentz structures:** interaction vertices that do occur in the SM Lagrangian, but which appear in the SMEFT with a different number of derivatives, different contractions of Lorentz or spinor indices, etc.
- **Modified couplings:** corrections to the coupling strengths of the interaction terms present in the SM Lagrangian.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d\geq 5} \frac{C_k^{(d)}}{\Lambda^{d-4}} \mathcal{O}_k^{(d)}$$

$$\mathcal{L}_{D=6} = \mathcal{L}_{D=6}^{\text{bosonic}} + \mathcal{L}_{D=6}^{\text{Yukawa}} + \mathcal{L}_{D=6}^{\text{current}} + \mathcal{L}_{D=6}^{\text{dipole}} + \mathcal{L}_{D=6}^{\text{4-fermion}}.$$

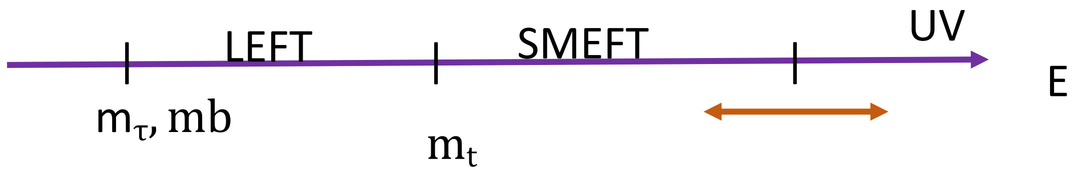
Gauge fields, Higgs

Warsaw basis, Grzadkowski et al, 1008.4884

SMEFT papers: Manohar et al., 1308.2627, 1309.0819, 1310,4838, 1312.2014

From SMEFT to low energies (LEFT)

How to connect this set-up to low energy observables?



1. Renormalisation group evolution (RGE) running of Wilson coefficents from the matching scale down to electroweak scale;

2. Below the weak scale ⟶ EFT that is an $SU(3)_c \otimes U(1)_{em}$ gauge theory and contains the SM fermions, but not the top quark (H, W, Z, t are integrated out (1908.05295, Dekens&Stoffer)

3. The LEFT Lagrangian consists of QCD and QED and a tower of additional higher-dimension effective operators

4. The matching condition at the electroweak scale requires that the LEFT and SMEFT S-matrix elements for the light-particle processes agree:

$$M_{LEFT} = M_{SMEFT}$$

$$\mathcal{M}^{\text{LEFT}}_{\text{tree, ren.}} + \mathcal{M}^{\text{LEFT}}_{\text{ct}} + \mathcal{M}^{\text{LEFT}}_{\text{loop}} = \mathcal{M}^{\text{SMEFT}}_{\text{tree, ren.}} + \mathcal{M}^{\text{SMEFT}}_{\text{ct}} + \mathcal{M}^{\text{SMEFT}}_{\text{loop}} .$$

N = 2499 dim-6 operators that conserve B and L — rich flavor structure!

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

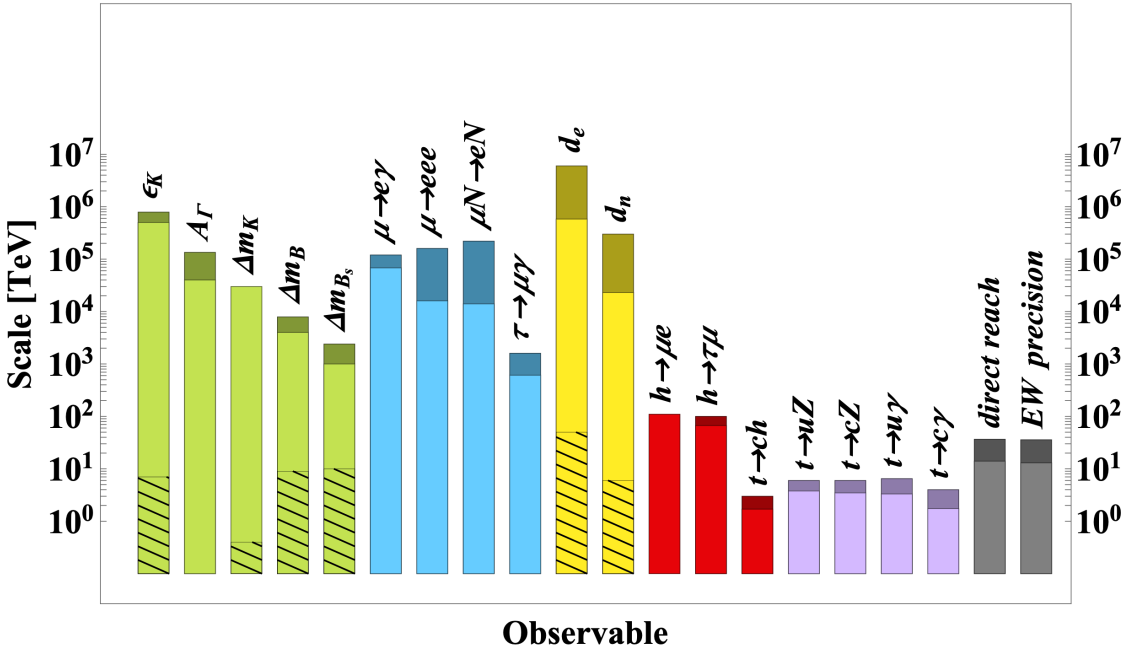
$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

- The best probes of the SMEFT operators are rare/forbidden processes in the SM
- LHC processes can be useful to probe these types of scenarios (with lower values for Λ)!



1910.11775

SMEFT CP-odd invariants 699 found in
Bonnefoy et al, 2112.03889

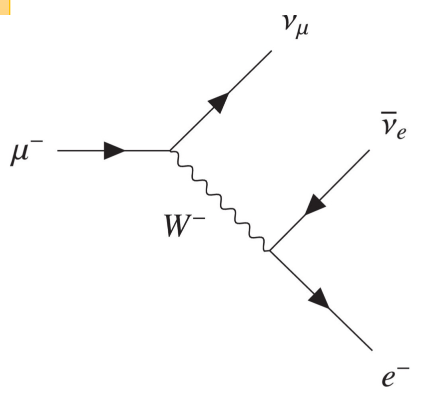
MFV factors (hatch filled surfaces).

Light (dark) colours correspond to present data
(mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS)

Comment:

There are a number of software tools one can use to generate Wilson ccoeficents and mixind
Wilson, Flavio, DsixTools, Matchmakereft, …

Lepton Flavour Universality (LFU)



the same coupling of lepton and its neutrino with W for all three lepton generations!

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \qquad \Gamma(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = \Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$$

valid for quarks too!

Basic property of the SM: universal g

$$\mathcal{L}_f = \bar{f} i D_\mu \gamma^\mu f \qquad f_L = Q_L, L_L$$

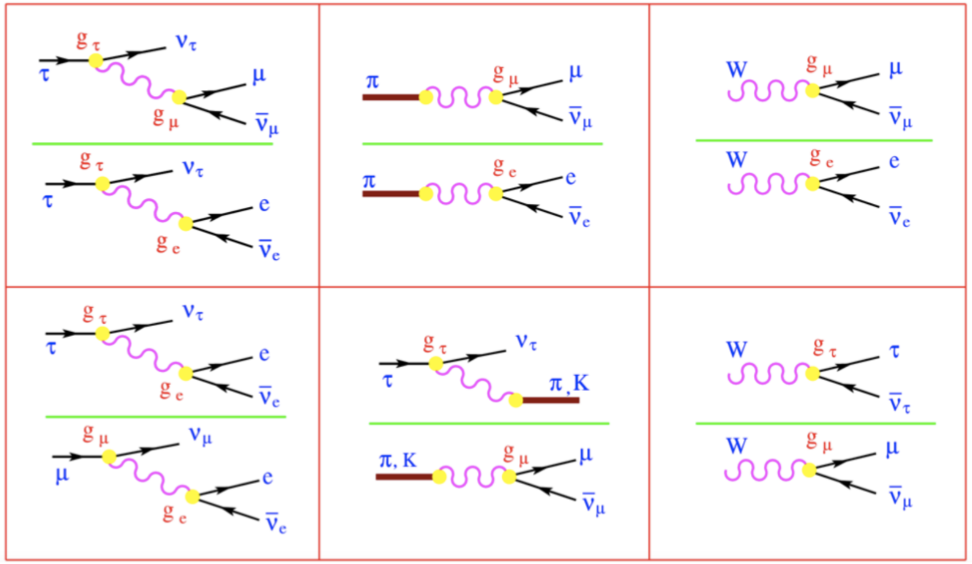
$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

$$D_\mu = \partial_\mu + ig\frac{1}{2}\vec{\tau} \cdot \vec{W}_\mu + ig'\frac{1}{2} Y_W B_\mu$$

$$\frac{g^2}{8m_W^2} = \frac{G_F}{\sqrt{2}}$$

the same for all SM fermions

Flavor changing charged… LFU



From Tony Pich at CHARM 2023,Siegen

$|g_\mu/g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0019 ± 0.0014
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0010 ± 0.0009
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0018
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu}/B_{W\to e}$	1.001 ± 0.003

$|g_\tau/g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0027 ± 0.0014
$B_{W\to\tau}/B_{W\to e}$	1.007 ± 0.010

$|g_\tau/g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0009 ± 0.0014
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9959 ± 0.0038
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.986 ± 0.008
$B_{W\to\tau}/B_{W\to\mu}$	1.001 ± 0.010

Experimental tests do not show violation of LFU

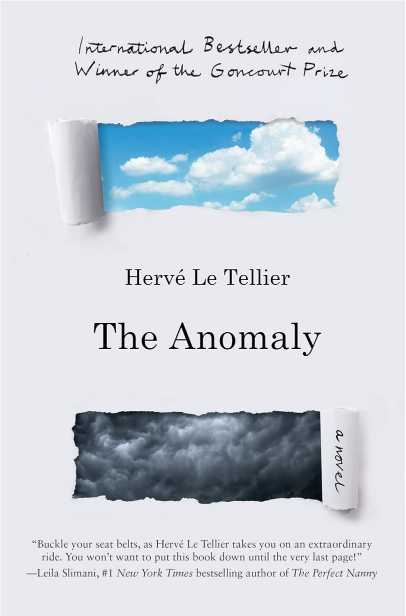
B-meson anomalies

$R_{D^{(*)}}$

Puzzle in $b \to s\,\mu\mu$ transition

A new anomaly?

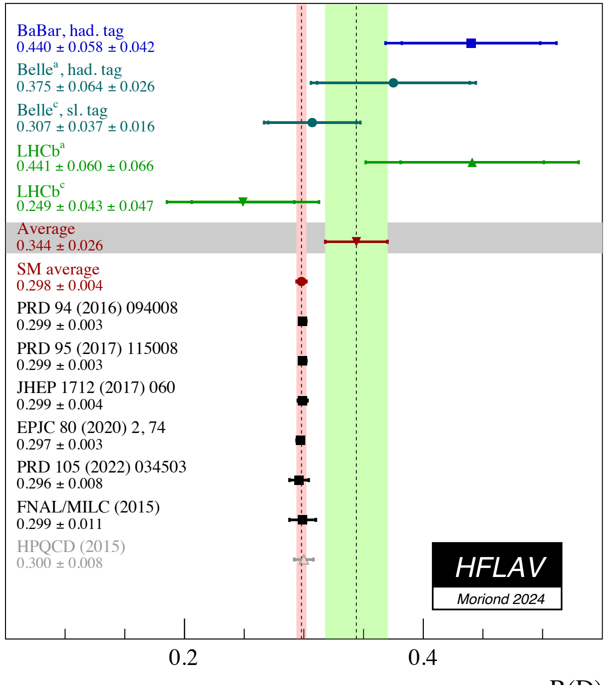
$$R_{\nu\nu}^{K^{(*)}} = \mathcal{B}(B \to K^{(*)}\nu\bar{\nu})/\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})^{\rm SM}$$

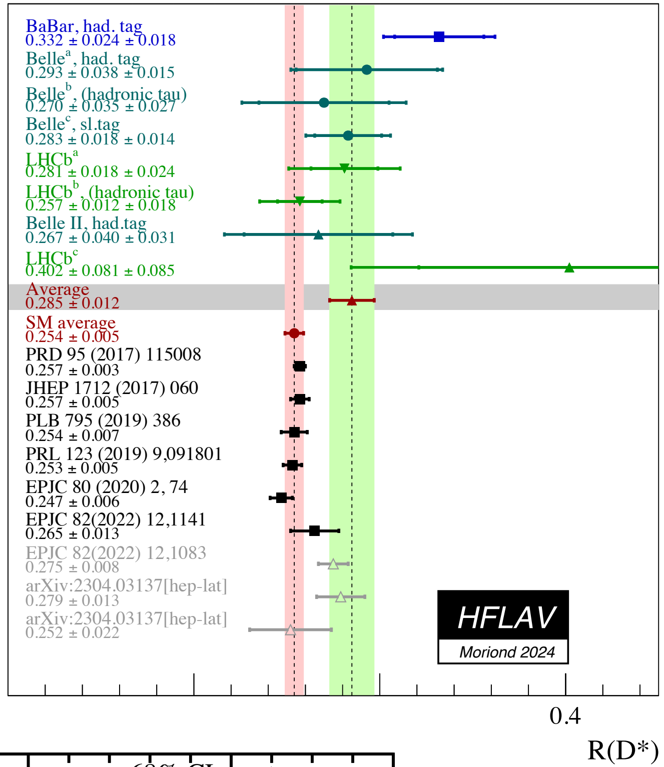


After analysing one anomaly, a new anomaly appers….

$R_{D^{(*)}}$ puzzle

$$R_{D^{(*)}} = \left.\frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)} l\bar{\nu})}\right|_{l\in\{e,\mu\}}$$

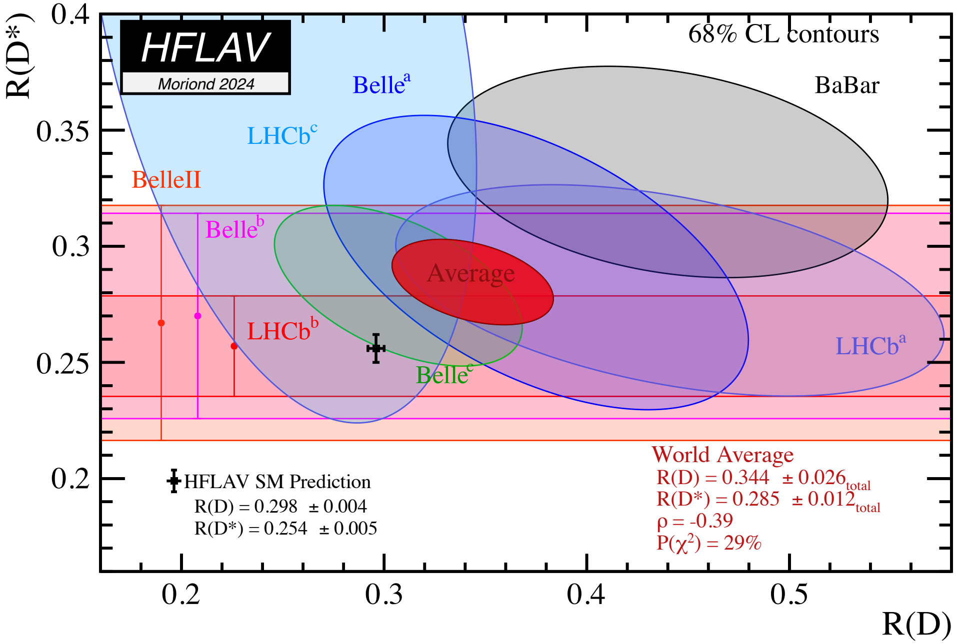




- R_D^{exp} and $R_{D^*}^{exp}$: dominated by BaBar!
- In $R_{J/\psi}^{exp}$ and $R_{\Lambda c}^{exp}$ limited precision.

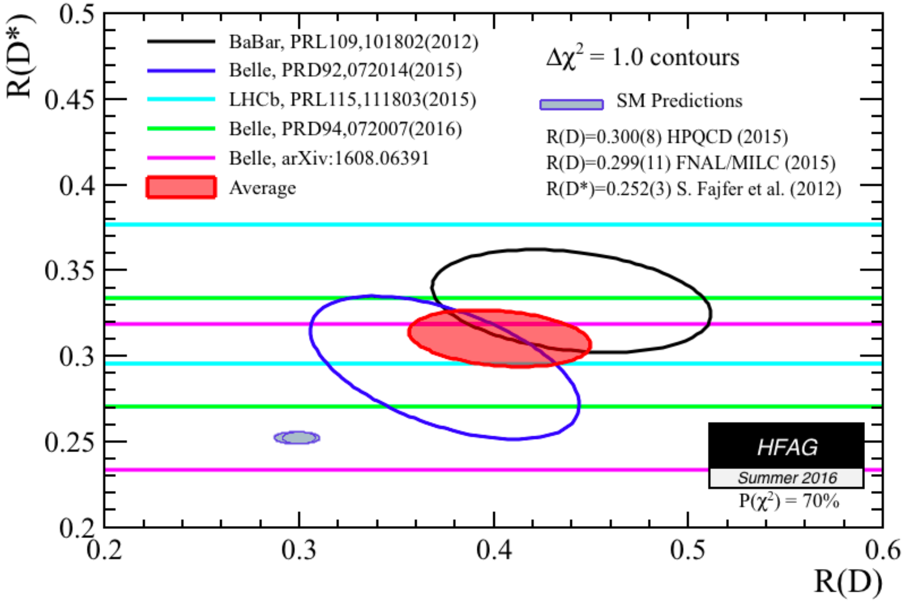
-Solution for the puzzle - New Physics (?!)

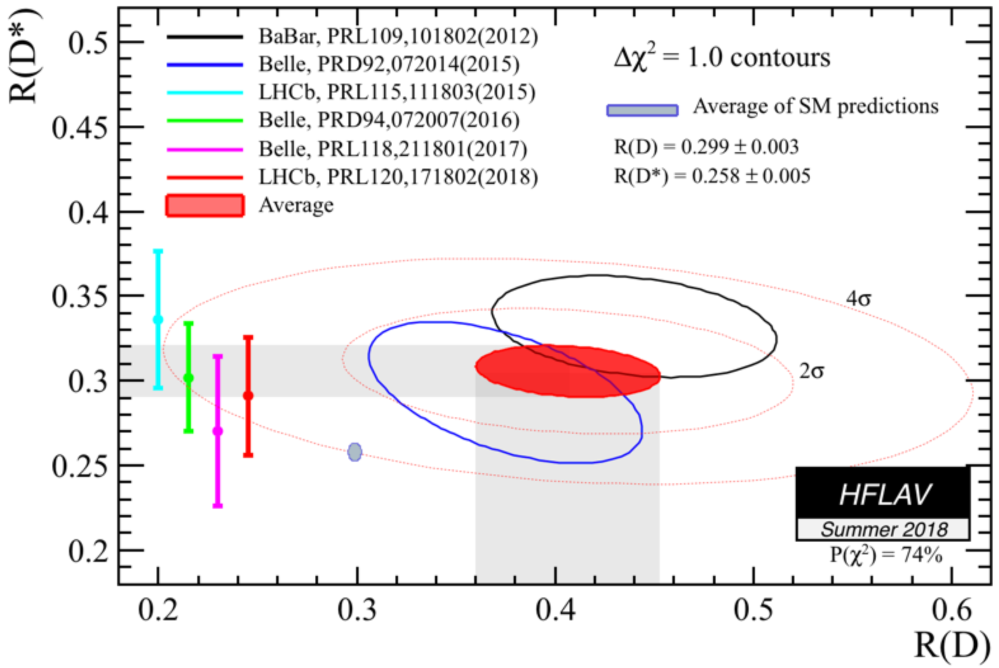
-Precise knowledge of form factors needed!

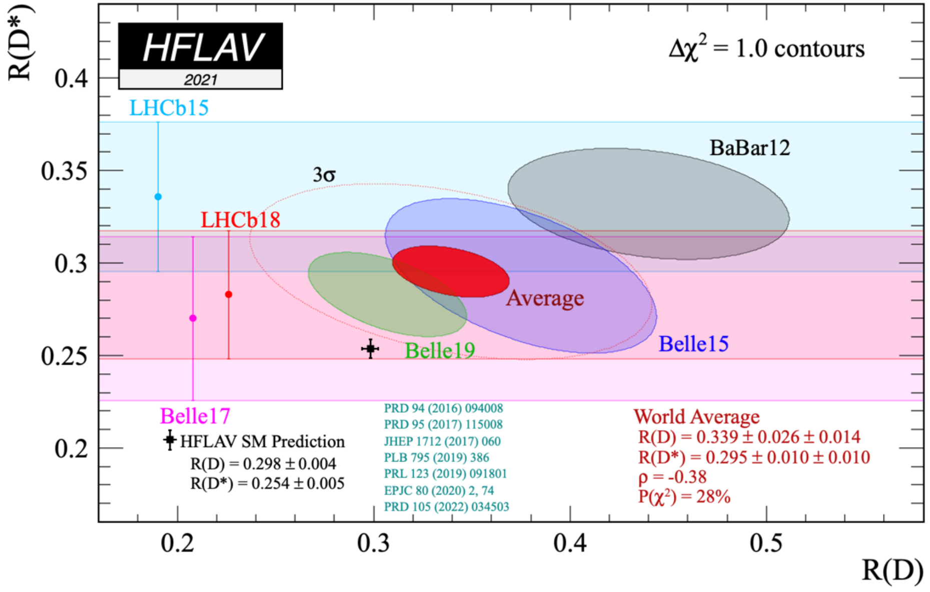


LHCb new results at Moriond 2024!

$R_{D(*)}$ over the years







There are still some issues!

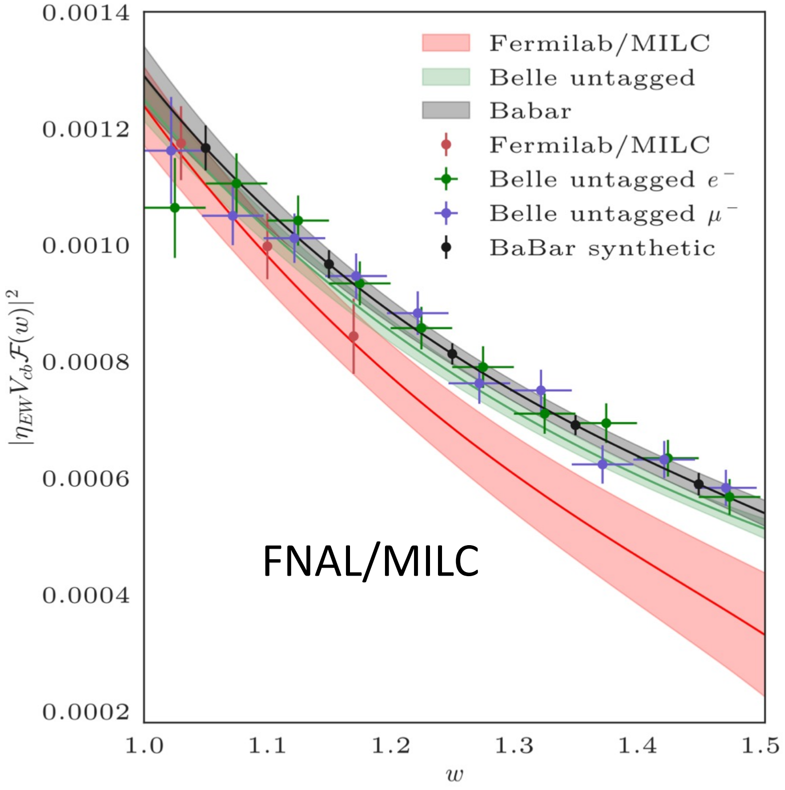
$$< D^{(*)}(p', (\epsilon))|\bar{c}\,\Gamma^\mu\, b|B(p) >= \sum_j K_j^\mu \mathcal{F}_j(q^2)$$

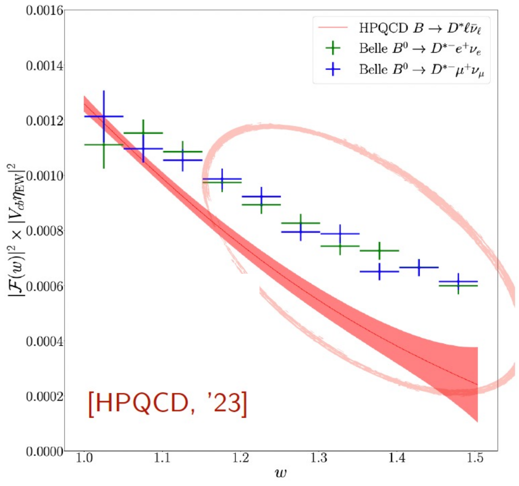
1) $B \to D$: one (two) form-factors with $f_0(0) = f_+(0)$ at $q^2 = 0$;
Lattice QCD at $q^2 \neq q^2_{max}$ for both form-factors.

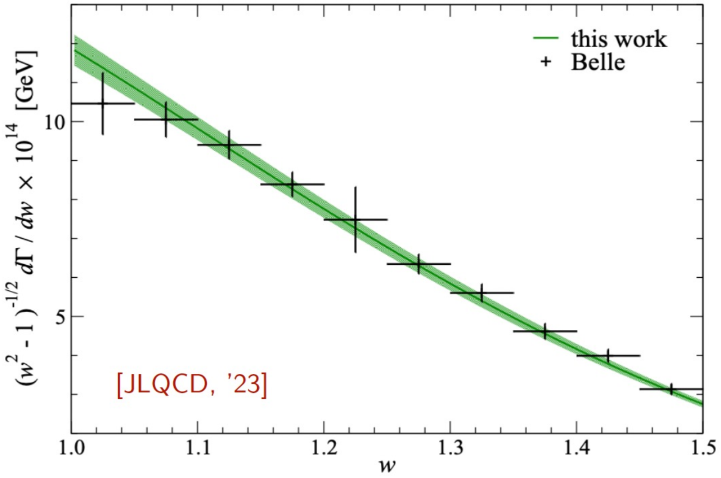
2) $B \to D^*$: three (four) form-factors;
First lattice results at $q^2 \neq q^2_{max}$! Tensions with $B \to D^* l\bar{\nu}$ exp. data

$$R_D^{\rm exp} = 0.344(26)\,, \qquad R_{D*}^{\rm exp} = 0.285(12)$$

$$R_D^{\rm SM} = 0.293(8)$$







$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2\, m_B\, m_{D^*}}$$

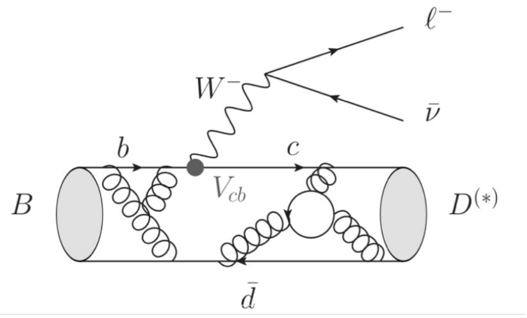
$$\langle D^*(k)|\bar{c}\gamma_\mu(1-\gamma_5)b|B(p)\rangle = \varepsilon_{\mu\nu\rho\sigma}\varepsilon^{*\nu}p^\rho k^\sigma \frac{2V(q^2)}{m_B+m_{D^*}} - i\varepsilon^*_\mu(m_B+m_{D^*})A_1(q^2)$$
$$+i(p+k)_\mu(\varepsilon^*\cdot q)\frac{A_2(q^2)}{m_B+m_{D^*}} + iq_\mu(\varepsilon^*\cdot q)\frac{2m_{D^*}}{q^2}\left[A_3(q^2)-A_0(q^2)\right]$$

- Lattice QCD computations of these form factors :

(FERMILAB MILC, 2105.14019, HPQCD , 2304.03137, JLQCD, Y. Aoki et al., 2306.05657)

- consistent for the dominant form factor, $A_1(q^2)$, but do not agree with the other form factors.

We used another approach to consider form factors is heavy quark effective theory (Caprini, Lellouch, Neubert -CLN), reducing the problem to four parameters and using all experimental information (HFLAV)



$$R_{D^*}^{\mathrm{SM}} = 0.247(2)$$

3σ smaller than the experimental avarege

b→ $s\,\mu\mu$ transition

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

It is important that LFU (e,μ) holds! – $RK_{(*)}$

$R^{\rm SM}_{K^{(*)}} = 1.00(1)$ Bordone et al., 1605.07633

$C_7^{SM} = 0.29;\ C_9^{SM} = 4.1;\ C_{10}^{SM} = -4.3;$

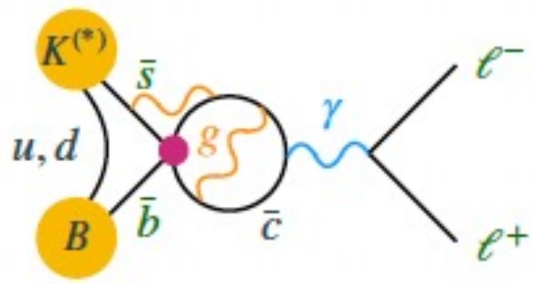
$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}}\frac{e^2}{16\pi^2}\sum_{q=s,d}\sum_{\ell=e,\mu}\sum_{i=9,10,S,P} V_{tb}V_{tq}^*(C_i^{bq\ell\ell}O_i^{bq\ell\ell} + C_i^{\prime bq\ell\ell}O_i^{\prime bq\ell\ell}) + \text{h.c.}\,.$$

Buras et al.,hep-ph/9311345;
Altmannshofer et al., 0811.1214;
Bobeth et al., hep-ph/9910220

$$O_9^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9^{\prime bq\ell\ell} = (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^{bq\ell\ell} = (\bar{q}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}^{\prime bq\ell\ell} = (\bar{q}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$
$$O_S^{bq\ell\ell} = m_b(\bar{q}P_R b)(\bar{\ell}\ell)\,, \qquad O_S^{\prime bq\ell\ell} = m_b(\bar{q}P_L b)(\bar{\ell}\ell)\,,$$
$$O_P^{bq\ell\ell} = m_b(\bar{q}P_R b)(\bar{\ell}\gamma_5 \ell)\,, \qquad O_P^{\prime bq\ell\ell} = m_b(\bar{q}P_L b)(\bar{\ell}\gamma_5 \ell)\,.$$

Angular observables, P_5' still remains (Descotes-Genon et al., 1207.2753, Matias et al., 1202.4266).

Still an issue

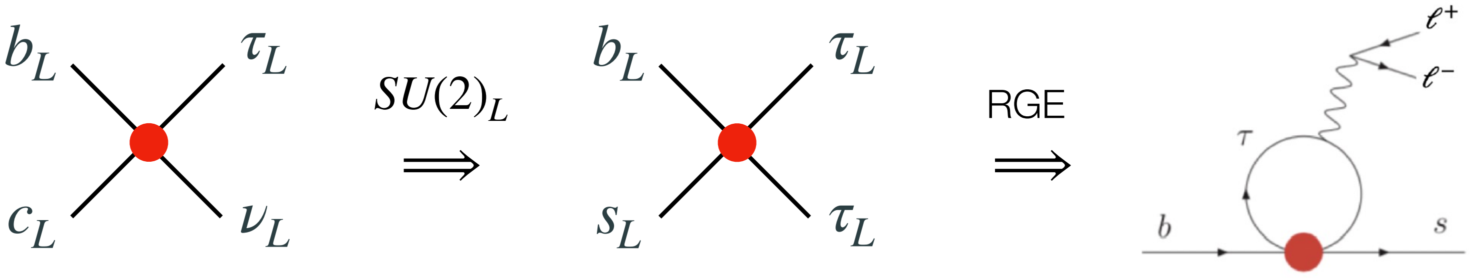


Bobeth, Haisch, arXiv:1109.1826; Crivellin et al., arXiv:1807.02068, Algueró et al., 1695189

NP in b → s μμ?

Universal contribution to C_9

Operators mix under running



$$\Delta C_9^U = C_9^U - C_9^{\mathrm{SM}}$$

Bobeth, Haisch, arXiv:1109.1826; Crivellin et al., arXiv:1807.02068, Algueró et al., 1695189

Universality in $\mu \leftrightarrow e$ is well established (at $\sim$ 5% level)

On theory side: CKM uncertainty, FF unknown at low q^2. To early to make a conclusion on the disagreement!

Looking for new physics through decays $b \to s \bar{\nu}\ \nu$

Olcyr Sumensari

SM

$$\mathcal{L}_{\rm eff}^{b\to s\nu\nu} = \frac{4G_F \lambda_t}{\sqrt{2}} \frac{\alpha_{\rm em}}{2\pi} \sum_i C_L^{\rm SM} (\bar{s}_L \gamma_\mu b_L)(\bar{\nu}_{Li} \gamma^\mu \nu_{Li})$$

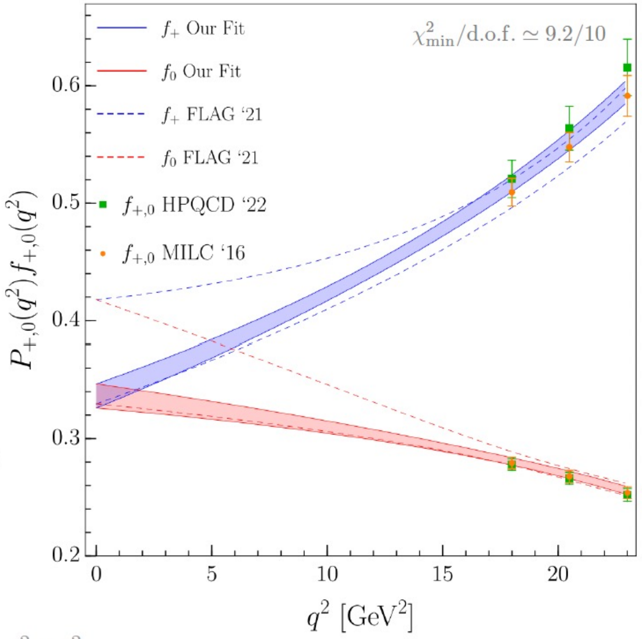
$\lambda_t = V_{tb} V_{ts}^*$

Buras et al.,1409.4557,
Altmannshofer et al., 0902.0160
Buras, 2209.03968

$$C_L^{\rm SM} = -X_t / \sin^2 \theta_W$$
$$= -6.32(7)$$

$$\mathcal{B}(B^\pm \to K^\pm \nu\nu) = (4.44 \pm 0.30) \times 10^{-6},$$
$$\mathcal{B}(B^\pm \to K^{\pm *} \nu\nu) = (9.8 \pm 1.4) \times 10^{-6},$$

Form factors – an issue again!
CKM matrix element dependent



Pole factor:
$P_i(q^2) = 1 - q^2/M_i^2$

$$R_{\nu\nu}^{K^{(*)}} = \mathcal{B}(B \to K^{(*)} \nu\bar{\nu}) / \mathcal{B}(B \to K^{(*)} \nu\bar{\nu})^{\rm SM}$$

$$R_{\nu\nu}^{K} = 5.4 \pm 1.5$$

Belle II 2023
2311.14647

$$BR(B^+ \to K^+ \nu\bar{\nu}) = (2.3 \pm 0.5^{+0.5}_{-0.4})$$

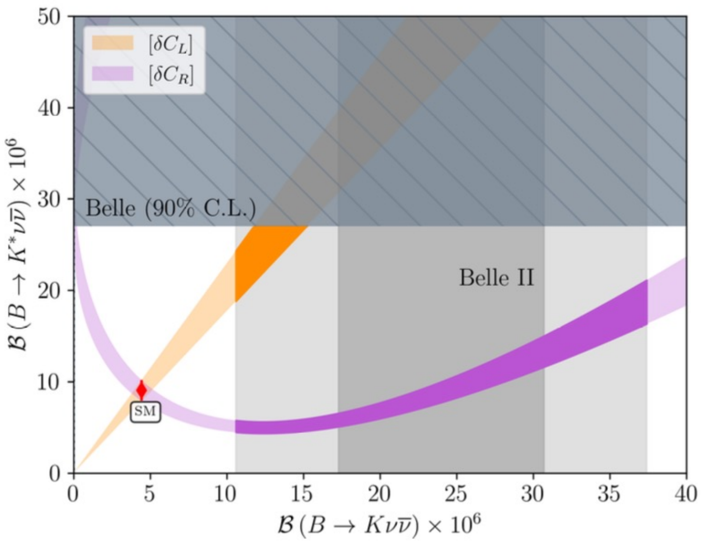
2.7 σ larger then SM prediction

A new anomaly?

Possibility for new physics through decays $b \to s \nu \bar{\nu}$

Assuming SM neutrinos a large contribution to the right-handed quark operator necessary!

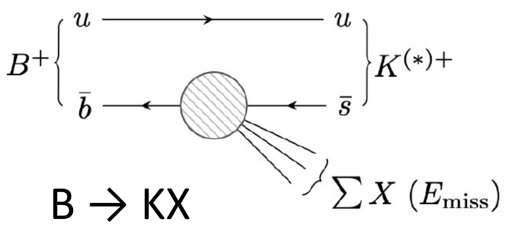
$$\mathcal{O}_R^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}(\bar{s}_R\gamma_\mu b_R)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j)\,,$$

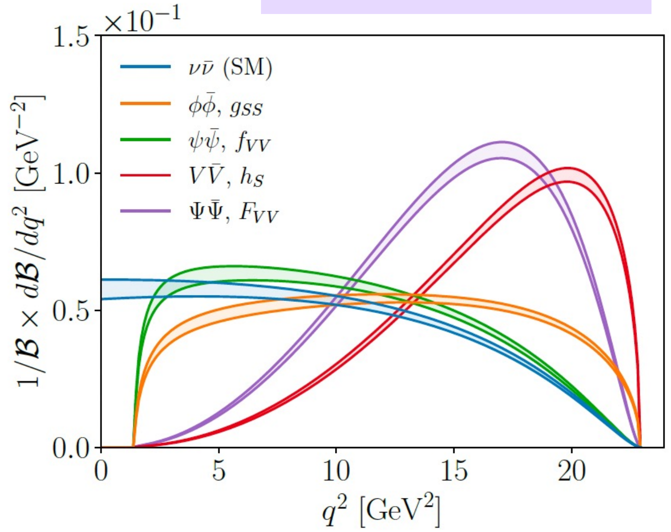


Allwicher et al, 2309.02246

$$\mathcal{B}(B \to K^{(*)}\nu\nu) = \mathcal{B}(B \to K^{(*)}\nu\nu)\Big|_{\rm SM}\left(1 + \delta\mathcal{B}^{\nu\nu}_{K^{(*)}}\right),$$

Invisible sector?





B → KX

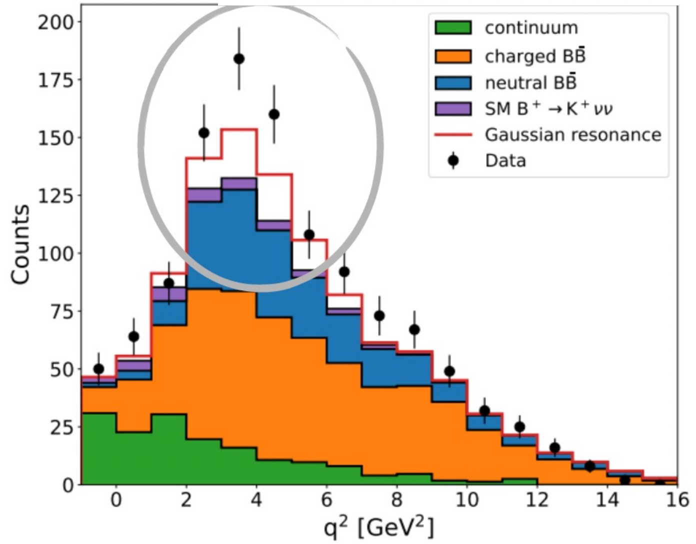
B $\to$K $\nu_L\nu_R$

B→K $\chi\chi$

B→K$\phi\phi$

Bolton, SF, Kamenik, Novoa-Brunet, 2403.13887

- two-body decay, best fit point (2.8 σ) $m_X \sim 2$ GeV



- for two inisible scalars or fermions $m\chi = 610\ MeV$ Bolton et al. '24

Searching for explanation in NP

Bause et al., 2309.00075, Allwicher et al, 2309.02246 Felkl et al., 2309.02940, He et al., 2309.12741, Altmannshofer et al. 2311.1469, Alonso-Alvarez et al. 2310.13043, Bolton, SF, Kamenik, Novoa-Brunet 2403.13887,…

New physics in the meson mixing

$$\mathcal{H}_{\rm eff}^{q} = \mathcal{H}_{{\rm eff},q}^{\rm SM} + \mathcal{H}_{{\rm eff},q}^{\rm NP}$$

$$\mathcal{H}_{\rm eff}^{\rm NP} = \sum_i \frac{C_i}{\Lambda^2_{{\rm NP},B_q}} Q_{i,q},$$

$$Q_{1,q} = (\bar{b}_L \gamma^\mu q_L)(\bar{b}_L \gamma^\mu q_L),$$

$$Q_{2,q} = (\bar{b}_R q_L)(\bar{b}_R q_L),$$

$$Q_{3,q} = (\bar{b}_R^\alpha q_L^\beta)(\bar{b}_R^\beta q_L^\alpha)$$

$$Q_{4,q} = (\bar{b}_R q_L)(\bar{b}_L q_R),$$

$$Q_{5,q} = (\bar{b}_R^\alpha q_L^\beta)(\bar{b}_L^\beta q_R^\alpha),$$

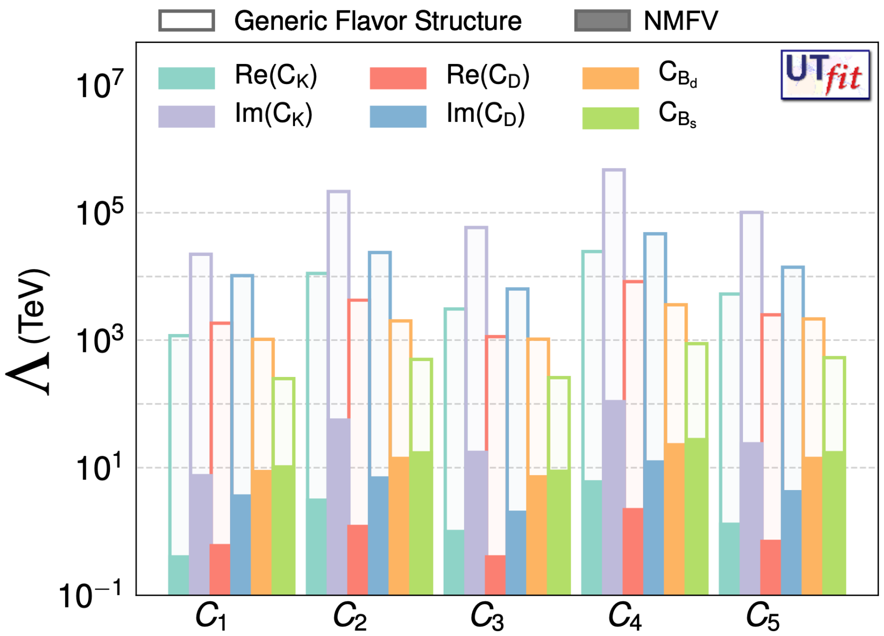
- Generic: $C(\Lambda) = \alpha/\Lambda^2$
- NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$

NP scale crucially depends on the assumed flavour structure in the dimensionless Wilson coefficient, Ci

$$\text{for NP=20\% SM,} \quad K-\bar{K}: \quad (\underbrace{V_{ts}^*}_{\lambda^2}\underbrace{V_{td}}_{\lambda^3})^2 \quad \Rightarrow \quad \Lambda_{\rm NP} \gtrsim 4\cdot 10^4\ {\rm TeV},$$

$$\text{for NP=20\% SM,} \quad B_d-\bar{B}_d: \quad (\underbrace{V_{tb}^*}_{1}\underbrace{V_{td}}_{\lambda^3})^2 \quad \Rightarrow \quad \Lambda_{\rm NP} \gtrsim 1.5\cdot 10^3\ {\rm TeV},$$

$$\text{for NP=20\% SM,} \quad B_s-\bar{B}_s: \quad (\underbrace{V_{tb}^*}_{1}\underbrace{V_{ts}}_{\lambda^2})^2 \quad \Rightarrow \quad \Lambda_{\rm NP} \gtrsim 3\cdot 10^2\ {\rm TeV}.$$



M. Bona @EPS 2023

A.J. Buras "Gauge Theory of Weak Decays: The Standard Model and the Expedition to New Physics Summits", Cambridge University Press

A.J. Buras, "Climbing NLO and NNLO summits of weak decays: 1988–2023", Physics Reports 1025 (2023) 0.

NP explaining B anomalies

Models of NP

Leptoquarks can accommodate $R_{D(*)}$, $R^{\nu\nu}{}_{K(*)}$. LQ= $(SU(3)_c, SU(2)_L, U(1)_Y)$

Scalar LQs they can modify Yukawa couplings (S_1(3,1,1/3), R_2(3,2,7,6) for $R_{D(*)}$)
They can hopefully help in understanding origin of flavour masses
and understanding flavour puzzle (why masses of quarks and leptons a so different).

Vector LQs prefarably should be gauge bosons, that requires full UV theory
Some GUTs, Pati-Salam-like theories (the candidate to explain $R_{D(*)}$ U_1 (3,1,2/3)).

Z' as a new gauge boson of additional U(1) gauge group (accompanied by 2HDM)
explanation of Charm CP violation, D meson mixing.

Vectorlike quarks and/or leptons.

"Scepticism is as important for a good journalist as it is for a good scientist." Freeman Dyson

New Physics in $R_{D(*)}$

$$\mathcal{L}_{\mathrm{b}\to\mathrm{c}\tau\nu} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})\,(\bar{c}_L\gamma^\mu b_L)\,(\bar{\tau}_L\gamma_\mu\nu_{\tau L}) + g_{V_R}\,(\bar{c}_R\gamma^\mu b_R)\,(\bar{\tau}_L\gamma_\mu\nu_{\tau L})$$

$$+ g_{S_L}\,(\bar{c}_R b_L)\,(\bar{\tau}_R\nu_{\tau L}) + g_T\,(\bar{c}_R\sigma^{\mu\nu}b_L)\,(\bar{\tau}_R\sigma_{\mu\nu}\nu_{\tau L}) +$$

$$+ \widetilde{g}_{S_R}(\bar{c}_L b_R)(\bar{\tau}_L N_R) + \widetilde{g}_T(\bar{c}_L\sigma^{\mu\nu}b_R)(\bar{\tau}_L\sigma_{\mu\nu}N_R)\Big] + \mathrm{h.c.}$$

$$\frac{R_{D(*)}}{R^{\mathrm{SM}}_{D(*)}} = |1+g_{V_L}|^2 + a_S^{D(*)}\left(|g_{S_L}|^2 + |\widetilde{g}_{S_R}|^2\right) + a_T^{D(*)}\left(|g_T|^2 + |\widetilde{g}_T|^2\right)$$

$$+ a_{SV}^{D(*)}\,\mathrm{Re}\left[(1+g_{V_L})\,g^*_{S_L}\right] + a_{TV}^{D(*)}\,\mathrm{Re}\left[(1+g_{V_L})\,g^*_T\right],$$

$$a_S^D = 1.08(1), \quad a_T^D = 0.83(5), \quad a_{SV}^D = 1.54(2), \quad a_{TV}^D = 1.09(3)$$

$$a_S^{D^*} = 0.037(4), \quad a_T^{D^*} = 8.56(35), \quad a_{SV}^{D^*} = -0.107(11), \quad a_{TV}^{D^*} = -2.91(11)$$

Constraints from flavor observables

Constraints from LFV

If NP couples to b constraints are coming from SU(2)$_L$ singlets

$$q_L^3 \sim \begin{bmatrix} V_{ib}^* u_L^i \\ b_L \end{bmatrix}$$

Constraints from flavor observables:

$(g-2)_\mu$

$B_c \to \tau\nu$ $\quad B \to \tau\nu$

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

$B_s^0 - \bar{B}_s^0$

$D^0 - \bar{D}^0$

$B \to D\mu\nu_\mu$

$K \to \mu\nu_\mu$

$D_{d,s} \to \tau, \mu\nu$

$K \to \pi\mu\nu_\mu$

$W \to \tau\bar{\nu},\ \tau \to \ell\bar{\nu}\nu$

Constraints from LFV:

$\tau \to \mu\gamma$

$\mu \to e\gamma$

$\tau \to K(\pi)\mu(e)$

$K \to \mu e$

$B \to K\mu e$

$\tau \to \mu\mu\mu$

$\tau \to \phi\mu$

$t \to c\ell^+\ell'^-$

Loop-induced constraints:

$Z \to$ ll, $\nu\nu$ and $\tau \to l\nu\nu$

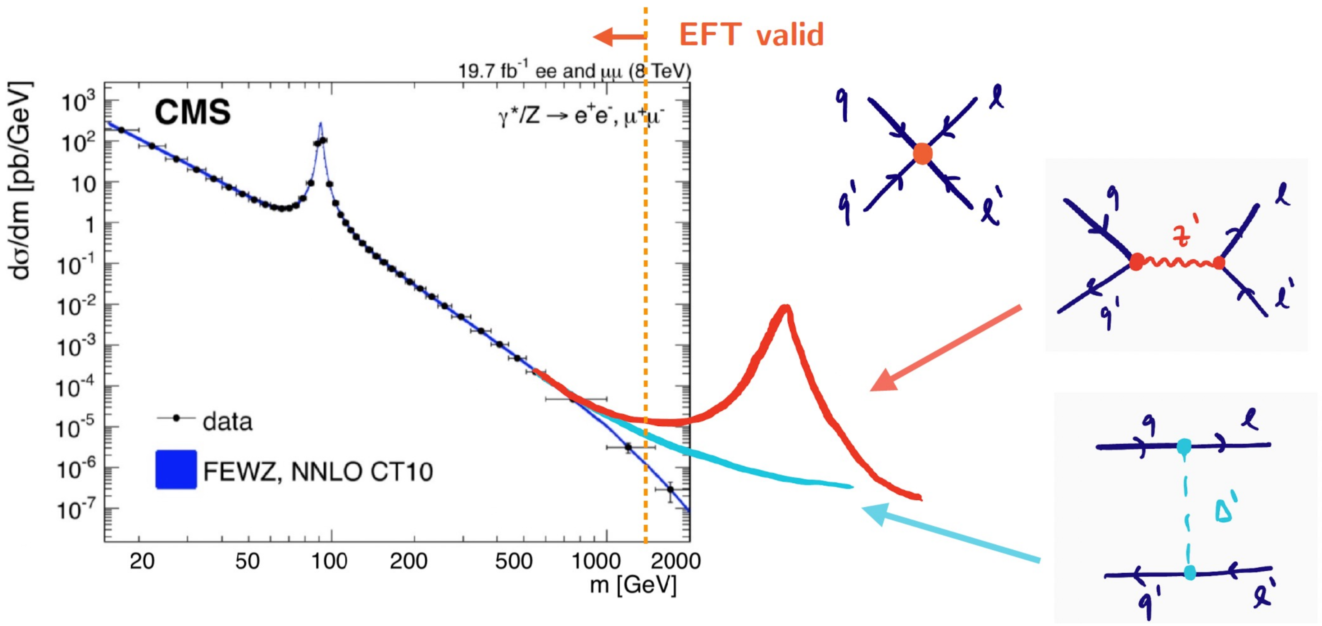
Becirevic et al., 1806.05689, 2206.09717,… Alonso et al., 1611.06676,…
Radiative constraints Feruglio et al.,1606.00524; Gherardi et. Al., 2008.09546,…
Cornella et al., 2103.16558,

Constraints at high energies

the high dilepton mass tails of pp → τν, τ τ processes (we use HighPT package, 2207.10756)

Both ATLAS (2002.12223) and CMS (2208.02717) have presented results of their studies of such Drell-Yan processes at high dilepton masses

High-pT searches (CMS and ATLAS) can probe the same four-fermion operators constrained by flavor-physics experiments (NA62, KOTO, BES-III, LHCb, Belle-II...).



Parton luminosities

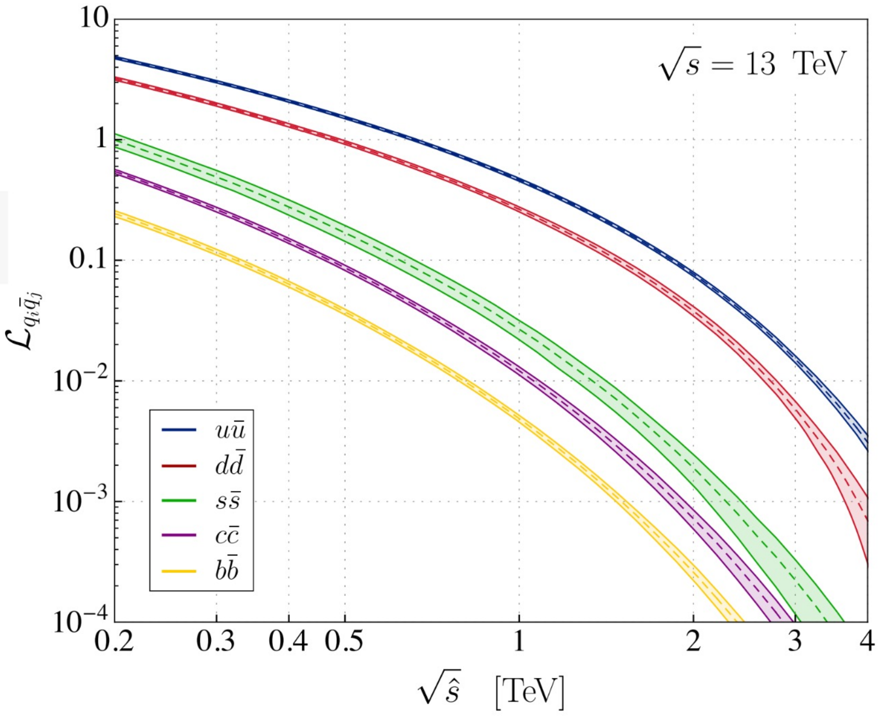
Partonic cross-section

$$\sigma(pp \to \ell\ell') = \sum_{ij} \int \frac{\mathrm{d}\tau}{\tau} \mathcal{L}_{q_i\bar{q}_j}(\tau)\, \hat{\sigma}(q_i\bar{q}_j \to \ell\ell')_{\hat{s}=s\tau}$$

$\tau = \hat{s}/s$

$\hat{s} = m^2_{\ell\ell'}$

$\sqrt{s} = 13$ TeV



$$\hat{\sigma} = \hat{\sigma}_{\rm SM} + \hat{\sigma}_{\rm int} + \hat{\sigma}_{\rm NP^2}$$

$\propto \frac{1}{\hat{s}}$

$\propto \frac{\hat{s}}{\Lambda^2} \mathrm{Re}(\mathcal{C}^{(6)})$

$\propto \frac{\hat{s}^2}{\Lambda^4} |\mathcal{C}^{(6)}|^2$

Four-fermion interactions

$d=6$	ψ^4	
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(\bar{q}_i \gamma_\mu q_j)$	Vector
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)(\bar{q}_i \gamma_\mu \tau^I q_j)$	
$\mathcal{O}_{lu}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(\bar{u}_i \gamma_\mu u_j)$	
$\mathcal{O}_{ld}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(\bar{d}_i \gamma_\mu d_j)$	
$\mathcal{O}_{eq}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(\bar{q}_i \gamma_\mu q_j)$	
$\mathcal{O}_{eu}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(\bar{u}_i \gamma_\mu u_j)$	
$\mathcal{O}_{ed}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(\bar{d}_i \gamma_\mu d_j)$	
$\mathcal{O}_{ledq}$ + h.c.	$(\bar{l}_\alpha e_\beta)(\bar{d}_i q_j)$	scalar
$\mathcal{O}_{lequ}^{(1)}$ + h.c.	$(\bar{l}_\alpha e_\beta)\varepsilon(\bar{q}_i u_j)$	
$\mathcal{O}_{lequ}^{(3)}$ + h.c.	$(\bar{l}_\alpha \sigma^{\mu\nu} e_\beta)\varepsilon(\bar{q}_i \sigma_{\mu\nu} u_j)$	tensor

Leptonic dipoles: $\psi^2 XH$

$d=6$	$\psi^2 XH$ + h.c.
$\mathcal{O}_{eW}$	$(\bar{l}_\alpha \sigma^{\mu\nu} e_\beta)\,\tau^I H W_{\mu\nu}^I$
$\mathcal{O}_{eB}$	$(\bar{l}_\alpha \sigma^{\mu\nu} e_\beta)\,H B_{\mu\nu}$

$d=6$	$\psi^2 H^2 D$
$\mathcal{O}_{Hl}^{(1)}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(H^\dagger i \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{Hl}^{(3)}$	$(\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)(H^\dagger i \overleftrightarrow{D}_\mu^I H)$
$\mathcal{O}_{He}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(H^\dagger i \overleftrightarrow{D}_\mu H)$

One can use a flavour symmetry (e.g., MFV, …) or a specific model.

$pp \to \tau\tau$

$pp \to ee,\ \mu\mu$

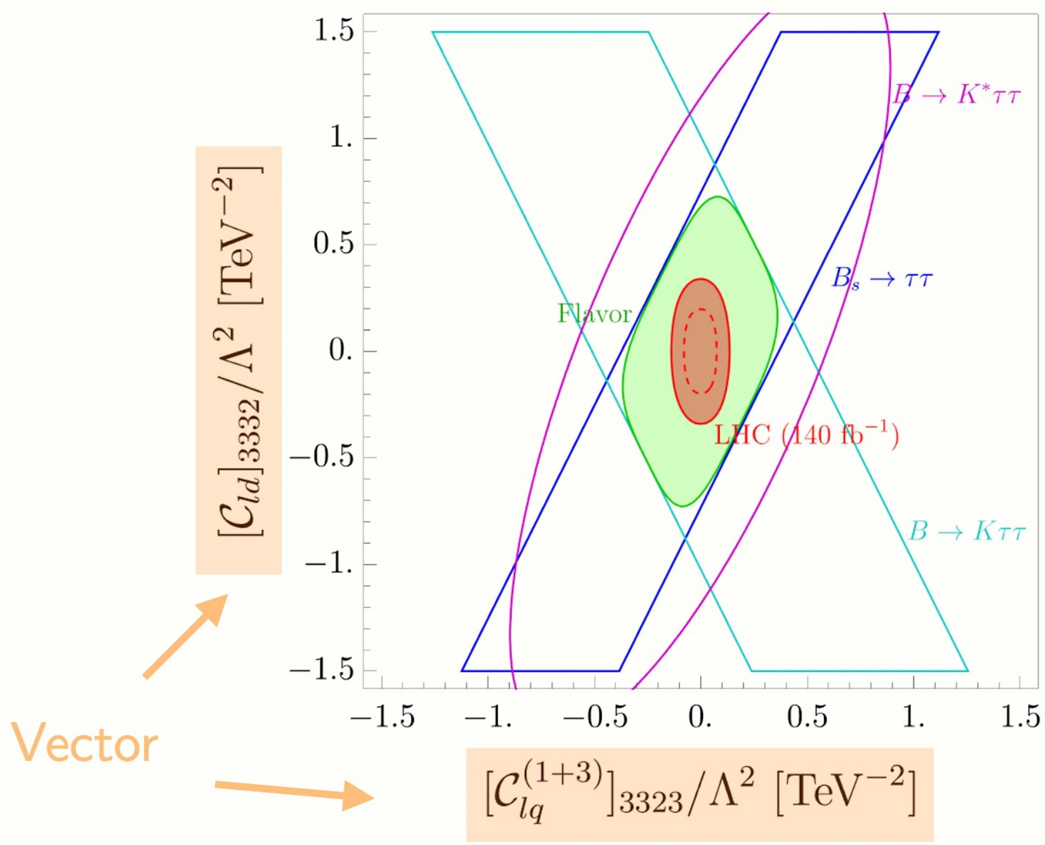
$pp \to \tau\nu$

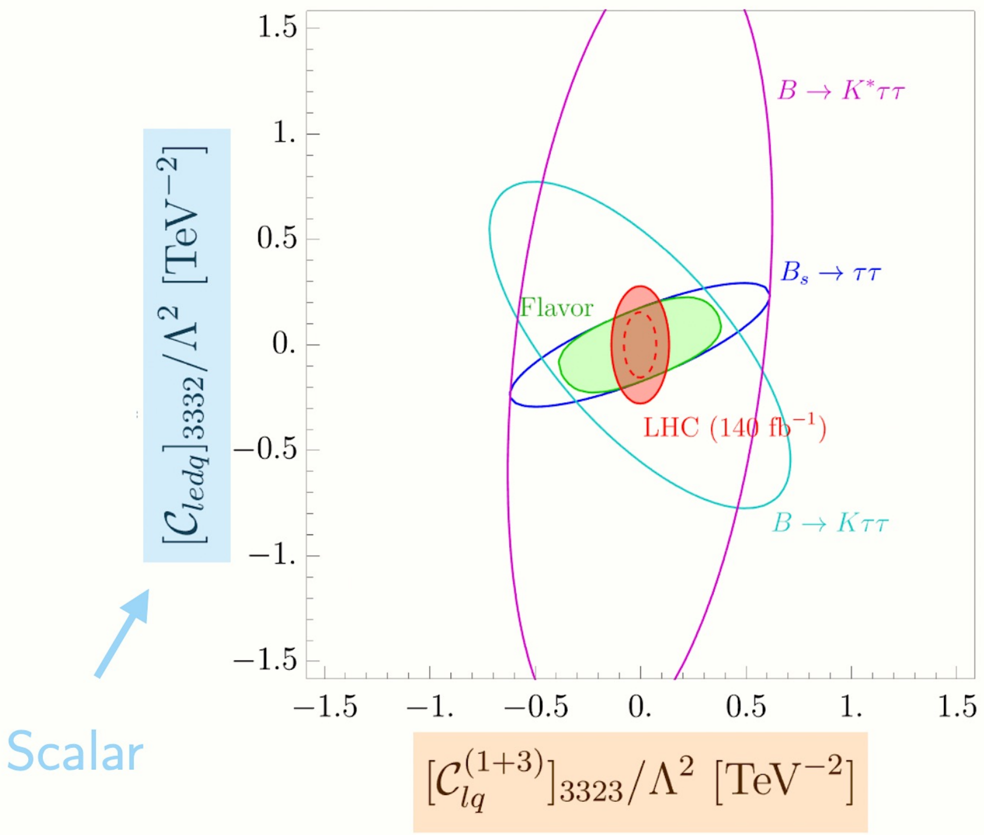
$pp \to e\nu,\ \mu\nu$

$pp \to e\mu,\ e\tau,\ \mu\tau$

HighPT: A Tool for high- Drell-Yan Tails Beyond the SM
Allwisher, Faroughy, Jaffredo, Sumensari, Wilsch (2207.10756,2207.10714)

HighPT





Flavour and collider constraints are competitive!

Scalar and Vector Leptoquarks as NP meditaors

$(SU(3), SU(2), U(1))$	Spin	Symbol	Type	F
$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2	$RL\,(S_{1/2}^L),\ LR\,(S_{1/2}^R)$	0
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L),\ \overline{LR}\,(\tilde{S}_{1/2}^{\overline{L}})$	0
$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S_0^L),\ RR\,(S_0^R),\ \overline{RR}\,(S_0^{\overline{R}})$	-2
$(\overline{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	$\overline{RR}\,(\bar{S}_0^{\overline{R}})$	-2
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3	$LL\,(V_1^L)$	0
$(\overline{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2	$RL\,(V_{1/2}^L),\ LR\,(V_{1/2}^R)$	-2
$(\overline{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}_{1/2}^L),\ \overline{LR}\,(\tilde{V}_{1/2}^{\overline{R}})$	-2
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$	$RR\,(\tilde{V}_0^R)$	0
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1	$LL\,(V_0^L),\ RR\,(V_0^R),\ \overline{RR}\,(V_0^{\overline{R}})$	0
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$	$\overline{RR}\,(\bar{V}_0^{\overline{R}})$	0

F=0, these LQs do not have diquark couplings and can not lead to the proton destabilisation.

Dorsner et al., 1603.04993

$Q=I_3+Y$

Scalar or vector leptoquarks?

- Scalar leptoquarks have Yukawa -like couplings

(they can contribute to fermion masses if they have v.e.v(

$$\bar{\ell}\, P_{L,R}\, q\, \Phi$$

$$P_{L,R} = 1/2(1 \pm \gamma_5)$$

- Vector leptoquarks should be gauge bosons

(however, usually gauge bosons as in GUTs have the mass at GUT scale)

If they are not gauge bosons we cannot handle loop corrections.

$$\bar{\ell}\gamma_\mu\, P_{L,R}\, q\, V^\mu$$

Scalar Leptoquarks in $R_{D(*)}$

Goal of our study is to establish whether or not any of the scalar leptoquarks, with a minimalistic set of Yukawa couplings, fits the current experimental world average of R_D and R_{D*}

Scenarios in which the scalar leptoquark couples to τ and either to c or to b quark.
These couplings are of Yukawa couplings

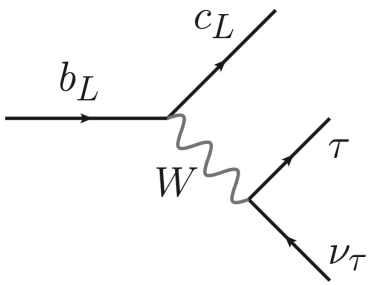
LQ $\rightarrow$(SU(3)$_c$, SU(2)$_L$, U(1)$_Y$)

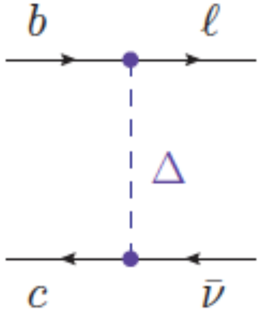
Electric charge
$Q = I_3 + Y$

$\tilde{R}_2 = (3,2,7/6)$

$R_2 = (3,2,1/6)$

$S_1 = (\bar{3},1,1/3)$





Damir Bečirević, Svjetlana Fajfer, Nejc Košnik, Lovre Pavičić, 2404.16772

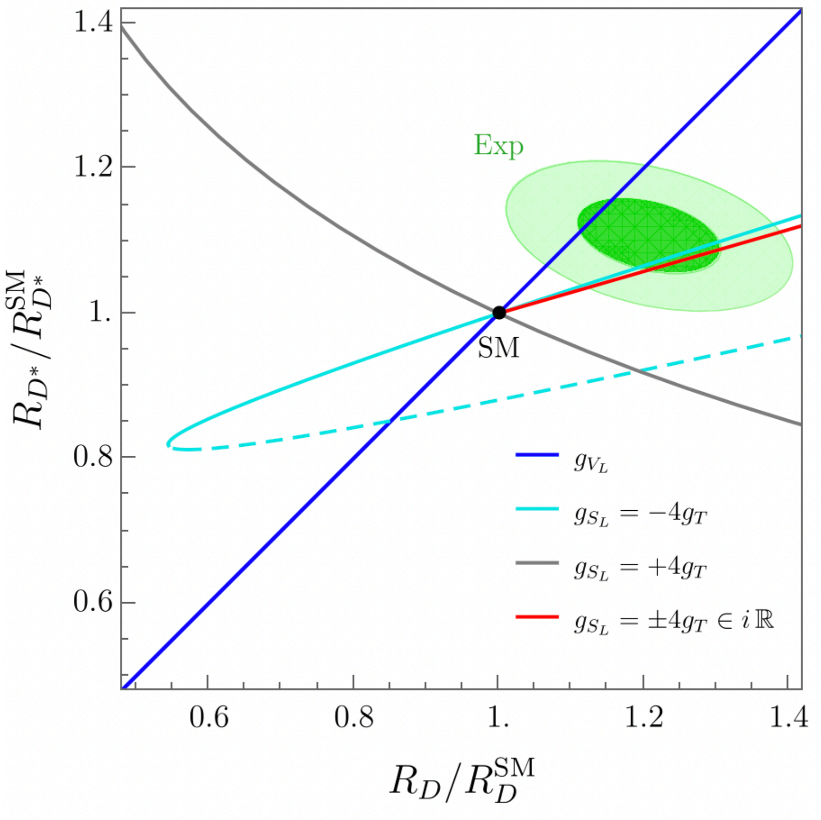
$R_{D^{(*)}}$ explanation – three years ago

$$\mathcal{L}_{cc} = -2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})(\bar{c}_L\gamma_\mu b_L)(\bar{\ell}_L\gamma^\mu\nu_L) + g_{V_R}(\bar{c}_R\gamma_\mu b_R)(\bar{\ell}_L\gamma^\mu\nu_L)$$
$$+ g_{S_R}(\bar{c}_L b_R)(\bar{\ell}_R\nu_L) + g_{S_L}(\bar{c}_R b_L)(\bar{\ell}_R\nu_L) + g_T(\bar{c}_R\sigma_{\mu\nu}b_L)(\bar{\ell}_R\sigma^{\mu\nu}\nu_L)\Big] + \text{h.c.}$$

Angelescu et al., 2103.12504.

Eff. coeff.	1σ range	$\chi^2_{\min}/\text{dof}$
$g_{V_L}(m_b)$	0.07 ± 0.02	$0.02/1$
$g_{S_R}(m_b)$	-0.31 ± 0.05	$5.3/1$
$g_{S_L}(m_b)$	0.12 ± 0.06	$8.8/1$
$g_T(m_b)$	-0.03 ± 0.01	$3.1/1$
$g_{S_L} = +4g_T \in \mathbb{R}$	-0.03 ± 0.07	$12.5/1$
$g_{S_L} = -4g_T \in \mathbb{R}$	0.16 ± 0.05	$2.0/1$
$g_{S_L} = \pm 4g_T \in i\,\mathbb{R}$	0.48 ± 0.08	$2.4/1$

Three years ago



$$U_1 = (3,1,2/3) : g_V$$
$$R_2 = (3,2,7/6) : g_{S_L} = 4g_T$$
$$S_1 = (\bar{3},1,1/3) : g_{S_L} = -4g_T, g_V$$

$R_2 = (3, 2, 7/6)$

In $SU(2)_L$ R_2 is in a represention of dimension 2 (weak isospin 1/2).
There are two states $R_2^{5/3}$ and $R_2^{2/3}$

$(Q=I_3 + Y)$

The minimal model: couplings to the third generations of leptons (ν_τ and τ only)

Notation: Q , L quark (lepton) weak doublets, q (l) weak singlets

$$y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix}, \qquad y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}$$

$$\mathcal{L}_{R_2} = y_R^{ij}\, \bar{Q}_i^a e_j R_2^a \;+\; y_L^{ij}\, \bar{u}_{Ri} R_2^{T,a} \epsilon^{ab} L_j^b + \text{h.c.}$$

$$\mathcal{L}_{R_2} = y_R^{b\tau} V_{jb}^* (\overline{u}_j P_R \tau) R_2^{5/3} + y_R^{b\tau} (\overline{b} P_R \tau) R_2^{2/3} - y_L^{c\tau} (\overline{c} P_L \tau) R_2^{5/3} + y_L^{c\tau} (\overline{c} P_L \nu_\tau) R_2^{2/3} + \text{h.c.}$$

- couplings are generated at the mass scale of R_2
- running to the mass scale m_b

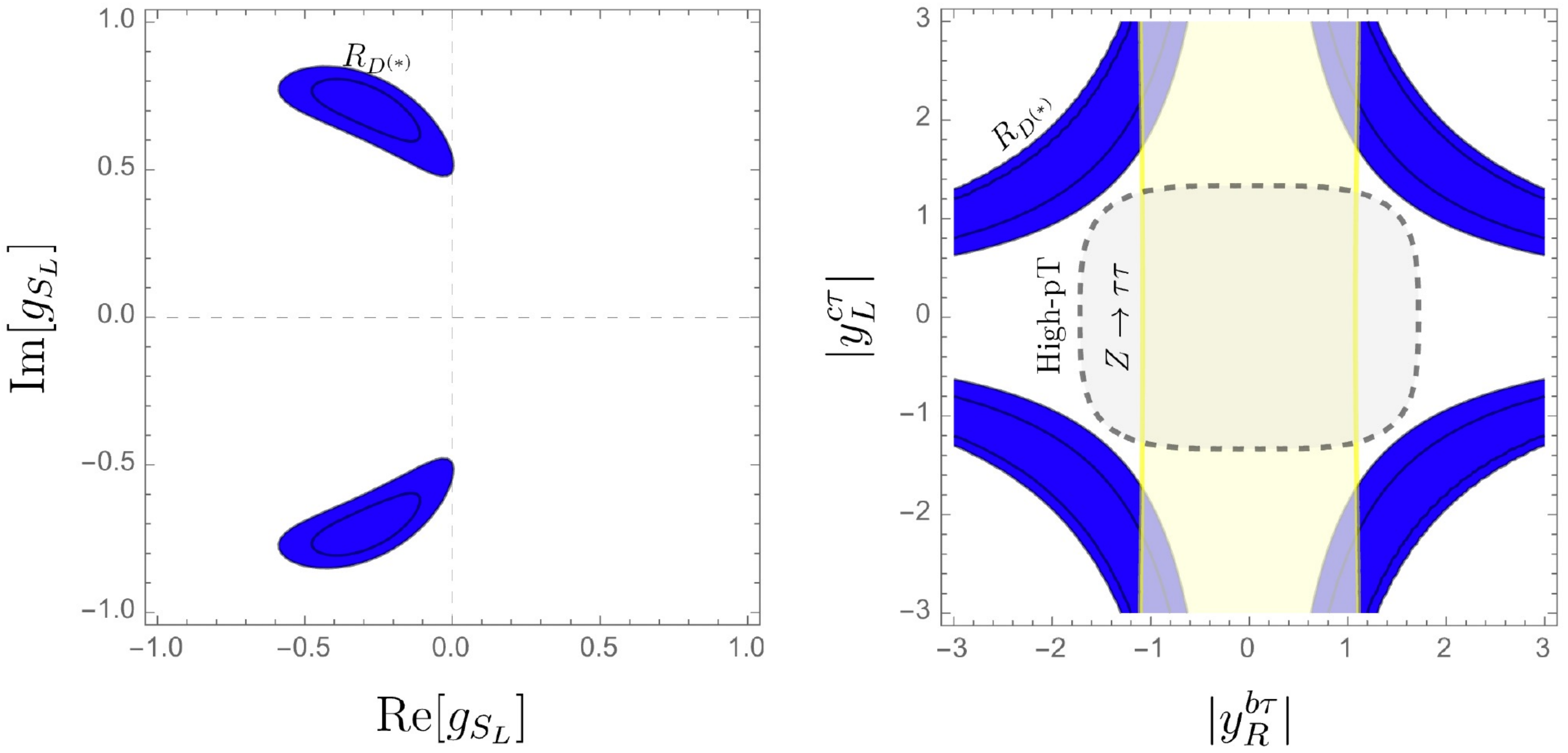
$$g_{S_L}(m_{R_2}) = 4 g_T(m_{R_2})$$
$$g_{S_L}(m_b) = 8.8 \times g_T(m_b)$$

One of the Yukawa couplings should be complex

$$g_{S_L}(m_b) = 0.60 \times \frac{1}{2} |y_R^{b\tau} y_L^{c\tau}| e^{i\varphi} \,.$$

Damir Bečirević, Svjetlana Fajfer, Nejc Košnik, Lovre Pavičić, 2404.16772

$m_{R_2} = 1.5$ TeV



R$_2$ is out of game!

$\tilde{R}_2 = (3, 2, 1/6)$

- $\tilde{R}_2$, triplet of colour group, doublet of weak with hypercgarge 1/6 two states states $\tilde{R}_2^{2/3}$ and $\tilde{R}_2^{-1/3}$

$$\mathcal{L} = -\tilde{y}_L^{ij}\overline{d}^i \tilde{R}_2^a \epsilon^{ab} L^{j,b} + \tilde{y}_R^{iN}\overline{Q}^{i,a} \tilde{R}_2^a N_R + \text{h.c.}$$

- Due to its quantum numbers in can couple to non-SM right-handed neutrino N_R

$$\mathcal{L} = -\tilde{y}_L^{b\tau}(\bar{b}P_L\tau)\tilde{R}_2^{2/3} + \tilde{y}_L^{b\tau}(\bar{b}P_L\nu)\tilde{R}_2^{-1/3} + \\ + \tilde{y}_R^{sN}(\bar{s}P_R N_R)\tilde{R}_2^{-1/3} + \tilde{y}_R^{sN}V_{js}(\bar{u}_j P_R N_R)\tilde{R}_2^{2/3} + \text{h.c.}$$

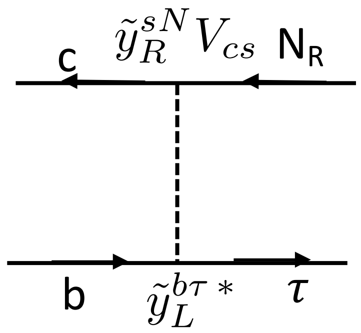
minimal set of couplings

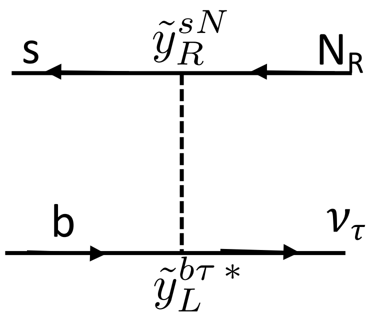
$$\tilde{y}_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \tilde{y}_L^{b\tau} \end{pmatrix}, \qquad \tilde{y}_R = \begin{pmatrix} 0 \\ \tilde{y}_R^{sN} \\ 0 \end{pmatrix},$$

In the branching ratio N_R cannot interfere with SM neutrino, therefore the NP effect is the

$$\mathcal{B} \propto |\mathcal{A}_{\text{SM}} + \cancel{\mathcal{A}_{\text{NP}}^{\nu_L}}|^2 + |\mathcal{A}_{\text{NP}}^{N_R}|^2$$

However, there is the tree diagram for $b \to s\nu\bar{N}_R$



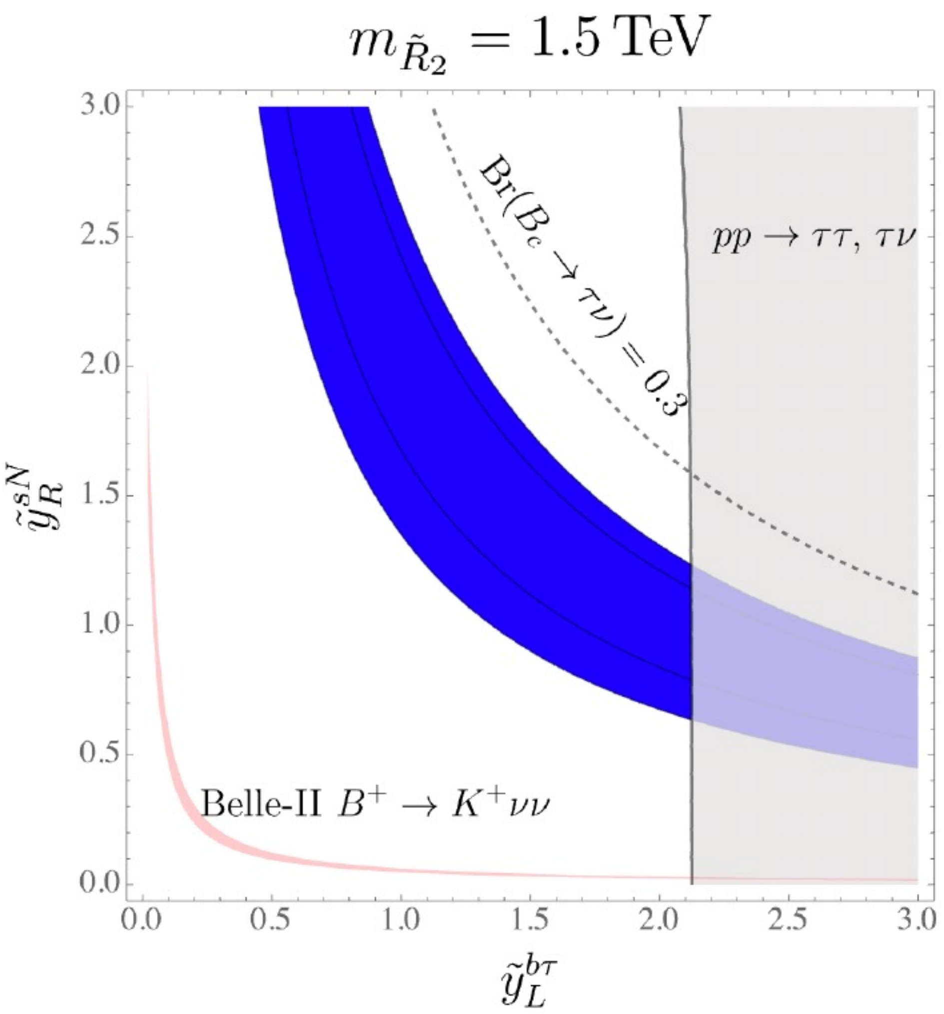


$R^{\nu\nu}_{K(*)}$ and scalar LQS

$$
\begin{aligned}
\mathcal{L}_{\text{eff}}^{\bar{q}^i q^j \bar{\nu}\nu'} = \sqrt{2} G_F \Big[& c^{LL}_{ij;\nu\nu'} (\bar{q}^i_L \gamma_\mu q^j_L)(\bar{\nu}_L \gamma^\mu \nu'_L) + c^{RR}_{ij;\nu\nu'} (\bar{q}^i_R \gamma_\mu q^j_R)(\bar{\nu}_R \gamma^\mu \nu'_R) \\
& + c^{LR}_{ij;\nu\nu'} (\bar{q}^i_L \gamma_\mu q^j_L)(\bar{\nu}_R \gamma^\mu \nu'_R) + c^{RL}_{ij;\nu\nu'} (\bar{q}^i_R \gamma_\mu q^j_R)(\bar{\nu}_L \gamma^\mu \nu'_L) \\
& + g^{LL}_{ij;\nu\nu'} (\bar{q}^i_L q^j_R)(\bar{\nu}_L \nu'_R) + h^{LL}_{ij;\nu\nu'} (\bar{q}^i_L \sigma^{\mu\nu} q^j_R)(\bar{\nu}_L \sigma_{\mu\nu} \nu'_R) \\
& + g^{RR}_{ij;\nu\nu'} (\bar{q}^i_R q^j_L)(\bar{\nu}_R \nu'_L) + h^{RR}_{ij;\nu\nu'} (\bar{q}^i_R \sigma^{\mu\nu} q^j_L)(\bar{\nu}_R \sigma_{\mu\nu} \nu'_L) \\
& + g^{LR}_{ij;\nu\nu'} (\bar{q}^i_L q^j_R)(\bar{\nu}_R \nu'_L) + g^{RL}_{ij;\nu\nu'} (\bar{q}^i_R q^j_L)(\bar{\nu}_L \nu'_R) \Big].
\end{aligned}
$$

Bause et al., 2309.00075, Allwicher et al, 2309.02246,
assumed that neutrinos are SM-like.
$\tilde{R}_2$
In this case the most suitable candidate is the operator with the right-handed quarks.
Only , (V_2) can have such interactions at the tree level !
Note that these couplings would not generate any contributions to $R_{D(*)}$!

LQ	$d_j \to d_i \nu\bar{\nu}'$ decays	$u_j \to u_i \nu\bar{\nu}'$ decays
S_3	$c^{LL} = \frac{v^2}{2m^2_{\rm LQ}} (y_3^{LL} U)_{j\nu'} (y_3^{LL} U)^*_{i\nu}$	$c^{LL} = \frac{v^2}{m^2_{\rm LQ}} (V^T y_3^{LL} U)_{j\nu'} (V^T y_3^{LL} U)^*_{i\nu}$
R_2		$c^{RL} = -\frac{v^2}{2m^2_{\rm LQ}} (y_2^{RL} U)_{i\nu'} (y_2^{RL} U)^*_{j\nu}$
$\tilde{R}_2$	$c^{RL} = -\frac{v^2}{2m^2_{\rm LQ}} (\tilde{y}_2^{RL} U)_{i\nu'} (\tilde{y}_2^{RL} U)^*_{j\nu}$ $c^{LR} = -\frac{v^2}{2m^2_{\rm LQ}} y^{\overline{LR}}_{2\,i\nu'} y^{\overline{LR}*}_{2\,j\nu}$ $g^{RR} = 4h^{RR} = -\frac{v^2}{2m^2_{\rm LQ}} (\tilde{y}_2^{RL} U)_{i\nu'} \tilde{y}^{\overline{LR}*}_{2\,j\nu}$ $g^{LL} = 4h^{LL} = -\frac{v^2}{2m^2_{\rm LQ}} \tilde{y}^{\overline{LR}}_{2\,i\nu'} (\tilde{y}_2^{RL} U)^*_{j\nu}$	$c^{LR} = -\frac{v^2}{2m^2_{\rm LQ}} (V \tilde{y}_2^{\overline{LR}})_{i\nu'} (V y_2^{\overline{LR}})^*_{j\nu}$
S_1	$c^{LL} = \frac{v^2}{2m^2_{\rm LQ}} (y_1^{LL} U)_{j\nu'} (y_1^{LL} U)^*_{i\nu}$ $c^{RR} = \frac{v^2}{2m^2_{\rm LQ}} y^{\overline{RR}}_{1\,j\nu'} y^{\overline{RR}*}_{1\,i\nu}$ $g^{RR} = -4h^{RR} = \frac{v^2}{2m^2_{\rm LQ}} (y_1^{LL} U)_{j\nu'} y^{\overline{RR}*}_{1\,i\nu}$ $g^{LL} = -4h^{LL} = \frac{v^2}{2m^2_{\rm LQ}} y^{\overline{RR}}_{1\,j\nu'} (y_1^{LL} U)^*_{i\nu}$	
$\bar{S}_1$		$c^{RR} = \frac{v^2}{2m^2_{\rm LQ}} \bar{y}^{\overline{RR}}_{1\,j\nu'} \bar{y}^{\overline{RR}*}_{1\,i\nu}$
U_3	$c^{LL} = -\frac{2v^2}{m^2_{\rm LQ}} (x_3^{LL} U)_{i\nu'} (x_3^{LL} U)^*_{j\nu}$	$c^{LL} = -\frac{v^2}{m^2_{\rm LQ}} (V x_3^{LL} U)_{i\nu'} (V x_3^{LL} U)^*_{j\nu}$
V_2	$c^{RL} = \frac{v^2}{m^2_{\rm LQ}} (x_2^{RL} U)_{j\nu'} (x_2^{RL} U)^*_{i\nu}$	
$\tilde{V}_2$		$c^{RL} = \frac{v^2}{m^2_{\rm LQ}} (\tilde{x}_2^{RL} U)_{j\nu'} (\tilde{x}_2^{RL} U)^*_{i\nu}$ $c^{LR} = \frac{v^2}{m^2_{\rm LQ}} (V^T \tilde{x}_2^{\overline{LR}})_{j\nu'} (V^T \tilde{x}_2^{\overline{LR}})^*_{i\nu}$ $g^{RL} = \frac{2v^2}{m^2_{\rm LQ}} (V^T \tilde{x}_2^{\overline{LR}})_{j\nu'} (\tilde{x}_2^{RL} U)^*_{i\nu}$ $g^{LR} = \frac{2v^2}{m^2_{\rm LQ}} (\tilde{x}_2^{RL} U)_{j\nu'} (V^T \tilde{x}_2^{\overline{LR}})^*_{i\nu}$
U_1		$c^{LL} = -\frac{v^2}{m^2_{\rm LQ}} (V x_1^{LL} U)_{i\nu'} (V x_1^{LL} U)^*_{j\nu}$ $c^{RR} = -\frac{v^2}{m^2_{\rm LQ}} x^{\overline{RR}}_{1\,i\nu'} x^{\overline{RR}*}_{1\,j\nu}$ $c^{LR} = \frac{2v^2}{m^2_{\rm LQ}} (V x_1^{LL} U)_{i\nu'} x^{\overline{RR}*}_{1\,j\nu}$ $c^{RL} = \frac{2v^2}{m^2_{\rm LQ}} x^{\overline{RR}}_{1\,i\nu'} (V x_1^{LL} U)^*_{j\nu}$
$\bar{U}_1$	$c^{RR} = -\frac{v^2}{m^2_{\rm LQ}} x^{RR}_{1\,i\nu'} x^{RR*}_{1\,j\nu}$	



If you want to explain RD(*) and Belle II result for B→ $K\ \nu\ \nu$ this cannot be achieved with this LQ!

See also Rosauro-Alcaraz and Santos Leal 2401.17440

Damir Bečirević, Svjetlana Fajfer, Nejc Košnik, Lovre Pavičić, 2404.16772

$\tilde{R}_2$ is out of game!

$$S_1 = (\bar{3}, 1, 1/3)$$

Being a weak singlet S_1 has only one stae with the electric charge 1/3.
It allows the the interactions with quark, lepton both being weak doublets, or weak singlets

Minimal setting

$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_L^{b\tau} \end{pmatrix}, \qquad y_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_R^{c\tau} \\ 0 & 0 & 0 \end{pmatrix},$$

Survival of the fittest!

$$\mathcal{L}_{S_1} = y_L^{b\tau} V_{ib}^* (\overline{u_i^C} P_L \tau) S_1 - y_L^{b\tau} (\overline{b^C} P_L \nu_\tau) S_1 + y_R^{c\tau} (\overline{c^C} P_R \tau) S_1 + \text{h.c.}$$

It generates

$$\begin{aligned}\mathcal{L}_{b\to c\tau\nu} = -2\sqrt{2} G_F V_{cb} \Big[& (1 + g_{V_L}) (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_{\tau L}) + g_{V_R} (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_{\tau L}) \\ & + g_{S_L} (\bar{c}_R b_L)(\bar{\tau}_R \nu_{\tau L}) + g_T (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L}) + \\ & + \tilde{g}_{S_R} (\bar{c}_L b_R)(\bar{\tau}_L N_R) + \tilde{g}_T (\bar{c}_L \sigma^{\mu\nu} b_R)(\bar{\tau}_L \sigma_{\mu\nu} N_R) \Big] + \text{h.c.}\end{aligned}$$

$$g_{V_L} = \frac{v^2}{4V_{cb}} \frac{V_{cb} |y_L^{b\tau}|^2}{m_{S_1}^2}$$

$$g_{S_L}(m_{S_1}) = -\frac{v^2}{4V_{cb}} \frac{y_L^{b\tau} y_R^{c\tau *}}{m_{S_1}^2}$$

$$g_{S_L}(m_b) = -8.8 \times g_T(m_b)$$

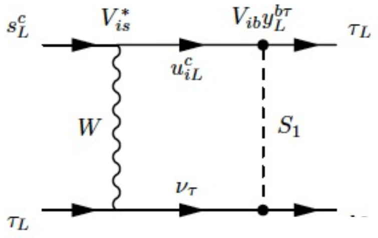
Damir Bečirević, SF, Nejc Košnik, Lovre Pavičić, 2404.16772

Consequences

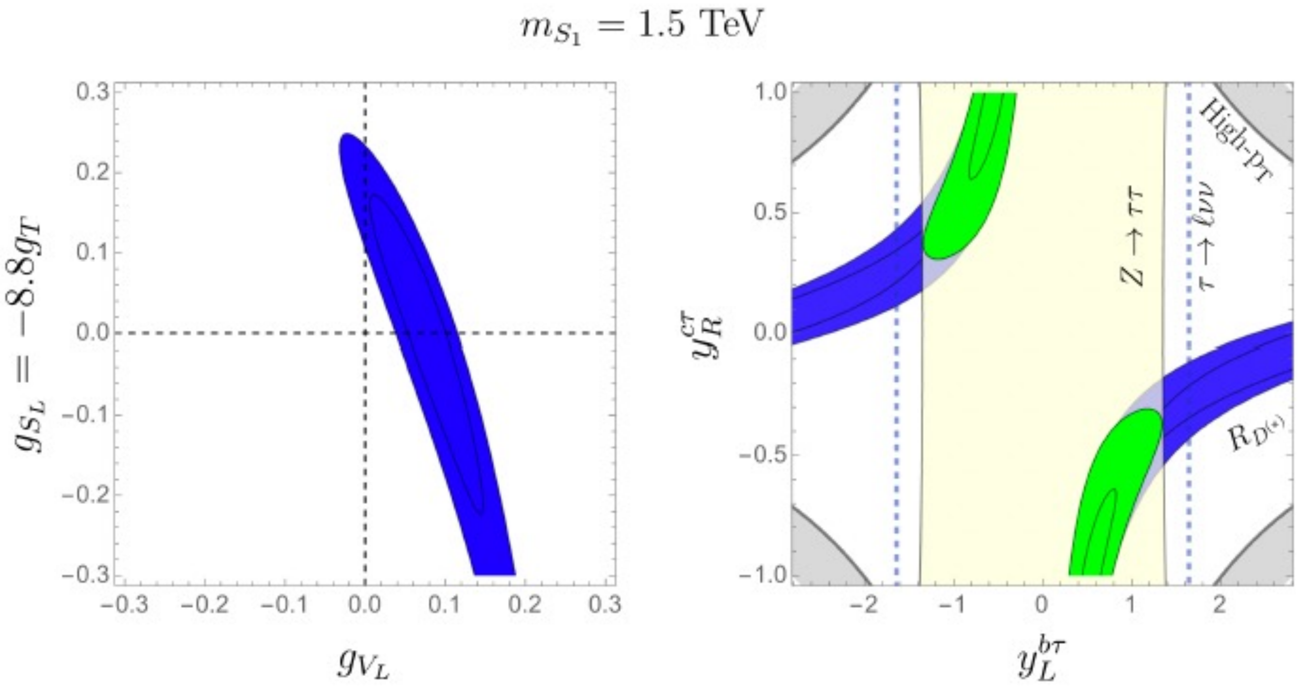
1) $$\frac{\mathcal{B}(B_c \to \tau\nu)^{S_1}}{\mathcal{B}(B_c \to \tau\nu)^{\rm SM}} \in [1.13, 1.48]\,,$$

$$\mathcal{B}(B_c \to \tau\nu)^{\rm SM} = (2.24 \pm 0.07)\% \times \left(\frac{V_{cb}}{0.0417}\right)^2$$

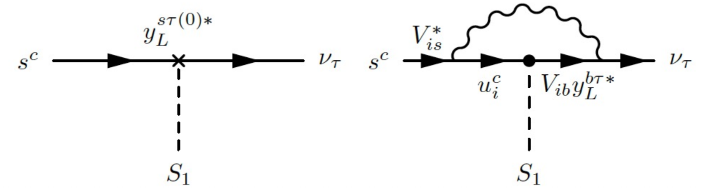
2) through the box or penguin diagrams involving one S_1 and one W-boson, a contribution to $b \to s\tau\,\tau$ or $b \to s\nu_\tau\,\nu_\tau$



$$\frac{\mathcal{B}(B_s \to \tau\tau)^{S_1}}{\mathcal{B}(B_s \to \tau\tau)^{\rm SM}} \in [0.73, 0.98]\,, \quad \frac{\mathcal{B}(B \to K\tau\tau)^{S_1}}{\mathcal{B}(B \to K\tau\tau)^{\rm SM}} \in [0.73, 0.98]$$



3) b → sν_τ ν_τ



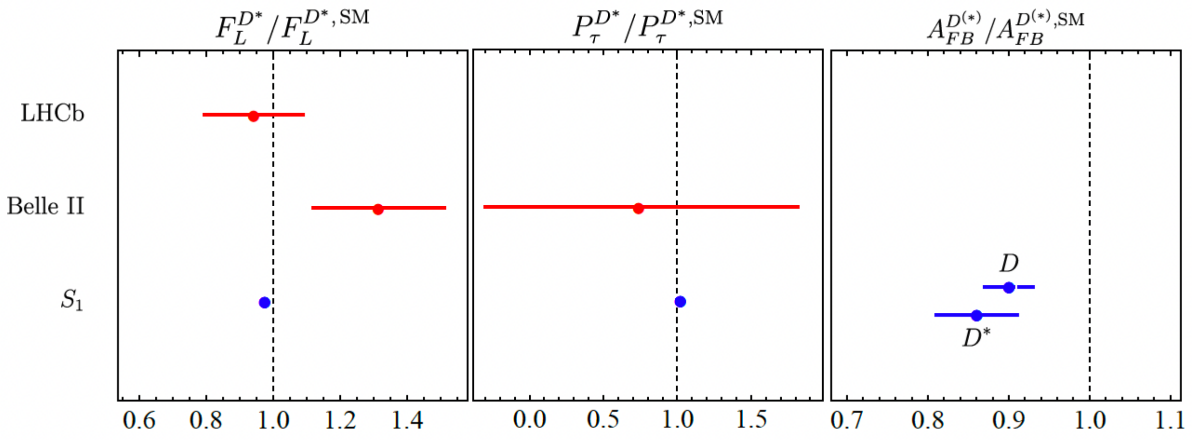
$$C_L^{S_1} = (-9.3 + 0.4\,i) \times 10^{-2}\,|y_L^{b\tau}|^2$$

(imaginary part comes from the fermions being on the mass shell in the loops)

$$\frac{\mathcal{B}(B \to K^{(*)}\nu\nu)^{S_1}}{\mathcal{B}(B \to K^{(*)}\nu\nu)^{\rm SM}} = \left|1 + \frac{\delta C_L^{S_1}}{3\,C_L^{\rm SM}}\right|^2 \in [1.001, 1.02] \quad (@2\sigma)$$

4) $V_{ub}|y_L^{b\tau}|^2$ can affect the $b \to u\tau\nu$ decay ($\mathcal{B}(B^- \to \tau\nu)$, $\mathcal{B}(B \to \pi\tau\nu)$. However, it gives 3 % enhancement of the SM predictions

5) We determine for B →D(*)$\tau\nu$ the fraction of the decay rate to a longitudinally polarized D∗, the τ −lepton polarization asymmetry, and the forward-backward asymmetries

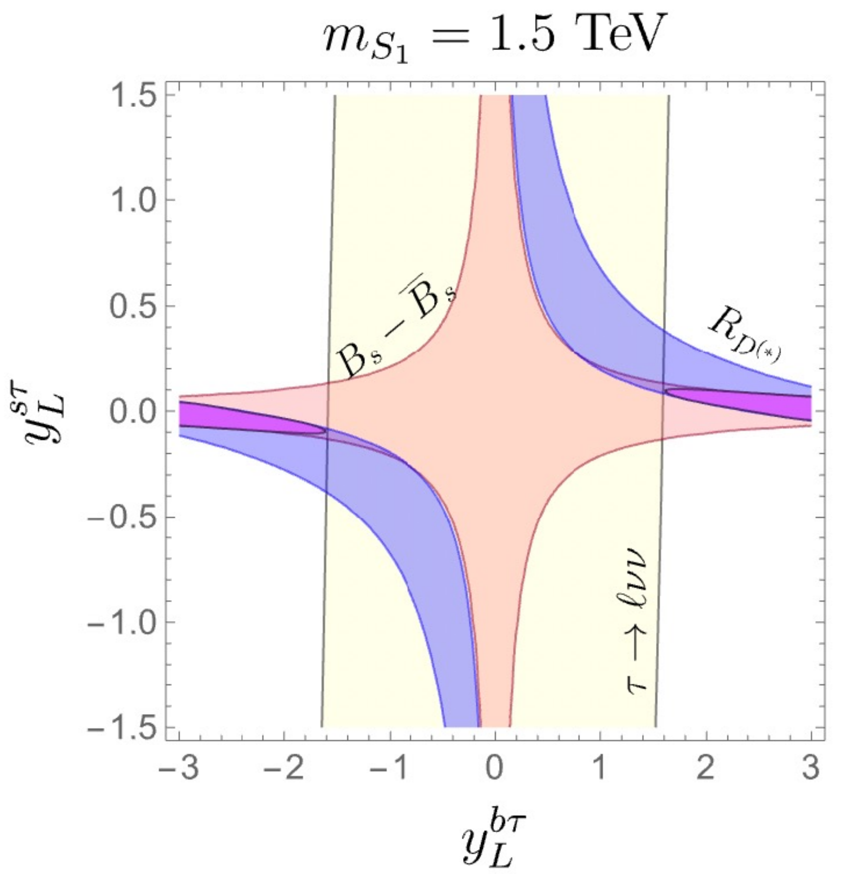


S_1 with V-A couplings or

$$g_{V_L} = -\frac{v^2}{m_{S_1}^2}\frac{V_{cs}}{V_{cb}} y_L^{s\tau} y_L^{b\tau}$$

$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y_L^{s\tau} \\ 0 & 0 & y_L^{b\tau} \end{pmatrix}, \qquad y_R = 0$$

No right-handed fermions ($y_R^{c\tau} = 0$)



S_1 (V-A) cannot survive!

Conclusions

Flavour puzzles persist

SMEFT a usefull tool for NP

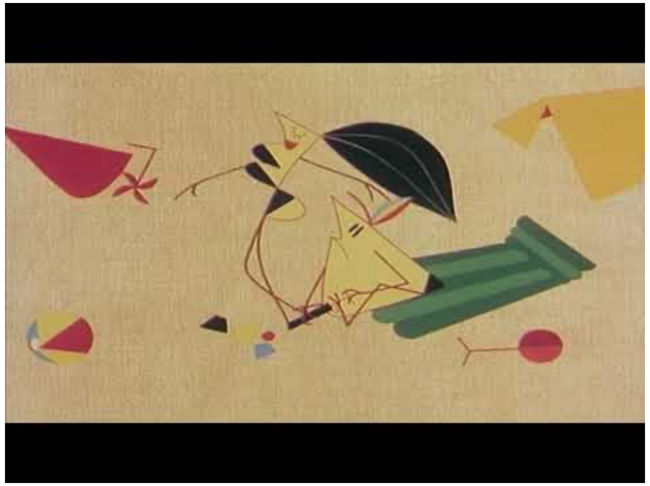
LFU tests

Leptoquarks

S_1 leptoquark and with Yukawa couplings to both left- and right-handed quark/lepton doublets is the only one viable candidate to explain the $R_{D(*)}$ puzzle!

LFU tests at LHC expected!

Thanks!



Surogat is a **1961** animated comedy short film by Croatian director **Dušan Vukotić**, produced by Zagreb Film. (Der Ersatz)

https://www.youtube.com/watch?v=zb0PA-TaS4g