Single Leptoquark Solutions to the B-physics Anomalies

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Hints of LFUV

Since 2014, Belle, Babar and LHCb - observed deviations from SM in universality ratios:

$$b \to s\ell\bar{\ell}: \quad \boxed{R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}}$$

$$b \to c\ell\bar{\nu}: \quad \boxed{R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\mu\bar{\nu})}}$$

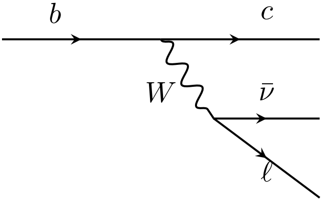
Theoretically clean observables:
- CKM cancellation,
- Most hadronic uncertainties cancel,
- High sensitivity to NP.

$$R_{K^{(*)}}^{\mathrm{Exp}} < R_{K^{(*)}}^{\mathrm{SM}}$$

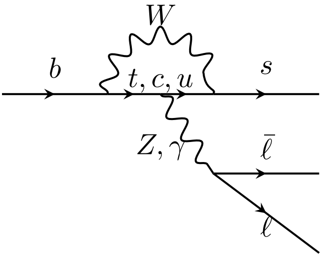
$$R_{D^{(*)}}^{\mathrm{Exp}} > R_{D^{(*)}}^{\mathrm{SM}}$$

Low energy observables

Semileptonic decays in the Standard Model



CC: Tree-level process



FCNC: Loop induced in the SM

EFT description, CC

Naively, NP scale $\sim$ few TeV.

$$\Lambda_{\rm NP} \gg \Lambda_{\rm EW} \gg m_b$$

Assumption: No RH neutrinos.

Effective Hamiltonian: CC

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(1 + g_{V_L})(\bar{c}_L \gamma_\mu b_L)(\bar{l}_L \gamma^\mu \nu_L) + g_{V_R}(\bar{c}_R \gamma_\mu b_R)(\bar{l}_L \gamma^\mu \nu_L)$$
$$+ g_{S_L}\ (\bar{c}_R b_L)(\bar{l}_R \nu_L) + g_{S_R}(\bar{c}_L b_R)(\bar{l}_R \nu_L) + g_{T_L}(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{l}_R \sigma^{\mu\nu} \nu_L) \Big] + \text{h.c.}$$

N.B. $g_i = 0 \Rightarrow$ SM (Fermi theory)

EFT description, FCNC

Naively, NP scale $\sim$ few 10s of TeV.

$$\Lambda_{\mathrm{NP}} \gg \Lambda_{\mathrm{EW}} \gg m_b$$

Assumption: No RH neutrinos.

Effective Hamiltonian: FCNC

$$\mathcal{H}_{\mathrm{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} \mathcal{C}_i(\mu) \mathcal{O}_i(\mu) \quad + \sum_{i=7,8,9,10,P,S,\dots} \mathcal{C}_i(\mu) \mathcal{O}_i \right] + \text{h.c.}$$

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

$$\mathcal{O}_7^{(\prime)} = m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

N.B. $\mathcal{C}_9, \mathcal{C}_{10}, \mathcal{C}_7 \neq 0$ in the SM.

Hadronic matrix elements

Expressed in terms of Form Factors:

$$\langle H_f | J_x | H_i \rangle = \sum_a K_x^a F_a$$

With K_x^a kinematic factors (scalar, vector or tensor), and F_a scalar functions of q^2.

Process	Number of FF
$B \to D\ell\nu$	2 (+ 1 tensor)
$B \to D^*\ell\nu$	4 (+ 3 tensor)
$\Lambda_b \to \Lambda_c\ell\nu$	6 (+ 4 tensor)

Can be obtained from:

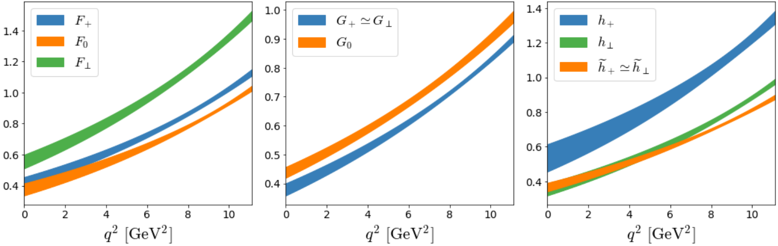
- Lattice QCD
- LCSR, HQET, ...

Hadronic inputs, example $\Lambda_b \to \Lambda_c \ell \nu$

Obtained from a fit to lattice results

$$f(q^2) = \frac{1}{1 - q^2/(m^f_{\rm pole})^2}\left[a_0^f + a_1^f z\left(q^2\right)\right]$$

$$z\left(q^2\right) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}} \qquad t_0 = q^2_{\rm max} \qquad t_+ = (m^f_{\rm pole})^2$$



[Detmold et al. '15] [Datta et al. '17]

Complication for FCNC: Non-local Form Factors

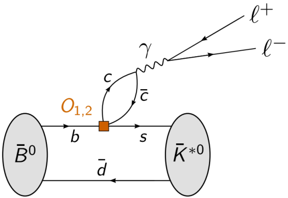
Example for $B \to K\bar{\ell}\ell$:

$$\mathcal{M} = \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^* \left[(\mathcal{A}_\mu + \mathcal{T}_\mu)\, \bar{u}_\ell \gamma^\mu v_\ell + \mathcal{B}_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell \right]$$

$$\mathcal{A}_\mu \propto \mathcal{C}_7, C_9 \qquad\qquad \mathcal{B}_\mu \propto C_{10}$$

$$\mathcal{T}_\mu = \frac{-16i\pi^2}{q^2} \sum_{i=1\cdots 6,8} C_i \int \mathrm{d}^4x \mathrm{e}^{iq\cdot x} \langle K^*|O_i(0) j_\mu(x)|B\rangle$$

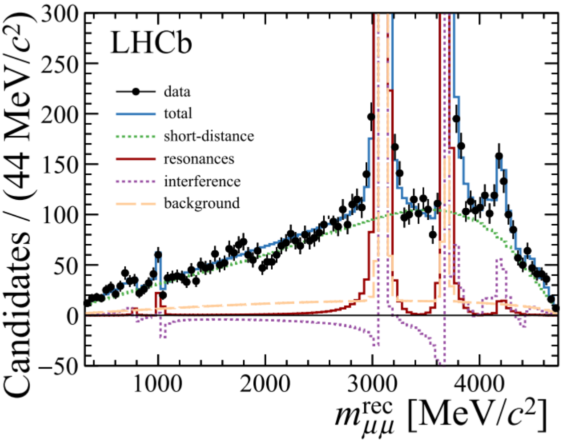
[Grinstein, Pirjol '04]



- Non-pertubative quantity,
- Poles at the J/Ψ, Ψ', etc,
- Hard to compute on the lattice.

Complication for FCNC: Non-local Form Factors

Solution: strong cuts on the q^2 region.



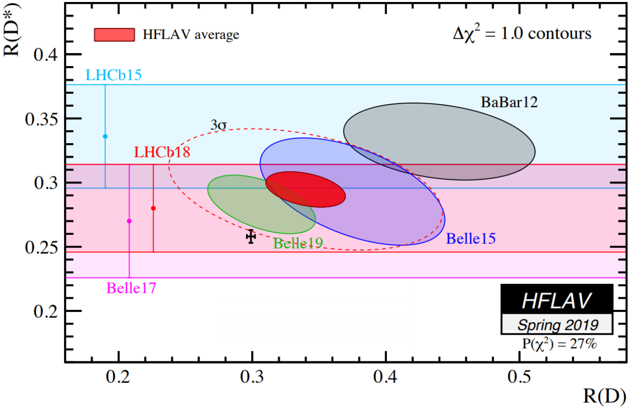
[LHCb ’16]

SM results and experimental status: CC

Results for $b \to c\ell\bar{\nu}$: $\quad R_Y = \frac{\mathcal{B}(X \to Y \tau\bar{\nu})}{\mathcal{B}(X \to Y \mu\bar{\nu})}$

	SM Prediction	Measurement	Tension
R_D	0.299(3)	0.340(30)	1.4σ
	[FNAL, MILC '15, HPQCD '15] cf. HFLAV	[BaBar, Belle, LHCb]	
R_{D^*}	0.258(5)	0.295(14)	2.5σ
	cf. HFLAV	[BaBar, Belle, LHCb]	
$R_{J/\Psi}$	0.260(4)	0.71(26)	1.7σ
	[HPQCD '20]	[LHCb]	
R_{D_s}	0.297(4)	Soon	-
	[HPQCD '17]	[LHCb]	
$R_{D_s^*}$	0.245(8)	Soon	-
	cf. HFLAV	[LHCb]	
R_{Λ_c}	0.333(13)	Soon	-
	[Detmold et al. '15]	[LHCb]	

Combined results, CC, compared to SM

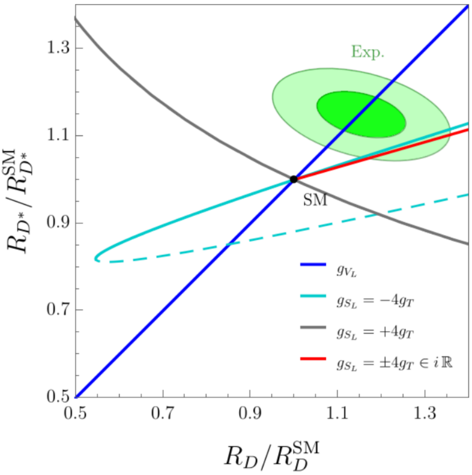


Exp: $R_D = 0.340 \pm 0.030$ $\quad R_{D^*} = 0.295 \pm 0.014$

SM: $R_D = 0.299 \pm 0.003$ $\quad R_{D^*} = 0.258 \pm 0.005$

[cf. HFLAV]

Combined results, CC, compared to SM+NP



Eff. coeff.	1σ range	$\chi^2_{\rm min}/{\rm dof}$
$g_{V_L}(m_b)$	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

$\chi^2_{\rm SM} = 12.7$ [this work]

How to disentangle the New Physics?

LFU ratios insufficient to isolate the Lorentz structure of new physics

- Need other observables
- Example: $\mathcal{B}(B_c \to \tau\bar{\nu}) \lesssim 30\%$

  $\Rightarrow g_P = g_{S_R} - g_{S_L}$ must be tiny

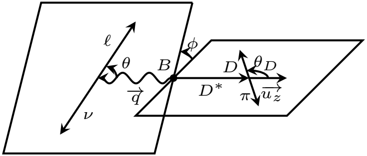
- Angular distributions

$$B \to D^*(\to D\pi)\ell\bar{\nu}$$

$$\Lambda_b \to \Lambda_c(\to \Lambda\pi)\ell\bar{\nu}$$

$\Rightarrow$ Plethora of observables, not yet available

Angular distribution



$$\frac{d^2\mathcal{B}\left(B \to D^* \tau \bar{\nu}\right)}{dq^2 d\cos\theta} = 4\pi\left[A_1 + B_1 \cos\theta + C_1 \cos^2\theta\right]$$

$$\begin{aligned}\frac{d^4\mathcal{B}\left(B \to D^*\left(\to D\pi^+\right)\tau\bar{\nu}\right)}{dq^2 d\cos\theta d\cos\theta_D d\phi} &= A_1 + A_2\cos\theta_D \\ &+ \left(B_1 + B_2\cos\theta_D\right)\cos\theta \\ &+ \left(C_1 + C_2\cos\theta_D\right)\cos^2\theta \\ &+ \left(D_3 \sin\theta_D\cos\phi + D_4\sin\theta_D\sin\phi\right)\sin\theta \\ &+ \left(E_3\sin\theta_D\cos\phi + E_4\sin\theta_D\sin\phi\right)\sin\theta\cos\theta.\end{aligned}$$

$\frac{d\mathcal{B}}{dq^2} \propto 3A_1 + C_1$

$A_{\rm fb} \propto \frac{B_1}{3A_1+C_1}$

Each coefficient is depends on different combinations of g_i and FF.

In particular $D_4, E_4 \propto Im(g_{S_L}) \Rightarrow$ Sensitive to new CP violating phase.

SM results and experimental status: FCNC

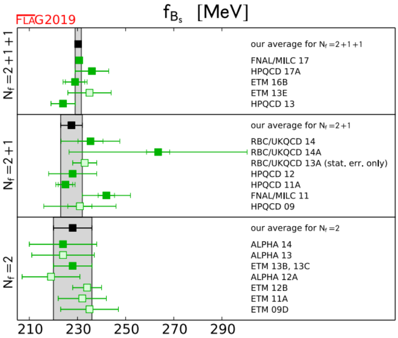
Results for $b \to s\ell\bar{\ell}$: $$R_Y = \frac{\mathcal{B}(X \to Y\mu^+\mu^-)}{\mathcal{B}(X \to Y e^+e^-)}$$

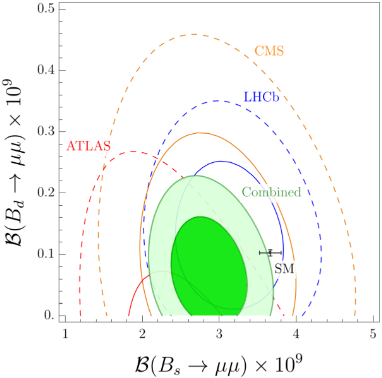
	SM Prediction	Measurement	Tension
$R_K^{[1.1,6]}$	$1.00(1)$ [G. Isidori et al.'20]	$0.847(42)$ [LHCb '21]	3.1σ
$R_{K^*}^{[1.1,6]}$	$1.00(1)$ [M. Bordone et al.'16]	$0.69^{+0.11}_{-0.07}$ [LHCb '17]	2.4σ
$R_{K^*}^{[0.045,1.1]}$	$0.91(3)$ [M. Bordone et al.'16]	$0.66^{+0.11}_{-0.08}$ [LHCb '17]	2.3σ
$R_{pK}^{[0.1,6]}$	~ 1	$0.85^{+0.14}_{-0.13}$ [LHCb]	1σ
R_ϕ	-	Soon [LHCb]	-

$B_s \to \mu\mu$

Not a ratio, but hadronic uncertainties are well under control:

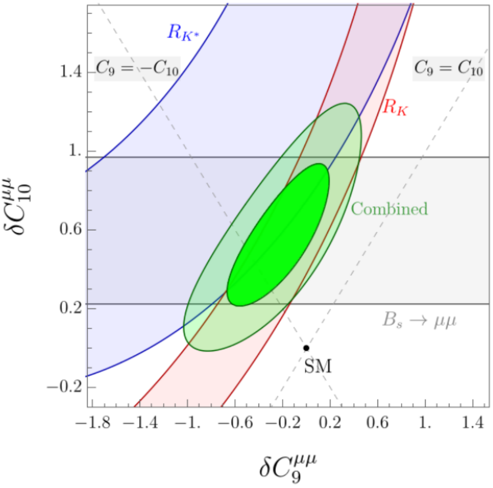
$$\langle 0|\bar{s}\gamma^\mu\gamma_5 b|B_s\rangle = i f_{B_s} p^\mu$$





SM Value	$\mathcal{B}(B_s \to \mu\mu) = 3.66(14) \times 10^{-9}$	[Beneke et al '19]
New LHCb result	$\mathcal{B}(B_s \to \mu\mu) = 3.09^{+0.48}_{-0.44} \times 10^{-9}$	
Our average	$\mathcal{B}(B_s \to \mu\mu) = 2.85(33) \times 10^{-9}$	

Combined results, FCNC, compared to SM



$\delta\mathcal{C}_9 = -\delta\mathcal{C}_{10} = -0.41 \pm 0.09 \qquad (4.6\sigma) \qquad$ [this work]

See [W. Altmannshofer, P. Stangl '21] for global analysis.

Summary

- Recent measurement at LHCb corroborates previous hints of LFUV.

- New physics at $\mathcal{O}(\text{TeV})$ described by means of EFT.

- LFU ratios and other low-energy observables put constraints on the Wilson coefficients, for both CC and FCNC.

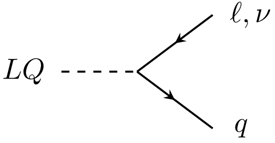
- These observables alone are not enough to disentangle the Lorentz structure of NP.

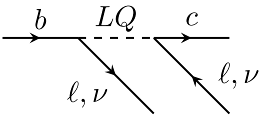
- More observables (angular distributions) needed!

Explicit scenarios of New Physics

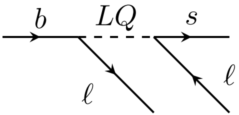
Which NP is compatible with this EFT?

- Should couple preferably to the 3$^{\text{rd}}$ family of fermions.
- Should violate LFU.

$\Rightarrow$ Leptoquarks solve both: 



CC



FCNC: Becomes a tree-level process

- Quite natural in GUT or composite Higgs theories

[D.Marzocca '18].

- Other possibilities exist: Z' (only FCNC), $2HDM$ (tension with $\mathcal{B}(B_c \to \tau\bar{\nu})$)

Classification of Leptoquarks

Name	$SU(3)_C \times SU(2)_L \times U(1)_Y$
S_1	$(\bar{3}, 1, 1/3)$
S_3	$(\bar{3}, 3, 1/3)$
R_2	$(3, 2, 7/6)$
U_1	$(3, 1, 2/3)$
U_3	$(3, 3, 2/3)$

Scalar LQ: S_1, S_3, R_2

Vector LQ: U_1, U_3

We directly exclude scenarios that

- only couple to RH particles ($\widetilde{S}_1$),
- allow for diquark couplings,
- pull R_K and R_{K^*} in different directions ($\widetilde{R}_2$ [D. Bečirević et al. '15]).

Example S_1

Lagrangian:

$$\mathcal{L}_{S_1} = y^L_{ij} \bar{Q}_L^{C\, i,a} \epsilon^{ab} L_L^{j,b} S_1 + y^R_{ij} \bar{u}^C_R e^j_R S_1 + \text{h.c.}$$

Matching:

$$g_{V_L} = \frac{v^2}{4V_{cb}} \frac{y_L^{b\ell'} (V y_L^*)_{c\ell}}{m^2_{S_1}}$$

$$g_{S_L} = -4 g_T = -\frac{v^2}{4V_{cb}} \frac{y_L^{b\ell'} (y_R^{c\ell'})^*}{m^2_{S_1}}$$

$$\mathcal{C}_9^{kl} + \mathcal{C}_{10}^{kl} = \frac{m_t^2 (V^* y_L)_{tk} (V^* y_L)^*_{tl}}{8\pi\alpha_{\text{em}} m^2_{S_1}} - \frac{v^2 (y_L \cdot y_L^\dagger)_{bs} (y_L^\dagger \cdot y_L)_{kl}}{32\pi\alpha_{\text{em}} m^2_{S_1} V_{tb} V^*_{ts}}$$

$$\mathcal{C}_9^{kl} - \mathcal{C}_{10}^{kl} = \frac{m_t^2 (y_R)_{tk} (y_R)^*_{tl}}{8\pi\alpha_{\text{em}} m^2_{S_1}} \left[\log \frac{m^2_{S_1}}{m_t^2} - f(x_t)\right] - \frac{v^2 (y_L \cdot y_L^\dagger)_{bs} (y_L^\dagger \cdot y_L)_{kl}}{32\pi\alpha_{\text{em}} m^2_{S_1} V_{tb} V^*_{ts}}$$

Minimal Assumptions to explain R_K:

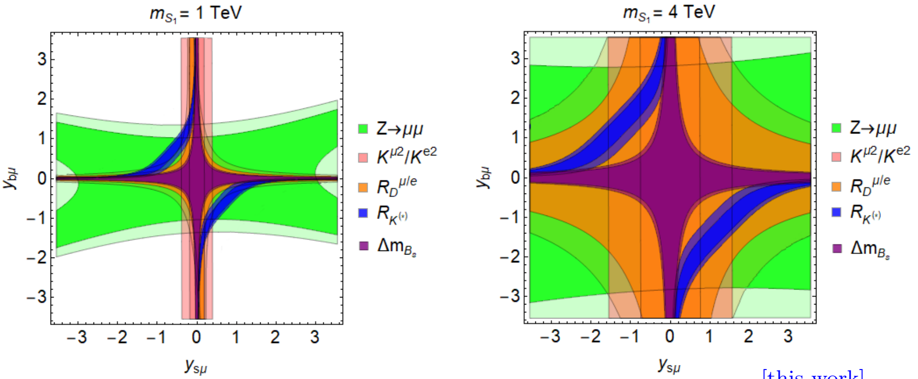
$$y^L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_{s\mu} & 0 \\ 0 & y_{b\mu} & 0 \end{pmatrix}, \quad y^R = 0.$$

Example S_1

Considered quantities:

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}, \qquad R_D^{\mu/e} = \frac{\mathcal{B}(B \to D\mu\bar{\nu})}{\mathcal{B}(B \to De\bar{\nu})}$$

$$K^{\mu 2/e2} = \frac{\mathcal{B}(K \to \mu\bar{\nu})}{\mathcal{B}(K \to e\bar{\nu})}, \qquad \Delta m_{B_s}, \qquad \mathcal{B}(Z \to \mu\mu), \qquad \mathcal{B}(B \to K\nu\nu)$$



[this work]

Leptoquark scenarios

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}\&R_{K^{(*)}}$	
$S_1(\bar{3},1,1/3)$	✓	✗	✗	Scalar LQ
$R_2(3,2,7/6)$	✓	✓/✗*	✗	Scalar LQ
$S_3(\bar{3},3,1/3)$	✗	✓	✗	Scalar LQ
$U_1(3,1,2/3)$	✓	✓	✓	Vector LQ
$U_3(3,3,2/3)$	✗	✓	✗	Vector LQ

$\Rightarrow$ Scalar Leptoquarks: need at least two:
$S_1 - S_3$ [D. Marzocca '18], $R_2 - S_3$ [D. Bečirević et al. '18]

$\Rightarrow$ U_1 Is the only one to accommodate both.

U_1 leptoquark

$$\mathcal{L}_{U_1} = x_L^{ij} \bar{Q}_i \gamma_\mu U_1^\mu L_j + x_R^{ij} \bar{d}_{Ri} \gamma_\mu U_1^\mu \ell_{Rj} + \text{h.c.},$$

Minimal Yukawa structure:

$$x_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x_L^{s\mu} & x_L^{s\tau} \\ 0 & x_L^{b\mu} & x_L^{b\tau} \end{pmatrix}, \quad x_R = 0.$$

Matching:

$$g_{V_L} = \frac{v^2 (V x_L)_{c\ell} (x_L^{b\tau})^*}{2 V_{cb} m_{U_1}^2} \qquad \mathcal{C}_9^{\mu\mu} = -\mathcal{C}_{10}^{\mu\mu} = -\frac{\pi v^2}{V_{tb} V_{ts}^* \alpha_{\text{em}}} \frac{x_L^{s\mu} (x_L^{b\mu})^*}{m_{U_1}^2}$$

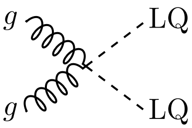
Compatible with $R_{D^{(*)}}$, $R_{K^{(*)}}$, $R_D^{\mu/e}$, $K^{\mu 2/e2}$, ...

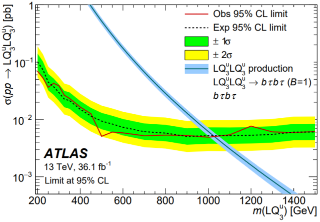
Needs UV completion! E.g $PS^3 = \left[SU(4) \times SU(2) \times SU(2)\right]^3$
$\rightarrow SU(4) \times SU(3) \times SU(2) \times U(1)$ [G. Isidori et al.]

Direct searches at LHC

Direct searches at LHC

$\boxed{LQ(3,X,X)}$





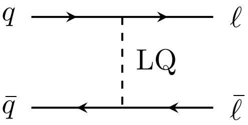
Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\text{int}}$
$jj\tau\bar{\tau}$	-	-	-
$b\bar{b}\tau\bar{\tau}$	1.0(0.8) TeV	1.5(1.3) TeV	36 fb^{-1}
$t\bar{t}\tau\bar{\tau}$	1.4(1.2) TeV	2.0(1.8) TeV	140 fb^{-1}
$jj\mu\bar{\mu}$	1.7(1.4) TeV	2.3(2.1) TeV	140 fb^{-1}
$b\bar{b}\mu\bar{\mu}$	1.7(1.5) TeV	2.3(2.1) TeV	140 fb^{-1}
$t\bar{t}\mu\bar{\mu}$	1.5(1.3) TeV	2.0(1.8) TeV	140 fb^{-1}
$jj\nu\bar{\nu}$	1.0(0.6) TeV	1.8(1.5) TeV	36 fb^{-1}
$b\bar{b}\nu\bar{\nu}$	1.1(0.8) TeV	1.8(1.5) TeV	36 fb^{-1}
$t\bar{t}\nu\bar{\nu}$	1.2(0.9) TeV	1.8(1.6)TeV	140 fb^{-1}

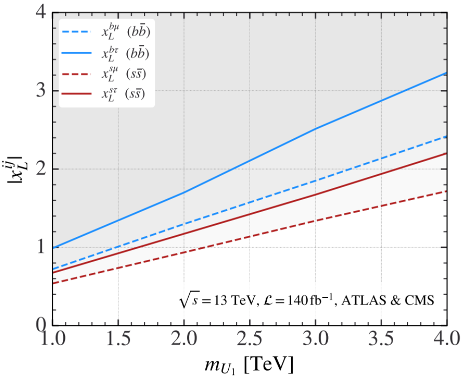
[Atlas, CMS '18-'20]

Assuming a branching fraction of 1 (0.5).

Dilepton tails at LHC

$$\frac{d\sigma}{dp_T}(pp \to \ell\ell)$$





[Atlas, CMS '18-'20]

$\Rightarrow$ Complementary with low energy observables.

[W. Altmannshofer, P. S. Bhupal Dev, A. Soni '17]

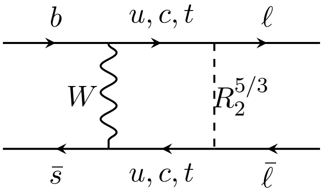
[A. Greljo, D. Marzocca '17] [Y. Afik, et al. '20]

Example: R_2

$$\mathcal{L}_{R_2} = y_R^{ij} \bar{Q}_i \ell_{R\,j} R_2 - y_L^{ij} \bar{u}_{R\,i} R_2 i\tau_2 L_j + \text{h.c.}$$

$$\mathcal{C}_9^{kl} = \mathcal{C}_{10}^{kl} \overset{\text{tree}}{=} -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\text{em}}} \frac{y_R^{sl}(y_R^{bk})^*}{m_{R_2}^2}$$

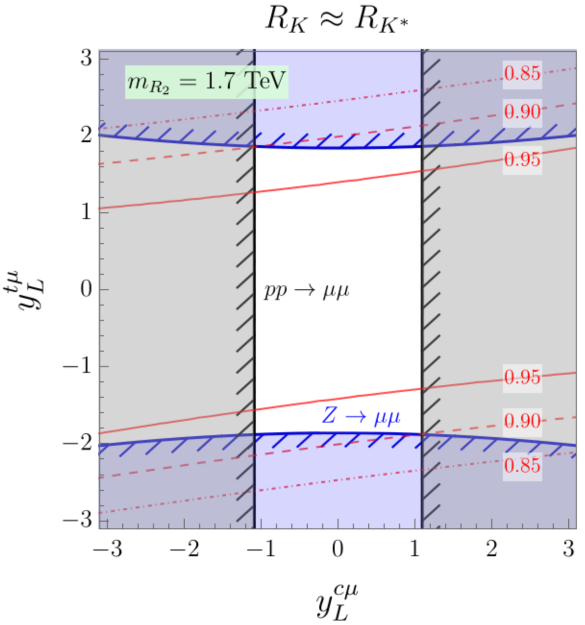
$$\mathcal{C}_9^{kl} = -\mathcal{C}_{10}^{kl} \overset{\text{loop}}{=} \sum_{u,u'\in\{u,c,t\}} \frac{V_{ub}V_{u's}^*}{V_{tb}V_{ts}^*} y_L^{u'k}(y_L^{ul})^* \mathcal{F}(x_u, x_{u'})$$



Minimal Yukawa structure for $R_{K^{(*)}}$:

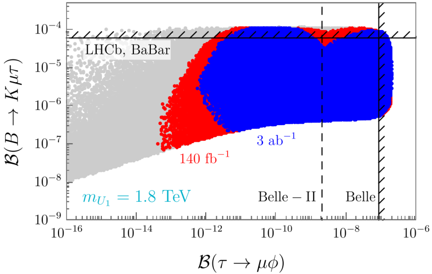
$$y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & 0 \\ 0 & y_L^{t\mu} & 0 \end{pmatrix}, \quad y_R = 0.$$

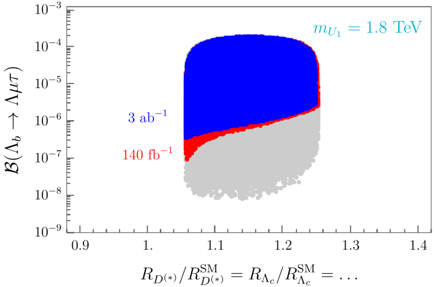
Example: R_2

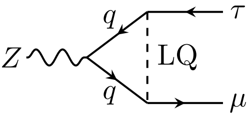


$R_K \approx R_{K^*}$
$m_{R_2} = 1.7$ TeV
0.85
0.90
0.95
0.95
0.90
0.85
$pp \to \mu\mu$
$Z \to \mu\mu$
$y_L^{t\mu}$
$y_L^{c\mu}$
3
2
1
0
−1
−2
−3
−3
−2
−1
0
1
2
3

Prediction: Lepton Flavor Violating decays







$$\left.\begin{array}{l} Z \to \tau\mu \\ \tau \to \mu\gamma \end{array}\right\} \text{Loop induced}$$

$\tau \to \mu\phi$

$B \to K^{(*)}\tau\mu$

$\Lambda_b \to \Lambda\tau\mu$

$$\boxed{\text{Direct searches} \Rightarrow \text{Minimal bounds on LFV decays.}}$$

Summary and perspectives

• Exciting new LHCb data on R_K and $B_s \to \mu\mu$ corroborates previous hints of LFUV, now 3.1σ below SM on R_K.

• When seen as an EFT, LFU ratios and other low-energy observables put constraints on the Wilson coefficients of the theory. $g_{V_L} > 0$, $g_{S_L} = -4g_T > 0$ or $g_{S_L} = \pm 4g_T \in i\mathbb{R}$ and $\mathcal{C}_9 = -\mathcal{C}_{10} < 0$ are preferred

• Lorentz structure of NP can be studied through angular distributions of semileptonic decays at Belle II.

• $\mathcal{O}(1\text{TeV})$ extensions of the SM by Leptoquarks states are a promising realization of this EFT.

• Direct searches impose bounds on masses and individual Yukawas.

• No truly minimal scenario exists, however 2 solutions:

  • $S_1 - S_3$, $R_2 - S_3$
  • U_1+UV completion

• Prediction Experimentally testable LFV decays rates.

Thank you