On a model with two scalar leptoquarks - R_2 and S_3

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[2103.12504] & [2206.09717]

Motivation: LFUV in CC and NC

- Hints of lepton flavor universality violation in $b \to s\ell\ell$ and $b \to c\ell\nu$

$$R_{D^{(*)}} = \frac{\mathcal{B}\left(B \to D^{(*)}\tau\nu\right)}{\mathcal{B}\left(B \to D^{(*)}\mu\nu\right)} \qquad R_{K^{(*)}} = \left.\frac{\mathcal{B}\left(B \to K^{(*)}\mu^+\mu^-\right)}{\mathcal{B}\left(B \to K^{(*)}e^+e^-\right)}\right|_{q^2\in\left[q^2_{\min},q^2_{\max}\right]} .$$

- EFT allows for ***model-independent*** constraints on ***New Physics*** couplings.
- Can we build an ***Explicit Scenario*** to explain both anomalies?

⟶ CC are tree-level in the SM, FCNC are loop-induced.

⟶ The NP couplings to FCNC must be much smaller than to CC in order to have a common NP scale.

Low Energy EFT

- Low energy observable, $m_b \sim m_b^{\overline{\text{MS}}}(m_b) \simeq 4.2\,\text{GeV}$.
- Assuming NP at a scale $\Lambda \gtrsim \mathcal{O}(1\,\text{TeV})$, can be computed using EFT.

Charged Lagrangian :

$$\mathcal{L}_{\text{NP}} \supset -\frac{4G_F V_{ij}}{\sqrt{2}} \sum_X g_X \mathcal{O}_X + \text{h.c.}$$

$$X \in V_L, V_R, S_R, S_L, T$$

Neutral Lagrangian :

$$\mathcal{L}_{\text{NP}} \supset -\frac{4G_F V_{ti} V_{tj}^*}{\sqrt{2}} \sum_X \left(\delta C_X \mathcal{O}_X + \delta C'_X \mathcal{O'}_X\right) + \text{h.c.}$$

$$X \in 9, 10, S, P, \ldots$$

$$\mathcal{O}_X = (\bar{q}_i \Gamma q_j)(\bar{\ell}_\alpha \Gamma \ell_\beta) \quad \text{with} \quad \Gamma \in P_{L/R}, \gamma^\mu P_{L/R}, \sigma^{\mu\nu} P_L$$

- In the SM:

$g_{V_L} = 1$ From tree-level W exchange.

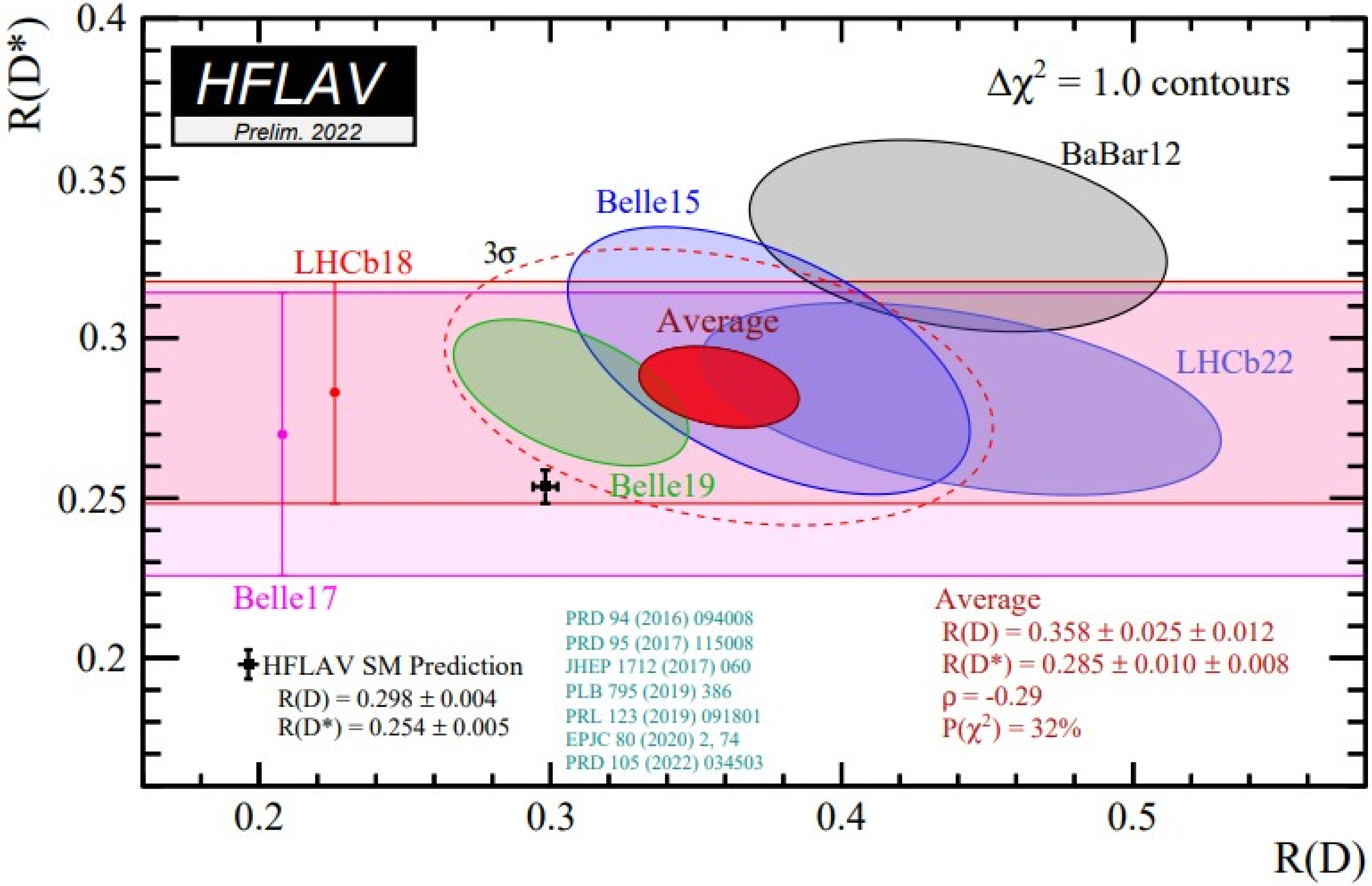
→ Vector – Axial current.

$g_i = 0 \quad (i \in V_R, S_{R/L}, T)$

$\delta\mathcal{C}_{9,10} \neq 0$

Vector ↗ ↖ Axial (leptonic)

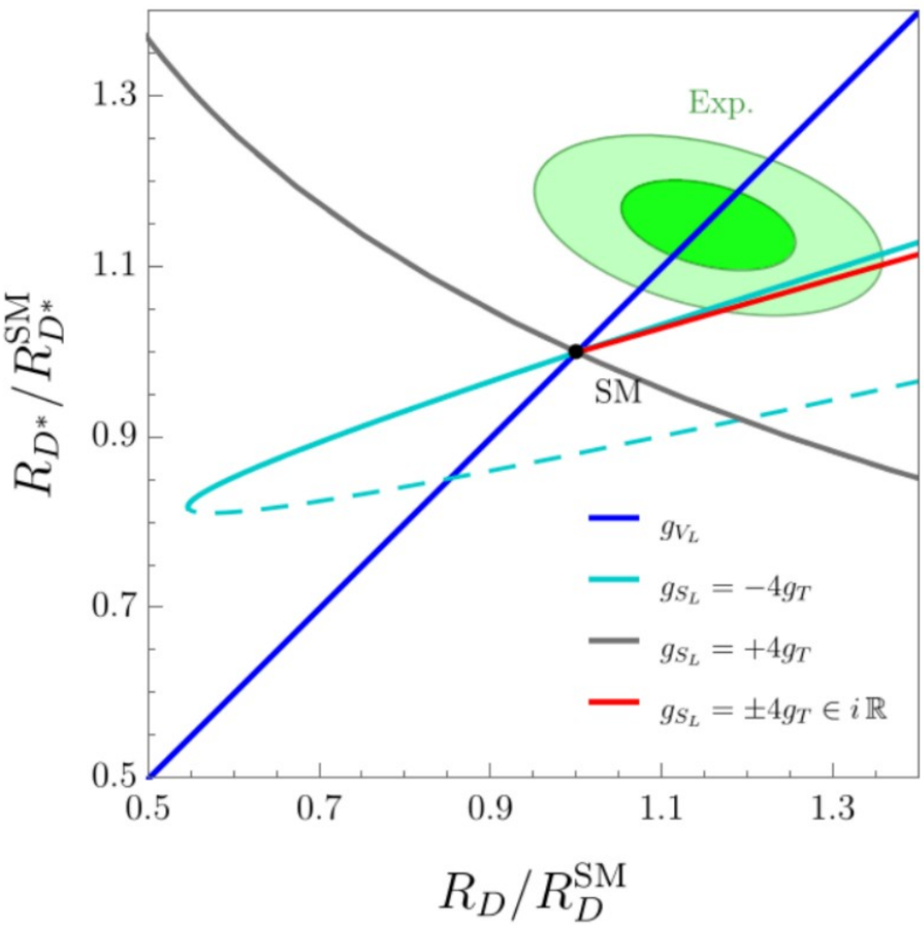
Experimental Status: Charged currents

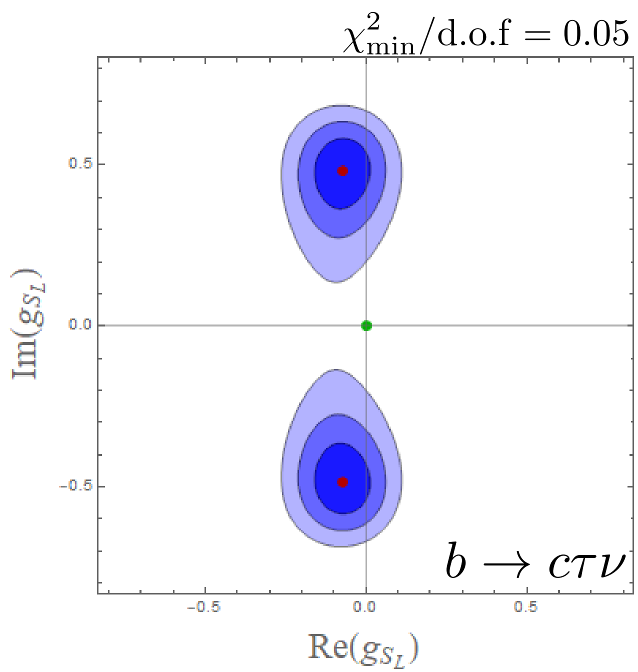


Charged currents: Fit scenarios

- Single Coefficient fit
- Motivated by NP scenarios

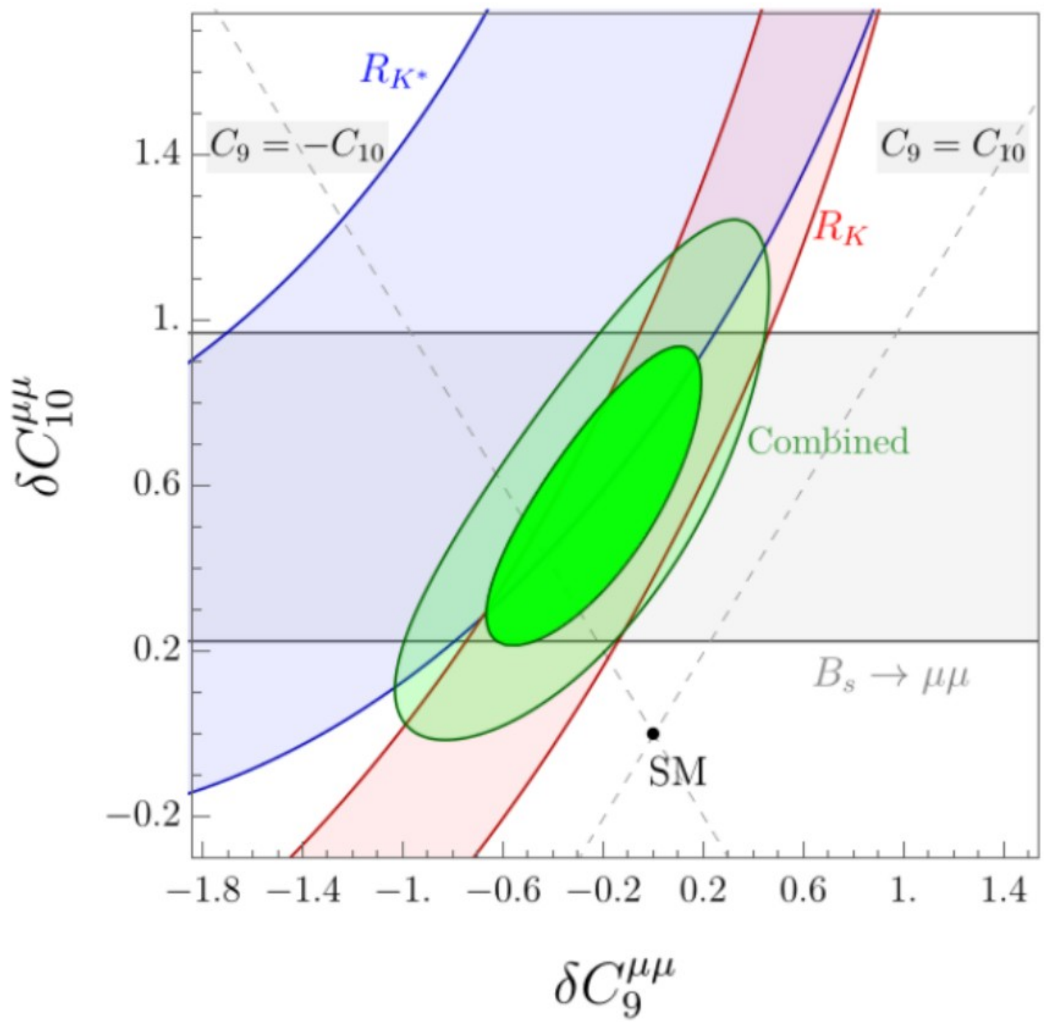
Wilson Coefficient	$R(D)$ and $R(D^*)$	$\chi^2_{\rm min}/$d.o.f
g_{V_L}	0.084 ± 0.029	0.06
g_{S_L}	-1.47 ± 0.08	0.5
g_T	-0.027 ± 0.011	1.2
$g_{S_L} = +4g_T \in i\mathbb{R}$	$\pm 0.49 \pm 0.10$	0.9
$g_{S_L} = -4g_T$	0.16 ± 0.06	0.7





$g_{S_L} = +4g_T$

Neutral currents, Fit scenarios

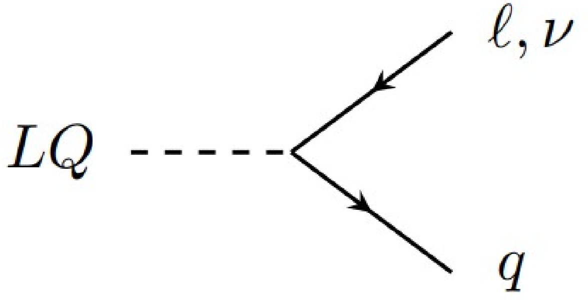


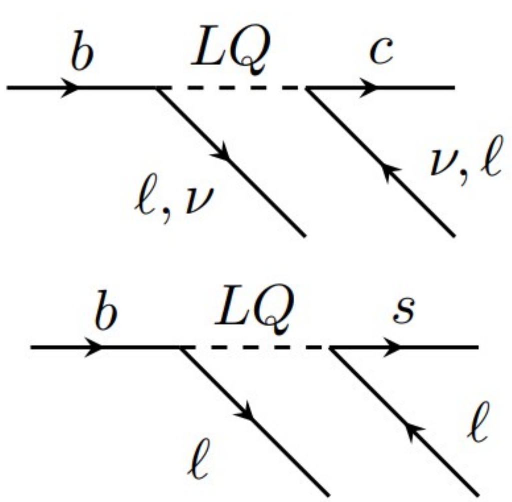
- Using only the cleanest observables.
- See e.g. [W. Altmannshofer, P. Stangl '21] for a global analysis.
- $\delta C_9 = -\delta C_{10} = -0.41 \pm 0.09$
- 4.6σ

Simplified models: Which NP to explain the anomalies?

- NP mediator should couple to quarks and leptons.
- Should allow for LFUV.

  → ***LEPTOQUARKS***





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

- FCNC become ***tree-level***

LQ and low energy constraints

- Only U_1 can explain both anomalies.

  → Being a vector state, it requires a UV-completion. [Isidori et al.]

- Combinations of 2 Scalars are also considered.

E.g. [Marzocca '18], [Becirevic '18],[This work]

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

$R_2 - S_3$ Model

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

$$\mathcal{L}_{R_2} = Y_R^{ij}\bar{Q}_i\ell_{Rj}R_2 + Y_L^{ij}\bar{u}_{Ri}L_j\widetilde{R_2}^{\dagger} + \text{h.c.}$$

$$= (VY_RE_R^{\dagger})^{ij}\bar{u}_{Li}\ell_{Rj}R_2^{5/3} + (Y_RE_R^{\dagger})^{ij}\bar{d}_{Li}\ell_{Rj}R_2^{2/3}$$
$$+(U_RY_L)^{ij}\bar{u}_{Ri}\nu_{Lj}R_2^{2/3} - (U_RY_L)^{ij}\bar{u}_{Ri}\ell_{Lj}R_2^{5/3} + \text{h.c.}$$

$S_3(\bar{3},3,1/3)$:

$$\mathcal{L}_{S_3} = Y^{ij}\bar{Q}_i^C i\tau_2(\tau\cdot S_3)L_j + \text{h.c.}$$

$$= -(Y)^{ij}\bar{d}_{Li}^C\nu_{Lj}S_3^{1/3} + \sqrt{2}(V^*Y)^{ij}\bar{u}_{Li}^C\nu_{Lj}S_3^{-2/3}$$
$$+\sqrt{2}(Y)^{ij}\bar{d}_{Li}^C\ell_{Lj}S_3^{4/3} - (V^*Y)^{ij}\bar{u}_{Li}^C\ell_{Lj}S_3^{1/3} + \text{h.c.}$$

- Assumptions:

$$Y_RE_R^{\dagger} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix},$$

- Only 4 NP parameters:
  $y_R^{b\tau},\ y_L^{c\mu},\ y_L^{c\tau},\ \theta.$

$$Y = -Y_L = -\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix}}_{=\,U_R}\begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix}, \longrightarrow \begin{array}{l} y^{b\mu} = \sin\theta\ y_L^{c\mu}, \\ y^{s\mu} = -\cos\theta\ y_L^{c\mu}. \end{array}$$

$R_2 - S_3$, simple GUT-inspired model

- R_2 and S_3 can be embedded in an $SU(5)$ grand unified symmetry.
- SM Fermions: $\bar{\mathbf{5}}_i = (L, \bar{d}_R)_i, \qquad \mathbf{10}_i = (\bar{e}_R, \bar{u}_R, Q)_i$
- Scalars: $R_2, R_2' \in \mathbf{45}, \mathbf{50}, \qquad S_3 \in \mathbf{45}$
- Couplings: $\mathbf{10}_i \bar{\mathbf{5}}_j \mathbf{45}, \qquad \mathbf{10}_i \mathbf{10}_j \mathbf{50}, \qquad \cancel{\mathbf{10}_i \overline{\mathbf{10}}_j \mathbf{45}}$

  ⟶ Forbidden by proton decay
- Mixing: $\mathbf{45}\ \overline{\mathbf{50}}\ \mathbf{24}$

  ⟶ R_2 and R_2' can mix so that only R_2 is light.
- Imposes $Y = -Y_L$.

Matching

- Charged Currents: $$\mathcal{L} \supset \frac{y_L^{c\tau} y_R^{b\tau *}}{{m_{R_2}}^2}\left[(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + \frac{1}{4}(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_L)\right]$$

$\longrightarrow$ $g_{S_L} = 4 g_T$

(At the matching scale)

- Neutral Currents: $$\mathcal{L} \supset \sin(2\theta)\frac{|y_L^{c\mu}|^2}{{m_{S_3}}^2}(\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$$

$\longrightarrow$ $C_9 = -C_{10}$

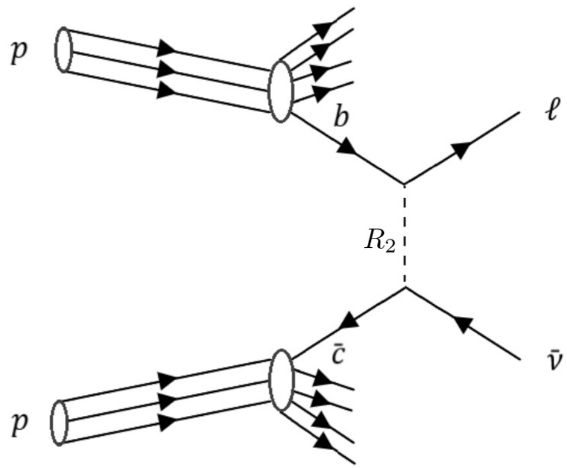
$\downarrow$ Needs to be small

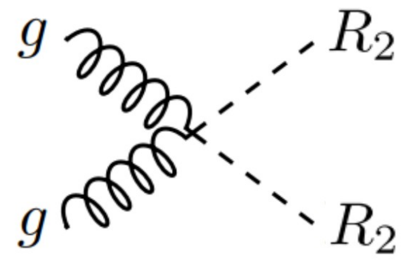
- Contribution to Δm_{B_s}:

$$\propto \frac{\sin(2\theta)^2}{16\pi^2}\frac{\left(|y_L^{c\mu}|^2 + |y_L^{c\tau}|^2\right)^2}{{m_{S_3}}^2}(\bar{s}_L \gamma^\mu b_L)(\bar{s}_L \gamma_\mu b_L)$$

$\longrightarrow$ Safe

High-p_T observables



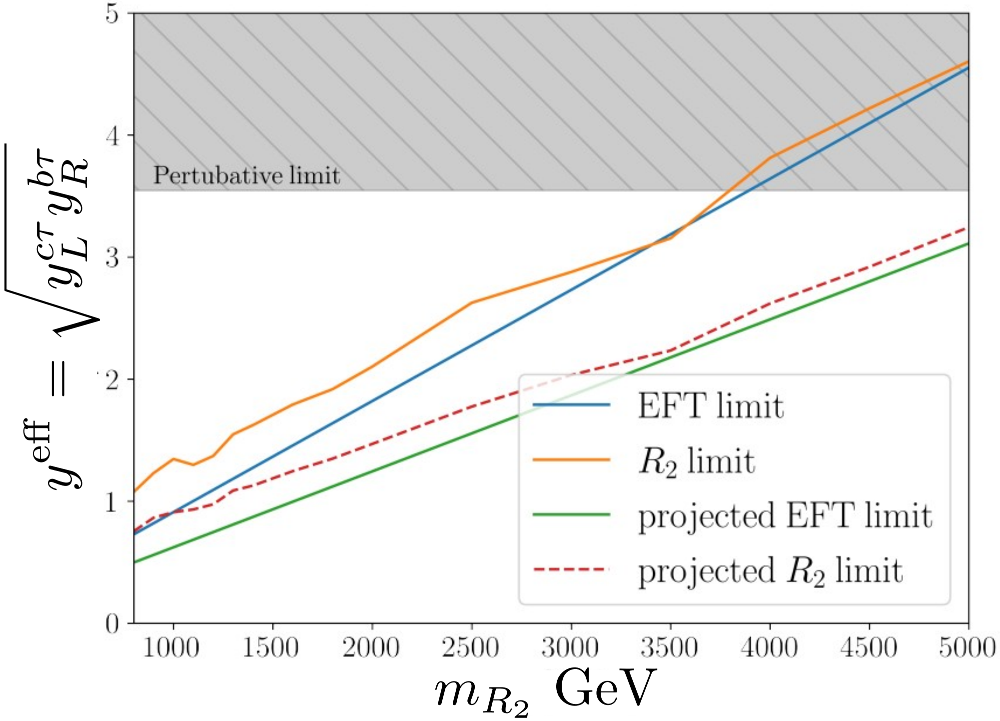


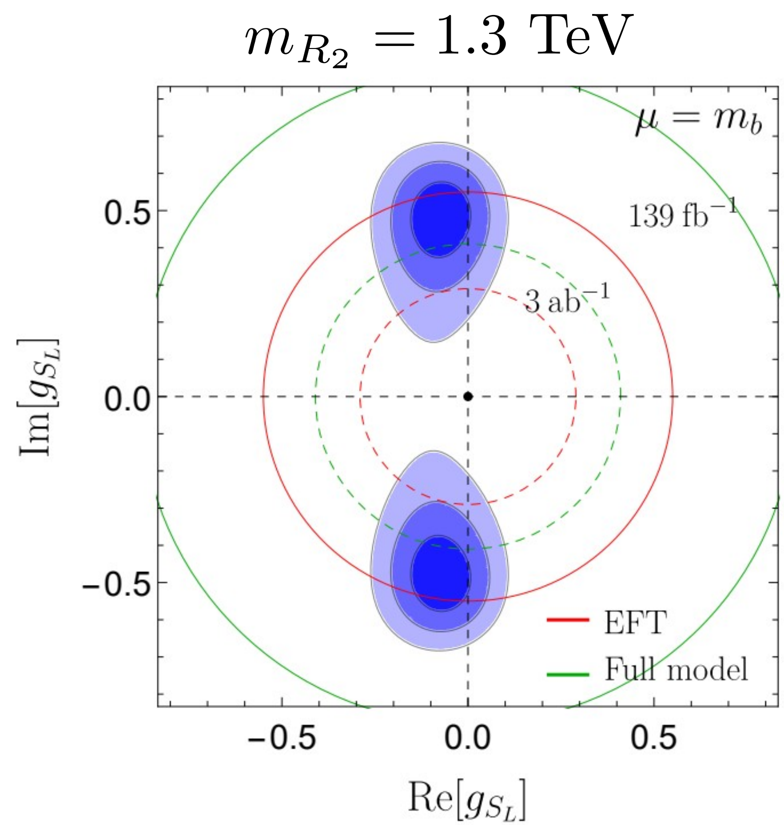
- 2 main signatures at LHC: ***pair-production*** and ***di-lepton***.
- Pair-production gives lower bounds on the masses: 1.3 TeV.
- Di-lepton partonic cross-section is ***energy-enhanced*** compared to SM.

⟶ can overcome the heavy quark suppression in the high-p_T tail.

$$\hat{\sigma}(\hat{s}) \simeq \frac{|V_{cb}|^2 G_F^2 \hat{s}}{18\pi}\left[\frac{3}{4}|g_{S_L}|^2 + 4|g_T|^2\right]$$

High-p_T observables





- EFT expansion overestimates the constraints for $m_{R_2} \lesssim 2$ TeV.
- High-p_T constraints are becoming competitive with flavor.

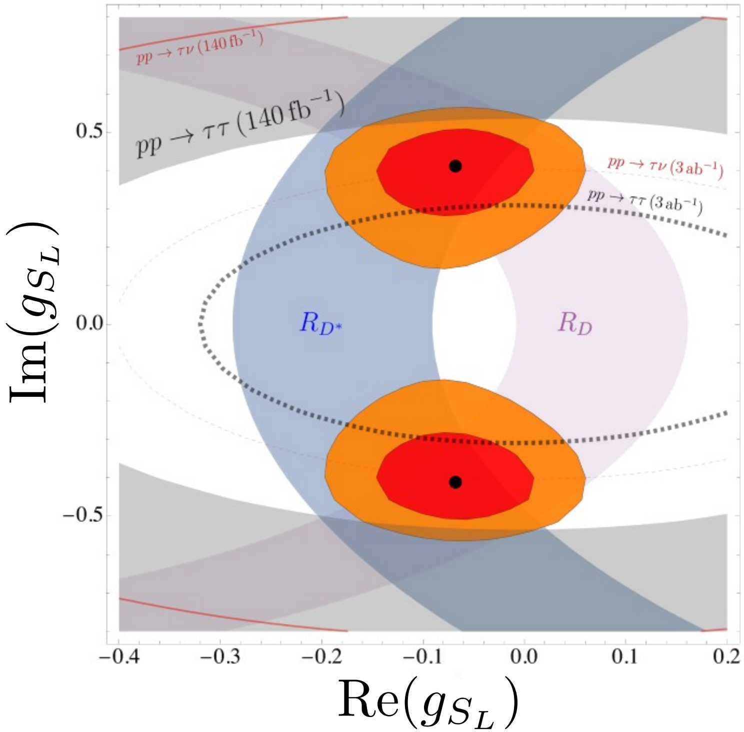
See talk by ***Lukas Allwicher***

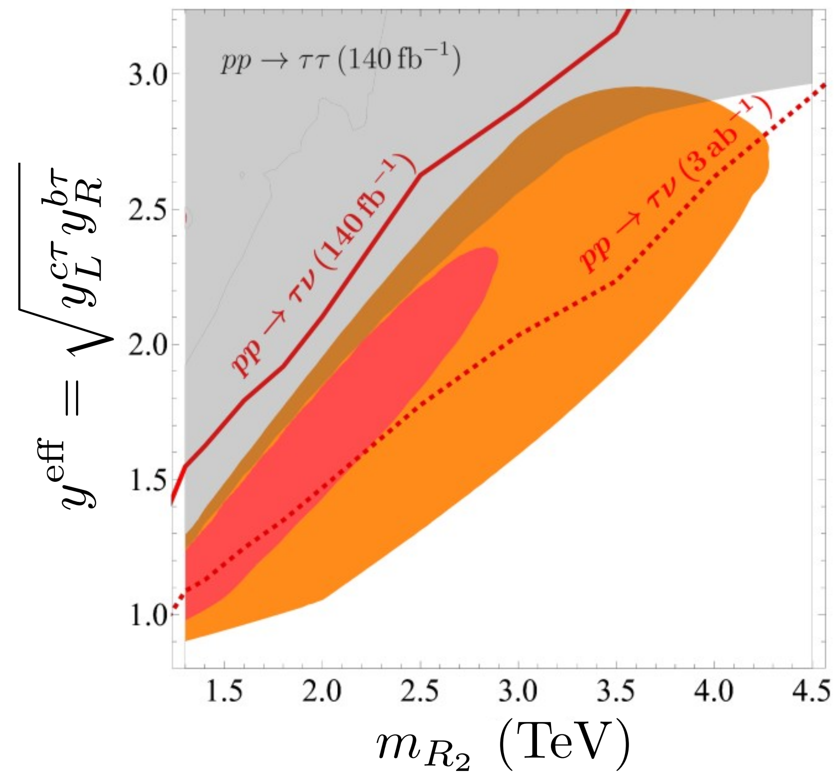
HighPT

[2207.10714]

Results

$m_{R_2} = 1.3 \text{ TeV}, m_{S_3} = 2.0 \text{ TeV}$

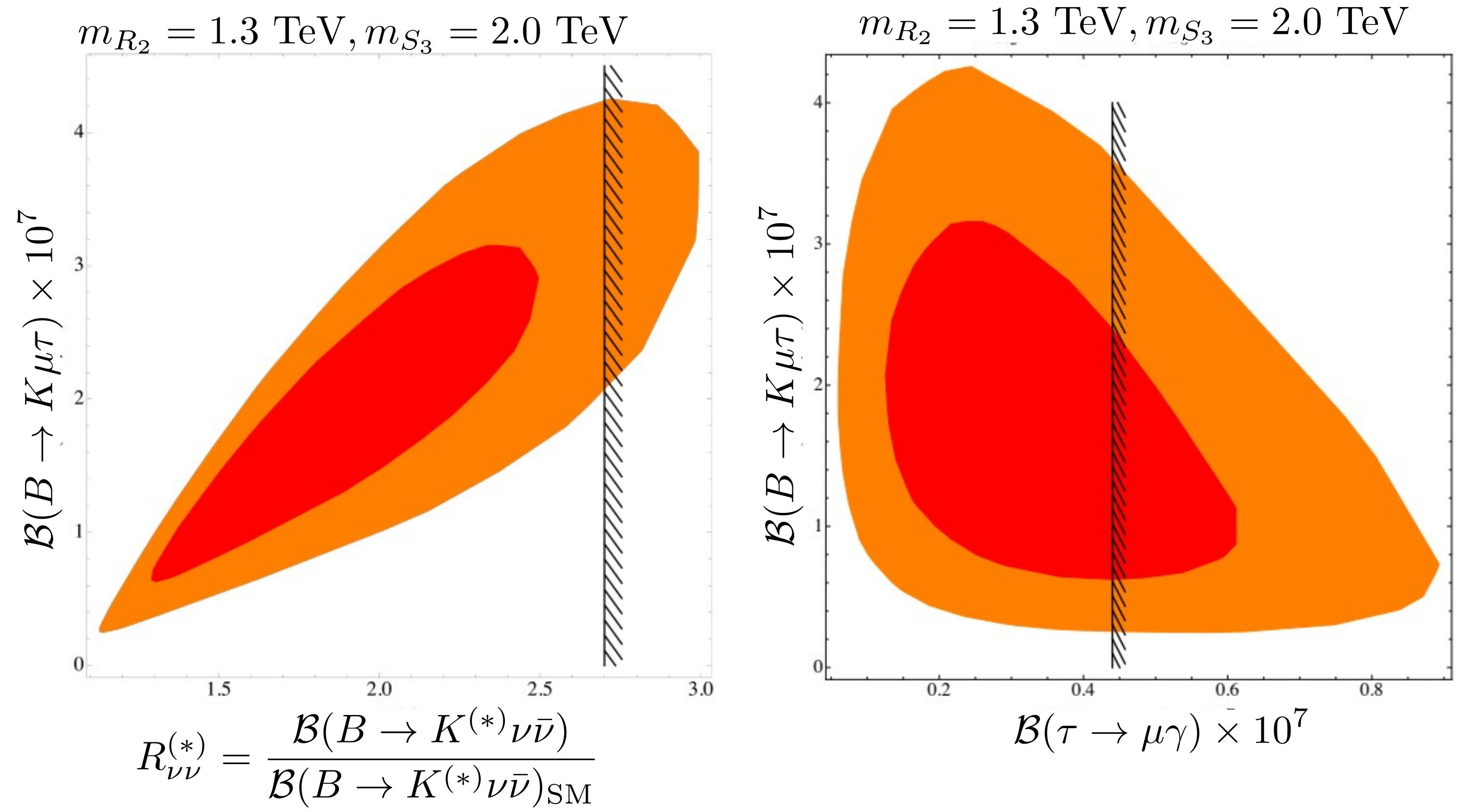




- Big regions of parameter space remains compatible with flavor.
- High-p_T constraints are starting to probe regions allowed by low-energy observables.
- Other constraints from:

$$B_c \to \tau\nu \qquad \Delta m_{B_s} \qquad \tau \to \mu\phi$$
$$Z \to \ell\ell \qquad B \to K^{(*)}\nu\nu \qquad B \to D^{(*)}\mu\nu/e\nu$$
$$W \to \ell\nu \qquad D_s \to \tau\nu/\mu\nu \qquad \ldots$$

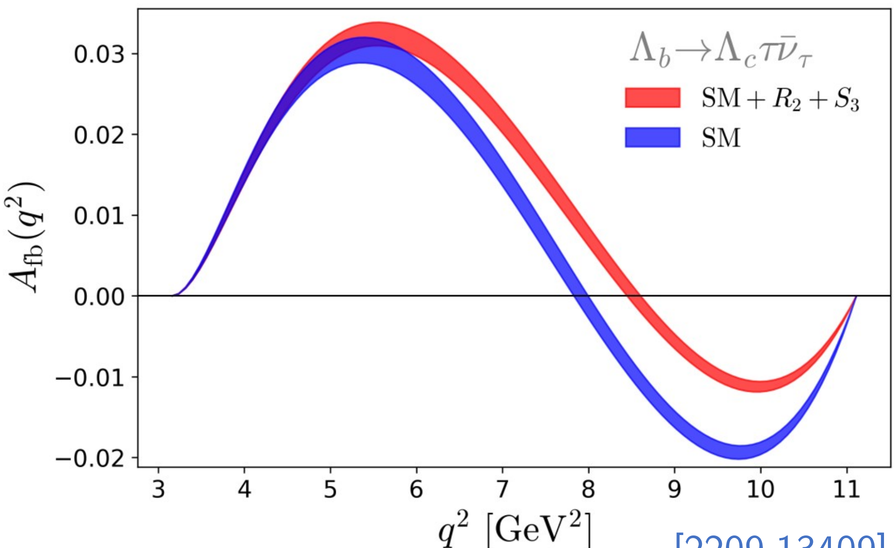
Some predictions : LFV and $R_{\nu\nu}^{(*)}$



- Large value of $R_{\nu\nu}^{(*)}$, $\longrightarrow$ can become a very strong constraint in the future.
- Lower bounds for LFV decays !

Some predictions: angular observables

$$B \to D\tau\bar{\nu}$$
$$B \to D^*(\to D\pi)\tau\bar{\nu}$$
$$\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\bar{\nu}$$



[2209.13409]

$\mathcal{A}_{\mathrm{fb}}$ Baryon

$\mathcal{A}_{\mathrm{fb}}$ Lepton

$$\frac{d^4\Gamma^{\lambda_l}}{dq^2 d\cos\theta d\cos\theta_\Lambda d\phi} = A_1^{\lambda_l} + A_2^{\lambda_l}\cos\theta_\Lambda + \left(B_1^{\lambda_l} + B_2^{\lambda_l}\cos\theta_\Lambda\right)\cos\theta + \left(C_1^{\lambda_l} + C_2^{\lambda_l}\cos\theta_\Lambda\right)\cos^2\theta + \left(D_3^{\lambda_l}\sin\theta_\Lambda\cos\phi + D_4^{\lambda_l}\sin\theta_\Lambda\sin\phi\right)\sin\theta + \left(E_3^{\lambda_l}\sin\theta_\Lambda\cos\phi + E_4^{\lambda_l}\sin\theta_\Lambda\sin\phi\right)\sin\theta\cos\theta$$

NP Phase

- ***Scalar*** and ***Tensor*** operators change the angular structure of semileptonic B decays.
- Some observables are sensitive to the ***CP-violating phase*** (D_4, E_4).

Conclusion

- Simplified models that can accommodate both kind of anomalies :

  $\longrightarrow$ 1 vector Leptoquark $\longrightarrow$ 2 Scalar Leptoquarks

- We proposed and explored a scenario involving R_2 and S_3 .

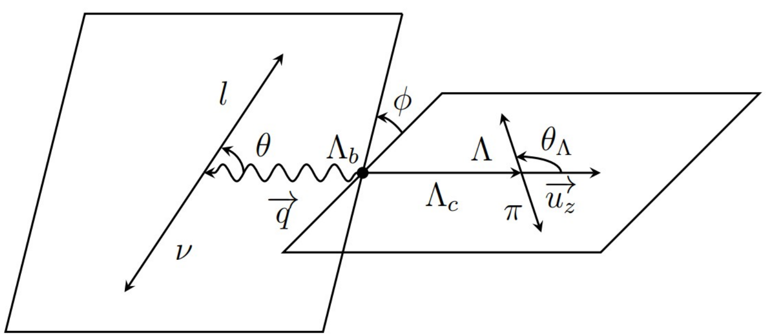
- With only 4 NP parameters and LQ masses, we can accommodate a plethora of low-energy observables.

- Direct Searches at LHC and the study of high-p_T tails provide complementary and competitive constraints to low-energy observable.

- We make several testable predictions:
  - Lower bounds on LFV decays,
  - $R_{\nu\nu}^{(*)}$,
  - Many observable hidden in the angular distributions of b-hadron decays: $B \to D^*(\to D\pi)\tau\bar{\nu}, \Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\bar{\nu}$.

Some observables

- ~~40~~ ~~20~~ 18 observables in total for Baryons.
- Some combinations can be measured by event counting:
  - $\Gamma_{\text{tot}} \propto A_1 + C_1/3$
  - $A_{\text{fb}}^{\ell} \propto B_1$ Forward-Backward Asymmetry (lepton)
  - $A_{\text{fb}}^{\Lambda} \propto A_2 + C_2/3$ Forward-Backward Asymmetry (Baryon)
  - ...



$\mathcal{A}_{\text{fb}}$ Baryon

$\mathcal{A}_{\text{fb}}$ Lepton

$$\frac{d^4\Gamma^{\lambda_l}}{dq^2 d\cos\theta d\cos\theta_\Lambda d\phi} = A_1^{\lambda_l} + A_2^{\lambda_l}\cos\theta_\Lambda + \left(B_1^{\lambda_l} + B_2^{\lambda_l}\cos\theta_\Lambda\right)\cos\theta + \left(C_1^{\lambda_l} + C_2^{\lambda_l}\cos\theta_\Lambda\right)\cos^2\theta + \left(D_3^{\lambda_l}\sin\theta_\Lambda\cos\phi + D_4^{\lambda_l}\sin\theta_\Lambda\sin\phi\right)\sin\theta + \left(E_3^{\lambda_l}\sin\theta_\Lambda\cos\phi + E_4^{\lambda_l}\sin\theta_\Lambda\sin\phi\right)\sin\theta\cos\theta$$

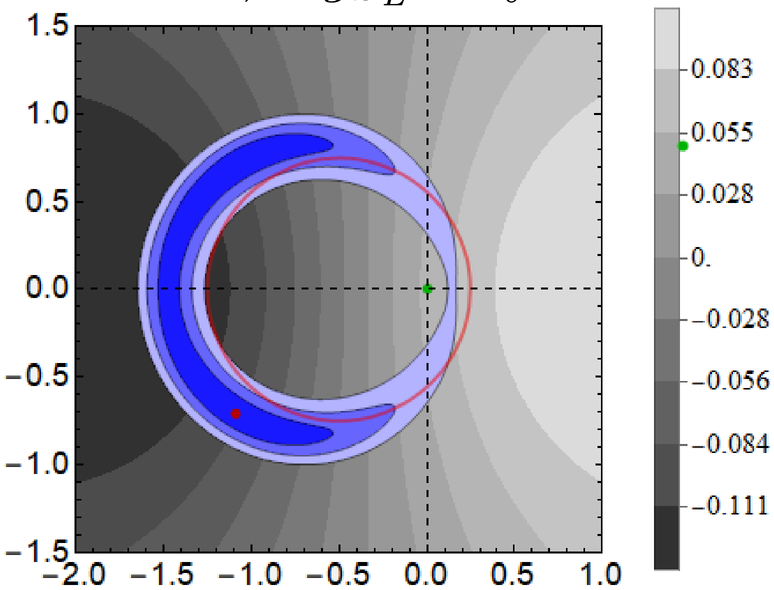
NP Phase

- g_{V_L} only affects the total Branching Fraction → Distribution is SM-like.
- D_4 and E_4 are sensitive to imaginary part of Wilson Coefficients.

→ New Physics phase

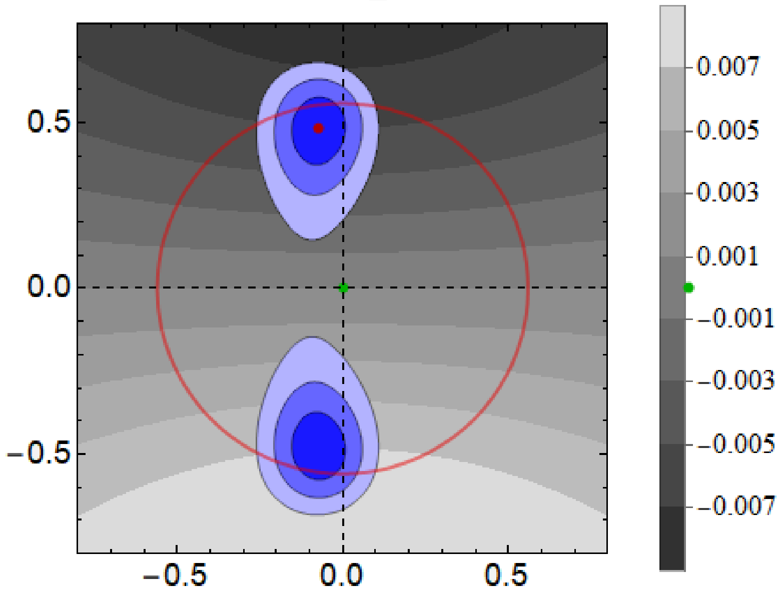
Some observables

$\mathcal{A}_{\rm fb}, \quad g_{S_L}$ only



$\mathcal{A}_{\rm fb}$ can easily flip sign.

$D_4, \quad g_{S_L} = 4 g_T$

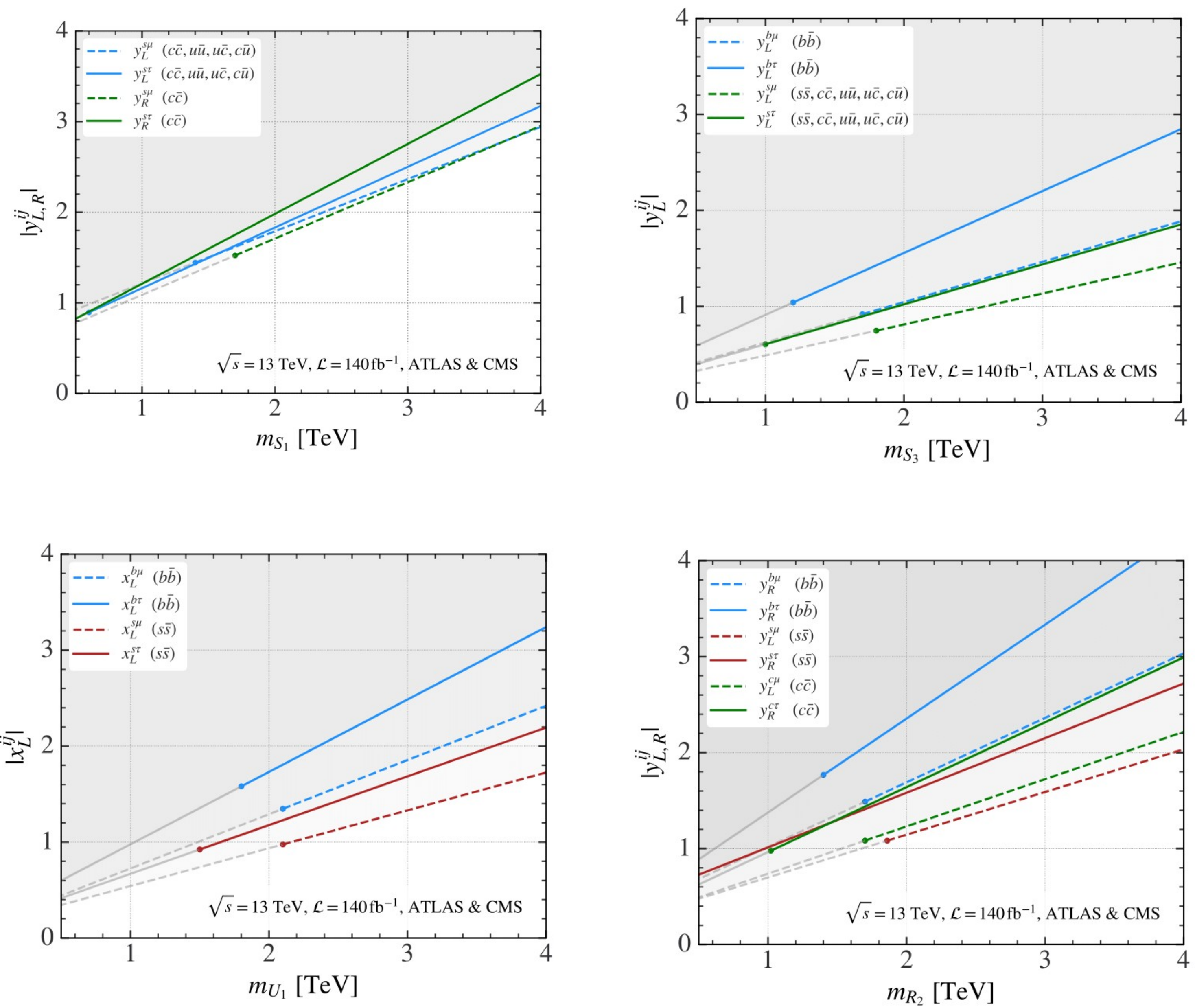


D_4 is exactly 0 in the SM.

D_4 is sensitive to the CP-phase.

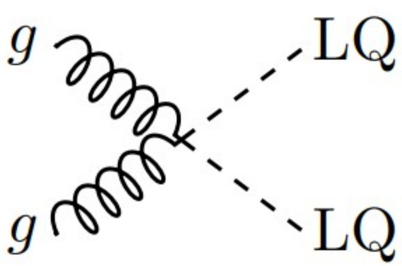
- Angular observables can help discriminate among various scenarios. [Even if $\mathcal{R}(\Lambda_c)$ and $\mathcal{R}(D^{(*)})$ are compatible with SM !]

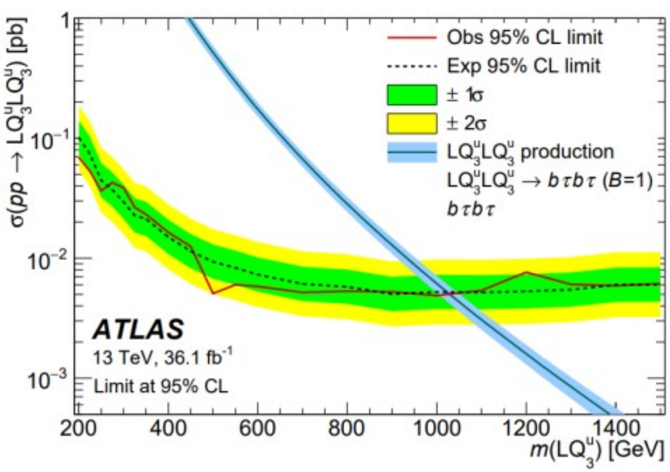
Backup: constraints on Leptoquarks



Backup: limits from pair production

$LQ(3, X, X)$



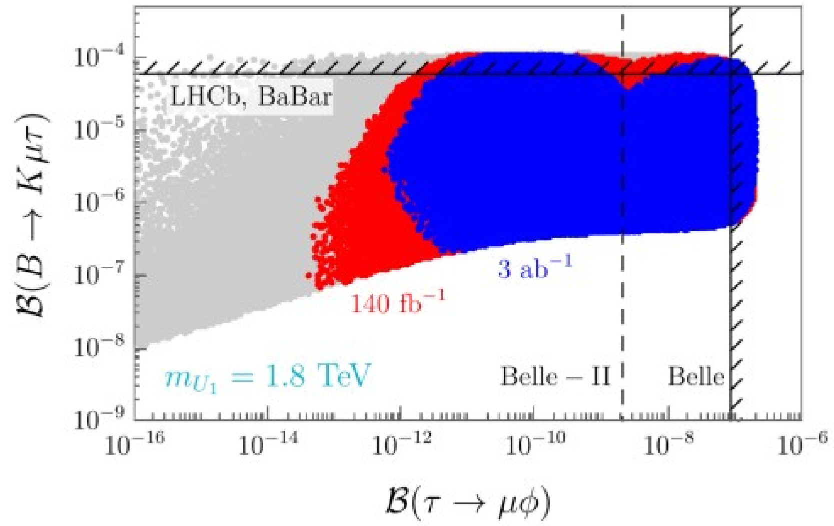


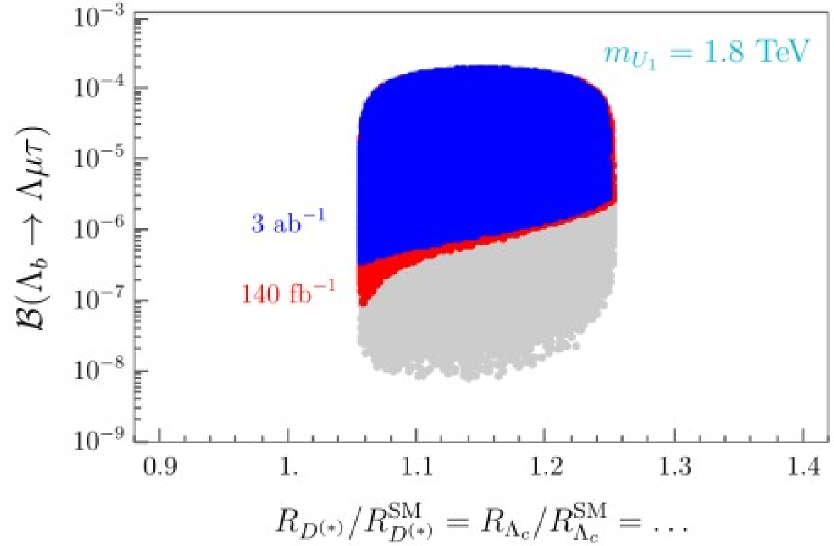
Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\rm int}$
$jj\tau\bar{\tau}$	-	-	-
$b\bar{b}\tau\bar{\tau}$	1.0(0.8) TeV	1.5(1.3) TeV	36 fb^{-1}
$t\bar{t}\tau\bar{\tau}$	1.4(1.2) TeV	2.0(1.8) TeV	140 fb^{-1}
$jj\mu\bar{\mu}$	1.7(1.4) TeV	2.3(2.1) TeV	140 fb^{-1}
$b\bar{b}\mu\bar{\mu}$	1.7(1.5)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

Backup: LFV decays





$Z \to \tau\mu$, $\tau \to \mu\gamma$ } Loop induced

$\tau \to \mu\phi$

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

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

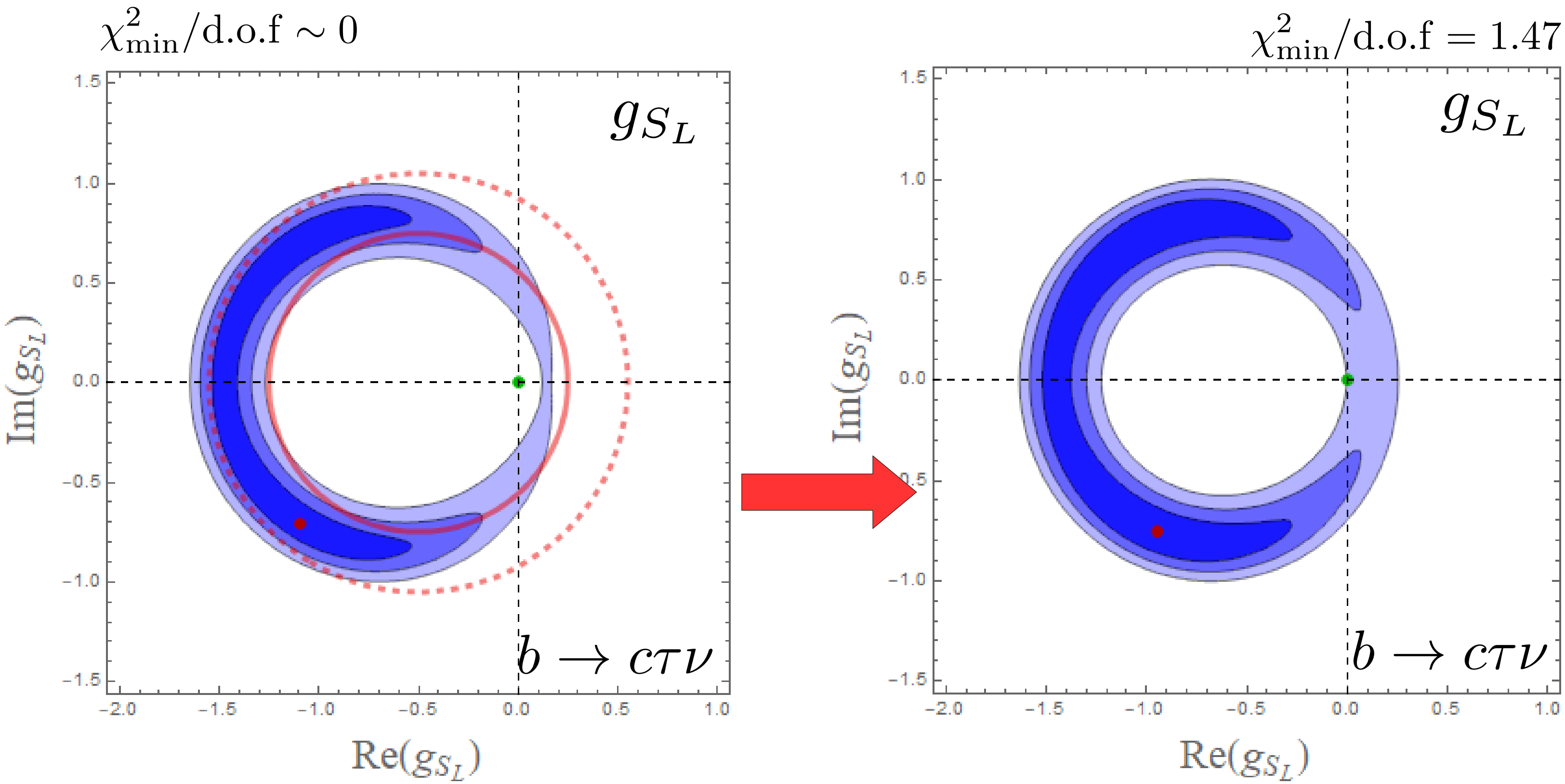
Direct searches $\Rightarrow$ Minimal bounds on LFV decays.

Results

- Best fit point :

$$
\begin{aligned}
y_L^{c\mu} &\in (0.16, 0.33)_{1\sigma}, (0.11, 0.40)_{2\sigma}, \\
y_L^{c\tau} &\in (0.87, 1.40)_{1\sigma}, (0.64, 1.54)_{2\sigma}, \\
\mathrm{Re}\left[y_R^{b\tau}\right] &\in (-0.37, 0.02)_{1\sigma}, (-0.58, 0.15)_{2\sigma}, \\
\left|\mathrm{Im}\left[y_R^{b\tau}\right]\right| &\in (0.83, 1.53)_{1\sigma}, (0.61, 1.87)_{2\sigma}, \\
\theta &\in \frac{\pi}{2}(1.01, 1.06)_{1\sigma}, \frac{\pi}{2}(1.01, 1.12)_{2\sigma},
\end{aligned}
$$

Backup : Old and new constraints



Wilson Coefficient	$R(D)$ and $R(D^*)$	$R(\Lambda_c)$	Combined	$\chi^2_{\rm min}/{\rm d.o.f}$
g_{V_L}	0.084 ± 0.029	-0.15 ± 0.14	0.077 ± 0.035	$0.06 \to 1.3$
g_{S_L}	-1.47 ± 0.08	-0.53 ± 0.54	-1.45 ± 0.11	$0.5 \to 2.1$
g_T	-0.027 ± 0.011	0.13 ± 0.14	-0.026 ± 0.013	$1.2 \to 1.7$
$g_{S_L} = +4g_T \in i\mathbb{R}$	$\pm 0.49 \pm 0.10$	0.0 ± 0.39	$\pm 0.47 \pm 0.13$	$0.9 \to 1.6$
$g_{S_L} = -4g_T$	0.16 ± 0.06	0.0 ± 0.39	0.15 ± 0.07	$0.7 \to 1.0$

Backup: Experimental Status: Neutral currents

- Results for $b \to s\ell\bar{\ell}$:

$$R_X = \frac{\mathcal{B}(Y \to X\mu^+\mu^-)}{\mathcal{B}(Y \to Xe^+e^-)}$$

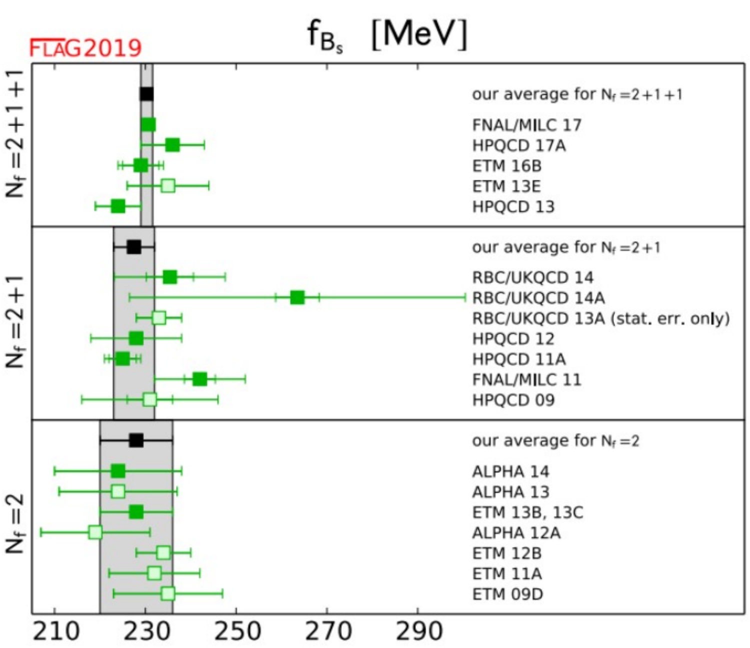
	SM prediction	Measurement	Tension
$R_K^{[1.1,6]}$	1.00(1) [G. Isidori et al.'20]	0.847(42) [LHCb '21]	3.1σ
$R_{K^*}^{[1.1,6]}$	1.00(1) [M. Bordone et al.'16]	0.69(10) [LHCb '17]	2.4σ
$R_{K^*}^{[0.045,1.1]}$	0.91(3) [M. Bordone et al.'16]	0.66(10) [LHCb '17]	2.3σ
$R_{pK}^{[0.1,6]}$	$\simeq 1$	0.85(14) [LHCb]	1σ

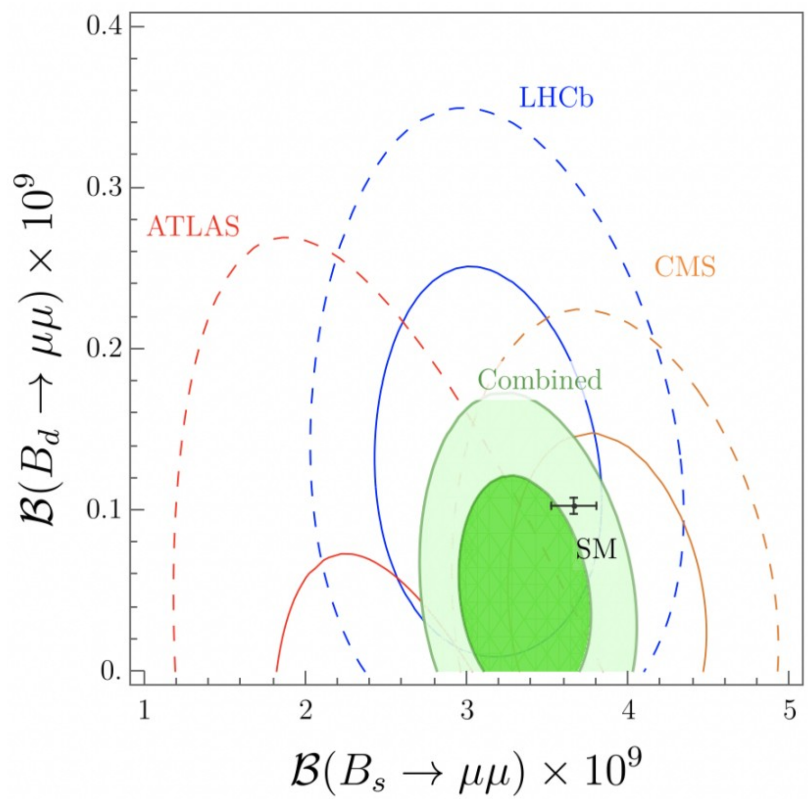
+ Some angular observables, which are more or less “safe”.

Backup: Another decay: $B_s \to \mu^+\mu^-$

- Can also probe the same quark transition $b\bar{s} \to \ell\bar{\ell}$.
- Not a ratio, but hadronic uncertainties are well under control.
- The hadronic matrix element depends on a single quantity:

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





Backup: FCNC update