EFFECTIVE FIELD THEORY FOR B MESON ANOMALIES

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DAVIDE IACOBACCI

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OUTLINE

EFFECTIVE FIELD THEORY FRAMEWORK

- General Remarks on EFTs
- Effective Field Theory in the Standard Model
- Effective Field Theory approaches for physics Beyond the Standard Model

B PHYSICS ANOMALIES

- Lepton Flavor Universality Tests and Anomalous Observables
- Fitting New Physics Wilson Coefficients
- Selection of Leptoquark Models

INTEGRATING OUT HEAVY DEGREES OF FREEDOM

- **EFTs PROVIDE A SIMPLIFIED ANALYSIS OF THE PROBLEM AT HAND**

- Suppose we are interested in the physics occurring at low energy scales $E \ll \Lambda, \; \Lambda \approx E_0$:

$$\phi(k) = \phi_L(k) + \phi_H(k) \; , \qquad \begin{array}{l} |k| << \Lambda \; , \; \text{for } \phi_L(k) \; , \\ |k| >> \Lambda \; , \; \text{for } \phi_H(k) \; . \end{array} \longrightarrow$$

Separation of scales!

- Integrating-out the heavy field from the partition function:

$$\int \mathcal{D}\phi_L \mathcal{D}\phi_H e^{iS[\phi_L,\phi_H]+i\int d^dx J_L(x)\phi_L(x)} = \int \mathcal{D}\phi_L e^{iS_\Lambda^{\text{eff}}[\phi_L]+i\int d^dx J_L(x)\phi_L(x)} \; ,$$

- The Wilsonian effective action is defined from:

$$e^{iS_\Lambda^{\text{eff}}[\phi_L]} = \int \mathcal{D}\phi_H e^{iS[\phi_L,\phi_H]} \; .$$

- $S_\Lambda^{eff}(\phi_L)$ is written as an infinite sum of local operators via Operator Product Expansion (OPE):

$$S_\Lambda^{\text{eff}}[\phi_L(x)] = \int d^4x \mathcal{L}_\Lambda^{\text{eff}}[\phi_L(x)] \; , \quad \mathcal{L}_\Lambda^{\text{eff}}[\phi_L(x)] = \sum_i c_i O_i[\phi_L(x)] \; .$$

- The Wilson coefficients c_i are determined through the ***matching procedure*** of the effective theory onto the full theory.

- The most general effective Lagrangian is formulated via OPE, ensuring compatibility with the symmetries of the theory.

POWER COUNTING SCHEME

- The integration of heavy degrees of freedom can be written in the form:

$$\int_{k\leq\Lambda} \mathcal{D}\phi_k e^{iS_\Lambda[\phi_k]} = \int_{k\leq\Lambda'} \mathcal{D}\phi'_k e^{iS'_{\Lambda'}[\phi'_k]} \ .$$

- By setting $\Lambda = s\Lambda'$, with $s < 1$, the integrating-out procedure corresponds to integration over momentum shells.
- Given the effective Lagrangian $\mathcal{L}_\Lambda^{\text{eff}} = \sum_{N,M} c_{N,M} O_{N,M} \ ,$
- Under the scale transformation: $x' = xs, \quad k' = k/s \ , \ \ c_{N,M} \to s^{N(d/2-1)+M-d} c_{N,M} = s^{d_i-d} c_{N,M} \ .$

$$O_i \sim \left(\frac{k}{\Lambda}\right)^{d_i-d} , \quad k << \Lambda \quad \longrightarrow \begin{cases} d_i < d & \text{relevant} \\ d_i = d & \text{marginal} \\ d_i > d & \text{irrelevant} \end{cases} \longrightarrow$$

POWER COUNTING

EXAMPLE: FERMI THEORY

The SM charged current Lagrangian is

$$\mathcal{L}_{CC} = -\frac{1}{2}(\partial_\mu W^\dagger_\nu - \partial_\nu W^\dagger_\mu)(\partial^\mu W^\nu - \partial^\nu W^\mu) + M_W^2 W^\dagger_\mu W^\mu - \frac{g}{\sqrt{2}}\left(W^\dagger_\mu J^\dagger_\mu + W_\mu J_\mu\right) ,$$

with the current given by

$$J^\dagger_\mu = \bar{u}_i \gamma_\mu V_{ij} P_L d_j + \bar{\nu}_{\ell_i} \gamma_\mu P_L \ell_i \ .$$

The generating functional can be written as

$$Z_{CC}[J, J^\dagger] = \frac{1}{Z_{CC}[0,0]} \int DW_\mu DW^\dagger_\mu e^{iS_{CC}[J,J^\dagger]} ,$$

where the action is given by

$$S_{CC}[J, J^\dagger] = \int d^D x \left[\int d^D y \, W(x)^\dagger_\mu K^{\mu\nu}_W (x-y) W_\nu(y) - \frac{g}{\sqrt{2}} \left(W^\dagger_\mu(x) J^{\dagger\,\mu}(x) + W_\mu(x) J^\mu(x) \right) \right] ,$$

with

$$K^{\mu\nu}_W = \delta^{(D)}(x-y)(\Box_y + M_W^2) - \partial^\mu_y \partial^\nu_y \ .$$

EXAMPLE: FERMI THEORY

We introduce the new field

$$W'_\mu(x) = W_\mu(x) - i\frac{g}{\sqrt{2}}\int d^D y D^W_{\mu\nu}(x-y)J^{\nu\,\dagger}(y) \ ,$$

where $D^W_{\mu\nu}(x-y)$ is the propagator:

$$D^W_{\mu\nu}(x-y) = \int \frac{d^D k}{(2\pi)^D}\frac{i}{k^2 - M_W^2 - i\epsilon}e^{-ik(x-y)}\left(g_{\mu\nu} - \frac{k_\mu k_\nu}{M_W^2}\right) \ .$$

We can then perform the functional integral and we get the effective action

$$W_{CC}[J, J^\dagger] = -\frac{g^2}{2}\int d^D x d^D y J^{\dagger\,\mu}(x)[iD^W_{\mu\nu}(x-y)]J^\nu(y) \ .$$

At energies lower than the W boson mass, we can expand in powers of k^2/M_W^2:

$$iD^W_{\mu\nu}(x-y) = \int \frac{d^D k}{(2\pi)^D}\sum_{n=0}^{\infty}\frac{1}{M_W^2}\left(\frac{k^2}{M_W^2}\right)^n\left(g_{\mu\nu} - \frac{(i\partial_\mu)(i\partial_\nu)}{M_W^2}\right)e^{-ik(x-y)} =$$

$$\sum_{n=0}^{\infty}\frac{(-1)^n}{M_W^2}\left(\frac{\Box_y}{M_W^2}\right)^n\left(g_{\mu\nu} + \frac{\partial_\mu\partial_\nu}{M_W^2}\right)\delta^{(D)}(x-y) \ .$$

EXAMPLE: FERMI THEORY

The effective action is:

$$W_{CC}[J, J^\dagger] = -\sum_{n=0}^{\infty} \int d^4x \frac{(-1)^n}{2M_W^2} J^{\mu\dagger}(x) \left(\frac{\Box_x}{M_W^2}\right)^n \left(g_{\mu\nu} + \frac{\partial_\mu \partial_\nu}{M_W^2}\right) J^\nu(x) \ .$$

At leading order, we find:

$$\mathcal{L}_{\text{weak}} \approx -\frac{g^2}{2M_W^2} J_\mu^\dagger(x) J^\mu(x) = -4\frac{G_F}{\sqrt{2}} J_\mu^\dagger(x) J^\mu(x) \ , \quad (\sqrt{2}G_F)^{-1/2} \approx 10^2 \text{ GeV}$$

INCLUDING QCD EFFECTS

- QCD short distance corrections need to be properly considered in the effective Lagrangian
- For example, when considering the generic process $q_1\bar{q}_3 \to q_2\bar{q}_4$, we write

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{q_1 q_2} V^*_{q_3 q_4} (C_1(\mu) Q_1 + C_2(\mu) Q_2) \ ,$$

FERMI THEORY

$$Q_2 = (\bar{q}_2 \gamma^\mu P_L q_1)(\bar{q}_3 \gamma_\mu P_L q_4)$$

INCLUDING QCD EFFECTS

$$Q_1 = (\bar{q}_2^\alpha \gamma^\mu P_L q_1^\beta)(\bar{q}_3^\beta \gamma_\mu P_L q_4^\alpha) \ , \quad Q_2 = (\bar{q}_2^\alpha \gamma^\mu P_L q_1^\alpha)(\bar{q}_3^\beta \gamma_\mu P_L q_4^\beta)$$

- Fermi Lagrangian is then generalised to:

$$\mathcal{L}_{\rm weak} = -4 \frac{G_F}{\sqrt{2}} \sum_i \lambda_i C_i(\mu) \mathcal{O}_i \ .$$

MATCHING PROCEDURE

- The Wilson coefficients C_i are determined through the **matching procedure:**

$$\mathcal{L}_\Lambda^{\text{eff}} = \sum_i C_i O_i$$

RUNNING

$$C_i(\mu_H) \xrightarrow{RGE} C_i(\mu_L)$$

GENERAL RECIPE

$$\mathcal{A}_{\text{eff}} = \mathcal{A}_{\text{fun}} \Rightarrow \sum_i C_i(\mu_H)\langle f|\mathcal{O}_i|i\rangle = \langle f|\mathcal{L}_{\text{fun}}|i\rangle\Big|_{\mu_H}$$

MATCHING CONDITION

COMPLETE BASIS OF DIM-6 OPERATORS FOR WEAK EFFECTIVE THEORY

Current-Current Operators

$$Q_1 = (\bar{s}_\alpha u_\beta)_{V-A}(\bar{u}_\beta d_\alpha)_{V-A} \quad Q_2 = (\bar{s}u)_{V-A}(\bar{u}d)_{V-A}$$

QCD Penguins Operators

$$Q_3 = (\bar{s}d)_{V-A}\sum_q(\bar{q}q)_{V-A} \quad Q_4 = (\bar{s}_\alpha d_\beta)_{V-A}\sum_q(\bar{q}_\beta q_\alpha)_{V-A}$$

$$Q_5 = (\bar{s}d)_{V-A}\sum_q(\bar{q}q)_{V+A} \quad Q_6 = (\bar{s}_\alpha d_\beta)_{V-A}\sum_q(\bar{q}_\beta q_\alpha)_{V+A}$$

Electroweak Penguins Operators

$$Q_7 = \frac{3}{2}(\bar{s}d)_{V-A}\sum_q e_q(\bar{q}q)_{V+A} \quad Q_8 = \frac{3}{2}(\bar{s}_\alpha d_\beta)_{V-A}\sum_q e_q(\bar{q}_\beta q_\alpha)_{V+A}$$

$$Q_9 = \frac{3}{2}(\bar{s}d)_{V-A}\sum_q e_q(\bar{q}q)_{V-A} \quad Q_{10} = \frac{3}{2}(\bar{s}_\alpha d_\beta)_{V-A}\sum_q e_q(\bar{q}_\beta q_\alpha)_{V-A}$$

Magnetic Penguins Operators

$$Q_{7\,\gamma} = \frac{e}{8\pi^2}m_b\bar{s}_\alpha\sigma^{\mu\nu}(1+\gamma_5)b_\alpha F_{\mu\nu} \quad Q_{8\,G} = \frac{g}{8\pi^2}m_b\bar{s}_\alpha\sigma^{\mu\nu}(1+\gamma_5)T^a_{\alpha\beta}b_\beta G^a_{\mu\nu}$$

Semi-Leptonic Operators

$$Q_{7\,V} = (\bar{s}d)_{V-A}(\bar{\ell}\ell)_{\mathrm{V}} \quad Q_{7\,A} = (\bar{s}d)_{V-A}(\bar{\ell}\ell)_{\mathrm{A}}$$

$$Q_{9\,V} = (\bar{b}s)_{V-A}(\bar{\ell}\ell)_{\mathrm{V}} \quad Q_{10\,A} = (\bar{b}s)_{V-A}(\bar{\ell}\ell)_{\mathrm{A}}$$

$$Q_{\nu\nu} = (\bar{s}d)_{V-A}(\bar{\nu}\nu)_{V-A} \quad Q_{\ell\nu} = (\bar{u}d)_{V-A}(\bar{\ell}\nu)_{V-A}$$

$\Delta S = 2$ and $\Delta B = 2$ Operators

$$Q_{\Delta S=2} = (\bar{s}d)_{V-A}(\bar{s}d)_{V-A} \quad Q_{\Delta B=2} = (\bar{b}d)_{V-A}(\bar{b}d)_{V-A}$$

WHAT ABOUT NEW PHYSICS EFFECTS?

SMEFT:
STANDARD MODEL EFFECTIVE THEORY

- SM Lagrangian can be seen as the leading order (dimension-4 term) of a broader EFT:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{d=5}^{\infty} \frac{1}{\Lambda^{d-4}} \sum_{i}^{n_d} C_i^{(d)} Q_i^{(d)}$$

- The leading dimension-6 Lagrangian that preserve baryon and lepton number consists in 59 operators.

- The search for New Physics is conducted in a **model independent** manner.

- When a specific UV model is selected one can write the Wilson coefficients in terms of the parameters of the UV theory.

X^3		H^6		H^4D^2		$\psi^2H^3 + \text{h.c.}$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar{L}_p e_r H)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$			Q_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$	Q_{uH}	$(H^\dagger H)(\bar{Q}_p u_r \widetilde{H})$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar{Q}_p d_r H)$
$Q_{\widetilde{W}}$	$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

X^2H^2		$\psi^2XH + \text{h.c.}$		ψ^2H^2D	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{L}_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}_p\gamma^\mu L_r)$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{L}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{L}_p\tau^I\gamma^\mu L_r)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{Q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{Q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}_p\gamma^\mu Q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{Q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{Q}_p\tau^I\gamma^\mu Q_r)$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{Q}_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
Q_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{Q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$Q_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{Q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{L}_p\gamma_\mu L_r)(\bar{L}_s\gamma^\mu L_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{L}_p\gamma_\mu L_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{Q}_p\gamma_\mu Q_r)(\bar{Q}_s\gamma^\mu Q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{L}_p\gamma_\mu L_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{Q}_p\gamma_\mu\tau^I Q_r)(\bar{Q}_s\gamma^\mu\tau^I Q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{L}_p\gamma_\mu L_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{L}_p\gamma_\mu L_r)(\bar{Q}_s\gamma^\mu Q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{Q}_p\gamma_\mu Q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{L}_p\gamma_\mu\tau^I L_r)(\bar{Q}_s\gamma^\mu\tau^I Q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{Q}_p\gamma_\mu Q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{Q}_p\gamma_\mu T^A Q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{Q}_p\gamma_\mu Q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{Q}_p\gamma_\mu T^A Q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

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

B. Grzadkowski, M. Iskrzynski, M. Misiak, J. Rosiek
JHEP 10 (2010) 085
E. E. Jenkins, A. Manohar, M. Trott
JHEP 10 (2013) 087

WEAK EFFECTIVE THEORY EXTENDED WITH NEW PHYSICS OPERATORS

- For example, the Semi-Leptonic operators are used to study B anomalies:

STANDARD MODEL	NEW PHYSICS		
$Q_{9\,V} = (\bar{b}s)_{V-A}(\bar{\ell}\ell)_{\mathrm{V}}$ $Q_{10\,A} = (\bar{b}s)_{V-A}(\bar{\ell}\ell)_{\mathrm{A}}$	$Q'_{9\,V} = (\bar{b}s)_{V+A}(\bar{\ell}\ell)_{\mathrm{V}}$ $Q'_{10\,A} = (\bar{b}s)_{V+A}(\bar{\ell}\ell)_{\mathrm{A}}$	$\longrightarrow$	**FCNC processes** $b \to s\ell\ell$
$Q_{\ell\nu} = (\bar{u}d)_{V-A}(\bar{\ell}\nu)_{V-A}$	$\mathcal{O}^{\ell}_{V_R} = (\bar{c}_R\gamma^{\mu}b_R)(\bar{\ell}_L\gamma_{\mu}\nu_{\ell L})$ $\mathcal{O}^{\ell}_{S_L} = (\bar{c}_Lb_R)(\bar{\ell}_R\nu_{\ell L})$ $\mathcal{O}^{\ell}_{S_R} = (\bar{c}_Rb_L)(\bar{\ell}_R\nu_{\ell L})$ $\mathcal{O}^{\ell}_{T} = (\bar{c}_R\sigma^{\mu\nu}b_L)(\bar{\ell}_R\sigma_{\mu\nu}\nu_{\ell L})$	$\longrightarrow$	**FCCC processes** $b \to c\ell\nu$

EFFECTIVE APPROACHES FOR NEW PHYSICS

Λ — $\mathcal{L}_{NP} \xrightarrow{\text{matching}} \mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \sum_d \frac{1}{\Lambda^{d-4}} \sum_k \tilde{C}_k^{(d)}(\Lambda) Q_k^{(d)}$

$\big\downarrow$ *RGE*

v — $\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(4)} + \sum_d \frac{1}{\Lambda^{d-4}} \sum_k \tilde{C}_k^{(d)}(v) Q_k^{(d)} \xrightarrow{\text{matching}} \mathcal{H}_{WET} = -\frac{4G_F}{\sqrt{2}} \sum_i C_i(v) \mathcal{O}_i$

Integrating-out W, Z, H, t $\longleftarrow$

$\big\downarrow$ *RGE*

μ_b — $\mathcal{H}_{WET} = -\frac{4G_F}{\sqrt{2}} \sum_i C_i(\mu_b) \mathcal{O}_i$

μ

TOP-DOWN

BOTTOM-UP

B PHYSICS ANOMALIES

New Physics Wilson Coefficients and Selection of New Physics Models

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OBSERVABLES OF NEUTRAL B MESON DECAYS

- $\boldsymbol{b \to s\, \ell^+ \ell^-}$

HADRONIC INSENSITIVE

- $R_K, R_{K^*}, BR(B_s \to \mu^+\mu^-)$.
- Well determined experimentally and theoretically due to suppression of hadronic uncertainties.

HADRONIC SENSITIVE

- Branching ratios of $B \to K^{(*)}\mu^+\mu^-$ and $B \to \phi\, \mu^+\mu^-$ in many $q^2 -$ bins.
- Angular observables in $B \to K^{(*)}\mu^+\mu^-$.
- Strongly affected by hadronic uncertainties.

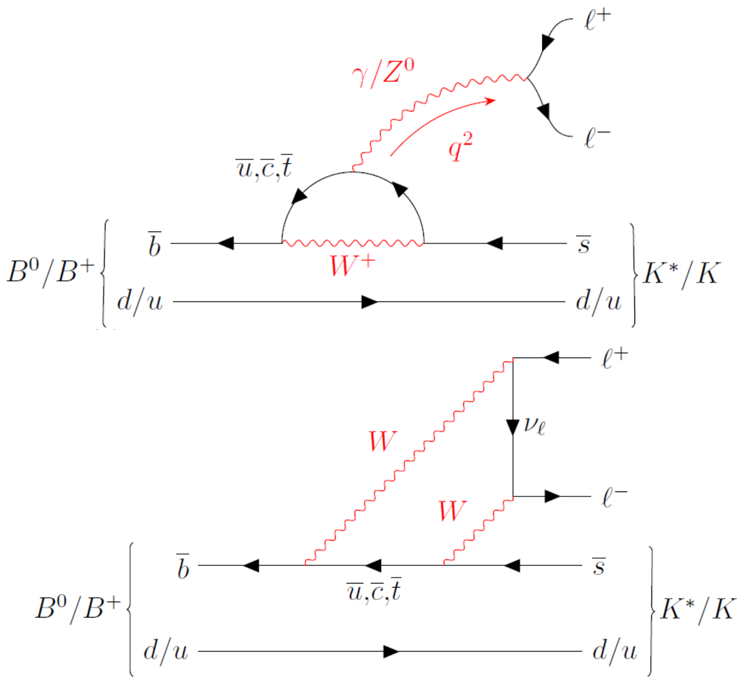
R_K, R_{K^*} and $BR(B_s \to \mu^+\mu^-)$

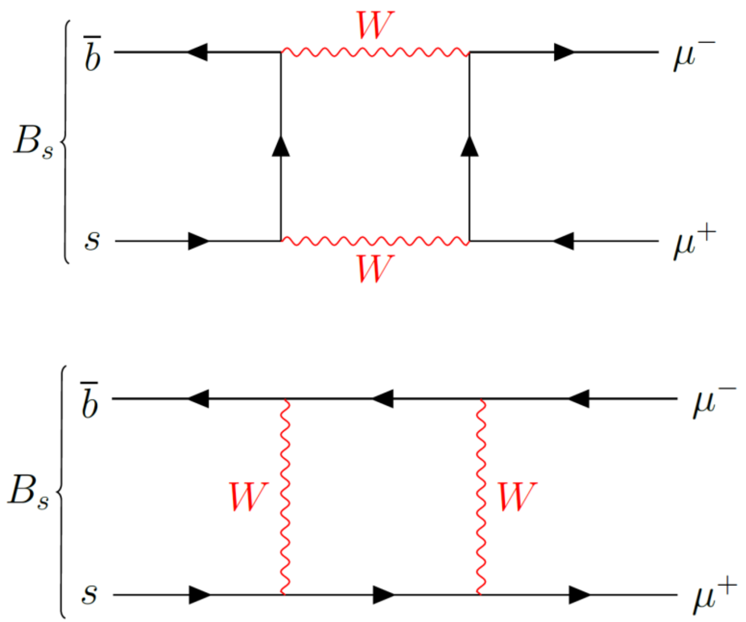
- $b \to s\,\ell^+\ell^-$ is suppressed in the SM.

➢ **Highly sensitive to New Physics!**

$$R_K = \frac{\mathrm{BR}\,(B^+ \to K^+\mu^+\mu^-)}{\mathrm{BR}\,(B^+ \to K^+e^+e^-)}, \quad R_{K^*} = \frac{\mathrm{BR}\,(B \to K^*\mu^+\mu^-)}{\mathrm{BR}\,(B \to K^*e^+e^-)}$$

- The ratios cancel large part of theoretical and experimental uncertainties.





$b \to s\ell^+\ell^-$ WEAK EFFECTIVE HAMILTONIAN

$$\mathcal{H}_{\rm eff} = -V_{tb}V_{ts}^*\frac{\alpha_{\rm em}}{4\pi v^2}\sum_{\ell,X,Y} C_{b_X\ell_Y}\mathcal{O}_{b_X\ell_Y} + \text{h.c.}\,,$$ with $$\mathcal{O}_{b_X\ell_Y} = (\bar{s}\gamma_\mu P_X b)(\bar{\ell}\gamma_\mu P_Y \ell)\,.$$ $\longrightarrow$ **CHIRAL BASIS**

- We split the Wilson coefficients as:

$$C_{b_X\ell_Y} = C^{SM}_{b_X\ell_Y} + C^{BSM}_{b_X\ell_Y}\,.$$

- We use the following analytic expression:

$$R_K = \frac{|C_{b_{L+R}\mu_{L-R}}|^2 + |C_{b_{L+R}\mu_{L+R}}|^2}{|C_{b_{L+R}e_{L-R}}|^2 + |C_{b_{L+R}e_{L+R}}|^2}\,,$$

$$R_{K^*} = \frac{(1-p)(|C_{b_{L+R}\mu_{L-R}}|^2 + |C_{b_{L+R}\mu_{L+R}}|^2) + p\left(|C_{b_{L-R}\mu_{L-R}}|^2 + |C_{b_{L-R}\mu_{L+R}}|^2\right)}{(1-p)(|C_{b_{L+R}e_{L-R}}|^2 + |C_{b_{L+R}e_{L+R}}|^2) + p\left(|C_{b_{L-R}e_{L-R}}|^2 + |C_{b_{L-R}e_{L+R}}|^2\right)}\,, \qquad p \approx 0.86\,,$$

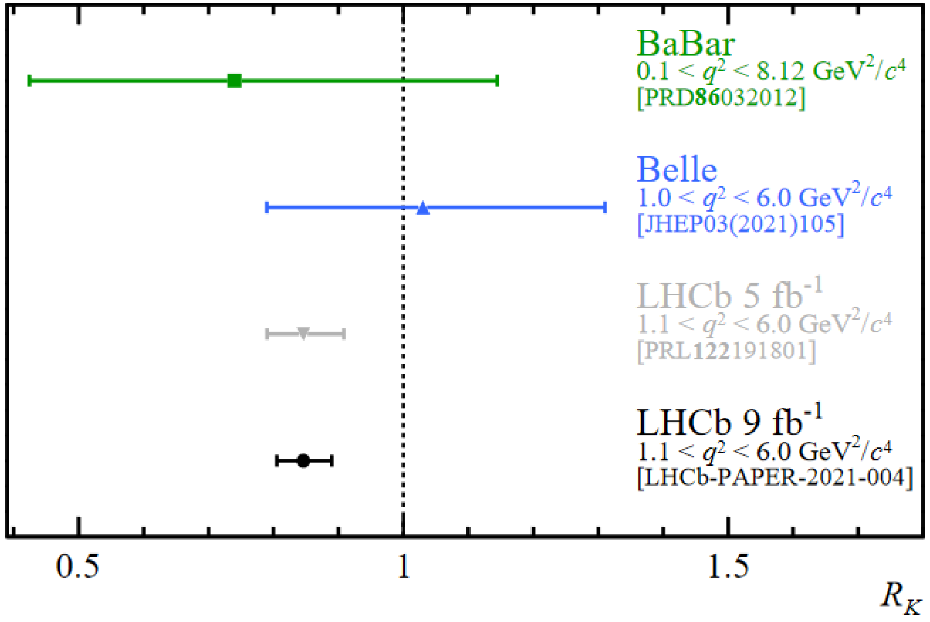
$$\text{BR}(B_s \to \mu^+\mu^-) = \text{BR}(B_s \to \mu^+\mu^-)_{\rm SM}\left|\frac{C_{b_{L-R}\mu_{L-R}}}{C^{\rm SM}_{b_{L-R}\mu_{L-R}}}\right|^2\,.$$

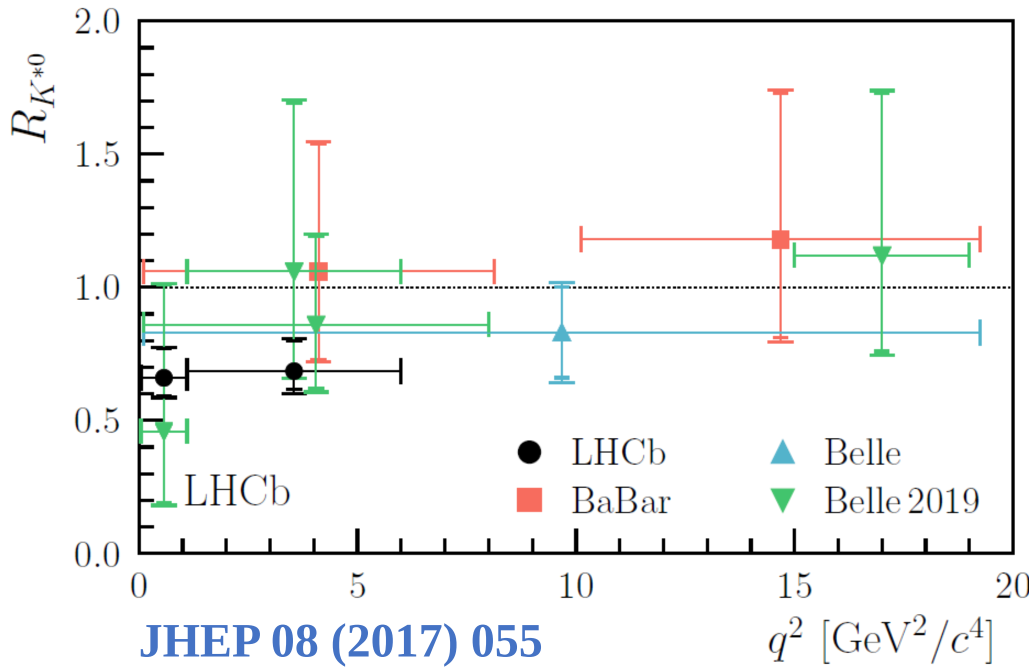
- We use the notation: $C_{b_{L+R}\ell_{L\pm R}} \equiv C_{b_L\ell_L} + C_{b_R\ell_L} \pm C_{b_L\ell_R} \pm C_{b_R\ell_R}\,.$

JHEP 09 (2017) 010
JHEP 08 (2022) 125

R_K and R_{K^*} (Before December 2022)

Nature Phys. 18 (2022) 277



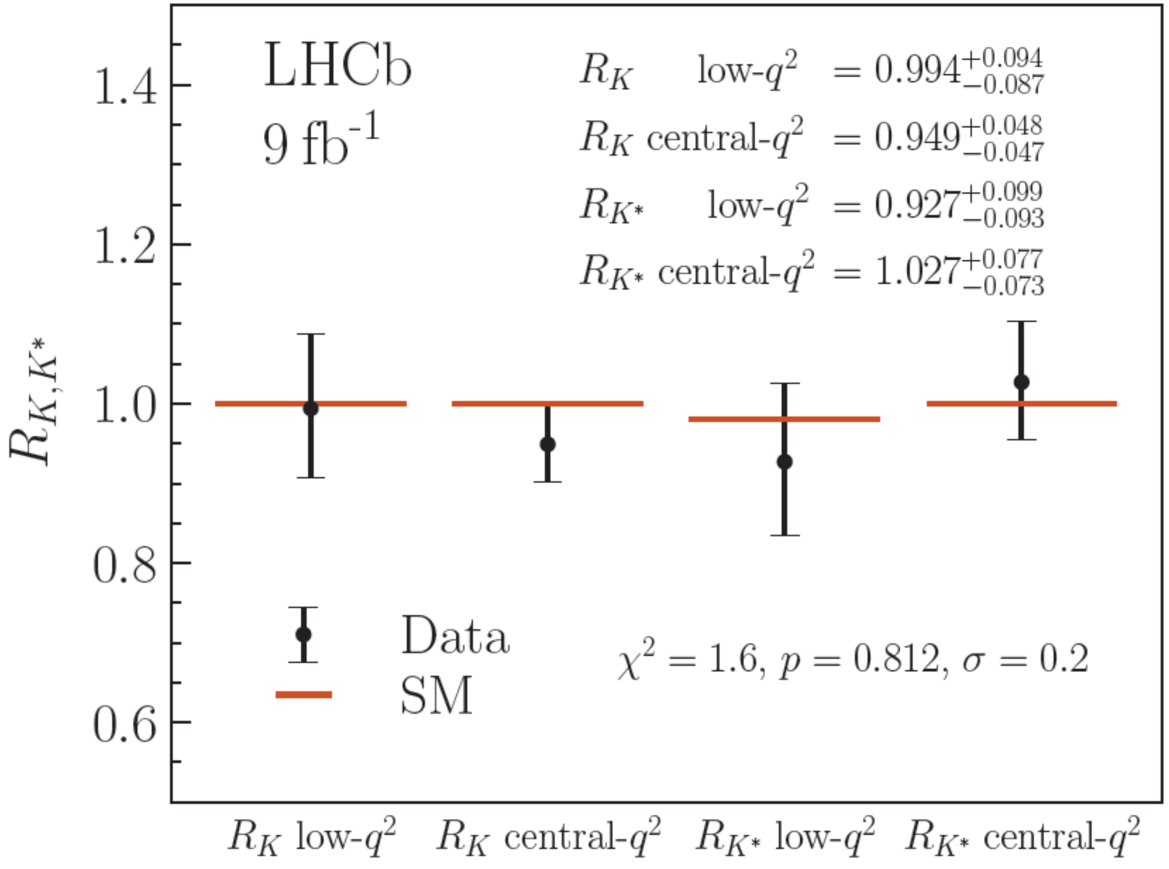


JHEP 08 (2017) 055
PRL 126 (2021) 161801

LHCb results in the low and central q^2 interval:

- $R_K[1.1, 6.0] = 0.846^{+0.042+0.013}_{-0.039-0.012}$ → 3.1 σ
- $R_{K^*}[1.1, 6.0] = 0.69^{+0.11}_{-0.07} \pm 0.05$ → 2.3 σ
- $R_{K^*}[0.045, 1.1] = 0.66^{+0.11}_{-0.07} \pm 0.03$ → 2.5 σ

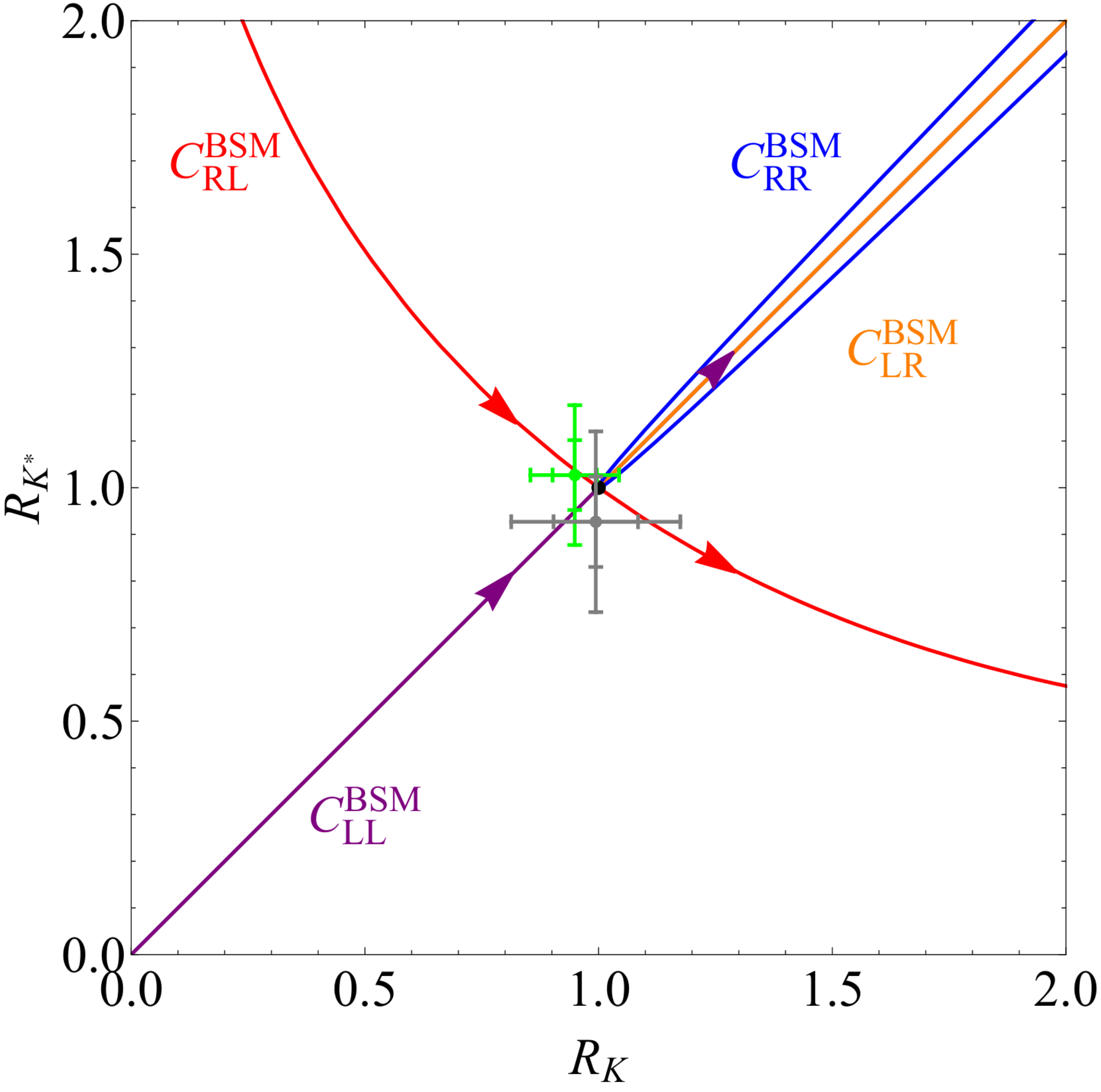
R_K and R_{K^*} (After December 2022)



→ **No more evidence of Lepton Flavor Universality Violation (LFUV)!**

PRL 131 (2023) 051803
PRD 108 (2023) 032002

R_K & R_{K^*} after December 2022



Results for $\mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-)$

- **BEFORE CMS DEC 2022**

$$BR(B_s \to \mu^+\mu^-)_{exp} = (2.85 \pm 0.33) \times 10^{-9}$$

- **AFTER CMS DEC 2022**

$$BR(B_s \to \mu^+\mu^-)_{exp} = (3.28 \pm 0.26\,) \times 10^{-9}$$

SM PREDICTION

$$BR(B_s \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.14\,) \times 10^{-9}$$

Phys. Lett. B 842 (2023) 137955

HADRONIC (IN)-SENSITIVE OBSERVABLES

- **HADRONIC INSENSITIVE OBSERVABLES**

R_K, R_{K^*} ⟶ Now Compatible with SM! ⟶ No more evidence of LFUV NP!

$BR(B_s \to \mu^+\mu^-)$ ⟶ Reduced tension with the SM [arXiv:2212.10311]

- **HADRONIC SENSITIVE OBSERVABLES**

$$
\begin{array}{ccc}
\langle A_{FB}\rangle(B^0 \to K^*\mu\mu) & \langle P_1\rangle(B^0 \to K^*\mu\mu) & \frac{d}{dq^2}\mathrm{BR}(B^\pm \to K^*\mu\mu) \\
\langle F_L\rangle(B^0 \to K^*\mu\mu) & \langle P_4'\rangle(B^0 \to K^*\mu\mu) & \frac{d}{dq^2}\mathrm{BR}(B^0 \to K^*\mu\mu) \\
\langle S_3\rangle(B^0 \to K^*\mu\mu) & \langle P_5'\rangle(B^0 \to K^*\mu\mu) & \frac{d}{dq^2}\mathrm{BR}(B_s \to \phi\mu\mu) \\
\langle S_4\rangle(B^0 \to K^*\mu\mu) & \langle P_6'\rangle(B^0 \to K^*\mu\mu) & \frac{d}{dq^2}\mathrm{BR}(B \to X_s ll) \\
\langle S_5\rangle(B^0 \to K^*\mu\mu) & \langle P_8'\rangle(B^0 \to K^*\mu\mu) & \frac{d}{dq^2}\mathrm{BR}(B \to X_s\mu\mu) \\
\langle S_7\rangle(B^0 \to K^*\mu\mu) & \frac{d}{dq^2}\mathrm{BR}(B^\pm \to K\mu\mu) & \frac{d}{dq^2}\mathrm{BR}(B \to X_s ee) \\
\langle S_8\rangle(B^0 \to K^*\mu\mu) & \frac{d}{dq^2}\mathrm{BR}(B^0 \to K\mu\mu) & \frac{d}{dq^2}\mathrm{BR}(B \to X_s ll)
\end{array}
$$

⟶ STILL ANOMALOUS!

JHEP 09 (2017) 010
JHEP 08 (2022) 125

TURNING ON MULTIPLE COEFFICIENTS

GLOBAL FIT USING BOTH THE HS AND HI OBSERVABLE:

BEFORE DEC 2022

$$C_{b_L\mu_L}^{\rm BSM} = -1.19 \pm 0.12,$$
$$C_{b_L\mu_R}^{\rm BSM} = -0.78 \pm 0.16,$$
$$C_{b_R\mu_L}^{\rm BSM} = 0.40 \pm 0.11,$$
$$C_{b_R\mu_R}^{\rm BSM} = 0.15 \pm 0.24.$$

7.2σ deviation from SM

AFTER DEC 2022

$$C_{b_L\mu_L}^{\rm BSM} = -0.65 \pm 0.10\ ,$$
$$C_{b_L\mu_R}^{\rm BSM} = -0.93 \pm 0.09\ ,$$
$$C_{b_R\mu_L}^{\rm BSM} = 0.20 \pm 0.15\ ,$$
$$C_{b_R\mu_R}^{\rm BSM} = -0.16 \pm 0.28\ .$$

4.3σ deviation from SM

- THERE ARE STILL HINTS FOR NEW PHYSICS.

JHEP 08 (2022) 125
NPB 1006 (2024) 116631

SINGLE WILSON COEFFICIENTS

• ANALYTIC CONSTRAINTS

Using analytic expressions for HI observables:

$$C^{\mathrm{BSM}}_{b_L\mu_L} \in [-0.53, 0.19]$$
$$C^{\mathrm{BSM}}_{b_L\mu_R} \in [-0.46, 1.51]$$
$$C^{\mathrm{BSM}}_{b_R\mu_L} \in [-0.46, 0.19]$$
$$C^{\mathrm{BSM}}_{b_R\mu_R} \in [-1.51, 0.46]$$

• FIT RESULTS

	New physics in the muon sector (Chiral basis)								
	Best-fit			1-σ range			$\sqrt{\chi^2_{\mathrm{SM}} - \chi^2_{\mathrm{best}}}$		
	HI	*HS*	*all*	*HI*	*HS*	*all*	*HI*	*HS*	*all*
$C^{\mathrm{BSM}}_{b_L\mu_L}$	-0.15	-1.31	-0.33	-0.05 -0.25	-1.05 -1.56	-0.24 -0.42	1.1	4.1	2.8
$C^{\mathrm{BSM}}_{b_L\mu_R}$	0.40	-0.66	-0.25	0.64 0.16	-0.47 -0.85	-0.10 -0.40	1.2	2.6	1.7
$C^{\mathrm{BSM}}_{b_R\mu_L}$	-0.05	0.08	-0.04	0.05 -0.15	0.19 -0.03	0.04 -0.12	0.3	0.5	0.3
$C^{\mathrm{BSM}}_{b_R\mu_R}$	-0.38	0.30	0.05	-0.13 -0.63	0.52 0.18	0.20 -0.10	1.1	1.6	0.2

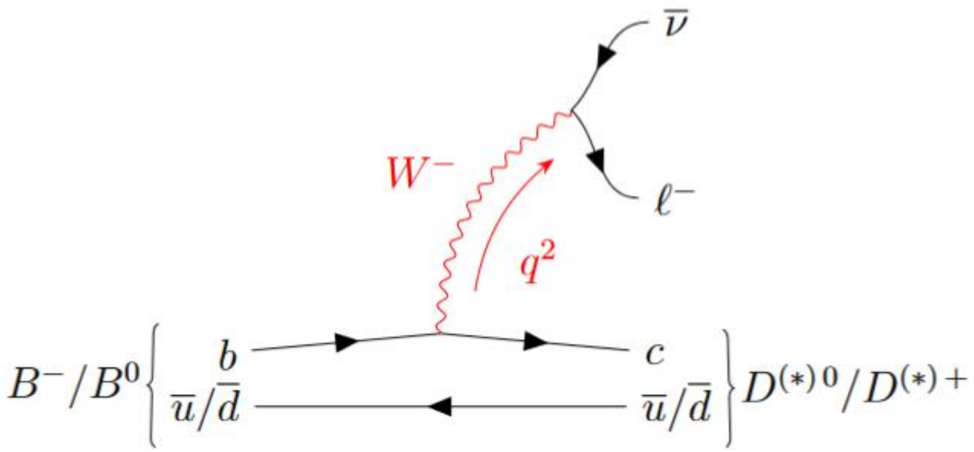
$\mathrm{R_D}$, $\mathrm{R_{D^*}}$ and $\mathrm{BR(B_c \to \tau\nu)}$

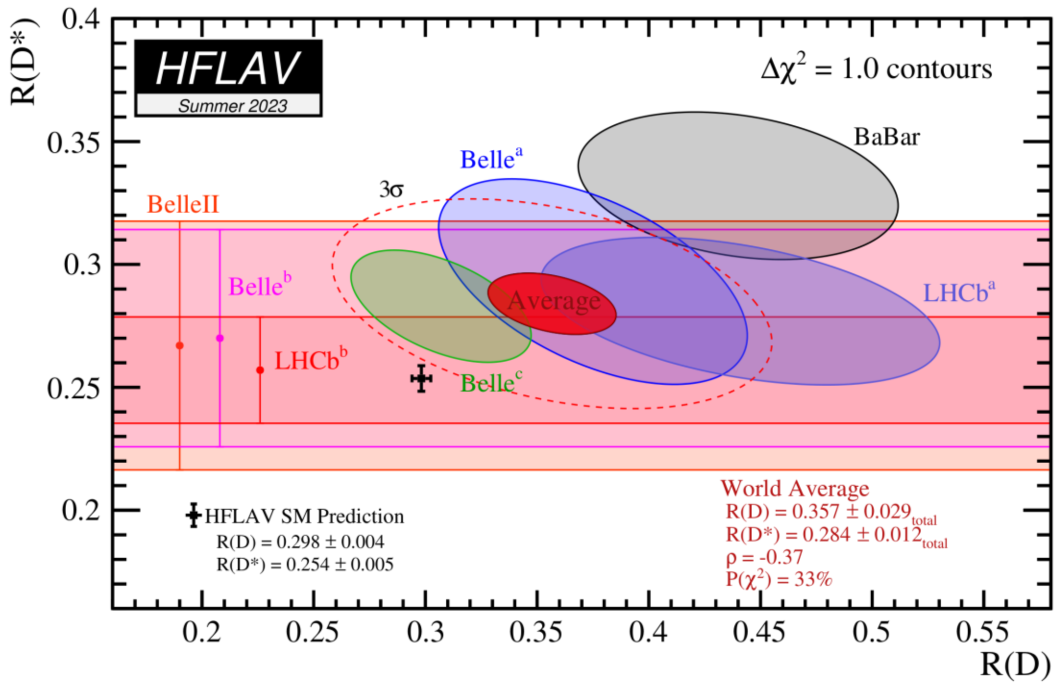
- $\boldsymbol{b \to c\, \ell^- \overline{\nu}_\ell}$

- $b \to c\, \ell^- \bar{\nu}_\ell$ is tree level in the SM.

$$R_D = \frac{\mathrm{BR}(B \to D\,\tau\,\overline{\nu}_\tau)}{\mathrm{BR}(B \to D\,\ell\,\overline{\nu}_\ell)}, \quad R_{D^*} = \frac{\mathrm{BR}(B \to D^*\tau\,\overline{\nu}_\tau)}{\mathrm{BR}(B \to D^*\ell\,\overline{\nu}_\ell)}, \quad \ell = e, \mu$$

- $R_D, R_{D^*}, BR(B_c \to \tau\nu)$ are theoretically and experimentally clean.





$b \to c\, \ell^- \bar{\nu}_\ell$ WEAK EFFECTIVE HAMILTONIAN

$$\mathcal{H}_{\rm eff} = -V_{cb}\frac{\alpha_{\rm em}}{4\pi v^2}[(1+C_{V_L})\mathcal{O}_{V_L}+C_{V_R}\mathcal{O}_{V_R}+C_{S_L}\mathcal{O}_{S_L}+C_{S_R}\mathcal{O}_{S_R}+C_T\mathcal{O}_T+{\rm h.c.}]$$

$$\begin{aligned}
\mathcal{O}^\ell_{V_L} &= (\bar{c}_L\gamma^\mu b_L)(\bar{\ell}_L\gamma_\mu\nu_{\ell L})\\
\mathcal{O}^\ell_{V_R} &= (\bar{c}_R\gamma^\mu b_R)(\bar{\ell}_L\gamma_\mu\nu_{\ell L})\\
\mathcal{O}^\ell_{S_L} &= (\bar{c}_L b_R)(\bar{\ell}_R\nu_{\ell L})\\
\mathcal{O}^\ell_{S_R} &= (\bar{c}_R b_L)(\bar{\ell}_R\nu_{\ell L})\\
\mathcal{O}^\ell_{T} &= (\bar{c}_R\sigma^{\mu\nu} b_L)(\bar{\ell}_R\sigma_{\mu\nu}\nu_{\ell L})
\end{aligned}$$

- We used the following analytic expression:

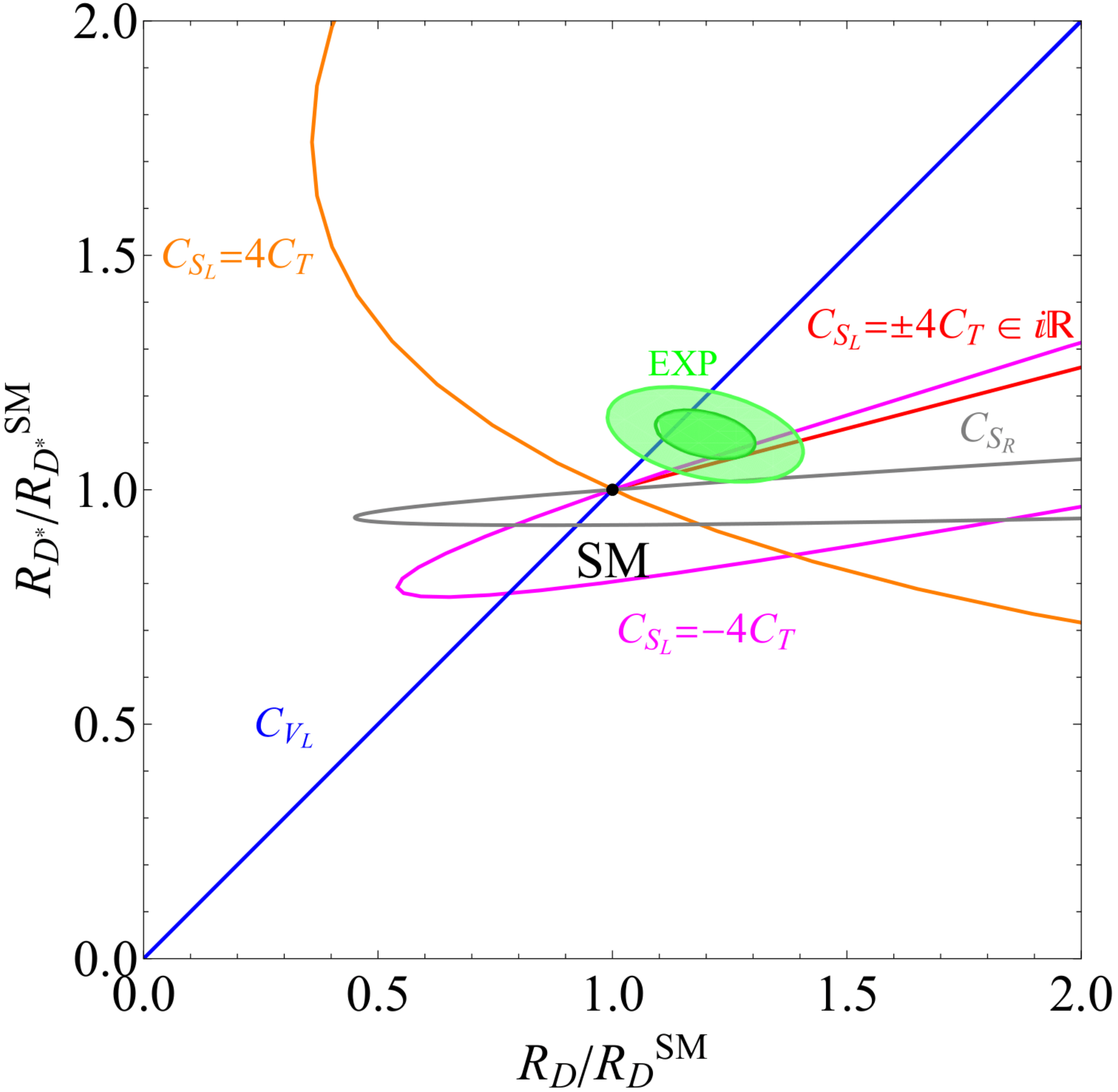
$$\begin{aligned}
\frac{R_D}{R_D^{SM}} &= |1+C_{V_L}+C_{V_R}|^2+1.01|C_{S_R}+C_{S_L}|^2+0.84|C_T|^2\\
&+1.49Re[(1+C_{V_L})(C^*_{S_R}+C^*_{S_L})]+1.08Re[(1+C_{V_L}+C_{V_R})C^*_T]\ ,
\end{aligned}$$

$$\begin{aligned}
\frac{R_{D^*}}{R_{D^*}^{SM}} &= |1+C_{V_L}|^2+|C_{V_R}|^2+0.04|C_{S_L}-C_{S_R}|^2+16.0|C_T|^2-1.83Re\left[(1+C_{V_L})C^*_{V_R}\right]\\
&-0.11Re\left[(1+C_{V_L}-C_{V_R})\left(C^*_{S_L}-C^*_{S_R}\right)\right]-5.17Re\left[(1+C_{V_L})\,C^*_T\right]+6.60Re\left[C_{V_R}C^*_T\right]\ ,
\end{aligned}$$

$$\frac{{\rm BR}(B_c^+\to\tau^+\nu_\tau)}{{\rm BR}(B_c^+\to\tau^+\nu_\tau)_{SM}} = |1+C_{V_L}-4.35(C_{S_L}-C_{S_R})|^2\ .$$

arXiv: 2210.10751

R_D & R_{D^*}



2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
$R_D/R_D{}^{\mathrm{SM}}$
$R_{D^*}/R_{D^*}{}^{\mathrm{SM}}$
$C_{S_L}=4C_T$
$C_{S_L}=\pm 4C_T \in i\mathbb{R}$
EXP
C_{S_R}
SM
$C_{S_L}=-4C_T$
C_{V_L}

NEW PHYSICS WILSON COEFFICIENTS

- **ANALYTIC BOUNDS**

Using analytic expressions for HI observables:

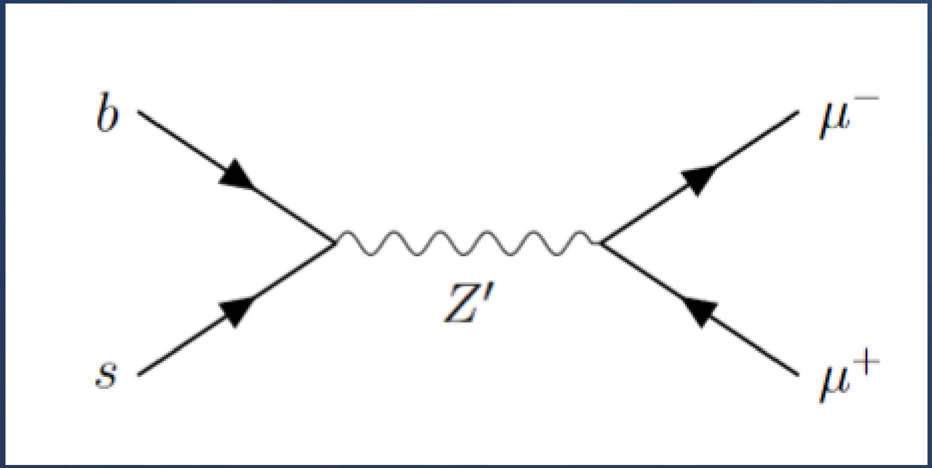
$$C_{V_L} \in [0.01, 0.10]$$
$$C_{S_R} \in [0.20, 0.23]$$
$$C_{S_L} = -8.9 C_T \in [0.05, 0.24]$$
$$|\mathrm{ImC_{S_L}}| = 8.9|\mathrm{ImC_T}| \in [0.31, 0.62]$$
$$|\mathrm{ImC_{S_L}}| = 8.4|\mathrm{ImC_T}| \in [0.30, 0.62]$$

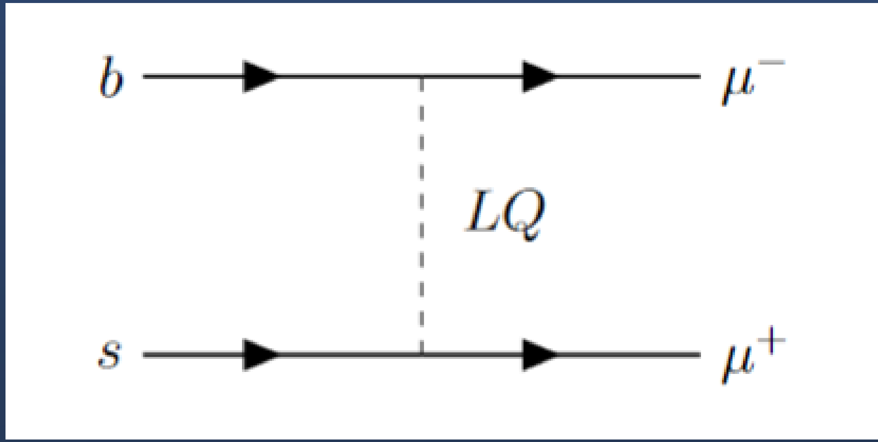
- **FIT RESULTS**

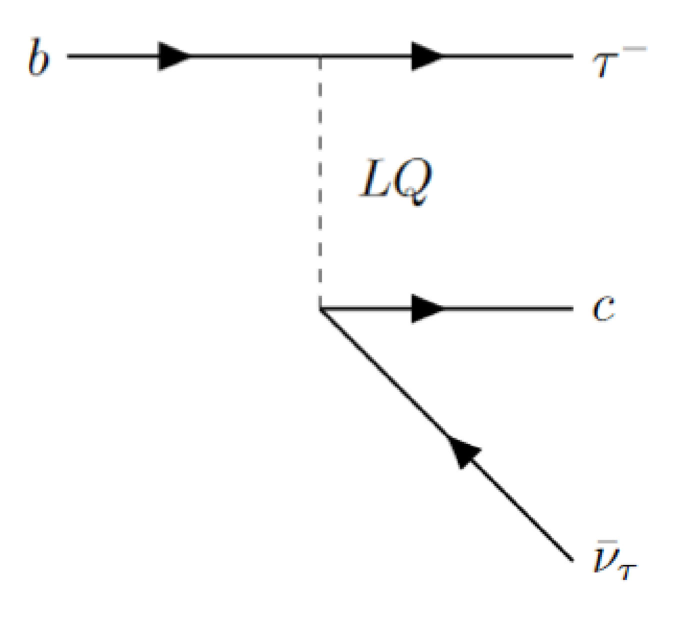
New physics in the tau sector

	Best-fit		1-σ range		$\sqrt{\chi^2_{\mathrm{SM}} - \chi^2_{\mathrm{best}}}$	
	HI	*all*	*HI*	*all*	*HI*	*all*
C_{V_L}	0.08	0.08	0.09 0.07	0.09 0.07	4.3	4.8
C_{S_R}	0.19	0.20	0.22 0.16	0.23 0.17	2.6	2.8
$C_{S_L} = -8.9 C_T$	0.18	0.18	0.21 0.15	0.20 0.16	4.0	4.2
$\lvert\mathrm{ImC_{S_L}}\rvert = 8.9\lvert\mathrm{ImC_T}\rvert$	0.53	0.55	0.58 0.48	0.60 0.50	4.1	4.4
$\lvert\mathrm{ImC_{S_L}}\rvert = 8.4\lvert\mathrm{ImC_T}\rvert$	0.53	0.55	0.58 0.48	0.60 0.50	4.2	4.4

SELECTION OF NEW PHYSICS MODELS







MINIMAL Z' BOSON

- Z' models can only address the $b \to s\, \ell^+ \ell^-$ sector.
- The minimal Z' model generates only the Wilson coefficient $C_{b_L \mu_L}^{BSM}$:

$$\mathcal{L}_{Z'} = g_{bs}(\bar{s}\gamma_\mu P_L b) + g_{\mu_L}(\bar{\mu}\gamma_\mu P_L \mu) + \text{h.c.} \ ,$$

$$C_{b_L \mu_L}^{\text{BSM}} = \frac{4\pi v^2}{V_{tb} V_{ts}^* \alpha_{\text{em}}} \frac{g_{bs} g_{\mu_L}}{m_{Z'}^2} \quad .$$

- Assuming order 1 couplings we find a lower bound on the NP scale around 50 TeV.

SCALAR LEPTOQUARKS

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

$$\mathcal{L}_{S_1} = y_{1\,ij}^{LL} \bar{Q}_L^{C\ i,a} S_1 (i\tau^2)^{ab} L_L^{j,b} + \ y_{1\,ij}^{RR} \bar{u}_R^{C\ i} S_1 e_R^j + \text{h.c.}\ .$$

$$C_{S_L} = -4C_T = -\frac{v^2}{2V_{cb}} \frac{y_{1\,b\tau}^{LL} (y_{1\,c\tau}^{RR\,*})}{m_{S_1}^2}\ ,$$

$$C_{V_L} = \frac{v^2}{2V_{cb}} \frac{y_{1\,b\tau}^{LL} (V y_1^{LL\,*})_{c\tau}}{m_{S_1}^2}\ .$$

$$C_{b_L \mu_R}^{\rm BSM} = \frac{m_t^2}{8\pi\alpha_{\rm em} m_{S_1}^2} \left(V^* y_1^{LL}\right)_{t\mu} \left(V^* y_1^{LL}\right)_{t\mu}^* - \frac{v^2}{16\pi\alpha_{\rm em} m_{S_1}^2} \frac{\left(y_1^{LL} \cdot y_1^{\dagger\,LL}\right)_{bs}}{V_{tb} V_{ts}^*} \left(y_1^{\dagger\,LL} \cdot y_1^{LL}\right)_{\mu\mu}\ ,$$

$$C_{b_L \mu_L}^{\rm BSM} = \frac{m_t^2}{8\pi\alpha_{\rm em} m_{S_1}^2} \left(y_{1\,t\mu}^{RR}\right) \left(y_{1\,t\mu}^{*\,RR}\right) \left[\log\left(\frac{m_{S_1}^2}{m_t^2}\right) - f(x_t)\right] - $$

$$- \frac{v^2}{16\pi\alpha_{\rm em} m_{S_1}^2} \frac{\left(y_1^{LL} \cdot y_1^{\dagger\,LL}\right)_{bs}}{V_{tb} V_{ts}^*} \left(y_1^{\dagger\,LL} \cdot y_1^{LL}\right)_{\mu\mu}\ ,$$

where

$$f(x_t) = 1 + \frac{3}{x_t - 1}\left(\frac{\log(x_t)}{x_t - 1} - 1\right), \quad x_t = \frac{m_t^2}{M_W^2}\ .$$

- $R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$

$$\mathcal{L}_{R_2} = -y_{2\,ij}^{RL} \bar{u}_R^i R_2^a (i\tau^2)^{ab} L_L^{j,b} + \ y_{2\,ij}^{LR} \bar{e}_R^i R_2^{a\ *}\ Q_L^{j,a} + \text{h.c.}\ .$$

$$C_{S_L} = 4C_T = \frac{v^2}{2V_{cb}} \frac{y_{2\,c\tau}^{LR} (y_{2\,b\tau}^{RL})^*}{m_{R_2}^2}\ .$$

$$C_{b_L \mu_R}^{\rm BSM} = -\frac{2\pi v^2}{V_{tb} V_{ts}^* \alpha_{\rm em}} \frac{y_{2\,s\mu}^{LR} y_{2\,b\mu}^{LR\ *}}{m_{R_2}^2}\ ,$$

- $S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

$$\mathcal{L}_{S_3} = y_{3\,ij}^{L} \bar{Q}_L^{C\ i,a}\ (i\tau^2)^{ab} \left(\tau^k S_3^k\right)^{bc}\ L_L^{j,c} + \text{h.c.}\ .$$

$$C_{b_L \mu_L}^{\rm BSM} = \frac{4\pi v^2}{V_{tb} V_{ts}^* \alpha_{\rm em}} \frac{y_{3\,b\mu}^{L} (y_{3\,s\mu}^{L})^*}{m_{S_3}^2}\ .$$

$$C_{V_L} = -\frac{v^2}{V_{cb}} \frac{\left(V y_3^L\right)^{c\tau} y_{3\,b\tau}^{L\ *}}{m_{U_3}^2}\ .$$

VECTOR LEPTOQUARKS

- Minimal $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

$$\mathcal{L}_{U_1} = x_{1\,ij}^{LL} \bar{Q}_L^{i,a} \gamma^\mu U_{1,\mu} L_L^{j,a} + \text{h.c.} \,.$$

$$C_{V_L} = \frac{v^2}{V_{cb}} \frac{\left(V x_1^{LL}\right)_{c\tau} x_{1\,b\tau}^{LL\,*}}{m_{U_1}^2} \,,$$

$$C_{b_L \mu_L}^{\text{BSM}} = -\frac{4\pi v^2}{V_{tb} V_{ts}^* \alpha_{\text{em}}} \frac{x_{1\,s\mu}^{LL} x_{1\,b\mu}^{LL\,*}}{m_{U_1}^2} \,.$$

- $V_2 = (\mathbf{3}, \mathbf{2}, 5/6)$

$$\mathcal{L}_{V_2} = x_{2\,ij}^{RL} \bar{d}_R^{C\;i} \gamma^\mu V_{2,\mu}^a (i\tau^2)^{ab} L_L^{j,b} + x_{2\,ij}^{LR} \bar{Q}_L^{C\;i,a} \gamma^\mu (i\tau^2)^{ab} V_{2,\mu}^b e_R^j + \text{h.c.} \,.$$

$$C_{b_L \mu_R}^{\text{BSM}} = -\frac{4\pi v^2}{V_{tb} V_{ts}^* \alpha_{\text{em}}} \frac{x_{2\,s\mu}^{LR} x_{2\,b\mu}^{LR\,*}}{m_{V_2}^2} \,,$$

$$C_{S_R} = -\frac{2v^2}{V_{cb}} \frac{\left(V x_2^{LR}\right)_{c\tau} x_{2\,b\tau}^{RL\,*}}{m_{V_2}^2} \,.$$

- $U_3 = (\mathbf{3}, \mathbf{3}, 2/3)$

$$\mathcal{L}_{U_3} = x_{3\,ij}^{LL} \bar{Q}_L^{i,a} \gamma^\mu \left(\tau^k U_{3,\mu}^k\right)^{ab} L_L^{j,b} + \text{h.c.} \,.$$

$$C_{b_L \mu_L}^{\text{BSM}} = -\frac{4\pi v^2}{V_{tb} V_{ts}^* \alpha_{\text{em}}} \frac{x_{3\,s\mu}^{LL} x_{3\,b\mu}^{LL\,*}}{m_{U_3}^2} \,,$$

$$C_{V_L} = -\frac{v^2}{V_{cb}} \frac{\left(V x_3^{LL}\right)^{c\tau} x_{3\,b\tau}^{LL\,*}}{m_{U_3}^2} \,.$$

SUMMARY OF LEPTOQUARK MODELS

- Scalar and Vector Leptoquarks can also address the $b \to c\, \ell^- \bar{\nu}_\ell$ sector.
- We assume order 1 couplings.

LQ Model	Wilson Coeff.	$b \to c$	$b \to s$	$b \to c + b \to s$
S_1	$C^{\rm BSM}_{b_L \mu_L}, C^{\rm BSM}_{b_L \mu_R}, C_{V_L}, C_{S_L} = -4C_T$	✓	✓	✓
R_2	$C^{\rm BSM}_{b_L \mu_R}, C_{S_L} = 4C_T$	✓	✓	(✓)
S_3	$C^{\rm BSM}_{b_L \mu_L}, C_{V_L}$	×	✓	×
U_1	$C^{\rm BSM}_{b_L \mu_L}, C_{V_L}$	✓	✓	(✓)
V_2	$C^{\rm BSM}_{b_L \mu_R}, C_{S_R}$	✓	✓	(✓)
U_3	$C^{\rm BSM}_{b_L \mu_L}, C_{V_L}$	×	✓	×

- S_1 with a mass in the TeV range can accommodate current data in $b \to c$ and $b \to s$ sectors.
- R_2, U_1, V_2 require a tuning in the couplings.

CONCLUSIONS

- **THE EFT FRAMEWORK ALLOWS TO SEARCH FOR NP EFFECTS IN A MODEL-INDEPENDENT MANNER**

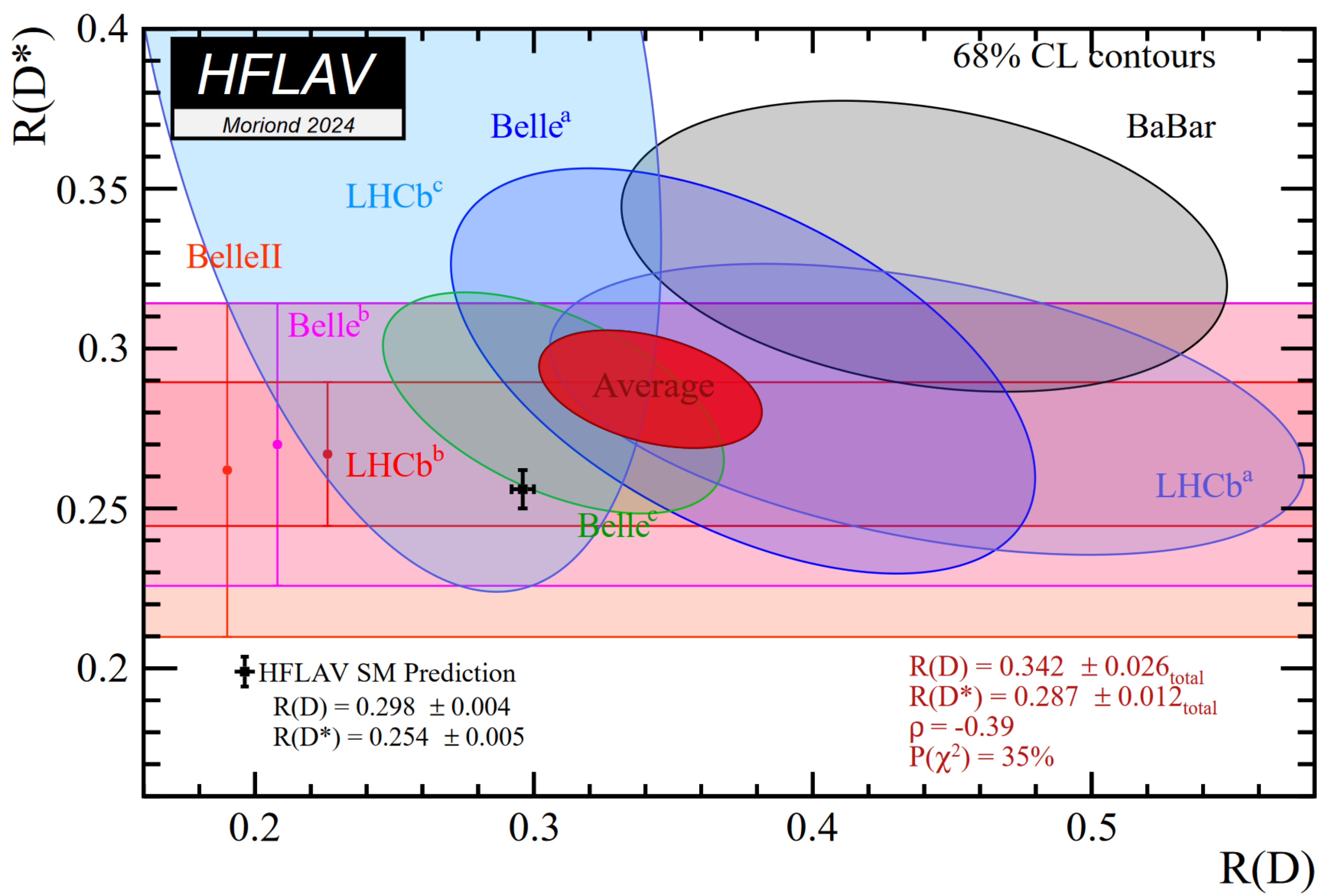
➢ R_K and R_{K^*} $\longrightarrow$ **No more evidence of LFUV**

➢ HS observables are anomalous, yielding an overall 4.3σ deviation from the SM.

➢ R_D and R_{D^*} $\longrightarrow$ **ANOMALOUS**

Scalar Leptoquark S1 can explain the data both in the $b \to c$ and $b \to s$ sectors.

- **Improving precision of current measurements**
- **Measurements of new LFU ratios R_H, where H can be a Meson or a Baryon**
- **Measurements of new angular observables and branching ratios**



LATEST LHCb MEASUREMENT IS COMPATIBLE WITH BOTH THE CURRENT WORLD AVERAGE AND WITH THE SM

THANK YOU
FOR YOUR ATTENTION!