



Institute of Particle Physics
粒子物理研究所

轻子味普适性理论研究

袁兴博

华中师范大学

时间有限，无法涵盖很多优秀的工作😭😭😭

LFU: origin and observable

Experimental summary and implications for New Physics

LFU violation in New Physics

Summary

Flavour Physics

► Flavour universal

- couplings $\propto \delta_{ij}$ in flavour space
- example: strong and electromagnetic interactions
- consequence of gauge invariance

► Flavour diagonal

- couplings $\propto \lambda_i \delta_{ij}$ (diagonal, but not necessarily universal)
- example: Yukawa interactions

► Flavour violation (changing)

- couplings involve different quarks
- no flavour violation in lepton sector ($m_\nu = 0$)
- example: W^\pm interactions in quark sector

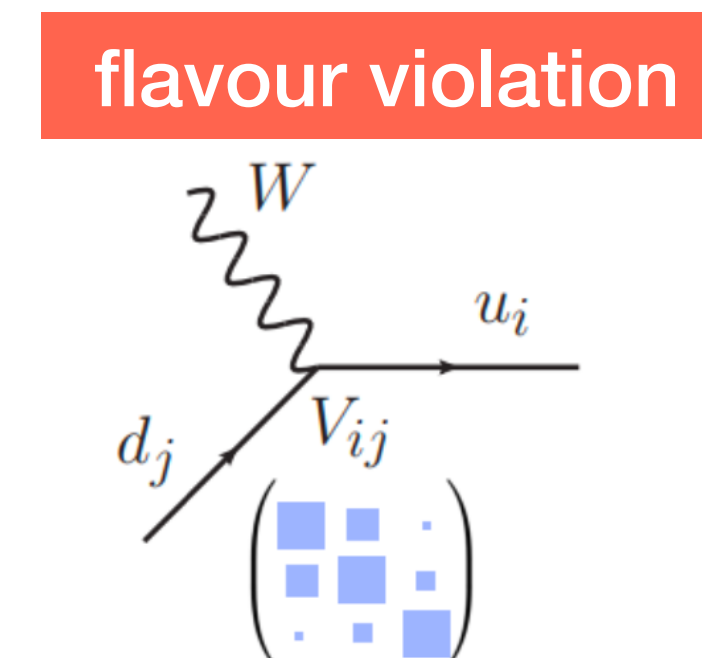
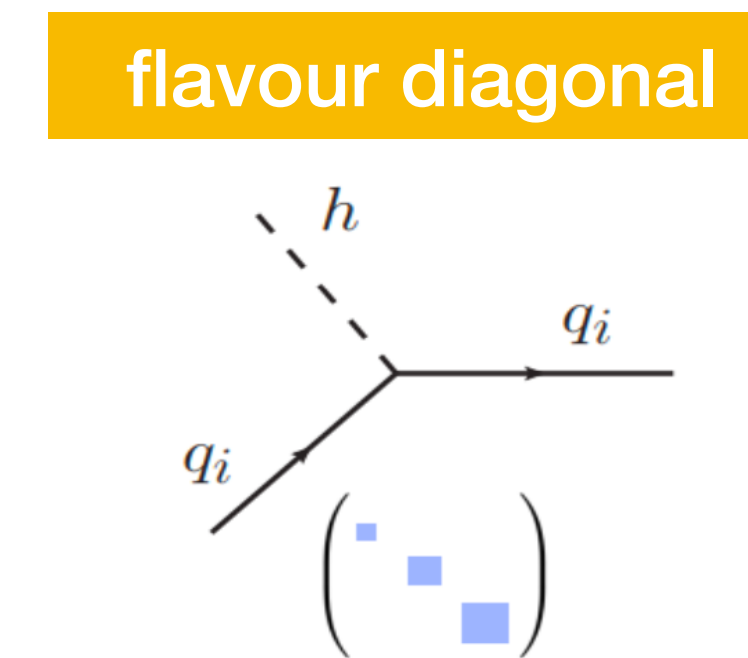
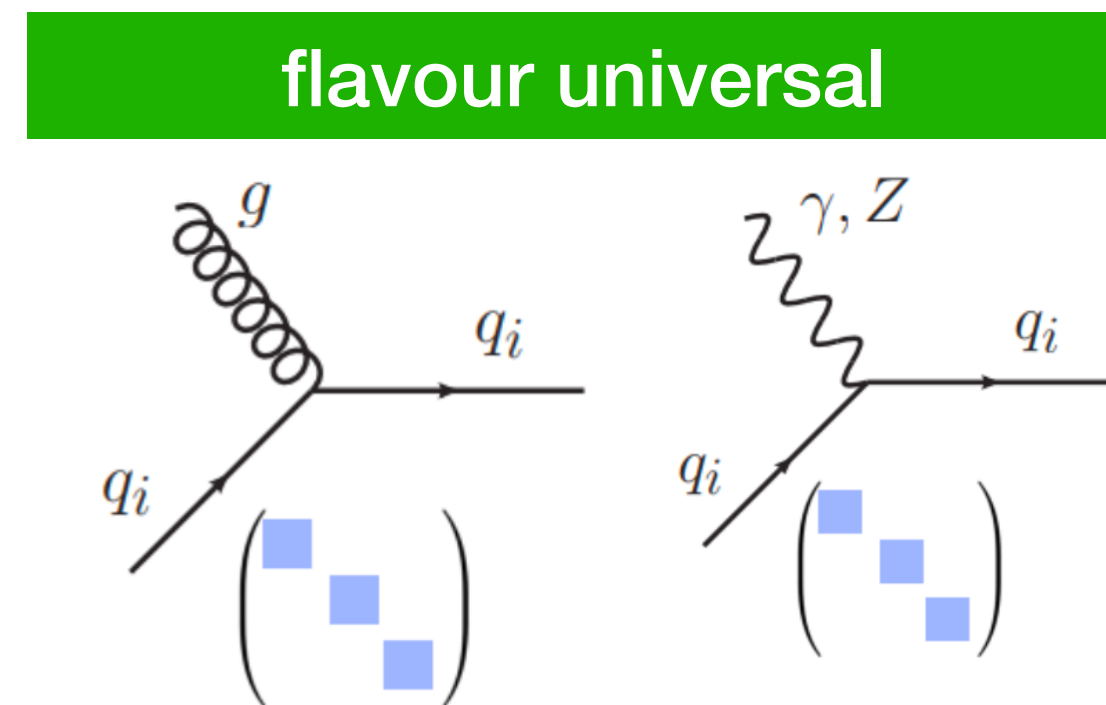
► Flavour Changing Neutral Current (FCNC)

- absent at the tree-level
- arise at the one-loop, but suppressed by GIM mechanism

► Why flavour physics

- New physics $\iff \mathcal{O}(10^9)$ $B\bar{B}$ events at BaBar and Belle
- structure of CKM and mass
- CP violation
- strong interaction

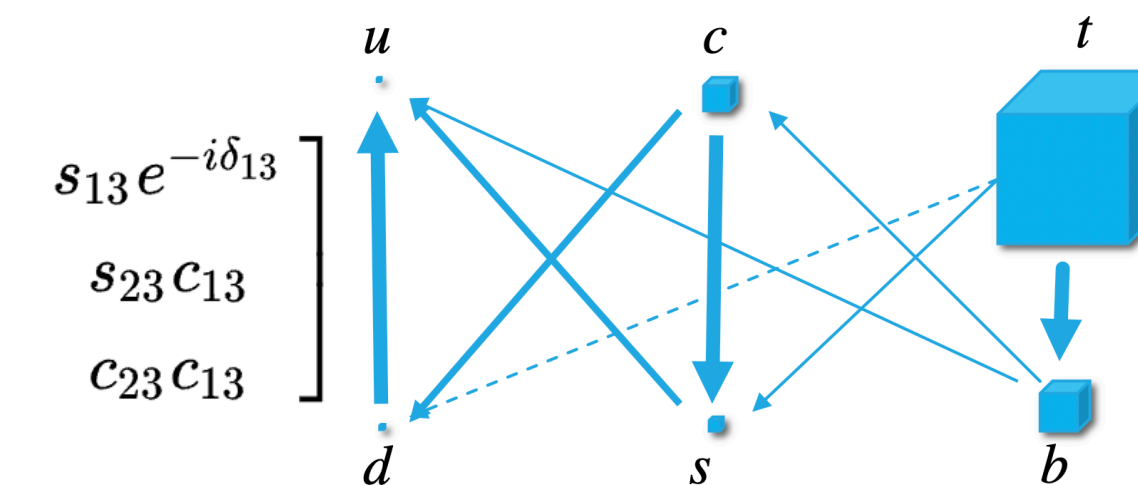
experimental status
no evidence of NP $> 5\sigma$
but, anomalies $2 \sim 4\sigma$



CKM matrix

► Cabibbo–Kobayashi–Maskawa matrix

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & 0 \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{13}e^{-i\delta_{13}} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{bmatrix}$$

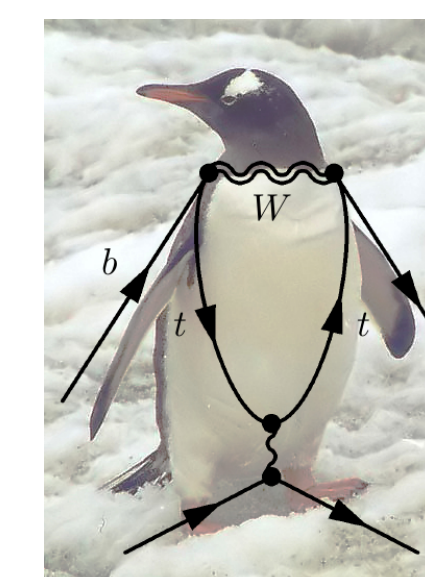
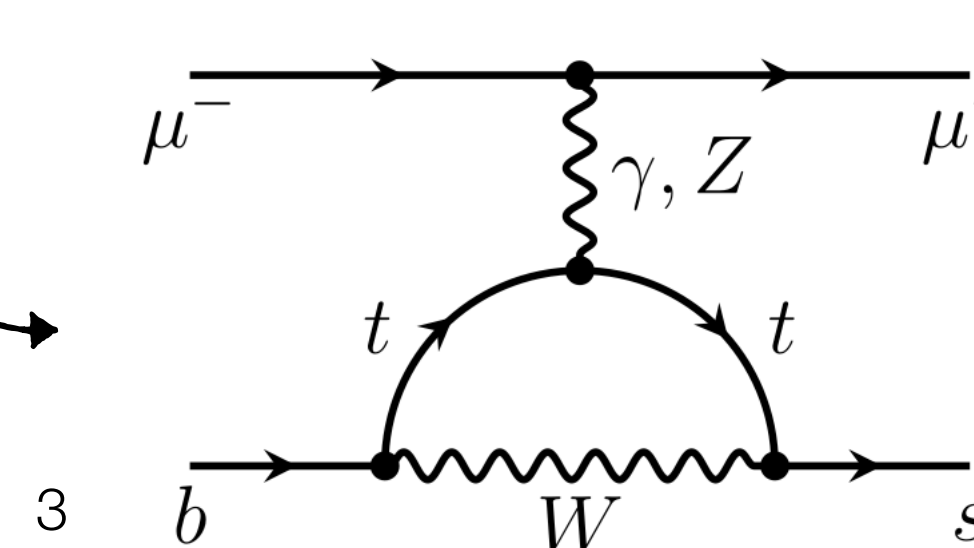


► 3 mixing angles and 1 CP phase

► CP violation in the Standard Model

not enough to explain the baryon asymmetry in our universe

new CP violation sources



penguin diagram

Origin of LFU

► Flavour universality in lepton sector

$$\bar{\ell}'_R \gamma^\mu Z_\mu Y \ell'_R \propto [\bar{e}'_R \quad \bar{\mu}'_R \quad \bar{\tau}'_R] \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} e'_R \\ \mu'_R \\ \tau'_R \end{bmatrix} = [\bar{e}_R \quad \bar{\mu}_R \quad \bar{\tau}_R] \underbrace{U_R^\dagger}_{\text{mass eigenbasis}} \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \underbrace{U_R}_{\text{mass eigenbasis}} \begin{bmatrix} e_R \\ \mu_R \\ \tau_R \end{bmatrix} = [\bar{e}_R \quad \bar{\mu}_R \quad \bar{\tau}_R] \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} e_R \\ \mu_R \\ \tau_R \end{bmatrix}$$

interaction eigenbasis \uparrow
 hypercharge of $U(1)_Y$
 $Y_{e_R} = Y_{\mu_R} = Y_{\tau_R} = -1$

$\ell'_R = U_R \ell_R$
 U_R : complex 3×3 unitary matrix

flavour universal

$$\bar{\ell}'_L \gamma^\mu W_\mu^- \nu'_L \propto [\bar{e}'_L \quad \bar{\mu}'_L \quad \bar{\tau}'_L] \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu'_{e,L} \\ \nu'_{\mu,L} \\ \nu'_{\tau,L} \end{bmatrix} = [\bar{e}_L \quad \bar{\mu}_L \quad \bar{\tau}_L] \underbrace{U_\ell^\dagger}_{\text{mass eigenbasis}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \underbrace{U_\nu}_{\text{mass eigenbasis}} \begin{bmatrix} \nu_{e,L} \\ \nu_{\mu,L} \\ \nu_{\tau,L} \end{bmatrix} = [\bar{e}_L \quad \bar{\mu}_L \quad \bar{\tau}_L] \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_{e,L} \\ \nu_{\mu,L} \\ \nu_{\tau,L} \end{bmatrix}$$

neglecting neutrino masses, one can always choose $U_\nu = U_\ell$

flavour universal

► Flavour **non**-universality in quark sector

$$\bar{u}'_L \gamma^\mu W_\mu^+ d'_L \propto [\bar{u}'_L \quad \bar{c}'_L \quad \bar{t}'_L] \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} d'_L \\ s'_L \\ b'_L \end{bmatrix} = [\bar{u}_L \quad \bar{c}_L \quad \bar{t}_L] \underbrace{U_u^\dagger}_{\text{mass eigenbasis}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \underbrace{U_d}_{\text{mass eigenbasis}} \begin{bmatrix} d_L \\ s_L \\ b_L \end{bmatrix} = [\bar{u}_L \quad \bar{c}_L \quad \bar{t}_L] \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d_L \\ s_L \\ b_L \end{bmatrix}$$

flavour non-universal and non-diagonal

Origin of LFU

accidental symmetry

i.e. symmetry holds for operators of dim=4, but broken by dim>4 operators

► Flavour universality in lepton sector

$$\bar{\ell}'_R \gamma^\mu Z_\mu Y \ell'_R \propto [\bar{e}'_R \ \bar{\mu}'_R \ \bar{\tau}'_R] \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} e'_R \\ \mu'_R \\ \tau'_R \end{bmatrix} = [\bar{e}_R \ \bar{\mu}_R \ \bar{\tau}_R] \underbrace{U_R^\dagger}_{\text{mass eigenbasis}} \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \underbrace{U_R}_{\text{mass eigenbasis}} \begin{bmatrix} e_R \\ \mu_R \\ \tau_R \end{bmatrix} = [\bar{e}_R \ \bar{\mu}_R \ \bar{\tau}_R] \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} e_R \\ \mu_R \\ \tau_R \end{bmatrix}$$

hypercharge of $U(1)_Y$
 $Y_{e_R} = Y_{\mu_R} = Y_{\tau_R} = -1$

$\ell'_R = U_R \ell_R$
 U_R : complex 3×3 unitary matrix

flavour universal

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neglecting neutrino masses, one can always choose $U_\nu = U_\ell$

flavour universal

► Flavour **non**-universality in quark sector

$$\bar{u}'_L \gamma^\mu W_\mu^+ d'_L \propto [\bar{u}'_L \ \bar{c}'_L \ \bar{t}'_L] \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} d'_L \\ s'_L \\ b'_L \end{bmatrix} = [\bar{u}_L \ \bar{c}_L \ \bar{t}_L] \underbrace{U_u^\dagger}_{\text{mass eigenbasis}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \underbrace{U_d}_{\text{mass eigenbasis}} \begin{bmatrix} d_L \\ s_L \\ b_L \end{bmatrix} = [\bar{u}_L \ \bar{c}_L \ \bar{t}_L] \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d_L \\ s_L \\ b_L \end{bmatrix}$$

flavour non-universal and non-diagonal

LFU Observable

► Definition

$$R_{\text{LFU}} \equiv \frac{\mathcal{O}(H \rightarrow \ell_1 (+\ell_1) + X)}{\mathcal{O}(H \rightarrow \ell_2 (+\ell_2) + X)}$$

examples:

$$R_K = \frac{\mathcal{B}(B \rightarrow K\mu^+\mu^-)}{\mathcal{B}(B \rightarrow Ke^+e^-)}$$

$$R(D^{(*)}) = \frac{\mathfrak{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathfrak{B}(B \rightarrow D^{(*)}\ell\nu)}$$

Experimental uncertainty largely cancelled.

$$\Delta_{\text{LFU}} \equiv \mathcal{O}(H \rightarrow \ell_1 (+\ell_1) + X) - \mathcal{O}(H \rightarrow \ell_2 (+\ell_2) + X)$$

► General analysis within New Physics

$$R_{\text{LFU}}^{\mu/e} \equiv \frac{\mathcal{O}(H \rightarrow \mu (+\mu) + X)}{\mathcal{O}(H \rightarrow e (+e) + X)} \approx \underset{\substack{\uparrow \\ \text{SM}}}{1} + \underset{\substack{\downarrow \\ \text{input parameter (mass, CKM, ...)}}}{c} \cdot \underset{\substack{\uparrow \\ \text{hadronic parameter}}}{h} \cdot \left(\underset{\substack{\uparrow \\ \text{NP couplings}}}{g_\mu^{\text{NP}}} - g_e^{\text{NP}} \right)$$

hadronic (decay constant, form factor, ...) and parameter (CKM factor, ...)
uncertainty largely cancelled in the SM part

hadronic uncertainty remains in the NP part

π, K, τ systems

A. Pich, Prog. Part. Nucl. Phys. 75 (2014) 41

B. Bryman, Cirigliano, Crivellin, Inguglia, Annu. Rev. Nucl. Part. Sci. 2022. 72:69-91

▶ π decay

$$R_{e/\mu}^P = \frac{\Gamma[P \rightarrow e\bar{\nu}_e(\gamma)]}{\Gamma[P \rightarrow \mu\bar{\nu}_\mu(\gamma)]} \quad \left(\frac{A_\mu}{A_e}\right)_{R_{e/\mu}^\pi} = 1.0010 \pm 0.0009$$

▶ K decay

$$R_{e/\mu}^K = \frac{\Gamma[K^+ \rightarrow e^+\nu(\gamma)]}{\Gamma[K^+ \rightarrow \mu^+\nu(\gamma)]} \quad \left(\frac{A_\mu}{A_e}\right)_{R_{e/\mu}^K} = 0.9978 \pm 0.0018$$

$$R_{e/\mu}^{K \rightarrow \pi} = \frac{\Gamma[K \rightarrow \pi e\nu(\gamma)]}{\Gamma[K \rightarrow \pi \mu\nu(\gamma)]} \quad \left(\frac{A_\mu}{A_e}\right)_{R_{e/\mu}^{K_L \rightarrow \pi}} = 1.0022 \pm 0.0024, \quad \left(\frac{A_\mu}{A_e}\right)_{R_{e/\mu}^{K^\pm \rightarrow \pi^\pm}} = 0.9995 \pm 0.0026$$

LFU holds @ $\mathcal{O}(0.1\%)$

▶ τ decay

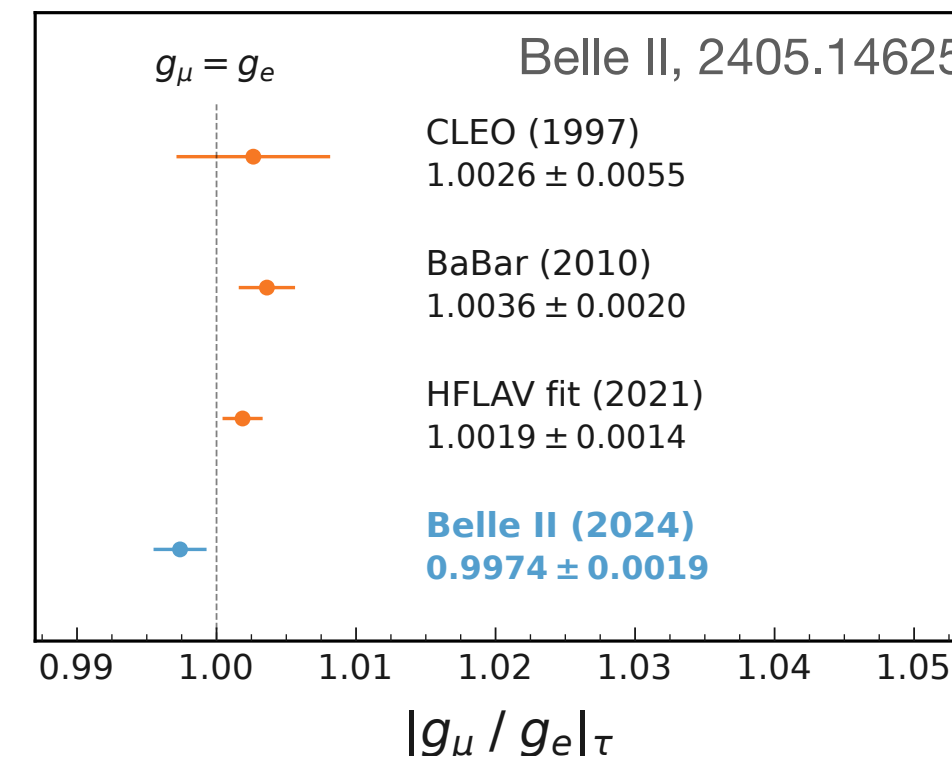
$$R_{\tau/e}^\tau = \frac{\text{Br}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau)}{\text{Br}(\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu)} \quad \left(\frac{A_\tau}{A_e}\right)_\tau = 1.0029 \pm 0.0014$$

$$R_{\tau/\mu}^\tau = \frac{\text{Br}(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau)}{\text{Br}(\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu)} \quad \left(\frac{A_\tau}{A_\mu}\right)_\tau = 1.0010 \pm 0.0014$$

$$R_{\mu/e}^\tau = \frac{\text{Br}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau)}{\text{Br}(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau)} \quad \left(\frac{A_\mu}{A_e}\right)_\tau = 1.0018 \pm 0.0014$$

$$R_{\tau/\mu}^{\tau\pi(K)} = \frac{\text{Br}[\tau \rightarrow \pi(K)\nu_\tau]}{\text{Br}[\pi(K) \rightarrow \mu\nu_\mu]} \quad \left(\frac{A_\tau}{A_\mu}\right)_\pi = 0.9964 \pm 0.0038$$

$$\left(\frac{A_\tau}{A_\mu}\right)_K = 0.9857 \pm 0.0078$$



Z and W boson

► Z boson decay

$$\frac{\Gamma(\mu^+ \mu^-)}{\Gamma(e^+ e^-)} \quad \Gamma_2/\Gamma_1$$

VALUE	DOCUMENT ID	TECN	COMMENT
1.0001 ± 0.0024 OUR AVERAGE			
0.9974 ± 0.0050	1 AABOUD	17Q ATLS	$E_{cm}^{pp} = 7 \text{ TeV}$
1.0009 ± 0.0028	2 LEP-SLC	06	$E_{cm}^{ee} = 88-94 \text{ GeV}$

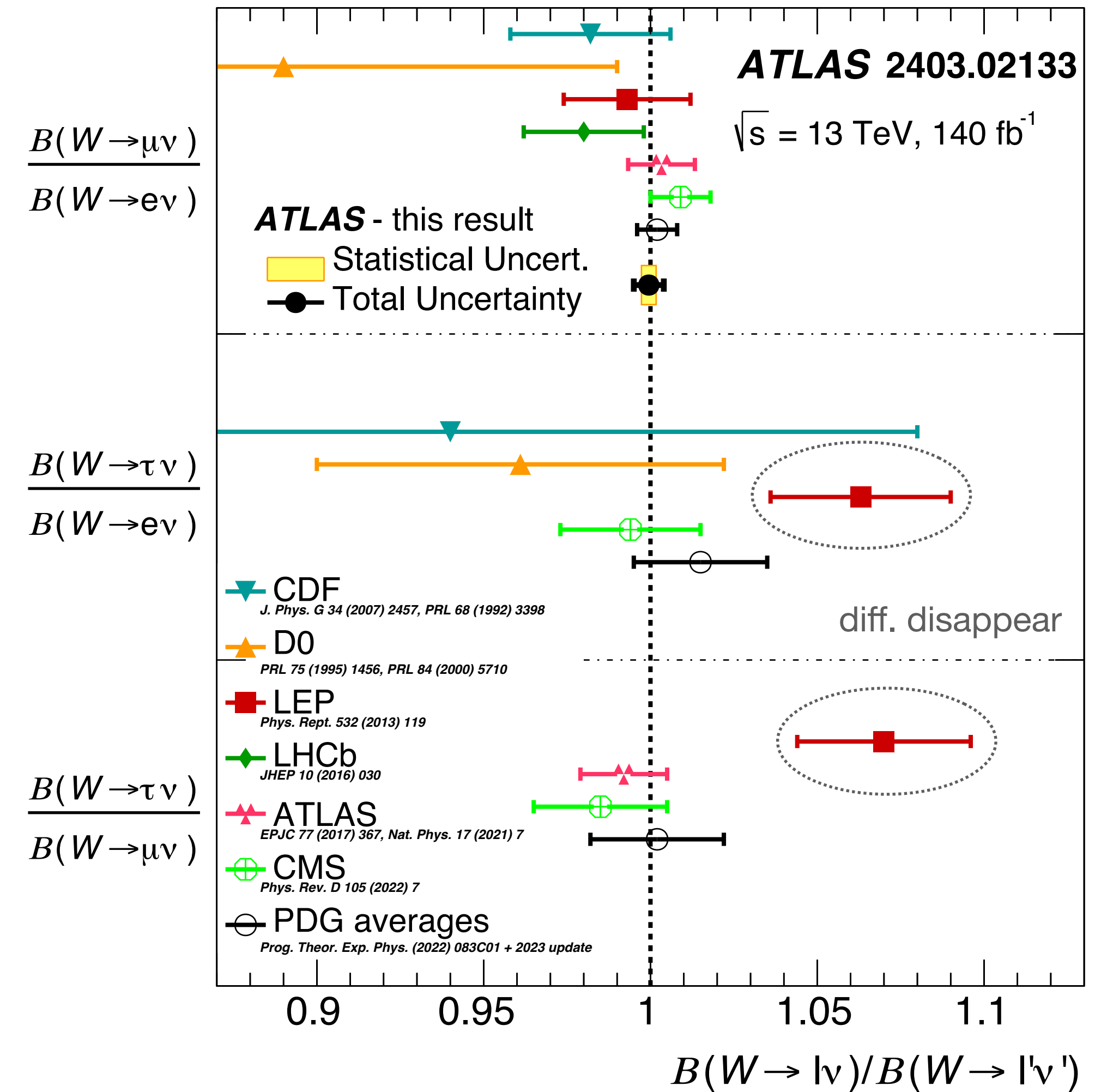
$$\frac{\Gamma(\tau^+ \tau^-)}{\Gamma(e^+ e^-)} \quad \Gamma_3/\Gamma_1$$

VALUE	DOCUMENT ID	TECN	COMMENT
1.0020 ± 0.0032 OUR AVERAGE			
1.02 ± 0.06	1 AAIJ	18AR LHCB	$E_{cm}^{pp} = 8 \text{ TeV}$
1.0019 ± 0.0032	2 LEP-SLC	06	$E_{cm}^{ee} = 88-94 \text{ GeV}$

$$\frac{\Gamma(\tau^+ \tau^-)}{\Gamma(\mu^+ \mu^-)} \quad \Gamma_3/\Gamma_2$$

VALUE	DOCUMENT ID	TECN	COMMENT
1.0010 ± 0.0026 OUR AVERAGE			
1.01 ± 0.05	1 AAIJ	18AR LHCB	$E_{cm}^{pp} = 8 \text{ TeV}$
1.0010 ± 0.0026	2 LEP-SLC	06	$E_{cm}^{ee} = 88-94 \text{ GeV}$

► W boson decay



Quarkonium

J/ψ

		PDG
Γ_5	$e^+ e^-$	$(5.971 \pm 0.032) \%$
Γ_7	$\mu^+ \mu^-$	$(5.961 \pm 0.033) \%$

$\psi(2S)$

Γ_7	$e^+ e^-$	$(7.94 \pm 0.22) \times 10^{-3}$
Γ_8	$\mu^+ \mu^-$	$(8.0 \pm 0.6) \times 10^{-3}$
Γ_9	$\tau^+ \tau^-$	$(3.1 \pm 0.4) \times 10^{-3}$

$$R_{\tau/\mu}^{\Upsilon(1S), \text{BaBar}} = 1.005 \pm 0.013_{\text{stat}} \pm 0.022_{\text{syst}},$$

$$R_{\tau/\mu}^{\Upsilon(1S), \text{CLEO}} = 1.02 \pm 0.02_{\text{stat}} \pm 0.05_{\text{syst}},$$

$$R_{\tau/\mu}^{\Upsilon(2S), \text{CLEO}} = 1.04 \pm 0.04_{\text{stat}} \pm 0.05_{\text{syst}},$$

$$R_{\tau/\mu}^{\Upsilon(3S), \text{CLEO}} = 1.05 \pm 0.08_{\text{stat}} \pm 0.05_{\text{syst}}.$$

$\Upsilon(1S)$

		PDG
Γ_1	$\tau^+ \tau^-$	$(2.60 \pm 0.10) \%$
Γ_2	$e^+ e^-$	$(2.39 \pm 0.08) \%$
Γ_3	$\mu^+ \mu^-$	$(2.48 \pm 0.04) \%$

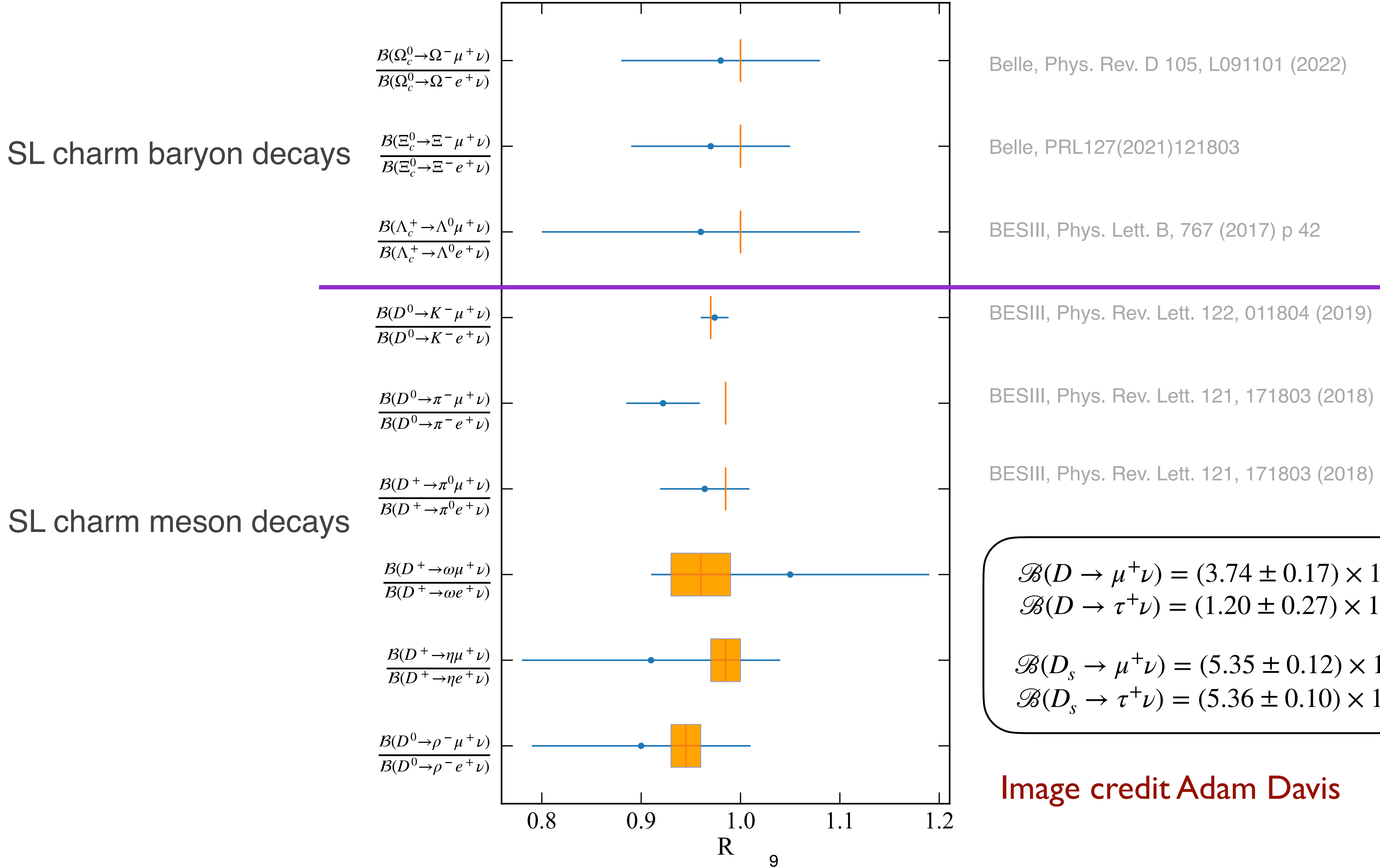
$\Upsilon(2S)$

Γ_3	$\tau^+ \tau^-$	$(2.00 \pm 0.21) \%$
Γ_4	$\mu^+ \mu^-$	$(1.93 \pm 0.17) \%$
Γ_5	$e^+ e^-$	$(1.91 \pm 0.16) \%$

$\Upsilon(3S)$

Γ_{13}	$\tau^+ \tau^-$	$(2.29 \pm 0.30) \%$
Γ_{14}	$\mu^+ \mu^-$	$(2.18 \pm 0.21) \%$
Γ_{15}	$e^+ e^-$	$(2.18 \pm 0.20) \%$

Charm sector: charged current



$$\mathcal{B}(D \rightarrow \mu^+ \nu) = (3.74 \pm 0.17) \times 10^{-4}$$

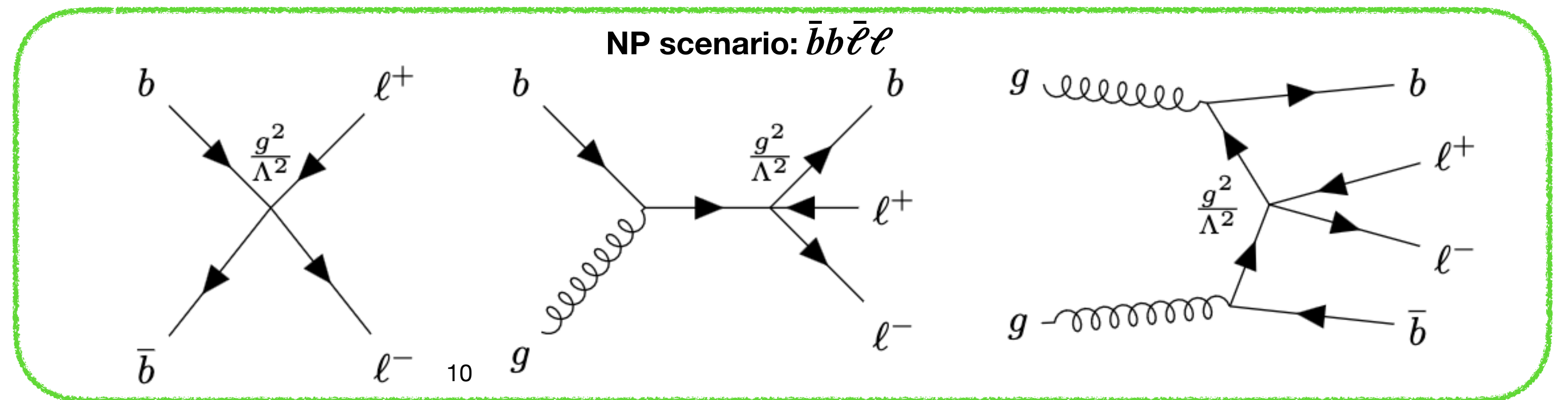
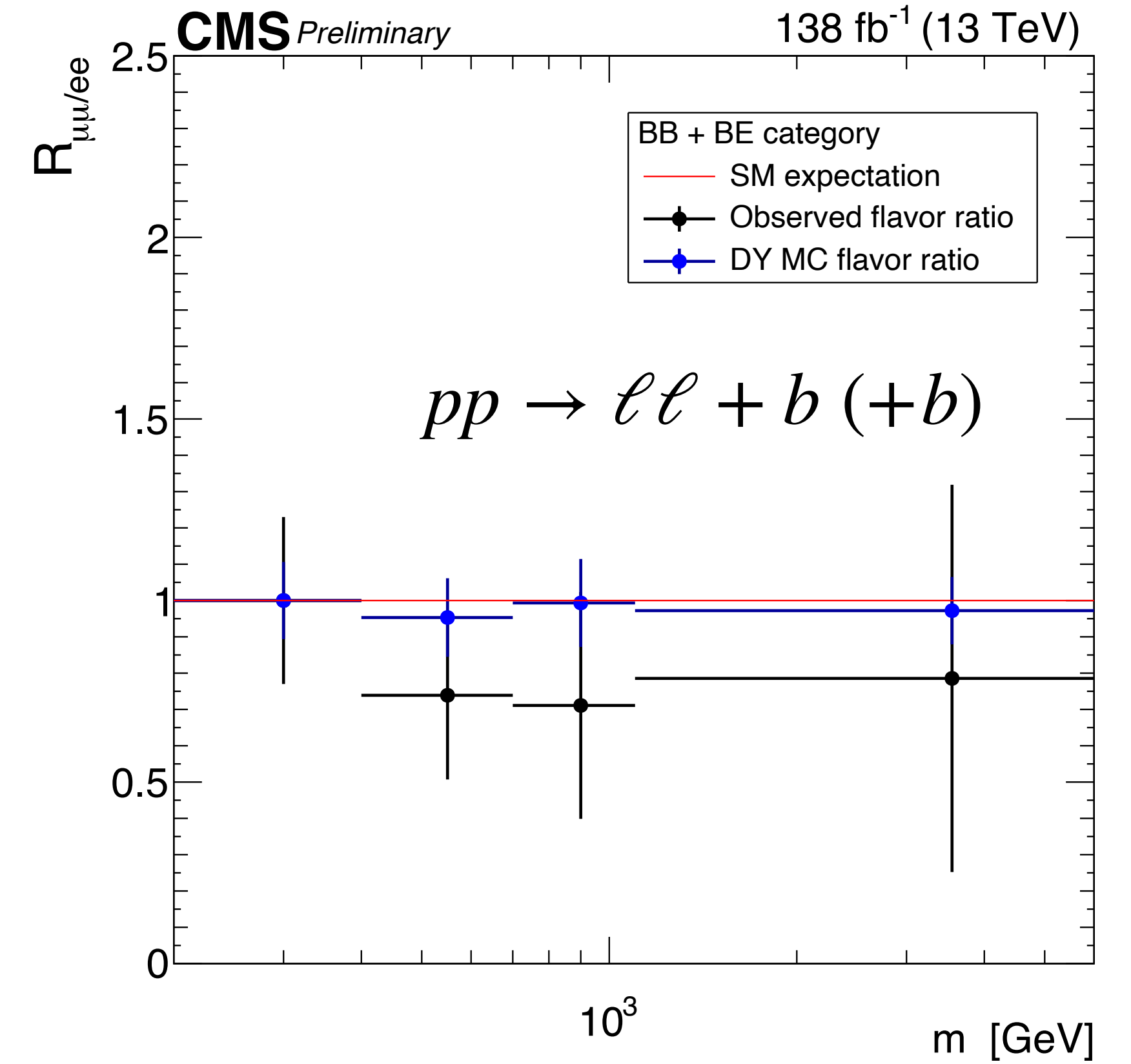
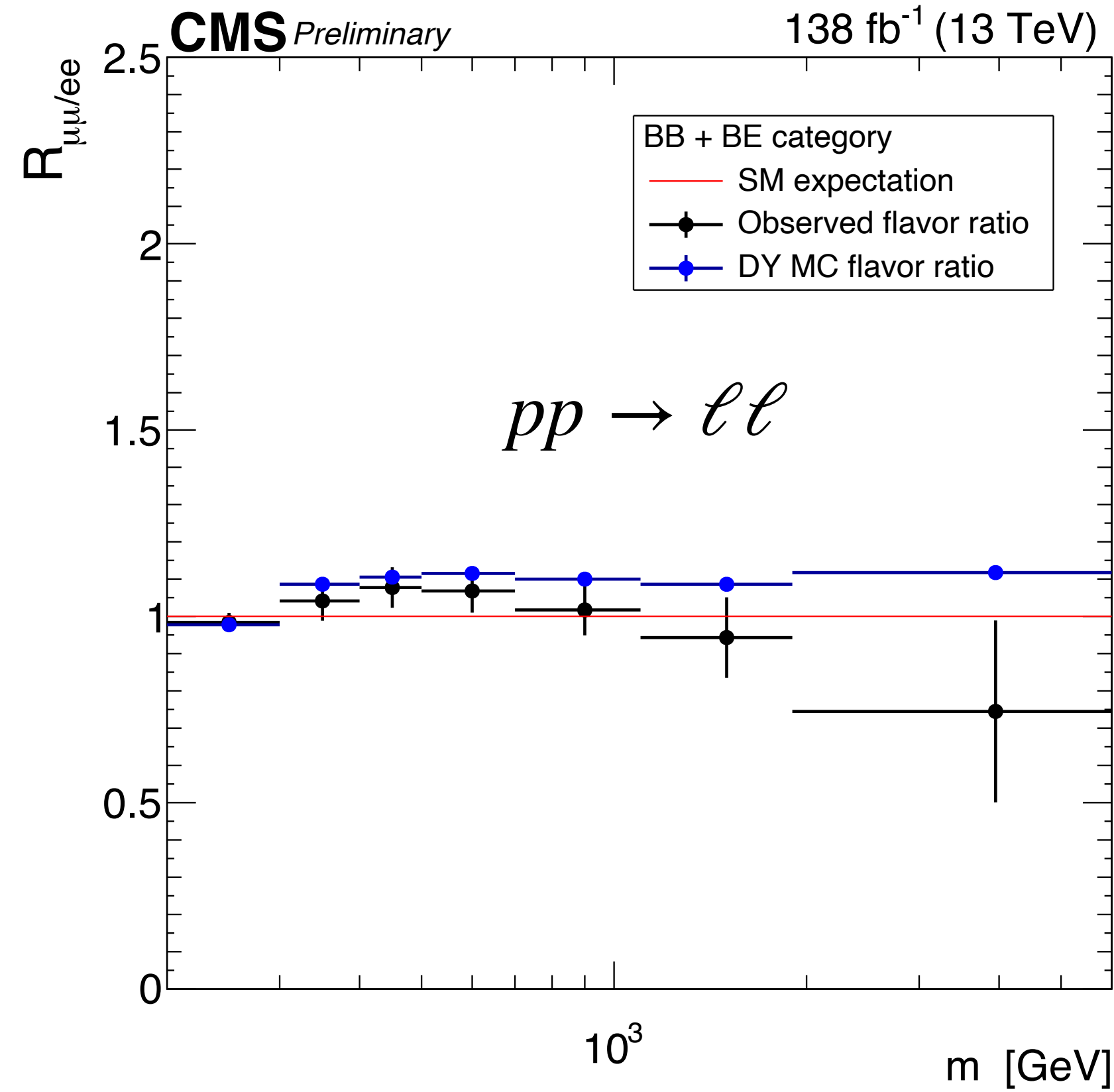
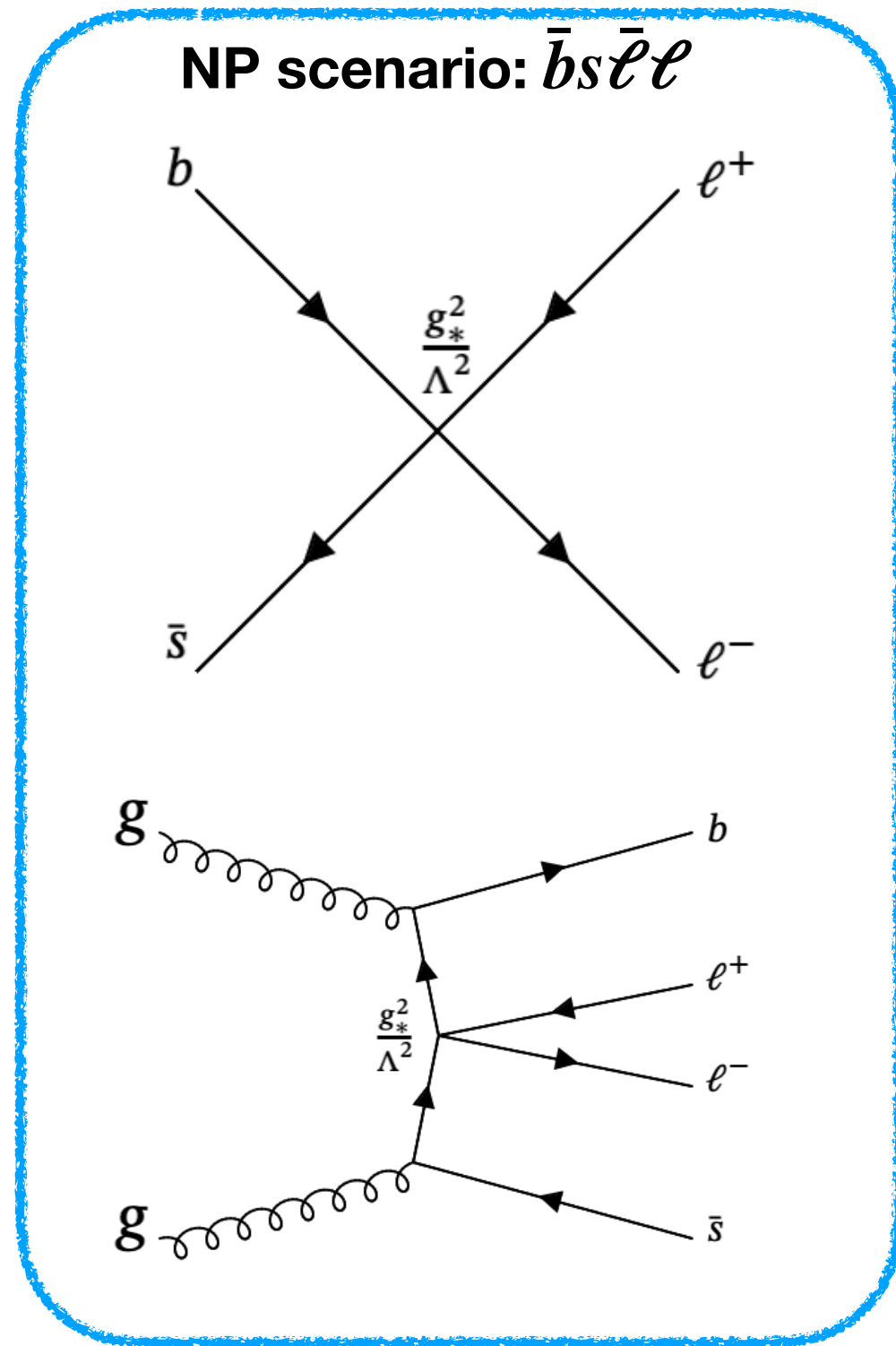
$$\mathcal{B}(D \rightarrow \tau^+ \nu) = (1.20 \pm 0.27) \times 10^{-3}$$

$$\mathcal{B}(D_s \rightarrow \mu^+ \nu) = (5.35 \pm 0.12) \times 10^{-3}$$

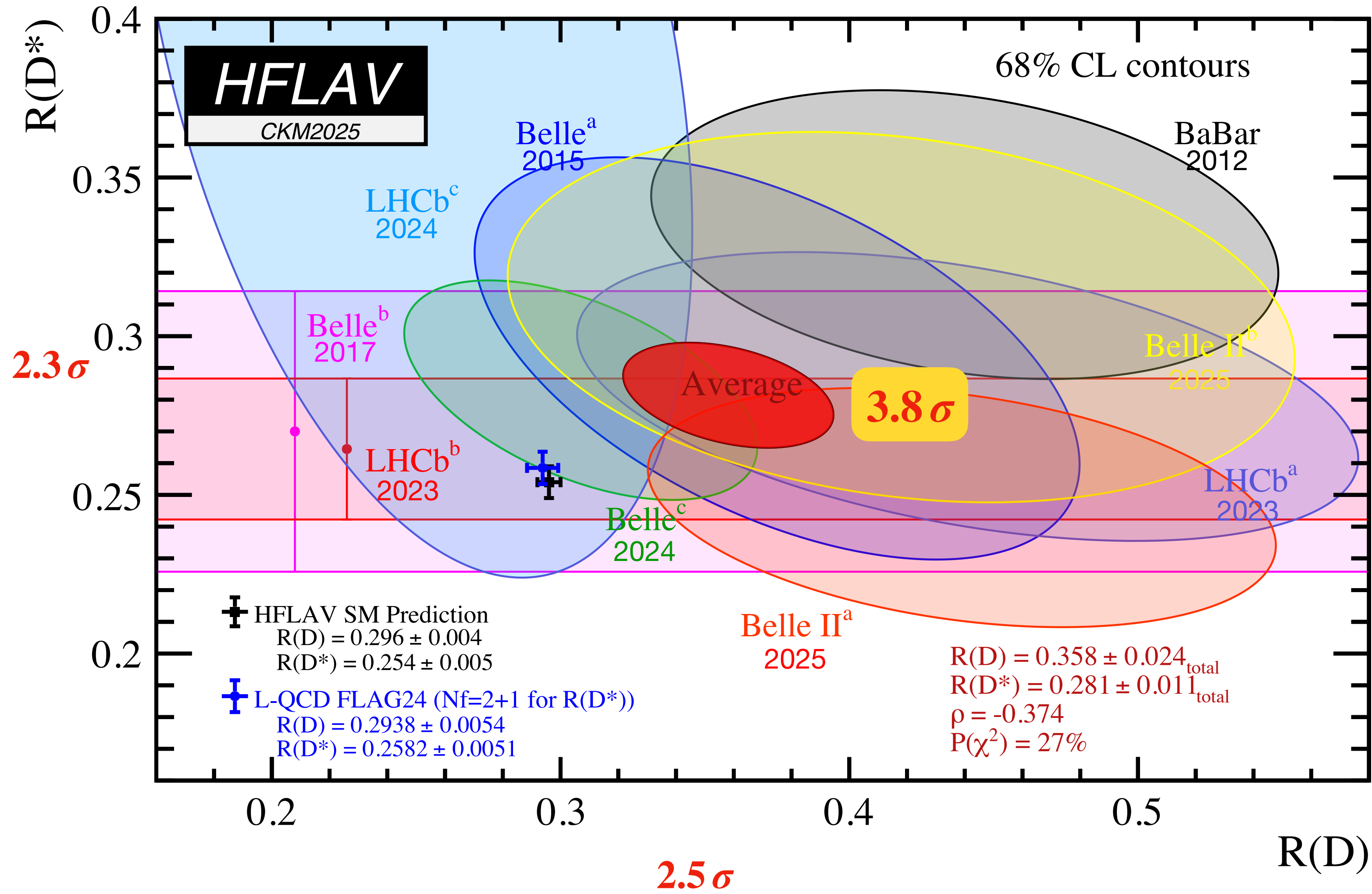
$$\mathcal{B}(D_s \rightarrow \tau^+ \nu) = (5.36 \pm 0.10) \times 10^{-2}$$

Image credit Adam Davis

Drell-Yan + b jets



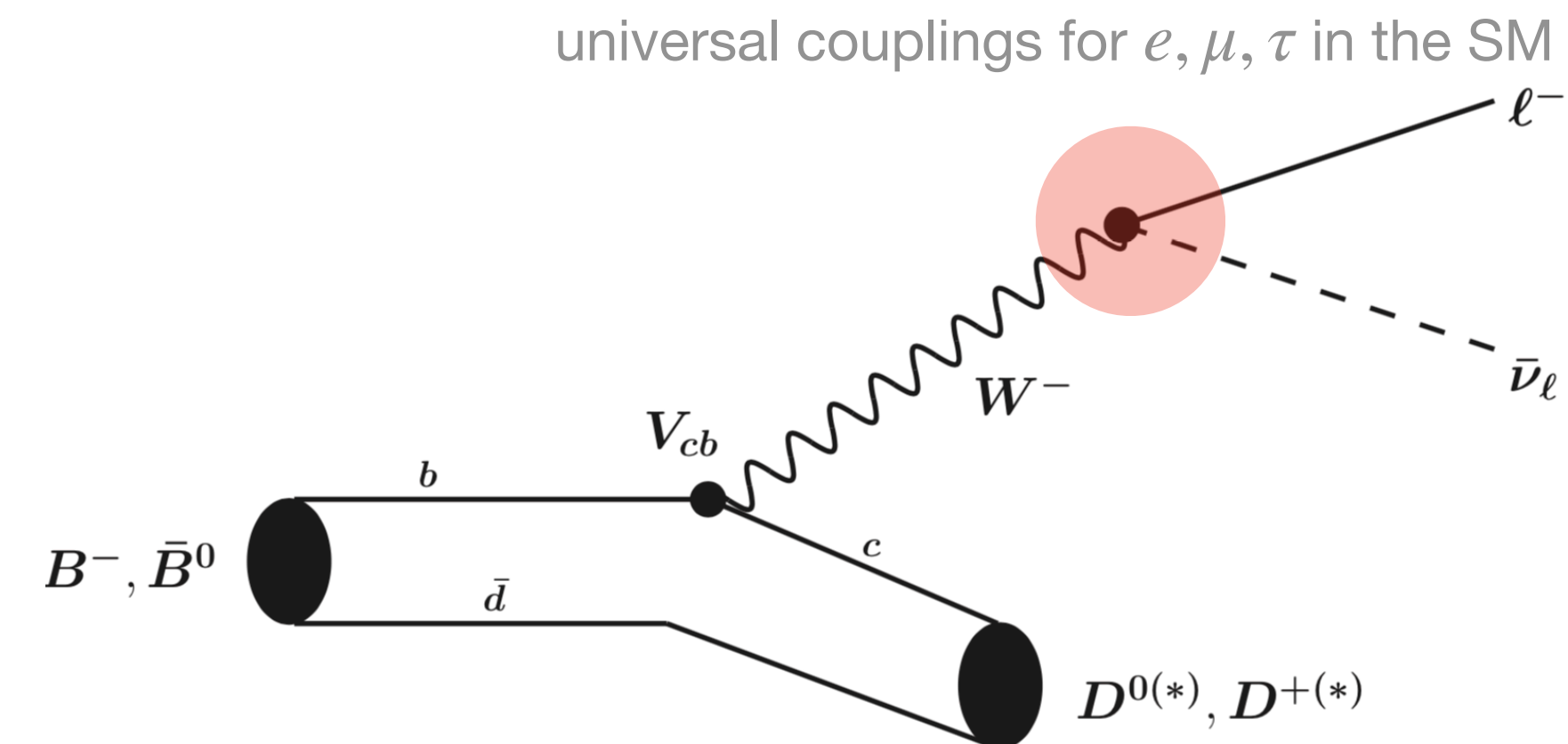
$R_{D^{(*)}}$ anomalies: exp



LFU Violation ratio τ v.s. e, μ

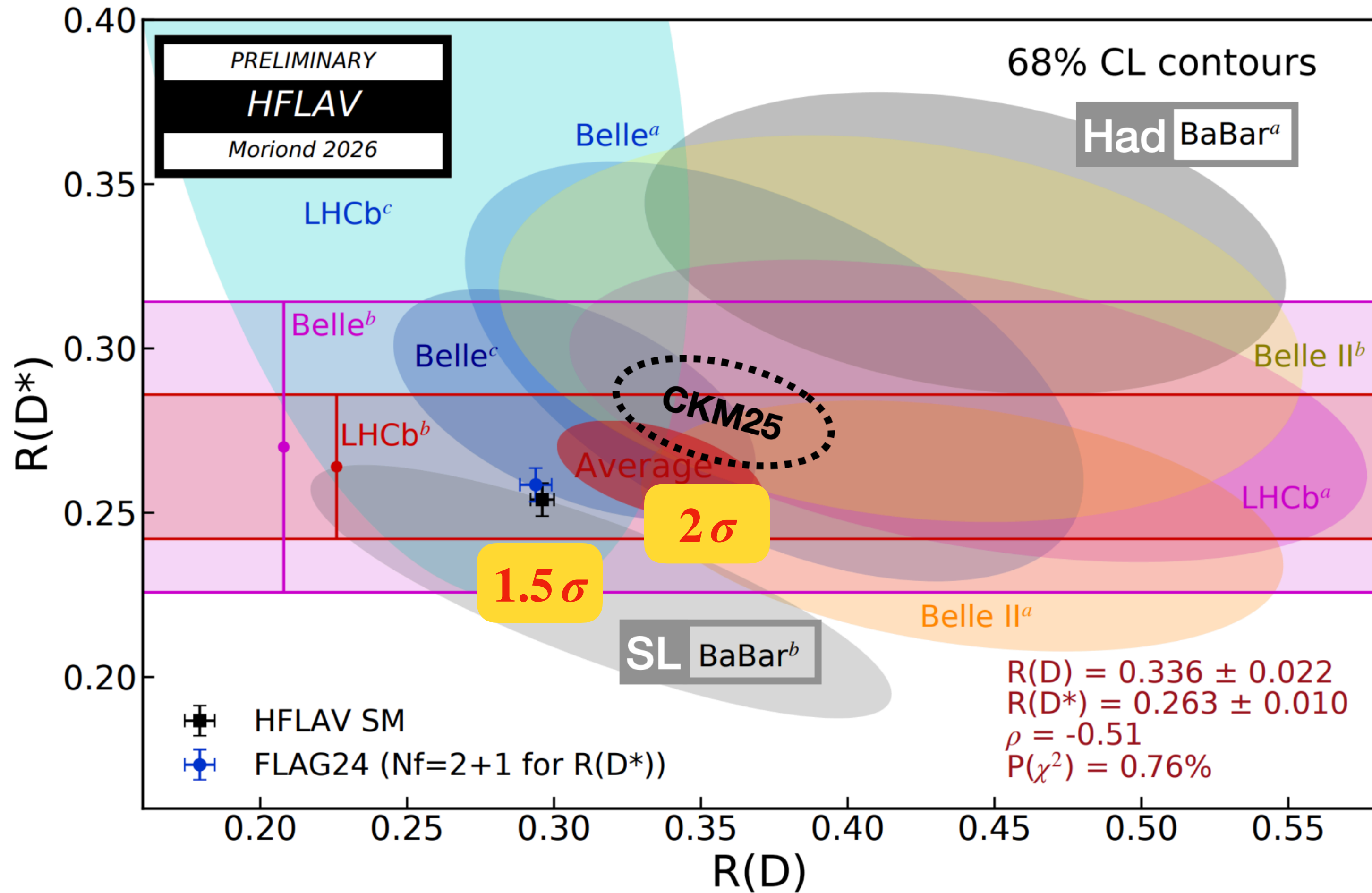
$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu)}{\mathcal{B}(B \rightarrow D^{(*)} \ell \nu)} \quad (\ell = e, \mu)$$

- ▶ QCD and EW contributions factorized
- ▶ hadronic and exp uncertainties cancelled
- ▶ tiny theoretical uncertainties



$R_{D^{(*)}}$ anomalies: exp

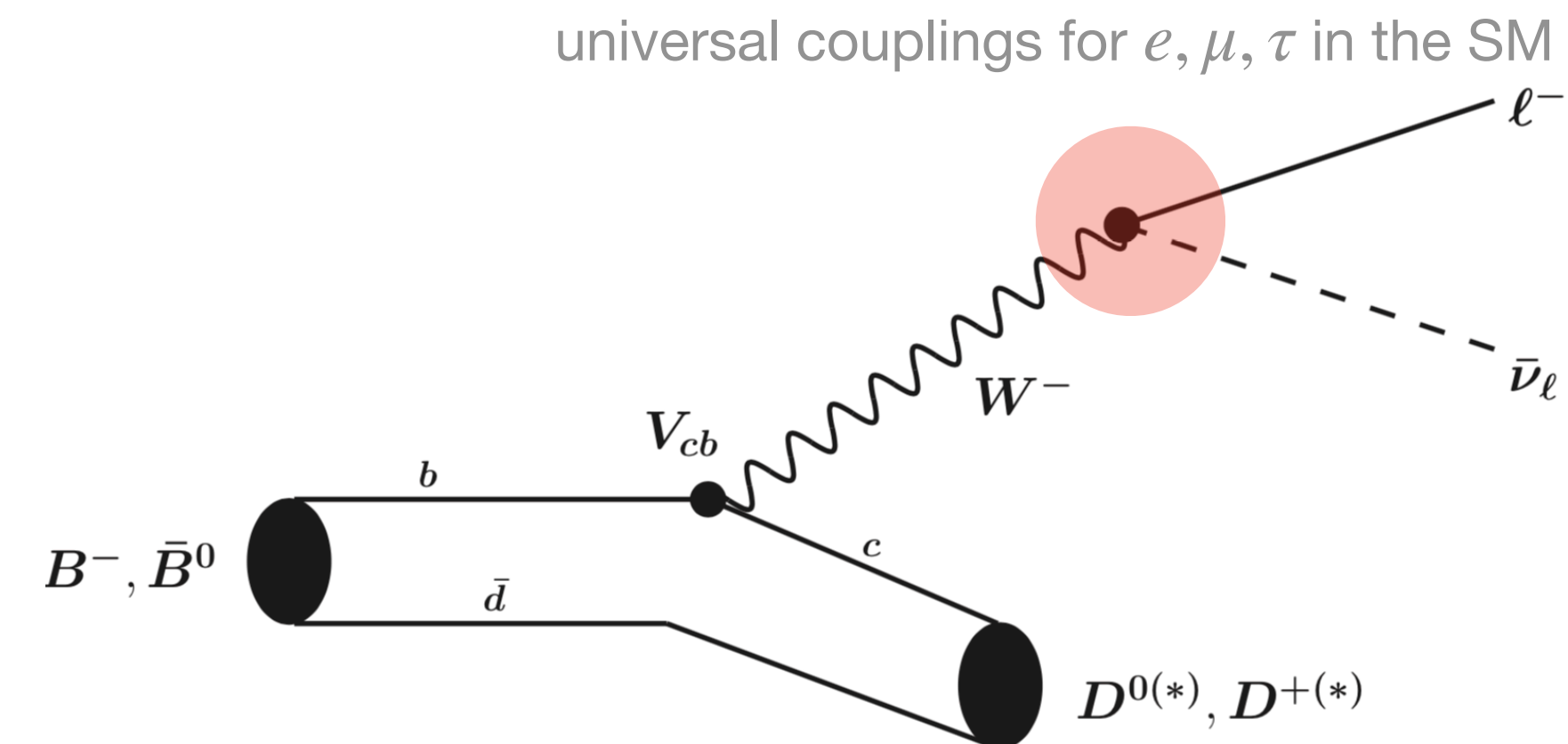
New BaBar results with semi-leptonic tag



LFU Violation ratio τ v.s. e, μ

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)} \quad (\ell = e, \mu)$$

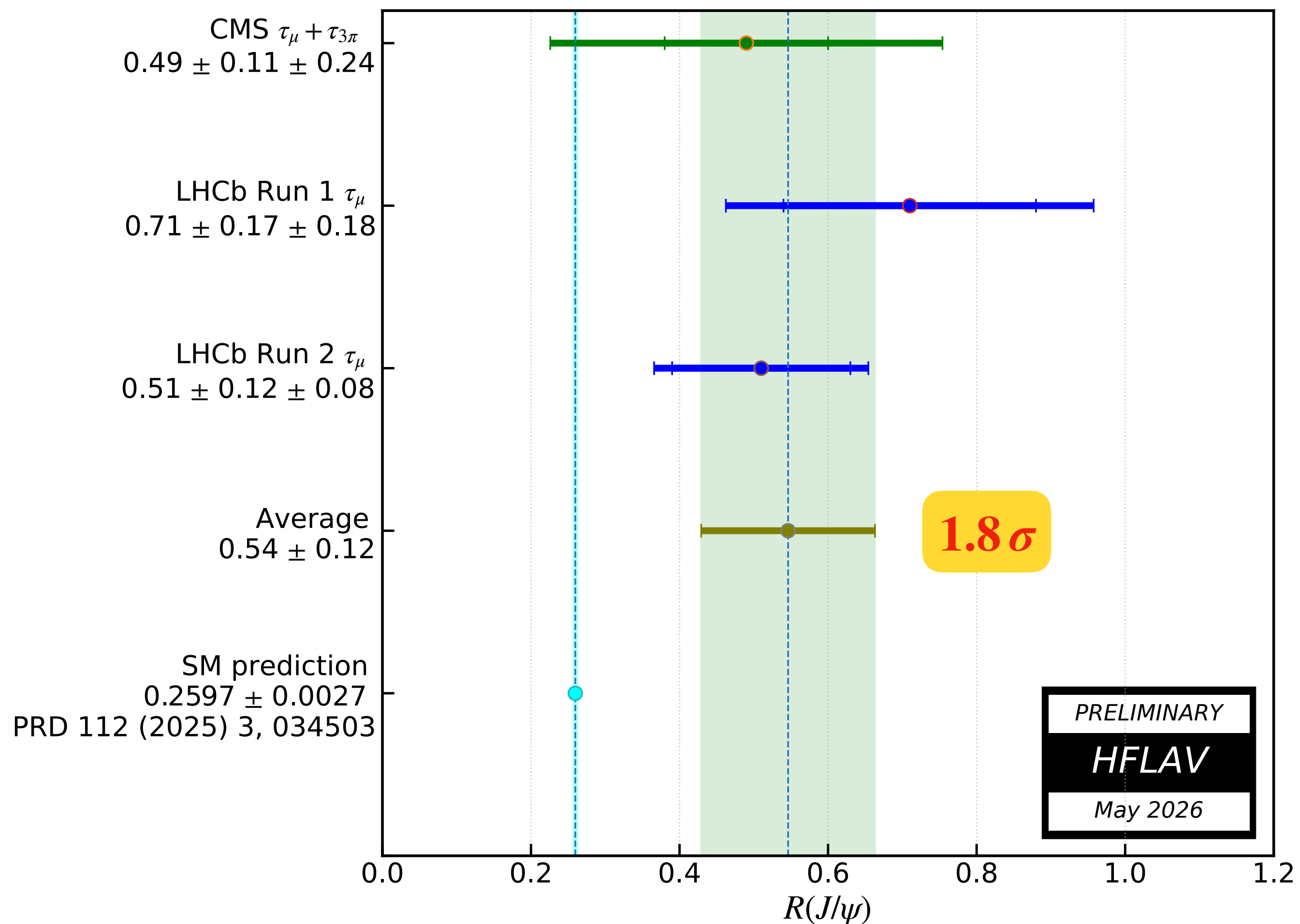
- ▶ QCD and EW contributions factorized
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see Lu Cao's talk for more details.

$R_{D^{(*)}}$ anomalies: exp

New LHCb measurements on $R(J/\psi)$

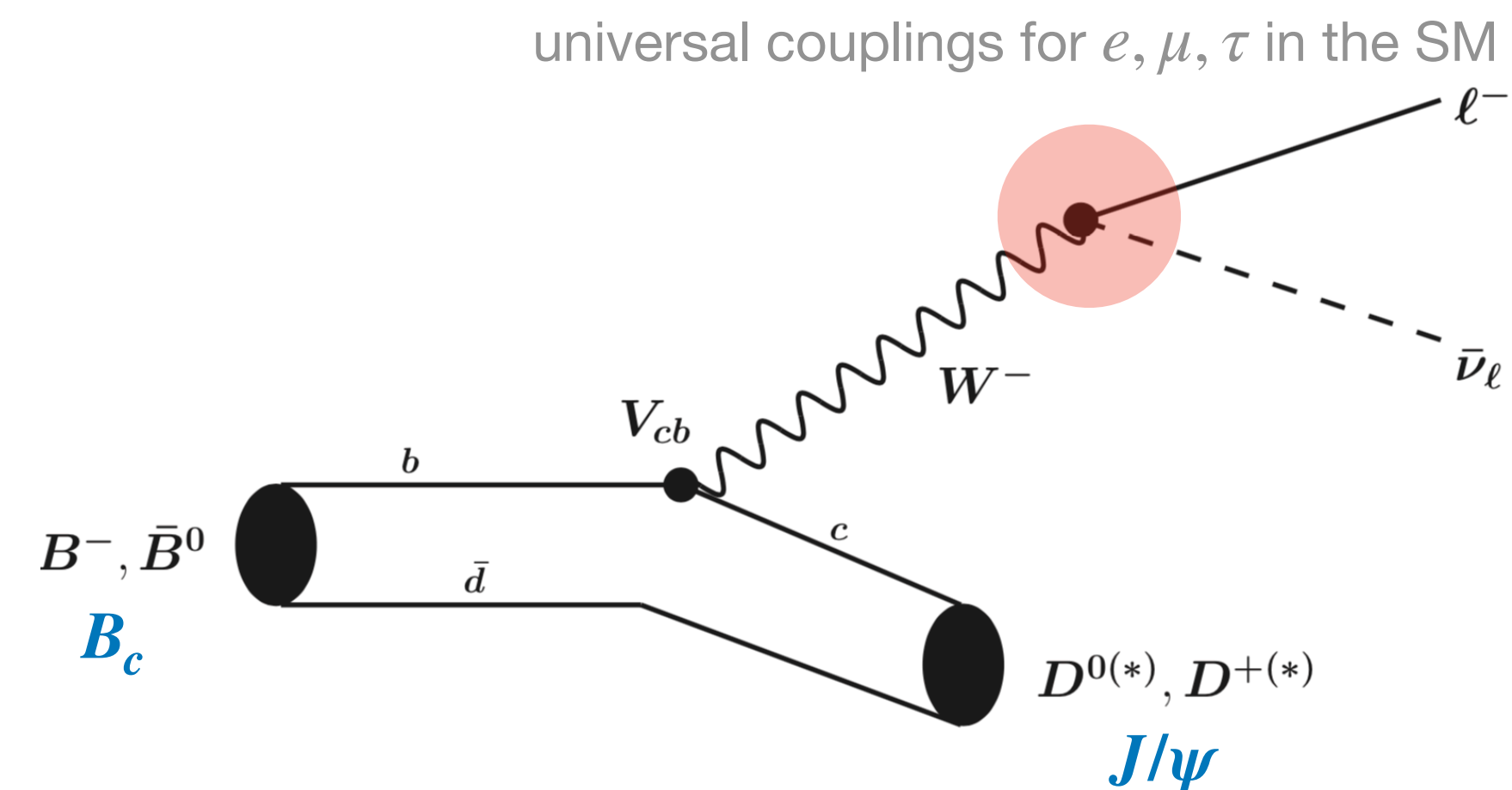


see Ji-Bo He's talk for more details.

LFU Violation ratio τ v.s. μ

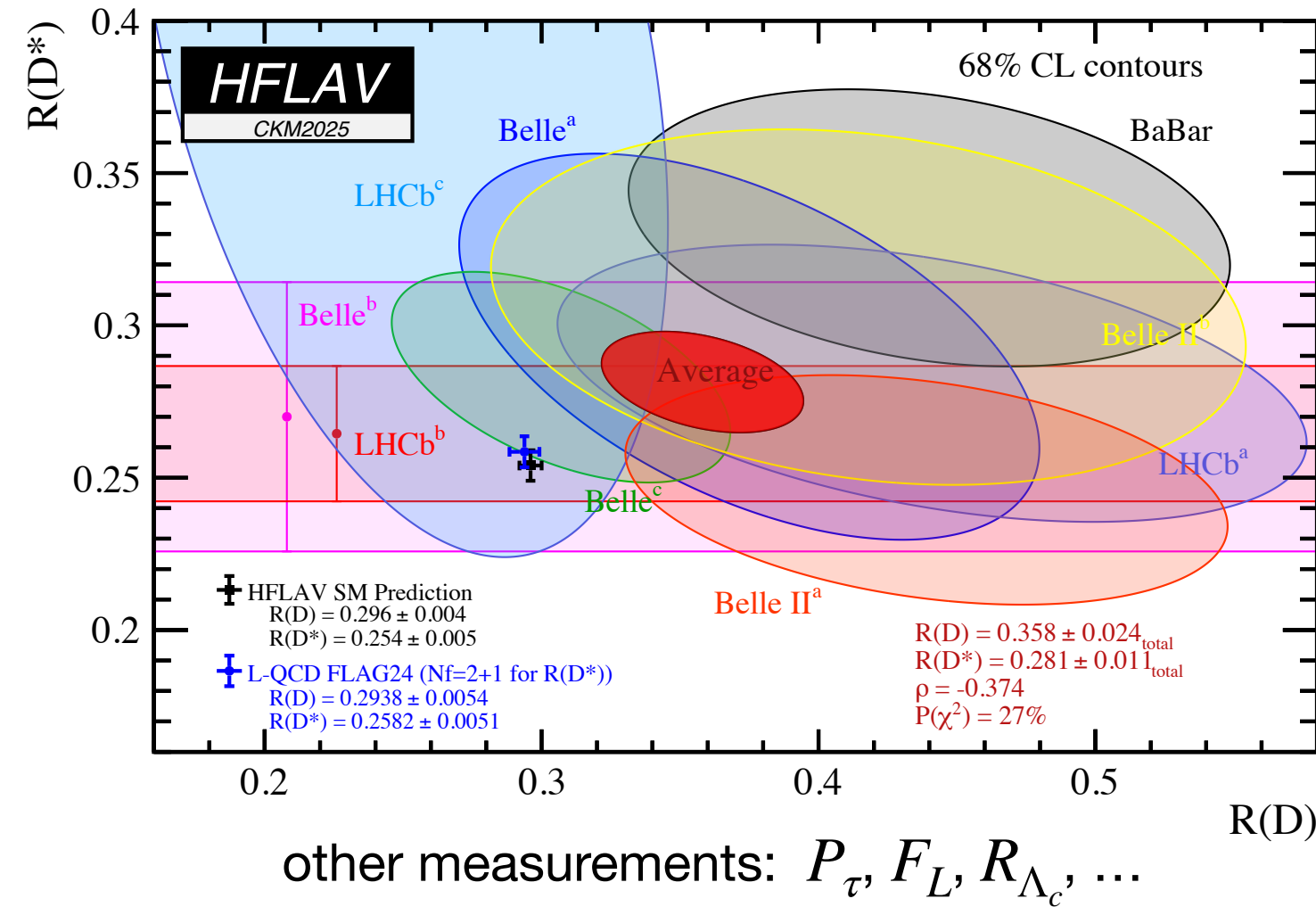
$$R(J/\psi) = \frac{\mathfrak{B}(B_c \rightarrow J/\psi\tau\nu)}{\mathfrak{B}(B_c \rightarrow J/\psi\mu\nu)}$$

- ▶ QCD and EW contributions factorized
- ▶ hadronic and exp uncertainties cancelled
- ▶ tiny theoretical uncertainties



$R_{D^{(*)}}$ anomalies: NP explanation

2405.06062, Iguro, Kitahara, Watanabe
1811.07920, Greljo, Camalich, Ruiz-A'lvarez
1810.04939, Q. Y. Hu, X. Q. Li, Y. D. Yang,



LEFT

$$\begin{aligned} \mathcal{O}_{V_L} &= (\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu) \\ \mathcal{O}_{V_R} &= (\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu) \\ \mathcal{O}_{S_L} &= (\bar{c}P_L b)(\bar{\ell}P_L \nu) \\ \mathcal{O}_{S_R} &= (\bar{c}P_R b)(\bar{\ell}P_L \nu) \\ \mathcal{O}_T &= (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu) \end{aligned}$$

highly constrained by B_c lifetime

best fit

$$\begin{aligned} C_{V_L} &= +0.08 & \text{Pull} &= 4.8 \\ C_{V_R} &= +0.01 \pm 0.41i & \text{Pull} &= 4.4 \\ C_{S_L} &= -0.79 \pm 0.86i & \text{Pull} &= 4.3 \\ C_{S_R} &= +0.18 & \text{Pull} &= 3.9 \\ C_T &= +0.02 \pm 0.13i & \text{Pull} &= 3.8 \end{aligned}$$

$\mathcal{B}(B_c \rightarrow \tau\nu) < 60\%$ assumed

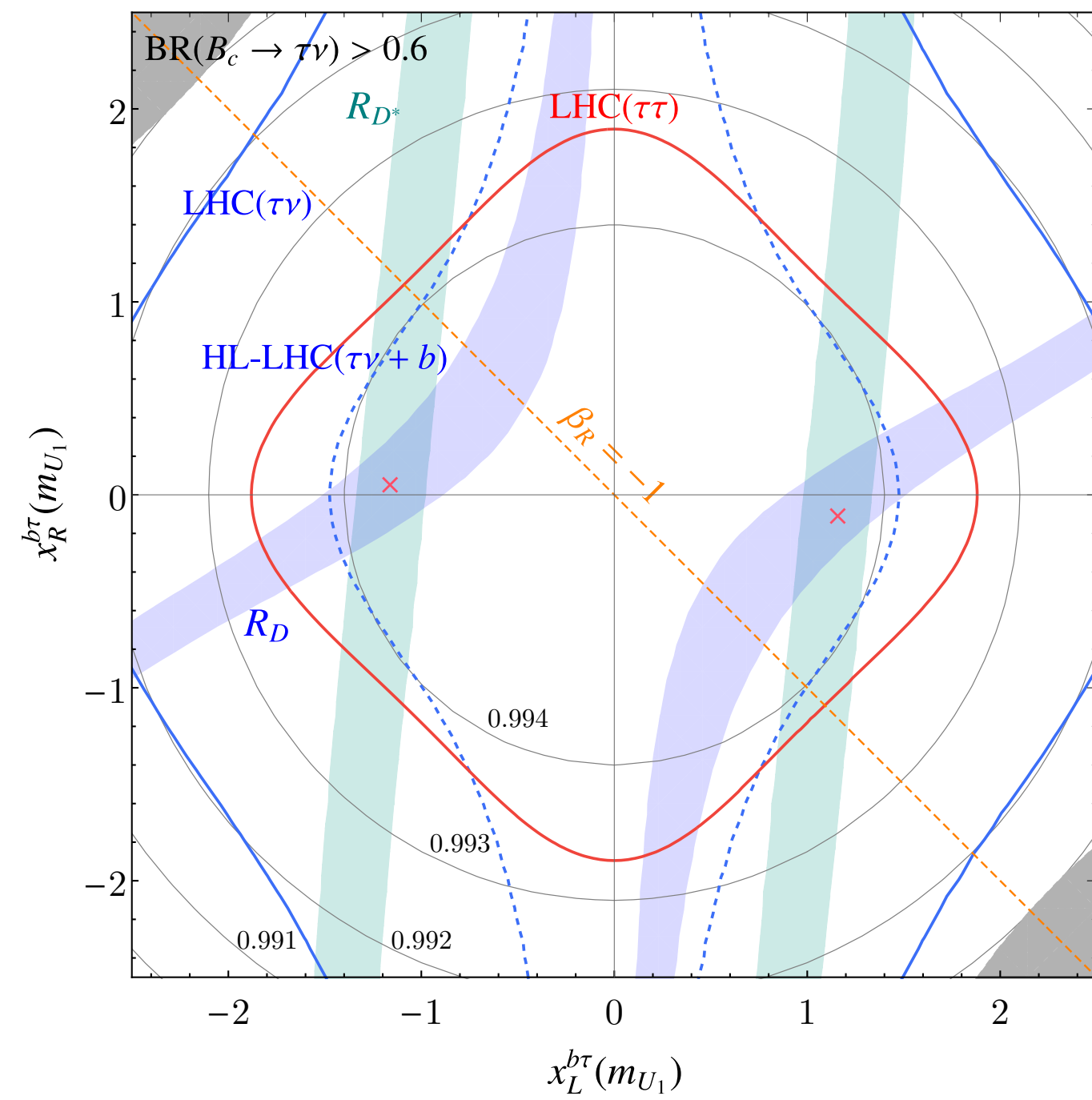
SMEFT

$$\mathcal{Q}_{lq}^{(3)} = (\bar{l}\gamma_\mu \tau^I l)(\bar{q}\gamma^\mu \tau^I q)$$

$$\mathcal{Q}_{ledq} = (\bar{l}_i e)(\bar{d}q_i)$$

$$\mathcal{Q}_{ledu}^{(1)} = (\bar{l}_i e)\epsilon_{ij}(\bar{q}_j u)$$

$$\mathcal{Q}_{ledu}^{(3)} = (\bar{l}_i \sigma_{\mu\nu} e)\epsilon_{ij}(\bar{q}_j \sigma^{\mu\nu} u)$$



Model

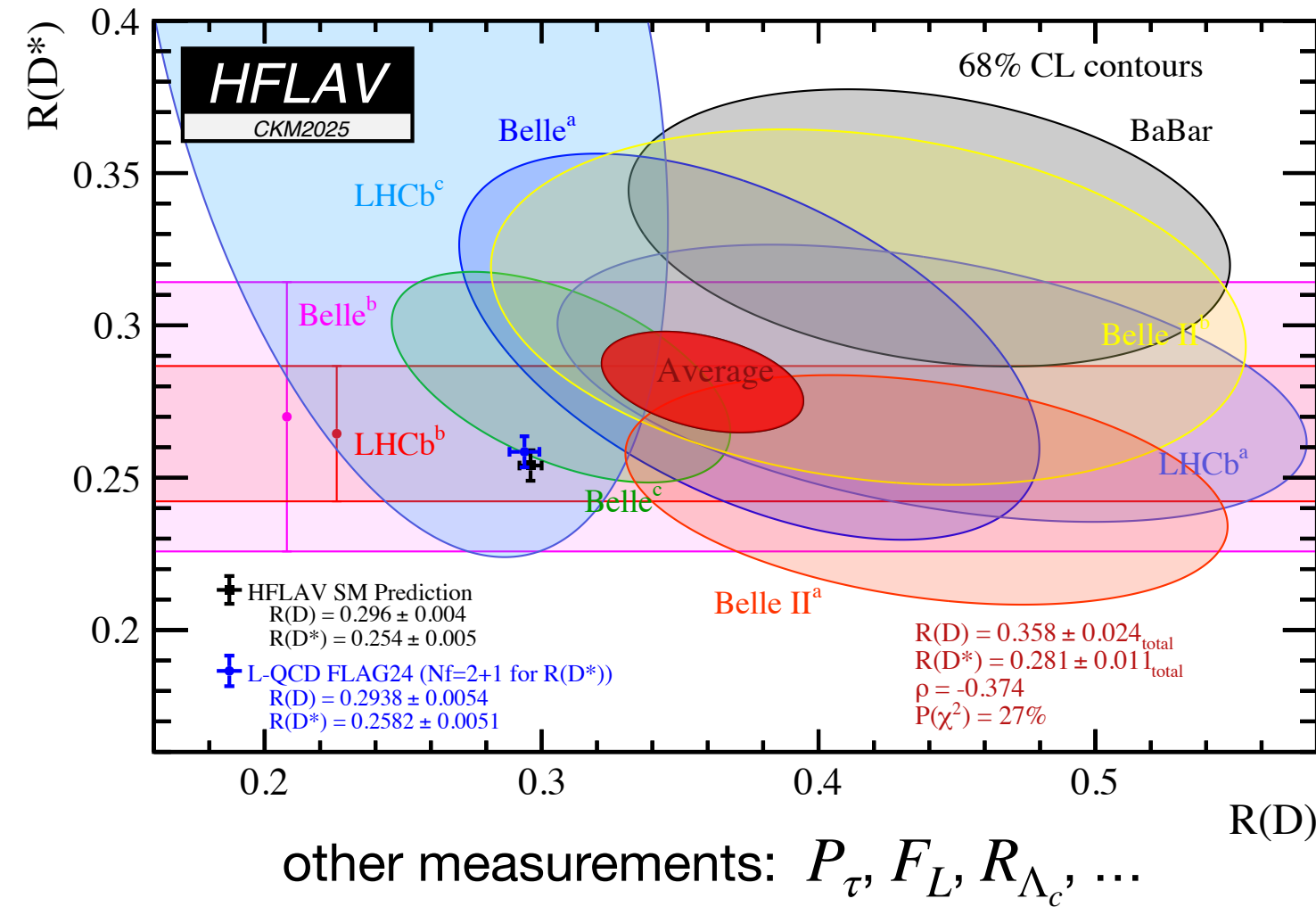
Model	Spin	Charge	Operators	R_D	R_{D^*}	LHC	Flavor
H^\pm	0	$(\mathbf{1}, \mathbf{2}, 1/2)$	\mathcal{O}_{S_L}	✓	✓	$b\tau\nu$	$B_c \rightarrow \tau\nu, F_L^{D^*}, P_\tau^{D^*}, M_W$
S_1	0	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$\mathcal{O}_{V_L}, \mathcal{O}_{S_L}, \mathcal{O}_T$	✓	✓	$\tau\tau$	$\Delta M_s, P_\tau^D, B \rightarrow K^{(*)}\nu\nu$
$R_2^{(2/3)}$	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	$\mathcal{O}_{S_L}, \mathcal{O}_T, (\mathcal{O}_{V_R})$	✓	✓	$b\tau\nu, \tau\tau$	$P_\tau^{D^*}, M_W, Z \rightarrow \tau\tau, d_N$
U_1	1	$(\mathbf{3}, \mathbf{1}, 2/3)$	$\mathcal{O}_{V_L}, \mathcal{O}_{S_R}$	✓	✓	$b\tau\nu, \tau\tau$	$\Delta M_s, R_{K^{(*)}}, B_s \rightarrow \tau\tau, d_N$
$V_2^{(1/3)}$	1	$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	\mathcal{O}_{S_R}	✓	2σ	$\tau\tau$	$B_s \rightarrow \tau\tau, B_u \rightarrow \tau\nu, M_W$

LHC provides important constraints.

(btw, they can be derived by ColliderAgent 2603.14553)

$R_D^{(*)}$ anomalies: NP explanation

2405.06062, Iguro, Kitahara, Watanabe
 1811.07920, Greljo, Camalich, Ruiz-A'lvarez
 1810.04939, Q. Y. Hu, X. Q. Li, Y. D. Yang,



LEFT

$$\mathcal{O}_{V_L} = (\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu)$$

$$\mathcal{O}_{V_R} = (\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu)$$

$$\mathcal{O}_{S_L} = (\bar{c}P_L b)(\bar{\ell}P_L \nu)$$

$$\mathcal{O}_{S_R} = (\bar{c}P_R b)(\bar{\ell}P_L \nu)$$

$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu)$$

highly constrained by B_c lifetime

best fit

$$C_{V_L} = +0.08 \quad \text{Pull} = 4.8$$

$$C_{V_R} = +0.01 \pm 0.41i \quad \text{Pull} = 4.4$$

$$C_{S_L} = -0.79 \pm 0.86i \quad \text{Pull} = 4.3$$

$$C_{S_R} = +0.18 \quad \text{Pull} = 3.9$$

$$C_T = +0.02 \pm 0.13i \quad \text{Pull} = 3.8$$

$B(B_c \rightarrow \tau\nu) < 60\%$ assumed

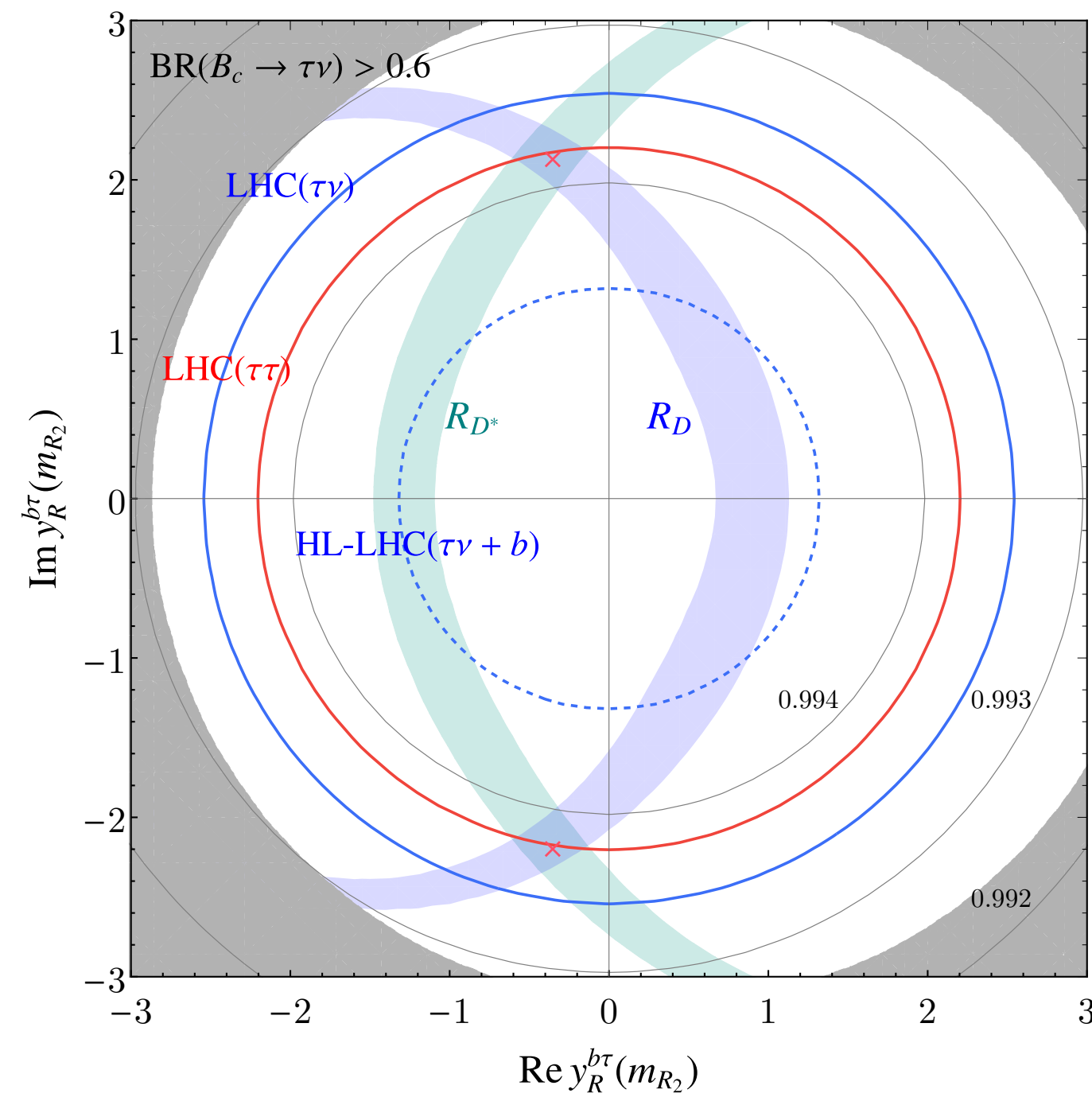
SMEFT

$$\mathcal{Q}_{lq}^{(3)} = (\bar{l}\gamma_\mu \tau^I l)(\bar{q}\gamma^\mu \tau^I q)$$

$$\mathcal{Q}_{ledq} = (\bar{l}_i e)(\bar{d} q_i)$$

$$\mathcal{Q}_{ledu}^{(1)} = (\bar{l}_i e)\epsilon_{ij}(\bar{q}_j u)$$

$$\mathcal{Q}_{ledu}^{(3)} = (\bar{l}_i \sigma_{\mu\nu} e)\epsilon_{ij}(\bar{q}_j \sigma^{\mu\nu} u)$$



Model

	Spin	Charge	Operators	R_D	R_{D^*}	LHC	Flavor
H^\pm	0	$(\mathbf{1}, \mathbf{2}, 1/2)$	\mathcal{O}_{S_L}	✓	✓	$b\tau\nu$	$B_c \rightarrow \tau\nu, F_L^{D^*}, P_\tau^{D^*}, M_W$
S_1	0	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$\mathcal{O}_{V_L}, \mathcal{O}_{S_L}, \mathcal{O}_T$	✓	✓	$\tau\tau$	$\Delta M_s, P_\tau^D, B \rightarrow K^{(*)}\nu\nu$
$R_2^{(2/3)}$	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	$\mathcal{O}_{S_L}, \mathcal{O}_T, (\mathcal{O}_{V_R})$	✓	✓	$b\tau\nu, \tau\tau$	$P_\tau^{D^*}, M_W, Z \rightarrow \tau\tau, d_N$
U_1	1	$(\mathbf{3}, \mathbf{1}, 2/3)$	$\mathcal{O}_{V_L}, \mathcal{O}_{S_R}$	✓	✓	$b\tau\nu, \tau\tau$	$\Delta M_s, R_{K^{(*)}}, B_s \rightarrow \tau\tau, d_N$
$V_2^{(1/3)}$	1	$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	\mathcal{O}_{S_R}	✓	2σ	$\tau\tau$	$B_s \rightarrow \tau\tau, B_u \rightarrow \tau\nu, M_W$

LHC provides important constraints.

(btw, they can be derived by ColliderAgent 2603.14553)

$R_{D^{(*)}}$ anomalies: correlation

sum rules for semi-leptonic decays

$$\frac{R_{\Lambda_c}}{R_{\Lambda_c}^{\text{SM}}} = (0.272 \pm 0.015) \frac{R_D}{R_D^{\text{SM}}} + (0.728 \mp 0.015) \frac{R_{D^*}}{R_{D^*}^{\text{SM}}} + \delta_{\Lambda_c} \quad \leftarrow \text{eliminate } |1 + C_{V_L}|^2, \text{Re}[(1 + C_{V_L})C_{S_L}^*]$$

$$\begin{aligned} \delta_{\Lambda_c} = & (-0.001 \pm 0.005) (|C_{S_L}^{c\tau}|^2 + |C_{S_R}^{c\tau}|^2) + (-0.007 \pm 0.005) \text{Re}(C_{S_L}^{c\tau} C_{S_R}^{c\tau*}) \\ & + (-2.681 \pm 6.907) |C_T^{c\tau}|^2 + (-0.561 \pm 1.439) \text{Re}(C_{V_R}^{c\tau} C_T^{c\tau*}) \\ & + \text{Re}[(1 + C_{V_L}^{c\tau}) \{(0.041 \pm 0.034)C_{V_R}^{c\tau*} + (0.594 \pm 1.274)C_T^{c\tau*}\}] \\ & + (-0.002 \pm 0.009) \text{Re}[(1 + C_{V_L}^{c\tau}) C_{S_R}^{c\tau*} + C_{S_L}^{c\tau} C_{V_R}^{c\tau*}] . \end{aligned} \quad (;$$

► based on LEFT, model-independent $R_{\Lambda_c}^{\text{LHCb}} = 0.242 \pm 0.076$

► for any tau-philic NP $R_{\Lambda_c}^{\text{SR}} = 0.372 \pm 0.017$

$$R_{\Lambda_c}^{\text{SM}} = 0.324 \pm 0.004$$

other modes

► $\frac{R_{X_c}}{R_{X_c}^{\text{SM}}} \simeq 0.288 \frac{R_D}{R_D^{\text{SM}}} + 0.712 \frac{R_{D^*}}{R_{D^*}^{\text{SM}}} + \delta_{X_c}$ $R_{X_c}^{\text{SR}} = 0.247 \pm 0.008$ $R_{X_c}^{\text{Belle II}} = 0.228 \pm 0.039$

► $\frac{R_{J/\psi}}{R_{J/\psi}^{\text{SM}}} \simeq \frac{R_{D^*}}{R_{D^*}^{\text{SM}}}$ $\frac{R_{J/\psi}^{\text{exp}}}{R_{J/\psi}^{\text{SM}}} - \frac{R_{D^*}^{\text{exp}}}{R_{D^*}^{\text{SM}}} = 1.2 \pm 0.7$

► $\frac{R_p}{R_p^{\text{SM}}} = (0.284 \pm 0.037) \frac{R_\pi}{R_\pi^{\text{SM}}} + (0.716 \mp 0.037) \frac{R_\rho}{R_\rho^{\text{SM}}} + \delta_p$

$$\begin{aligned} \frac{R_P}{R_P^{\text{SM}}} = & |1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau}|^2 + a_P^{SS} |C_{S_L}^{q\tau} + C_{S_R}^{q\tau}|^2 + a_P^{TT} |C_T^{q\tau}|^2 \\ & + a_P^{VS} \text{Re}[(1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau})(C_{S_L}^{q\tau*} + C_{S_R}^{q\tau*})] + a_P^{VT} \text{Re}[(1 + C_{V_L}^{q\tau} + C_{V_R}^{q\tau})C_T^{q\tau*}] \end{aligned}$$

$$\begin{aligned} \frac{R_V}{R_V^{\text{SM}}} = & |1 + C_{V_L}^{q\tau}|^2 + |C_{V_R}^{q\tau}|^2 + a_V^{SS} |C_{S_L}^{q\tau} - C_{S_R}^{q\tau}|^2 + a_V^{TT} |C_T^{q\tau}|^2 \\ & + a_V^{V_L V_R} \text{Re}[(1 + C_{V_L}^{q\tau})C_{V_R}^{q\tau*}] + a_V^{VS} \text{Re}[(1 + C_{V_L}^{q\tau} - C_{V_R}^{q\tau})(C_{S_L}^{q\tau*} - C_{S_R}^{q\tau*})] \\ & + a_V^{V_L T} \text{Re}[(1 + C_{V_L}^{q\tau})C_T^{q\tau*}] + a_V^{V_R T} \text{Re}[C_{V_R}^{q\tau} C_T^{q\tau*}] , \end{aligned}$$

$$\begin{aligned} \frac{R_H}{R_H^{\text{SM}}} = & |1 + C_{V_L}^{q\tau}|^2 + |C_{V_R}^{q\tau}|^2 + a_H^{SS} [|C_{S_L}^{q\tau}|^2 + |C_{S_R}^{q\tau}|^2] + a_H^{TT} |C_T^{q\tau}|^2 \\ & + a_H^{V_L V_R} \text{Re}[(1 + C_{V_L}^{q\tau})C_{V_R}^{q\tau*}] + a_H^{VS_1} \text{Re}[(1 + C_{V_L}^{q\tau})C_{S_L}^{q\tau*} + C_{V_R}^{q\tau} C_{S_R}^{q\tau*}] \\ & + a_H^{VS_2} \text{Re}[(1 + C_{V_L}^{q\tau})C_{S_R}^{q\tau*} + C_{V_R}^{q\tau} C_{S_L}^{q\tau*}] + a_H^{S_L S_R} \text{Re}[C_{S_L}^{q\tau} C_{S_R}^{q\tau*}] \\ & + a_H^{V_L T} \text{Re}[(1 + C_{V_L}^{q\tau})C_T^{q\tau*}] + a_H^{V_R T} \text{Re}[C_{V_R}^{q\tau} C_T^{q\tau*}] , \end{aligned}$$

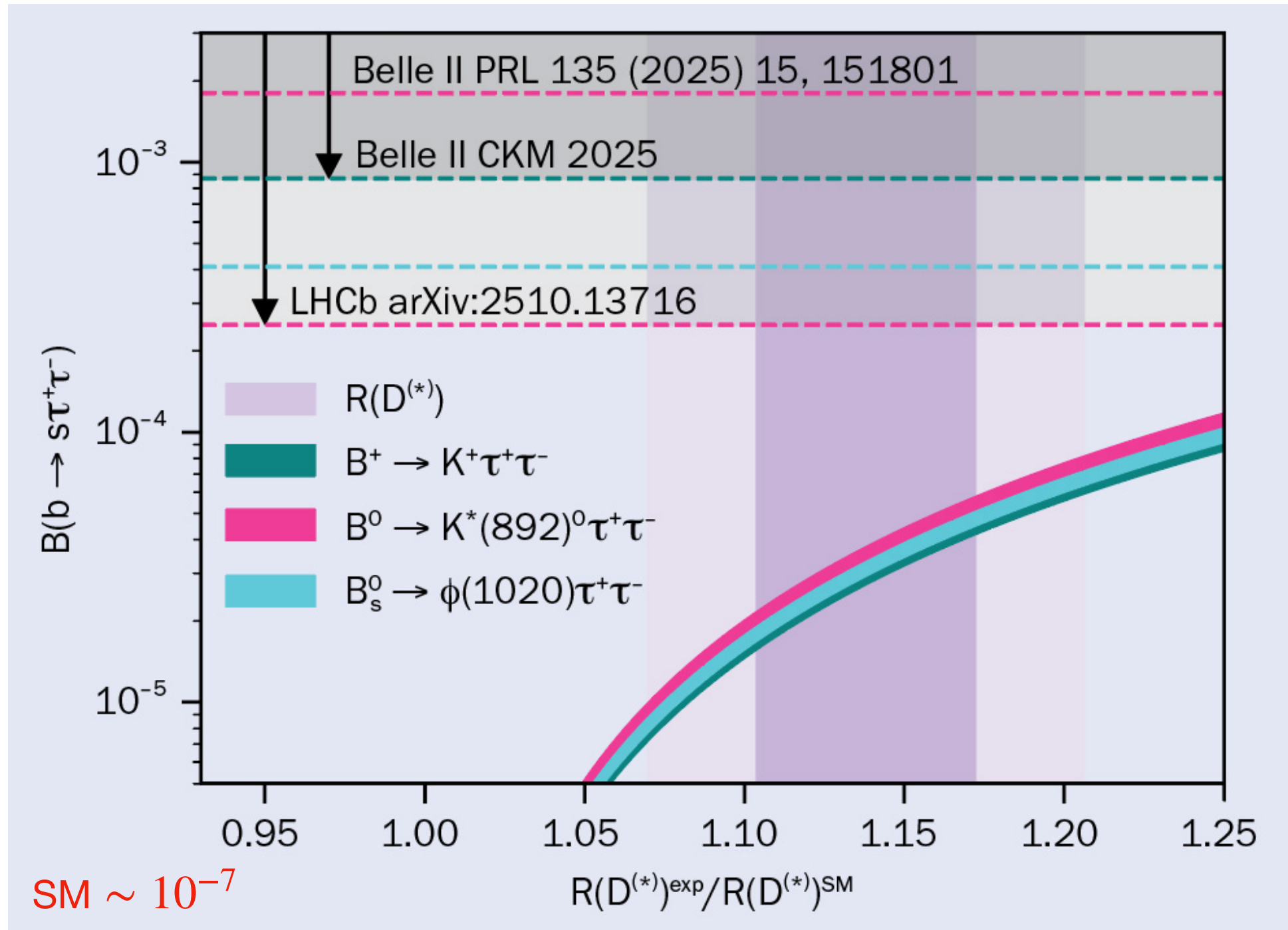
2 σ deviation

1811.09603, Blanke, Crivellin, de Boer, Kitahara, Moscati, Nierste, Nišandžić
 1905.08253, Blanke, Crivellin, Kitahara, Moscati, Nierste, Nišandžić
 2211.14172, Fedele, Blanke, Crivellin, Iguro, Kitahara, Nierste, Watanabe
2410.21384, 段文烽, Iguro, 李新强, Watanabe, 杨亚东
 2501.09382, Endo, Iguro, Mishima, Watanabe, *heavy quark symmetry*
 2506.16027, Endo, Iguro, Kretz, Mishima, Watanabe, *angular observable*
 2508.06322, Endo, Iguro, Mishima, Watanabe,
 2509.02006, Endo, Iguro, Mishima, Watanabe,

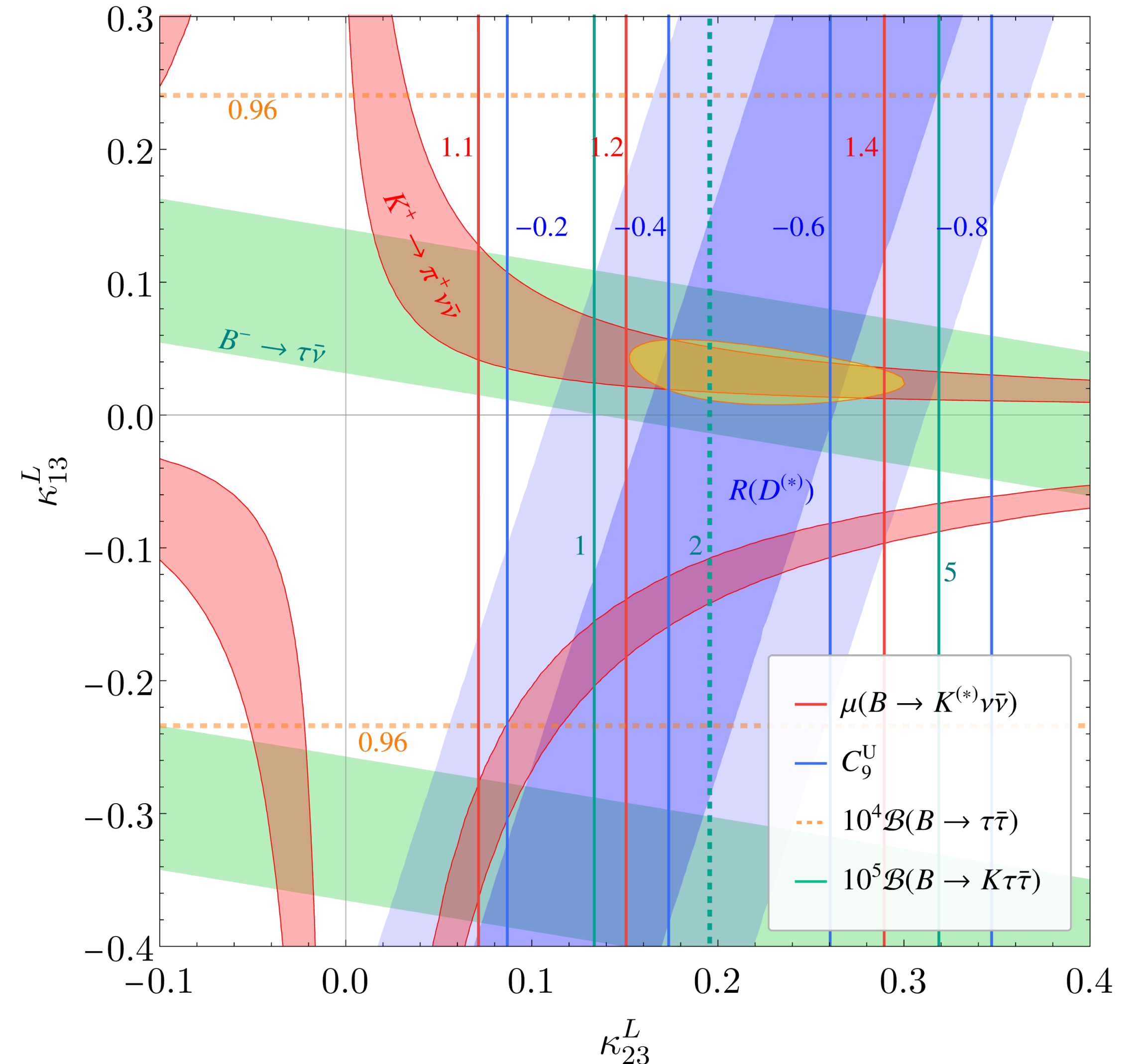
more precise measurements are needed !

$R_{D^{(*)}}$ anomalies: correlation

correlation with $b \rightarrow s\tau^+\tau^-$ in SMEFT



correlations in U_1 leptoquark



$$O_{ijkl}^{(1)} = [\bar{Q}_i \gamma_\mu Q_j] [\bar{L}_k \gamma^\mu L_l] \quad C^{(1)} \mathcal{O}^{(1)} \rightarrow C_{23}^{(1)} ([\bar{s}_L \gamma_\mu b_L] [\bar{\tau}_L \gamma^\mu \tau_L] + [\bar{s}_L \gamma_\mu b_L] [\bar{\nu}_\tau \gamma^\mu \nu_\tau]),$$

$$O_{ijkl}^{(3)} = [\bar{Q}_i \gamma_\mu \sigma^I Q_j] [\bar{L}_k \gamma^\mu \sigma^I L_l] \quad C^{(3)} \mathcal{O}^{(3)} \rightarrow C_{23}^{(3)} (2V_{cs} [\bar{c}_L \gamma_\mu b_L] [\bar{\tau}_L \gamma^\mu \nu_\tau] + [\bar{s}_L \gamma_\mu b_L] [\bar{\tau}_L \gamma^\mu \tau_L]$$

down basis with $C^{(1)} = C^{(3)}$ $- [\bar{s}_L \gamma_\mu b_L] [\bar{\nu}_\tau \gamma^\mu \nu_\tau]) + C_{33}^{(3)} (2V_{cb} [\bar{c}_L \gamma_\mu b_L] [\bar{\tau}_L \gamma^\mu \nu_\tau]),$

LHCb, 2510.13716

Capdevila, Crivellin, Descotes-Genon, Hofer, Matias, 1712.01919

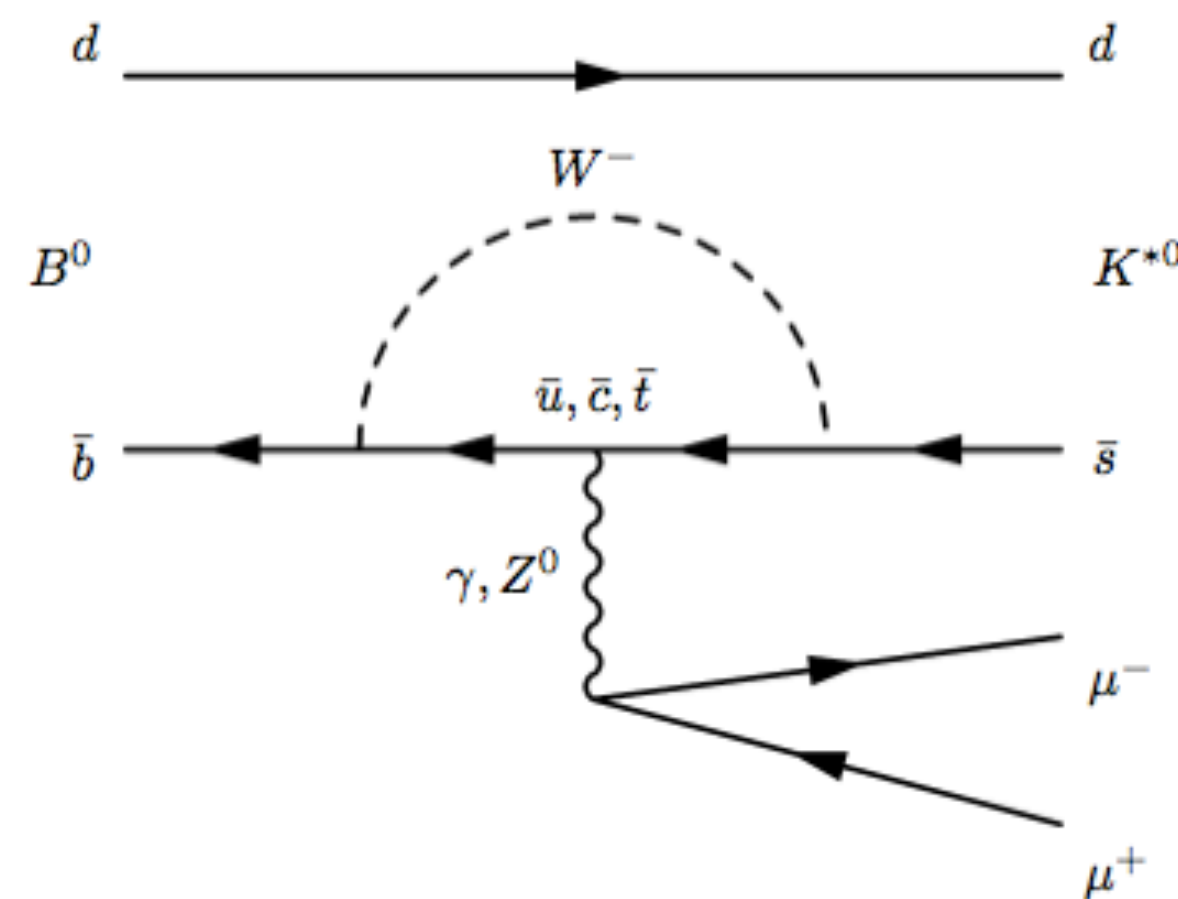
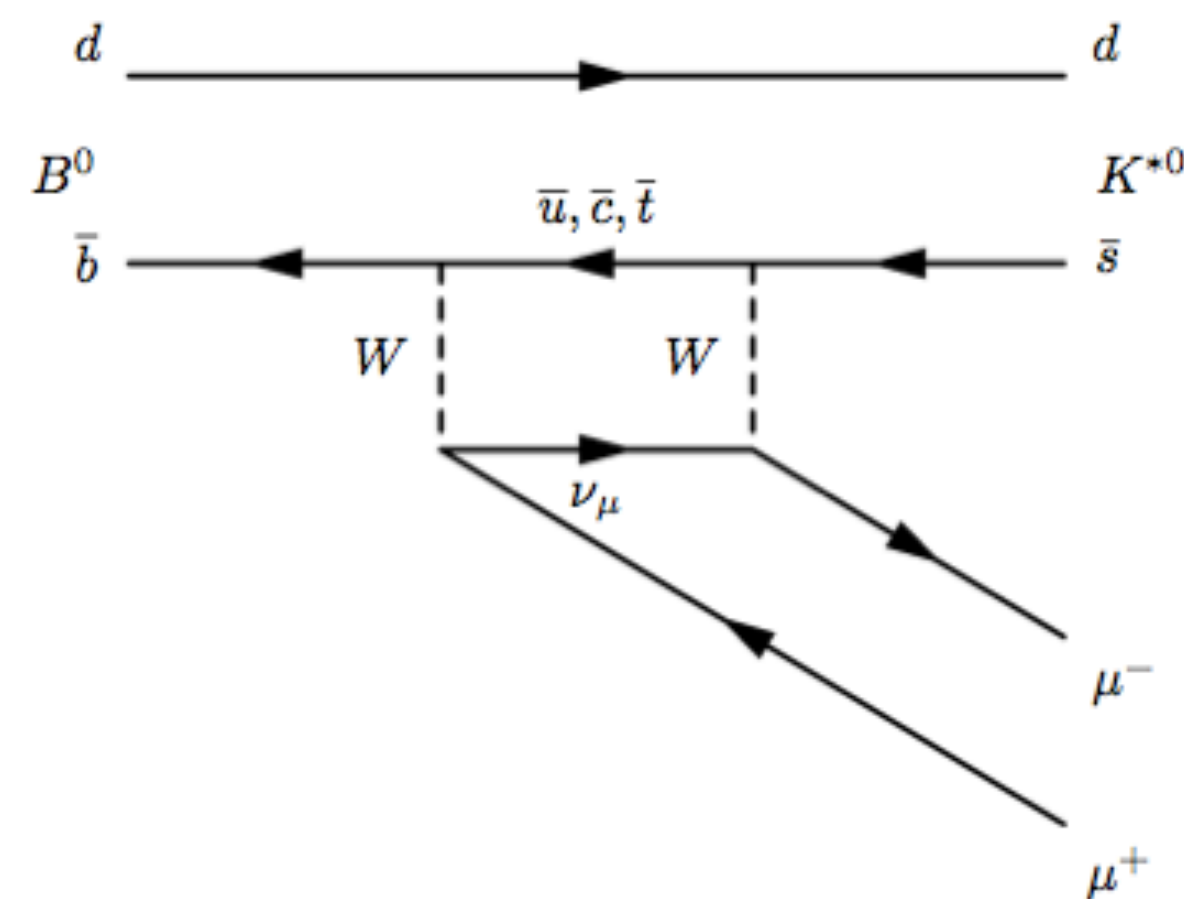
$m_{U_1} = 2 \text{ TeV}, \kappa_{33}^L = 1.5$

κ_{23}^L

Crivellin, Iguro, Kitahara, 2505.05552

$b \rightarrow s \ell^+ \ell^-$ decays

- ▶ $B_s \rightarrow \ell^+ \ell^-$
- ▶ $B \rightarrow X_s \ell^+ \ell^-$
- ▶ $B \rightarrow K \ell^+ \ell^-$
- ▶ $B \rightarrow K^* \ell^+ \ell^-$
- ▶ $B_s \rightarrow \phi \ell^+ \ell^-$
- ▶ $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$



▶ Flavour-Changing Neutral Current (FCNC)

▶ Tree-level: forbidden

⇒ Sensitive to New Physics

▶ Loop-level: suppressed by GIM, $\mathcal{B} \lesssim \mathcal{O}(10^{-6})$

▶ Many observables: branching ratio, angular distribution, LFV ratio

▶ NP effects can be sizable compared to the SM amplitude

▶ This transition is LFU in the SM

$b \rightarrow s \ell^+ \ell^-$: observables

- ▶ $B_s \rightarrow \ell^+ \ell^-$
- ▶ $B \rightarrow X_s \ell^+ \ell^-$
- ▶ $B \rightarrow K \ell^+ \ell^-$
- ▶ $B \rightarrow K^* \ell^+ \ell^-$
- ▶ $B_s \rightarrow \phi \ell^+ \ell^-$
- ▶ $\Lambda_b \rightarrow \Lambda \ell^+ \ell^-$

theoretical cleanliness

- ▶ Branching Ratio
- ▶ Angular Distribution
- ▶ Lepton Flavour Universality (LFU) ratio

function of $(C_{7\gamma}, C_9, C_{10})$

LFU ratio in $B \rightarrow K \ell^+ \ell^-$

$$R_K = \frac{\mathcal{B}(B \rightarrow K \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K e^+ e^-)}$$

- ▶ $R_K^{\text{SM}} \approx 1$
- ▶ Hadronic uncertainties cancel
- ▶ $\mathcal{O}(10^{-2})$ QED correction

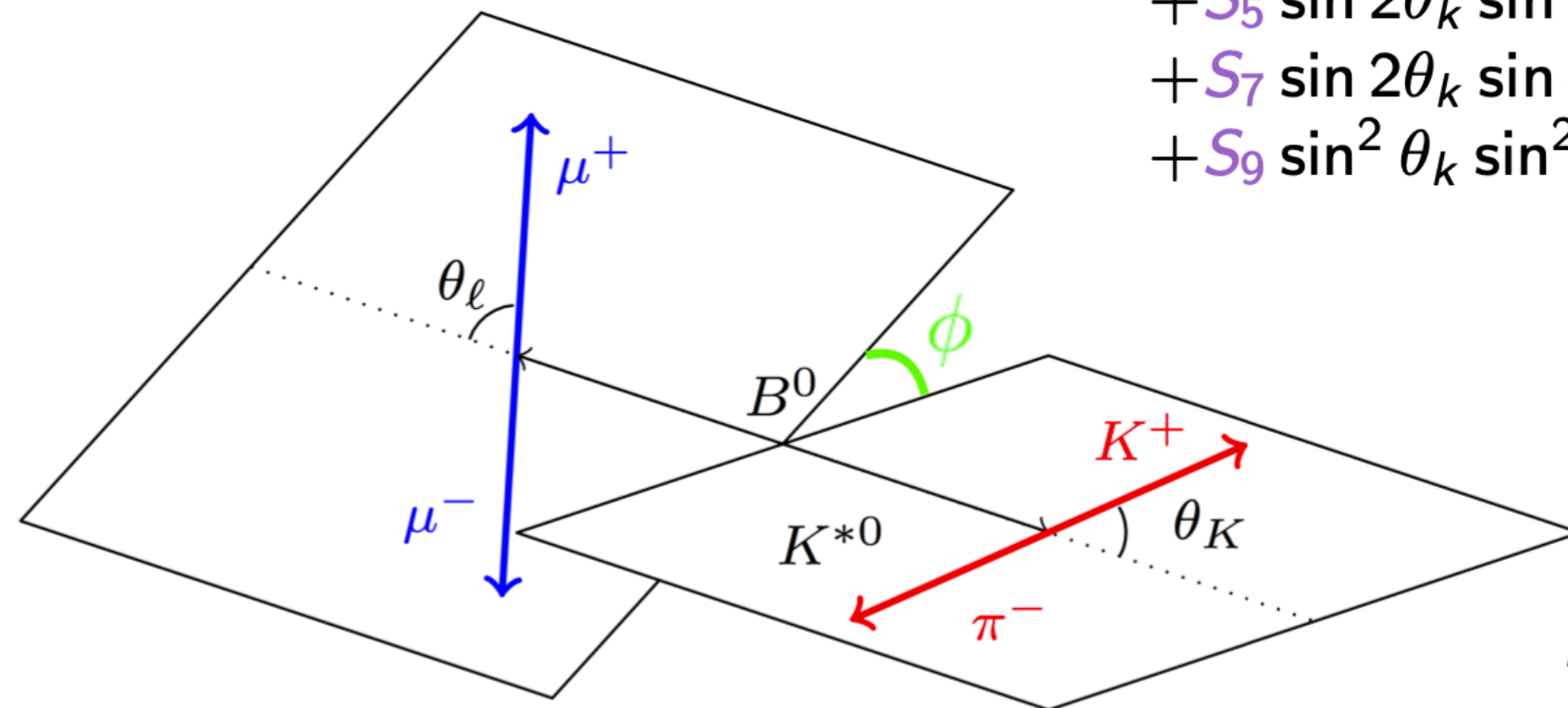
deviation from unity



Physics beyond the SM

Angular distribution of $B \rightarrow K^*(\rightarrow K\pi) \mu^+ \mu^-$

$$\begin{aligned} \frac{1}{d(\Gamma+\bar{\Gamma})/dq^2} \frac{d^4(\Gamma+\bar{\Gamma})}{d\Omega d\Omega' dq^2} &= \frac{9}{32\pi} \left[\frac{3}{4} (1 - F_L) \sin^2 \theta_k + F_L \cos^2 \theta_k \right. \\ &+ \frac{1}{4} (1 - F_L) \sin^2 \theta_k \cos 2\theta_\ell - F_L \cos^2 \theta_k \cos 2\theta_\ell \\ &+ S_3 \sin^2 \theta_k \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_k \sin 2\theta_\ell \cos \phi \\ &+ S_5 \sin 2\theta_k \sin \theta_\ell \cos \phi + \frac{4}{3} A_{FB} \sin^2 \theta_k \cos \theta_\ell \\ &+ S_7 \sin 2\theta_k \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_k \sin 2\theta_\ell \sin \phi \\ &\left. + S_9 \sin^2 \theta_k \sin^2 \theta_\ell \sin 2\phi \right], \end{aligned}$$



angular observables

$F_L, A_{FB}, S_i = f(C_7, C_9, C_{10})$,
combinations of K^{*0} decay amplitudes

$$P_1 = \frac{2S_3}{1 - F_L}$$

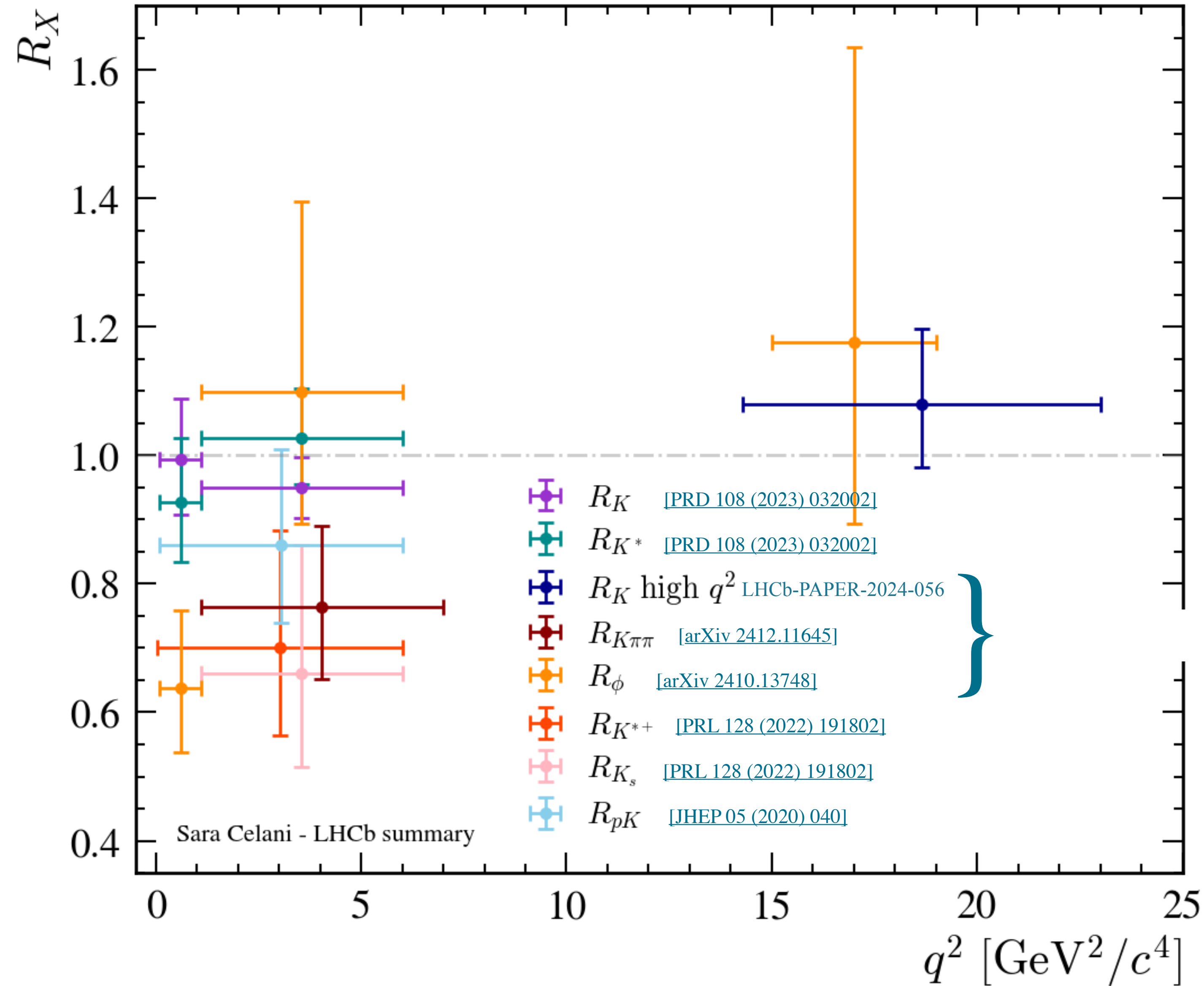
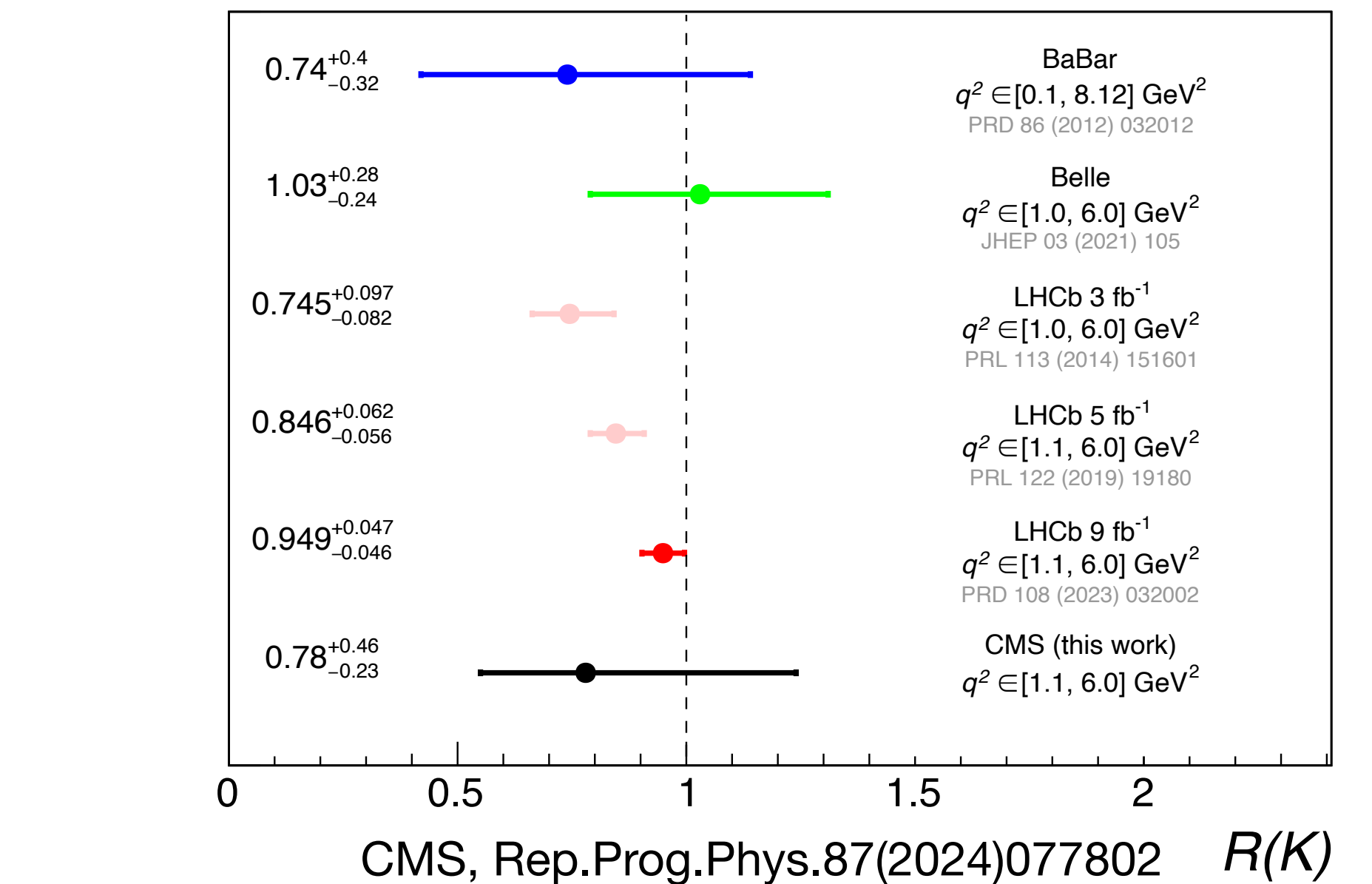
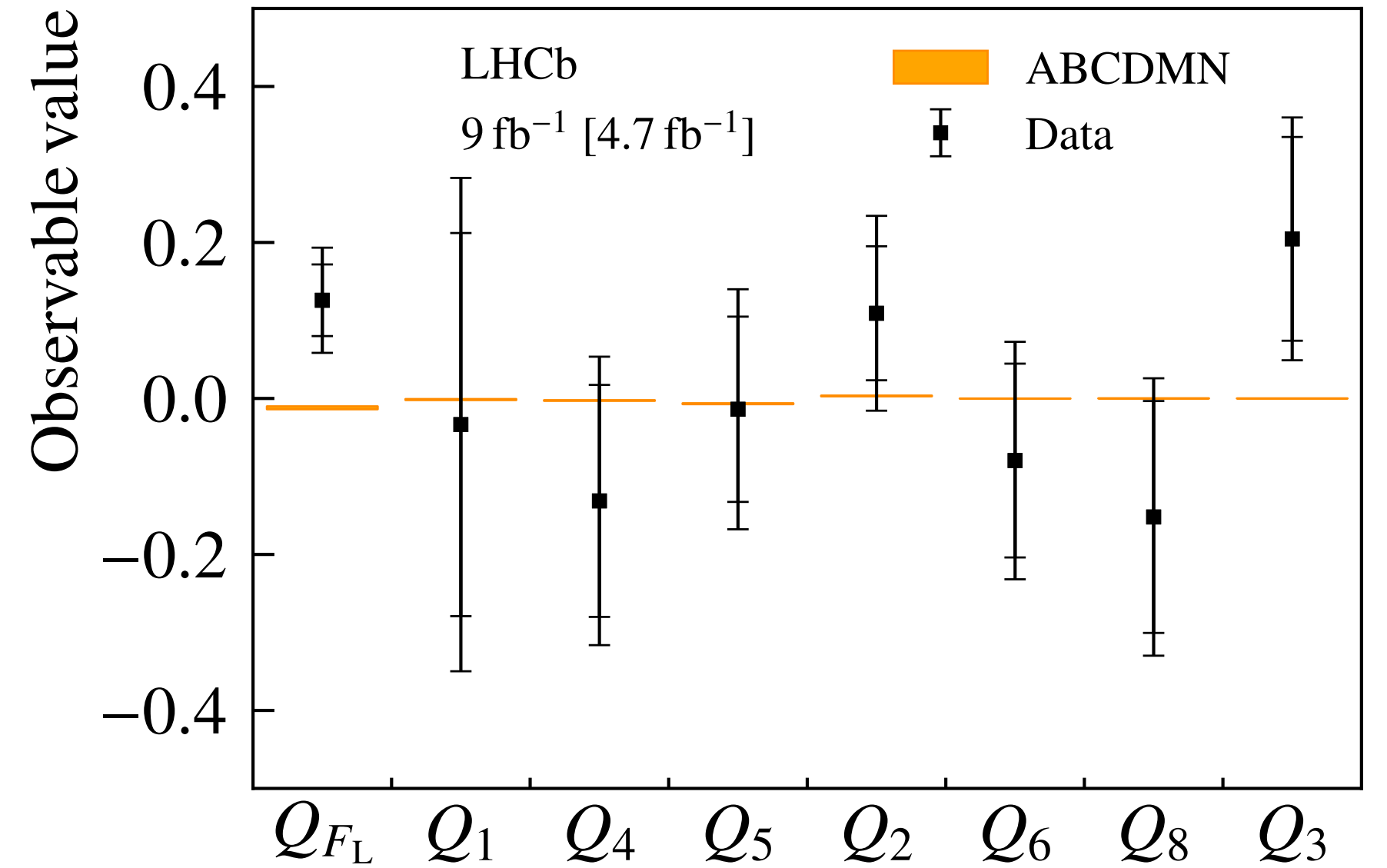
$$P_2 = \frac{2 A_{FB}}{3(1 - F_L)}$$

$$P_3 = -\frac{S_9}{1 - F_L}$$

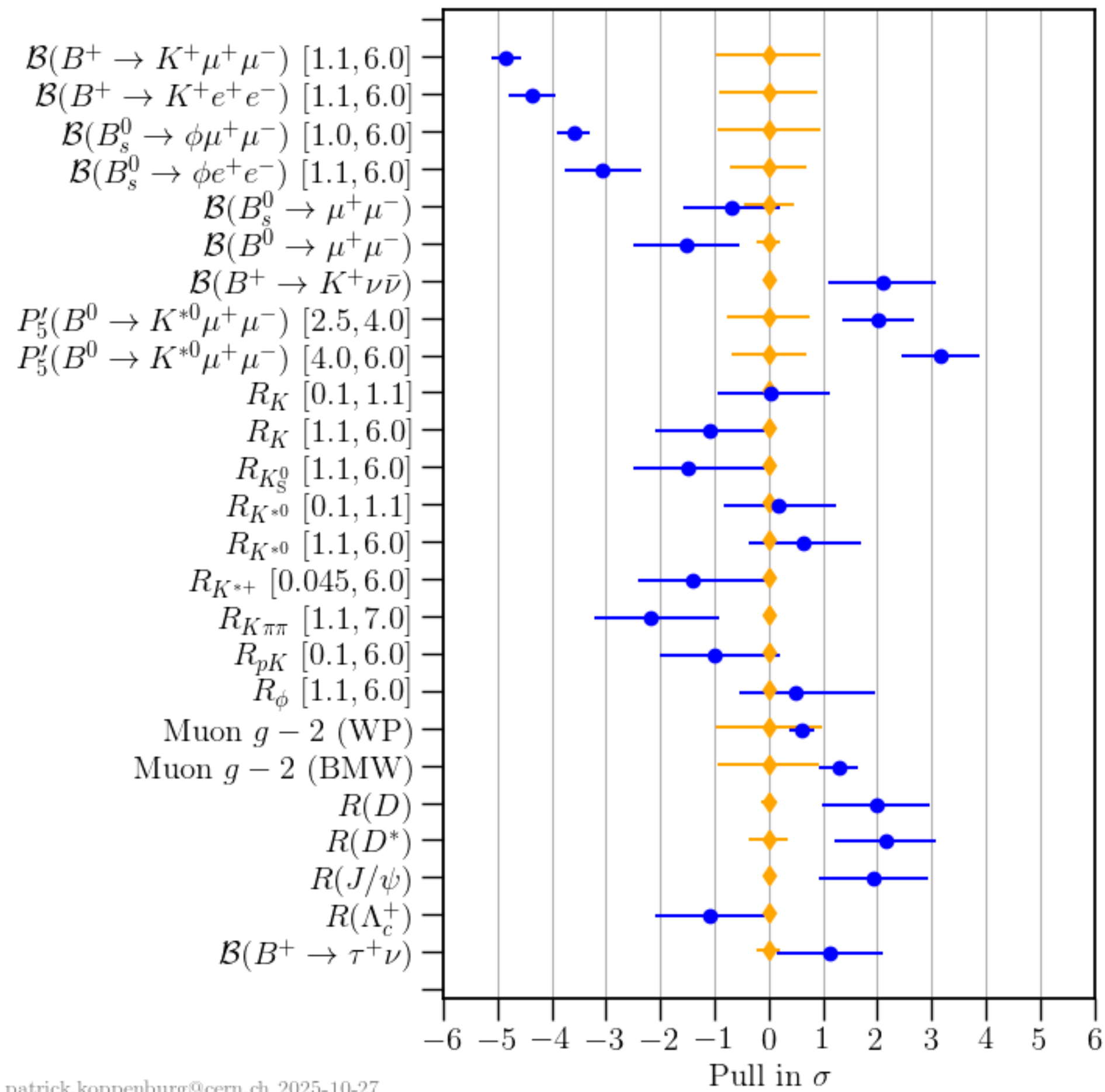
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1 - F_L)}}$$

$b \rightarrow s \ell^+ \ell^-$: LFU

LHCb, arXiv: 2502.10291



Flavour anomalies: New Physics interpretation



patrick.koppenburg@cern.ch 2025-10-27



???

SMEFT: SM Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + C_i^{\text{NP}} O_i^{\text{NP}}$$

$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$

$$O_{\ell q}^{(1)} = (\bar{L}_p \gamma_\mu L_r)(\bar{Q}_s \gamma^\mu Q_t)$$

$$O_{ed}^{(1)} = (\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$$

... ..

LEFT: Low Energy Effective Field Theory

$$\mathcal{H}_{\text{eff}} = (C_i^{\text{SM}} + C_i^{\text{NP}}) O_i^{\text{SM}} + C_j^{\text{NP}} O_j^{\text{NP}} \quad SU(3)_C \otimes U(1)_{\text{em}}$$

$$O_9 = (\bar{b} \gamma^\mu P_L s)(\bar{\ell} \gamma_\mu \ell) \quad O_{10} = (\bar{b} \gamma^\mu P_L s)(\bar{\ell} \gamma_\mu \gamma_5 \ell)$$

$$O_{\text{VLL}} = (\bar{c} \gamma^\mu P_L b)(\bar{\tau} \gamma^\mu P_L \nu) \quad O_{\text{SR}} = (\bar{c}_L b_R)(\bar{\ell}_R \nu_{TL})$$

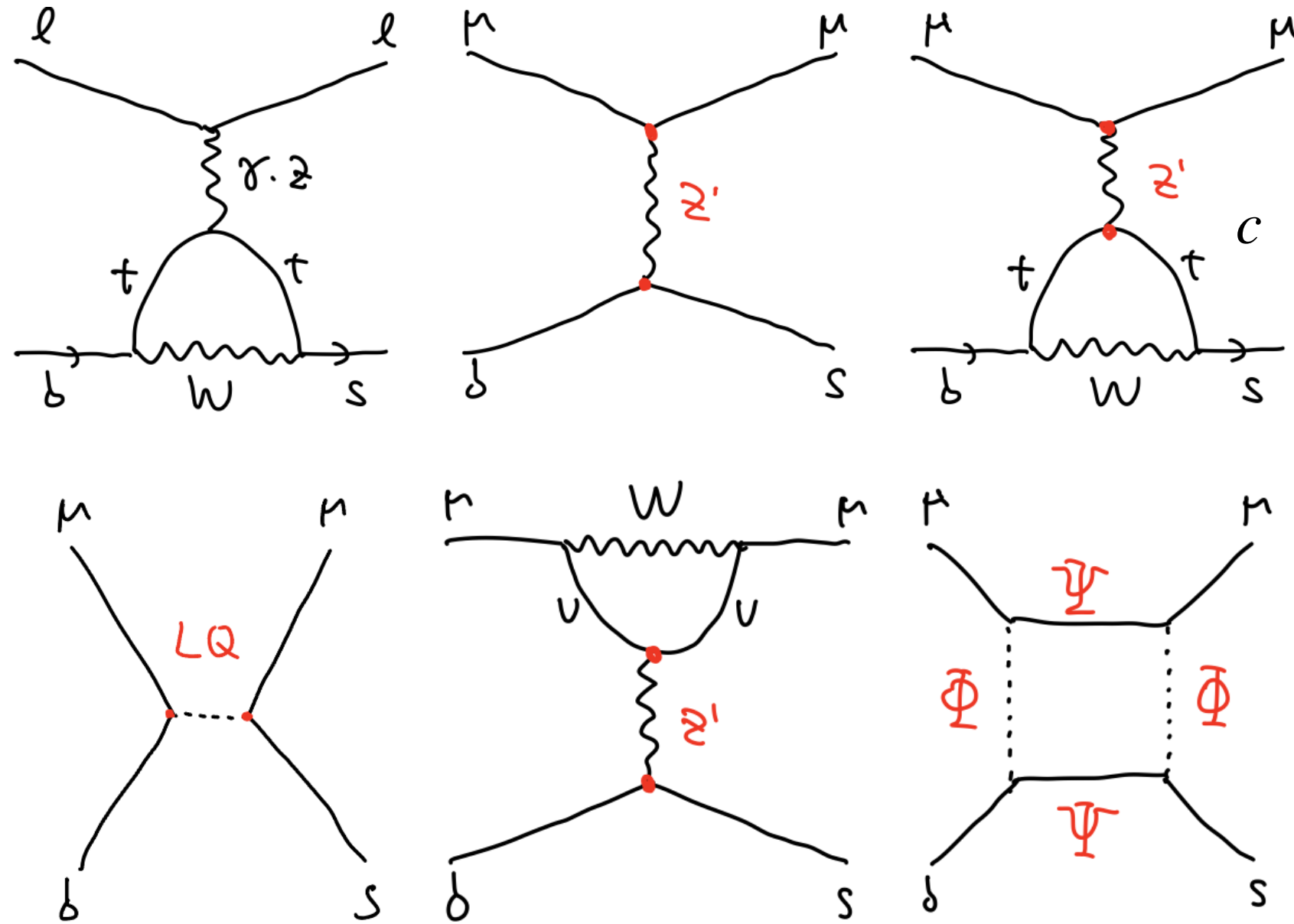
$$O_{\text{VRL}} = (\bar{c} \gamma^\mu P_R b)(\bar{\tau} \gamma^\mu P_L \nu) \quad O_{\text{SL}} = (\bar{c}_R b_L)(\bar{\ell}_R \nu_{TL})$$

$$O_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\ell}_R \sigma_{\mu\nu} \nu_{TL})$$

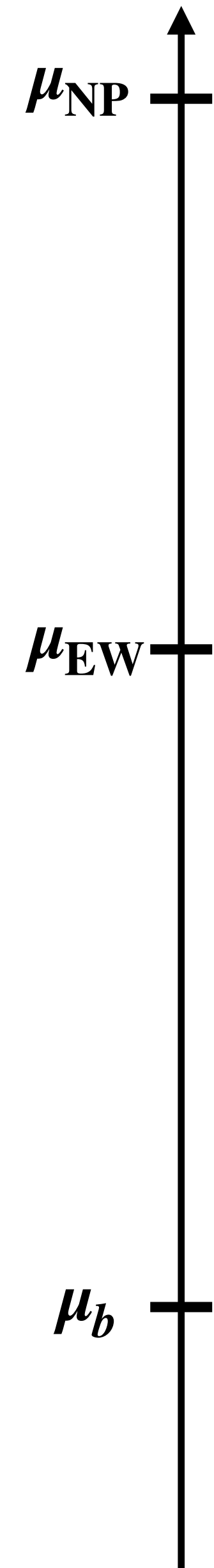
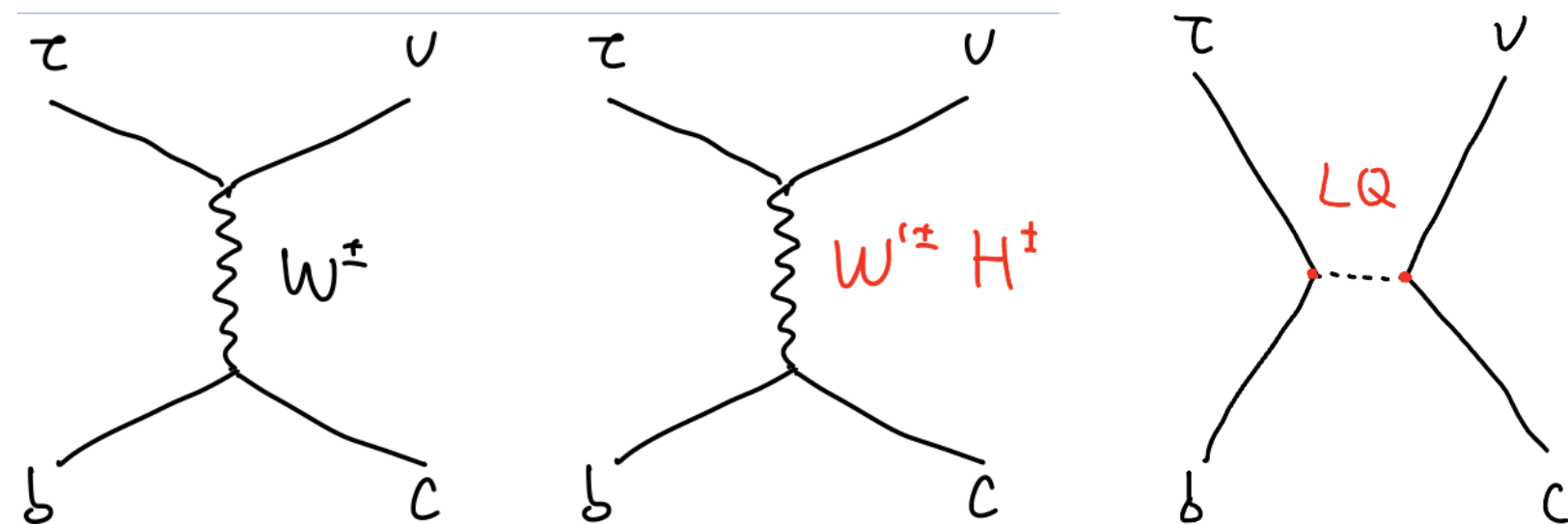
Flavour anomalies: New Physics interpretation

► $b \rightarrow s \ell^+ \ell^-$ anomalies

X.Q.Li, Y.D.Yang, XBY, et al, 2112.14215, 2205.02205, 2307.05290



► $b \rightarrow c \tau \nu$ anomalies



???

SMEFT: SM Effective Field Theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + C_i^{\text{NP}} O_i^{\text{NP}}$$

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

$$O_{\ell q}^{(1)} = (\bar{L}_p \gamma_\mu L_r) (\bar{Q}_s \gamma^\mu Q_t)$$

$$O_{ed}^{(1)} = (\bar{e}_p \gamma_\mu e_r) (\bar{d}_s \gamma^\mu d_t)$$

.....

LEFT: Low Energy Effective Field Theory

$$\mathcal{H}_{\text{eff}} = (C_i^{\text{SM}} + C_i^{\text{NP}}) O_i^{\text{SM}} + C_j^{\text{NP}} O_j^{\text{NP}} \quad SU(3)_C \otimes U(1)_{\text{em}}$$

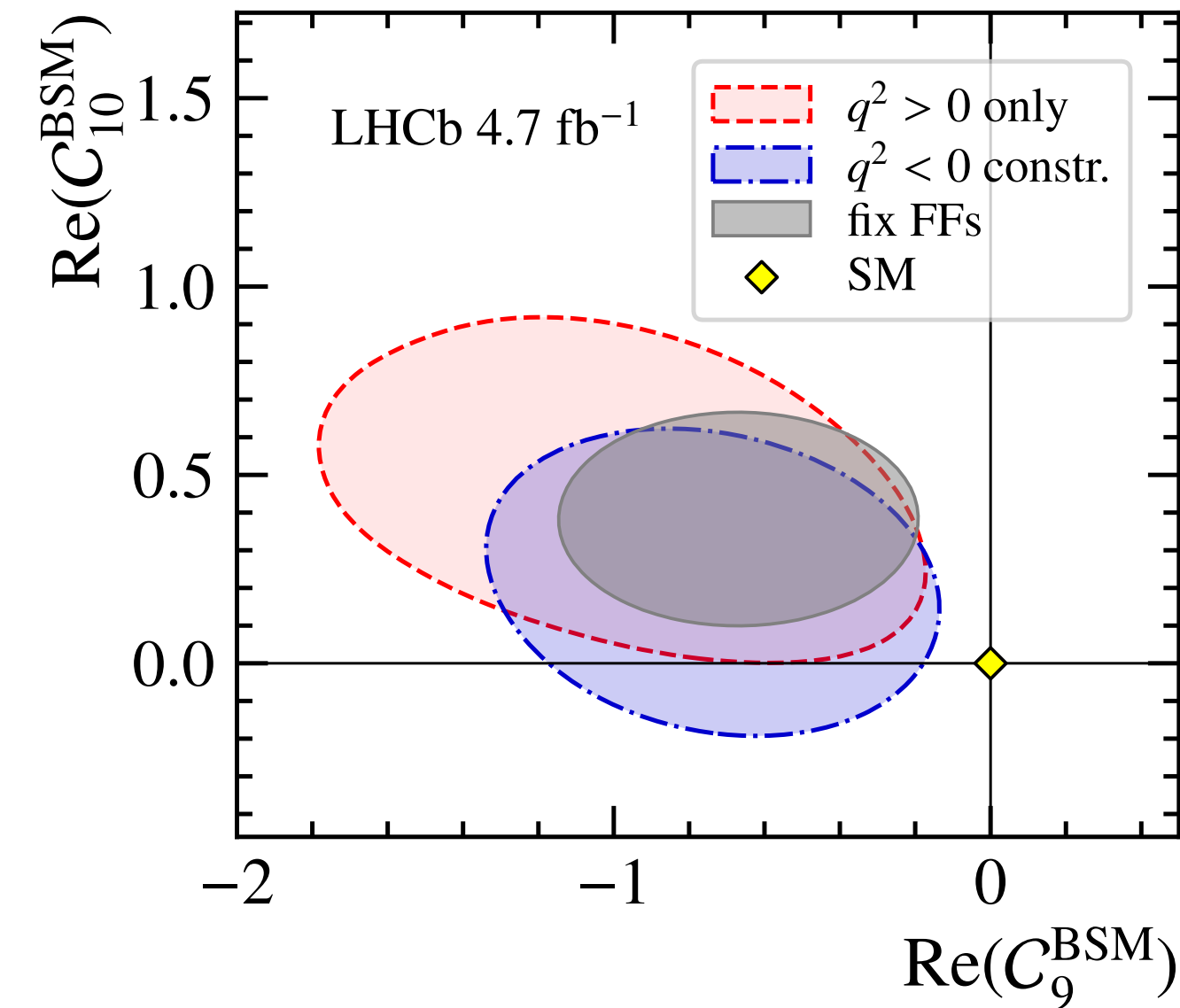
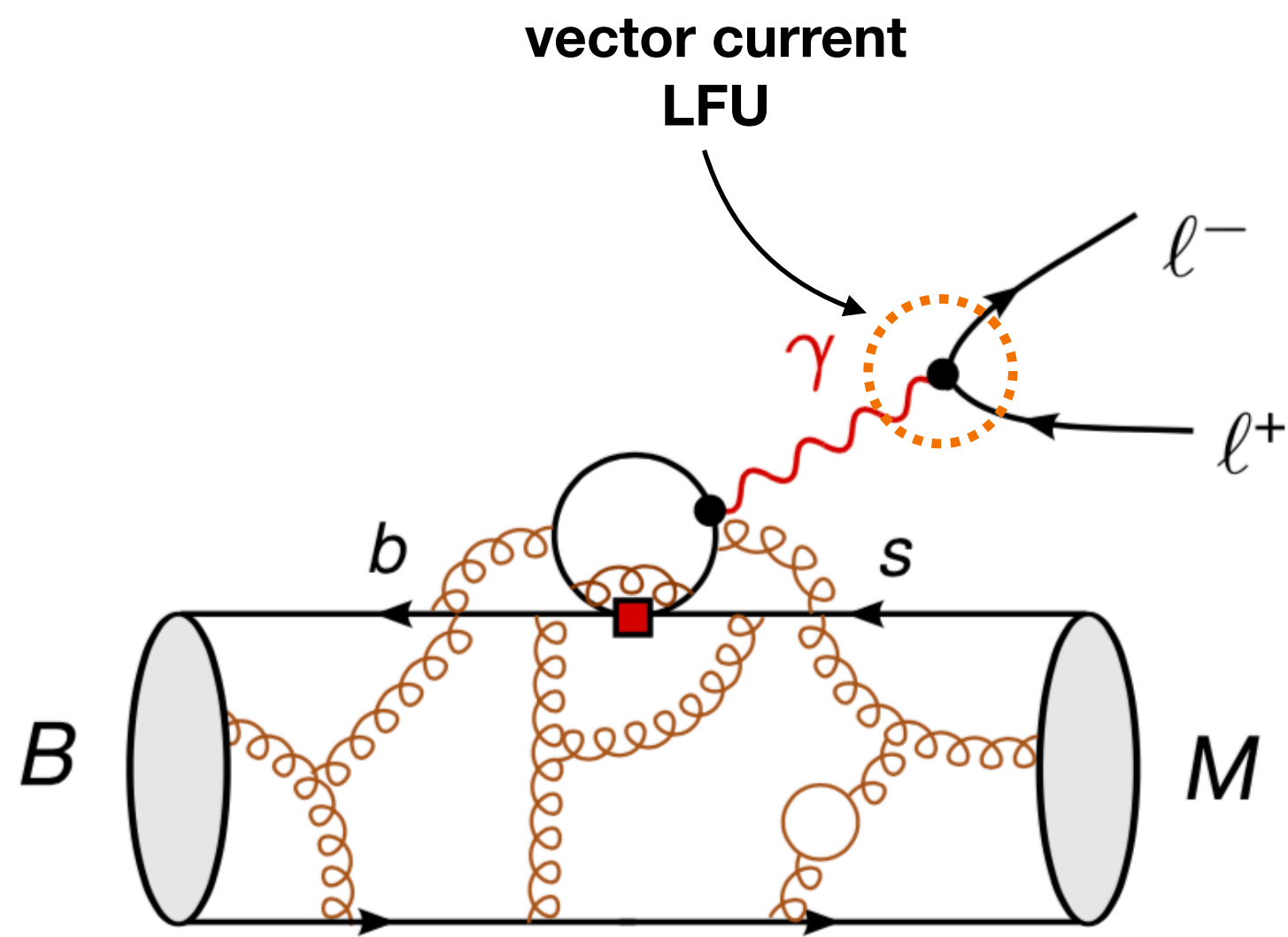
$$O_9 = (\bar{b} \gamma^\mu P_L s) (\bar{\ell} \gamma_\mu \ell) \quad O_{10} = (\bar{b} \gamma^\mu P_L s) (\bar{\ell} \gamma_\mu \gamma_5 \ell)$$

$$O_{\text{VLL}} = (\bar{c} \gamma^\mu P_L b) (\bar{\tau} \gamma^\mu P_L \nu) \quad O_{\text{SR}} = (\bar{c}_L b_R) (\bar{\ell}_R \nu_{TL})$$

$$O_{\text{VRL}} = (\bar{c} \gamma^\mu P_R b) (\bar{\tau} \gamma^\mu P_L \nu) \quad O_{\text{SL}} = (\bar{c}_R b_L) (\bar{\ell}_R \nu_{TL})$$

$$O_T = (\bar{c}_R \sigma^{\mu\nu} b_L) (\bar{\ell}_R \sigma_{\mu\nu} \nu_{TL})$$

Charm-loop contribution



▶ Global fit prefer to $C_{9e} = C_{9\mu} \neq C_9^{\text{SM}} \iff \mathcal{B}(B_s \rightarrow \mu^+ \mu^-)_{\text{exp}}$ is consistent with SM

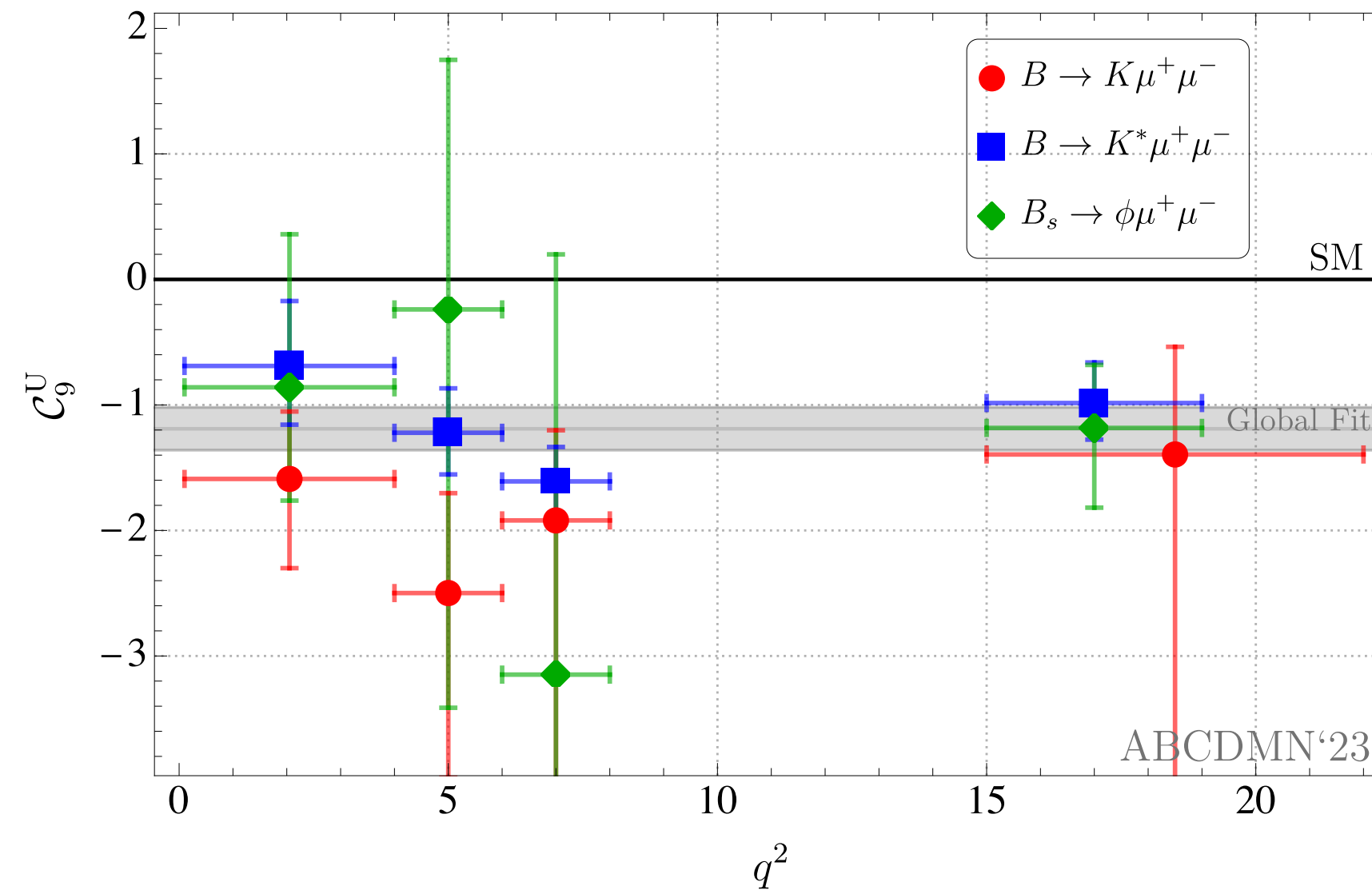
▶ Charm-loop could mimic $C_{9e} = C_{9\mu}$

$$C_{9e} = C_{9\mu} = C_9^{\text{SM}} + \Delta C_9^{U, \text{charm loop}} + \Delta C_9^{U, \text{NP}}$$

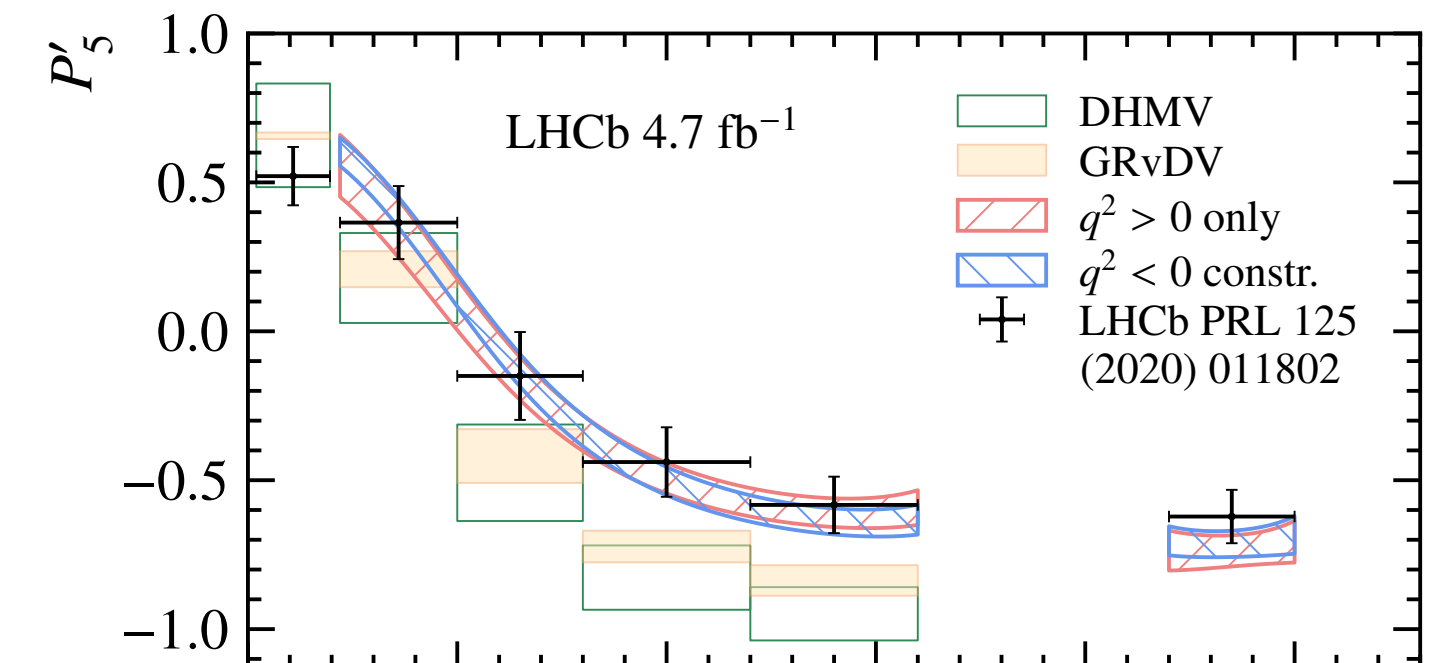
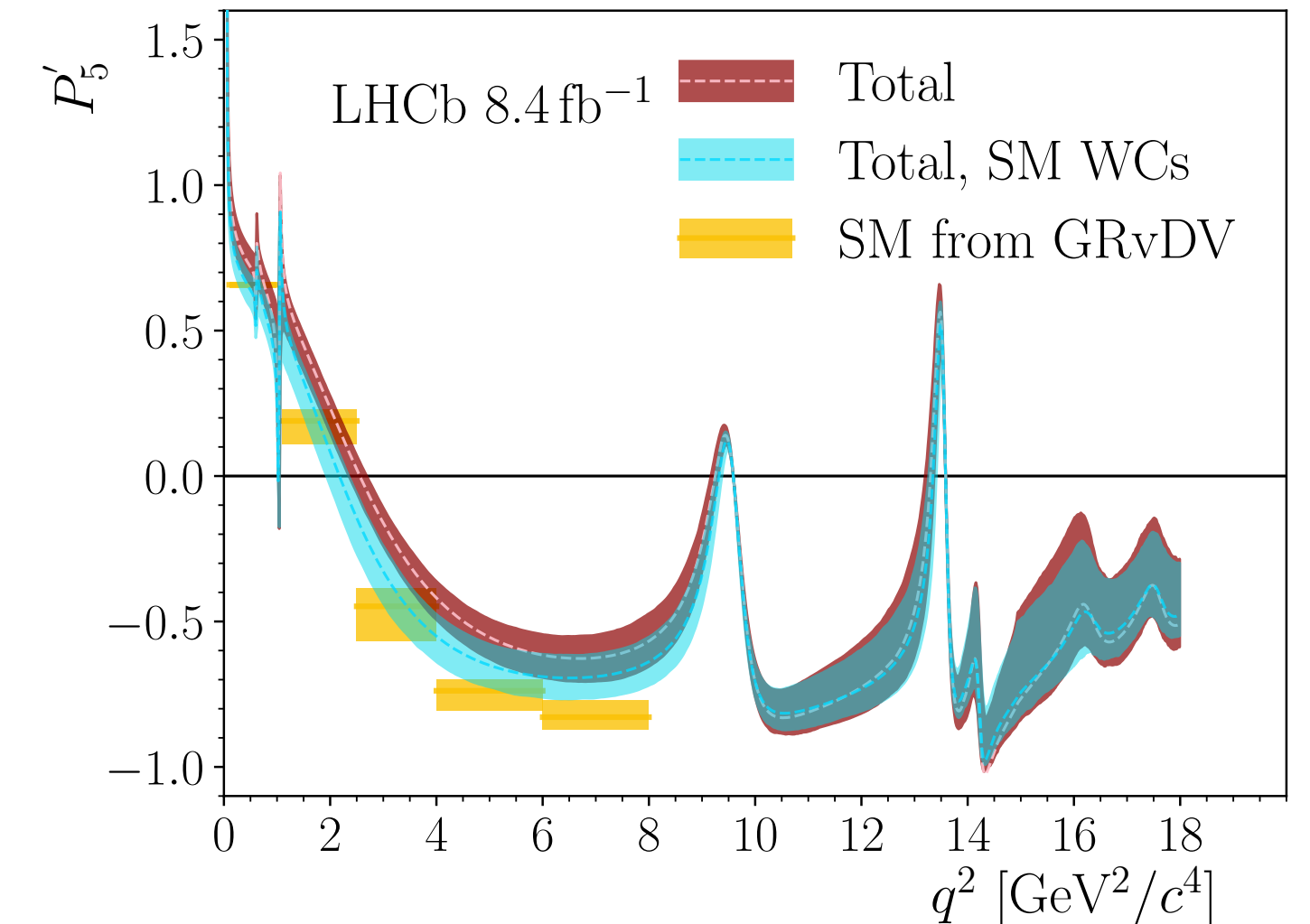
$$O_9 = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \ell)$$

$$O_{10} = (\bar{b}\gamma^\mu P_L s)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

▶ Charm-loop contribution is expected to be $\Delta C_9^U(q^2)$, but not ΔC_9^U

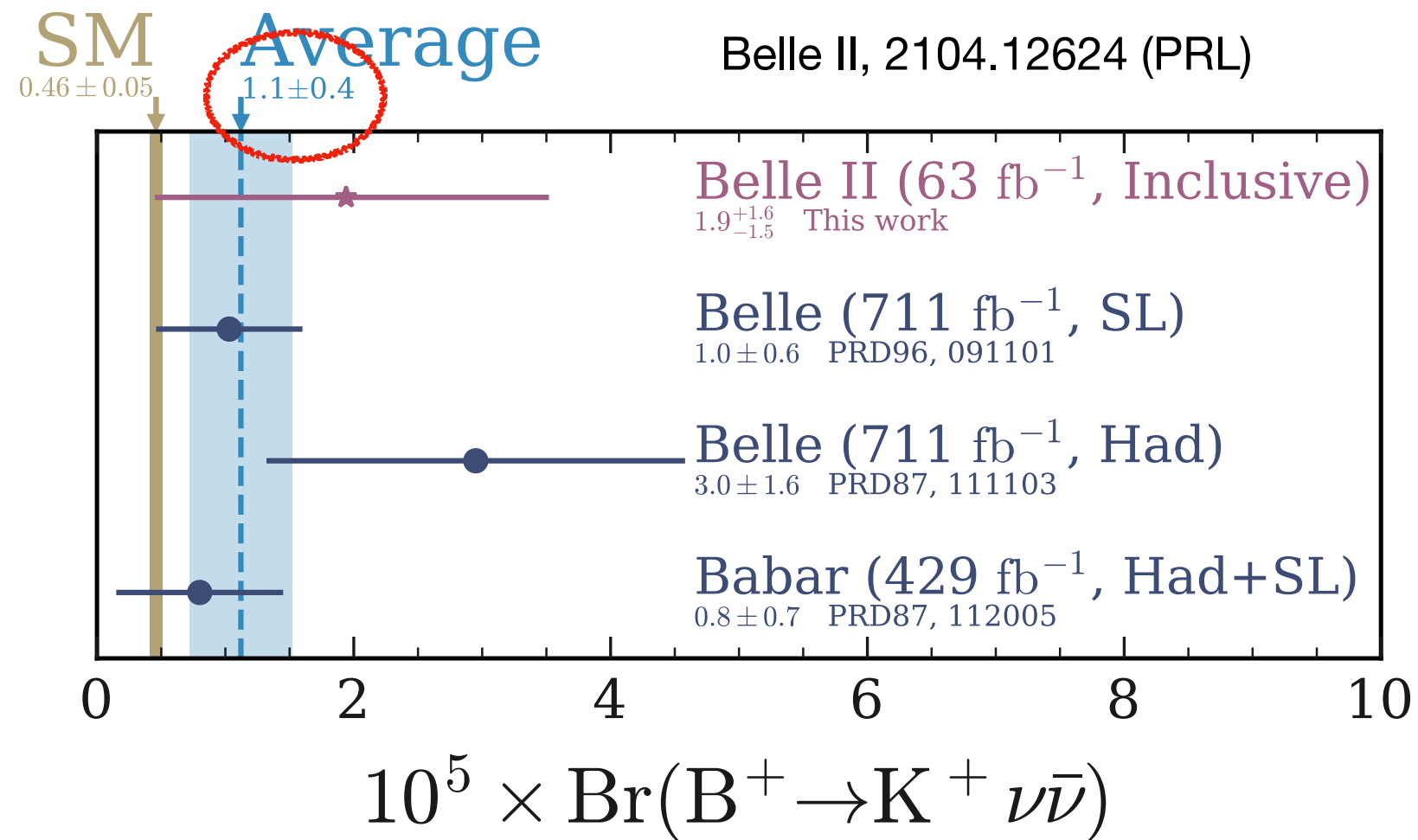


LHCb, PRL132(2024)131801
 LHCb, PRD109(2024)052009
 LHCb, 2405.17347 (charmonium region is open)

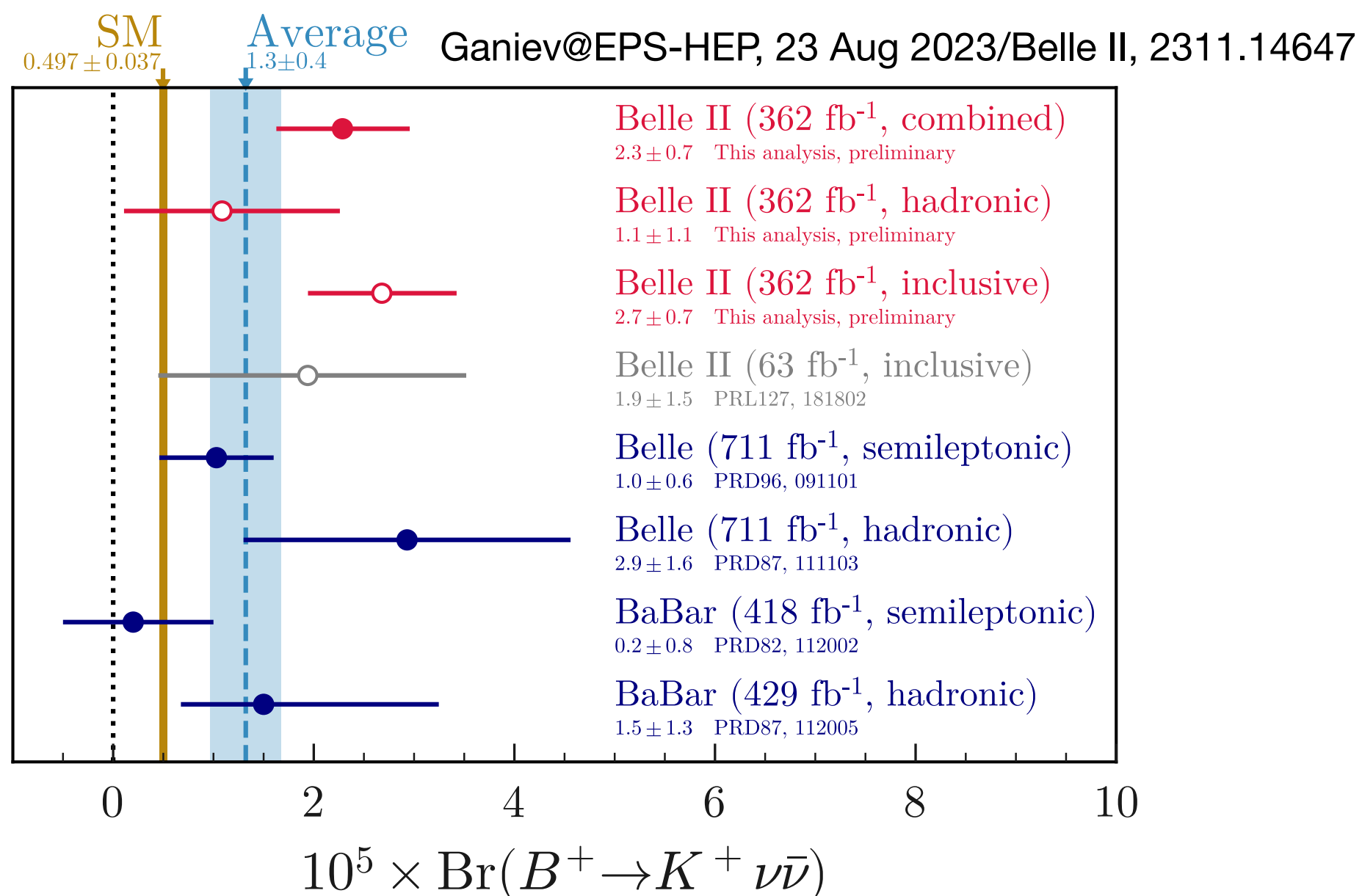


$b \rightarrow s\nu\bar{\nu}$: exp & theory

▶ 2021 Apr



▶ 2023 Aug



Impact of $B \rightarrow K\nu\bar{\nu}$ measurements on beyond the Standard Model theories #69
 Thomas E. Browder (Hawaii U.), Nilendra G. Deshpande (Oregon U.), Rusa Mandal (Siegen U.), Rahul Sinha (IMSC, Chennai and Bhubaneswar, Inst. Phys.) (Jul 2, 2021)
 Published in: *Phys.Rev.D* 104 (2021) 5, 053007 · e-Print: 2107.01080 [hep-ph]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [34 citations](#)

A tale of invisibility: constraints on new physics in $b \rightarrow s\nu\bar{\nu}$ #65
 Tobias Felki (New South Wales U.), Sze Lok Li (New South Wales U.), Michael A. Schmidt (New South Wales U.) (Nov 8, 2021)
 Published in: *JHEP* 12 (2021) 118 · e-Print: 2111.04327 [hep-ph]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [24 citations](#)

150+ theory papers !

Phenomenological study of a gauged $L_\mu - L_\tau$ model with a scalar leptoquark #42
 Chuan-Hung Chen (Taiwan, Natl. Cheng Kung U. and NCTS, Taipei), Cheng-Wei Chiang (Taiwan, Natl. Taiwan U. and NCTS, Taipei), Chun-Wei Su (Taiwan, Natl. Taiwan U.) (May 16, 2023)
 Published in: *Phys.Rev.D* 109 (2024) 5, 5 · e-Print: 2305.09256 [hep-ph]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [3 citations](#)

Explaining the $B^+ \rightarrow K^+ \nu \bar{\nu}$ excess via a massless dark photon #16
 E. Gabrielli, L. Marzola, K. Mürsepp, M. Raidal (Feb 8, 2024)
 e-Print: 2402.05901 [hep-ph]
[pdf](#) [cite](#) [claim](#) [reference search](#) [4 citations](#)

Higgs portal interpretation of the Belle II $B^+ \rightarrow K^+ \nu \bar{\nu}$ measurement #29
 David McKeen (TRIUMF), John N. Ng (TRIUMF), Douglas Tuckler (TRIUMF and Simon Fraser U.) (Dec 1, 2023)
 Published in: *Phys.Rev.D* 109 (2024) 7, 075006 · e-Print: 2312.00982 [hep-ph]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [10 citations](#)

Decoding the $B \rightarrow K \nu \bar{\nu}$ excess at Belle II: kinematics, operators, and masses #27
 Kåre Fridell, Mitrajyoti Ghosh, Takemichi Okui, Kohsaku Tobioka (Dec 19, 2023)
 e-Print: 2312.12507 [hep-ph]
[pdf](#) [cite](#) [claim](#) [reference search](#) [10 citations](#)

Light new physics in $B \rightarrow K^{(*)} \nu \bar{\nu}$? #30
 Wolfgang Altmannshofer (UC, Santa Cruz, Inst. Part. Phys.), Andreas Crivellin (Zurich U.), Huw Haigh (Vienna, OAW), Gianluca Inguglia (Vienna, OAW), Jorge Martin Camalich (IAC, La Laguna) (Nov 24, 2023)
 Published in: *Phys.Rev.D* 109 (2024) 7, 075008 · e-Print: 2311.14629 [hep-ph]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [15 citations](#)

Understanding the first measurement of $B(B \rightarrow K \nu \bar{\nu})$ #38
 Lukas Allwicher (Zurich U.), Damir Becirevic (IJCLab, Orsay), Gioacchino Piazza (IJCLab, Orsay), Salvador Rosairo-Alcaraz (IJCLab, Orsay), Olcyr Sumensari (IJCLab, Orsay) (Sep 5, 2023)
 Published in: *Phys.Lett.B* 848 (2024) 138411 · e-Print: 2309.02246 [hep-ph]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [26 citations](#)

$B \rightarrow K \nu \bar{\nu}$, MiniBooNE and muon $g - 2$ anomalies from a dark sector #31
 Alakabha Datta (Mississippi U. and SLAC and UC, Santa Cruz), Danny Marfatia (Hawaii U.), Lopamudra Mukherjee (Nankai U.) (Oct 23, 2023)
 Published in: *Phys.Rev.D* 109 (2024) 3, L031701 · e-Print: 2310.15136 [hep-ph]
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Implications of an enhanced $B \rightarrow K \nu \bar{\nu}$ branching ratio #39
 Rigo Bause (Tech. U., Dortmund (main)), Hector Gisbert (INFN, Padua and Padua U.), Gudrun Hiller (Tech. U., Dortmund (main) and Sussex U.) (Aug 31, 2023)
 Published in: *Phys.Rev.D* 109 (2024) 1, 015006 · e-Print: 2309.00075 [hep-ph]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [31 citations](#)

$B \rightarrow K^* M_X$ vs $B \rightarrow K M_X$ as a probe of a scalar-mediator dark matter scenario #33
 Alexander Berezhnoy (SINP, Moscow), Dmitri Melikhov (SINP, Moscow and Dubna, JINR and Vienna U.) (Sep 29, 2023)
 Published in: *EPL* 145 (2024) 1, 14001 · e-Print: 2309.17191 [hep-ph]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [10 citations](#)

B meson anomalies and large $B^+ \rightarrow K^+ \nu \bar{\nu}$ in non-universal $U(1)'$ models #40
 Peter Athron (Nanjing Normal U.), R. Martinez (Colombia, U. Natl.), Cristian Sierra (Nanjing Normal U.) (Aug 25, 2023)
 Published in: *JHEP* 02 (2024) 121 · e-Print: 2308.13426 [hep-ph]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [22 citations](#)

Flavor anomalies in leptoquark model with gauged $U(1)_{\nu_\mu - L_\tau}$ #34
 Chuan-Hung Chen (Taiwan, Natl. Cheng Kung U. and Unlisted, TW), Cheng-Wei Chiang (Taiwan, Natl. Taiwan U. and Unlisted, TW) (Sep 22, 2023)
 Published in: *Phys.Rev.D* 109 (2024) 7, 075004 · e-Print: 2309.12904 [hep-ph]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [9 citations](#)

SMEFT predictions for semileptonic processes #4
 Siddhartha Karmakar, Amol Dighe, Rick S. Gupta (Apr 15, 2024)
 e-Print: 2404.10061 [hep-ph]
[pdf](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

Revisiting models that enhance $B^+ \rightarrow K^+ \nu \bar{\nu}$ in light of the new Belle II measurement #35
 Belle-II Collaboration · Xiao-Gang He (Tsung-Dao Lee Inst., Shanghai and Taiwan, Natl. Taiwan U.) et al. (Sep 22, 2023)
 Published in: *Phys.Rev.D* 109 (2024) 7, 075019 · e-Print: 2309.12741 [hep-ph]
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [16 citations](#)

Implications of $B \rightarrow K \nu \bar{\nu}$ under Rank-One Flavor Violation hypothesis #5
 David Marzocca, Marco Nardecchia, Alfredo Stanzione, Claudio Toni (Apr 9, 2024)
 e-Print: 2404.06533 [hep-ph]
[pdf](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

A new look at $\bar{b} \rightarrow s$ observables in 331 models #18
 Francesco Loporco (Jan 22, 2024)
 e-Print: 2401.11999 [hep-ph]
[pdf](#) [cite](#) [claim](#) [reference search](#) [1 citation](#)

The quark flavor-violating ALPs in light of B mesons and hadron colliders #20
 Tong Li (Nankai U.), Zhuoni Qian (Hangzhou Normal U.), Michael A. Schmidt (Sydney U. and New South Wales U.), Man Yuan (Nankai U.) (Feb 21, 2024)
 Published in: *JHEP* 05 (2024) 232 · e-Print: 2402.14232 [hep-ph]
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Correlating $B \rightarrow K^{(*)} \nu \bar{\nu}$ and flavor anomalies in SMEFT #19
 Feng-Zhi Chen, Qiaoyi Wen, Fanrong Xu (Jan 21, 2024)
 e-Print: 2401.11552 [hep-ph]
[pdf](#) [cite](#) [claim](#) [reference search](#) [8 citations](#)

Scalar dark matter explanation of the excess in the Belle II $B^+ \rightarrow K^+ + \text{invisible}$ measurement #9
 Xiao-Gang He, Xiao-Dong Ma, Michael A. Schmidt, German Valencia, Raymond R. Volkas (Mar 19, 2024)
 e-Print: 2403.12485 [hep-ph]
[pdf](#) [cite](#) [claim](#) [reference search](#) [2 citations](#)

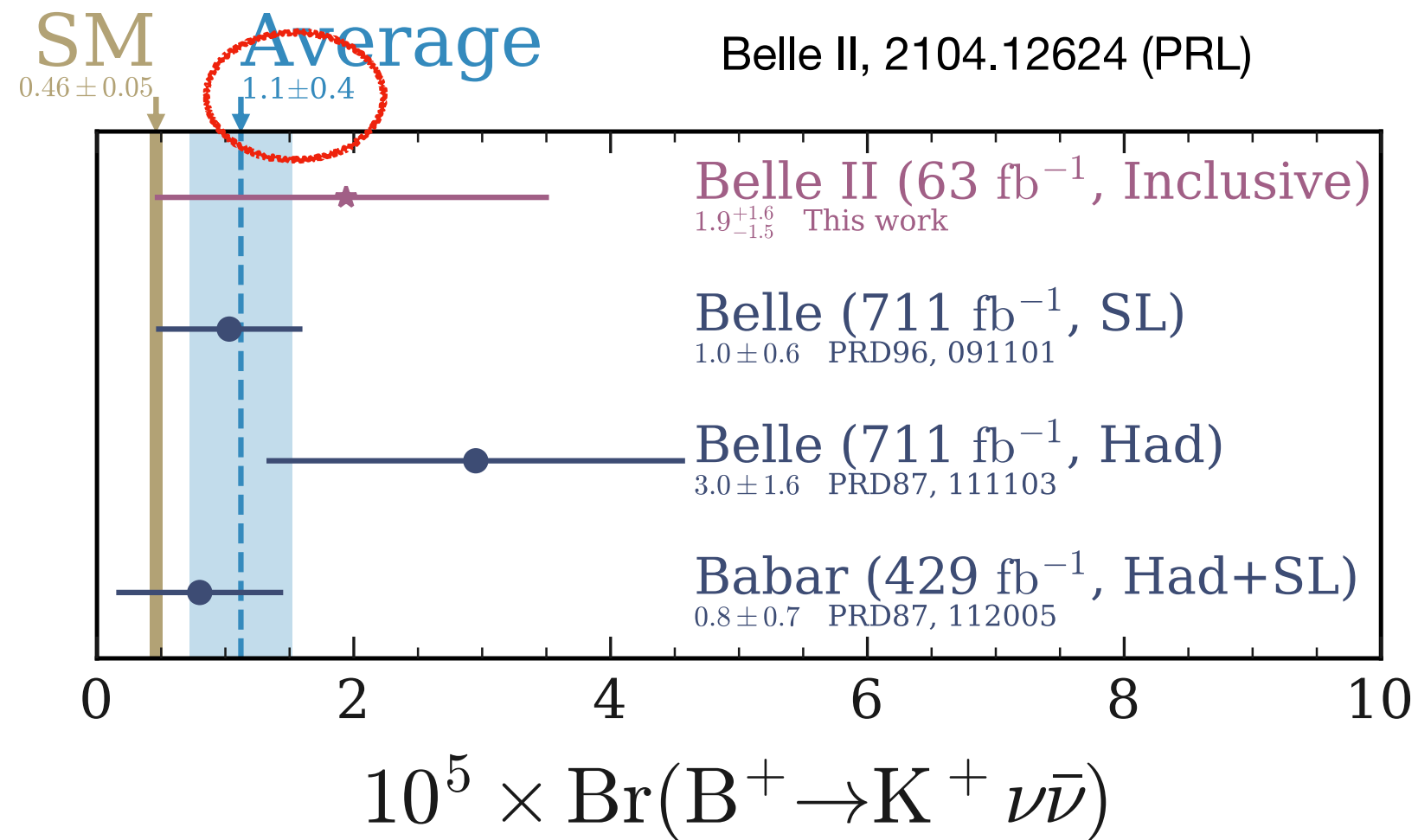
Recent $B^+ \rightarrow K^+ \nu \bar{\nu}$ Excess and Muon $g - 2$ Illuminating Light Dark Sector with Higgs Portal #20
 Shu-Yu Ho, Jongkuk Kim, Pyungwon Ko (Jan 18, 2024)
 e-Print: 2401.10112 [hep-ph]
[pdf](#) [cite](#) [claim](#) [reference search](#) [4 citations](#)

Status and prospects of rare decays at Belle-II #10
 Elisa Manoni (Mar 12, 2024)
 Published in: *PoS WFAI2023* (2024) 024 · Contribution to: *WFAI 2023*, 024
[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

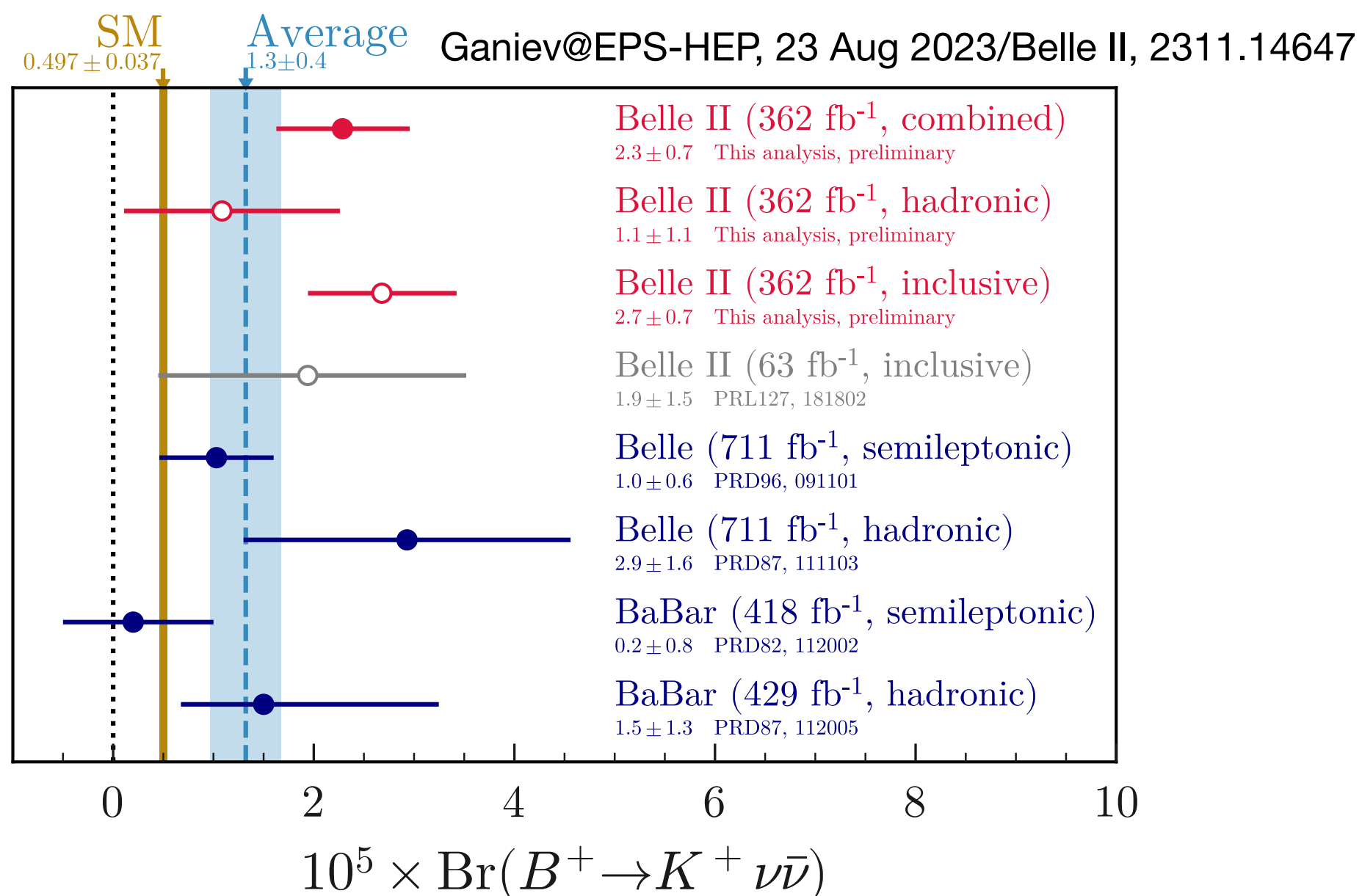
Rare B and K decays in a scotogenic model #11
 Chuan-Hung Chen, Cheng-Wei Chiang (Mar 5, 2024)
 e-Print: 2403.02897 [hep-ph]
[pdf](#) [cite](#) [claim](#) [reference search](#) [2 citations](#)

$b \rightarrow s\nu\bar{\nu}$: exp & theory

► 2021 Apr



► 2023 Aug



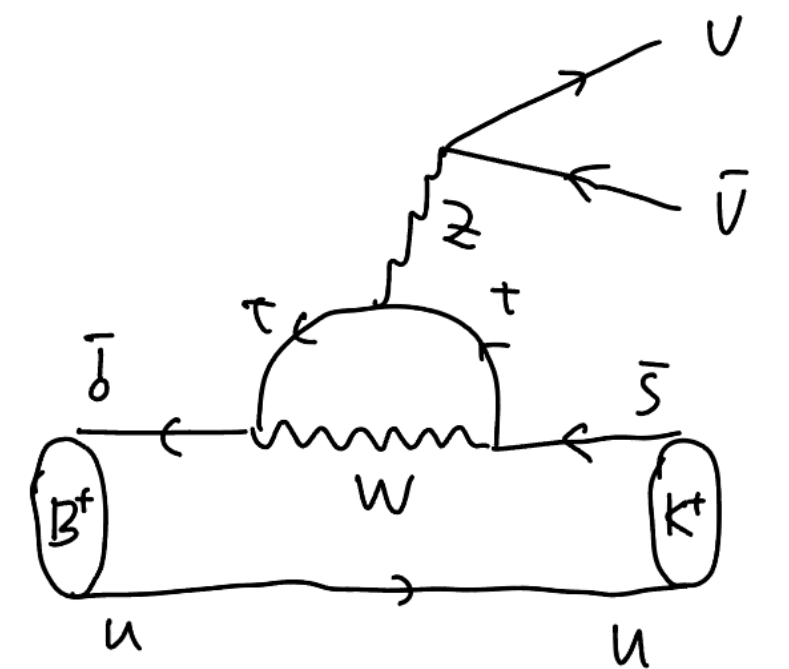
► Exp vs SM [10⁻⁶]

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}} = 4.16 \pm 0.57$$

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}} = 23 \pm 7$$

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}} \gtrsim 10 \text{ (} 2\sigma \text{ lower bound)}$$

2.7 σ difference
NP/SM $\gtrsim 2$



► Theoretical prediction

Factorization

$$\mathcal{A} \propto C_L \cdot \langle K | \bar{s} \gamma^\mu b | \bar{B} \rangle \cdot \bar{\nu} \gamma_\mu \nu$$

Wilson coef quark current neutrino current

theoretically, simple and clean
one of the cleanest channels in flavour physics

$$\mathcal{O}_L = (\bar{s} \gamma_\mu P_L b) (\bar{\nu} \gamma^\mu P_L \nu) \text{ in the SM}$$

$$\mathcal{O}_L = (\bar{s} P_L b) (\bar{\nu} P_L \nu) \times$$

$$\mathcal{O}_R = (\bar{s} \gamma_\mu P_R b) (\bar{\nu} \gamma^\mu P_L \nu) \text{ possible in BSM}$$

$$\mathcal{O}_R = (\bar{s} P_R b) (\bar{\nu} P_R \nu) \times$$

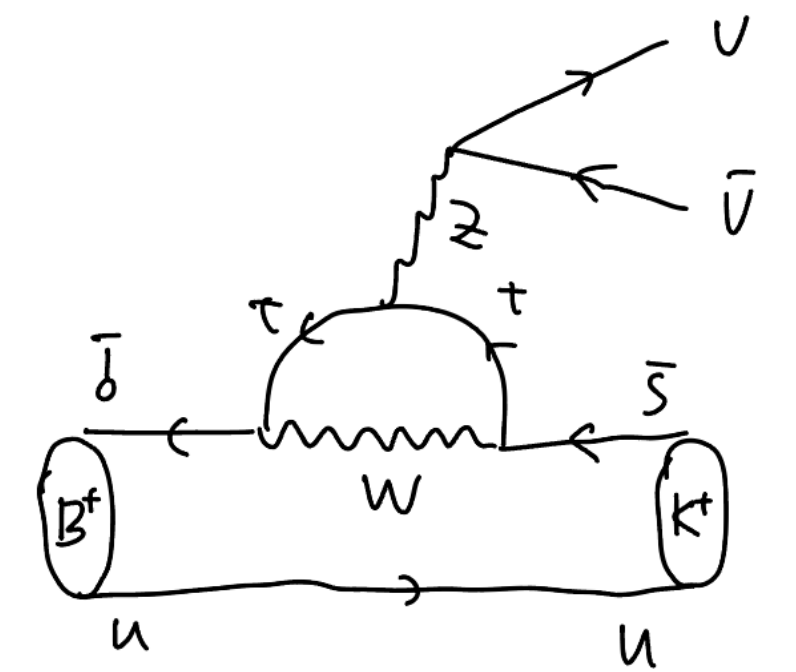
simple interaction but complicated flavour

$$\mathcal{O}_T = (\bar{s} \sigma_{\mu\nu} b) (\bar{\nu} \sigma^{\mu\nu} \nu) \times$$

operator structure highly
constrained by LH neutrino

$$\mathcal{O}_{T5} = (\bar{s} \sigma_{\mu\nu} \gamma_5 b) (\bar{\nu} \sigma^{\mu\nu} \nu) \times$$

$b \rightarrow s\nu\bar{\nu}$: exp & theory



	Observable	SM	Exp	Unit
$b \rightarrow s$	$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$	4.16 ± 0.57	$23 \pm 5_{-4}^{+5}$	10^{-6}
	$\mathcal{B}(B^0 \rightarrow K^0 \nu \bar{\nu})$	3.85 ± 0.52	< 26	10^{-6}
	$\mathcal{B}(B^+ \rightarrow K^{*+} \nu \bar{\nu})$	9.70 ± 0.94	< 61	10^{-6}
	$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})$	9.00 ± 0.87	< 18	10^{-6}
	$\mathcal{B}(B_s \rightarrow \phi \nu \bar{\nu})$	9.93 ± 0.72	< 5400	10^{-6}
	$\mathcal{B}(B_s \rightarrow \nu \bar{\nu})$	≈ 0	< 5.9	10^{-4}
$b \rightarrow d$	$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})$	1.40 ± 0.18	< 140	10^{-7}
	$\mathcal{B}(B^0 \rightarrow \pi^0 \nu \bar{\nu})$	6.52 ± 0.85	< 900	10^{-8}
	$\mathcal{B}(B^+ \rightarrow \rho^+ \nu \bar{\nu})$	4.06 ± 0.79	< 300	10^{-7}
	$\mathcal{B}(B^0 \rightarrow \rho^0 \nu \bar{\nu})$	1.89 ± 0.36	< 400	10^{-7}
	$\mathcal{B}(B^0 \rightarrow \nu \bar{\nu})$	≈ 0	< 1.4	10^{-4}
$s \rightarrow d$	$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	8.42 ± 0.61	$10.6_{-3.4}^{+4.0} \pm 0.9$	10^{-11}
	$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$	3.41 ± 0.45	< 300	10^{-11}

► Exp vs SM [10⁻⁶]

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}} = 4.16 \pm 0.57$$

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}} = 23 \pm 7$$

$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}} \gtrsim 10 \text{ (} 2\sigma \text{ lower bound)}$$

2.7 σ difference
NP/SM $\gtrsim 2$

► Theoretical prediction

Factorization

$$\mathcal{A} \propto C_L \cdot \langle K | \bar{s} \gamma^\mu b | \bar{B} \rangle \cdot \bar{\nu} \gamma_\mu \nu$$

Wilson coef quark current neutrino current

theoretically, simple and clean
one of the cleanest channels in
flavour physics

$$\mathcal{O}_L = (\bar{s} \gamma_\mu P_L b)(\bar{\nu} \gamma^\mu P_L \nu) \text{ in the SM}$$

$$\mathcal{O}_L = (\bar{s} P_L b)(\bar{\nu} P_L \nu) \quad \times$$

$$\mathcal{O}_R = (\bar{s} \gamma_\mu P_R b)(\bar{\nu} \gamma^\mu P_L \nu) \text{ possible in BSM}$$

$$\mathcal{O}_R = (\bar{s} P_R b)(\bar{\nu} P_R \nu) \quad \times$$

simple interaction but **complicated** flavour

$$\mathcal{O}_T = (\bar{s} \sigma_{\mu\nu} b)(\bar{\nu} \sigma^{\mu\nu} \nu) \quad \times$$

operator structure highly
constrained by LH neutrino

$$\mathcal{O}_{T5} = (\bar{s} \sigma_{\mu\nu} \gamma_5 b)(\bar{\nu} \sigma^{\mu\nu} \nu) \quad \times$$

$B^0 \rightarrow K^{*0} \nu \bar{\nu}$ can put strong constraints on related BSM effects.

$b \rightarrow s\nu\bar{\nu}$: SMEFT

B.F.Hou, X.Q.Li, M.Shen, Y.D.Yang, **XB**Y, 2402.19208

SMEFT notation: $l = \begin{pmatrix} \nu \\ e \end{pmatrix}_L, q = \begin{pmatrix} u \\ d \end{pmatrix}_L, d = d_R$

► Prediction

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})}{\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})} = \frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}}}{\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SM}}} = 0.46 \pm 0.07$$

► prediction

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SM}} = (9.00 \pm 0.87) \times 10^{-6}$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SMEFT}} = (50^{+17}_{-16}) \times 10^{-6} \quad \text{conflict}$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{exp}} < 18 \times 10^{-6}$$

► Only $\mathcal{O}_{lq}^{(3)}$ is relevant with $R_{D^{(*)}}$

► \mathcal{O}_{ld} can explain the $B^+ \rightarrow K^+ \nu \bar{\nu}$ data

► \mathcal{O}_{ld} also induce $O'_{9,ij}$ and $O'_{10,ij}$

► They can't improve the $b \rightarrow s\ell\ell$ fit

► O'_{9e} and $O'_{10\mu}$ worsen the fit. (LFUV, $\tau\tau \gg ee, \mu\mu$)

► $O'_{9,ij}$ and $O'_{10,ij}$ with $i = j = \tau$ has no effect.

► $O'_{9,ij}$ and $O'_{10,ij}$ with $i \neq j$ (i.e. LFV) has no effect.

SMEFT

$$\mathcal{Q}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{q}_p \gamma^\mu q_r),$$

$$\mathcal{Q}_{Hq}^{(3)} = (H^\dagger i \overleftrightarrow{D}_\mu^I H) (\bar{q}_p \tau^I \gamma^\mu q_r),$$

$$\mathcal{Q}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{d}_p \gamma^\mu d_r),$$

$$\mathcal{Q}_{ld} = (\bar{l}_p \gamma^\mu l_r) (\bar{d}_s \gamma_\mu d_t),$$

$$\mathcal{Q}_{lq}^{(1)} = (\bar{l}_p \gamma^\mu l_r) (\bar{q}_s \gamma_\mu q_t),$$

$$\mathcal{Q}_{lq}^{(3)} = (\bar{l}_p \gamma^\mu \tau^I l_r) (\bar{q}_s \tau^I \gamma_\mu q_t),$$

$$\mathcal{O}_L^{\nu_i \nu_j} = (\bar{s} \gamma_\mu P_L b) (\bar{\nu}_i \gamma^\mu P_L \nu_j)$$

$$\mathcal{O}_R^{\nu_i \nu_j} = (\bar{s} \gamma_\mu P_R b) (\bar{\nu}_i \gamma^\mu P_L \nu_j)$$

μ_{EW}

LEFT

μ_b

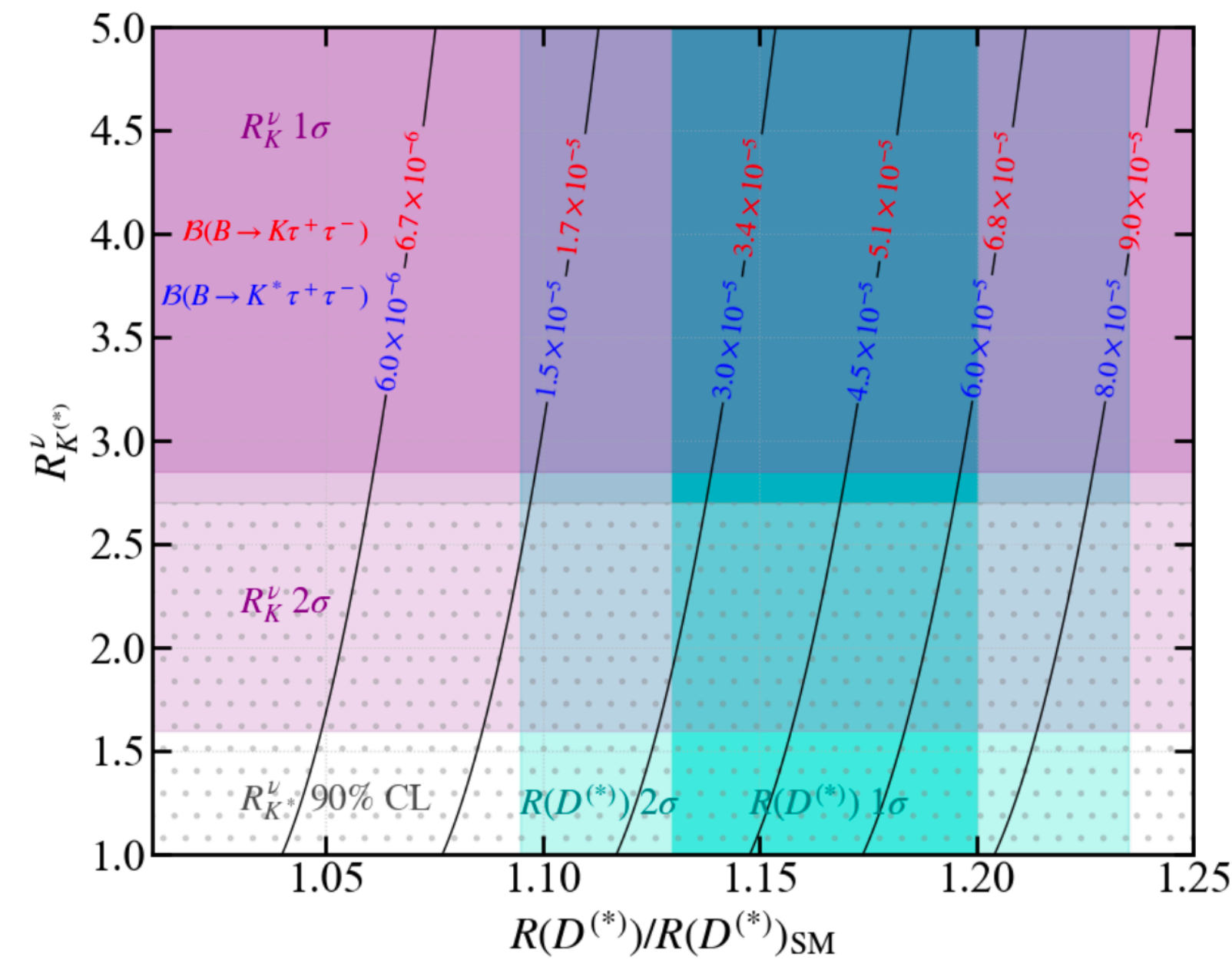
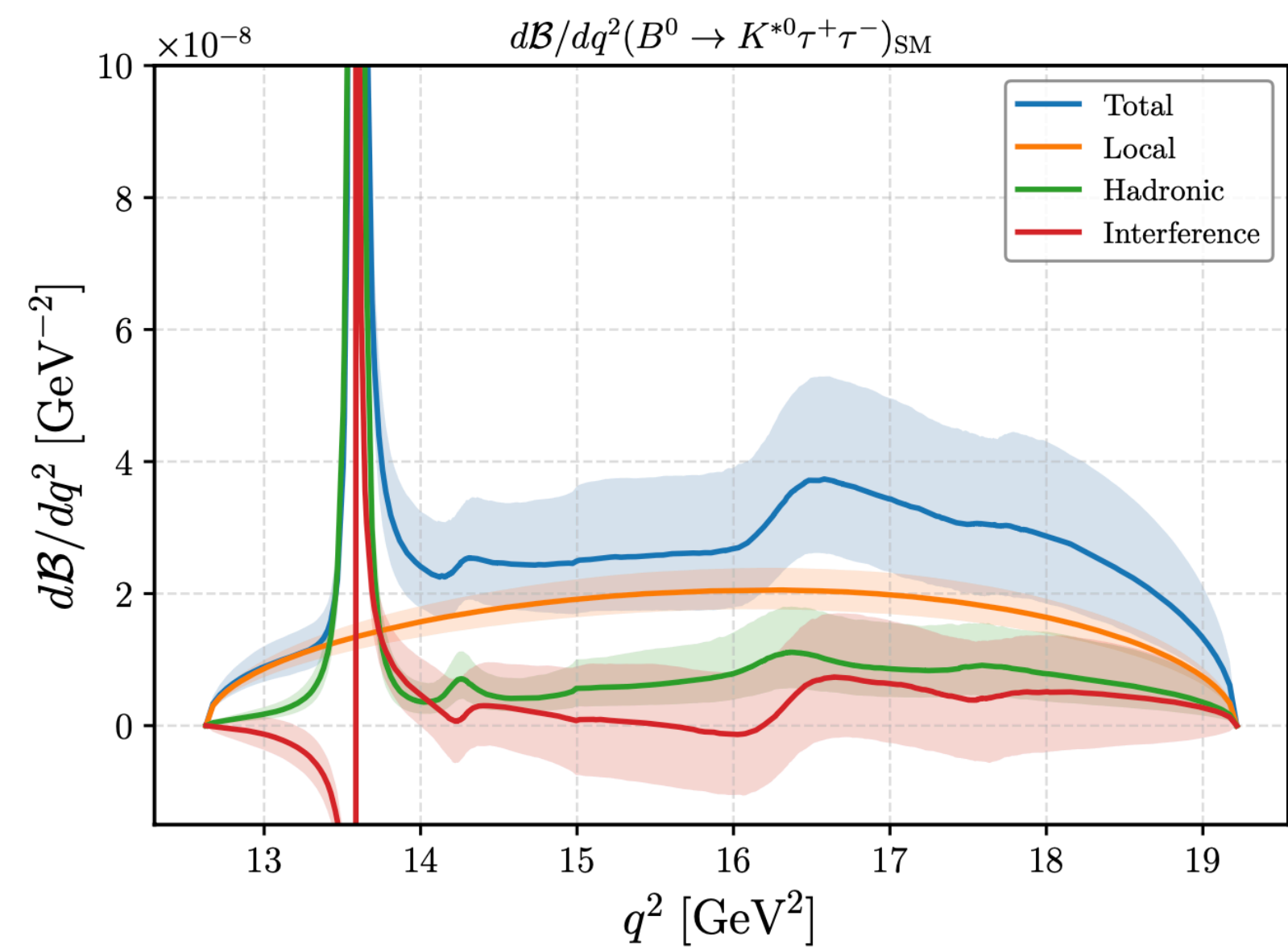
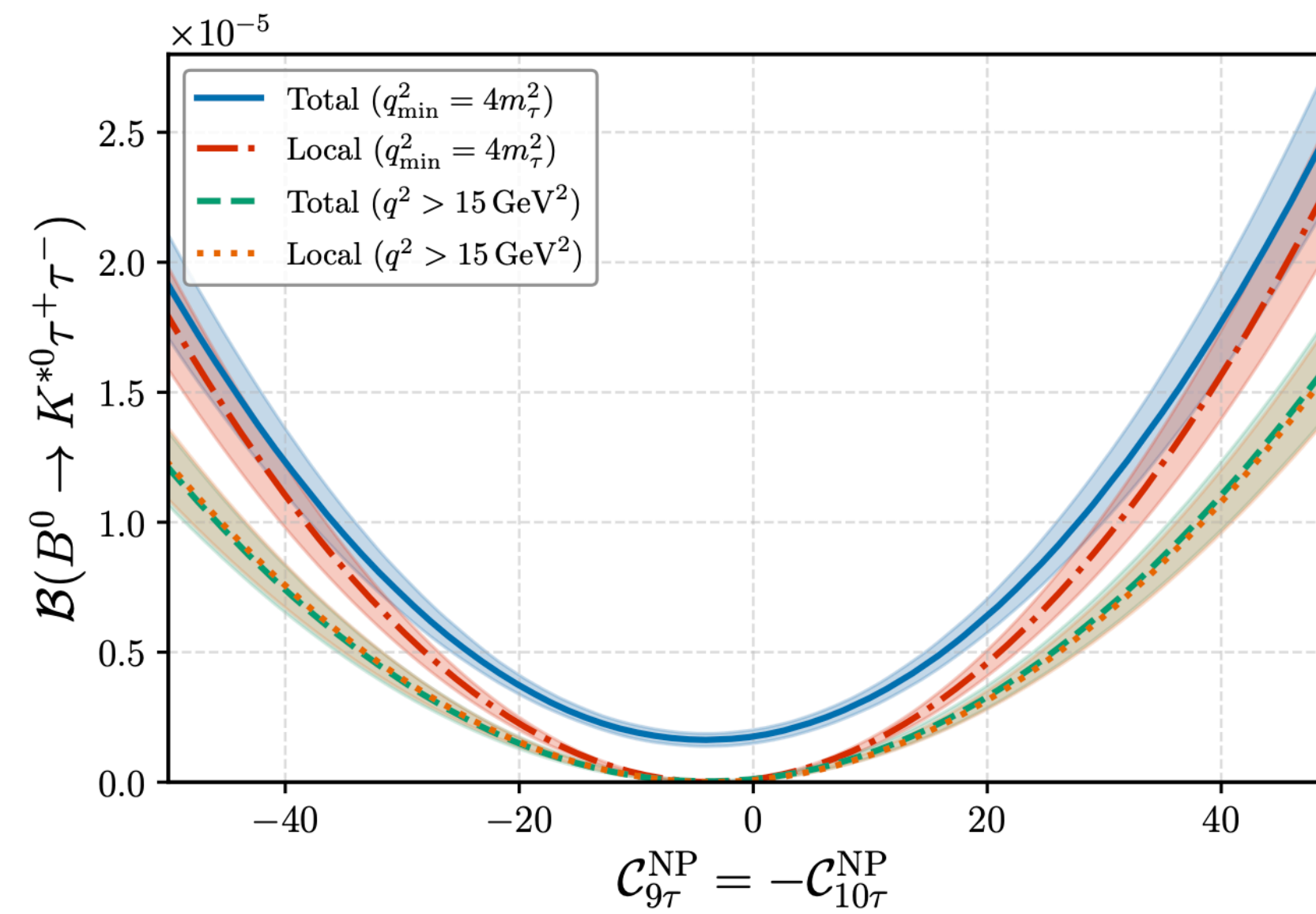
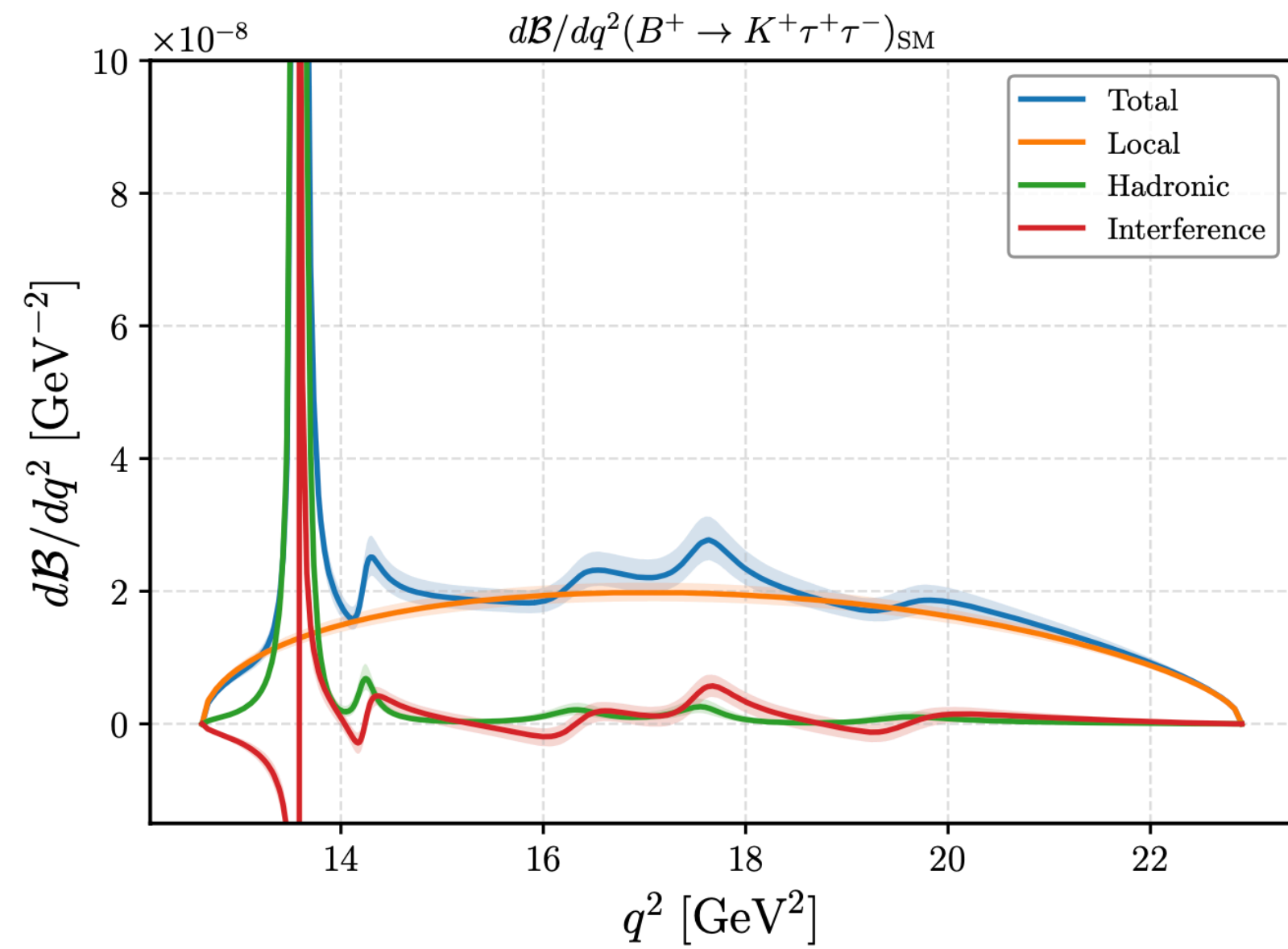
$$O'_{9,ij} = (\bar{b} \gamma^\mu P_{RS}) (\bar{\ell}_i \gamma_\mu \ell_j)$$

$$O'_{10,ij} = (\bar{b} \gamma^\mu P_{RS}) (\bar{\ell}_i \gamma_\mu \gamma_5 \ell_j)$$

induce $\bar{s}bZ$ interaction,
Thus, universally affect
 $b \rightarrow se^+e^-, \mu^+\mu^-, \tau^+\tau^-$

$B \rightarrow K^{(*)} \tau \tau$: resonance effects

Baltà, Crivellin, Escribano, Matias, Novoa-Brunet, 2605.21291



correlation in SMEFT

LFU violation in NP

▶ LFU in SM

$$\bar{\ell}'_R \gamma^\mu Z_\mu Y \ell'_R \propto [\bar{e}'_R \quad \bar{\mu}'_R \quad \bar{\tau}'_R] \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} e'_R \\ \mu'_R \\ \tau'_R \end{bmatrix} = [\bar{e}_R \quad \bar{\mu}_R \quad \bar{\tau}_R] \underbrace{U_R^\dagger}_{\text{mass eigenbasis}} \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \underbrace{U_R}_{\text{mass eigenbasis}} \begin{bmatrix} e_R \\ \mu_R \\ \tau_R \end{bmatrix} = [\bar{e}_R \quad \bar{\mu}_R \quad \bar{\tau}_R] \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} e_R \\ \mu_R \\ \tau_R \end{bmatrix}$$

↑ interaction eigenbasis

hypercharge of $U(1)_Y$
 $Y_{e_R} = Y_{\mu_R} = Y_{\tau_R} = -1$

$\ell'_R = U_R \ell_R$
 U_R : complex 3×3 unitary matrix

flavour universal

▶ LFU violation in NP

$$\bar{\ell}'_R \gamma^\mu Z'_\mu Y' \ell'_R \propto [\bar{e}'_R \quad \bar{\mu}'_R \quad \bar{\tau}'_R] \begin{bmatrix} Y'_{e_R} & 0 & 0 \\ 0 & Y'_{\mu_R} & 0 \\ 0 & 0 & Y'_{\tau_R} \end{bmatrix} \begin{bmatrix} e'_R \\ \mu'_R \\ \tau'_R \end{bmatrix} = [\bar{e}_R \quad \bar{\mu}_R \quad \bar{\tau}_R] U_R^\dagger \begin{bmatrix} Y'_{e_R} & 0 & 0 \\ 0 & Y'_{\mu_R} & 0 \\ 0 & 0 & Y'_{\tau_R} \end{bmatrix} U_R \begin{bmatrix} e_R \\ \mu_R \\ \tau_R \end{bmatrix} = [\bar{e}_R \quad \bar{\mu}_R \quad \bar{\tau}_R] \begin{bmatrix} \epsilon_{11} & \epsilon_{12} & \epsilon_{13} \\ \epsilon_{21} & \epsilon_{22} & \epsilon_{23} \\ \epsilon_{31} & \epsilon_{32} & \epsilon_{33} \end{bmatrix} \begin{bmatrix} e_R \\ \mu_R \\ \tau_R \end{bmatrix}$$

hypercharge of $U(1)'$
 $Y'_{e_R} \neq Y'_{\mu_R} \neq Y'_{\tau_R}$

flavour non-universality is generated,
 but flavour violation usually can't be avoided.

▶ We learn that

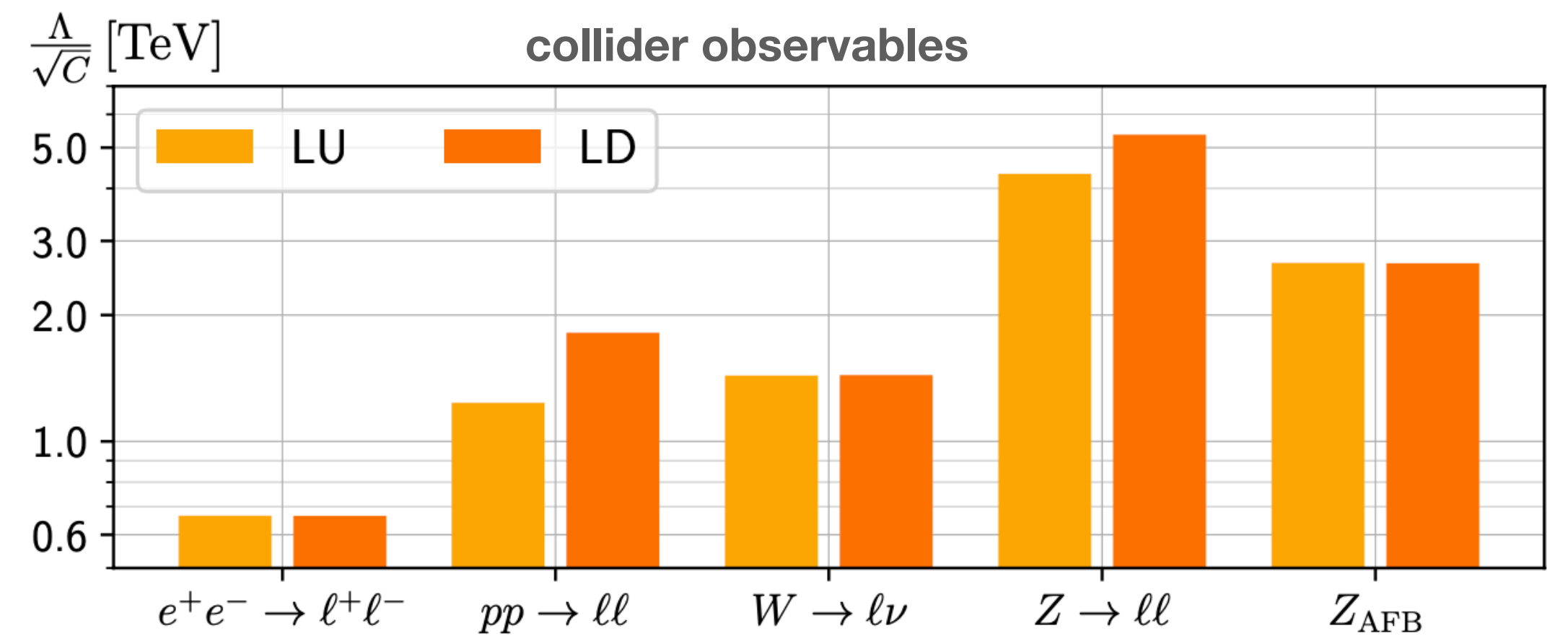
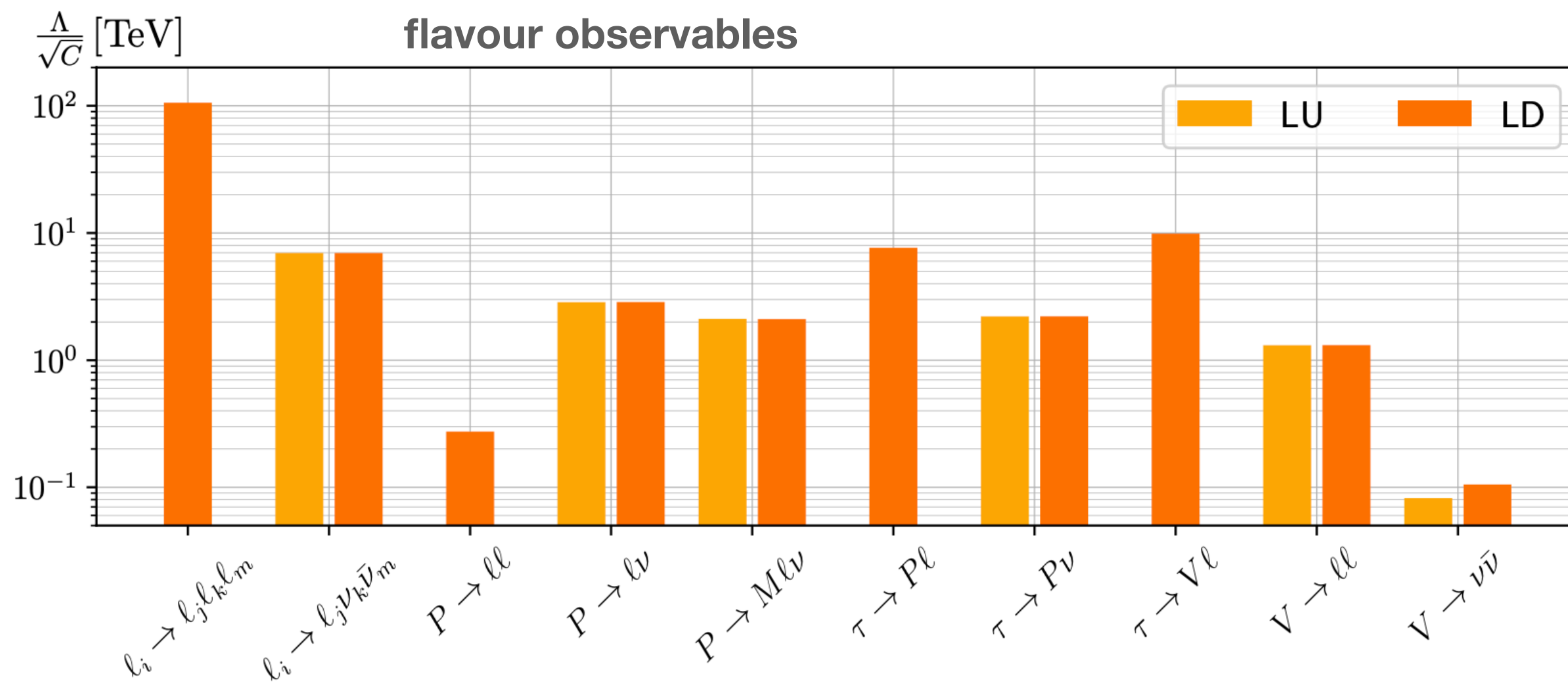
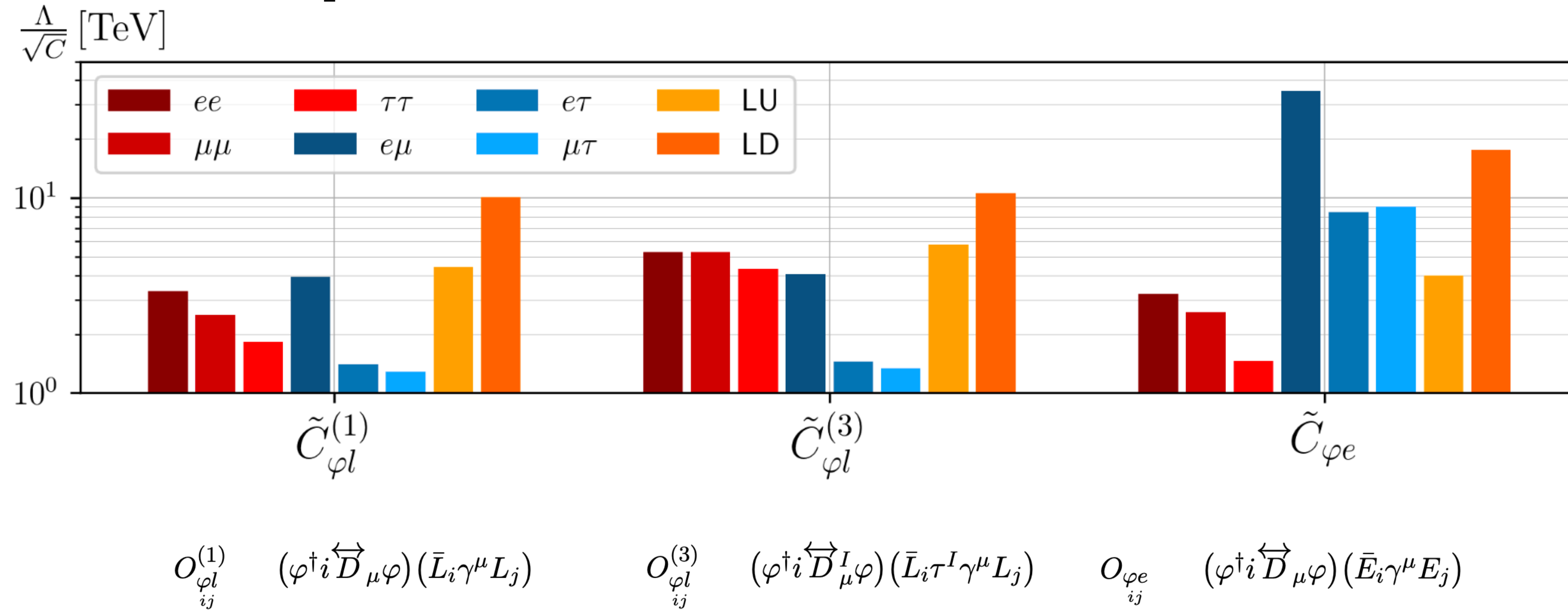
$$b \rightarrow s\mu\mu / b \rightarrow see \neq \text{SM} \implies \begin{cases} b \rightarrow se\mu, b \rightarrow set, b \rightarrow s\mu\tau \\ b \rightarrow d\mu\mu / b \rightarrow dee, s \rightarrow d\mu\mu / s \rightarrow dee, b\bar{b} \rightarrow \mu\mu / b\bar{b} \rightarrow ee, \dots \end{cases}$$

$$b \rightarrow c\tau\nu / b \rightarrow c\mu\nu \neq \text{SM} \implies b \rightarrow u\tau\nu / b \rightarrow u\mu\nu, c \rightarrow s\tau\nu / c \rightarrow s\mu\nu, \dots$$

What's the magnitude of NP effects in these related channels? Can they satisfy the current exp bound? Flavour structure !

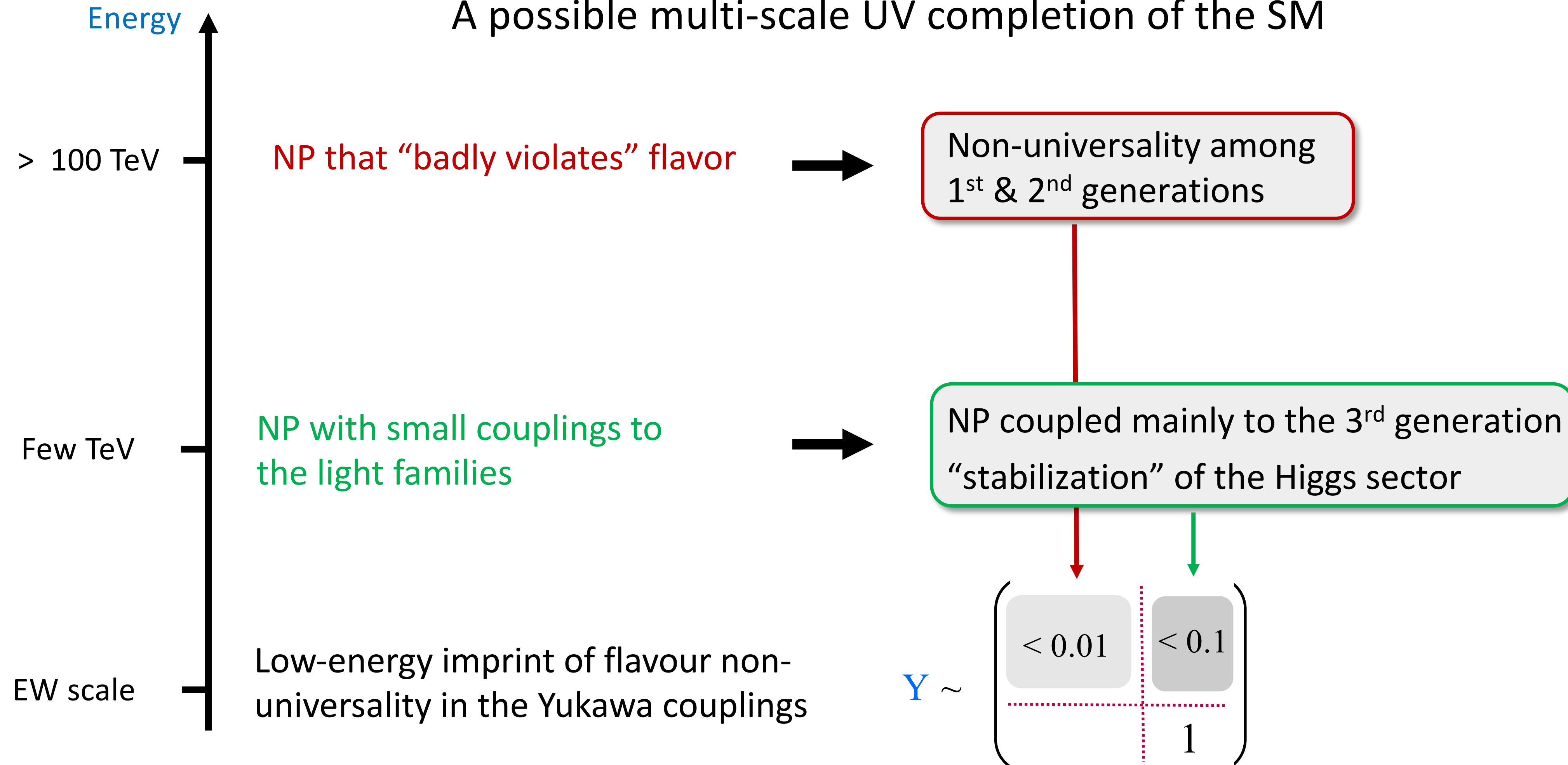
Lepton flavour specific SMEFT fit

Grunwald, Hiller, Kröninger, Nollen, 2511.07089

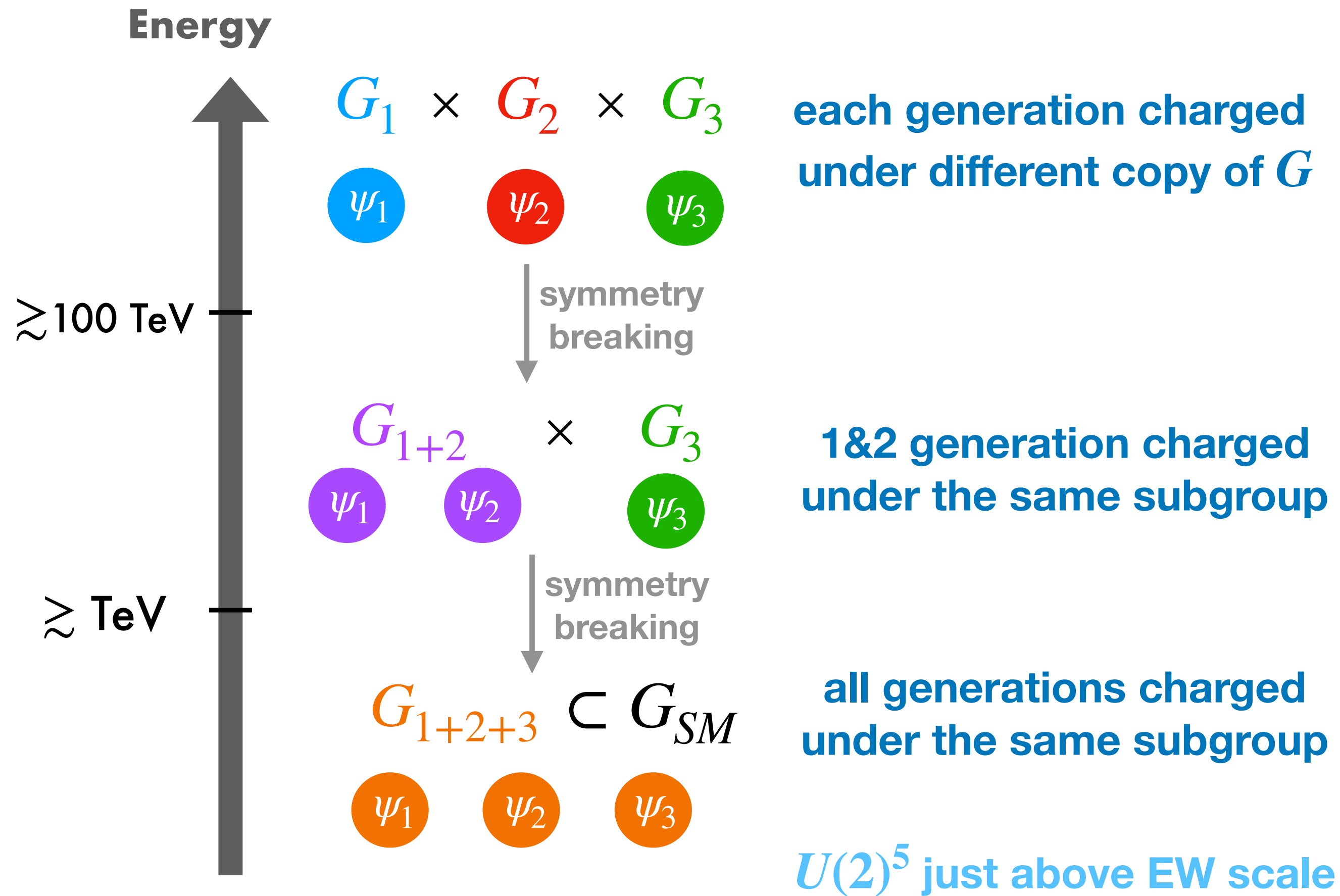


A Possible UV Picture from EFT Analysis

A possible multi-scale UV completion of the SM



Flavour Deconstruction



Renner's talk@EPS 2025

- ▶ Flavour non-universal interactions already at the TeV scale.
- ▶ NP flavour problem and Higgs hierarchy problem is connected.

Gauge Model of Generation Nonuniversality

Xiao-yuan Li^(a) and Ernest Ma

Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, Hawaii 96822

(Received 13 October 1981)

An electroweak gauge model is discussed, where generations are associated with separate gauge groups with different couplings. The observed μ - e universality is the result of a mass-scale inequality, $\nu_{03} \ll \nu_{12}$, in much the same way as strong isospin is the result of $m_u, m_d \ll 1 \text{ GeV}$. However, in contrast to the standard model, it is now possible to have (1) a longer τ lifetime, (2) an observable B^0 - \bar{B}^0 mixing, and (3) many gauge bosons W_i, Z_i in place of W, Z with $M_{W_i} > M_W$ and $M_{Z_i} > M_Z$.

Arkani-Hamed, Cohen, Georgi, hep-th/0104005

Craig, Green, Katz, 1103.3708

Covone, Davighi, Isidori, Pesut/2407.10950

Fuentes-Martín, Lizana/2402.09507

Davighi, Gosnay, Miller, Renner/2312.13346

Barbieri, Isidori/2312.14004

Isidori/2308.11612

Navarro, King/2305.07690

Davighi, Stefanek/2305.16280

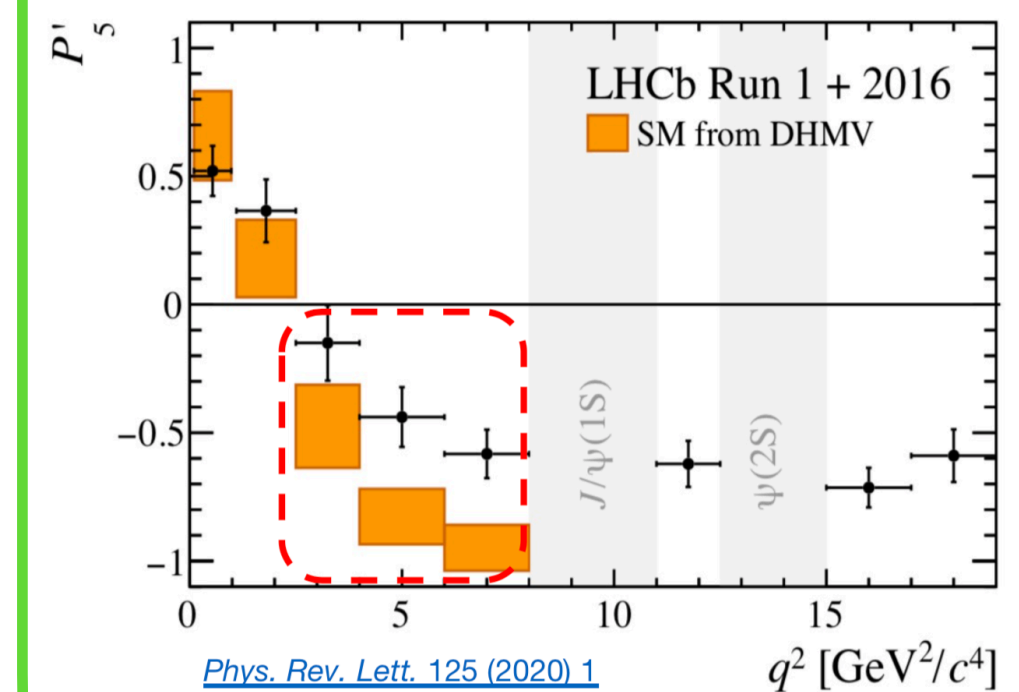
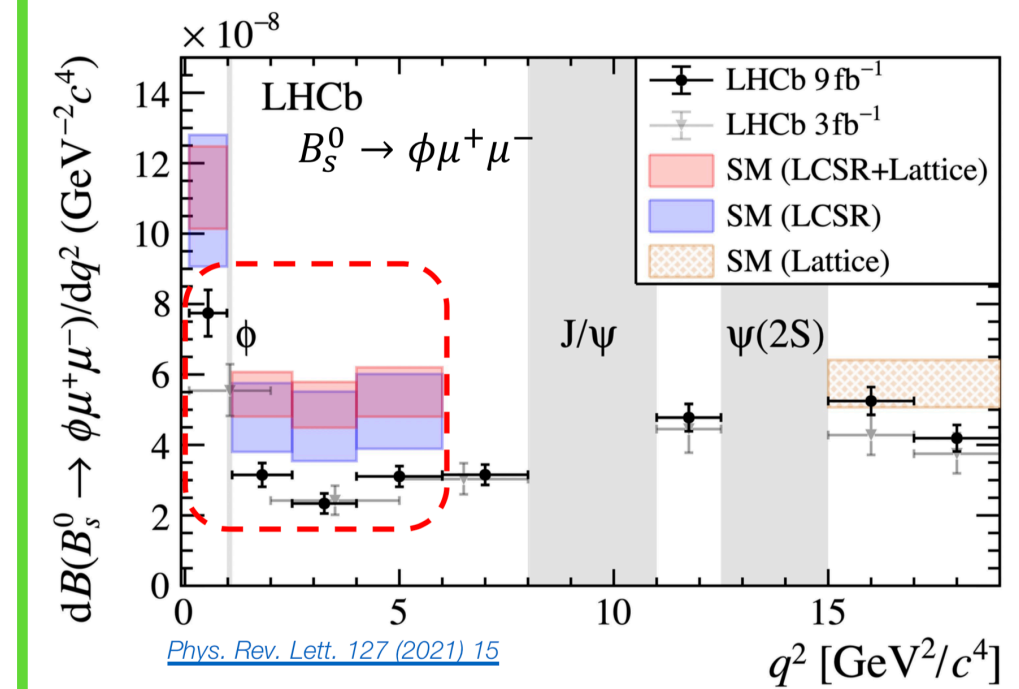
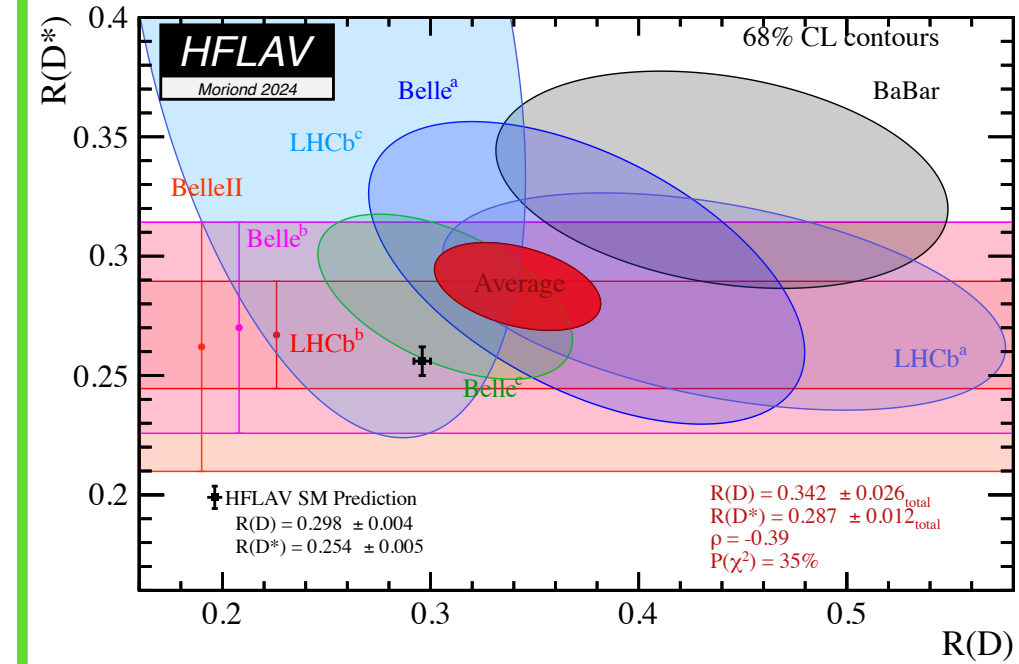
Davighi, Isidori/2303.01520

active research field

Summary

exp measurement

more precise data needed !



SMEFT

inverse problem
(e.g., Fermi theory to SM)

RGE
(well understood !)

LEFT/WET

QCD corrections
form factor
non-local matrix element

NP model

non-universal
gauge interaction

leptoquark

big question

flavour structure in the SM

EW hierarchy problem

Grand Unified Theory

Dark matter

Strong CP

Neutrino mass