Flavor Physics at LHC, LFUV in B-decays

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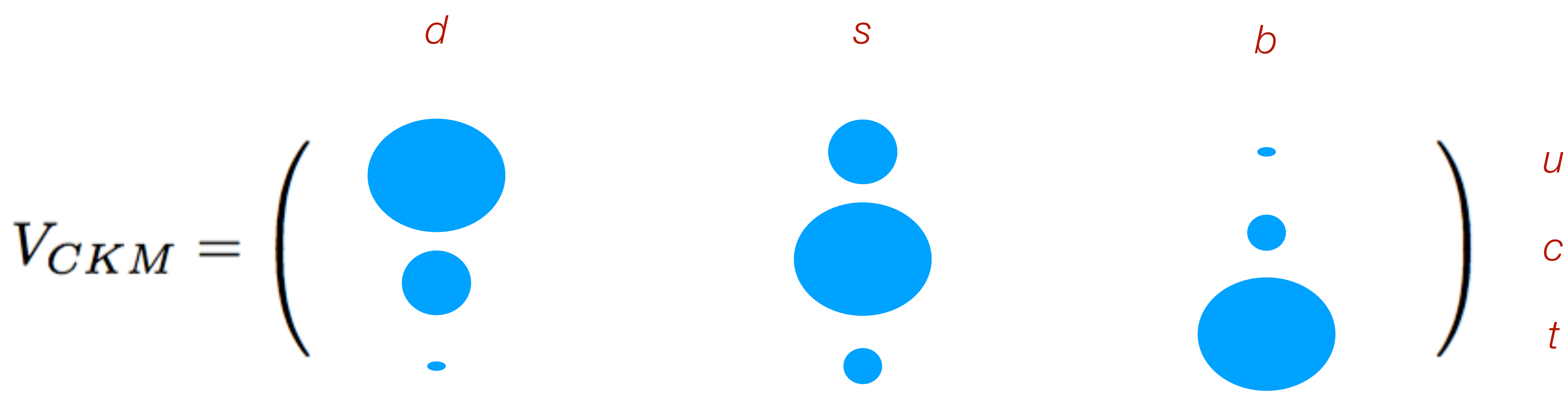
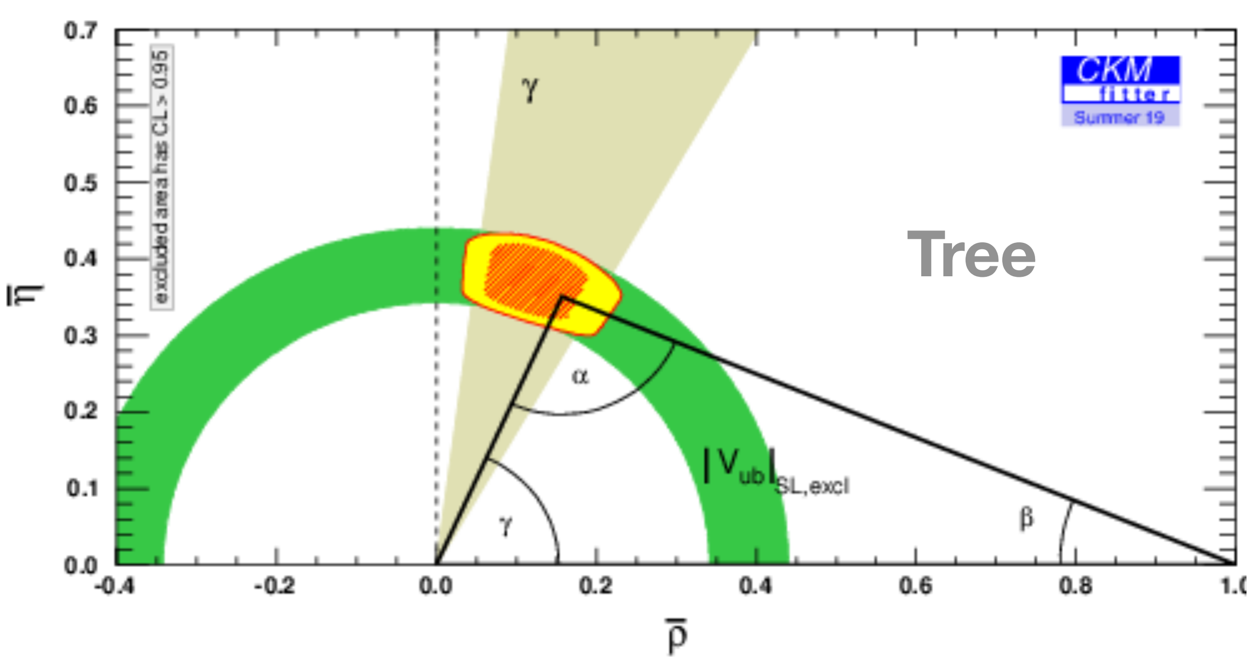
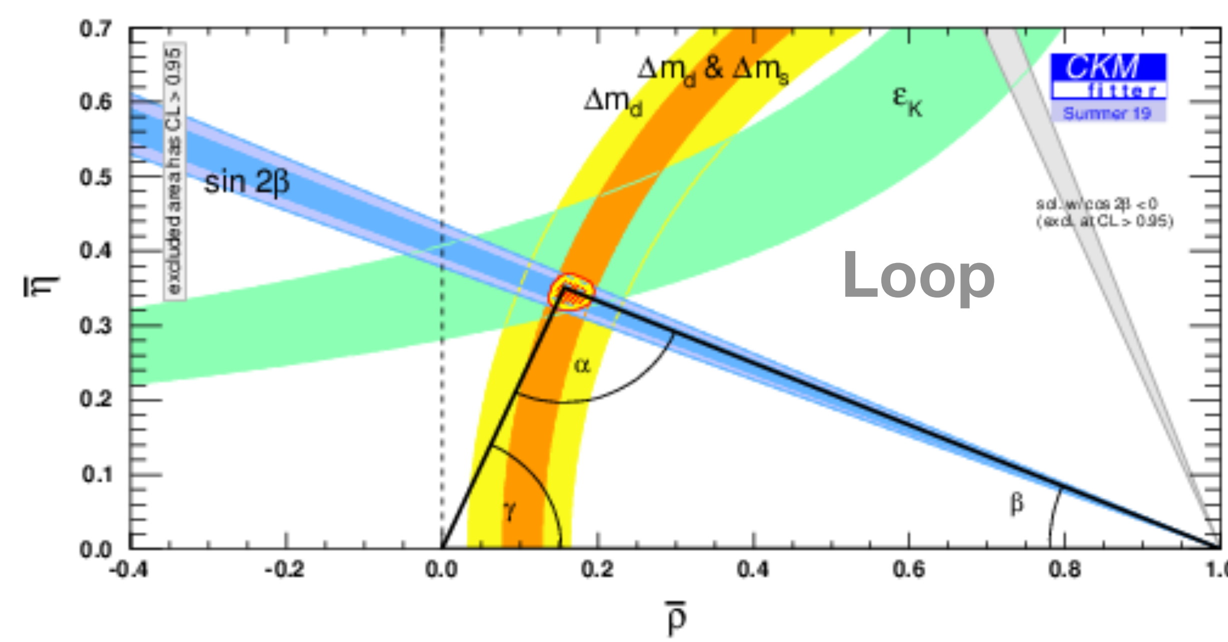
based on works done with A. Angelescu, I. Doršner, S. Fajfer, D. Faroughy, F. Jaffredo, N. Košnik, O. Sumensari

CKM-ology

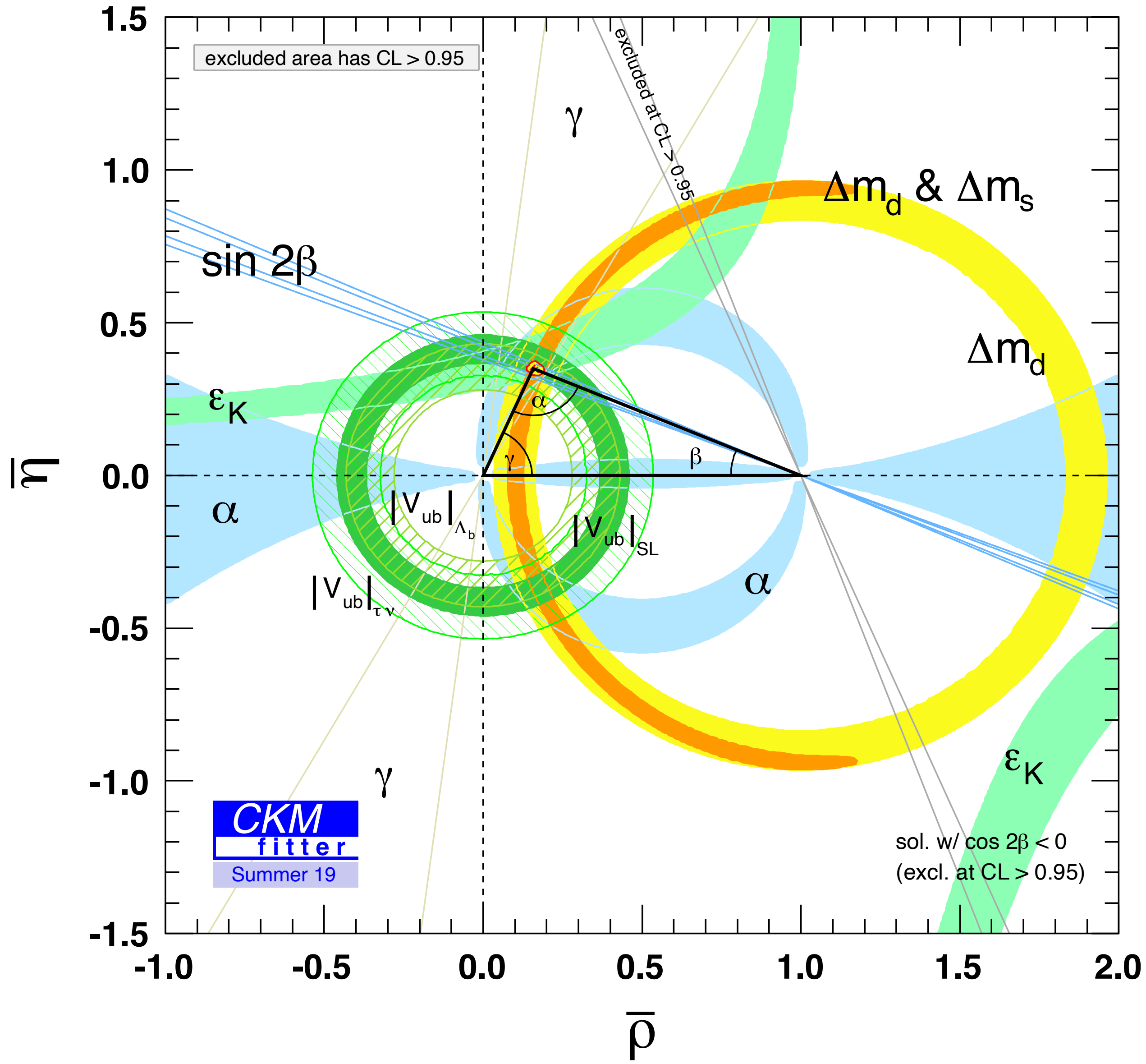


- Fix CKM entries through tree level processes & over-constrain by loop-induced ones [progress through precision!]

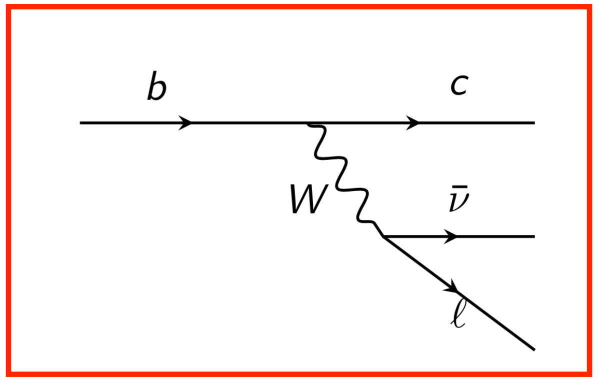




CKM-ology

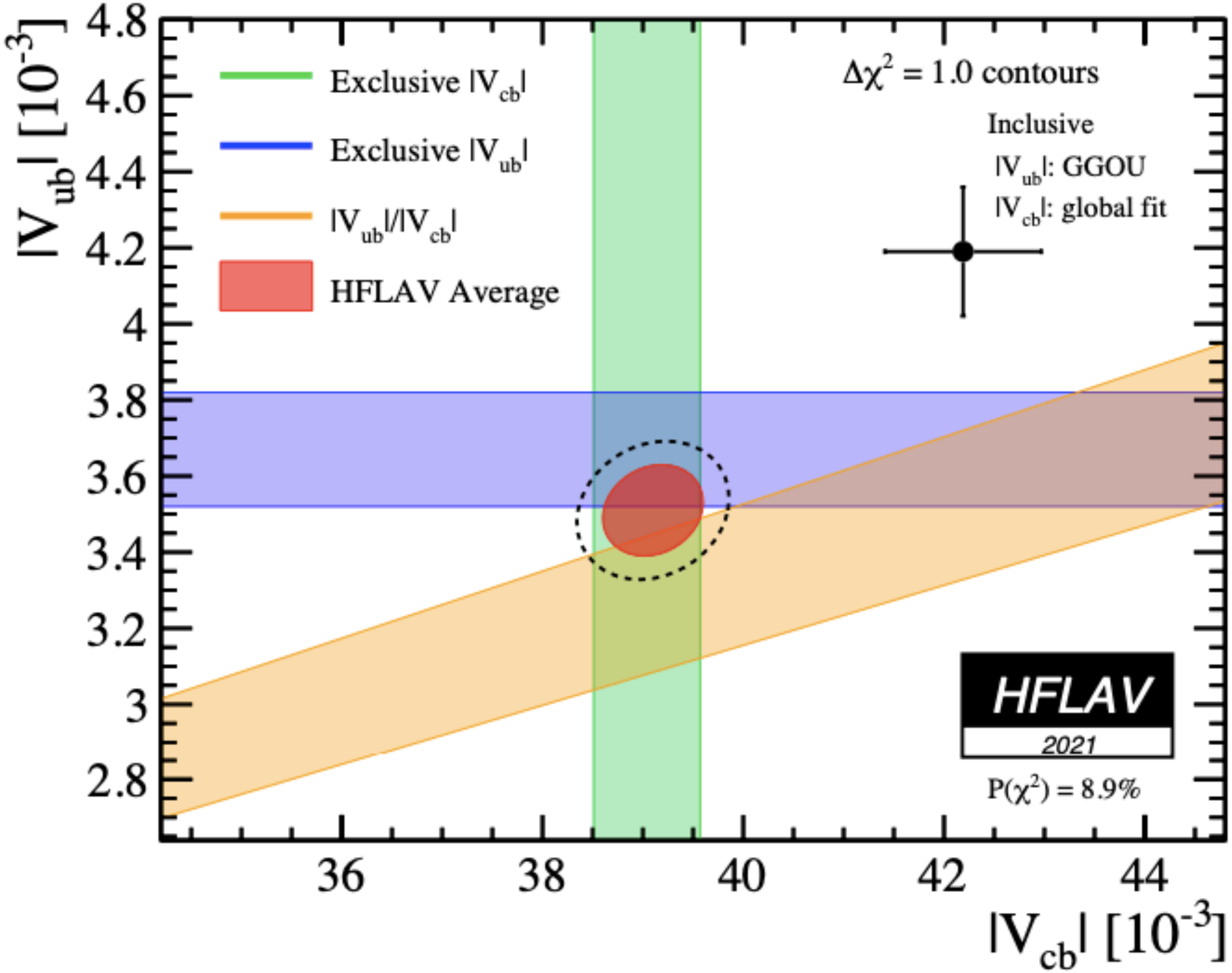


✘ Still open: inclusive v exclusive V_{ub} and V_{cb}?
Is V_{ud} well controlled? V_{us} keeps coming back (EM)…



CKM-ology - Small flavor ‘anomaly’

- ✘ Still open: inclusive v exclusive V_{ub} and V_{cb}?



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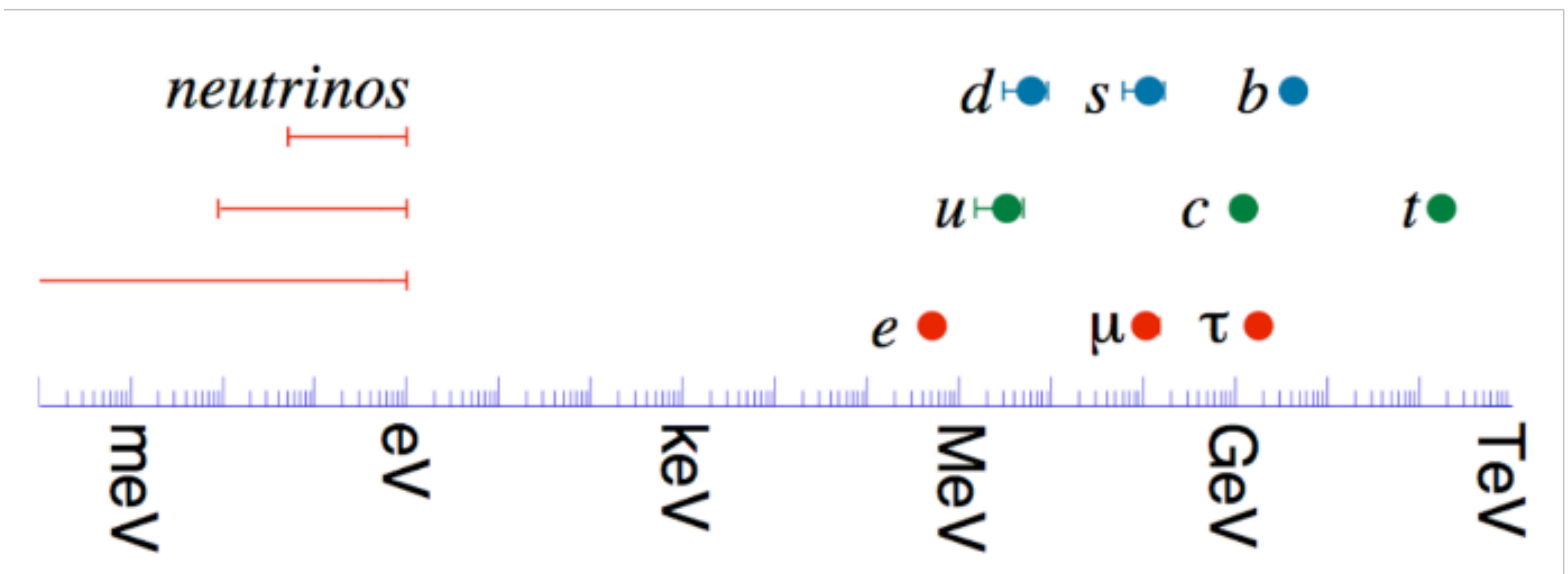
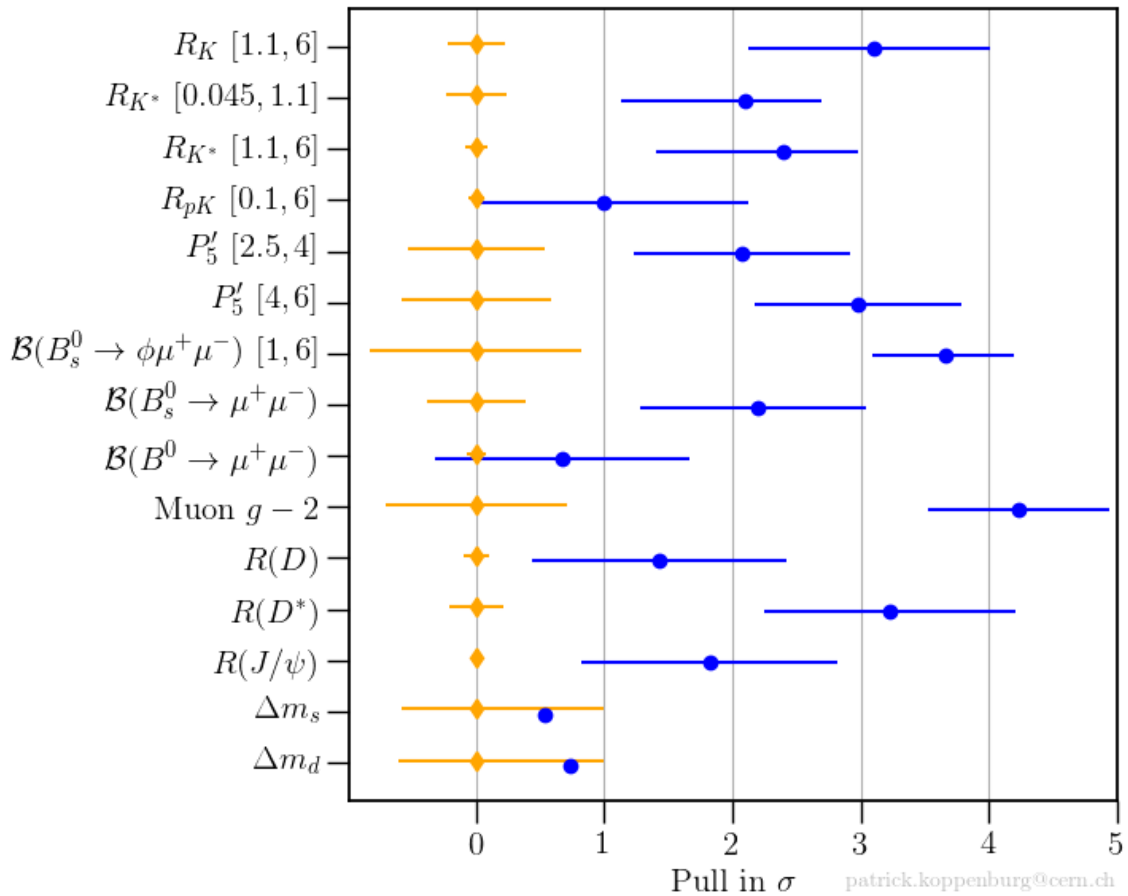
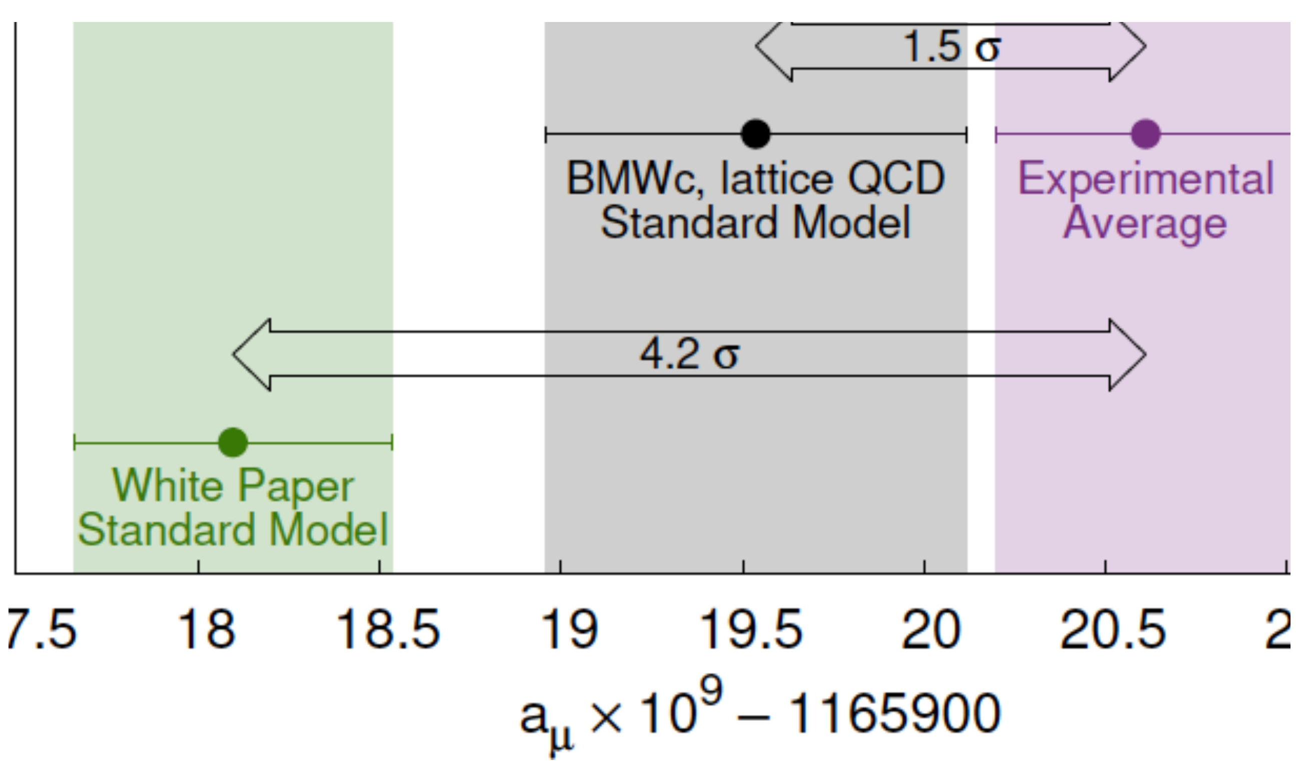
Flavor Physics

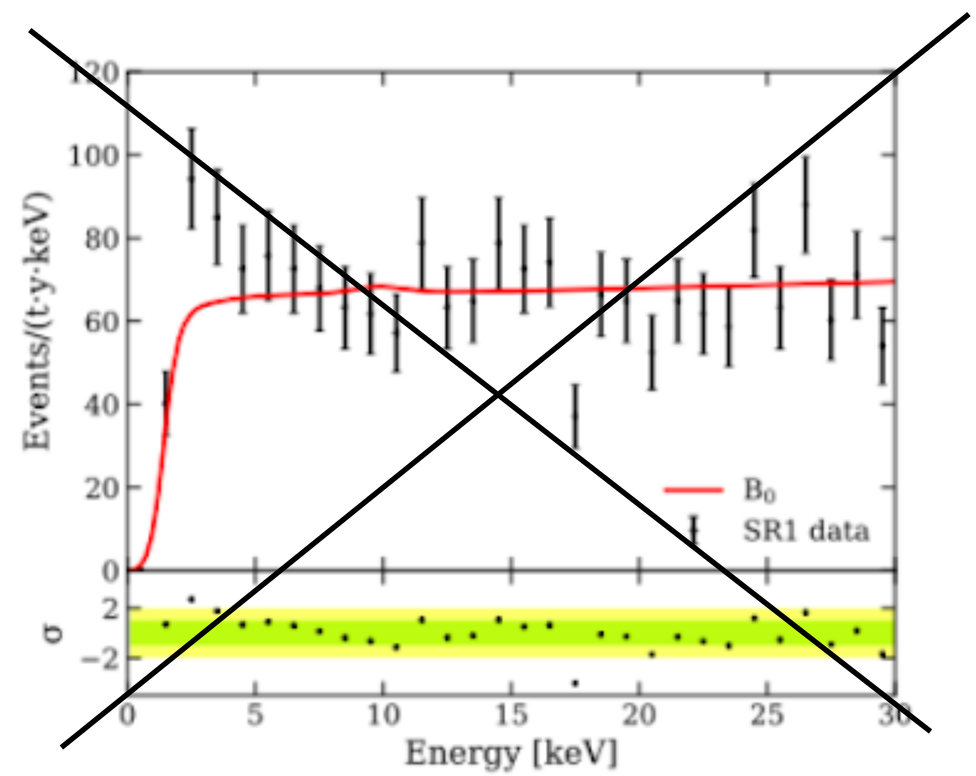
- ✘ Why three generations?
- ✘ Why such hierarchy of masses and mixing?
- ✘ Why so small CPV phase?



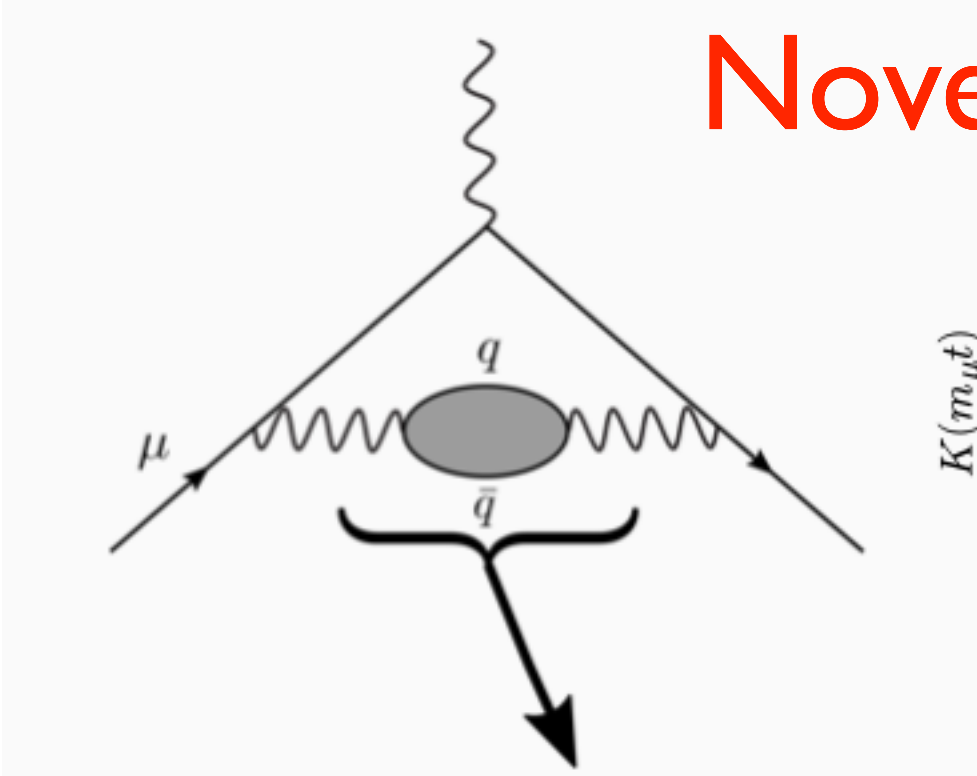
Flavor Anomalies







Novelties re $(g\text{-}2)_\mu$



$$\Pi_{\mu\nu}(Q) = \int d^4x\, e^{iQ\cdot x} \langle J_\mu(x) J_\nu(0)\rangle = \left(\delta_{\mu\nu}Q^2 - Q_\mu Q_\nu\right)\Pi(Q^2)$$

$$\Downarrow$$

$$a_\mu^{\mathrm{LO-HVP}} = 4\alpha_{em}^2 \int_0^\infty dQ^2 \frac{1}{m_\mu^2} f\left(\frac{Q^2}{m_\mu^2}\right)\cdot\left(\Pi(Q^2) - \Pi(0)\right).$$

$$a_\mu^{\mathrm{LO-HVP}} = 2\alpha_{em}^2 \int_0^\infty dt\; t^2 K(m_\mu t)\, V(t), \quad V(t) \equiv \frac{1}{3}\sum_{i=1,2,3} \int d\vec{x}\, \langle J_i(\vec{x},t) J_i(0)\rangle$$

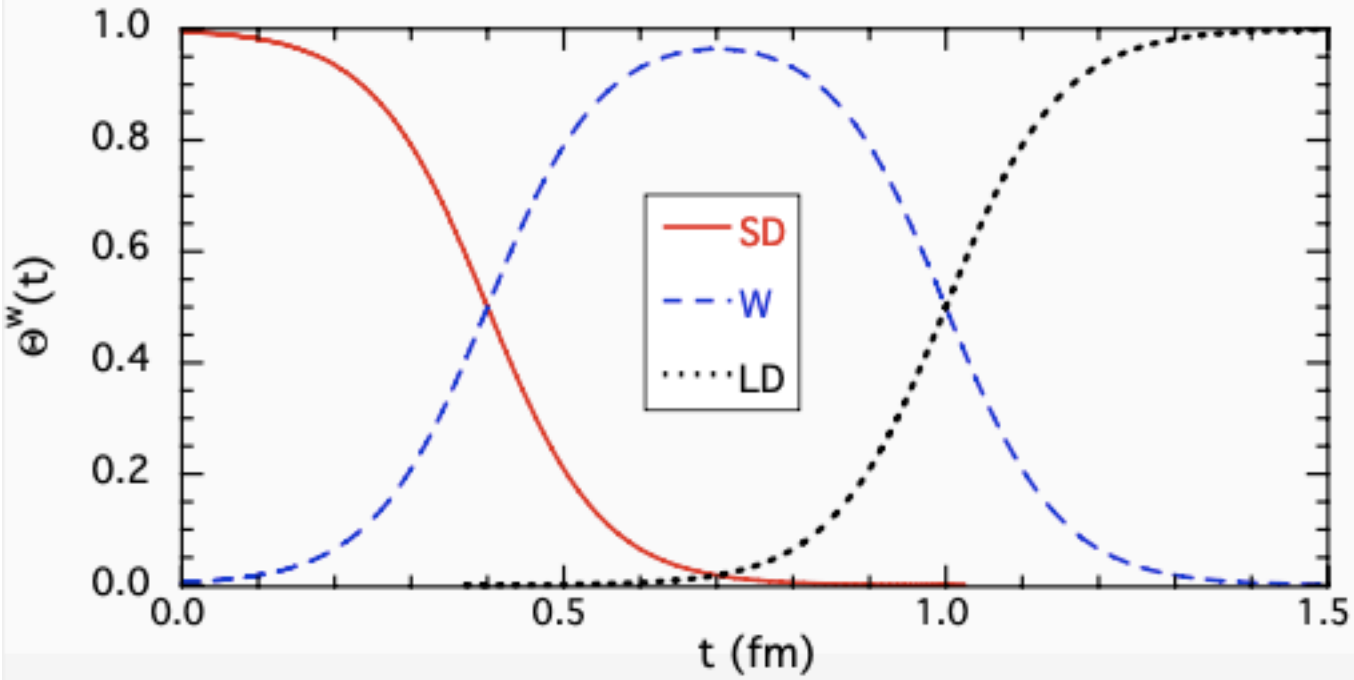
See talk by L. Varnhorst

Novelties re $(g\text{-}2)_\mu$

$$a_\mu^{SD} = 2\alpha_{em}^2 \int_0^\infty dt\; t^2 K(m_\mu t)\, V(t) \cdot \Theta^{SD}(t)$$

$$a_\mu^{W} = 2\alpha_{em}^2 \int_0^\infty dt\; t^2 K(m_\mu t)\, V(t) \cdot \Theta^{W}(t)$$

$$a_\mu^{LD} = 2\alpha_{em}^2 \int_0^\infty dt\; t^2 K(m_\mu t)\, V(t) \cdot \Theta^{LD}(t)$$



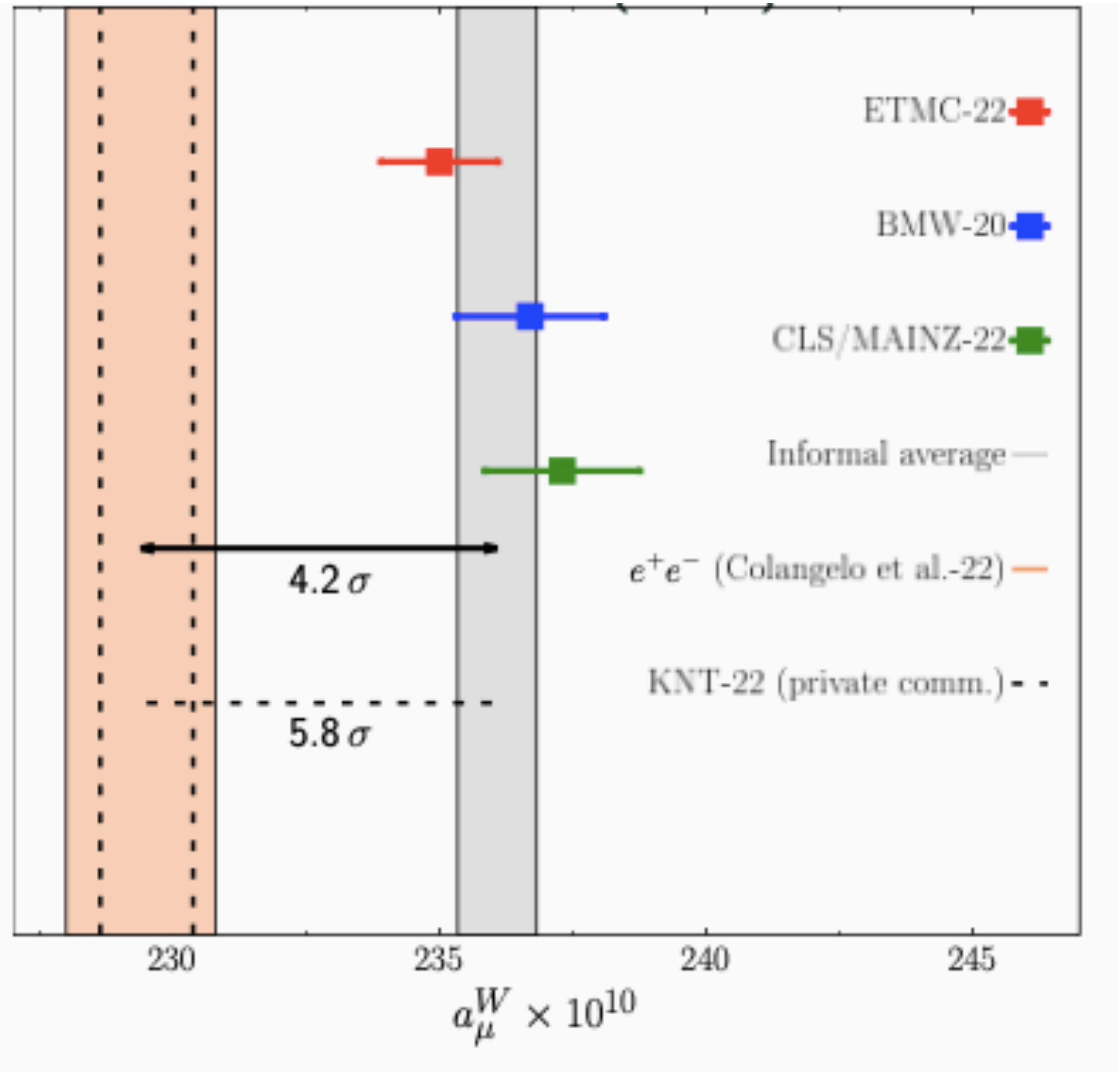
$$\Theta^{SD}(t) + \Theta^{W}(t) + \Theta^{LD}(t) = 1$$

$$\Downarrow$$

$$a_\mu^{\mathrm{LO-HVP}} = a_\mu^{\mathrm{SD}} + a_\mu^{\mathrm{W}} + a_\mu^{\mathrm{LD}}$$

$$\underbrace{2\alpha_{em}^2 \int_0^\infty dt\; t^2 K(m_\mu t)\, V(t)}_{\text{lattice, SM}} = a_\mu^{\mathrm{LO-HVP}} = \underbrace{\frac{2\alpha_{em}^2 m_\mu^2}{9\pi^2} \int_{2M_\pi}^\infty \frac{dE}{E^2}\, \tilde{K}(E)\, R^{had}(E)}_{\text{dispersive, experimental}}$$

Novelties re $(g\text{-}2)_\mu$



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$$\underbrace{2\alpha_{em}^2 \int_0^\infty dt\; t^2 K(m_\mu t)\; V(t)}_{\text{lattice, SM}} \;=\; a_\mu^{\mathrm{LO-HVP}} \;=\; \underbrace{\frac{2\alpha_{em}^2 m_\mu^2}{9\pi^2} \int_{2M_\pi}^\infty \frac{dE}{E^2}\; \tilde{K}(E)\; R^{had}(E)}_{\text{dispersive, experimental}}$$

Lepton Flavor Universality Violation

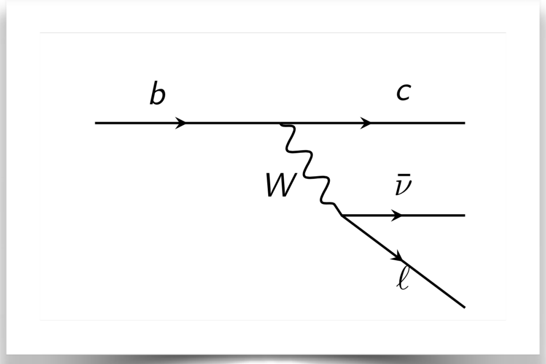
$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \qquad \& \qquad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\bigg|_{q^2\in[q^2_{\rm min},q^2_{\rm max}]} \qquad \& \qquad R^{\rm exp}_{K^{(*)}} < R^{\rm SM}_{K^{(*)}}$$

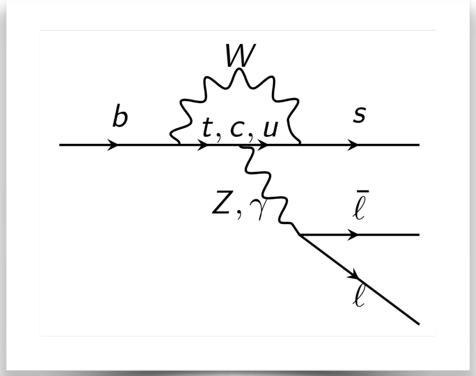
- CKM factor cancels
- Bulk of hadronic uncertainties cancel

Lepton Flavor Universality Violation

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \quad \& \quad R^{\text{exp}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}}$$



$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\bigg|_{q^2\in[q^2_{\text{min}},q^2_{\text{max}}]} \quad \& \quad R^{\text{exp}}_{K^{(*)}} < R^{\text{SM}}_{K^{(*)}}$$



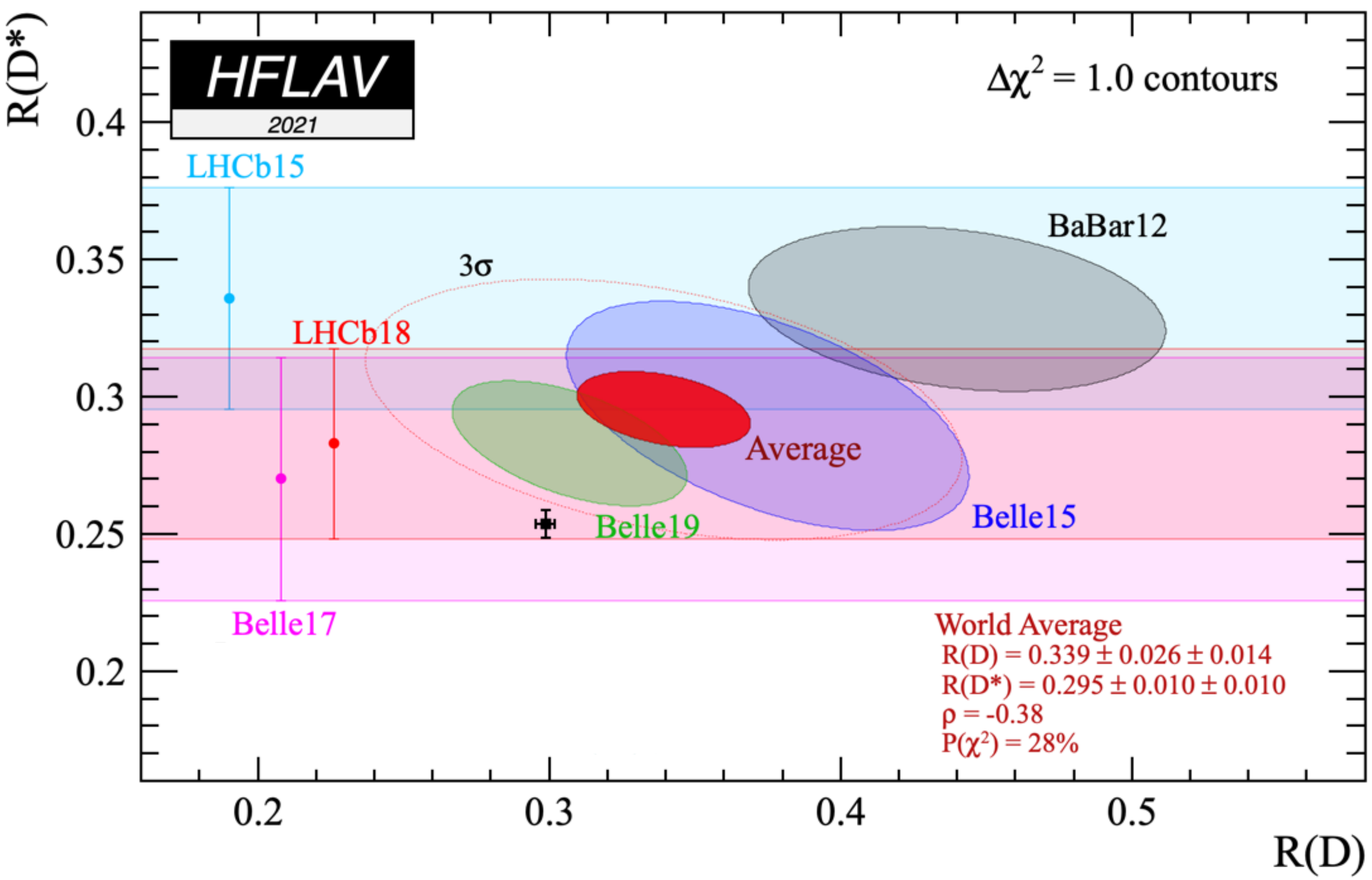
$$R^{\text{exp}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}} \quad \Rightarrow \quad \Lambda_{\text{NP}} \lesssim 3 \text{ TeV}$$

$$R^{\text{exp}}_{K^{(*)}} < R^{\text{SM}}_{K^{(*)}} \quad \Rightarrow \quad \Lambda_{\text{NP}} \lesssim 30 \text{ TeV}$$

LFUV
need studying NP effects

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \qquad \& \qquad R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}}$$

$$R^{\rm exp}_{D^{(*)}} > R^{\rm SM}_{D^{(*)}} \quad \Rightarrow \quad \Lambda_{\rm NP} \lesssim 3\ \text{TeV}$$



LHCb

- $B_c \to J/\psi\, \ell\bar{\nu}$

$$R^{\rm exp}_{J/\psi} > R^{\rm SM}_{J/\psi}$$

- $\Lambda_b \to \Lambda_c\, \ell\bar{\nu}$

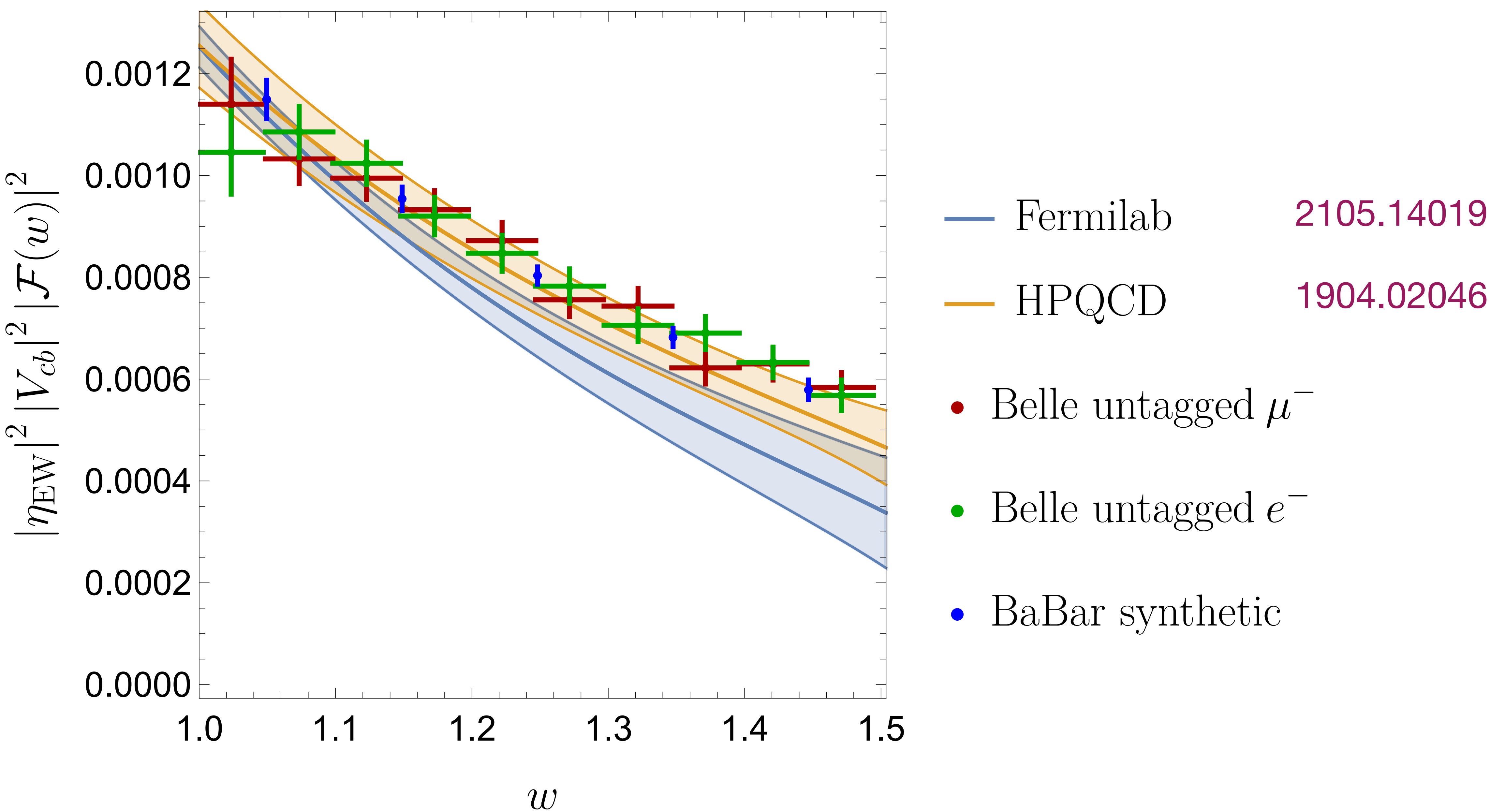
$$R^{\rm exp}_{\Lambda_c} \approx R^{\rm SM}_{\Lambda_c}$$

NEW and can be improved... a lot

2201.03497

We still do not have a control over hadronic uncertainties with

$$\frac{d\mathcal{B}(B \to D^*\ell\bar{\nu})}{dq^2} = \frac{1}{2m_B m_{D^*}} \frac{d\mathcal{B}(B \to D^*\ell\bar{\nu})}{dw} \propto |V_{cb}|^2 |\mathcal{F}(w)|^2$$



- Assuming with HPQCD that $\mathcal{F}(w)^{B_s \to D_s^*} = \mathcal{F}(w)^{B \to D^*}$

We still do not have a full/good control over hadronic uncertainties

Mode	$B \to D\ell\bar{\nu}$	$B \to D^*\ell\bar{\nu}$	$\Lambda_b \to \Lambda_c\ell\bar{\nu}$
$\langle V_\mu \rangle$	**2** ✓	**1** ✓	**3** ✓
$\langle A_\mu \rangle$		**3** ✓	**3** ✓
$\langle T_{\mu\nu} \rangle$	**1** ×	**3** ×	**4** ✓

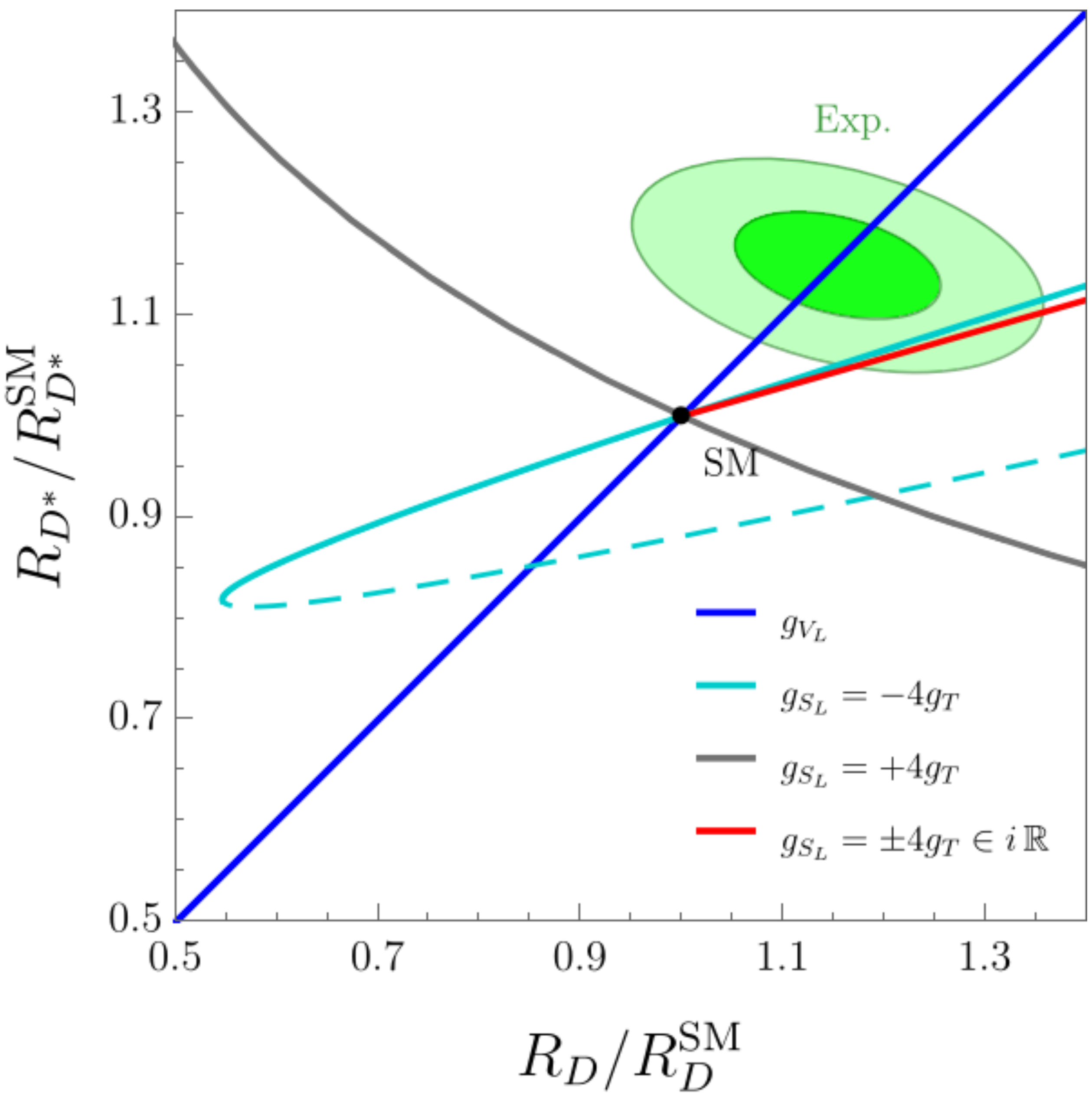
1503.07237	1904.02046	1503.01421
1505.03925	2105.14019	1702.02243

EFT - exclusive $b \to c\ell\nu$

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

EFT - exclusive $b \to c\ell\nu$

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



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EFT - exclusive $b \to c\ell\nu$

$g_{V_L}(m_b)$	0.07 ± 0.02	$0.02/1$	✔
$g_{S_R}(m_b)$	-0.31 ± 0.05	$5.3/1$	✘
$g_{S_L}(m_b)$	0.12 ± 0.06	$8.8/1$	✘
$g_T(m_b)$	-0.03 ± 0.01	$3.1/1$	✔
$g_{S_L} = +4g_T \in \mathbb{R}$	-0.03 ± 0.07	$12.5/1$	✘
$g_{S_L} = -4g_T \in \mathbb{R}$	0.16 ± 0.05	$2.0/1$	✔
$g_{S_L} = \pm 4g_T \in i\,\mathbb{R}$	0.48 ± 0.08	$2.4/1$	✔

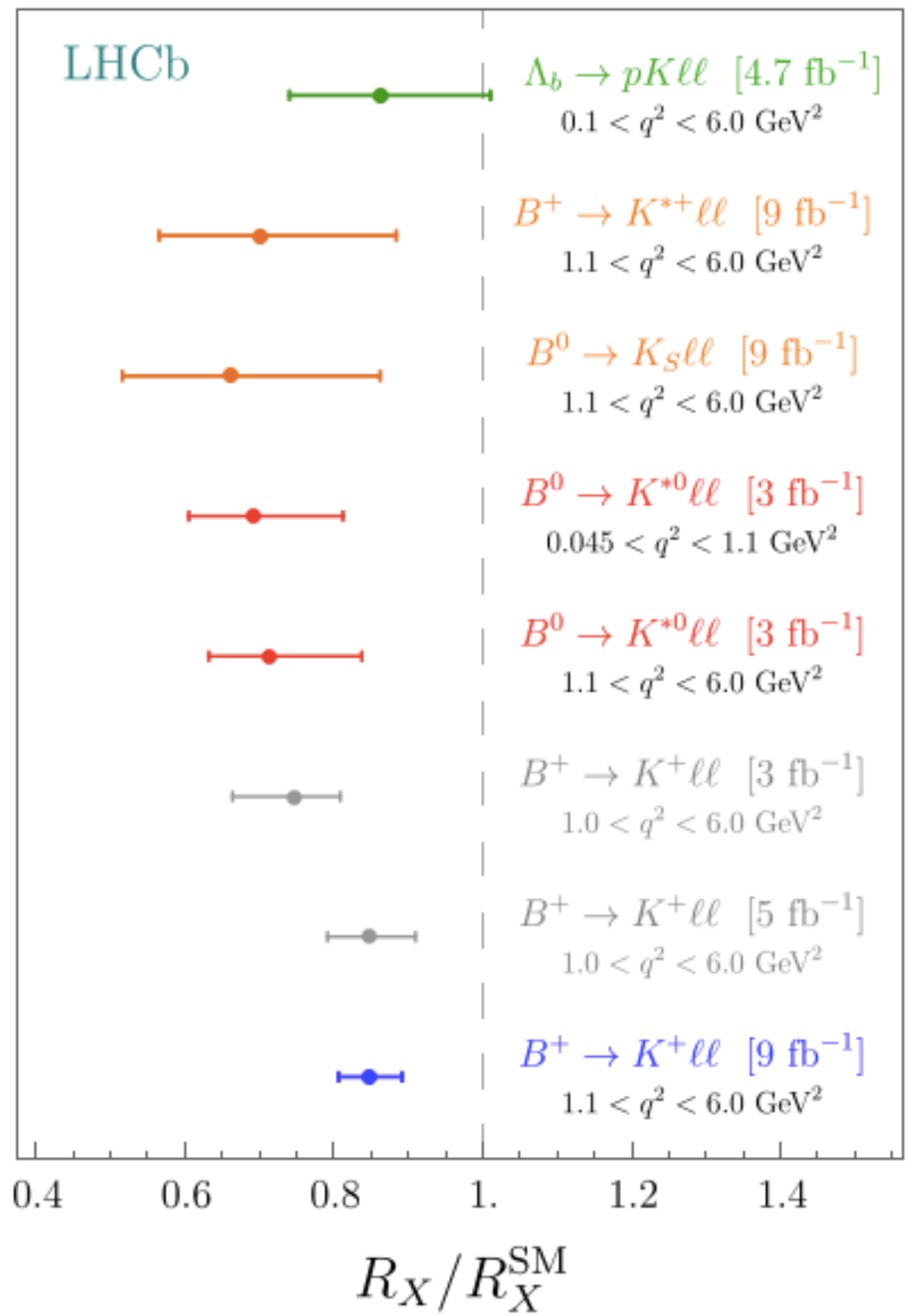
EFT - exclusive $b \to c \ell \nu$

Model	$g_{\text{eff}}^{b\to c\tau\bar{\nu}}(\mu = m_\Delta)$	$R_{D^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	g_{V_L}, $g_{S_L} = -4\, g_T$	✓
$R_2 = (3, 2, 7/6)$	$g_{S_L} = 4\, g_T$	✓
$S_3 = (\bar{3}, 3, 1/3)$	g_{V_L}	✗
$\dots$	$\dots$	$\dots$
$U_1 = (3, 1, 2/3)$	g_{V_L}, g_{S_R}	✓
$U_3 = (3, 3, 2/3)$	g_{V_L}	✗
$\dots$	$\dots$	$\dots$

$g_{V_L}(m_b)$	0.07 ± 0.02	$0.02/1$	✔
	± 0.05	$5.3/1$	✘
	± 0.06	$8.8/1$	✘
	± 0.01	$3.1/1$	✔
	± 0.07	$12.5/1$	✘
$g_{S_L} = -4 g_T \in \mathbb{R}$	0.16 ± 0.05	$2.0/1$	✔
$g_{S_L} = \pm 4 g_T \in i\,\mathbb{R}$	0.48 ± 0.08	$2.4/1$	✔

Main worry remain the hadronic uncertainties in the D^* case:
No clear LQCD info regarding the shapes of FFs
Keep also in mind the SD part of the soft photon problem is missing

MORE LFUV
need studying NP effects



MORE LFUV
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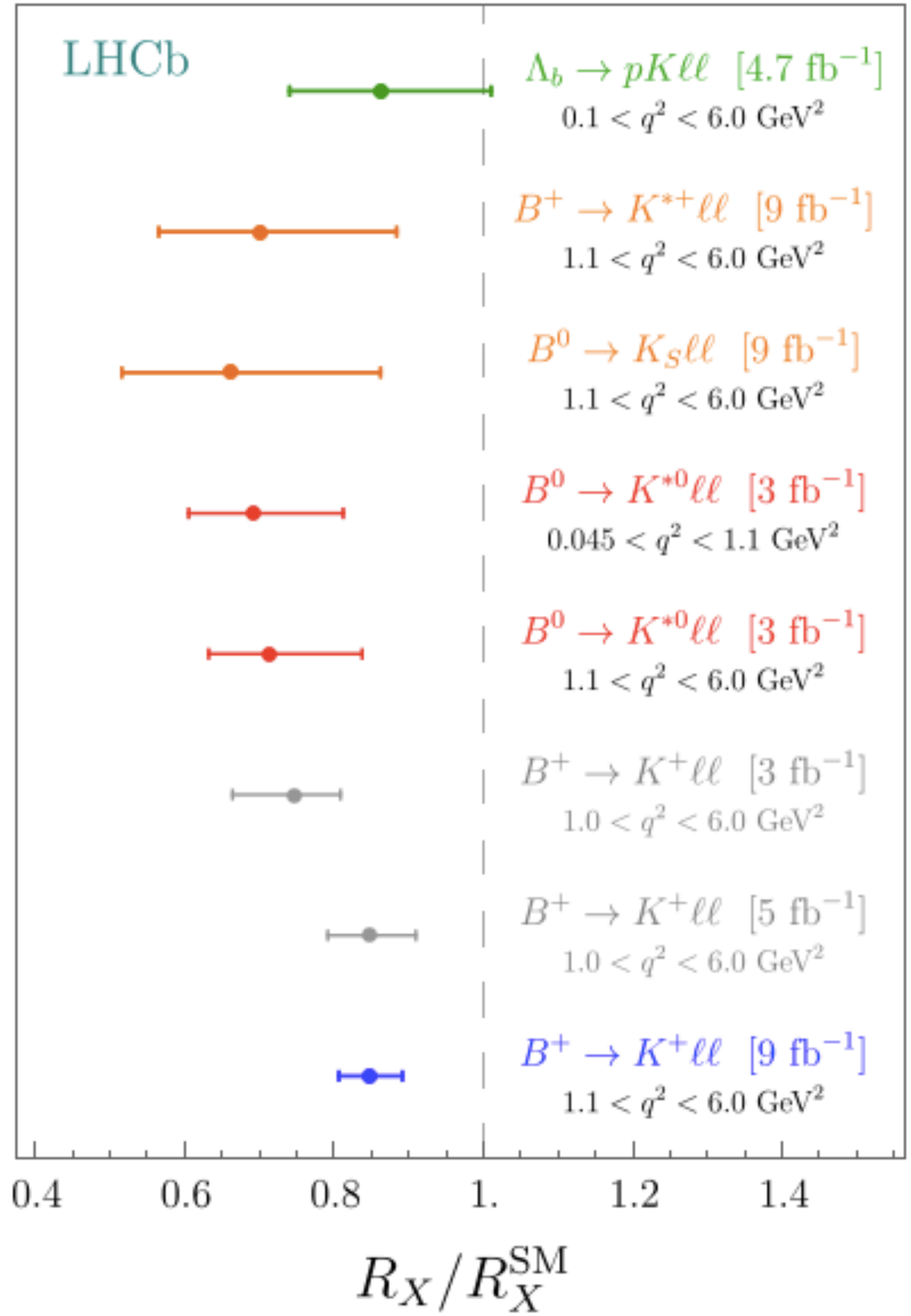


$$R_{K^*}^{[1.1,6]} = 0.71(10)^{\rm LHCb} \quad \text{vs} \quad R_{K^*}^{[1,6]} = 1.00(1)^{\rm SM}$$

$$R_{K}^{[1.1,6]} = 0.847(42)^{\rm LHCb} \quad \text{vs} \quad R_{K}^{[1,6]} = 1.00(1)^{\rm SM}$$

EFT - exclusive $b \to s\ell\ell$

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

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma^5 \ell)$$

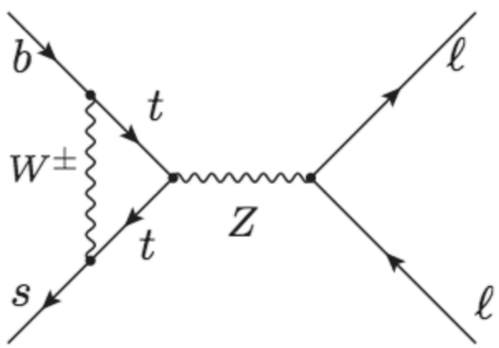
$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell) \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

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

$$\text{Exp} : \mathcal{B}(B_s \to \mu\mu) = (2.85 \pm 0.33) \times 10^{-9}$$

$$\text{SM} : \mathcal{B}(B_s \to \mu\mu) = (3.66 \pm 0.14) \times 10^{-9}$$

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



$\mathrm{Exp}: \mathcal{B}(B_s \to \mu\mu) = (2.85 \pm 0.33) \times 10^{-9}$

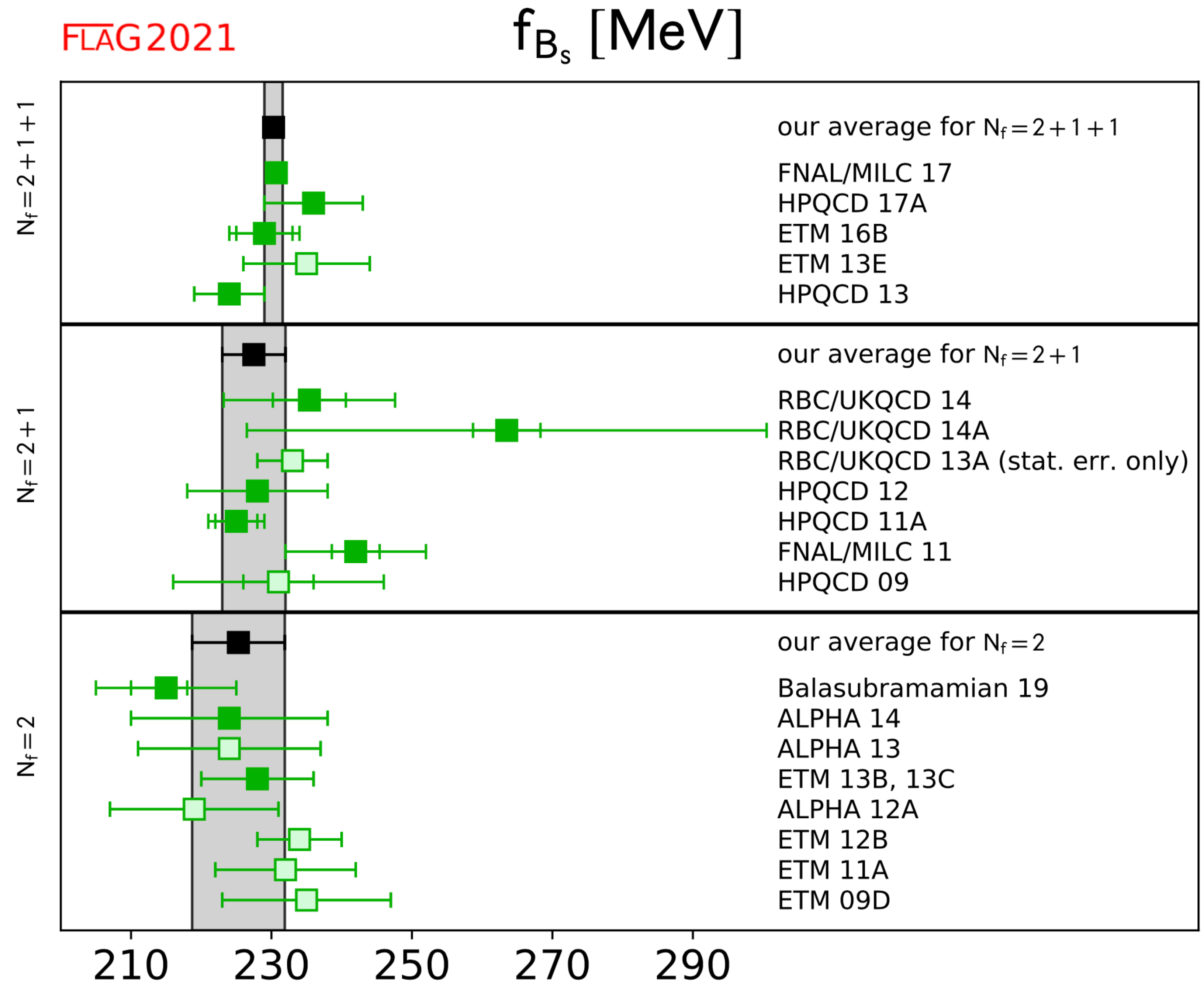
12%

$\mathrm{SM}: \mathcal{B}(B_s \to \mu\mu) = (3.66 \pm 0.14) \times 10^{-9}$

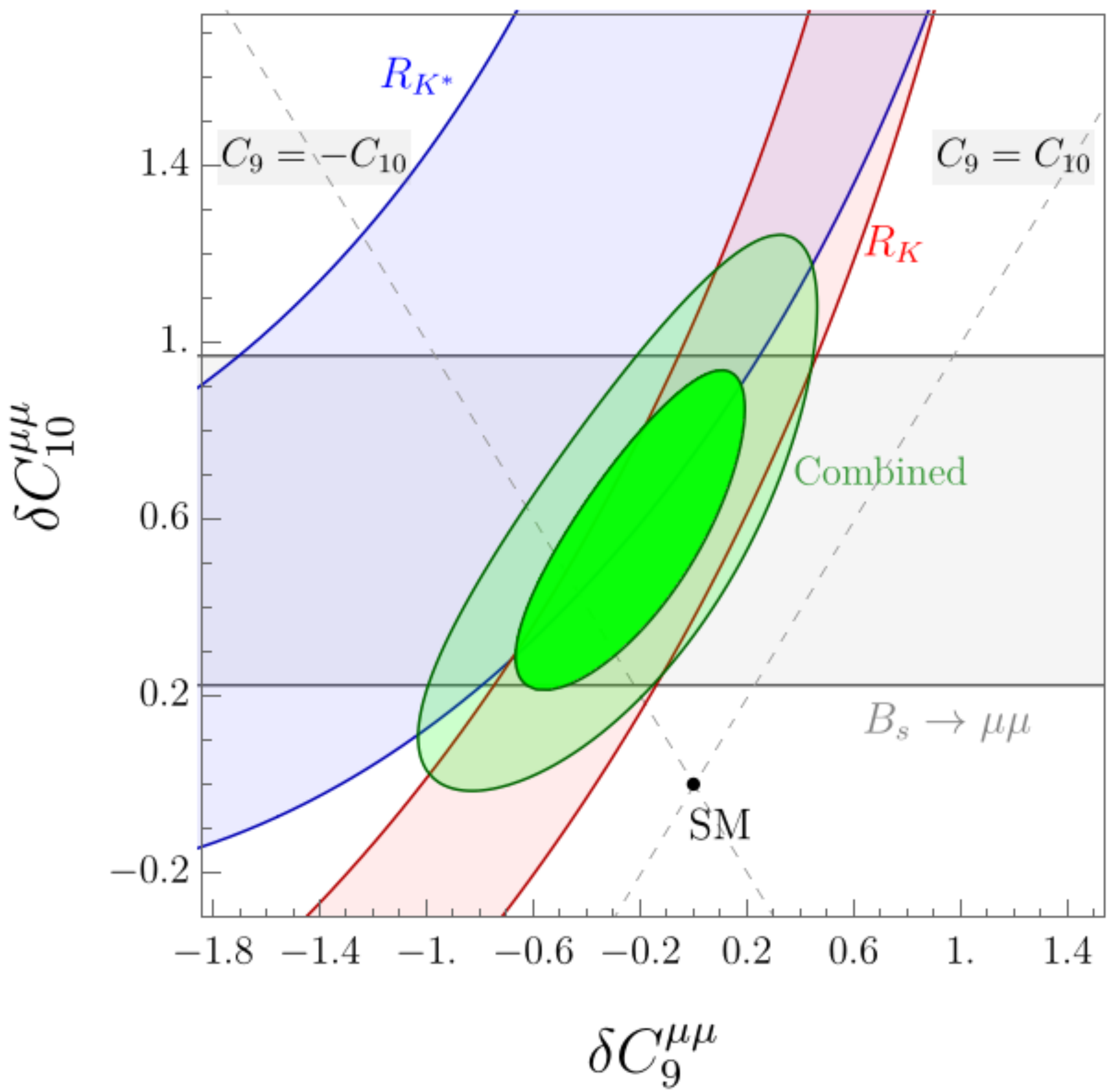
4%

$$O = \frac{1}{\Lambda^2} C_{ij} \bar{Q}_i \gamma^\mu Q_j H^\dagger D_\mu H$$

C_{ij}	1	$V_{ti}V_{tj}^*$
$B_s \to \mu^+\mu^-$	> 10 TeV	> 2.5 TeV
$K \to \pi\nu\bar{\nu}$	> 100 TeV	> 1.8 TeV



Fit to clean quantities: $\mathcal{B}(B_s \to \mu\mu)$ and $R_{K^{(*)}}$



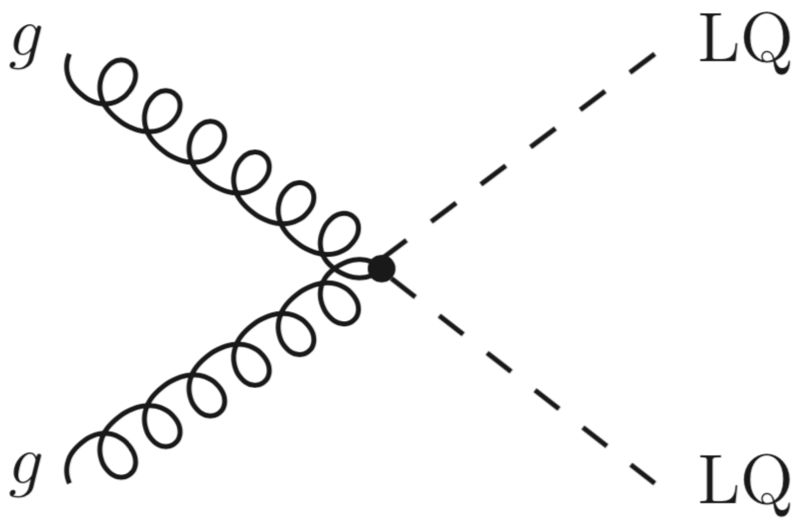
What LQ scenario?

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

N.B. U_1 is the only one to accommodate both!

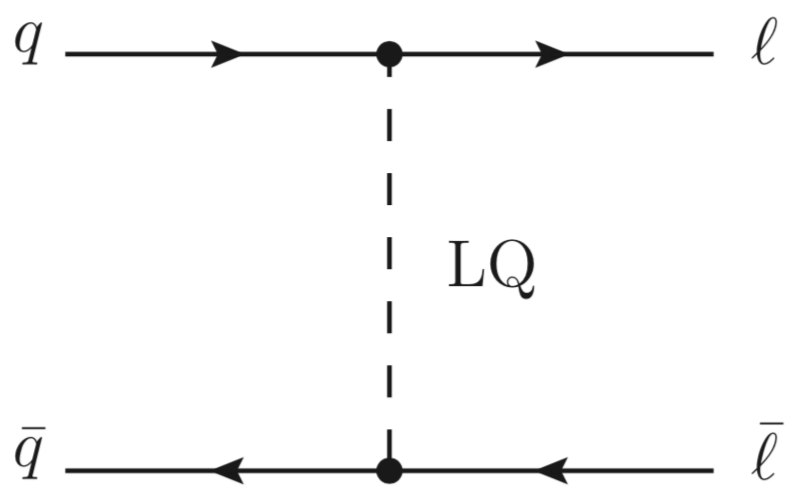
Observable
$b \to s\mu\mu$
$b \to c\tau\nu$
$\mathcal{B}(\tau \to \mu\phi)$
$\mathcal{B}(B \to \tau\nu)$
$\mathcal{B}(D_s \to \mu\nu)$
$\mathcal{B}(D_s \to \tau\nu)$
$r_K^{e/\mu}$
$r_K^{\tau/\mu}$
$R_D^{\mu/e}$

From direct searches
Atlas and CMS 2018-2021

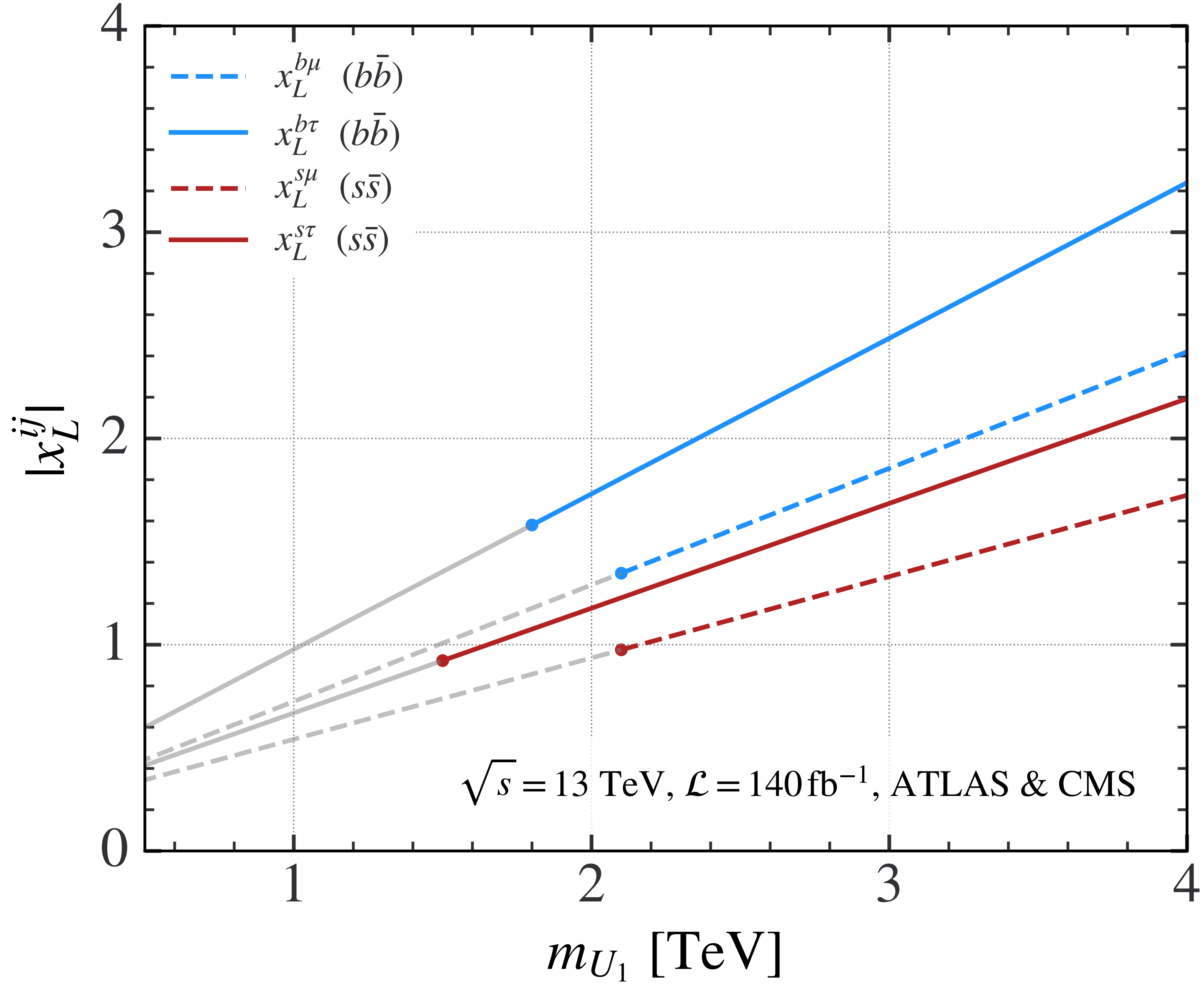


Decays	Scalar LQ limits	Vector LQ limits	$\mathcal{L}_{\rm int}$
$jj\,\tau\bar{\tau}$	–	–	–
$b\bar{b}\,\tau\bar{\tau}$	1.0 (0.8) TeV	1.5 (1.3) TeV	36 fb^{-1}
$t\bar{t}\,\tau\bar{\tau}$	1.4 (1.2) TeV	2.0 (1.8) TeV	140 fb^{-1}
$jj\,\mu\bar{\mu}$	1.7 (1.4) TeV	2.3 (2.1) TeV	140 fb^{-1}
$b\bar{b}\,\mu\bar{\mu}$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

From dilepton spectra at high p_T Atlas and CMS 2018-2021

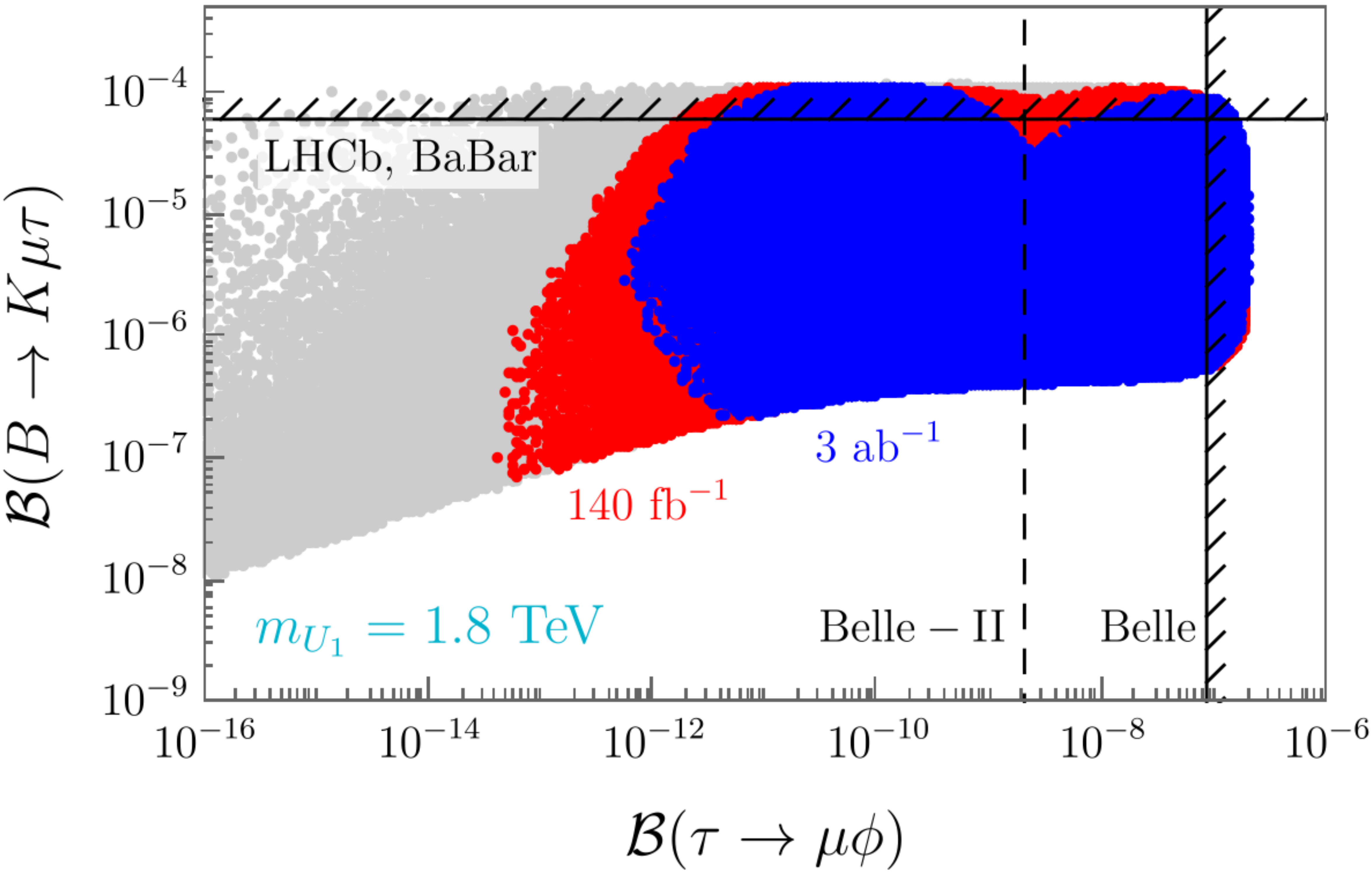


Example U1

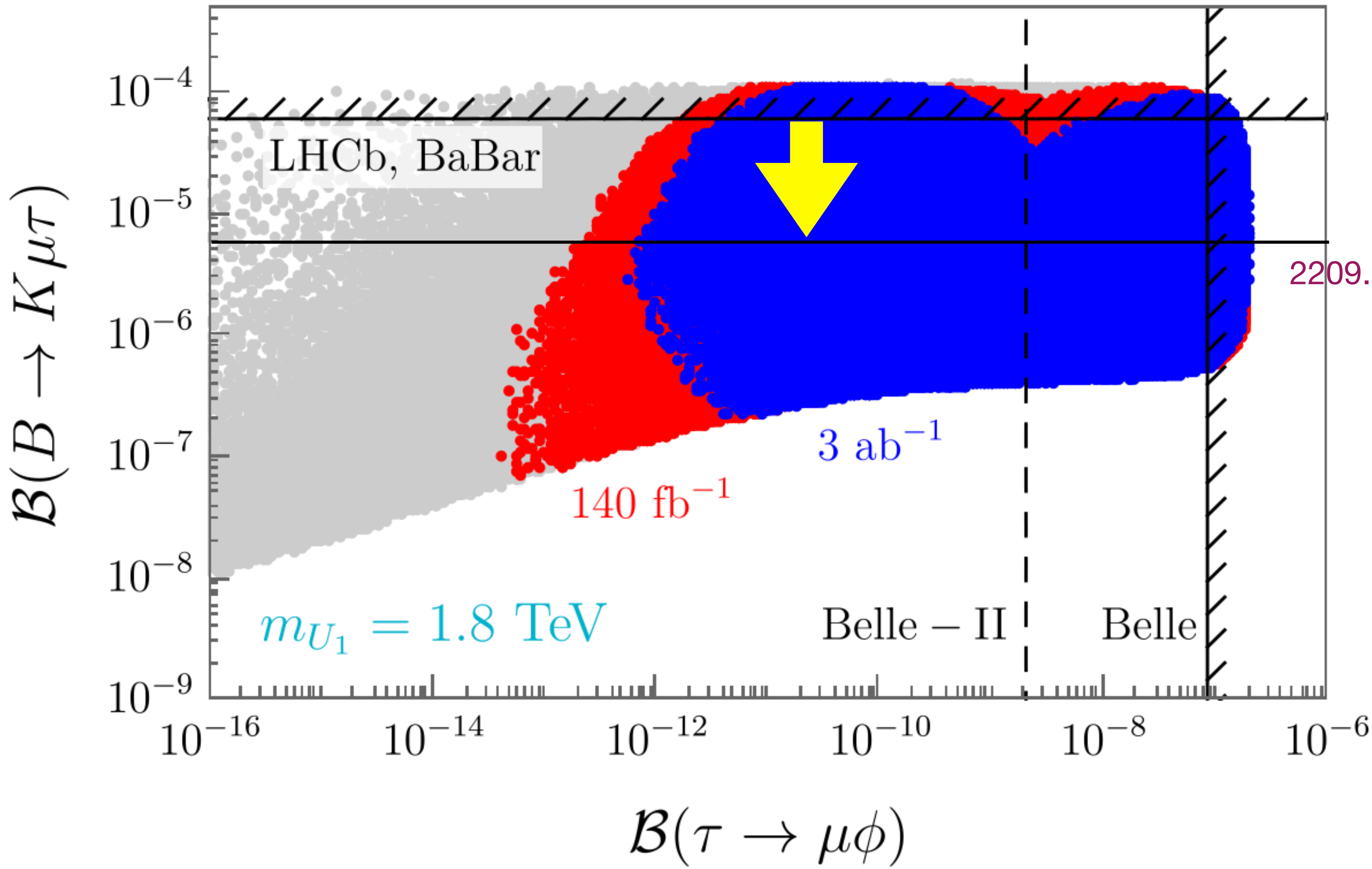


$$\mathcal{L}_{U_1} = x_L^{ij}\,\overline{Q}_i \gamma_\mu L_j\, U_1^\mu + x_R^{ij}\,\overline{d}_{R_i}\gamma_\mu \ell_{Rj} U_1^\mu + \text{h.c.}$$

LFV predictions



LFV predictions



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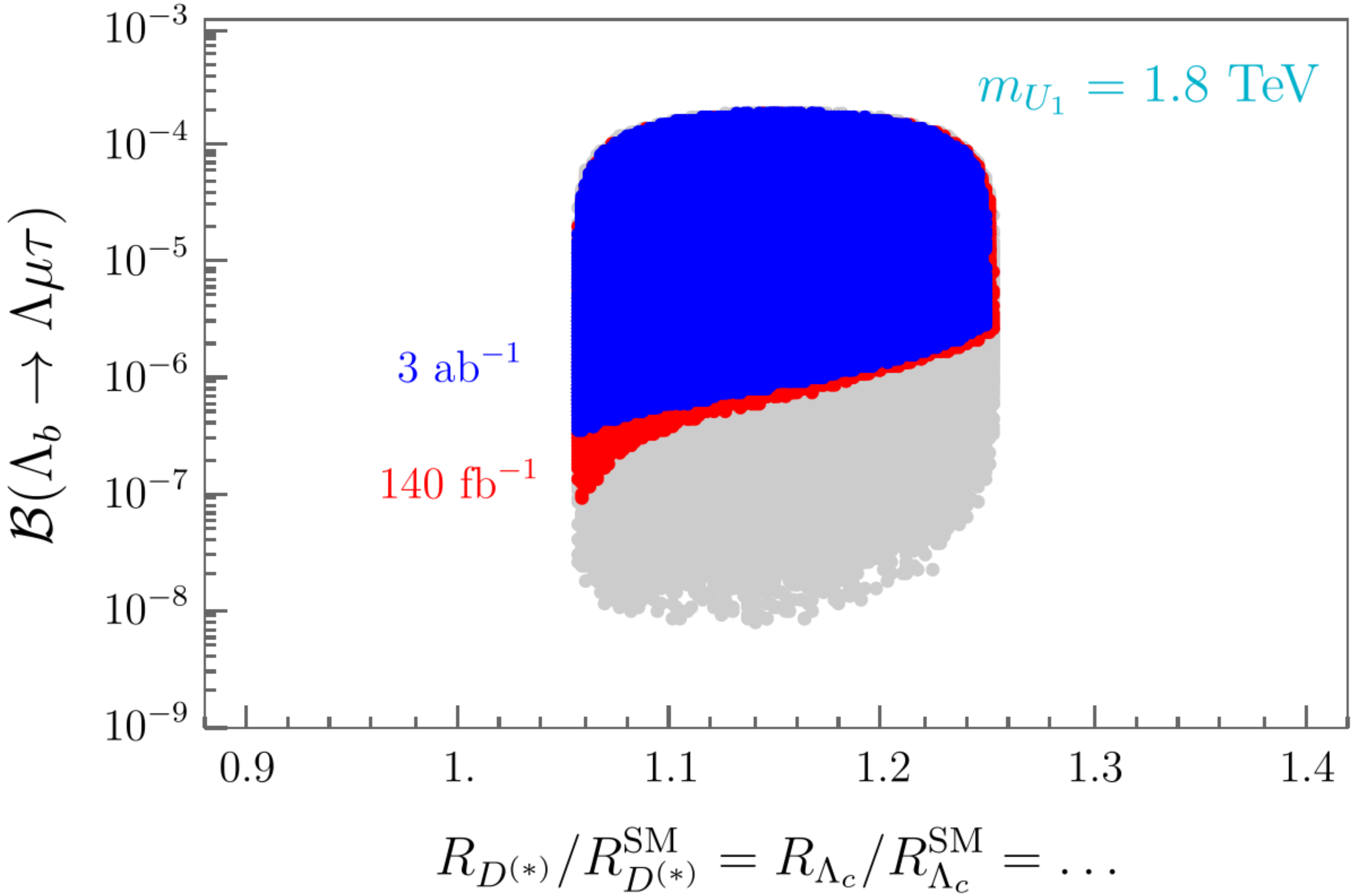
LFV predictions



- Way to go 1: Combine two scalar LQs [S_1 with S_3, or R_2 with S_3]
- Way to go 2: Vector LQ (U_1)
  Non-renormalizable and thus requires UV-completion which can be an opportunity to tackle the hierarchy problem!

Concerning R2

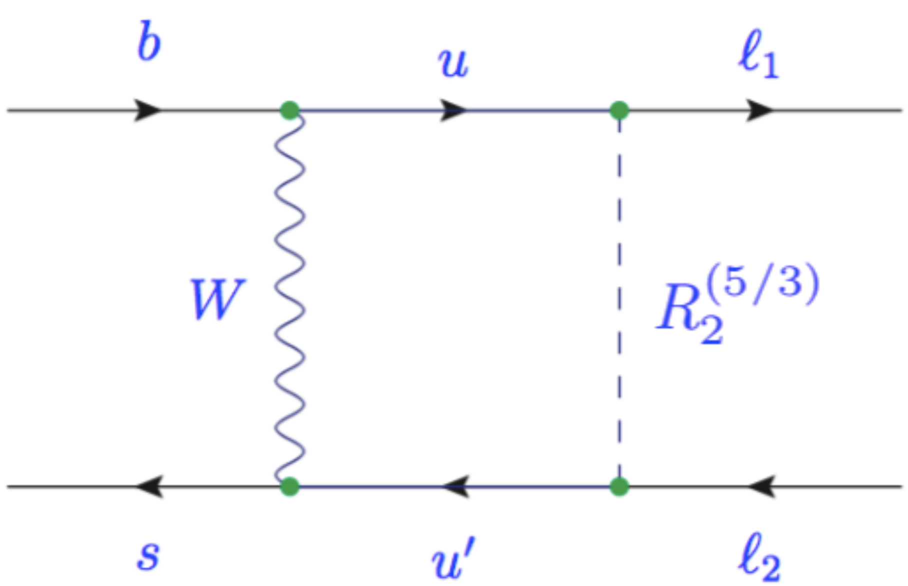
Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗	✗
$R_2 = (3, 2, 7/6)$	✓	✓*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

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

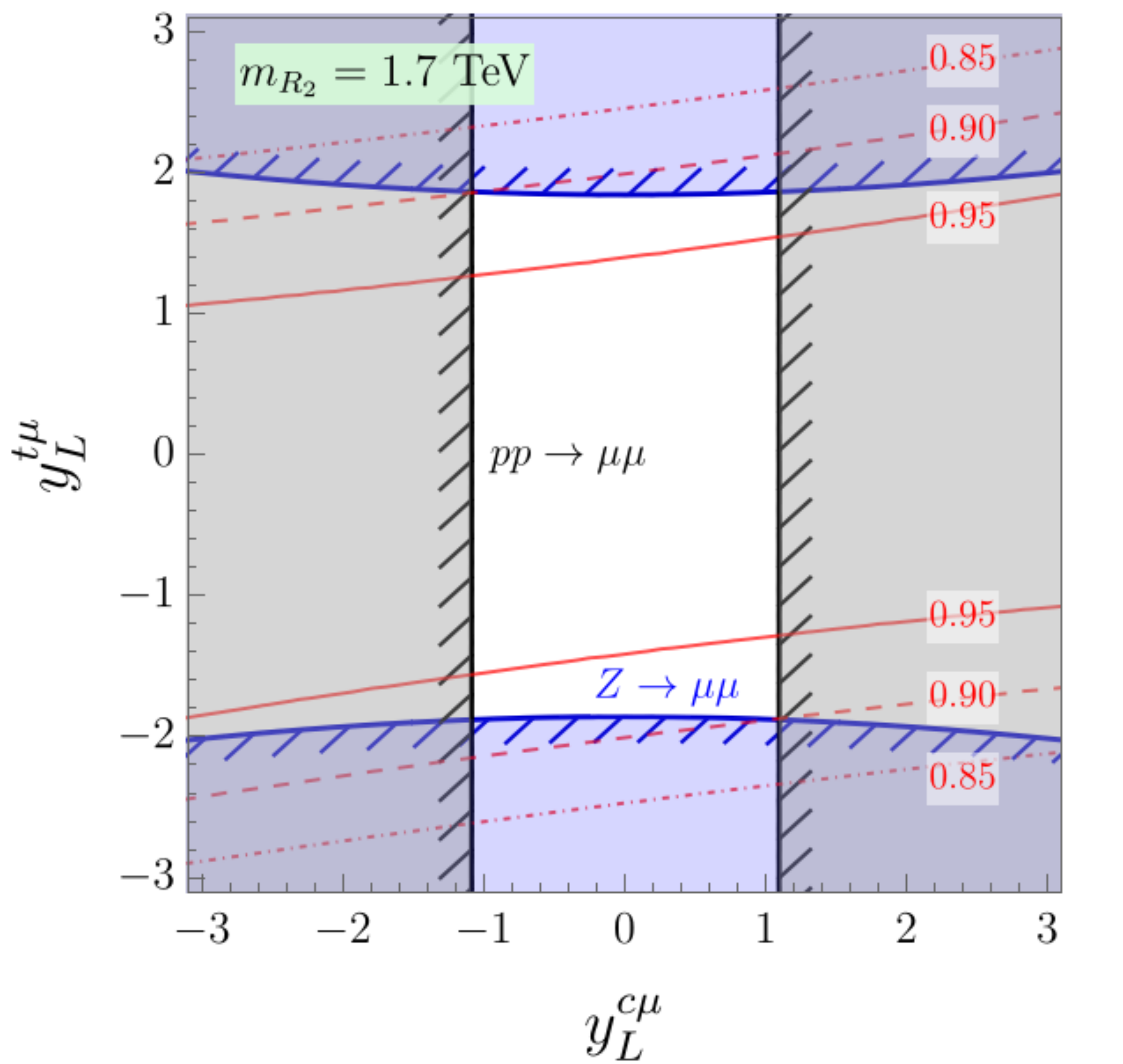
$$C_9^{kl} = C_{10}^{kl} \overset{\text{tree}}{=} -\frac{\pi v^2}{2V_{tb}V_{ts}^*\alpha_{\text{em}}}\frac{y_R^{sl}\left(y_R^{bk}\right)^*}{m_{R_2}^2}$$

$$C_9^{kl} = -C_{10}^{kl} \overset{\text{loop}}{=} \sum_{u,u'\in\{u,c,t\}} \frac{V_{ub}V_{u's}^*}{V_{tb}V_{ts}^*} y_L^{u'k}\left(y_L^{ul}\right)^* \mathcal{F}(x_u, x_{u'})$$

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



$R_K \approx R_{K^*}$



S_1 & S_3 Model(s)

- In flavor basis

$$\mathcal{L}_{\rm Yuk} \supset \left(y^L_{S_1}\right)_{ij} \bar{Q}^C_i i\tau_2 L_j S_1 + \left(y^L_{S_3}\right)_{ij} \bar{Q}^C_i i\tau_2 L_j (\vec{\tau}\cdot\vec{S}_3) + \text{h.c.}$$

$$S_1 = (\bar{3}, 1, 1/3), \quad S_3 = (\bar{3}, 3, 1/3)$$

- Specifying models

M1:
1703.09226

$$y^L_{S_1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda_{s\mu} & \lambda_{s\tau} \\ 0 & \lambda_{b\mu} & \lambda_{b\tau} \end{pmatrix}, \qquad y^L_{S_3} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda_{s\mu} & \lambda_{s\tau} \\ 0 & -\lambda_{b\mu} & -\lambda_{b\tau} \end{pmatrix}$$

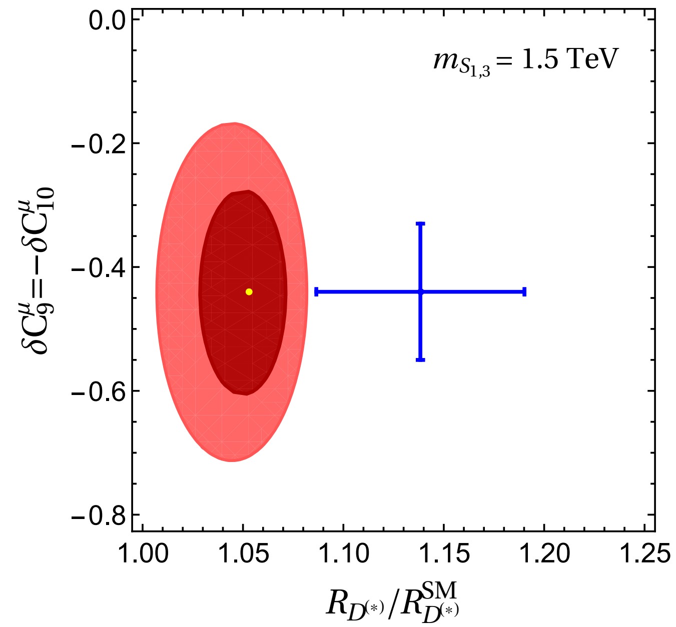
M2:
1706.07808

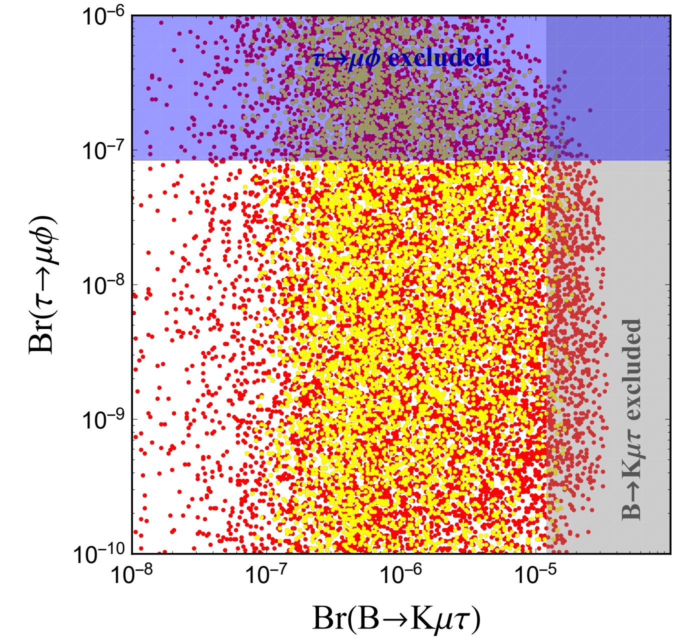
$$y^L_{S_1} = g_{S_1} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \beta_{s\mu} & \beta^{S_1}_{s\tau} \\ 0 & \beta_{b\mu} & 1 \end{pmatrix}, \qquad y^L_{S_3} = g_{S_3} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \beta_{s\mu} & \beta^{S_3}_{s\tau} \\ 0 & \beta_{b\mu} & 1 \end{pmatrix}$$

M3:
2008.09548

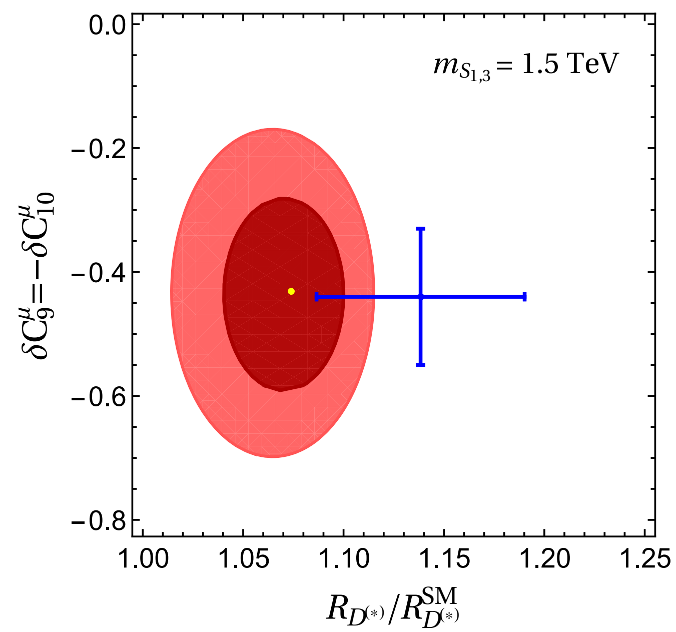
$$y^L_{S_1} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y^{S_1}_{s\tau} \\ 0 & 0 & y^{S_1}_{b\tau} \end{pmatrix}, \qquad y^L_{S_3} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y^{S_3}_{s\mu} & y^{S_3}_{s\tau} \\ 0 & y^{S_3}_{b\mu} & y^{S_3}_{b\tau} \end{pmatrix}$$

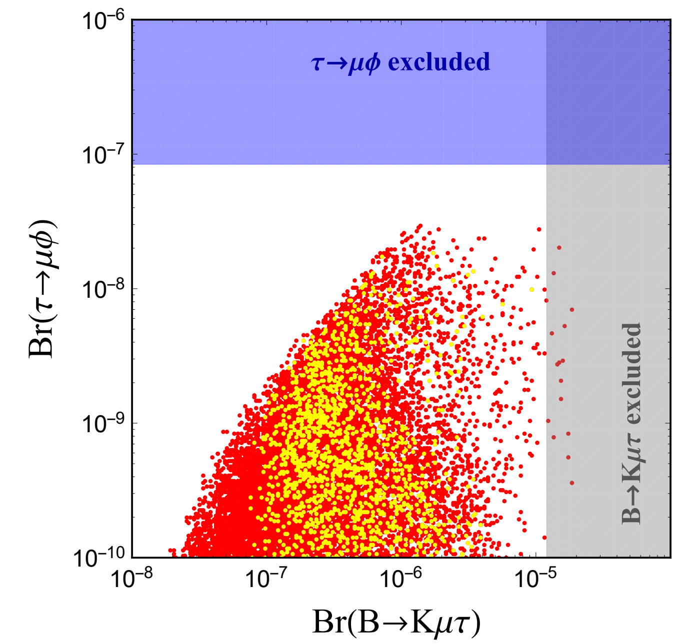
M1:



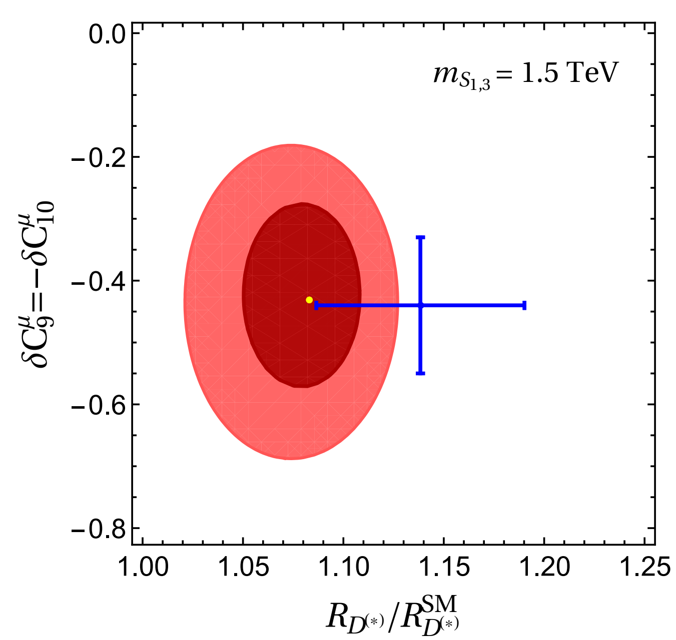


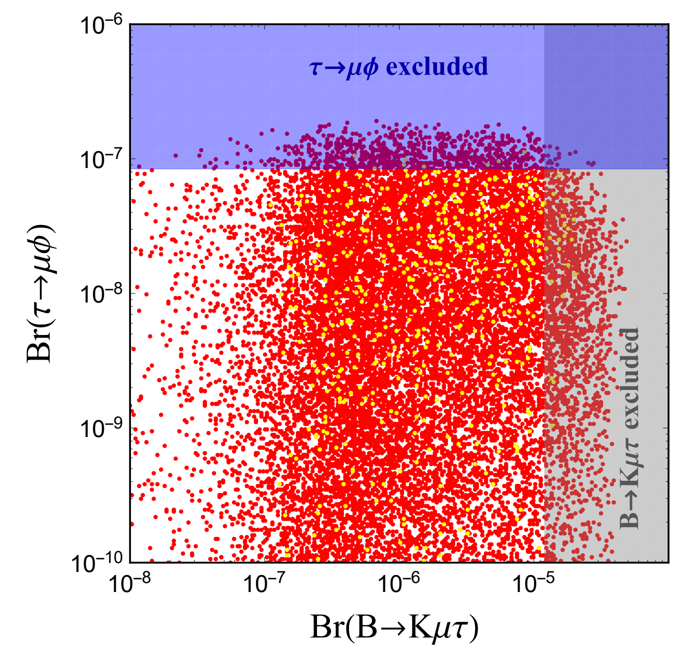
M2:





M3:





Adding RH couplings considered in 2008.09548 and 1912.04224

S_3 & R_2 Model

1806.05689

- In flavor basis

$$\mathcal{L} \supset y_R^{ij}\, \bar{Q}_i \ell_{Rj} R_2 + y_L^{ij}\, \bar{u}_{Ri} L_j \widetilde{R}_2^\dagger + y^{ij}\, \bar{Q}_i^C i\tau_2 (\tau_k S_3^k) L_j + \text{h.c.}$$

$$R_2 = (3, 2, 7/6),\ S_3 = (\bar{3}, 3, 1/3)$$

- In mass-eigenstates basis

$$\begin{aligned}\mathcal{L} \supset\ & (V_{\text{CKM}}\, y_R\, E_R^\dagger)^{ij}\, \bar{u}'_{Li} \ell'_{Rj} R_2^{(5/3)} + (y_R\, E_R^\dagger)^{ij}\, \bar{d}'_{Li} \ell'_{Rj} R_2^{(2/3)} \\ & + (U_R\, y_L\, U_{\text{PMNS}})^{ij}\, \bar{u}'_{Ri} \nu'_{Lj} R_2^{(2/3)} - (U_R\, y_L)^{ij}\, \bar{u}'_{Ri} \ell'_{Lj} R_2^{(5/3)} \\ & - (y\, U_{\text{PMNS}})^{ij}\, \bar{d}'^C_{Li} \nu'_{Lj} S_3^{(1/3)} - \sqrt{2}\, y^{ij}\, \bar{d}'^C_{Li} \ell'_{Lj} S_3^{(4/3)} \\ & + \sqrt{2} (V_{\text{CKM}}^*\, y\, U_{\text{PMNS}})_{ij}\, \bar{u}'^C_{Li} \nu'_{Lj} S_3^{(-2/3)} - (V_{\text{CKM}}^*\, y)_{ij}\, \bar{u}'^C_{Li} \ell'_{Lj} S_3^{(1/3)} + \text{h.c.}\end{aligned}$$

and assume

$$\underline{y_R = y_R^T \qquad y = -y_L}$$

$$y_R\, E_R^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_R^{b\tau} \end{pmatrix},\quad U_R\, y_L = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_L^{c\mu} & y_L^{c\tau} \\ 0 & 0 & 0 \end{pmatrix},\quad U_R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

Parameters: m_{R_2}, m_{S_3}, $y_R^{b\tau}$, $y_L^{c\mu}$, $y_L^{c\tau}$ and θ

Embedding to SU(5) GUT feasible

Effective Lagrangian at $\mu \approx m_{\rm LQ}$:

- $b \to c\tau\bar{\nu}$: **NB**. $\Lambda_{\rm NP}/g_{\rm NP} \approx 1$ TeV

$$\propto \frac{y_L^{c\tau}\, y_R^{b\tau\,*}}{m_{R_2}^2}\left[(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + \frac{1}{4}(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L)\right] + \dots$$

- $b \to s\mu\mu$: **NB**. $\Lambda_{\rm NP}/g_{\rm NP} \approx 30$ TeV

$$\propto \sin 2\theta\, \frac{|y_L^{c\mu}|^2}{m_{S_3}^2}\,(\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$$

- Δm_{B_s}:

$$\propto \sin^2 2\theta\, \frac{\left[\left(y_L^{c\mu}\right)^2 + \left(y_L^{c\tau}\right)^2\right]^2}{m_{S_3}^2}(\bar{s}_L \gamma^\mu b_L)^2$$

⇒ Suppression mechanism of $b \to s\mu\mu$ wrt $b \to c\tau\bar{\nu}$ for small $\sin 2\theta$.

⇒ Phenomenology suggests $\theta \approx \pi/2$ and $y_R^{b\tau}$ complex

Effective Lagrangian at $\mu \approx m_{\rm LQ}$:

- $b \to c\tau\bar{\nu}$: **NB**. $\Lambda_{\rm NP}/g_{\rm NP} \approx 1$ TeV

$$\propto \frac{y_L^{c\tau}\, y_R^{b\tau\,*}}{m_{R_2}^2}\left[(\bar{c}_R b_L)(\bar{\tau}_R \nu_L) + \frac{1}{4}(\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_L)\right] + \dots$$

- $b \to s\mu\mu$: **NB**. $\Lambda_{\rm NP}/g_{\rm NP} \approx 30$ TeV

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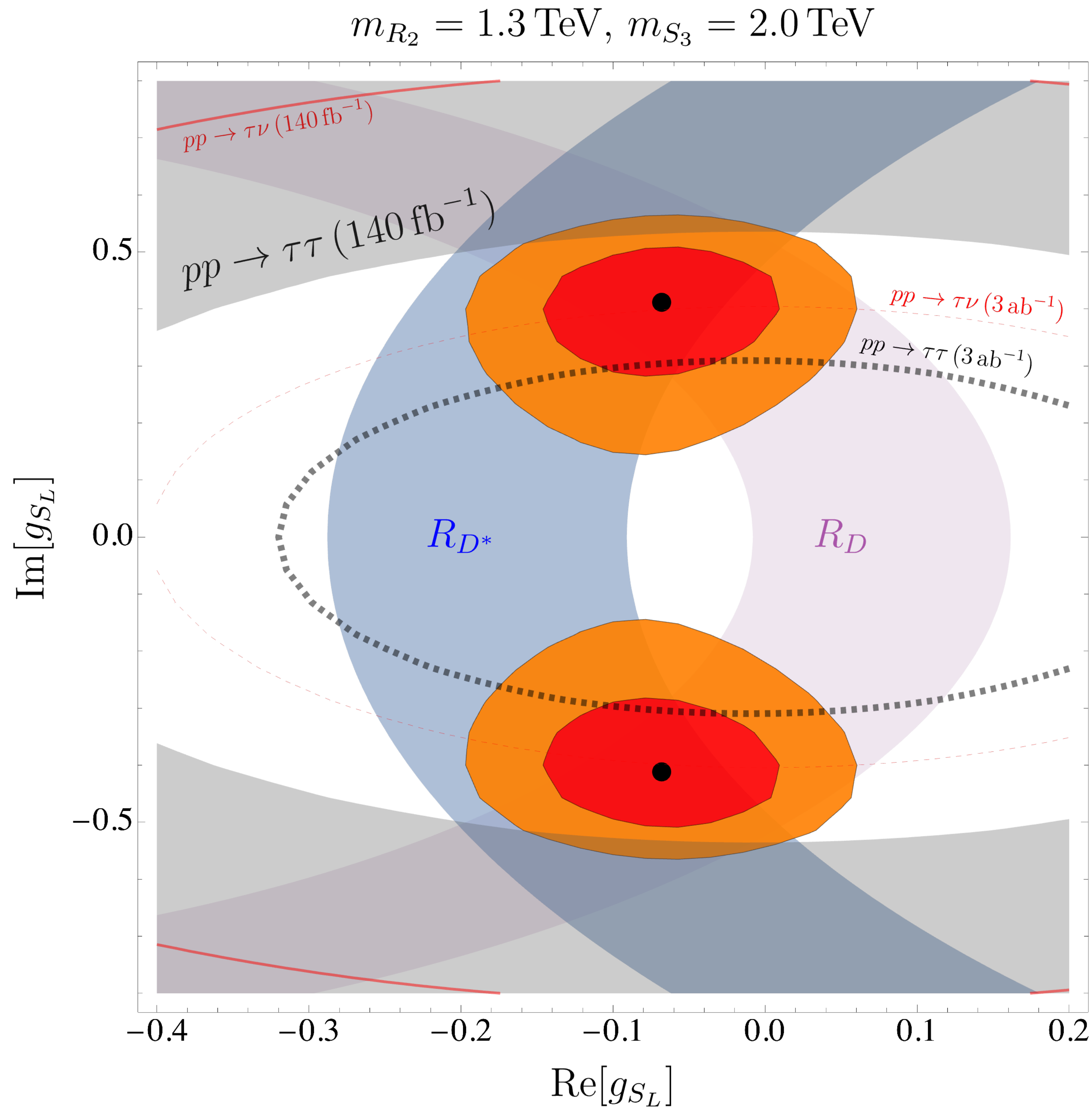
$\Rightarrow$ Suppression mechanism of $b \to s\mu\mu$ wrt $b \to c\tau\bar{\nu}$ for small $\sin 2\theta$.

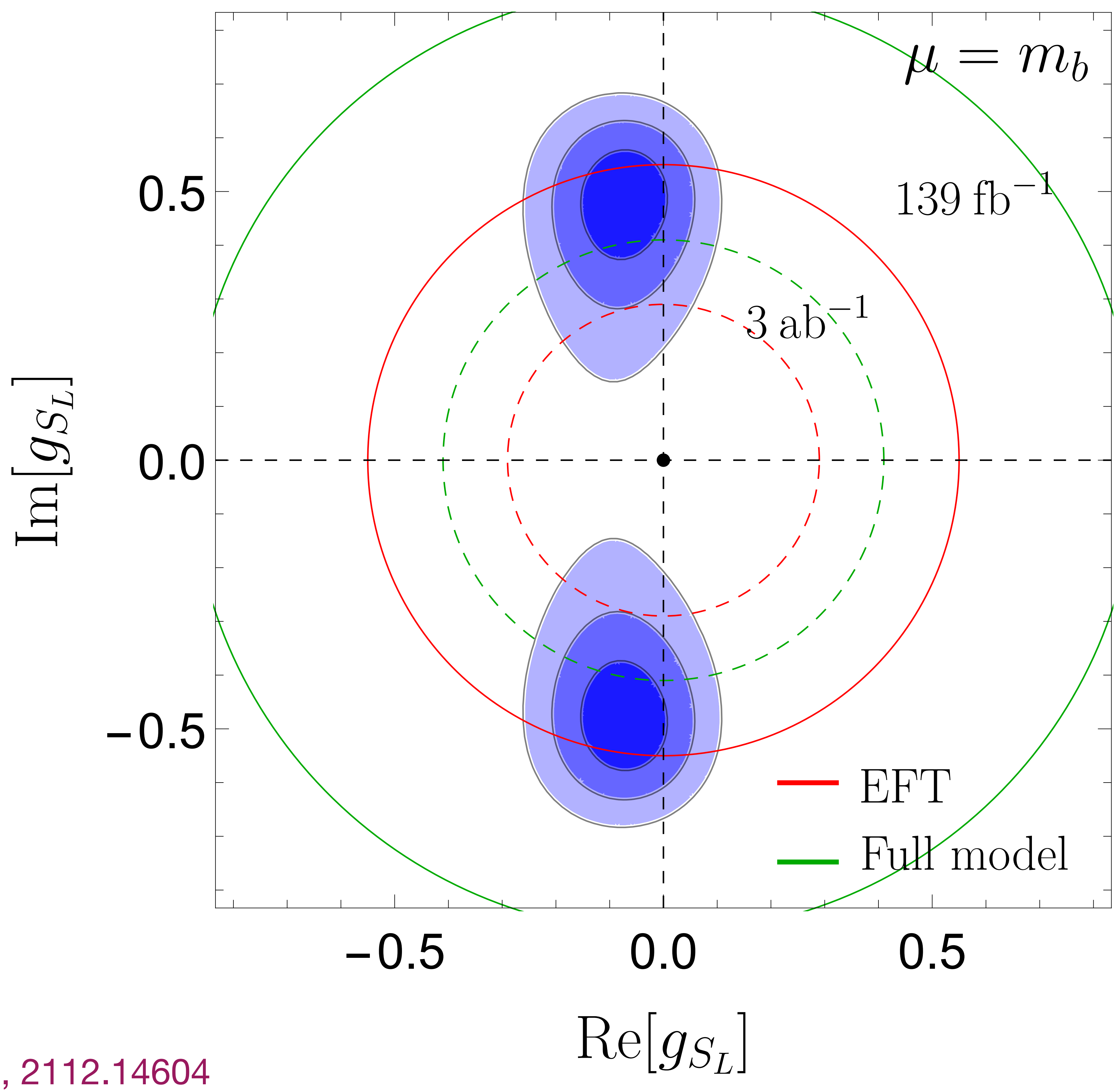
$\Rightarrow$ Phenomenology suggests $\theta \approx \pi/2$ and $y_R^{b\tau}$ complex

2206.09717



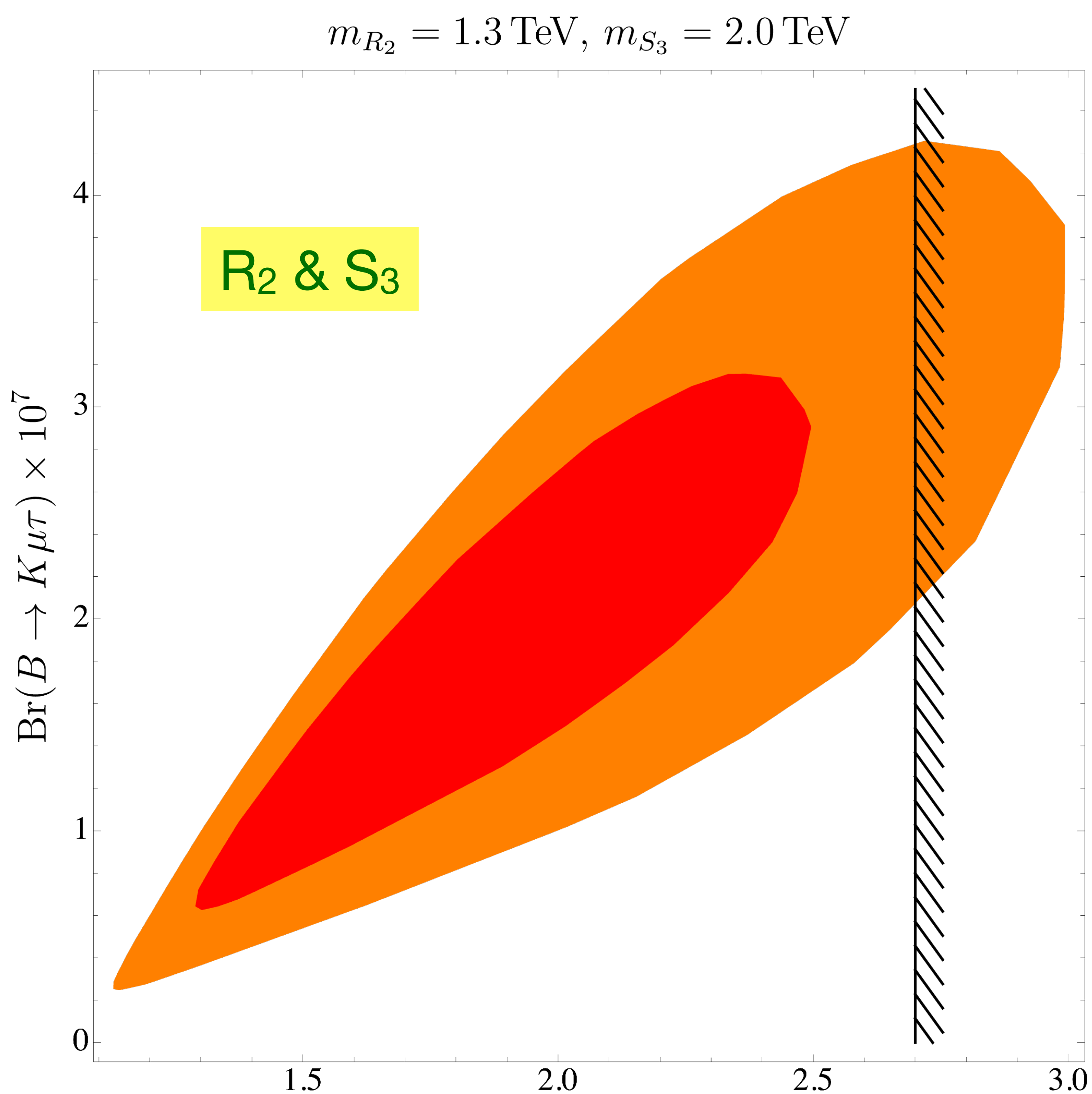
Neutrinos incorporated in 2004.07880

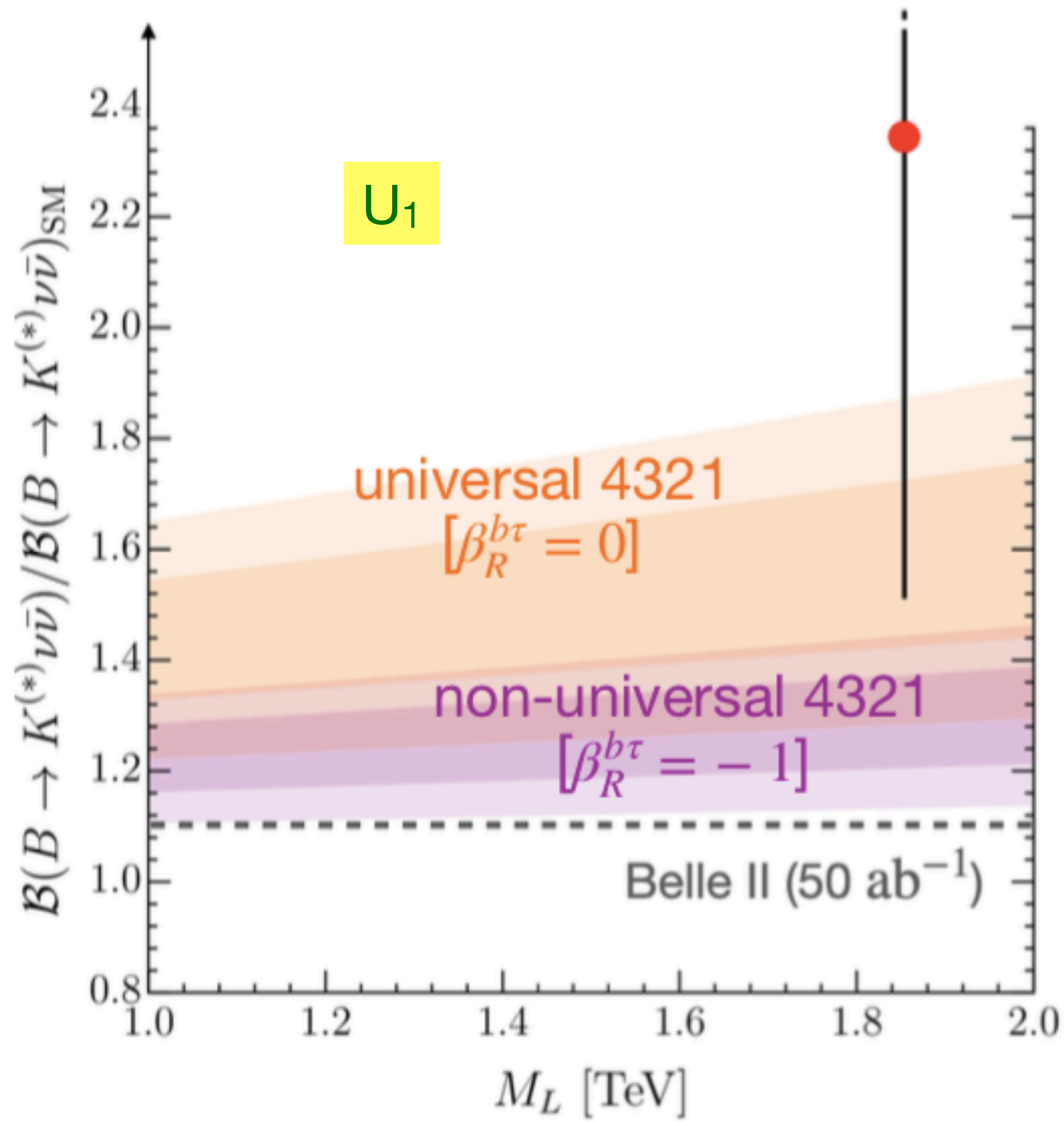
Bounds derived from $pp \to \tau\nu$ at high p_T not useful



2111.04748, 2112.14604

Interesting pheno, ex.





$$R^{(*)}_{\nu\nu} = \frac{\mathcal{B}(B \to K^{(*)}\nu\nu)}{\mathcal{B}(B \to K^{(*)}\nu\nu)^{\mathrm{SM}}}$$

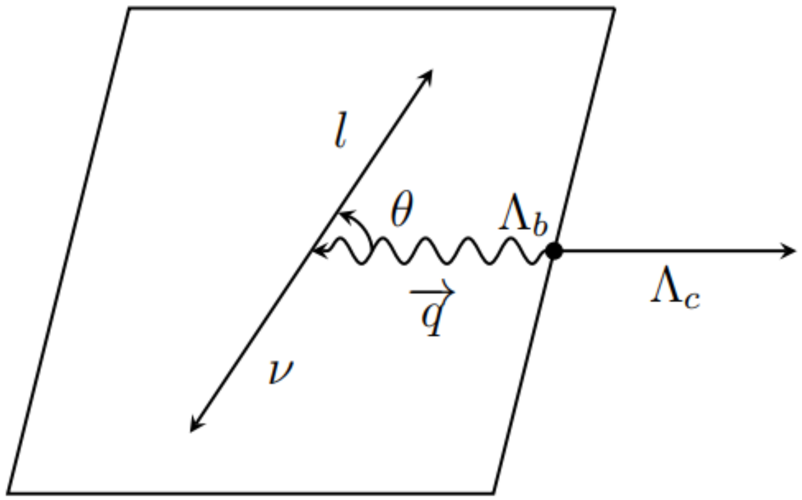
2206.09717
1806.05689

2103.16558
2009.11296

Belle-II results imminent

Angular observables can help disentangling among various NP scenarios

Many works with mesons: $\mathbf{B} \to \mathbf{D}\ell\bar{\nu}$ $\mathbf{B} \to \mathbf{D}^*\ell\bar{\nu}$



Let us now play with baryons:

$$\frac{d^2\Gamma}{dq^2 d\cos\theta} = \frac{\sqrt{\lambda_{\Lambda_b\Lambda_c}(q^2)}}{1024\pi^3 M_{\Lambda_b}^3}\left(1 - \frac{m_l^2}{q^2}\right)\sum_{\lambda_l\lambda_b\lambda_c}\left|\mathcal{M}_{\lambda_c}^{(3)\lambda_b\lambda_l}\right|^2$$

$$\frac{\mathrm{d}^2\Gamma(\Lambda_b \to \Lambda_c^{\lambda_c}\ell^{\lambda_l}\nu)}{\mathrm{d}q^2\mathrm{d}\cos\theta} = a_{\lambda_c}^{\lambda_l}(q^2) + b_{\lambda_c}^{\lambda_l}(q^2)\cos\theta + c_{\lambda_c}^{\lambda_l}(q^2)\cos^2\theta$$

12-2=10 observables

Each $a_{\lambda_c}^{\lambda_l}(q^2)$, $b_{\lambda_c}^{\lambda_l}(q^2)$, $c_{\lambda_c}^{\lambda_l}(q^2)$ is a function of kinematics, form factors and the NP couplings g_{V_L}, g_{S_L}, g_{S_R}, g_T.

Angular observables $\Lambda_b \to \Lambda_c \ell \bar{\nu}$

1907.12554 1908.02328 1909.10769 1702.02243 1502.04864 2209.13409

Three powerful observables:

- $$\mathcal{A}_{\rm fb}(q^2) = \frac{1}{\Gamma}\left[\int_0^1 - \int_{-1}^0\right] \frac{d\Gamma}{d\cos\theta} d\cos\theta$$

- $$\mathcal{A}_{\pi/3}(q^2) = \frac{1}{\Gamma}\left[\int_0^{\pi/3} + \int_{2\pi/3}^{\pi} - \int_{\pi/3}^{2\pi/3}\right] \frac{d\Gamma}{d\cos\theta} \sin\theta\, d\theta$$

- $$\mathcal{A}_{\lambda}(q^2) = \frac{1}{\Gamma}\left[\frac{d\Gamma^+}{dq^2} - \frac{d\Gamma^-}{dq^2}\right]$$

Examples:

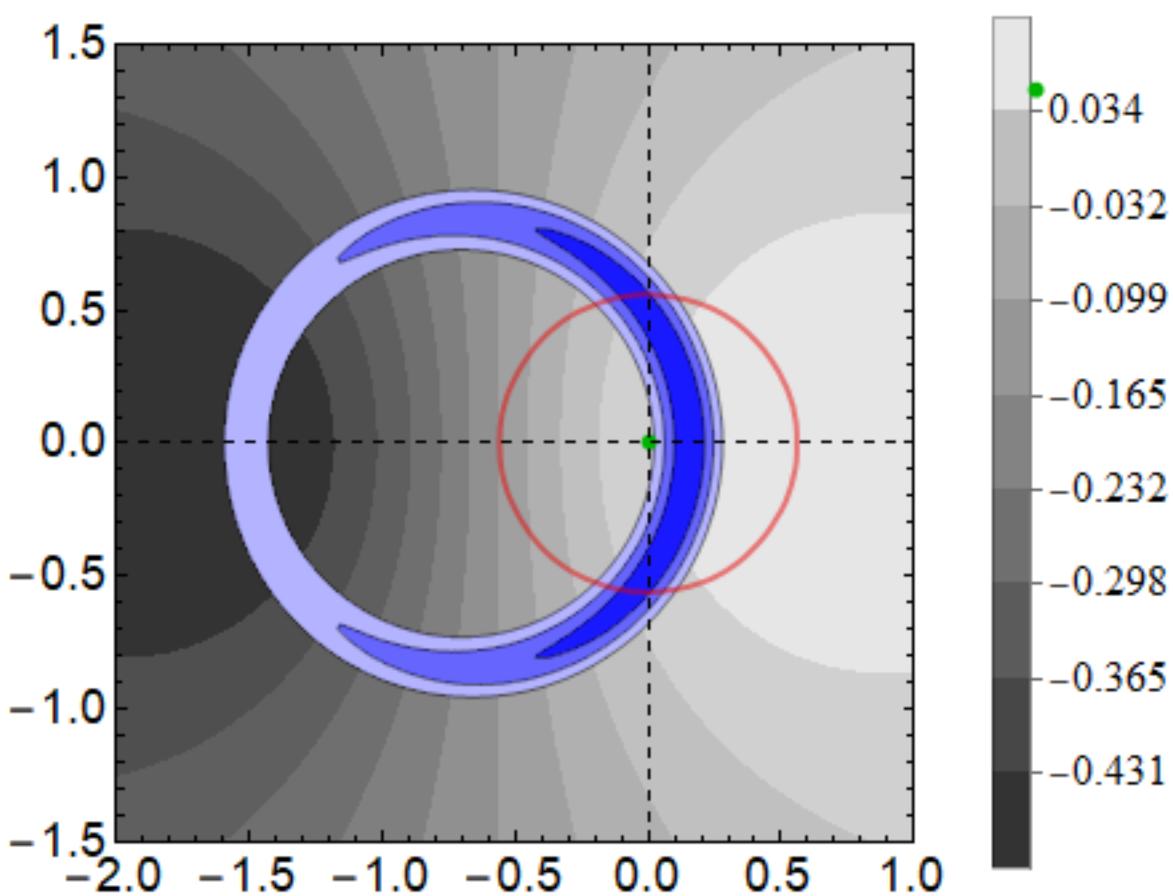
$U_1 : g_{V_L}$ $\quad R_2 : g_{S_L} = 4\, g_T$ $\quad S_1 : g_{S_L} = -4\, g_T$

Angular observables $\Lambda_b \to \Lambda_c \ell \bar{\nu}$

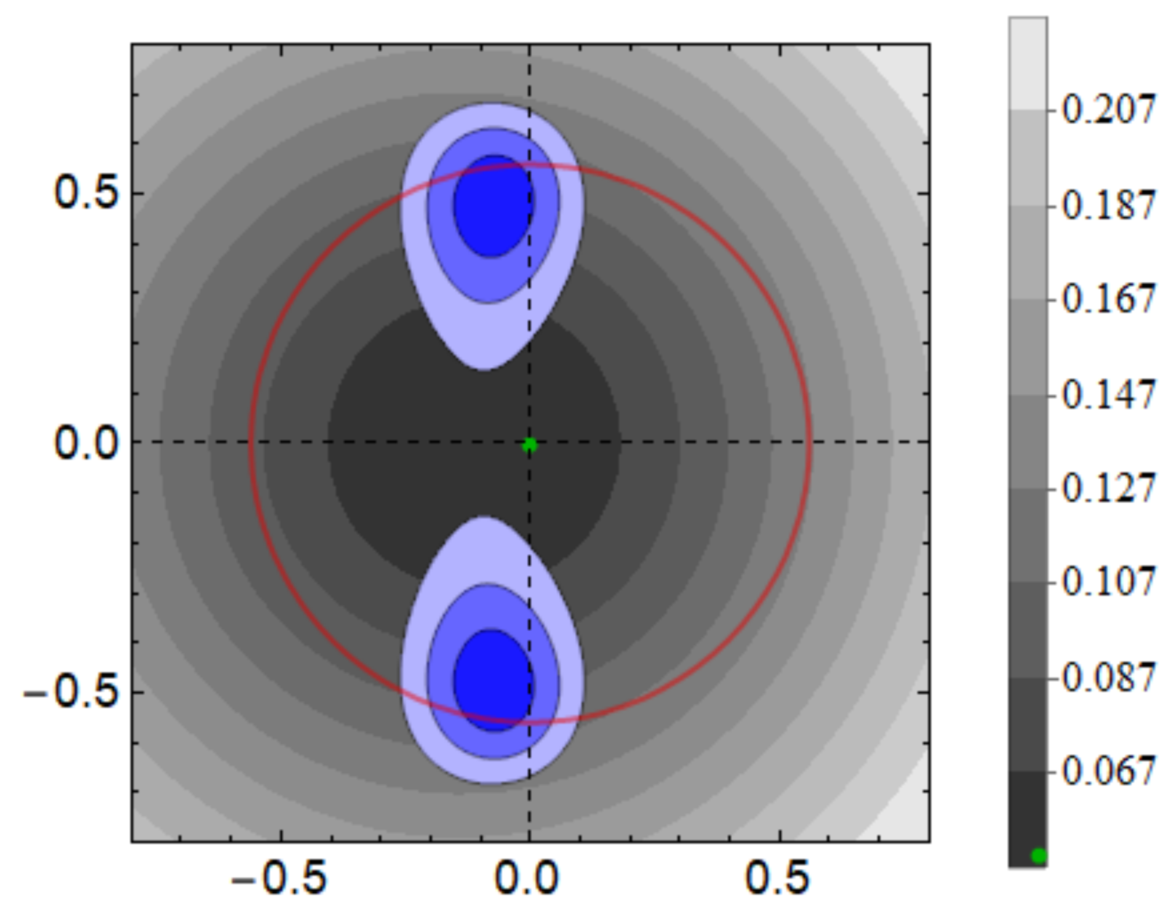
2209.13409

Three powerful observables:

$$\langle \mathcal{A}_{\rm fb}^{\tau} \rangle$$



S_1



R_2

$\Lambda_b \longrightarrow \Lambda_c(\to \Lambda\pi)\ell\nu$

2209.13409

NB: $\mathcal{B}(\Lambda_c \to \Lambda\pi) = 1.30(7)\%$ or $\mathcal{B}(\Lambda_c \to pK_S) = 1.59(8)\%$

Many more angular observables and checking on Im[g_x] ≠ 0

...

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

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

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

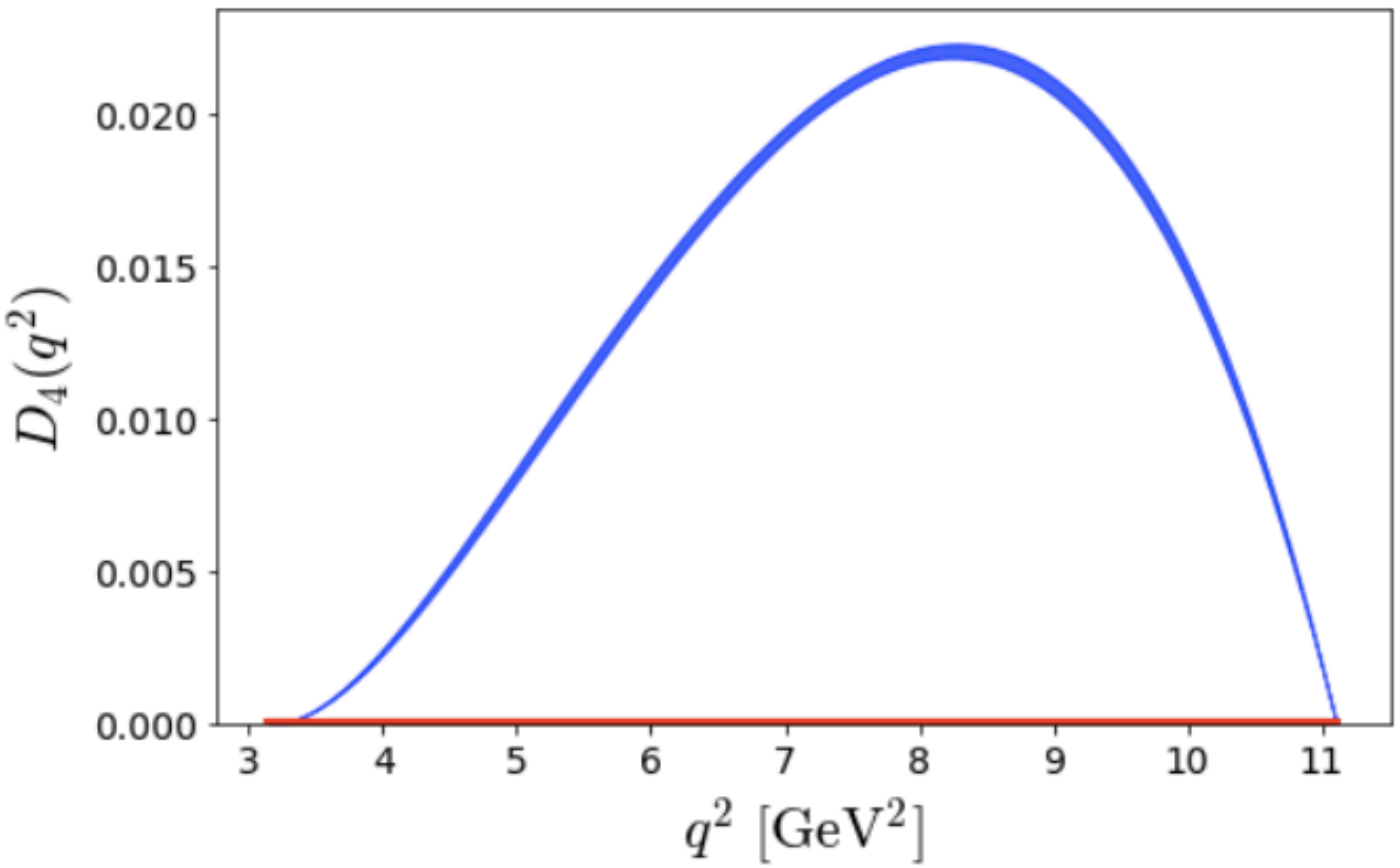
2209.13409

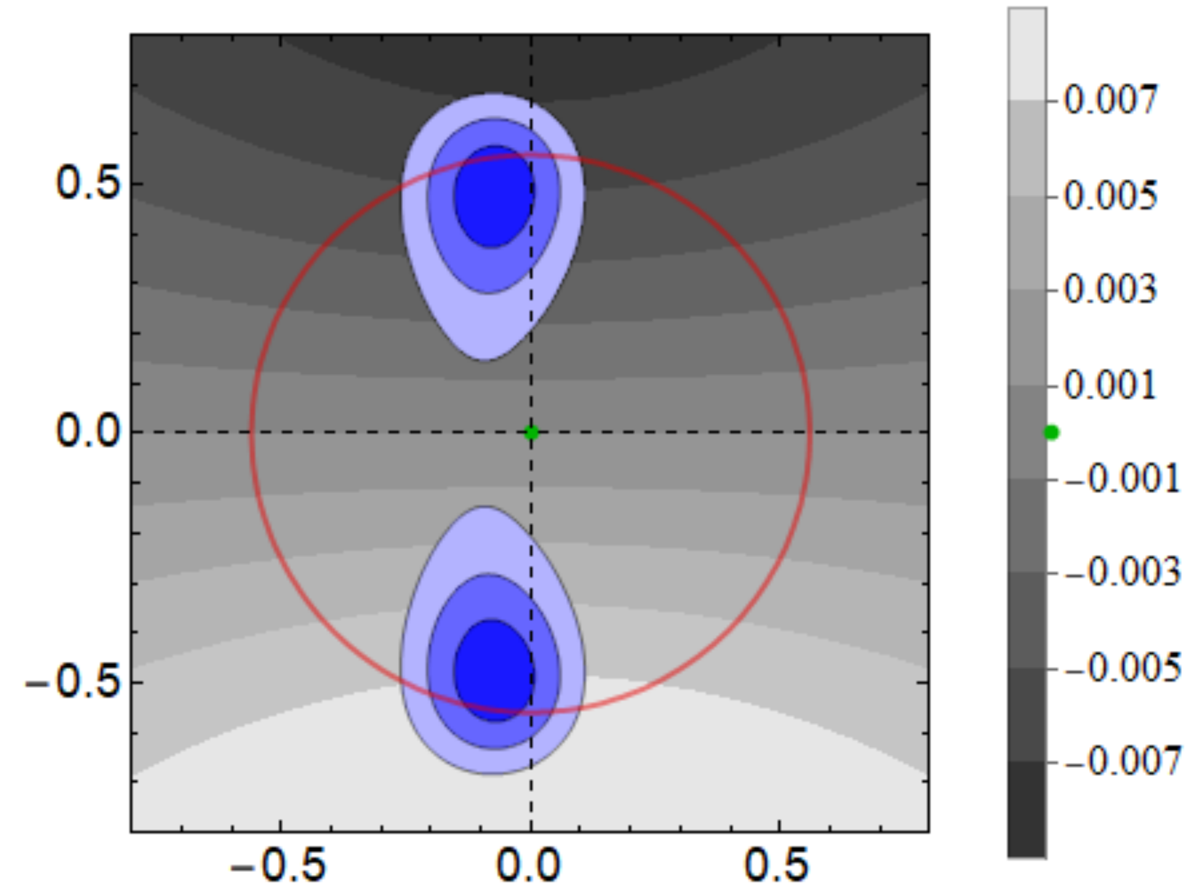
$\Lambda_b \longrightarrow \Lambda_c(\to \Lambda\pi)\ell\nu$

NB: $\mathcal{B}(\Lambda_c \to \Lambda\pi) = 1.30(7)\%$ or $\mathcal{B}(\Lambda_c \to pK_S) = 1.59(8)\%$

Many more angular observables and checking on Im[g_X] ≠ 0

$\langle D_4^\tau \rangle$





R_2

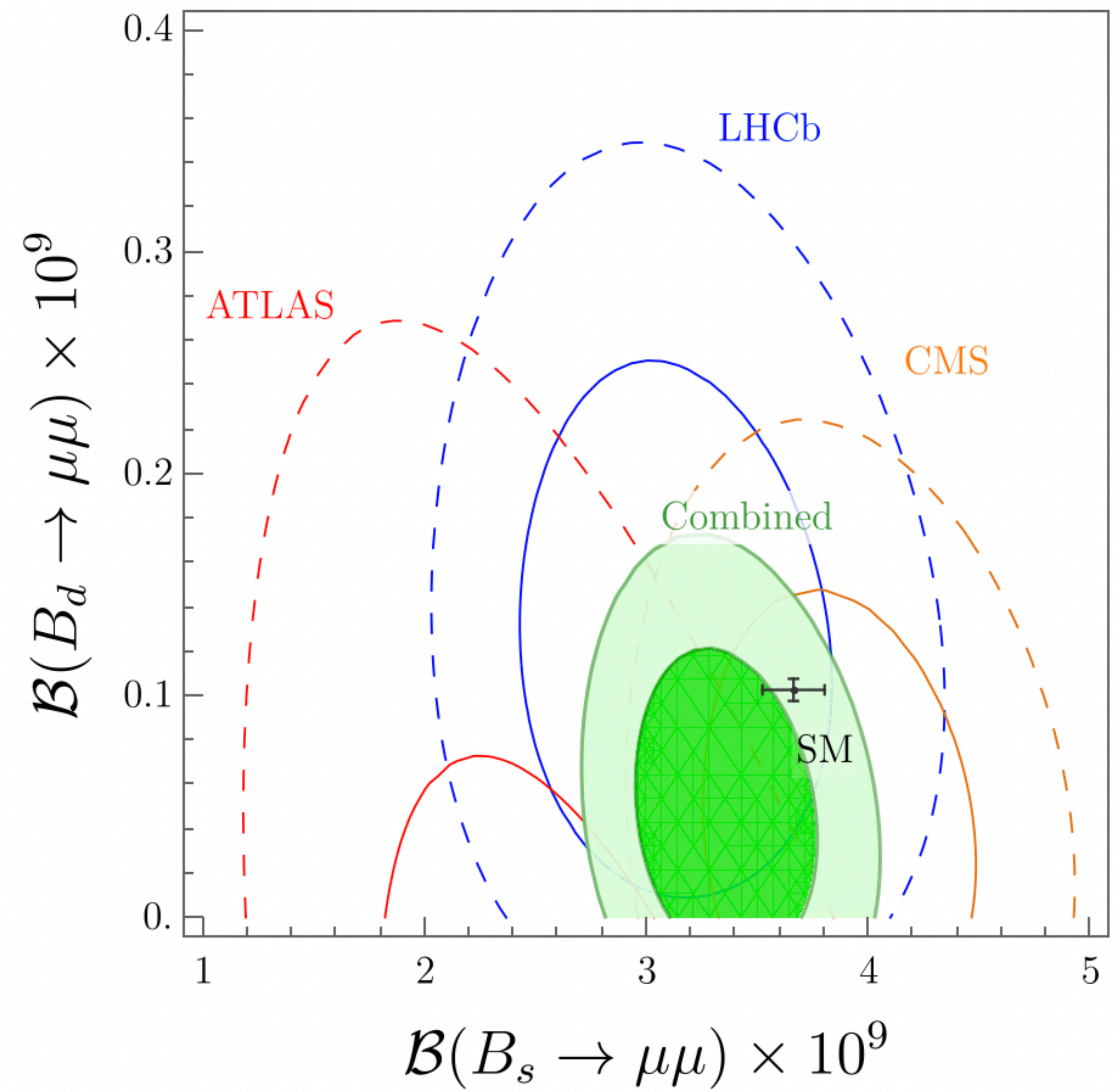
CONCLUDING REMARKS

- To tackle the flavor issues need more and better data: NP effects through high p_T tails of *pp* scattering are to be combined with constraints obtained from low energy observables.
- EFT treatment is a modern tool to describe deviations wrt SM.
- Current data, and LFUV in particular, favor leptoquark scenarios: U_1, S_1 & S_3, R_2 & S_3.
- R_D and R_{D^*} are too few observables to understand the source of LFUV. Too many NP solutions exist and could be filtered through angular $B \to D^{(*)} \tau \nu$ and $\Lambda_b \to \Lambda_c \tau \nu$ observables.
- Even if R_D and R_{D^*} were SM-like, angular observables can help unveiling a presence of BSM physics.
- What about R_K and R_{K^*}? [From rumors to actual results. Please help!]
- $\mathcal{B}(B_s \to \mu\mu)$ this summer…

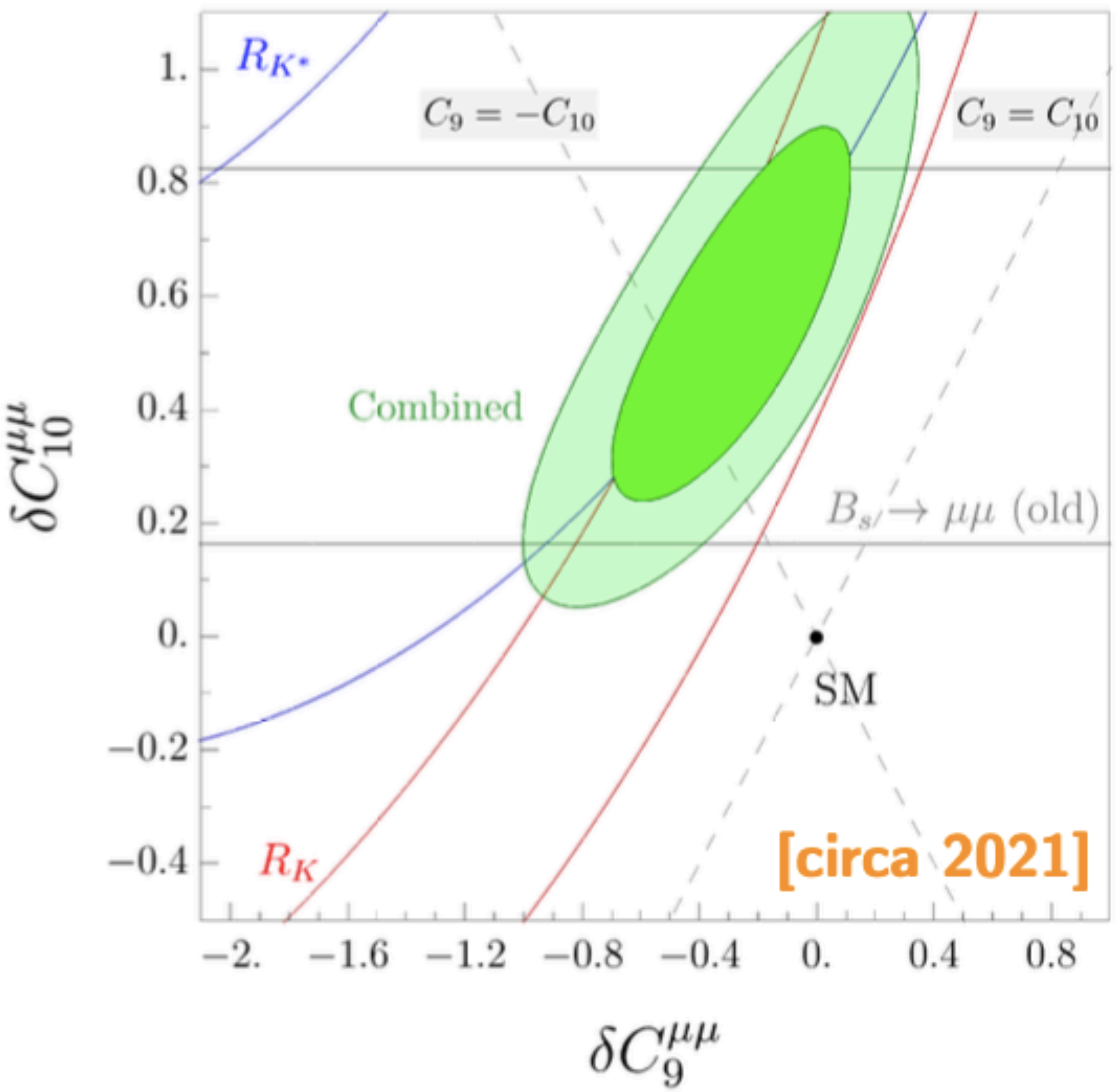
CONCLUDING REMARKS

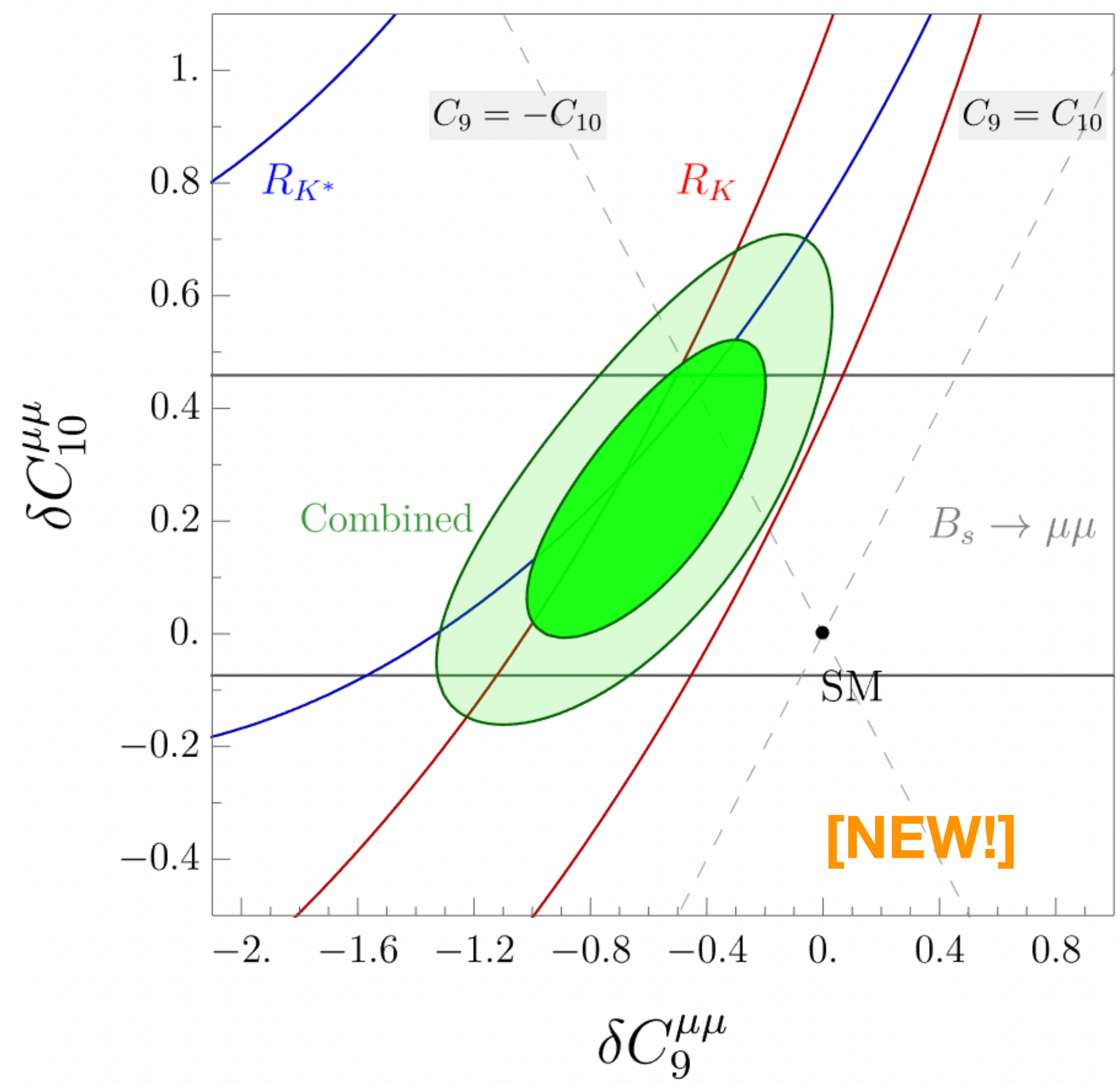
- New LHCb determination of fs/fd shifted their $B(B_s \to \mu\mu)$ upwards
- New CMS washed out the deficit of $B(B_s \to \mu\mu)$ wrt SM

CMS-PAS-BPH-21-006



CONCLUDING REMARKS





Quo vadis homini?

I šta ćemo sad?

Experiment is hard…