Implications of $B \to K\nu\bar{\nu}$ under Rank-One Flavor Violation hypothesis

Claudio Toni

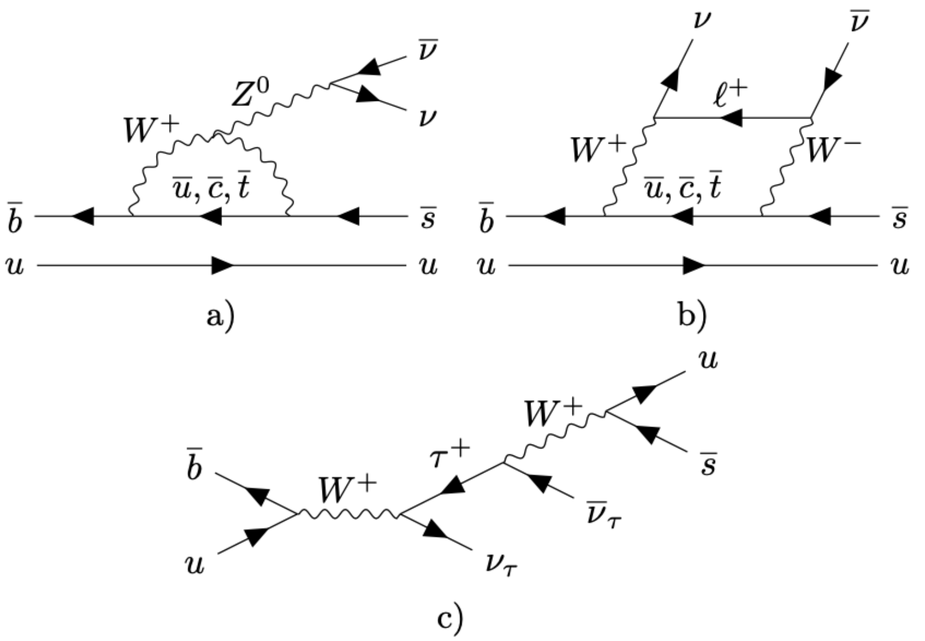
based on the work w/
David Marzocca, Marco Nardecchia and Alfredo Stanzione
arxiv:2404.06533, submitted to JHEP

Zurich, «The Flavour Path to New Physics» workshop , 5 June 2024

$d_i \to d_j \nu\bar{\nu}$ searches and Belle II excess

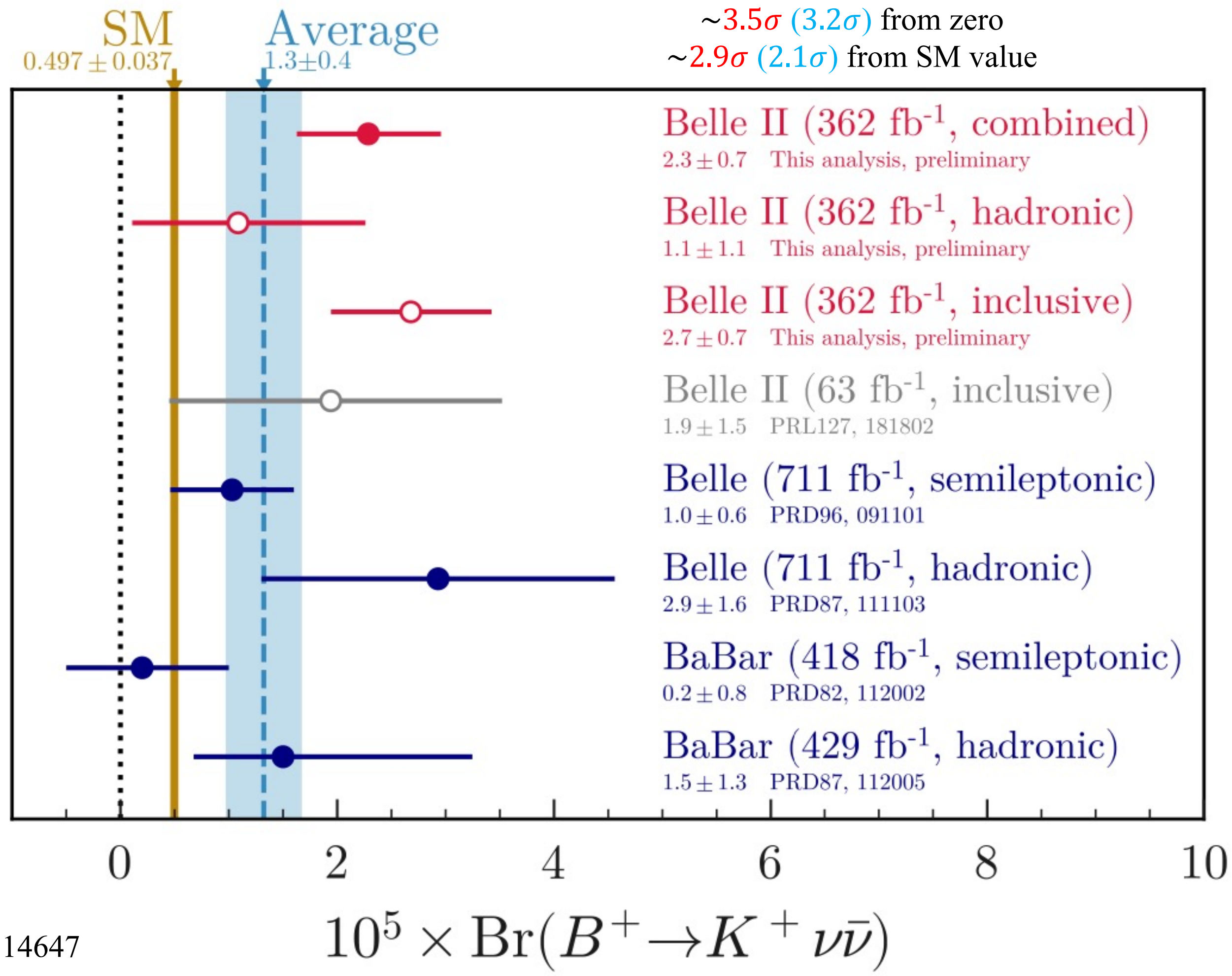
FCNC decays with neutrinos are potentially powerful probe of BSM physics as:

- they are significantly suppressed in SM
- long-distance contributions are generally sub-leading



$\propto O(G_F^2)$

First exp. evidence of $B^+ \to K^+\nu\bar{\nu}$!



Belle II collaboration, arxiv:2311.14647

Belle II excess as an hint of NP

NP assumed to be heavy
(for the complementary case,
see next talk by Martin Novoa-Brunet)

BSM effects encoded in EFT operators

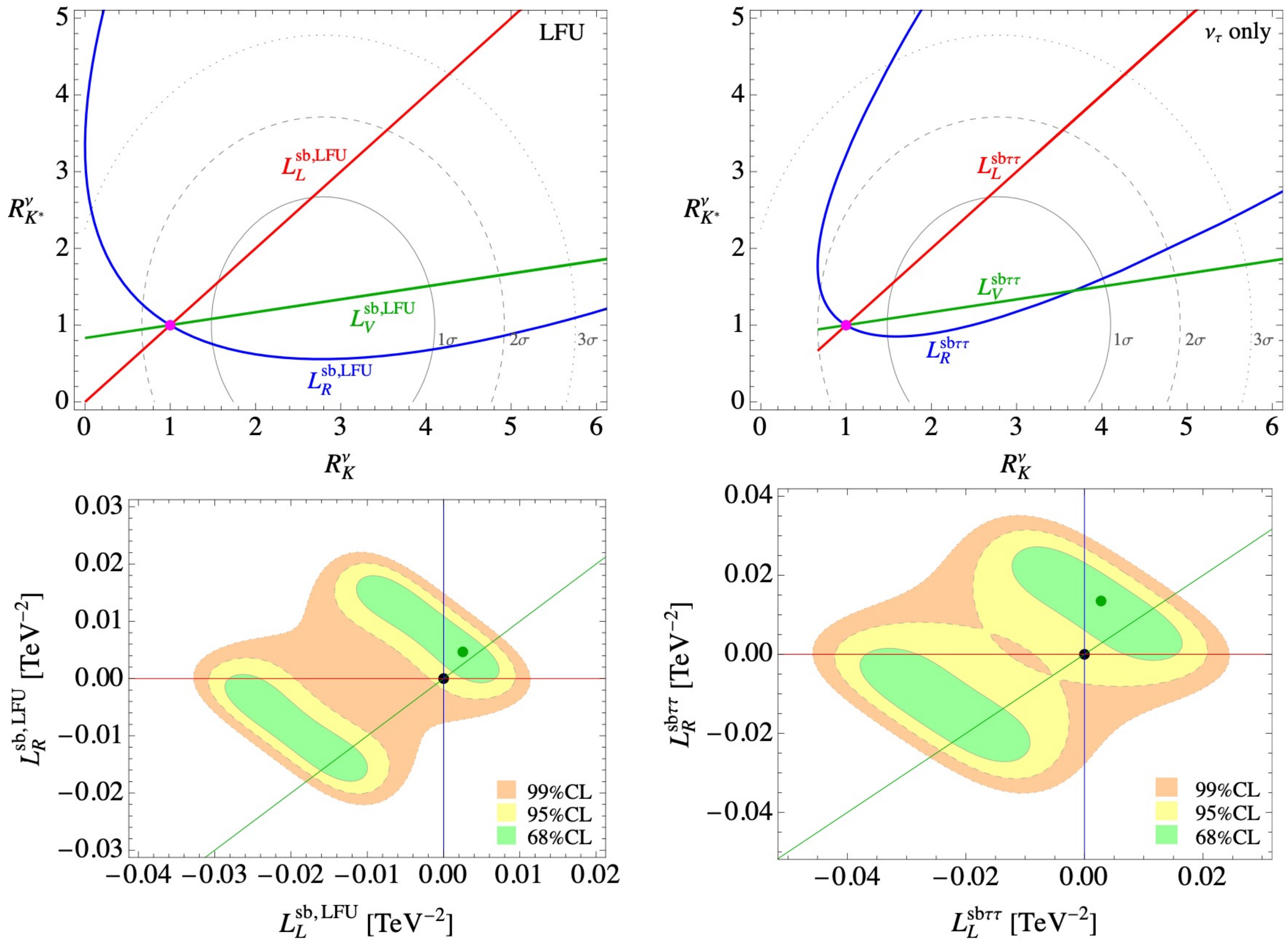
$$\mathcal{L}_{\rm LEFT}^{bs\nu\nu} = \sum_{\alpha\beta} \Big[L_R^{sb\alpha\beta} (\bar{s}_R \gamma_\mu b_R)(\bar{\nu}_L^\alpha \gamma^\mu \nu_L^\beta) + (L_L^{sb\alpha\beta} + L_L^{sb,\,\rm SM}\delta^{\alpha\beta})(\bar{s}_L \gamma_\mu b_L)(\bar{\nu}_L^\alpha \gamma^\mu \nu_L^\beta) \Big],$$

$$L_V^{sb\alpha\beta} = L_R^{sb\alpha\beta} + L_L^{sb\alpha\beta},$$

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

Effective scale of NP from the fit $\sim O(10\ \text{TeV})$

The chiral structure of NP depends on $R^\nu_{K^*}$ value!



$B^+ \to K^+\nu\bar{\nu}$ and ROFV

NP generically induces more EFT operators

$$\mathcal{L}_{\rm LEFT}^{bs\nu\nu,{\rm BSM}} \subset \mathcal{L}_{\rm LEFT}^{\rm NP} = \sum_{ij\alpha\beta} \left[L_L^{ij\alpha\beta} (\bar{d}_L^i \gamma_\mu d_L^j)(\bar{\nu}_L^\alpha \gamma^\mu \nu_L^\beta) + L_R^{ij\alpha\beta} (\bar{d}_R^i \gamma_\mu d_R^j)(\bar{\nu}_L^\alpha \gamma^\mu \nu_L^\beta) \right]$$

Identifying correlations among observables is crucial to establish the existence and the nature of BSM physics behind the measured anomalies!

$B^+ \to K^+ \nu\bar{\nu}$ and ROFV

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$$\mathcal{L}^{bs\nu\nu,\text{BSM}}_{\text{LEFT}} \subset \mathcal{L}^{\text{NP}}_{\text{LEFT}} = \sum_{ij\alpha\beta} \left[L_L^{ij\alpha\beta} (\bar{d}^i_L \gamma_\mu d^j_L)(\bar{\nu}^\alpha_L \gamma^\mu \nu^\beta_L) + L_R^{ij\alpha\beta} (\bar{d}^i_R \gamma_\mu d^j_R)(\bar{\nu}^\alpha_L \gamma^\mu \nu^\beta_L) \right]$$

Identifying correlations among observables is crucial to establish the existence and the nature of BSM physics behind the measured anomalies!

Rank-One Flavor Violation (ROFV)

NP couples along a specific direction $\hat{n}$ in the $U(3)_q$ quark flavor space

This scenario is naturally realized in many well-motivated BSM models:

- Single leptoquark mediator
- Z' coupled to one flavor in the interaction basis
- Vector-like quark mixes with SM quarks
- NP coupled linearly to SM quarks

$$\mathcal{L} \supset \lambda_i \bar{q}^i \mathcal{O}_{\text{NP}} + \text{h.c.}$$

$B^+ \to K^+ \nu\bar{\nu}$ and ROFV

NP generically induces more EFT operators

$$\mathcal{L}_{\text{LEFT}}^{bs\nu\nu,\text{BSM}} \subset \mathcal{L}_{\text{LEFT}}^{\text{NP}} = \sum_{ij\alpha\beta} \left[L_L^{ij\alpha\beta} (\bar{d}_L^i \gamma_\mu d_L^j)(\bar{\nu}_L^\alpha \gamma^\mu \nu_L^\beta) + L_R^{ij\alpha\beta} (\bar{d}_R^i \gamma_\mu d_R^j)(\bar{\nu}_L^\alpha \gamma^\mu \nu_L^\beta) \right]$$

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Rank-One Flavor Violation (ROFV)

NP couples along a specific direction $\hat{n}$ in the $U(3)_q$ quark flavor space

$$\hat{n}_i = \begin{pmatrix} \hat{n}_{1\text{st}} \\ \hat{n}_{2\text{nd}} \\ \hat{n}_{3\text{rd}} \end{pmatrix} = \begin{pmatrix} e^{i\alpha_{db}} \sin\theta \cos\phi \\ e^{i\alpha_{sb}} \sin\theta \sin\phi \\ \cos\theta \end{pmatrix}$$

$$L_{L,R,V}^{ij\alpha\beta} = C_{L,R,V} \times \hat{n}_i \hat{n}_j^* \times \begin{cases} \delta^{\alpha\beta} & \text{for LFU}, \\ \delta^{\tau\alpha}\delta^{\tau\beta} & \text{for only tau flavour}, \end{cases}$$

ROFV in LEFT

The combination relevant for $B^+ \to K^+ \nu \bar{\nu}$ is fixed to the best-fit value

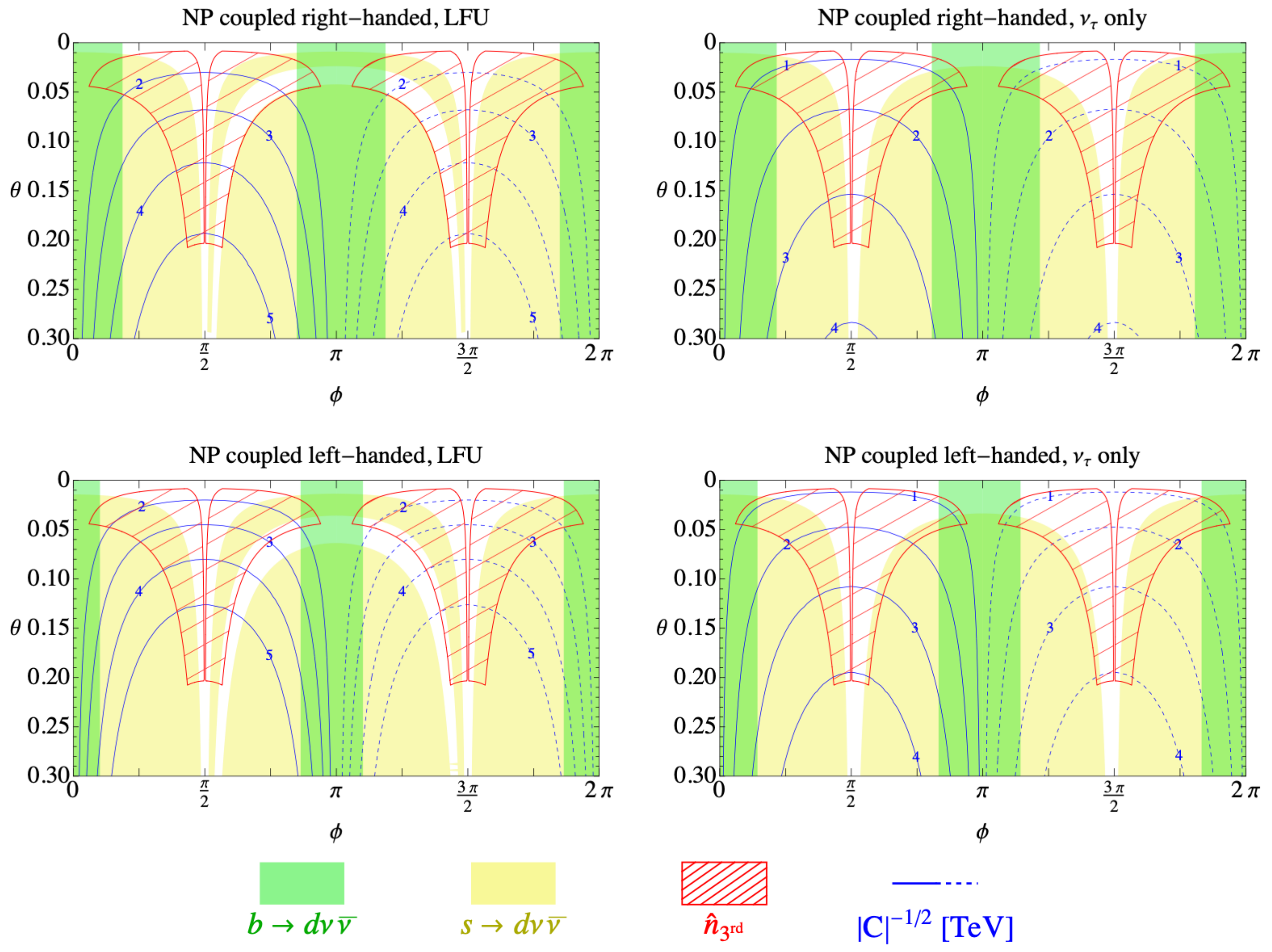
$$C_{L,R,V} \cos\theta \sin\theta \sin\phi = L^{sb}_{L,R,V}\Big|_{\text{best-fit}}$$

	LFU	ν_τ only
RH	$L_R^{sb,\text{LFU}} \approx (11.5\,\text{TeV})^{-2}$	$L_R^{sb\tau\tau} \approx (7.7\,\text{TeV})^{-2}$
LH	$L_L^{sb,\text{LFU}} \approx (14.2\,\text{TeV})^{-2}$	$L_L^{sb\tau\tau} \approx (9.2\,\text{TeV})^{-2}$

$$\alpha_{sb} = \alpha_{db} = 0$$

Regions of the (ϕ, θ) plane excluded at 95% C.L.

- NP should be third family aligned
- NP lies at few TeV
- LFU slightly disfavored



$\hat{n}_{3\text{rd}} \sim (\mathcal{O}(V_{td}), \mathcal{O}(V_{ts}), \mathcal{O}(1))$

Going to the SMEFT

In SMEFT new correlations arise due to the SM structure:

- rare decays $B_s(K_{L,S}) \to \mu^+\mu^-$
- meson-mixing constraints
- high-p_T dilepton tails
- Higgs and EW fit

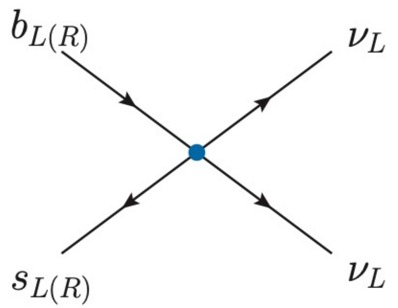
$$l_L^\alpha = (\nu_L^\alpha, \ell_L^\alpha) \qquad q_L^i = (V_{ji}^* u_L^j, d_L^i)^t$$

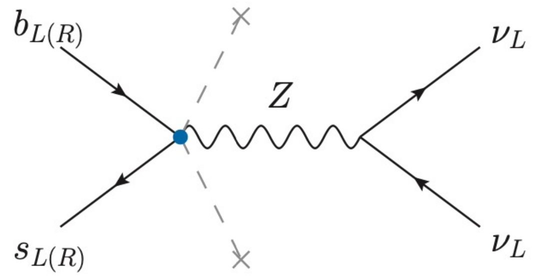
Up to dimension six, there are 6 relevant SMEFT operators

$$\begin{aligned} L_L^{ij\alpha\beta} &= C_{lq}^{(1)\alpha\beta ij} - C_{lq}^{(3)\alpha\beta ij} + C_{Hq}^{(1)ij}\delta_{\alpha\beta} + C_{Hq}^{(3)ij}\delta_{\alpha\beta}\,, \\ L_R^{ij\alpha\beta} &= C_{ld}^{\alpha\beta ij} + C_{Hd}^{ij}\delta_{\alpha\beta}\,. \end{aligned}$$

$$\begin{aligned} \mathcal{O}_{lq}^{(1)\alpha\beta ij} &= \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu q_L^j\right) \\ \mathcal{O}_{lq}^{(3)\alpha\beta ij} &= \left(\bar{l}_L^\alpha \gamma_\mu \sigma_a l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu \sigma_a q_L^j\right) \\ \mathcal{O}_{ld}^{\alpha\beta ij} &= \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{d}_R^i \gamma^\mu d_R^j\right) \end{aligned}$$

$$\begin{aligned} \mathcal{O}_{Hq}^{(1)ij} &= \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_L^i \gamma^\mu q_L^j\right)\,, \\ \mathcal{O}_{Hq}^{(3)ij} &= \left(H^\dagger \sigma_a \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_L^i \gamma^\mu \sigma_a q_L^j\right)\,, \\ \mathcal{O}_{Hd}^{ij} &= \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_R^i \gamma^\mu d_R^j\right)\,. \end{aligned}$$





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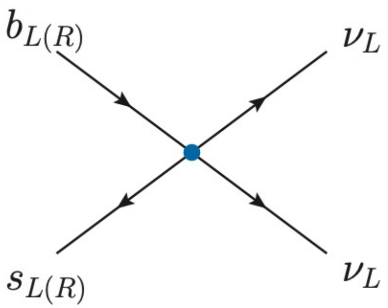
Up to dimension six, there are 6 relevant SMEFT operators

$$L_L^{ij\alpha\beta} = C_{lq}^{(1)\alpha\beta ij} - C_{lq}^{(3)\alpha\beta ij} + C_{Hq}^{(1)ij}\delta_{\alpha\beta} + C_{Hq}^{(3)ij}\delta_{\alpha\beta}\,,$$
$$L_R^{ij\alpha\beta} = C_{ld}^{\alpha\beta ij} + C_{Hd}^{ij}\delta_{\alpha\beta}\,.$$

$$\mathcal{O}_{lq}^{(1)\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu q_L^j\right)$$
$$\mathcal{O}_{lq}^{(3)\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu \sigma_a l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu \sigma_a q_L^j\right)$$
$$\mathcal{O}_{ld}^{\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{d}_R^i \gamma^\mu d_R^j\right)$$



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Enhancement of R_K^ν above ~25% is highly disfavored due the constraints from $B_s \to \mu^+\mu^-$ and ΔM_{B_s}!

Single-mediator models

$$\mathcal{O}_{lq}^{(1)\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu q_L^j\right)$$

$$\mathcal{O}_{lq}^{(3)\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu \sigma_a l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu \sigma_a q_L^j\right)$$

$$\mathcal{O}_{ld}^{\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{d}_R^i \gamma^\mu d_R^j\right)$$

Loop-level mediators are expected to have light and relatively strongly coupled states, disfavored by direct searches at the LHC

		Spin	$G_{\rm SM}$	Interaction term	SMEFT coeff.
Colorless vector mediators	V'	1	$(\mathbf{1},\mathbf{3},0)$	$\left[g_q^{ij}(\bar{q}_L^i\gamma^\mu\sigma_a q_L^j) + g_\ell^{\alpha\beta}(\bar{l}_L^\alpha\gamma^\mu\sigma_a l_L^\beta)\right] V'_{a\mu}$	$C_{lq}^{(3)}$
	Z'_L	1	$(\mathbf{1},\mathbf{1},0)$	$\left[g_q^{ij}(\bar{q}_L^i\gamma^\mu q_L^j) + g_\ell^{\alpha\beta}(\bar{l}_L^\alpha\gamma^\mu\sigma_a l_L^\beta)\right] Z'_{L\mu}$	$C_{lq}^{(1)}$
	Z'_R	1	$(\mathbf{1},\mathbf{1},0)$	$\left[g_q^{ij}(\bar{d}_R^i\gamma^\mu d_R^j) + g_\ell^{\alpha\beta}(\bar{l}_L^\alpha\gamma^\mu\sigma_a l_L^\beta)\right] Z'_{R\mu}$	C_{ld}
Leptoquarks	S_1	0	$(\bar{\mathbf{3}},\mathbf{1},1/3)$	$\lambda_{i\alpha}^*(\overline{q_L^{i,c}}\epsilon l_L^\alpha)S_1$	$C_{lq}^{(1)} = -C_{lq}^{(3)}$
	S_3	0	$(\bar{\mathbf{3}},\mathbf{3},1/3)$	$\lambda_{i\alpha}^*(\overline{q_L^{i,c}}\epsilon\sigma_a l_L^\alpha)(S_3)_a$	$C_{lq}^{(1)} = 3C_{lq}^{(3)}$
	U_3	1	$(\mathbf{3},\mathbf{3},2/3)$	$\lambda_{i\alpha}(\overline{q_L^i}\gamma_\mu\sigma_a l_L^\alpha)(U_3^\mu)_a$	$C_{lq}^{(1)} = -3C_{lq}^{(3)}$
	$\tilde{R}_2$	0	$(\mathbf{3},\mathbf{2},1/6)$	$\lambda_{i\alpha}\overline{d_R^i}(l_L^\alpha\epsilon\tilde{R}_2)$	C_{ld}
	V_2	1	$(\bar{\mathbf{3}},\mathbf{2},5/6)$	$\lambda_{i\alpha}^*\overline{d_R^{i,c}}\gamma_\mu(l_L^\alpha\epsilon V_2^\mu)$	C_{ld}

Single-mediator models

$$\mathcal{O}_{lq}^{(1)\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu q_L^j\right)$$
$$\mathcal{O}_{lq}^{(3)\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu \sigma_a l_L^\beta\right)\left(\bar{q}_L^i \gamma^\mu \sigma_a q_L^j\right)$$
$$\mathcal{O}_{ld}^{\alpha\beta ij} = \left(\bar{l}_L^\alpha \gamma_\mu l_L^\beta\right)\left(\bar{d}_R^i \gamma^\mu d_R^j\right)$$

Four-quark operators, constrained by meson-mixing, arise from the same interaction terms

$$\mathcal{O}_{qq}^{(1)ijkl} = \left(\bar{q}_L^i \gamma_\mu q_L^j\right)\left(\bar{q}_L^k \gamma^\mu q_L^l\right) \,,$$
$$\mathcal{O}_{qq}^{(3)ijkl} = \left(\bar{q}_L^i \gamma_\mu \sigma_a q_L^j\right)\left(\bar{q}_L^k \gamma^\mu \sigma_a q_L^l\right) \,,$$
$$\mathcal{O}_{dd}^{ijkl} = \left(\bar{d}_R^i \gamma_\mu d_R^j\right)\left(\bar{d}_R^k \gamma^\mu d_R^l\right) \,,$$
$$\mathcal{O}_{qd}^{(1)ijkl} = \left(\bar{q}_L^i \gamma_\mu q_L^j\right)\left(\bar{d}_R^k \gamma^\mu d_R^l\right) \,,$$

Colorless vector mediators: V', Z'_L, Z'_R

Leptoquarks: S_1, S_3, U_3, $\tilde{R}_2$, V_2

	Spin	$G_{\rm SM}$	Interaction term	SMEFT coeff.
V'	1	$(\mathbf{1},\mathbf{3},0)$	$\left[g_q^{ij}(\bar{q}_L^i\gamma^\mu\sigma_a q_L^j) + g_\ell^{\alpha\beta}(\bar{l}_L^\alpha\gamma^\mu\sigma_a l_L^\beta)\right] V'_{a\mu}$	$C_{lq}^{(3)}$
Z'_L	1	$(\mathbf{1},\mathbf{1},0)$	$\left[g_q^{ij}(\bar{q}_L^i\gamma^\mu q_L^j) + g_\ell^{\alpha\beta}(\bar{l}_L^\alpha\gamma^\mu\sigma_a l_L^\beta)\right] Z'_{L\mu}$	$C_{lq}^{(1)}$
Z'_R	1	$(\mathbf{1},\mathbf{1},0)$	$\left[g_q^{ij}(\bar{d}_R^i\gamma^\mu d_R^j) + g_\ell^{\alpha\beta}(\bar{l}_L^\alpha\gamma^\mu\sigma_a l_L^\beta)\right] Z'_{R\mu}$	C_{ld}
S_1	0	$(\bar{\mathbf{3}},\mathbf{1},1/3)$	$\lambda_{i\alpha}^*(\overline{q_L^{i,c}}\epsilon l_L^\alpha)S_1$	$C_{lq}^{(1)} = -C_{lq}^{(3)}$
S_3	0	$(\bar{\mathbf{3}},\mathbf{3},1/3)$	$\lambda_{i\alpha}^*(\overline{q_L^{i,c}}\epsilon\sigma_a l_L^\alpha)(S_3)_a$	$C_{lq}^{(1)} = 3C_{lq}^{(3)}$
U_3	1	$(\mathbf{3},\mathbf{3},2/3)$	$\lambda_{i\alpha}(\overline{q_L^i}\gamma_\mu\sigma_a l_L^\alpha)(U_3^\mu)_a$	$C_{lq}^{(1)} = -3C_{lq}^{(3)}$
$\tilde{R}_2$	0	$(\mathbf{3},\mathbf{2},1/6)$	$\lambda_{i\alpha}\overline{d_R^i}(l_L^\alpha\epsilon\tilde{R}_2)$	C_{ld}
V_2	1	$(\bar{\mathbf{3}},\mathbf{2},5/6)$	$\lambda_{i\alpha}^*\overline{d_R^{i,c}}\gamma_\mu(l_L^\alpha\epsilon V_2^\mu)$	C_{ld}

Power ranking of the simplified models

🥇

🥈

🥉

4.

5.

Power ranking of the simplified models

🥇

🥈

🥉

4.

5. $U_3 \sim (\mathbf{3}, \mathbf{3}, 2/3)$

It can not accommodate the Belle II excess with 1σ

Power ranking of the simplified models

4. $Z' \sim (\mathbf{1}, \mathbf{1}, 0)$ and $V' \sim (\mathbf{1}, \mathbf{3}, 0)$ — Disfavored as meson-mixing arises already at tree-level

5. $U_3 \sim (\mathbf{3}, \mathbf{3}, 2/3)$

Power ranking of the simplified models

🥇

🥈

🥉 $V_2 \sim (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$ — Good fit but stringent PU bound on coupling

4. $Z' \sim (\mathbf{1}, \mathbf{1}, 0)$ and $V' \sim (\mathbf{1}, \mathbf{3}, 0)$

5. $U_3 \sim (\mathbf{3}, \mathbf{3}, 2/3)$

Power ranking of the simplified models

1.

2. $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ and $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$ — Slightly disfavored as they coupled to LH quarks

3. $V_2 \sim (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$

4. $Z' \sim (\mathbf{1}, \mathbf{1}, 0)$ and $V' \sim (\mathbf{1}, \mathbf{3}, 0)$

5. $U_3 \sim (\mathbf{3}, \mathbf{3}, 2/3)$

Power ranking of the simplified models

1. $\tilde{R}_2 \sim (\mathbf{3}, \mathbf{2}, 1/6)$

2. $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$ and $S_3 \sim (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

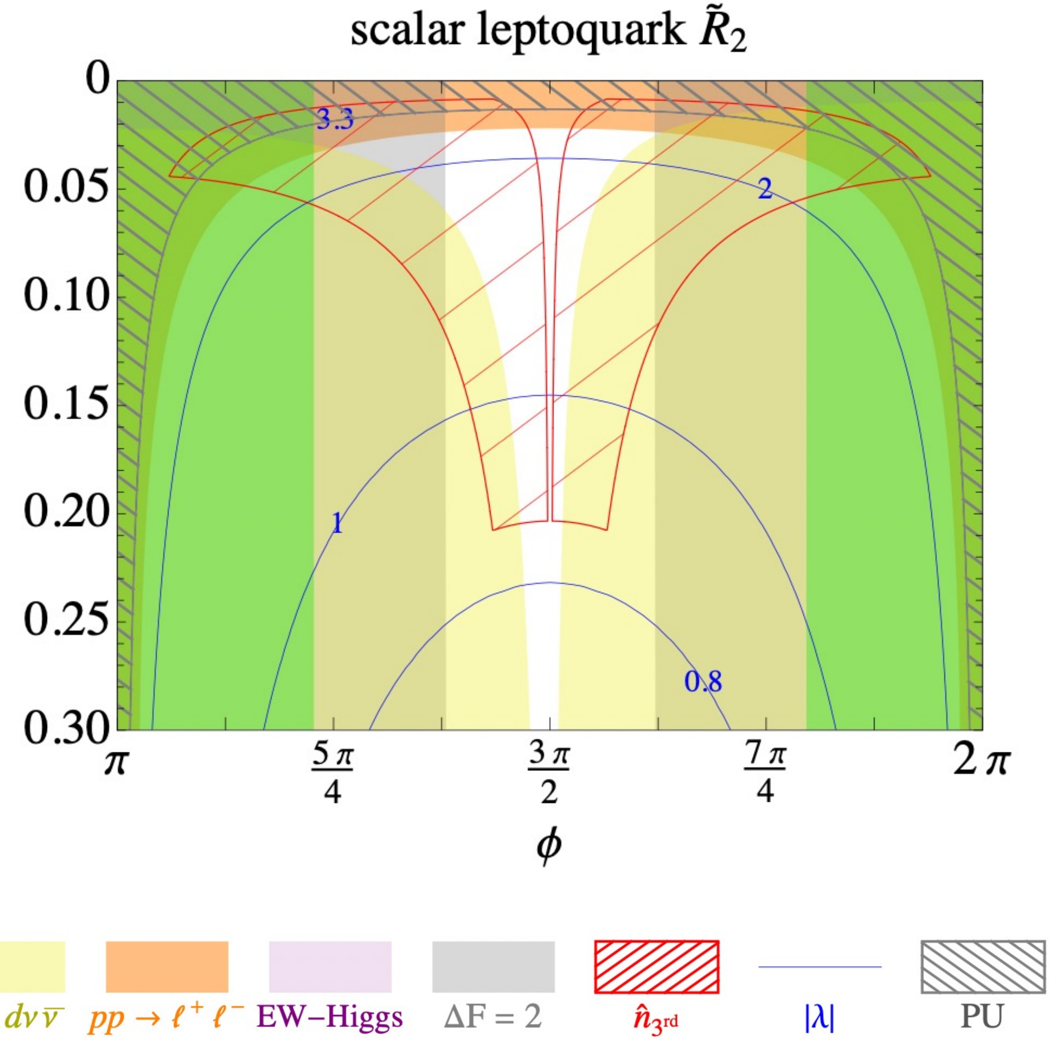
3. $V_2 \sim (\bar{\mathbf{3}}, \mathbf{2}, 5/6)$

4. $Z' \sim (\mathbf{1}, \mathbf{1}, 0)$ and $V' \sim (\mathbf{1}, \mathbf{3}, 0)$

5. $U_3 \sim (\mathbf{3}, \mathbf{3}, 2/3)$

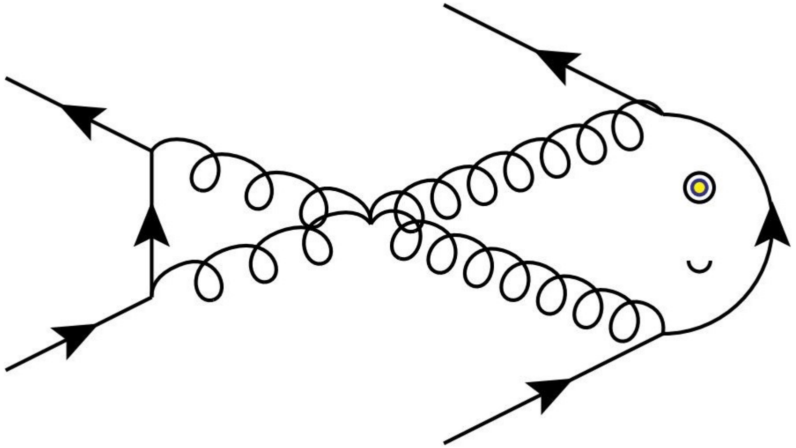
$$C_{ld}^{\tau\tau sb}\Big|_{\tilde{R}_2,\text{best-fit}} \approx (7.5\ \text{TeV})^{-2}$$

$m_{LQ} = 2$ TeV



Regions of the (ϕ, θ) plane excluded at 95% C.L.

The End



THANK YOU
FOR THE
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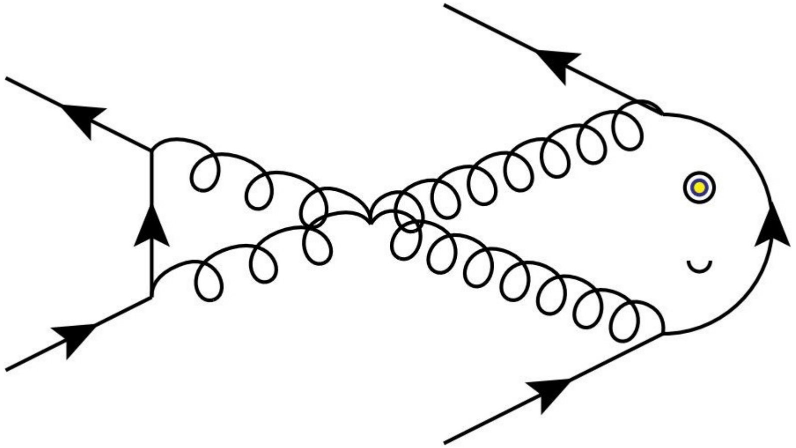
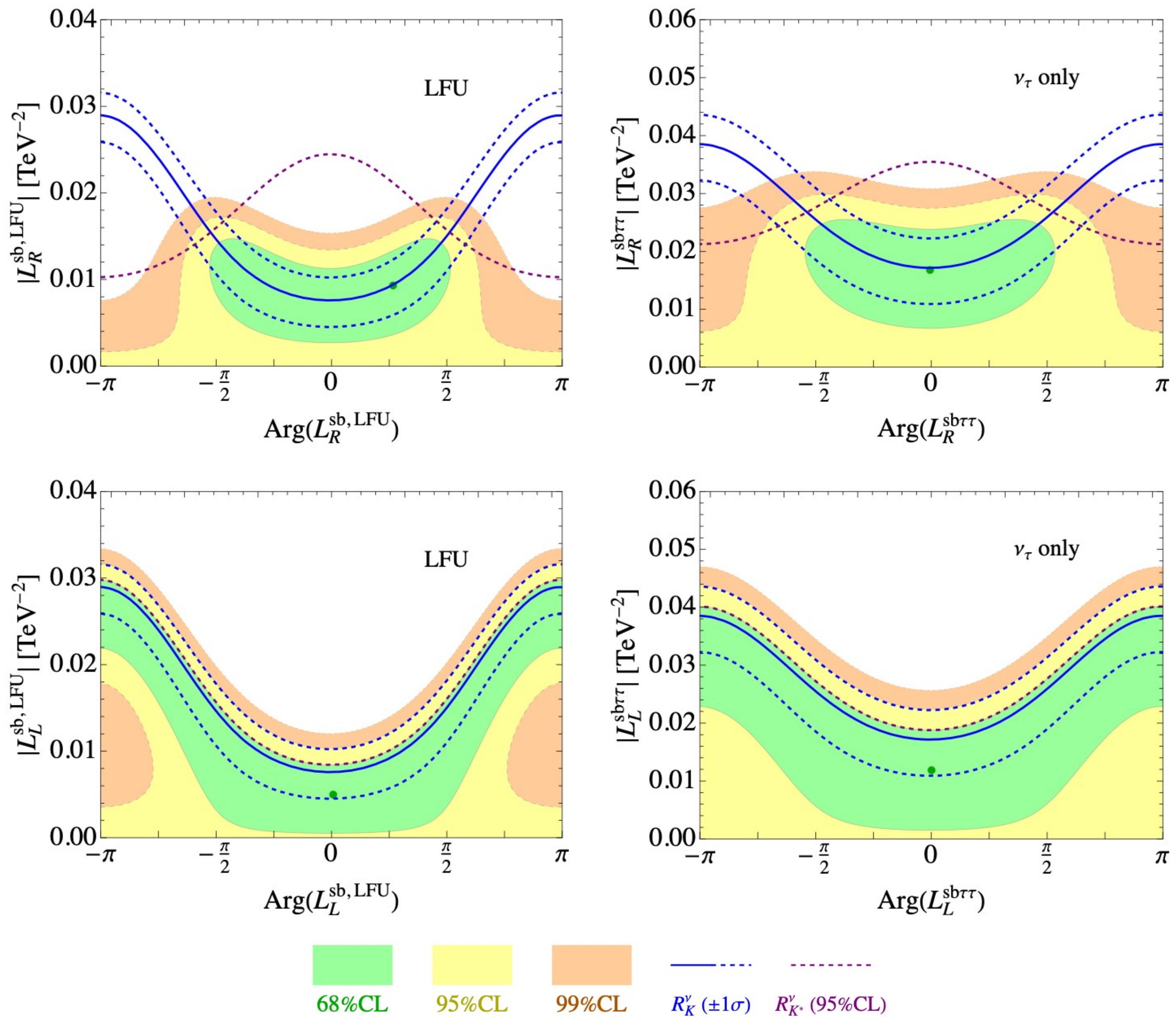


BACK UP SLIDES

LEFT fits



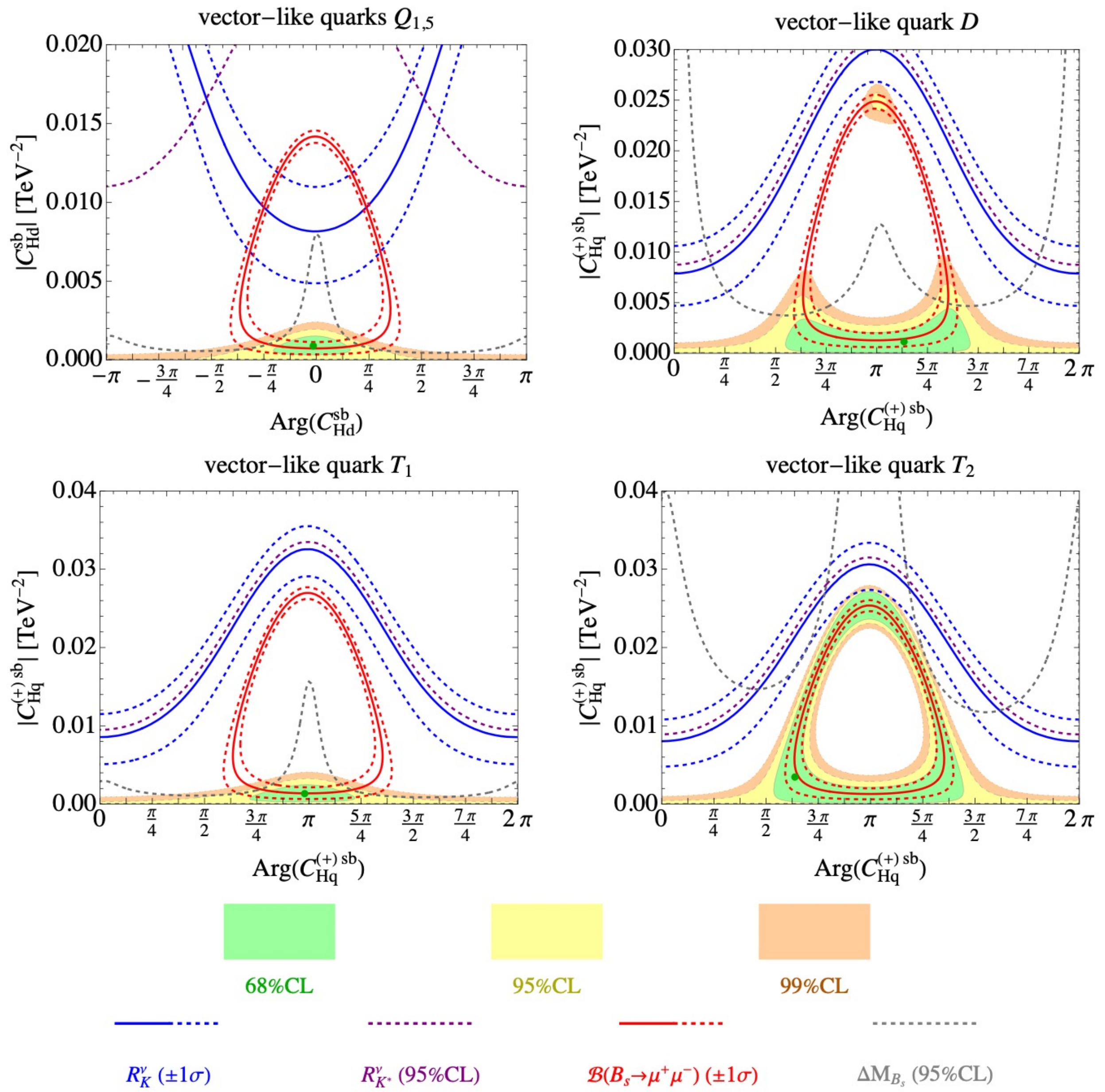
LFU
ν_τ only
$|L_R^{sb,LFU}|$ [TeV^{-2}]
$|L_R^{sb\tau\tau}|$ [TeV^{-2}]
$|L_L^{sb,LFU}|$ [TeV^{-2}]
$|L_L^{sb\tau\tau}|$ [TeV^{-2}]
Arg($L_R^{sb,LFU}$)
Arg($L_R^{sb\tau\tau}$)
Arg($L_L^{sb,LFU}$)
Arg($L_L^{sb\tau\tau}$)
68%CL
95%CL
99%CL
R_K^ν ($\pm 1\sigma$)
$R_{K^*}^\nu$ (95%CL)

Higgs-quark operators

$$\mathcal{O}_{Hq}^{(1)ij} = \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_L^i \gamma^\mu q_L^j\right) ,$$
$$\mathcal{O}_{Hq}^{(3)ij} = \left(H^\dagger \sigma_a \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_L^i \gamma^\mu \sigma_a q_L^j\right) ,$$
$$\mathcal{O}_{Hd}^{ij} = \left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_R^i \gamma^\mu d_R^j\right) .$$

Simplified model	**Spin**	**SM irrep**	**SMEFT couplings**
D	$1/2$	$(\mathbf{3},\mathbf{1},-1/3)$	$C_{Hq}^{(1)} = C_{Hq}^{(3)}$
T_1	$1/2$	$(\mathbf{3},\mathbf{3},-1/3)$	$C_{Hq}^{(1)} = -3C_{Hq}^{(3)}$
T_2	$1/2$	$(\mathbf{3},\mathbf{3},2/6)$	$C_{Hq}^{(1)} = 3C_{Hq}^{(3)}$
Q_1	$1/2$	$(\mathbf{3},\mathbf{2},1/6)$	C_{Hd}
Q_5	$1/2$	$(\mathbf{3},\mathbf{2},-5/6)$	C_{Hd}

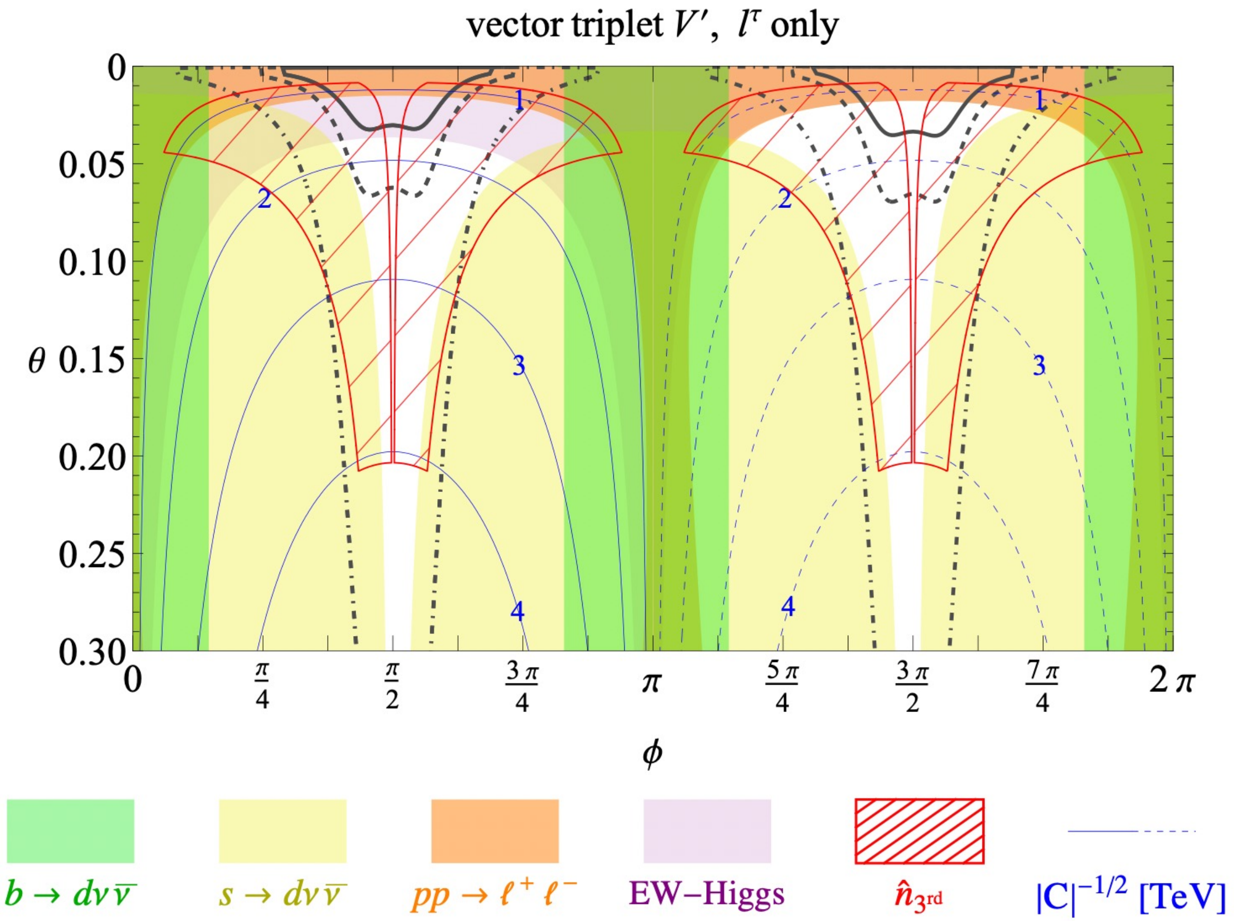
Enhancement of R_K^ν above ~25% is highly disfavored due the constraints from $B_s \to \mu^+\mu^-$ and ΔM_{B_s}!



Colorless vectors

$C_{lq}^{(-)\tau\tau sb}\Big|_{\text{best-fit}} \approx (9.1\,\text{TeV})^{-2}$

$|g_q/g_\ell| = 0.1(\text{solid}),\ 0.05(\text{dashed})\ \text{and}\ 0.01(\text{dot-dashed})$



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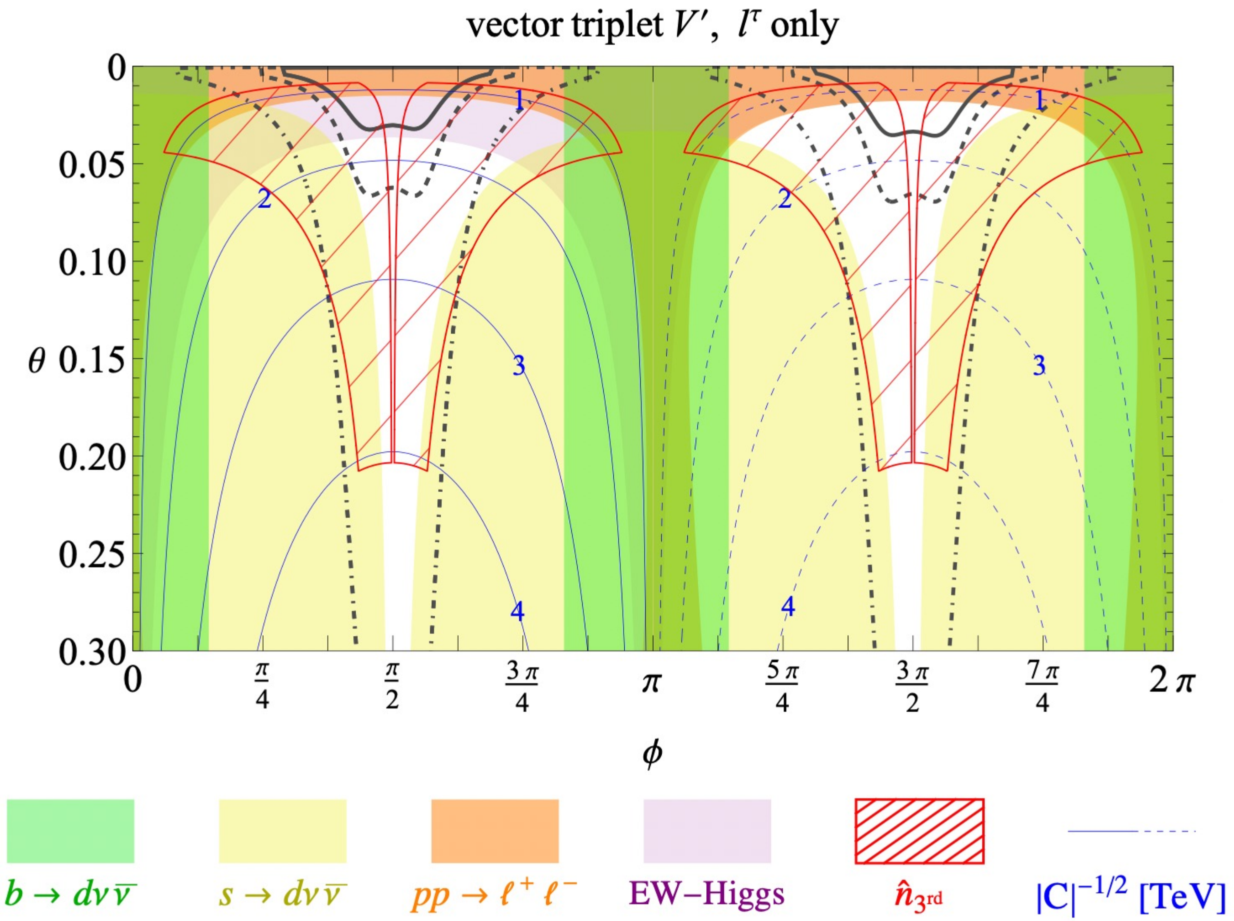


$$M_{V'} \lesssim 1391\ \text{GeV}\left(\frac{|g_q/g_\ell|^{\max}}{0.05}\right)^{1/2}|\sin\theta\cos\theta\sin\phi|^{\frac{1}{2}}$$

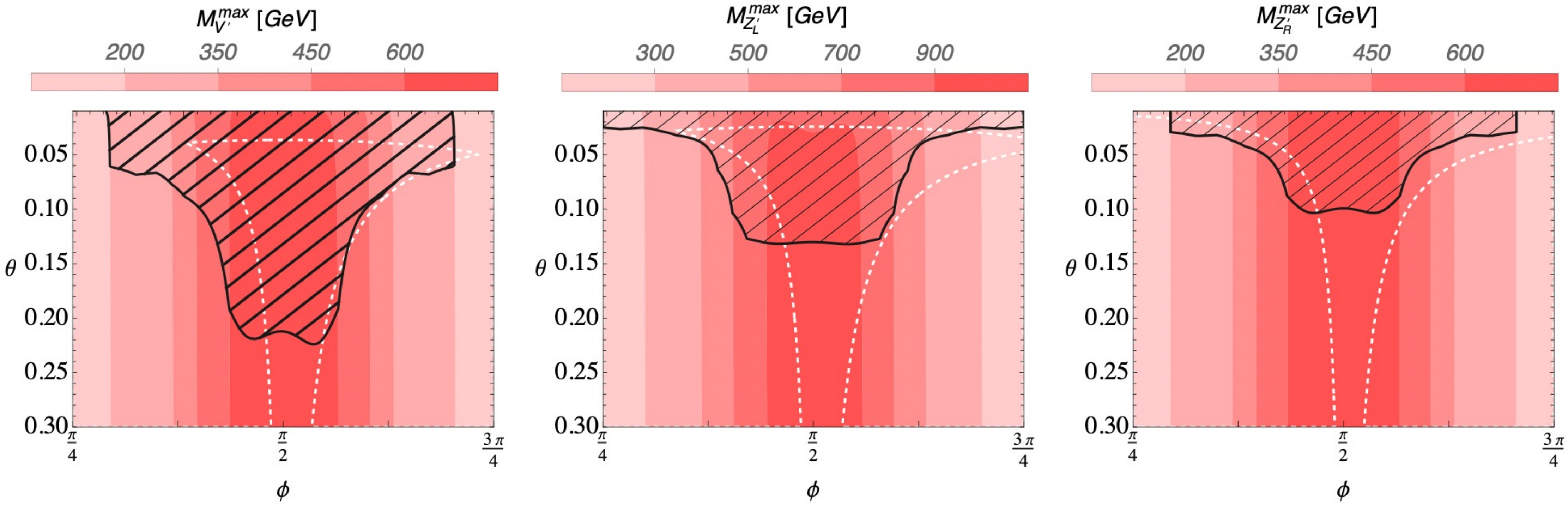
$$\approx 762\ \text{GeV}\left(\frac{|g_q/g_\ell|^{\max}}{0.05}\right)^{1/2}\left|\frac{\theta}{0.3}\right|^{1/2},$$

Colorless vectors

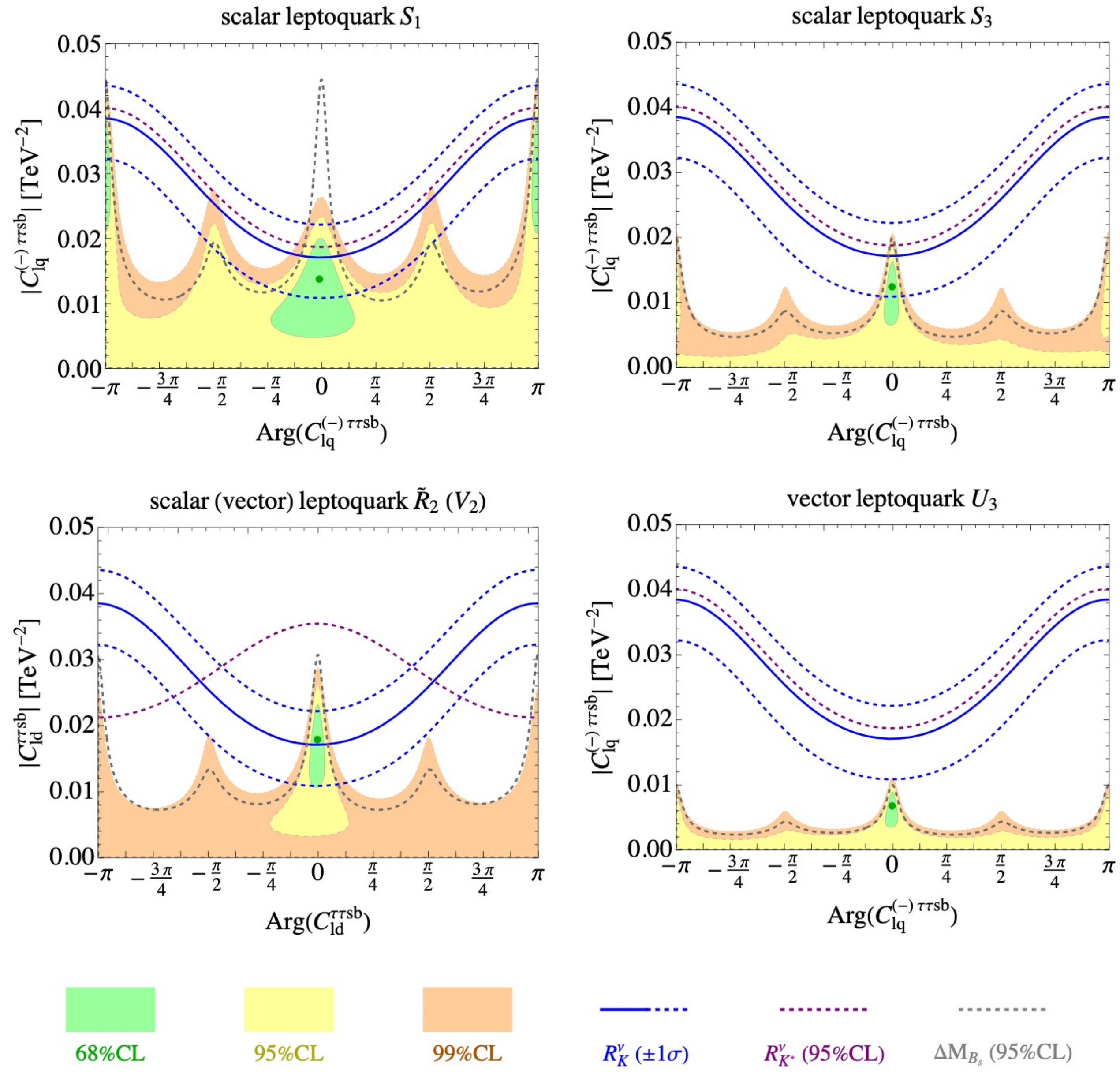
- High-p_T dilepton tails bound does not hold anymore!
  - We consider the constraints from direct searches

$$M_{V'} \lesssim 1391 \text{ GeV} \left(\frac{|g_q/g_\ell|^{\max}}{0.05}\right)^{1/2} |\sin\theta\cos\theta\sin\phi|^{\frac{1}{2}}$$
$$\approx 762 \text{ GeV} \left(\frac{|g_q/g_\ell|^{\max}}{0.05}\right)^{1/2} \left|\frac{\theta}{0.3}\right|^{1/2},$$

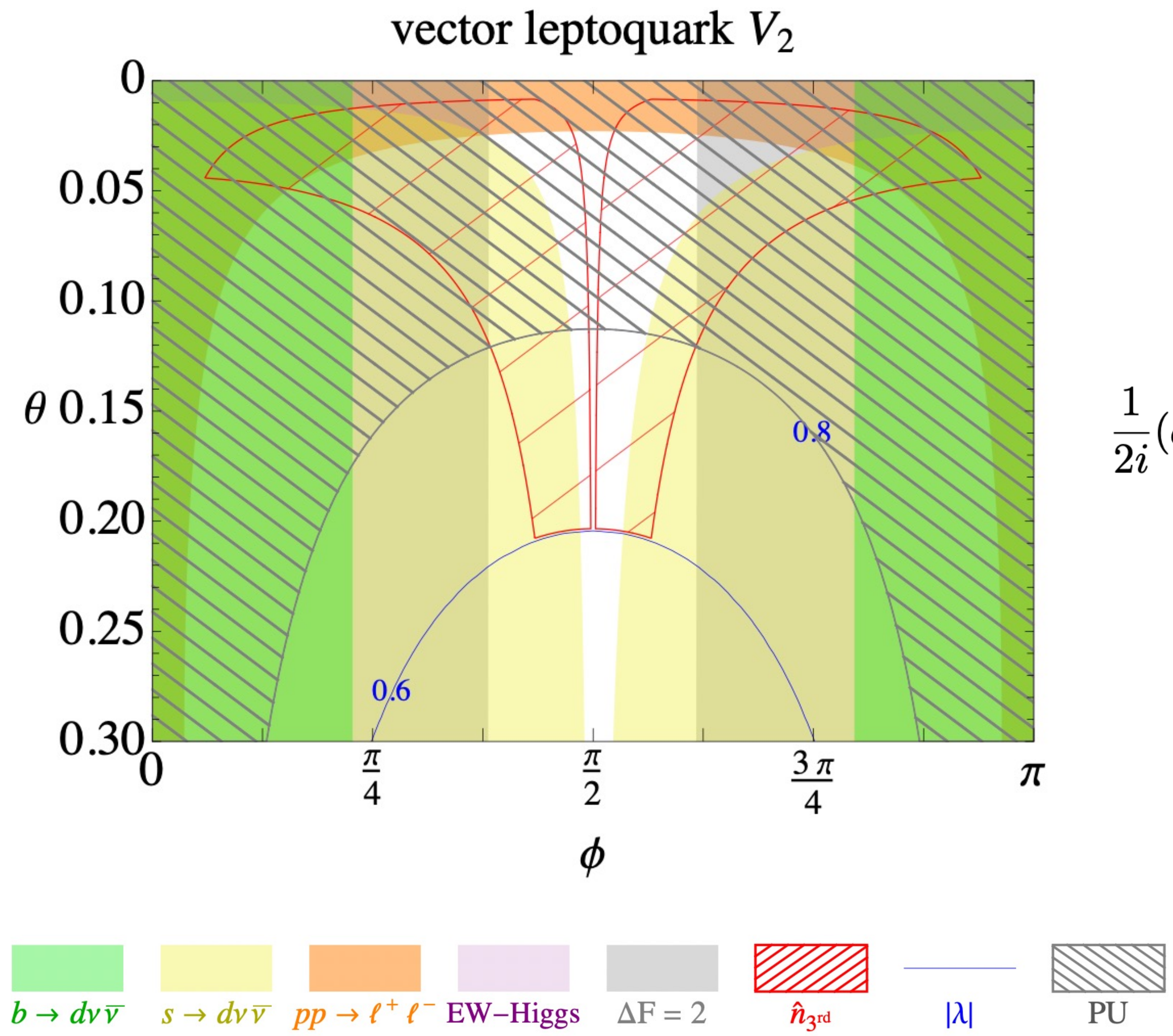
$$\sigma(pp \to V'^0 \to \tau^+\tau^-) \approx \frac{4\pi^2}{3}\mathcal{B}(V'^0 \to \tau^+\tau^-) \sum_{i,j=u,d,s,c,b} \frac{\Gamma(V'^0 \to q^i\bar{q}^j)}{M_{V'}} \frac{2}{s_0} \mathcal{L}_{q^i\bar{q}^j}(M_{V'})$$



Leptoquark fits



PU bound



$$a^J_{fi} = \frac{1}{32\pi}\int_{-1}^{1} \mathrm{d}\cos\theta\, d^J_{\mu_i\mu_f}(\theta)\mathcal{T}_{fi}(\sqrt{s},\cos\theta)$$

$$\frac{1}{2i}(a^J_{fi} - a^{J*}_{if}) = \sum_h a^{J*}_{hf}a^J_{hi}\ , \qquad |a^{J,\mathrm{tree}}_{ii}| \leq \frac{1}{2}$$

$$|\lambda| \lesssim \begin{cases} 3.2 & \text{for } S_1\ , \\ 3.3 & \text{for } \tilde{R}_2\ , \\ 0.8 & \text{for } V_2\ . \end{cases}$$

LNV scenario

$$\mathcal{O}_{d\nu}^{S,LL} = (\overline{d_R} d_L)(\overline{\nu^C}\nu) + \text{h.c.}\,,$$
$$\mathcal{O}_{d\nu}^{S,LR} = (\overline{d_L} d_R)(\overline{\nu^C}\nu) + \text{h.c.}\,,$$
$$\mathcal{O}_{d\nu}^{T,LL} = (\overline{d_R}\sigma^{\mu\nu} d_L)(\overline{\nu^C}\sigma_{\mu\nu}\nu) + \text{h.c.}\,,$$

$$O_{\bar{d}LQLH1}^{prst} = \epsilon_{ji}\epsilon_{mn}\left(\overline{d_p} L_r^i\right)\left(\overline{Q_s^c}^j L_t^m\right) H^n\,.$$