Fundamental Interactions at Future Colliders (LFC24)

Flavour at Future e^+e^- machines

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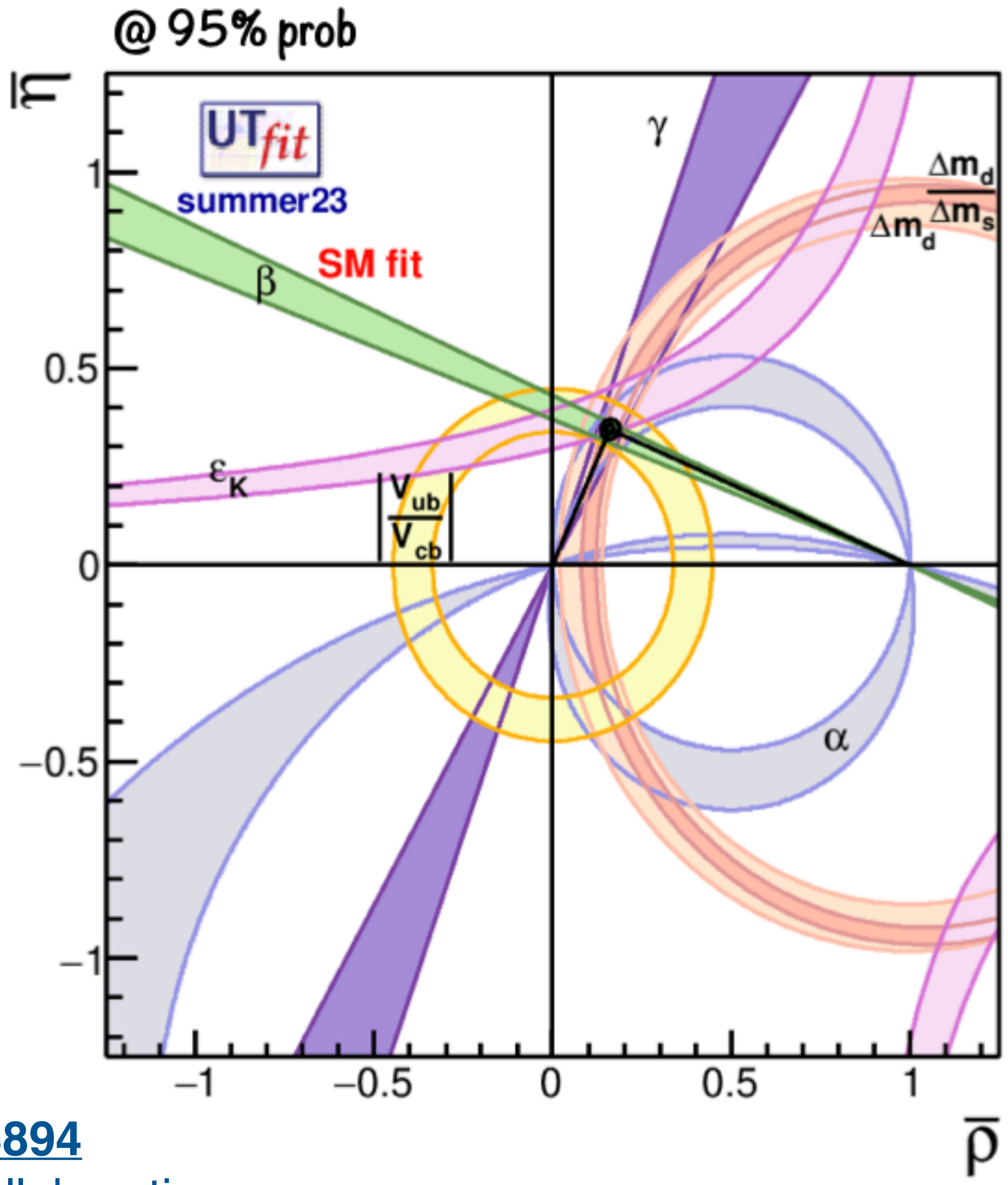
CSIC Consejo Superior de Investigaciones Científicas

The Status of Flavour Physics

Flavour Physics allows for a fantastic playground to test the Standard Model and probe for New Physics effects. The unitarity of the CKM matrix is a fundamental consistency check



$$\bar{\rho} = 0.160 \pm 0.009 \sim 6\%$$
$$\bar{\eta} = 0.346 \pm 0.009 \sim 3\%$$

$$\lambda = 0.2251 \pm 0.0008$$
$$A = 0.827 \pm 0.010$$

Wolfenstein parameters determined with ever-increasing precision, but (un)fortunately all measurements are in perfect agreement!

2212.03894
UTfit Collaboration

The Flavour NP reach

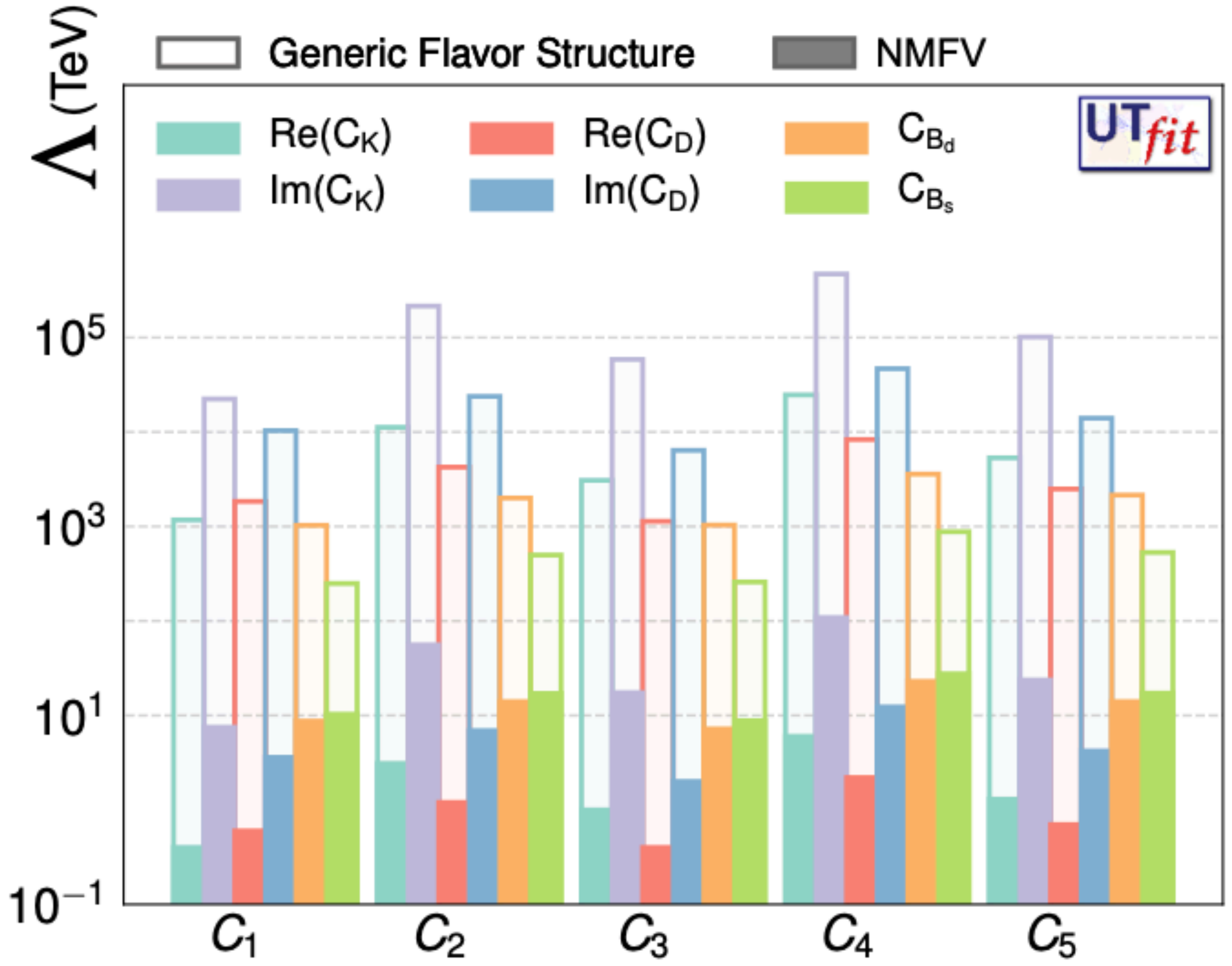
To describe heavy NP effects, it is customary to employ effective Hamiltonians, where the UV degrees of freedom are integrated out and which allow model-independent analyses

couplings parametrizing low-scale footprints of heavy degrees of freedom

$$H^{\mathrm{eff}}(x) = \sum \frac{c_{\mathcal{O}}}{\Lambda^{dim_{\mathcal{O}}-4}} \mathcal{O}(x)$$

high scale of the heavy degrees of freedom, setting as a cutoff of the eff. theory

series of local operator built as monomials in low-energies fields and derivatives



Within reach of future colliders!

FCC-ee as a B factory

In current baseline FCC-ee design, runs will yield $6 \times 10^{12}\ Z$ bosons
Enormous potential as a B factory, when compared with Belle II and LHCb

Attribute	$\Upsilon(4S)$	pp	Z^0	
All hadron species		✓	✓	
High boost		✓	✓	
Enormous production cross-section		✓		#1
Negligible trigger losses	✓		✓	
Low backgrounds	✓		✓	
Initial energy constraint	✓		(✓)	#2

#1: lack of high production x-section compensated by much larger instantaneous luminosity

#2: *b* and *c* hadrons momenta not known a priori, but their distributions are very well understood

Particle count (10^9)	$B^0(\bar{B}^0)$	$B^\pm$	$B_s^0(B_s^0)$	$B_c^\pm$	$\Lambda_b(\bar{\Lambda}_b)$	$c(\bar{c})$	$\tau^\pm$
Belle-II	55	55	0.6	N.A.	N.A.	130	90
FCC-ee	770	770	170	7	150	1400	400

Overview

- $b \to q\ell\nu$
- $b \to s\nu\nu$
- $h \to bs,\ h \to cu$
- τ Physics

Overview

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- $b \to s\nu\nu$
- $h \to bs$, $h \to cu$
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$B \to \tau\nu$: the SM status

- Helicity suppressed, tree-level decay
- Main uncertainties come from CKM elements (UTA) and decay constants (Lattice)

$$\mathcal{B}(B_q^+ \to \tau^+\nu_\tau)^{\rm SM} = \tau_{B_q^+} \frac{G_F^2 |V_{qb}|^2 f_{B_q^+}^2 m_{B_q^+} m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B_q^+}^2}\right)^2, \quad q = u, c$$

$|V_{cb}|^{\rm UTA} = 42.22(51) \times 10^{-3}, f_{B_c} = 427(6)$ MeV

$|V_{ub}|^{\rm UTA} = 3.70(11) \times 10^{-3}, f_{B^+} = 190.0(1.3)$ MeV

$$\Rightarrow \begin{aligned} \mathcal{B}(B_c^+ \to \tau^+\nu_\tau)^{\rm SM} &= 2.29(9) \times 10^{-2} \\ \mathcal{B}(B^+ \to \tau^+\nu_\tau)^{\rm SM} &= 0.87(5) \times 10^{-4} \end{aligned}$$

2212.03894
UTfit Collaboration

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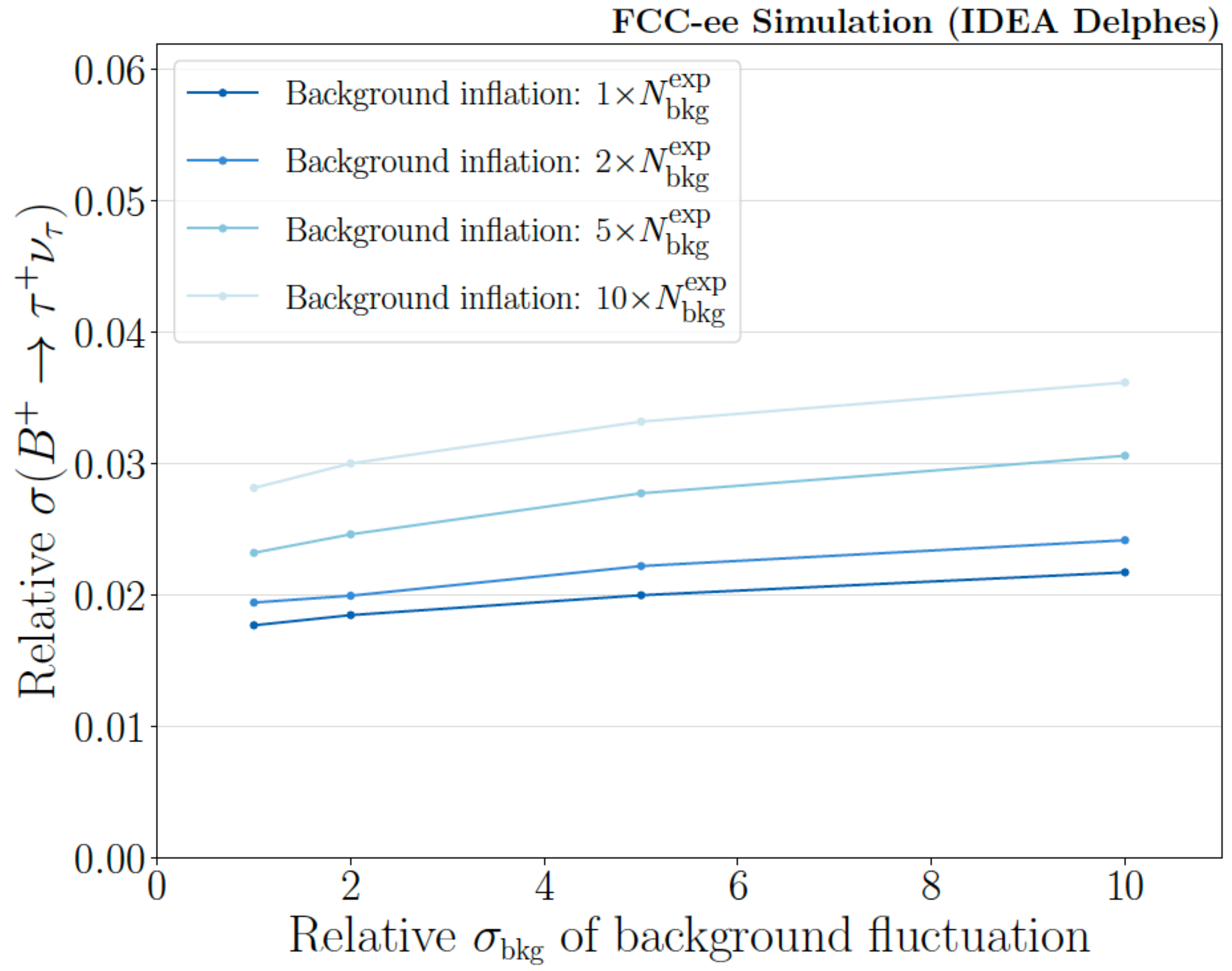
According to present Lattice estimates, decay constants errors could be halved in the next decade!

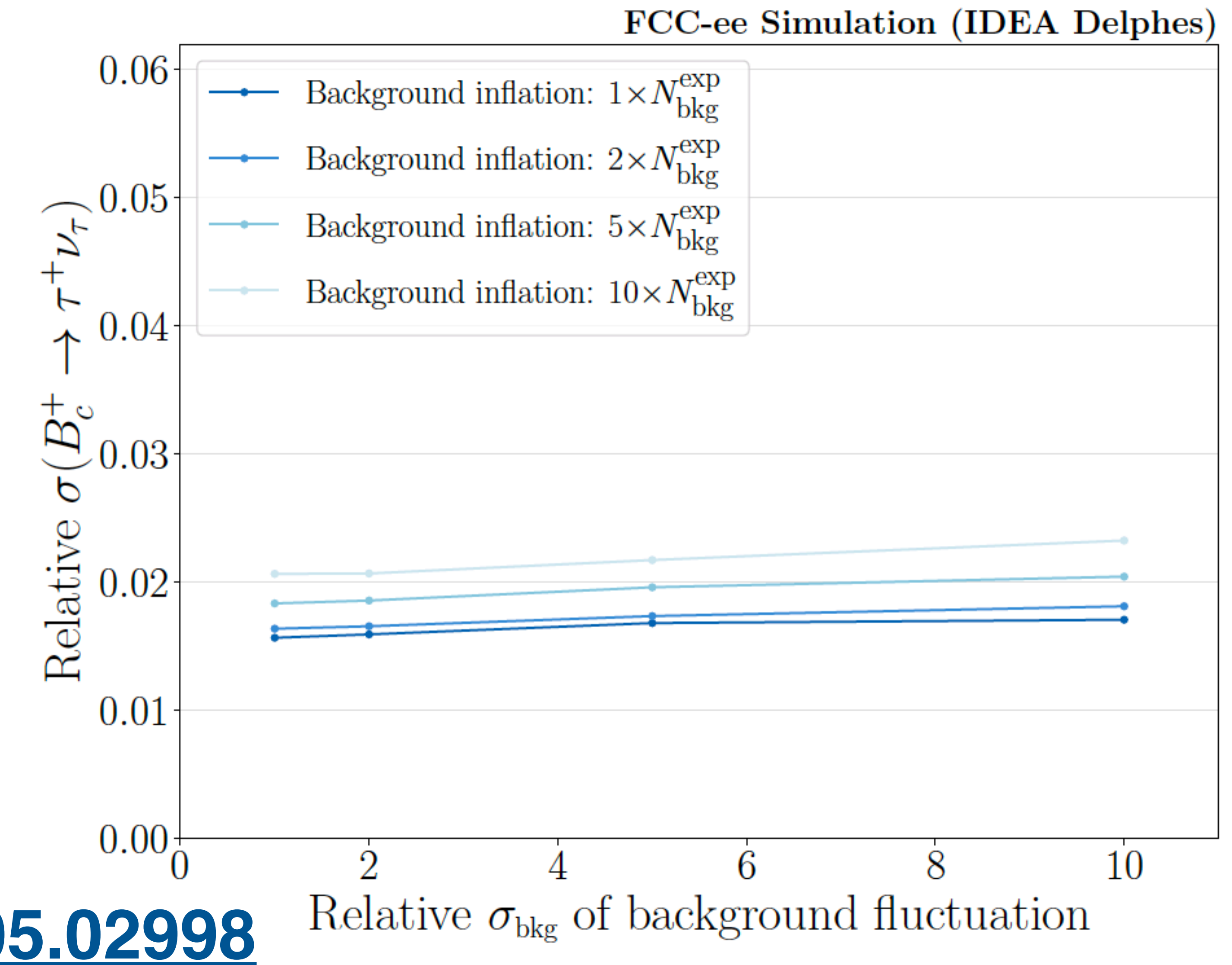
$B \to \tau\nu$ @ FCC-ee

- $B^+ \to \tau^+\nu$



Signal yield precision expected in the range $\approx 2-4\,\%$, easily translating in an analogous precision for the Br

- $B_c^+ \to \tau^+\nu$



Signal yield precision expected in the range $\approx 2\,\%$, not easily translating in an analogous precision for the Br due to poor knowledge of hadronisation fraction $f(B_c^\pm)$. Strategy:

$$\mathscr{R} = \frac{N(B_c^+ \to \tau^+\nu_\tau)}{N(B_c^+ \to J/\psi\mu^+\nu_\mu)} = \frac{\mathscr{B}(B_c^+ \to \tau^+\nu_\tau)}{\mathscr{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

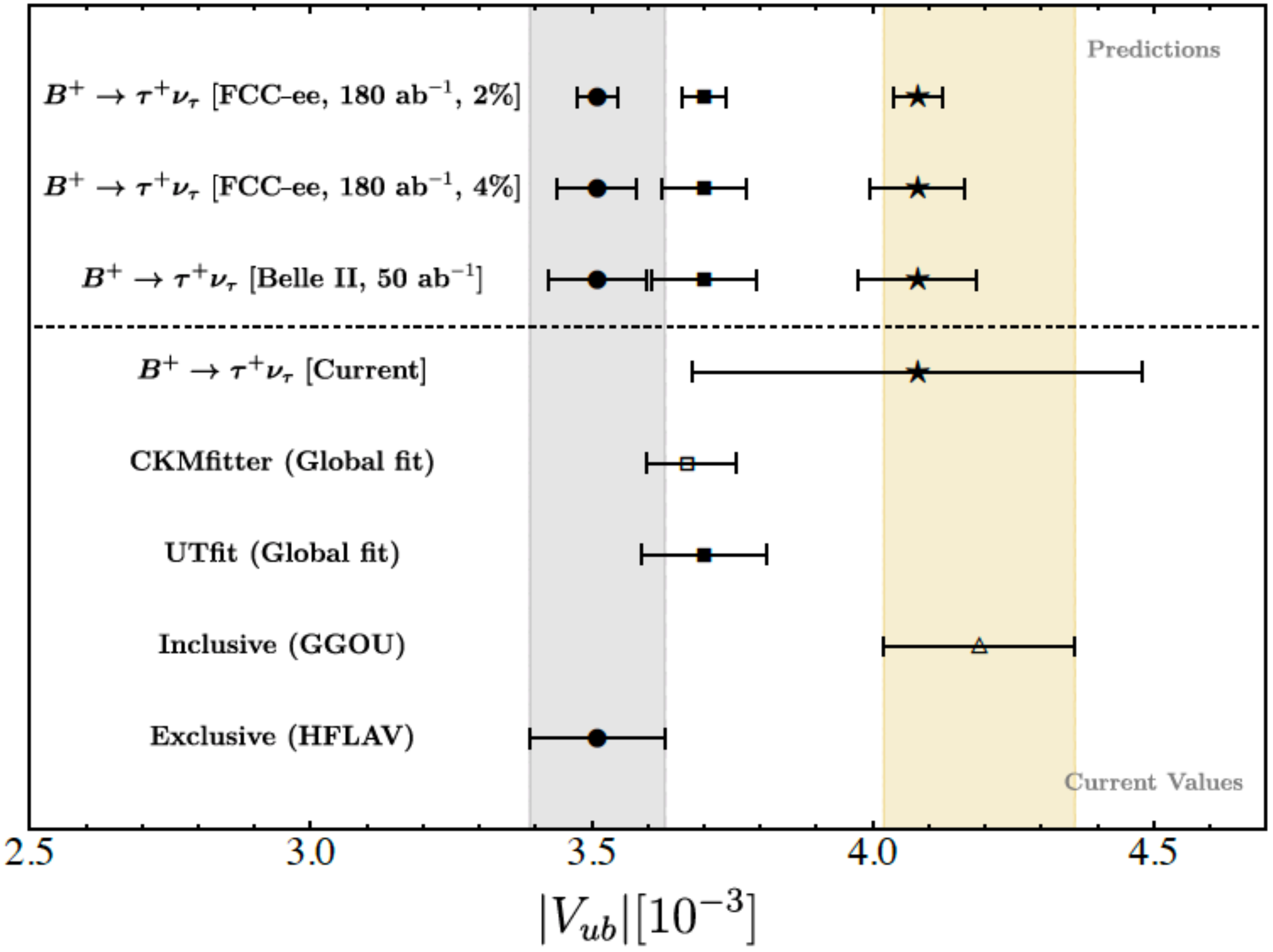
It is possible to extract the Br modulo CKM multiplying by

$$\Gamma_{\rm theo}(B_c^+ \to J/\psi\mu^+\nu_\mu)/|V_{cb}|^2$$

2305.02998
Zuo, MF, Helsen, Hill, Iguro, Klute

$|V_{ub}|$ from $B \to \tau\nu$ at FCC-ee

The direct measurement of $B^+ \to \tau^+\nu$ allows for an excl. determination of $|V_{ub}|$ from this channel



Potential to play a role in the determination of $|V_{ub}^{\text{excl.}}|$ in the future, contrary to present situation!

2305.02998
Zuo, MF, Helsen, Hill, Iguro, Klute

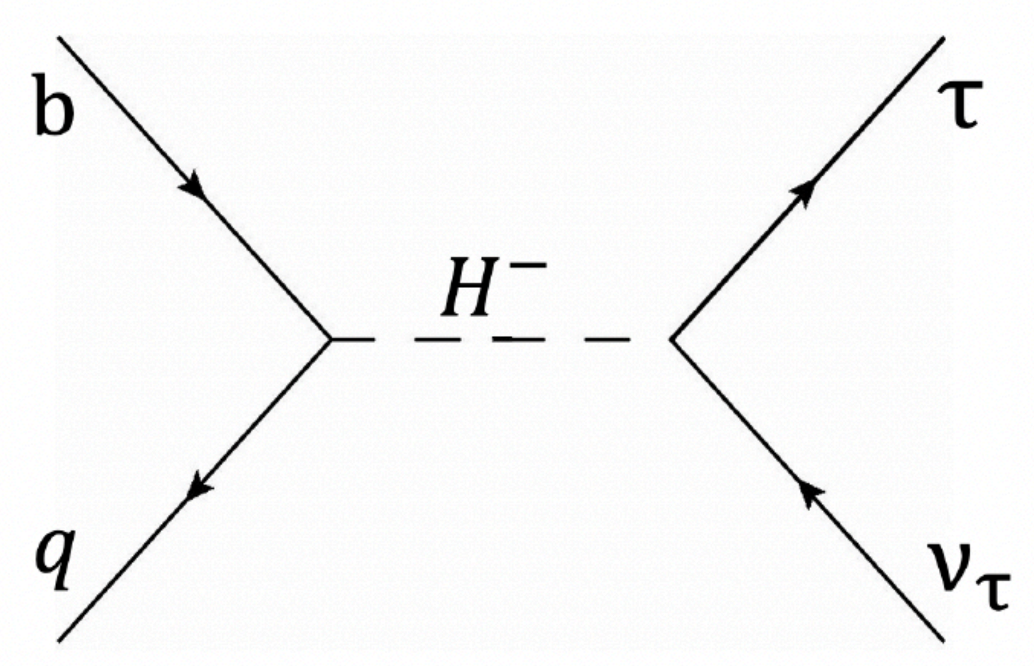
$B \to \tau\nu$: NP implications

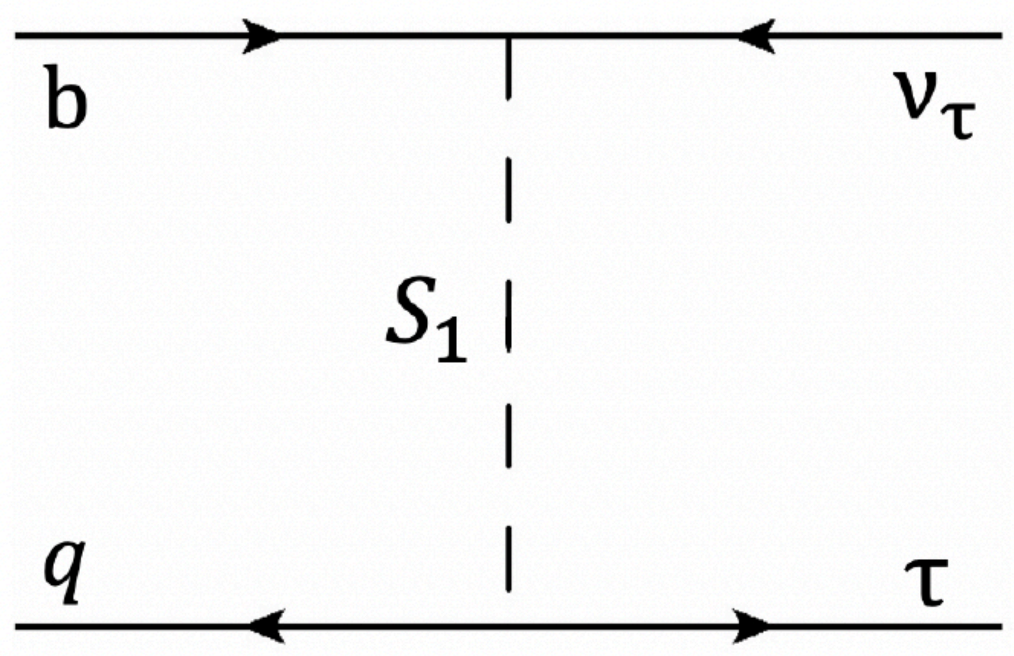
Extremely sensitive to scalar BSM extensions (2HDM, LQ), which lift helicity suppression

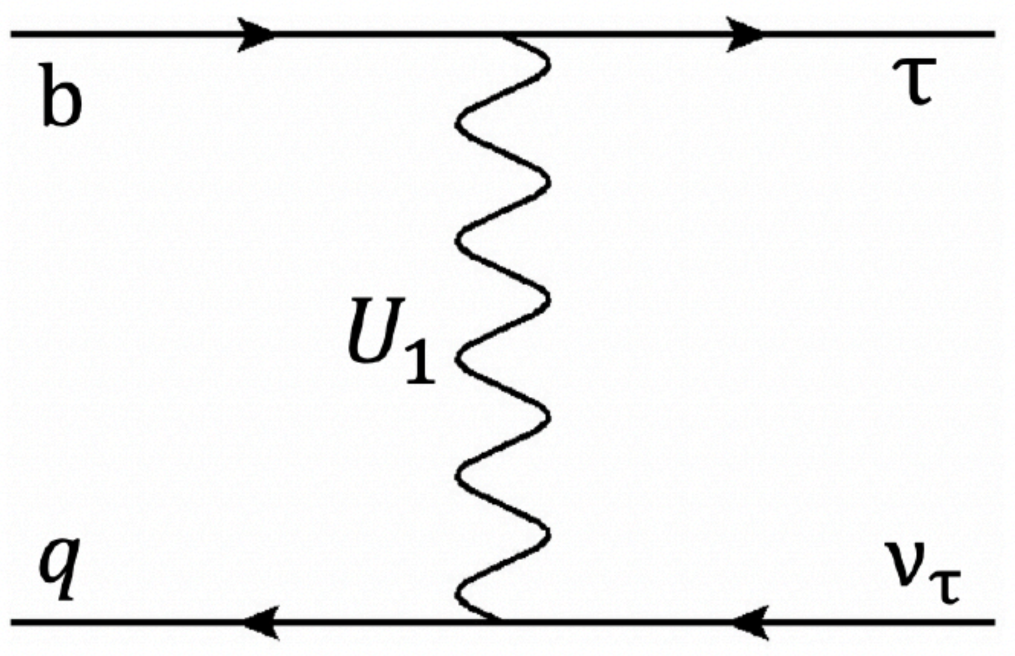
$$\mathcal{B}(B_q^+ \to \tau^+\nu_\tau) = \mathcal{B}(B_q^+ \to \tau^+\nu_\tau)^{\rm SM} \times \left| 1 - (C^q_{V_R} - C^q_{V_L}) + (C^q_{S_R} - C^q_{S_L}) \frac{m^2_{B_q}}{m_\tau(m_b + m_q)} \right|^2$$

$$O_{V_{L(R)}} = (\bar{q}_{L(R)}\gamma_\mu b_{L(R)})(\bar{\tau}_L\gamma_\mu\nu_L)$$

$$O_{S_{L(R)}} = (\bar{q}_{R(L)} b_{L(R)})(\bar{\tau}_R\nu_L)$$





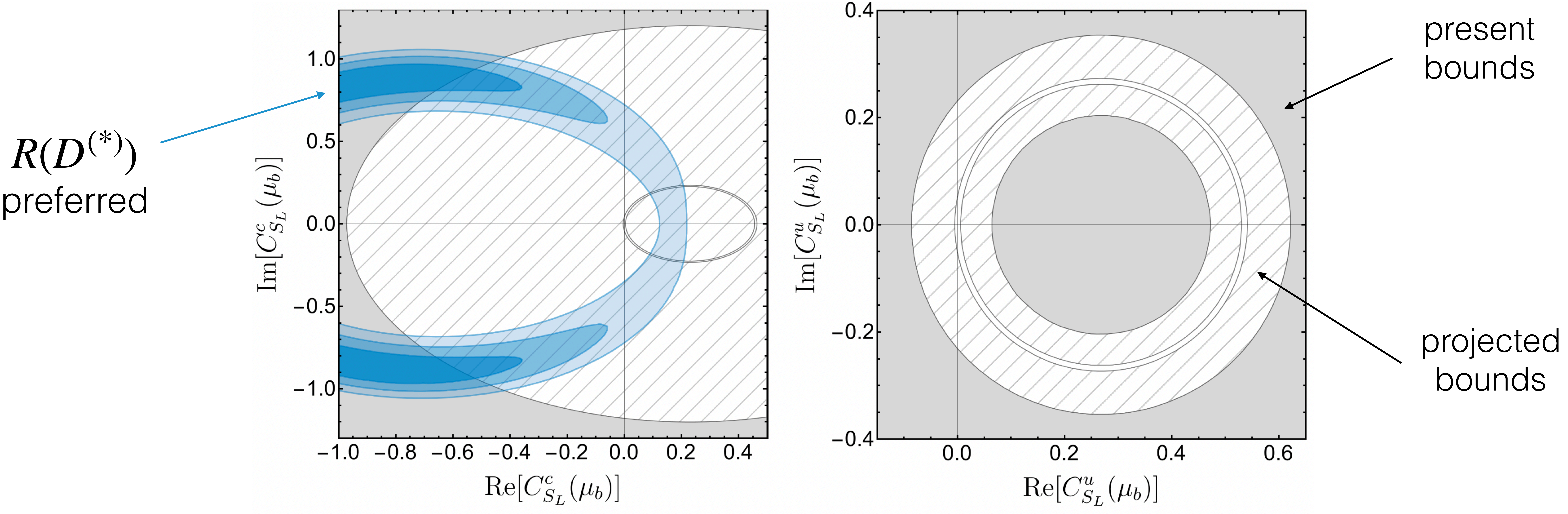


[**2305.02998**](https://arxiv.org/abs/2305.02998)

Zuo, MF, Helsen, Hill, Iguro, Klute

$B \to \tau\nu$: G2HDM

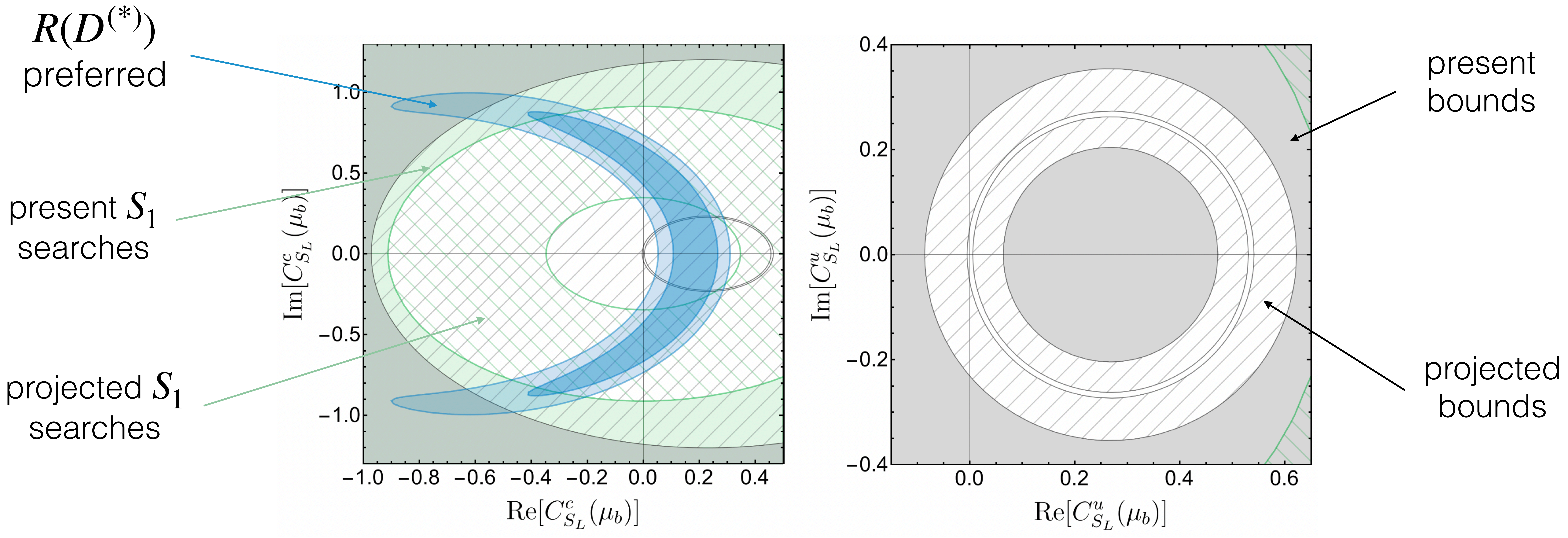
$$\mathscr{L}_{\rm G2HDM} \supset y_Q^q H^-(\bar{b}P_R q) - y_\tau H^-(\bar{\tau}P_L\nu_\tau) + \text{h.c.} \qquad \Rightarrow \qquad C_{S_L}^q = \frac{1}{2\sqrt{2}G_F V_{qb}} \frac{y_Q^{q*} y_\tau}{m_{H^-}^2}$$



[2305.02998](https://arxiv.org/abs/2305.02998)
Zuo, MF, Helsen, Hill, Iguro, Klute

$B \to \tau\nu$: S_1 Leptoquark

$$\mathscr{L}_{S_1} = y_L^{ij}\overline{Q_i^C} i\tau_2 L_j S_1 + y_R^{ij}\overline{u_{Ri}^C} l_{Rj} S_1 + \text{h.c.} \quad \Rightarrow \quad C_{S_L}^q(\mu_{LQ}) = -4C_T^q(\mu_{LQ}) = -\frac{1}{4\sqrt{2}G_F V_{qb}} \frac{y_L^{b\nu}\left(y_R^*\right)^{q\tau}}{m_{S_1}^2}$$



2305.02998
Zuo, MF, Helsen, Hill, Iguro, Klute

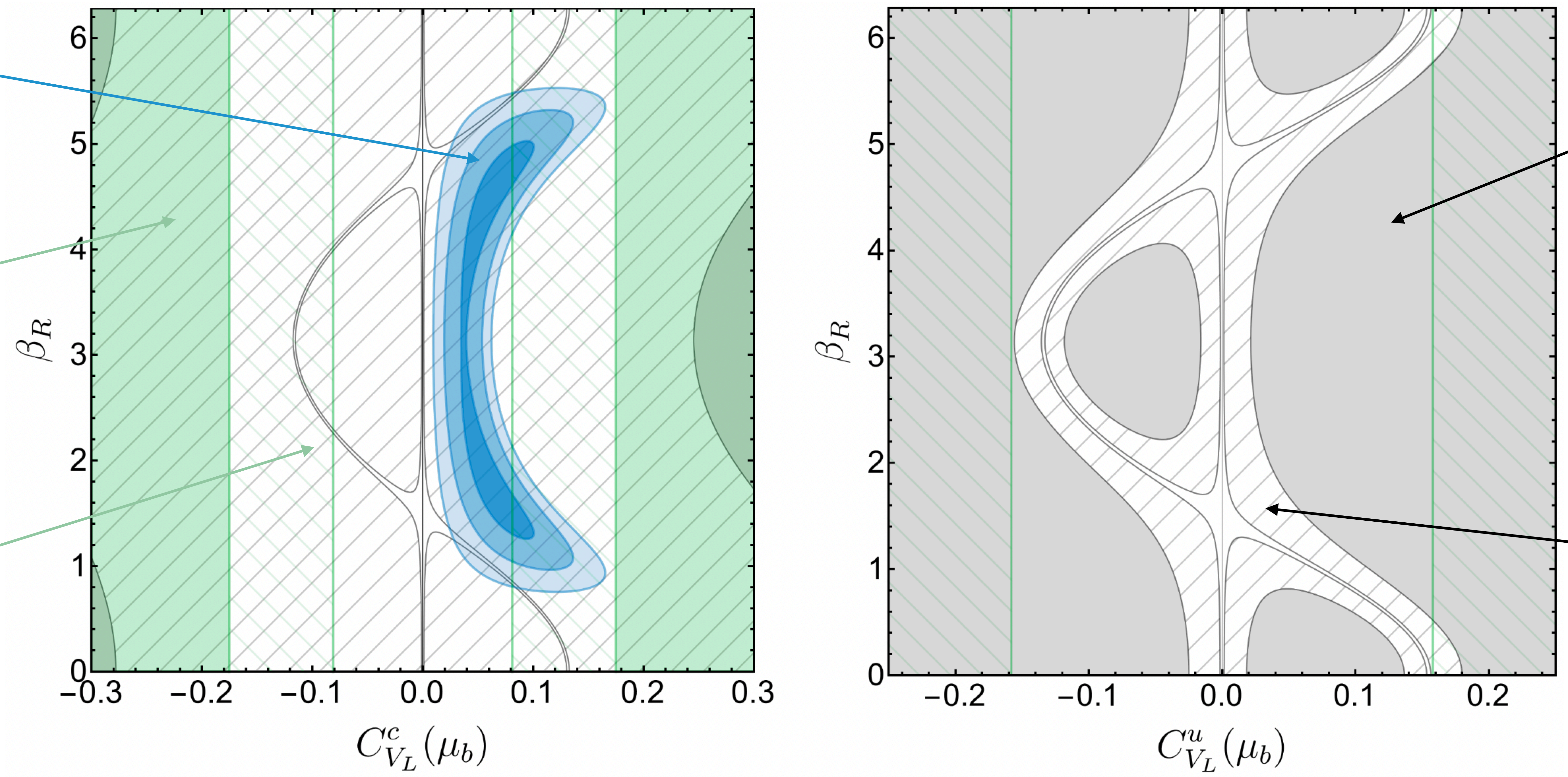
$B \to \tau\nu$: U_1 Leptoquark

$$\mathscr{L}_{U_1} = \hat{z}_L^{ij}\overline{Q}_i\gamma_\mu L_j U_1^\mu + \hat{z}_R^{ij}\overline{d}_{Ri}\gamma_\mu l_{Rj} U_1^\mu + \text{h.c.} \qquad \Rightarrow \qquad C_{V_L}^q(\mu_{\rm LQ}) = \frac{\left(Vz_L\right)^{q\tau}\left(z_L^*\right)^{b\tau}}{2\sqrt{2}G_F V_{qb} m_{U_1}^2}, \quad C_{S_R}^q(\mu_{\rm LQ}) = -\frac{\left(Vz_L\right)^{q\tau}\left(z_R^*\right)^{b\tau}}{\sqrt{2}G_F V_{qb} m_{U_1}^2}$$

$R(D^{(*)})$ preferred

present U_1 searches

projected U_1 searches



present bounds

projected bounds

U_1 would be the gauge boson of a new U(2) interacting only with SM 3rd gen.

$\hat{z}_L^{b\tau} = \hat{z}_R^{b\tau}$ implies, in the mass basis, $z_R^{b\tau} = e^{-i\beta_R} z_L^{b\tau}$

2305.02998
Zuo, MF, Helsen, Hill, Iguro, Klute

1909.02519
Fuentes-Martin, Isidori, Pagès, Yamamoto

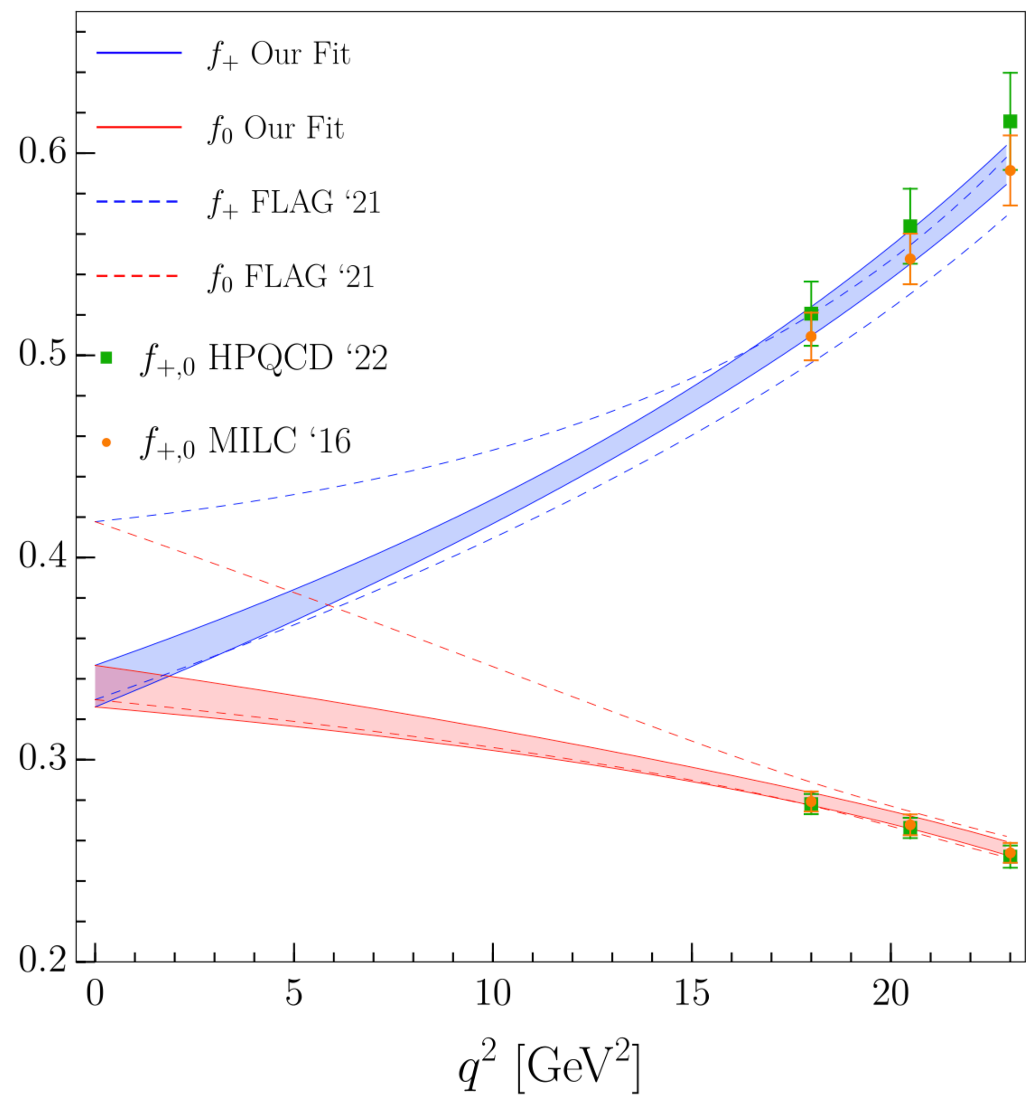
Overview

- $b \to q\ell\nu$
- $b \to s\nu\nu$
- $h \to bs,\ h \to cu$
- τ Physics

$B \to K^{(*)}\nu\nu$: the SM status

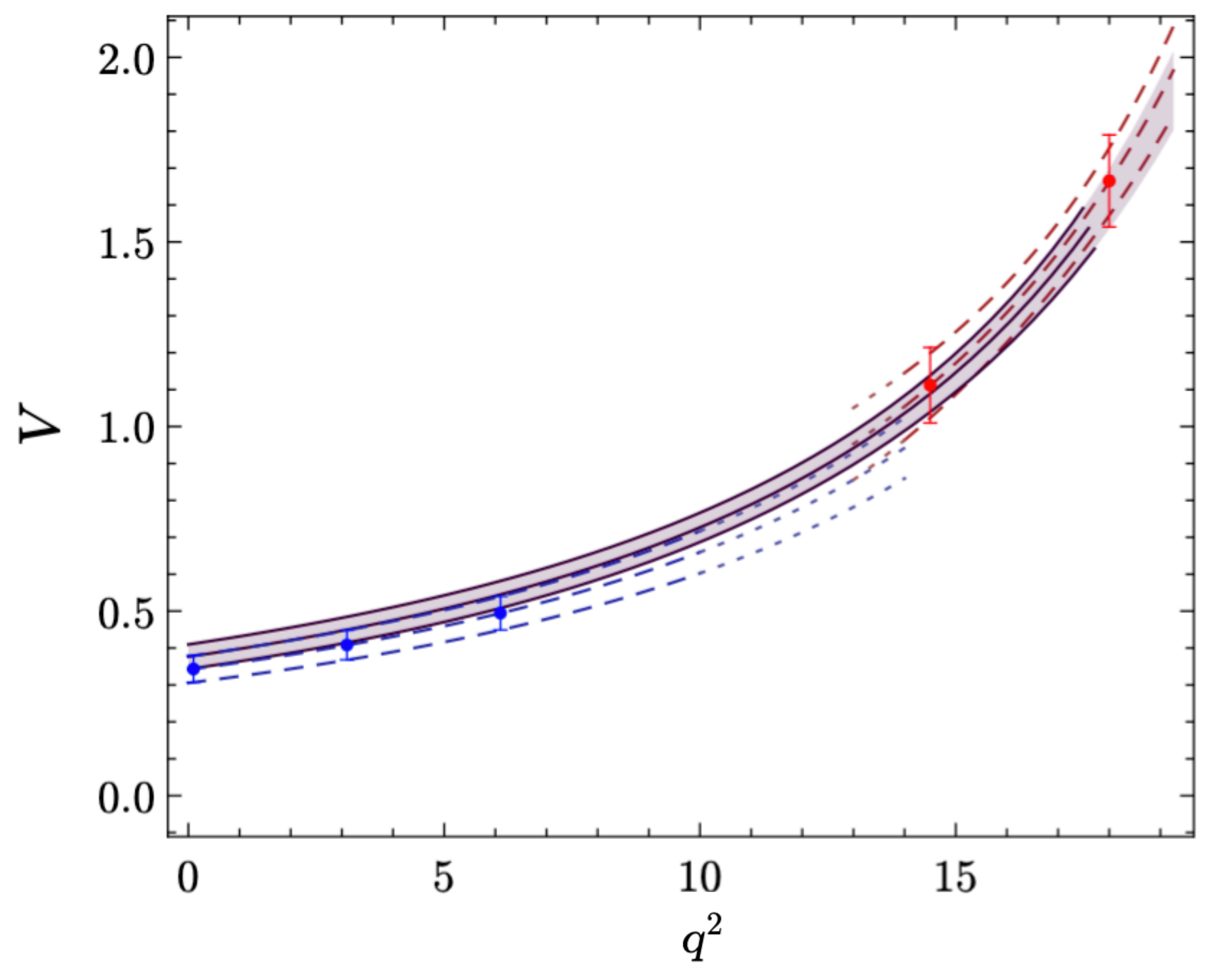
- Loop-level decay dominated by short-distance effects (C_L), negligible long-distance
- Main uncertainties come from CKM elements $|\lambda_t| = |V_{tb}V_{ts}^*|$ (UTA) and Form Factors (Lattice)

$$\langle \bar{K}(k)|\bar{s}\gamma^\mu b|\bar{B}(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_K^2}{q^2}q^\mu\right]f_+(q^2) + \frac{m_B^2 - m_K^2}{q^2}q^\mu f_0(q^2)$$



$$\langle K^*(k,\varepsilon)|\bar{c}\gamma_\mu b|\bar{B}(p)\rangle = -i\epsilon_{\mu\nu\alpha\beta}\varepsilon^{*\nu}p^\alpha k^\beta \frac{2V(q^2)}{m_B + m_{K^*}}$$

$$\langle K^*(k,\varepsilon)|\bar{c}\gamma_\mu\gamma_5 b|\bar{B}(p)\rangle = \varepsilon_\mu^*(m_B + m_{K^*})A_1(q^2) - (p+k)_\mu(\varepsilon^* q)\frac{A_2(q^2)}{m_B + m_{K^*}}$$
$$-q_\mu(\varepsilon^* q)\frac{2m_{K^*}}{q^2}\left[\frac{m_B + m_{K^*}}{2m_{K^*}}A_1(q^2) - \frac{m_B - m_{K^*}}{2m_{K^*}}A_2(q^2) - A_0(q^2)\right]$$



2301.06990
Bečirević, Piazza, Sumensari

1503.05534
Bharucha, Straub, Zwicky

$B \to K^{(*)}\nu\nu$: the SM status

$$\frac{d\mathcal{B}}{dq^2}(B \to K\nu\bar{\nu}) = \mathcal{N}_K(q^2)\,|C_L^{\rm SM}|^2\,|\lambda_t|^2\,\left[f_+(q^2)\right]^2$$

$$\frac{d\mathcal{B}}{dq^2}(B \to K^*\nu\bar{\nu}) = \mathcal{N}_{K^*}(q^2)|C_L^{\rm SM}|^2|\lambda_t|^2\mathcal{F}(q^2)$$

$$\mathcal{O}_L^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j)$$

$$\mathcal{O}_R^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}(\bar{s}_R\gamma_\mu b_R)(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j)$$

$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) \times 10^6$	$\sigma_{\mathcal{B}_{K^+}}/\mathcal{B}_{K^+}$	$\mathcal{B}(B^0 \to K_S\nu\bar{\nu}) \times 10^6$	$\sigma_{\mathcal{B}_{K_S}}/\mathcal{B}_{K_S}$
$(5.06 \pm 0.14 \pm 0.28)$	0.06	$(2.05 \pm 0.07 \pm 0.12)$	0.07

$\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu}) \times 10^6$	$\sigma_{\mathcal{B}_{K^{*+}}}/\mathcal{B}_{K^{*+}}$	$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu}) \times 10^6$	$\sigma_{\mathcal{B}_{K^{*0}}}/\mathcal{B}_{K^{*0}}$
$(10.86 \pm 1.30 \pm 0.59)$	0.12	$(9.05 \pm 1.25 \pm 0.55)$	0.15

2301.06990
Bečirević, Piazza, Sumensari

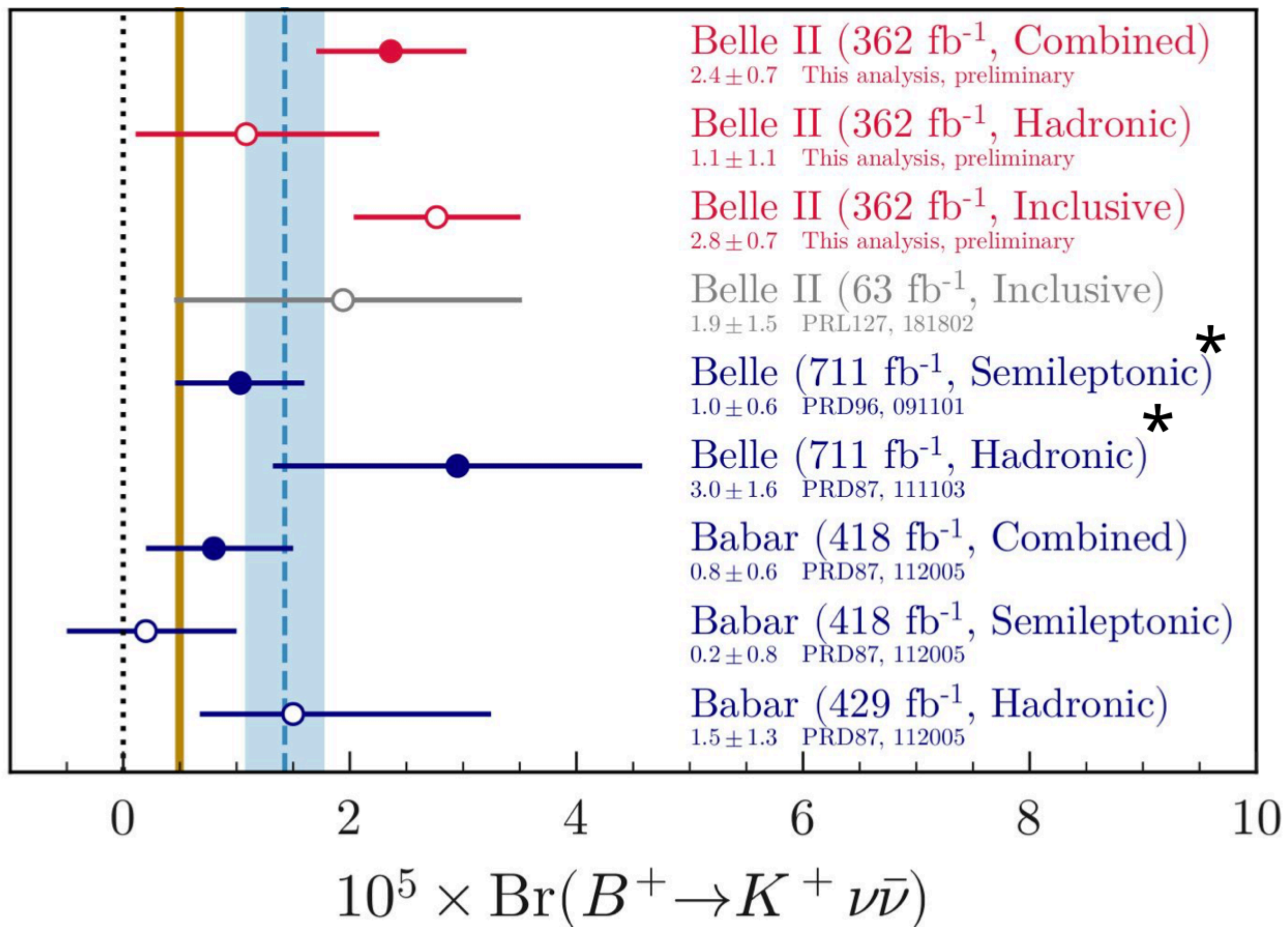
$B \to K^{(*)}\nu\nu$: the current NP status

Sensitive to BSM effect on both left-handed and right-handed operator

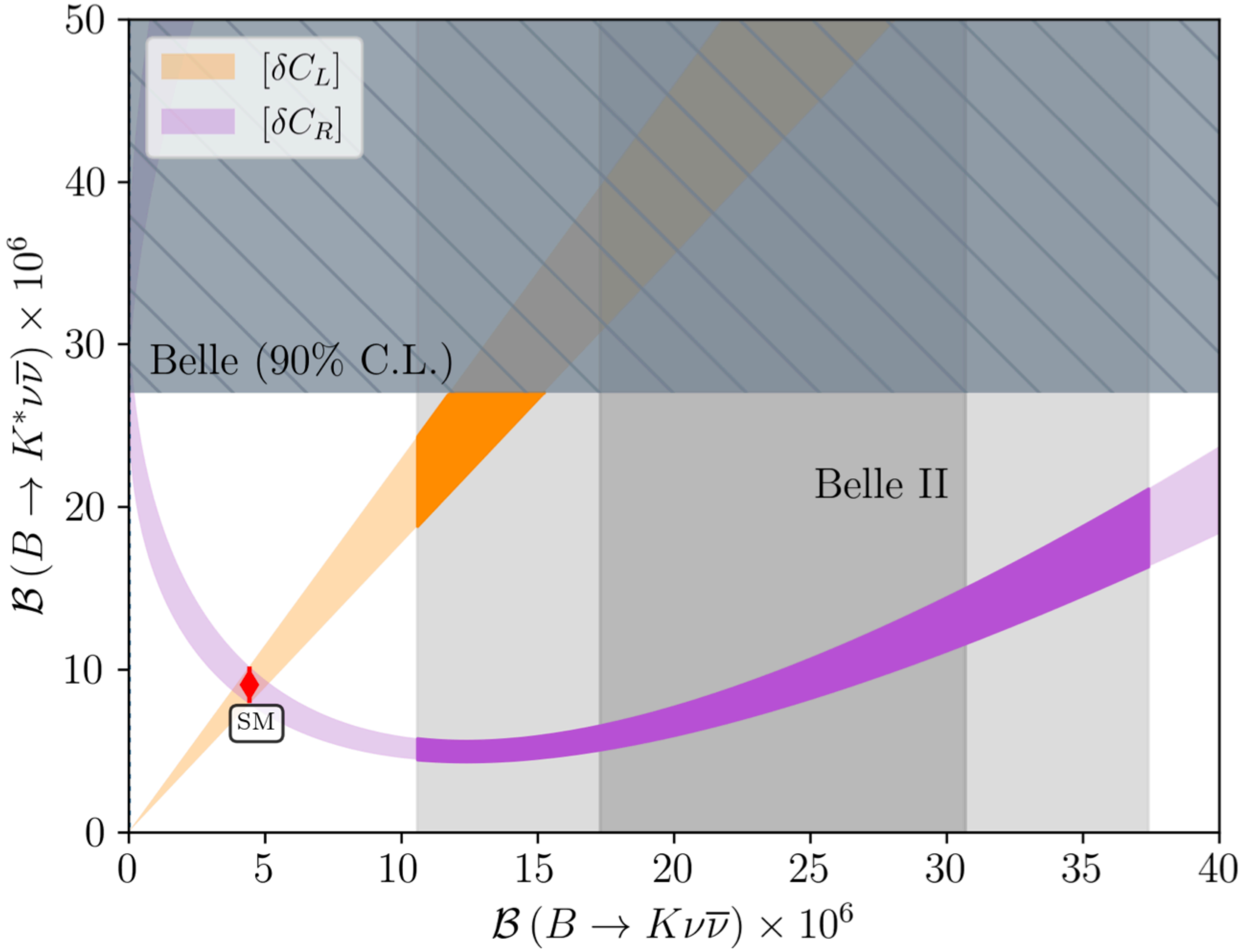
$$\frac{d\mathcal{B}(B \to K^* \nu\bar{\nu})}{dq^2} = 3\,\tau_B |N_B|^2 |\lambda_t|^2 \left(|C_L - C_R|^2(\rho_{A_1}^{K^*} + \rho_{A_{12}}^{K^*}) + |C_L + C_R|^2 \rho_V^{K^*}\right)$$

$\rho_i \propto f_i$

$$\frac{d\mathcal{B}(B \to K \nu\bar{\nu})}{dq^2} = 3\,\tau_B\,|N_B|^2 |C_L + C_R|^2 |\lambda_t|^2 \rho_+^K$$



$\Rightarrow$



2311.14647
Belle II

2309.02246
Allwicher, Bečirević, Piazza, Rosauro-Alcaraz, Sumensari

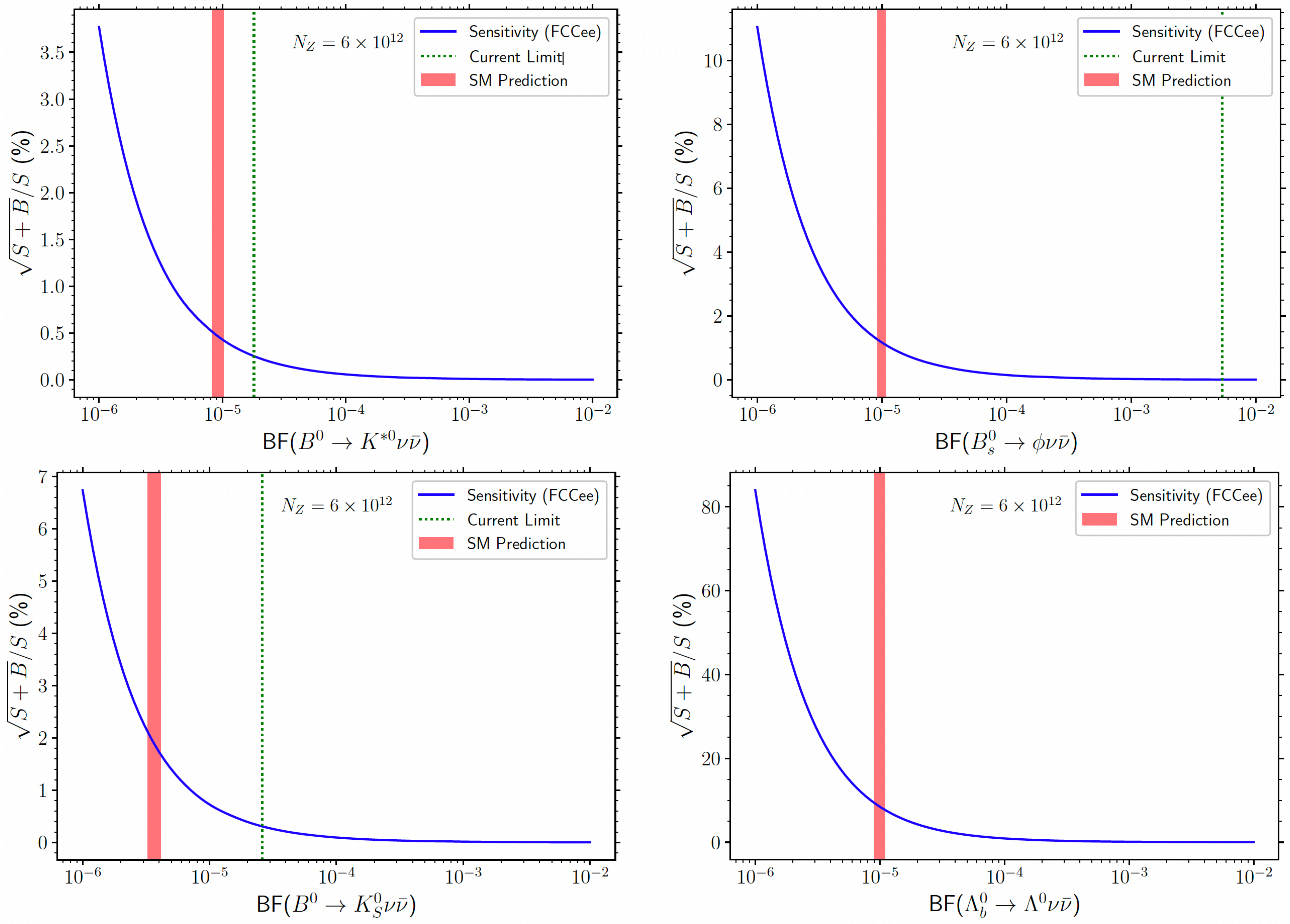
Possible interpretation also in terms of weakly interacting light NP (axions)

$B^0 \to H^0 \nu\nu$ @ FCC-ee

Sensitivity study performed on B^0 decays in Hadron + neutrinos

~ 0.53 %

~ 1.20 %



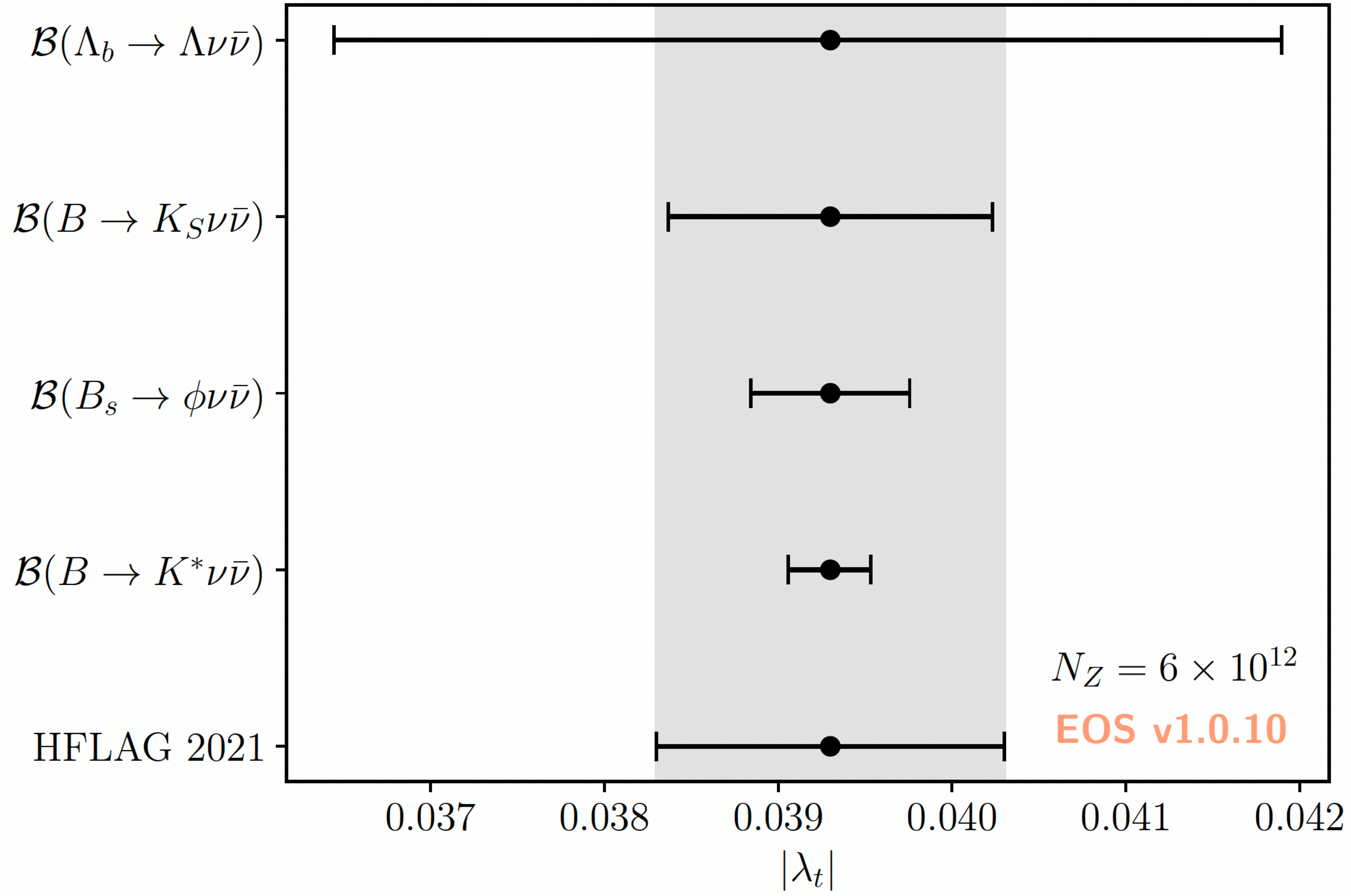
~ 3.37 %

~ 9.86 %

2309.11353
Amhis, Kenzie, Reboud, Wiederhold

$|\lambda_t|$ from $B^0 \to H^0\nu\nu$ @ FCC-ee

Several independent measurements for $|\lambda_t|$ form the different hadronic channels



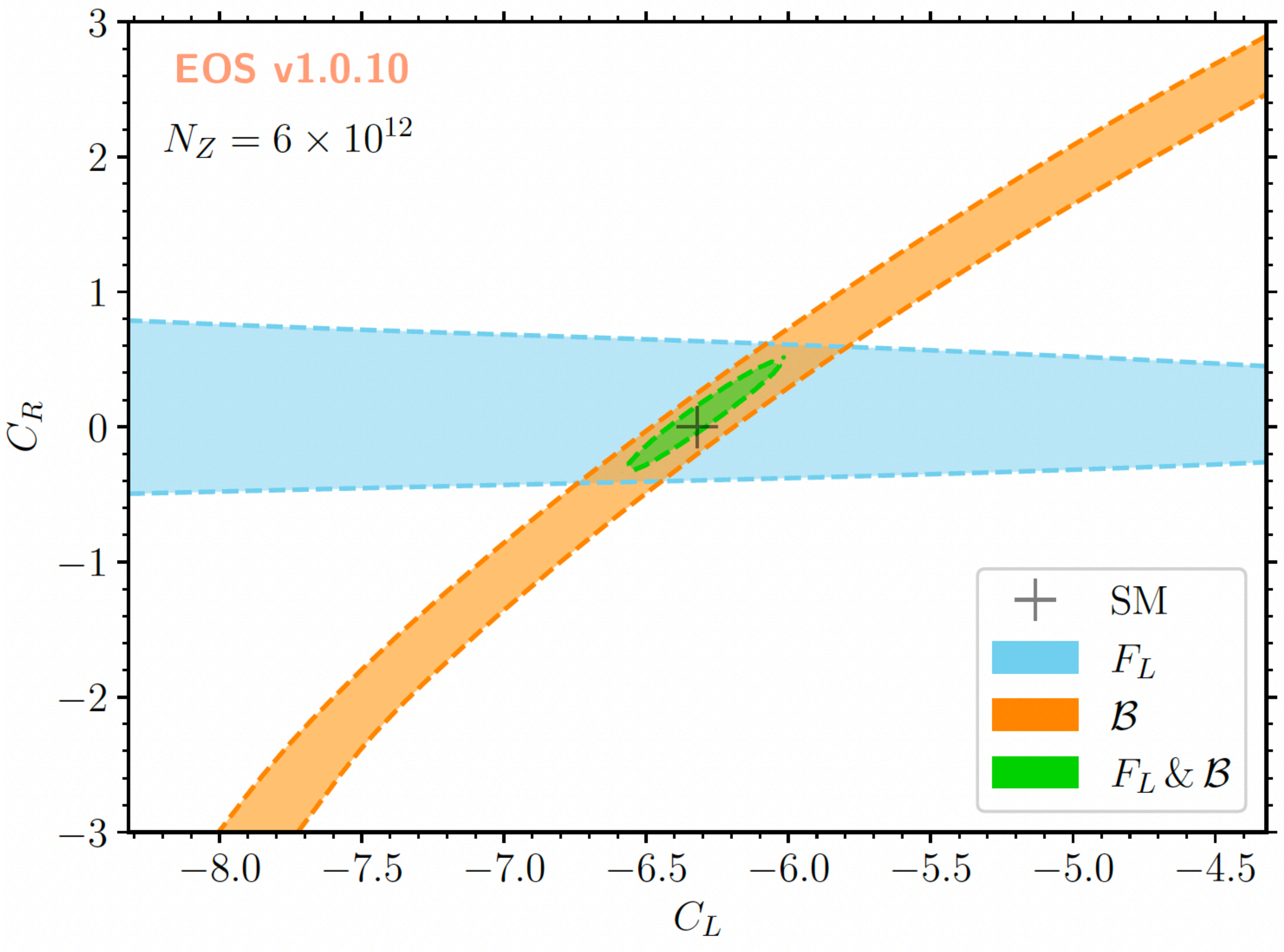
HFLAG value based on unitarity and $|V_{cb}| = (40.0 \pm 1.0) \times 10^{-3}$ from $B \to D\ell\nu$

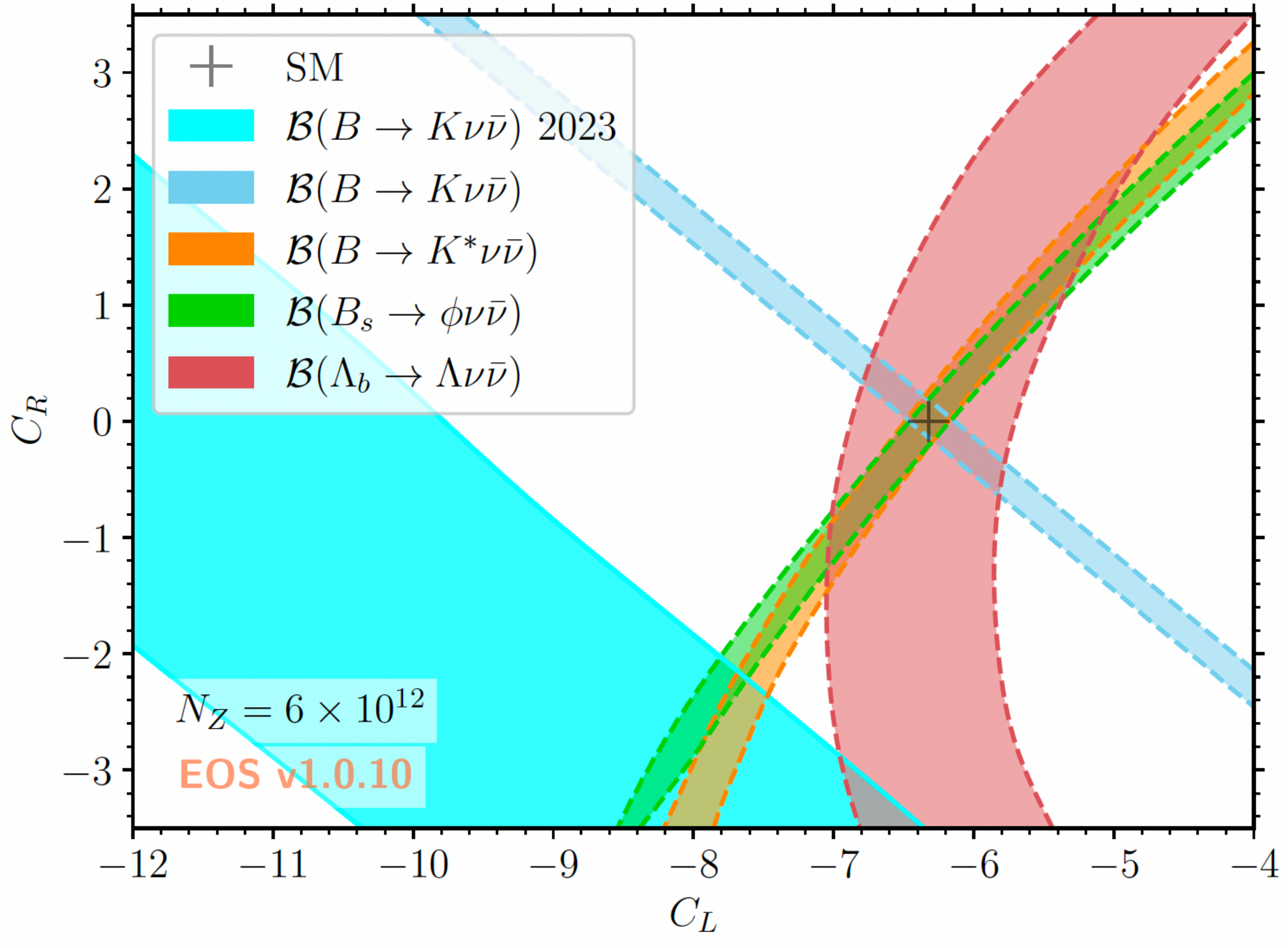
2309.11353

Amhis, Kenzie, Reboud, Wiederhold

$B^0 \to H^0\nu\nu$: the future NP status

Different channels constrain differently (but complementarily) the NP WCs





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Amhis, Kenzie, Reboud, Wiederhold

Overview

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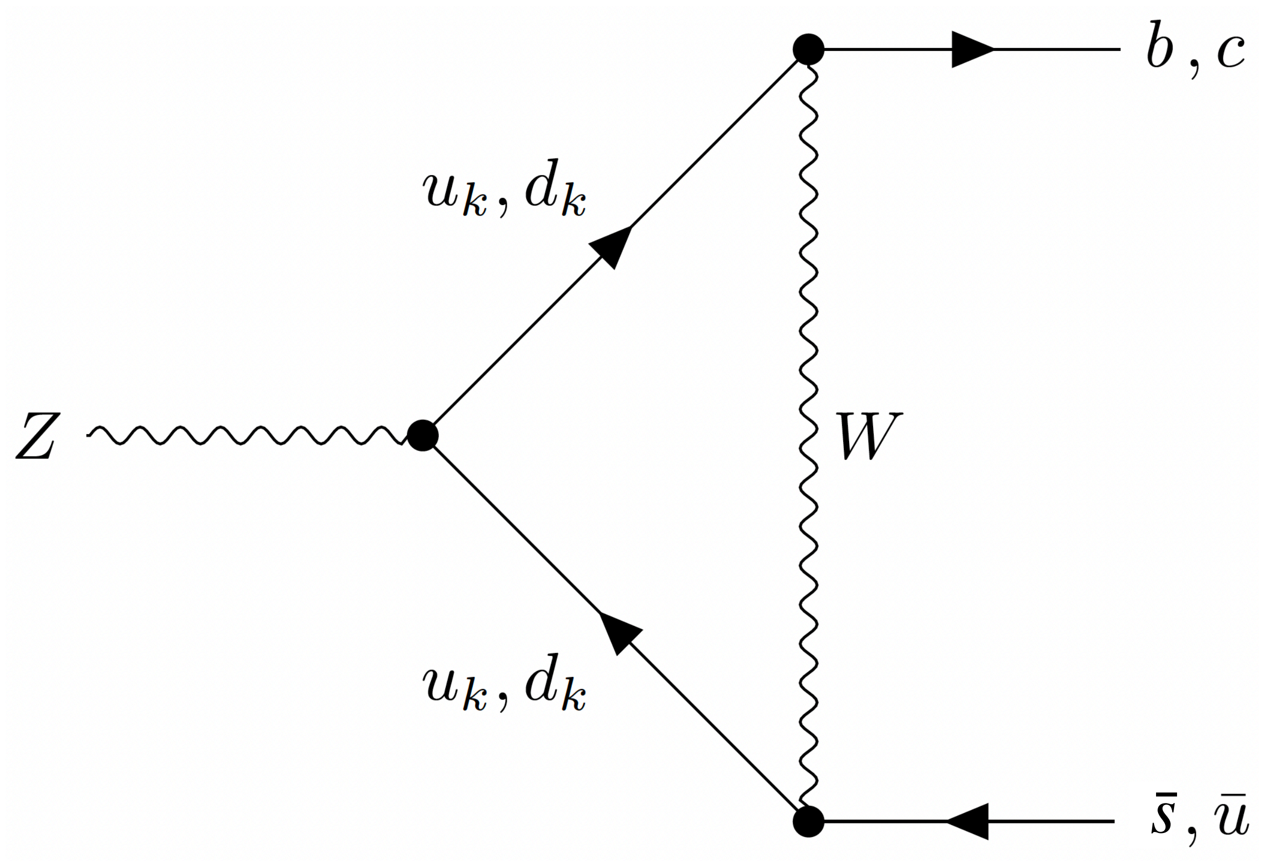
$h/Z \to q\bar{q}'$ decays: the SM status

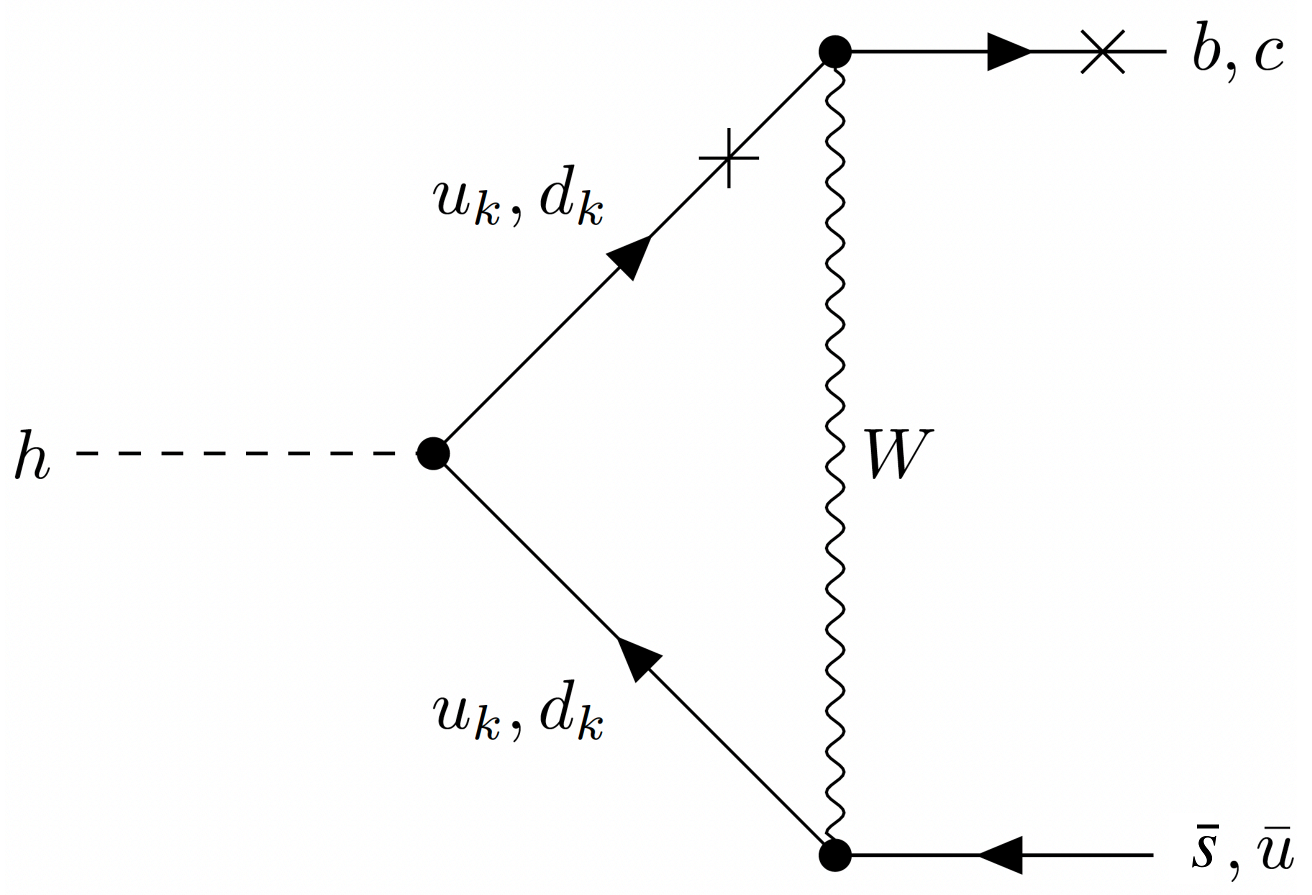
- Loop-level decay suppressed by GIM mechanism, requiring two mass insertions for the higgs
- Main uncertainties come from CKM elements (UTA) and higher order QCD corrections

$$\Gamma(h/Z \to q\bar{q}') = N_C \frac{|\overline{M}(h/Z \to q\bar{q}')|^2}{16\pi m_{h/z}}$$



$$\overline{M}_{\text{NDA}}(Z \to b\bar{s}) \sim g^3 m_Z \frac{V_{tb}V_{ts}^*}{(4\pi)^2}$$

$$\overline{M}_{\text{NDA}}(Z \to c\bar{u}) \sim g^3 m_Z \sum_{k=d,s,b} \left(\frac{m_k}{m_Z}\right)^2 \frac{V_{ck}V_{uk}^*}{(4\pi)^2}$$

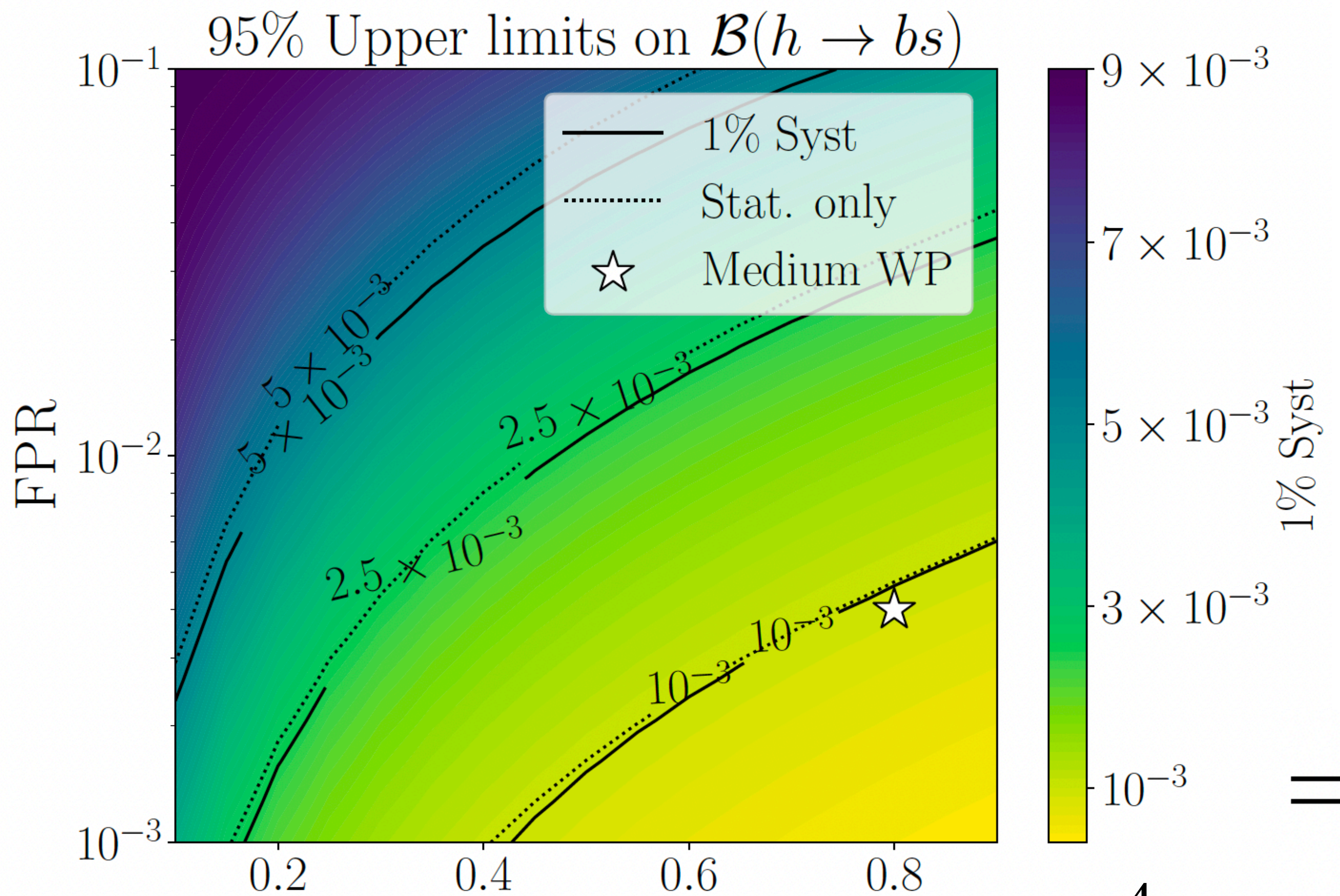


$$\overline{M}_{\text{NDA}}(h \to b\bar{s}) \sim g^2 m_h y_b y_t^2 \frac{V_{tb}V_{ts}^*}{(4\pi)^2}$$

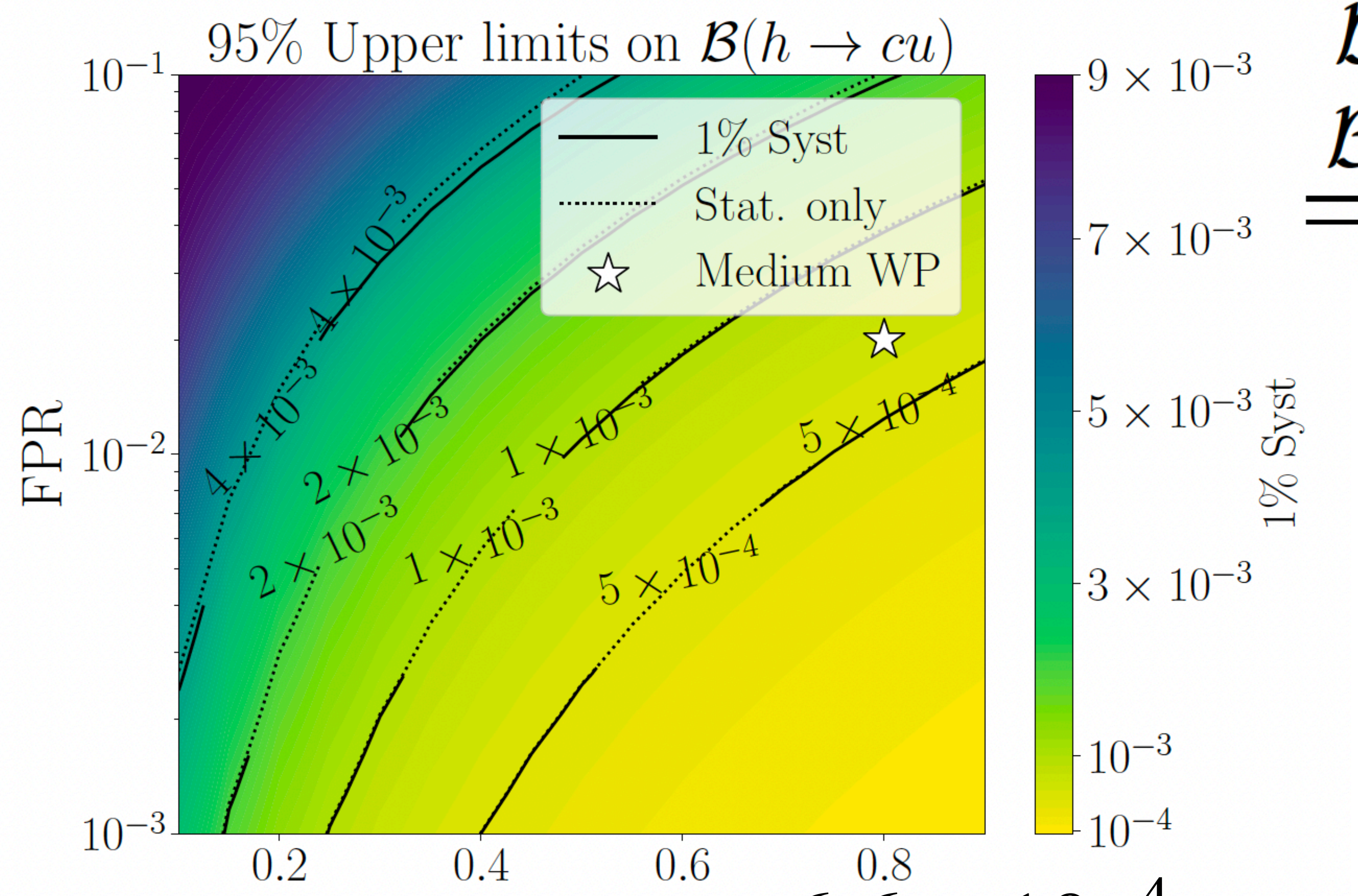
$$\overline{M}_{\text{NDA}}(h \to c\bar{u}) \sim g^2 m_h y_c \sum_{k=d,s,b} y_k^2 \frac{V_{ck}V_{uk}^*}{(4\pi)^2}$$

2306.17520
Kamenik, Korajac, Szewc, Tammaro, Zupan

$h/Z \to q\bar{q}'$ decays @ FCC-ee



$\sim 9.6 \times 10^{-4}$

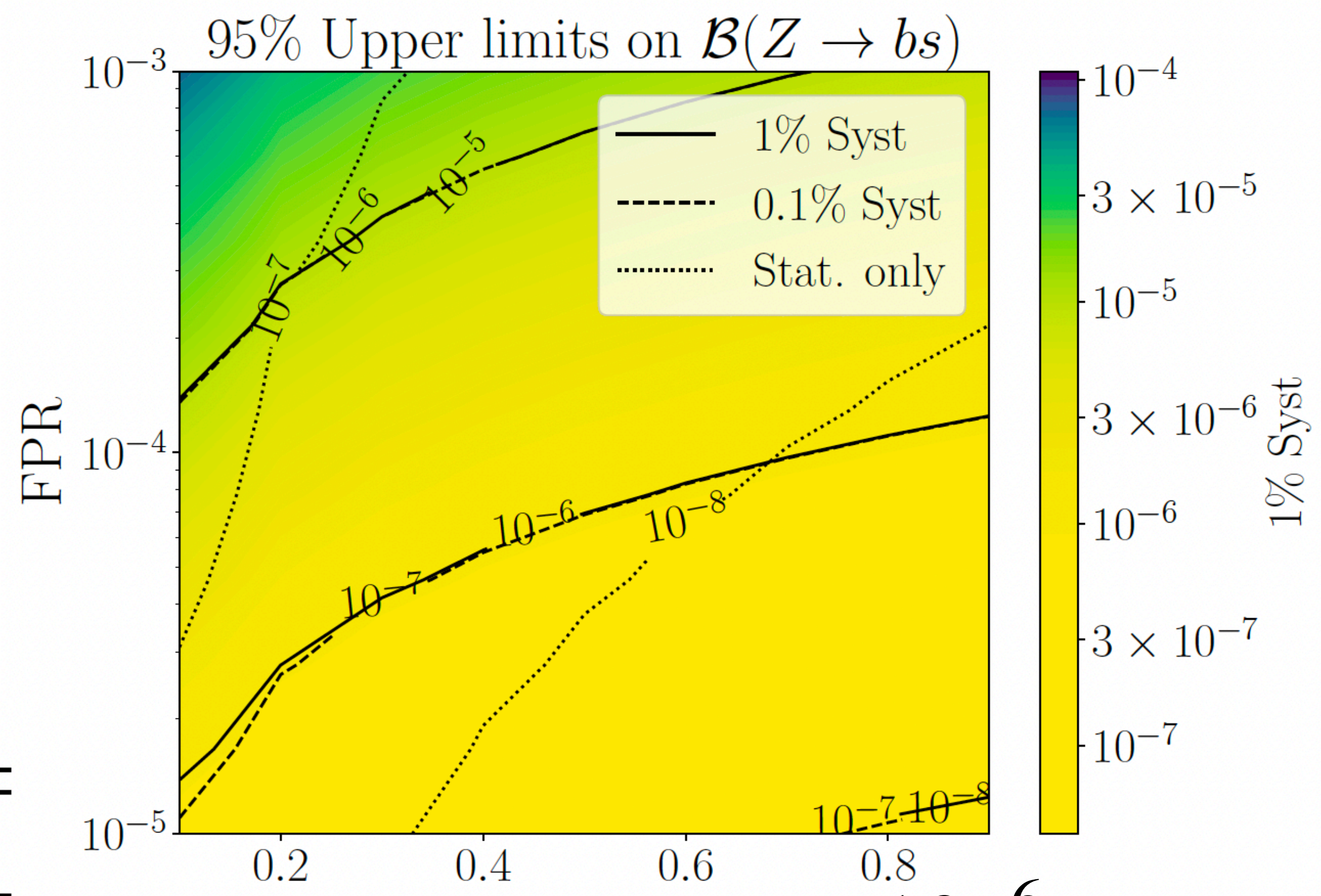


$\sim 6.6 \times 10^{-4}$

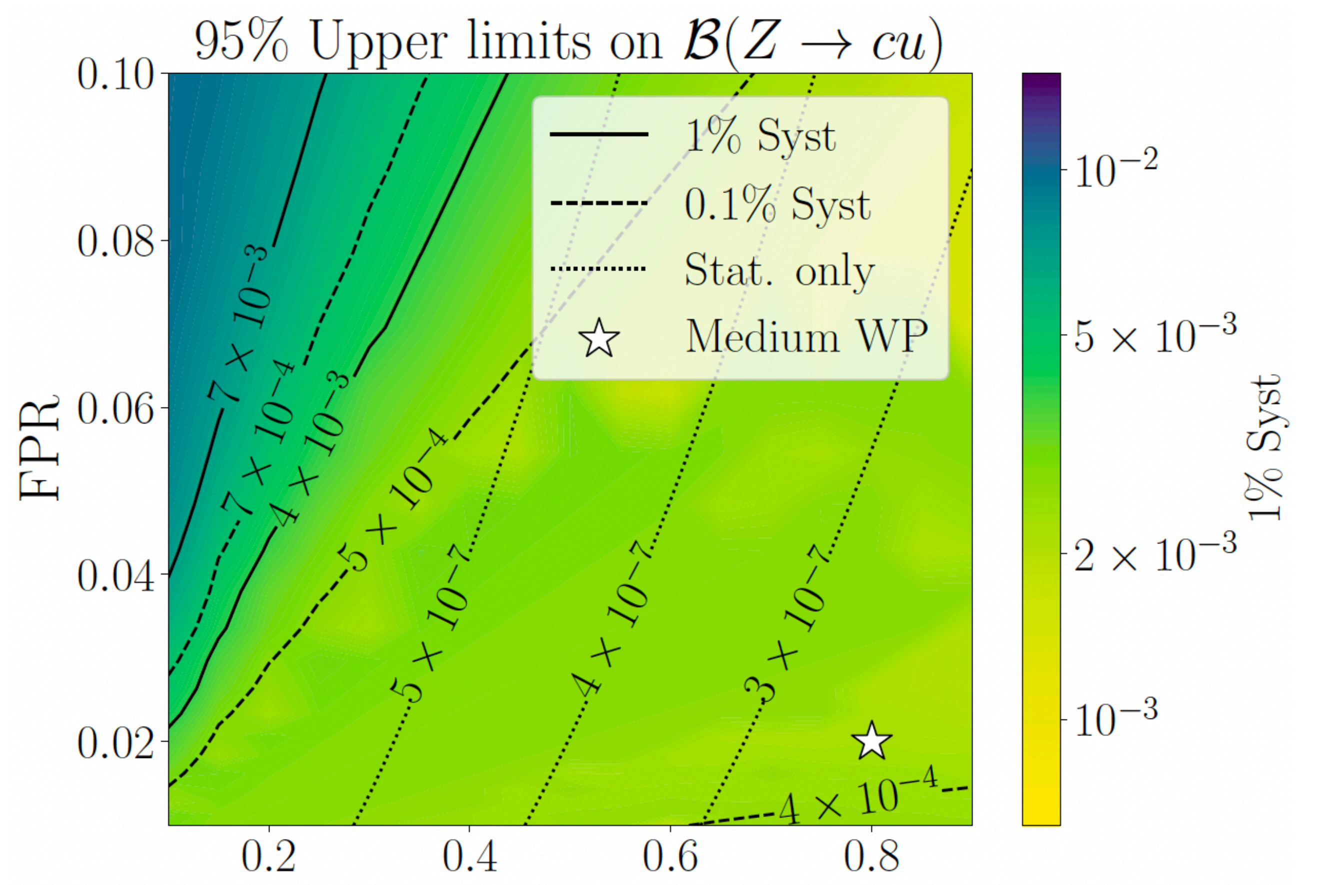
direct searches

mesons mixing/decays

Decay	SM prediction	exp. bound	indir. constr.
$\mathcal{B}(h \to bs)$	$(8.9 \pm 1.5) \cdot 10^{-8}$	0.16	2×10^{-3}
$\mathcal{B}(h \to cu)$	$(2.7 \pm 0.5) \cdot 10^{-20}$	0.16	2×10^{-2}
$\mathcal{B}(Z \to bs)$	$(4.2 \pm 0.7) \cdot 10^{-8}$	2.9×10^{-3}	6×10^{-8}
$\mathcal{B}(Z \to cu)$	$(1.4 \pm 0.2) \cdot 10^{-18}$	2.9×10^{-3}	4×10^{-7}



$\sim 10^{-6}$



$\sim 2 \times 10^{-3}$

Obtained reaches strongly depend on performances of *b*-, *c*-, *s*- and *u*-taggers!

2306.17520
Kamenik, Korajac, Szewc, Tammaro, Zupan

$h \to q\bar{q}'$ decays: 2HDM implications @ FCC-ee

$$\mathcal{L}_{\rm 2HDM} \supset -\frac{\sqrt{2}m_i}{v}\delta_{ij}\bar{q}_L^i H_1 d_R^j - \sqrt{2}\,Y_{ij}^d\,\bar{q}_L^i H_2 d_R^j - \frac{\sqrt{2}m_i}{v}\delta_{ij}\bar{q}_L'^i \tilde{H}_1 u_R^j - \sqrt{2}\,Y_{ij}^u\,\bar{q}_L'^i \tilde{H}_2 u_R^j$$

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + iA) \end{pmatrix}$$

mass basis $\Rightarrow$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix}\begin{pmatrix} h \\ H \end{pmatrix}$$

After integrating out heavy scalars, contributions to meson mixing through

$$C_2 = -\frac{\left(Y_{bs}^{d*}\right)^2}{2}\left(\frac{s_\alpha^2}{m_h^2} + \frac{c_\alpha^2}{m_H^2} - \frac{1}{m_A^2}\right),$$

$$C_2' = -\frac{\left(Y_{sb}^{d}\right)^2}{2}\left(\frac{s_\alpha^2}{m_h^2} + \frac{c_\alpha^2}{m_H^2} - \frac{1}{m_A^2}\right),$$

$$C_4 = -\left(Y_{bs}^{d*}Y_{sb}^{d}\right)\left(\frac{s_\alpha^2}{m_h^2} + \frac{c_\alpha^2}{m_H^2} + \frac{1}{m_A^2}\right).$$

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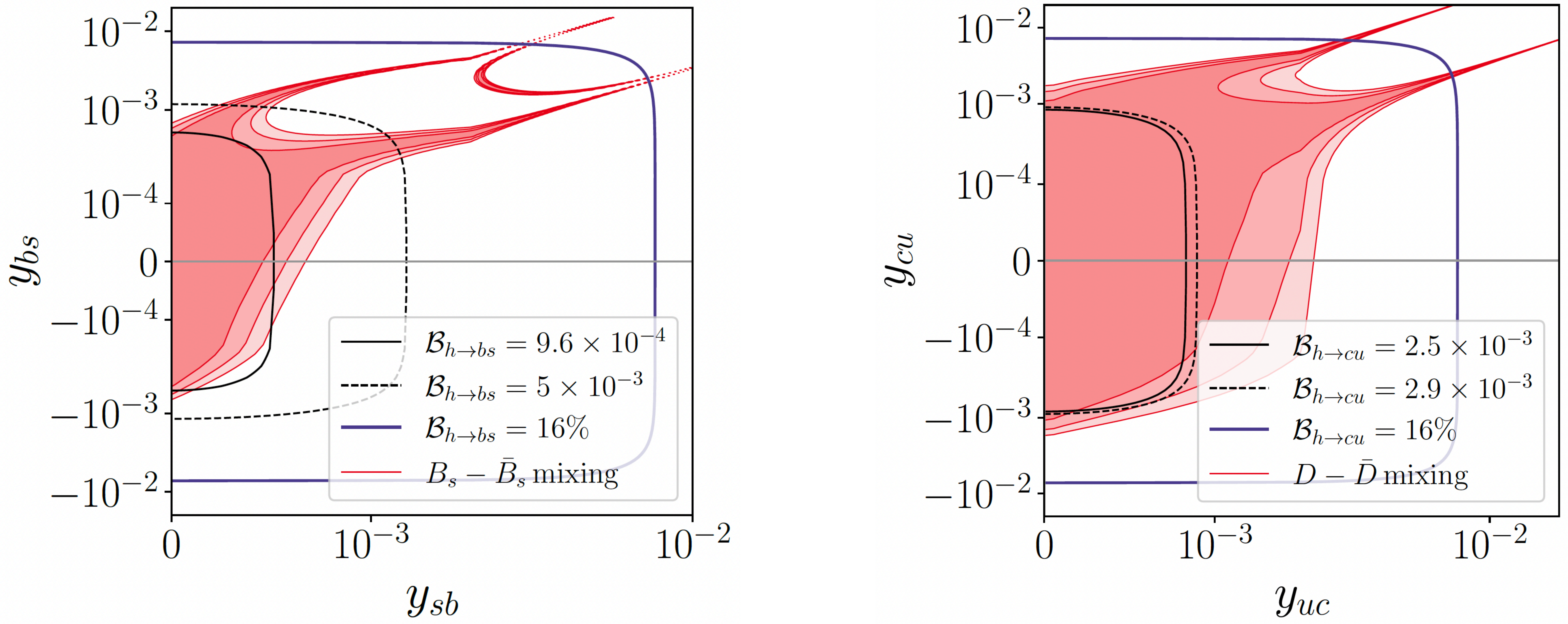
$h \to q\bar{q}'$ decays: 2HDM implications @ FCC-ee

1st limit: H and A contributions numerically small, $y_{bs,sb} = Y^d_{bs,sb} s_\alpha, \qquad y_{cu,uc} = Y^u_{cu,uc} s_\alpha$



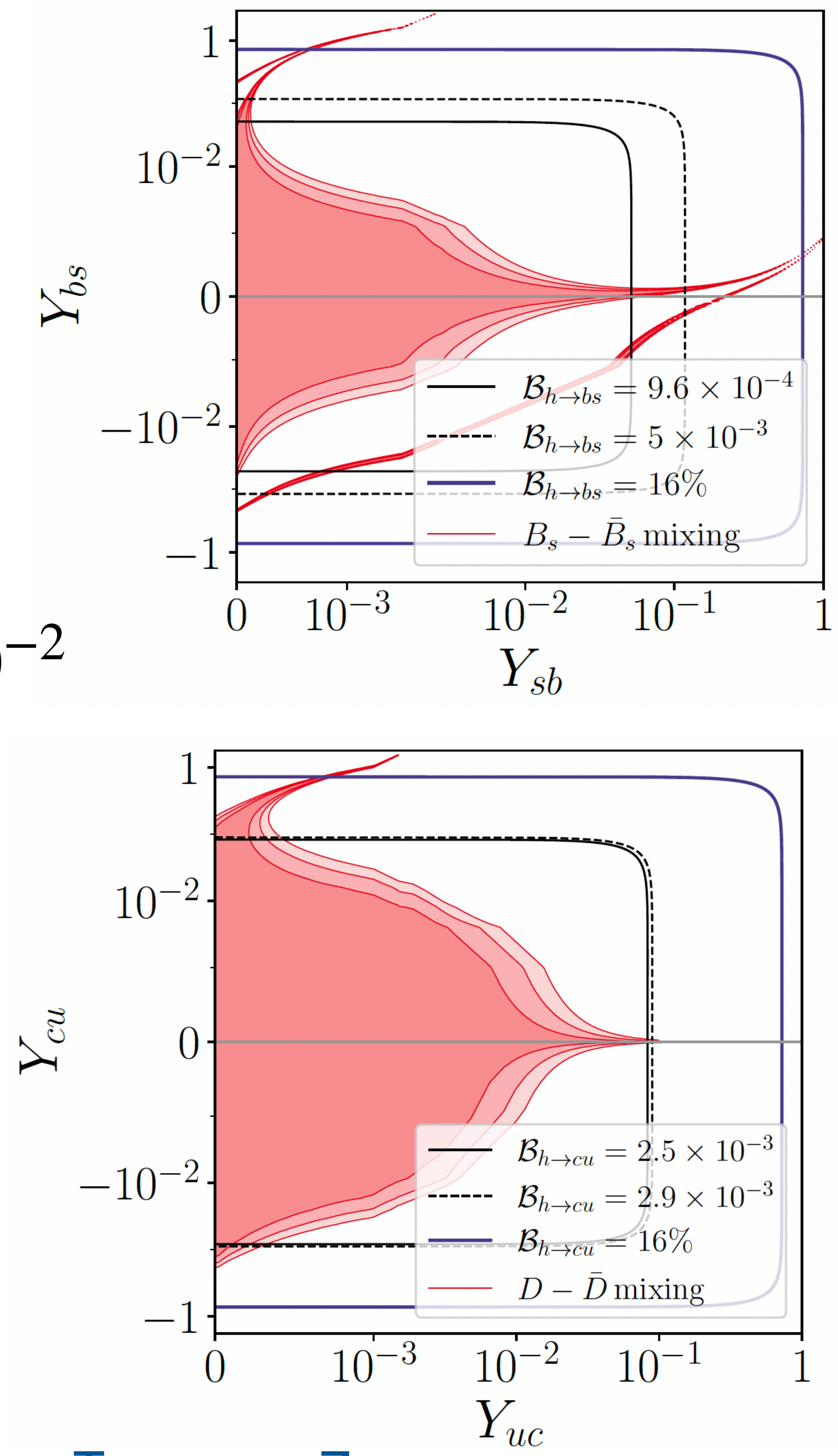
[2306.17520](https://arxiv.org/abs/2306.17520)

Kamenik, Korajac, Szewc, Tammaro, Zupan

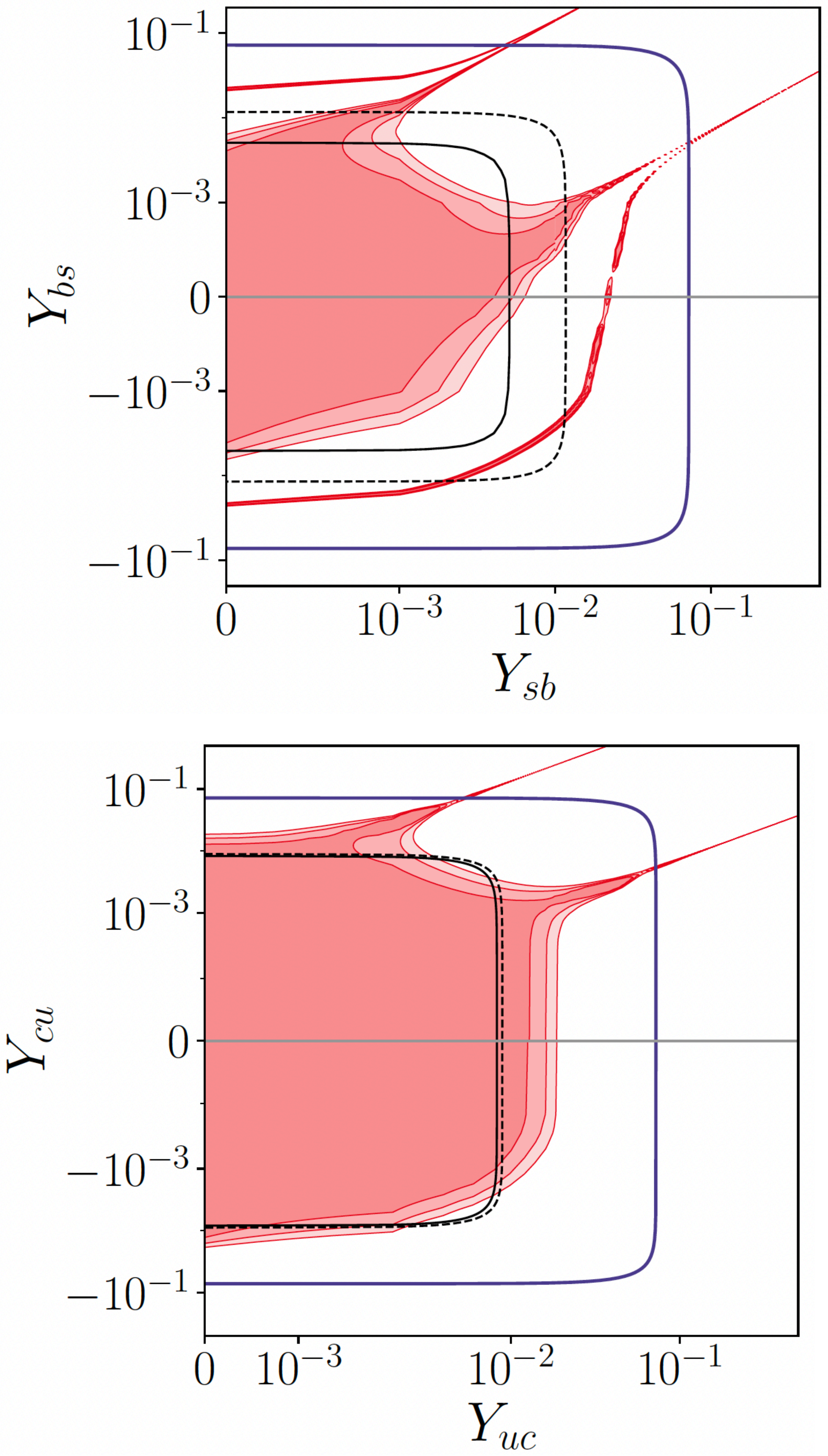
$h \to q\bar{q}'$ decays: 2HDM implications @ FCC-ee

2nd limit: H and A contributions numerically relevant, $m_H = m_A = 1\ \mathrm{TeV}$

$\sin\alpha = 1 \times 10^{-2}$



$\sin\alpha = 1 \times 10^{-1}$



2306.17520

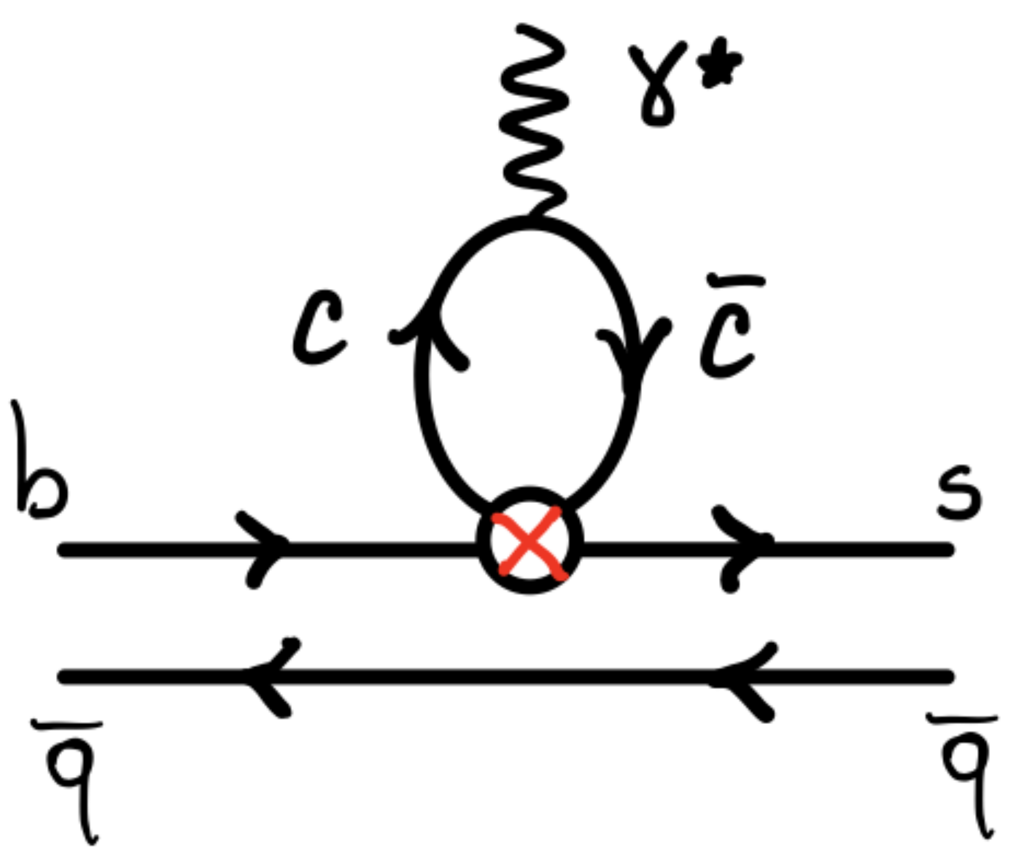
Kamenik, Korajac, Szewc, Tammaro, Zupan

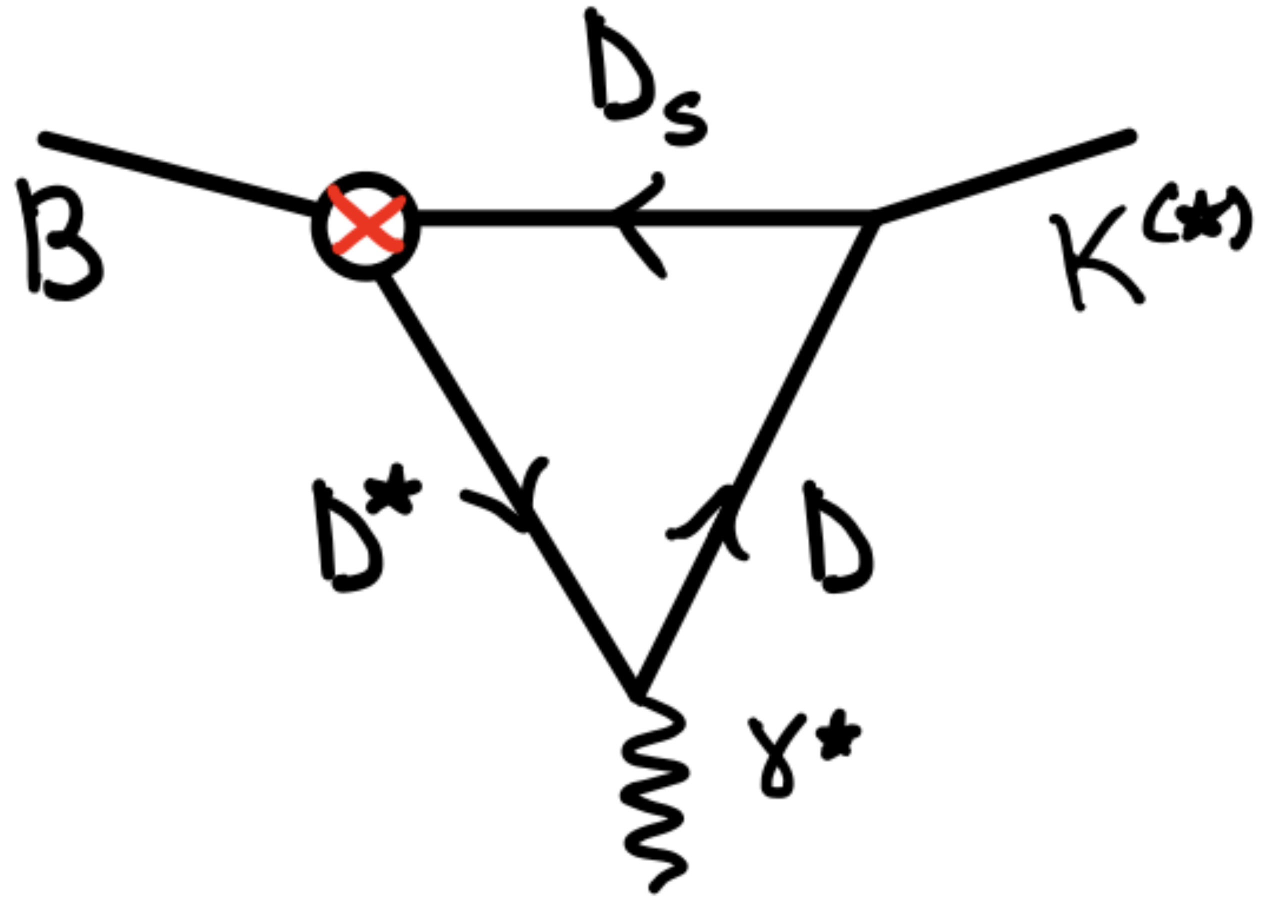
Overview

- $b \to q\ell\nu$
- $b \to s\nu\nu$
- $h \to bs,\, h \to cu$
- τ Physics

$B \to K^*\tau\tau$ decays: the SM status

- Loop-level decays dominated by short-distance effects ($C_{9,10}$), important long-distance
- Additional uncertainties coming from non-perturbative charming penguins



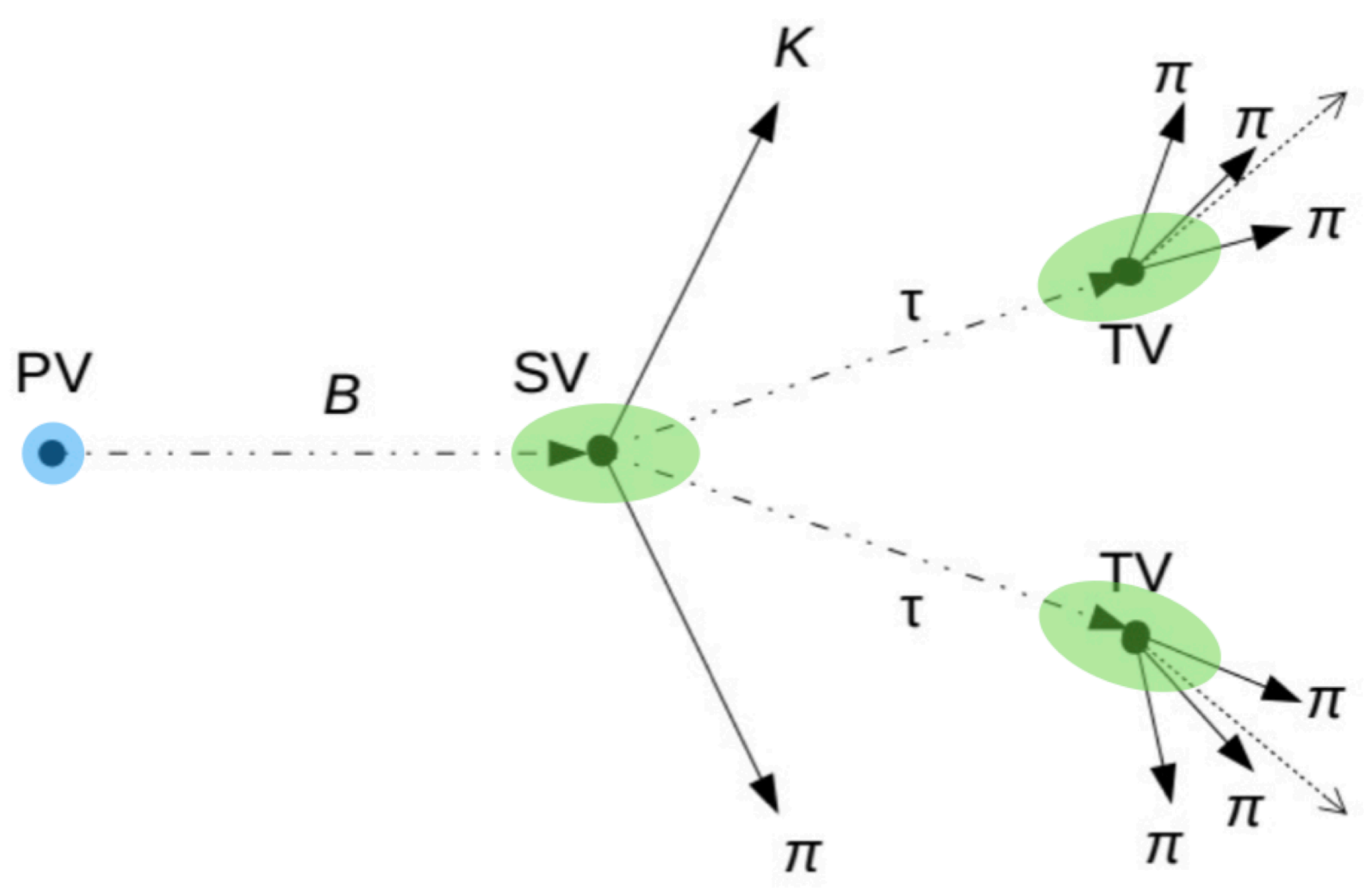


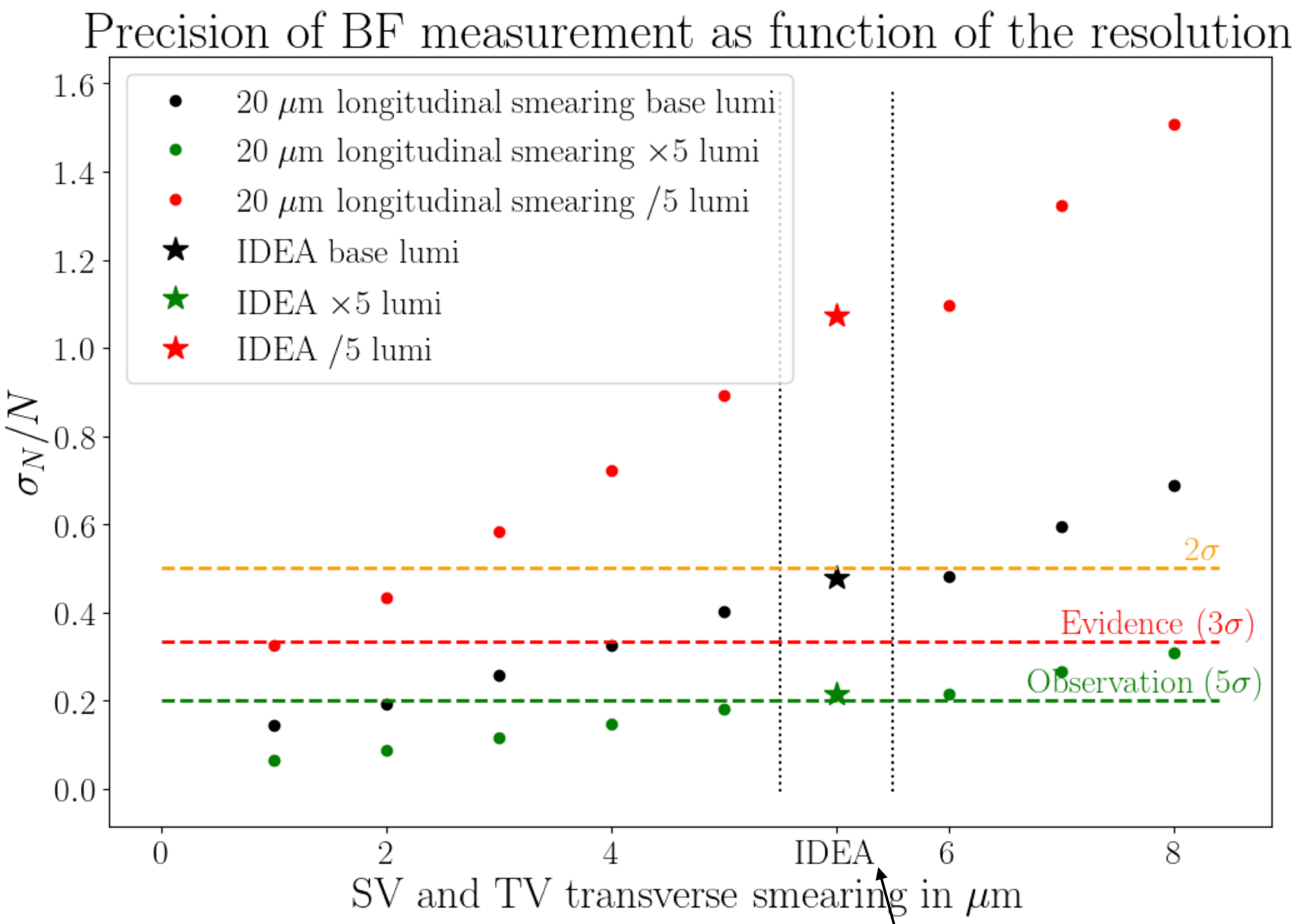
$$Br(B \to K^*\tau\tau) = \mathcal{O}(10^{-7})$$

Present limit from BaBar, $\mathcal{O}(10^{-3} - 10^{-4})$

$B \to K^*\tau\tau$ decays @ FCC-ee

Undergoing feasibility study, based on hadronic τ reconstructions





present day state-of-the-art vertex detector

[FCC Week 2023](#)
Talk by T. Miralles

LFU in τ decays: the SM status

τ lifetime and lepton universality, with main uncertainties coming from mass measurements

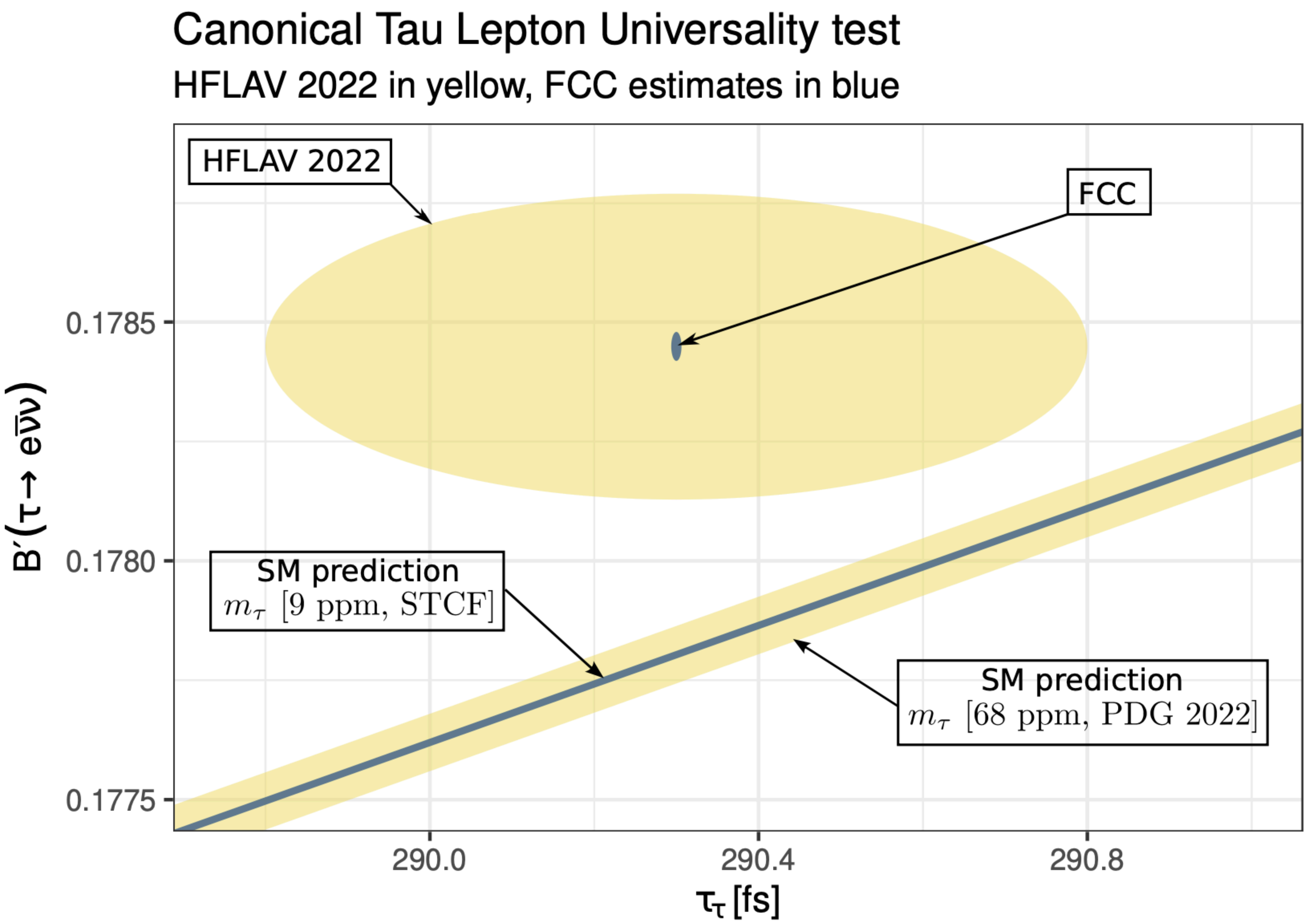
$$\left(\frac{g_\mu}{g_\mathrm{e}}\right)^2 = \frac{\mathcal{B}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{B}(\tau \to \mathrm{e}\bar{\nu}\nu)} \cdot \frac{f_{\tau\mathrm{e}}}{f_{\tau\mu}}$$

$$\left(\frac{g_\tau}{g_\ell}\right)^2 = \frac{\mathcal{B}(\tau \to \ell\,\bar{\nu}\nu)}{\mathcal{B}(\mu \to \ell\,\bar{\nu}\nu)} \cdot \frac{\tau_\mu m_\mu^5}{\tau_\tau m_\tau^5}$$

(up to small and known radiative, EW and PS corrections)

Current data supports lepton universality $\delta(g_\tau/g_e) \simeq \delta(g_\tau/g_\mu) = \mathcal{O}(10^{-3})$

LFU in τ decays @ FCC-ee



CLFV2023
Talk by A. Lusiani

Conclusions

- FCC-ee is far away in the future, but there is already a lot to be done in terms of sensitivity studies: some channels already explored, many still to be addressed

- Data collected at FCC-ee will have huge potential to enrich the determinations of CKM parameters, potentially including channels currently not relevant

- Many different NP scenarios (more or less inspired by current anomalous data) to be tested, with strongly increased potential for discovery