2025 European Edition of the International Workshop on the CEPC

Measuring charged-current leptonic B decays and CKM matrix elements

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based on arXiv:2305.02998 in collaboration with:

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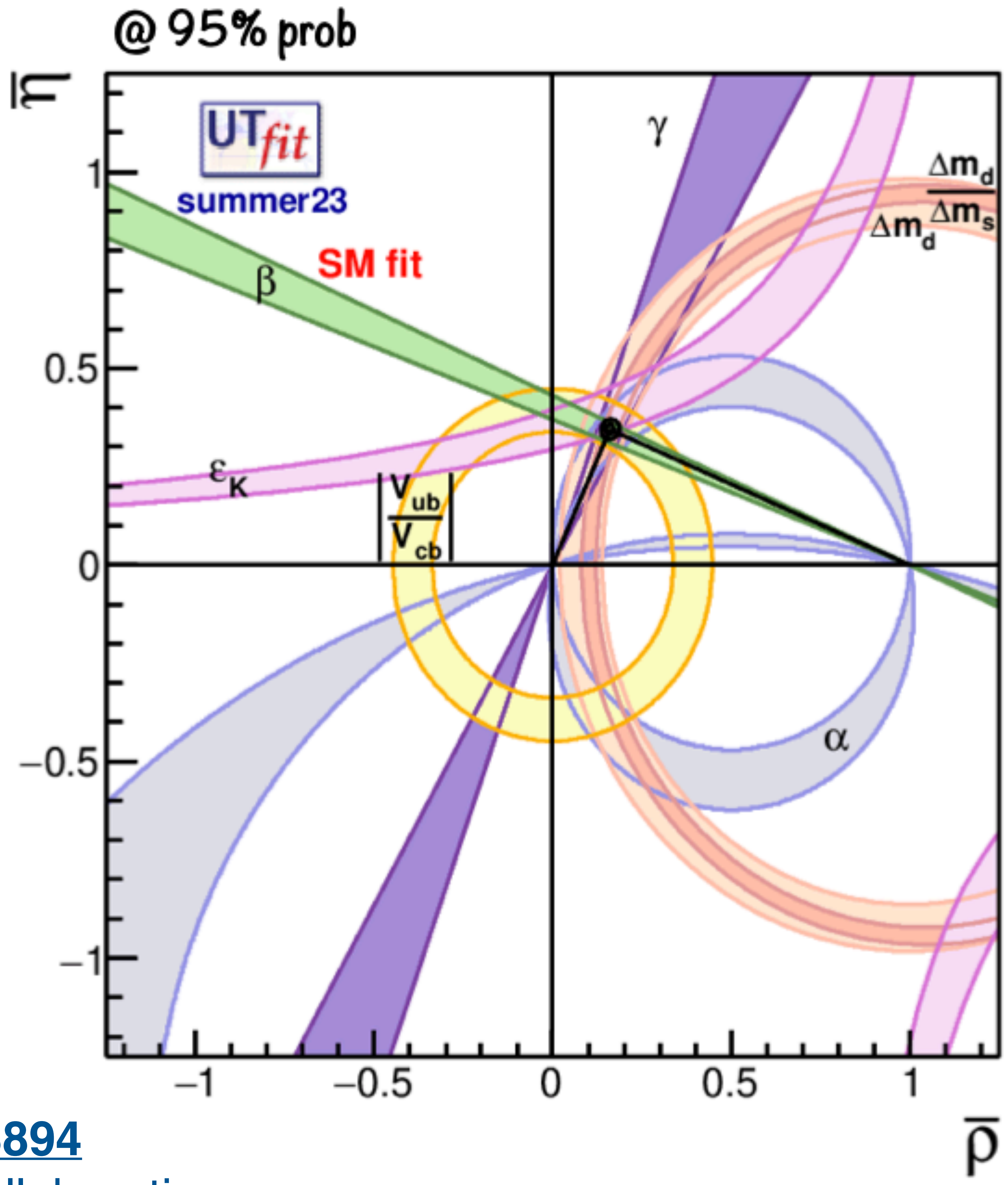
The Status of Flavour Physics

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



$$\boxed{\begin{aligned} \bar{\rho} &= 0.160 \pm 0.009 \sim 6\% \\ \bar{\eta} &= 0.346 \pm 0.009 \sim 3\% \end{aligned}}$$

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

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

2212.03894
UTfit Collaboration

The Flavour NP reach

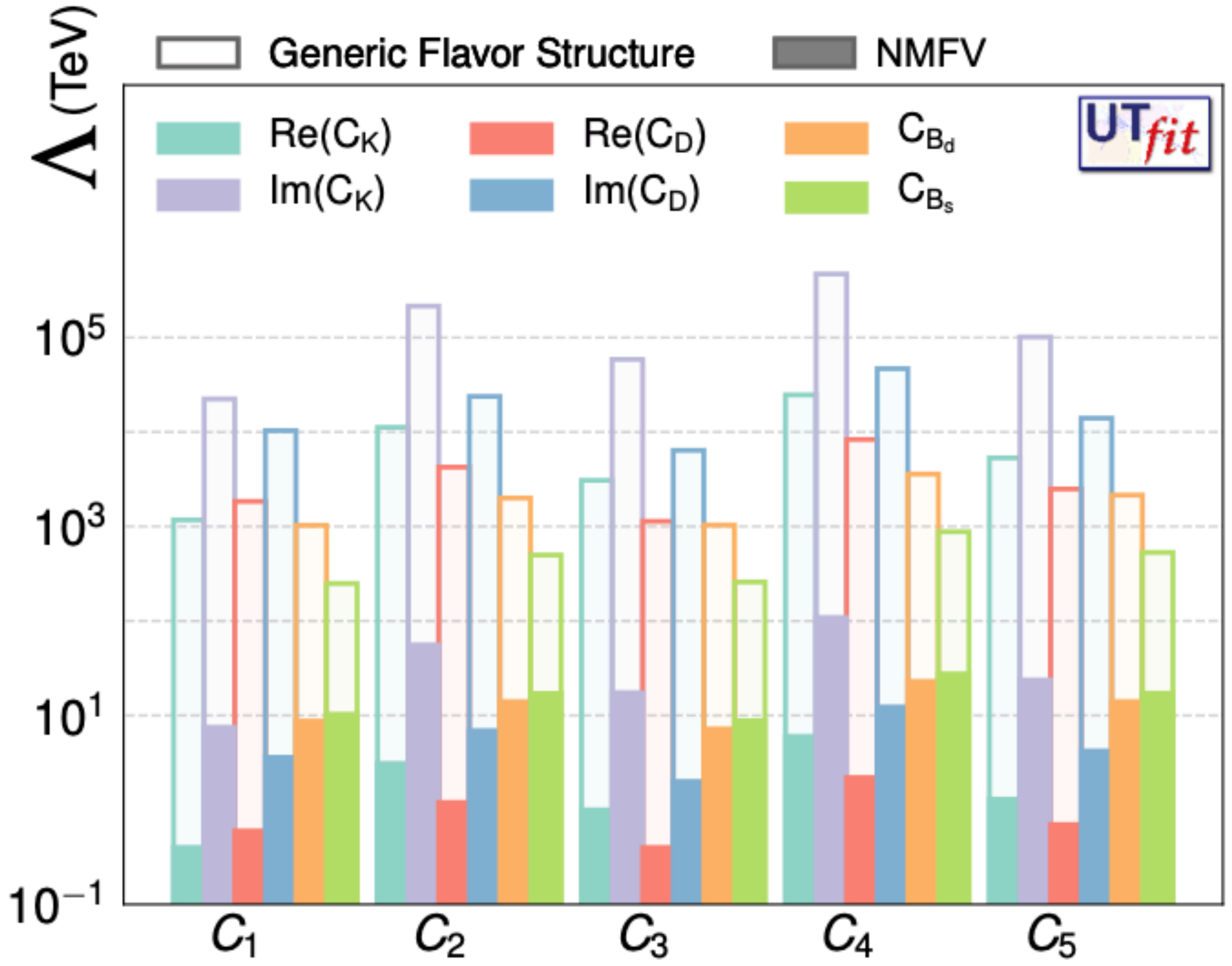
To describe heavy NP effects, it is customary to employ effective Hamiltonians, where the UV degrees of freedom are integrated out and which allow model-independent analyses

couplings parametrizing low-scale footprints of heavy degrees of freedom

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

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!

Disclaimer #1

Our analysis originated from a collaboration with experimentalists involved in FCC(-ee)

Nevertheless, all the results obtained are qualitatively analogous to what could be obtained at CEPC!

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

$B \to \tau\nu$: the SM status

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

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

$|V_{cb}|^{\rm UTA} = 42.22(51) \times 10^{-3}, f_{B_c} = 427(6)$ 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](https://arxiv.org/abs/2212.03894)
UTfit Collaboration

[2111.09849](https://arxiv.org/abs/2111.09849)
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According to present Lattice estimates, decay constants errors could be halved in the next decade!

Disclaimer #2

I will try to go over the important points of a measurement of $B \to \tau\nu$ at FCC-ee

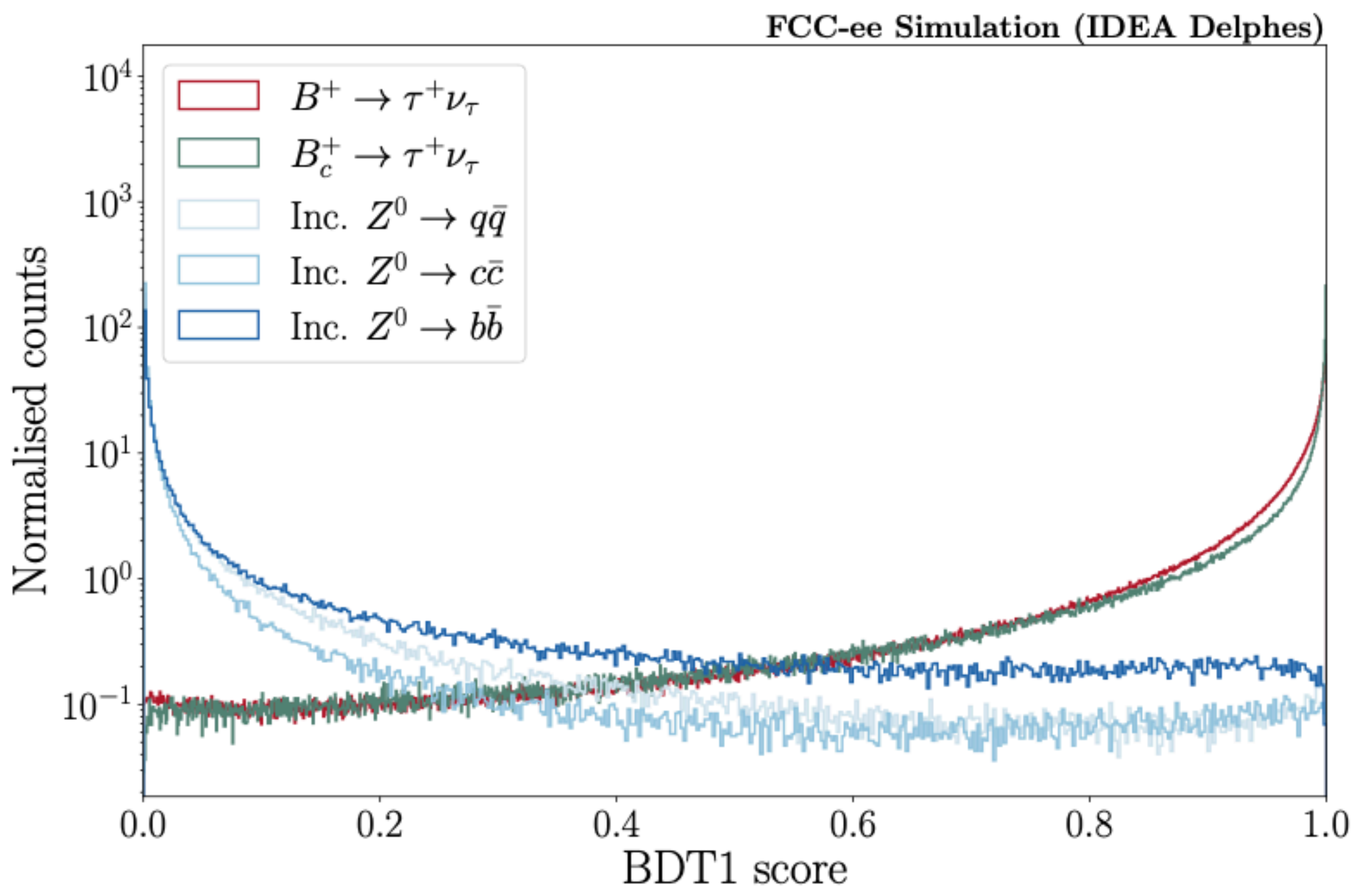
Remember I'm a theorist, please be gentle :)

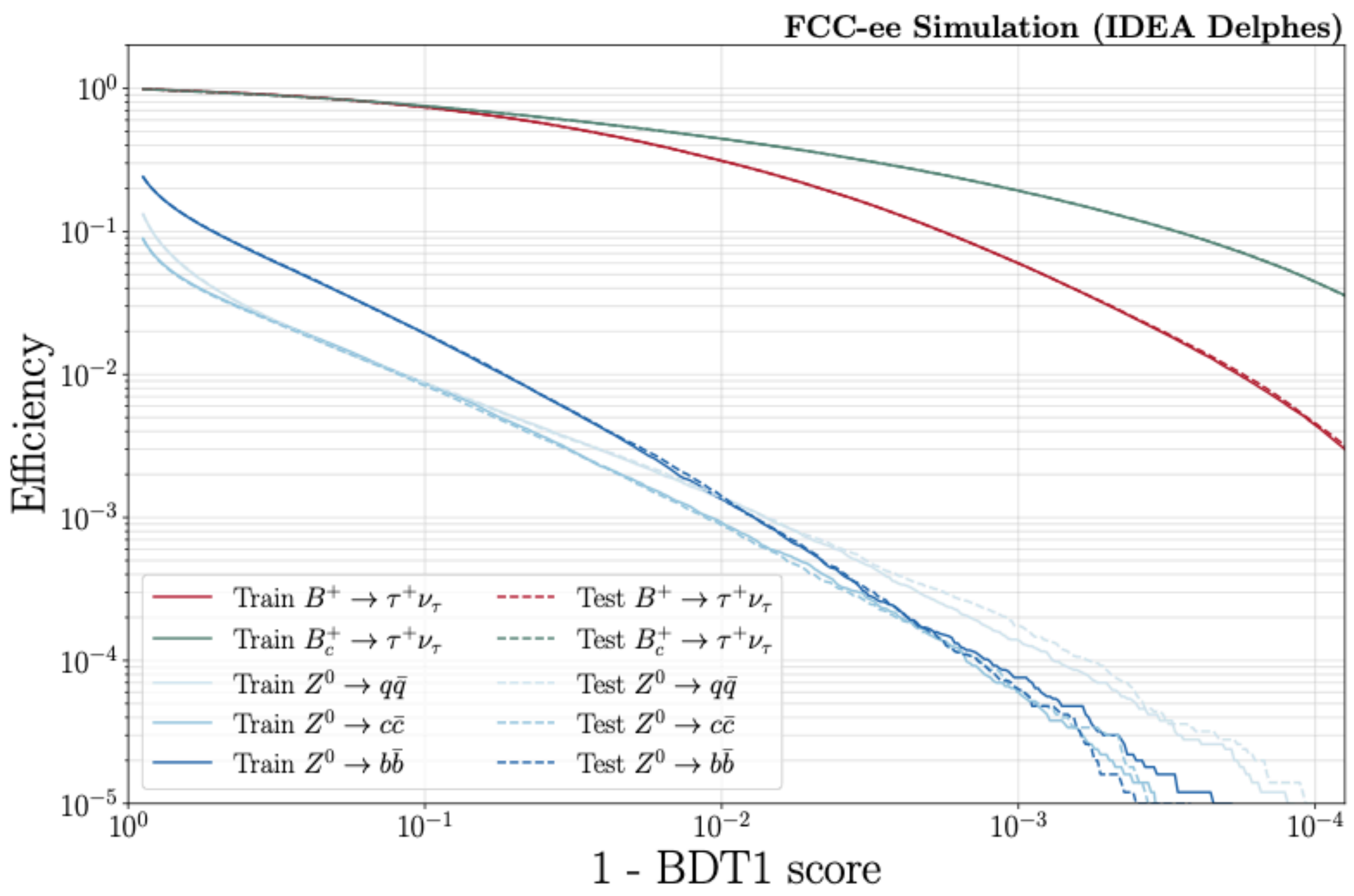
$B \to \tau\nu$ @ FCC-ee

Main analysis difficulty: separate signal from background, mostly composed by
$$Z \to b\bar{b}, Z \to c\bar{c}, Z \to q\bar{q}$$
$$\Downarrow$$

Achieved by the implementation of 2 Boosted Decision Tree (BDT) classifiers

- BDT1: loosely separates sig. from bkg. using event level kinematic (not specific decay processes)





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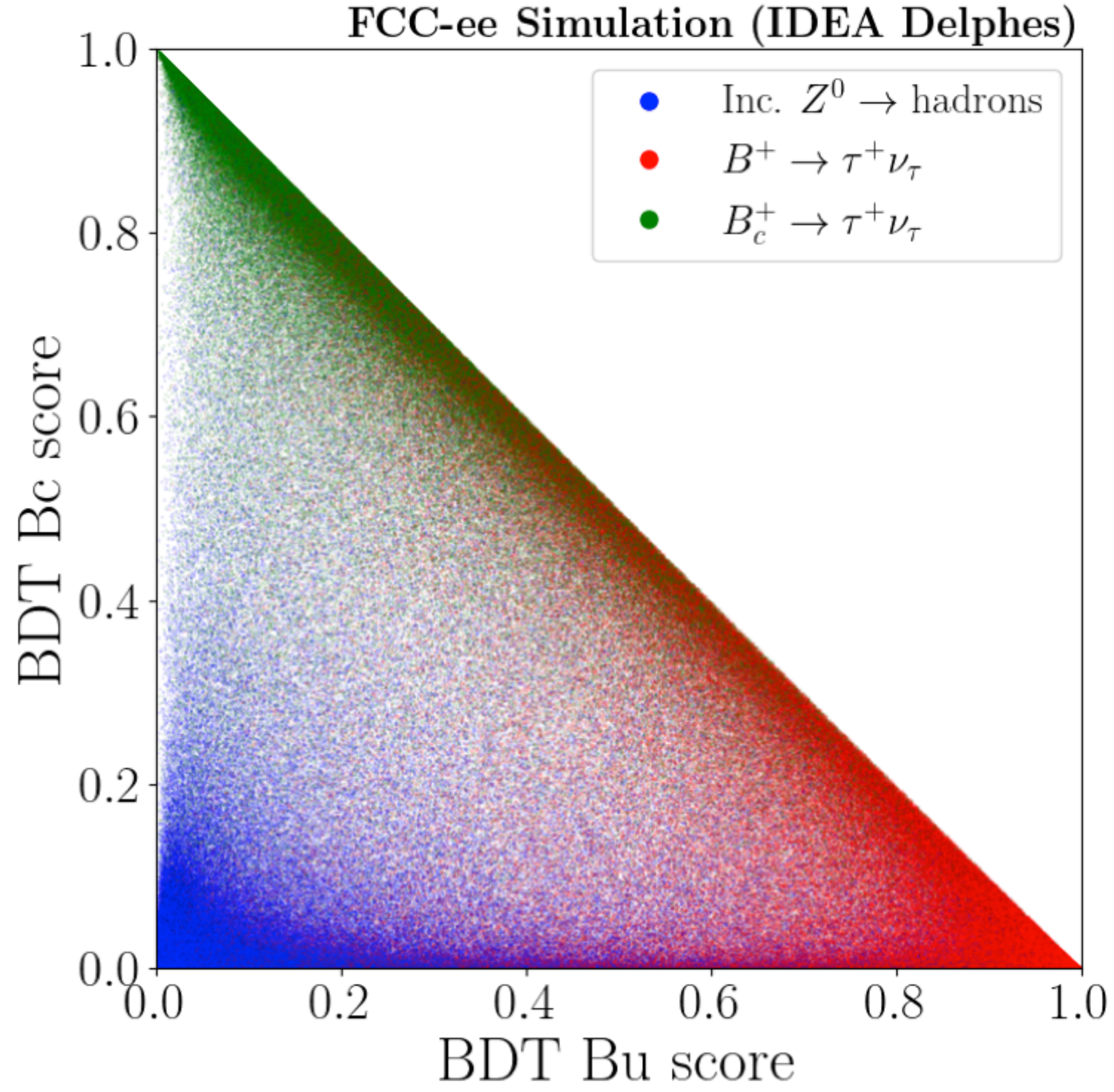
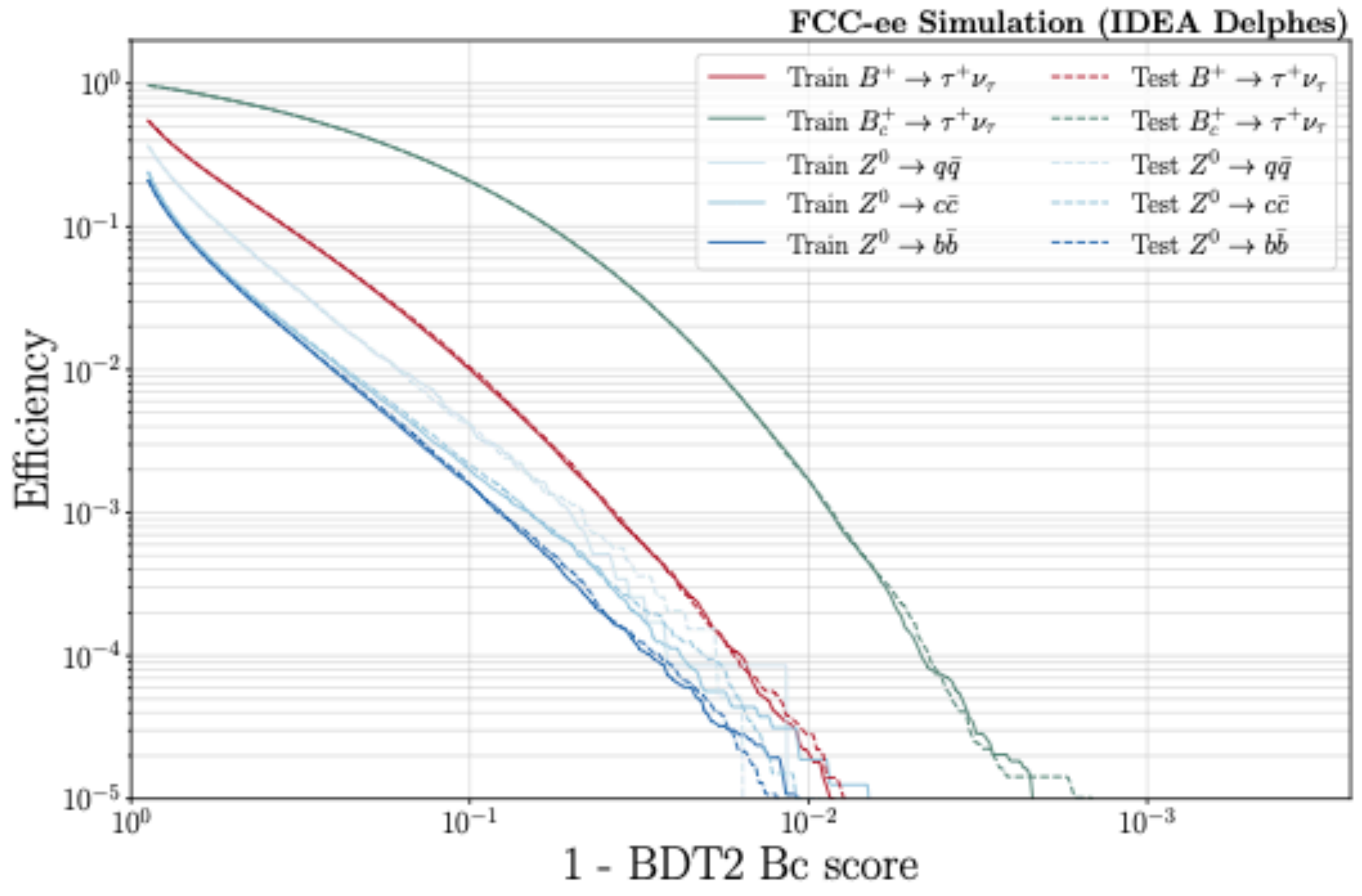
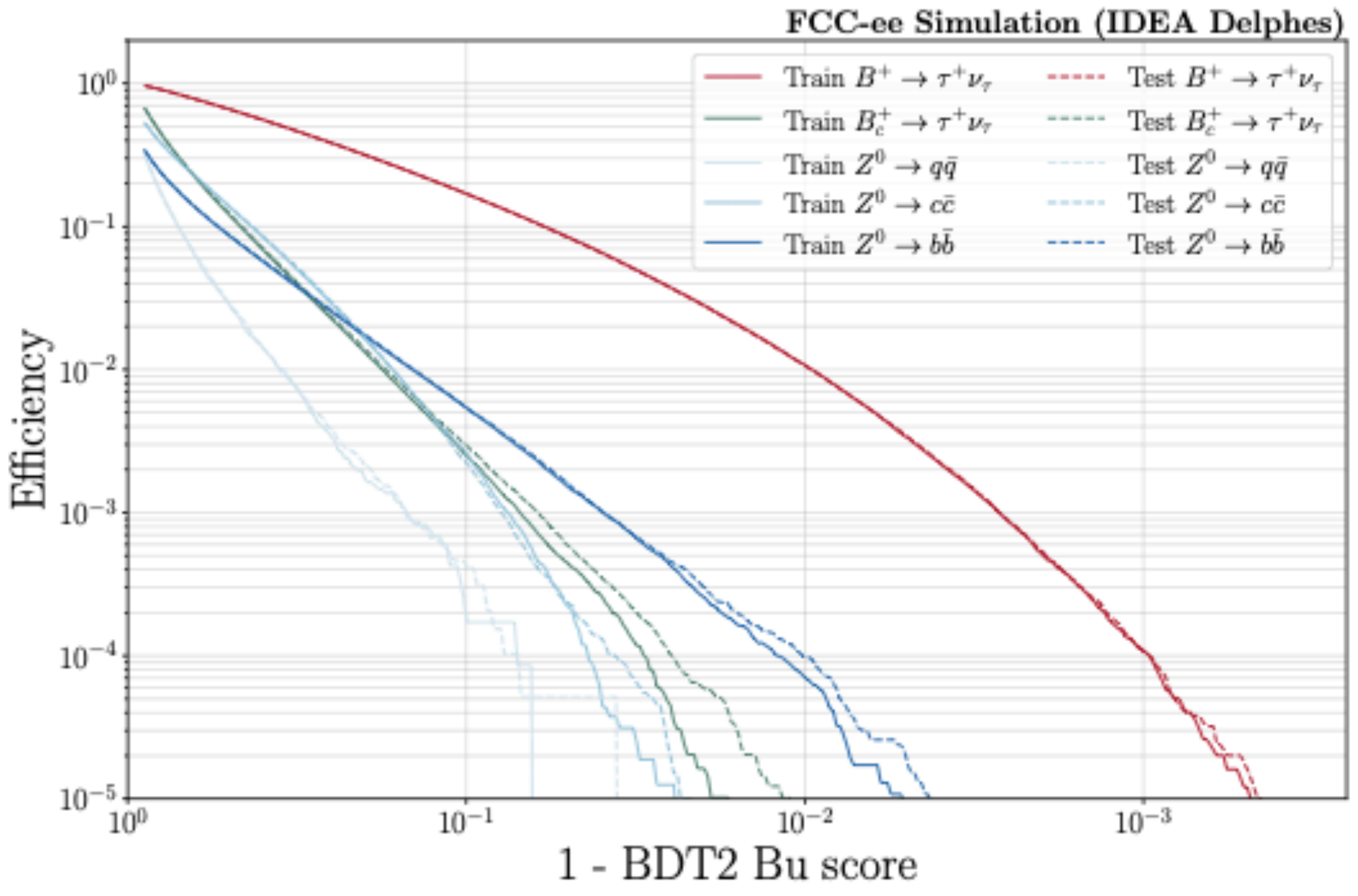
$B \to \tau\nu$ @ FCC-ee

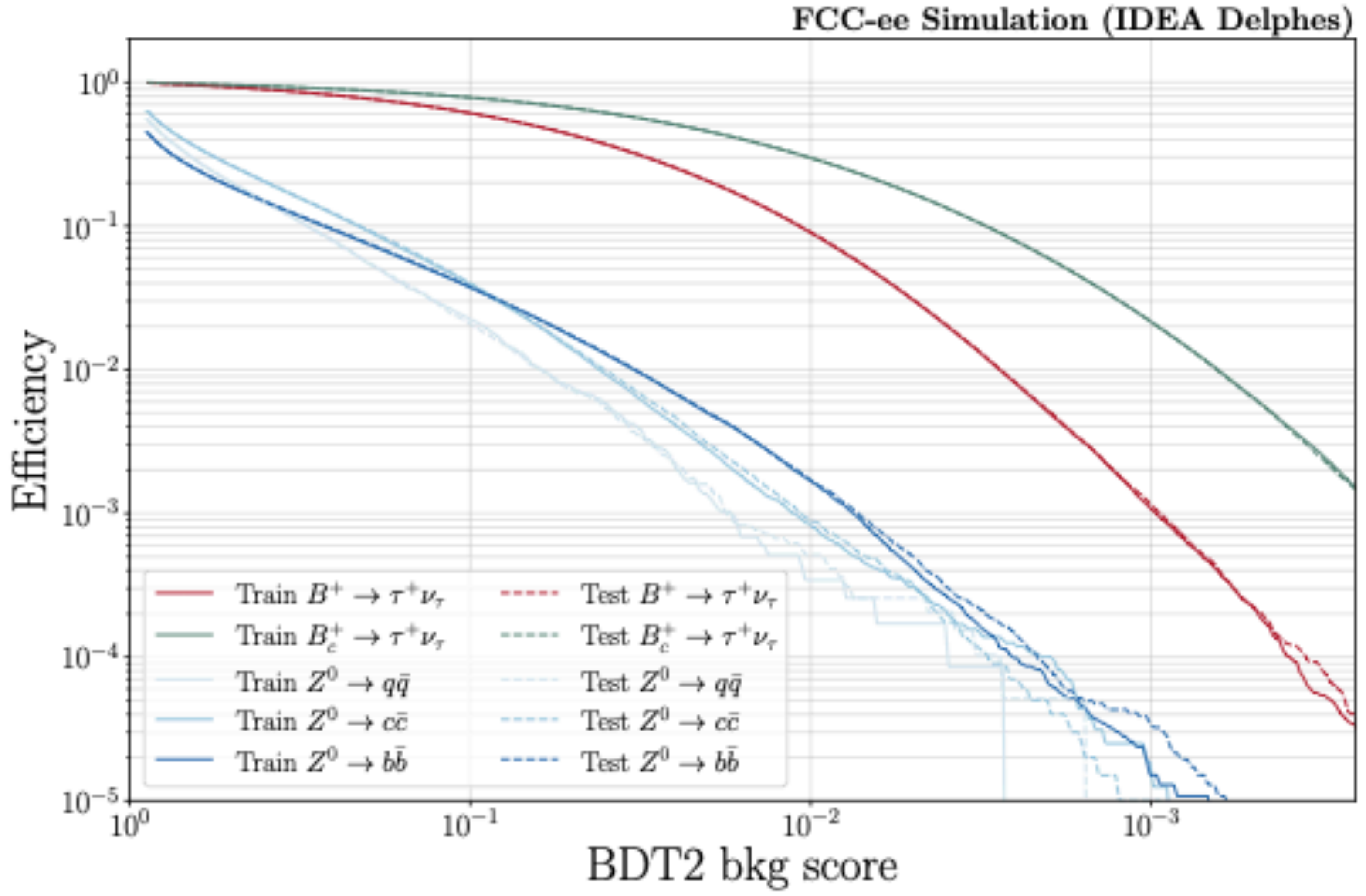
- BDT2: further refines using kinematic details of the decay processes



$\Rightarrow$







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

The final yields are obtained estimated the optimal selections for BDT1, BDT2 event and BDT2 signal, separately for the 2 channels

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

  BDT1>0.99946, BDT2 Bu>0.640, BDT2 bkg < 0.0123

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

  BDT1>0.99993, BDT2 Bc>0.782, BDT2 bkg < 0.0088

$\Rightarrow$

Process	Bc category	Bu category
$N(B_c^+ \to \tau^+\nu_\tau)$	12000.8	569.0
$N(B^+ \to \tau^+\nu_\tau)$	1373.6	12011.4
$N(Z \to b\bar{b})$	437.4	3334.6
$N(Z \to c\bar{c})$	100.7	34.2

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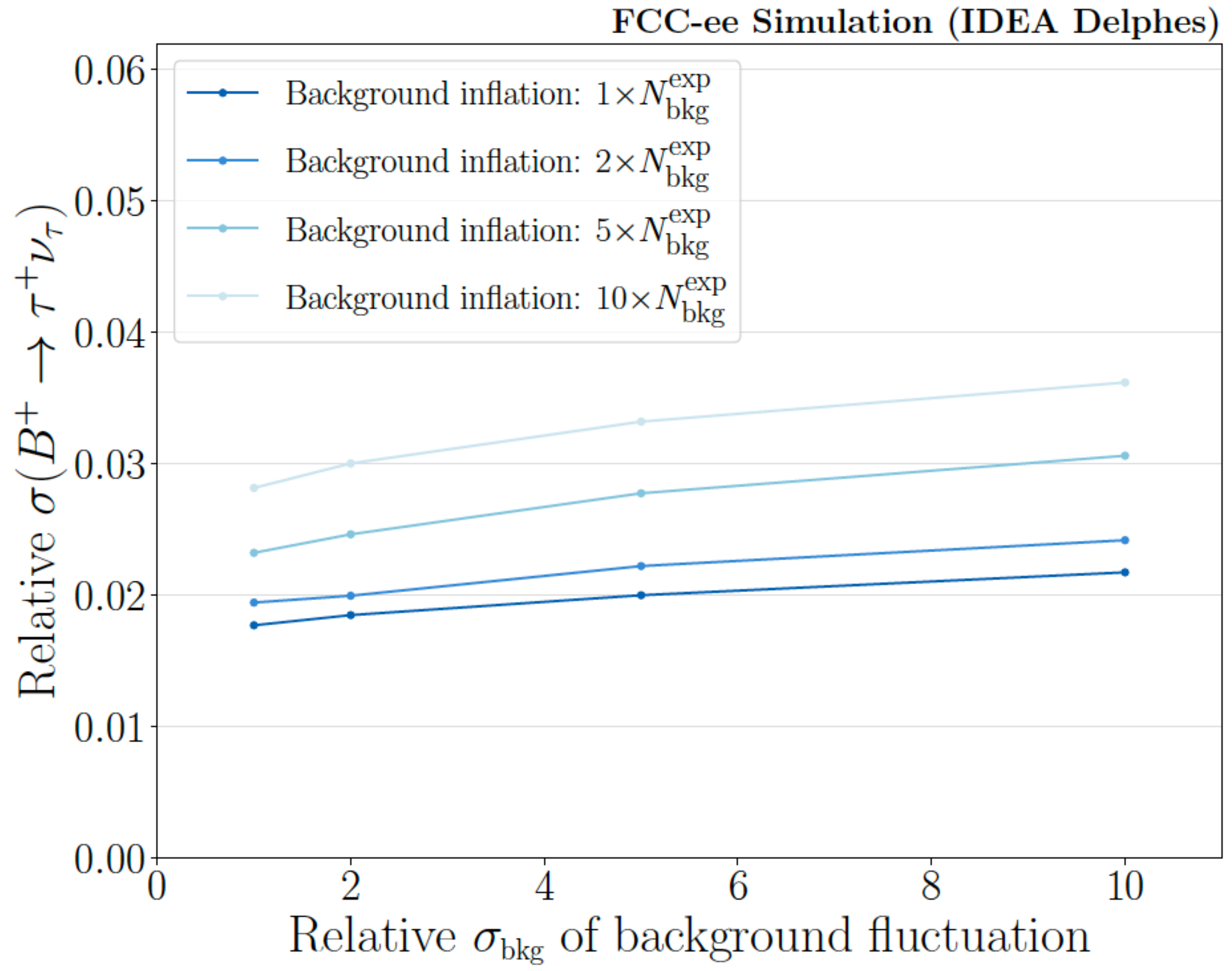
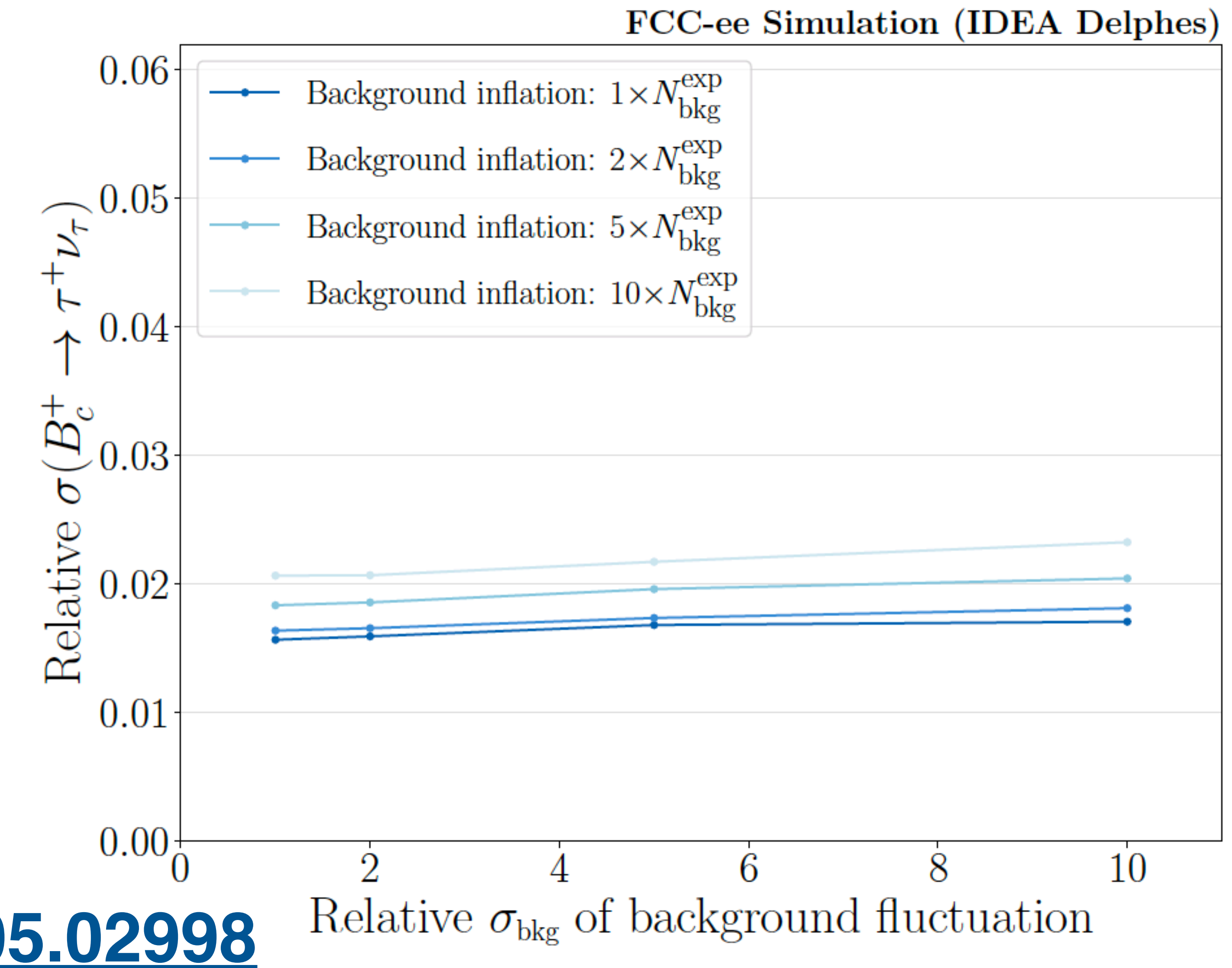
$B \to \tau\nu$ @ FCC-ee

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



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:

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

It is possible to extract the Br modulo CKM multiplying by

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

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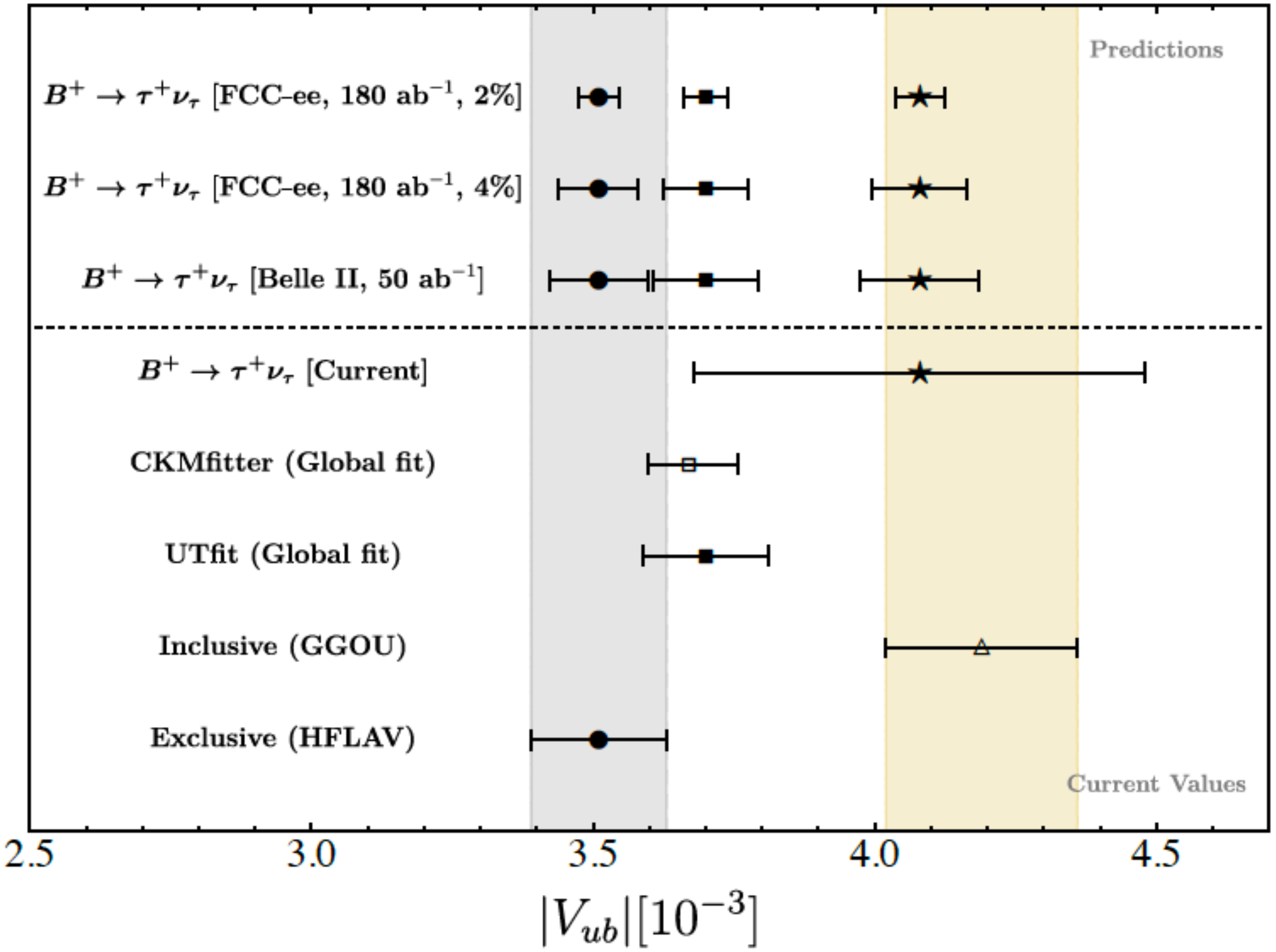
$|V_{ub}|$ from $B \to \tau\nu$ @ FCC-ee

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!

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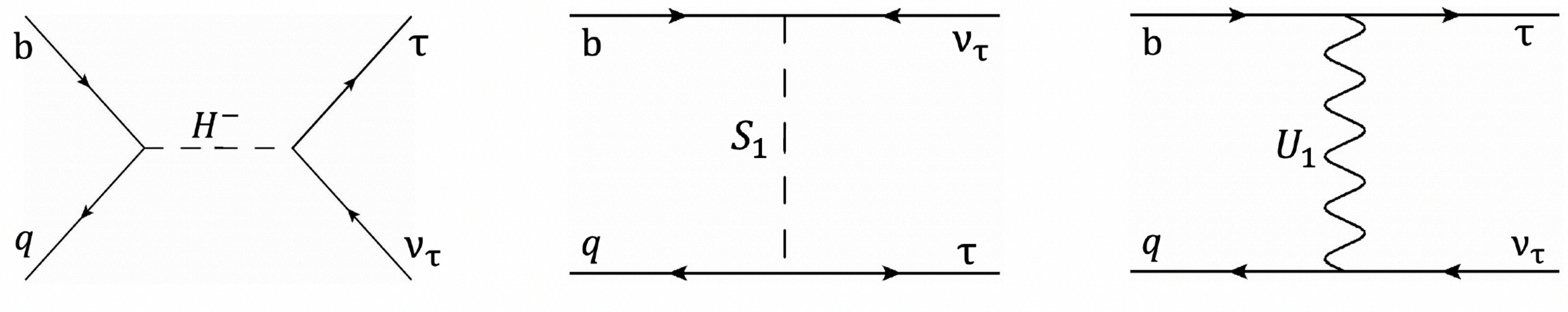
$B \to \tau\nu$: NP implications

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

$$\boxed{\mathcal{B}(B_q^+ \to \tau^+\nu_\tau) = \mathcal{B}(B_q^+ \to \tau^+\nu_\tau)^{\mathrm{SM}} \times \left| 1 - \left(C_{V_R}^q - C_{V_L}^q\right) + \left(C_{S_R}^q - C_{S_L}^q\right) \frac{m_{B_q}^2}{m_\tau(m_b + m_q)} \right|^2}$$

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



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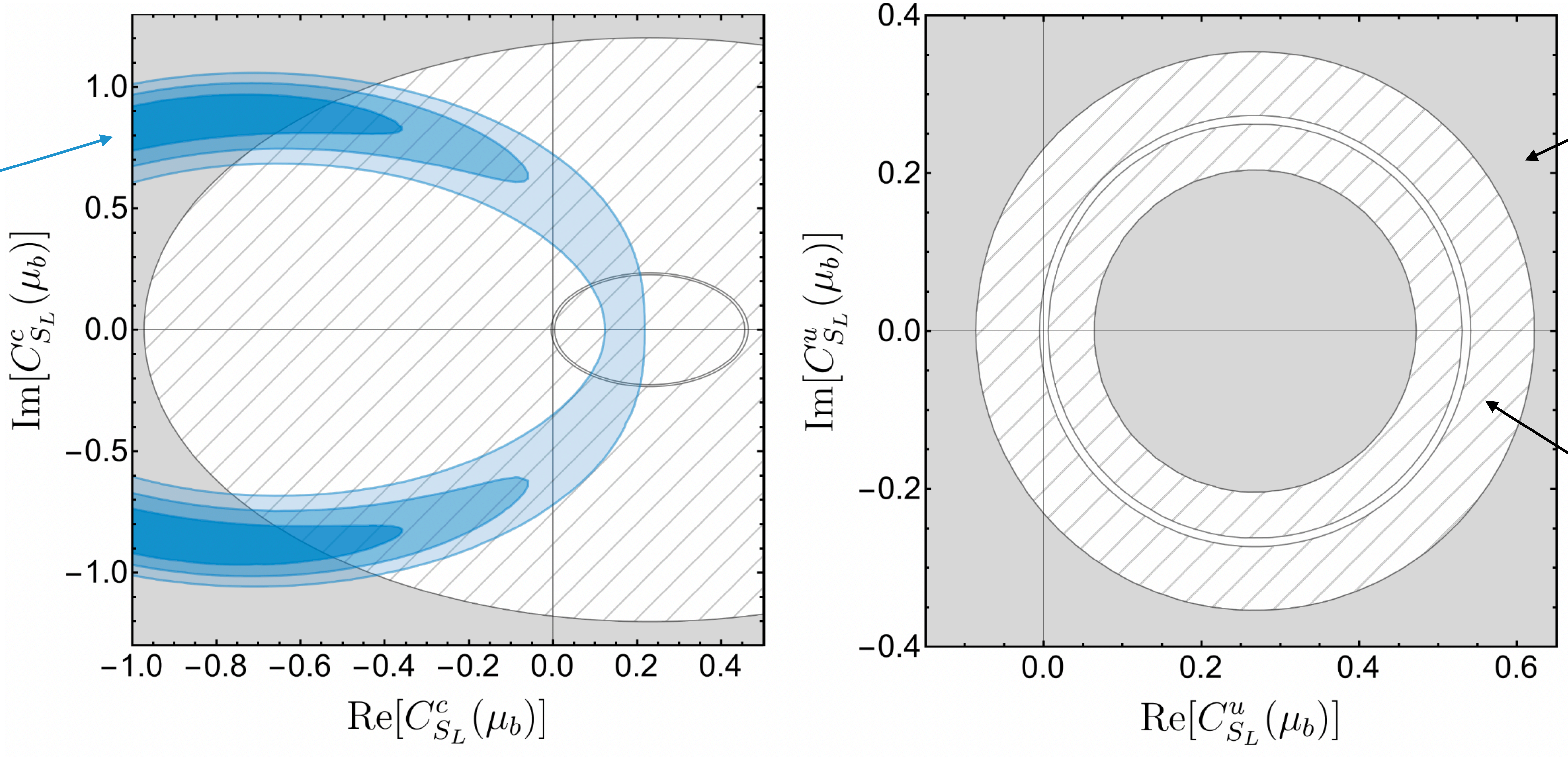
$B \to \tau\nu$: G2HDM

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

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



present bounds

projected bounds

[2305.02998](https://arxiv.org/abs/2305.02998)
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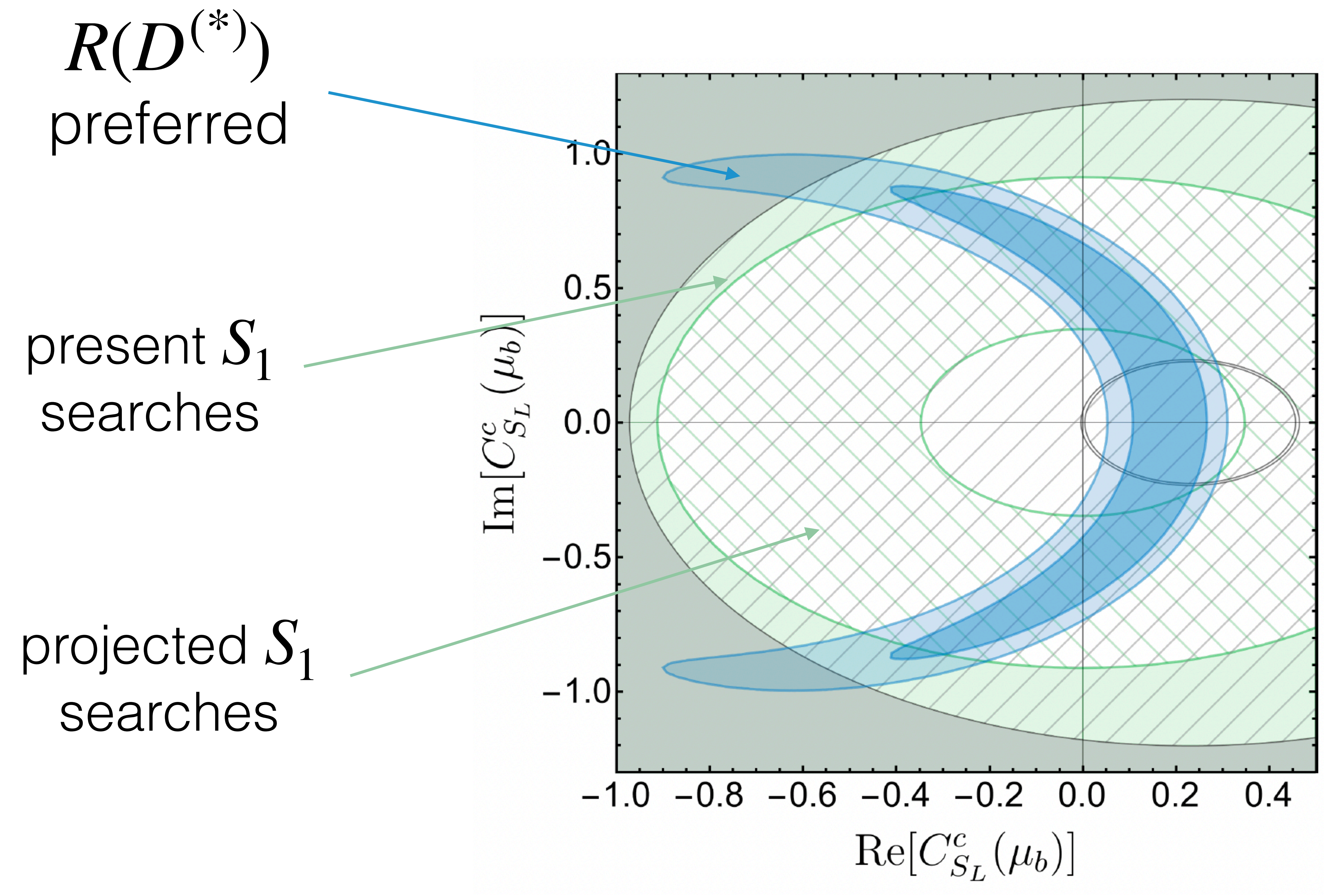
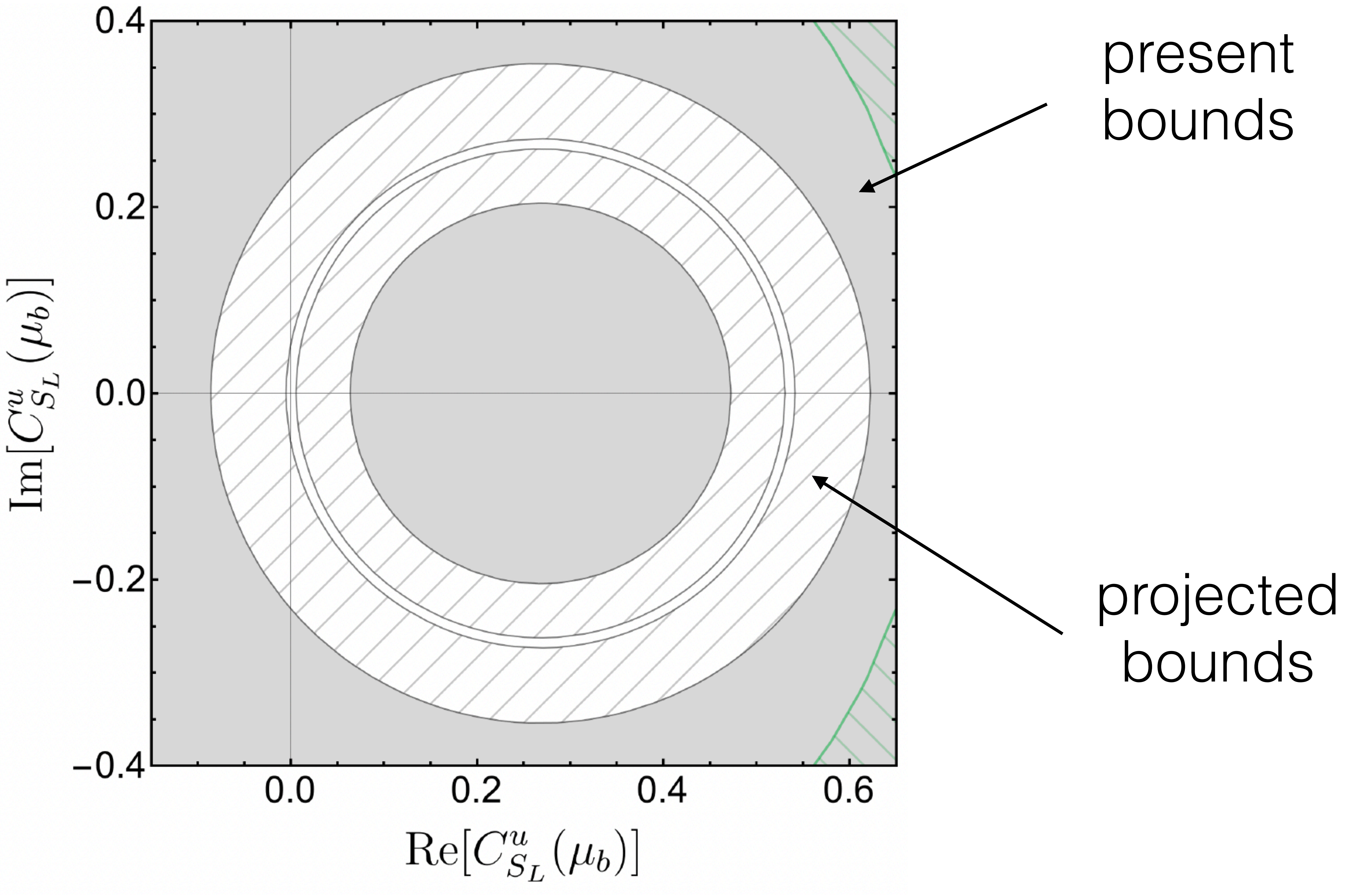
$B \to \tau\nu$: S_1 Leptoquark

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





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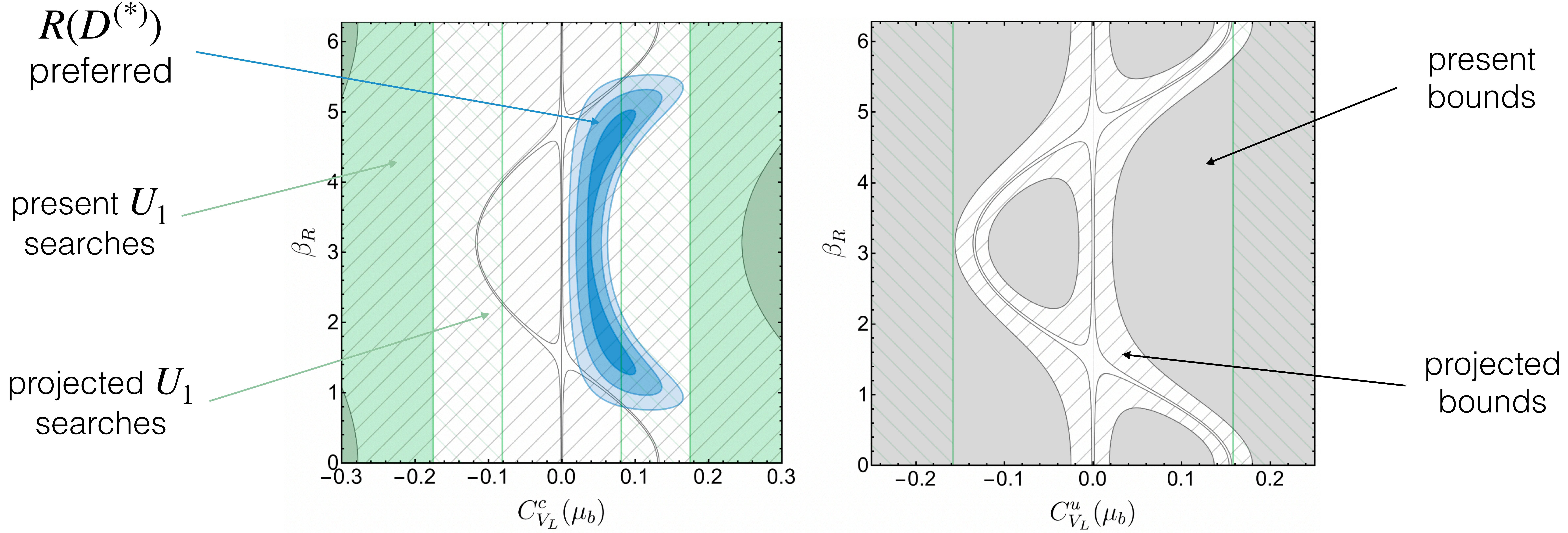
$B \to \tau\nu$: U_1 Leptoquark

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



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
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1909.02519
Fuentes-Martin, Isidori, Pagès, Yamamoto

Conclusions

- CEPC 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 CEPC 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