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Indirect Constraints on Higgs-mediated FCNCs

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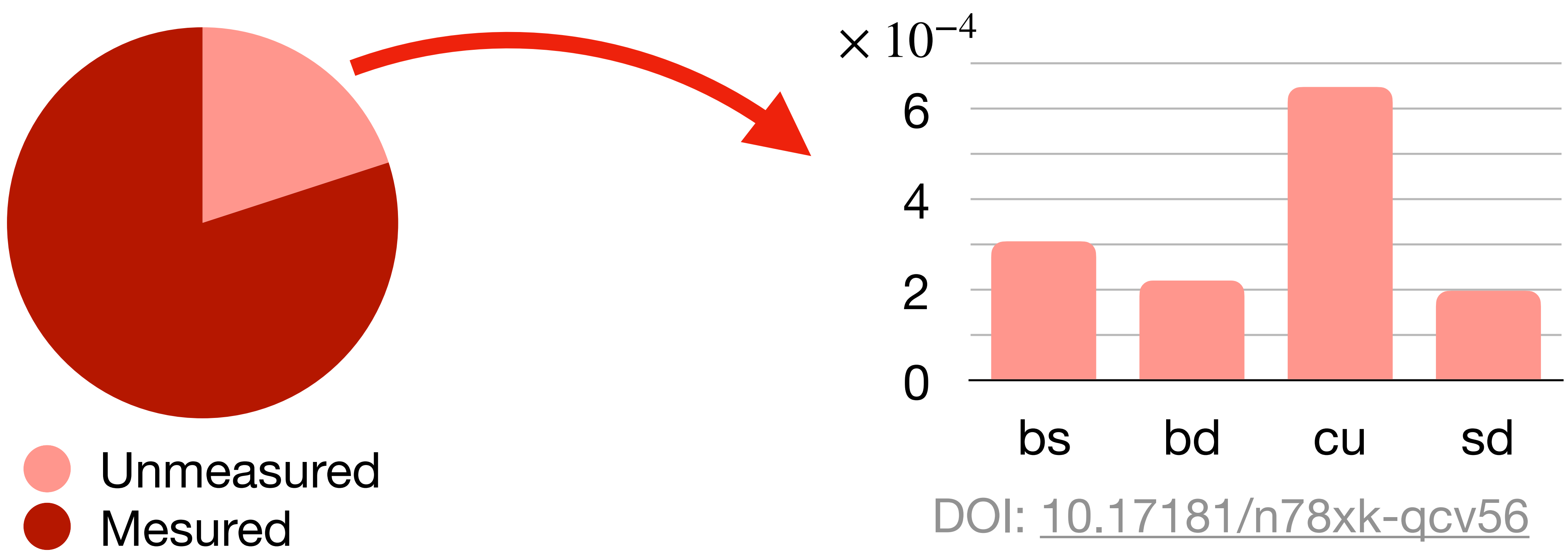
Introduction and Motivation

10+ Years After the Higgs Discovery

- Higgs (2012) completed SM
- Only a few couplings ($t,\ W,\ Z,\tau$) precisely measured
- Light-quark and off-diagonal currently unmeasured
  - Higgs factories (e.g. FCC-ee) $\rightarrow$ sensitivity to on off-diagonal

$\mathrm{BR}(h \rightarrow X)$

FCC-ee sensitivity to $\mathrm{BR}(h \rightarrow qq')$



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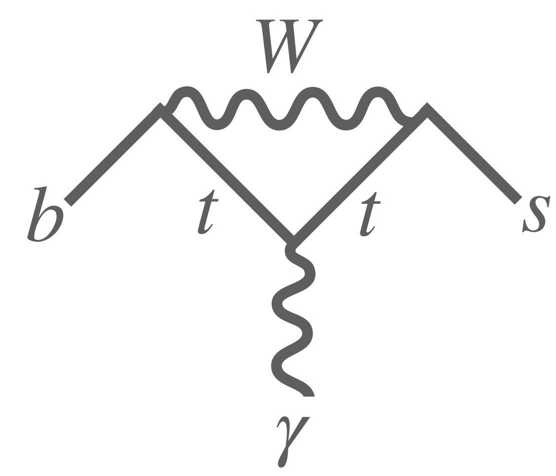
Flavor-Changing Neutral Currents



1. FCNCs are forbidden at tree level in SM

- Suppressed due to GIM mechanism
- Sensitive to New Physics (NP)
- Via loops → virtual heavy particles

2. Intensity vs. energy

- New particles modify effective couplings, even if too heavy to produce
- Complementary to direct searches at the energy frontier
- Rare processes → indirect search for new particles

Rare FCNC processes act as precision microscopes for heavy new physics. If we observe a Higgs-mediated FCNC, it's BSM.

Setup and Matching

Effective Lagrangian and Matching

- Effective Lagrangian:

$$\mathscr{L}_{eff} \supset y_{sb}(\bar{s}_L b_R)h + y_{bs}(\bar{b}_L s_R)h + y_{db}(\bar{d}_L b_R)h + y_{bd}(\bar{b}_L d_R)h$$
$$+ y_{cu}(\bar{c}_L u_R)h + y_{uc}(\bar{u}_L c_R)h + y_{sd}(\bar{s}_L d_R)h + y_{ds}(\bar{d}_L s_R)h + \mathrm{h.c.}$$

- Relevant operators and matching (example for B_s):

$$\mathcal{O}_S^{bs\ell\ell} = \frac{\alpha_e}{(4\pi)}\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* m_b \left(\bar{s}_L b_R\right)\left(\bar{\ell}\ell\right) \longrightarrow C_S^{bs\ell\ell} = -\frac{(4\pi)}{\alpha_e}\frac{\sqrt{2}}{4G_F}\frac{1}{V_{tb}V_{ts}^* m_b}\frac{m_\ell}{m_h^2 m_W}\frac{g}{2} y_{sb}$$

$$\mathcal{O}_S'^{\,bs\ell\ell} = \frac{\alpha_e}{(4\pi)}\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* m_b \left(\bar{s}_R b_L\right)\left(\bar{\ell}\ell\right) \longrightarrow C_S'^{\,bs\ell\ell} = -\frac{(4\pi)}{\alpha_e}\frac{\sqrt{2}}{4G_F}\frac{1}{V_{tb}V_{ts}^* m_b}\frac{m_\ell}{m_h^2 m_W}\frac{g}{2} y_{bs}^*$$

$$\mathcal{O}_{S,LL}^{bsbs} = \left(\bar{s}_R b_L\right)\left(\bar{s}_R b_L\right) \longrightarrow C_{S,LL}^{bsbs} = \frac{1}{2m_h^2} y_{bs}^{*2}$$

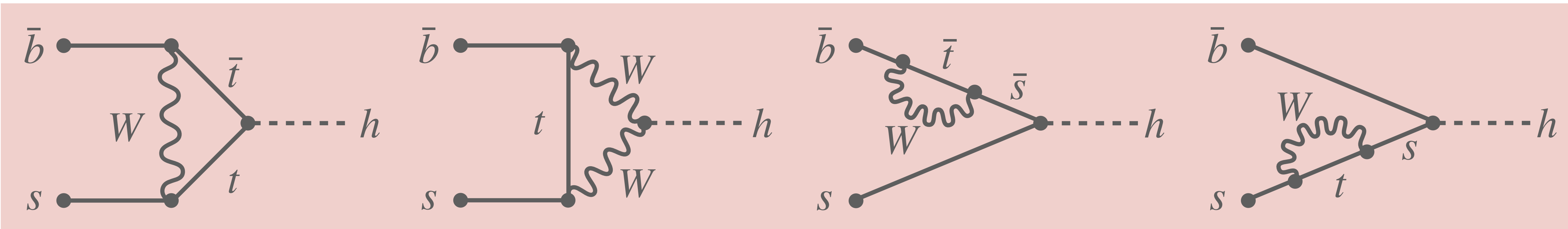
$$\mathcal{O}_{S,RR}^{bsbs} = \left(\bar{s}_L b_R\right)\left(\bar{s}_L b_R\right) \longrightarrow C_{S,RR}^{bsbs} = \frac{1}{2m_h^2} y_{sb}^{2}$$

$$\mathcal{O}_{S,LR}^{bsbs} = \left(\bar{s}_R b_L\right)\left(\bar{s}_L b_R\right) \longrightarrow C_{S,LR}^{bsbs} = \frac{1}{m_h^2} y_{bs}^{*} y_{sb}$$

Standard Model Prediction

Standard Model Prediction

- Unitary gauge (example for $\bar{b}s$):

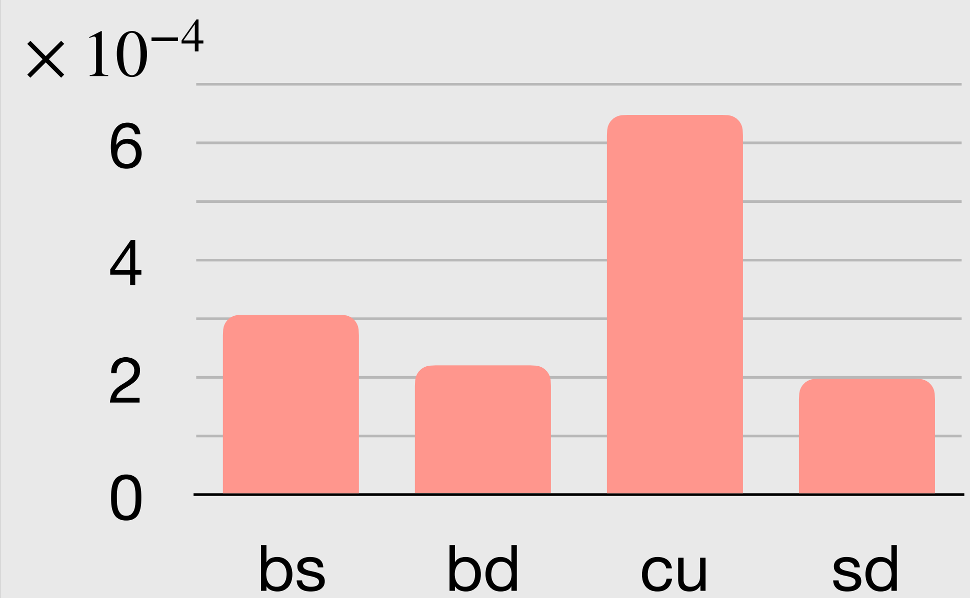


- Results:

		$\mathrm{BR}(h \to qq')$
y_{bs}	$(-1.45 - 0.03\,i) \times 10^{-7}$	4.64×10^{-8}
y_{sb}	$(-8.77 + 0.16\,i) \times 10^{-6}$	
y_{bd}	$(1.43 - 0.57\,i) \times 10^{-9}$	2.04×10^{-9}
y_{db}	$(1.71 + 0.68\,i) \times 10^{-6}$	
y_{uc}	$(4.79 - 3.96\,i) \times 10^{-12}$	2.34×10^{-20}
y_{cu}	$(1.16 + 0.96\,i) \times 10^{-14}$	
y_{sd}	$(-6.08 + 2.45\,i) \times 10^{-11}$	1.81×10^{-15}
y_{ds}	$(-1.60 - 0.65\,i) \times 10^{-9}$	

Remember:

FCC-ee $\mathrm{BR}(h \to qq')$



Current Indirect Bounds

Computation of the Bounds

- Running of Wilson coefficients done with **`wilson`**
- Low-energy flavor observables computed with **`flavio`**
- Considered observables:

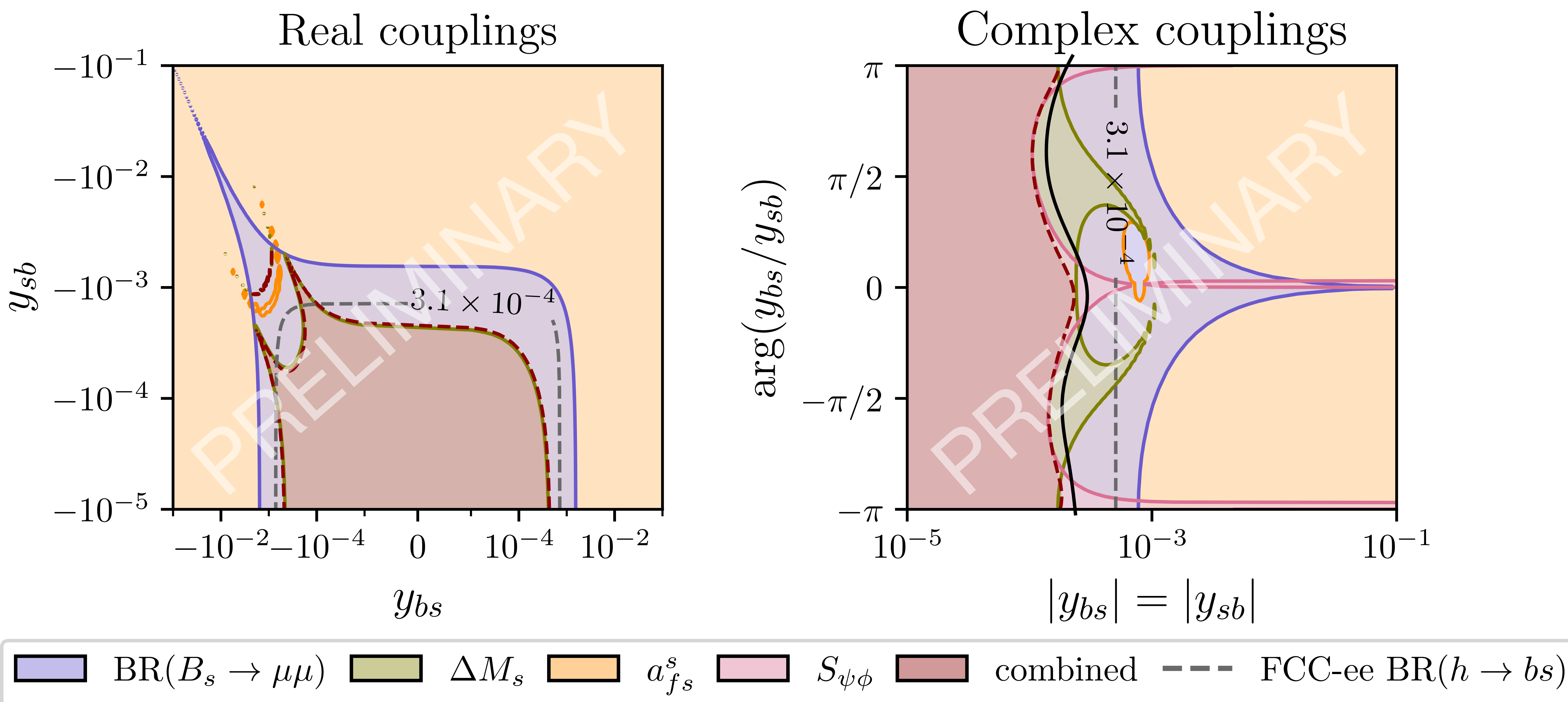
Decay

$$\mathrm{BR}(B_s(B_d, D^0, K^0) \to \mu^+\mu^-)$$

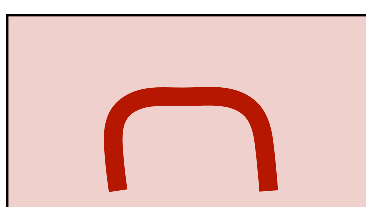
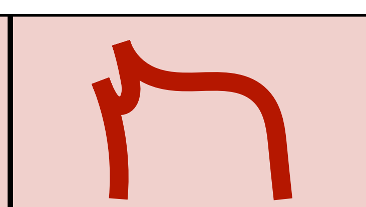
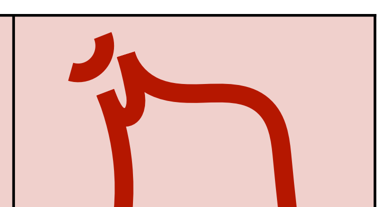
Mixing

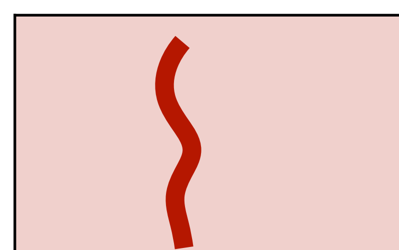
- $B_{s(d)} - \bar{B}_{s(d)}$: $\Delta M_{s(d)}, \quad a_{fs}^{s(d)}, \quad S_{\psi\phi(K)}$
- $D^0 - \bar{D}^0$: $x_D, \quad \left|\frac{q}{p}\right|_D, \quad \phi_D$
- $K^0 - \bar{K}^0$: $\left|\varepsilon_K\right|, \quad \Delta M_K$

Bounds on y_{bs} and y_{sb}

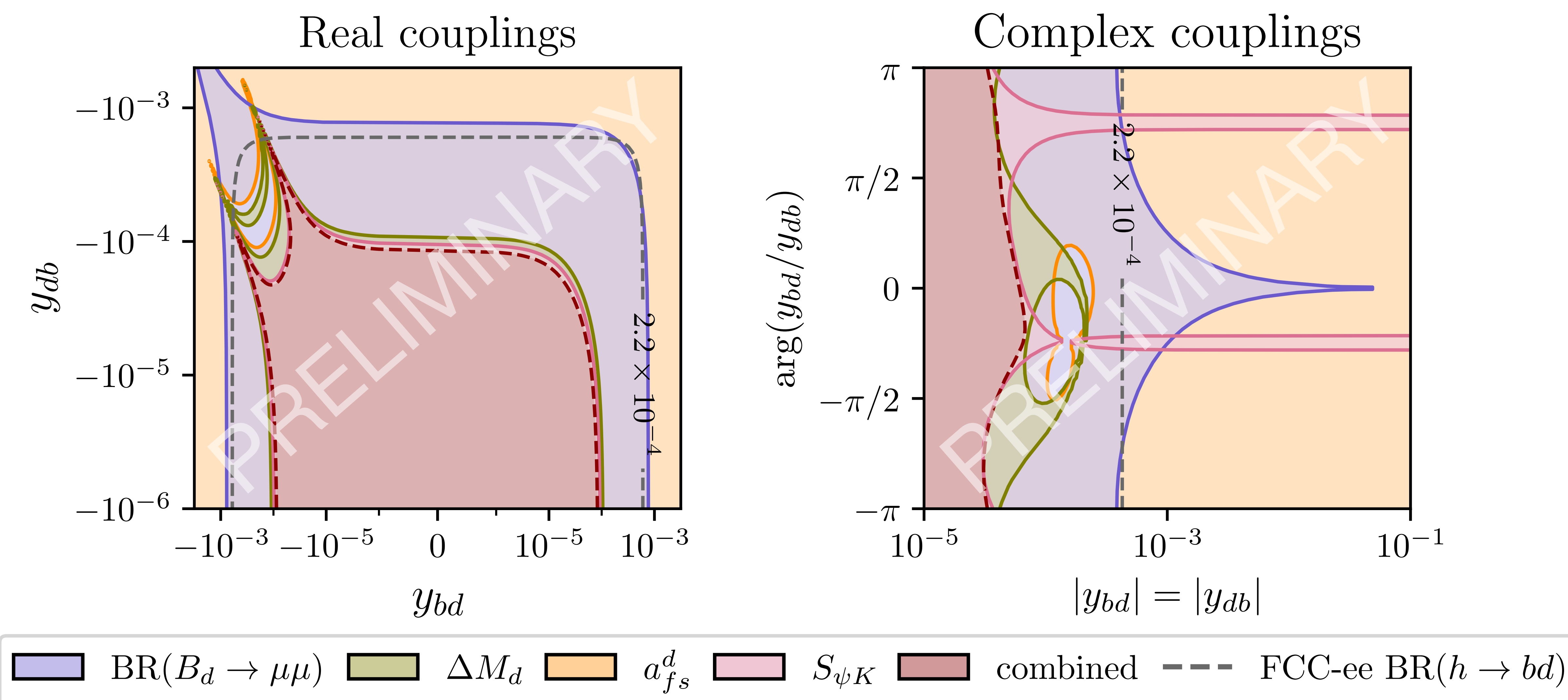


Upper limit $\mathrm{BR}(h \to bs)$

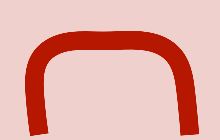
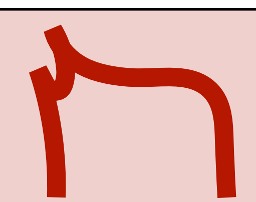
		
1.0×10^{-4}	1.3×10^{-3}	3.2×10^{-3}

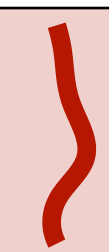
	6.5×10^{-5}

Bounds on y_{bd} and y_{db}



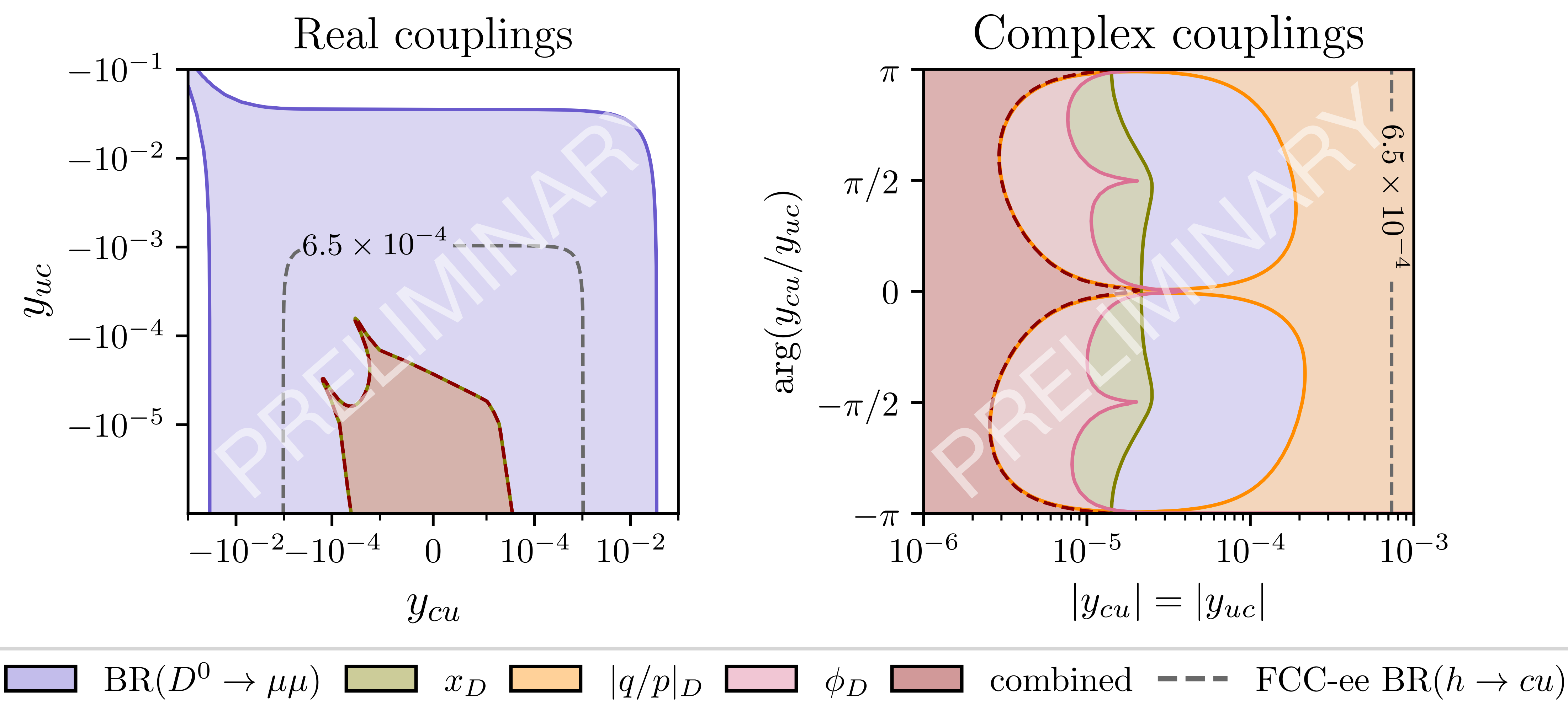
Upper limit $\mathbf{BR(h \to bd)}$

	
5.0×10^{-6}	4.0×10^{-4}

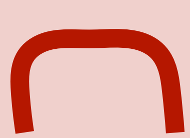
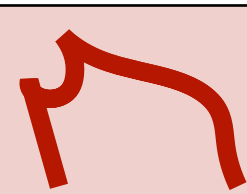
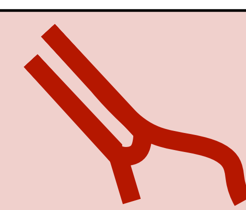
	5.5×10^{-6}

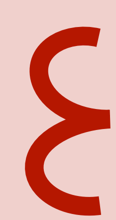
Bounds on y_{uc} and y_{cu}

- Challenge: no reliable SM prediction → set SM to zero and inflate uncertainties to allow NP to saturate present experimental value within uncertainties

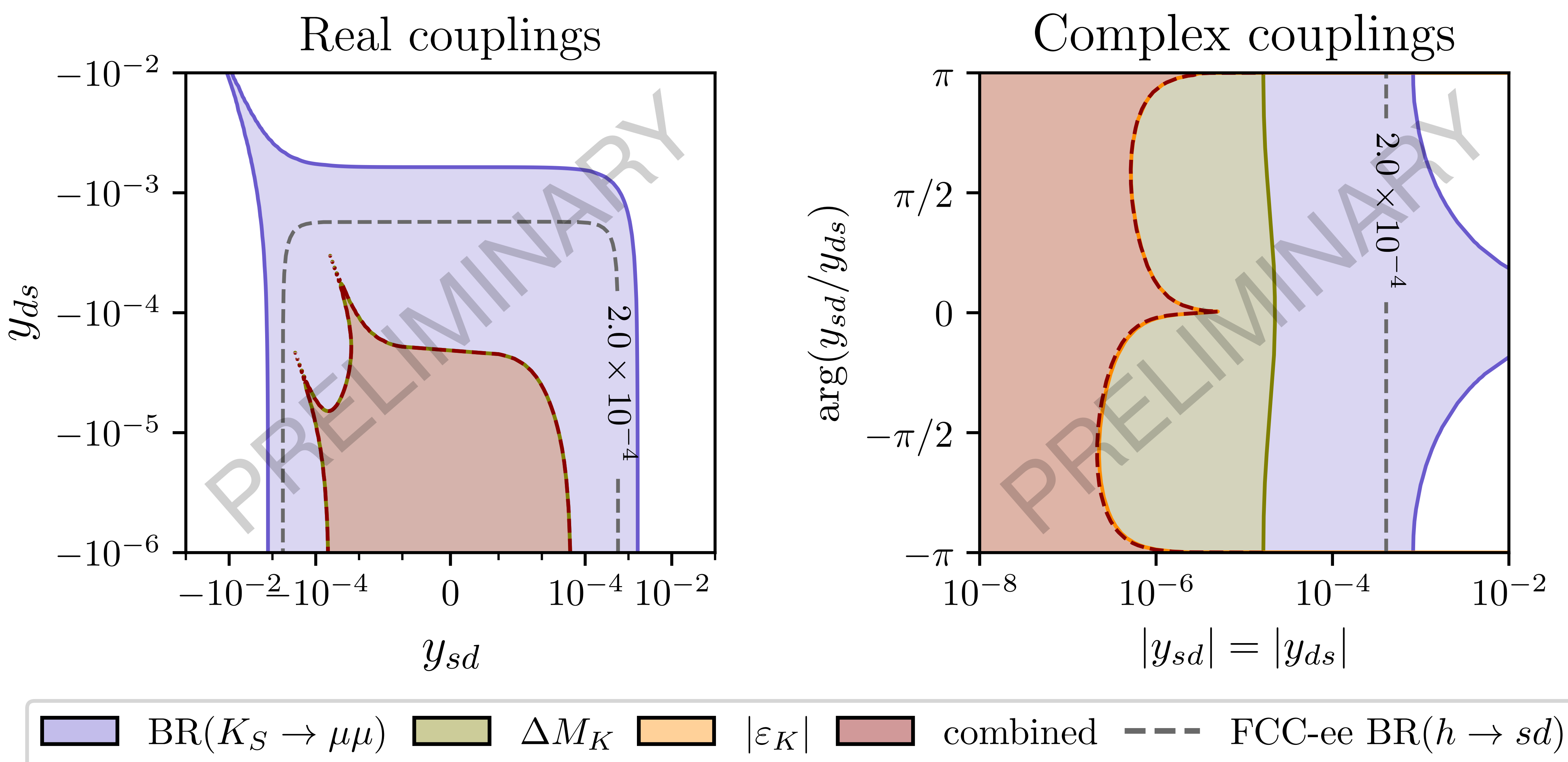


Upper limit $\mathrm{BR}(h \to uc)$

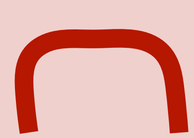
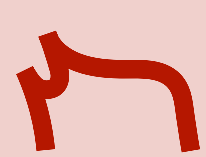
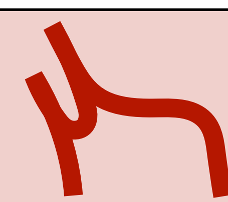
		
1.0×10^{-6}	1.6×10^{-5}	8.0×10^{-1}

	5.2×10^{-7}

Bounds on y_{sd} and y_{ds}



Upper limit $\mathbf{BR(h \to sd)}$

		
1.1×10^{-6}	5.54×10^{-5}	1.5×10^{-3}

	
3.6×10^{-7}	3.1×10^{-8}

Projection of Bounds

Projections

- The mean of the projected (and current) observable measurement set to SM
- Projected uncertainties of CKM matrix parameters:

CKM parameter	$\lvert V_{us}\rvert$	$\lvert V_{ub}\rvert$	$\lvert V_{cb}\rvert$	γ
Projected uncertainty	2.3×10^{-4}	3.2×10^{-5}	1.7×10^{-4}	3.5×10^{-3}
Current uncertainty	6.1×10^{-4}	1.4×10^{-4}	5.1×10^{-4}	6.3×10^{-2}

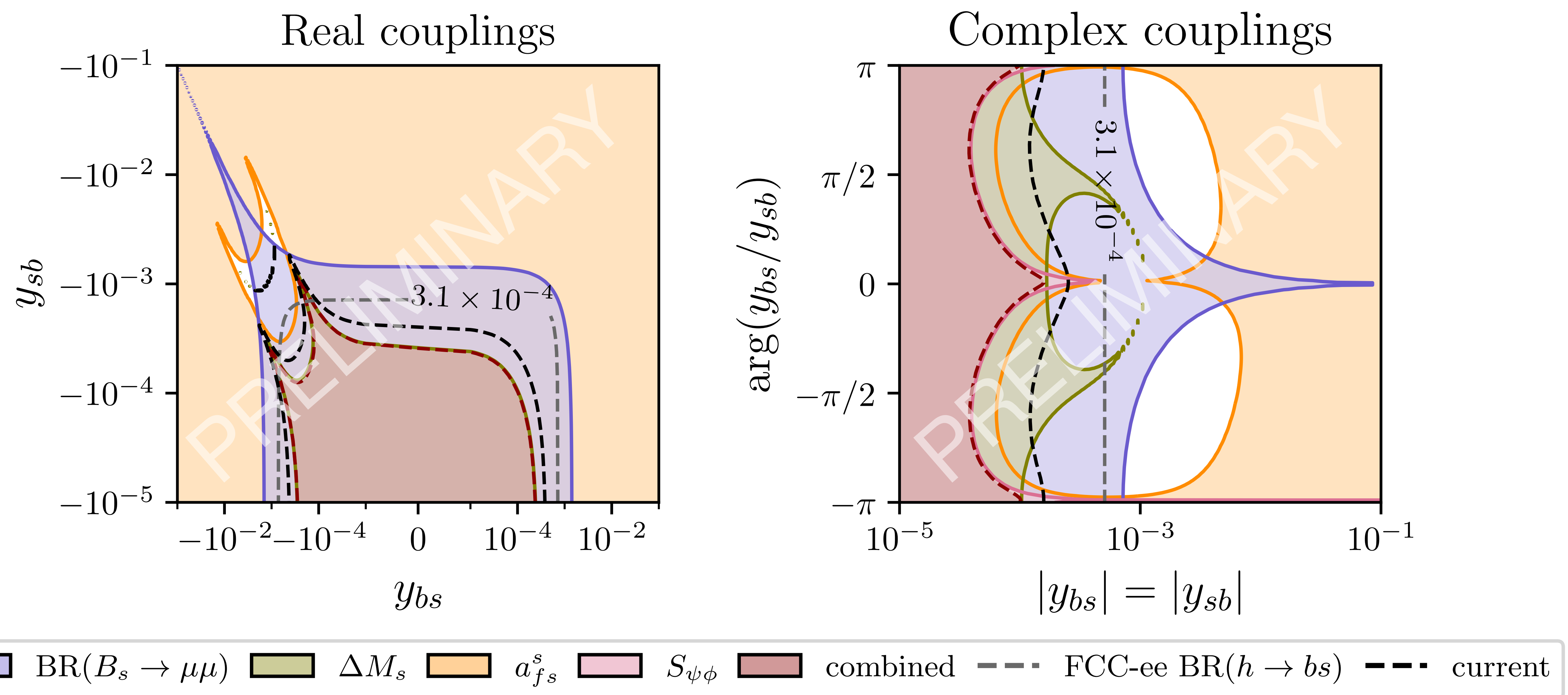
arXiv: 2006.04824

- Bag parameters $B_n^{(s(d))} \to$ 1% uncertainty
- Projected uncertainties of (some) observable measurements:

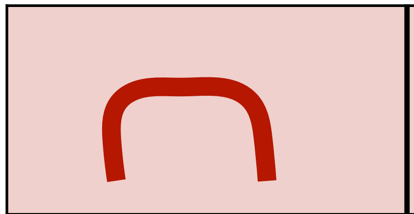
Observable	$S_{\psi\phi}$	$S_{\psi K}$	a_{fs}^s	a_{fs}^d	$BR(B_s \to \mu\mu)$	$BR(B_d \to \mu\mu)$
Projected uncertainty	2.3×10^{-4}	8.0×10^{-4}	3.2×10^{-5}	3.2×10^{-5}	1.6×10^{-10}	1.2×10^{-11}
Current uncertainty	1.9×10^{-2}	1.7×10^{-2}	4.1×10^{-3}	1.7×10^{-3}	2.8×10^{-10}	5.4×10^{-11}

arXiv: 2006.04824, ESPPU 2025 Calvi et. al.

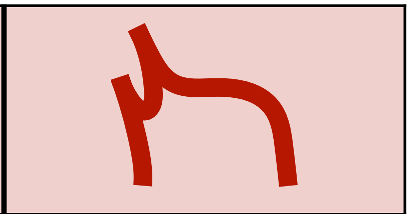
Bounds on y_{bs} and y_{sb}



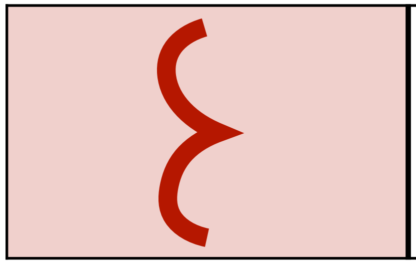
Upper limit $\mathbf{BR(h \to bs)}$



4.0 x 10^{-5}

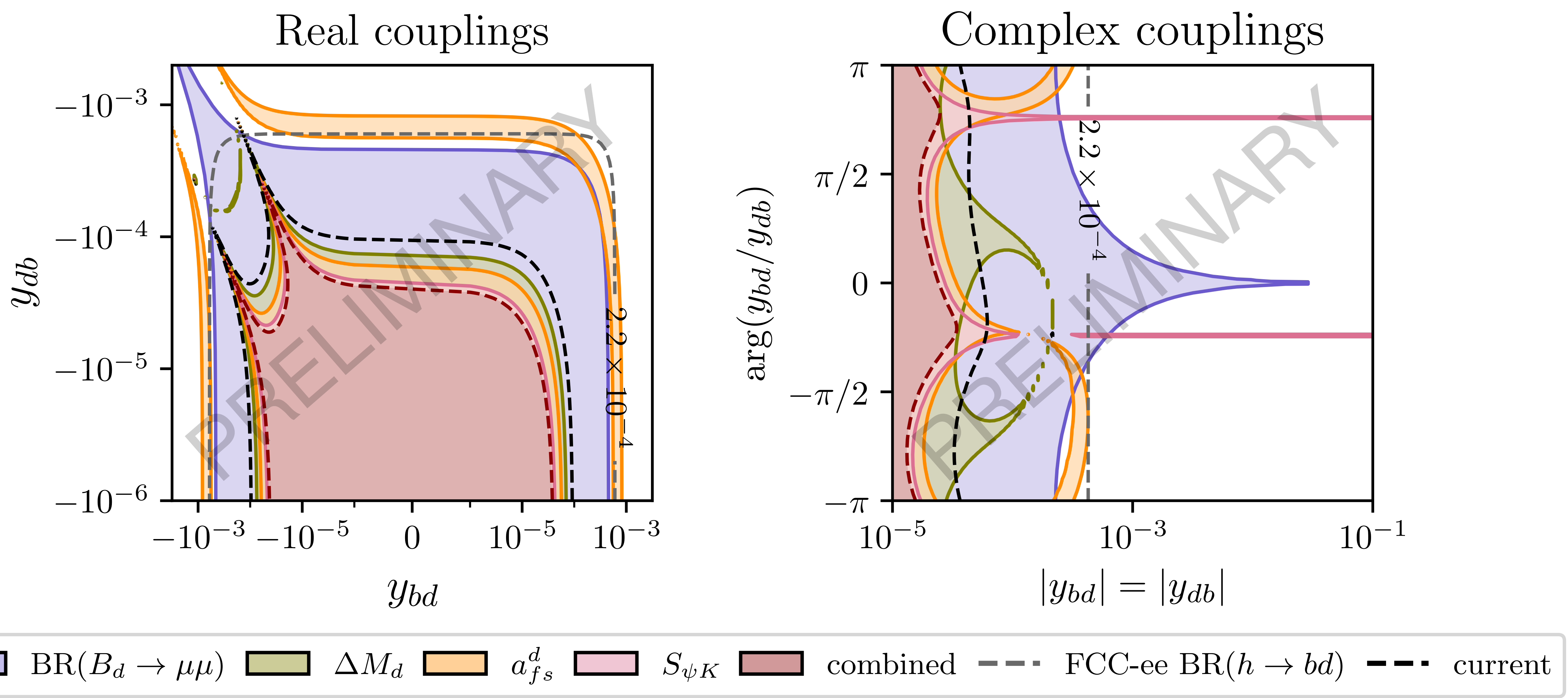


8.5 x 10^{-4}

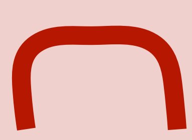
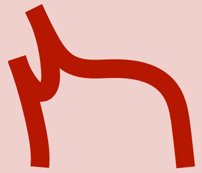


3.0 x 10^{-5}

Bounds on y_{bd} and y_{db}

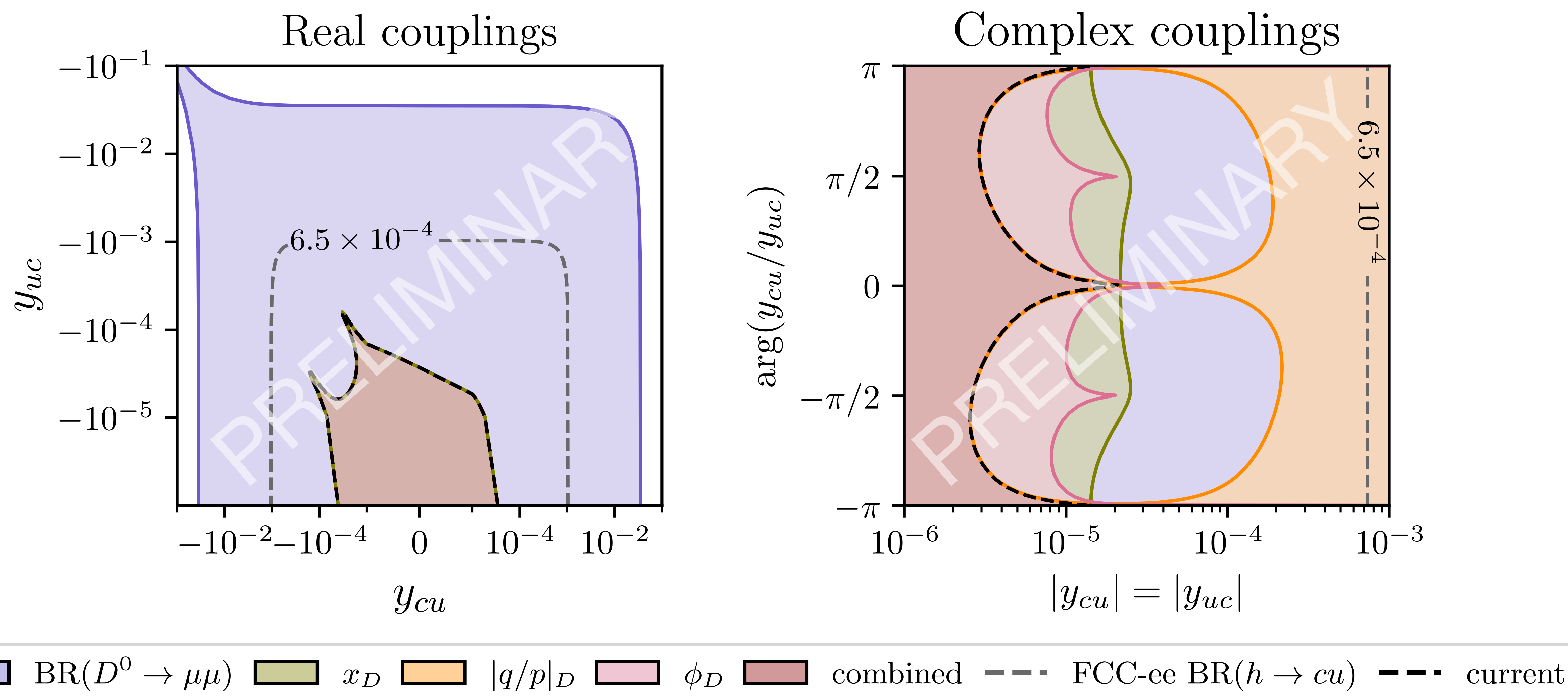


Upper limit $\mathbf{BR(h \to bd)}$

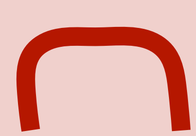
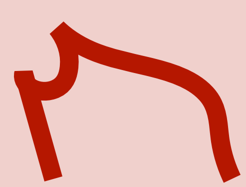
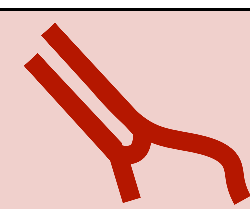
	
1.1×10^{-6}	7.8×10^{-5}

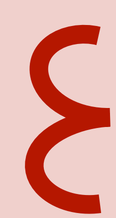
	1.4×10^{-6}

Bounds on y_{uc} and y_{cu}

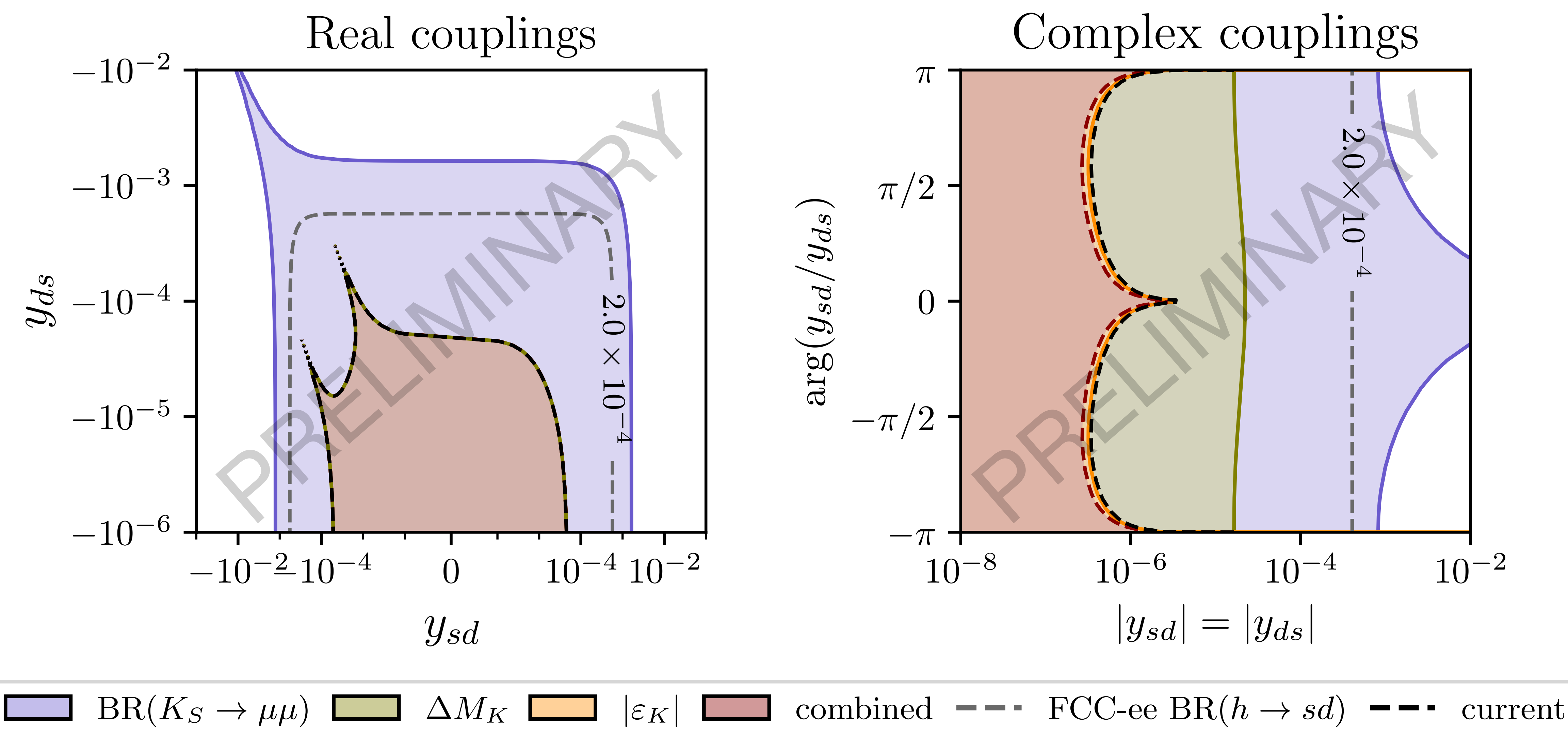


Upper limit BR(h → uc)

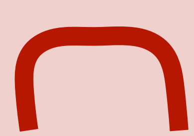
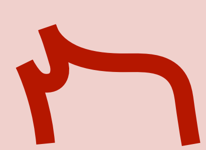
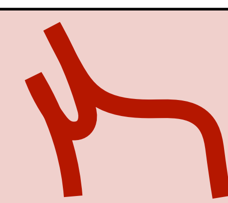
		
1.0×10^{-6}	1.6×10^{-5}	8.0×10^{-1}

	5.2×10^{-7}

Bounds on y_{sd} and y_{ds}



Upper limit BR(h → sd)

				
1.1×10^{-6}	5.54×10^{-5}	1.5×10^{-3}	3.3×10^{-7}	8.5×10^{-9}

Summary

Summary

- SM prediction of Higgs FCNCs is tiny
- Projected direct bounds on FCC-ee relatively big
- Indirect current bounds mostly stronger than projected direct bounds
- Future improvement of the indirect bounds
- All bounds much higher than SM prediction
- If any Higgs FCNCs measured → New Physics

Additional Slides

Matching the Effective Lagrangian to SMEFT

- SMEFT Lagrangian: $\mathscr{L}_{\rm SMEFT} \supset -\frac{C_{dH}^{ij}}{\Lambda^2}\bar{Q}_L^i H d_R^j + \mathrm{h.c.}$
- SM Lagrangian: $\mathscr{L}_{\rm SM} \supset -y_{ij}^{SM}\bar{Q}_L^i H d_R^j + \mathrm{h.c.}$

- Expand Higgs in unitary gauge: $H \to \begin{pmatrix} 0 \\ v+h \end{pmatrix}$

$$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{SMEFT} \supset \underbrace{-\frac{1}{\sqrt{2}}\left(y_{ij}^{SM}v + \frac{v^3}{2\Lambda^2}C_{dH}^{ij}\right)}_{m_{ij}}\bar{d}_L^i d_R^j - \frac{1}{\sqrt{2}}\left(y_{ij}^{SM} + \frac{3v^2}{2\Lambda^2}C_{dH}^{ij}\right)\bar{d}_L^i d_R^j h$$

- The effective Lagrangian: $\mathscr{L}_{\rm eff} \supset y_{ij}\bar{d}_L^i d_R^j h + \mathrm{h.c.}$

$$\longrightarrow \quad \boxed{\mathbf{y_{ij} = -\frac{m_{ij}}{v} + \frac{1}{\sqrt{2}}\frac{v^2}{\Lambda^2}C_{dH}^{ij}}}$$

Definitions of the Mixing Observables

$$\frac{d}{dt}\begin{pmatrix} |P^0(t)\rangle \\ |\bar{P}^0(t)\rangle \end{pmatrix} = \left(-iM - \frac{1}{2}\Gamma\right)\begin{pmatrix} |P^0(t)\rangle \\ |\bar{P}^0(t)\rangle \end{pmatrix}$$

- $B_{s(d)} - \bar{B}_{s(d)}$ mixing observables:

$$\Delta M_q = M_H - M_L = 2\sqrt{\frac{|M_{12}|^2 - 1/4|\Gamma_{12}|^2 + \sqrt{(|M_{12}|^2 - 1/4|\Gamma_{12}|^2)^2 + 1/4(M_{12}\Gamma_{12}^* + M_{12}^*\Gamma_{12})^2}}{2}}$$

$$a_{fs}^q = \left|\frac{M_{12}}{\Gamma_{12}}\right| \sin(\arg(-M_{12}/\Gamma_{12})) \qquad S_{\psi K(\phi)} = \sin(2\beta_{(s)})$$

- $D^0 - \bar{D}^0$ mixing observables:

$$x_D = \frac{\Delta M_D}{\Gamma_D} \quad y_D = \frac{\Delta\Gamma_D}{2\Gamma_D} \quad \frac{q}{p} = \sqrt{\left(\frac{M_{12}^* - i/2\Gamma_{12}^*}{M_{12} - i/2\Gamma_{12}}\right)} \quad \phi_D = \arg\left(\frac{q}{p}\right)$$

- $K^0 - \bar{K}^0$ mixing observables:

$$\varepsilon_K = \frac{A(K_L \to \pi\pi)}{A(K_S \to \pi\pi)} \quad \Delta M_K = M_{K_L} - M_{K_S}$$