Flavor violating Higgs and Z decays at FCC-ee

8th FCC Physics Workshop, CERN

Arman Korajac (INFN Pisa)

Based on the work:

J. F. Kamenik, AK, M. Szewc, M. Tammaro and J. Zupan, ***Phys. Rev. D, 109.L011301***

arXiv: 2306.17520

OUTLINE

- Current status of H/Z flavor-violating decays
- Analysis framework
- Results
- Conclusions

CURRENT STATUS

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} ★
$\mathcal{B}(h \to bd)$	$(3.8 \pm 0.6) \cdot 10^{-9}$	0.16 ▲	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} ●
$\mathcal{B}(Z \to bd)$	$(1.8 \pm 0.3) \cdot 10^{-9}$	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} ●

$$\mathcal{B}(h \to bs) \equiv \mathcal{B}(h \to \bar{b}s + b\bar{s})$$

▲ $h \to$ undet (ATLAS + CMS, 2207.00043)

■ $Z \to$ had (hep-ex/0012018)

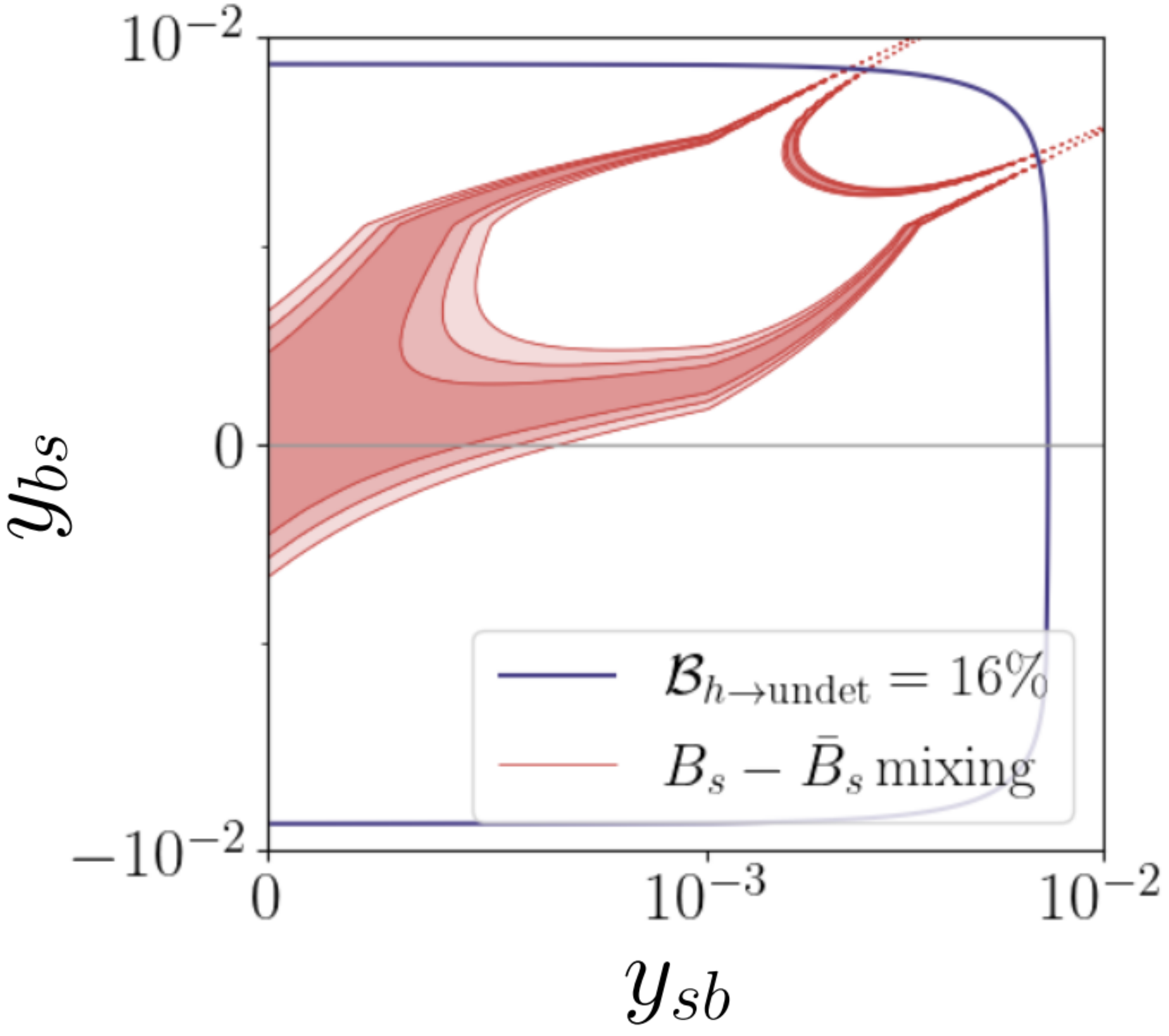
★ Meson mixing (no large cancellations)

● Global fits (flavio, smelli)

CURRENT STATUS

Global fits

$$\mathcal{L} \supset g_{sb}^L(\bar{s}_L\gamma_\mu b_L)Z^\mu + g_{sb}^R(\bar{s}_R\gamma_\mu b_R)Z^\mu$$
$$+y_{sb}(\bar{s}_L b_R)h + y_{bs}(\bar{b}_L s_R)h + \text{h.c.}$$

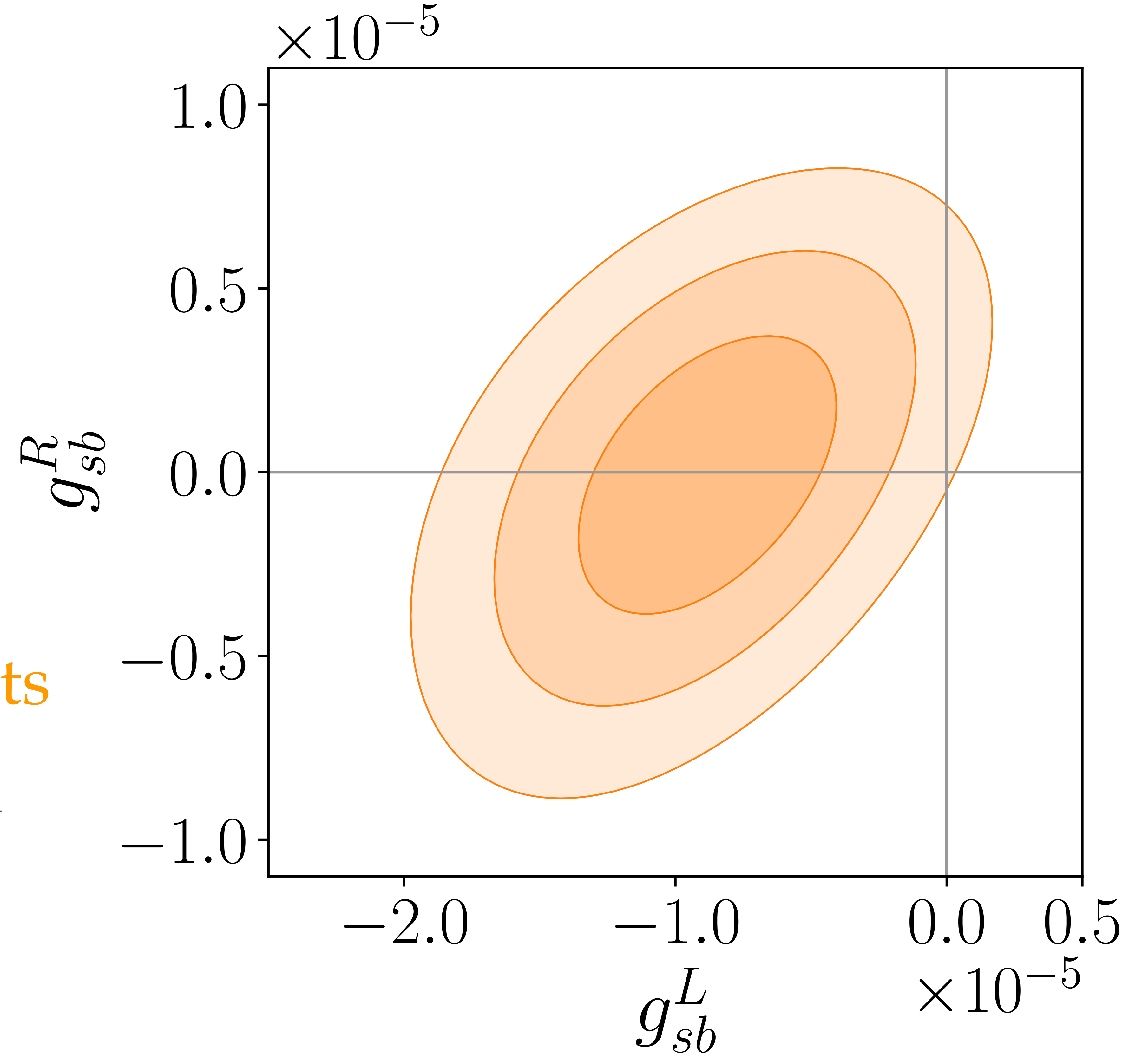


Meson mixing

$h \to$ undet

$b \to s\ell\ell$ fits

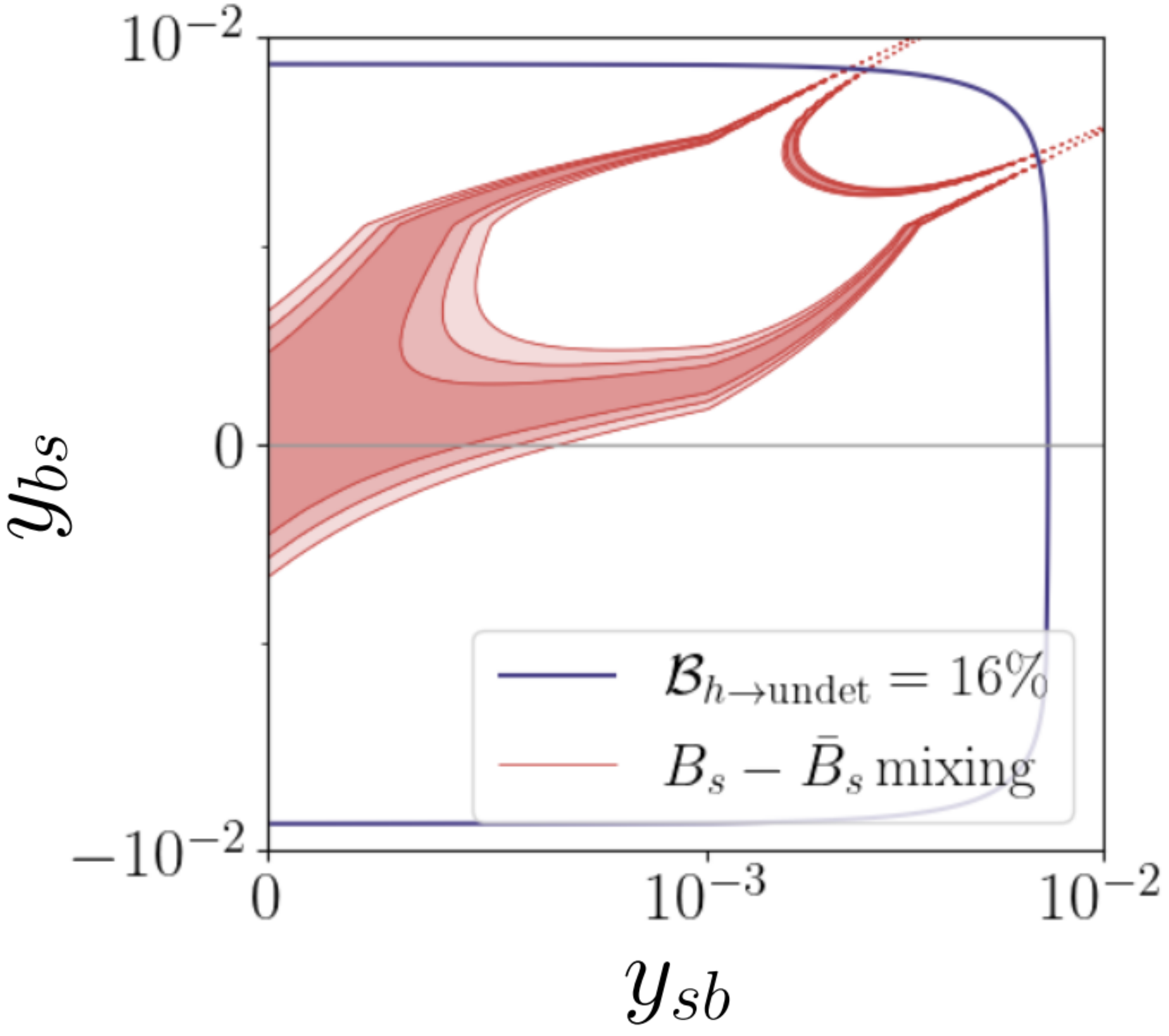
flavio, smelli



CURRENT STATUS

Global fits

Can the FCC-ee do better?



Meson mixing

$h \to$ undet

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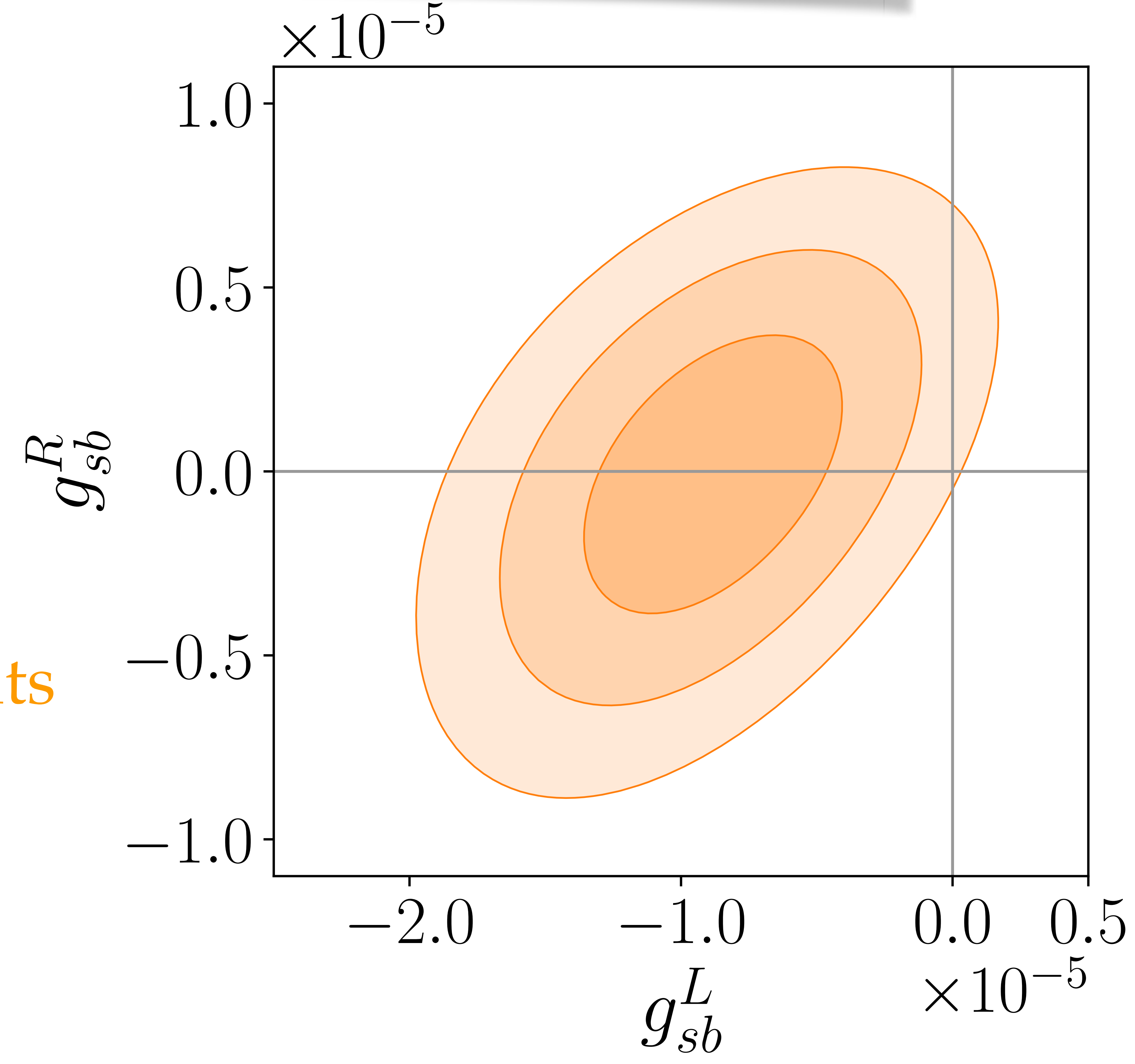


Analysis framework

Analysis framework

- Maximum likelihood estimate (**MLE**) for the FV branching ratios for H and Z
- The likelihood is going to be a function of the FV branching ratio (**POI**) and **nuisance parameters**:
  - Branching ratios of the background processes (flavor-conserving decays with mis-tagged jets)
  - Jet tagging efficiencies ϵ_α^β
  - Detector acceptance $\mathscr{A}$, number of produced Z's or Higgses $N_{Z/h}$

No Monte Carlo generated data needed in this case (has been done: see the ZHvvjj fit, results compatible!)

Analysis framework

1) Controlled / clean background

$$\sqrt{s} = m_Z$$

1905.03764

FCC Conceptual Design Reports
G. Marchiori's talk at "Higgs Performance meeting"
(indico.cern.ch/event/1221257)

Parameters	Nominal value	Rel. uncert. (in %)
$\mathcal{B}(Z \to uu + dd)$	27.01%	5.0
$\mathcal{B}(Z \to ss)$	15.84%	3.8
$\mathcal{B}(Z \to cc)$	12.03%	1.7
$\mathcal{B}(Z \to bb)$	15.12%	0.33
N_Z	5×10^{12}	10^{-3}
$\mathcal{A}$	0.994	10^{-3}

$$\sqrt{s} = 240\,\text{GeV}$$

Z(nunu)H(jj) @ FCC-ee

See yesterday's talk by Alexis

Parameters	Nominal Value	Rel. uncert. (%)
$\mathcal{B}(h \to gg)$	1.4%	1.2
$\mathcal{B}(h \to ss)$	0.024%	160
$\mathcal{B}(h \to cc)$	2.9%	2.8
$\mathcal{B}(h \to bb)$	56%	0.4
N_h	6.7×10^5	0.5
$\mathcal{A}$	0.70	0.1

Other backgrounds (ττ for Z, DY, WW, ZZ for *h*) can be neglected

G. Marchiori's talk at "FCC Physics Workshop" (indico.cern.ch/event/1176398/)

ParticleNet: 1902.08570
Jet-Flavor tagging at FCC-ee: 2210.10322
Bedeschi, Gouskos, Selvaggi, 2202.03285

Analysis framework

2) Advancements in jet flavor tagging

Providing tagging & mistag efficiencies ϵ_β^α

The q-tagger rates for Higgs:

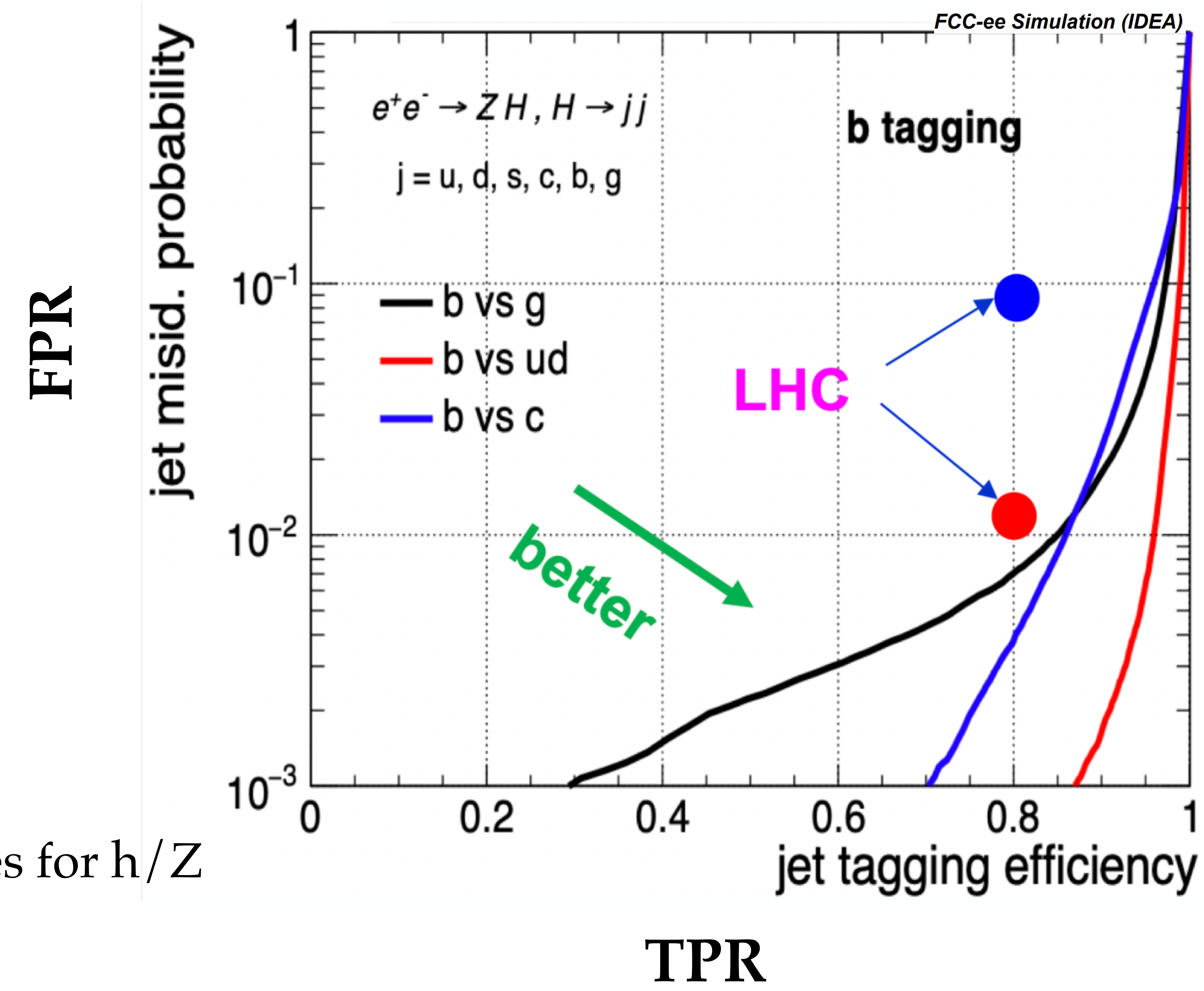
$$\epsilon_\beta^q = \{g, s, c, b\}$$

The q-tagger rates for Z:

$$\epsilon_\beta^q = \{ud, s, c, b\}$$

Applying 2 taggers, we have 8 tagger efficiencies for h/Z

Assuming 1% systematics



Analysis framework

ATLAS: 2201.11428
CMS: 2004.12181
Faroughy, Kamenik, Szewc, Zupan: 2209.01222

3) Probabilistic model

$$\mathcal{L}(\mu,\nu) = \prod_{(n_b,n_s)} \text{Pois}\Big(N^A_{(n_b,n_s)} | \bar{N}_{(n_b,n_s)}(\mu,\nu)\Big)\, p(\nu)$$

Tag bins

$$(n_b, n_s) = \{(0,0),(0,1),(1,0),(2,0),(0,2),(1,1)\}$$

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Expected number of events in bin (n_b, n_s) - sum over each decay channel

$$\bar{N}_{(n_b,n_s)} = \sum_{f=\text{bkg},bs} p(n_b, n_s | f, \nu) \bar{N}_f(\nu)$$

$$\bar{N}_f = \mathcal{B}(Z/h \to f) N_{Z/h} \mathcal{A}$$

$$\bar{N}_{bs} = \mu \, \mathcal{B}(Z/h \to bs)_{\text{SM}} \, N_{Z/h} \mathcal{A}$$

Analysis framework

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↓

Expected number of events in bin (n_b, n_s) - sum over each decay channel

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$$\bar{N}_f = \mathcal{B}(Z/h \to f) N_{Z/h} \mathcal{A}$$

$$\bar{N}_{bs} = \mu\, \mathcal{B}(Z/h \to bs)_{\text{SM}}\, N_{Z/h} \mathcal{A}$$

Given the final-state config f, the probability our event is found in bin (n_b, n_s)

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↓

Asimov dataset

$\mu = 0$ (upper limits)

$\nu_i = \nu_{i,0}$

Analysis framework

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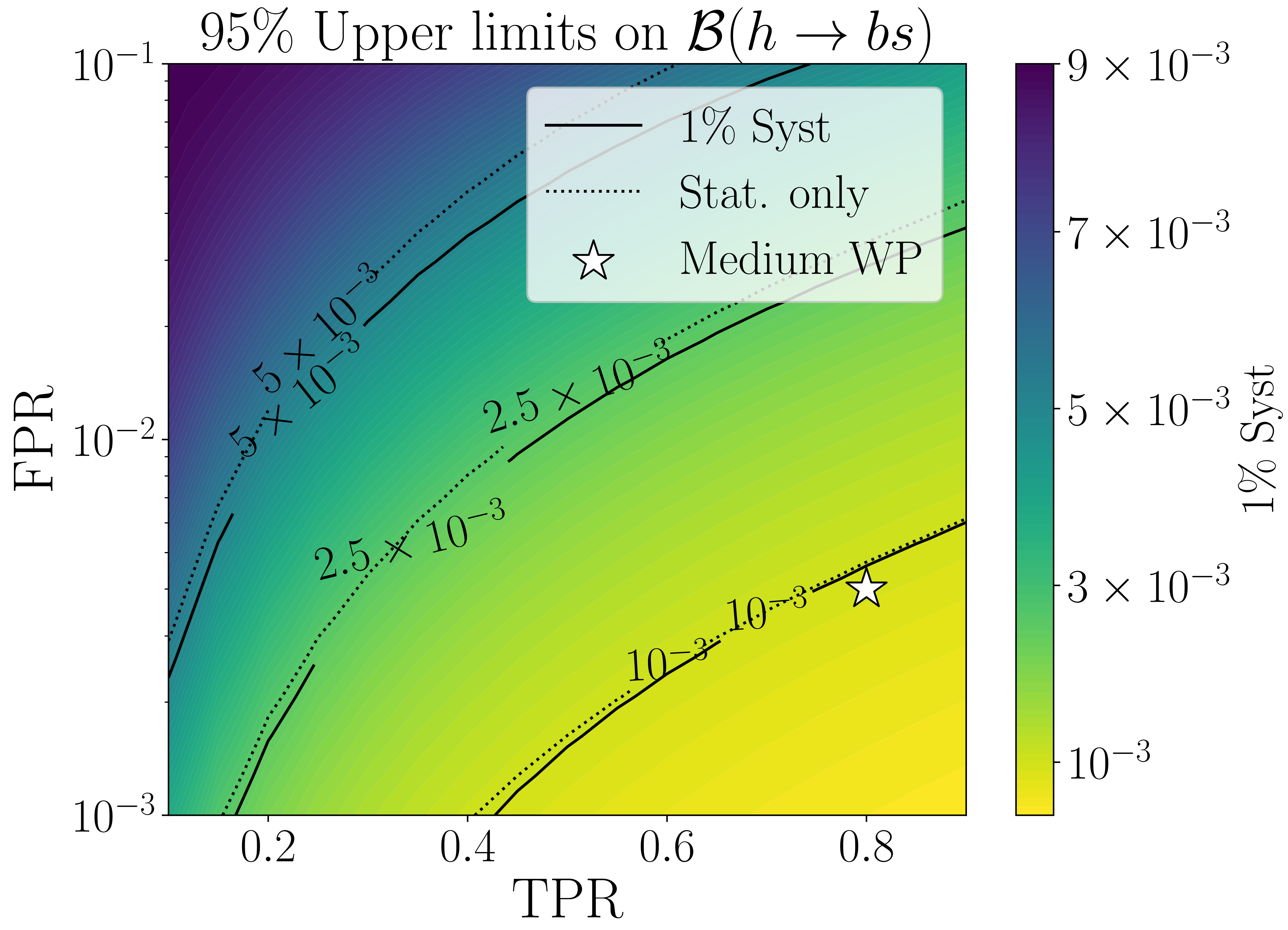
3) Probabilistic model

$$\mathcal{L}(\mu, \nu) = \prod_{(n_b, n_s)} \mathrm{Pois}\left(N^A_{(n_b,n_s)} | \bar{N}_{(n_b,n_s)}(\mu, \nu) \right) p(\nu)$$

Insert now the tagging efficiencies and other nuisance parameters and derive bounds on the branching ratios!

The assessment of the FCC-ee potential - Higgs



For the Higgs, statistics dominated

2D scan. Common TPR $\epsilon_b^b = \epsilon_s^s$ and FPR $\epsilon_{gcb}^s = \epsilon_{gsc}^b$

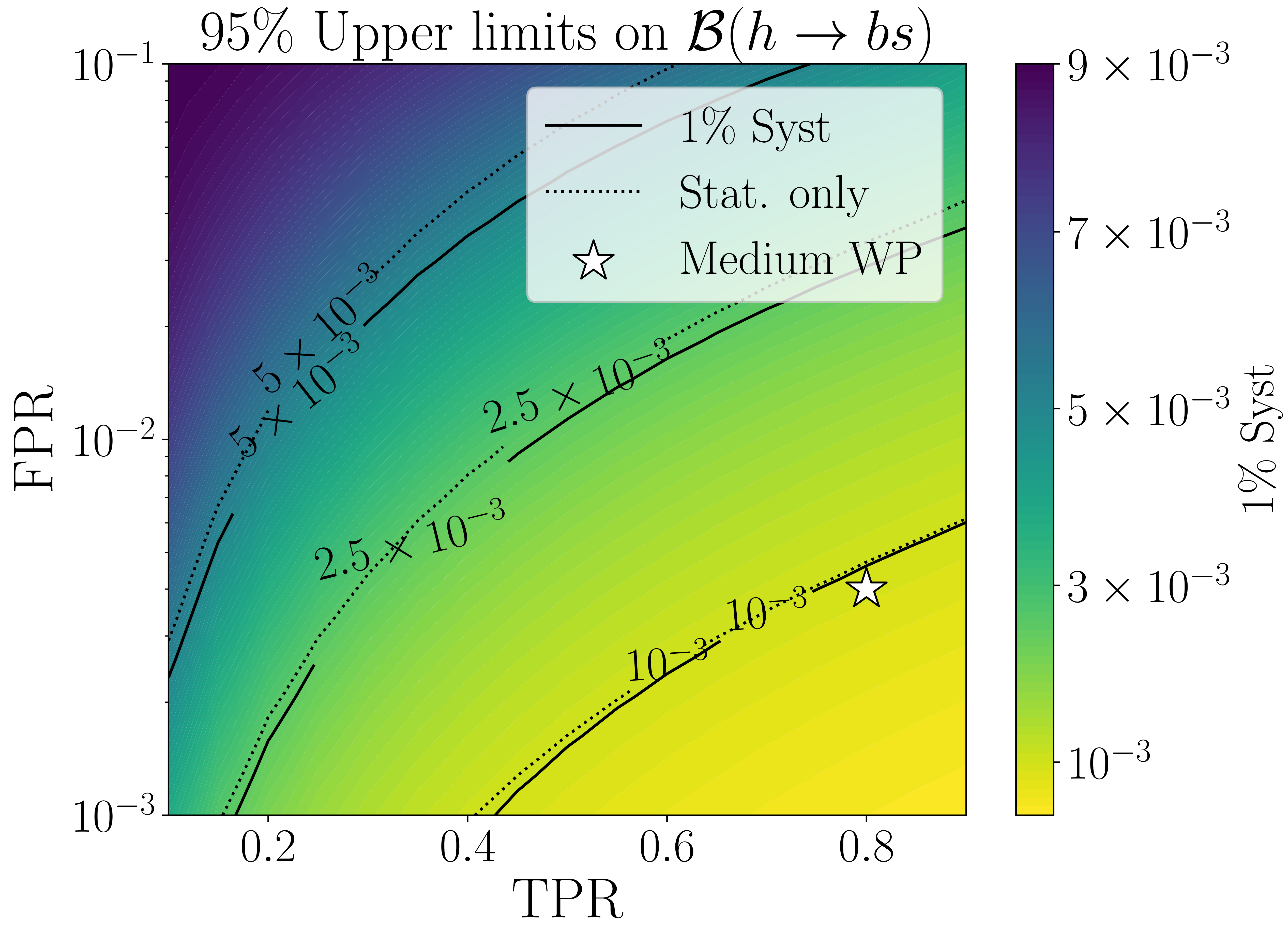
Obtain identical results w.r.t. full analysis if we take on the plot the point TPR = 0.8, FPR = max($\epsilon_b^s, \epsilon_s^b$) (Medium WP):

$$\epsilon^b_{\beta;\mathrm{Med}} = \{0.007, 0.0001, 0.003, 0.80\}$$

$$\epsilon^s_{\beta;\mathrm{Med}} = \{0.09, 0.80, 0.06, 0.004\}$$

$$\epsilon^q_\beta = \{g, s, c, b\}$$

The assessment of the FCC-ee potential - Higgs



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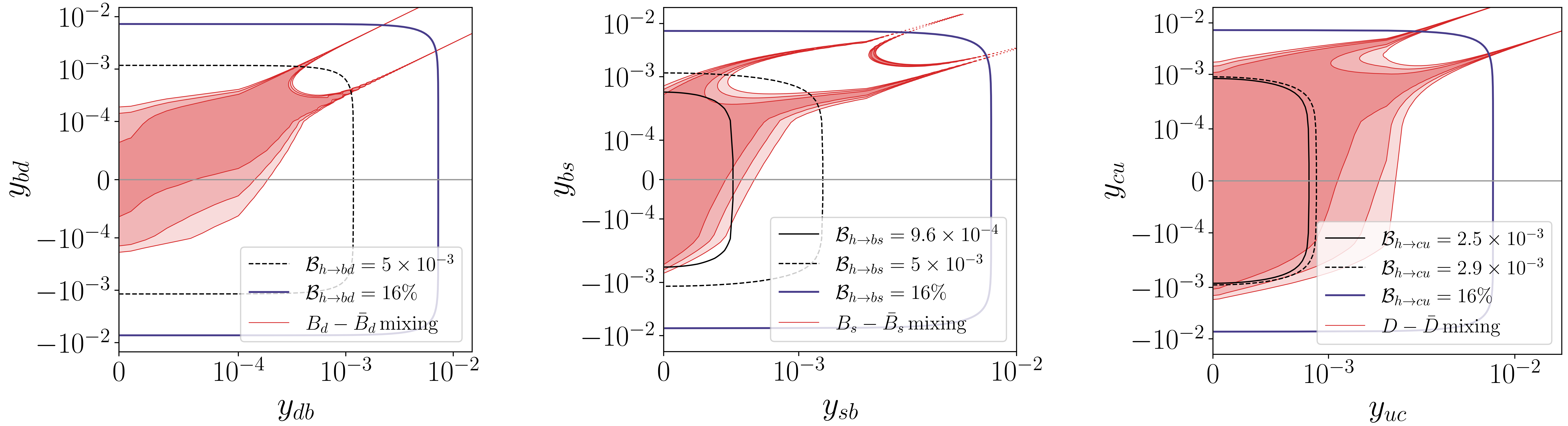
$$\epsilon^s_{\beta;\text{Med}} = \{0.09, 0.80, 0.06, \boxed{0.004}\}$$

$$\epsilon^q_\beta = \{g, s, c, b\}$$

$$\mathcal{B}(h \to bs) \lesssim 9.6 \times 10^{-4}$$ @ 95 % CL

The assessment of the FCC-ee potential - Higgs

Can set relevant phenomenological bounds for the Higgs flavor-violating couplings w.r.t. low-energy measurements



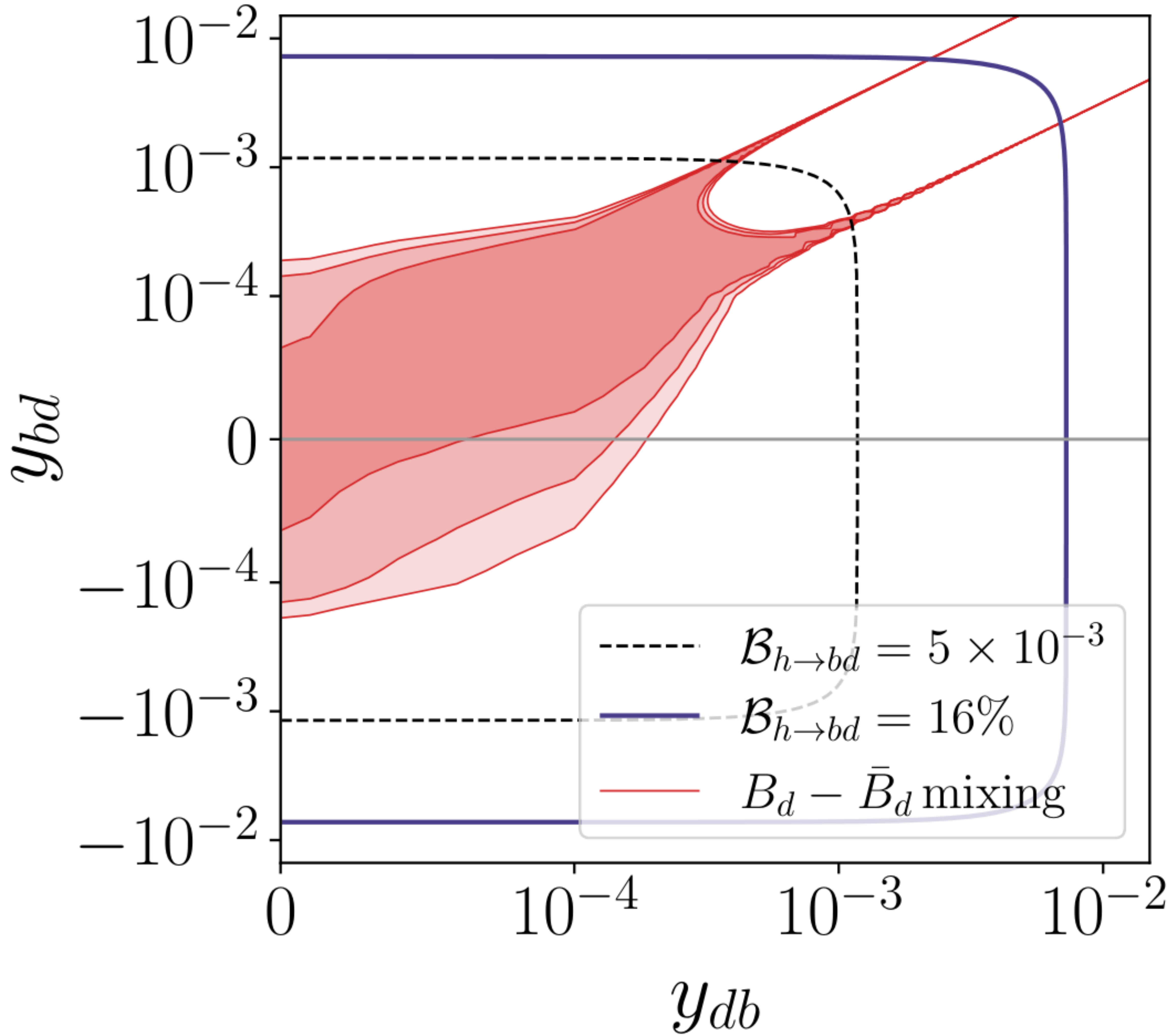
The assessment of the FCC-ee potential - Higgs

Can set relevant phenomenological bounds for the Higgs flavor-violating couplings w.r.t. low-energy measurements

$$\mathcal{L} \supset y_{db}(\bar{d}_L b_R)h + y_{bd}(\bar{b}_L d_R)h + \text{h.c.}$$

Matching to WET, wilson for running, flavio/smelli

Dashed line - Using only the b tagger



The assessment of the FCC-ee potential - Higgs

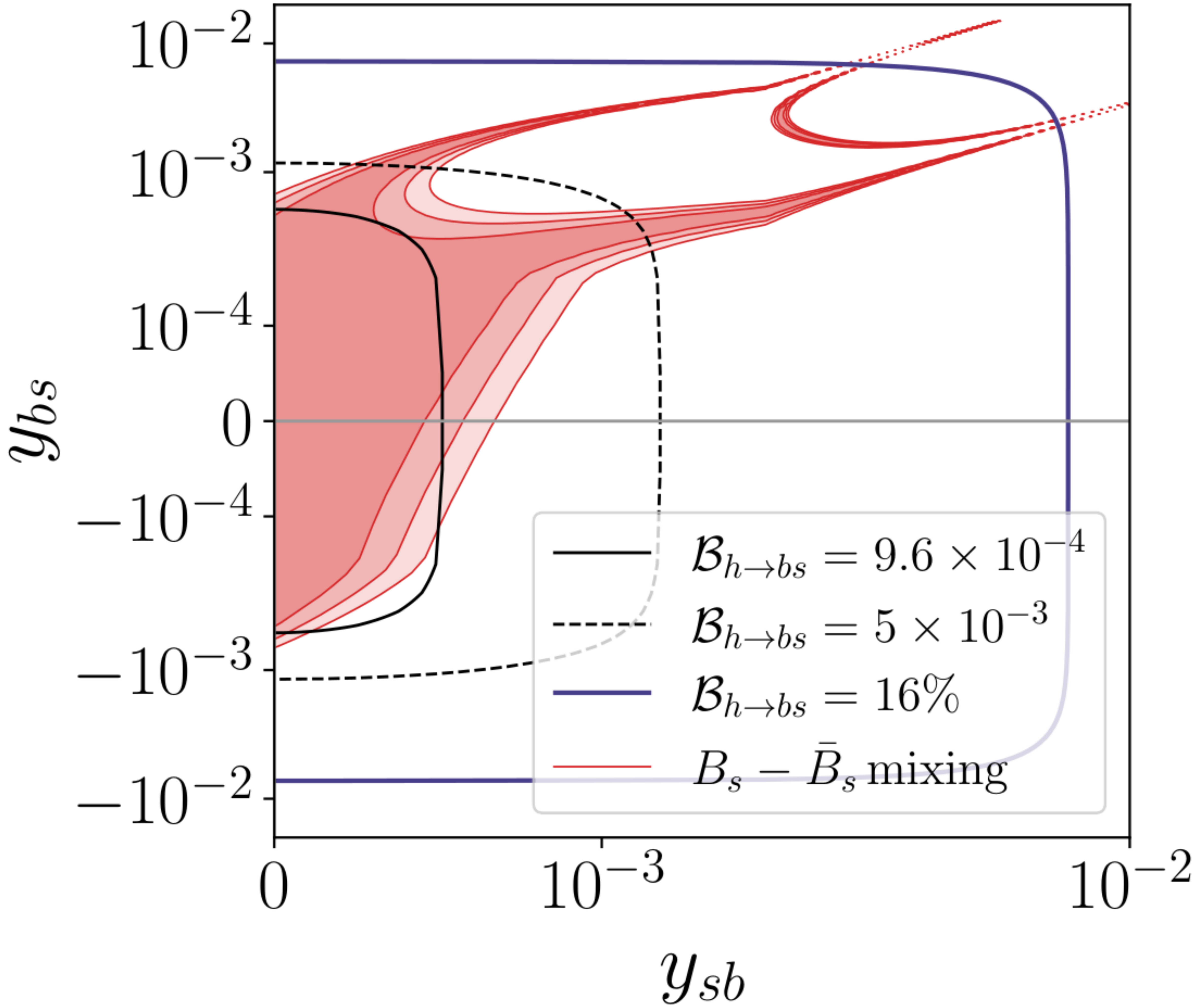
Can set relevant phenomenological bounds for the Higgs flavor-violating couplings w.r.t. low-energy measurements

$$\mathcal{L} \supset y_{sb}(\bar{s}_L b_R)h + y_{bs}(\bar{b}_L s_R)h + \text{h.c.}$$

Matching to WET, wilson for running, flavio/smelli

Solid line - Using both b and s taggers

Dashed line - Using only the b tagger



The assessment of the FCC-ee potential - Higgs

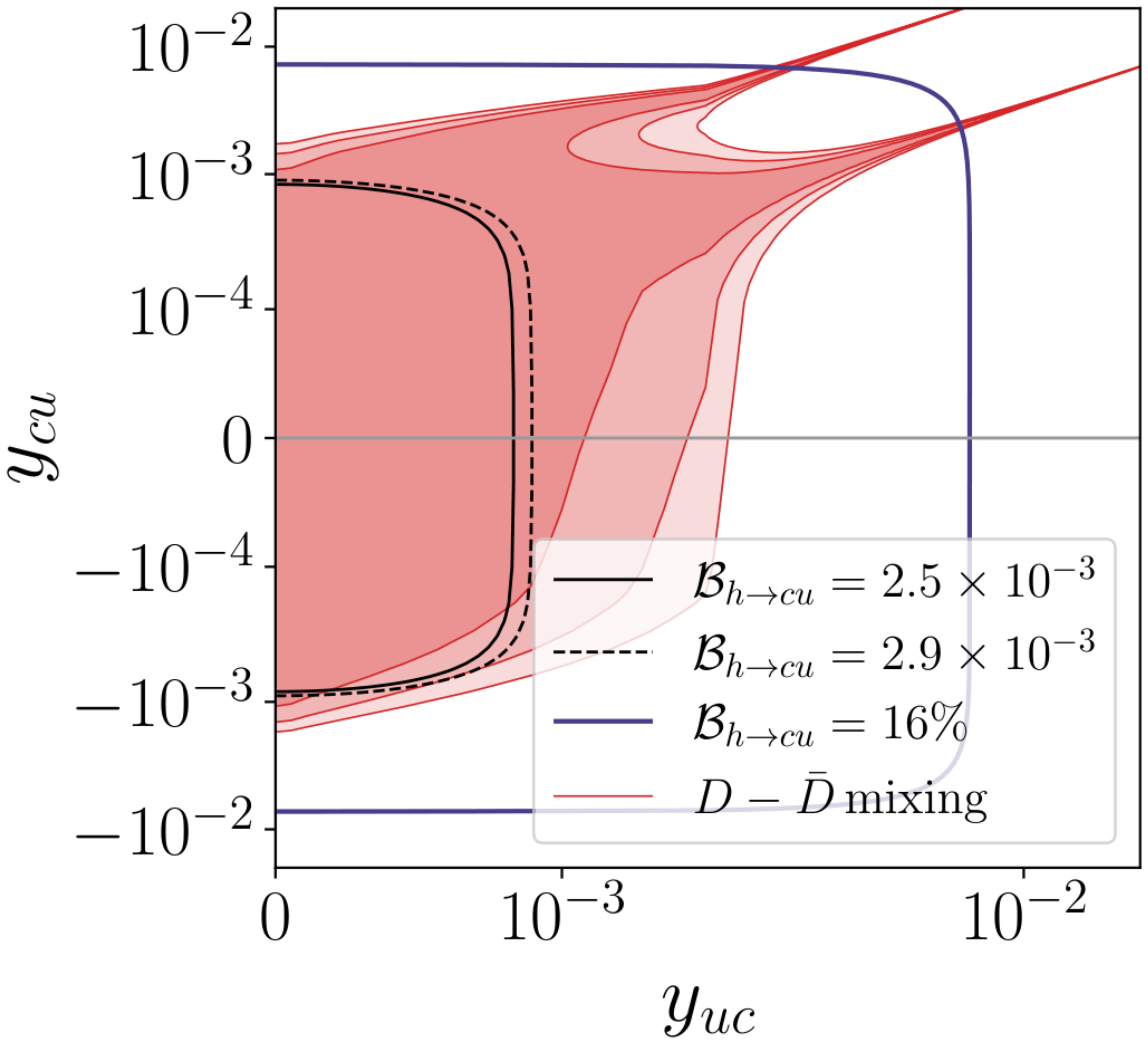
Can set relevant phenomenological bounds for the Higgs flavor-violating couplings w.r.t. low-energy measurements

$$\mathcal{L} \supset y_{uc}(\bar{u}_L c_R)h + y_{cu}(\bar{c}_L u_R)h + \text{h.c.}$$

Matching to WET, wilson for running, flavio/smelli

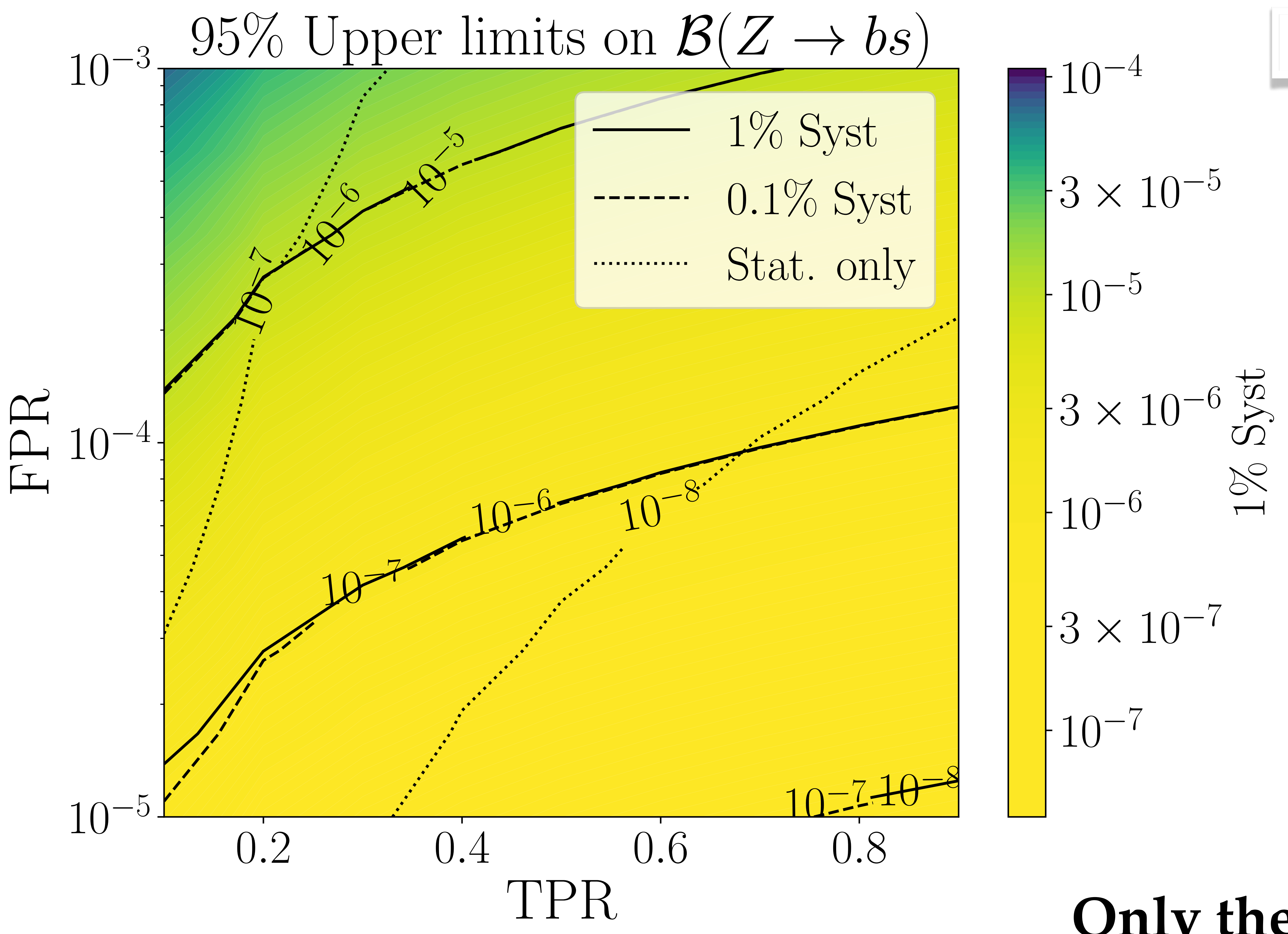
Different Working Points (solid / dashed line)

No u-tagger used (however, performance would be improved!)



The assessment of the FCC-ee potential - Z

For the Z, cannot put relevant bounds. Systematics (rel. error on tagging efficiencies ϵ_α^β , 1%) dominated



Decay	SM prediction	exp. bound	indir. constr.
$\mathcal{B}(Z \to bs)$	$(4.2 \pm 0.7) \cdot 10^{-8}$	2.9×10^{-3}	6×10^{-8}

(TPR, FPR, $\Delta\epsilon_\beta^\alpha/\epsilon_\beta^\alpha$)	$\mathcal{B}(Z \to bs)$ (95% CL)
(0.4, 10^{-4}, 1%)	1.8×10^{-6}
(0.4, 10^{-4}, 0.1%)	1.8×10^{-7}
(0.2, 10^{-5}, 1%)	4.2×10^{-7}
(0.2, 10^{-5}, 0.1%)	4.2×10^{-8}

Only then SM precision reachable (with very ambitious tagger performance)

$\epsilon_b^s \gtrsim 10^{-3}$, limited by vertexing at FCC-ee

Barchetta, Collins, Riedler: 2112.13019

The assessment of the FCC-ee potential

Model-dependent analyses - type-III 2HDM

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

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

$\downarrow$ Match

$$\mathcal{L}_{\rm WET} \supset C_2(\bar{s}_R b_L)^2 + C_2'(\bar{s}_L b_R)^2 + C_4(\bar{s}_L b_R)(\bar{s}_R b_L)$$

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

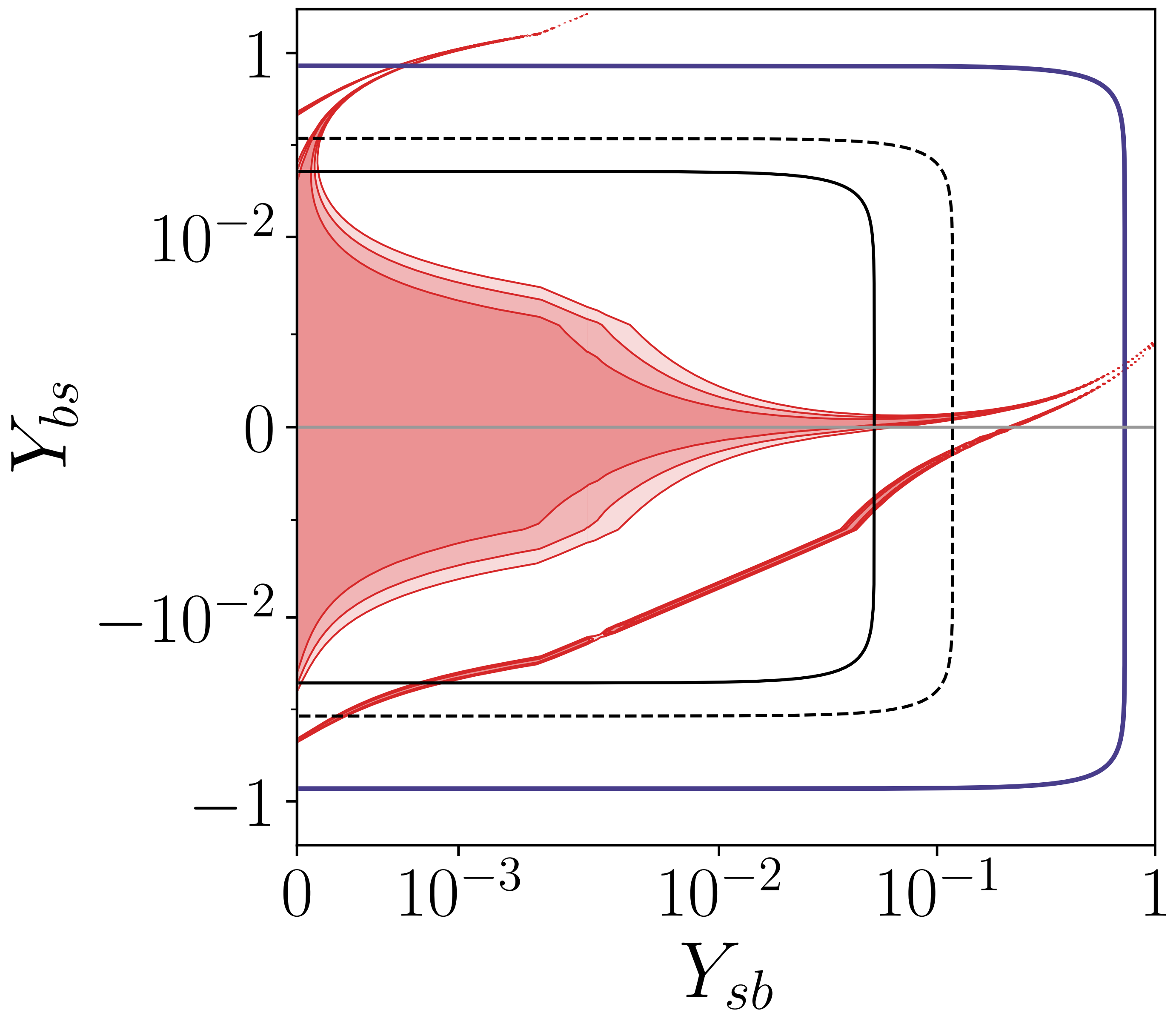
$$C_2' = -\frac{\left(Y_{sb}^{d}\right)^2}{2}\left(\frac{s_\alpha^2}{m_h^2} + \frac{c_\alpha^2}{m_H^2} - \frac{1}{m_A^2}\right),$$

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

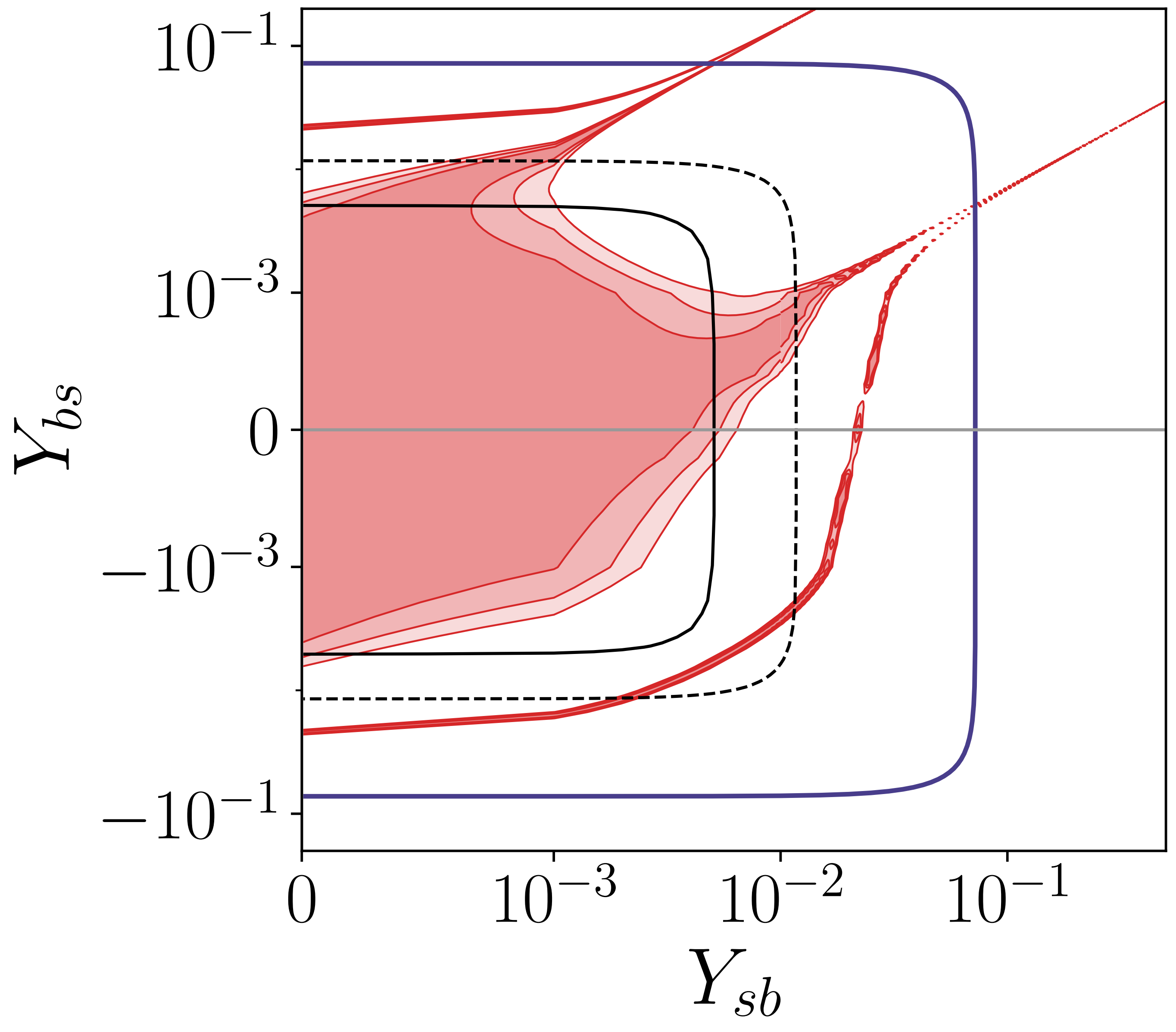
The assessment of the FCC-ee potential

Model-dependent analyses - type-III 2HDM

$$\mathcal{L}_{\text{WET}} \supset C_2(\bar{s}_R b_L)^2 + C_2'(\bar{s}_L b_R)^2 + C_4(\bar{s}_L b_R)(\bar{s}_R b_L)$$



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



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

$m_H = m_A = 1\,\text{TeV}$

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

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

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

$\mathscr{B}_{h\to bs} = 9.6 \times 10^{-4}$

$\mathscr{B}_{h\to bs} = 5 \times 10^{-3}$

$\mathscr{B}_{h\to bs} = 0.16$

The assessment of the FCC-ee potential

Model-dependent analyses - Insertion of vectorlike quarks

$(D_L, D_R) \sim (\mathbf{1}, -1/3)$

$$\mathcal{L}^D_{\rm VLQ} \supset \frac{g}{2c_W} X^d_{ij} (\bar{d}^i \gamma^\mu P_L d^j) Z_\mu + X^d_{ij} \frac{m_j}{v} (\bar{d}^i P_R d^j) h + \text{h.c.}$$

↓ Match

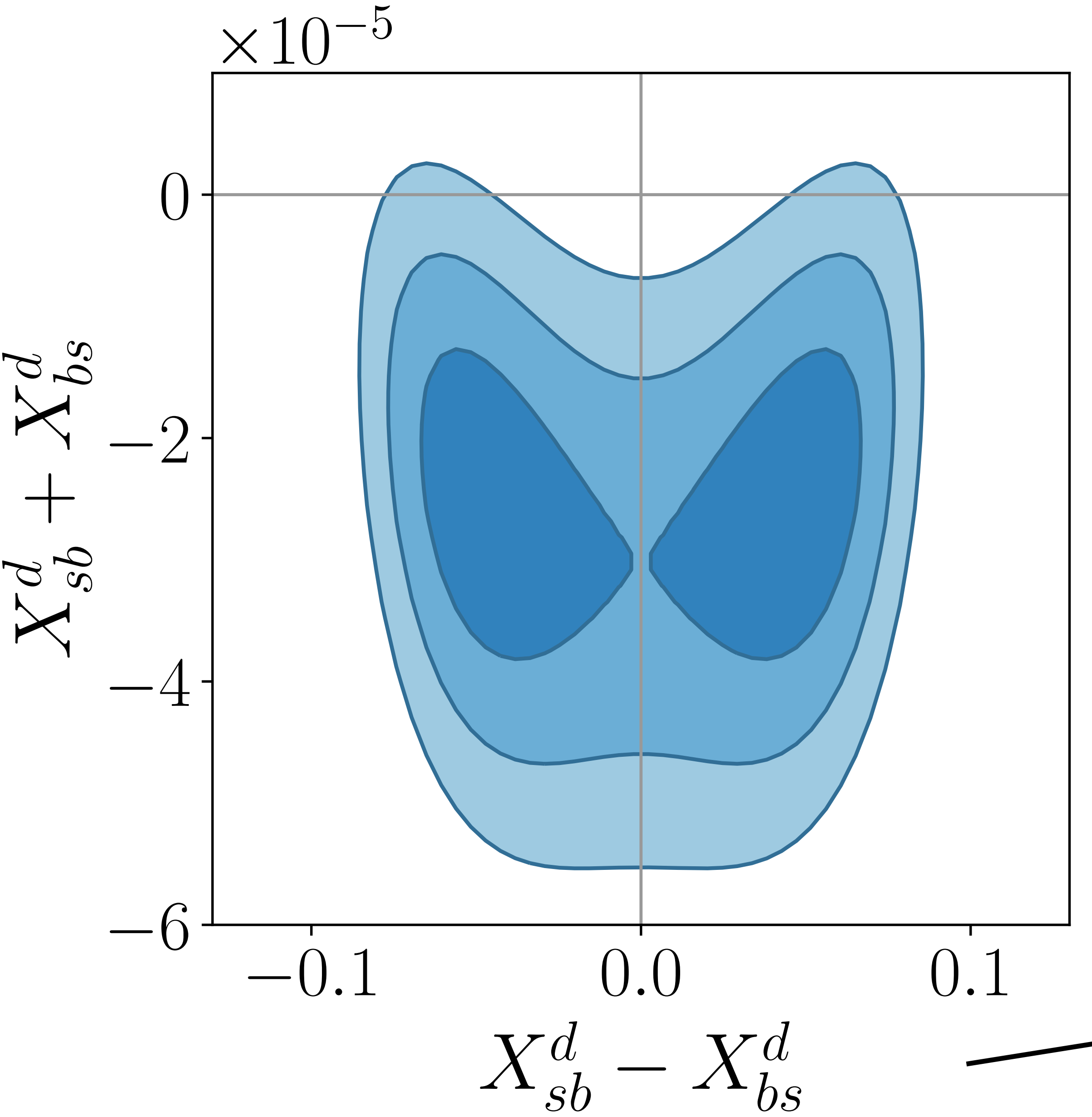
$$g^L_{sb} = \frac{g}{2c_W}(X^d_{sb} + X^{d*}_{bs}), \quad g^R_{sb} = 0, \quad y_{sb} = X^d_{sb} m_b/v, \quad y_{bs} = X^d_{bs} m_s/v$$

$(Q_L, Q_R) \sim (\mathbf{2}, 1/6)$

$$\mathcal{L}^Q_{\rm VLQ} \supset \frac{g}{2c_W} X^Q_{ij} (\bar{d}^i \gamma^\mu P_R d^j) Z_\mu + X^Q_{ij} \frac{m_j}{v} (\bar{d}^i P_R d^j) h + \text{h.c.}$$

↓ Match

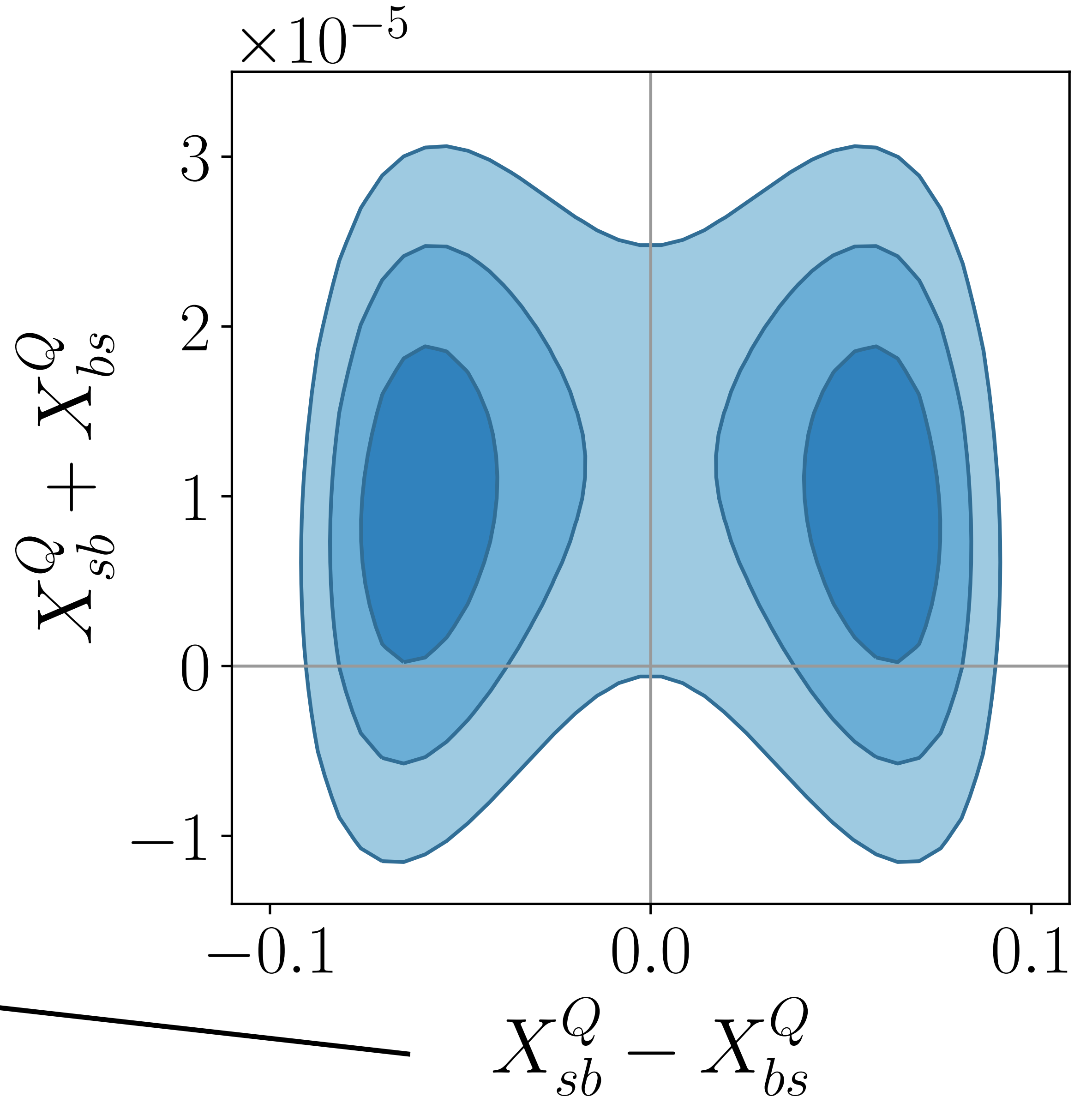
$$g^R_{sb} = \frac{g}{2c_W}(X^Q_{sb} + X^{Q*}_{bs}), \quad g^L_{sb} = 0, \quad y_{sb} = X^Q_{sb} m_b/v, \quad y_{bs} = X^Q_{bs} m_s/v$$



$$\mathcal{L} \supset g^L_{sb}(\bar{s}_L \gamma_\mu b_L) Z^\mu + g^R_{sb}(\bar{s}_R \gamma_\mu b_R) Z^\mu$$
$$+ y_{sb}(\bar{s}_L b_R) h + y_{bs}(\bar{b}_L s_R) h + \text{h.c.}$$

Pulls from
$b \to s\ell\ell$ data

$B_s - \bar{B}_s$ mixing



Conclusion

- **The role of FCC-ee for flavor physics is irrefutable**
- **The FCC-ee is probing very interesting regions of parameter spaces for H and Higgs-related models**
  - **Excluding flat directions**
- **FCC-ee not competitive with low-energy measurements for Z regarding FV BRs**

Conclusion

Decay	SM prediction	exp. bound	indir. constr.	FCC-ee bound
$\mathcal{B}(h \to bs)$	$(8.9 \pm 1.5) \cdot 10^{-8}$	0.16 ▲	2×10^{-3} ★	9.6×10^{-4}
$\mathcal{B}(h \to bd)$	$(3.8 \pm 0.6) \cdot 10^{-9}$	0.16 ▲	10^{-3} ★	5×10^{-3}
$\mathcal{B}(h \to cu)$	$(2.7 \pm 0.5) \cdot 10^{-20}$	0.16 ▲	2×10^{-2} ★	2.5×10^{-3}
$\mathcal{B}(Z \to bs)$	$(4.2 \pm 0.7) \cdot 10^{-8}$	2.9×10^{-3} ■	6×10^{-8} ●	$\mathcal{O}(10^{-6})$
$\mathcal{B}(Z \to bd)$	$(1.8 \pm 0.3) \cdot 10^{-9}$	2.9×10^{-3} ■	6×10^{-8} ●	$\mathcal{O}(10^{-6})$
$\mathcal{B}(Z \to cu)$	$(1.4 \pm 0.2) \cdot 10^{-18}$	2.9×10^{-3} ■	4×10^{-7} ●	2.3×10^{-3}

Thank you!

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Backup

Z FCNC fits

$$-\mathcal{H}_{\rm WET} = \frac{4G_F}{\sqrt{2}} \frac{\alpha_{\rm em}}{4\pi} V_{tb}^* V_{ts} \sum_\ell \Big(C_9 \mathcal{O}_9 + C_9' \mathcal{O}_9' + C_{10}\mathcal{O}_{10} + C_{10}'\mathcal{O}_{10}' + C_\nu \mathcal{O}_\nu + C_\nu' \mathcal{O}_\nu' + \dots \Big)$$

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu b_{L(R)})(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu b_{L(R)})(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,, \qquad \mathcal{O}_\nu^{(\prime)} = (\bar{s}\gamma_\mu b_{L(R)})(\bar{\nu}_\ell \gamma^\mu (1-\gamma_5)\nu_\ell)$$

$$C_i = C_i^{\rm SM} + \delta C_i$$

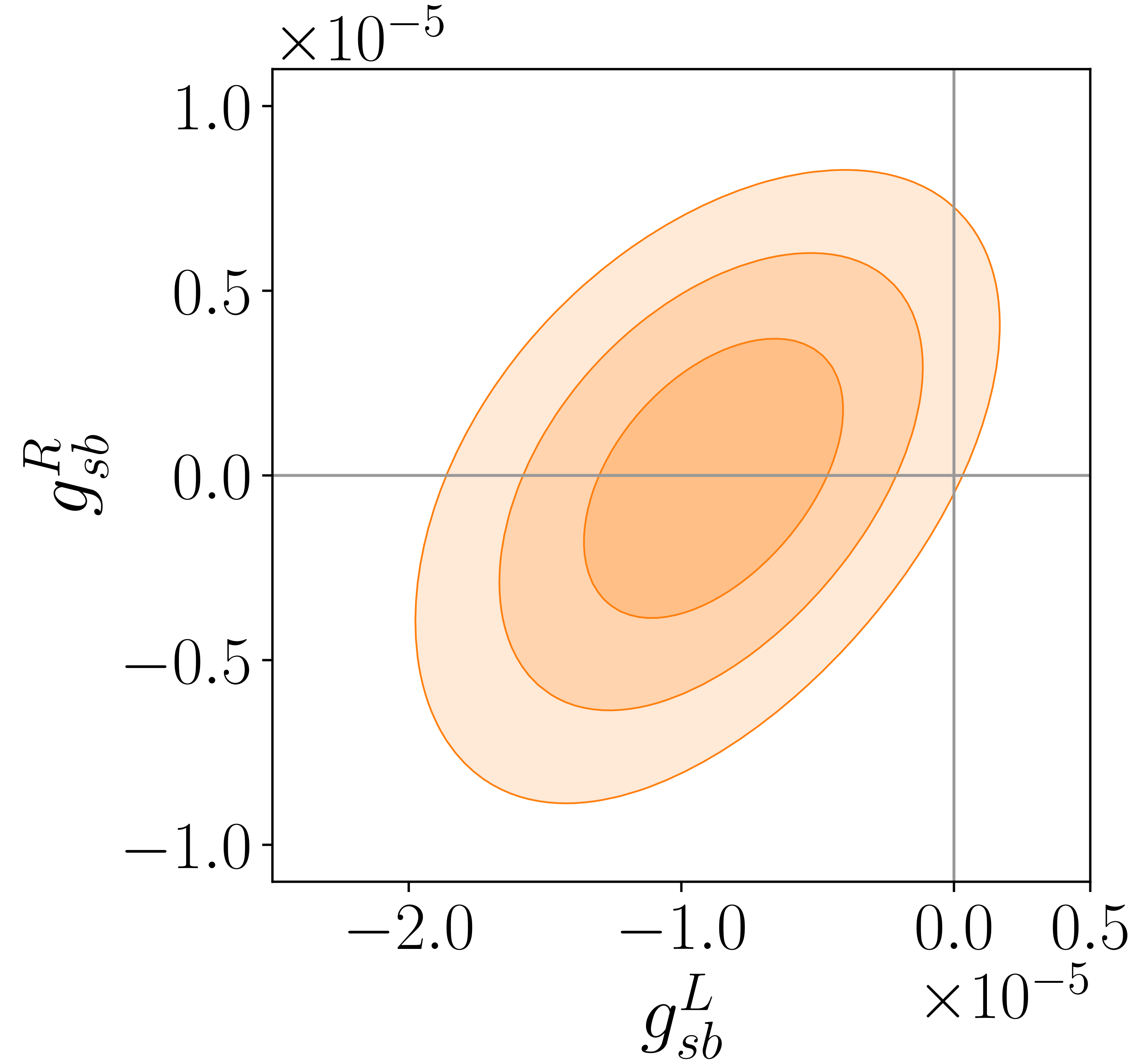
$$-\mathcal{H}_{\Delta F=2} = C_{VL}(\bar{s}\gamma_\mu b_L)^2 + C_{VR}(\bar{s}\gamma_\mu b_R)^2 + C_{VLR}(\bar{s}\gamma_\mu b_L)(\bar{s}\gamma_\mu b_R)$$

$$\delta C_{9,\ell\ell}^{(\prime)} = \mathcal{N} g_{sb}^{L(R)} g_{Z\ell\ell,V} \simeq 6.04\times 10^3 g_{sb}^{L(R)}$$

$$\delta C_{10,\ell\ell}^{(\prime)} = \mathcal{N} g_{sb}^{L(R)} g_{Z\ell\ell,A} \simeq -5.67\times 10^4 g_{sb}^{L(R)}$$

$$\delta C_{\nu}^{(\prime)} = \mathcal{N} g_{sb}^{L(R)} g_{Z\nu\nu} \simeq -5.67\times 10^4 g_{sb}^{L(R)}\,,$$

$$C_{VL} = \frac{(g_{sb}^L)^2}{2m_Z^2}\,, \qquad C_{VR} = \frac{(g_{sb}^R)^2}{2m_Z^2}\,, \qquad C_{VLR} = \frac{g_{sb}^L g_{sb}^R}{m_Z^2}$$



Global minimum not reachable in this 2D parameter space

Z FCNC fits

$$-\mathcal{H}_{\rm WET} = \frac{4G_F}{\sqrt{2}}\frac{\alpha_{\rm em}}{4\pi}V_{tb}^*V_{ts}\sum_\ell\left(C_9\mathcal{O}_9 + C_9'\mathcal{O}_9' + C_{10}\mathcal{O}_{10} + C_{10}'\mathcal{O}_{10}' + C_\nu\mathcal{O}_\nu + C_\nu'\mathcal{O}_\nu' + \dots\right)$$

$$C_i = C_i^{\rm SM} + \delta C_i$$

$$\mathcal{O}_9^{(\prime)} = \left(\bar{s}\gamma_\mu b_{L(R)}\right)\left(\bar{\ell}\gamma^\mu\ell\right), \qquad \mathcal{O}_{10}^{(\prime)} = \left(\bar{s}\gamma_\mu b_{L(R)}\right)\left(\bar{\ell}\gamma^\mu\gamma_5\ell\right), \qquad \mathcal{O}_\nu^{(\prime)} = \left(\bar{s}\gamma_\mu b_{L(R)}\right)\left(\bar{\nu}_\ell\gamma^\mu(1-\gamma_5)\nu_\ell\right)$$

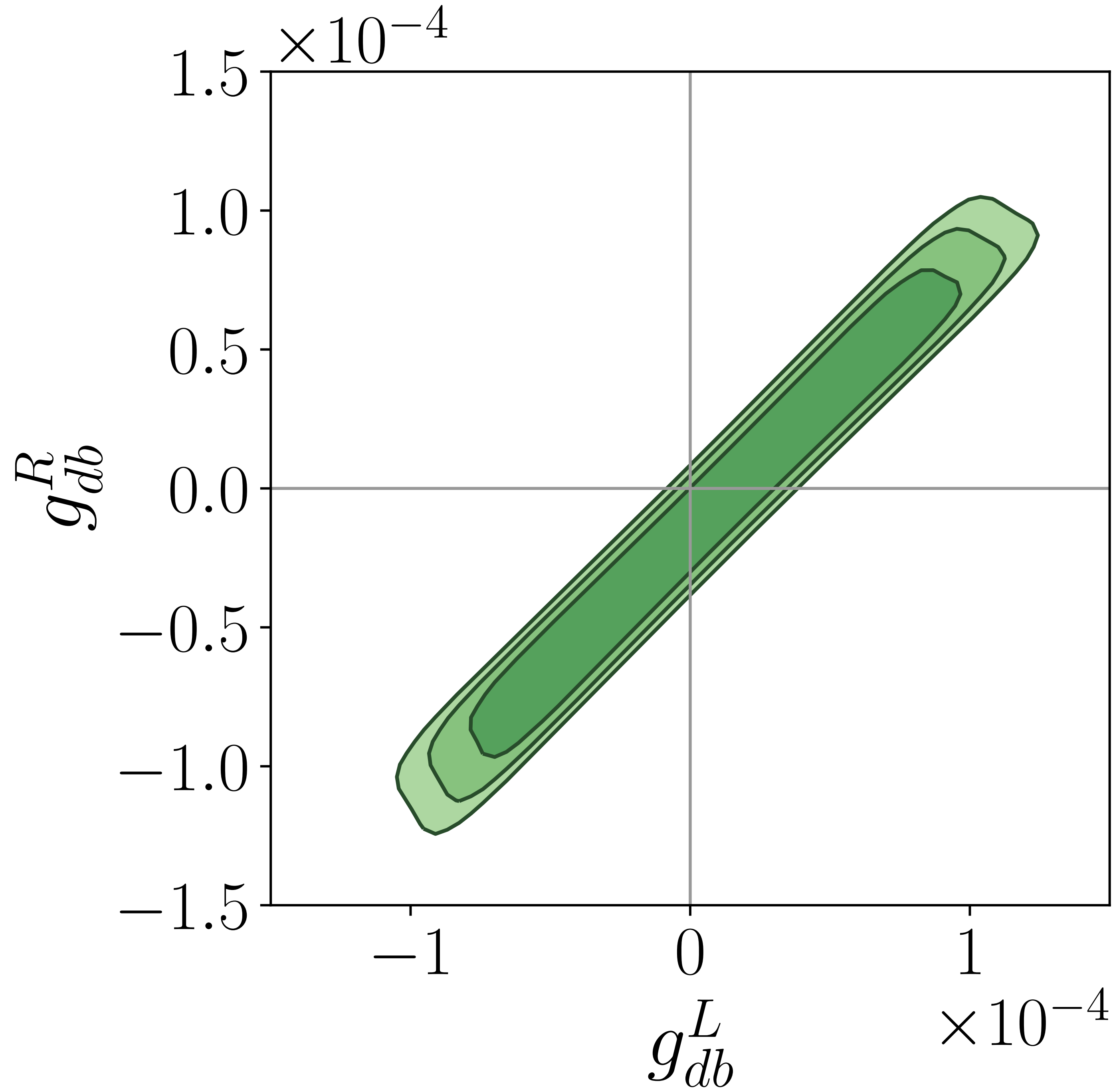
$$-\mathcal{H}_{\Delta F=2} = C_{VL}(\bar{s}\gamma_\mu b_L)^2 + C_{VR}(\bar{s}\gamma_\mu b_R)^2 + C_{VLR}(\bar{s}\gamma_\mu b_L)(\bar{s}\gamma_\mu b_R)$$

$$\delta C_{9,\ell\ell}^{(\prime)} = \mathcal{N} g_{sb}^{L(R)} g_{Z\ell\ell,V} \simeq 6.04\times 10^3 g_{sb}^{L(R)}$$

$$\delta C_{10,\ell\ell}^{(\prime)} = \mathcal{N} g_{sb}^{L(R)} g_{Z\ell\ell,A} \simeq -5.67\times 10^4 g_{sb}^{L(R)}$$

$$\delta C_{\nu}^{(\prime)} = \mathcal{N} g_{sb}^{L(R)} g_{Z\nu\nu} \simeq -5.67\times 10^4 g_{sb}^{L(R)},$$

$$C_{VL} = \frac{(g_{sb}^L)^2}{2m_Z^2}, \qquad C_{VR} = \frac{(g_{sb}^R)^2}{2m_Z^2}, \qquad C_{VLR} = \frac{g_{sb}^L g_{sb}^R}{m_Z^2}$$



Z FCNC fits

$$-\mathcal{H}_{\text{WET}} = \frac{4G_F}{\sqrt{2}}\frac{\alpha_{\text{em}}}{4\pi}V_{tb}^*V_{ts}\sum_{\ell}\left(C_9\mathcal{O}_9 + C_9'\mathcal{O}_9' + C_{10}\mathcal{O}_{10} + C_{10}'\mathcal{O}_{10}' + C_\nu\mathcal{O}_\nu + C_\nu'\mathcal{O}_\nu' + \dots\right)$$

$$C_i = C_i^{\text{SM}} + \delta C_i$$

$$\mathcal{O}_9^{(\prime)} = \left(\bar{s}\gamma_\mu b_{L(R)}\right)\left(\bar{\ell}\gamma^\mu\ell\right), \qquad \mathcal{O}_{10}^{(\prime)} = \left(\bar{s}\gamma_\mu b_{L(R)}\right)\left(\bar{\ell}\gamma^\mu\gamma_5\ell\right), \qquad \mathcal{O}_\nu^{(\prime)} = \left(\bar{s}\gamma_\mu b_{L(R)}\right)\left(\bar{\nu}_\ell\gamma^\mu(1-\gamma_5)\nu_\ell\right)$$

$$-\mathcal{H}_{\Delta F=2} = C_{VL}(\bar{s}\gamma_\mu b_L)^2 + C_{VR}(\bar{s}\gamma_\mu b_R)^2 + C_{VLR}(\bar{s}\gamma_\mu b_L)(\bar{s}\gamma_\mu b_R)$$

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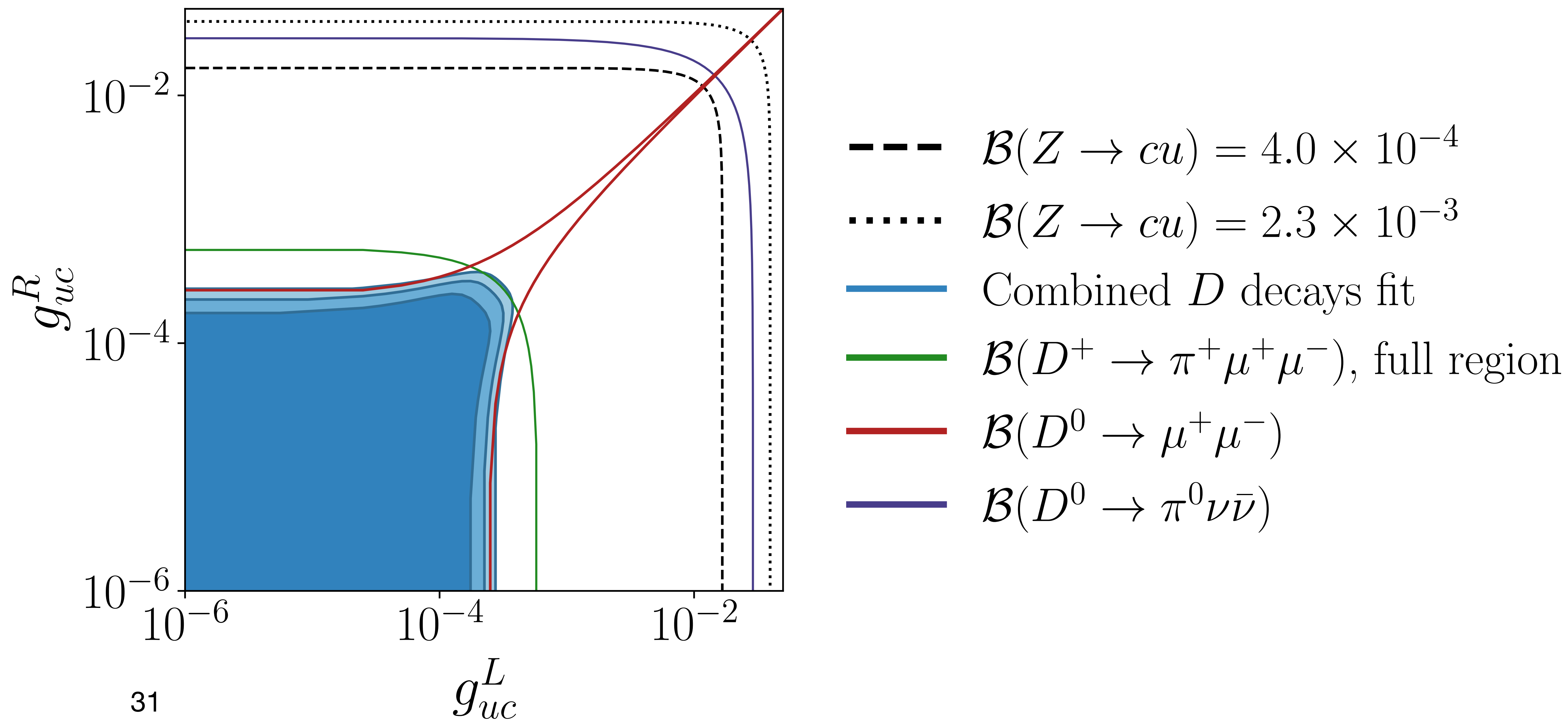
$$\delta C_{10,\ell\ell}^{(\prime)} = \mathcal{N}g_{sb}^{L(R)}g_{Z\ell\ell,A} \simeq -5.67\times10^4 g_{sb}^{L(R)}$$

$$\delta C_{\nu}^{(\prime)} = \mathcal{N}g_{sb}^{L(R)}g_{Z\nu\nu} \simeq -5.67\times10^4 g_{sb}^{L(R)},$$

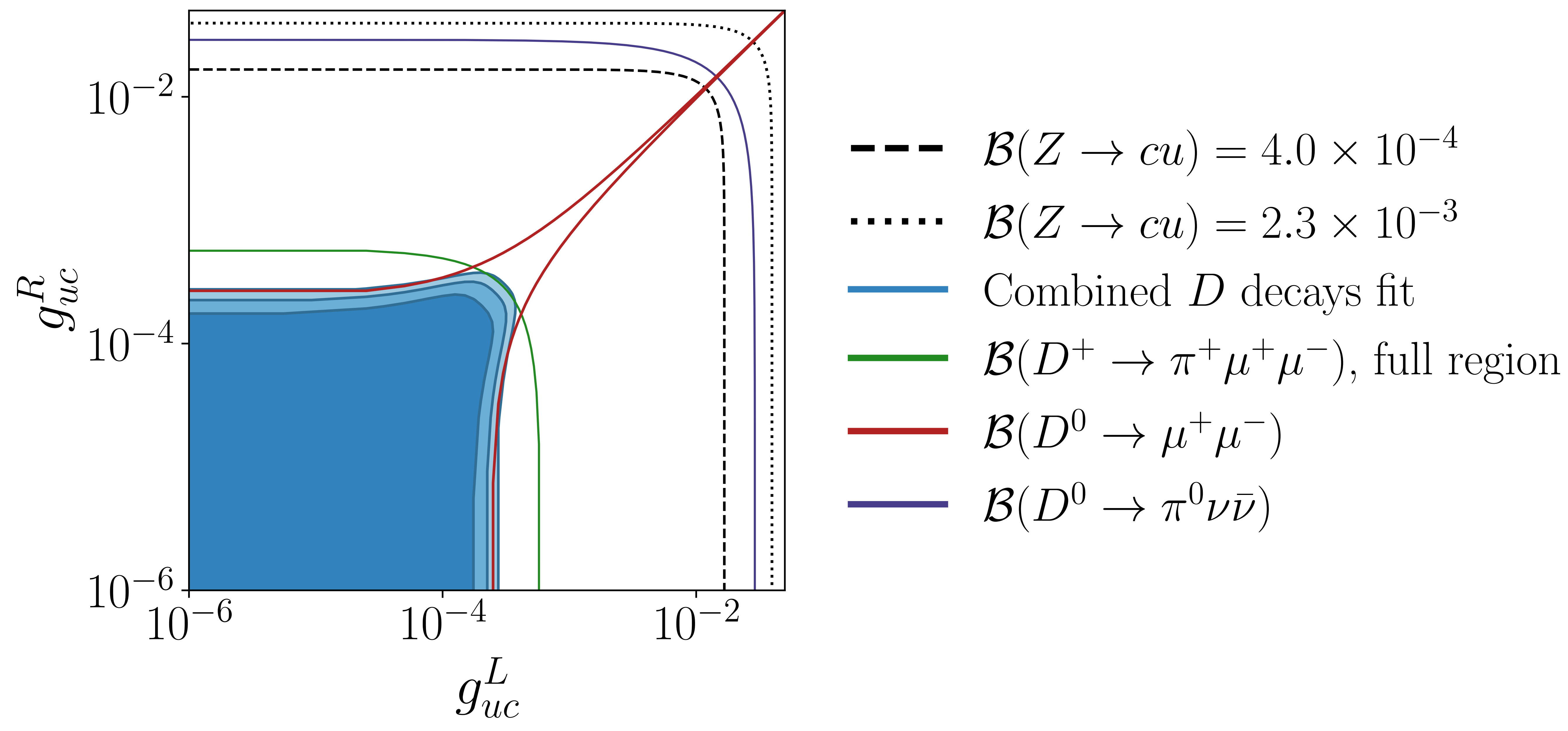
$$C_{VL} = \frac{(g_{sb}^L)^2}{2m_Z^2}, \qquad C_{VR} = \frac{(g_{sb}^R)^2}{2m_Z^2}, \qquad C_{VLR} = \frac{g_{sb}^L g_{sb}^R}{m_Z^2}$$



The assessment of the FCC-ee potential

For the Z, that is not the case

$$\mathcal{L} \supset g_{sb}^L(\bar{s}_L\gamma_\mu b_L)Z^\mu + g_{sb}^R(\bar{s}_R\gamma_\mu b_R)Z^\mu$$
$$+y_{sb}(\bar{s}_L b_R)h + y_{bs}(\bar{b}_L s_R)h + \text{h.c.}$$



VLQs - Lagrangians

$$-\mathcal{L}_{\rm int} \supset y_d^{ij}\bar{q}_L^i H d_R^j + y_u^{ij}\bar{q}_L^i \tilde{H} u_R^j + y_D^i \bar{q}_L^i H D_R + M_D \bar{D}_L D_R + \text{h.c.}$$

$$-\mathcal{L}_Q = y_d^{ij}\bar{q}_L^i H d_R^j + y_u^{ij}\bar{q}_L^i \tilde{H} u_R^j + y_D^i \bar{Q}_L H d_R^i + y_U^i \bar{Q}_L \tilde{H} u_R^i + M_Q \bar{Q}_L Q_R + \text{h.c.}$$

$$\mathcal{L}_{\rm VLQ}^D \supset \frac{g}{2c_W} X_{ij}^d (\bar{d}^i \gamma^\mu P_L d^j) Z_\mu + X_{ij}^d \frac{m_j}{v} (\bar{d}^i P_R d^j) h + \text{h.c.}$$

$$g_{sb}^L = \frac{g}{2c_W}(X_{sb}^d + X_{bs}^{d*}), \quad g_{sb}^R = 0, \quad y_{sb} = X_{sb}^d m_b/v, \quad y_{bs} = X_{bs}^d m_s/v$$

$$(D_L, D_R) \sim (\mathbf{1}, -1/3)$$

$$\mathcal{L}_{\rm VLQ}^Q \supset \frac{g}{2c_W} X_{ij}^Q (\bar{d}^i \gamma^\mu P_R d^j) Z_\mu + X_{ij}^Q \frac{m_j}{v} (\bar{d}^i P_R d^j) h + \text{h.c.}$$

$$g_{sb}^R = \frac{g}{2c_W}(X_{sb}^Q + X_{bs}^{Q*}), \quad g_{sb}^L = 0, \quad y_{sb} = X_{sb}^Q m_b/v, \quad y_{bs} = X_{bs}^Q m_s/v$$

$$(Q_L, Q_R) \sim (\mathbf{2}, 1/6)$$

Analysis framework

ATLAS: 2201.11428
CMS: 2004.12181
Faroughy, Kamenik, Szewc, Zupan: 2209.01222

3) Probabilistic model

$$\mathcal{L}(\mu, \nu) = \prod_{(n_b, n_s)} \text{Pois}\left(N^A_{(n_b, n_s)} | \bar{N}_{(n_b, n_s)}(\mu, \nu)\right) p(\nu)$$

$$(n_b, n_s) = \{(0,0), (0,1), (1,0), (2,0), (0,2), (1,1)\}$$

Analysis framework

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3) Probabilistic model

$$\mathcal{L}(\mu, \nu) = \prod_{(n_b, n_s)} \text{Pois}\Big(N^A_{(n_b,n_s)} | \bar{N}_{(n_b,n_s)}(\mu, \nu)\Big)\, p(\nu)$$

$$(n_b, n_s) = \{(0,0), (0,1), (1,0), (2,0), (0,2), (1,1)\}$$

$$\bar{N}_{(n_b,n_s)} = \sum_{f=\text{bkg}, bs} p(n_b, n_s | f, \nu) \bar{N}_f(\nu)$$

Analysis framework

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3) Probabilistic model

$$\bar{N}_{(n_b,n_s)} = \sum_{f=\text{bkg},bs} p(n_b, n_s|f,\nu)\bar{N}_f(\nu)$$

$$p(n_b, n_s|f,\nu) = \sum_{n_{b;1}=0}^{\min(n_b,1)} \sum_{n_{s;1}=0}^{\min(n_s,1-n_{b;1})} p(n_{b;1}|j_1)p(n_{s;1}|j_1,n_{b;1})p(n_{b;2}|j_2)p(n_{s;2}|j_2,n_{b;2})$$

Possible configurations for the bin $(n_b, n_s) = (1,1)$:

$$(n_{b;1}, n_{b;2}, n_{s;1}, n_{s;2}) = (1,0,0,1)$$

$$(n_{b;1}, n_{b;2}, n_{s;1}, n_{s;2}) = (0,1,1,0)$$

Analysis framework

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3) Probabilistic model

$$\bar{N}_{(n_b,n_s)} = \sum_{f=\mathrm{bkg},bs} p(n_b, n_s|f,\nu)\bar{N}_f(\nu)$$

$$p(n_b, n_s|f,\nu) = \sum_{n_{b;1}=0}^{\min(n_b,1)} \sum_{n_{s;1}=0}^{\min(n_s,1-n_{b;1})} p(n_{b;1}|j_1)p(n_{s;1}|j_1,n_{b;1})p(n_{b;2}|j_2)p(n_{s;2}|j_2,n_{b;2})$$

$$\mathrm{Binom}(k,n,p) \equiv \binom{n}{k} p^k (1-p)^{n-k}$$

(anti)-b-tagging probability if $n_{b;1} = 1(0)$:

$$p(n_{b;1}|j_1) = \mathrm{Binom}(n_{b;1}, 1, \epsilon_1^b)$$

(anti)-s-tagging probability if $n_{s;1} = 1(0)$, conditioned over the $n_{b;1}$ flavor tagging:

$$p(n_{s;1}|j_1,n_{b;1}) = \mathrm{Binom}\left(n_{s;1}, 1-n_{b;1}, \frac{\epsilon_1^s}{1-\epsilon_1^b}\right)$$