

Flavor changing *H* and *Z* decays @ FCC-ee

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arXiv: 2306.17520 with

J. F. Kamenik & A. Korajac (JSI), M. Szewc & J. Zupan (U. Cincinnati)



Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

Current status

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

▲ $h \rightarrow$ BSM (CMS+ATLAS, 2207.00043)

■ $\Gamma(Z \rightarrow \text{had})$ (hep-ex/0012018)

★ Meson mixings

● Global fits (mostly semi-leptonic)

- **Goal:** assess the potential of FCC-ee to explore FC decays

- **Ingredients:**

- Clean environment of e^+e^- colliders
- State-of-the-art and future flavor taggers
- Probabilistic model

1st ingredient: controlled BG

Z pole running

$$\sqrt{s} = m_Z$$

$$e^+e^- \rightarrow Z \rightarrow qq'$$

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

1905.03764

FCC Conceptual Design Reports

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

hZ running

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

$$e^+e^- \rightarrow Z^* \rightarrow hZ (Z \rightarrow \ell^+\ell^-, h \rightarrow qq')$$

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

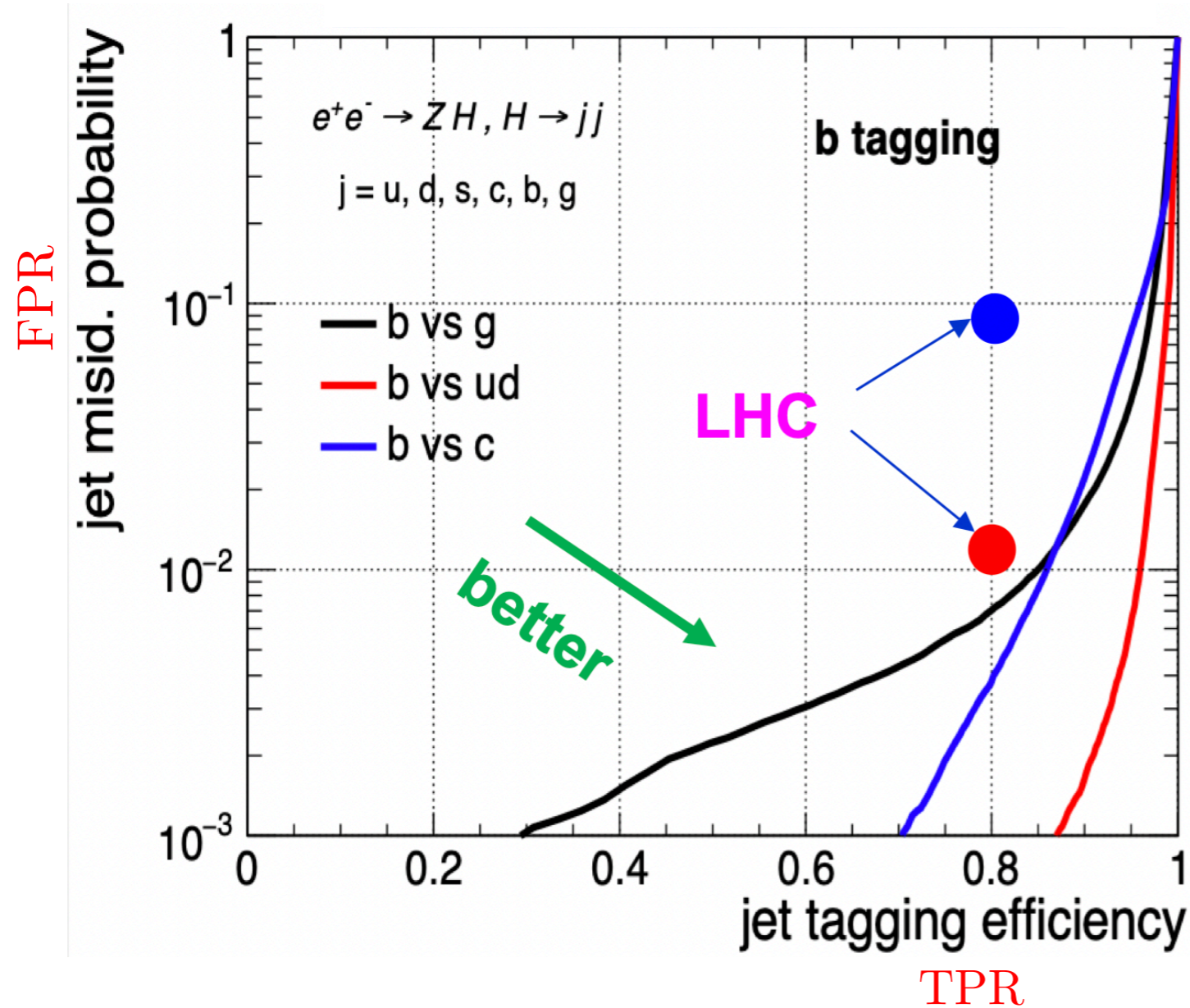
Other backgrounds ($\tau^+\tau^-$ for Z, DY, WW, ZZ for h) are negligible

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

2nd ingredient: Jet flavor taggers

Many talks on the topic in this conference...

ParticleNet: 1902.08570
 Jet-Flavor tagging at FCC-ee: 2210.10322



$$\beta = \{g(ud), s, c, b\}$$

$$\epsilon_{\beta; \text{Loose}}^b = \{0.02, 0.001, 0.02, 0.90\}$$

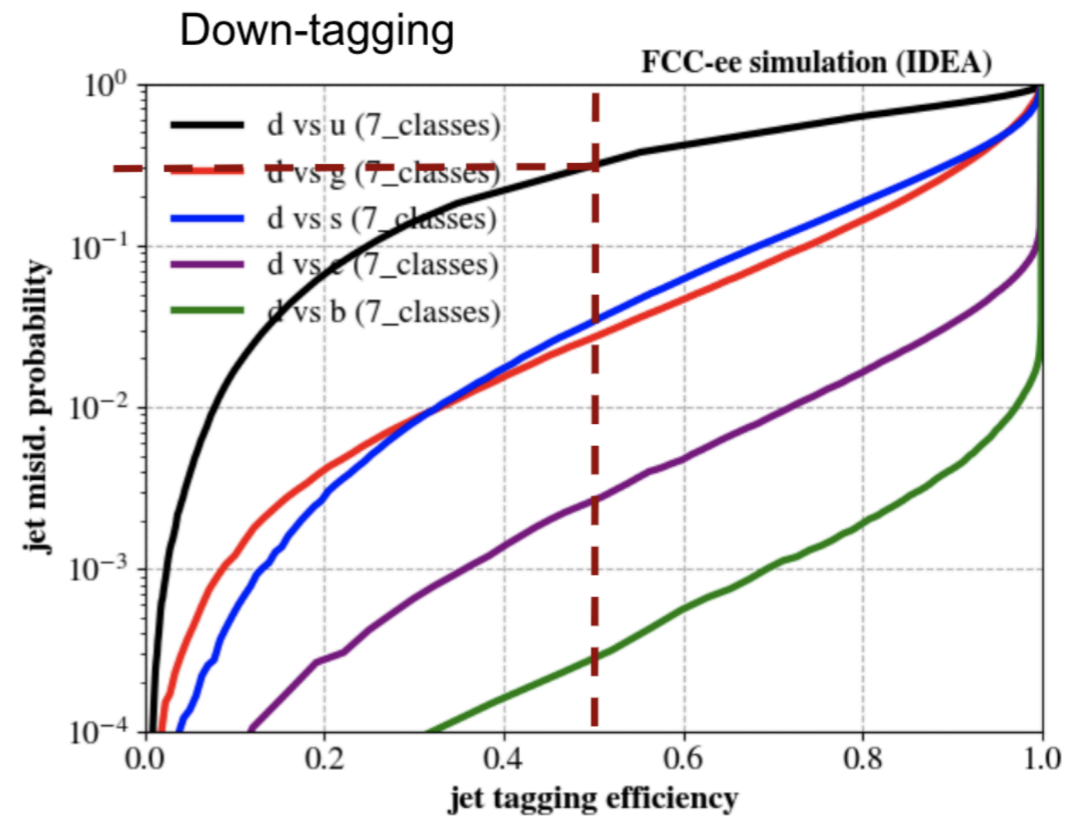
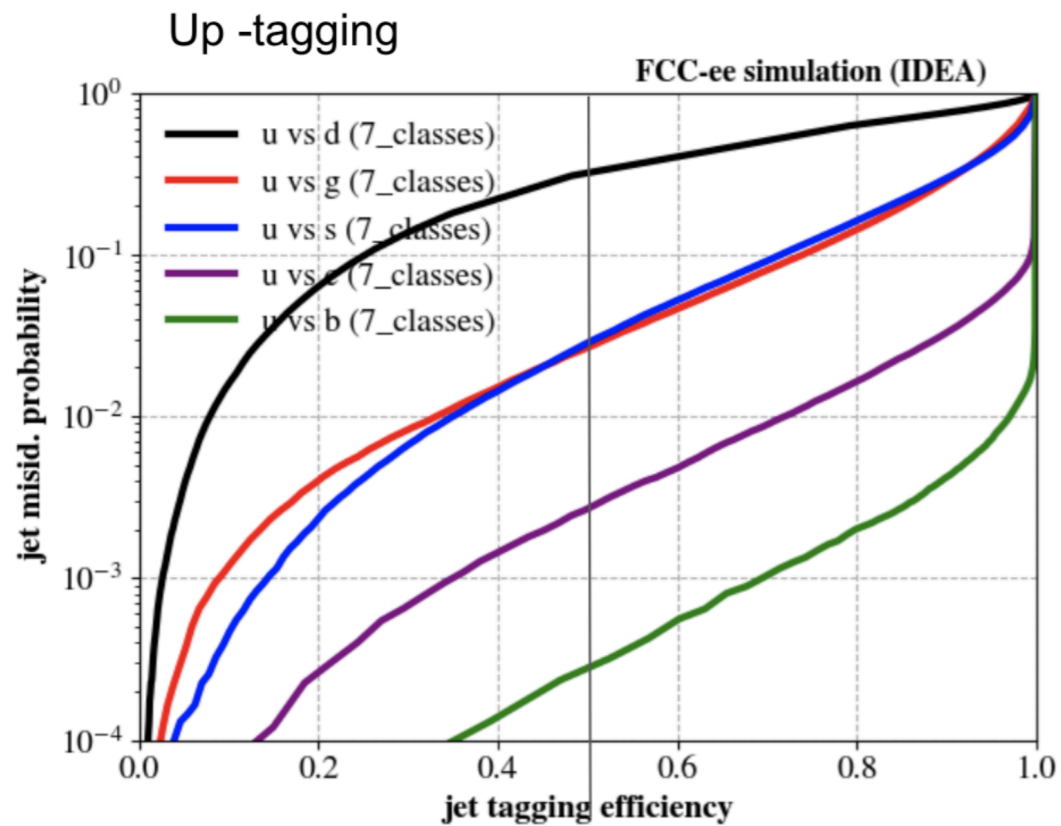
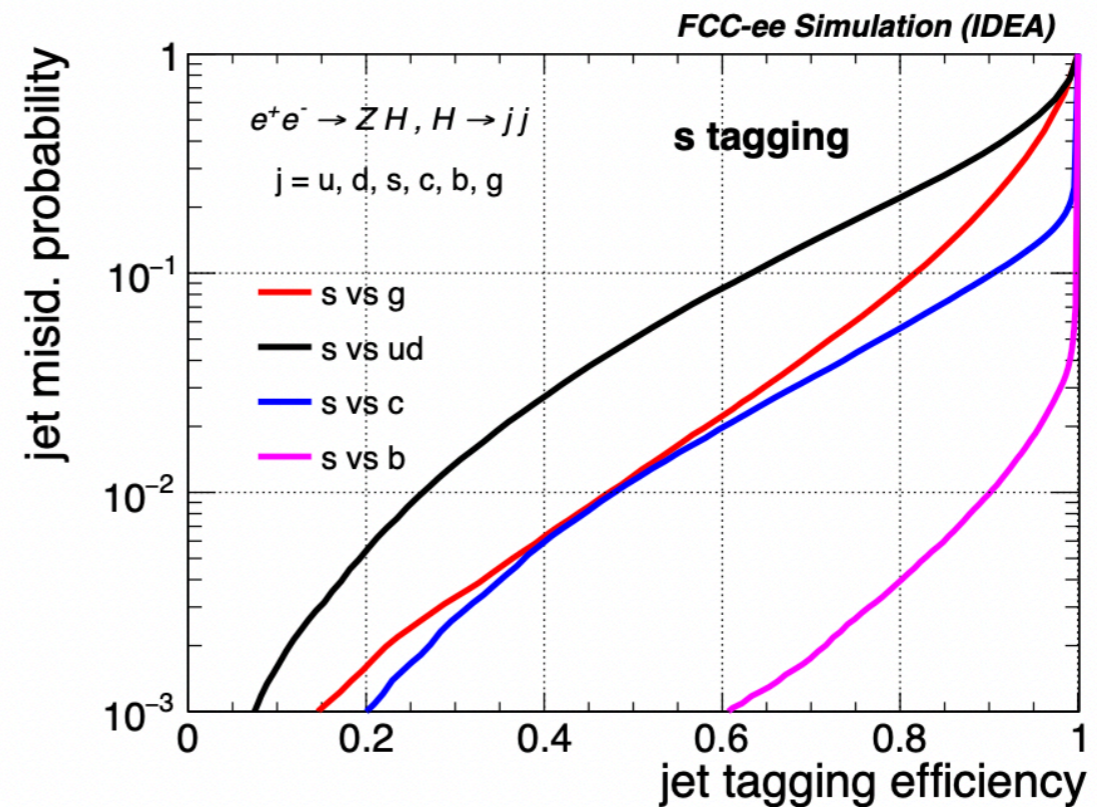
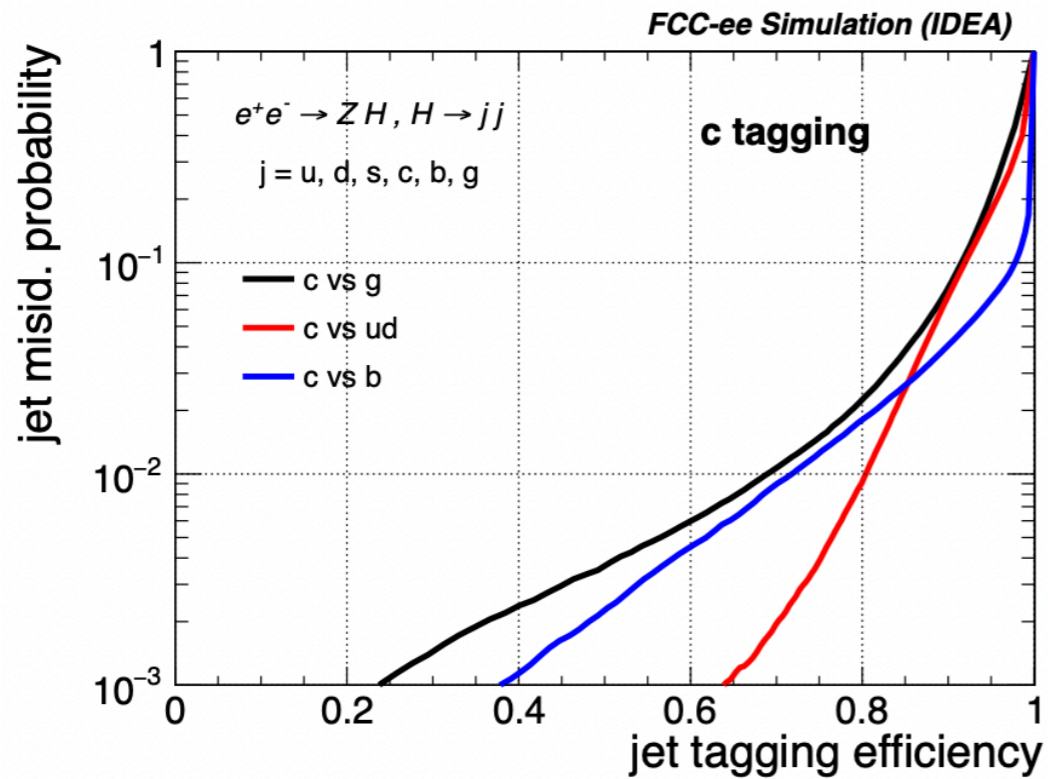
$$\epsilon_{\beta; \text{Med}}^b = \{0.007, 0.0001, 0.003, 0.80\}$$

Currently $\mathcal{O}(\text{few})\%$ syst. on ϵ_{β}^q

ATLAS: 1907.05120
 CMS: 1712.07158

Bedeschi, Gouskos, Selvaggi: 2202.03285
 Gouskos' talk at "FCC Physics Workshop" (indico.cern.ch/event/1176398/)

2nd ingredient: Jet flavor taggers

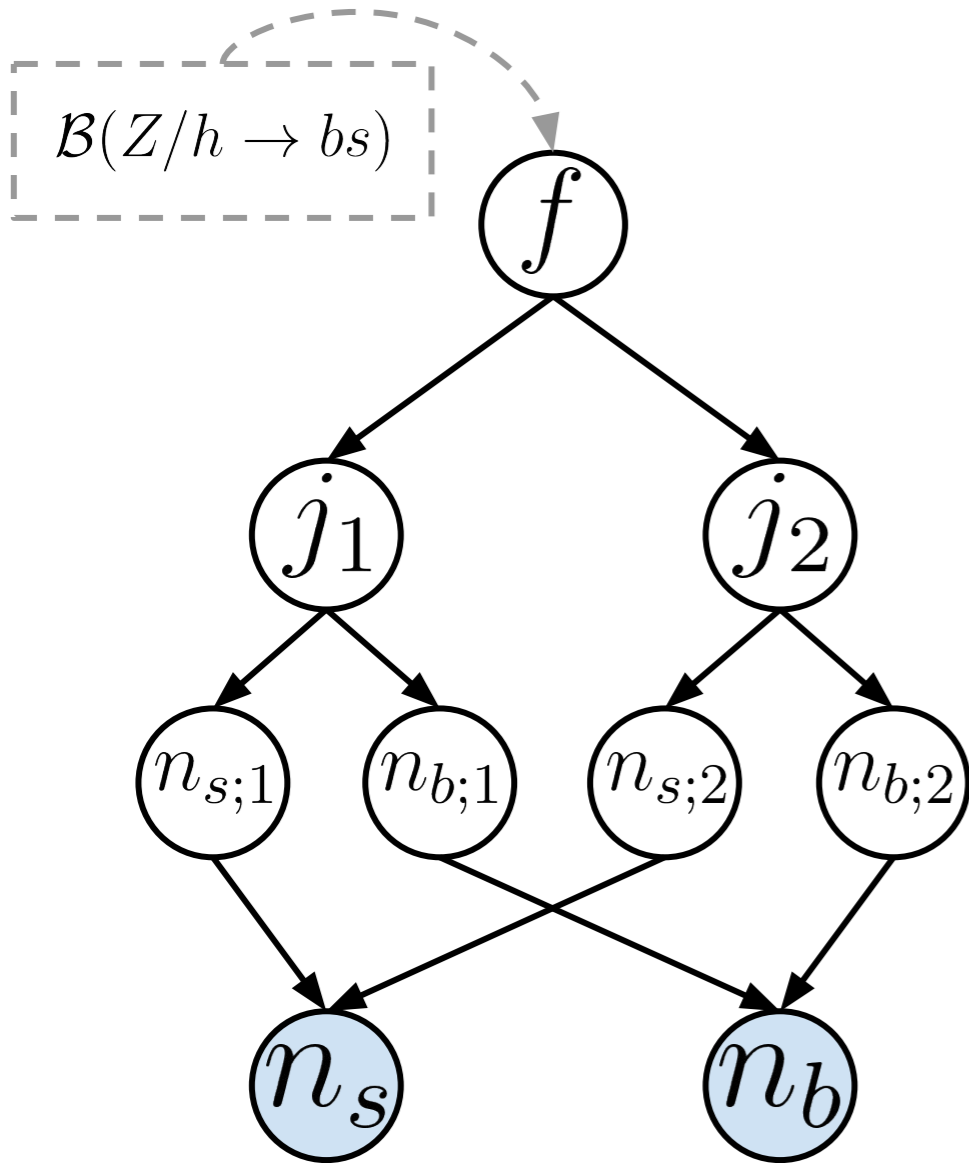


3rd ingredient: Probabilistic model

ATLAS: 2201.11428

CMS: 2004.12181

Faroughy, Kamenik, Szewc, Zupan: 2209.01222



Distribute events into tag bins

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

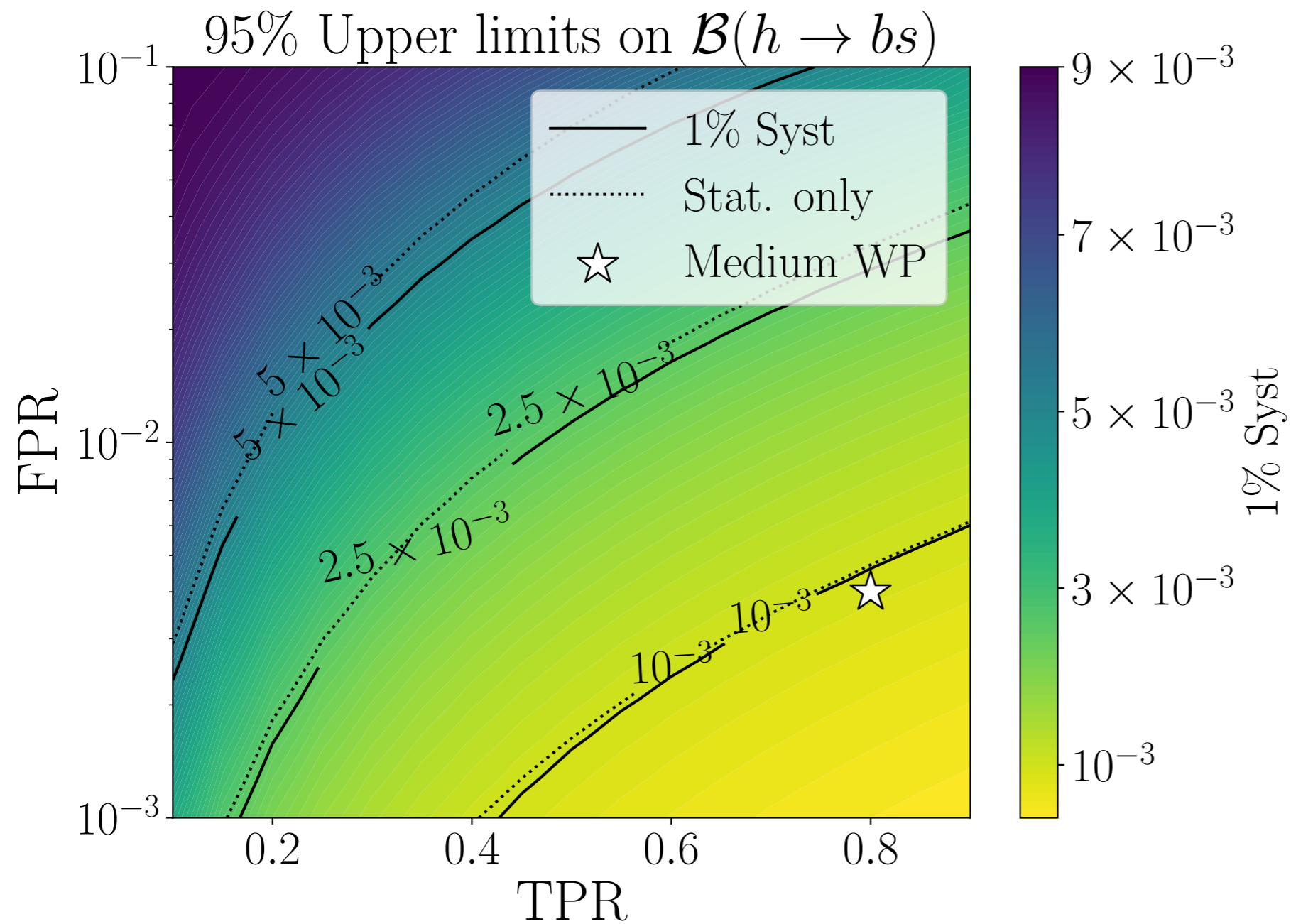
Expected number of events per channel

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



Expected number of events per tag bin

$$\bar{N}_{(n_b, n_s)} = \sum_f p(n_b, n_s | f, \nu) \bar{N}_f(\nu)$$



Take common TPR and FPR (for plots)

Medium WP

$(\text{TPR}, \text{FPR}) = (0.8, 0.004)$

$\text{FPR} = \max(\epsilon_s^b, \epsilon_b^s)$

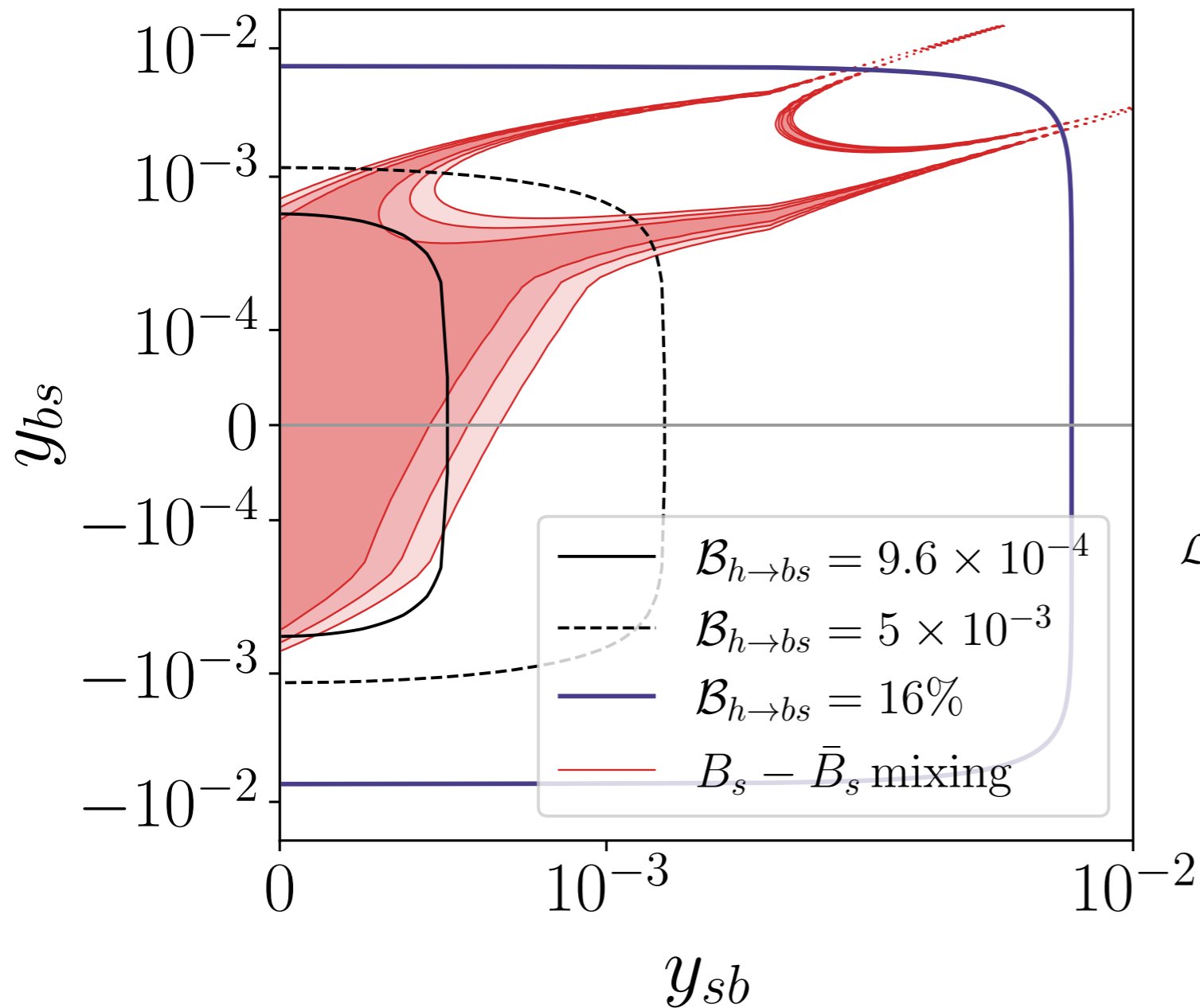
FCC-ee reach

$$\mathcal{B}(h \rightarrow bs) \lesssim 9.6 \times 10^{-4}$$

Indirect constraints

$$\mathcal{B}(h \rightarrow bs) \lesssim 1.6 \times 10^{-3}$$

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



Match to WET + wilson + flavio

$$\mathcal{L}_{\text{WET}} \supset C_2(\bar{s}_R b_L)^2 + C'_2(\bar{s}_L b_R)^2 + C_4(\bar{s}_L b_R)(\bar{s}_R b_L)$$

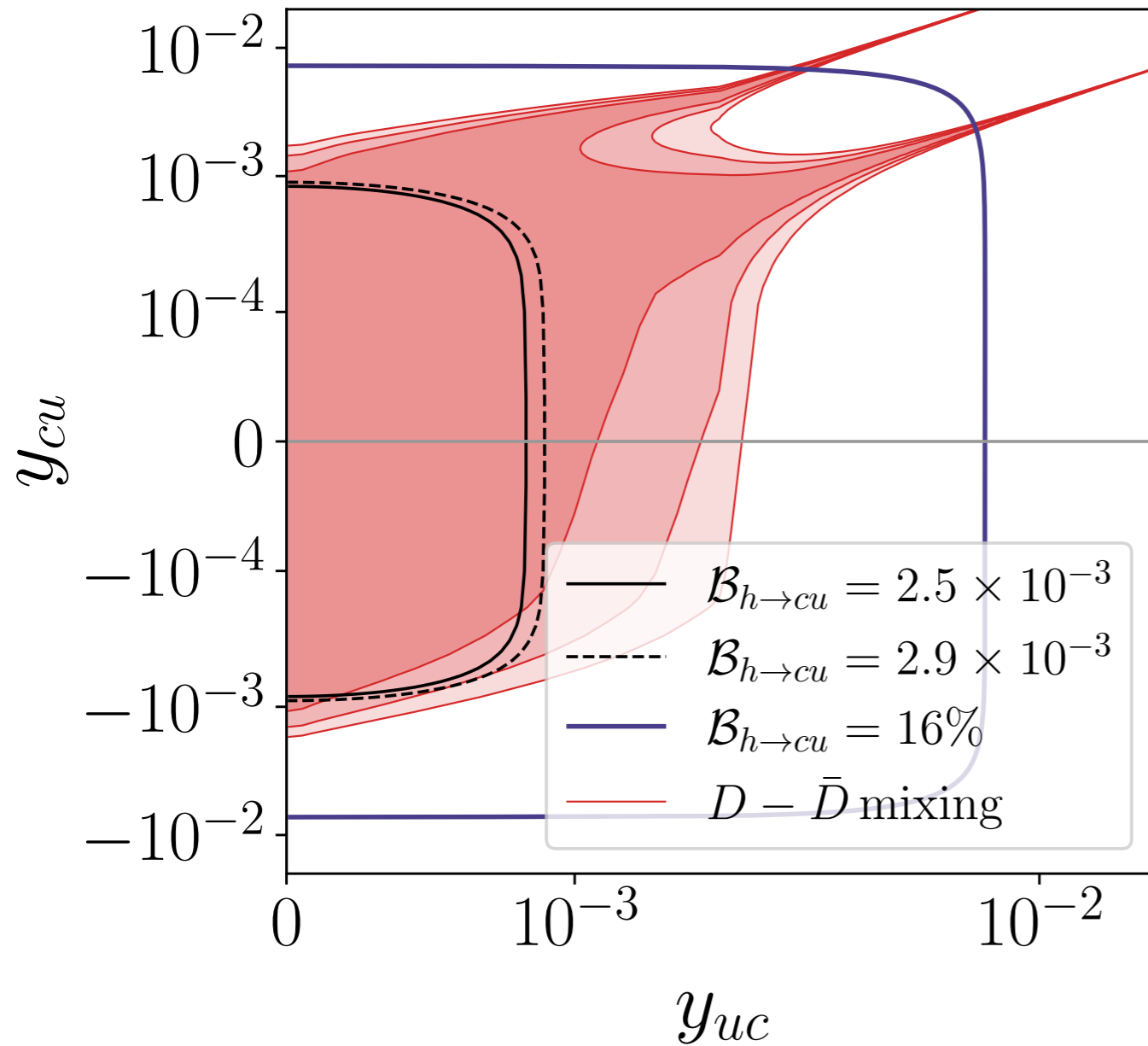
FCC-ee reach

Indirect constraints

$$\mathcal{B}(h \rightarrow bs) \lesssim 9.6 \times 10^{-4}$$

$$\mathcal{B}(h \rightarrow bs) \lesssim 1.6 \times 10^{-3}$$

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



Indirect constraints

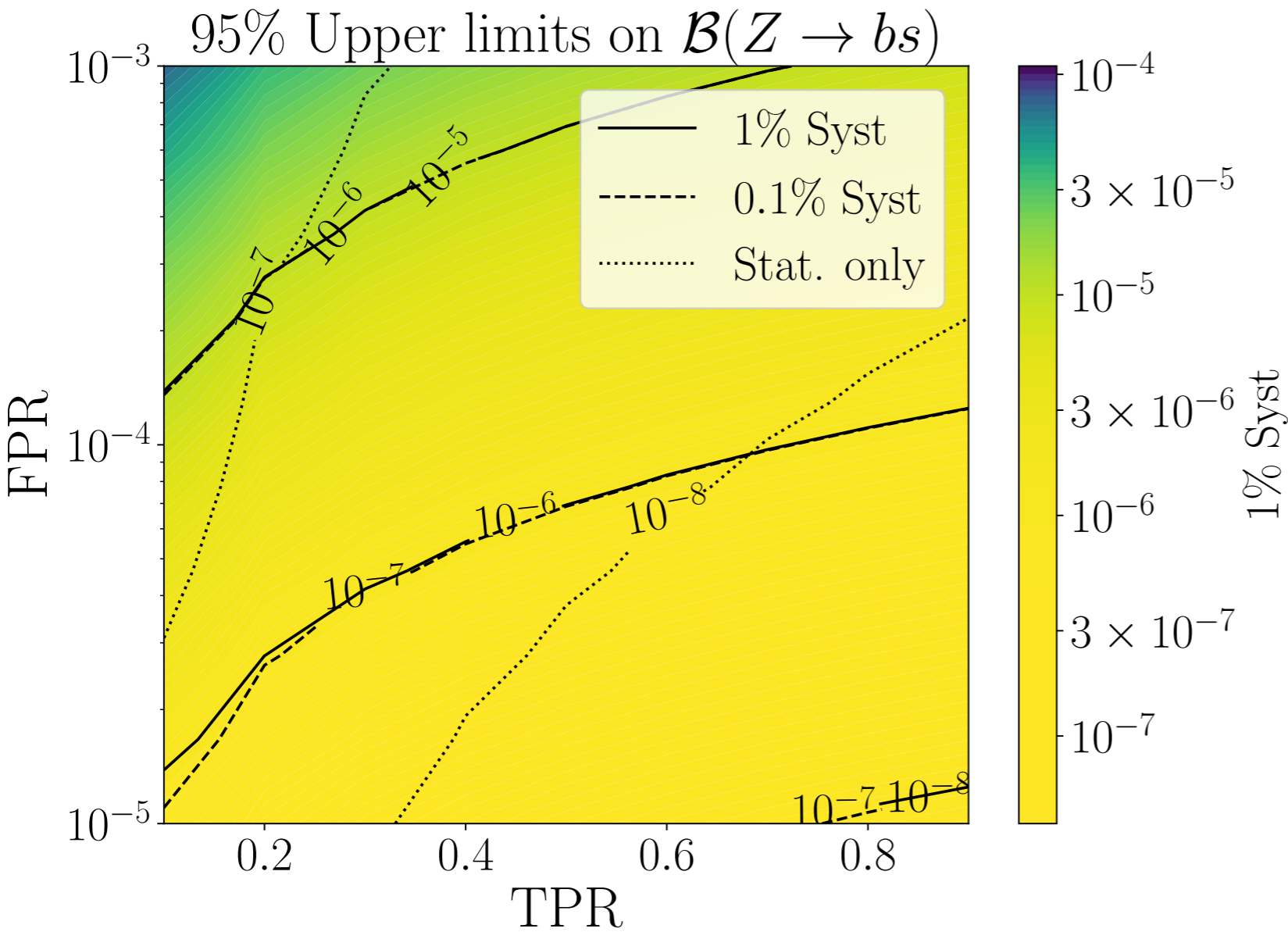
$$\mathcal{B}(h \rightarrow cu) \lesssim 2 \times 10^{-2}$$

FCC-ee reach (no u-tagger)

$$\mathcal{B}(h \rightarrow cu) \lesssim 2.5 \times 10^{-3}$$

FCC-ee reach (with u-tagger)

$$\mathcal{B}(h \rightarrow cu) \lesssim 6.6 \times 10^{-4}$$



TPR

$$\epsilon_b^b = \epsilon_s^s$$

FPR

$$\epsilon_{udsc}^b = \epsilon_{udcb}^s$$

$\epsilon_b^s \lesssim 10^{-4}$ limited by vertexing

3-5 μ m estimated

Barchetta, Collins, Riedler: 2112.13019

(TPR, FPR, $\Delta\epsilon_\beta^\alpha/\epsilon_\beta^\alpha$)	$\mathcal{B}(Z \rightarrow bs)$ (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}

Is 0.1% feasible?

See M. Selvaggi's plenary talk

← SM level

- **Goal:** assess the potential of FCC-ee to explore FC decays

- **Ingredients:**

- Clean environment of e^+e^- colliders
- State-of-the-art and improved flavor taggers
- Analysis technique we propose

- **Take home messages:**

- Upper limits at FCC-ee are above the SM level
- Improve limits on Higgs FC couplings
- Results depend on taggers performances

- **Work in Progress:** estimate sensitivity to CKM elements via W decays

[See also S. Monteil's talk from yesterday](#)

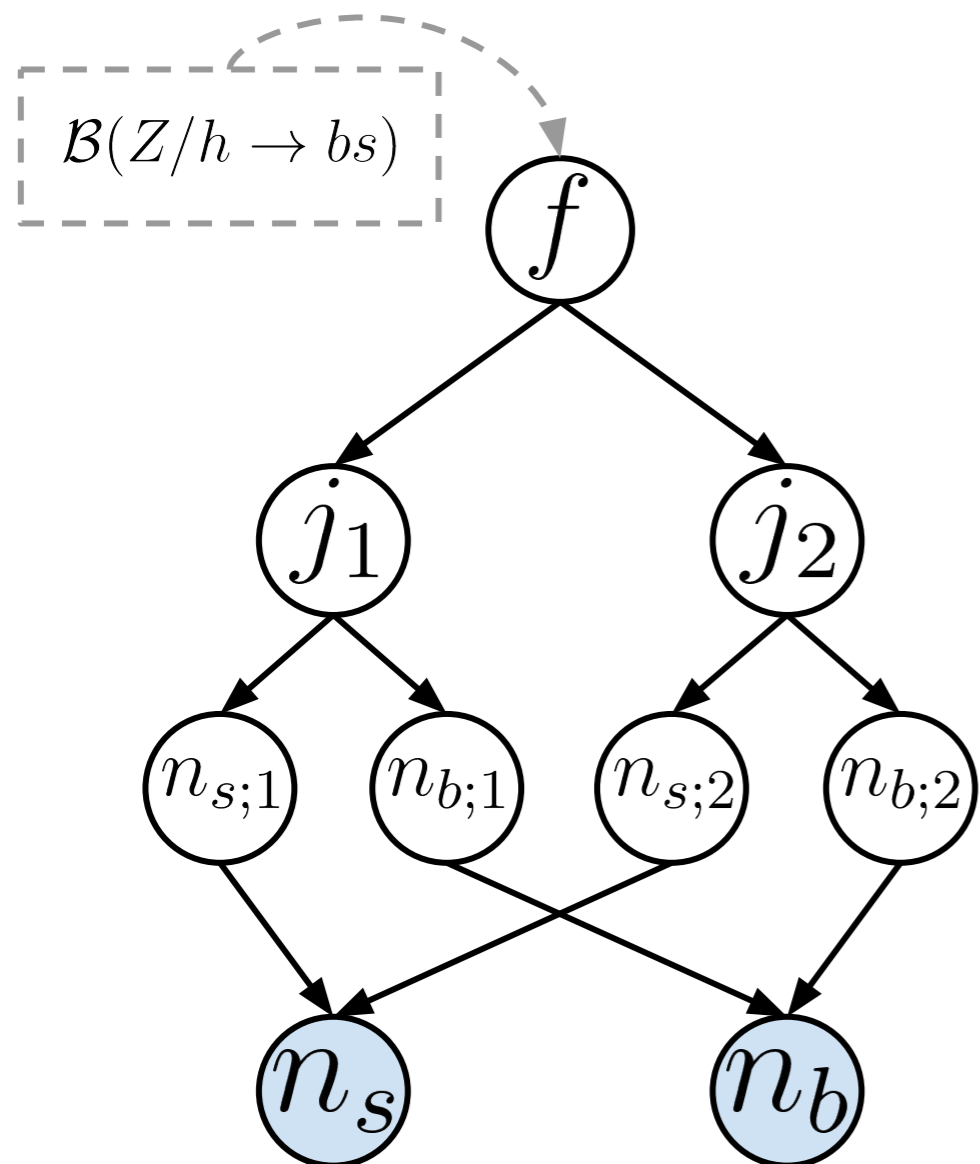
Backup slides

Probabilistic model

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

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

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



Flavor conserving decays

$$p(n_b, n_s | f, \nu) = \text{Binom}(n_b, 2, \epsilon_1^b) \text{Binom}\left(n_s, 2 - n_b, \frac{\epsilon_1^s}{1 - \epsilon_1^b}\right)$$

Efficiencies are implicit function of the nuisance parameters

$$\nu = \{\mathcal{B}(h \rightarrow f), \mathcal{B}(Z \rightarrow f'), \epsilon_\beta^\alpha, N_{Z/h}, \mathcal{A}\}$$

Likelihood

Poisson dist. $\mathcal{P}(k|\lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$

$$\mathcal{L}(\mu, \nu) = \mathcal{P}(N_{(n_b, n_s)} | \bar{N}_{(n_b, n_s)}(\mu, \nu)) p(\nu)$$

↓ Constrained to nominal values by other measurements

$$p(\nu) = \prod_i \mathcal{N}(\nu_{i,0}; \nu_i, \sigma_i)$$

Profile likelihood ratio

Cowan, Cranmer, Gross, Vitells: 1007.1727

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\nu}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\nu})}$$

$\hat{\nu}(\mu), \hat{\mu}, \hat{\nu}$ are maximum likelihood estimates (MLE)

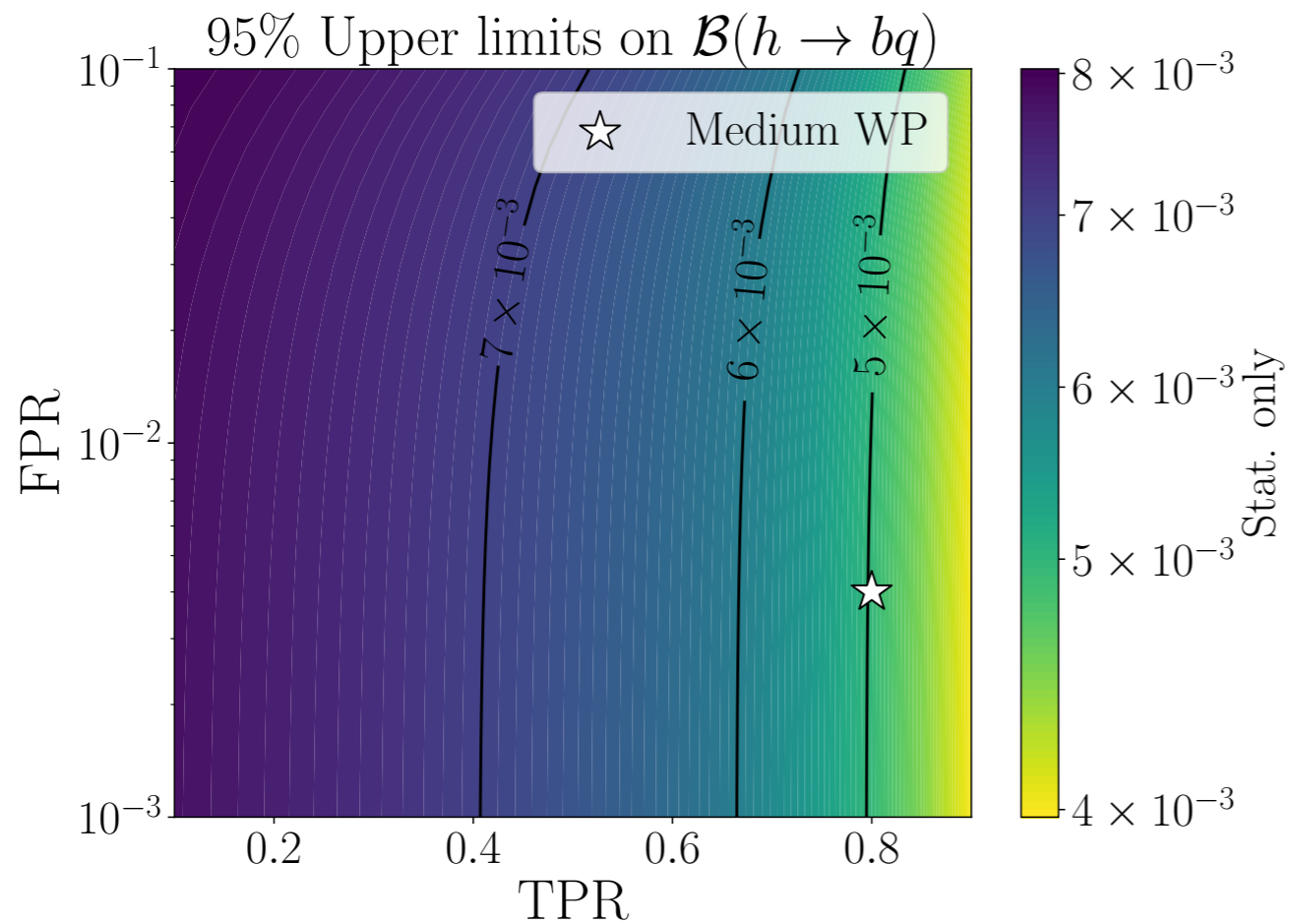
Test statistics

$$t_\mu = -2 \text{Ln } \lambda(\mu)$$

Confidence interval $\mu_{\text{true}} = 1$, solve for $t_\mu = 1$ (68%)

Upper limits

$\mu_{\text{true}} = 0$, solve for $t_\mu = (\Phi^{-1}(1 - 0.05))^2$ (95%)



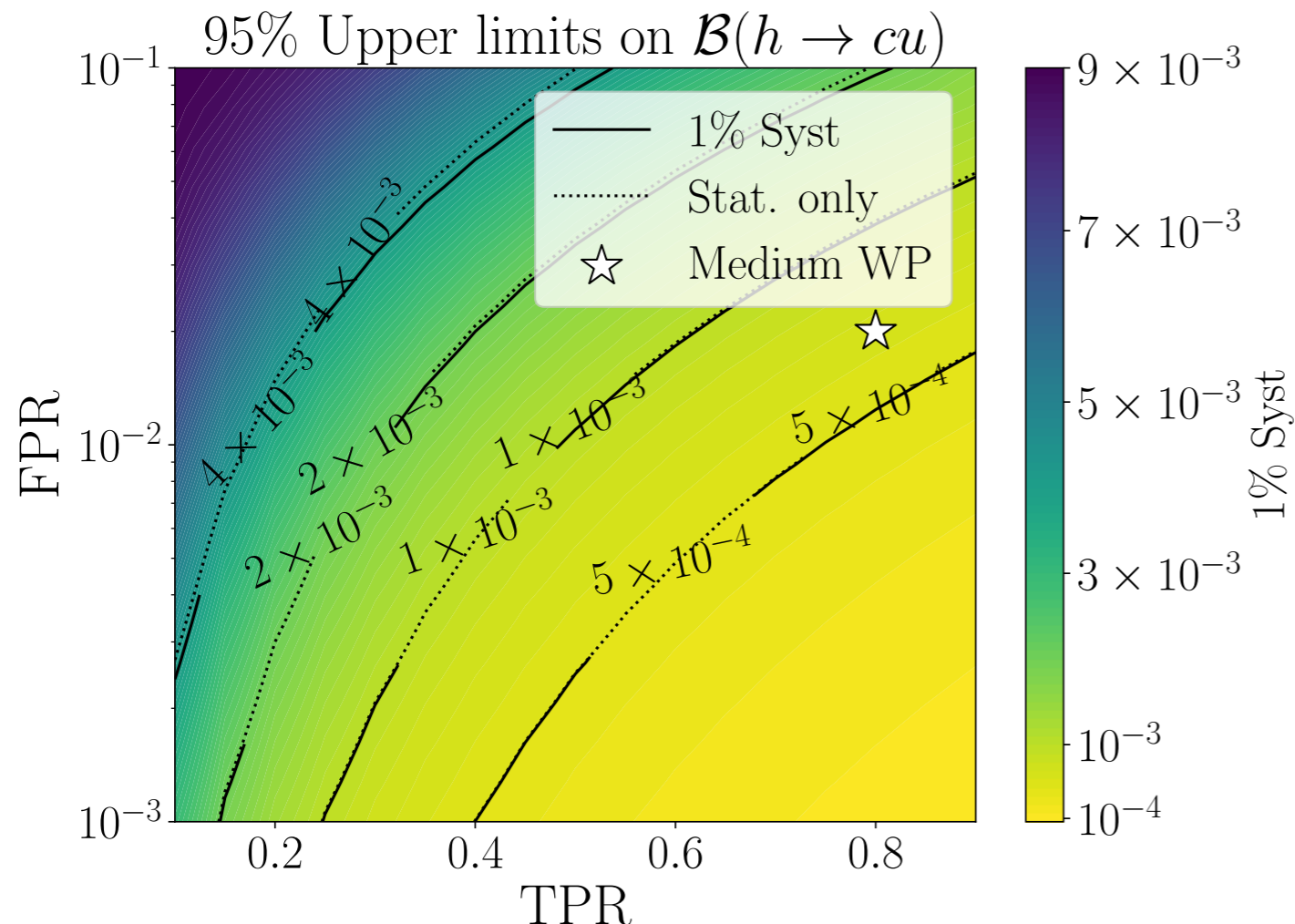
$$\mathcal{B}(h \rightarrow bq) = \mathcal{B}(h \rightarrow bs) + \mathcal{B}(h \rightarrow bd)$$

Medium WP

$$(\text{TPR}, \text{FPR}) = (0.8, 0.004)$$

FCC-ee reach (no d-tagger)

$$\mathcal{B}(h \rightarrow bq) \lesssim 5 \times 10^{-3}$$



Medium WP

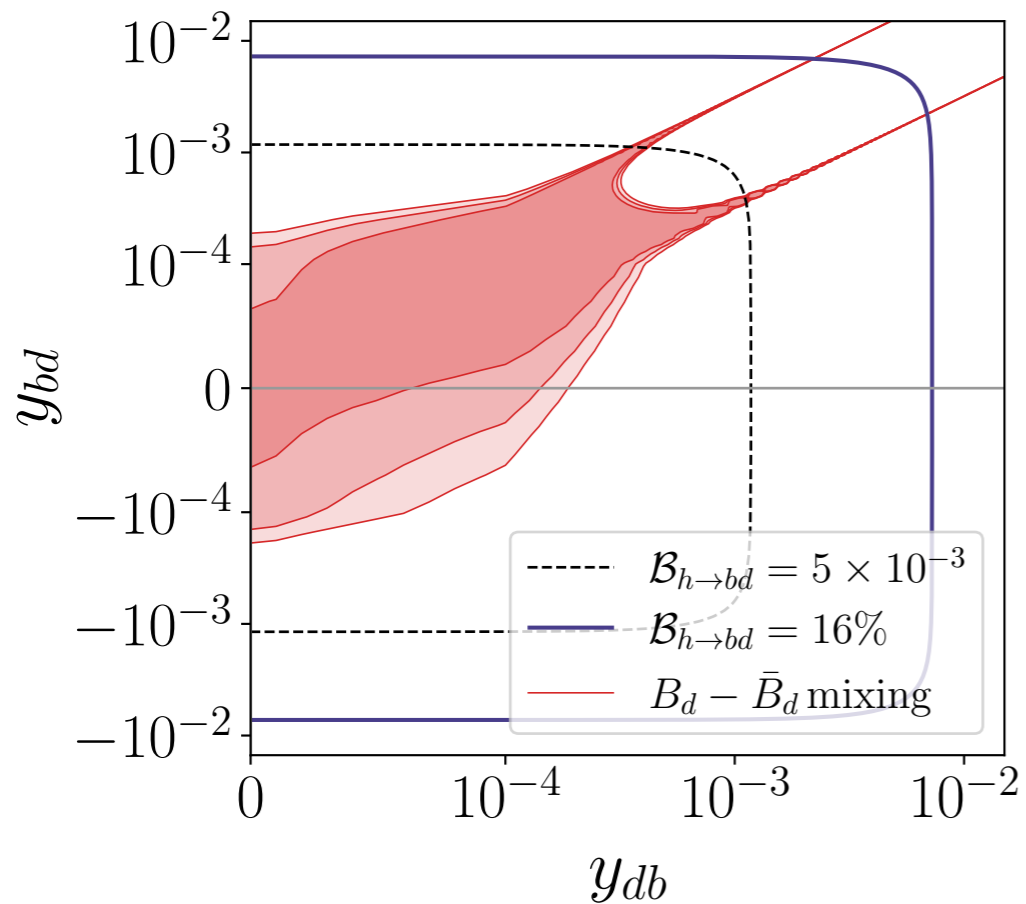
$$(\text{TPR}, \text{FPR}) = (0.8, 0.02)$$

FCC-ee reach (no u-tagger)

$$\mathcal{B}(h \rightarrow cu) \lesssim 2.5 \times 10^{-3}$$

FCC-ee reach (with u-tagger)

$$\mathcal{B}(h \rightarrow cu) \lesssim 6.6 \times 10^{-4}$$

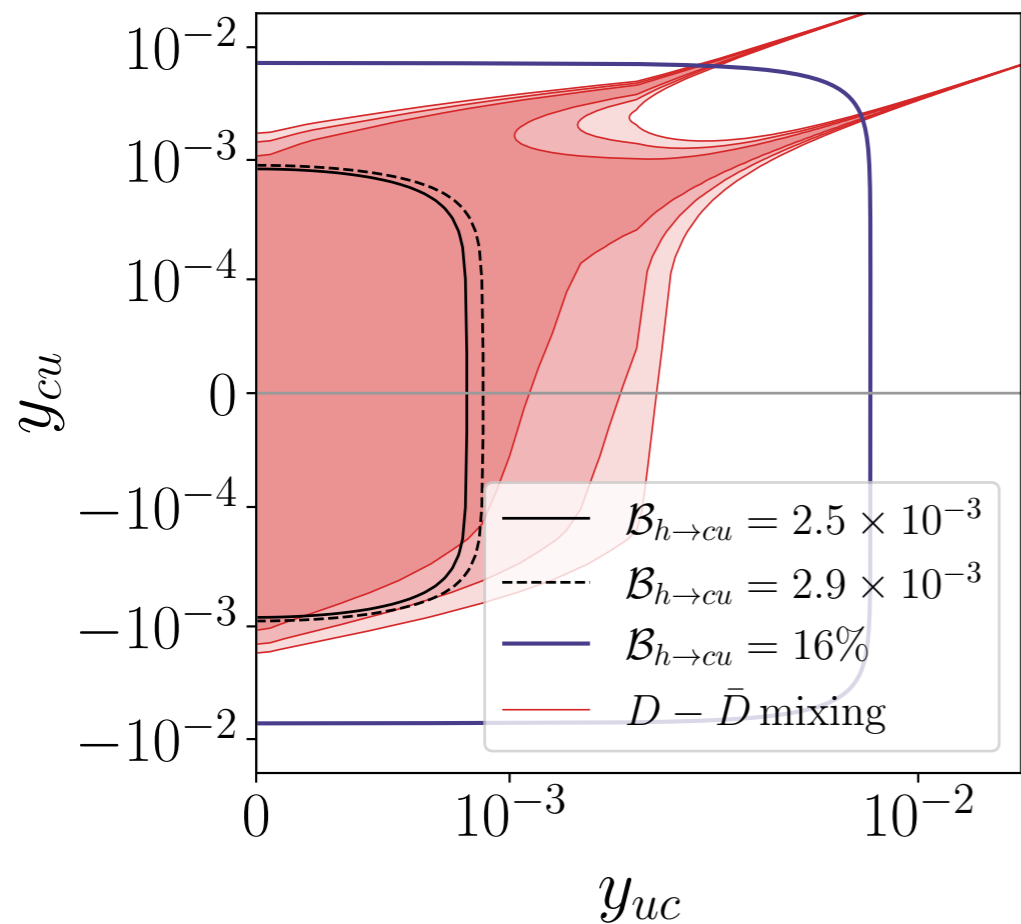


Indirect constraints

$$\mathcal{B}(h \rightarrow bd) \lesssim 10^{-3}$$

FCC-ee reach

$$\mathcal{B}(h \rightarrow bq) \lesssim 5 \times 10^{-3}$$



Indirect constraints

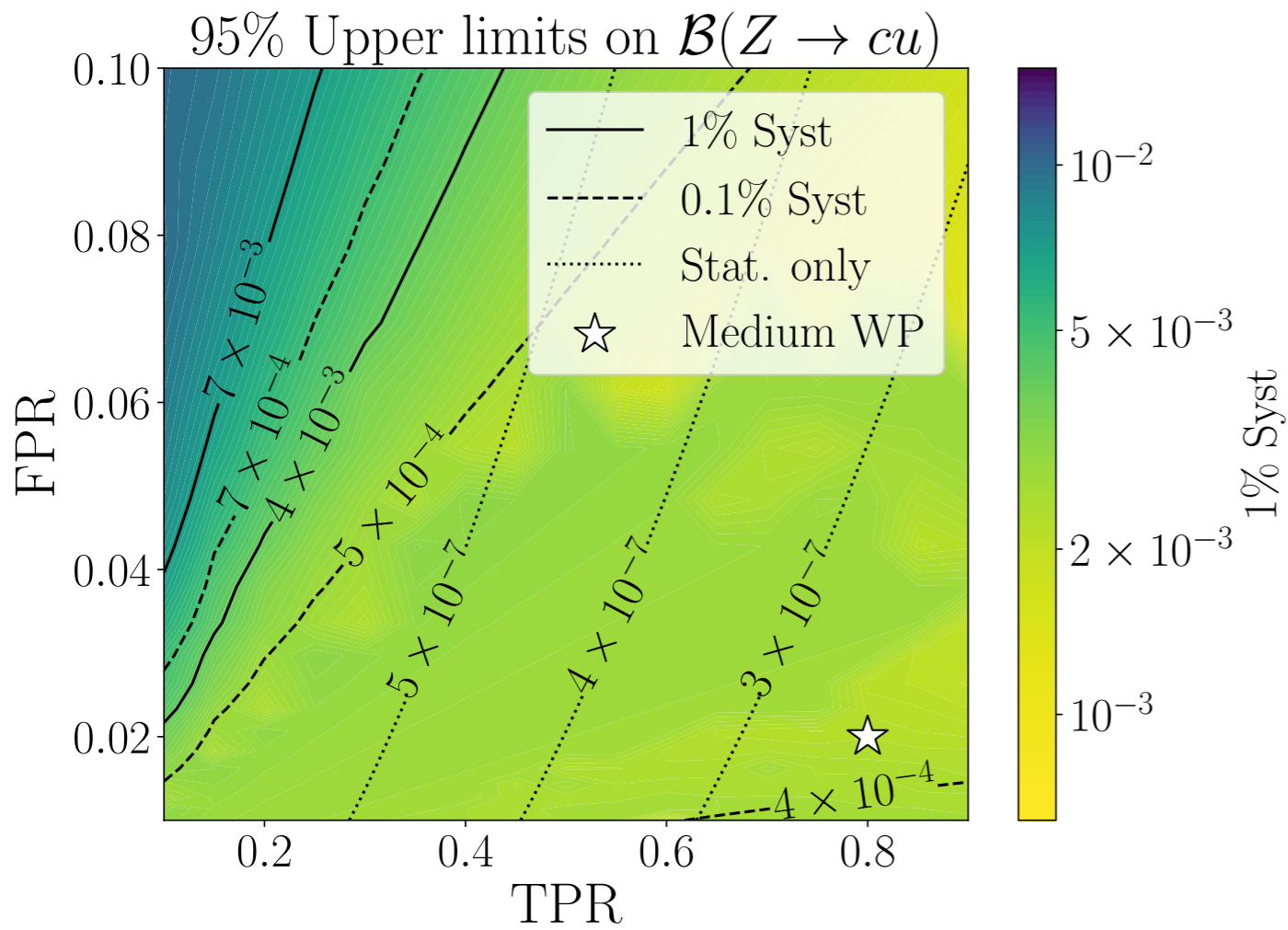
$$\mathcal{B}(h \rightarrow cu) \lesssim 2 \times 10^{-2}$$

FCC-ee reach (no u-tagger)

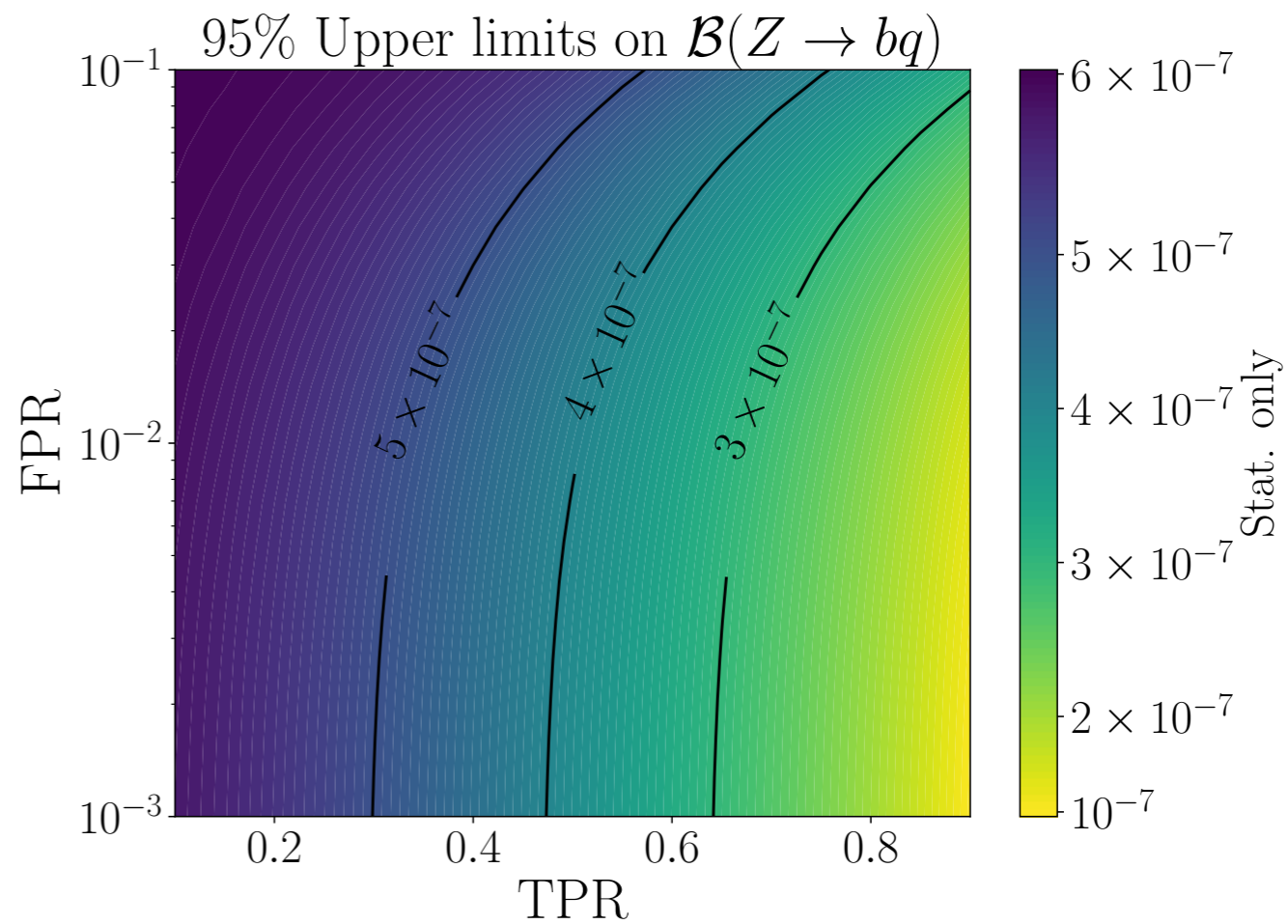
$$\mathcal{B}(h \rightarrow cu) \lesssim 2.5 \times 10^{-3}$$

FCC-ee reach (with u-tagger)

$$\mathcal{B}(h \rightarrow cu) \lesssim 6.6 \times 10^{-4}$$



Similar backgrounds and tagger performances



New Physics fits (Z)

$$\Delta B = \Delta S = 1$$

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

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_{\mu}b_{L(R)}) (\bar{\ell}\gamma^{\mu}\ell)$$

$$\mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_{\mu}b_{L(R)}) (\bar{\ell}\gamma^{\mu}\gamma_5\ell)$$

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

$$\Delta F = 2$$

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

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

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

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

$$\delta C_{\nu}^{(\prime)} = \mathcal{N} g_{sb}^{L(R)} g_{Z\nu\nu}$$

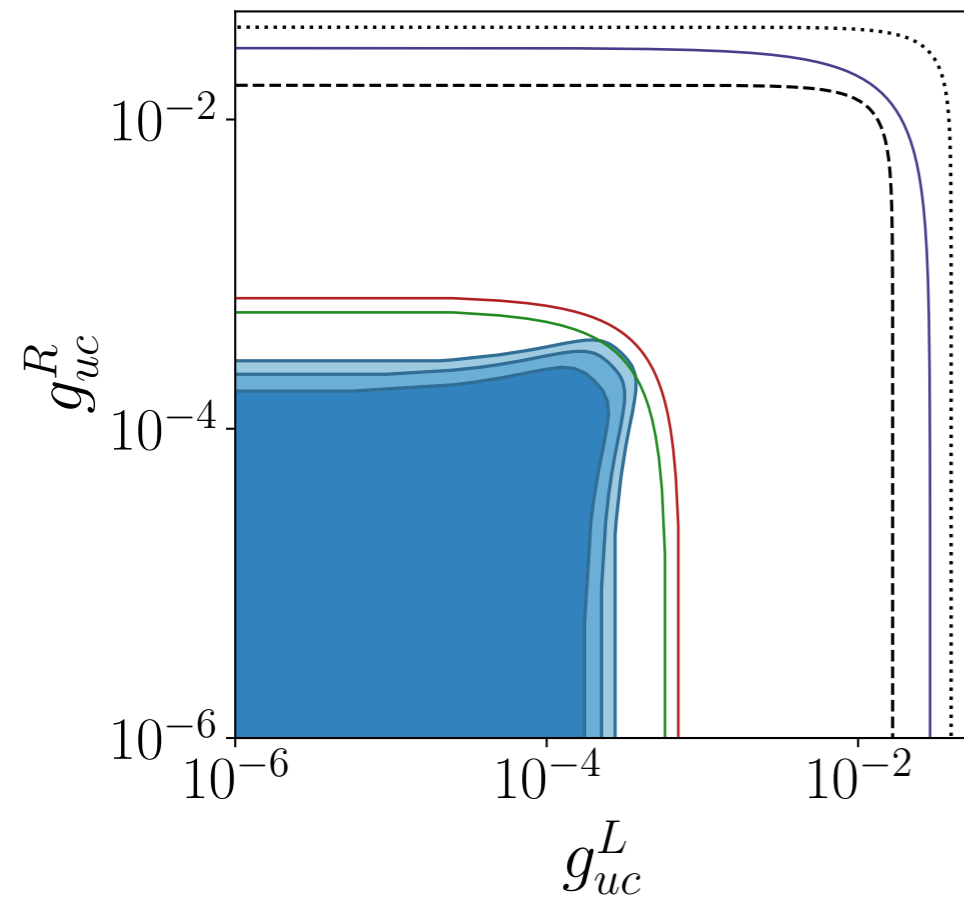
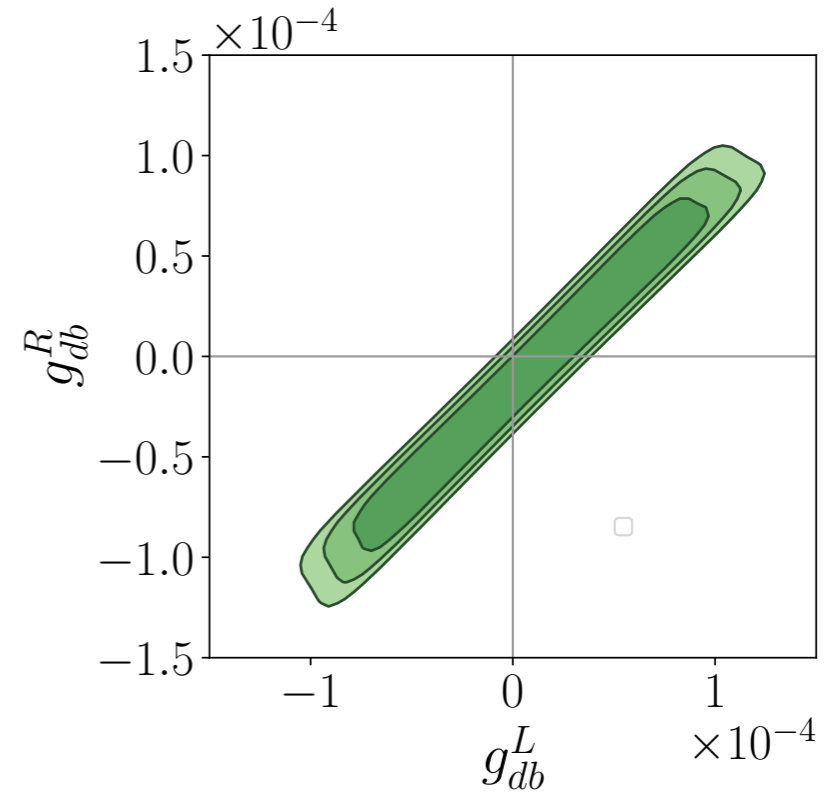
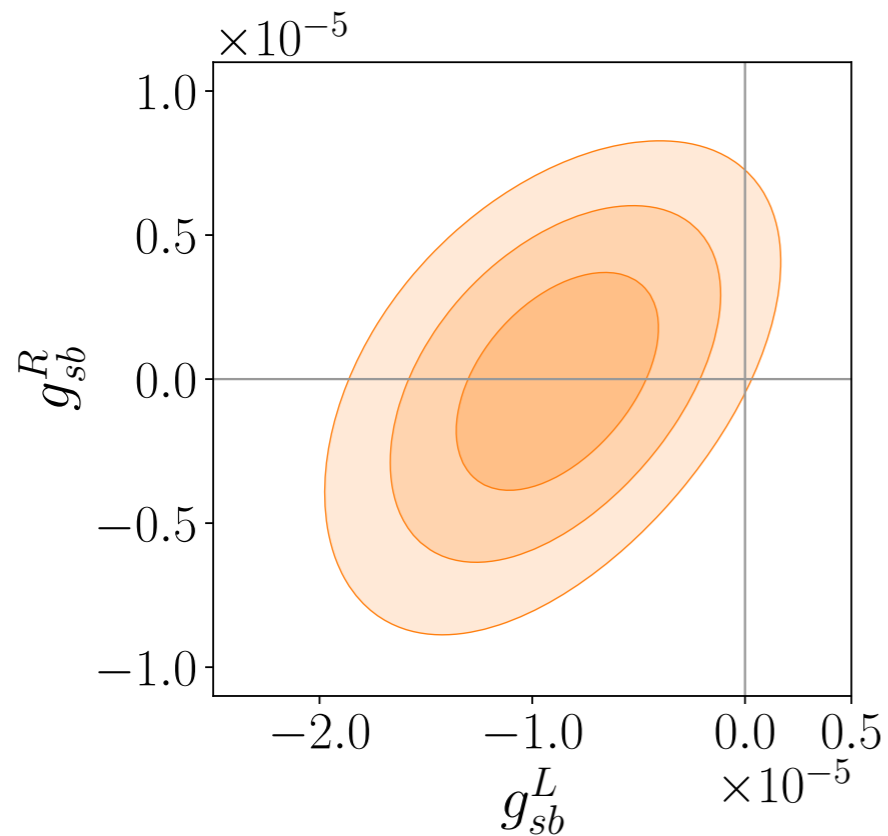
$$C_{VL} = \frac{(g_{sb}^L)^2}{2m_Z^2}$$

$$C_{VR} = \frac{(g_{sb}^R)^2}{2m_Z^2}$$

$$C_{VLR} = \frac{g_{sb}^L g_{sb}^R}{m_Z^2}$$

Lepton couplings are assumed to be SM

New Physics fits (Z)



- $\mathcal{B}(Z \rightarrow cu) = 4.04 \times 10^{-4}$
- $\mathcal{B}(Z \rightarrow cu) = 2.28 \times 10^{-3}$
- Combined D decays fit
- $\mathcal{B}(D^+ \rightarrow \pi^+ \mu^+ \mu^-)$, full region
- $\mathcal{B}(D^+ \rightarrow \pi^+ \mu^+ \mu^-)$, high q^2
- $\mathcal{B}(D^0 \rightarrow \pi^0 \nu \bar{\nu})$

LHCb: 2212.11203, 1304.6365
 Belle: 1003.2345
 BESIII: 2112.14236
 Bause, Golz, Hiller, Tayduganov: 1909.11108

NP model: Vector-like Quarks (1)

Introduce $SU_L(2)$ singlets (D_L, D_R) with $Y = -1/3$

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



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

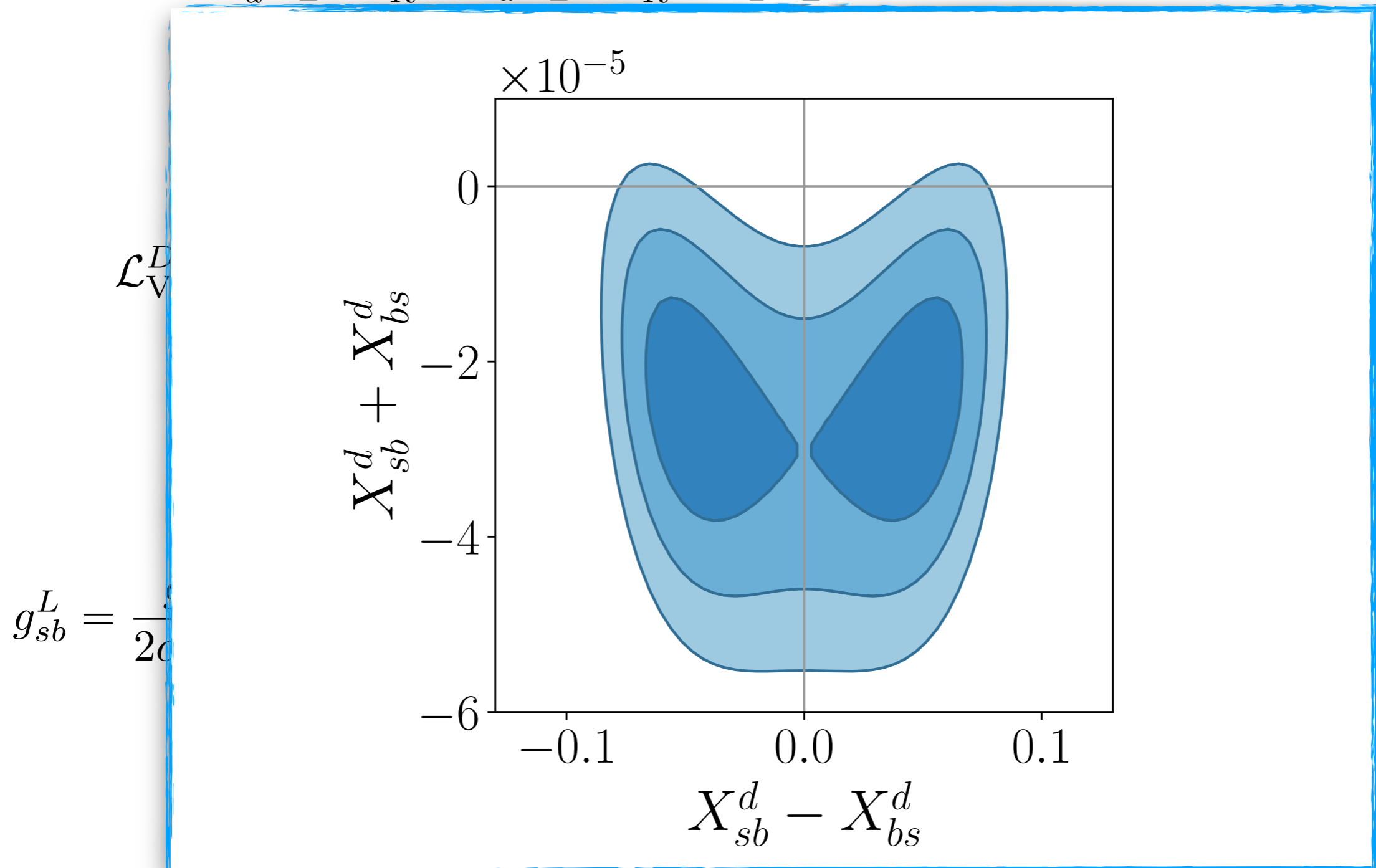
$$g_{sb}^L = \frac{g}{2c_W} (X_{sb}^d + X_{bs}^{d*}), \quad g_{sb}^R = 0, \quad y_{sb} = X_{sb}^d m_b/v, \quad y_{bs} = X_{bs}^d m_s/v$$

Both h and Z couplings generated

NP model: Vector-like Quarks (1)

Introduce $SU_L(2)$ singlets (D_L, D_R) with $Y = -1/3$

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



NP model: Vector-like Quarks (2)

Introduce $SU_L(2)$ doublets (Q_L, Q_R) with $Y = 1/6$

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



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

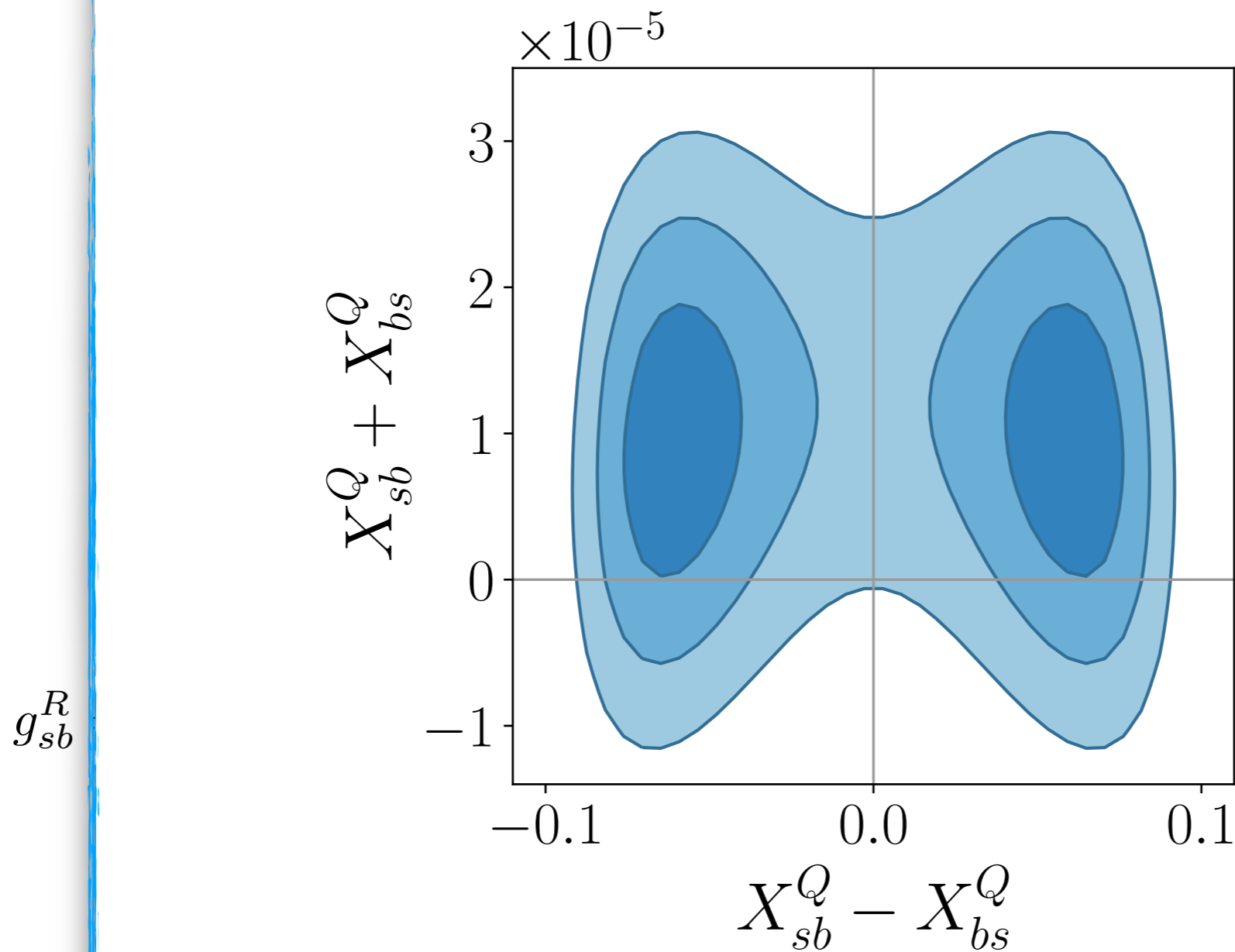
$$g_{sb}^R = \frac{g}{2c_W} (X_{sb}^Q + X_{bs}^{Q*}), \quad g_{sb}^L = 0, \quad y_{sb} = X_{sb}^Q m_b/v, \quad y_{bs} = X_{bs}^Q m_s/v$$

Both h and Z couplings generated

NP model: Vector-like Quarks (2)

Introduce $SU_L(2)$ doublets (Q_L, Q_R) with $Y = 1/6$

$$-\mathcal{L}_Q = \alpha^{ij} \bar{q}^i H d^j + \alpha^{ij} \bar{q}^i \tilde{H} u^j + \alpha^i \bar{Q}_L H d^i + \alpha^i \bar{Q}_L \tilde{H} u^i + M_Q \bar{Q}_L Q_R + \text{h.c.}$$



g_{sb}^R

NP model: Two Higgs Doublet Model

Type III: no discrete symmetry preventing FCNCs

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

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h_1 + iG^0) \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2 + iA) \end{pmatrix}$$

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

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

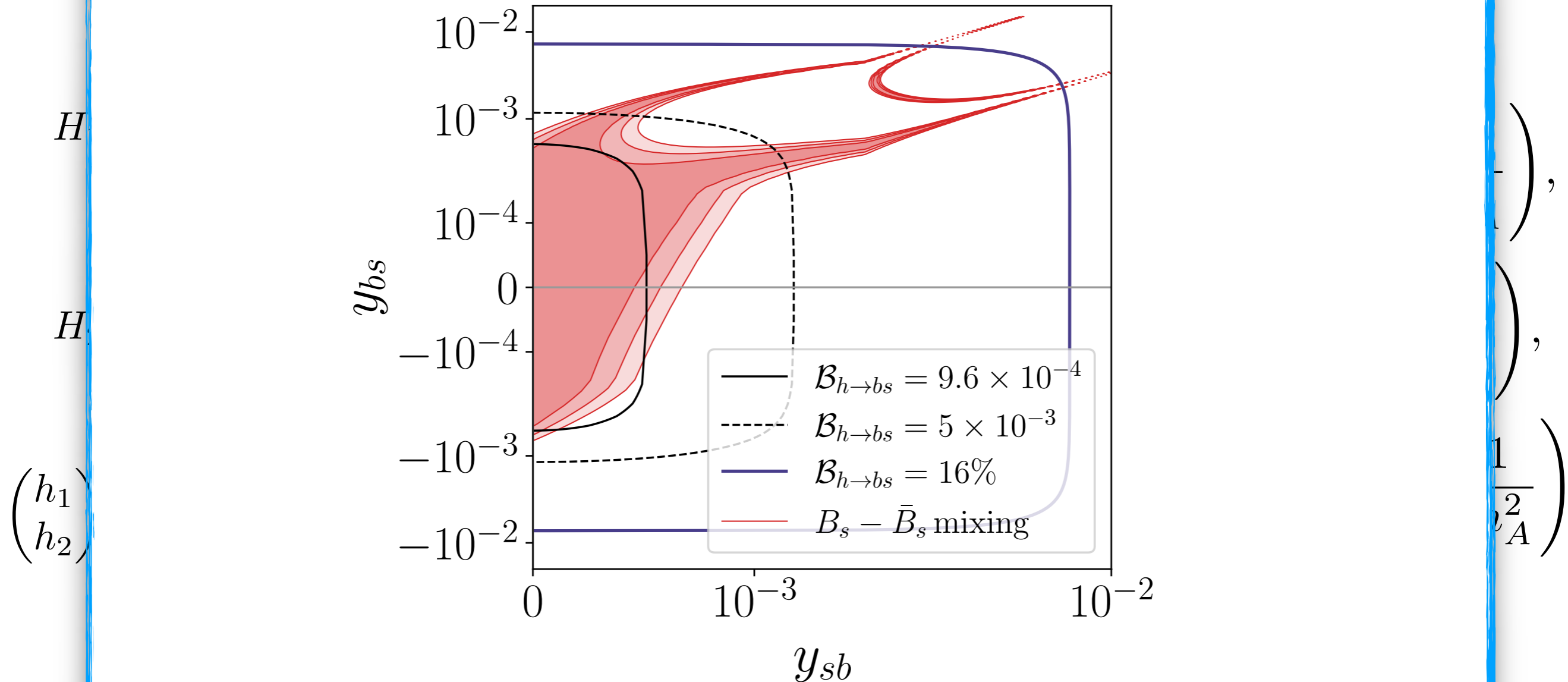
$$C'_2 = -\frac{(Y_{sb}^d)^2}{2} \left(\frac{s_\alpha^2}{m_h^2} + \frac{c_\alpha^2}{m_H^2} - \frac{1}{m_A^2} \right),$$

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

NP model: Two Higgs Doublet Model

Type III: no discrete symmetry preventing FCNCs

$$m_{H,A} \rightarrow \infty \quad y_{ij} = Y_{ij}^q \sin \alpha$$

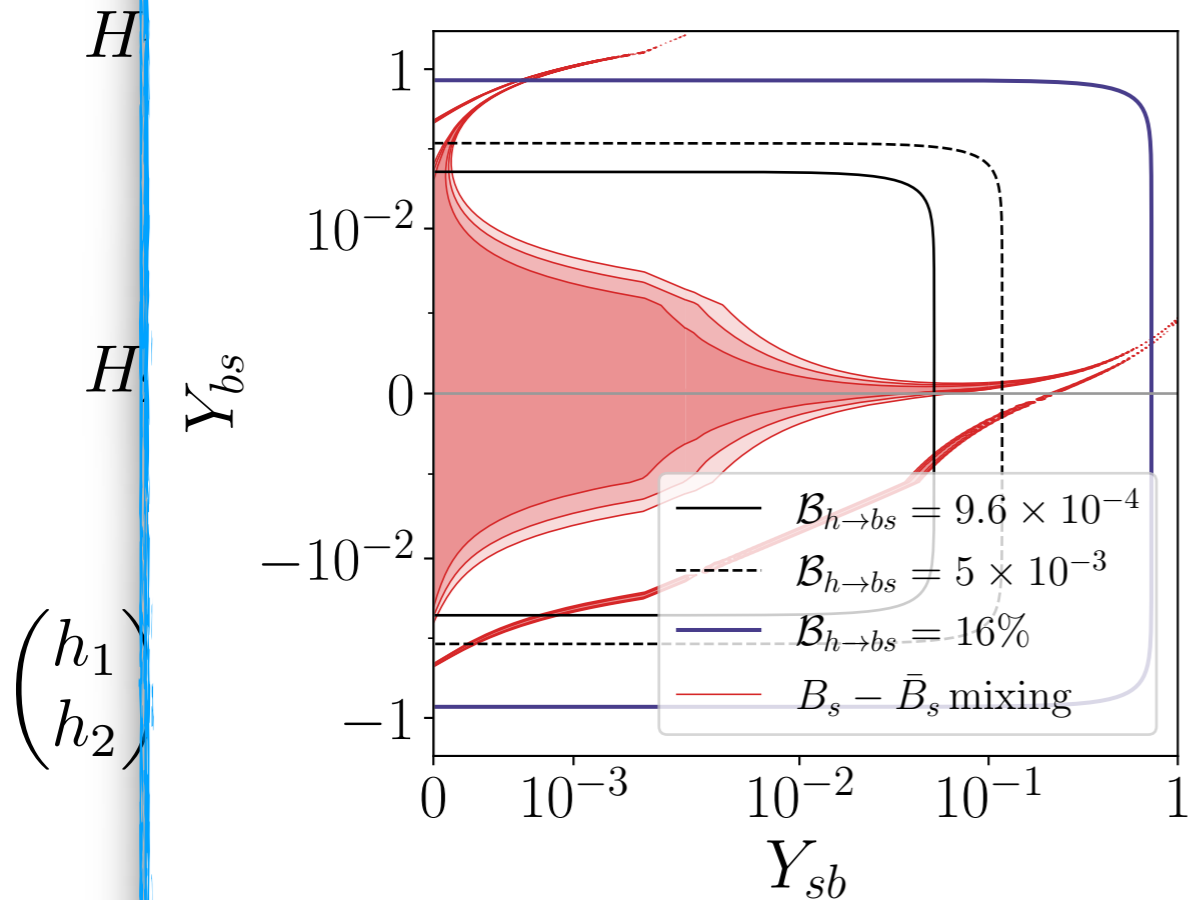


NP model: Two Higgs Doublet Model

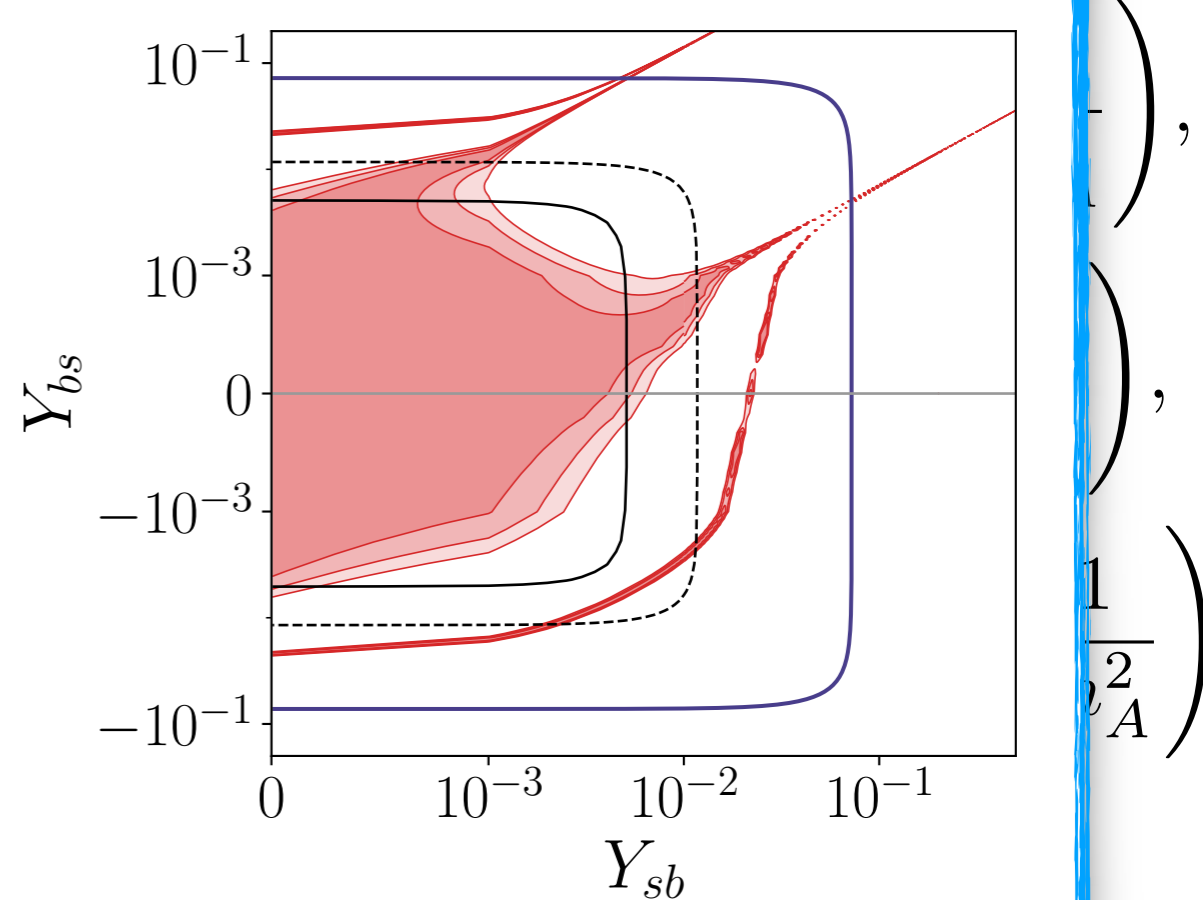
Type III: no discrete symmetry preventing FCNCs

$$m_{H,A} = 1 \text{ TeV}$$

$\sin \alpha = 0.01$



$\sin \alpha = 0.1$

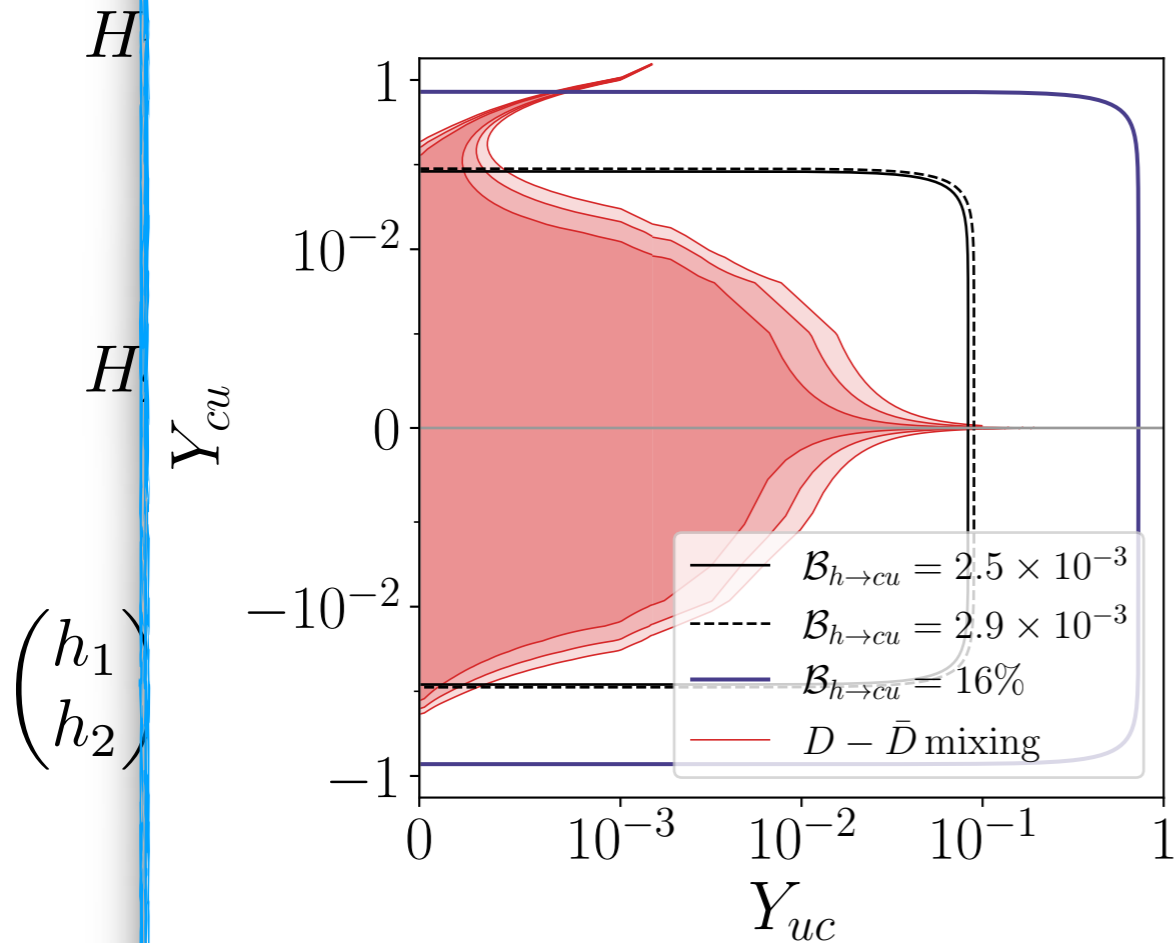


NP model: Two Higgs Doublet Model

Type III: no discrete symmetry preventing FCNCs

$$m_{H,A} = 1 \text{ TeV}$$

$\sin \alpha = 0.01$



$\sin \alpha = 0.1$

