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

Michele Tammaro

@FCC Pheno Workshop, 05/07/2023

arXiv: 2306.17520 with

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

Jožef Stefan Institute

- 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
    - 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

Effective Lagrangian

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

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} ●

▲ $h \to$ BSM (CMS+ATLAS, 2207.00043)

★ Meson mixings

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

● Global fits (mostly semi-leptonic)

Z pole running

$$\sqrt{s} = m_Z$$

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

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}

1905.03764

FCC Conceptual Design Reports

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

hZ running

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

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

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

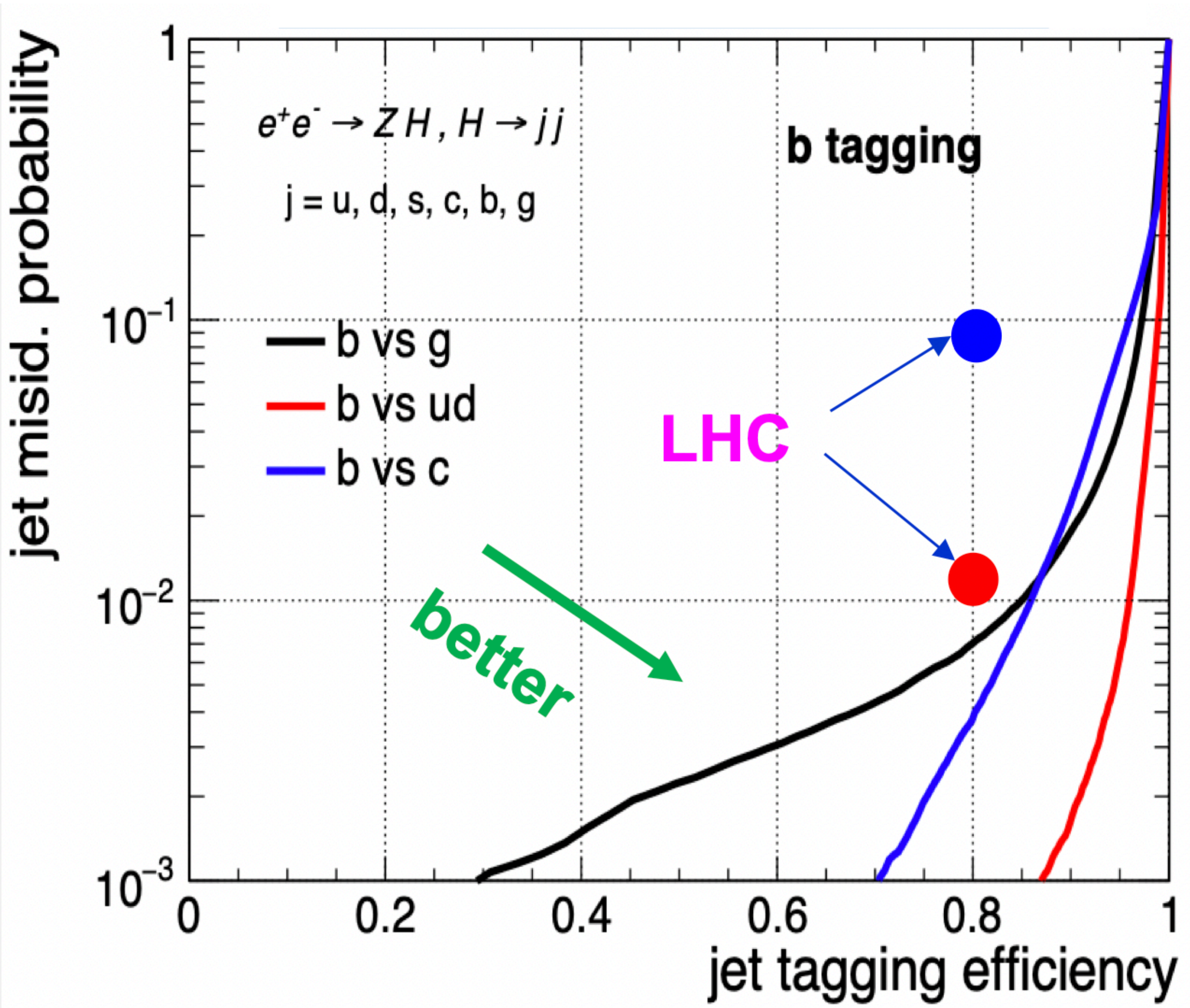
G. Marchiori's talk at "FCC Physics Workshop" (indico.cern.ch/event/1176398/)

Jet flavor taggers @FCC-ee

Tools to classify flavor of jets from input data

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

FPR



TPR

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

q-tagger rates

$$\epsilon^q_\beta \quad \beta = \{g(ud), s, c, b\}$$

WPs for *h* decays

$$\epsilon^b_{\beta;\mathrm{Loose}} = \{0.02,\ 0.001,\ 0.02,\ 0.90\}$$

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

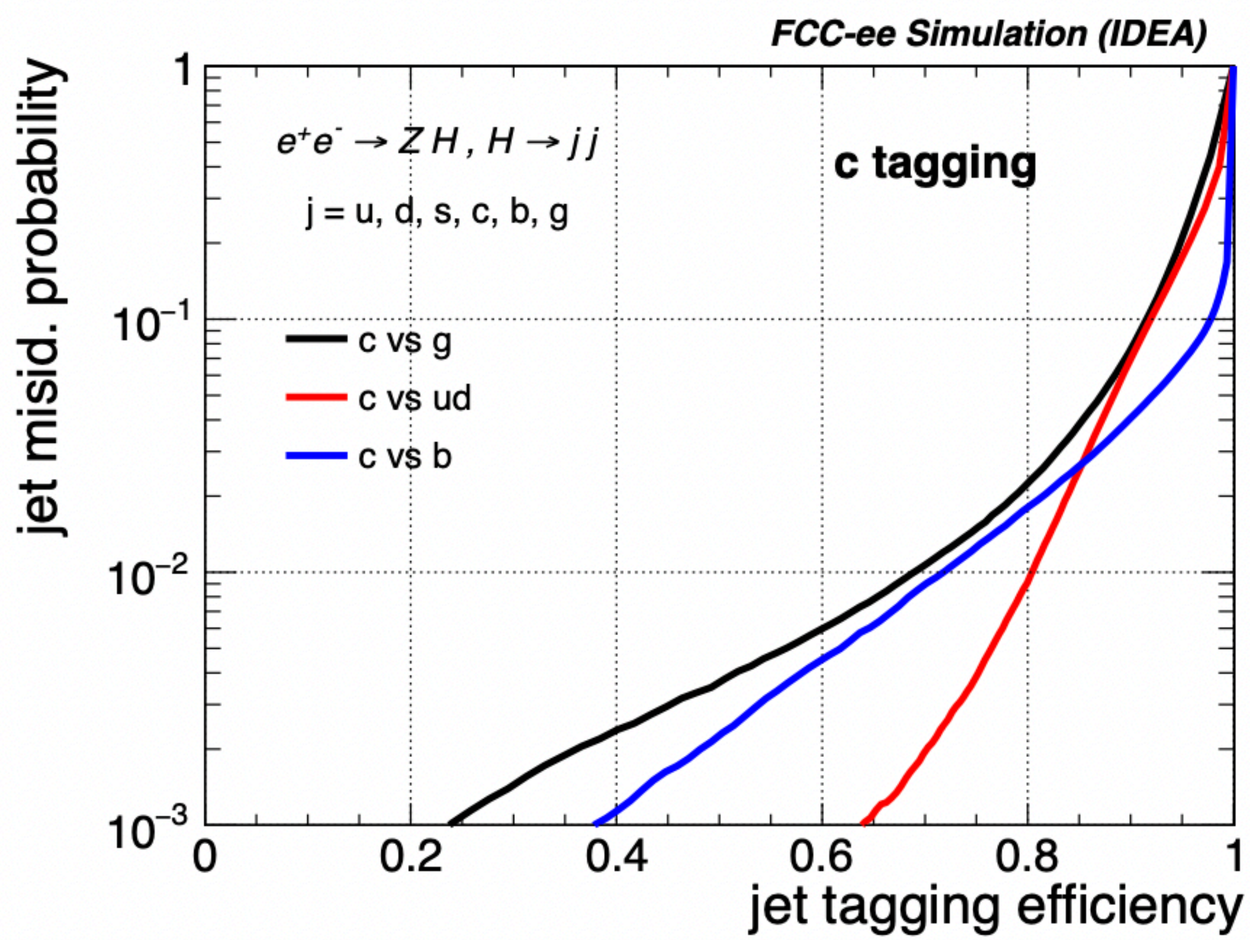
Currently $\mathcal{O}(few)\%$ syst. on ϵ^q_β

ATLAS: 1907.05120
CMS: 1712.07158

Jet flavor taggers @FCC-ee

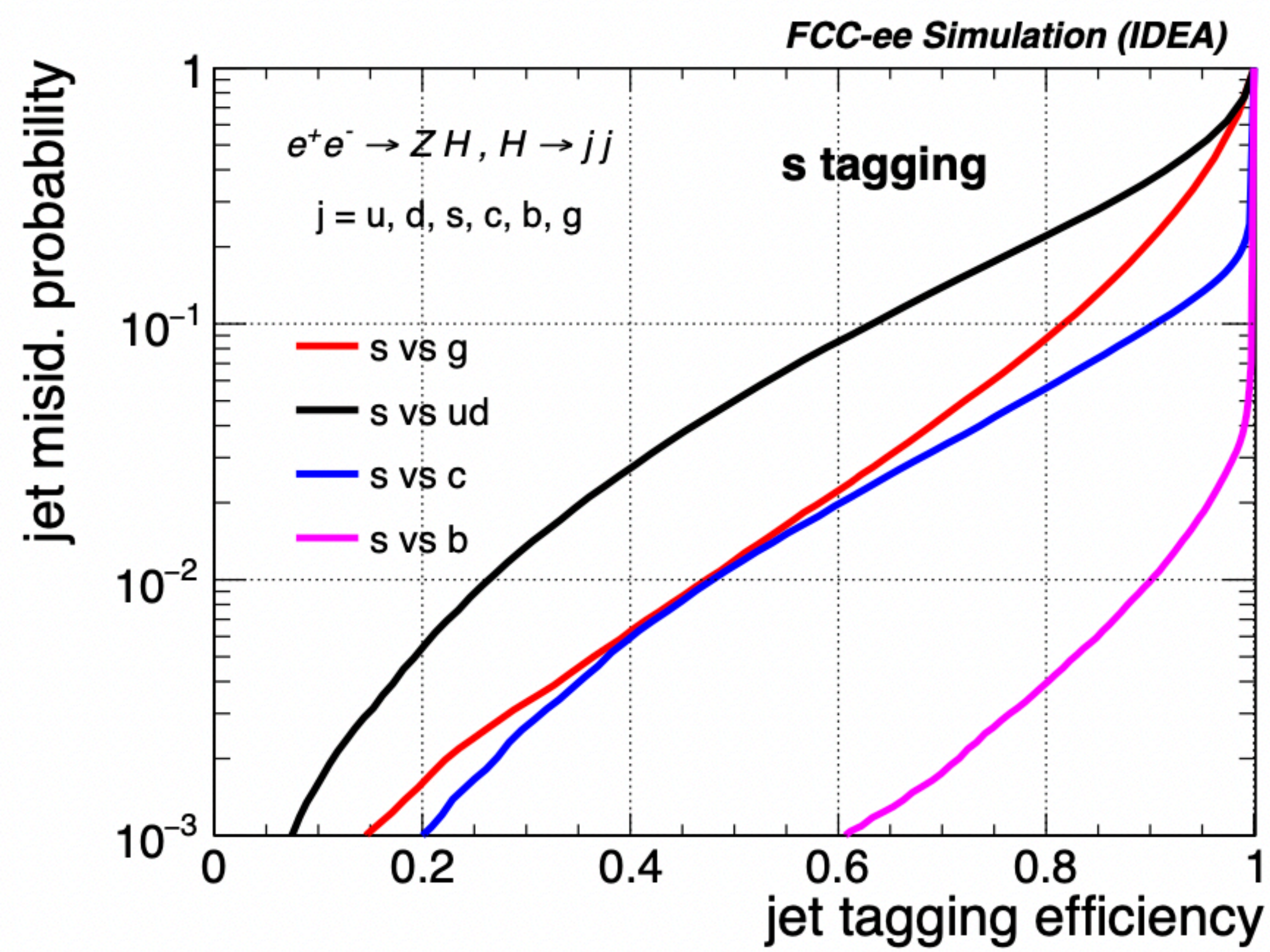
Tools to classify flavor of jets from input data

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



$$\epsilon^{c}_{\beta;\mathrm{Loose}} = \{0.07,\ 0.07,\ 0.90,\ 0.04\},$$
$$\epsilon^{c}_{\beta;\mathrm{Med}} = \{0.02,\ 0.008,\ 0.80,\ 0.02\},$$

$$\epsilon^{s}_{\beta;\mathrm{Loose}} = \{0.20,\ 0.90,\ 0.10,\ 0.01\},$$
$$\epsilon^{s}_{\beta;\mathrm{Med}} = \{0.09,\ 0.80,\ 0.06,\ 0.004\},$$



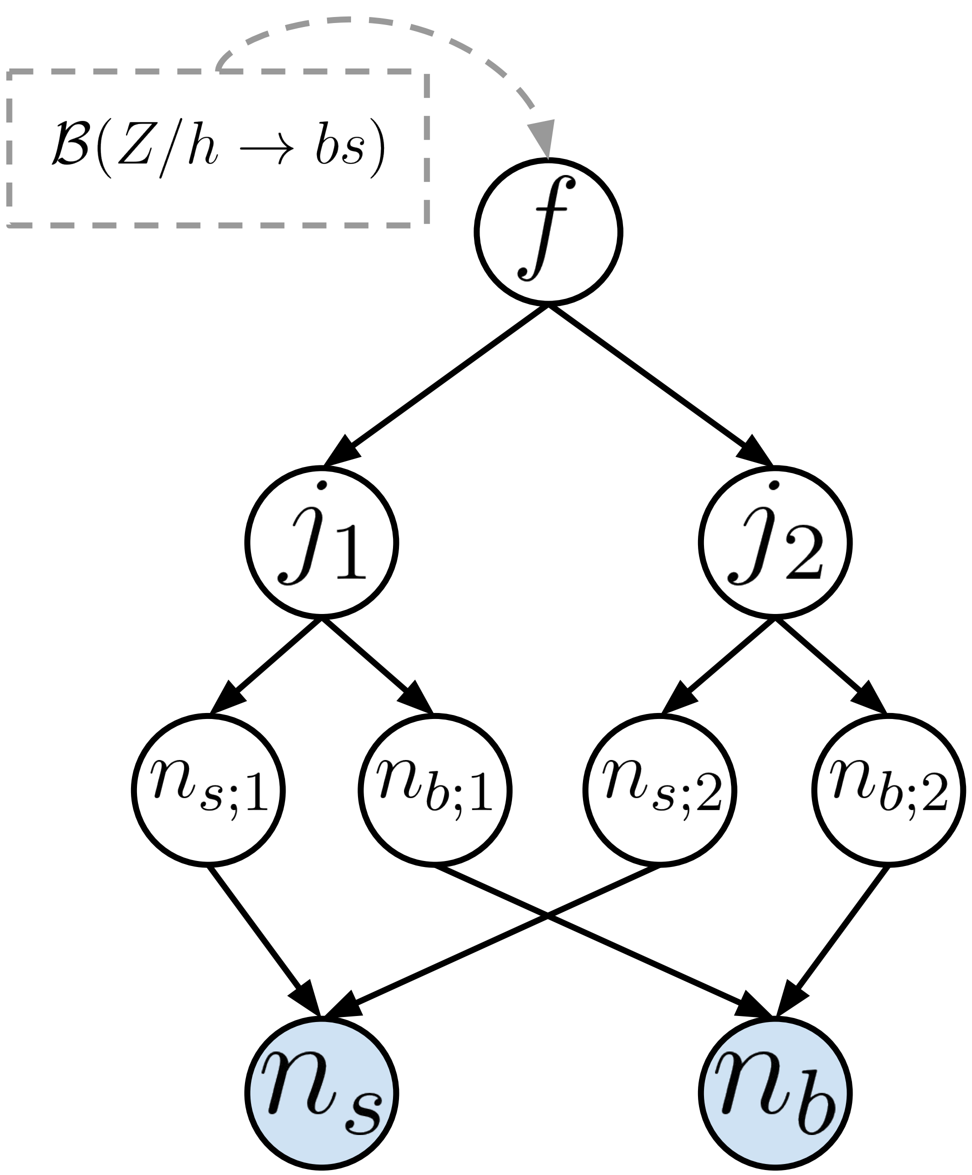
Bedeschi, Gouskos, Selvaggi: 2202.03285
Gouskos' talk at "FCC Physics Workshop" (indico.cern.ch/event/1176398/)

Probabilistic model

Distribute events into tag bins

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

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



Expected number of events per channel

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

Expected number of events per tag bin

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

Nuisance parameters:

$$\nu = \{\mathcal{B}(h \to f), B(Z \to f'), \epsilon^\alpha_\beta, N_{Z/h}, \mathcal{A}\}$$

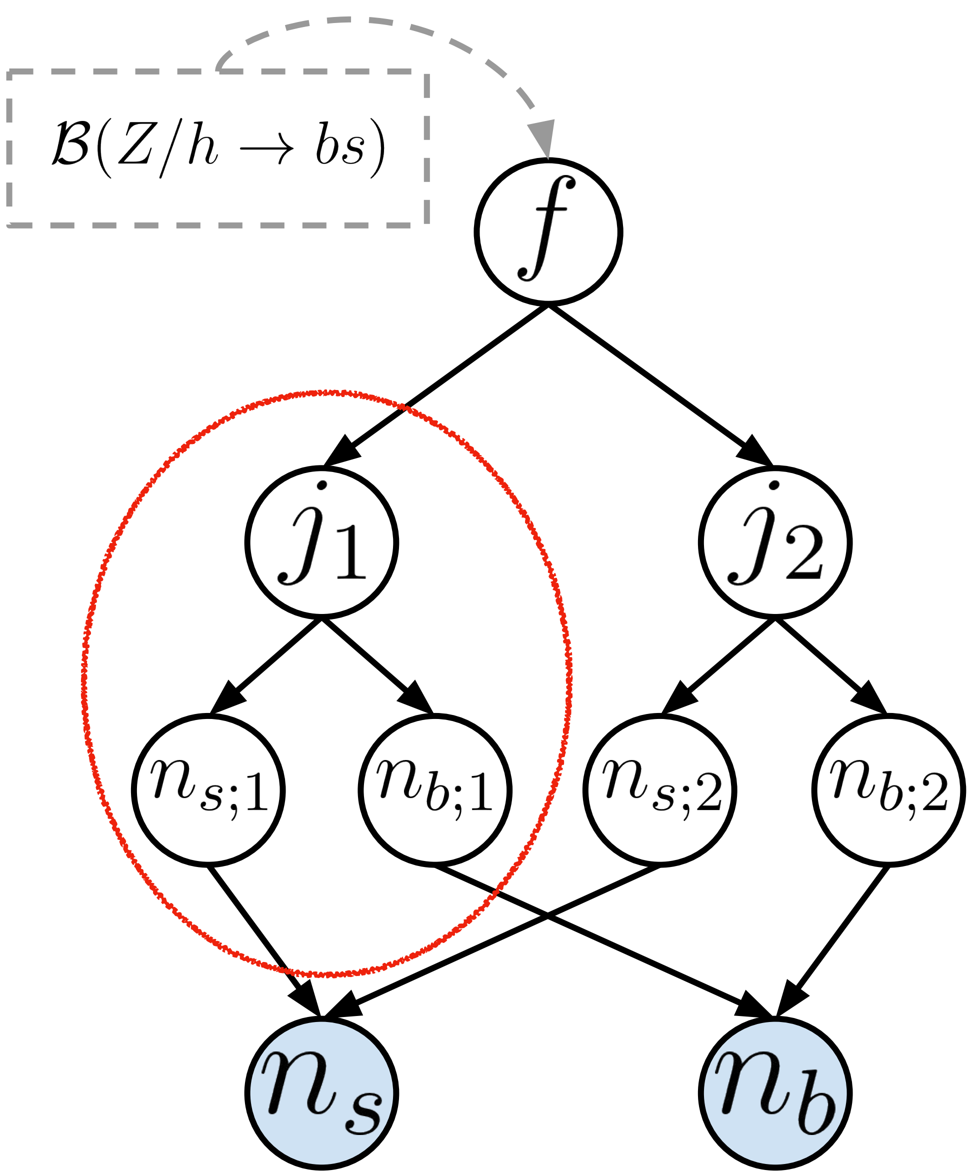
Probabilistic model

Distribute events into tag bins

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

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

$n_{q;1} = 0, 1$ flavor tagging of jet j_1



Apply b-tagger

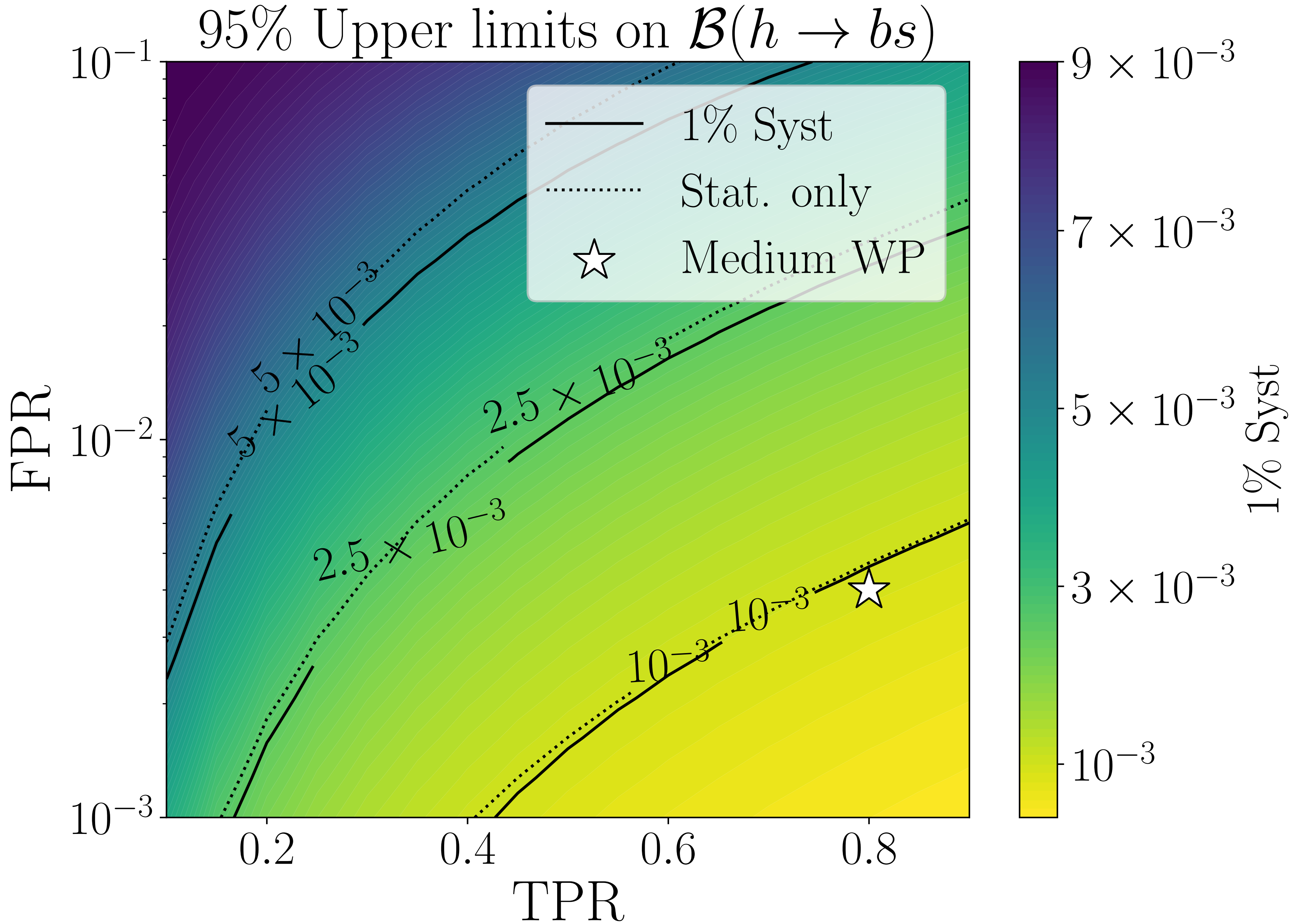
$$p(n_{b;1}|j_1) = \text{Binom}(n_{b;1}, 1, \epsilon_1^b)$$

Apply s-tagger (conditioned)

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

Repeat for j_2 and sum over all possible taggings

N.B.: we are assuming orthogonal and p_T independent taggers



Take common TPR and FPR (for plots)

Medium WP

(TPR, FPR) = (0.8, 0.004)

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

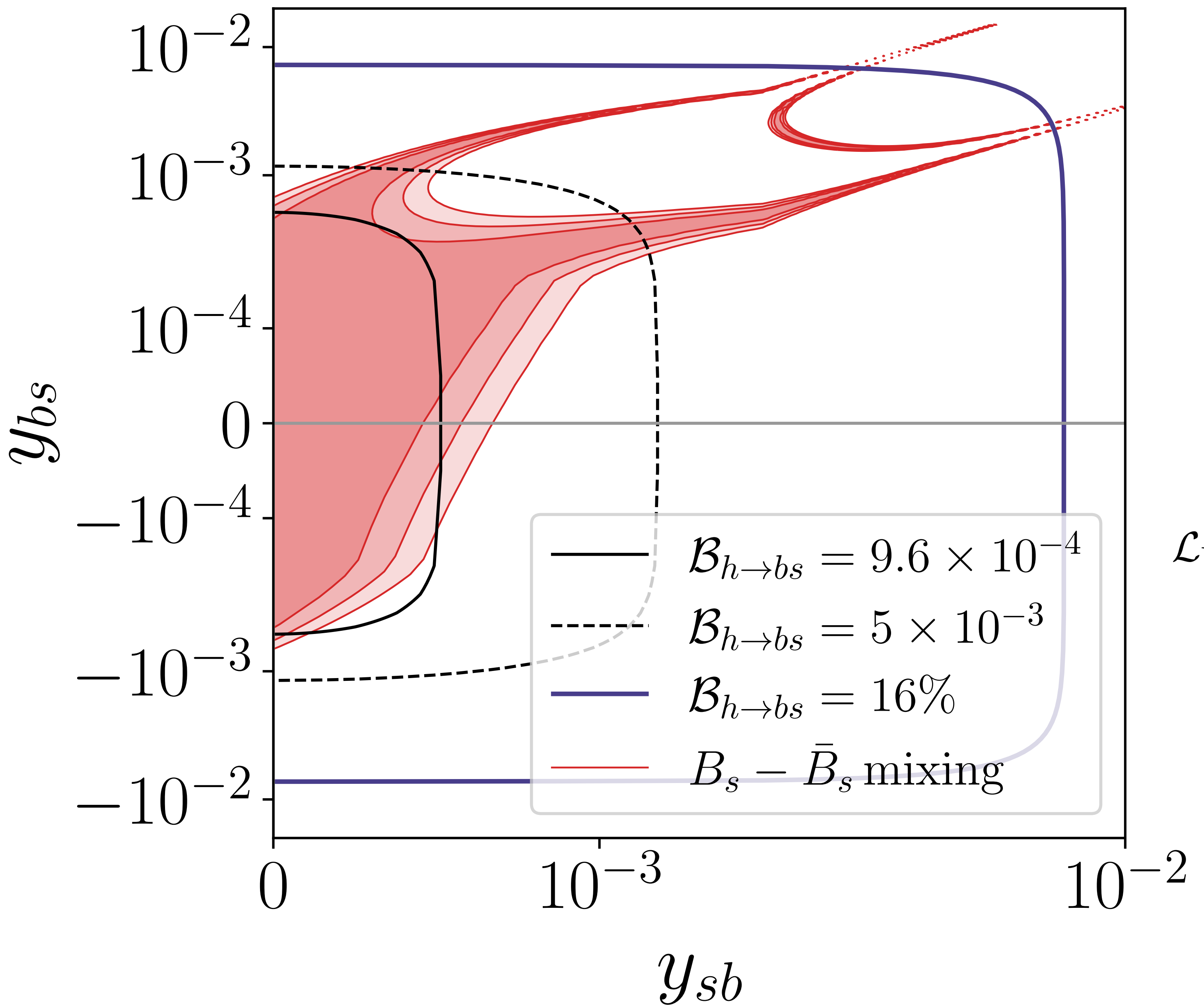
FCC-ee reach

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

Indirect constraints

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

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



Match to WET + `wilson` + `flavio`

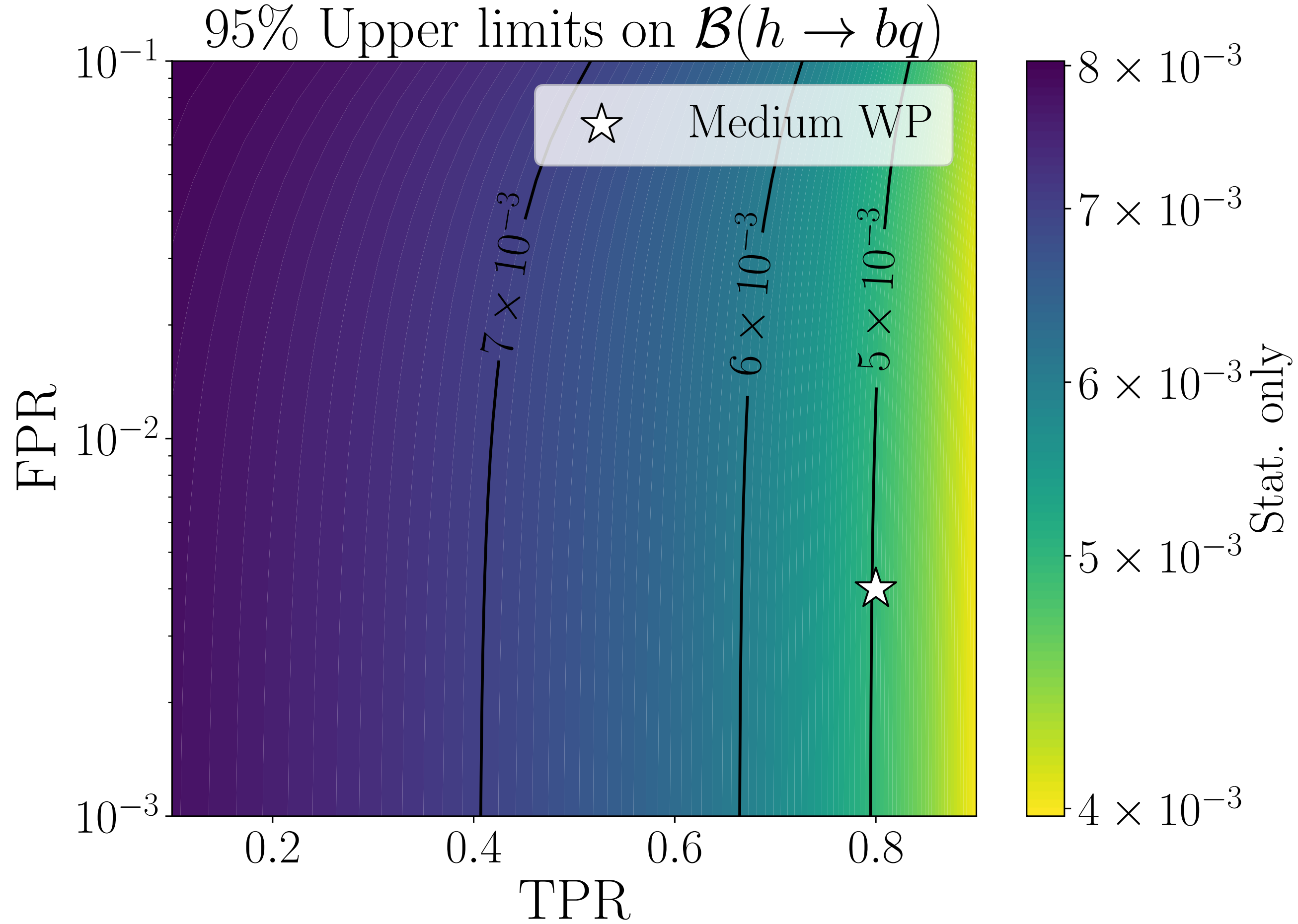
$$\mathcal{L}_{\text{WET}} \supset C_2(\bar{s}_R b_L)^2 + C_2'(\bar{s}_L b_R)^2 + C_4(\bar{s}_L b_R)(\bar{s}_R b_L)$$

FCC-ee reach

Indirect constraints

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

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



No *d*-tagger

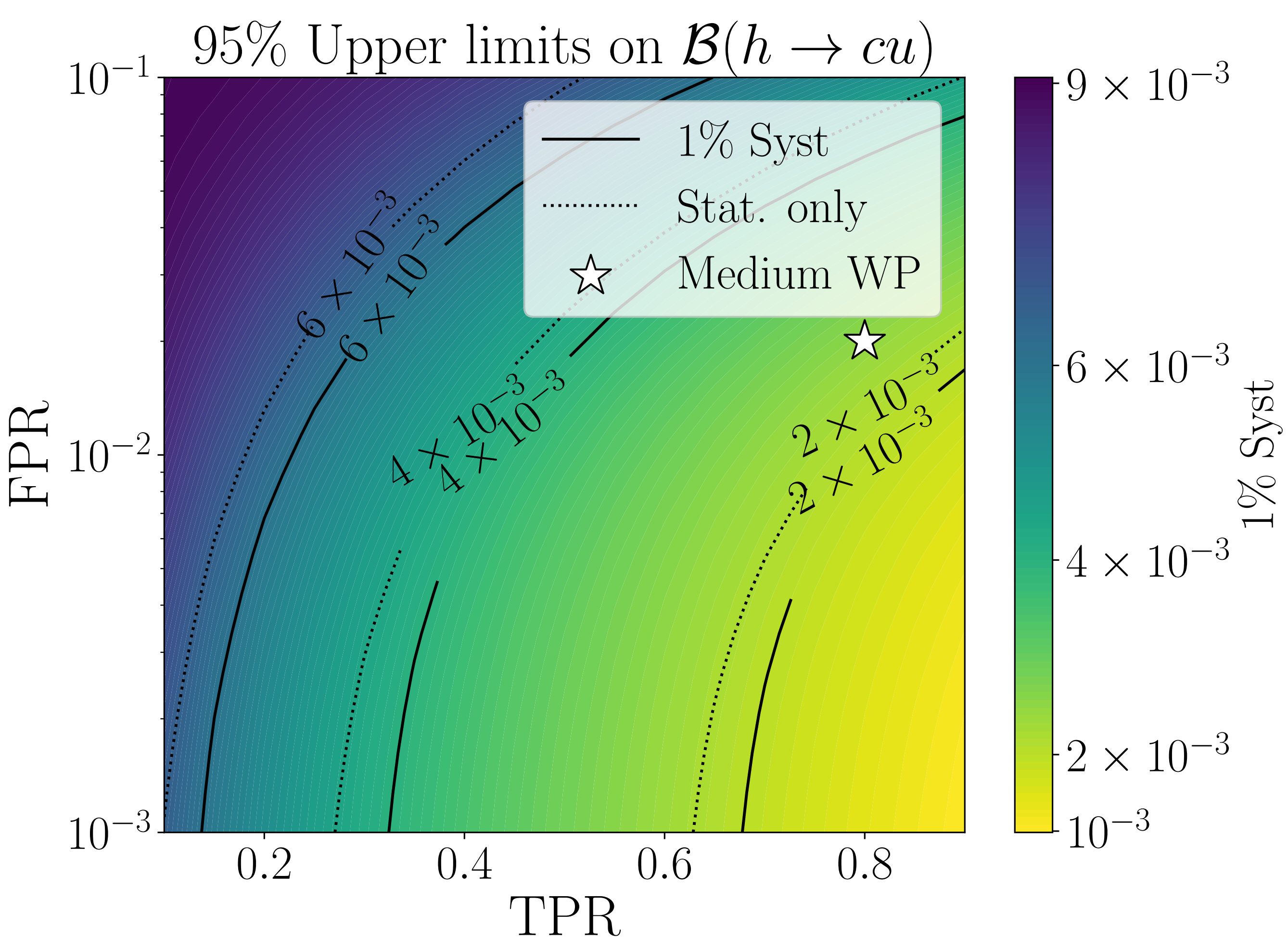
$$\mathcal{B}(h \to bq) = \mathcal{B}(h \to bs) + \mathcal{B}(h \to bd)$$

Medium WP

(TPR, FPR) = (0.8, 0.004)

FCC-ee reach

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



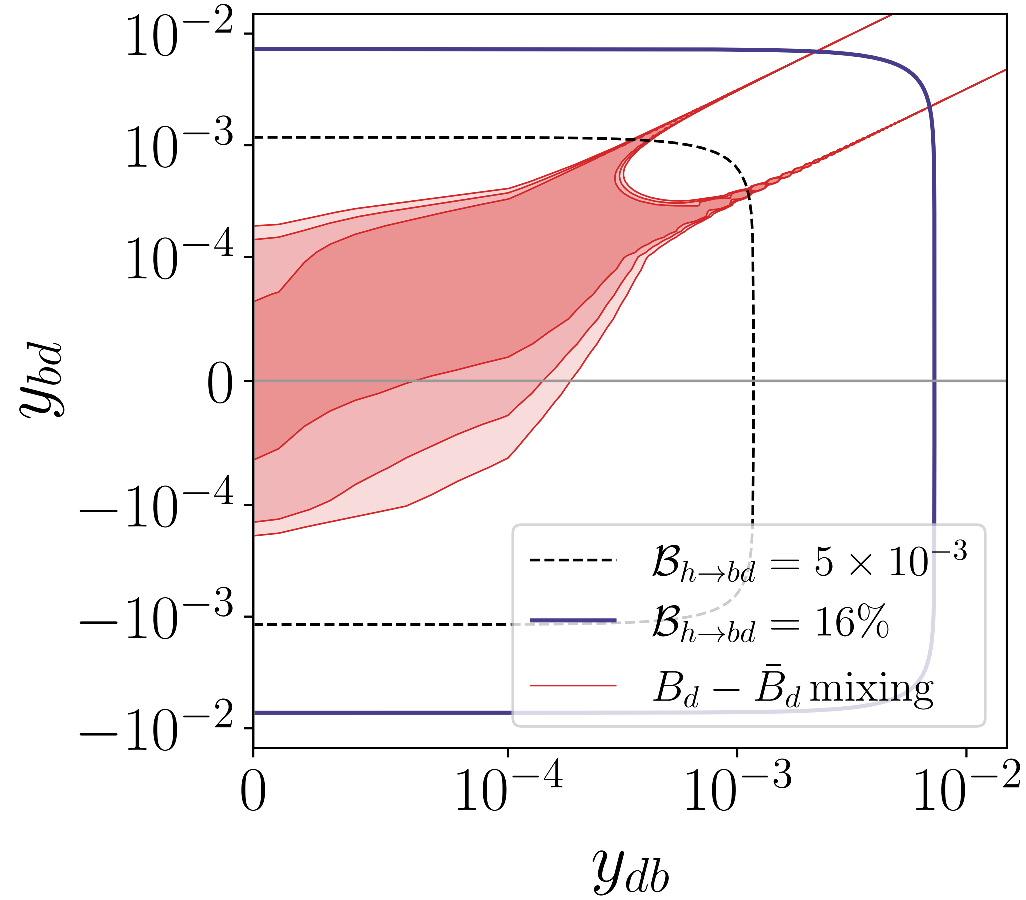
No *u*-tagger

Medium WP

(TPR, FPR) = (0.8, 0.02)

FCC-ee reach

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

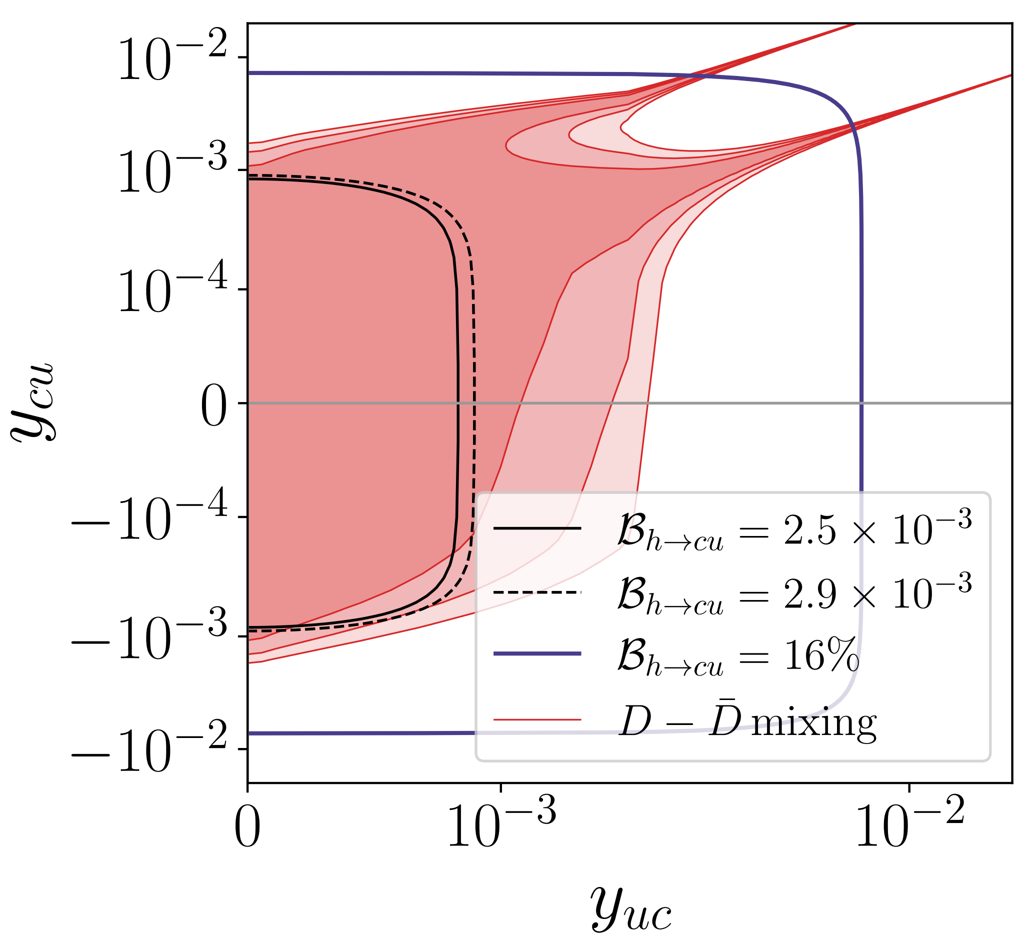


Indirect constraints

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

FCC-ee reach

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

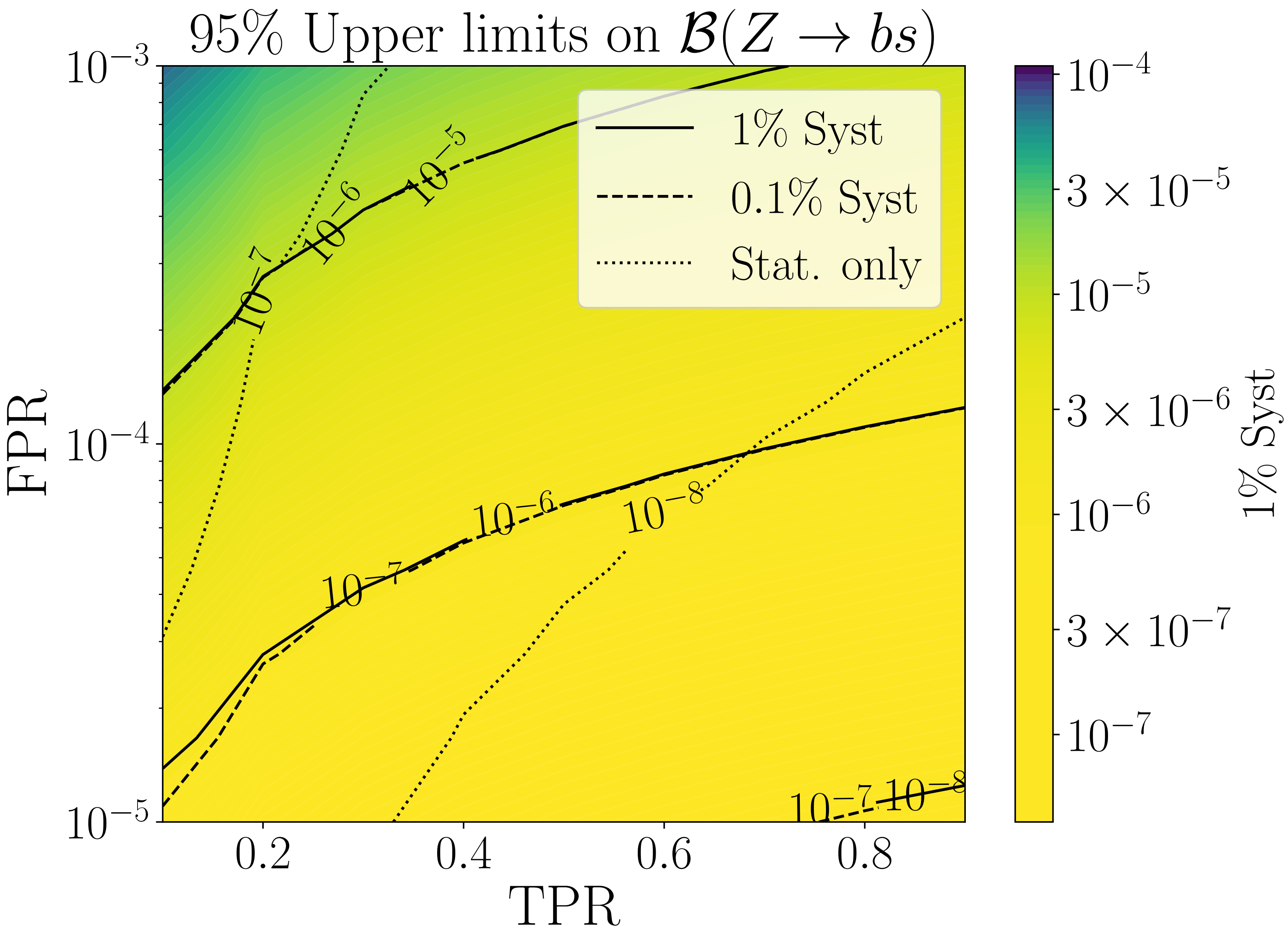


Indirect constraints

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

FCC-ee reach

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



TPR $\epsilon^b_b = \epsilon^s_s$

FPR $\epsilon^b_{udsc} = \epsilon^s_{udcb}$

$\epsilon^s_b \lesssim 10^{-4}$ limited by vertexing

3-5μm estimated

Barchetta, Collins, Riedler: 2112.13019

$(\mathrm{TPR}, \mathrm{FPR}, \Delta\epsilon^\alpha_\beta/\epsilon^\alpha_\beta)$	$\mathcal{B}(Z \to bs)$ (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}

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

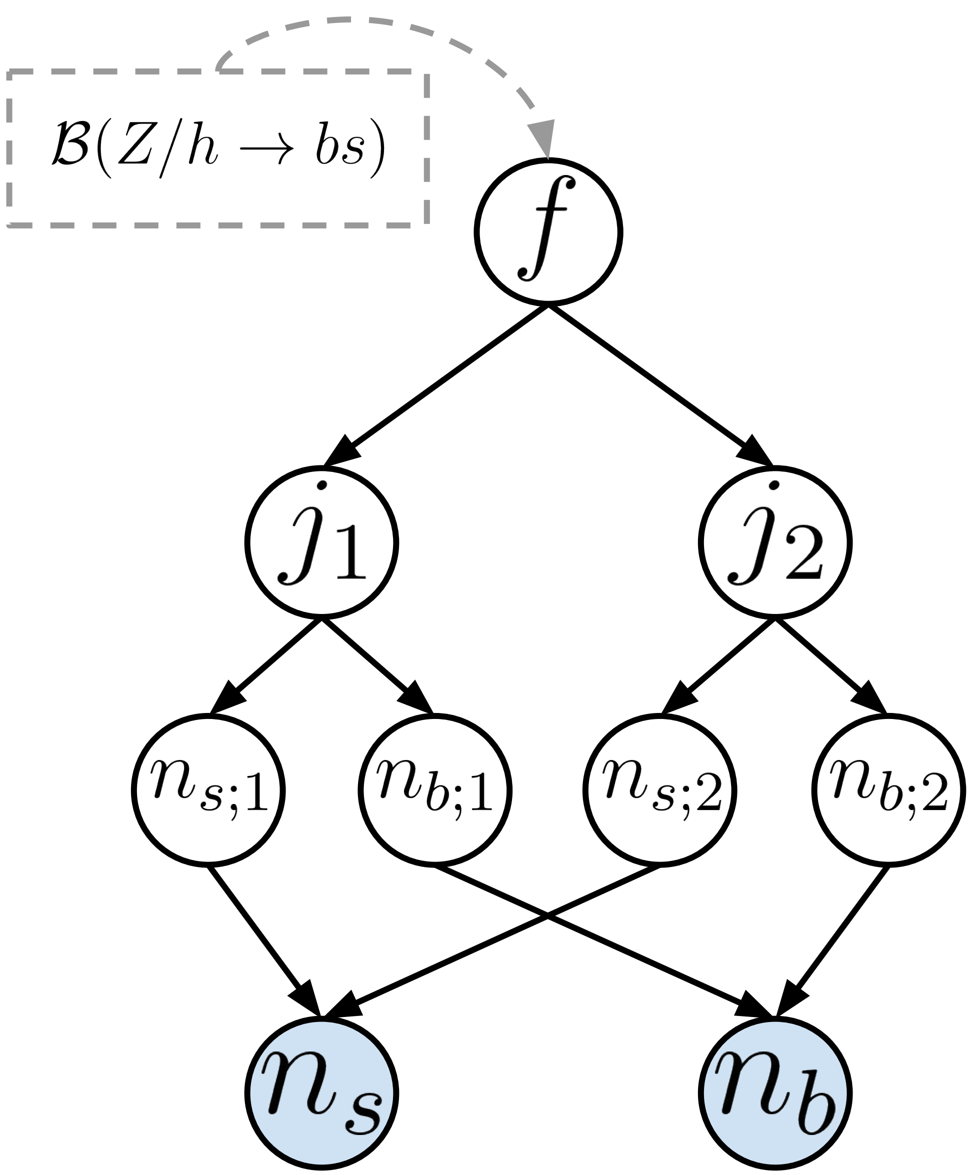
- Also: can be repeated at ILC/CEPC and HL-LHC (with some more care)

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

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

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

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

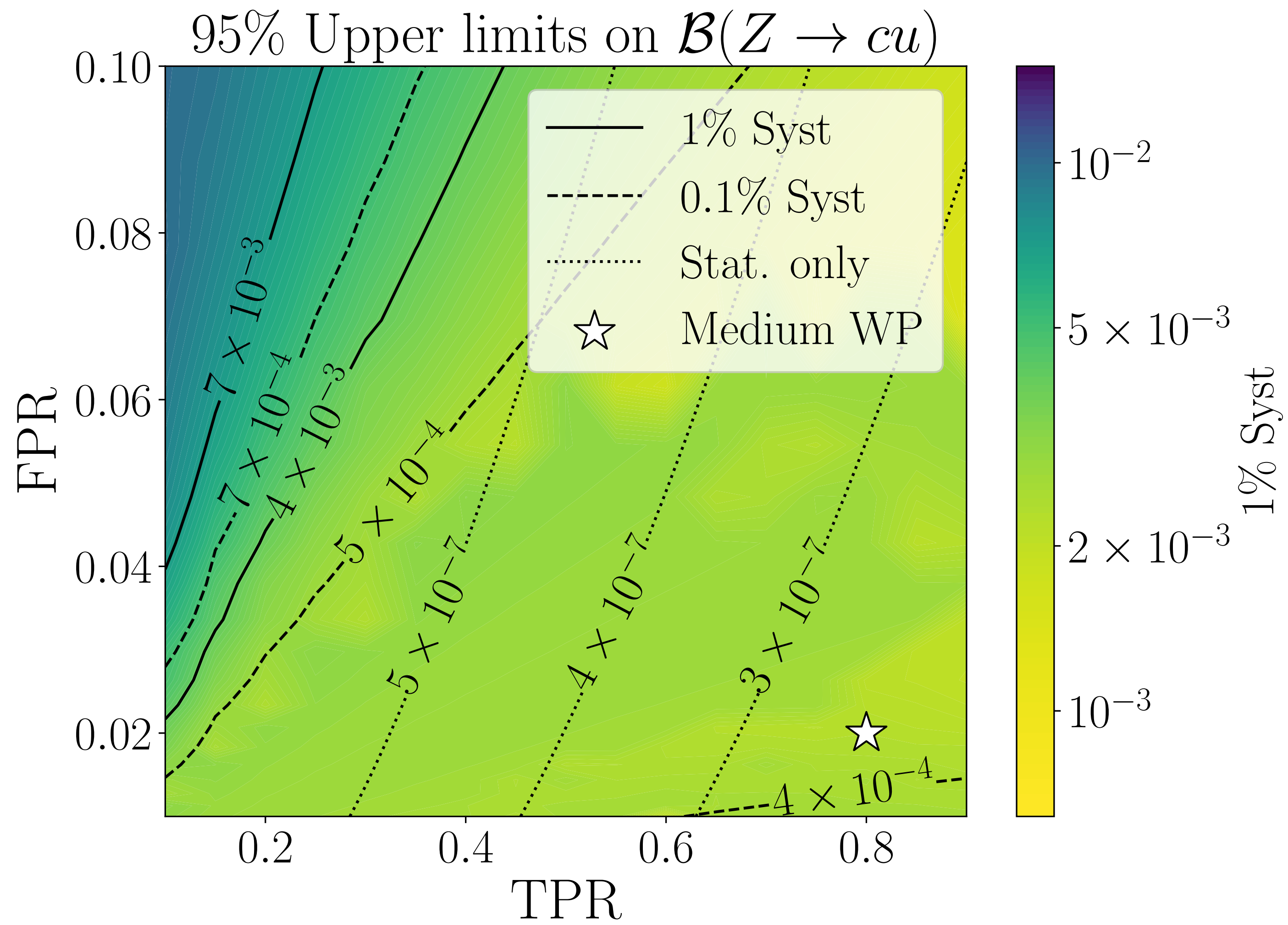
$\hat{\hat{\nu}}(\mu), \hat{\mu}, \hat{\nu}$ are maximum likelihood estimates (MLE)

Test statistics

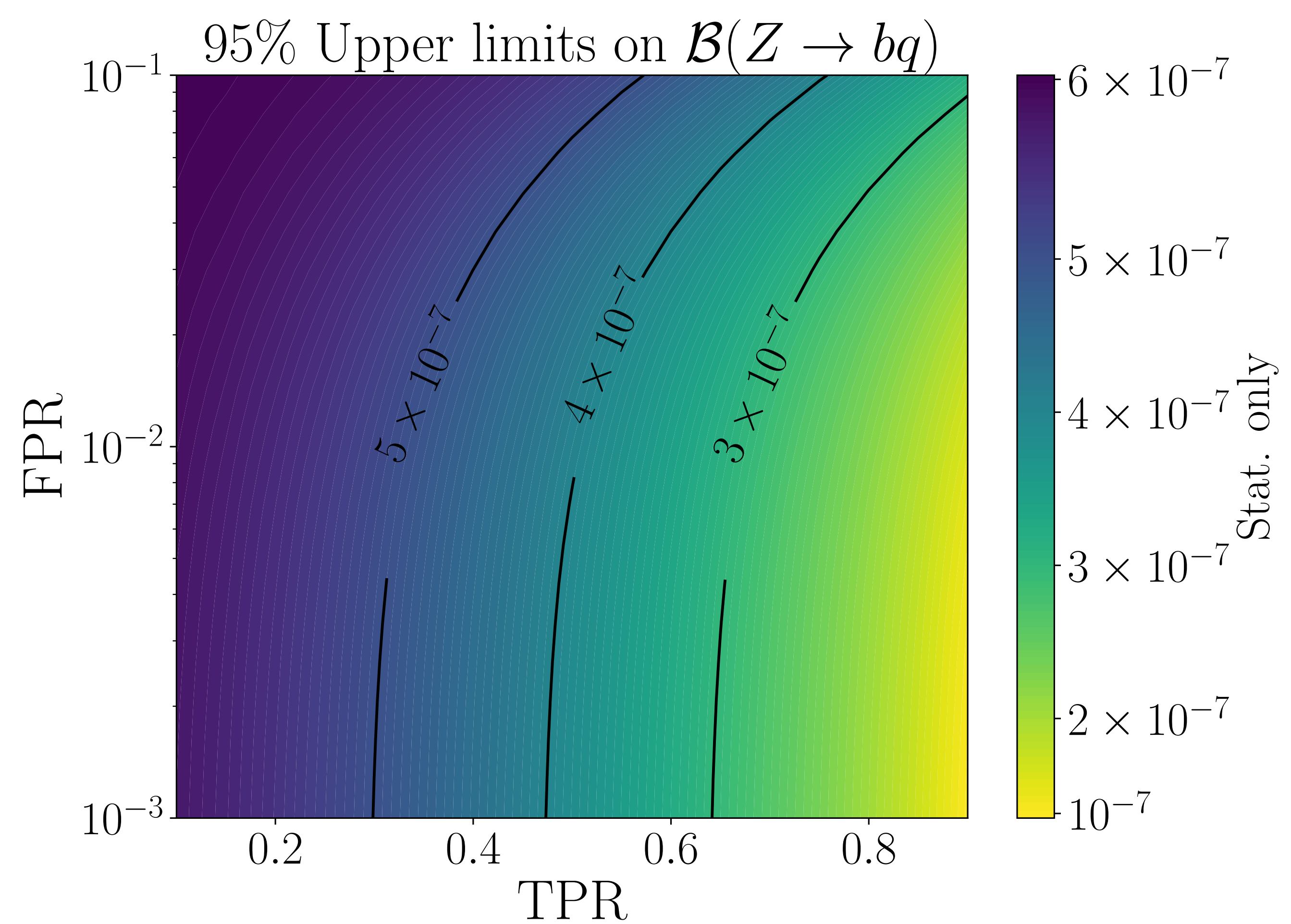
$$t_\mu = -2 \text{ Ln } \lambda(\mu)$$

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%)



Similar backgrounds and tagger performances



New Physics fits (Z)

$\Delta B = \Delta S = 1$

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

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

$\Delta F = 2$

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

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

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

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

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

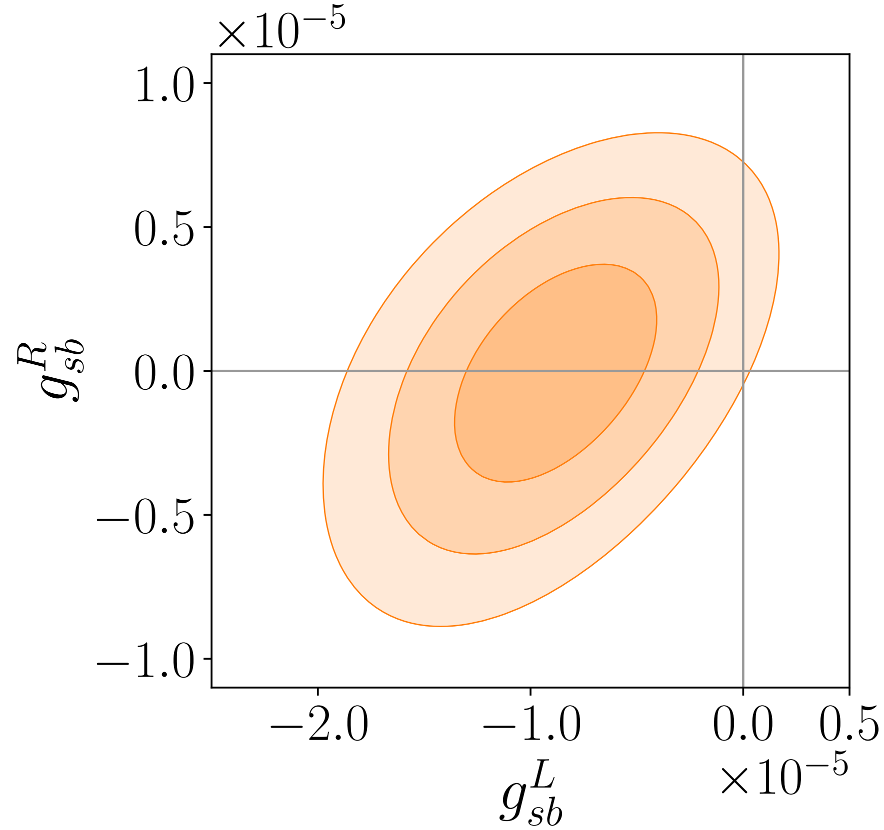
$$C_{VL} = \frac{(g_{sb}^L)^2}{2m_Z^2}$$

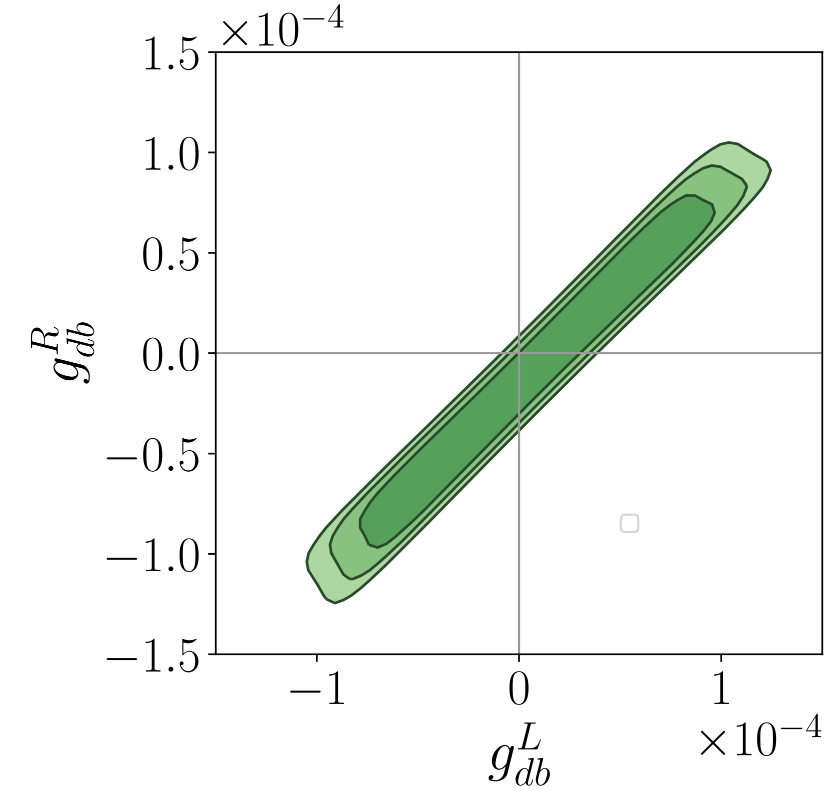
$$C_{VR} = \frac{(g_{sb}^R)^2}{2m_Z^2}$$

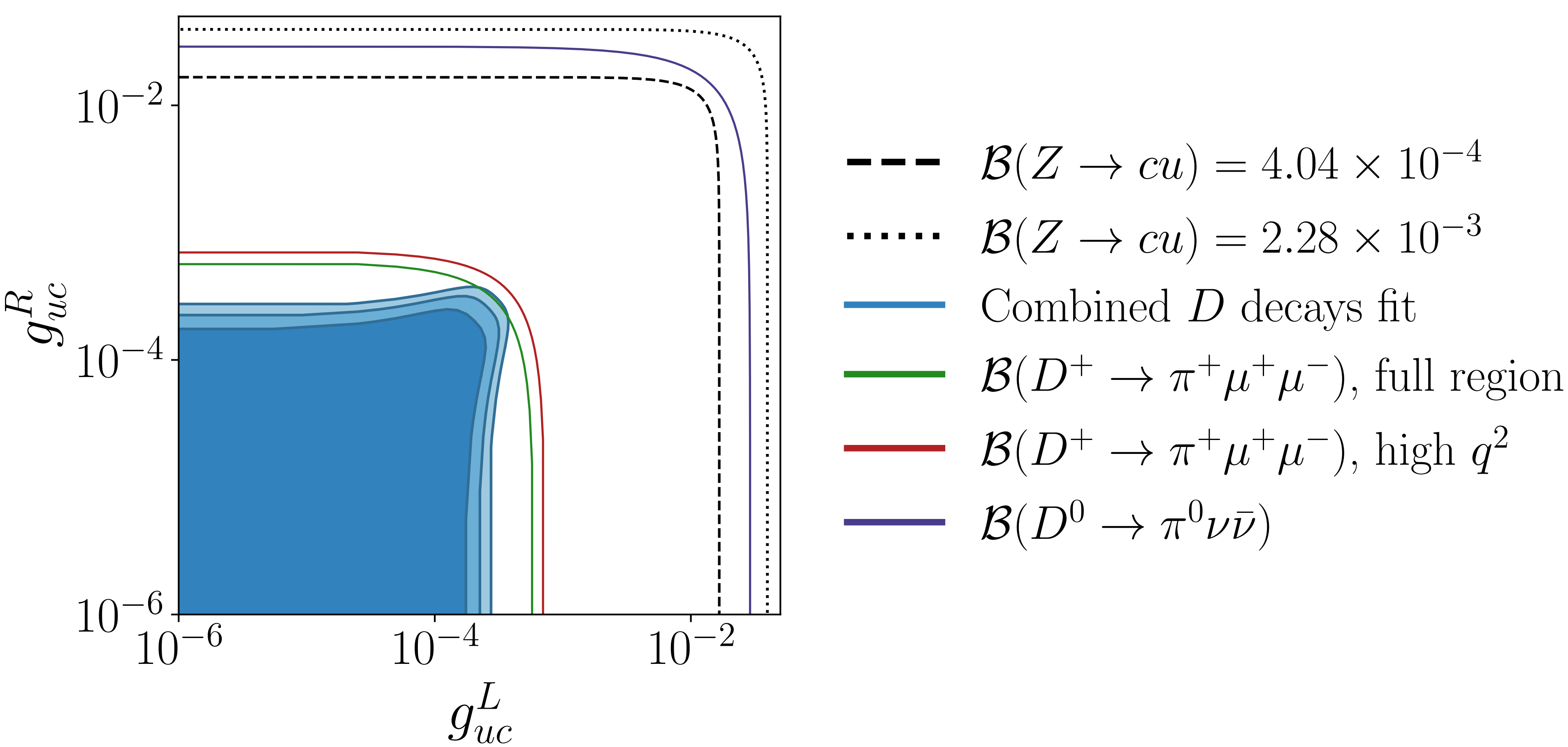
$$C_{VLR} = \frac{g_{sb}^L g_{sb}^R}{m_Z^2}$$

Lepton couplings are assumed to be SM

New Physics fits (Z)







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 $Y = -1/3$

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

↓

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

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

Both *h* and *Z* couplings generated

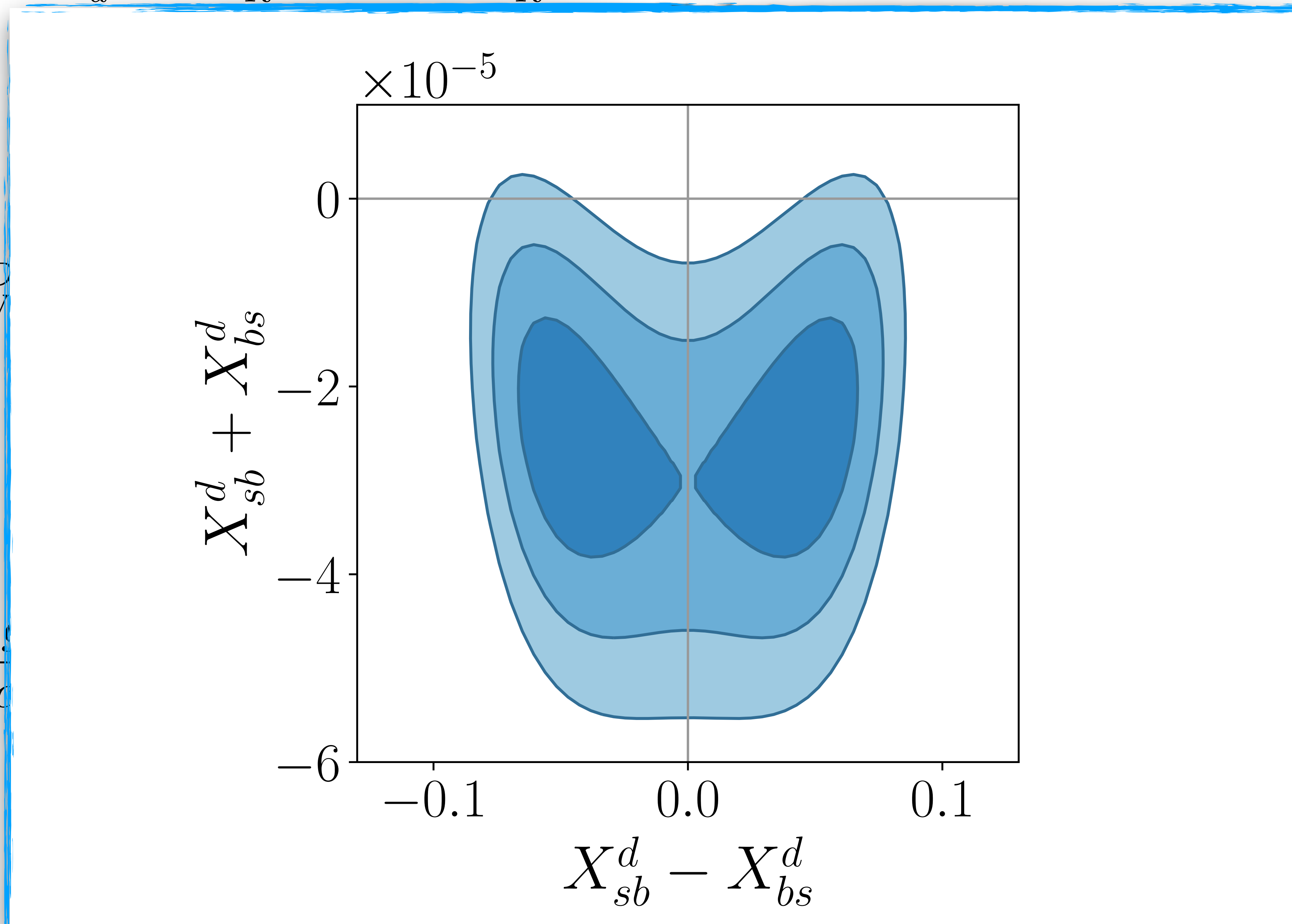
NP model: Vector-like Quarks (1)

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

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

$\mathcal{L}_{\rm V}^{D}$

$g_{sb}^L = \frac{}{2c}$



NP model: Vector-like Quarks (2)

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

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

↓

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

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

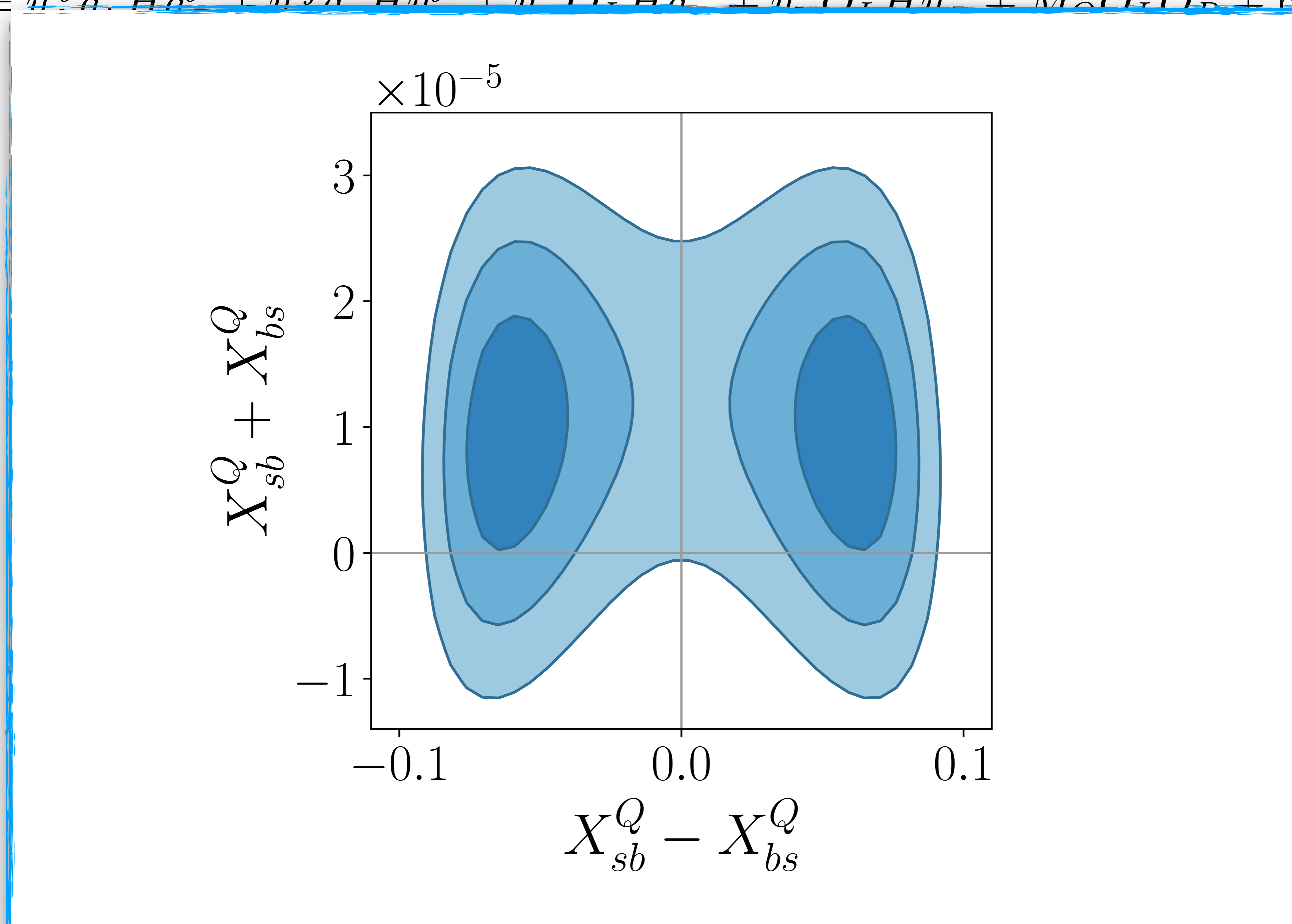
Both h and Z couplings generated

NP model: Vector-like Quarks (2)

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

$$-\mathcal{L}_Q = y^{ij}_d \bar{q}^i_L H d^j_R + y^{ij}_u \bar{q}^i_L \tilde{H} u^j_R + y^i_d \bar{Q}_L H d^i_R + y^i_u \bar{Q}_L \tilde{H} u^i_R + M_Q \bar{Q}_L Q_R + \text{h.c.}$$

g^R_{sb}



NP model: Two Higgs Doublet Model

Type III: no discrete symmetry preventing FCNCs

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

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

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

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

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

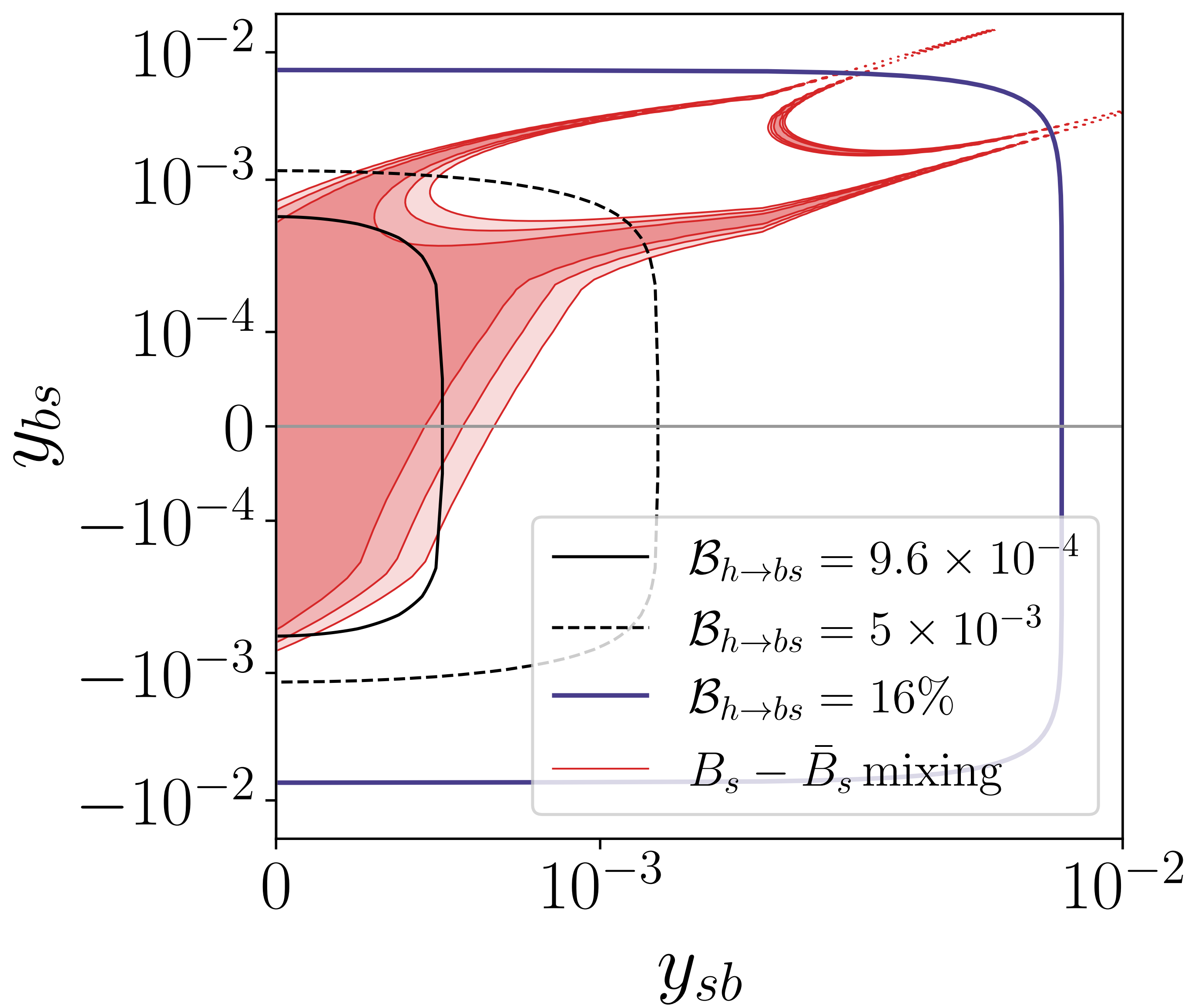
$$C_2' = -\frac{\left(Y_{sb}^{d}\right)^2}{2}\left(\frac{s_\alpha^2}{m_h^2} + \frac{c_\alpha^2}{m_H^2} - \frac{1}{m_A^2}\right),$$

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

NP model: Two Higgs Doublet Model

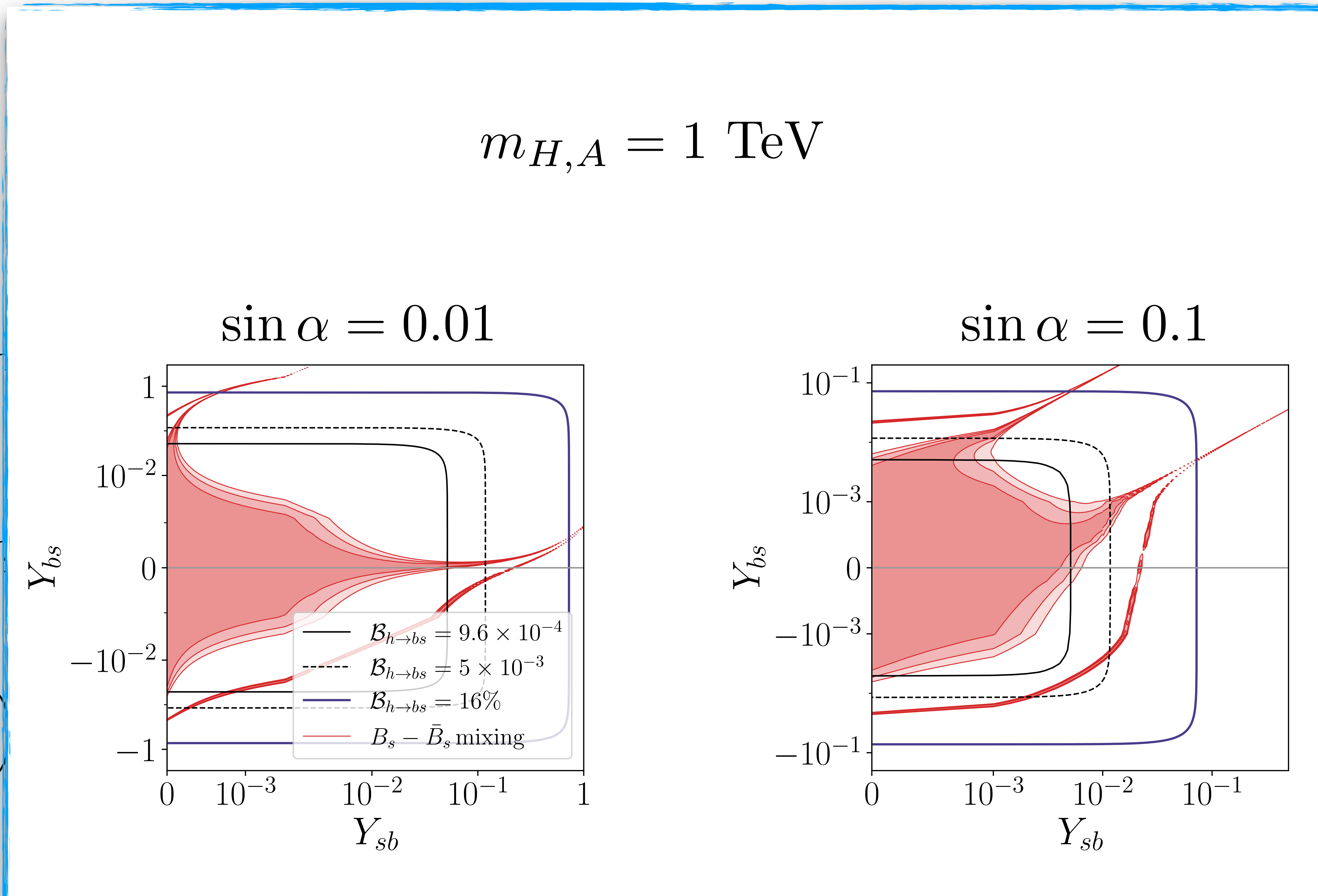
Type III: no discrete symmetry preventing FCNCs

$$m_{H,A} \to \infty \qquad y_{ij} = Y^q_{ij} \sin\alpha$$



NP model: Two Higgs Doublet Model

Type III: no discrete symmetry preventing FCNCs



NP model: Two Higgs Doublet Model

Type III: no discrete symmetry preventing FCNCs

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