Flavor changing h/Z/W decays @ future lepton colliders

Michele Tammaro

@TPPC Meeting, 02/02/2024

arXiv: 2306.17520 with

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

(and some work in progress with D. Marzocca, M. Schune & M. Szewc)

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

The landscape of future lepton colliders

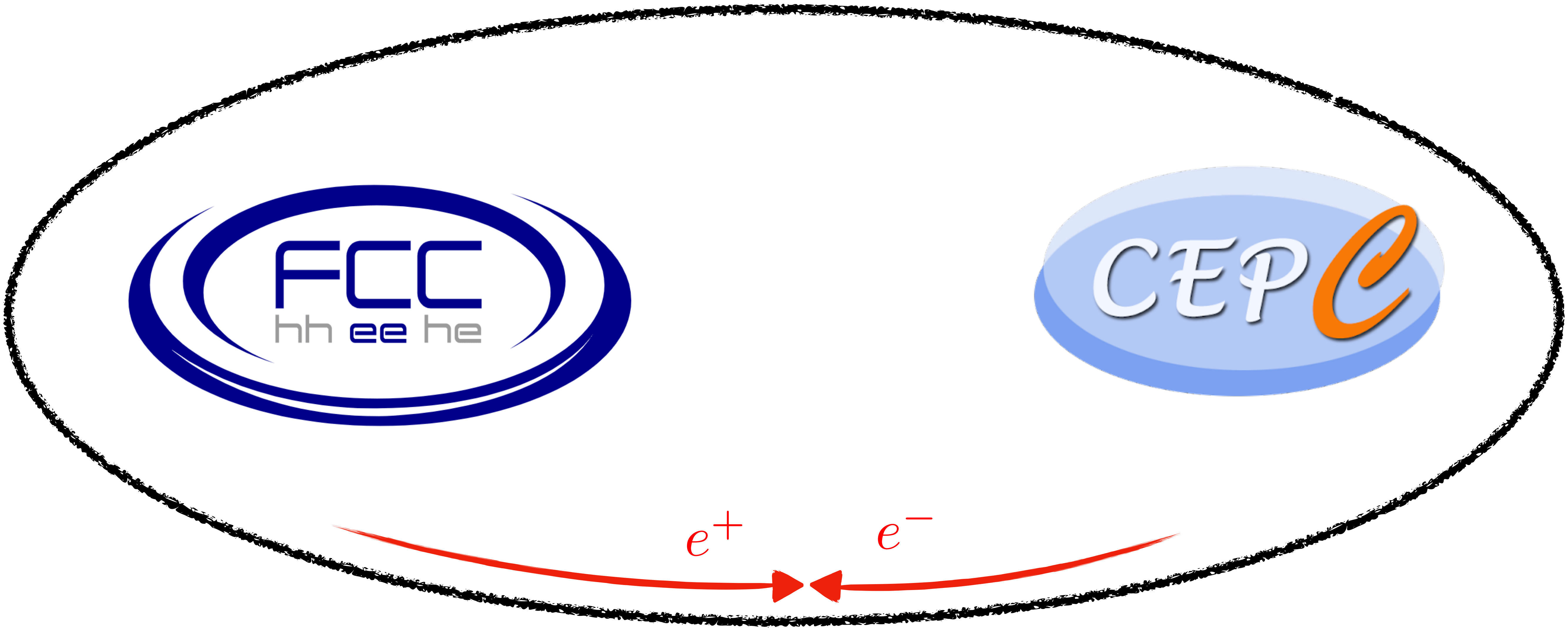
FCC
hh ee he

CEPC

international linear collider

International
MUON Collider
Collaboration

The landscape of future lepton colliders



$$\text{Z pole} \to N_Z \sim 5 \times 10^{12}$$

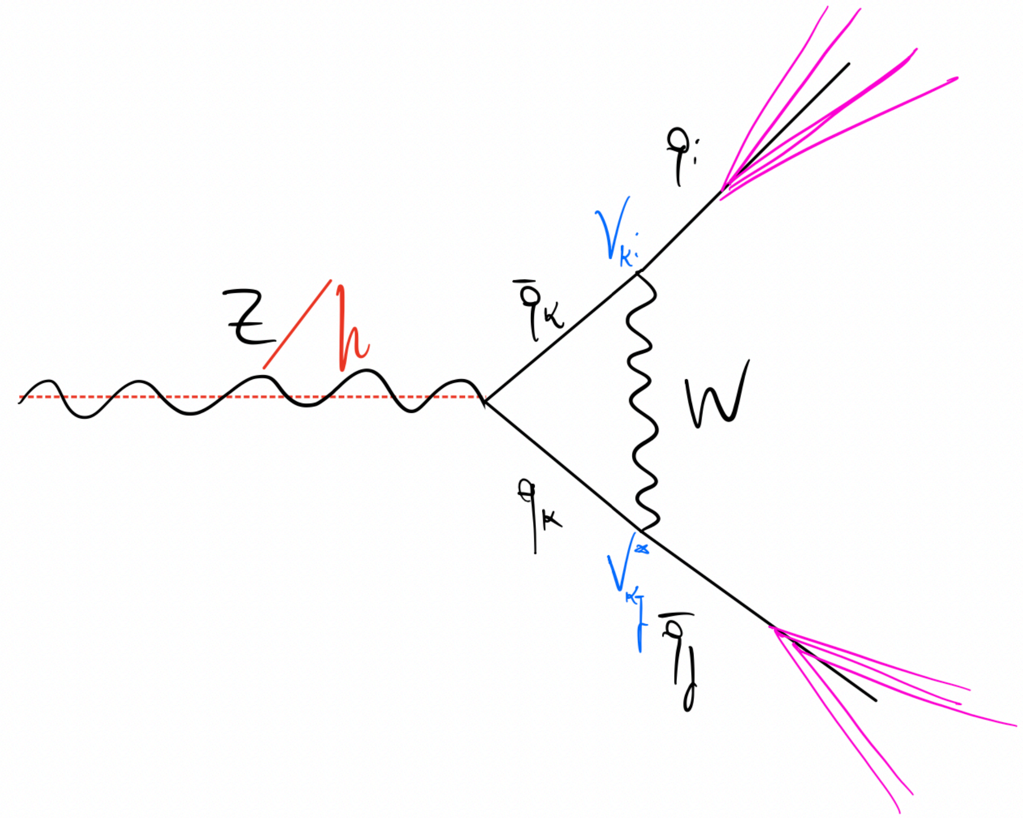
$$\text{Zh thr.} \to N_h \sim 6 \times 10^{5}$$

$$\text{WW thr.} \to N_W \sim 2 \times 10^{8}$$

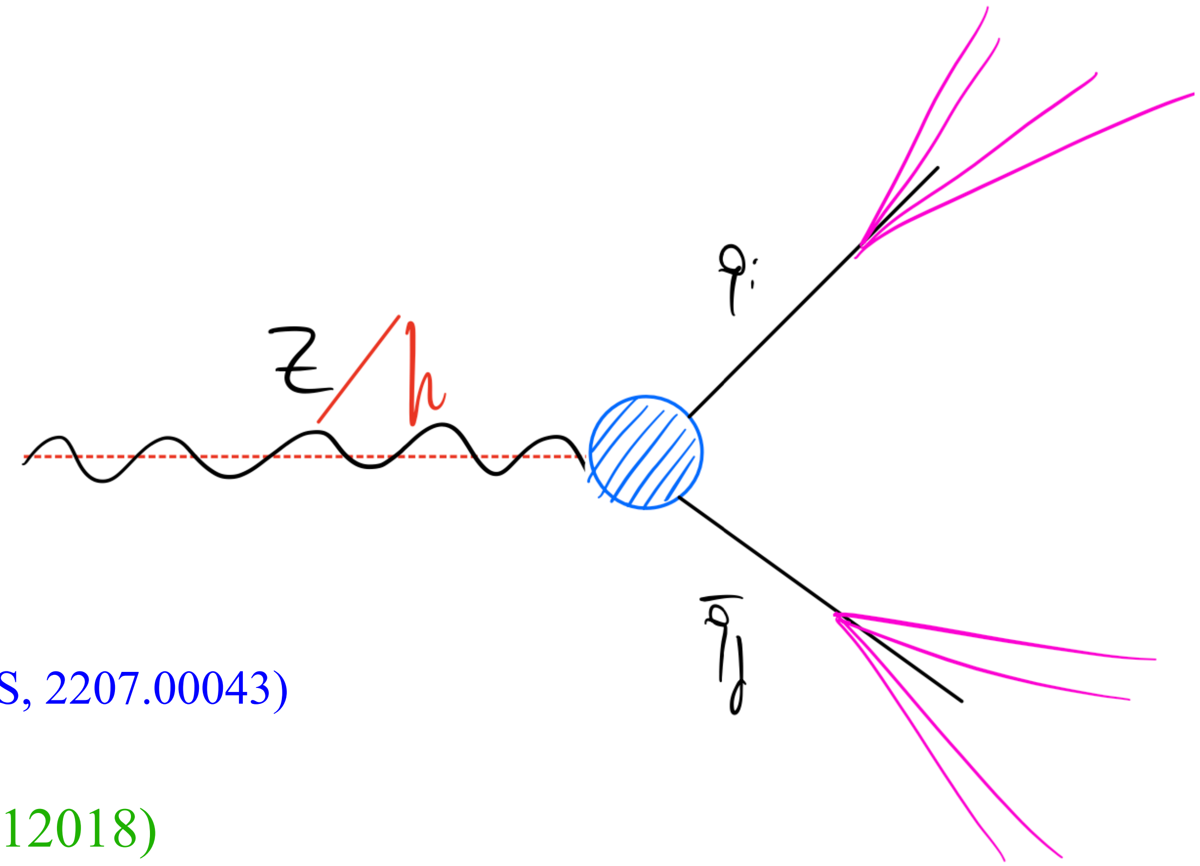
$$\text{t}\bar{\text{t}} \text{ thr.} \to N_t \sim 10^{6}$$

- Goal: assess the potential of e^+e^- colliders to explore FC decays

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



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} ●



▲ $h \to \text{BSM}$ (CMS+ATLAS, 2207.00043)

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

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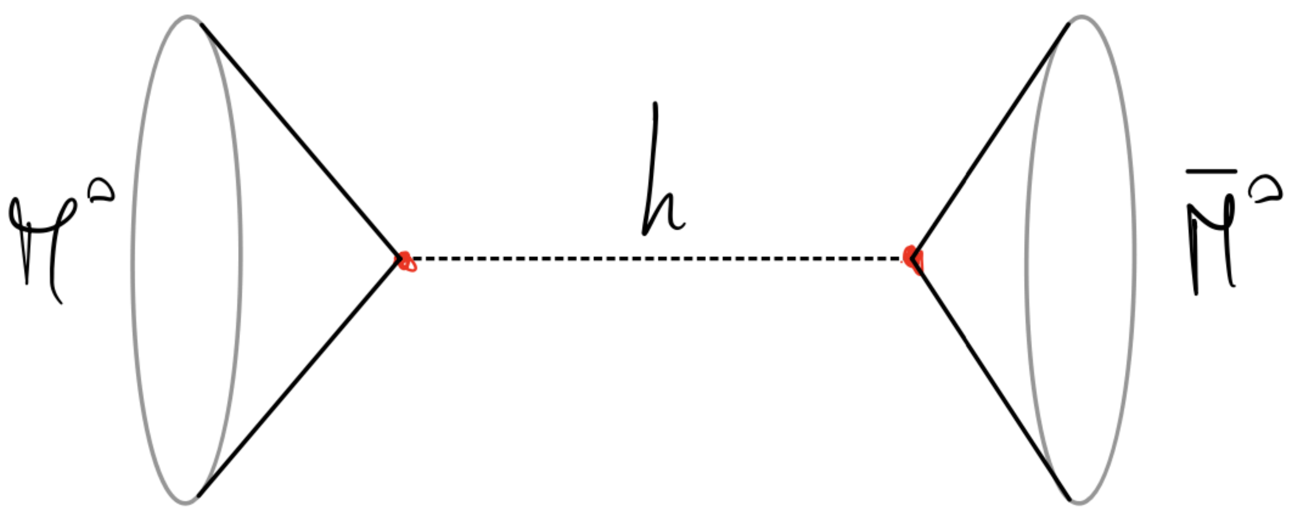

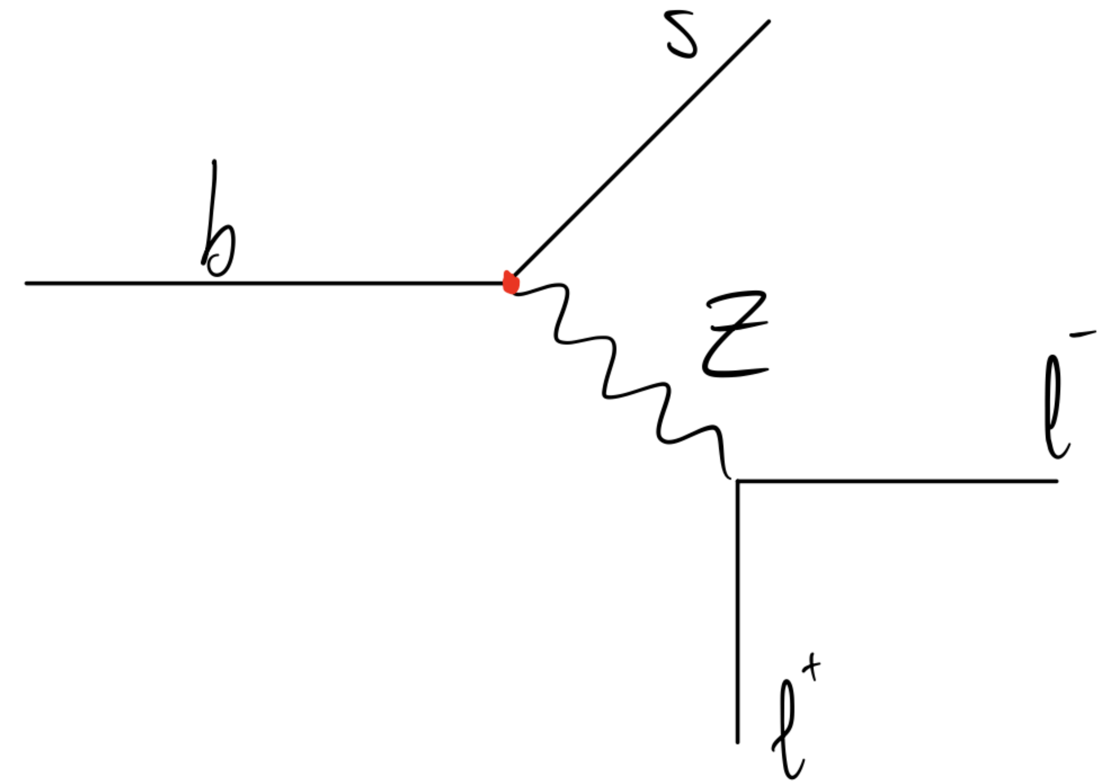

★ Meson mixings

● Global fits (mostly semi-leptonic)

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1st ingredient: controlled BG

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

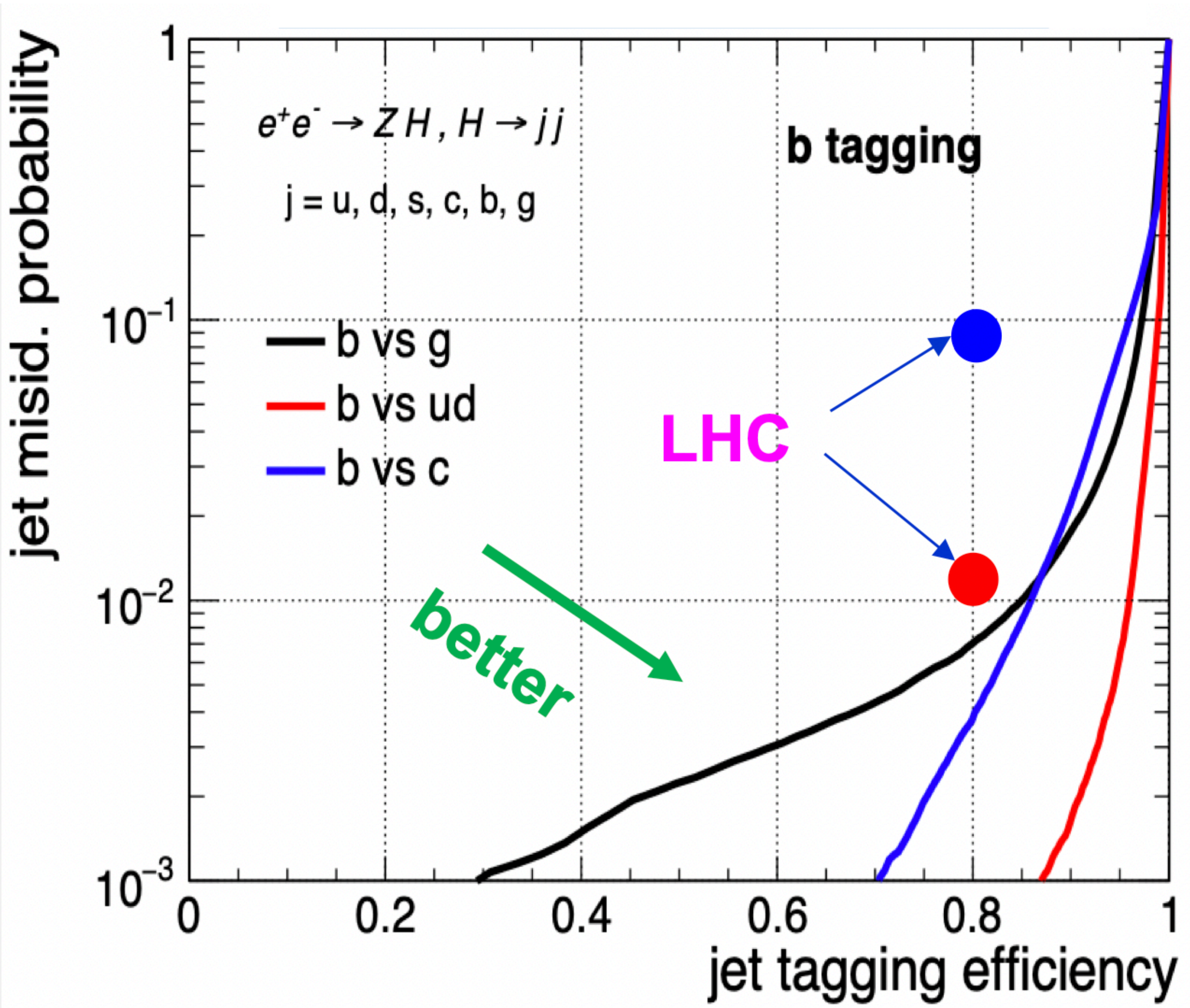
G. Marchiori's talk at "FCC Physics Workshop" (indico.cern.ch/event/1176398/)

2nd ingredient: Jet flavor taggers

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/)

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

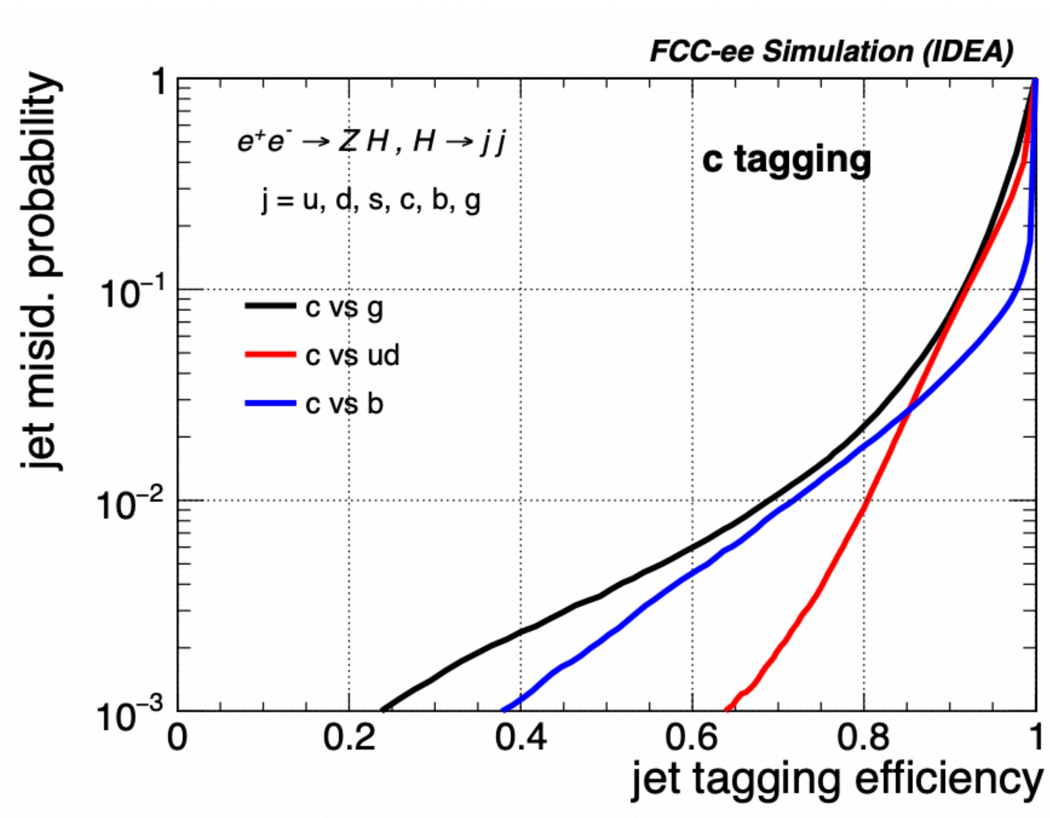
$$\epsilon^b_{\beta;\mathrm{Loose}} = \{0.02,\ 0.001,\ 0.02,\ 0.90\}$$

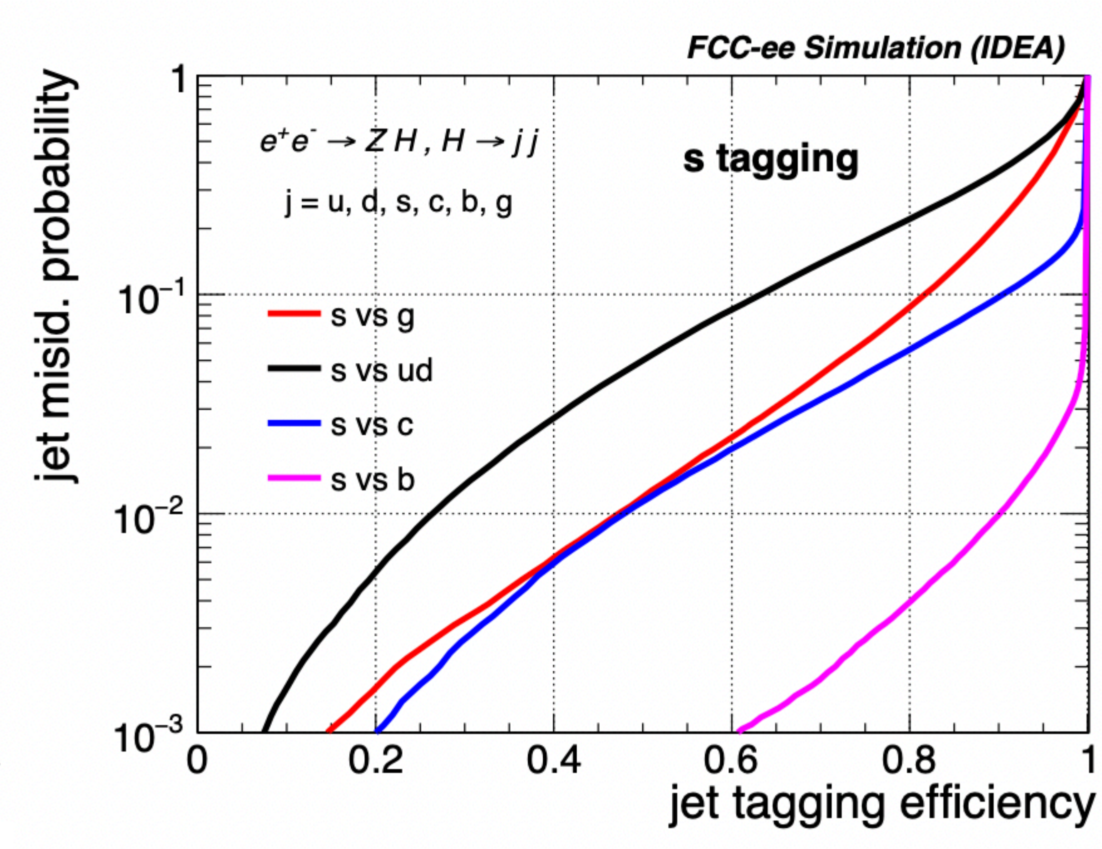
$$\epsilon^b_{\beta;\mathrm{Med}} = \{0.007,\ 0.0001,\ 0.003,\ 0.80\}$$

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

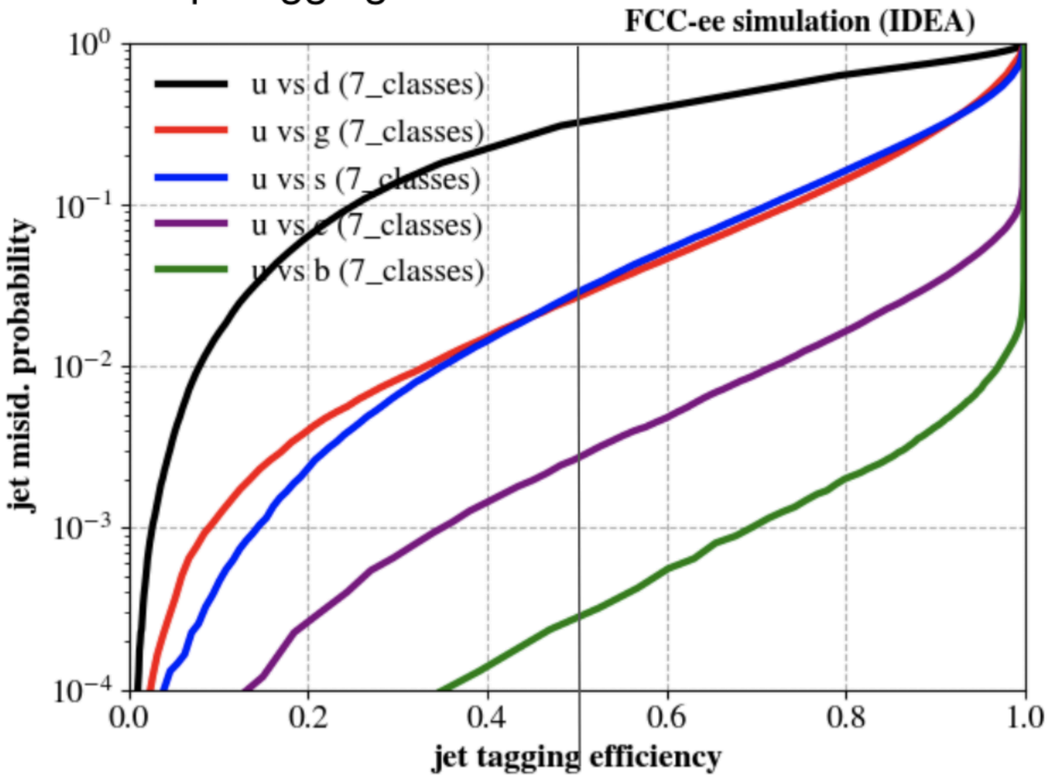
ATLAS: 1907.05120
CMS: 1712.07158

2nd ingredient: Jet flavor taggers

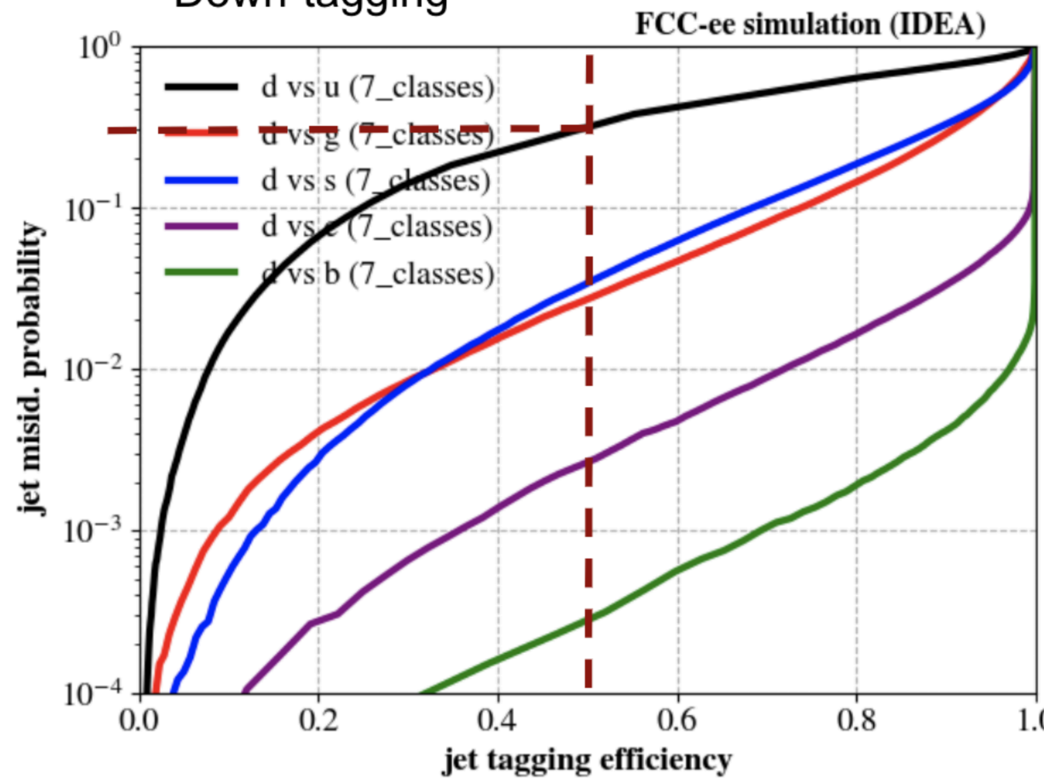




Up -tagging

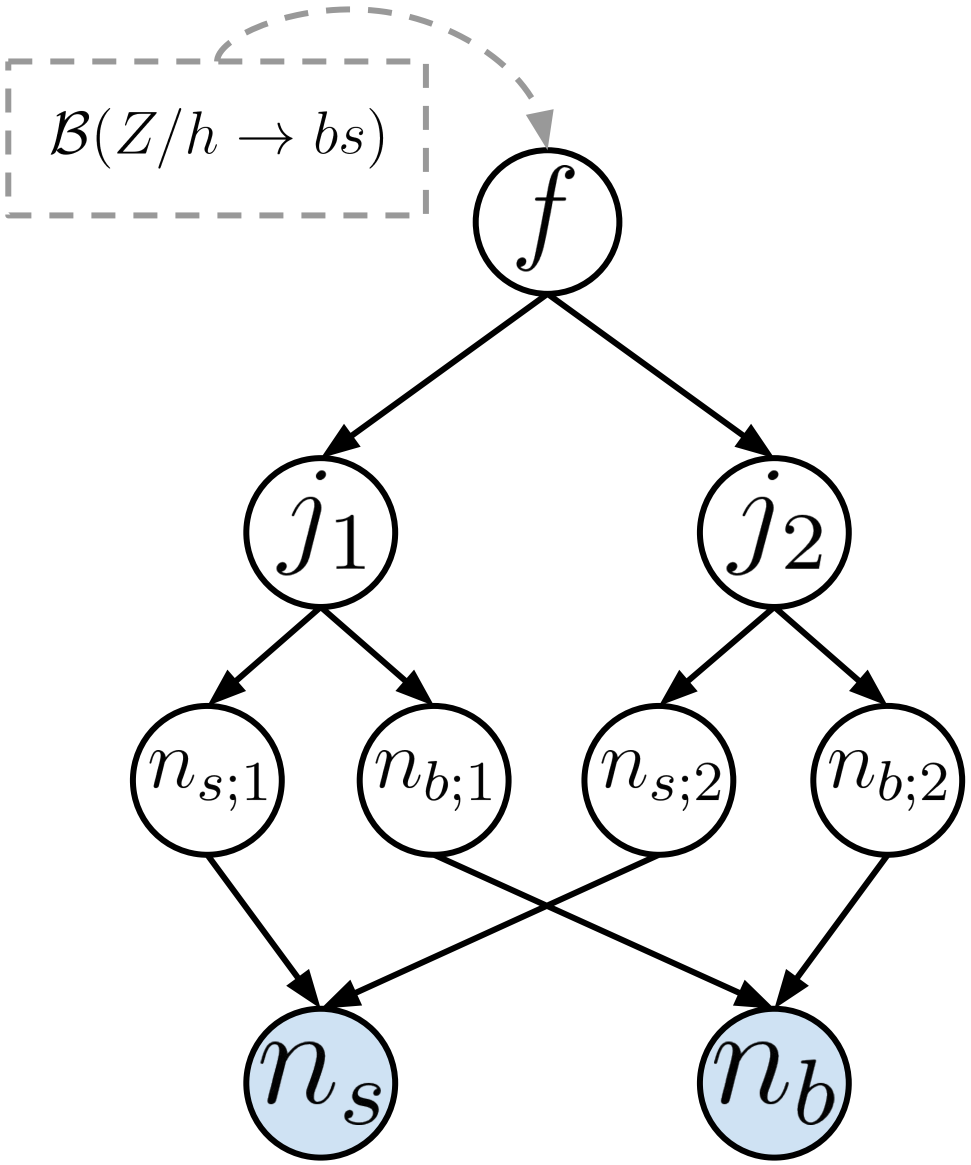


Down-tagging



Selvaggi's talk at "FCC Phenomenology Workshop" (https://indico.cern.ch/event/1278845/)

3rd ingredient: Probabilistic model



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

Distribute events into tag bins

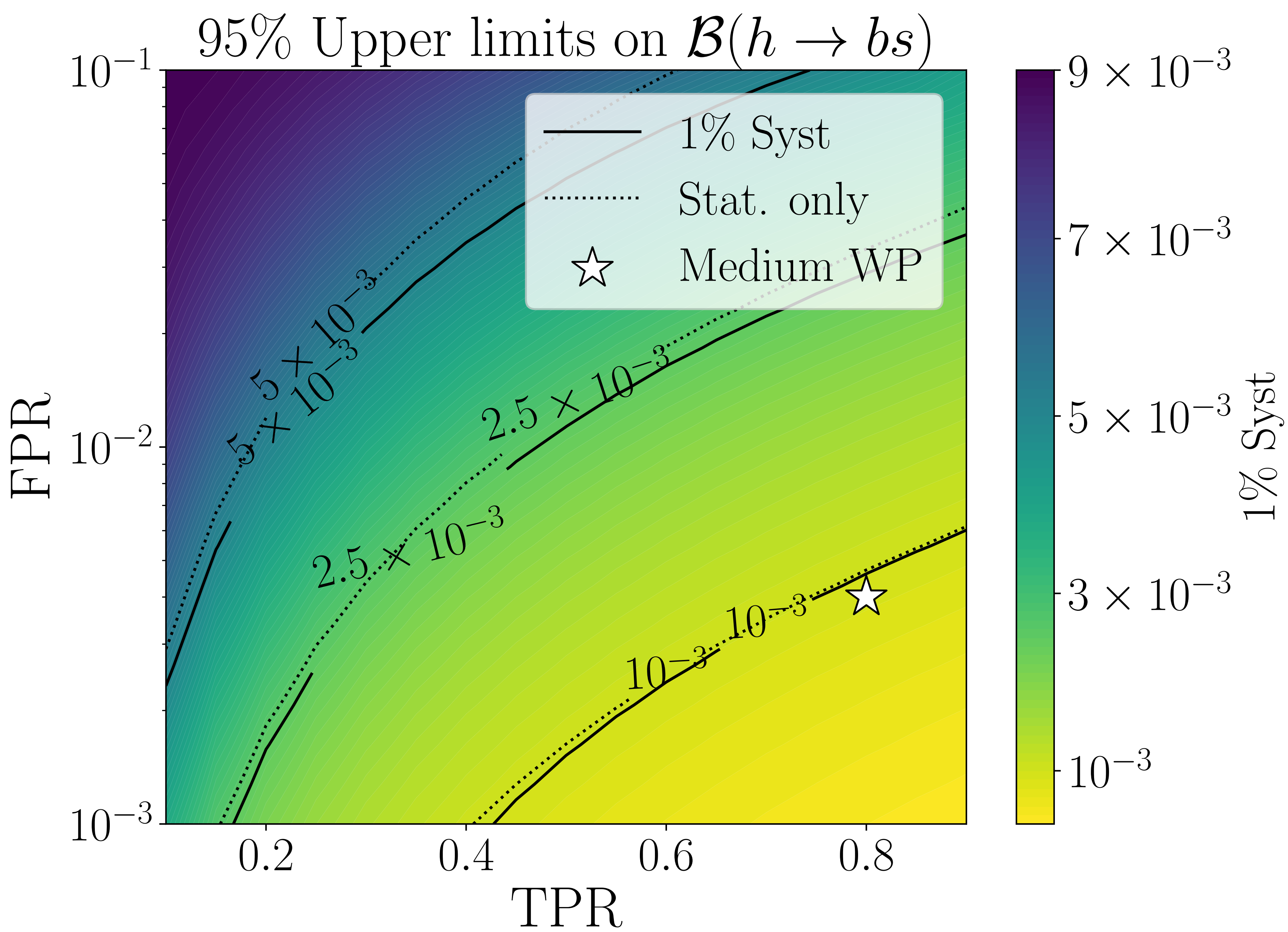
$$(n_b, n_s) = \{(0,0), (0,1), (1,0), (2,0), (0,2), (1,1)\}$$

Expected number of events per channel

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

Expected number of events per tag bin

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



Take common TPR and FPR (for plots)

Medium WP

(TPR, FPR) = (0.8, 0.004)

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

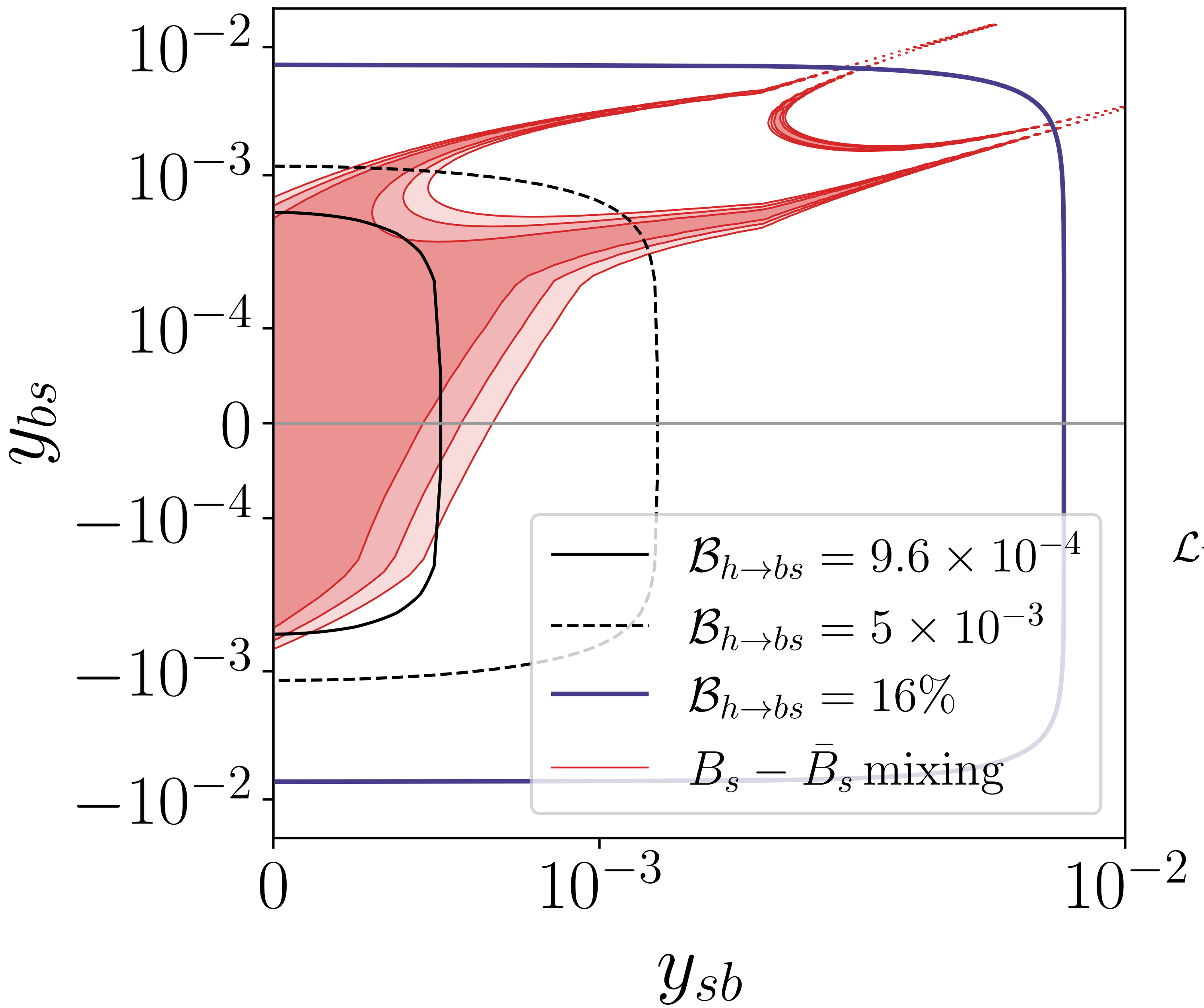
FCC-ee reach

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

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**

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

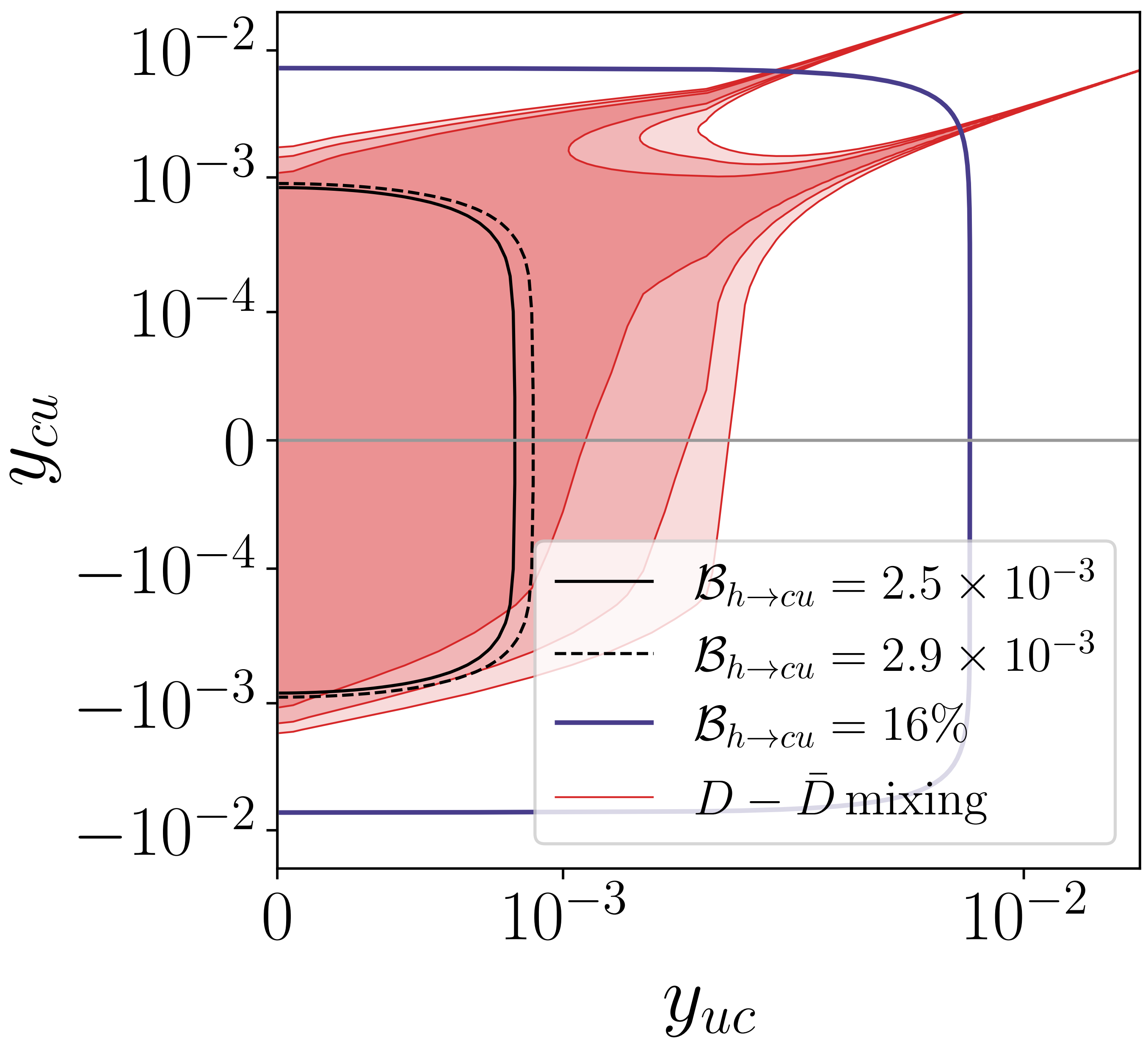
FCC-ee reach

Indirect constraints

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

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

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



Indirect constraints

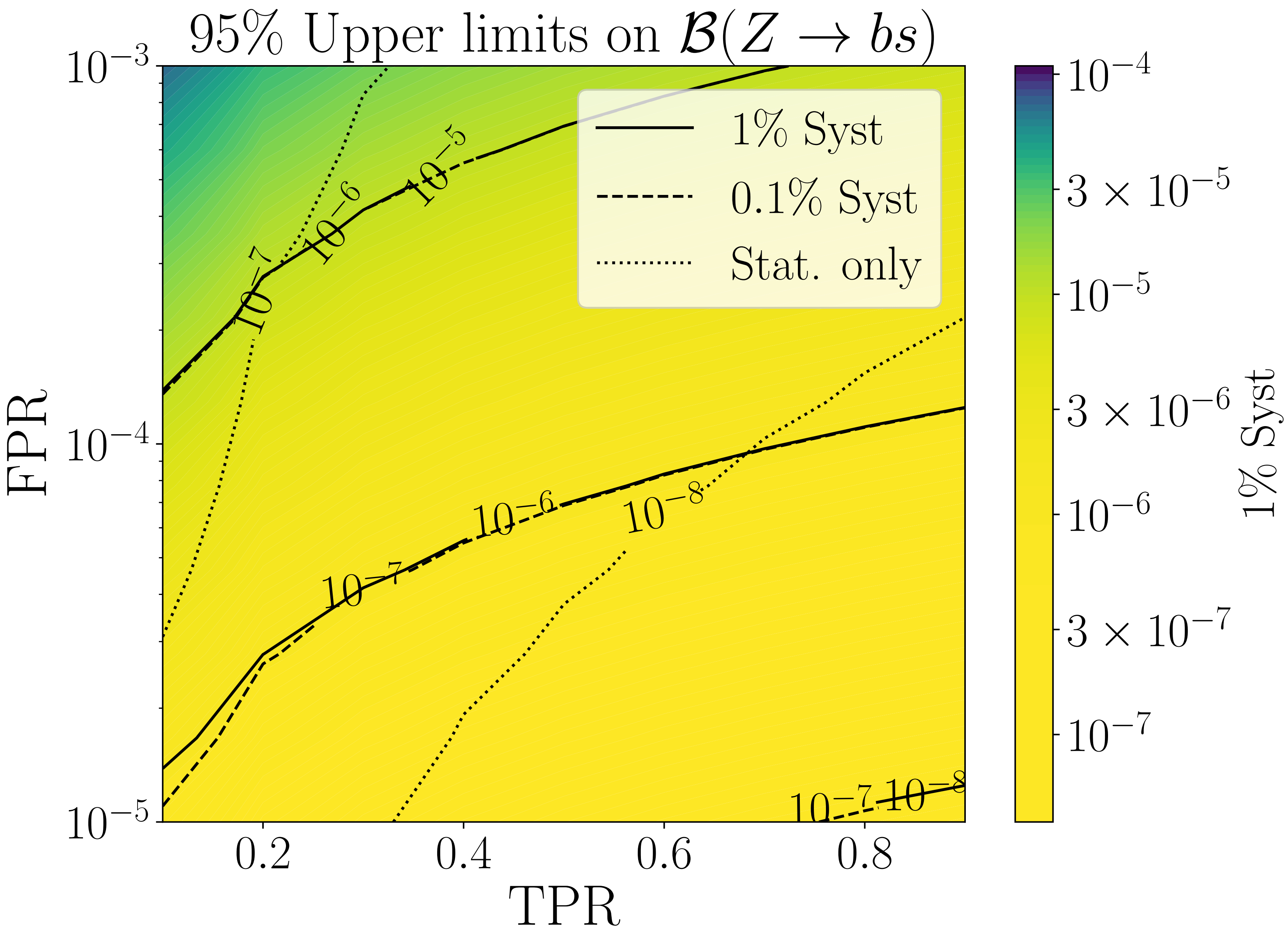
$$\mathcal{B}(h \to cu) \lesssim 2 \times 10^{-2}$$

FCC-ee reach (no u-tagger)

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

FCC-ee reach (with u-tagger)

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



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

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

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

3-5μm estimated

Barchetta, Collins, Riedler: 2112.13019

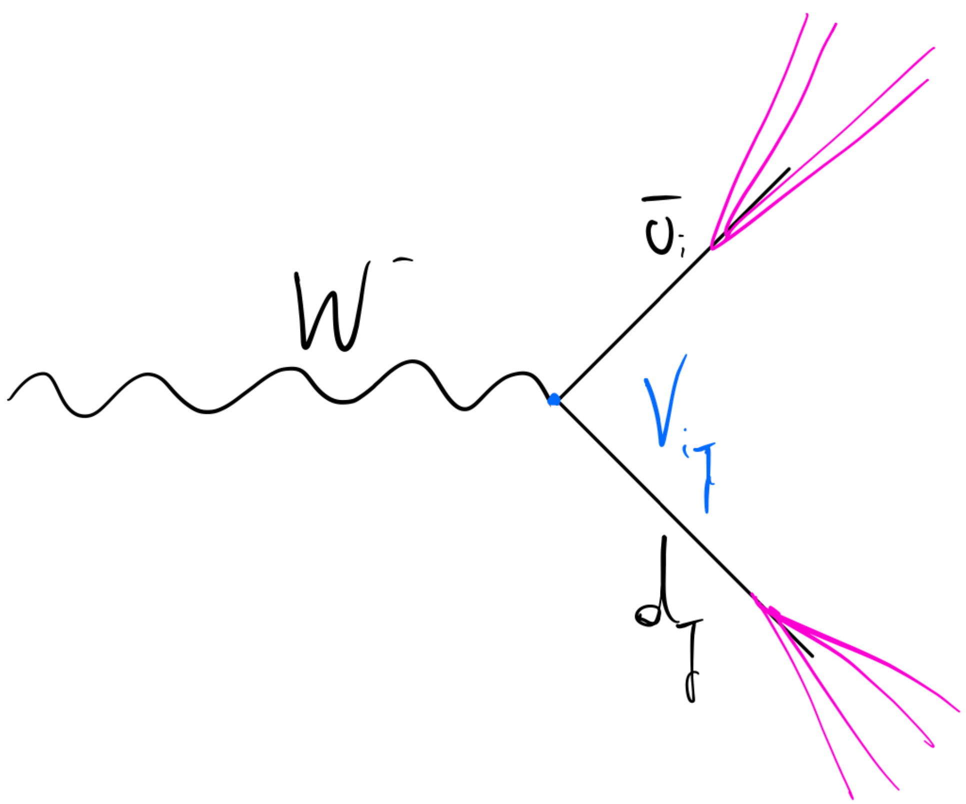
$(\mathrm{TPR}, \mathrm{FPR}, \Delta\epsilon_\beta^\alpha/\epsilon_\beta^\alpha)$	$\mathcal{B}(Z \to bs)$ (95% CL)
$(0.4,\ 10^{-4},\ 1\%)$	1.8×10^{-6}
$(0.4,\ 10^{-4},\ 0.1\%)$	1.8×10^{-7}
$(0.2,\ 10^{-5},\ 1\%)$	4.2×10^{-7}
$(0.2,\ 10^{-5},\ 0.1\%)$	4.2×10^{-8}

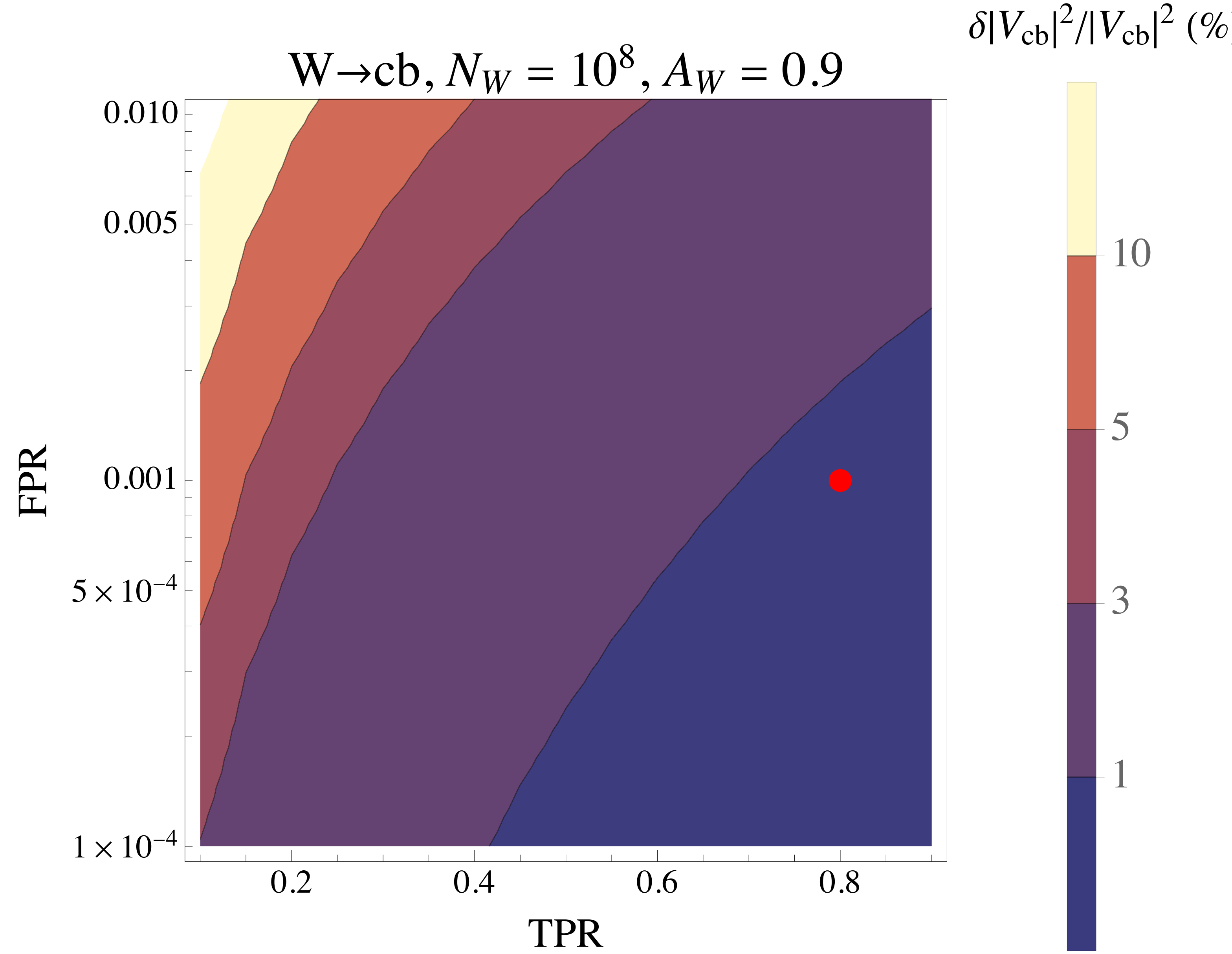
← SM level

Is 0.1% feasible?

See Selvaggi's talk at 7th FCC Workshop (https://indico.cern.ch/event/1307378/)

WiP: Measuring the CKM





$$\begin{pmatrix} |V_{ud}| \\ |V_{us}| \\ |V_{cd}| \\ |V_{cs}| \\ |V_{cb}| \\ |V_{ub}| \end{pmatrix}, =, \begin{pmatrix} 0.97373 \\ 0.22430 \\ 0.22100 \\ 0.97500 \\ 0.040800 \\ 0.0038200 \end{pmatrix}, \pm, \begin{pmatrix} 0.000193 \\ 0.000564 \\ 0.000401 \\ 0.000109 \\ 0.000180 \\ 0.00386 \end{pmatrix}, \text{Rel}_{\%}=, \begin{pmatrix} 0.020 \\ 0.25 \\ 0.18 \\ 0.011 \\ 0.44 \\ 1.0\times10^{2} \end{pmatrix}, \rho =, \begin{pmatrix} 1.000 & -0.657 & -0.117 & 0.031 & 0.004 & -0.056 \\ -0.657 & 1.000 & 0.043 & -0.093 & 0.003 & 0.015 \\ -0.117 & 0.043 & 1.000 & -0.439 & -0.024 & -0.072 \\ 0.031 & -0.093 & -0.439 & 1.000 & -0.049 & -0.001 \\ 0.004 & 0.003 & -0.024 & -0.049 & 1.000 & -0.090 \\ -0.056 & 0.015 & -0.072 & -0.001 & -0.090 & 1.000 \end{pmatrix}$$

Thanks to D. Marzocca

- 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

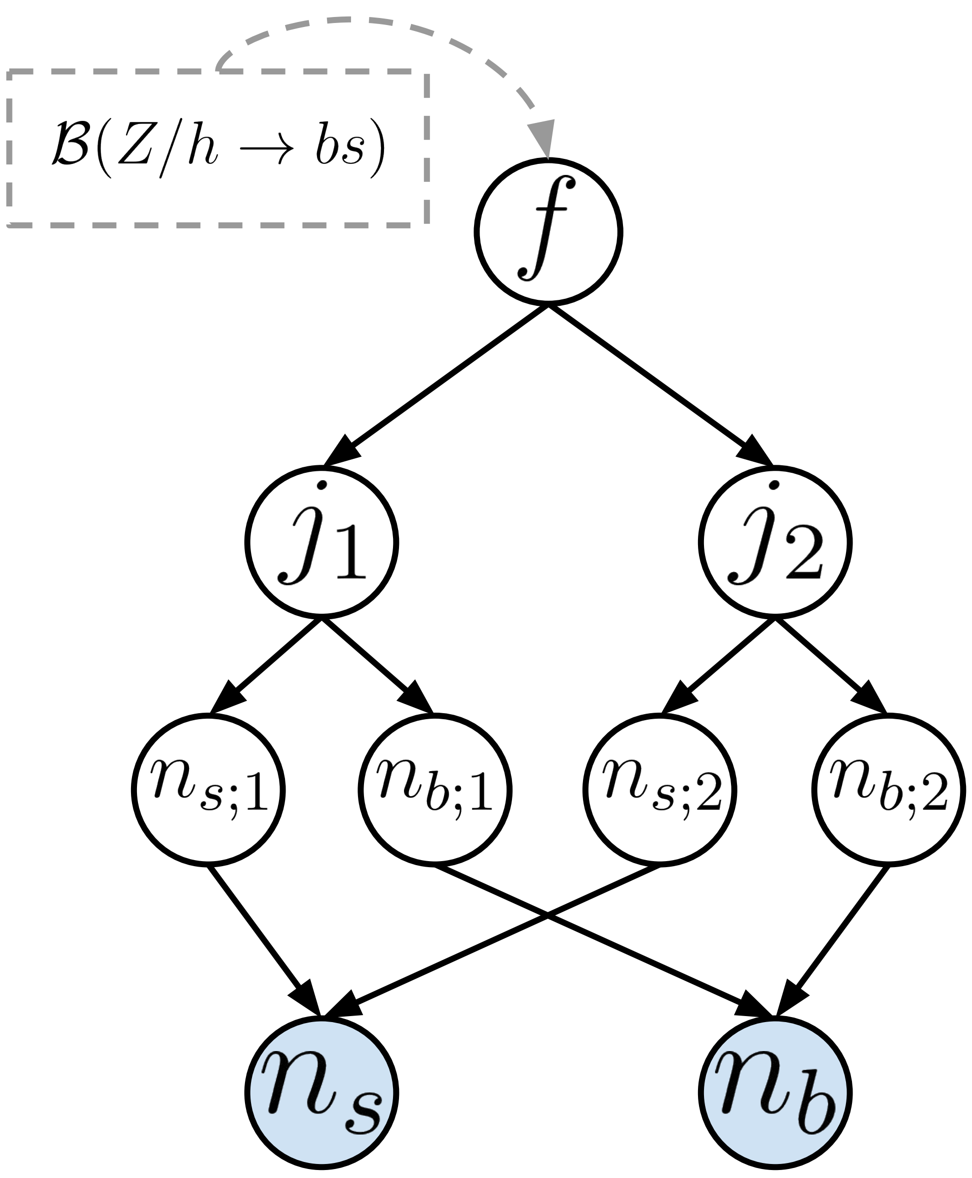
- Take home messages:
    - Upper limits at FCC-ee are above the SM level
    - Improve limits on Higgs FC couplings
    - Results depend on taggers performances

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

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

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

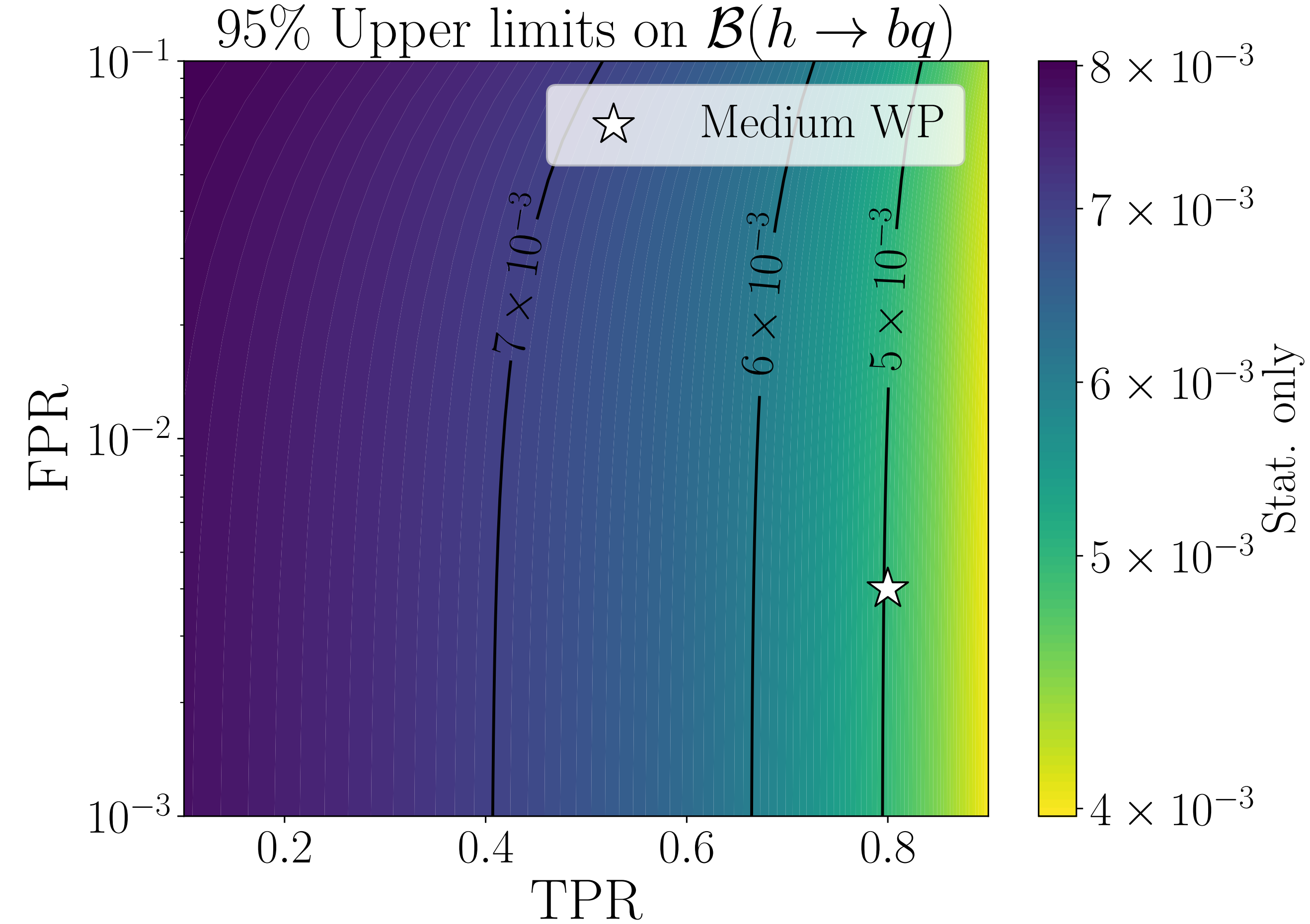
$\hat{\hat{\nu}}(\mu), \hat{\mu}, \hat{\nu}$ are maximum likelihood estimates (MLE)

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%)



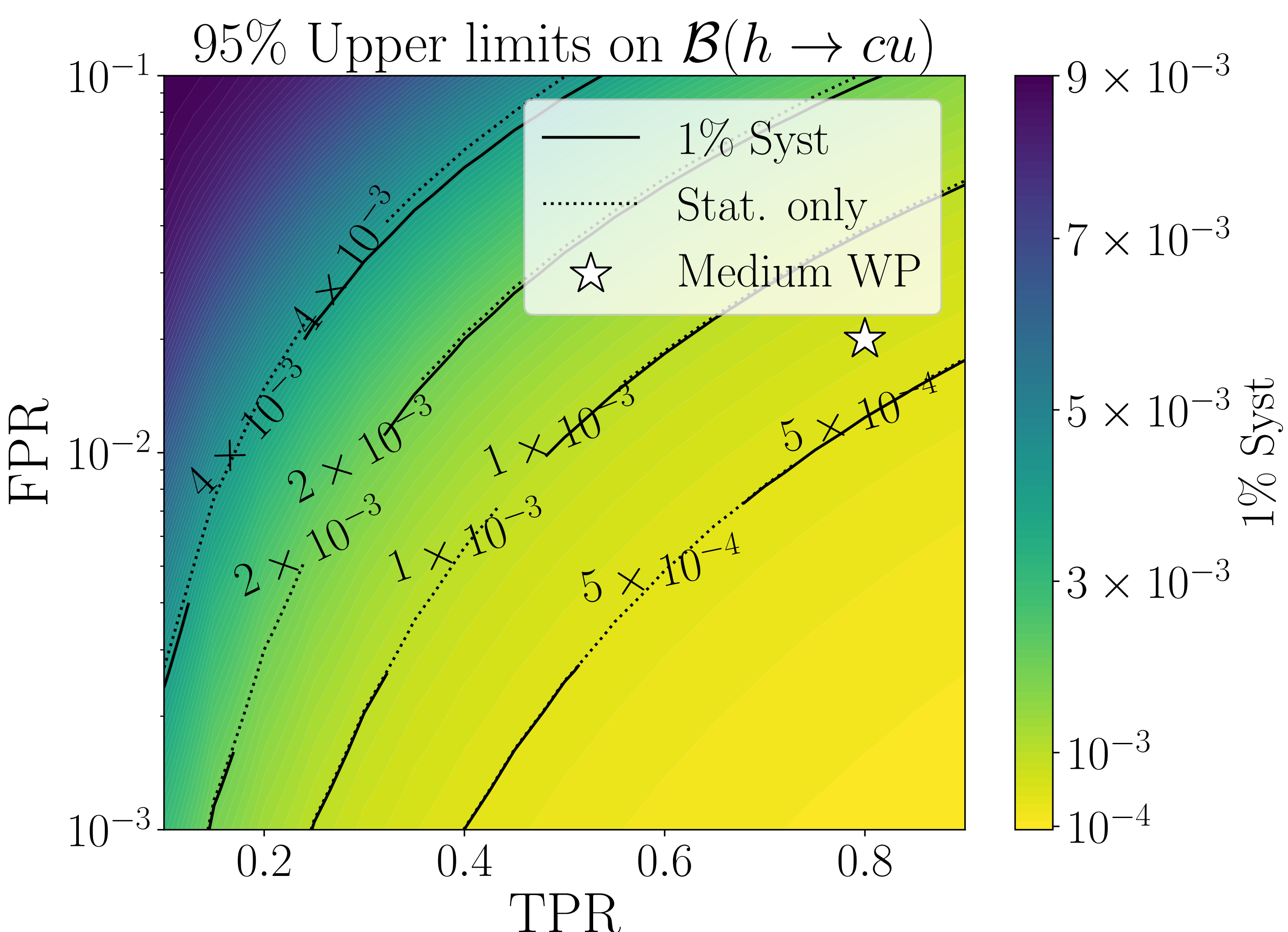
$$\mathcal{B}(h \to bq) = \mathcal{B}(h \to bs) + \mathcal{B}(h \to bd)$$

Medium WP

(TPR, FPR) = (0.8, 0.004)

FCC-ee reach (no d-tagger)

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



Medium WP

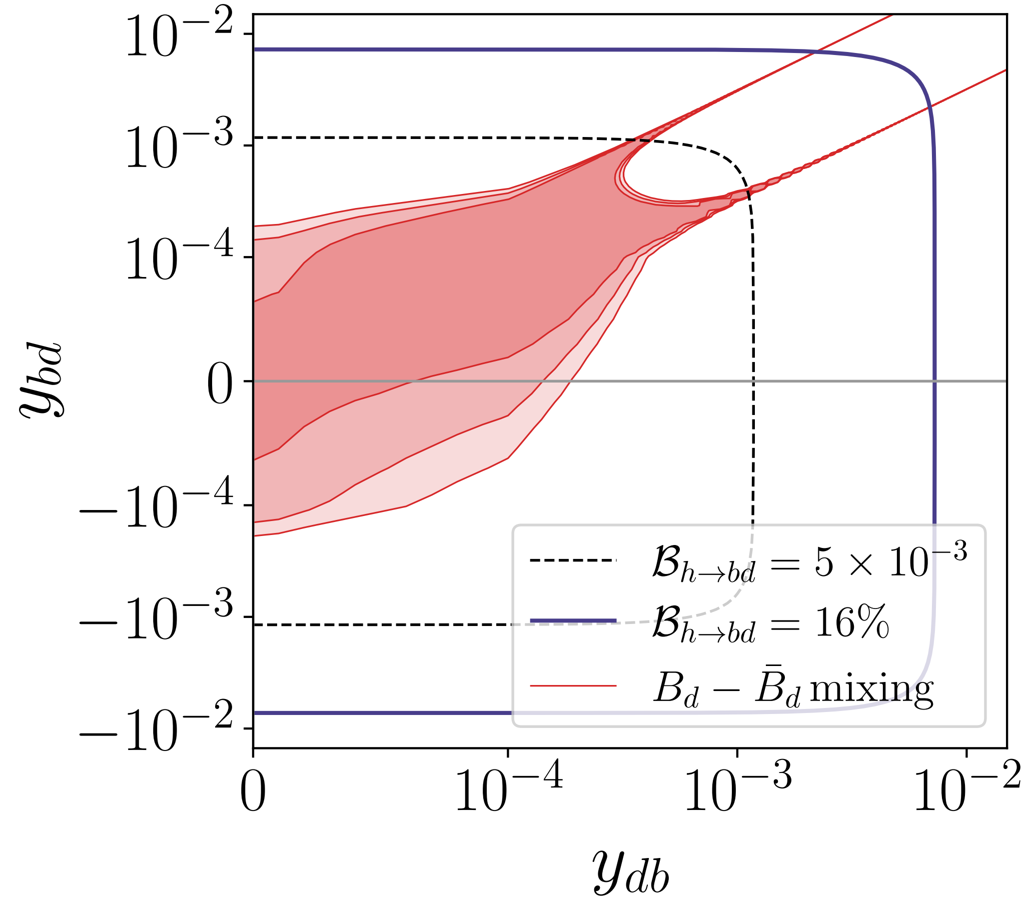
(TPR, FPR) = (0.8, 0.02)

FCC-ee reach (no u-tagger)

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

FCC-ee reach (with u-tagger)

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

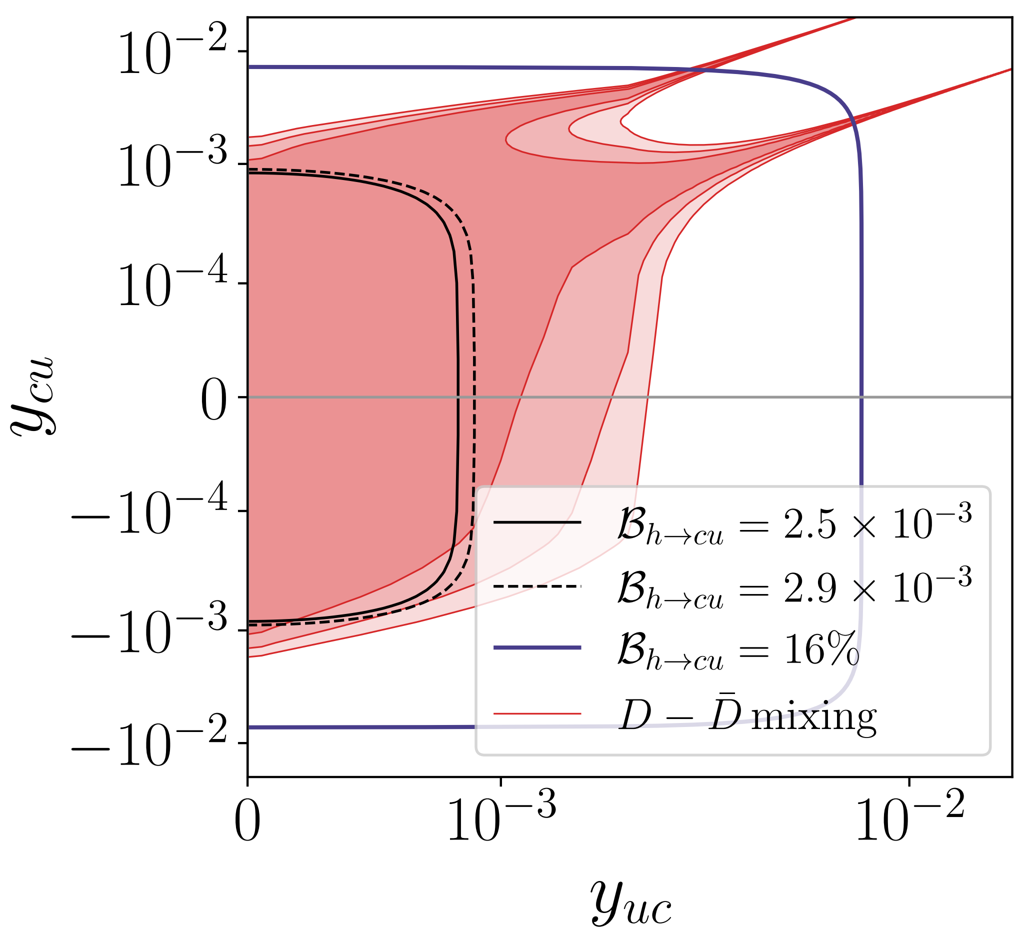


Indirect constraints

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

FCC-ee reach

$$\mathcal{B}(h \to bq) \lesssim 5\times10^{-3}$$



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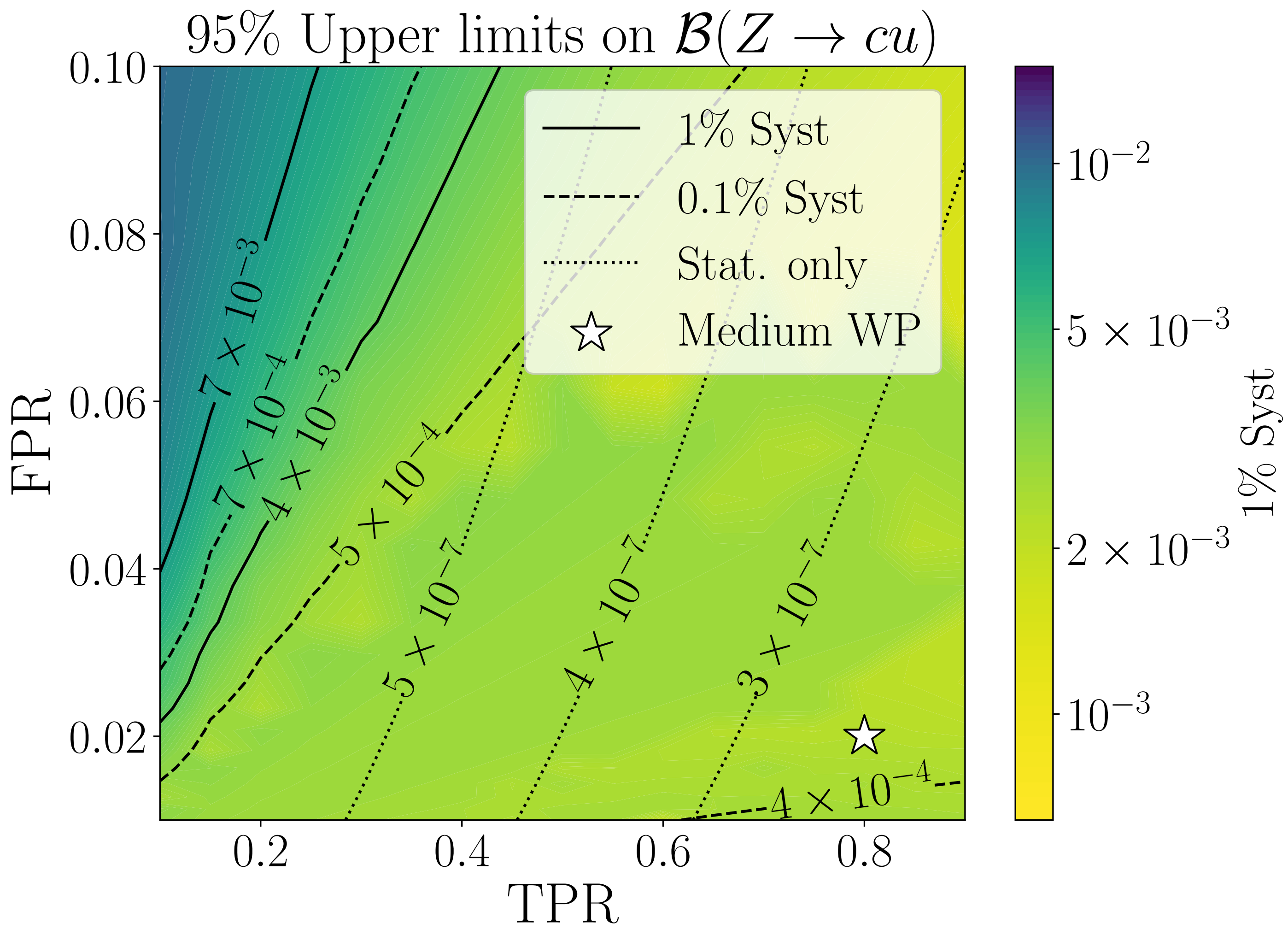
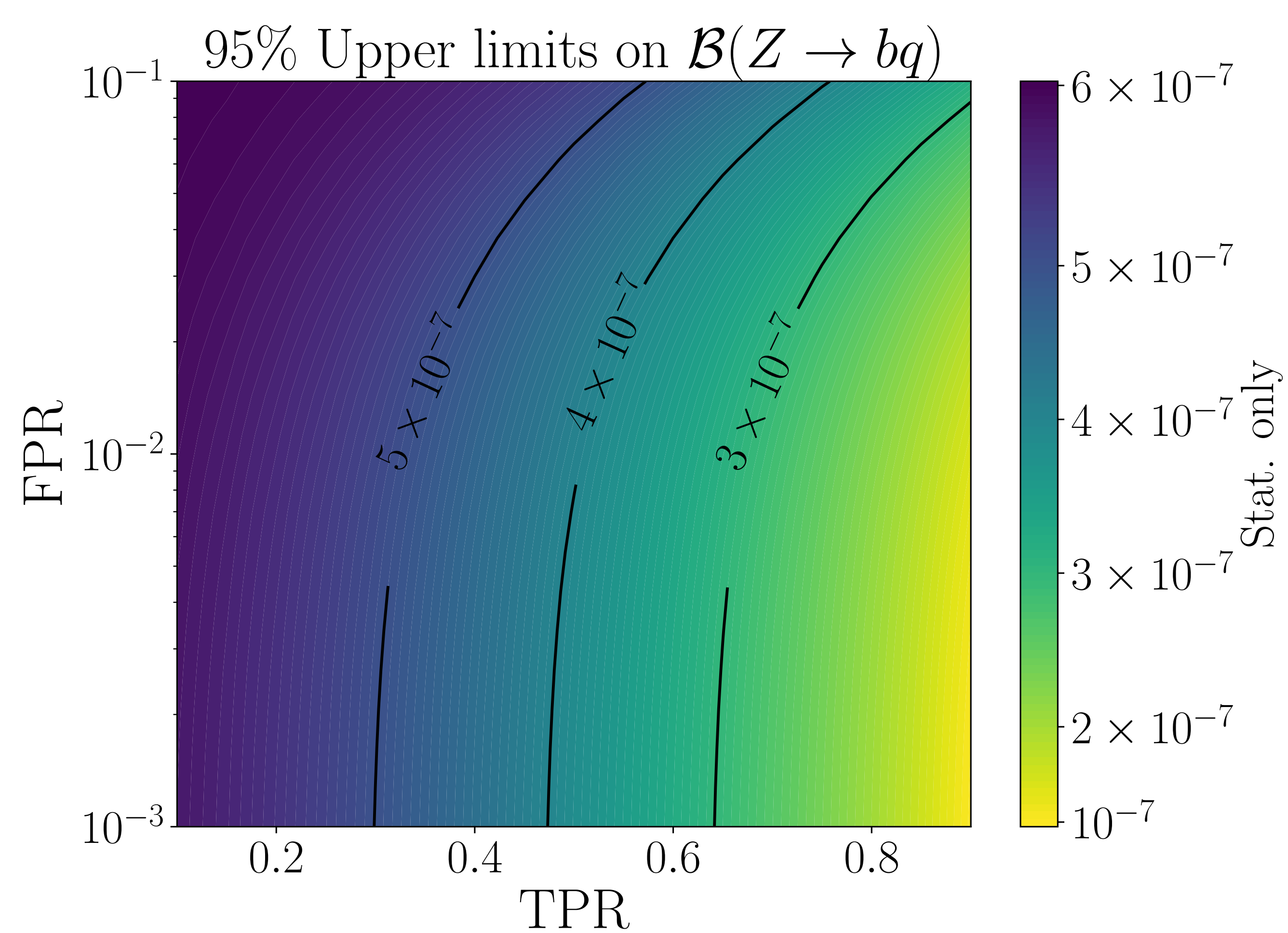


Similar backgrounds and tagger performances



New Physics fits (Z)

$\Delta B = \Delta S = 1$

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

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

$\Delta F = 2$

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

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

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

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

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

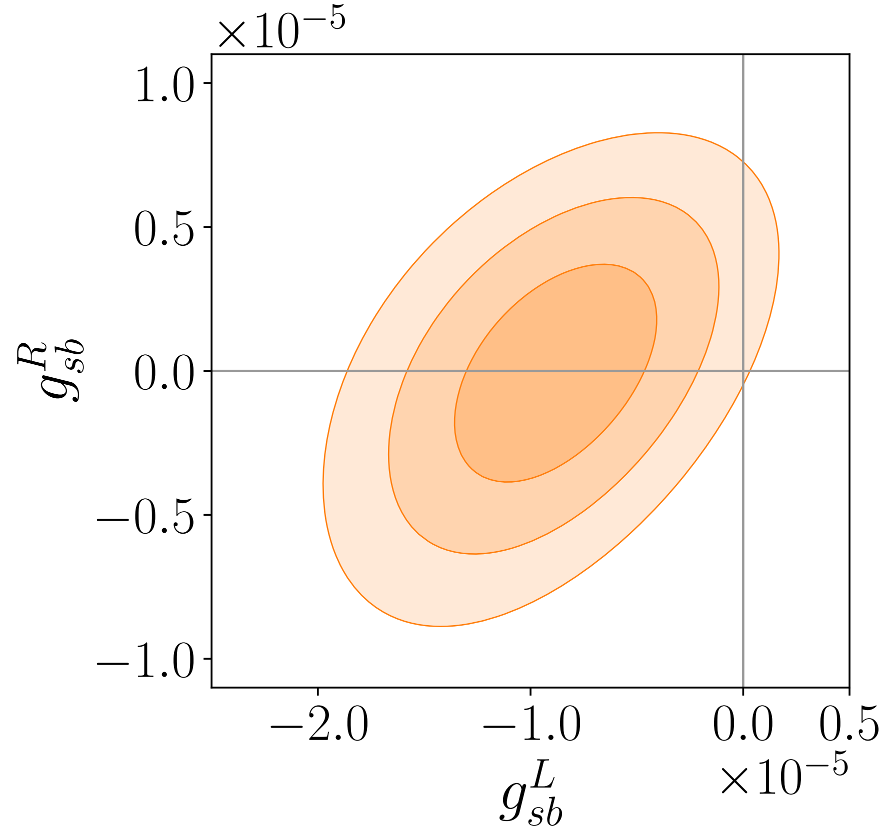
$$C_{VL} = \frac{(g_{sb}^L)^2}{2m_Z^2}$$

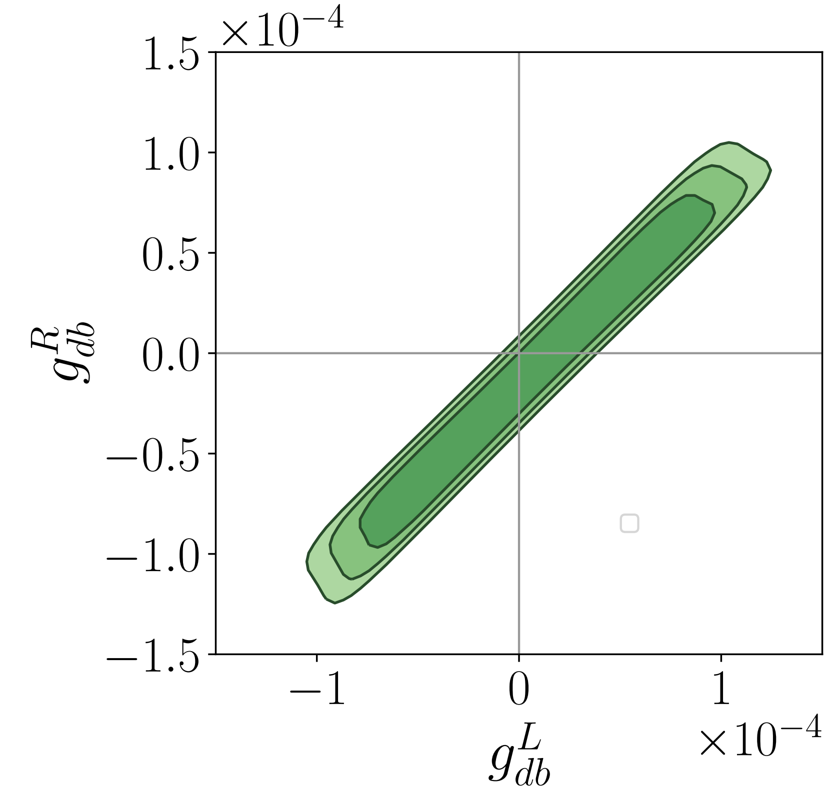
$$C_{VR} = \frac{(g_{sb}^R)^2}{2m_Z^2}$$

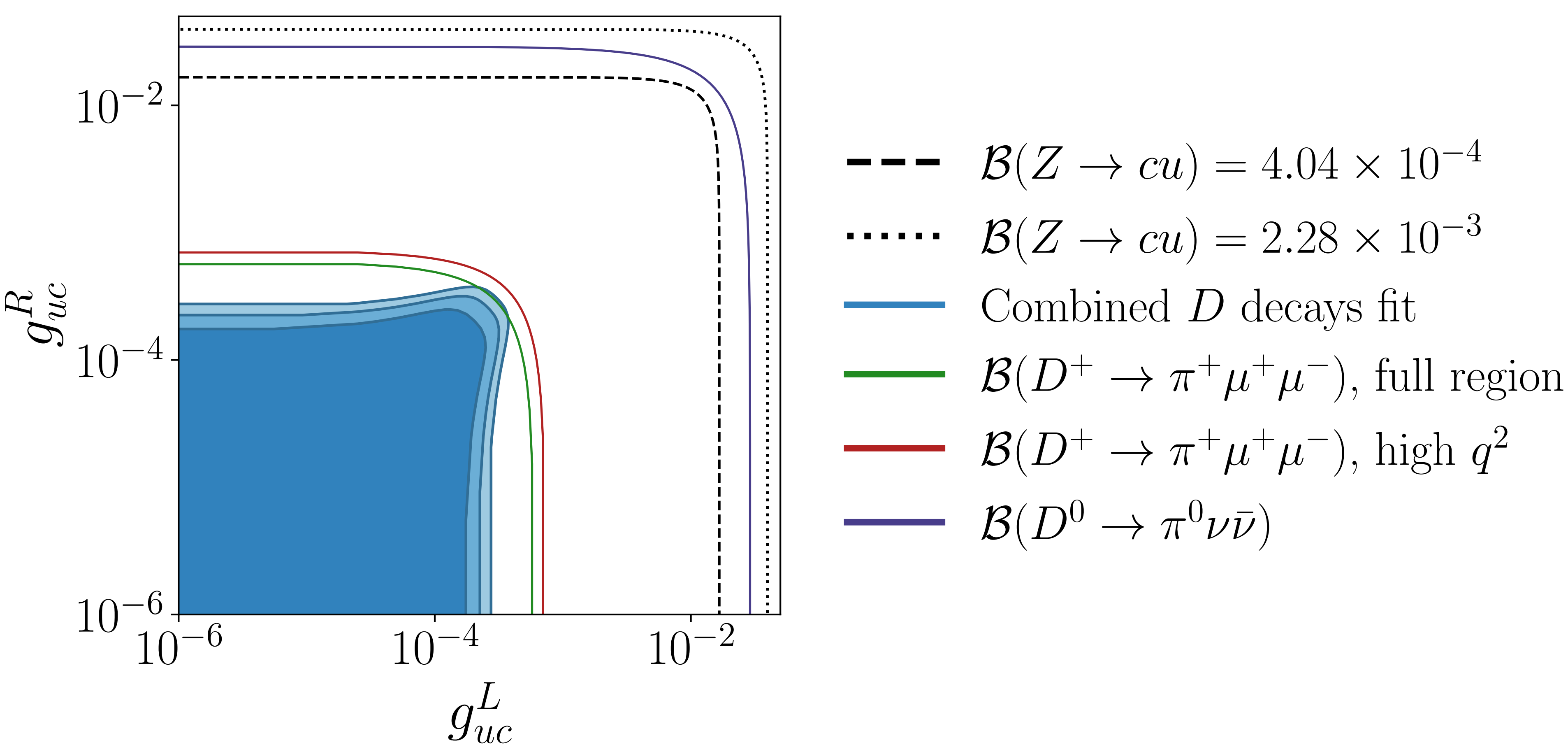
$$C_{VLR} = \frac{g_{sb}^L g_{sb}^R}{m_Z^2}$$

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

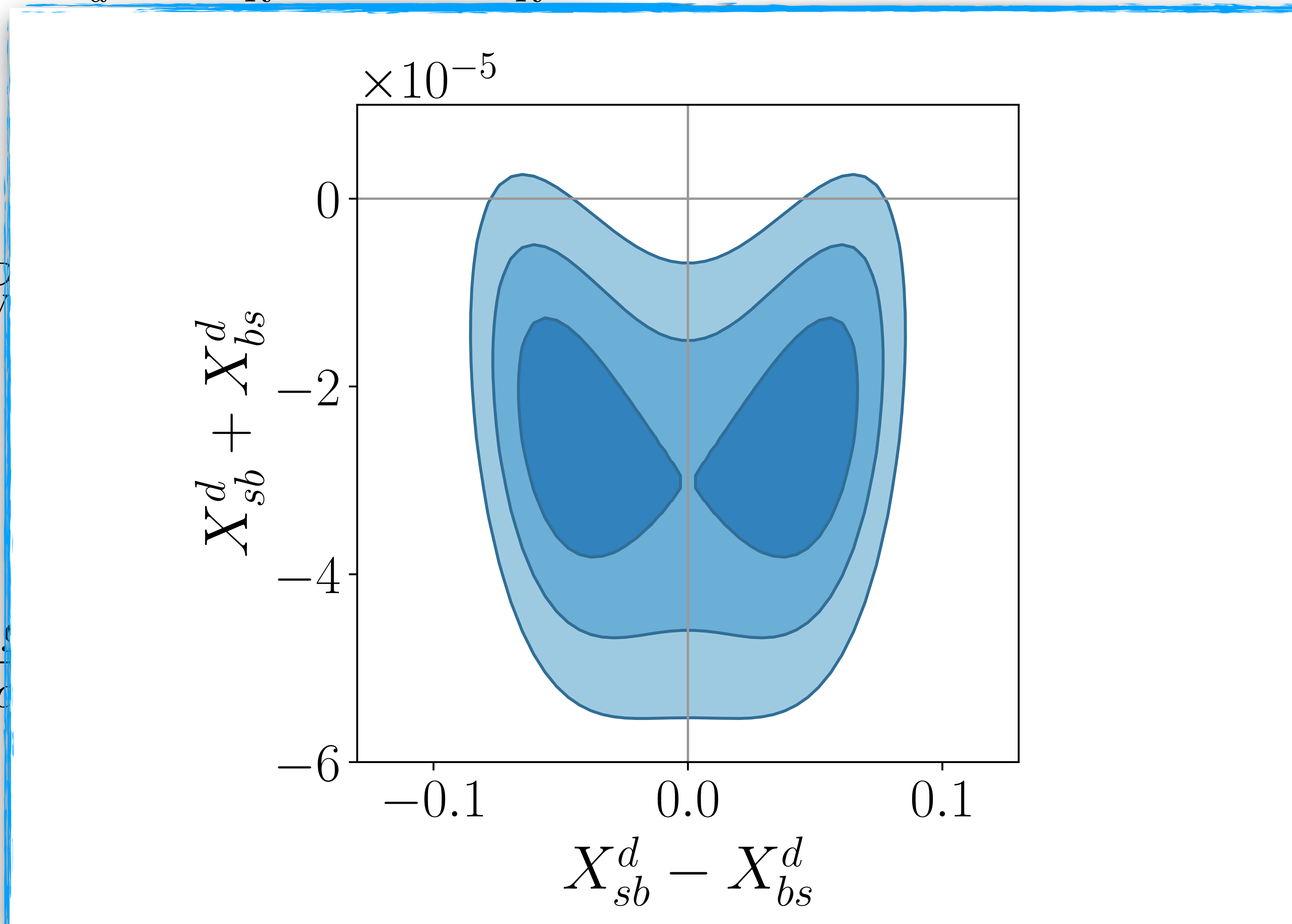
NP model: Vector-like Quarks (1)

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 $Y = 1/6$

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

↓

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

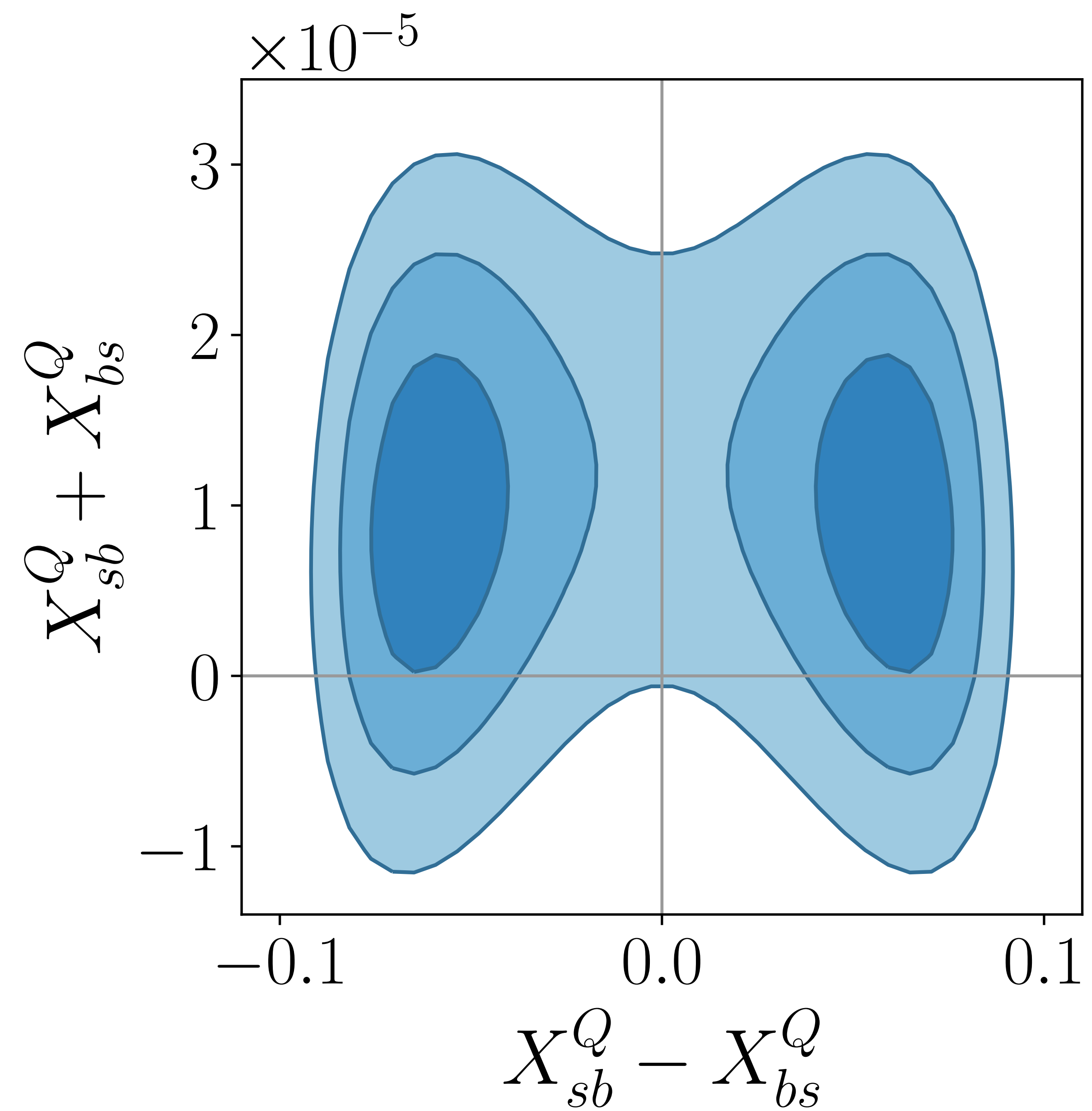
$$g_{sb}^R = \frac{g}{2c_W}(X_{sb}^Q + X_{bs}^{Q*}), \quad g_{sb}^L = 0, \quad y_{sb} = X_{sb}^Q m_b/v, \quad y_{bs} = X_{bs}^Q m_s/v$$

Both h and Z couplings generated

NP model: Vector-like Quarks (2)

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

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



g^R_{sb}

NP model: Two Higgs Doublet Model

Type III: no discrete symmetry preventing FCNCs

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

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

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

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

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

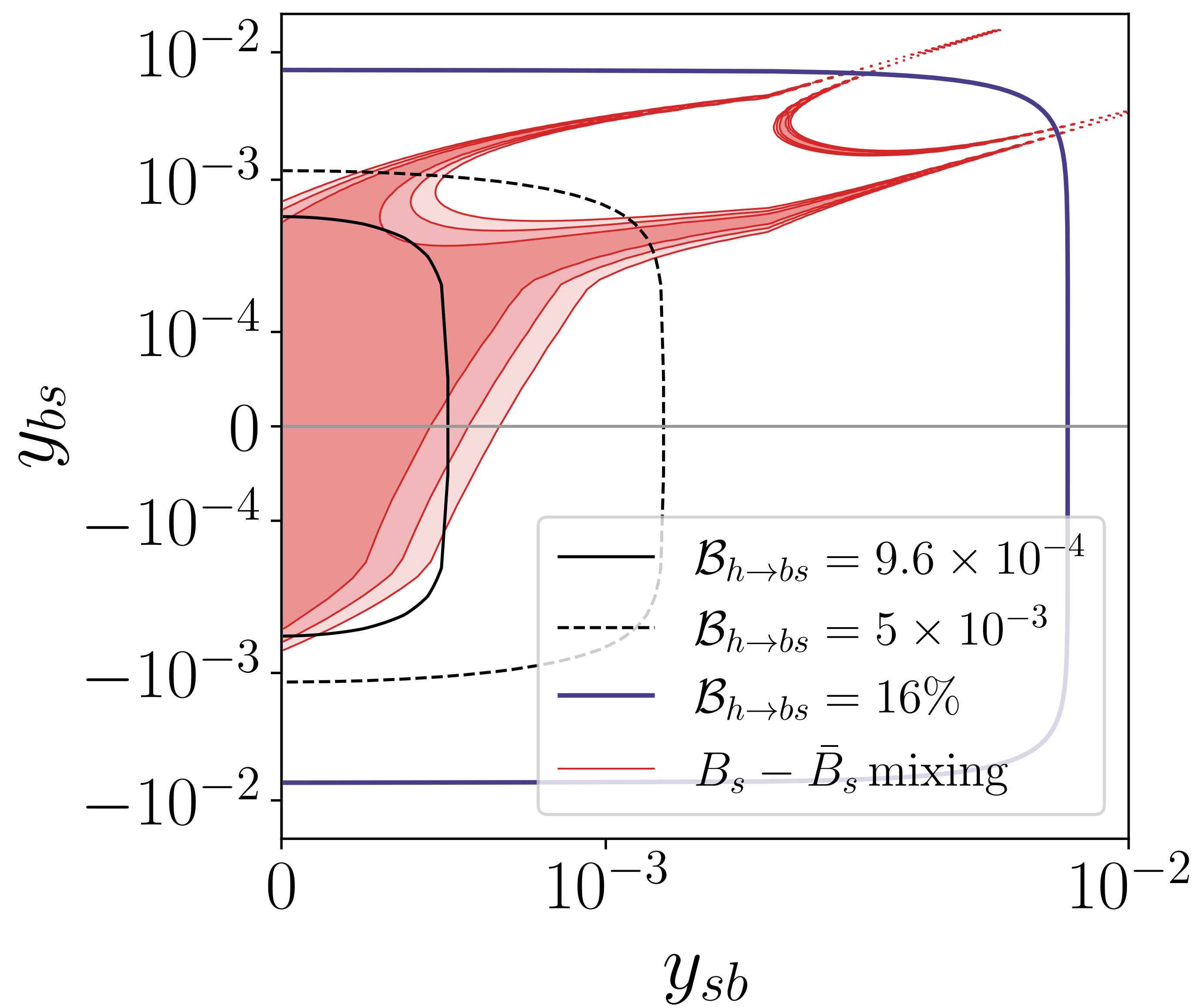
$$C_2' = -\frac{\left(Y_{sb}^{d}\right)^2}{2}\left(\frac{s_\alpha^2}{m_h^2} + \frac{c_\alpha^2}{m_H^2} - \frac{1}{m_A^2}\right),$$

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

NP model: Two Higgs Doublet Model

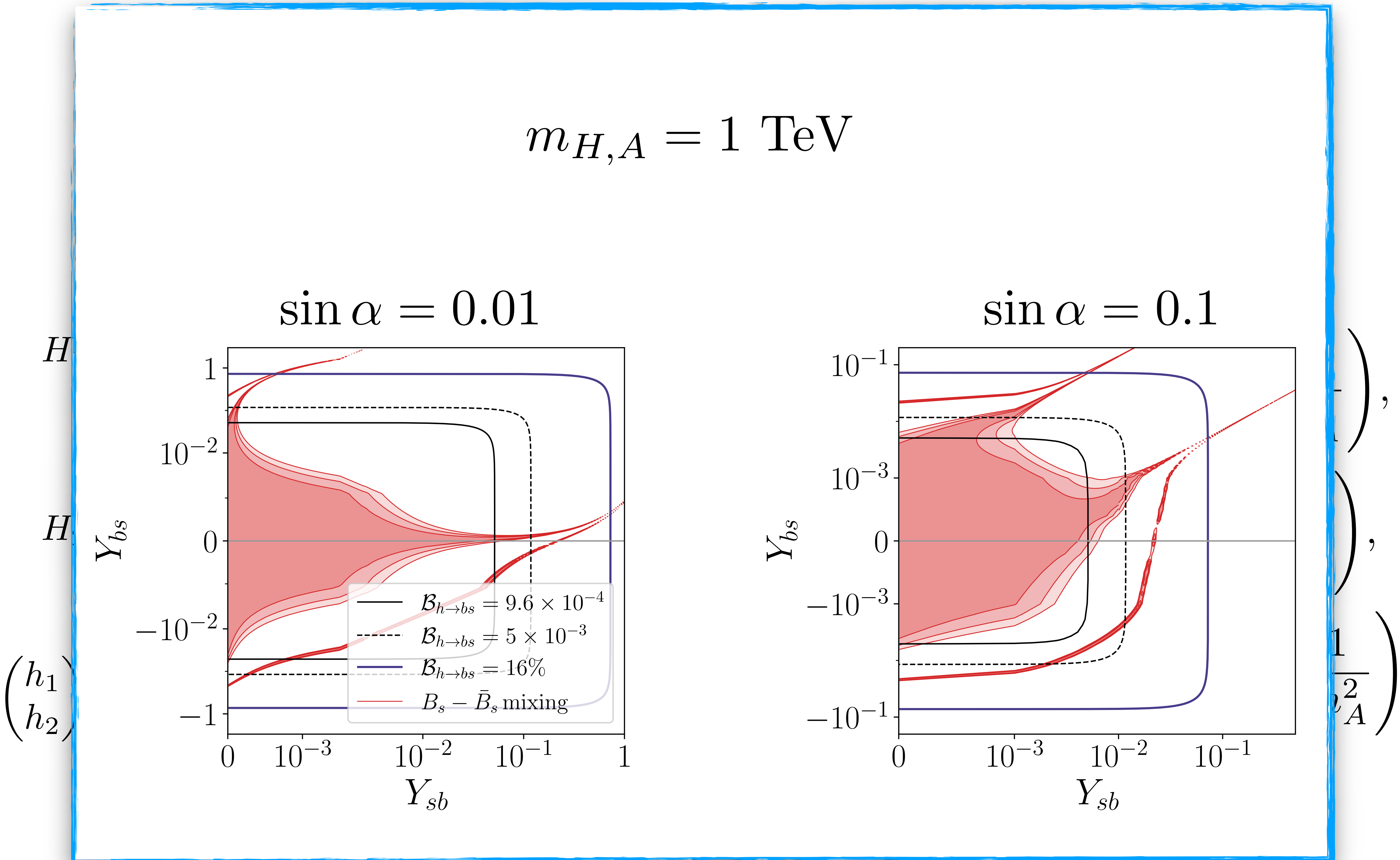
Type III: no discrete symmetry preventing FCNCs

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



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