Flavor violating Higgs and Z decays at FCC-ee

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See A. Youssef's talk

MLHAD

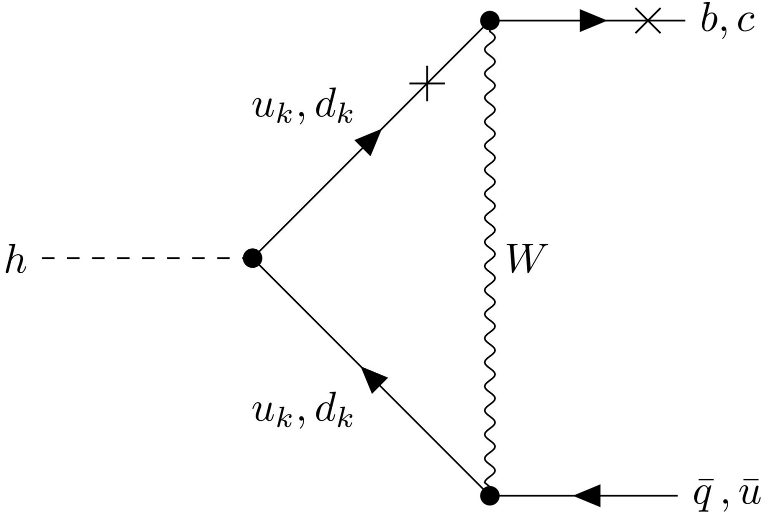
This talk

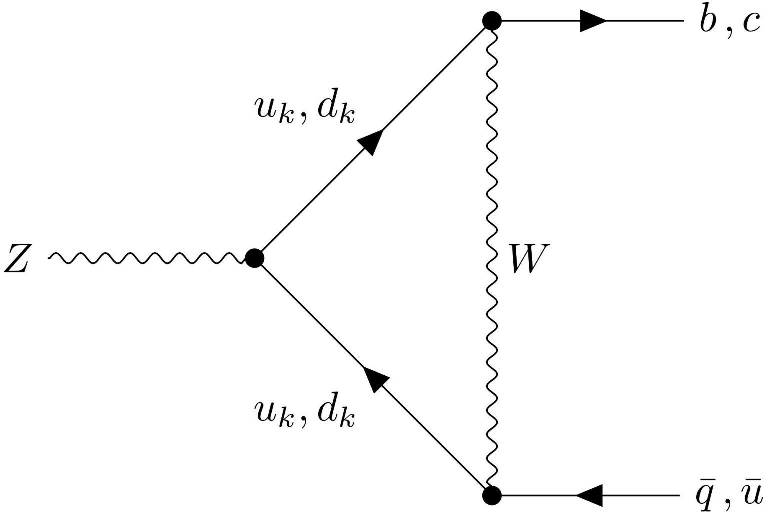
Based on recent work by J.F. Kamenik, A. Korajac, M.S., M. Tammaro and J. Zupan

We translate **advances in flavor tagging** with **novel statistical analysis techniques** to bounds on **Z/h** $\rightarrow$ **bs, cu couplings** in future high energy **high statistics** ee-colliders

We compare to **updated SM predictions** and **BSM benchmarks** and find that FCC-ee can place bounds on **h**$\rightarrow$**bs,cu** that are **phenomenologically relevant**

Flavor Changing Neutral Currents





SM Prediction

We update the **SM predictions** for **B(h/Z→bs,bd,cu)** obtaining

$$\Gamma(h \to b\bar{s}) = (1.8 \pm 0.3) \times 10^{-10}\text{GeV} \qquad \Gamma(h \to b\bar{d}) = (7.9 \pm 1.3) \times 10^{-12}\text{GeV}$$

$$\Gamma(Z \to b\bar{s}) = (5.2 \pm 0.9) \times 10^{-8}\text{GeV} \qquad \Gamma(Z \to b\bar{d}) = (2.3 \pm 0.4) \times 10^{-9}\text{GeV}$$

with h/Z→cu being O(10^6) smaller than h/Z→bs.

The main uncertainties are **CKM matrix elements** uncertainties (**~2%**) + **higher order QCD corrections**, which we estimate via partial two-loop mixed QCD-EW corrections (**~17%**)

Constraints

Indirect constraints much better than direct and Z→qq’ much more constrained than h→qq’

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}

FCC-ee

Very **clean environment** with **high statistics** + **controlled backgrounds** → **Precision machine**.

For h→qq’, we can consider **Zh production with dileptonic Z** (Z→MET can be used as well but backgrounds differ) → $\mathbf{N_h = 6.7 \times 10^5}$ before Z decay

For Z→qq’, we simply look at the **Z pole** → $\mathbf{N_Z = 5 \times 10^{12}}$

Analysis strategy

Our proposal is very simple. Let's take as an example $Z/h \to bs$.

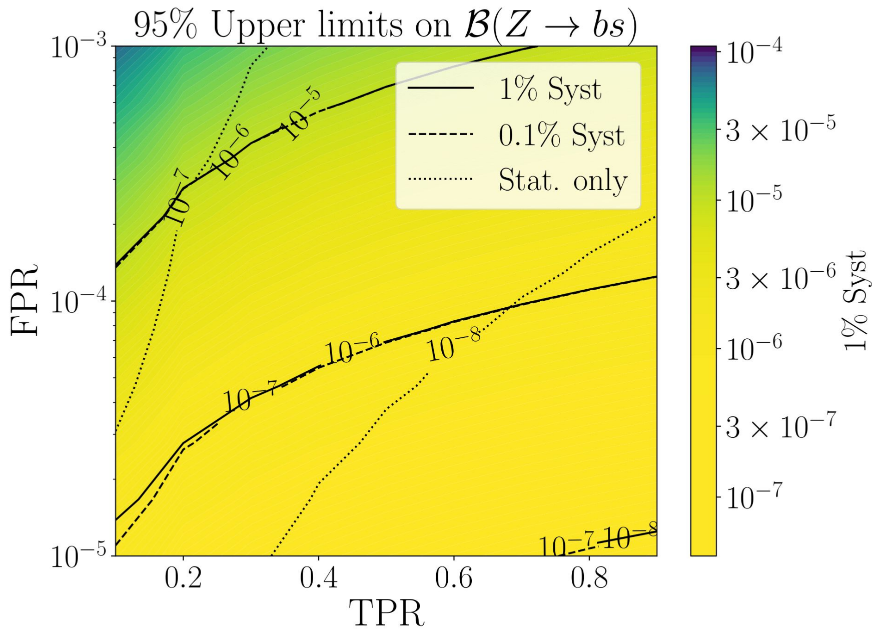
- We **select events** based on the appropriate di-jet channel, $Z(\to \ell\ell)h(\to jj)$ or $Z \to jj$. We obtain the total number of events **N**.
- We **tag each jet** in each event using **two orthogonal b- and s-taggers**.
- We obtain the **measured events in each (n_b,n_s) bin, $N_{b,s}$**. $(n_b,n_s) = \{(0,0),(0,1),(1,0),(1,1),(0,2),(2,0)\}$.
- We describe the relationship between $N_{b,s}$ and N with a **probabilistic model depending on B($Z/h \to bs$)**.
- We use this model to **perform statistical tests on B($Z/h \to bs$)**.

Results: Z⟶bs

We scan over possible orthogonal b- and s-taggers with systematics. **TPR and FPR assume common efficiencies for both taggers**.

If no systematic uncertainties, the SM value could be reached. Z→qq' we are **systematics dominated**.

When the systematics are **very small but non-zero**, the upper limits are generally **above the SM values and the indirect constraints**.

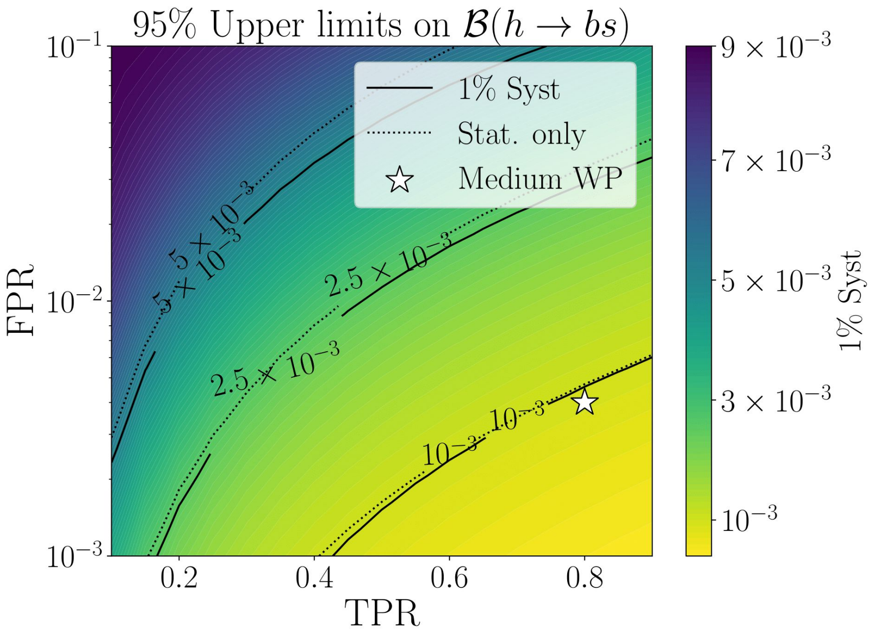


Results: h→bs

We scan over possible orthogonal b- and s-taggers with systematics. **TPR and FPR assume common efficiencies for both taggers**.

The systematic uncertainties (**small**, but **achievable** with future dedicated calibrations) are **not too impactful here.** The analysis is **statistics dominated**.

The addition of the s-tagger **greatly increases the performance** of the analysis and yields an **upper limit on B(h→bs) that could be better than indirect constraints**.



Constraints on BSM effects

We use an **effective lagrangian** to capture any BSM effects in B(h/Z→bs) (we can do something similar for bd, cu)

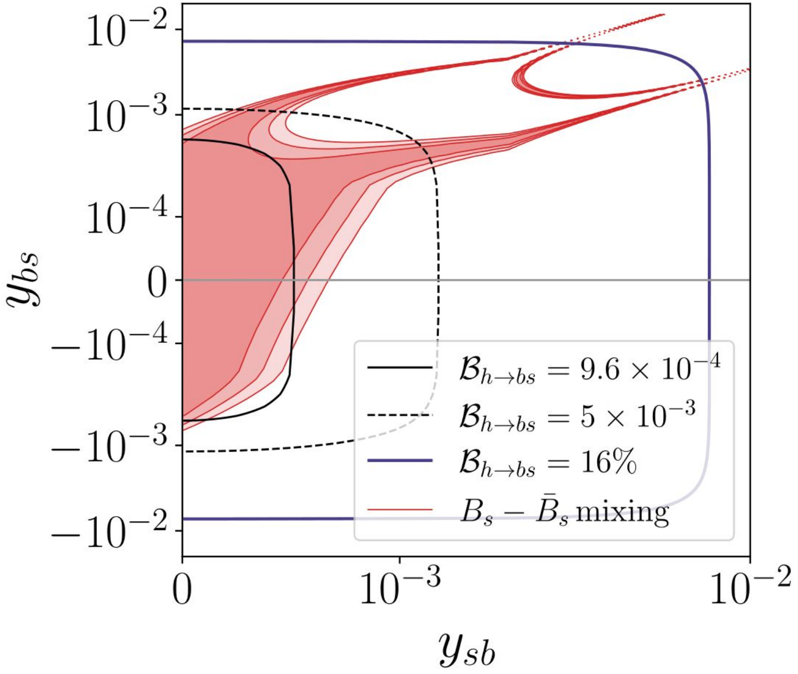
$$\mathcal{L} \supset y_{sb}(\bar{s}_L b_R)h + y_{bs}(\bar{b}_L s_R)h + \text{h.c.}$$

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

Results: h→bs

When comparing explicitly with low-energy constraints, we observe how **the FCC-ee can probe regions indirect searches cannot.**

Black lines are **upper limits** from **FCC-ee**, **magenta** lines are **upper limits** from **LHC** and **red** regions correspond to the **allowed parameter space** at 1-, 2- and 3-σ level from **low-energy constraints**



Outlook

The FCC-ee has the potential to **explore flavor changing decays of the Higgs and Z bosons**, with similar expectations for the CEPC.

We **updated the SM predictions** for the $h/Z \to bs$, bd, cu branching ratios. These are **orders of magnitude smaller than the FCC-ee reach**, so any signal in these channels would unambiguously imply existence of New Physics

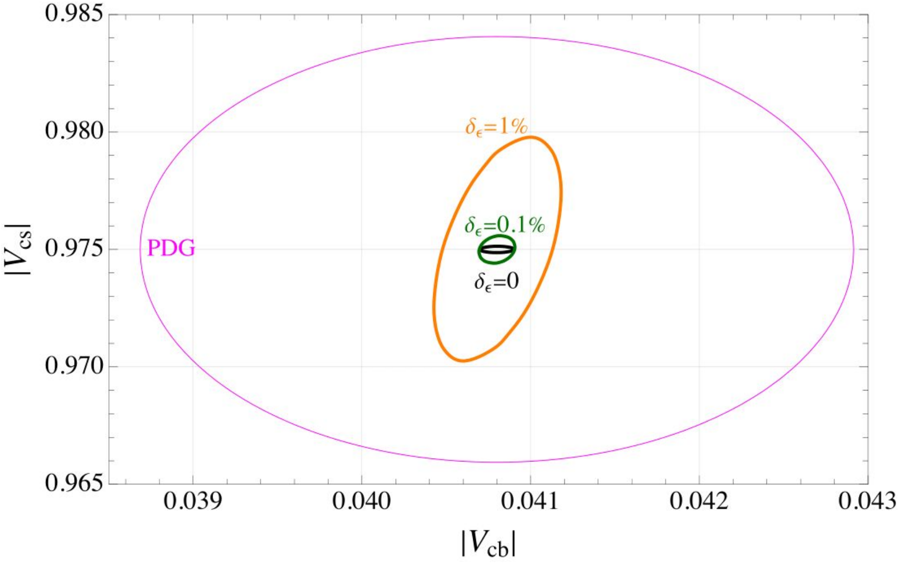
For $B(Z \to bs, bd, cu)$, indirect constraints already push towards the SM value which is **unreachable** without **almost perfectly calibrated perfect taggers**.

The projected sensitivities to $B(h \to bs, cu)$ go **well beyond the current constraints** from indirect probes. Even with only the b-tagger, the projected reach could probe significant portions of unconstrained NP parameter space.

And more…

In arxiv:2405.08880 (by D. Marzocca, M.S. and M. Tammaro), similar techniques for **$|V_{cs}|$ and $|V_{cb}|$ determination via WW→all hadronic @ FCC-ee**

- Lattice free determination
- Possible solution to tension between inclusive vs exclusive $|V_{cb}|$ from meson decays.



Thanks!

Backup slides

Flavor Changing Neutral Currents

We update the **SM predictions** for **B(h→bs,bd,cu)** (see arXiv:1506.02718 and arXiv:2009.07166) and **B(Z→bs,bd)** (see Phys. Rev. D 22, 214 (1980)., Phys. Rev. D 27, 570 (1983) and Phys. Rev. D 27, 579 (1983))

We compute the **one-loop decay amplitude**

$$\Gamma(h/Z \to b\bar{q}) = N_C \frac{|\bar{\mathcal{M}}(h/Z \to q\bar{q}')|^2}{16\pi m_{h/Z}}$$

We perform the computation numerically with FeynArts+FeynCalc+LoopTools. We cross-checked results with Package-X and also checked that all the m_q-independent terms in the amplitude vanish due to the CKM unitarity;

Flavor Changing Neutral Currents

The experimental inputs are (when necessary we run to the appropriate scale through 3-loop RGE)

param.	value	param.	value	param	value
$\|V_{tb}\|$	$0.999142^{+0.000018}_{-0.000023}$	$\|V_{ts}\|$	$0.04065^{+0.00040}_{-0.00055}$	$\|V_{td}\|$	$0.008519^{+0.000075}_{-0.000146}$
$m_t(m_Z)$	171.512 ± 0.329 GeV	$m_t(m_h)$	167.036 ± 0.315 GeV		
$m_b(m_Z)$	2.871 ± 0.024 GeV	$m_b(m_h)$	2.796 ± 0.024 GeV		
m_Z	91.1876 ± 0.0021 GeV	m_W	80.377 ± 0.012 GeV	m_h	125.25 ± 0.17 GeV
$\alpha^{-1}(m_Z)$	127.955 ± 0.009	$\alpha^{-1}(m_h)$	127.506 ± 0.009	$s^2_W(m_Z)$	0.23122 ± 0.00004
$\alpha_s(m_Z)$	0.1179 ± 0.0009	$\alpha_s(m_h)$	0.1126 ± 0.0008	$\alpha_s(m_t)$	0.1076 ± 0.0007

Flavor Changing Neutral Currents

The **direct constraints** are from LHC searches for $h \to$ others and from LEP measurements of the Z hadronic width.

The **main (or only) indirect constraints** are B_s mixing for $h \to bs$, B_d mixing for $h \to bd$, D mixing for $h \to cu$, $b \to s\ell^+\ell^-$ transitions for $Z \to bs$, B_d mixing for $Z \to bd$ and $B(D^0 \to \mu^+\mu^-)$ for $Z \to cu$

Putting it all together: **indirect constraints much better than direct** and **$Z \to qq'$ much more constrained than $h \to qq'$**

Analysis strategy

As a first approximation, we can **disregard all backgrounds that aren't Zh,h→bb,cc,ss,gg or Z→qq**, mainly the $\tau^+\tau^-$ for Z→bs and the Drell-Yan, W W, ZZ for h→bs.

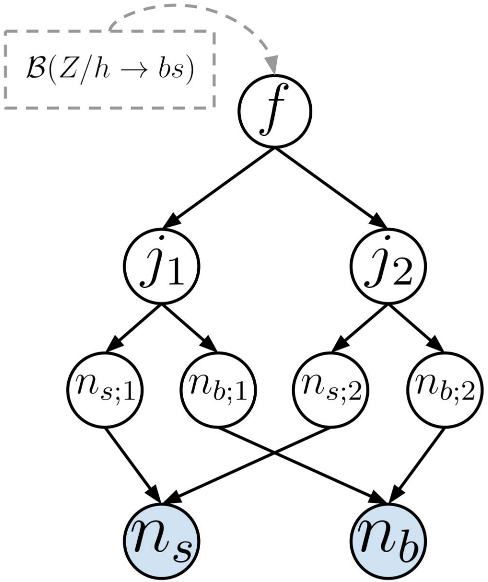
These other processes correspond to **subleading effects** and could be **reduced through optimized selection** or **incorporated into the analysis** as a re-scaling of the flavor-conserving contributions.

Because we are doing a proof-of-concept, we **avoid the use of dedicated MC simulations** and consider our model to be enough of a **faithful representation of the real physics** that it can be used to generate pseudo-data.

Analysis strategy

We follow arXiv:2209.01222 (see also arXiv:2201.11428,, arXiv:2004.12181) to **leverage orthogonal taggers** to extract information regarding small FCNC.

For example, for h/Z→bs, we **categorize di-jet events** in terms of the number of **s-tagged n_s** and **b-tagged n_b** jets. The expected populations will depend on **BR(h/Z→bs)**



Analysis strategy

We write the **probabilistic model** in terms of efficiencies and of the relevant Branching ratios.

$$\bar{N}_{(n_b,n_s)} = \sum_f p(n_b, n_s | f, \nu) \bar{N}_f(\nu) \qquad \bar{N}_f = \mathcal{B}(Z/h \to f) N_{Z/h} \mathcal{A}$$

We define a **parameter of interest** $\mu = \dfrac{\mathcal{B}(Z/h \to bs)}{\mathcal{B}(Z/h \to bs)_{\mathrm{SM}}}$

and an **appropriate likelihood**

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

Analysis strategy

We **profile the likelihood** over a set of nuisance parameters and construct the **profile likelihood ratio**

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

which is used to compute the **test statistic**

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

With this we compute **95% CL upper limits** assuming $\mu_{\text{true}} = 0$ and solving for $t_\mu = (\Phi^{-1}(0.95))^2$. Due to the high statistics and simplicity of the strategy, we can use an **Asimov dataset** instead of using ensembles of pseudo-data.

Nuisance Parameters

Nuisance Param.	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
ϵ_β^α	See text	1.0
N_h	6.7×10^5	0.5
$\mathcal{A}$	0.70	0.1

Nuisance param.	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
ϵ_β^α	See text	1.0
N_Z	5×10^{12}	10^{-3}
$\mathcal{A}$	0.994	10^{-3}

Possible BSM benchmarks

The h→bs effects can be generated in a **Two Higgs Doublet Model (2HDM)**. If we **decouple the heavy scalar H and pseudoscalar A** and assuming **no diagonal couplings of the second doublet**, we obtain

$$\mathcal{L}_{\text{Yukawa}} \supset -\left(\frac{m_i}{v}\delta_{ij}c_\alpha - Y^d_{ij}s_\alpha\right)\bar{d}_{Li}d_{Rj}h + \text{h.c.} + \ldots$$

All SM predictions are re-scaled by $c_\alpha^{\ 2}$ and the couplings we are interested in will be $\mathbf{y_{qq'} = Y_{qq'}\, s_\alpha}$

Possible BSM benchmarks

The $Z \to bs$ and $h \to bs$ effects can be generated at the same time with **Vector-Like Quarks**. e.g. vector-like singlet down-type quarks, (D_L, D_R), singlets under $SU(2)_L$ and with hypercharge -⅓. We obtain the FCNC from the mixture with the SM down-type quarks after EWSB

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

we can read $\mathbf{g_{qq'}}$ **and** $\mathbf{y_{qq'}}$ **as different combinations of** $\mathbf{X_{qq'}}$. We can do the same with a vector-like doublet with hypercharge ⅙ to get different chiralities.

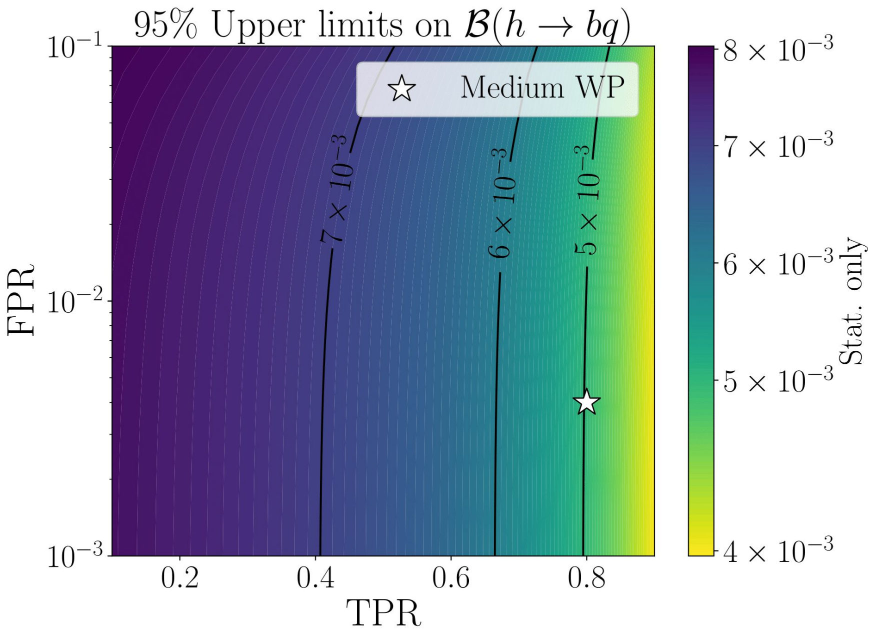
Results: Higgs

We obtain limits on **B(h→bs)+B(h→bd)** by using **only a b-tagger**.

We scan over possible taggers by assuming **identical True Positive Rates (TPRs)** and **False Positive Rates (FPRs)** for **all taggers**.

With no systematics, we observe that for FPR < 10^{-2} (after the FPR saturates) and TPR in [0.4,0.8] we are **already in an interesting region for BSM limits**.

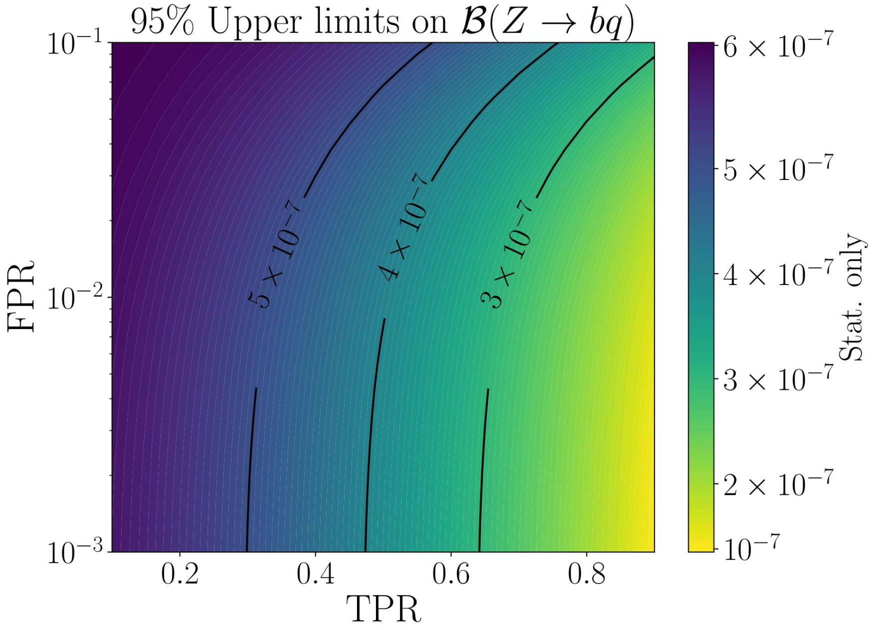
We show with a star a tagger based on reported taggers in the literature.



Results: Z boson

For BR(Z→bs)+BR(Z→bd) with **a b-tagger**, the limits are **lower than for h→qq'** due to the **higher statistics** even if there is **no asymmetry between Z→bb and Z→ss** to enhance the analysis.

However, the **indirect limits are much better** and this **analysis is not competitive**.



Results: h→bs

We also use **explicit Tight and Medium WPs** derived from **reported taggers**

$$\text{Loose}: \quad \epsilon^b_{\beta;\text{Loose}} = \{0.02,\ 0.001,\ 0.02,\ 0.90\}, \quad \epsilon^s_{\beta;\text{Loose}} = \{0.20,\ 0.90,\ 0.10,\ 0.01\},$$

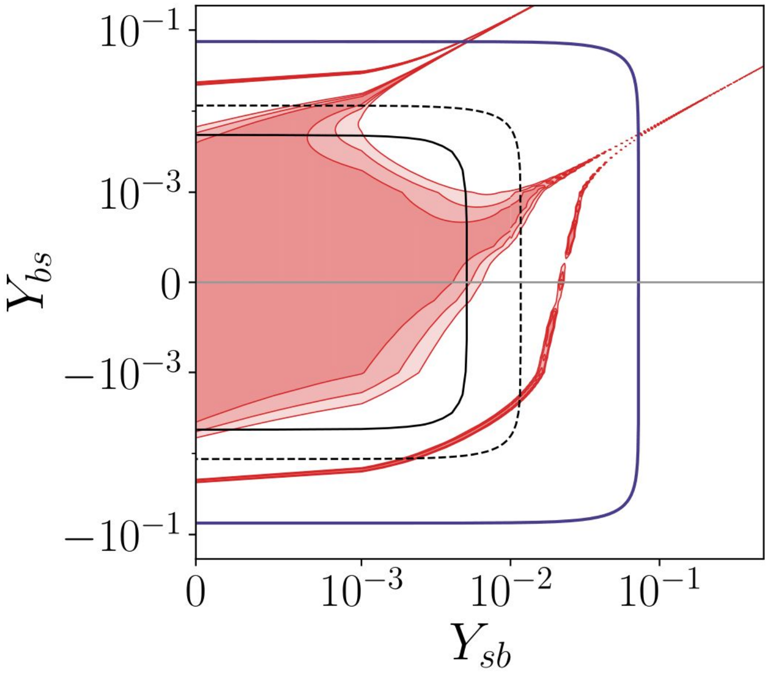
$$\text{Medium}: \quad \epsilon^b_{\beta;\text{Med}} = \{0.007,\ 0.0001,\ 0.003,\ 0.80\}, \quad \epsilon^s_{\beta;\text{Med}} = \{0.09,\ 0.80,\ 0.06,\ 0.004\},$$

All WPs are **similar** and provide **competitive limits**. Additionally, they are consistent with the approximate scan shown before.

ϵ^b_β	ϵ^s_β	$\mathcal{B}(h \to bs)$ (95% CL)
$\epsilon^b_{\beta;\text{Loose}}$	$\epsilon^s_{\beta;\text{Loose}}$	1.3×10^{-3}
$\epsilon^b_{\beta;\text{Loose}}$	$\epsilon^s_{\beta;\text{Med}}$	9.6×10^{-4}
$\epsilon^b_{\beta;\text{Med}}$	$\epsilon^s_{\beta;\text{Loose}}$	1.4×10^{-3}
$\epsilon^b_{\beta;\text{Med}}$	$\epsilon^s_{\beta;\text{Med}}$	1.0×10^{-3}

Results: h⟶bs + 2HDM

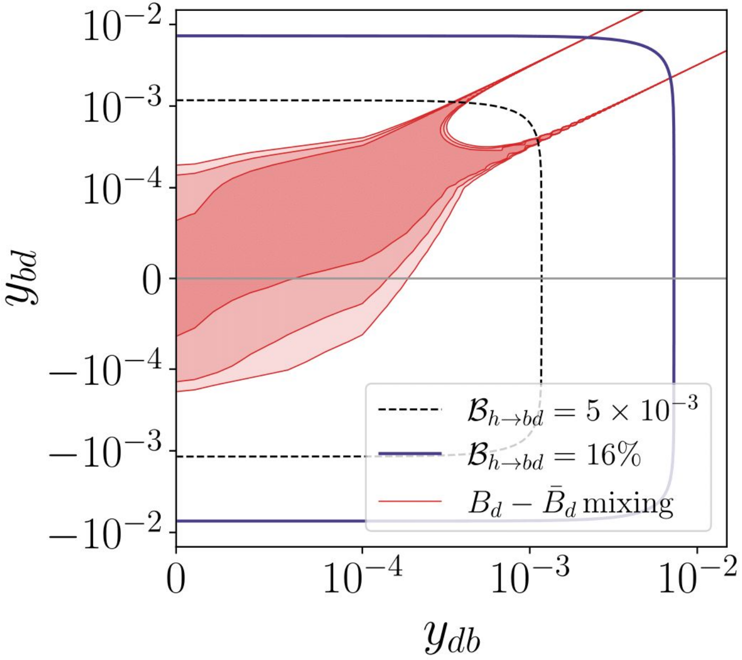
We consider m_H=m_A = 1 TeV and different values of s_α. Although the details change, the conclusions hold: **the FCC-ee can probe regions indirect searches cannot.**



Results: h⟶bd

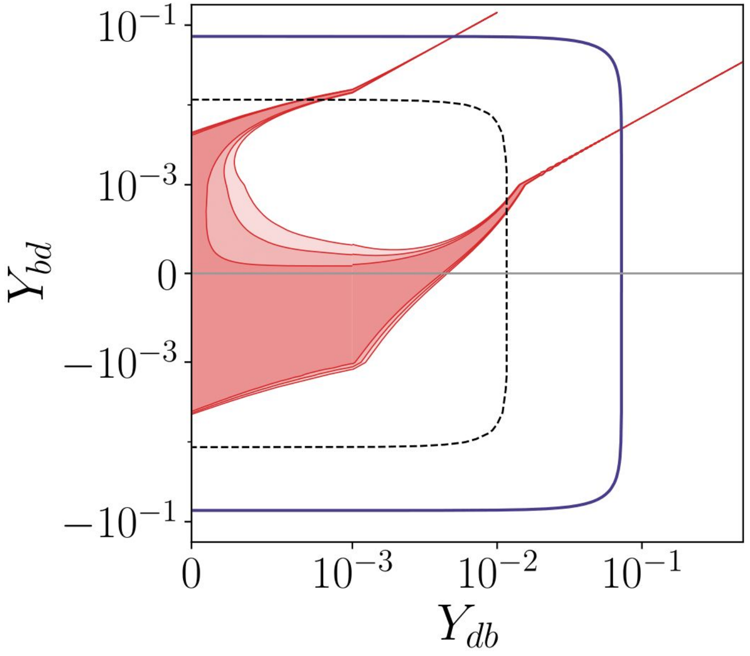
When comparing explicitly with low-energy constraints, we observe how **the FCC-ee can probe regions indirect searches cannot.**

The right plot assumes **no effects from H and A**.



Results: h⟶bd + 2HDM

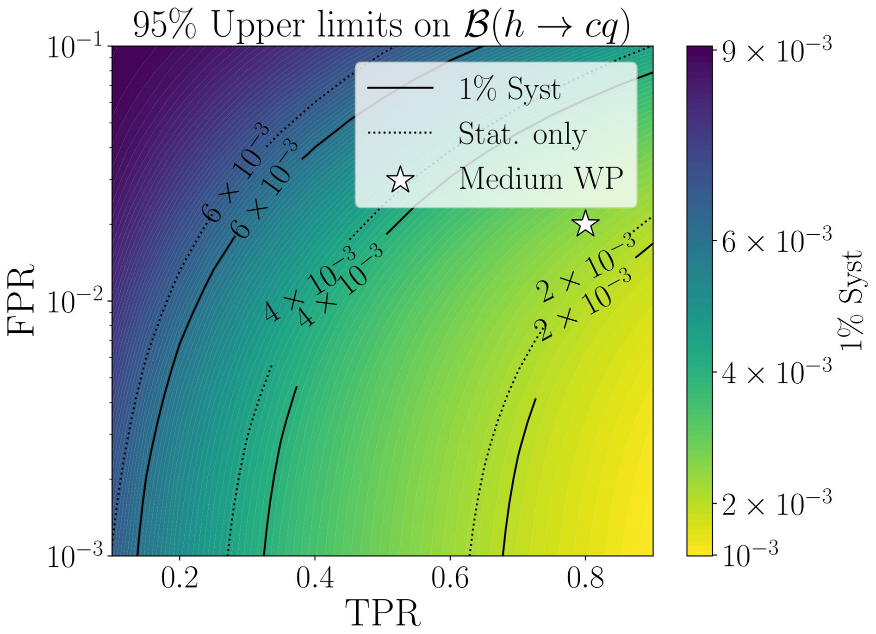
If we consider $m_H = m_A$ = 1 TeV and different values of s_α although the details change, the conclusions hold: **the FCC-ee can probe regions indirect searches cannot.**



Results: $h \longrightarrow cu$

We consider only a **c-tagger** as there is no state-of-the-art u-tagger.

With only a c-tagger, whose systematics are mildly impactful, **the upper limits are competitive for BSM benchmarks**.



Results: h⟶cu

Again, we can use the reported efficiencies for the c-tagger

$$\text{Loose}: \quad \epsilon^c_{\beta;\text{Loose}} = \{0.07,\, 0.07,\, 0.90,\, 0.04\},$$

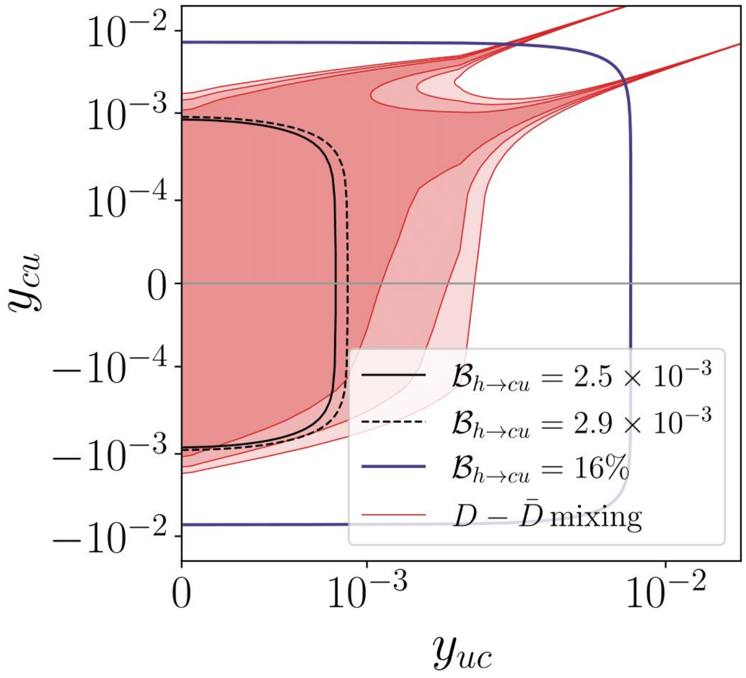
$$\text{Medium}: \quad \epsilon^c_{\beta;\text{Med}} = \{0.02,\, 0.008,\, 0.80,\, 0.02\},$$

Both WPs are pretty similar and consistent with the scan. More importantly, **they provide competitive limits**.

ϵ^c_β	$\mathcal{B}(h \to cu)$ (95% CL)
$\epsilon^c_{\beta;\text{Loose}}$	2.9×10^{-3}
$\epsilon^c_{\beta;\text{Med}}$	2.5×10^{-3}

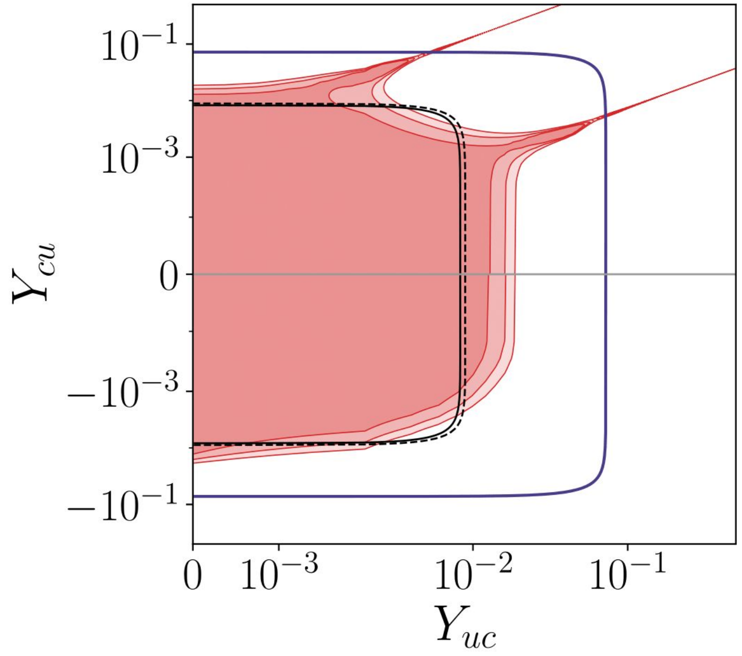
Results: h→cu

We again see how the **FCC-ee probes regions beyond the reach of indirect searches**.



Results: h⟶cu + 2HDM

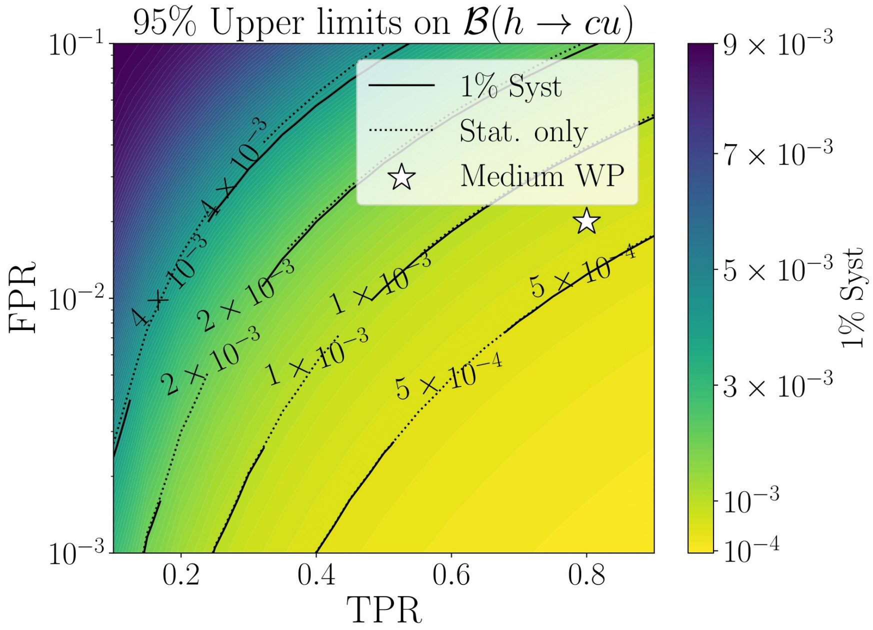
If we consider $m_H = m_A$ = 1 TeV and different values of s_α although the details change, the conclusions hold: **the FCC-ee can probe regions indirect searches cannot.**



Results: h→cu

If we add an idealized u-tagger, the performance **greatly increases** again.

Additionally, the Medium WP can go higher in FPR and still have less mistags in $(n_c,n_u)=(1,1)$ than for $(n_b,n_s)=(1,1)$ due to **the smallness of h→uu+dd** compared to h→ss.



Analysis strategy

From the likelihood + test statistic we obtain **confidence intervals**, **discovery significance** and/or **upper limits** on BR(h/Z→bs)

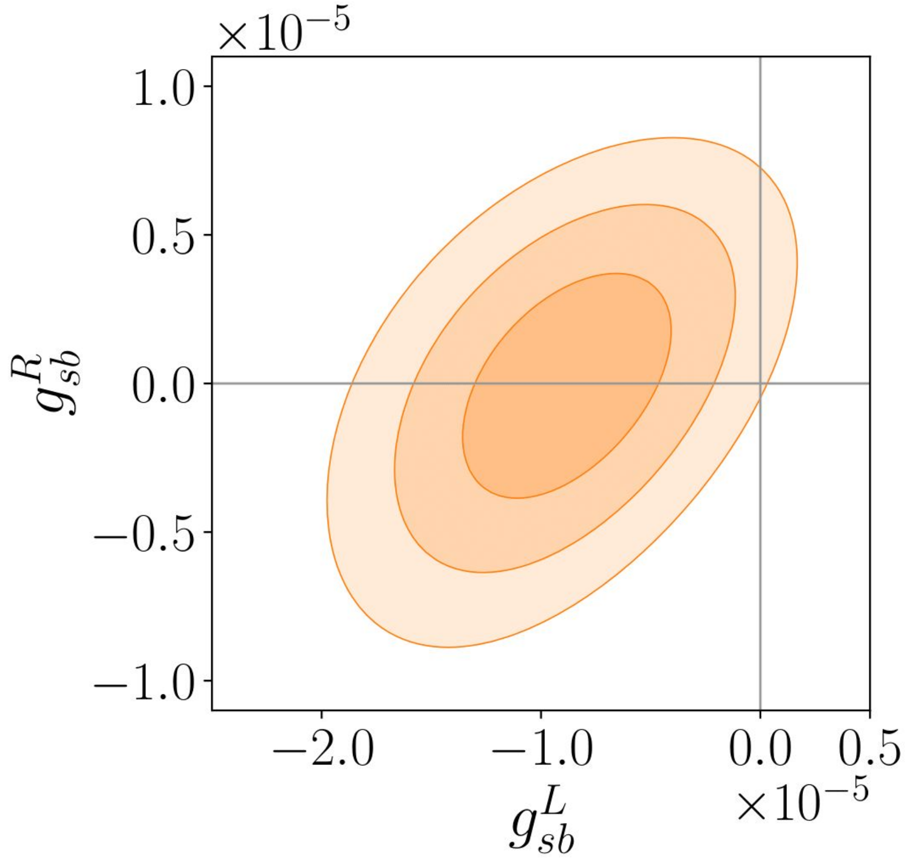
$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\hat{\nu}}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\nu})} \qquad t_\mu = -2 \text{ Ln } \lambda(\mu)$$

Besides the **95% CL upper limits**, we can also compute

- **68% confidence intervals** assuming μ_{true}=1 and solving for t_μ = 1
- **Discovery significance** assuming μ_{true}=1 and computing for Z = $\sqrt{t_0}$.

Results: Z⟶bs

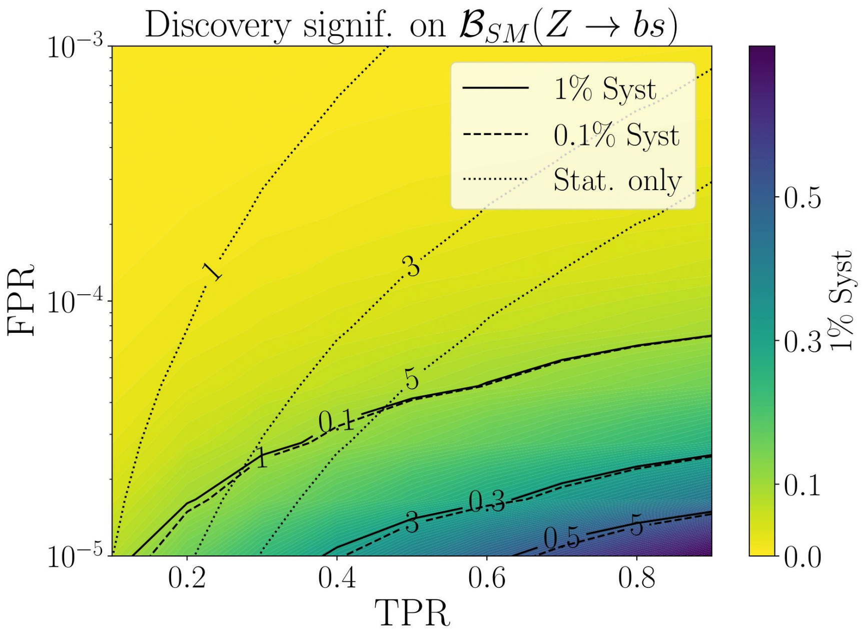
The indirect limits on the couplings are at the SM prediction level. It’s hard to show them in the same scale as the FCC-ee limits!



Results: $Z \to bs$

We can reframe this in terms of the **discovery significance**.

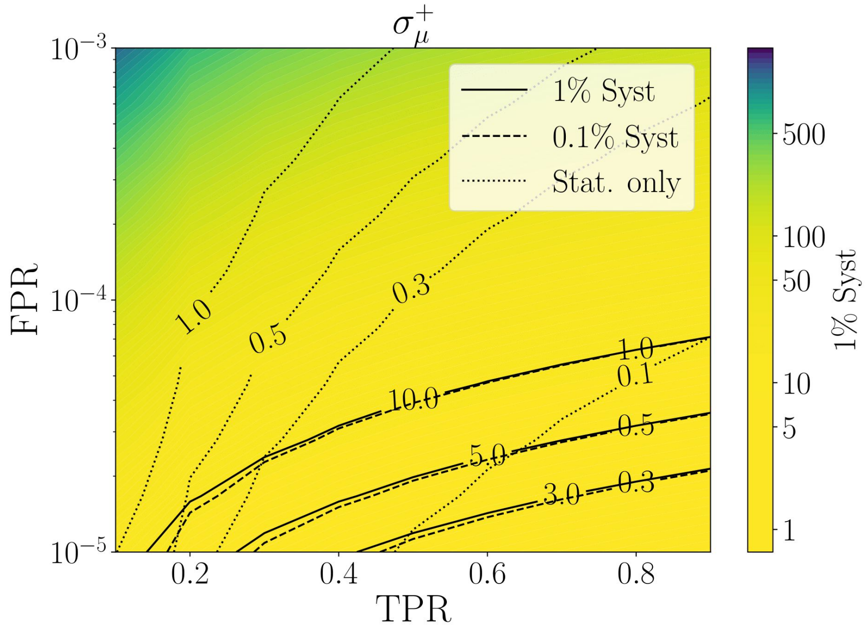
We see how the SM value **cannot be discovered** with this strategy except with almost no uncertainties and pushing the limits of the taggers.



Results: Z⟶bs

Another complementary viewpoint is the **upper limit of the 95% confidence interval** on the signal strength in units of its MLE estimate.

We observe how **systematic uncertainties degrade the performance**, with a 30% achievable with very small uncertainties only for almost perfect taggers.



Results: Z→bs

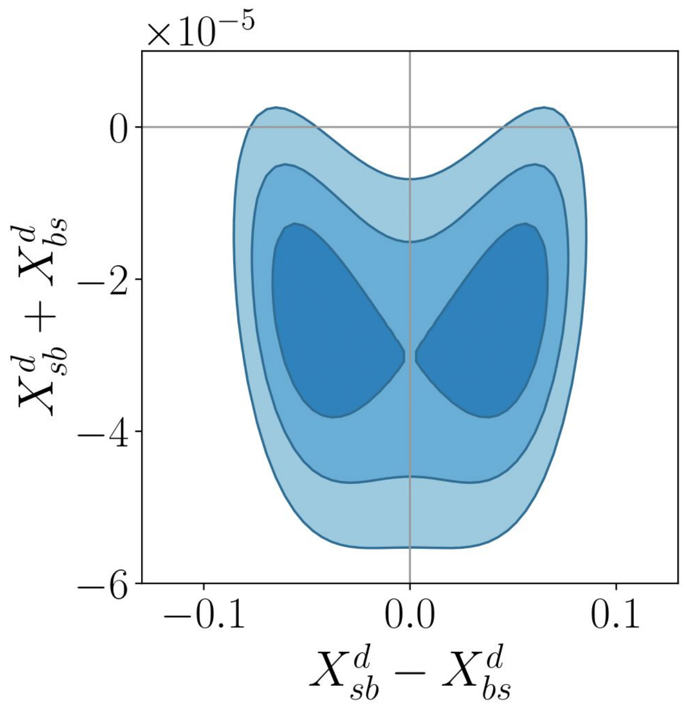
We see how we need the combination of **very small uncertainties** and **very small FPR** to be competitive with indirect constraints.

(TPR, FPR, $\Delta\epsilon^\alpha_\beta/\epsilon^\alpha_\beta$)	σ^+_μ for $\mu_{\text{true}}=1$	Discov. signif. (in σ)	$\mathcal{B}(Z\to bs)$ (95% CL)
(0.4, 10^{-4}, 1%)	0.40(stat.)+32(syst.)	0.032	1.8×10^{-6}
(0.4, 10^{-4}, 0.1%)	0.40(stat.)+3.2(syst.)	0.32	1.8×10^{-7}
(0.2, 10^{-5}, 1%)	0.36(stat.)+6.3 (syst.)	0.16	4.2×10^{-7}
(0.2, 10^{-5}, 0.1%)	0.36(stat.)+0.63 (syst.)	1.4	4.2×10^{-8}

VLQ from h→bs + Z→bs

$X_{bs}+X_{sb}$ is **strongly constrained**, mostly by $b\to s\ell^+\ell^-$ transitions generated by Z→bs and reflects the preference for negative values of $g_{bs,sb}$.

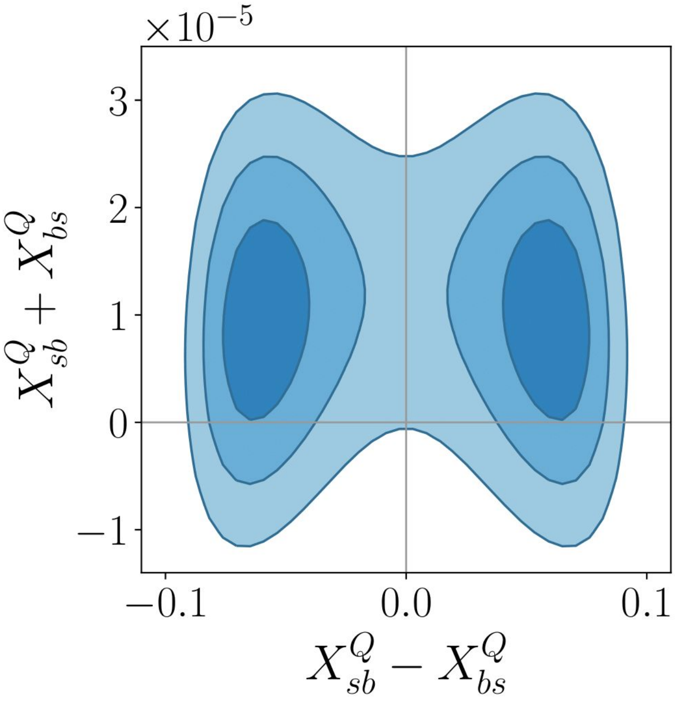
$X_{bs}-X_{sb}$ is **more weakly** constrained, reflecting mostly B_s mixing generated from both h→bs and Z→bs and reflecting the weaker constraints on both y_{sb} and g_{sb} (the bs couplings are suppressed by a m_b/m_s factor)



VLQ from h⟶bs + Z⟶bs

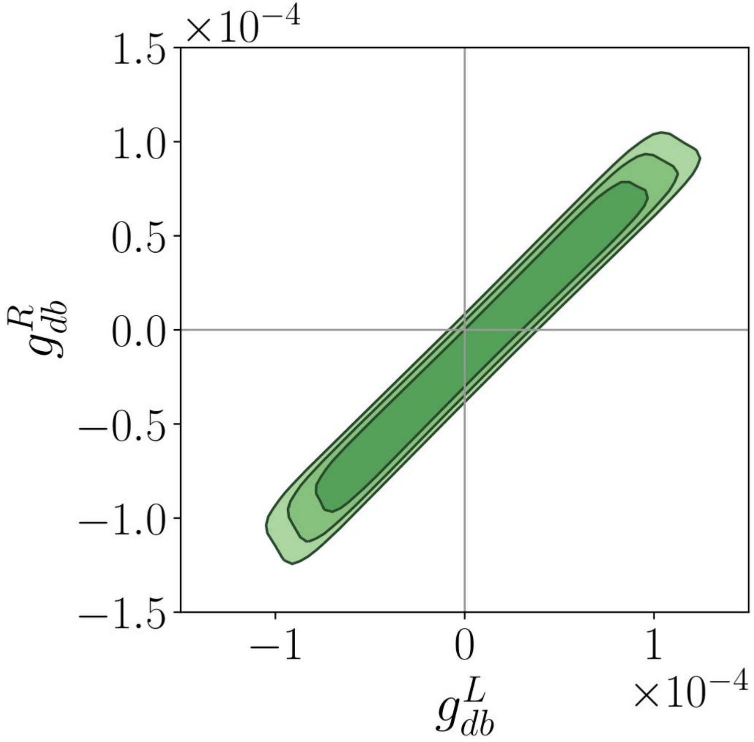
The results are mostly unchanged if we use an $SU(2)_L$ doublet instead of a singlet.

The differences arise due to the change in chiralities, with the right-handed currents now generated more constrained than the left-handed currents of the singlet case.



Results: Z→bd

The indirect limits on the couplings are close to the the SM prediction level. It's hard to show them in the same scale as the FCC-ee limits!

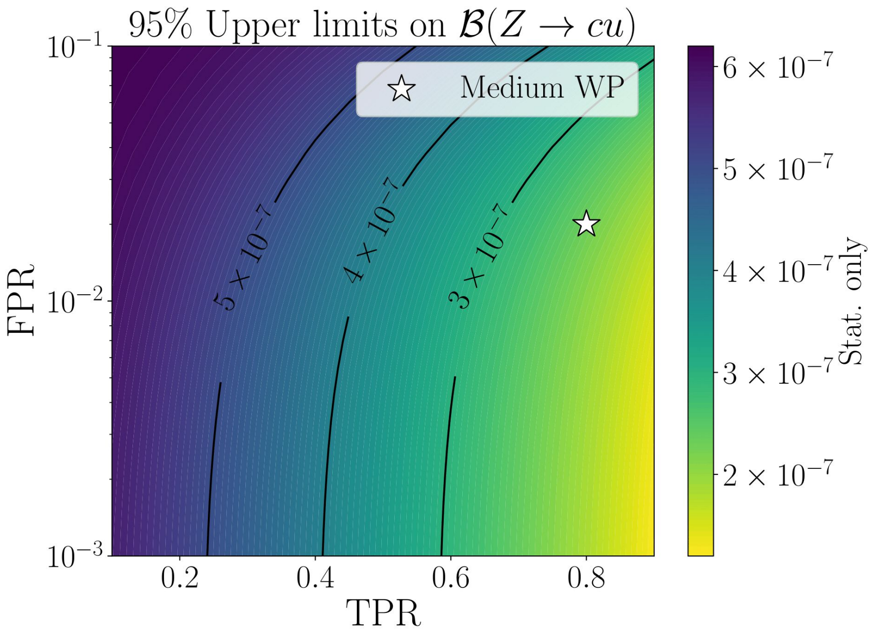


Results: Z→cu

The situation is similar for Z→cu.

With no u-tagger, the results are **almost identical to the Z→bq case**.

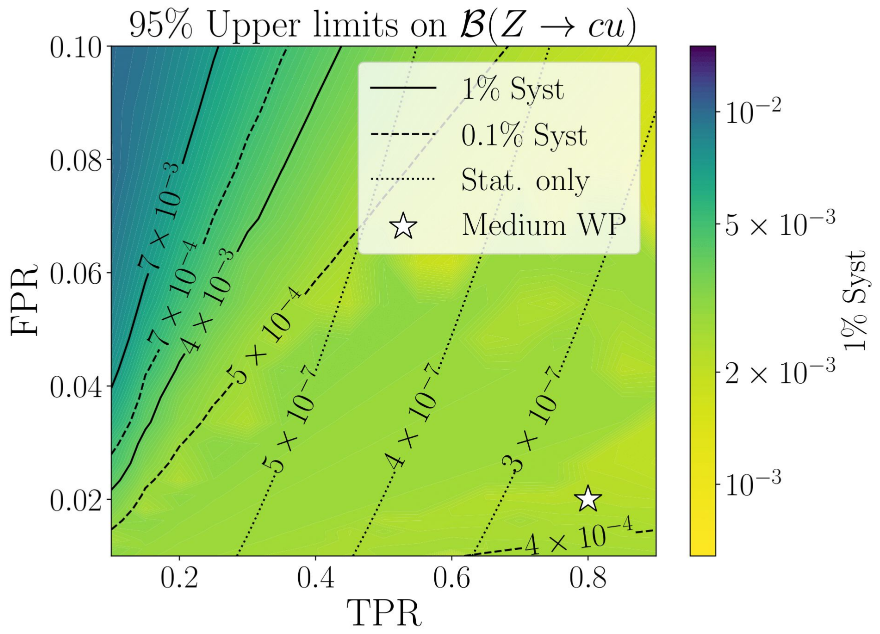
We again observe how the results are **not competitive with the indirect constraints**.



Results: Z⟶cu

Systematics **hinder the already suboptimal** performance, as the analysis is **systematics dominated**.

We do not implement an idealized u-tagger because it cannot distinguish between u- and d-quarks. This causes the Z⟶uu+dd background to be ~twice as large as Z⟶ss for equivalent TPR,FPR.



Results: Z→cu

The indirect limits on the couplings are not at the SM prediction level, but still much lower than the FCC-ee reach.