Flavour at FCC-ee

Jernej F. Kamenik

Univerza *v Ljubljani*

Institut "Jožef Stefan"

ZPW2024

9/1/2024

Flavour changing Z and Higgs decays at FCC-ee

Jernej F. Kamenik

collaboration with A. Korajac, M. Szewc, M. Tammaro, J. Zupan
2306.17520

Univerza v Ljubljani

Institut "Jožef Stefan"

ZPW2024

9/1/2024

Introduction

- Flavour is one of most puzzling aspects of SM

Symmetric, quantized

Ad hoc

$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}}(A_a, \psi_i) + D_\mu \phi^\dagger D^\mu \phi - V_{\mathrm{eff}}(\phi, A_a, \psi_i)$$

Introduction

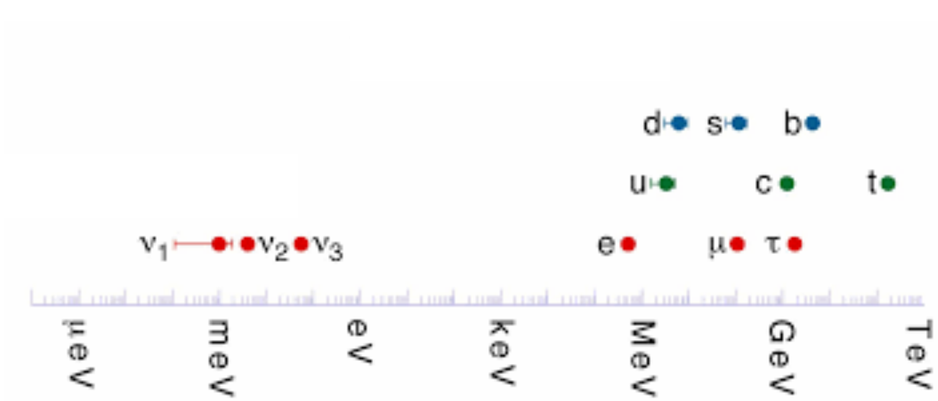
- Flavour is one of most puzzling aspects of SM

Symmetric, quantized

Ad hoc

$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}}(A_a, \psi_i) + D_\mu \phi^\dagger D^\mu \phi - V_{\mathrm{eff}}(\phi, A_a, \psi_i)$$

$$V_{\mathrm{eff}} = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + Y^{ij} \psi_L^i \psi_R^j \phi + \frac{y^{ij}}{\Lambda} \psi_L^{iT} \psi_L^j \phi^T \phi + \ldots$$



most parameters curious patterns

Introduction

- Flavour is one of most puzzling aspects of SM
  - ad hoc, many parameters, peculiar patterns

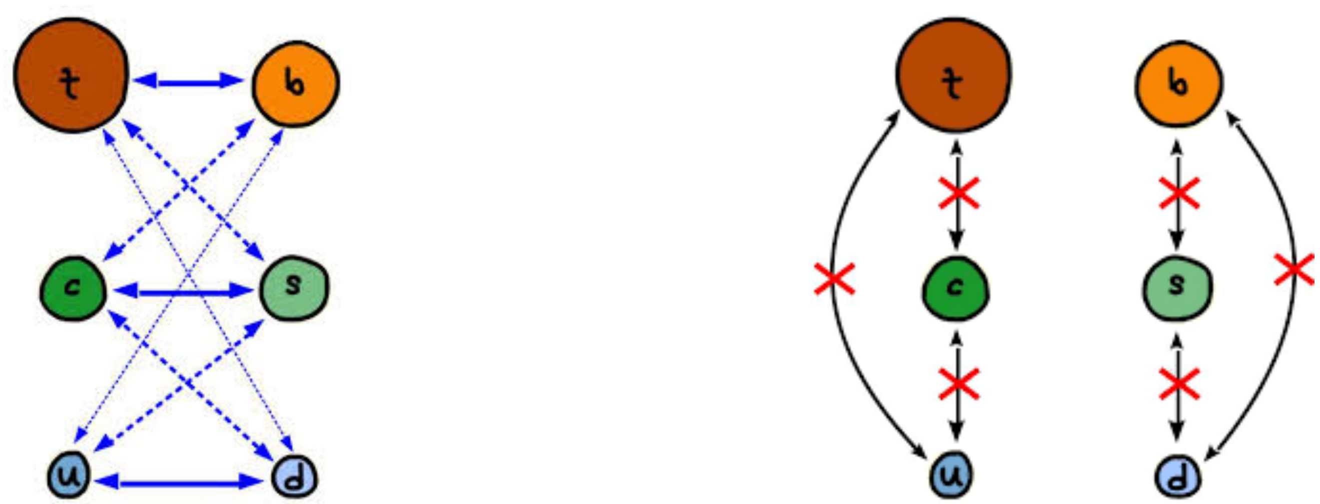
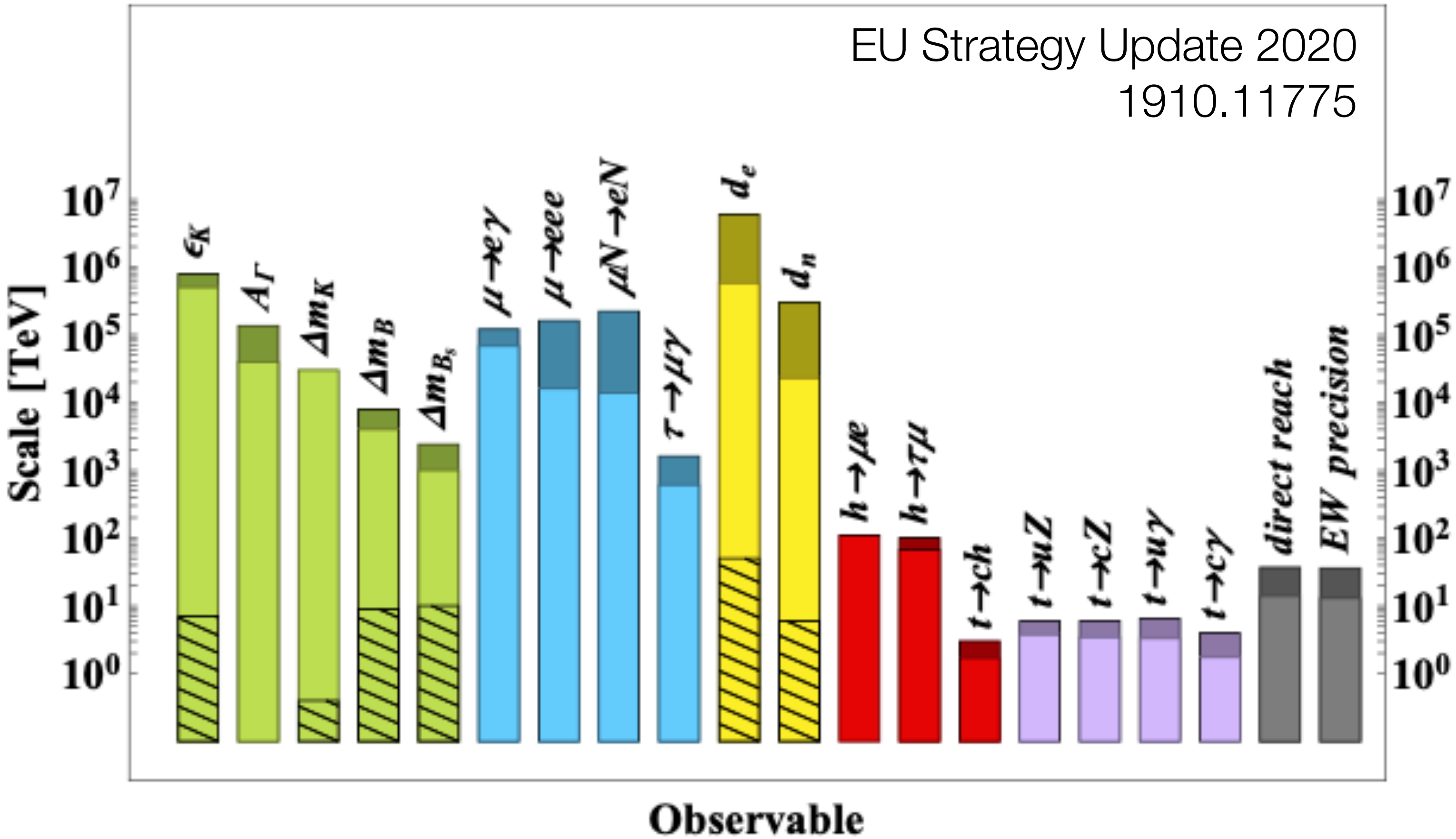


figure by
W. Altmannshofer

➡ strong suppression of (most) flavor changing processes within SM - unexplained!

Introduction

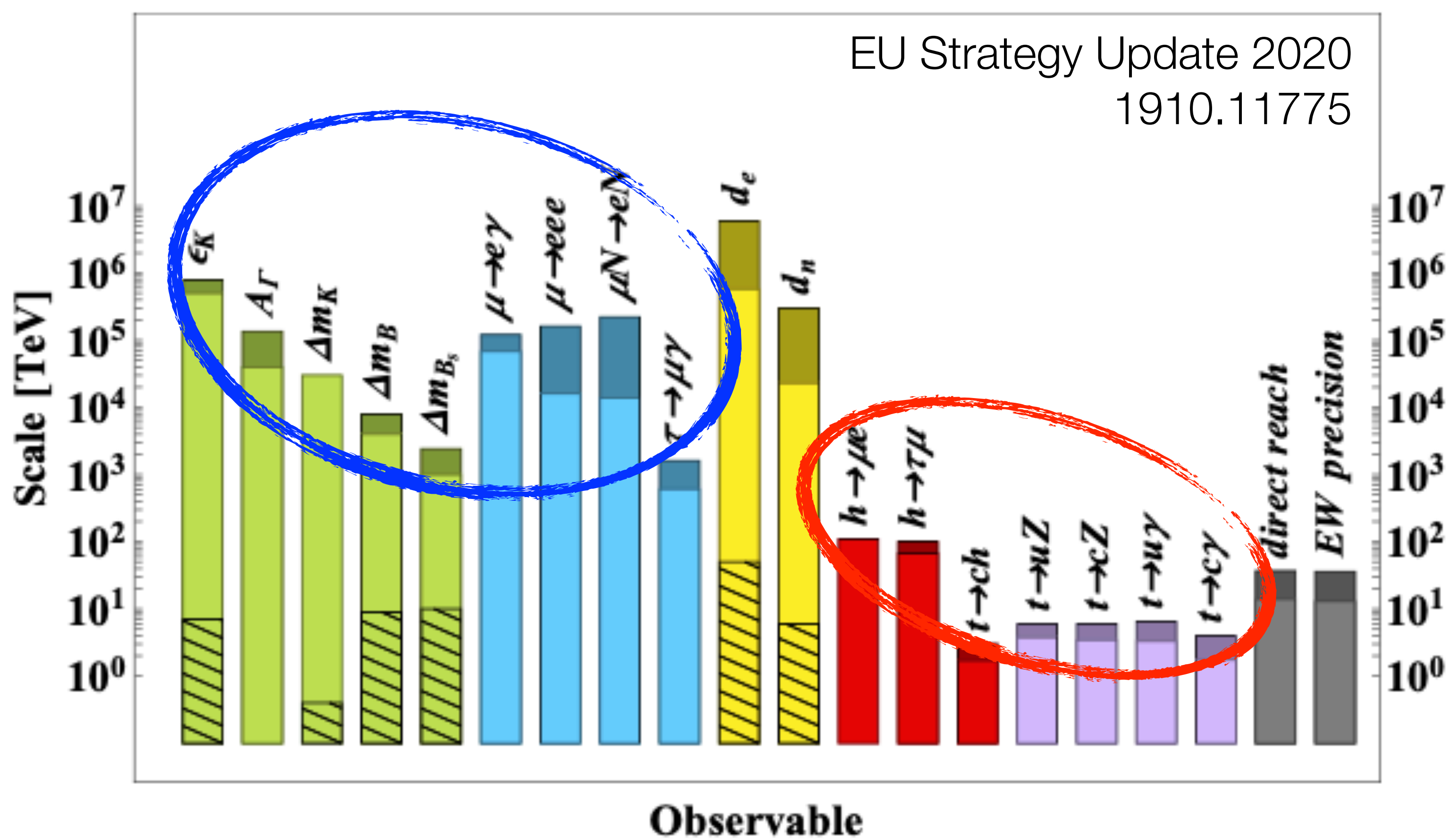
- Flavour is one of most puzzling aspects of SM
  - ➡ strong suppression of flavor changing processes within SM - unexplained!
  - ➡ allows to probe deep UV dynamics



Introduction

- Flavour is one of most puzzling aspects of SM
  - ➡ strong suppression of flavor changing processes within SM - unexplained!
  - ➡ allows to probe deep UV dynamics

indirect / low energy probes of FCNCs



direct probes of FCNCs coupled to SM bosons

Flavour Physics @ FCC(-ee)

- Planned high-pT & high statistics experiments at FCC-ee would record O(10^{13}) Z boson, O(10^6) Higgs decays
  - clean e^+e^- collisions, boosted decay products - Flavour factory
  - allows to go beyond ultimate precision of LHCb and Belle II

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

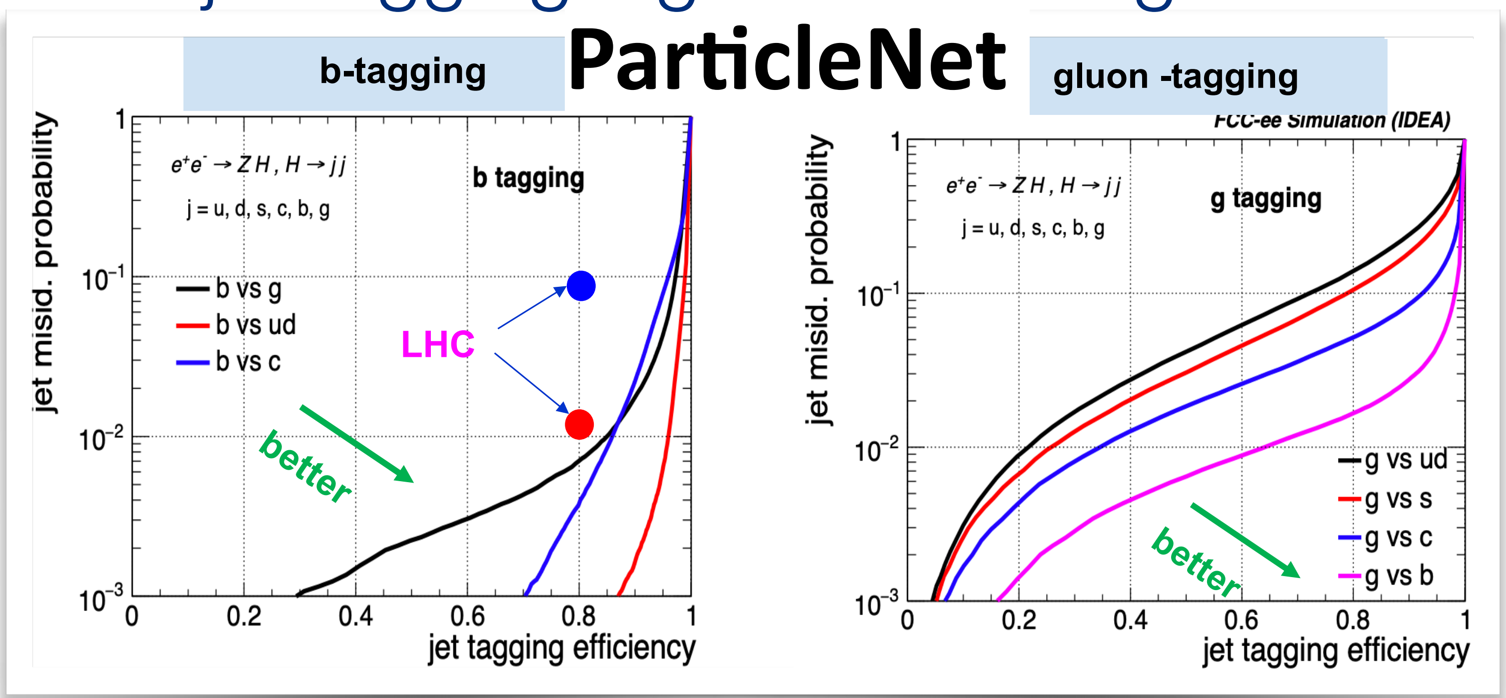
Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-ee	400	400	100	100	800	220

Flavour Physics @ FCC(-ee)

- Planned high-pT & high statistics experiments at FCC-ee would record O(10^{13}) Z boson, O(10^6) Higgs decays
  - clean e^+e^- collisions, boosted decay products - Flavour factory
  - allows to go beyond ultimate precision of LHCb and Belle II
    - CKM ($|V_{cb}|$ & $|V_{ub}|$) determination, rare decays of c- and b-hadrons ($b \to s\ \tau^+\tau^-$, $\nu\nu$) and CP violation in the heavy-quark sector (γ, a_{SL})
    - tau lepton properties (mass, lifetime) and rare decays
    - …(many avenues remain unexplored)

Competitive Flavour Probes with SM bosons?

- Planned high-pT & high statistics experiments at FCC-ee would record O(10^{13}) Z boson, O(10^{6}) Higgs decays
- Recent advances in jet physics and statistics
  - revolution of jet tagging algorithms using ML



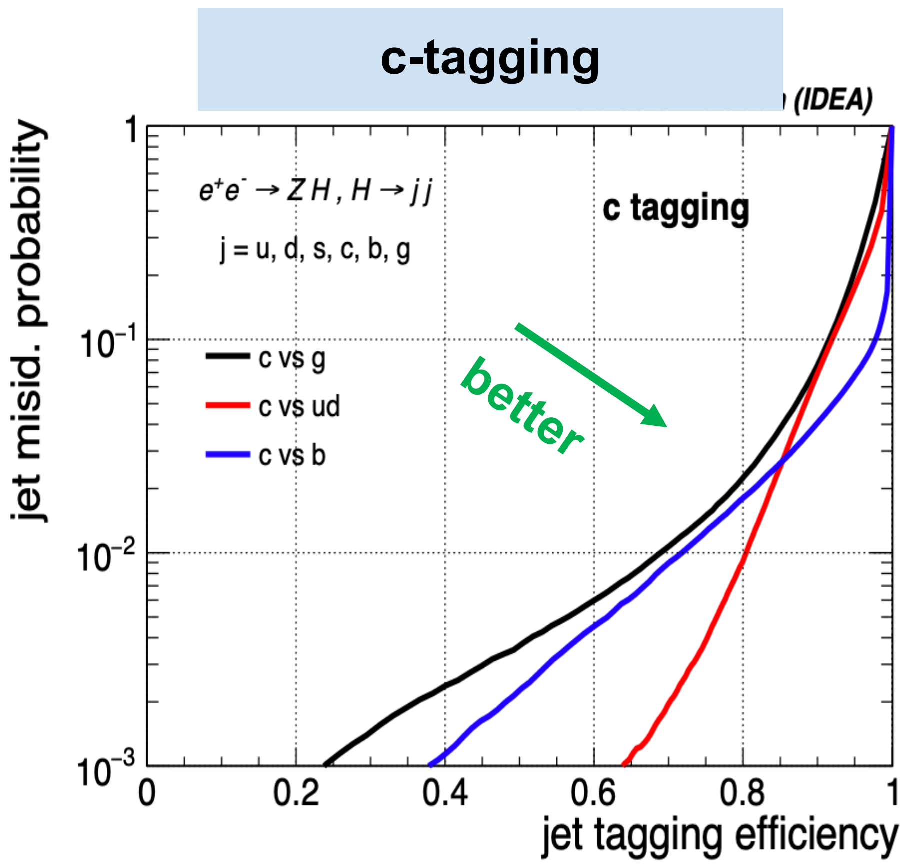
Bedeschi et al., 2202.03285

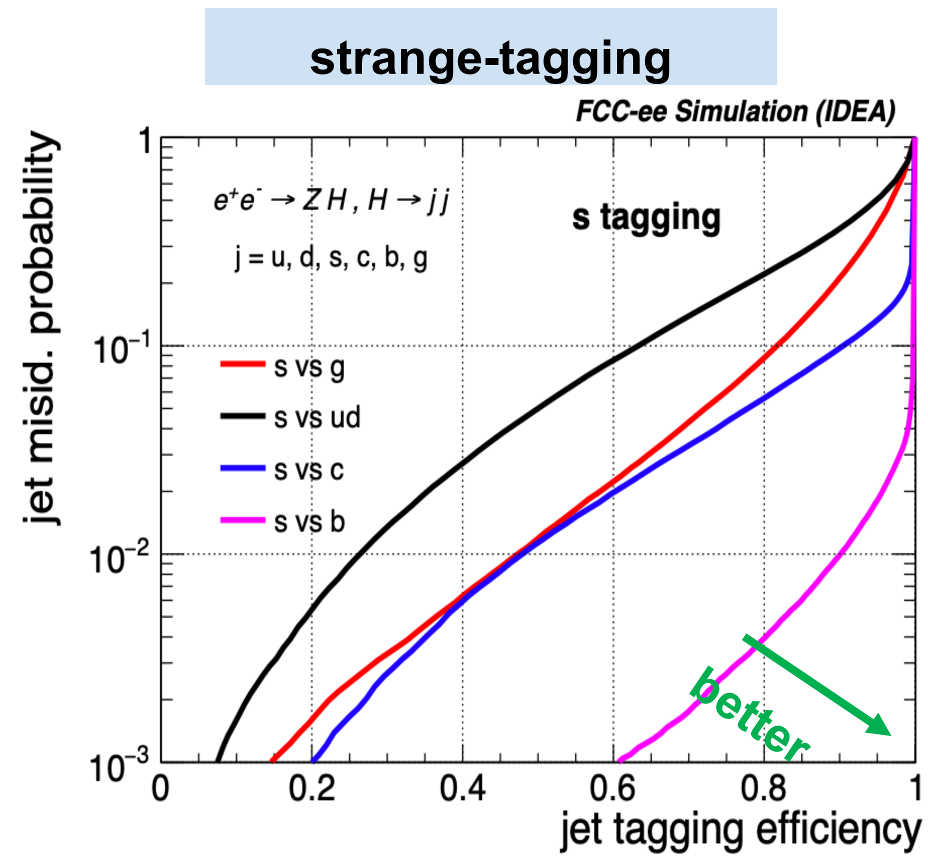
  - novel analysis techniques exploiting solvable probabilistic models for complicated events (tractable likelihoods vs. of cut & count)

➡ Novel tests of flavor conversion in and beyond SM

Tagging on-shell FCNCs @ FCC-ee

- FCC-ee with clean environment & excellent vertexing would allow for efficient charm & even strange quark flavor tagging





Bedeschi et al., 2202.03285

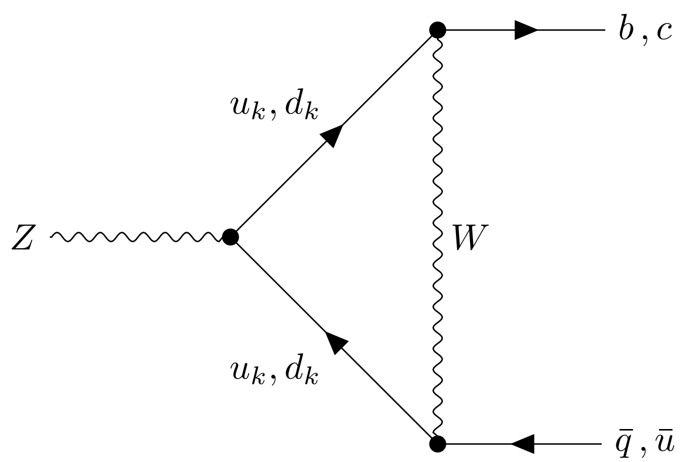
- One can contemplate Z/h→qq’ decay searches

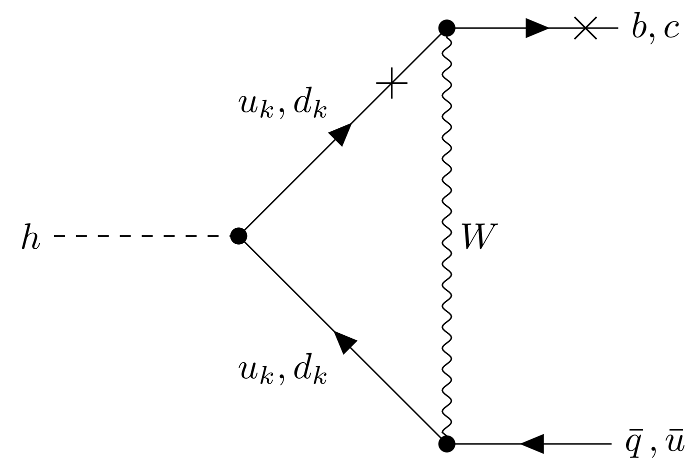
Tagging on-shell FCNCs @ FCC-ee

- While FCNCs forbidden at tree-level in SM, they are generated at 1-loop, e.g.

$$\mathcal{B}(Z \to bs) = (4.2 \pm 0.7) \times 10^{-8}\,,$$

$$\mathcal{B}(h \to b\bar{s}) = (2.7 \pm 0.5) \times 10^{-7}$$





$$\mathcal{M}_{\rm NDA}(Z \to b\bar{q}) \sim g^3 m_Z \frac{V_{tb}V_{tq}^*}{(4\pi)^2}\,, \quad \mathcal{M}_{\rm NDA}(h \to b\bar{q}) \sim g^2 y_t^2 y_b m_h \frac{V_{tb}V_{tq}^*}{(4\pi)^2}\,,$$

Tagging on-shell FCNCs @ FCC-ee

- While FCNCs forbidden at tree-level in SM, they are generated at 1-loop
- BSM Z & Higgs FCNCs are induced in models of VL fermions, multi-Higgs models

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

  - Example: VL D-quark

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

Tagging on-shell FCNCs @ FCC-ee

- While FCNCs forbidden at tree-level in SM, they are generated at 1-loop
- BSM Z & Higgs FCNCs are induced in models of VL fermions, multi-Higgs models

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

- Example: integrating out VL D-quark

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

➡ $$g_{sb}^{L} = \frac{g}{2c_W}\left(X^d_{23} + X^{d*}_{32}\right), \quad g_{sb}^{R} = 0,$$
$$y_{sb} = -X^d_{23}m_b/v, \quad y_{bs} = -X^d_{32}m_s/v$$

Tagging on-shell FCNCs @ FCC-ee

- While FCNCs forbidden at tree-level in SM, they are generated at 1-loop
- BSM Z & Higgs FCNCs are induced in models of VL fermions, multi-Higgs models

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

  - Example: type III THDM

$$\mathcal{L}_{\text{2HDM}} \supset -\frac{\sqrt{2}m_i}{v}\delta_{ij}\bar{Q}^i H_1 d^j_R - \sqrt{2}\,Y^d_{ij}\,\bar{Q}^i H_2 d^j_R - \frac{\sqrt{2}m_i}{v}\delta_{ij}\bar{Q}^i \tilde{H}_1 u^j_R - \sqrt{2}\,Y^u_{ij}\,\bar{Q}^i \tilde{H}_2 u^j_R$$

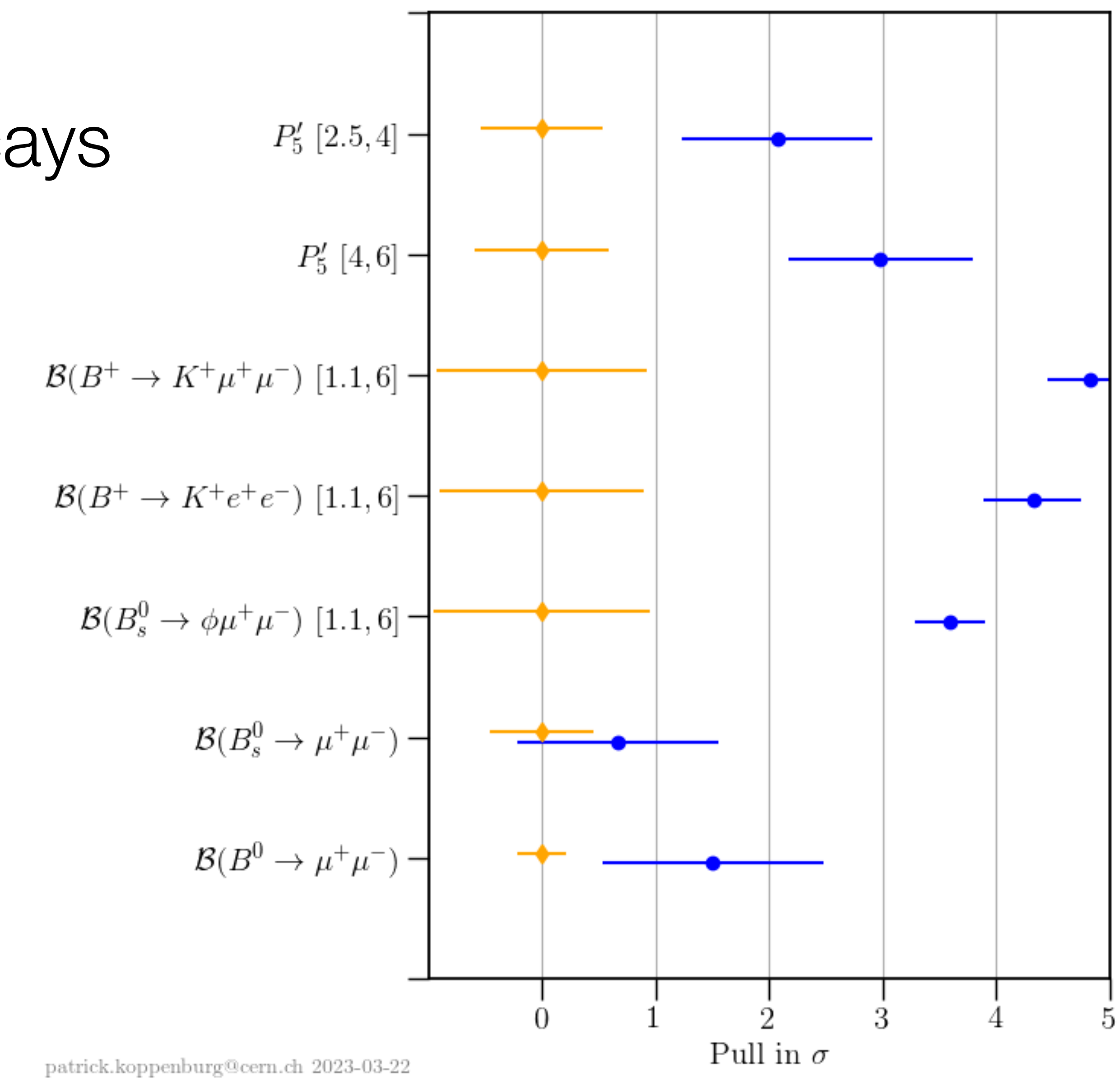
$$\Rightarrow \mathcal{L}_{\text{Yukawa}} \supset -\Big(\frac{m_i}{v}\delta_{ij}\cos\alpha - Y^d_{ij}\sin\alpha\Big)\bar{d}_{Li}d_{Rj}h + \text{h.c.} \qquad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} h \\ H \end{pmatrix}$$

$$\downarrow$$

$$y_{ij} = Y^d_{ij}\sin\alpha$$

Tagging on-shell FCNCs @ FCC-ee

- At present Z/h FCNCs mostly constrained by low energy observables
  - Rare (semi)leptonic B & D decays



Tagging on-shell FCNCs @ FCC-ee

- At present Z/h FCNCs mostly constrained by low energy observables
  - Rare (semi)leptonic B & D decays

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

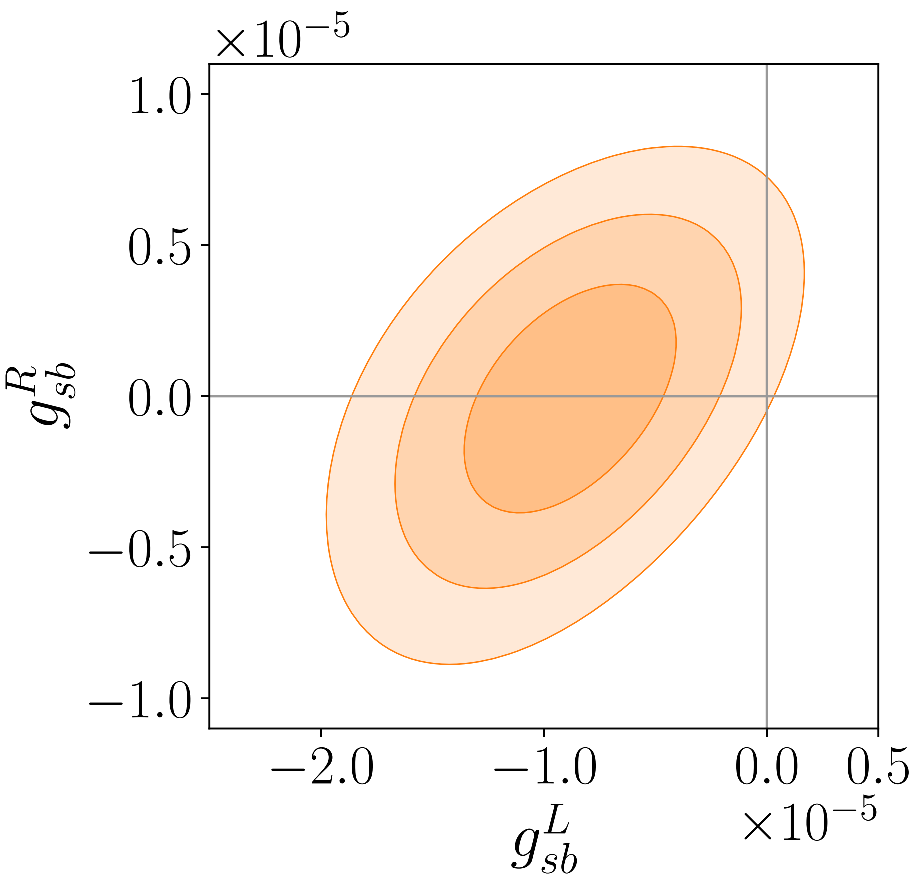
$$\delta C_{9,\ell\ell}^{(\prime)} = \mathcal{N} g_{sb}^{L(R)} g_{Z\ell\ell,\rm vec} \simeq 6.04 \times 10^3 g_{sb}^{L(R)} ,$$

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

$$g_{Z\ell\ell,\rm vec} = g\big(T_\ell^3 - 2\,Q_\ell s_W^2\big)/(2c_W)$$

$$g_{Z\ell\ell,\rm ax} = -gT_\ell^3/(2c_W)$$

$$\mathcal{N} = \sqrt{2}\pi/\big(G_F \alpha_{\rm em} V_{tb} V_{ts}^* m_Z^2\big)$$



Tagging on-shell FCNCs @ FCC-ee

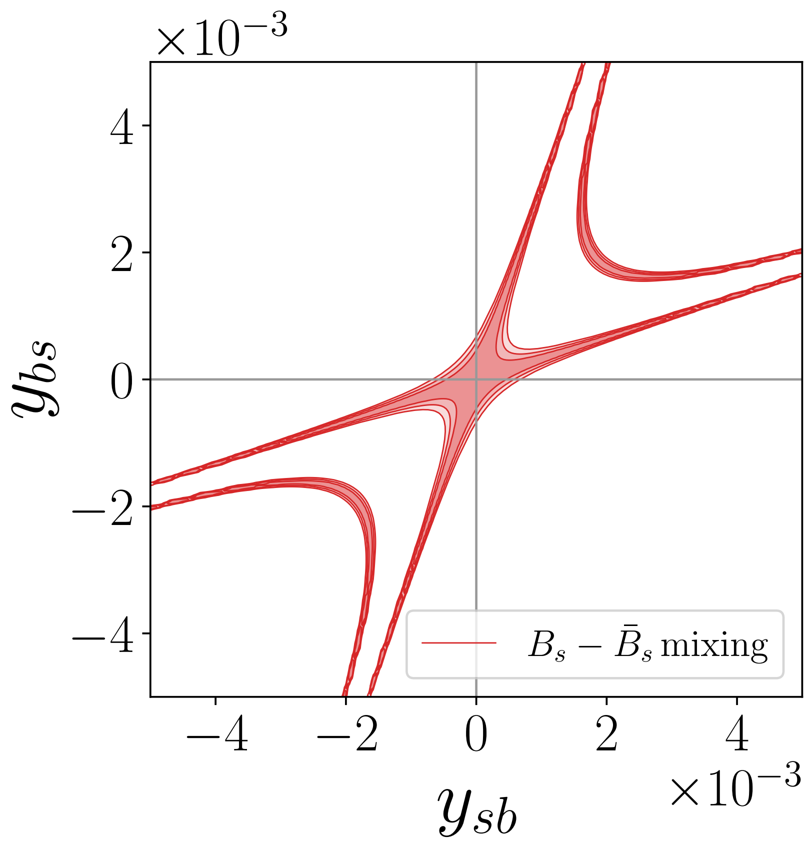
- At present Z/h FCNCs mostly constrained by low energy observables
    - Rare (semi)leptonic B & D decays
    - Neutral meson oscillations

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

$$C_2 = -\frac{\left(y_{bs}^*\right)^2}{2m_h^2},$$

$$C_2' = -\frac{\left(y_{sb}\right)^2}{2m_h^2},$$

$$C_4 = -\frac{\left(y_{bs}^* y_{sb}\right)}{m_h^2}.$$



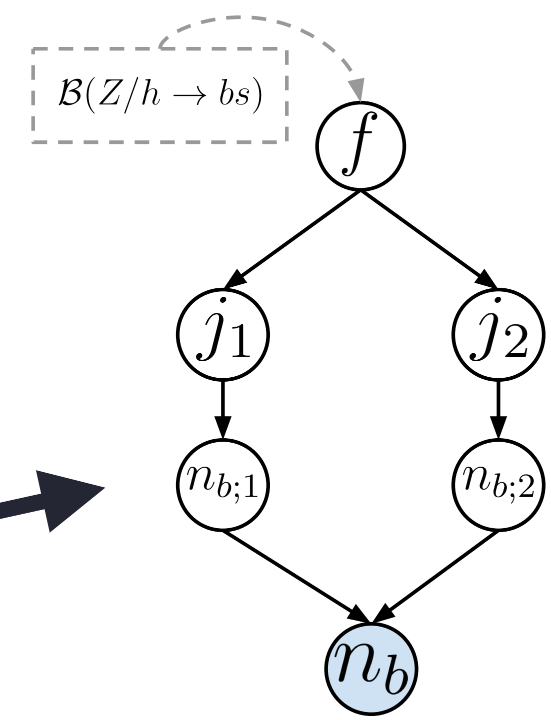
Tagging on-shell FCNCs @ FCC-ee

- Main strategy: apply orthogonal b/s or c/u taggers
  - Categorize events by # of jets
  - construct explicit probabilistic model for events (example with only b-tags)

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

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

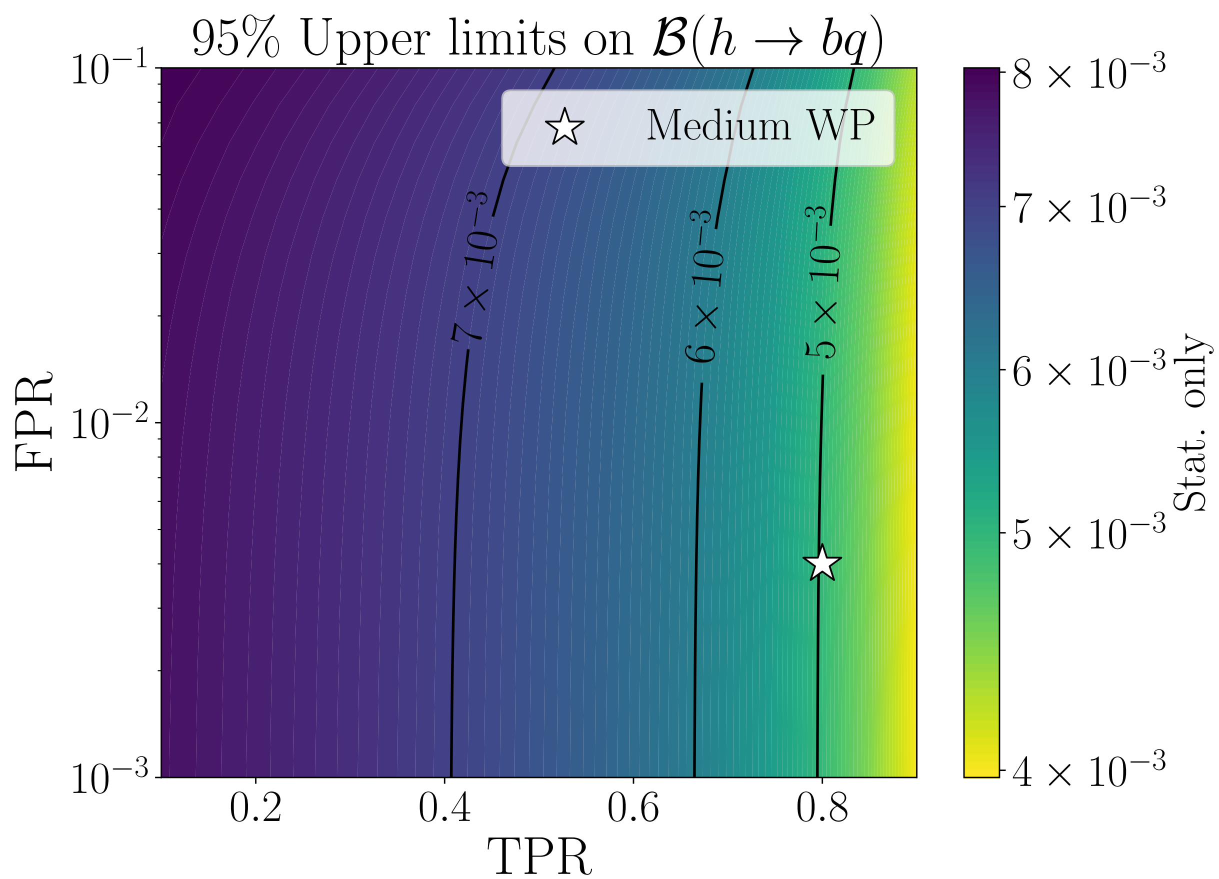
$$\epsilon^b_{\beta;\mathrm{Med}} = \{\underset{g}{0.007},\ \underset{s}{0.0001},\ \underset{c}{0.003},\ \underset{b}{0.80}\},$$

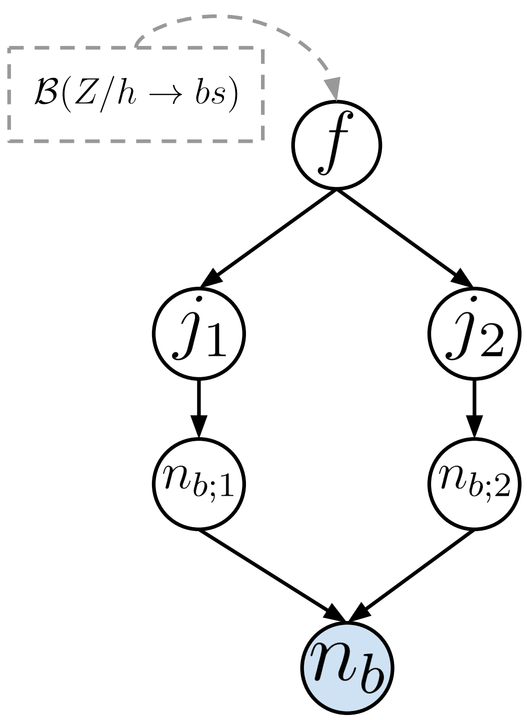


  - infer the rate through *tractable* likelihood maximization (profiling)

Tagging on-shell FCNCs @ FCC-ee

- Main strategy: apply orthogonal b/s or c/u taggers
  - construct explicit probabilistic model for events (example with only b-tags)





Tagging on-shell FCNCs @ FCC-ee

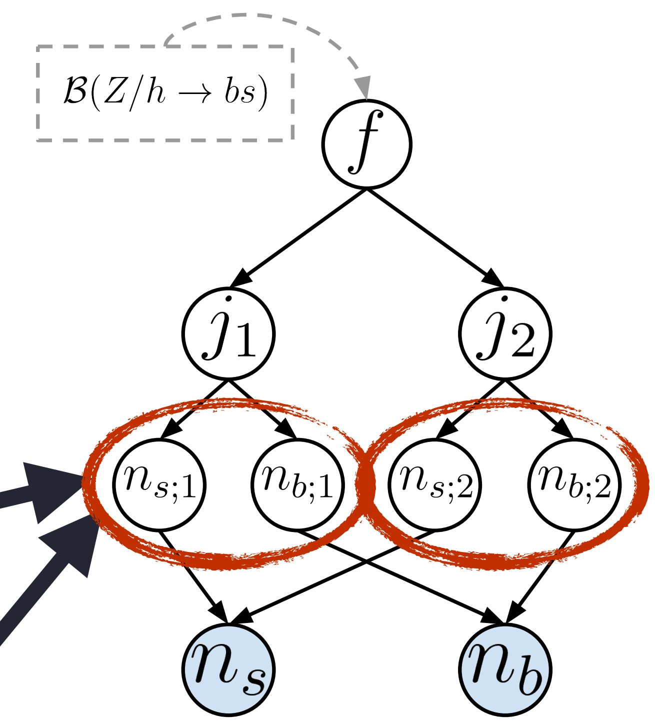
- Main strategy: apply orthogonal b/s or c/u taggers
  - construct explicit probabilistic model for events (example with b- & s-tags)

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

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

$$\begin{array}{rl} & \quad\;\; g \qquad\quad s \qquad\quad c \qquad\quad b \\ \epsilon^b_{\beta;\mathrm{Med}} &= \{0.007,\ 0.0001,\ 0.003,\ 0.80\}, \\ \epsilon^s_{\beta;\mathrm{Loose}} &= \{0.20,\ 0.90,\ 0.10,\ 0.01\}, \end{array}$$

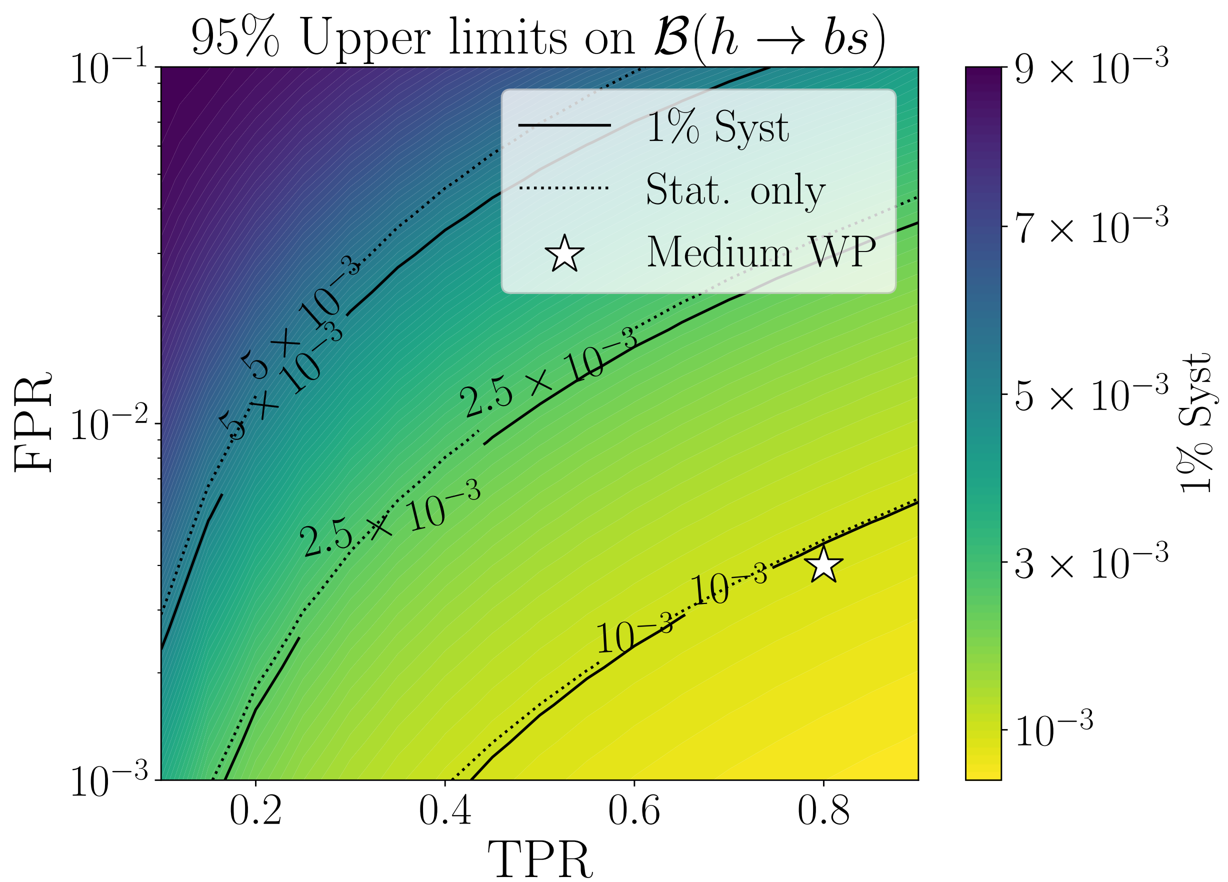
$$\begin{array}{rl} \epsilon^s_{\beta;\mathrm{Med}} &= \{0.09,\ 0.80,\ 0.06,\ 0.004\} \\ \epsilon^b_{\beta;\mathrm{Loose}} &= \{0.02,\ 0.001,\ 0.02,\ 0.90\} \end{array}$$

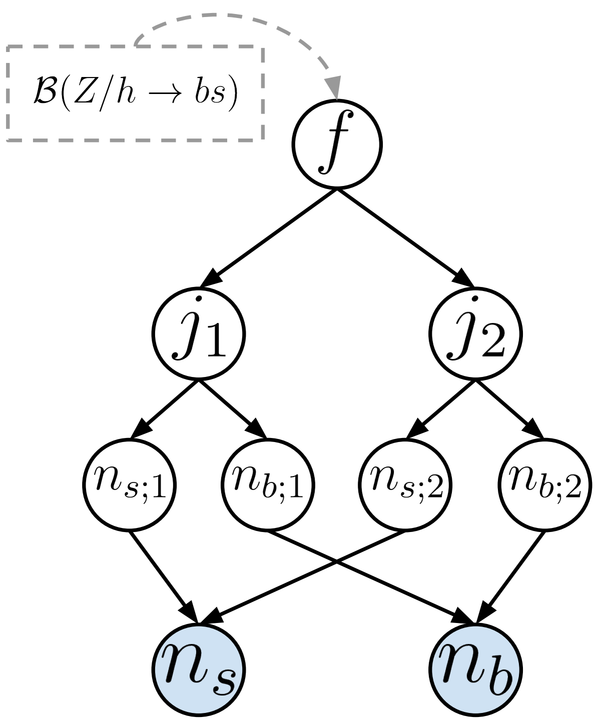


consistency condition!
(ensured via pre-anti-tagging)

Tagging on-shell FCNCs @ FCC-ee

- Main strategy: apply orthogonal b/s or c/u taggers
  - construct explicit probabilistic model for events (example with b- & s-tags)

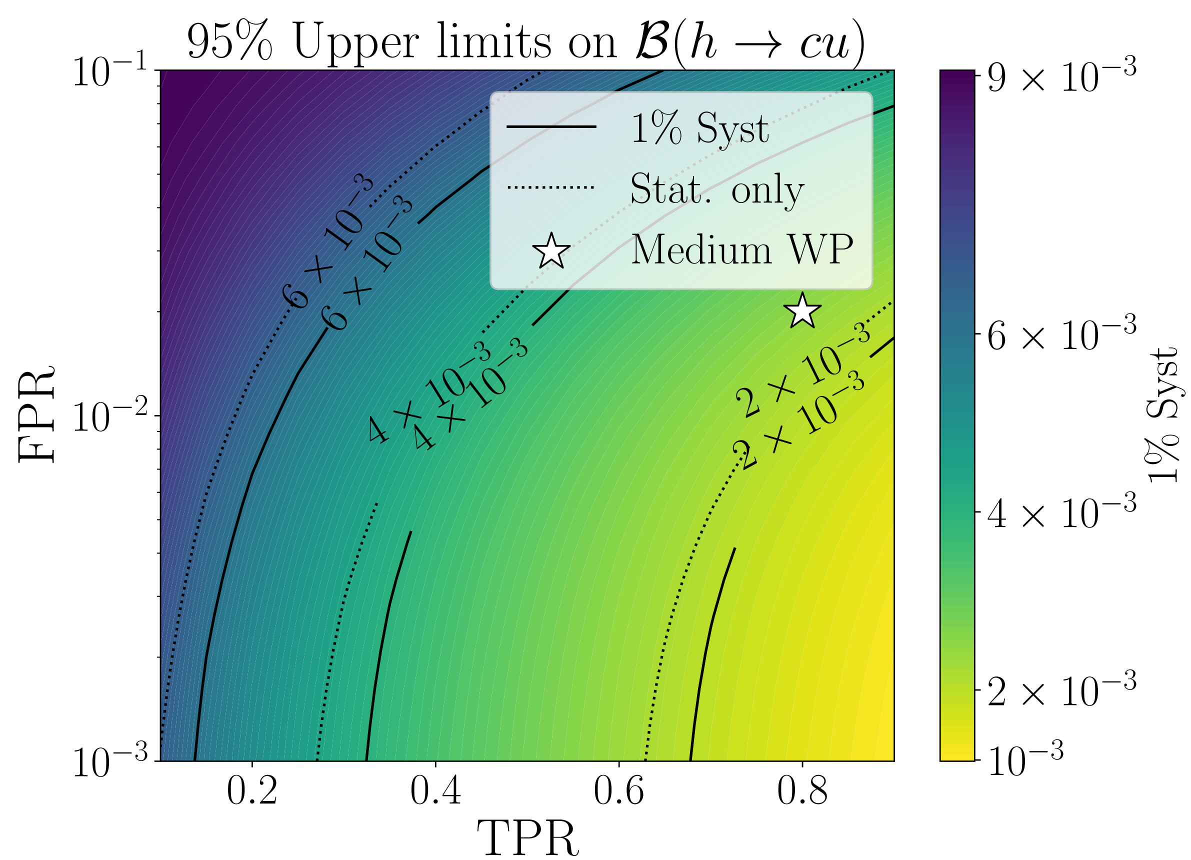


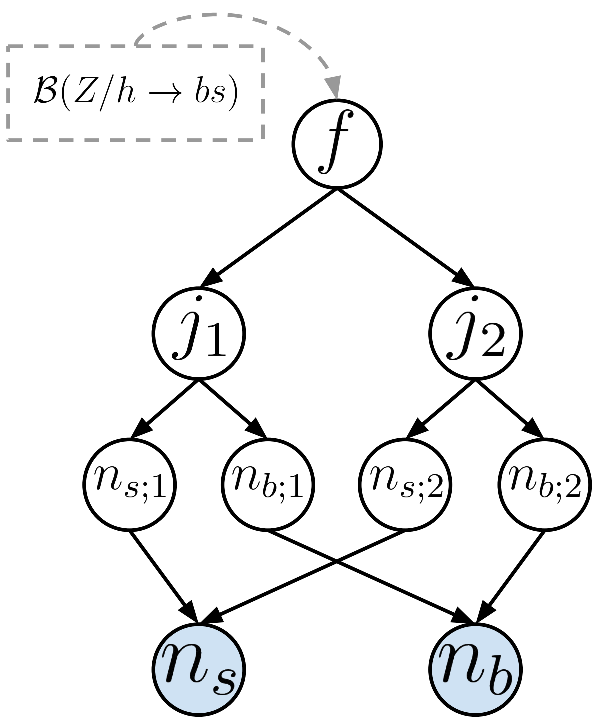


➡ Sensitivity reach statistics dominated!

Tagging on-shell FCNCs @ FCC-ee

- Main strategy: apply orthogonal b/s or c/u taggers
  - construct explicit probabilistic model for events (example with c-tag & c-anti-tag)

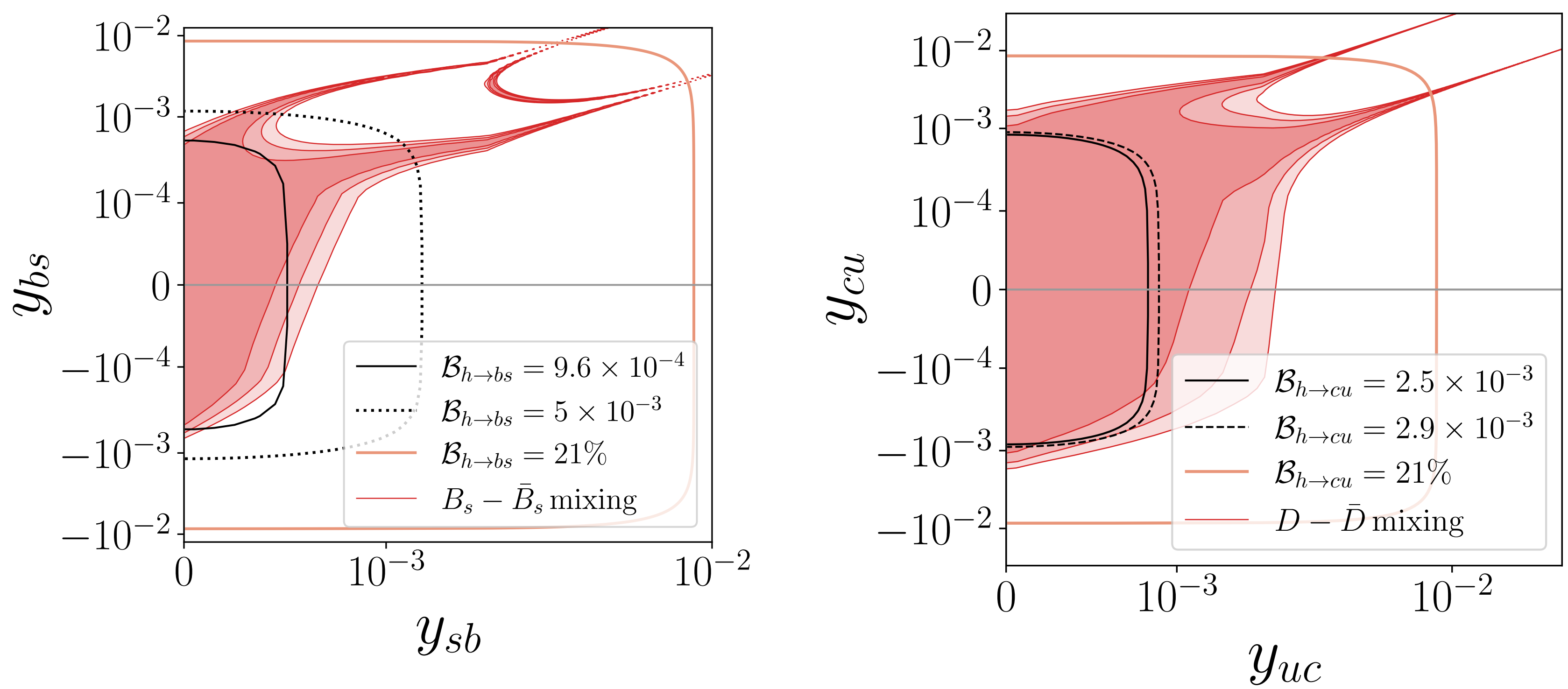




- Possible improvements with dedicated light-quark tagging?

Tagging on-shell FCNCs @ FCC-ee

- Does it matter?

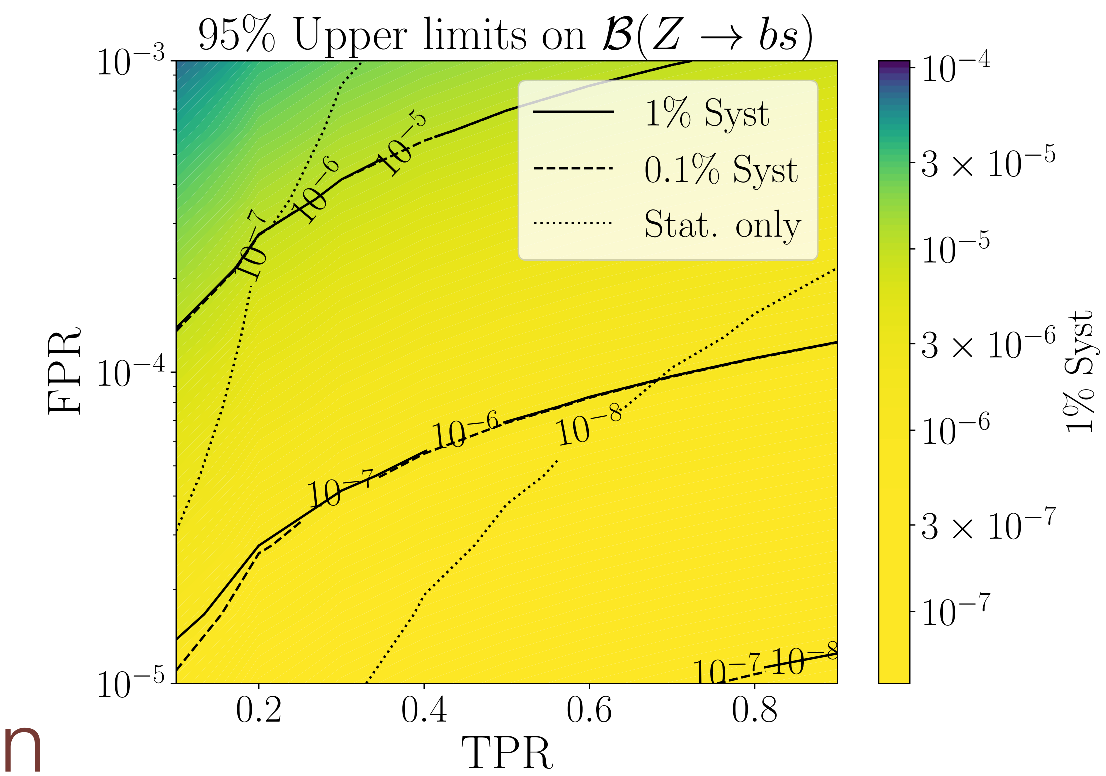


- Current direct constraint from bound on Higgs width
- At FCC-ee direct Higgs measurements complementary & competitive with meson mixing constraints!

Tagging on-shell FCNCs @ FCC-ee

- Z FCNCs
  - Their effects already observed/measured indirectly in $b \to s\ ll$ transitions - can on-shell measurements compete?
    - sensitivity @ FCC-ee limited by tagger systematics!
    - reaching SM requires improvements in tagging (detector limitations)

➡ ~10^{-3} *b*-quarks decay within projected vertexing resolution



Conclusions

- FCC-ee could be a powerful and competitive probe of flavour physics post-2030
  - Effort underway to understand exp. precision with which rare decays of c- and b-hadrons and CP violation in heavy-quark sector & LFV processes could be measured
    - Flavour Physics defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements
    - In the coming phase important interplay of physics performance with detector concepts
    - On theory side: go beyond benchmark modes — fill in possible gaps

Conclusions

- Recent advances in jet tagging allow for high-energy colliders such as the prospective FCC-ee to place phenomenologically relevant bounds on rare *Z* and Higgs decays involving flavored jets
- Introduction of "orthogonal" sets of taggers for multi-class classification & explicit likelihood models
  - Bounds on *h/Z* FCNCs at FCC-ee complementary to meson mixing, rare meson decays
    - In case of anomalies observed at low energies, could help disentangle possible UV sources
    - Probing SM *Z*-FCNCs would possibly require detector-level improvements

Conclusions

- Recent advances in jet tagging allow for high-energy colliders such as the prospective FCC-ee to place phenomenologically relevant bounds on rare *Z* and Higgs decays involving flavored jets
- Introduction of “orthogonal” sets of taggers for multi-class classification & explicit likelihood models
  - Bounds on *h/Z* FCNCs at FCC-ee complementary to meson mixing, rare meson decays
  - Related applications to W decays:
    - Prospects for direct $|V_{tx}|$ extraction at HL-LHC

      D. Faroughy et al., 2209.01222
    - Extraction of $|V_{cb}|$ from W decays (at FCC-ee)

      M.-H. Schune, FCC PE Workshop 2020