

H/Z & *W* flavor changing decays @ future lepton colliders

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@FCC Italy&France Workshop 2024, 5/11/2024

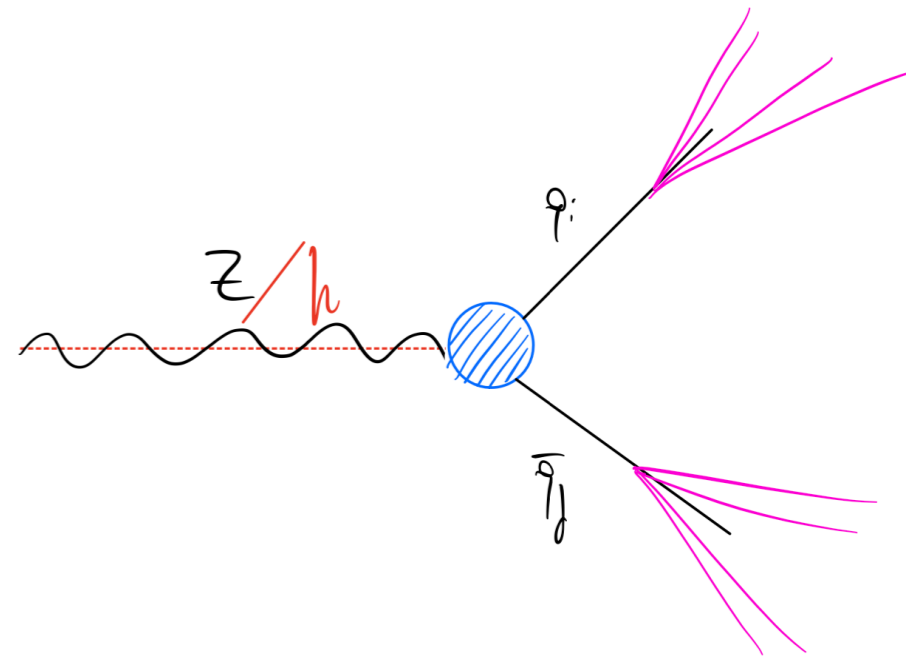
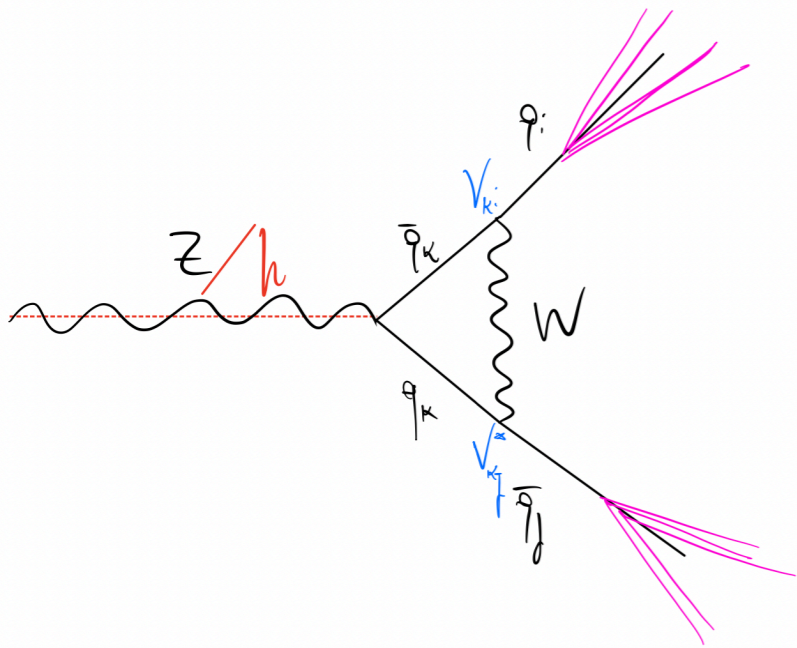
based on

J. F. Kamenik, A. Korajac, M. Szewc, MT, J. Zupan, 2306.17520

D. Marzocca, M. Szewc, MT, 2405.08880



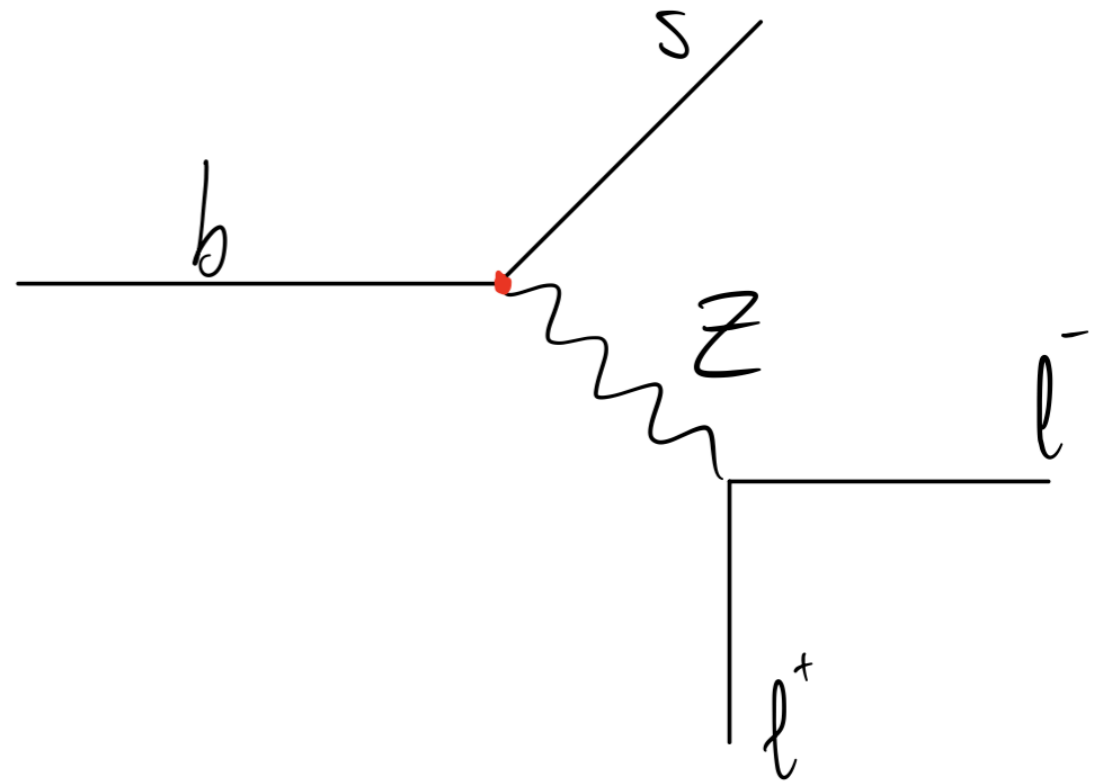
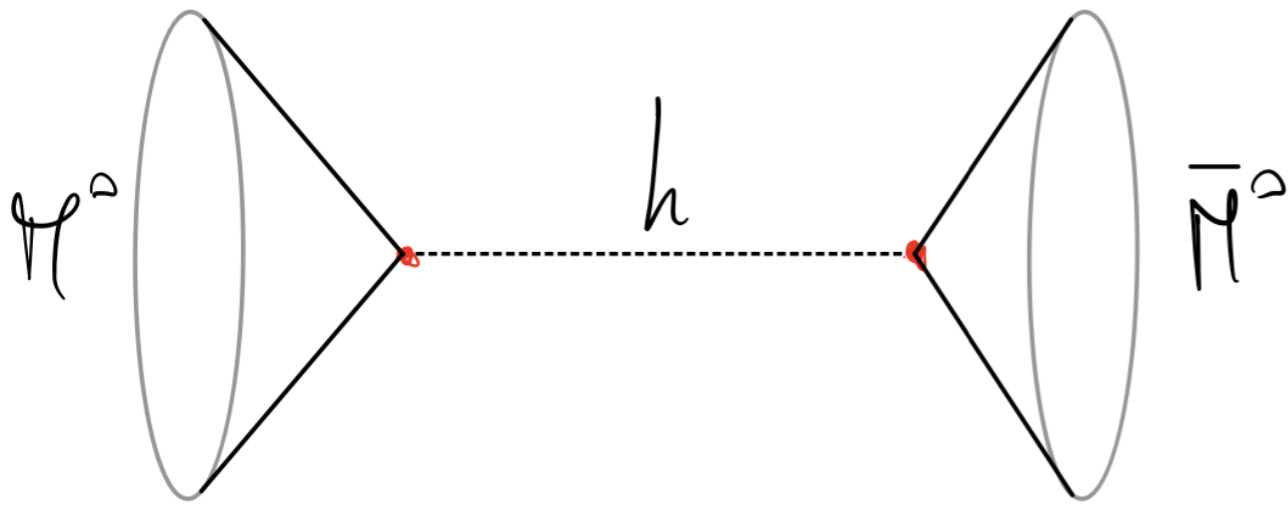
Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE



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

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

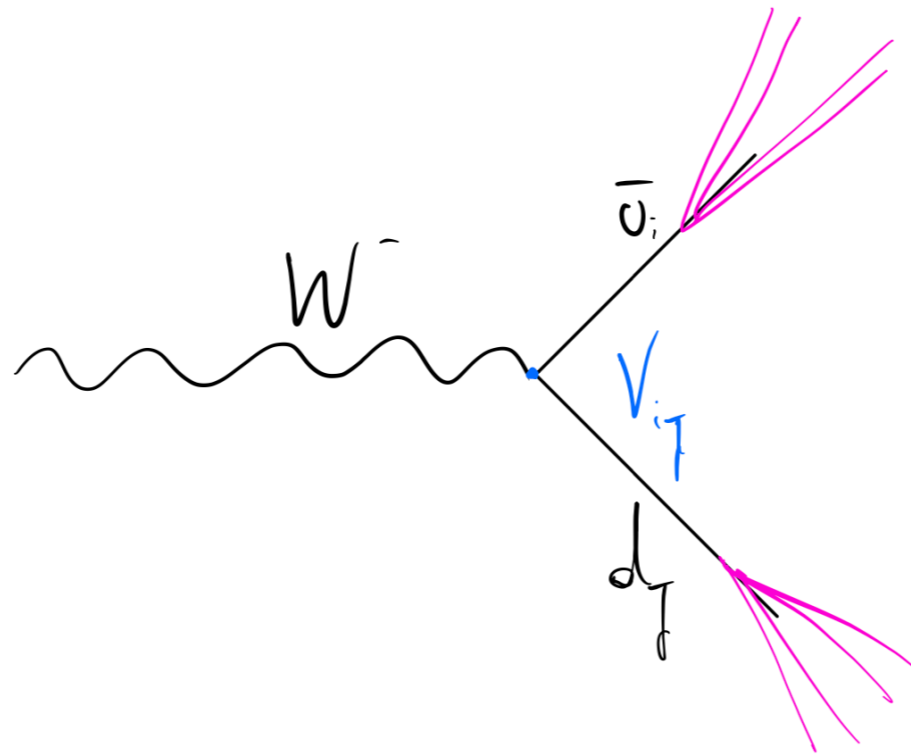
Decay	SM prediction	exp. bound	indir. constr.
$\mathcal{B}(h \rightarrow bs)$	$(8.9 \pm 1.5) \cdot 10^{-8}$	0.16 ▲	2×10^{-3} ★
$\mathcal{B}(h \rightarrow bd)$	$(3.8 \pm 0.6) \cdot 10^{-9}$	0.16 ▲	10^{-3} ★
$\mathcal{B}(h \rightarrow cu)$	$(2.7 \pm 0.5) \cdot 10^{-20}$	0.16 ▲	2×10^{-2} ★
$\mathcal{B}(Z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



★ Meson mixings

● Global fits (mostly semi-leptonic)

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Semileptonic channel for V_{cb}

V_{ts} from $t \rightarrow Ws$

Liang et al.: 2406.01675

Xunwu's talk at ECFA Workshop: <https://indico.in2p3.fr/event/32629>

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix}$$

$ V_{ij} $	Current	
$ V_{cs} $	0.975 ± 0.006	(0.6%)
$ V_{cb} $	$(40.8 \pm 1.4) \times 10^{-3}$	(3.4%)

Produce on-shell H/Z/W bosons

**With large statistics and low
background**

Apply flavor taggers

Count events

A diagram of an electron-positron collider beam. Two red curved arrows point towards each other, meeting at a central point. The left arrow is labeled 'e+' and the right arrow is labeled 'e-', representing the collision of a positron and an electron.

e^+ e^-

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

Zh thr: $N_H \sim 10^6$

WW thr: $N_W \sim 6 \times 10^8$

$t\bar{t}$ thr: $N_t \sim 10^6$

Signals

Z pole running

$$\sqrt{s} = m_Z$$

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

hZ running

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

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

Backgrounds

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)

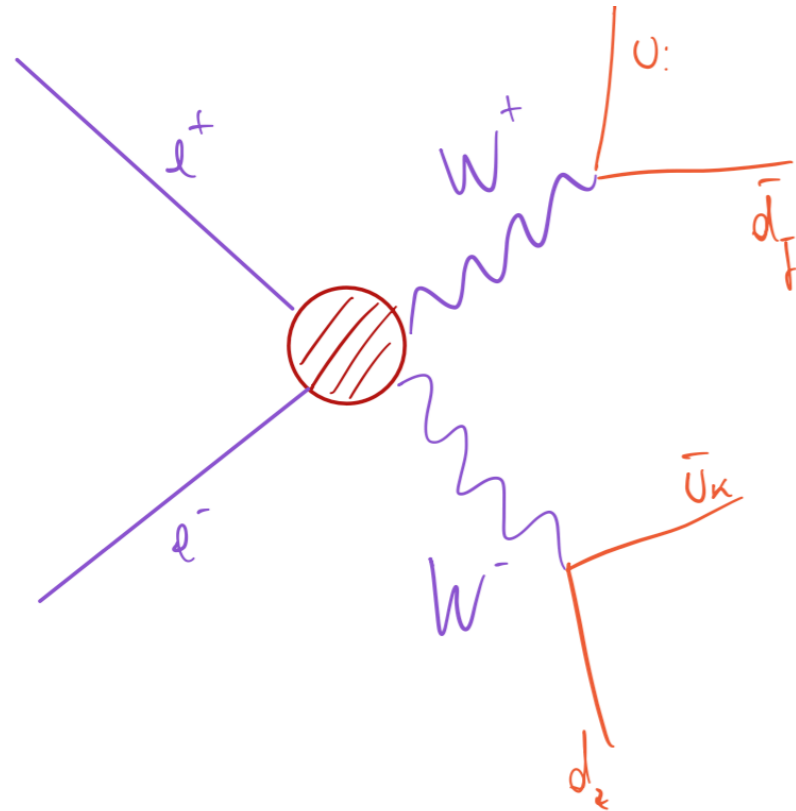
Parameters	Nominal Value	Rel. uncert. (%)
$\mathcal{B}(h \rightarrow gg)$	1.4%	1.2
$\mathcal{B}(h \rightarrow ss)$	0.024%	160
$\mathcal{B}(h \rightarrow cc)$	2.9%	2.8
$\mathcal{B}(h \rightarrow bb)$	56%	0.4
N_h	6.7×10^5	0.5
\mathcal{A}	0.70	0.1

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/)

Signal

$$e^+e^- \rightarrow W^+W^- \rightarrow 4j$$



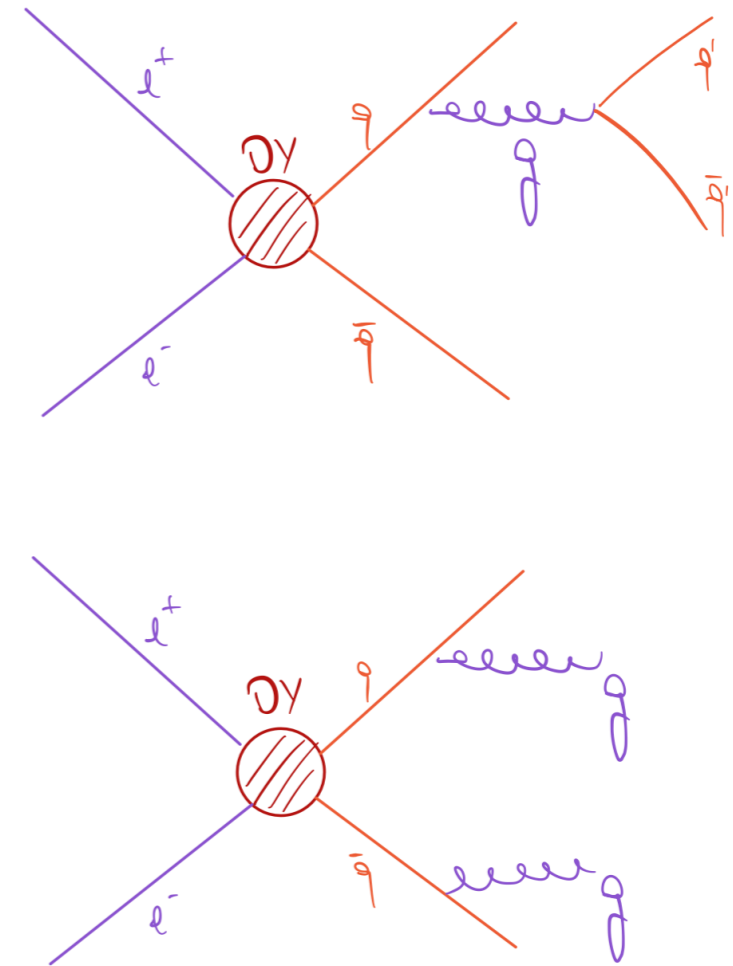
Semileptonic channel for V_{cb}

Liang et al.: 2406.01675

$$\sqrt{s} \simeq 161 \text{ GeV}$$

Backgrounds (Drell-Yan)

$$e^+e^- \rightarrow 4j, 2j2g$$



10^6 events with MadGraph (parton level only)

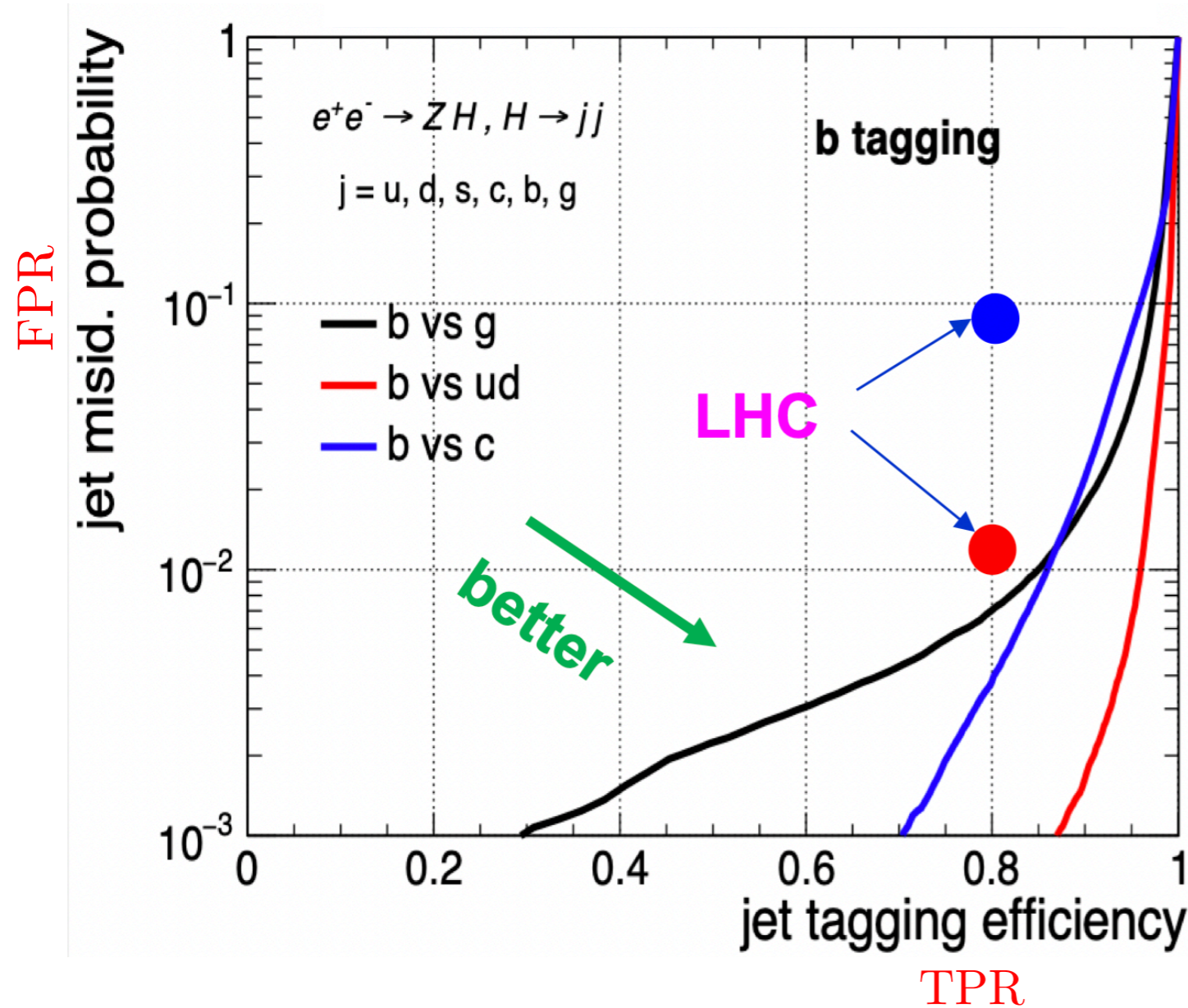
$$(m_{ij}, m_{kz}) \supset (m_W \pm \sigma_W, m_W \pm \sigma_W)$$

$\sim 10^3$ events pass

Jet flavor taggers

Tools to classify flavor of jets from input data

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



$$\beta = \{b, s, c, u, d, g\}$$

$$\epsilon_{\beta}^b = \{0.8, 0.0001, 0.003, 0.0005, 0.0005, 0.007\}$$

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

ATLAS: 1907.05120
 CMS: 1712.07158

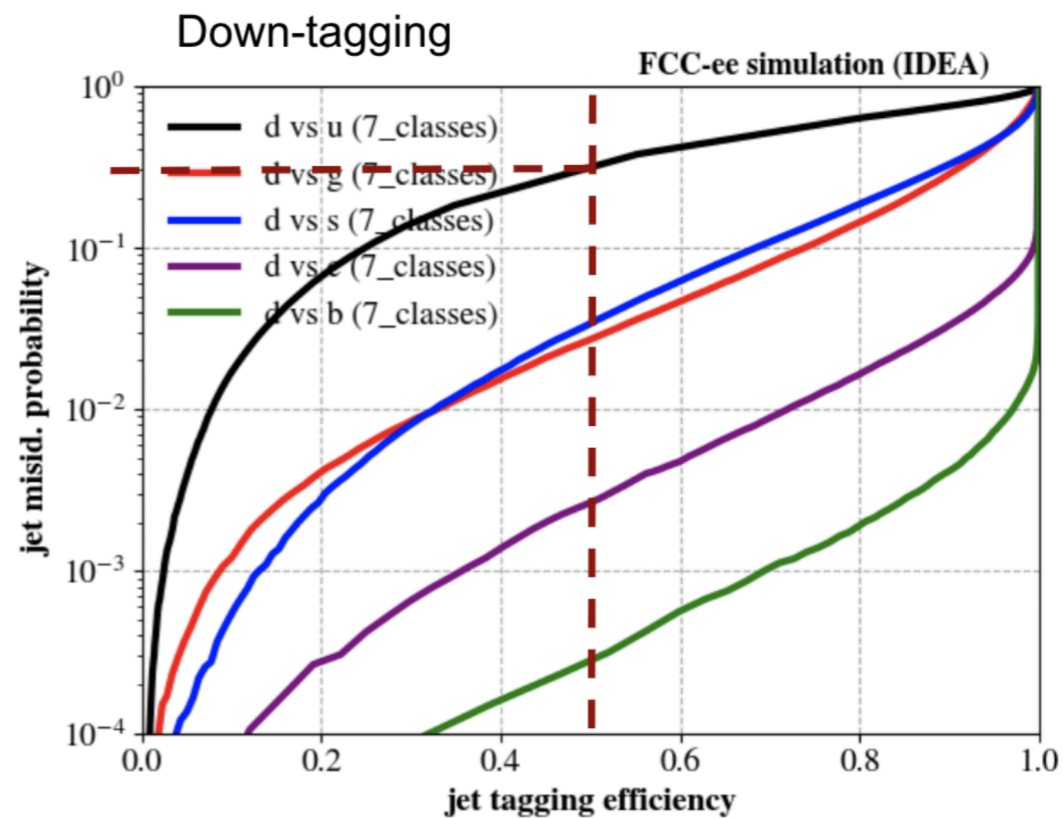
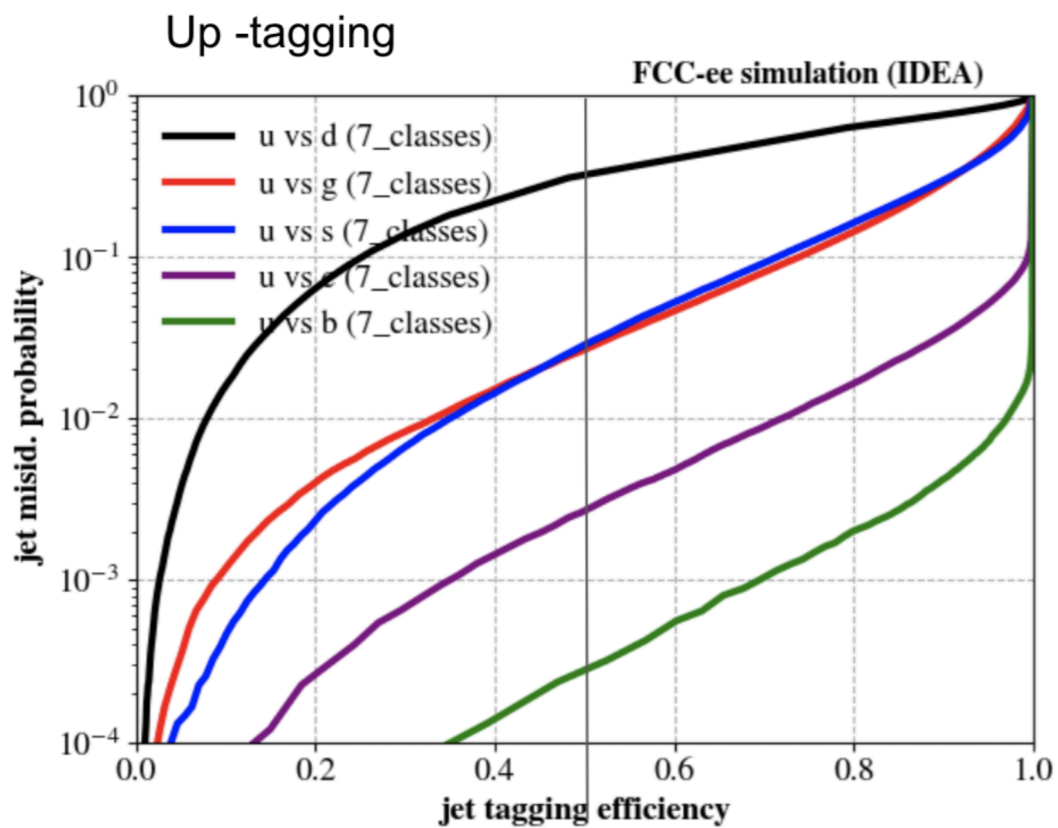
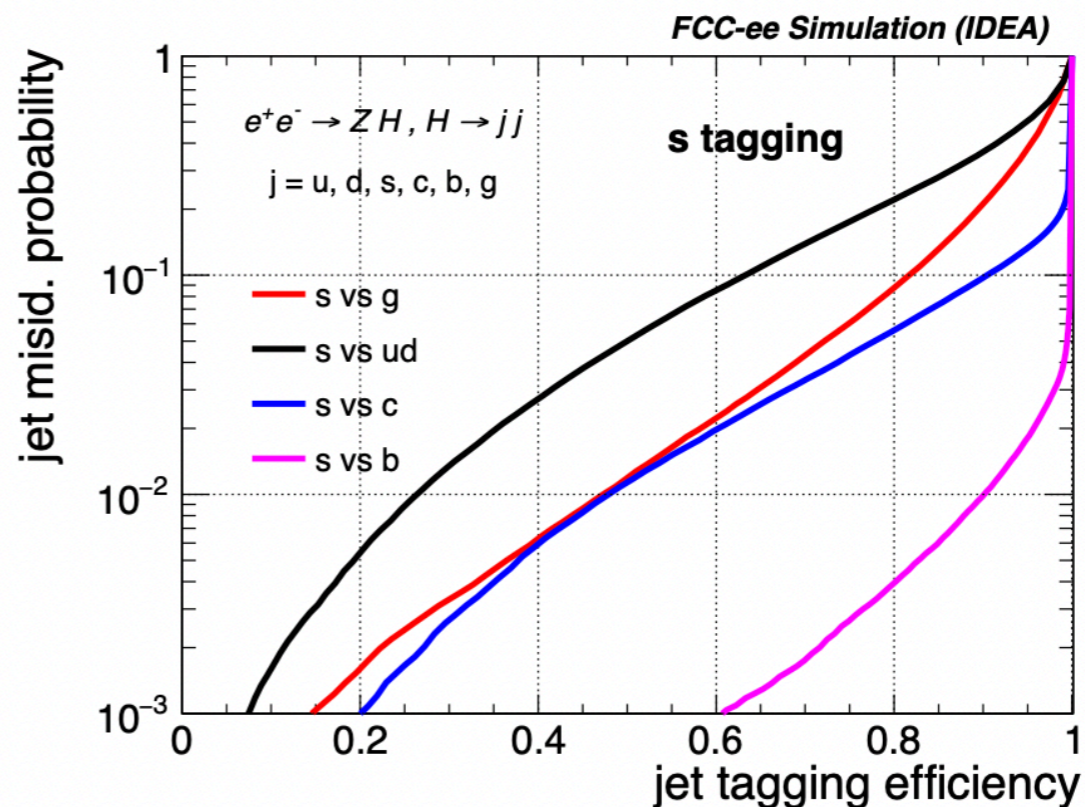
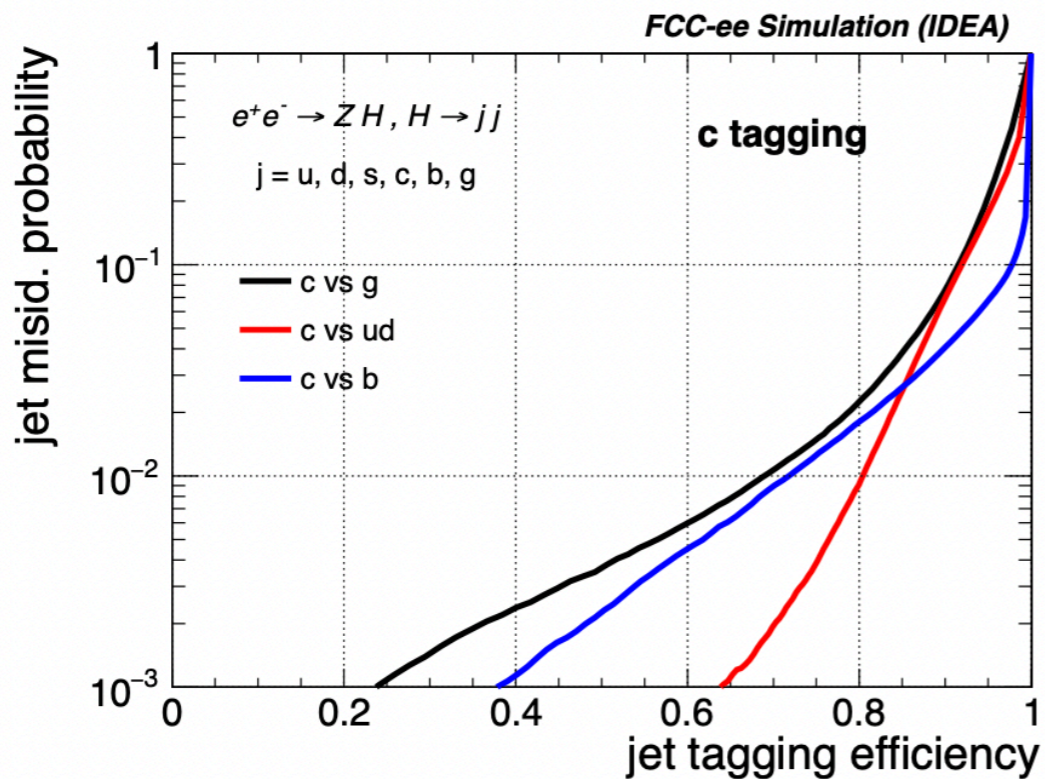
Calibration at Z-pole

Could go to 0.1%

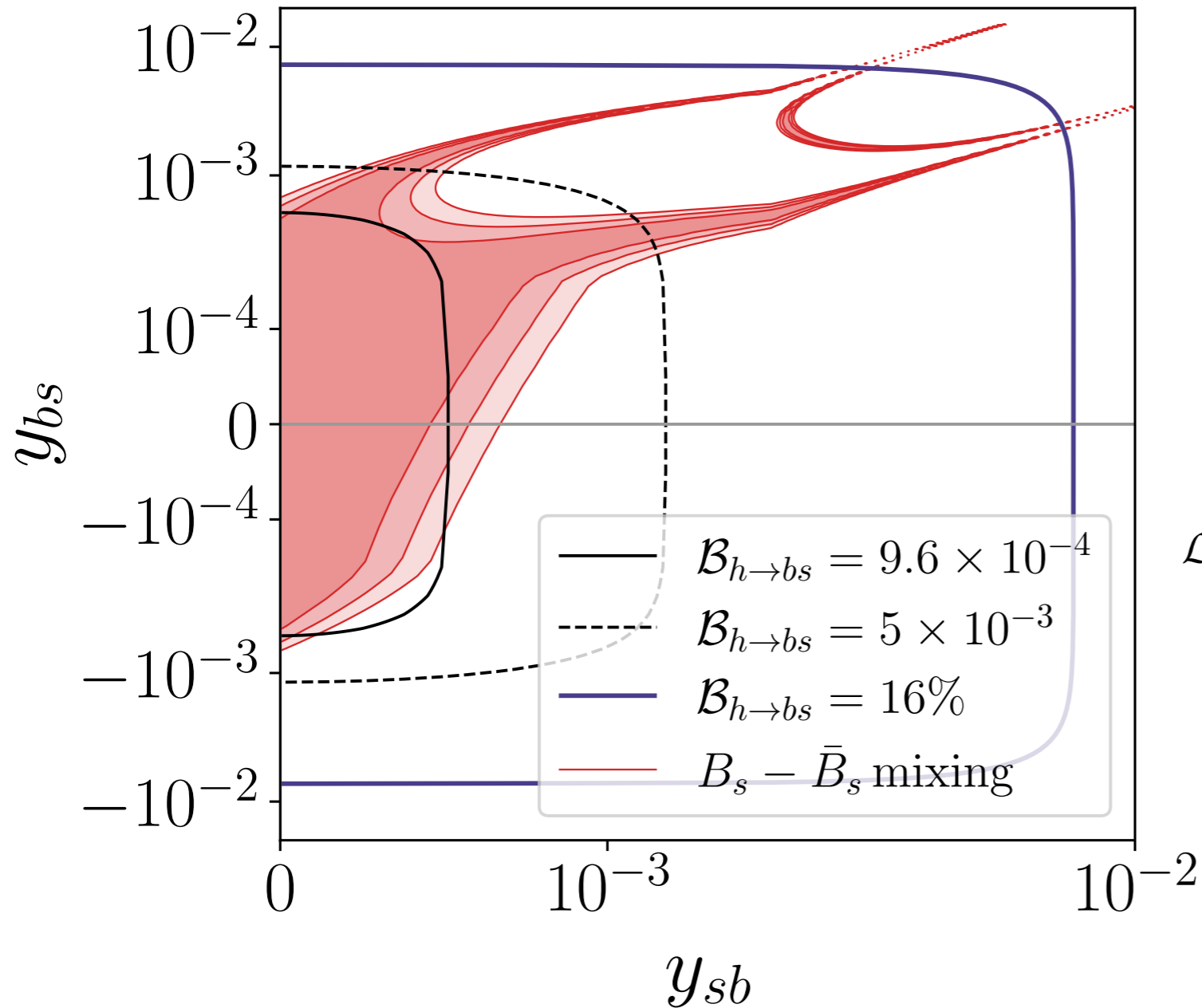
Bedeschi, Gouskos, Selvaggi: 2202.03285
 Gouskos' talk at "FCC Physics Workshop" (indico.cern.ch/event/1176398/)

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

Jet flavor taggers



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



Match to WET + wilson + flavio

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

Theoretical uncertainties on meson mixing parameters will still be dominating by ~2030:
2006.04824

FCC-ee reach

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

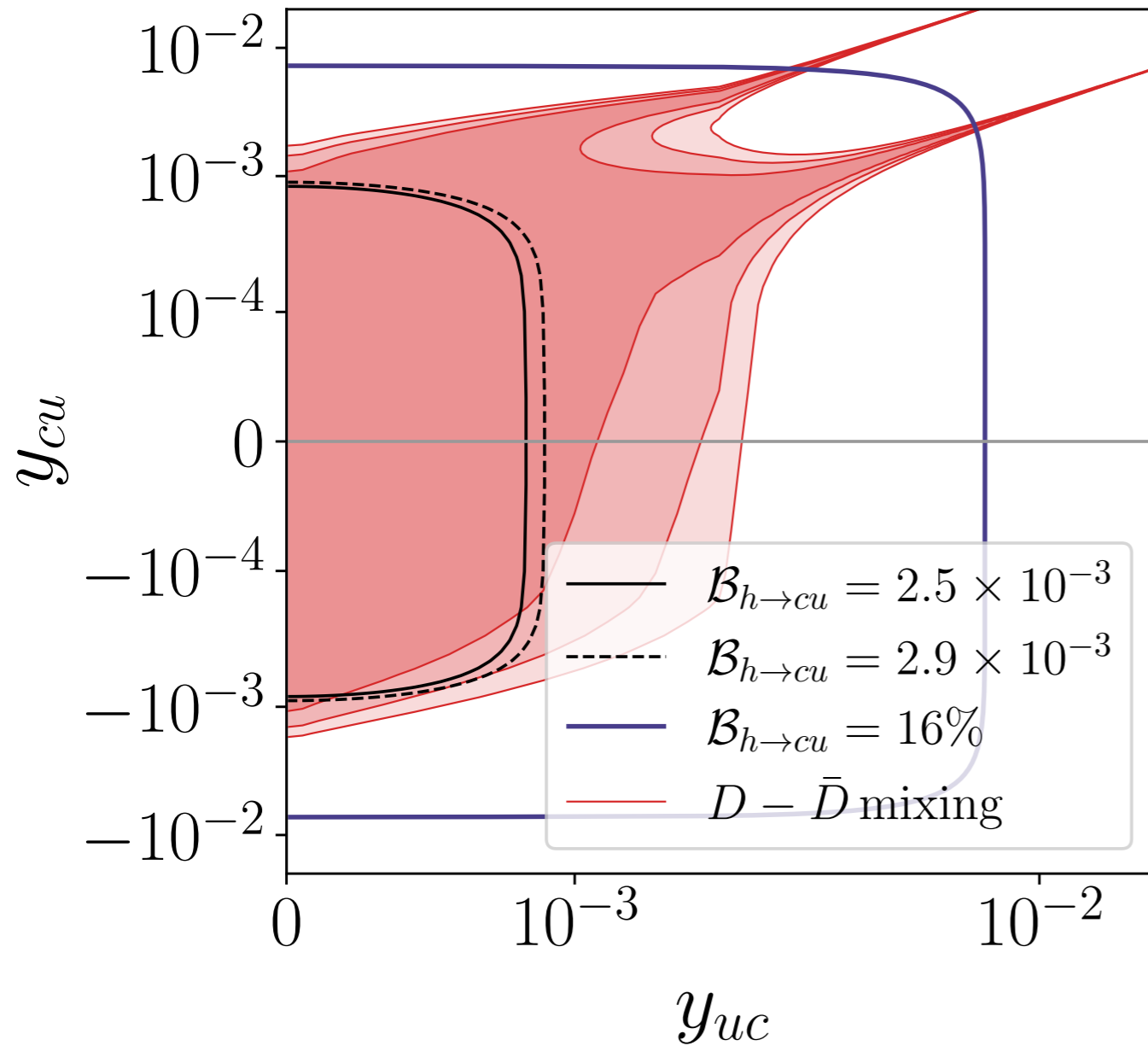
CepC reach [Liang et al.: 2310.03440](#)

$$\mathcal{B}(h \rightarrow bs) \lesssim 2 - 9 \times 10^{-4}$$

Indirect constraints

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

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



Theoretical uncertainties on meson mixing parameters will still be dominating by ~2030:
2006.04824

Indirect constraints

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

FCC-ee reach (no u-tagger)

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

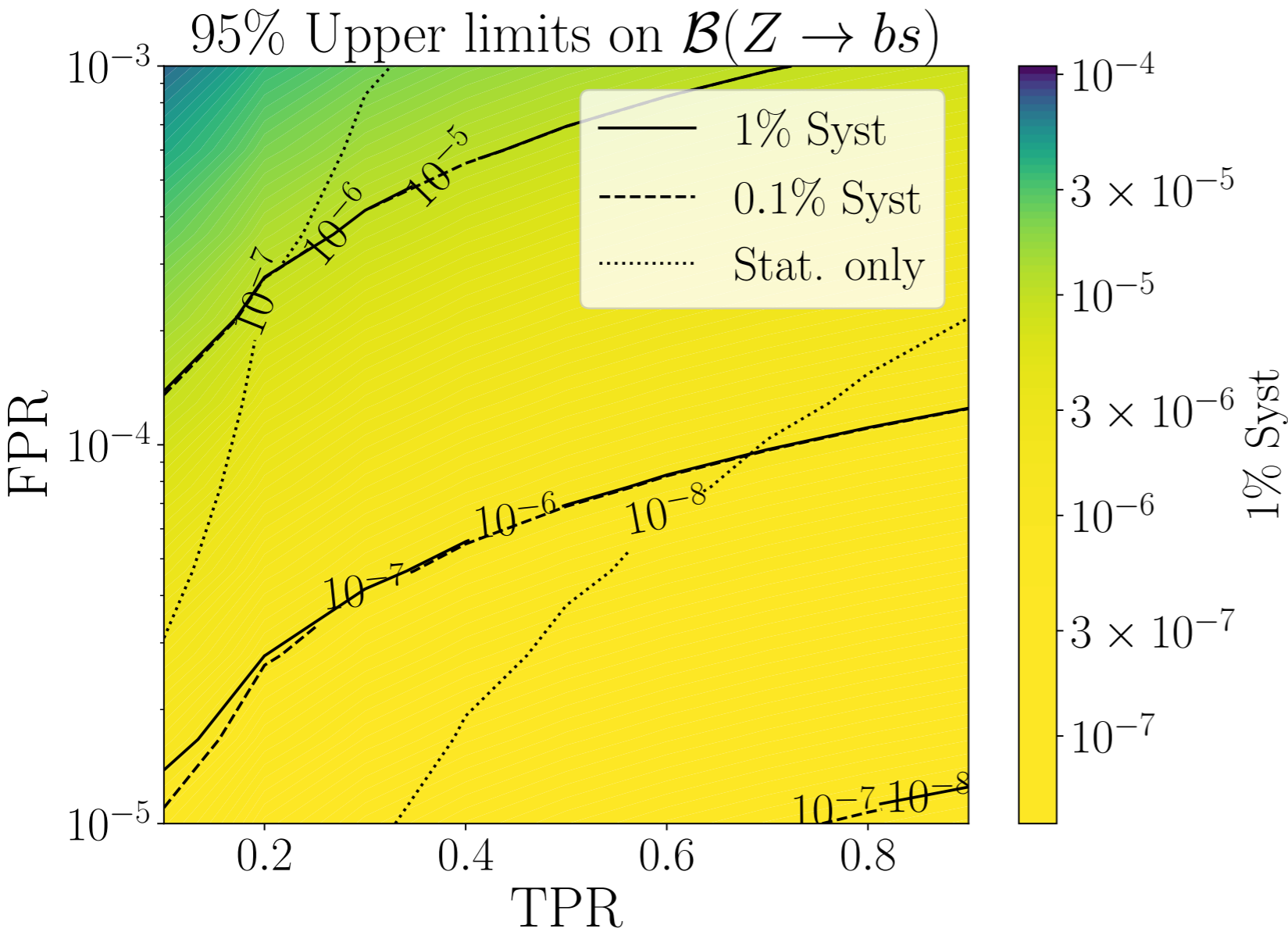
FCC-ee reach (with u-tagger)

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

CepC reach

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

Liang et al.: 2310.03440



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?

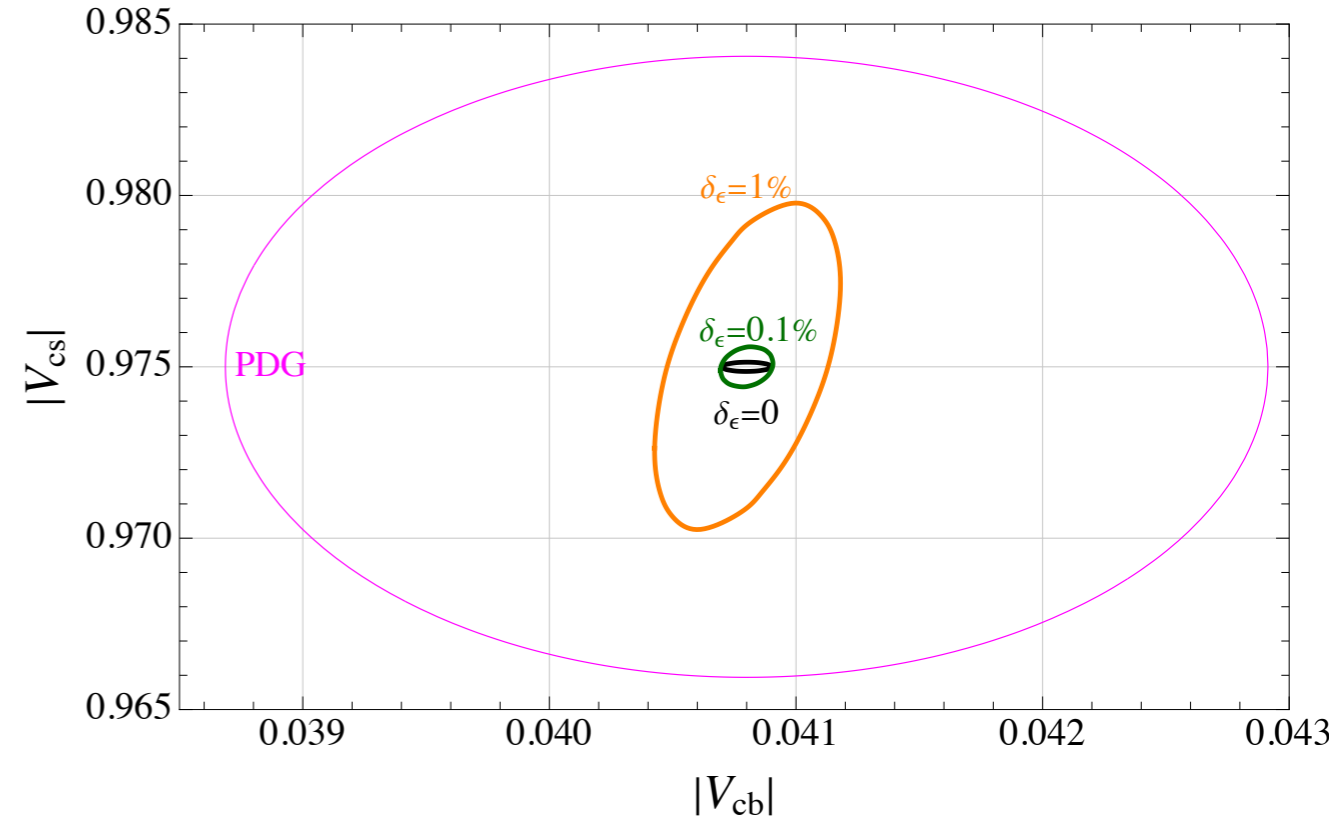
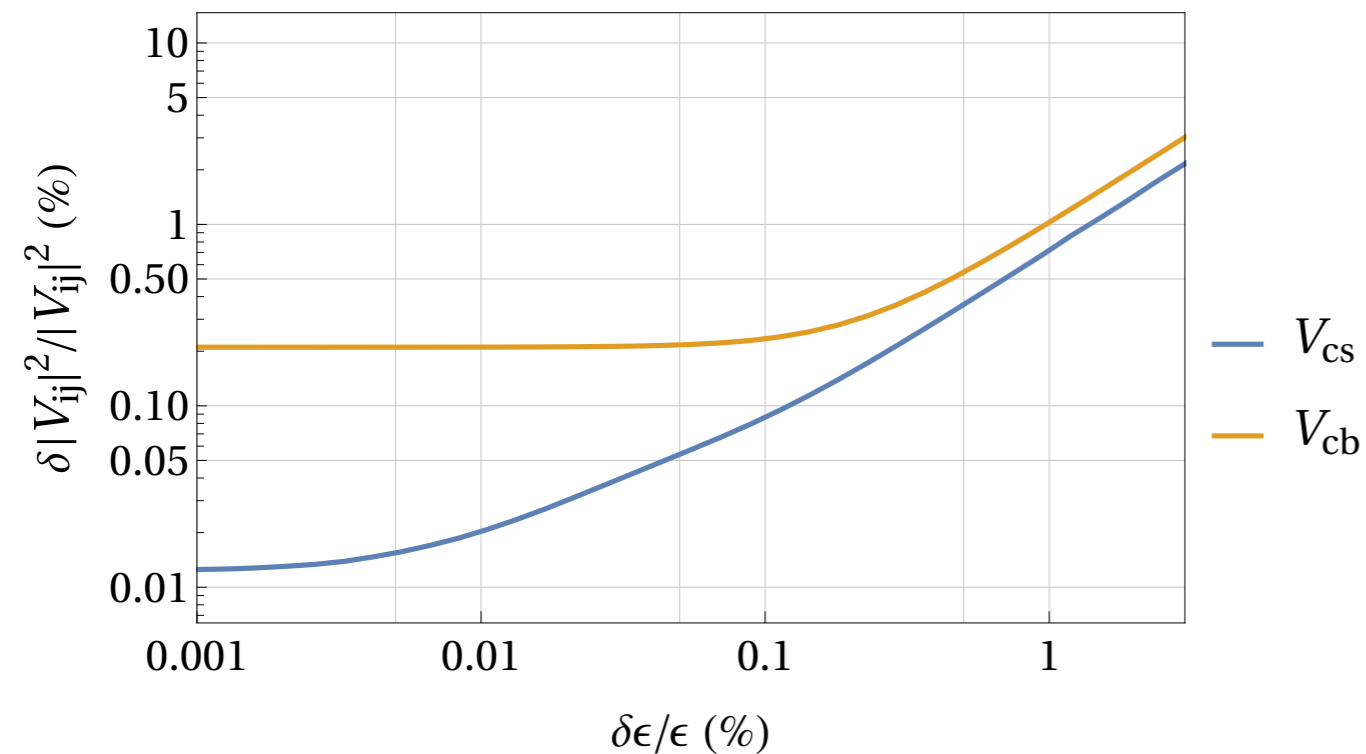
See Selvaggi's talk at 7th FCC Workshop
[\(https://indico.cern.ch/event/1307378/\)](https://indico.cern.ch/event/1307378/)

← SM level

Project % sensitivity on $|V_{ij}|$

$ V_{ij} $	Current (PDG)		FCC-ee ($\delta_\epsilon = 1\%$)	FCC-ee ($\delta_\epsilon = 0.1\%$)	FCC-ee (Stat. only)
$ V_{cs} $	0.975 ± 0.006	(0.6%)	0.36%	0.05%	0.008%
$ V_{cb} $	$(40.8 \pm 1.4) \times 10^{-3}$	(3.4%)	0.52%	0.16%	0.14%

See 2406.01675 for CepC



Take home messages

- Upper limits for H/Z at FCC-ee and CepC are above the SM level
- Improve limits on Higgs FC couplings
- Results depend on taggers performances and systematics
- “Lattice-free” determination of V_{cb} and V_{cs} (and others?)

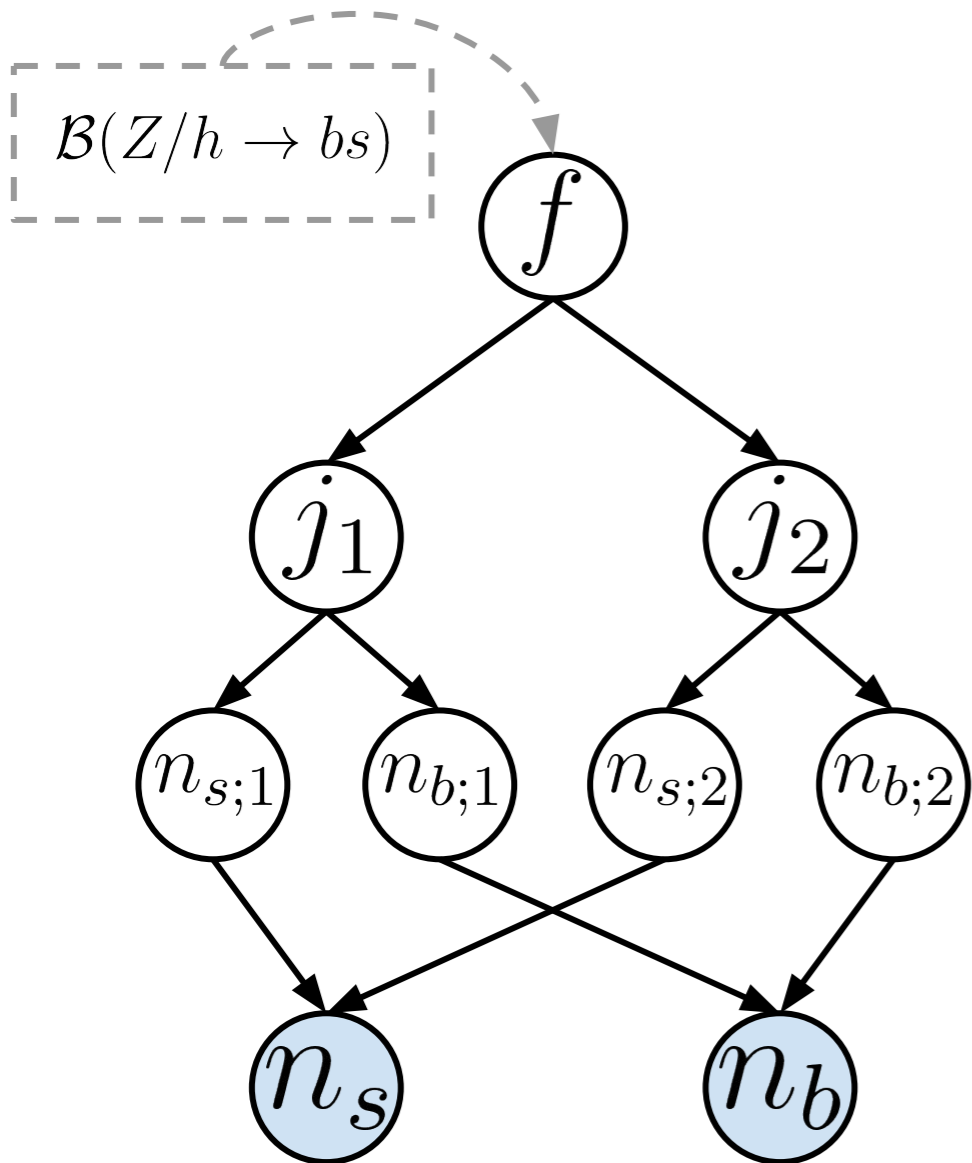
Backup slides

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

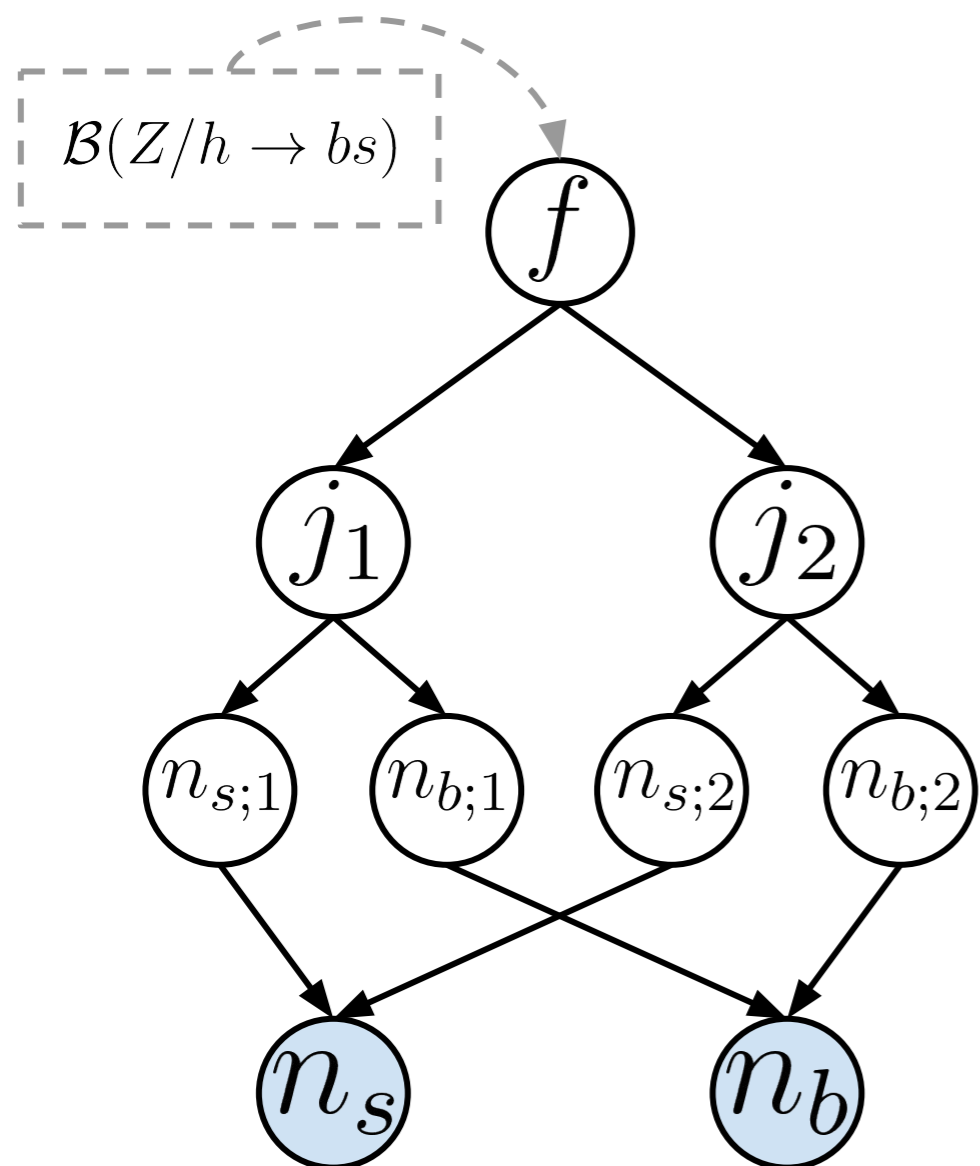
$$\bar{N}_{(n_b, n_s)} = \sum_f p(n_b, n_s | f, \nu) \bar{N}_f(\nu)$$

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

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

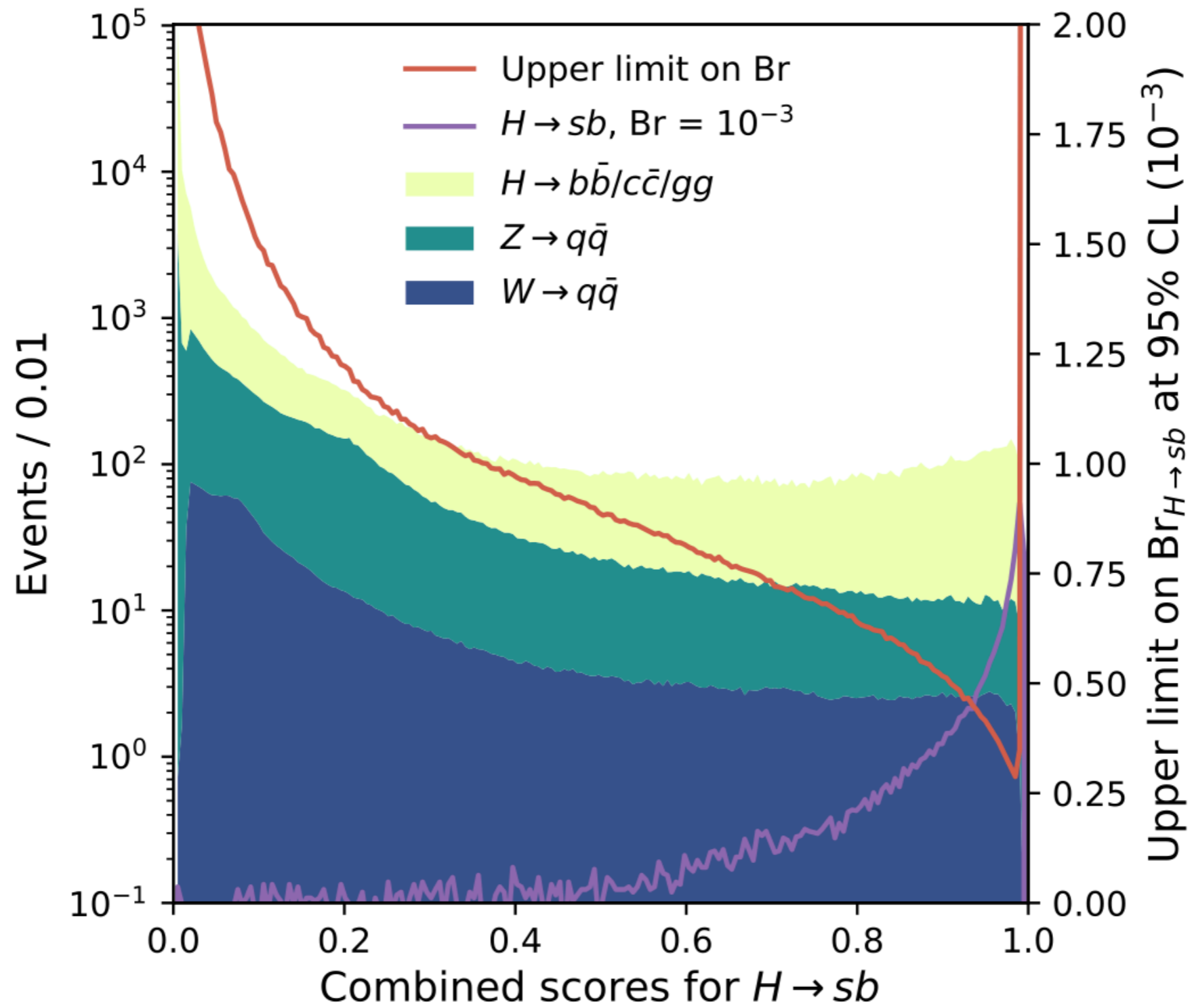
Confidence interval $\mu_{\text{true}} = 1$, solve for $t_\mu = 1$ (68%)

Upper limits

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

Hbs at CePC

From Liang et al.: 2310.03440



Background

$$e^+e^- \rightarrow \bar{q}q \rightarrow (\bar{q}g)(qg)$$

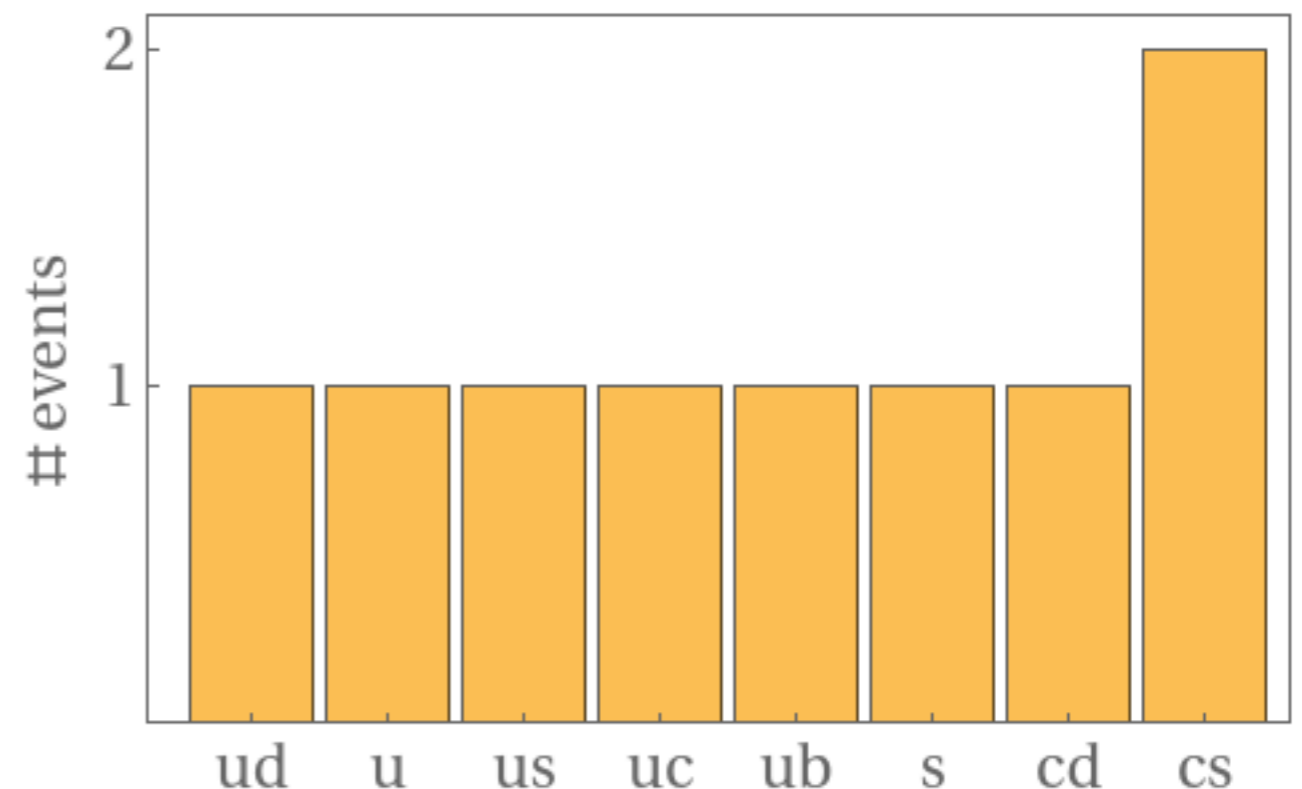
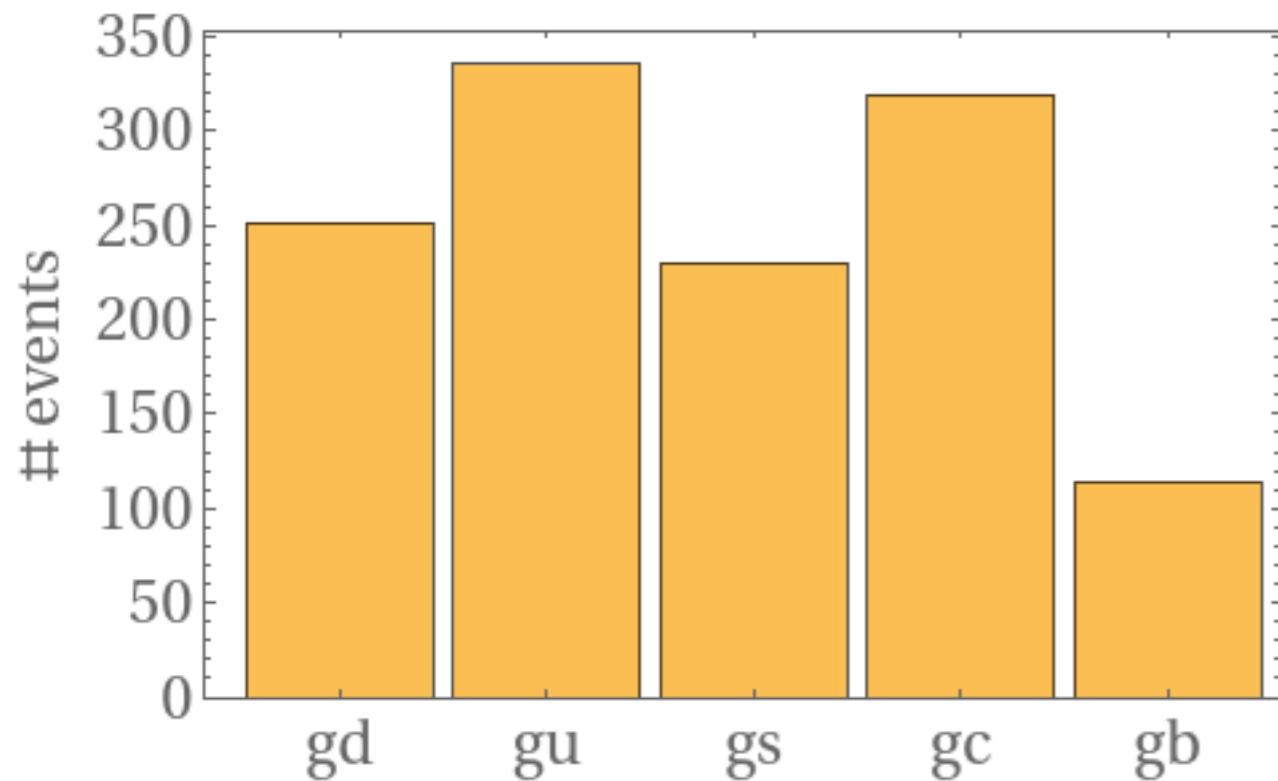
10^6 events with MadGraph (parton level only)

$$\rightarrow (\bar{q}jj)q$$

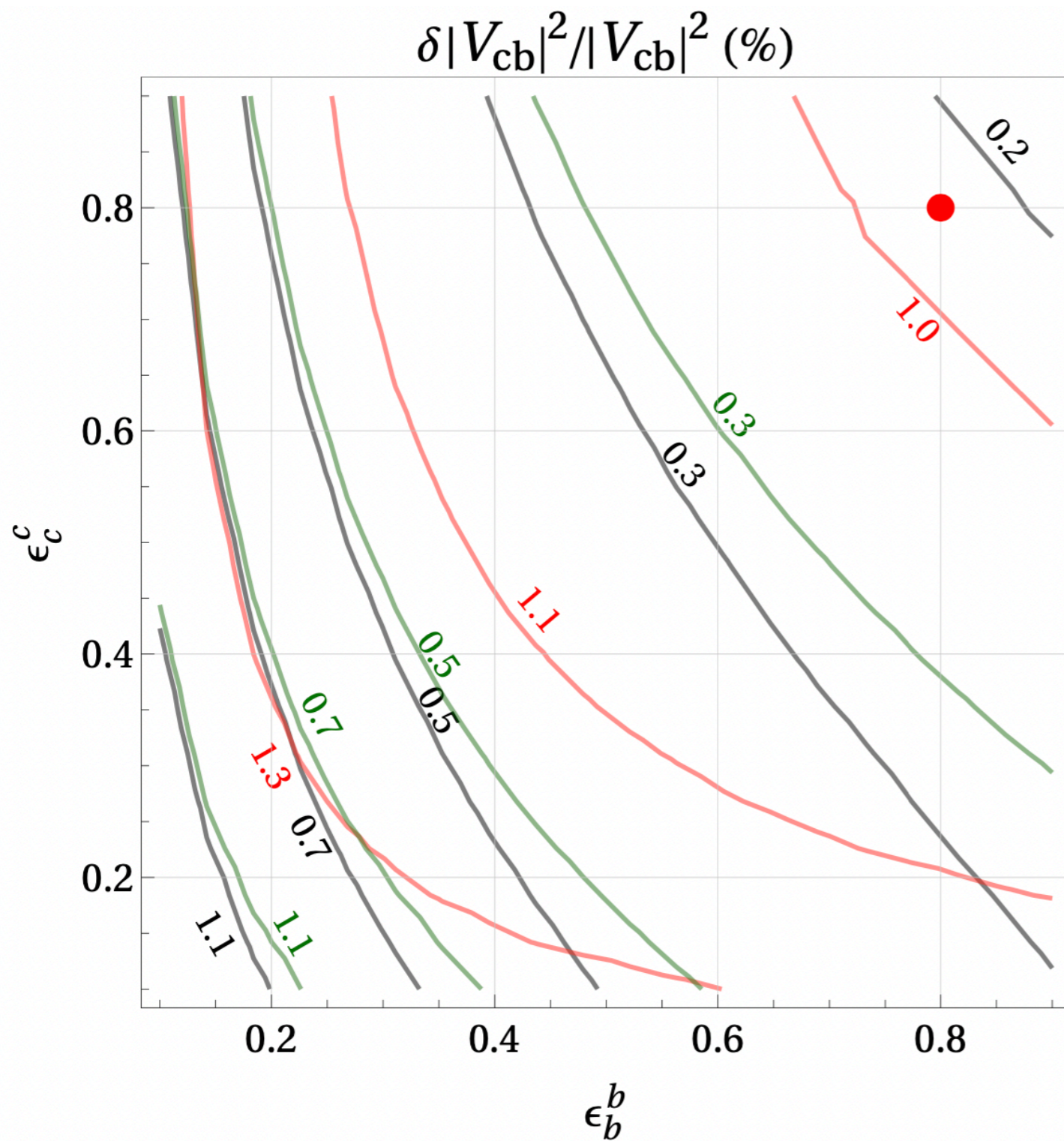
$\eta < 2 \text{ GeV}$ $\Delta R > 0.1$ $p_T > 0.5 \text{ GeV}$

Selection: at least one couple of invariant masses such that

$$(m_{ij}, m_{kz}) \supset (m_W \pm \sigma_W, m_W \pm \sigma_W)$$



Results 2: scan parameters



Reminder

$\epsilon_\beta^q \equiv q$ -tagger probability to tag β -jet

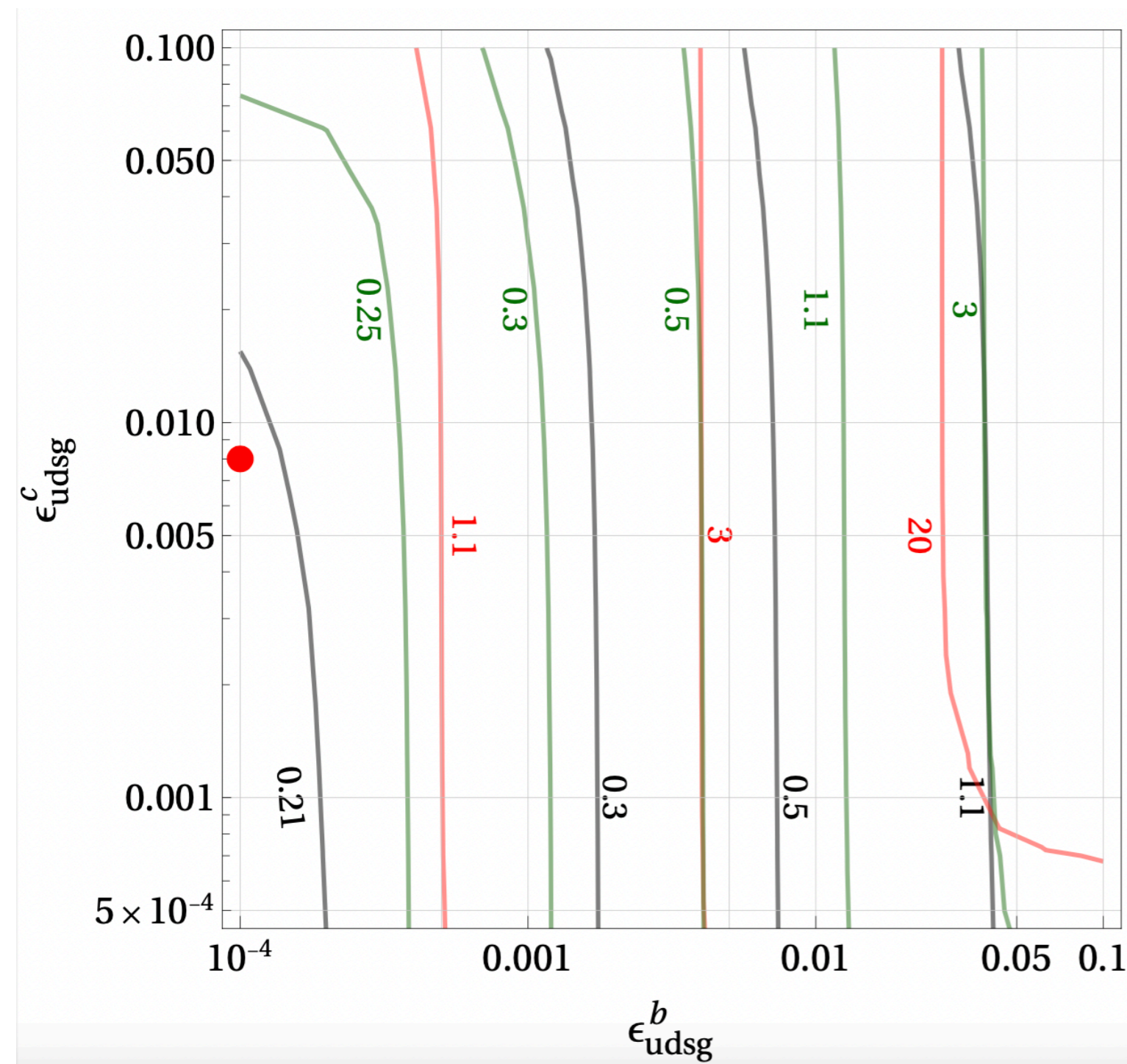
● FCC-ee Working Point

– No systematics

– 0.1% systematics

– 1% systematics

Results 2: scan parameters



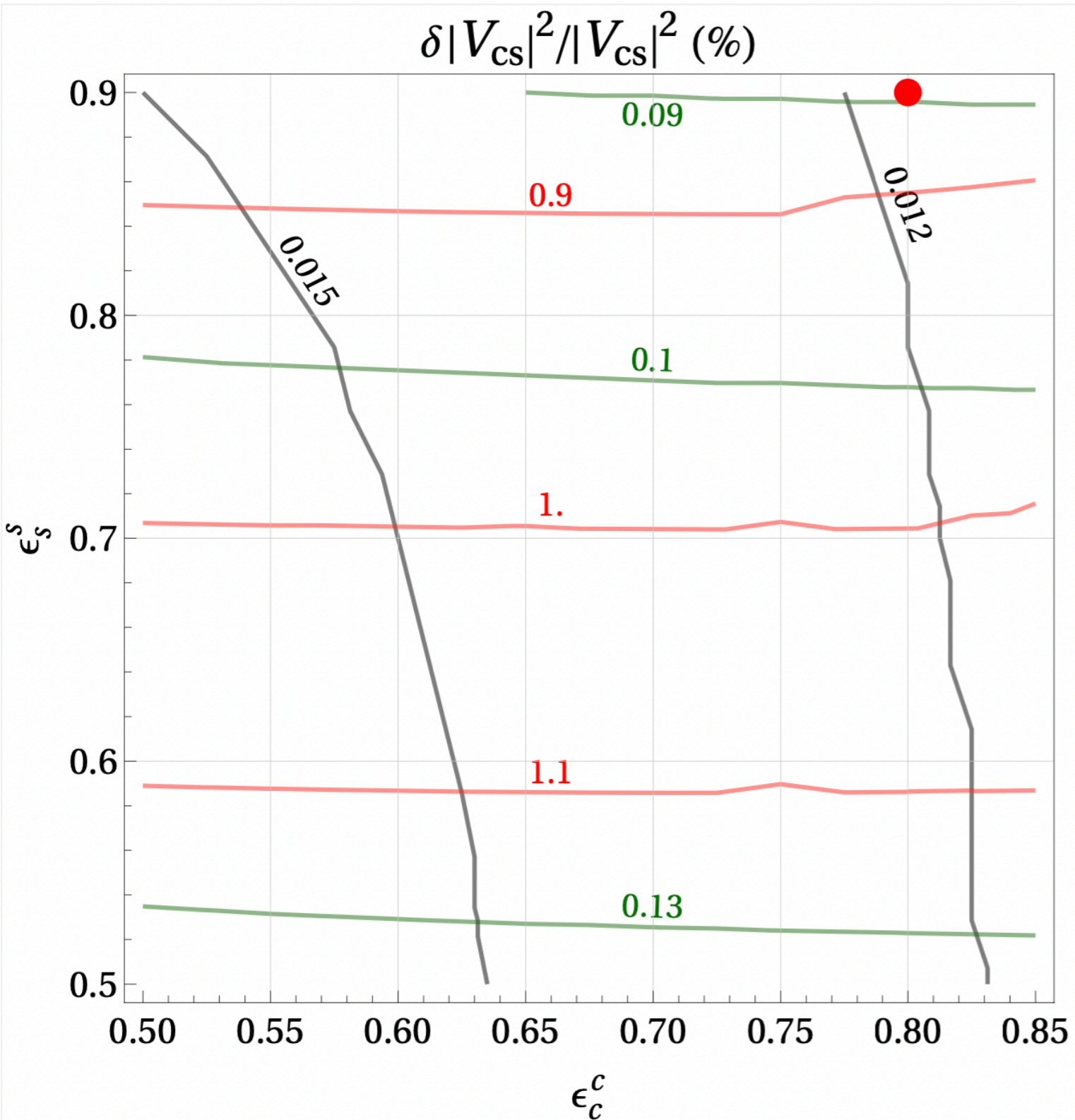
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- FCC-ee Working Point
- No systematics
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- 1% systematics

Final precision dictated by $b \rightarrow$ light-jet mistags

Results 2: scan parameters



Reminder

$\epsilon_\beta^q \equiv q$ -tagger probability to tag β -jet

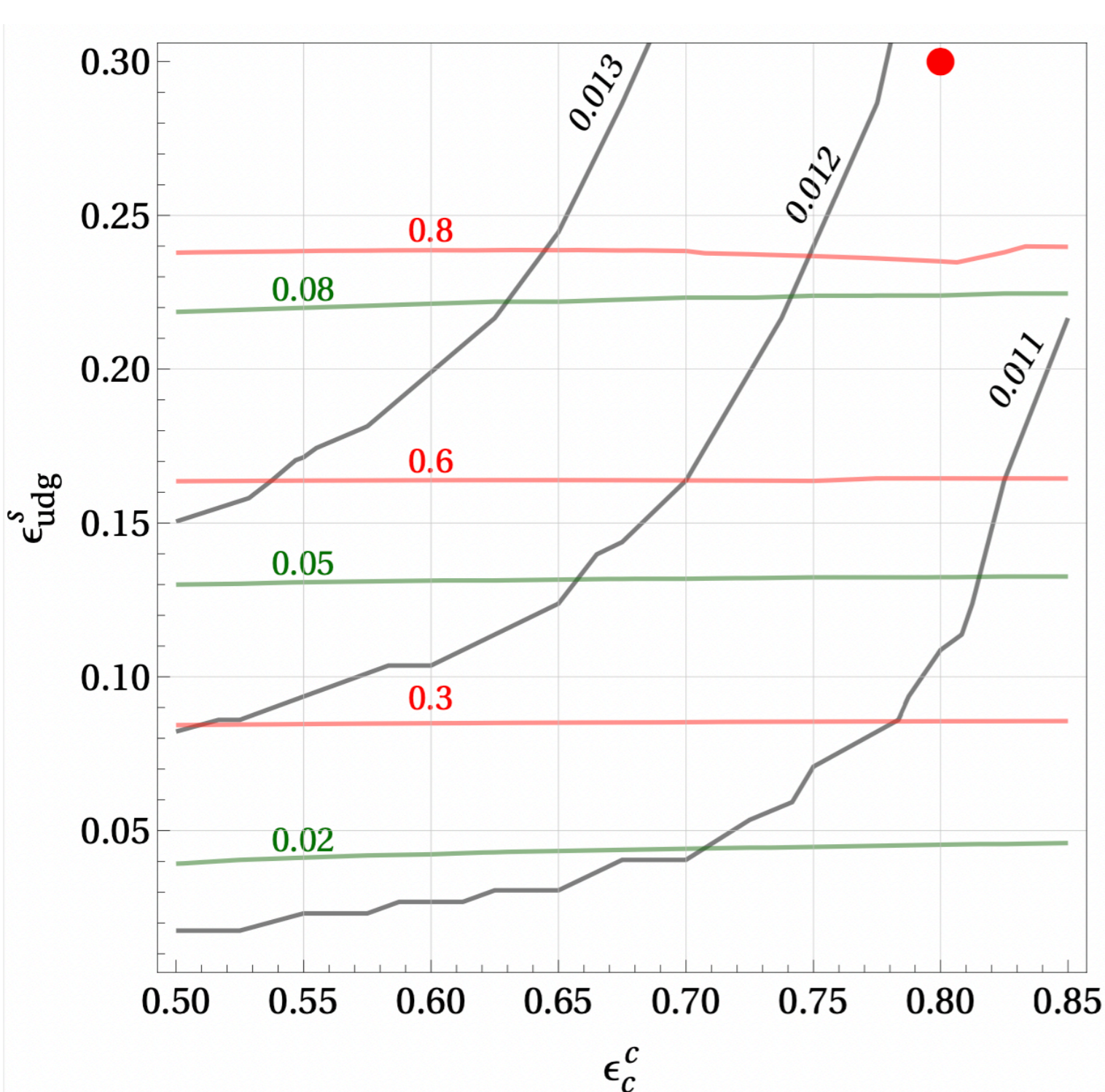
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Results 2: scan parameters



Reminder

$\epsilon_\beta^q \equiv q$ -tagger probability to tag β -jet

● FCC-ee Working Point

– No systematics

– 0.1% systematics

– 1% systematics

Final precision dictated by s-tagger performance