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

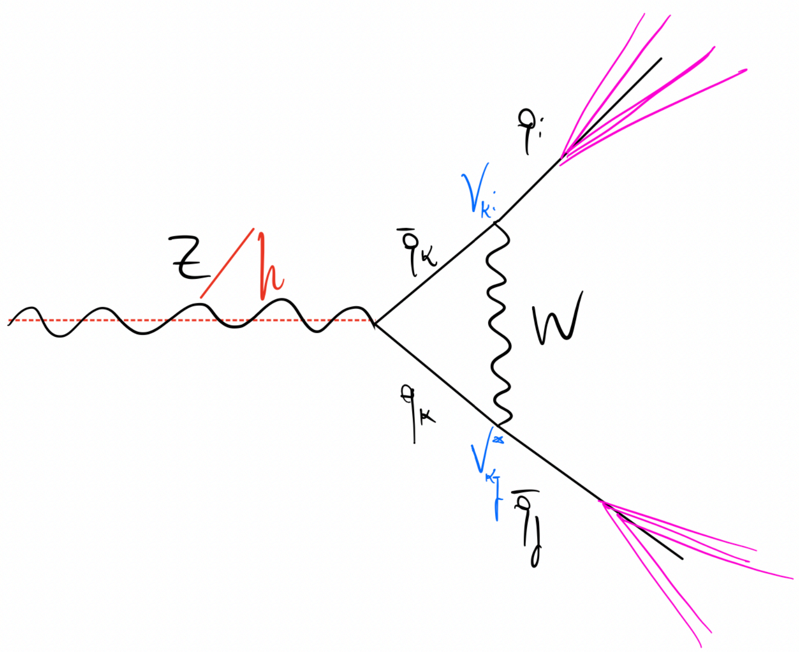
Michele Tammaro

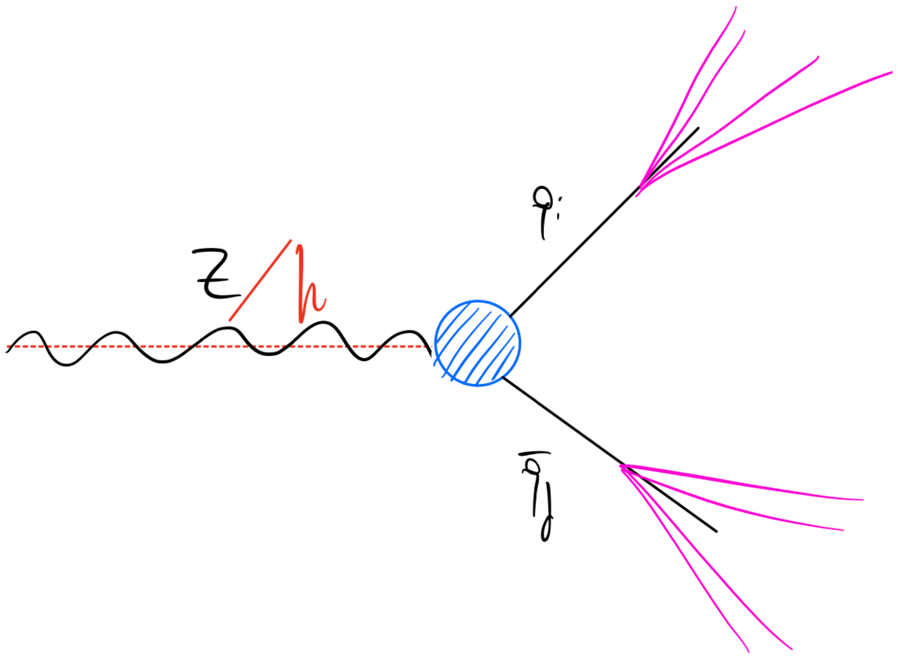
@LFC24, 18/09/2024

based on

J. F. Kamenik, A. Korajac, M. Szewc, MT, J. Zupan, 2306.17520
D. Marzocca, M. Szewc, MT, 2405.08880

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI FIRENZE

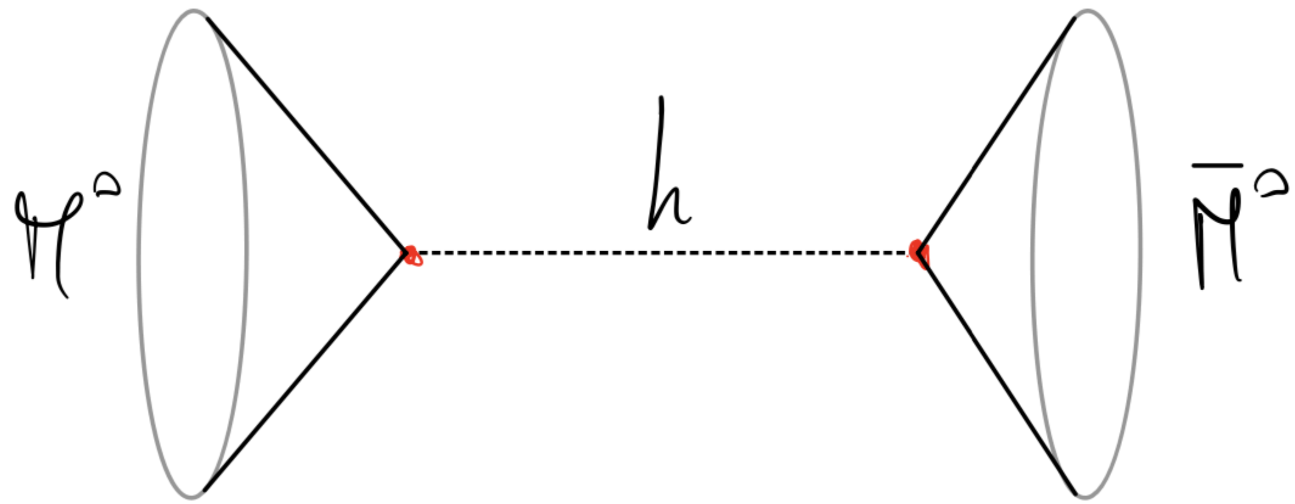


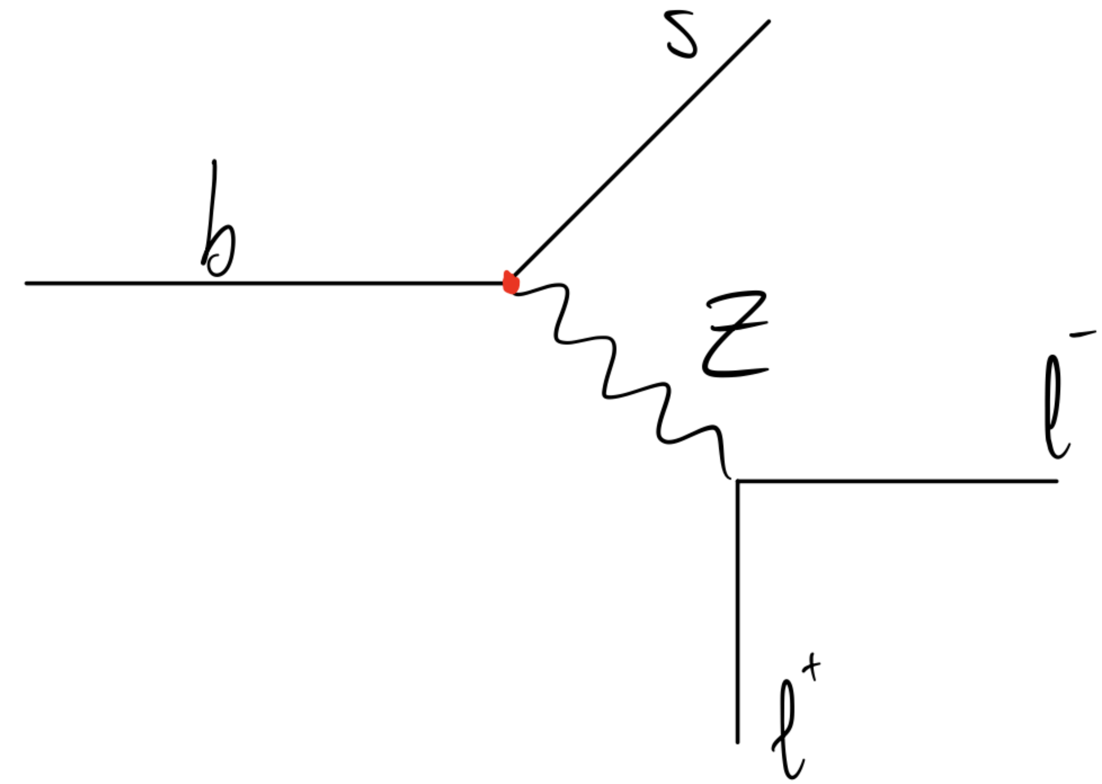


▲ $h \to \text{BSM}$ (CMS+ATLAS, 2207.00043)

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

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} ●





★ Meson mixings

● Global fits (mostly semi-leptonic)

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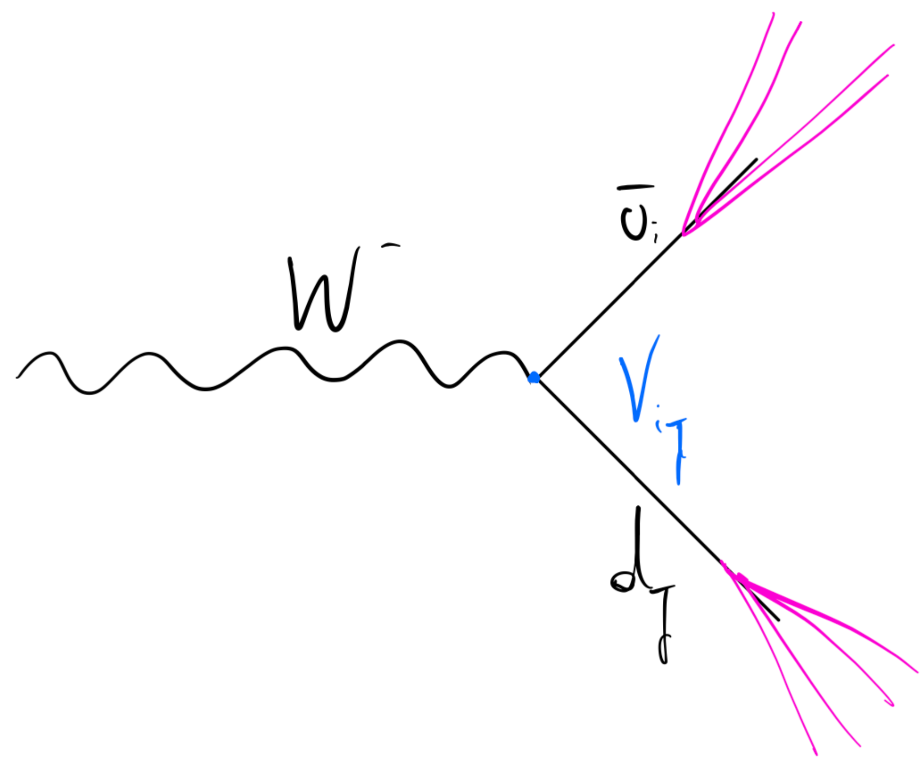


$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix}$$

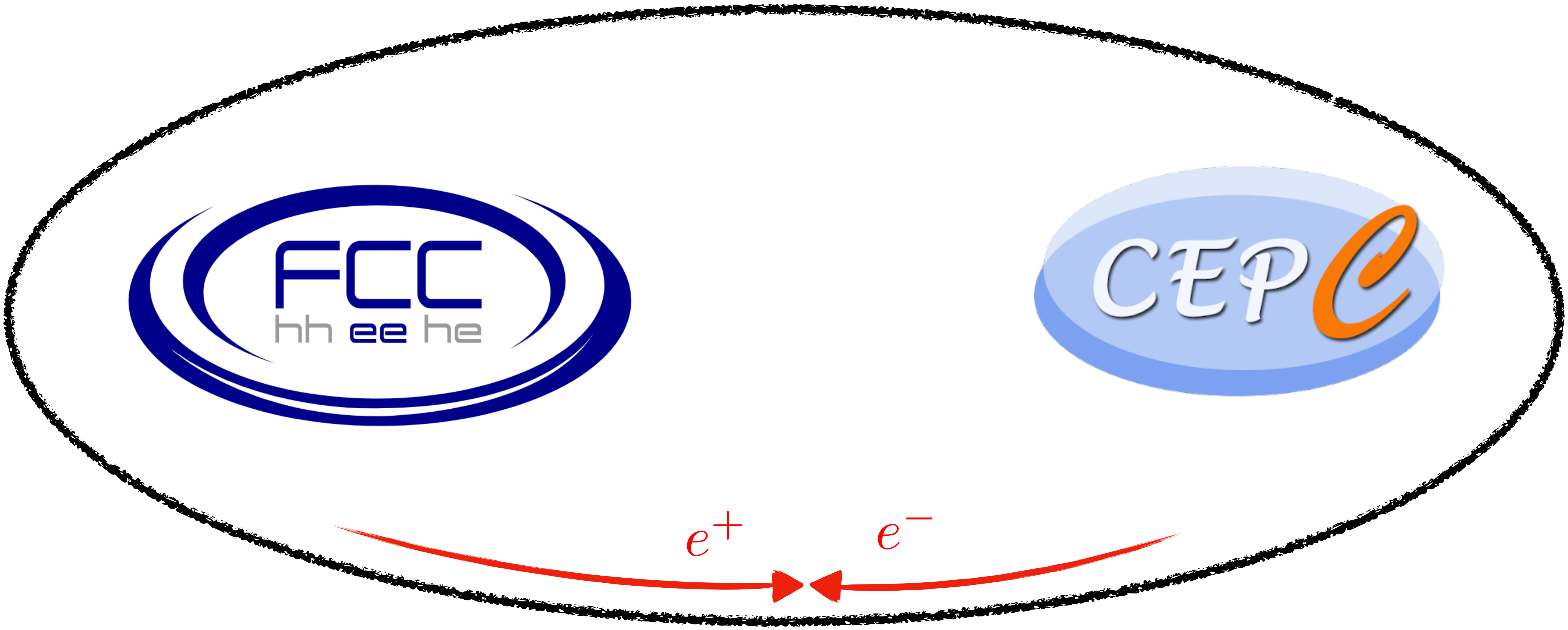
$\lvert V_{ij}\rvert$	Current	
$\lvert V_{cs}\rvert$	0.975 ± 0.006	(0.6%)
$\lvert V_{cb}\rvert$	$(40.8 \pm 1.4) \times 10^{-3}$	(3.4%)

Produce on-shell H/Z/W bosons

With large statistics and low background

Apply flavor taggers

Count events



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

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

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

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

Signals

Backgrounds

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

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

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

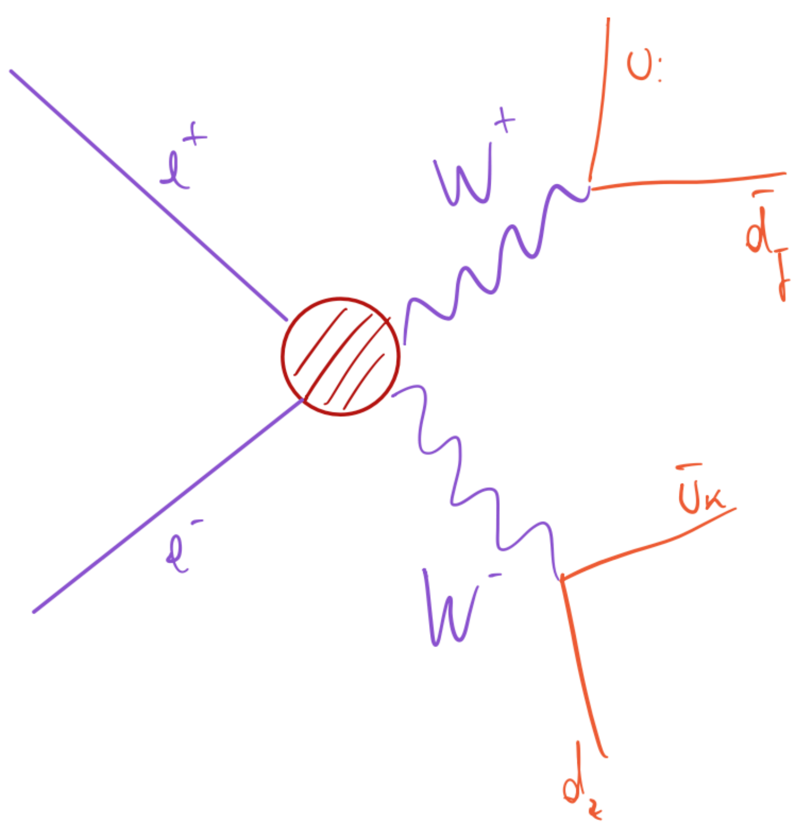
Parameters	Nominal Value	Rel. uncert. (%)
$\mathcal{B}(h \to gg)$	1.4%	1.2
$\mathcal{B}(h \to ss)$	0.024%	160
$\mathcal{B}(h \to cc)$	2.9%	2.8
$\mathcal{B}(h \to bb)$	56%	0.4
N_h	6.7×10^5	0.5
$\mathcal{A}$	0.70	0.1

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/)

Signal

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

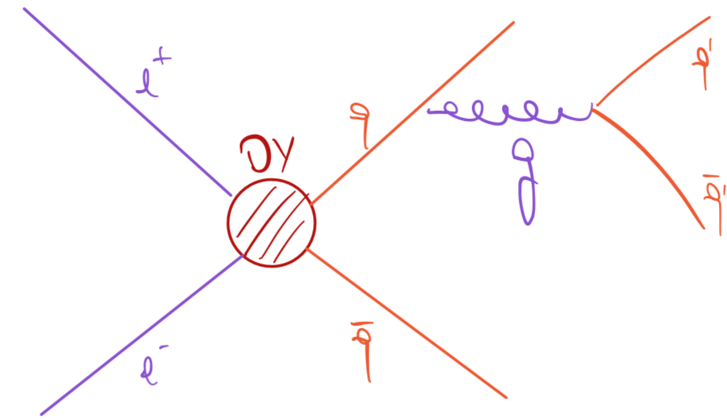


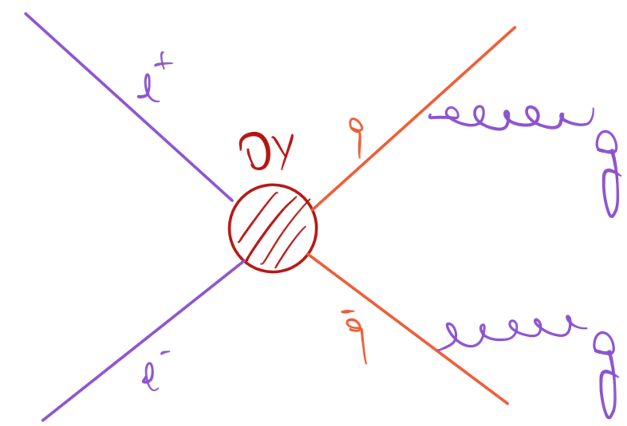
Semileptonic channel for Vcb

Liang et al.: 2406.01675

Backgrounds (Drell-Yan)

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





10^6 events with MadGraph (parton level only)

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

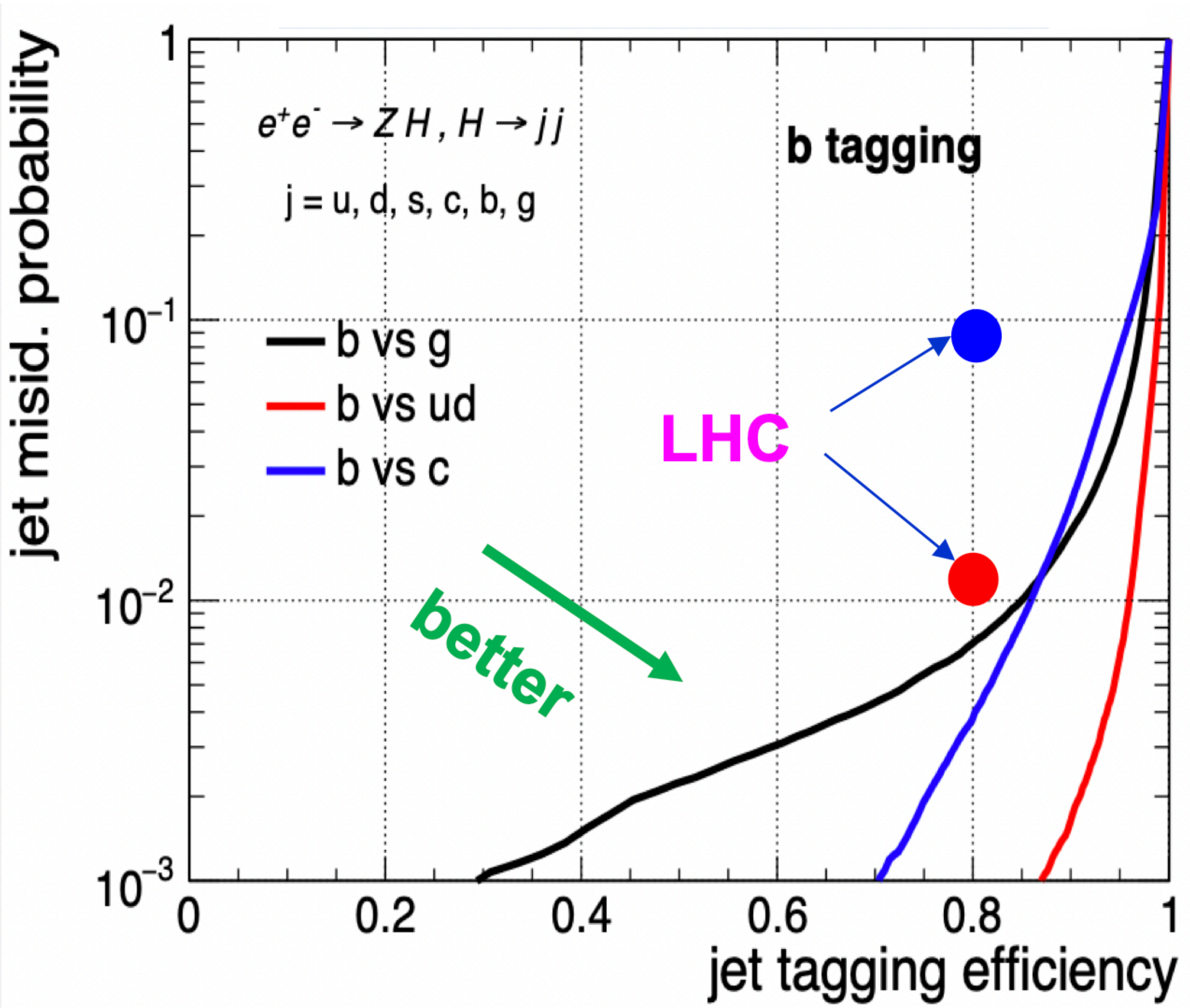
$\sim 10^3$ events pass

Jet flavor taggers

Tools to classify flavor of jets from input data

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

FPR



TPR

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

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

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

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

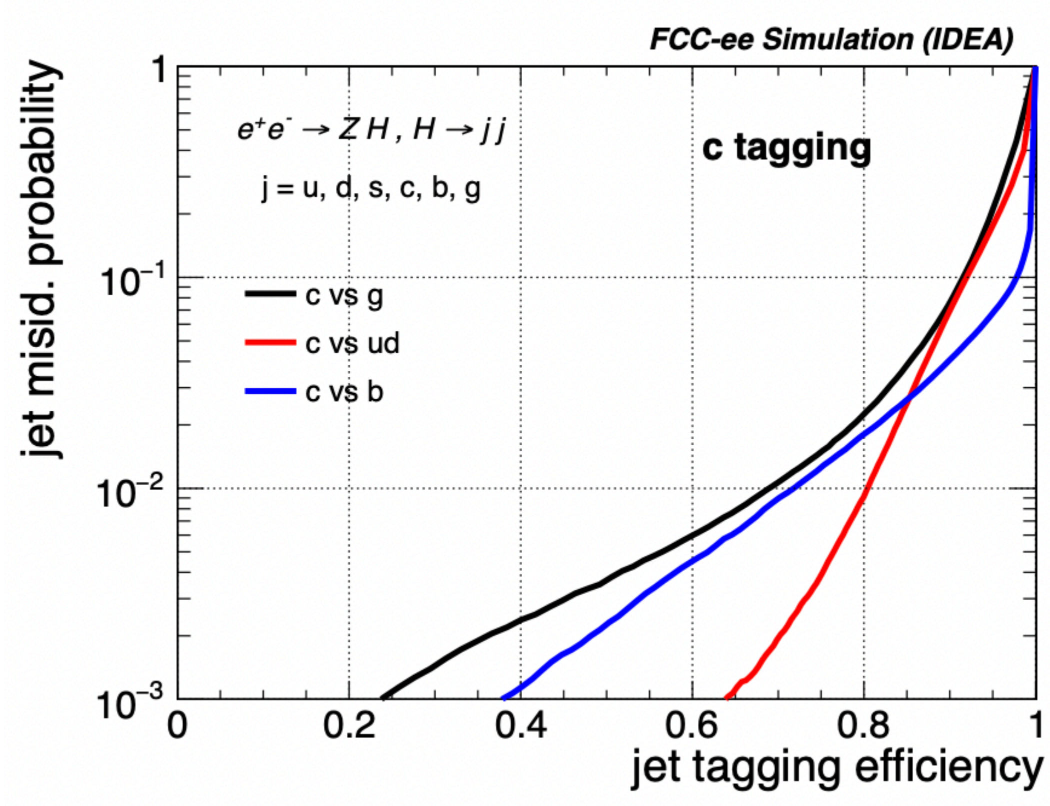
ATLAS: 1907.05120
CMS: 1712.07158

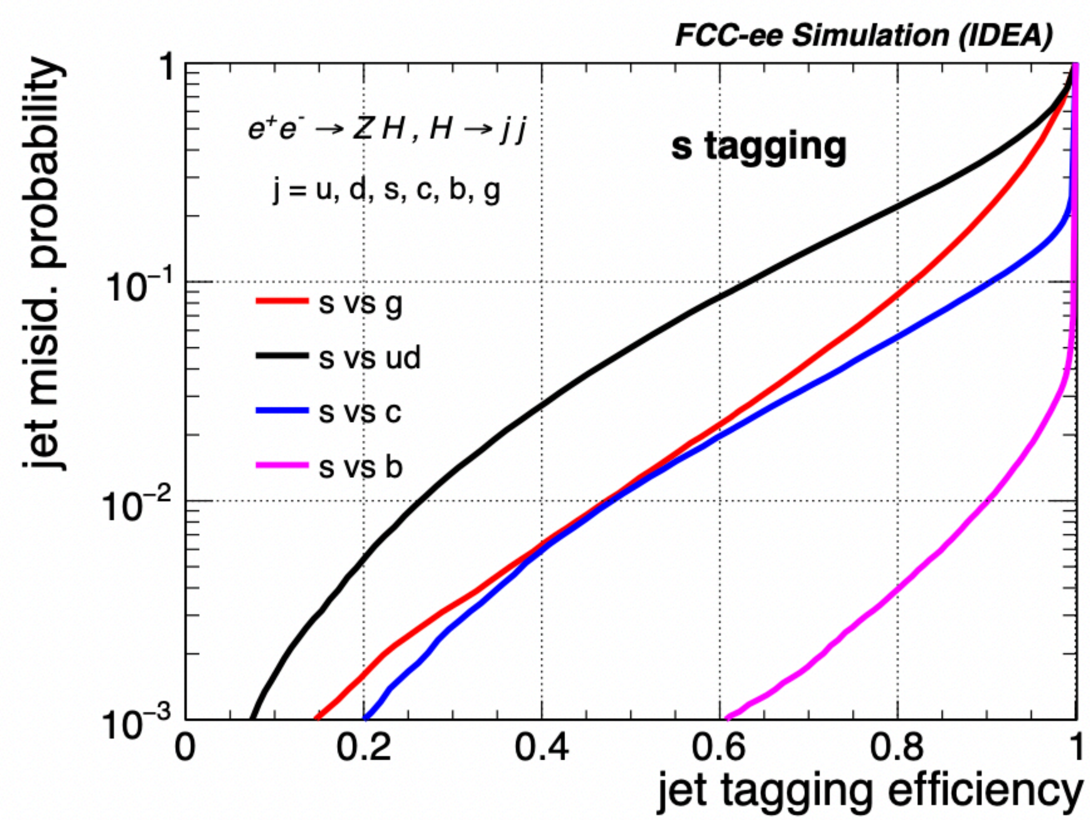
Calibration at Z-pole

Could go to 0.1%

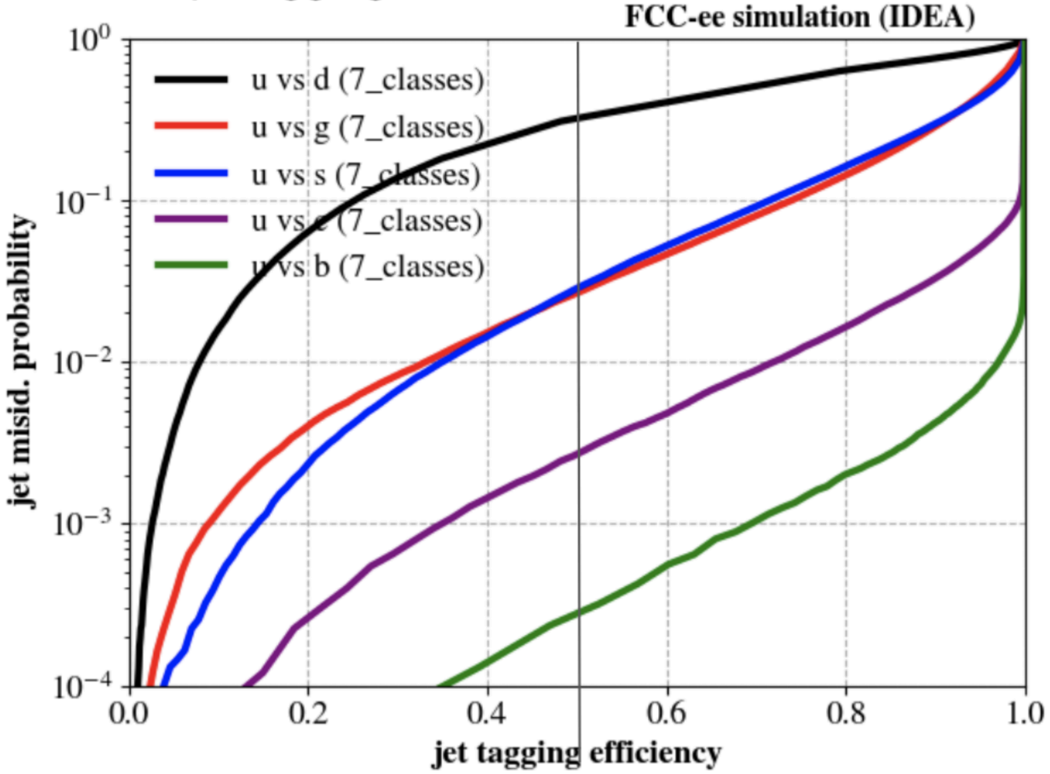
M. Selvaggi's talk at 7th FCC Workshop (https://indico.cern.ch/event/1307378/)

Jet flavor taggers

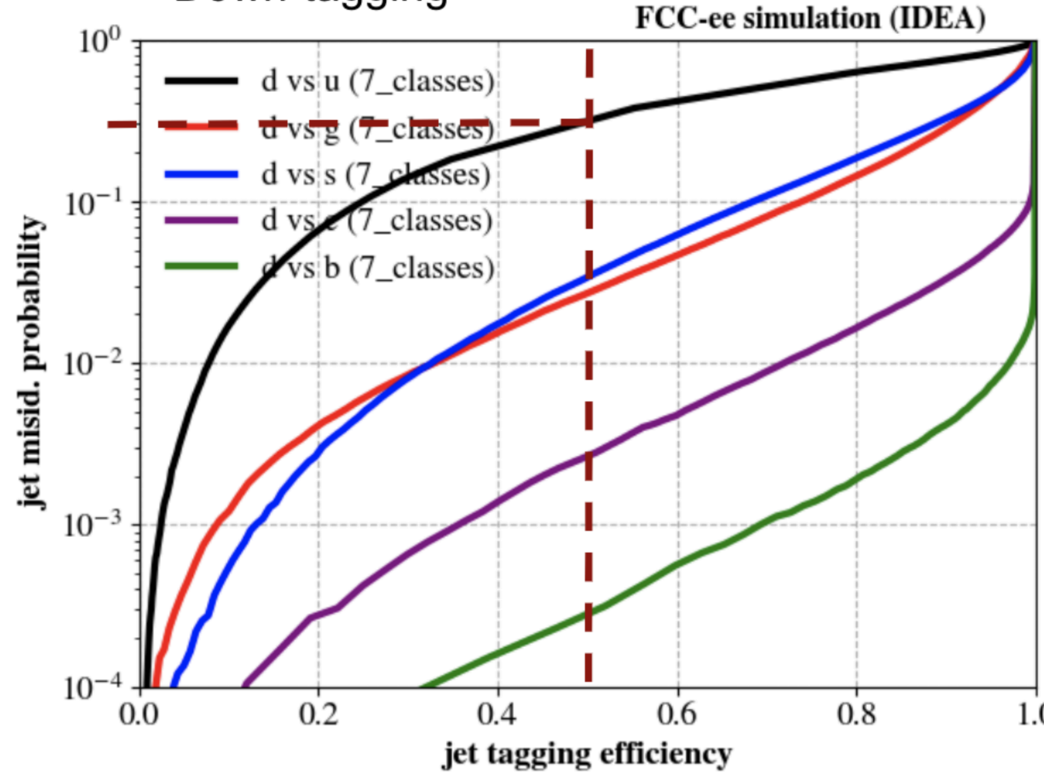




Up -tagging



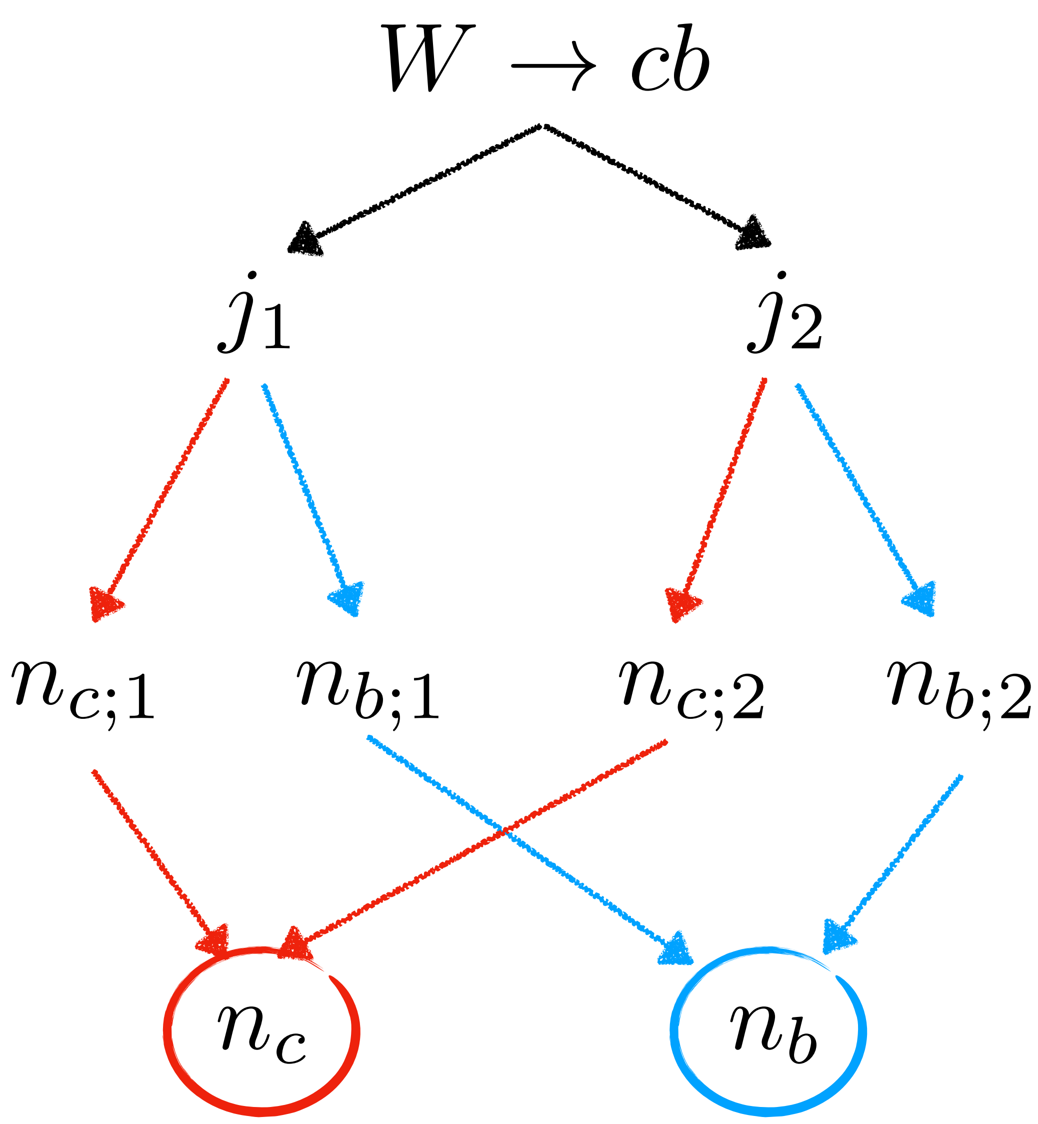
Down-tagging



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

Probabilistic model

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



Distribute events into tag bins

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

Expected number of events per channel

$$\bar{N}_f = \mathcal{B}(W \to f) N_W \mathcal{A}$$

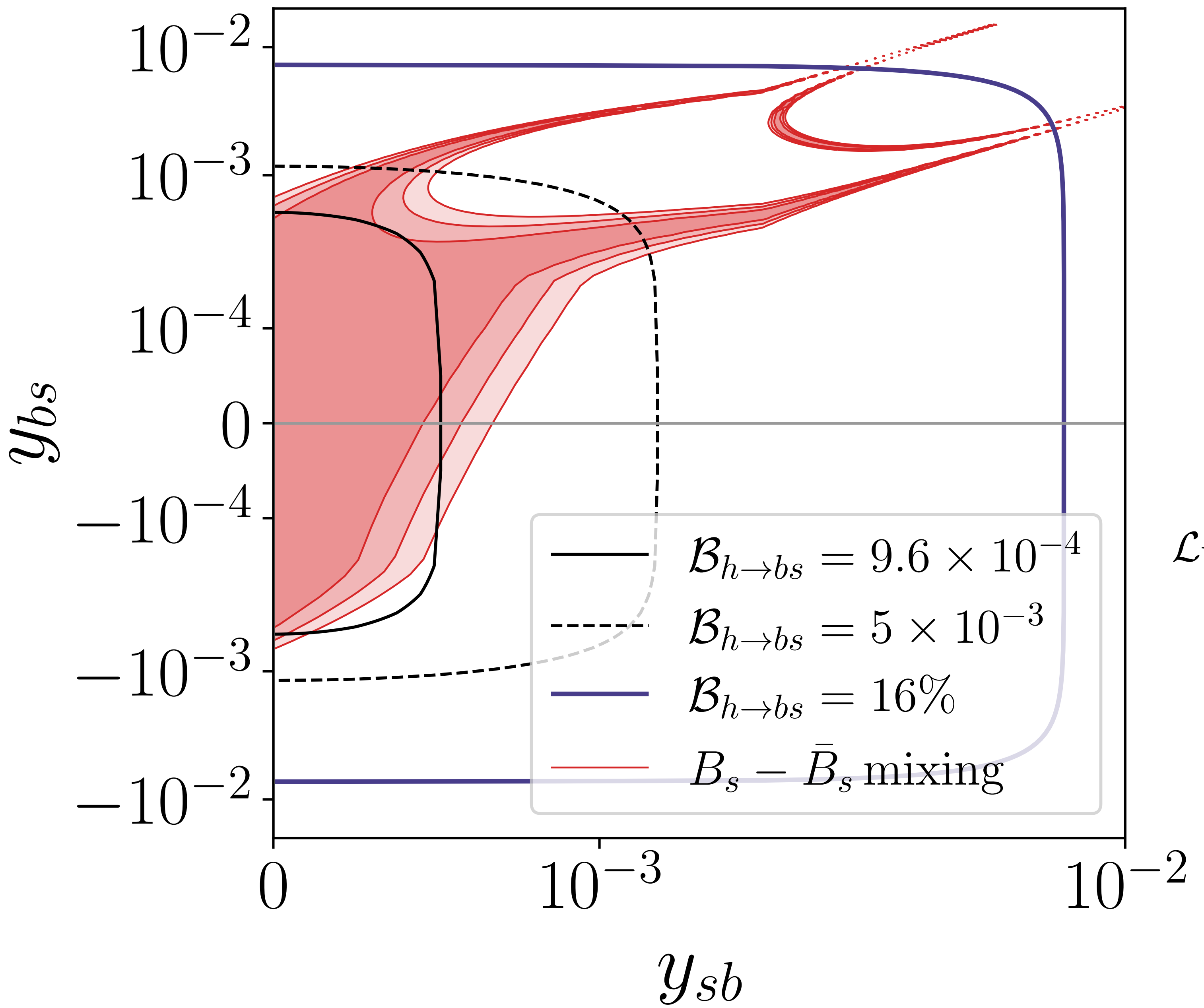
↓

Expected number of events per tag bin

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

Nuisance parameters $\nu = \{N_W,\ \mathcal{A},\ \epsilon^q_\beta,\ \dots\}$

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



Match to WET + **wilson** + **flavio**

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

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

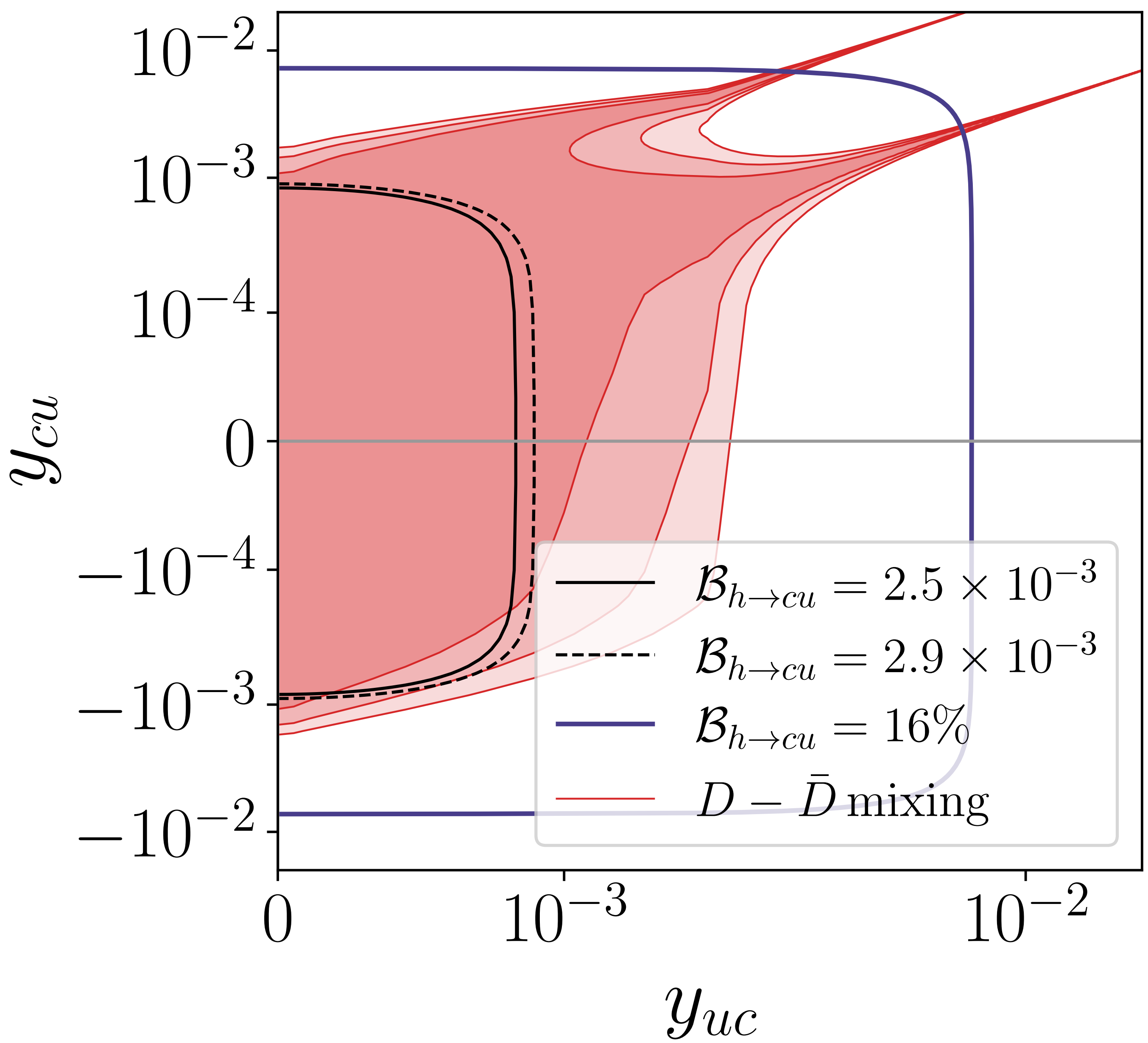
FCC-ee reach

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

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

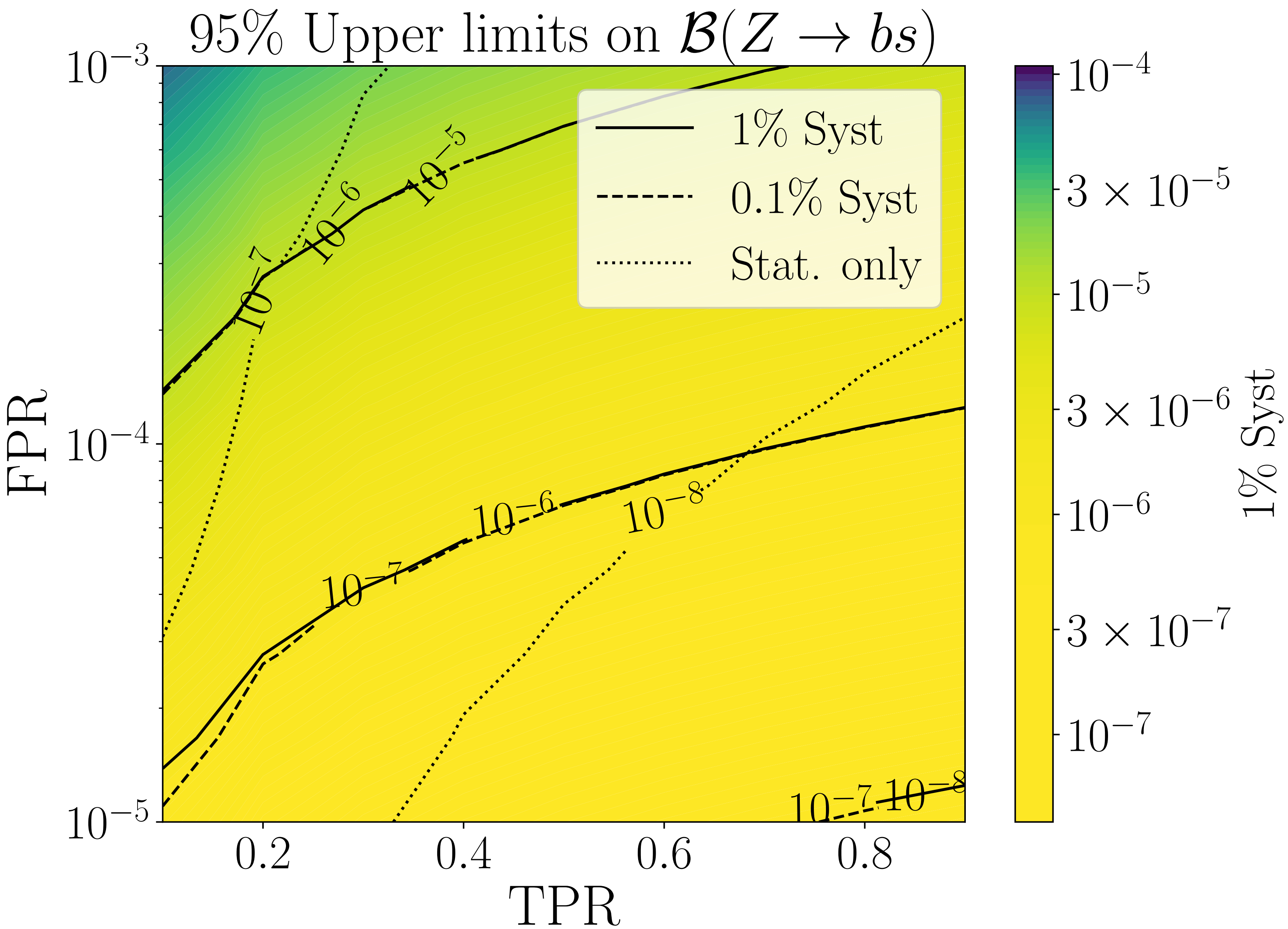
FCC-ee reach (no u-tagger)

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

FCC-ee reach (with u-tagger)

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

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



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}

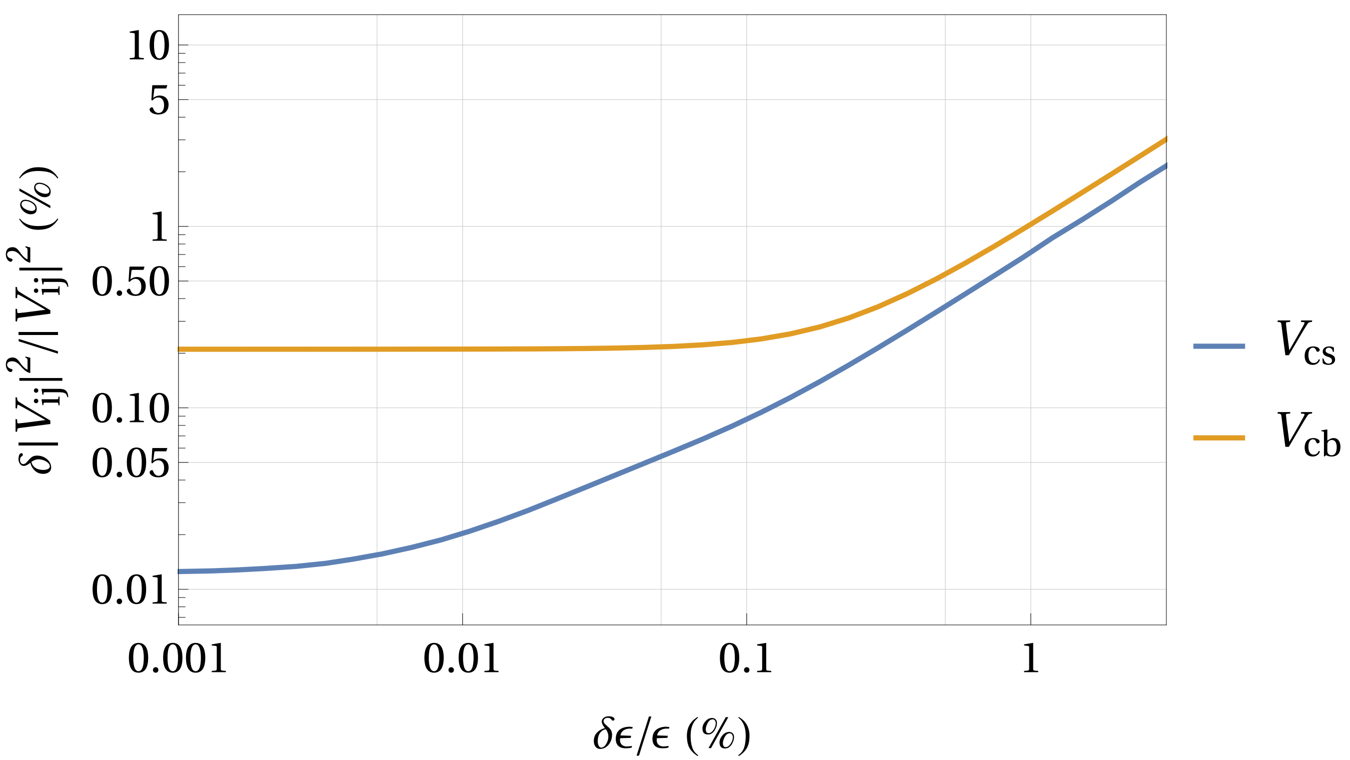
SM level

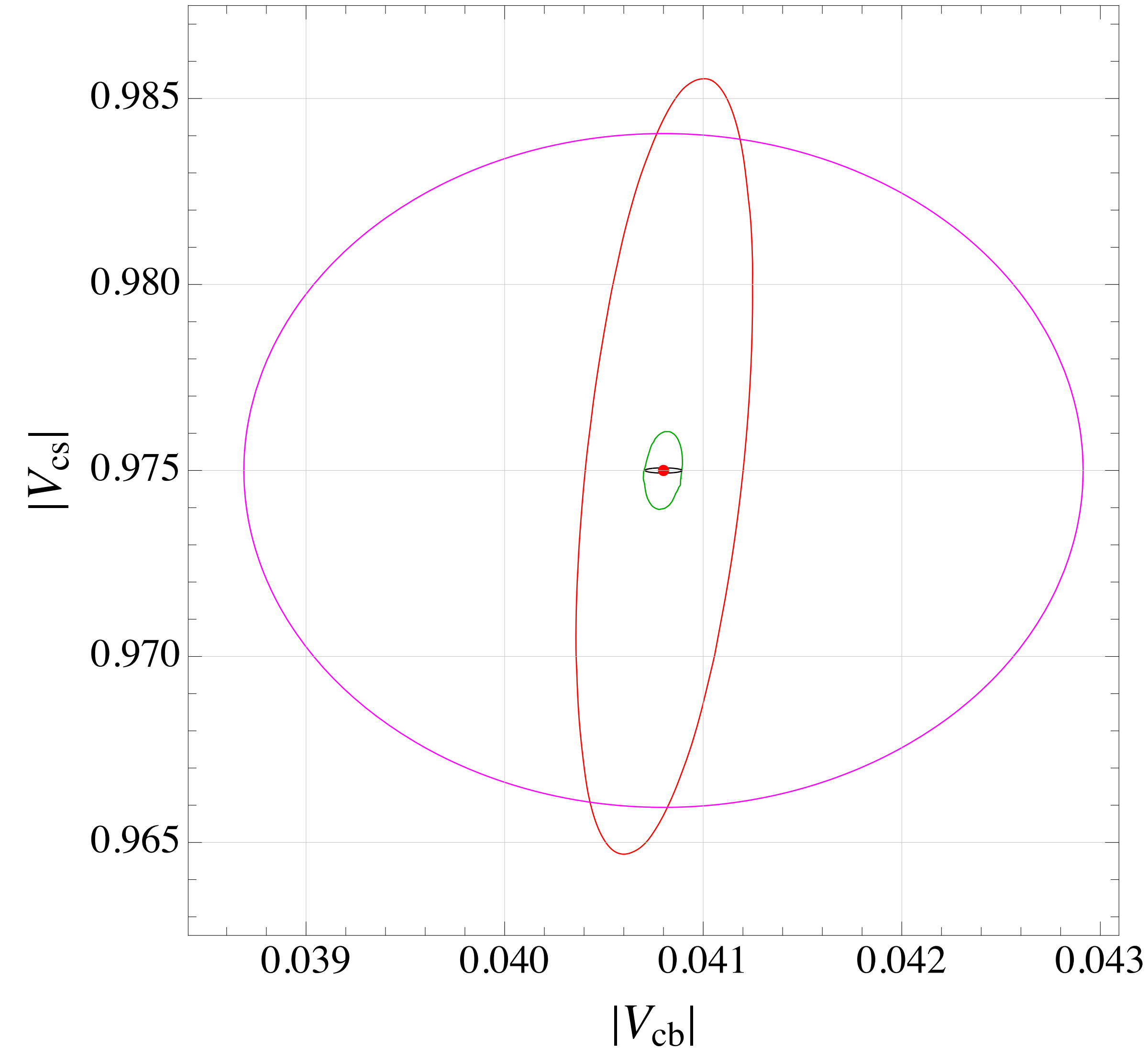
Is 0.1% feasible?

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

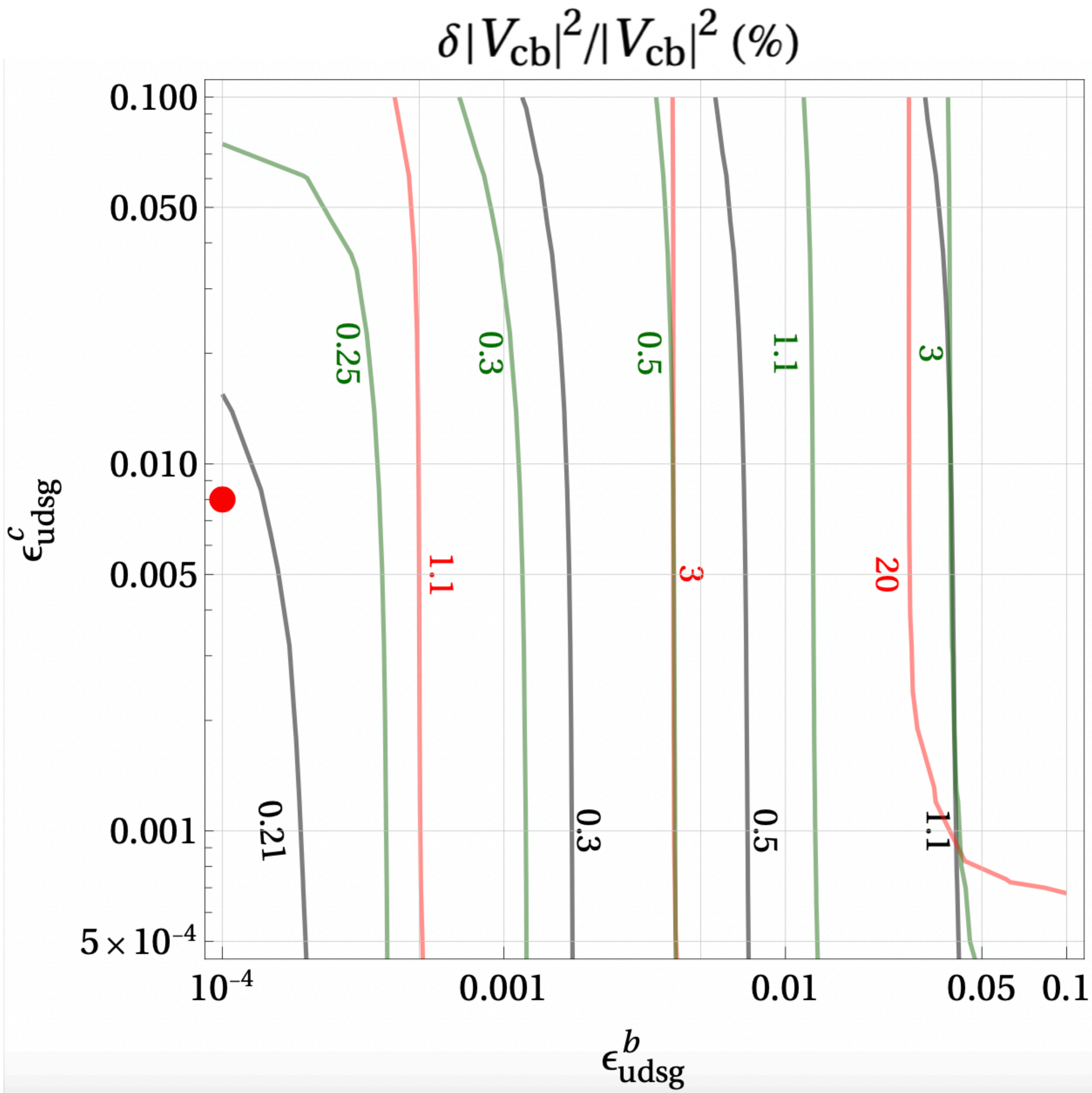
Project % sensitivity on $|V_{ij}|$

$\|V_{ij}\|$	Current		FCC-ee (0.1%)	FCC-ee (1%)
$\|V_{cs}\|$	0.975 ± 0.006	(0.6%)	0.086	0.72
$\|V_{cb}\|$	$(40.8 \pm 1.4) \times 10^{-3}$	(3.4%)	0.23	1.0





Scan over parameters



Reminder

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

● FCC-ee Working Point

– No systematics

– 0.1% systematics

– 1% systematics

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

Take home messages

- Upper limits at FCC-ee are above the SM level
- Improve limits on Higgs FC couplings
- Results depend on taggers performances
- “Lattice-free” determination of Vcb and Vcs (and others?)
- Results depend on taggers performances and systematics
- …what about a Muon Collider?

Backup slides

Probabilistic model

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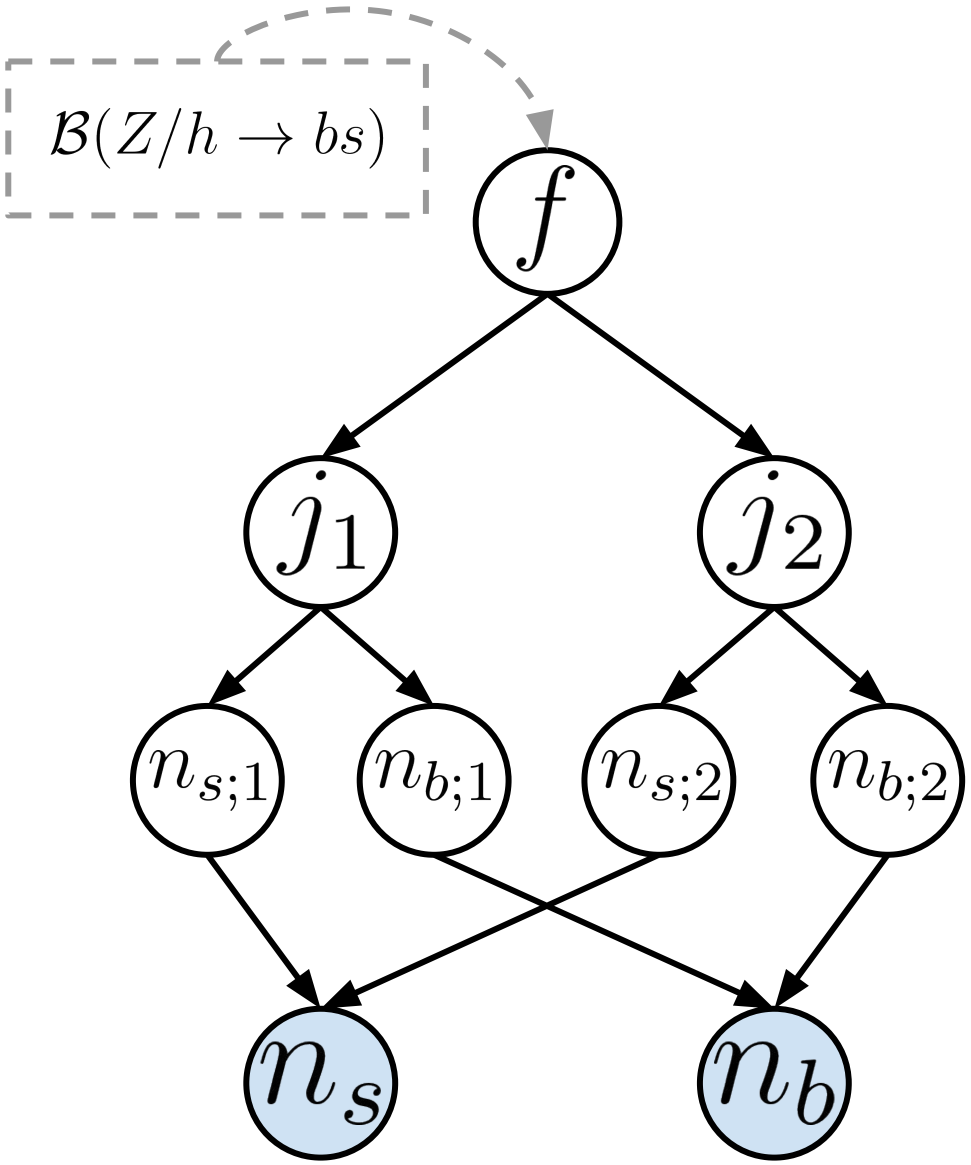

Distribute events into tag bins

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Expected number of events per channel

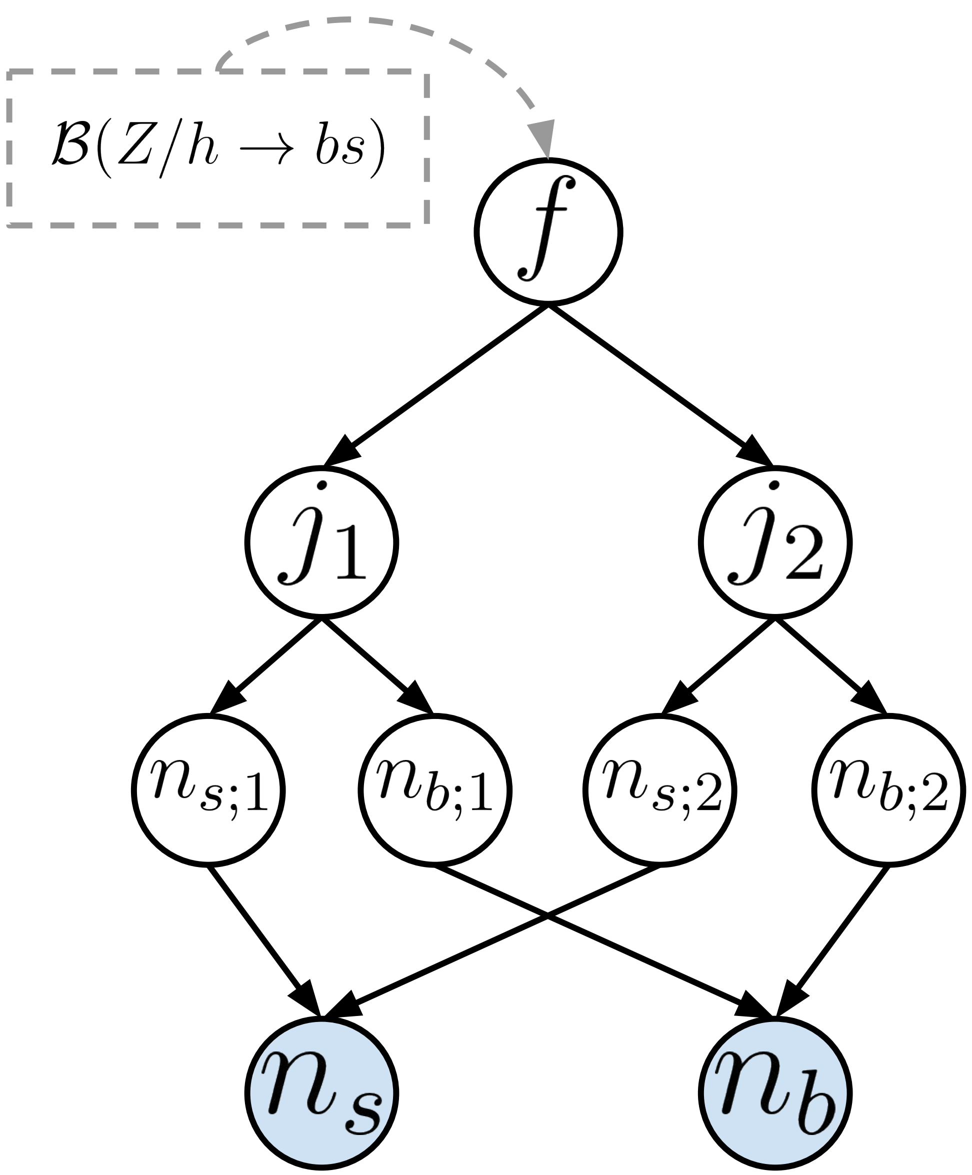
$$\bar{N}_f = \mathcal{B}(Z/h \to f) N_{Z/h} \mathcal{A}$$

Expected number of events per tag bin

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

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

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

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%)

Background

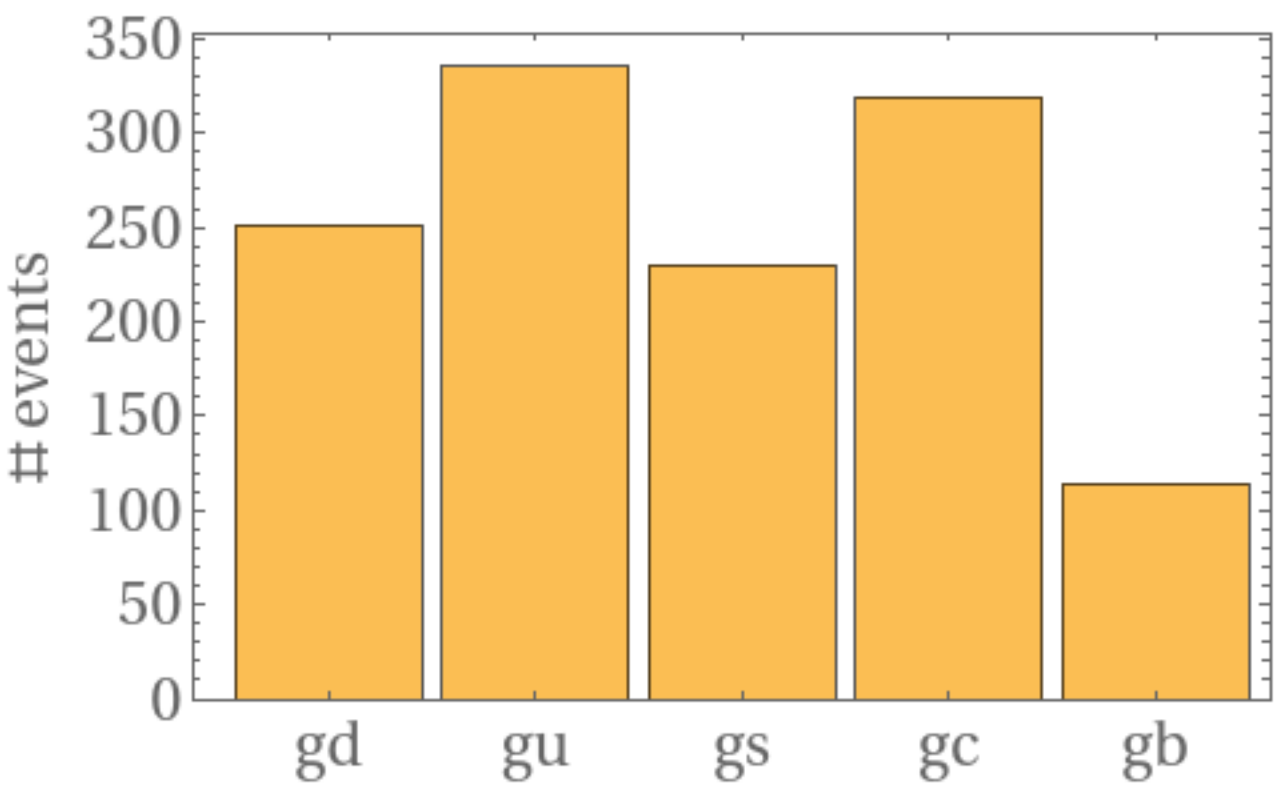
$$e^+e^- \to \bar{q}q \quad \begin{array}{l} \to (\bar{q}g)(qg) \\ \to (\bar{q}jj)q \end{array}$$

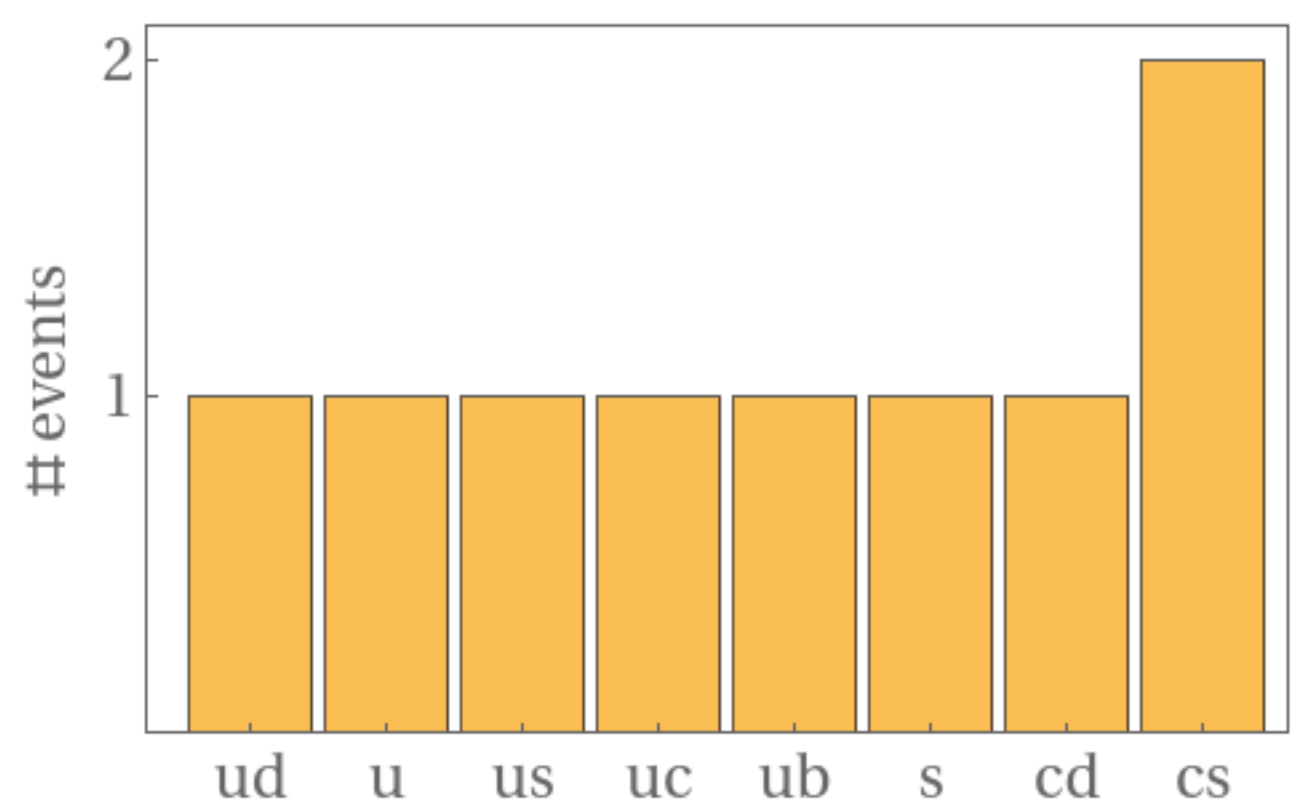
10^6 events with MadGraph (parton level only)

$\eta < 2$ GeV $\quad \Delta R > 0.1 \quad p_T > 0.5$ GeV

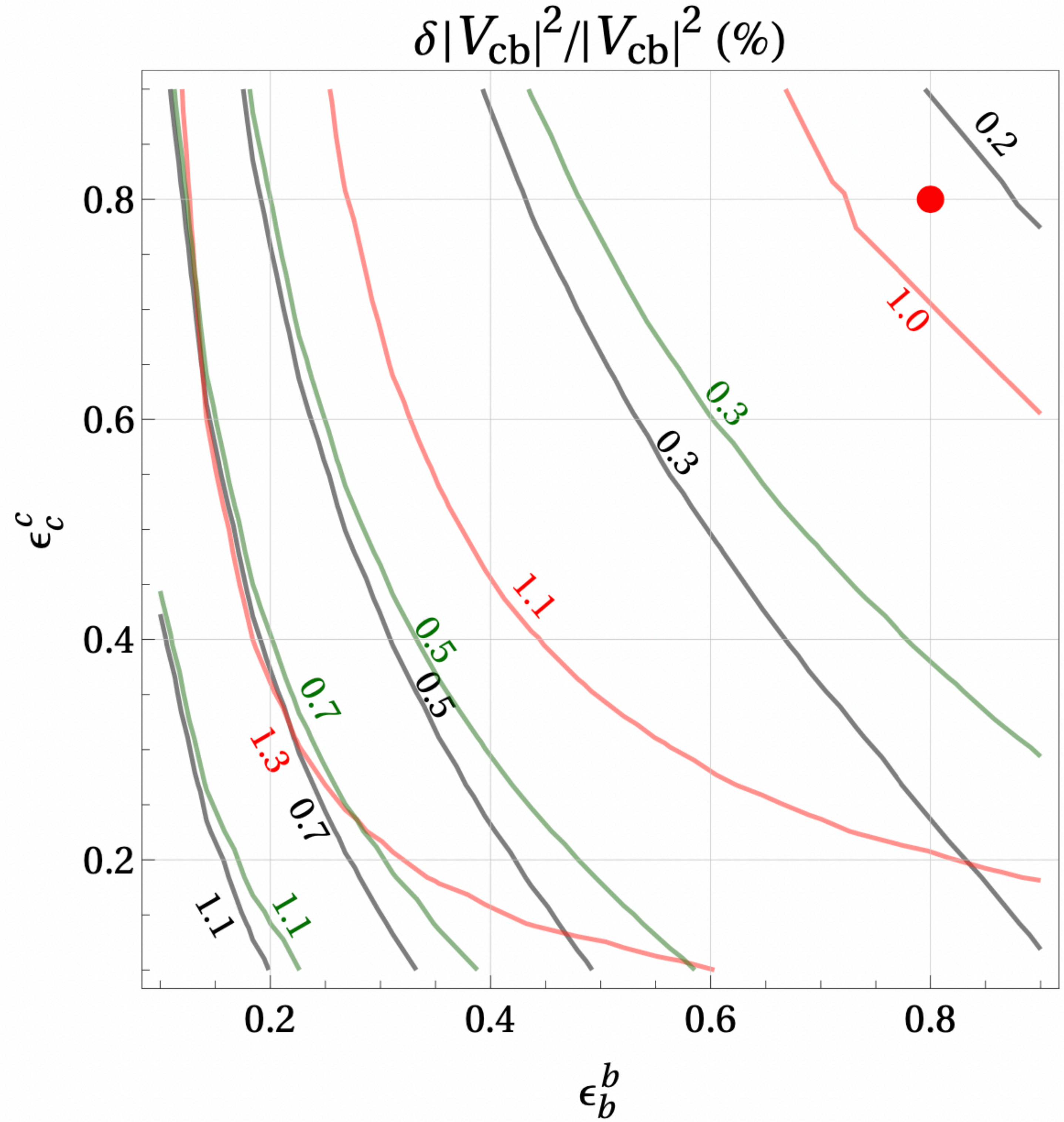
Selection: at least one couple of invariant masses such that

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





Results 2: scan parameters



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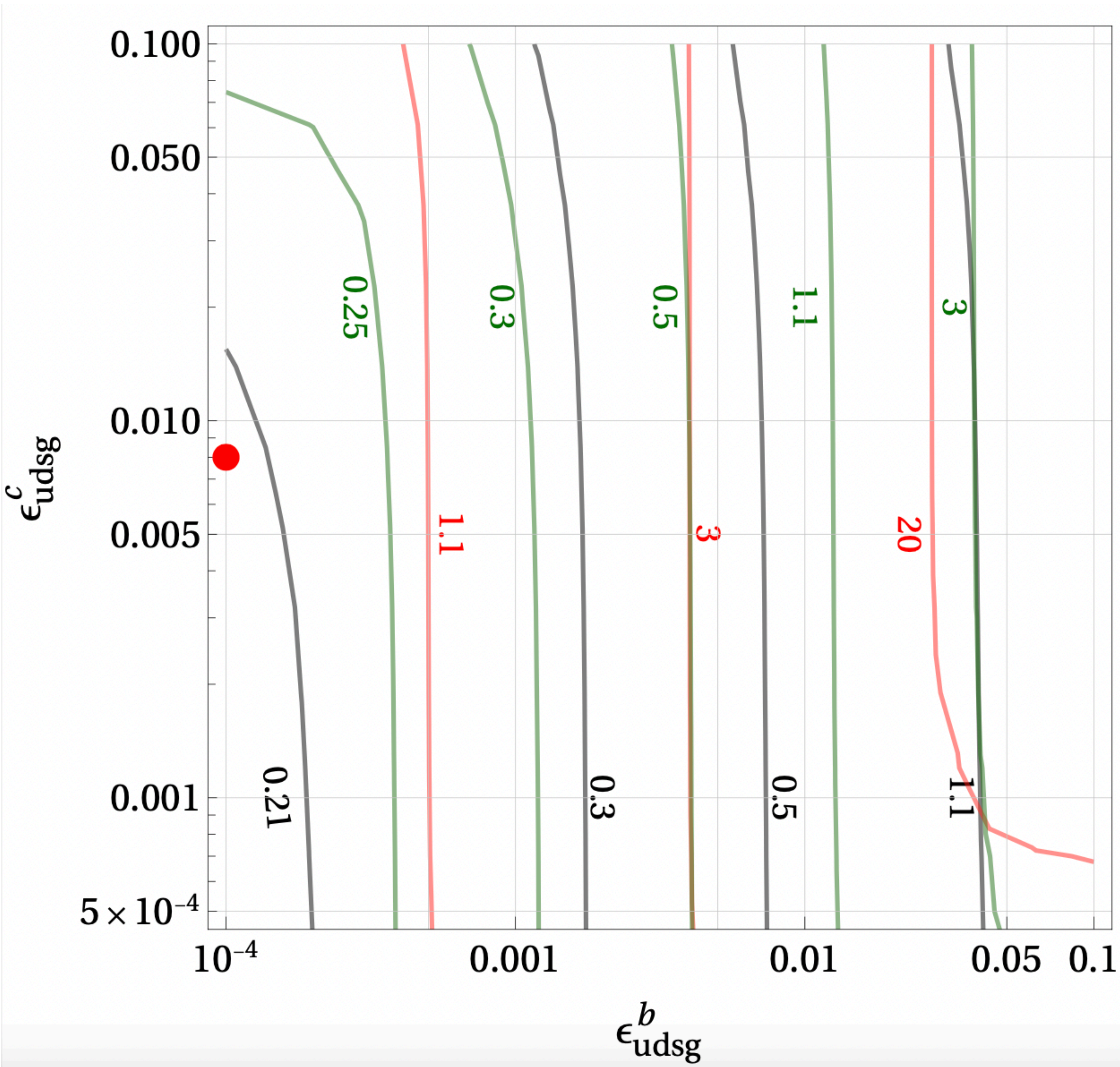

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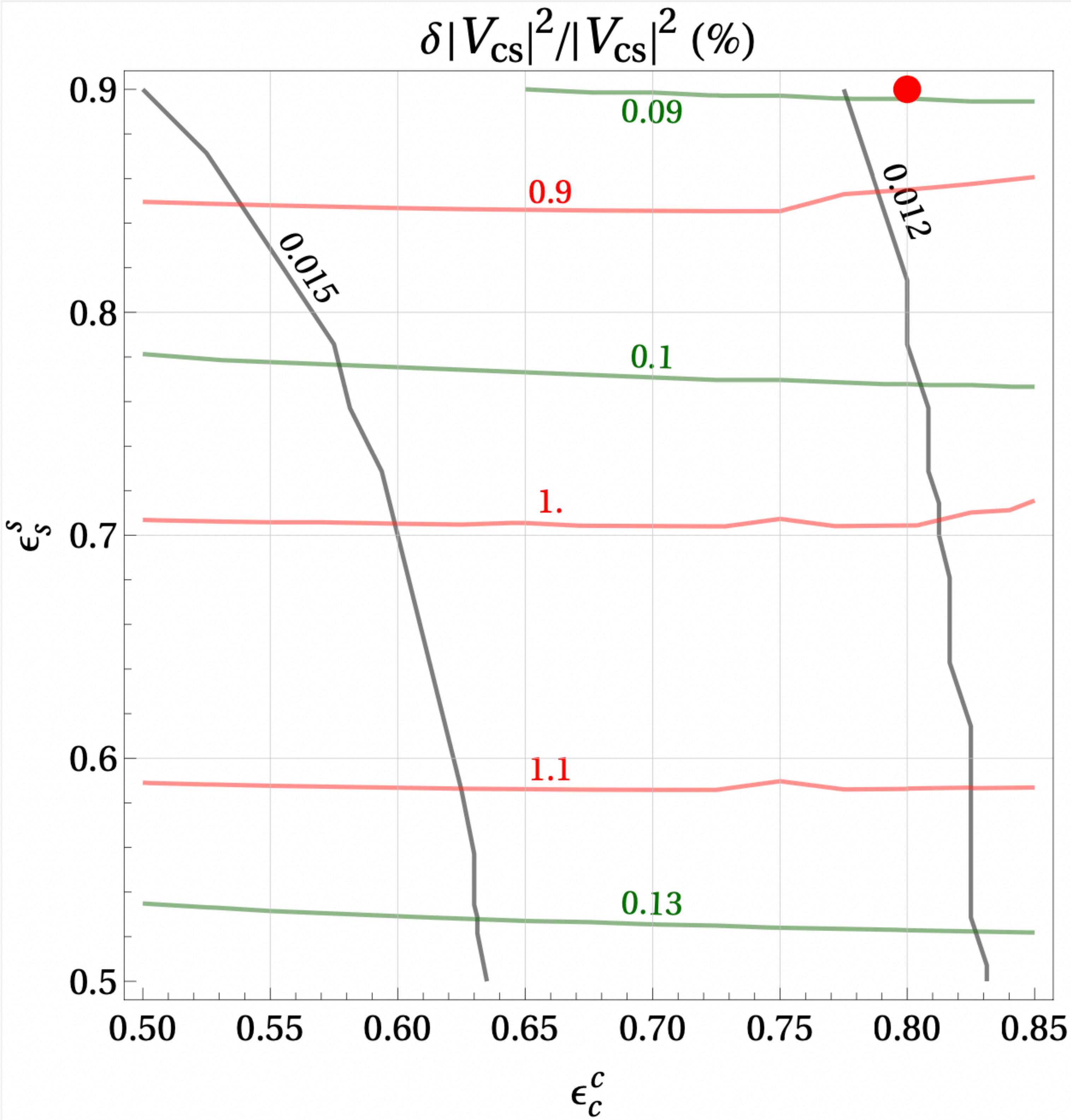

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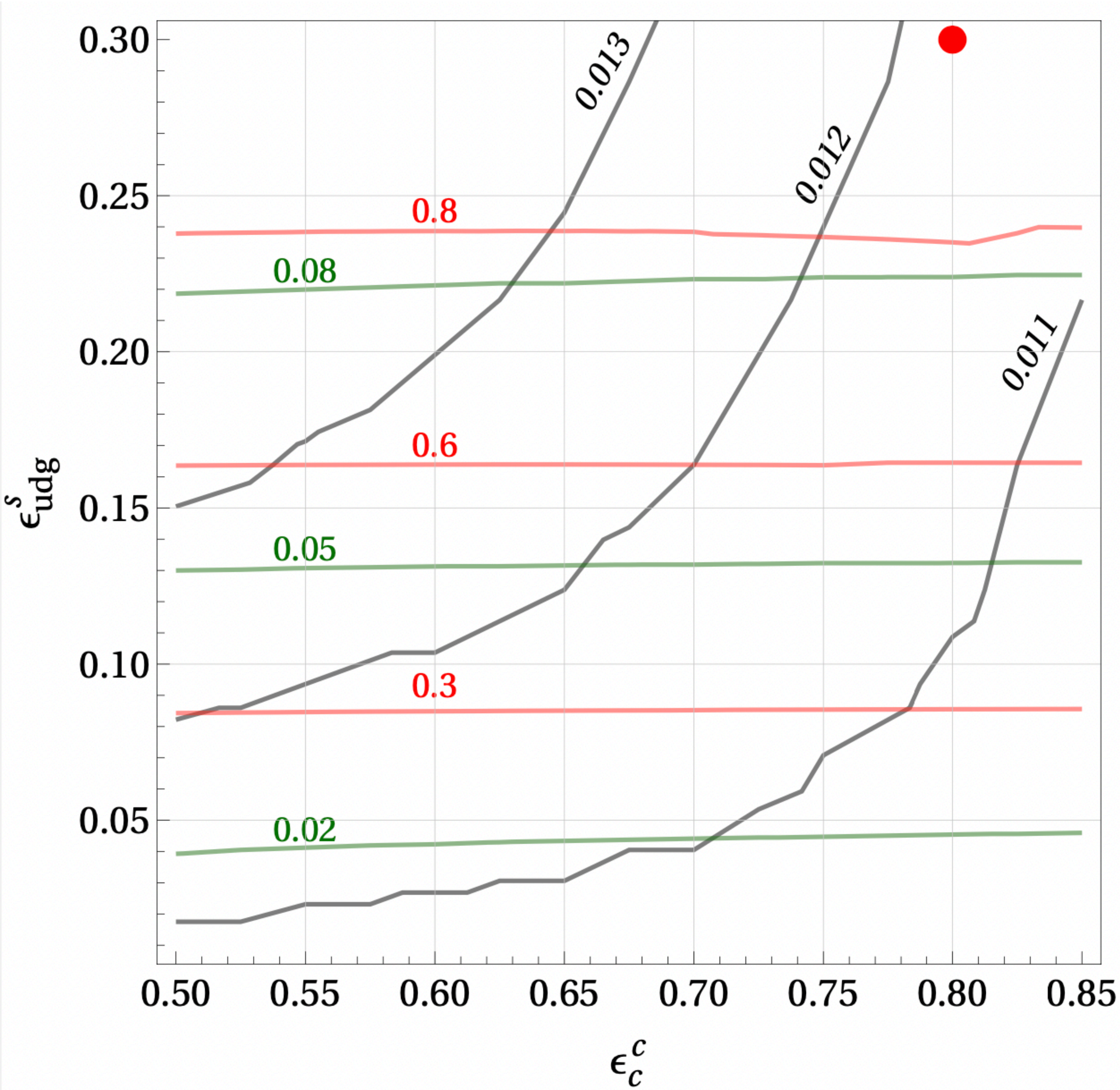

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– 1% systematics

Final precision dictated by s-tagger performance