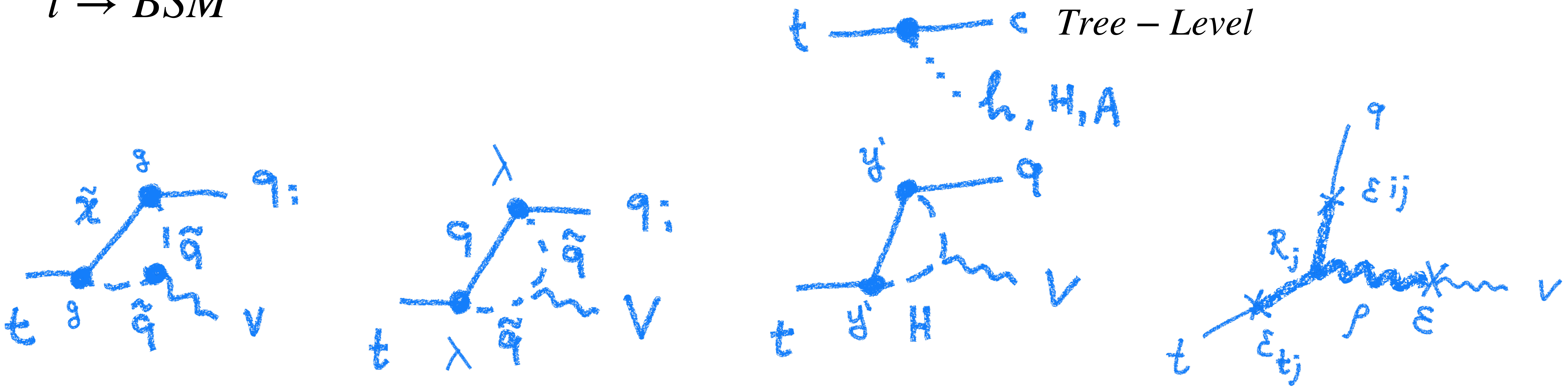
Top Exotic decays and Flavor Changing Neutral Currents at the top factory

Focus topic expert team meeting

Oct. 7th 2024

Top quark decay at the Top Factory

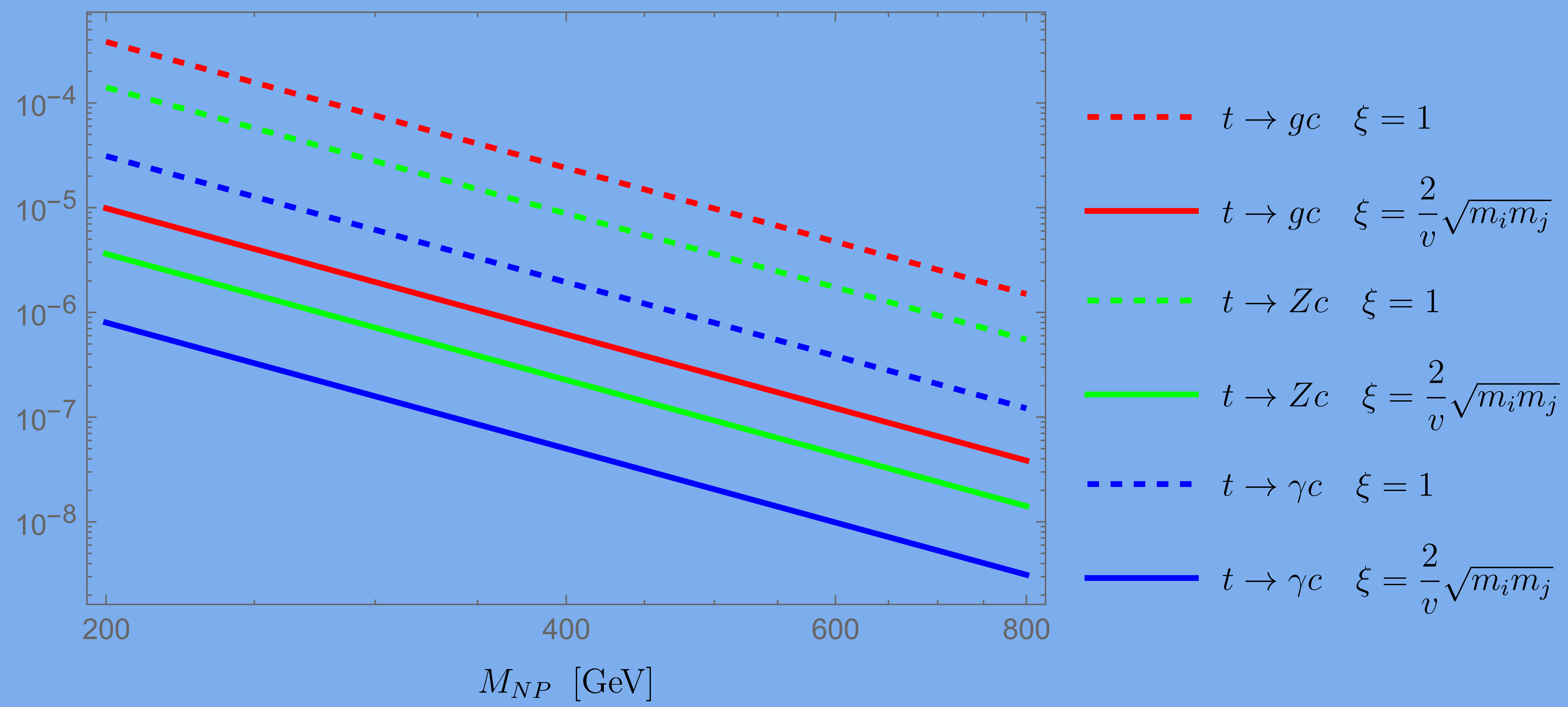
$t \rightarrow BSM$



$$BR^{i \rightarrow k}_{loop} \propto \left(g_{SM} \frac{\xi_{ij}\xi_{jk}}{16\pi^2} \right)^2 \left(\frac{m_t}{M_{NP}} \right)^4 = 4 \cdot 10^{-5} \cdot g^2_{SM} \cdot \left(\frac{m_t}{M_{NP}} \right)^4 \cdot (\xi_{ij}\xi_{jk})^2$$

Even a mere factor 2 stronger bounds on the particles originating flavor violation makes a factor 16 in the FCNC BR. This can take a "border-line observable at top factory" BR=10^{-5} down to 10^{-6} and ruin the party.

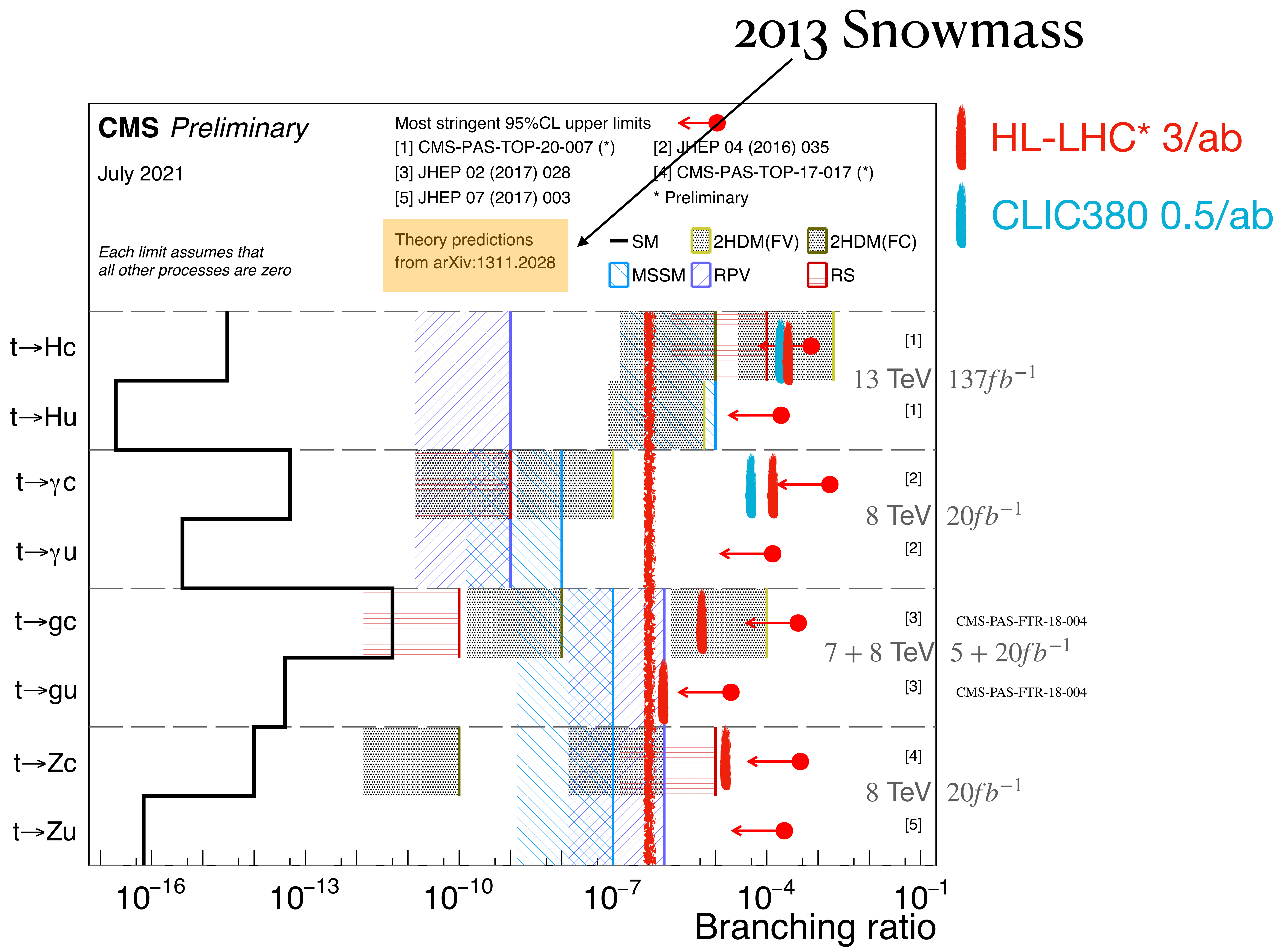
Top quark decay at the Top Factory



$$BR_{loop}^{i \to k} \propto \left(g_{SM} \frac{\xi_{ij}\xi_{jk}}{16\pi^2} \right)^2 \left(\frac{m_t}{M_{NP}} \right)^4 = 4 \cdot 10^{-5} \cdot g_{SM}^2 \cdot \left(\frac{m_t}{M_{NP}} \right)^4 \cdot (\xi_{ij}\xi_{jk})^2$$

Even a mere factor 2 stronger bounds on the particles originating flavor violation makes a factor 16 in the FCNC BR. This can take a “border-line observable at top factory” BR=10^{-5} down to 10^{-6} and ruin the party.

Top quark decay at the Top Factory



- **Last refresh of BSM benchmarks is quite old**
- Regardless of the focus topics a refresh seems needed for the final report
- Quick assessment concluded that most results may be still relevant (e.g. RS had already 3 TeV new physics scale)
- Inquiry for update/revalidation of the BSM benchmarks has started
- Relation to EFT to be investigated further

Staus for Snowmass 2013

arXiv:1311.2028

Table 1-7. *SM and new physics model predictions for branching ratios of top FCNC decays. The SM predictions are taken from [119], on 2HDM with flavor violating Yukawa couplings [119, 120] (2HDM (FV) column), the 2HDM flavor conserving (FC) case from [121], the MSSM with 1TeV squarks and gluinos from [122], the MSSM for the R-parity violating case from [123, 124], and warped extra dimensions (RS) from [125, 126] .*

Process	SM	2HDM(FV) ($Model-III$)	2HDM(FC) ($\max(Model-I, Model-II)$)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\lesssim 10^{-4}$	$\lesssim 10^{-8}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\lesssim 10^{-7}$	$\lesssim 10^{-9}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	$\lesssim 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\lesssim 10^{-5}$	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	$\lesssim 10^{-4}$

Sagar Airen's talk

This talk

observable at top factory

not observable at top factory

Use MSSM instead

Sagar Airen’s talk

Top Flavor in 2HDMs

with

Miriam Bulliri (Roma1 Sapienza) and Federico Mescia (LNF Frascati)

Nomenclature for 2HDMs (no pretense to be complete)

Table 1. The most familiar 2HDMs.

2207.06771

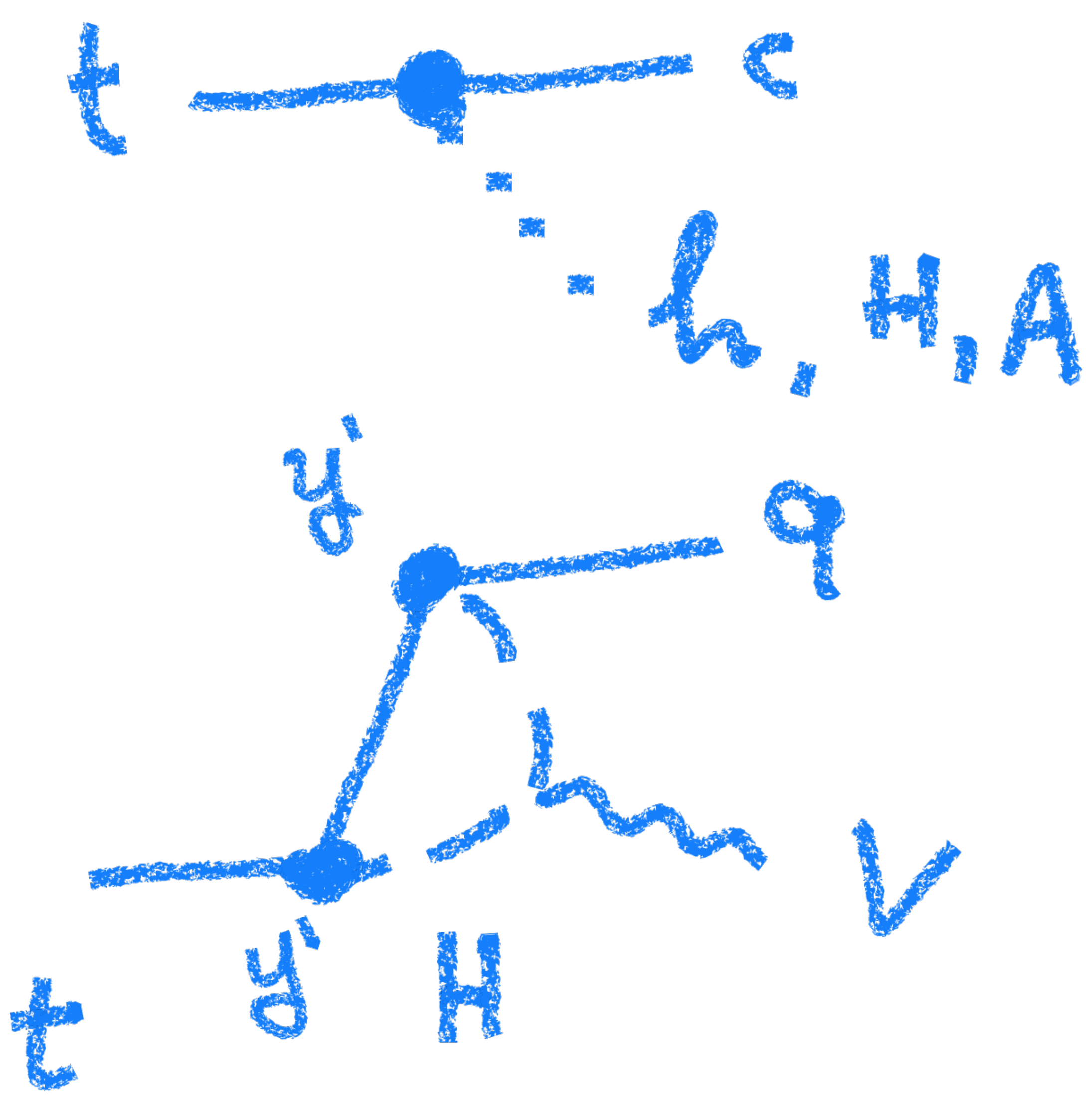
	Model	u_R^i	d_R^i	e_R^i	
$\phi_1 \to -\phi_1$	Type I	Φ_2	Φ_2	Φ_2	a.k.a. *NFC – Type I* or *Inert*
$\phi_2 \to -\phi_2, u_R \to -u_R$	Type II	Φ_2	Φ_1	Φ_1	a.k.a. "up-specifc" or *NFC – Type II*
$\phi_1 \to -\phi_1, e_R \to -e_R$	Lepton-specific	Φ_2	Φ_2	Φ_1	a.k.a. "lepton-specifc"
$\phi_1 \to -\phi_1, d_R \to -d_R$	Flipped	Φ_2	Φ_1	Φ_2	a.k.a. "down-specifc"

NFC=Natural Flavor Conservation

Symmetries can be advocated to fix which Higgs doublet interacts with which kind of fermions.

2HDM-FV

$t \to cV$ in 2HDM-FV



htc coupling tuned away by "alignment" making *h* SM-like (flavor conserving and SM strength as LHC measurements suggest quite strongly)

$$g_{hVV} = \sin(\beta - \alpha) \simeq 1 - \frac{1}{2}\cos^2(\beta - \alpha) + \ldots$$

FV coupling of *h*

$m_{H,A,H^+} > m_t$ so that they do not have a tree-level decay

$$\mathcal{L}_{\mathrm{Y}} = \mathcal{L}_{\mathrm{Y,SM}} + \frac{1}{\sqrt{2}}\bar{d}\xi^d dH + \frac{1}{\sqrt{2}}\bar{u}\xi^u uH + \frac{1}{\sqrt{2}}\bar{\ell}\xi^\ell \ell H - \frac{i}{\sqrt{2}}\bar{d}\gamma_5\xi^d dA - \frac{i}{\sqrt{2}}\bar{u}\gamma_5\xi^u uA$$
$$-\frac{i}{\sqrt{2}}\bar{\ell}\gamma_5\xi^\ell \ell A + \left[\bar{u}\left(\xi^u V_{\mathrm{CKM}} P_L - V_{\mathrm{CKM}}\xi^d P_R\right) dH^+ - \bar{\nu}\xi^\ell P_R \ell H^+ + \mathrm{h.c.}\right],$$

both the doublets couple to all the quarks and leptons, but flavor violation is only in the doublet that does not take a VEV

$t \to cg$ in 2HDM-FV

Atwood et al 1996

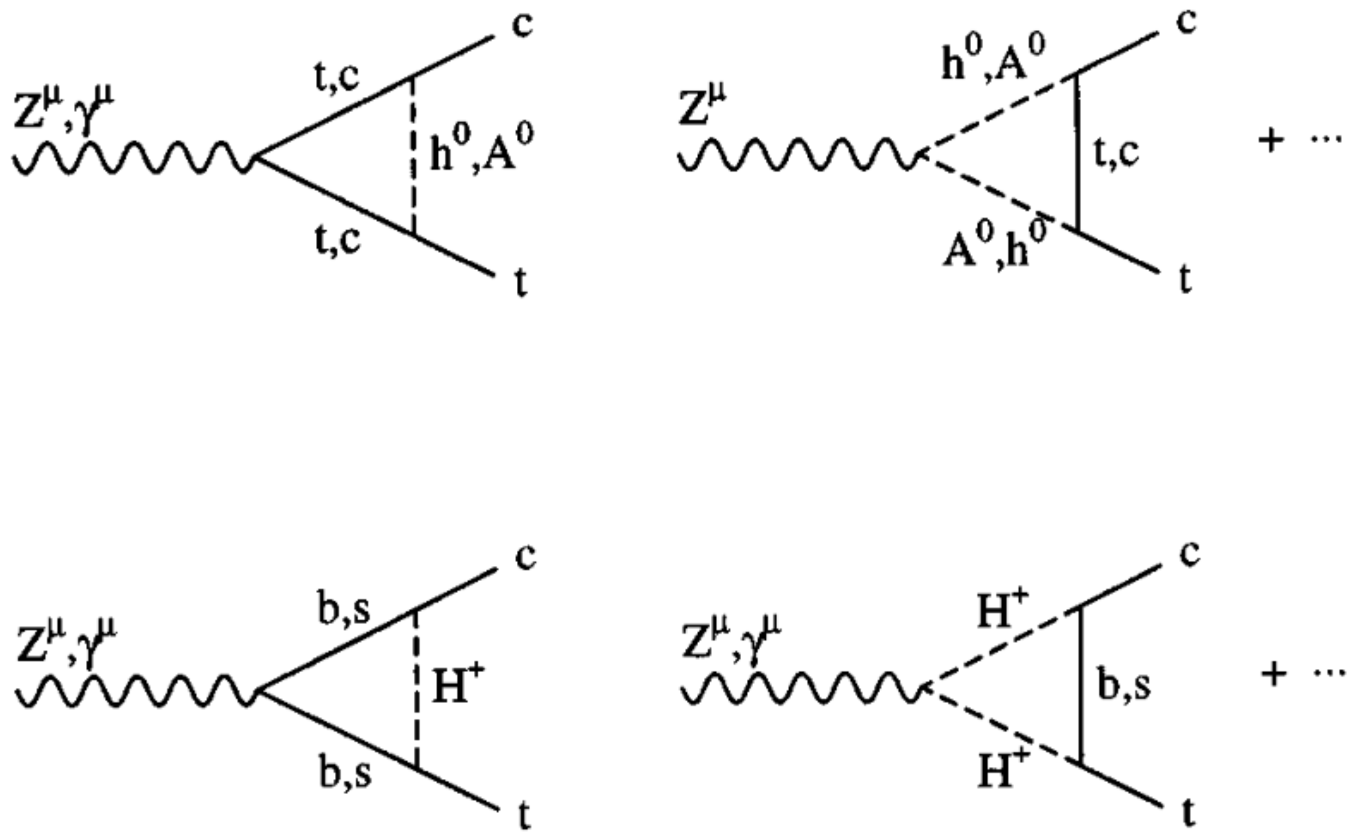


TABLE I. Values of $B(t\to c\gamma)$, $B(t\to cZ)$, and $B(t\to cg)$ for $m_t \simeq 180$ GeV, in the SM and in the 2HDM's denoted as model I, model II, and model III. Each range is obtained by varying m_c, m_h, m_A, $\tan\beta, \ldots$ over a broad region of the parameter space of the corresponding model, as explained in the text. For model III, we have fixed $\lambda_{ij} \simeq \lambda = 1$ in the FC couplings.

Decay	SM	"up-specifc" Model I *NFC – Type II*	*Inert* Model II *NFC – Type I*	Model III *FV*
$t\to c\gamma$	$\sim 5\times10^{-12}$	10^{-13}–10^{-11}	10^{-13}–10^{-9}	10^{-12}–10^{-7}
$t\to cZ$	$\sim 10^{-13}$	10^{-13}–10^{-11}	10^{-13}–10^{-10}	10^{-8}–10^{-6}
$t\to cg$	$\sim 5\times10^{-11}$	10^{-11}–10^{-9}	10^{-11}–10^{-8}	10^{-8}–10^{-4}

$$\simeq \left(\frac{1}{16\pi^2}\right)^2 BR(t\to gc)$$

$t \to cg$ in 2HDM-FV

Atwood et al 1996

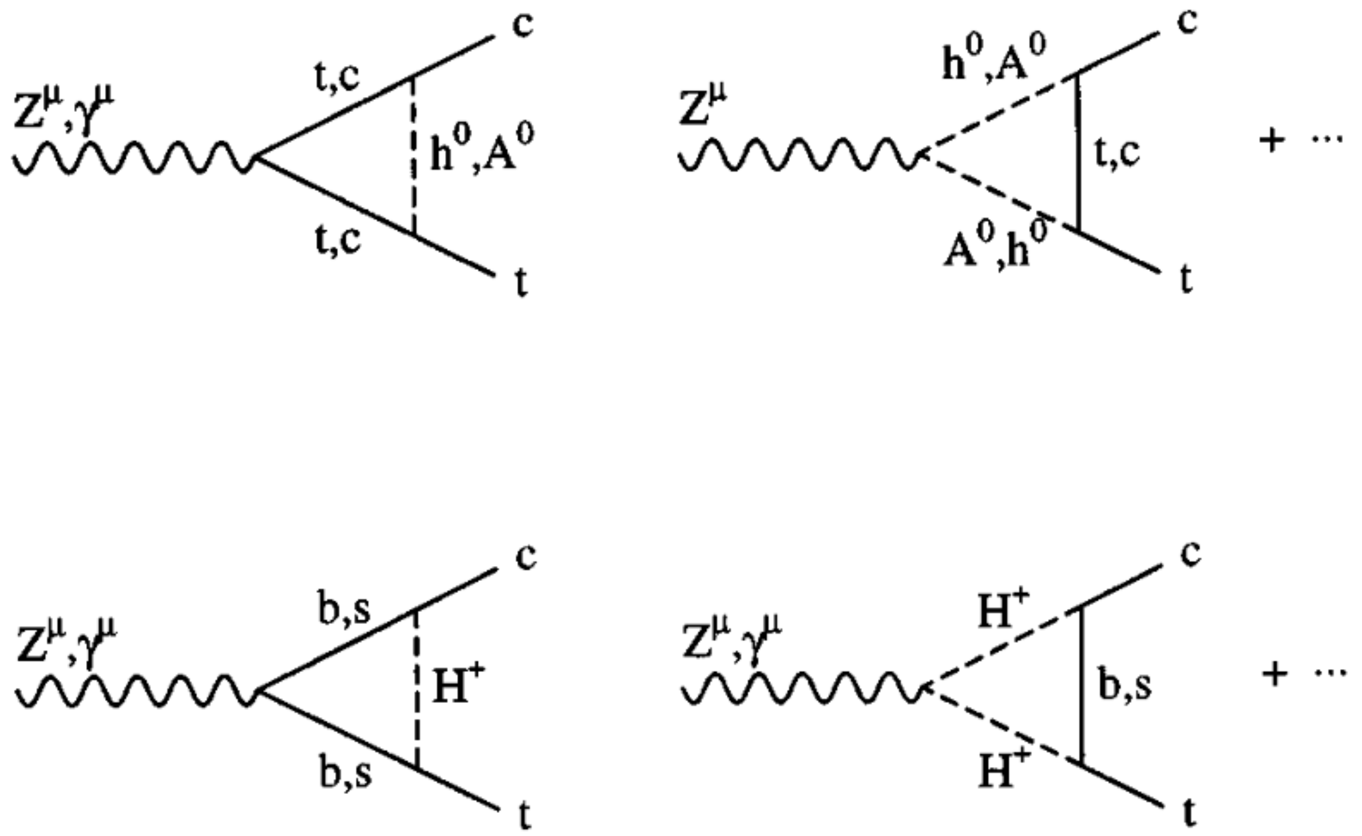


TABLE I. Values of $B(t\to c\gamma)$, $B(t\to cZ)$, and $B(t\to cg)$ for $m_t \simeq 180$ GeV, in the SM and in the 2HDM's denoted as model I, model II, and model III. Each range is obtained by varying m_c, m_h, m_A, $\tan\beta, \ldots$ over a broad region of the parameter space of the corresponding model, as explained in the text. For model III, we have fixed $\lambda_{ij} \simeq \lambda = 1$ in the FC couplings.

Decay	SM	"up-specifc" Model I *NFC – Type II*	*Inert* Model II *NFC – Type I*	Model III *FV*
$t\to c\gamma$	$\sim 5\times 10^{-12}$	10^{-13}–10^{-11}	10^{-13}–10^{-9}	10^{-12}–10^{-7}
$t\to cZ$	$\sim 10^{-13}$	10^{-13}–10^{-11}	10^{-13}–10^{-10}	10^{-8}–10^{-6}
$t\to cg$	$\sim 5\times 10^{-11}$	10^{-11}–10^{-9}	10^{-11}–10^{-8}	10^{-8}–10^{-4}

$\simeq \left(\frac{1}{16\pi^2}\right)^2 BR(t\to gc)$

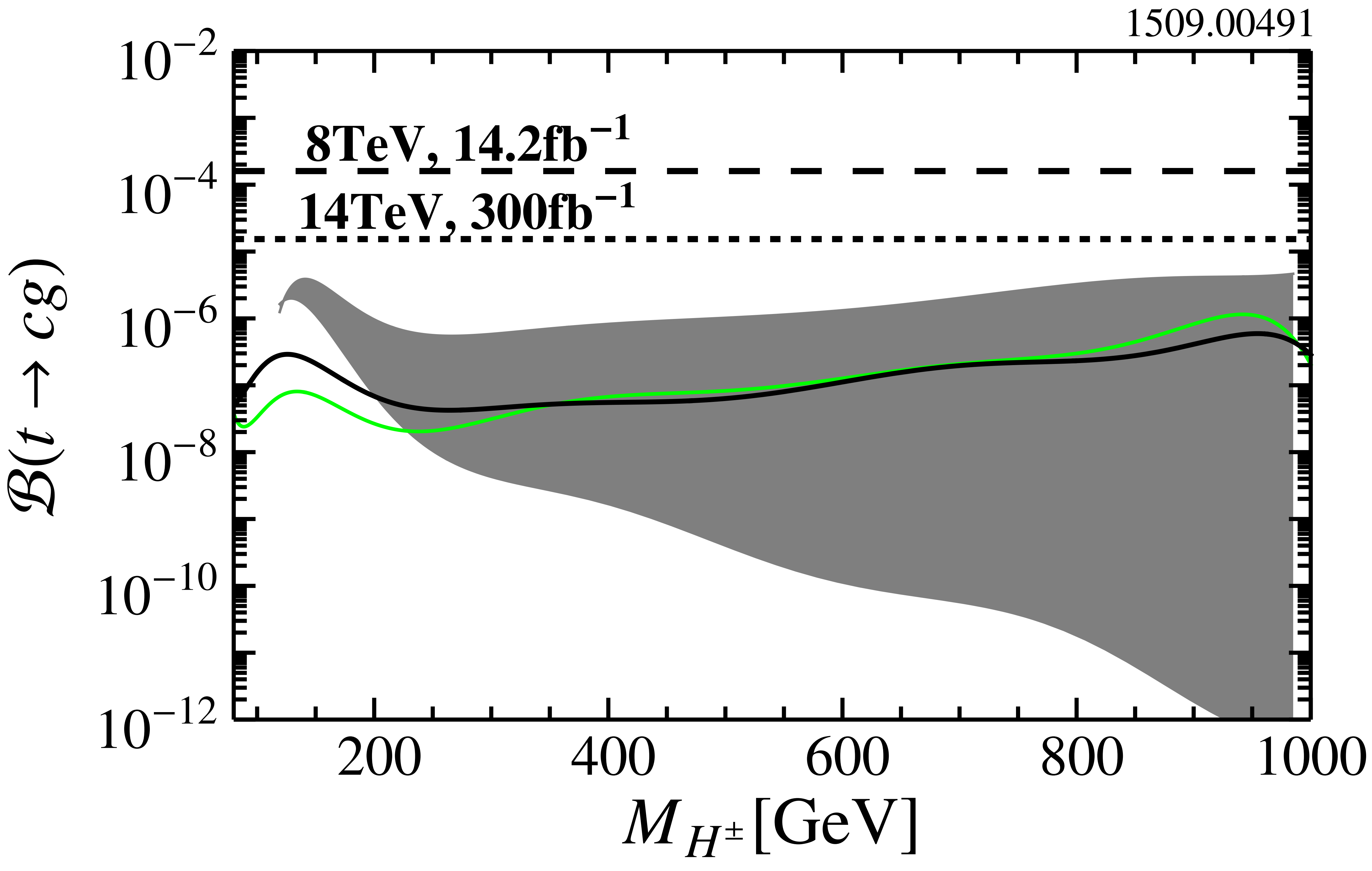
what goes in the summary plots

$t \to cg$ in 2HDM-FV

Kim et al, 1509.00491 2015

observable	SM	EXP
$\mathcal{B}(B \to \tau\nu) \cdot 10^4$	0.85 ± 0.14	1.14 ± 0.22
$R(D)$	0.297 ± 0.017	$0.391 \pm 0.041 \pm 0.028$
$R(D^*)$	0.252 ± 0.003	$0.322 \pm 0.018 \pm 0.012$
$\Delta m_d[\text{ps}^{-1}]$	0.51 ± 0.06	0.510 ± 0.003
$\Delta m_s[\text{ps}^{-1}]$	16.93 ± 1.16	17.757 ± 0.021
$\mathcal{B}(B \to X_s\gamma) \cdot 10^4$	3.36 ± 0.23	$3.43 \pm$ 0.22 was 0.66 — 3x better
$\mathcal{B}(t \to cg)$	$< 10^{-10}$	$< 1.6 \times 10^{-4}$ (95% CL)
$\sigma(pp \to tt)$	-	< 62 fb (95% CL)
R_b	0.21576 ± 0.00003	0.21629 ± 0.00066
ρ_0	1	$1.00040 \pm$ 0.00024 was 0.0025 — 10x better

0.0018



Hardly tenable to consider $BR > 10^{-6}$

Bulliri et al. Work in progress to remove effect from R(D) and R(D*) in 1509.00491 and update limits from ρ and $b \to X_s\gamma$

$t \to cg$ in 2HDM-FV

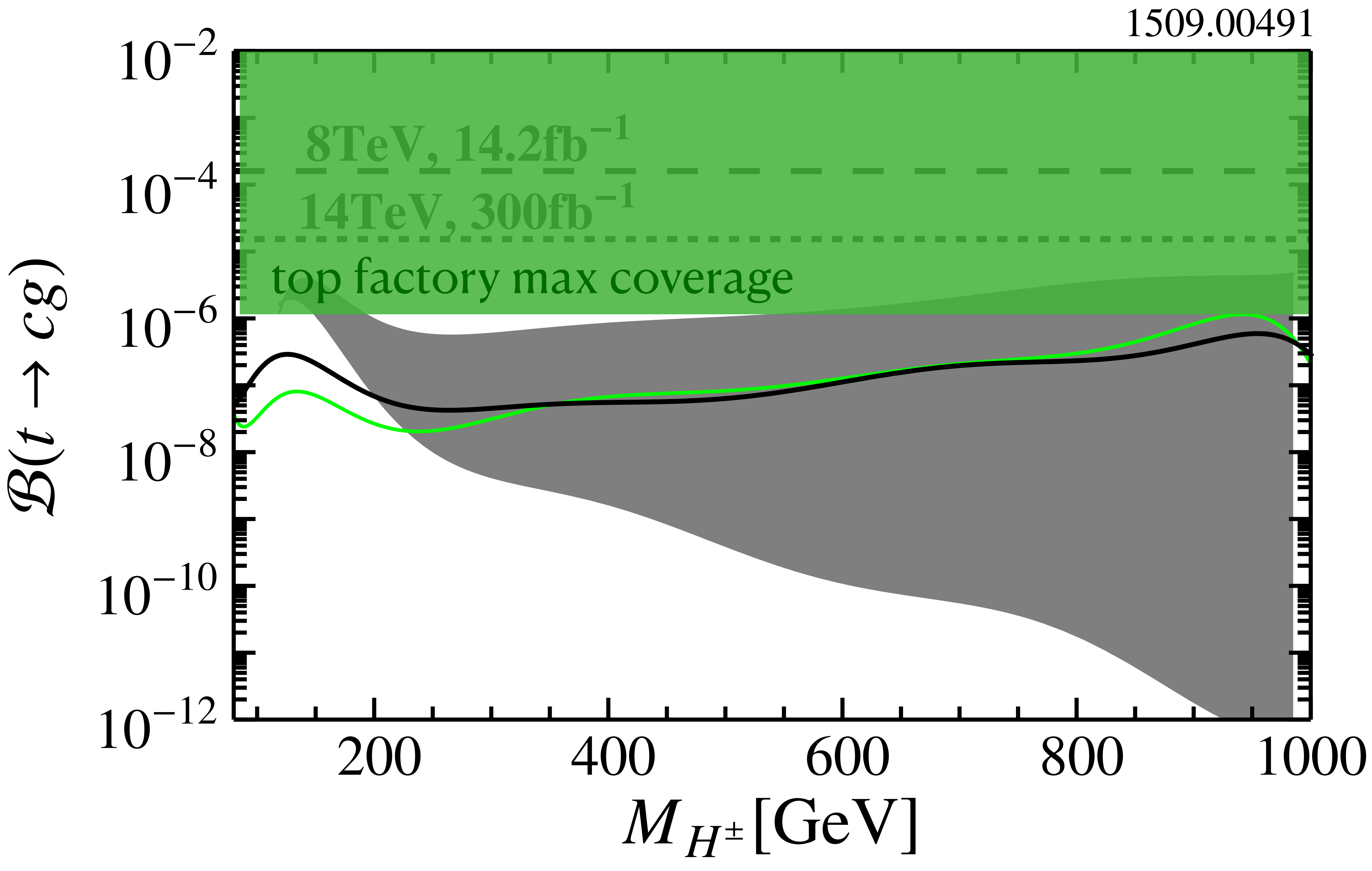
Kim et al, 1509.00491 2015

observable	SM	EXP
$\mathcal{B}(B \to \tau\nu) \cdot 10^4$	0.85 ± 0.14	1.14 ± 0.22
$R(D)$	0.297 ± 0.017	$0.391 \pm 0.041 \pm 0.028$
$R(D^*)$	0.252 ± 0.003	$0.322 \pm 0.018 \pm 0.012$
$\Delta m_d[\mathrm{ps}^{-1}]$	0.51 ± 0.06	0.510 ± 0.003
$\Delta m_s[\mathrm{ps}^{-1}]$	16.93 ± 1.16	17.757 ± 0.021
$\mathcal{B}(B \to X_s\gamma) \cdot 10^4$	3.36 ± 0.23	$3.43 \pm$ 0.22 was 0.66
$\mathcal{B}(t \to cg)$	$< 10^{-10}$	$< 1.6 \times 10^{-4}$ (95% CL)
$\sigma(pp \to tt)$	-	< 62 fb (95% CL)
R_b	0.21576 ± 0.00003	0.21629 ± 0.00066
ρ_0	1	$1.00040 \pm$ 0.00024 was 0.0025

0.0018

3x better

10x better



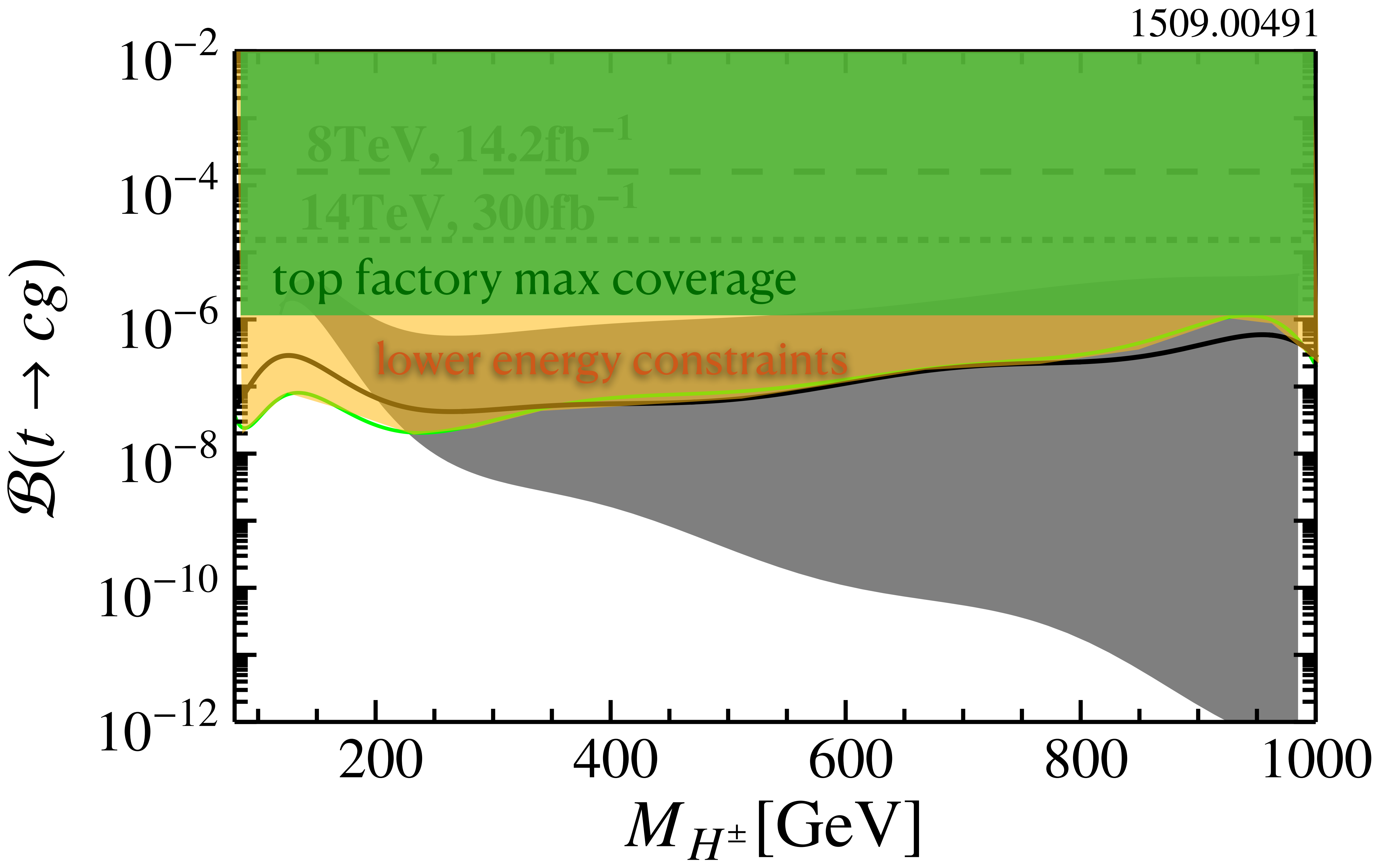
Hardly tenable to consider $BR > 10^{-6}$

Bulliri et al. Work in progress to remove effect from R(D) and R(D*) in 1509.00491 and update limits from ρ and $b \to X_s\gamma$

$t \to cg$ in 2HDM-FV

Kim et al, 1509.00491 2015

observable	SM	EXP	
$\mathcal{B}(B \to \tau\nu) \cdot 10^4$	0.85 ± 0.14	1.14 ± 0.22	
$R(D)$	0.297 ± 0.017	$0.391 \pm 0.041 \pm 0.028$	
$R(D^*)$	0.252 ± 0.003	$0.322 \pm 0.018 \pm 0.012$	
$\Delta m_d[\text{ps}^{-1}]$	0.51 ± 0.06	0.510 ± 0.003	
$\Delta m_s[\text{ps}^{-1}]$	16.93 ± 1.16	17.757 ± 0.021	
$\mathcal{B}(B \to X_s\gamma) \cdot 10^4$	3.36 ± 0.23	$3.43 \pm$ 0.22 was 0.66	3x better
$\mathcal{B}(t \to cg)$	$< 10^{-10}$	$< 1.6 \times 10^{-4}$ (95% CL)	
$\sigma(pp \to tt)$	-	< 62 fb (95% CL)	
R_b	0.21576 ± 0.00003	0.21629 ± 0.00066	
ρ_0	1	$1.00040 \pm$ 0.00024 was 0.0025 0.0018	10x better



Hardly tenable to consider $BR > 10^{-6}$

Bulliri et al. Work in progress to remove effect from R(D) and R(D*) in 1509.00491 and update limits from ρ and $b \to X_s\gamma$

Summary

- **Sagar Airen's work on RS and single top for Ztc coupling**

  - $BR(t \to cZ)$ has a new and a stronger limit in the RS model, which brings it safely below 10^{-6}
  - RS was the only model out of the comprehensive 2013 Snowmass survey capable of producing $BR > 10^{-6}$, thus $t \to cZ$ appears less interesting for the direct observation of FCNC top decays at a top factory capable of producing 10^6 $t\bar{t}$ pairs
  - single-top production at 240 GeV $e^+e^- \to (Z,\gamma)^* \to tc$ turns out to be a stronger probe of the Ztc coupling than direct observation of the decay $t \to Zc$ (see e.g. 1906.04573 for CEPC).
  - We find that the superior probing power of single top production holds pretty independently of the analysis details, and can even be attained at energies somewhat lower than 240 GeV (as to stress the robustness of single top, or if we ever need to run below 240 GeV)

Summary

- **Kim et al. + Miriam Bulliri's work on 2HDM-FV and the gtc coupling**

- $BR(t \to cg)$ has a new and a stronger limit in the 2HDM-FV model, which brings it safely below 10^{-6}
- 2HDM-FV was the only model out of the comprehensive 2013 Snowmass survey capable of producing $BR > 10^{-6}$, thus $t \to cg$ appears less interesting for the direct observation of FCNC top decays at a top factory capable of producing 10^6 $t\bar{t}$ pairs

CMS-PAS-FTR-18-004

Table 3: The expected exclusion 1D limits at 95% C.L. on the FCNC couplings and the corresponding branching fractions for an integrated luminosity of 300 fb^{-1} and 3000 fb^{-1}. In addition, a comparison with statistic-only uncertainties is shown.

Integrated luminosity	$\mathcal{B}(\mathrm{t} \to \mathrm{ug})$	$\lvert\kappa_{\mathrm{tug}}\rvert/\Lambda$	$\mathcal{B}(\mathrm{t} \to \mathrm{cg})$	$\lvert\kappa_{\mathrm{tcg}}\rvert/\Lambda$
300 fb^{-1}	$9.8 \cdot 10^{-6}$	0.0029 TeV^{-1}	$99 \cdot 10^{-6}$	0.0091 TeV^{-1}
3000 fb^{-1}	$3.8 \cdot 10^{-6}$	0.0018 TeV^{-1}	$32 \cdot 10^{-6}$	0.0052 TeV^{-1}
3000 fb^{-1} Stat. only	$1.0 \cdot 10^{-6}$	0.0009 TeV^{-1}	$4.9 \cdot 10^{-6}$	0.0020 TeV^{-1}

Outlook and status for ECFA2024

- Ztc coupling is best probed at 240 GeV via single-top production at e^+e^-
- Currently there is not candidate model to generate a $BR > 10^{-6}$ (does not mean one cannot make one)
- gtc coupling is best probed at the LHC via single top production
- Currently there is not candidate model to generate a $BR > 10^{-6}$ (does not mean one cannot make one)

Process	SM	2HDM(FV) [$Model-III$]	2HDM(FC) [$\max(Model-I, Model-II)$]	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\leq 10^{-6}$	$\leq 10^{-10}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\leq 10^{-7}$	$\leq 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\leq 10^{-4}$	$\leq 10^{-8}$	$\leq 10^{-7}$	$\leq 10^{-6}$	$\leq 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\leq 10^{-8}$	$\leq 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\leq 10^{-7}$	$\leq 10^{-9}$	$\leq 10^{-8}$	$\leq 10^{-9}$	$\leq 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\leq 10^{-5}$	$\leq 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

Sagar Airen's talk

Kim et al. + Bulliri eta al. (forthcoming)

observable at top factory

not observable at top factory

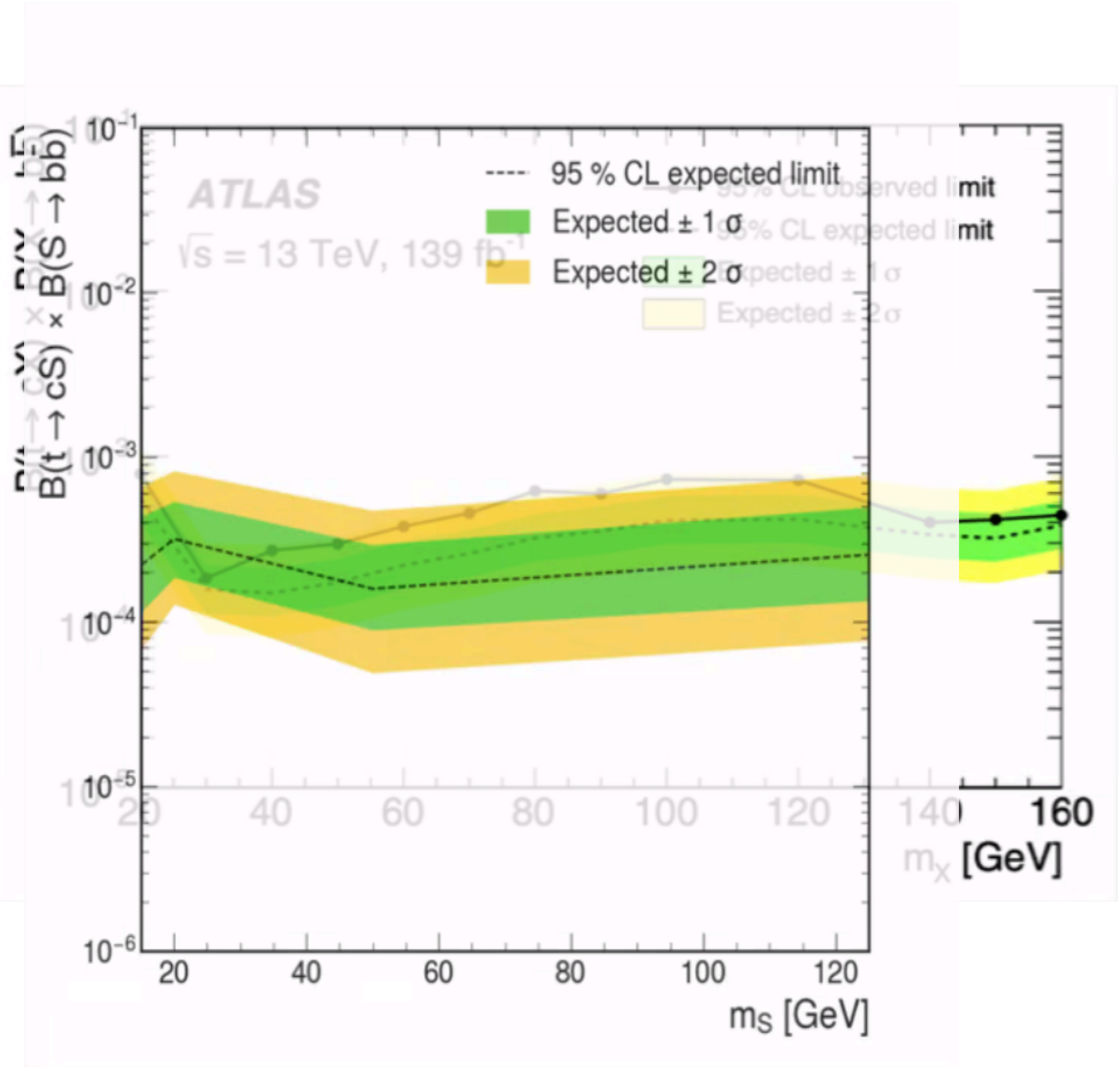
Use MSSM instead

- No known show-stoppers for htc coupling, motivates pursuing also ϕtc BSM scalar ϕ → Kevin Mota's talk

Next steps

1. Please upload your slides now. We have a summary plot at the Paris meeting.
2. We will have Kevin and Krill results circulated. Marina Cobal agreed already to review it, please make yourself known if you wish to participate in the summarizing of that result for the report.
3. Update of FCNC will be reviewed as well with similar process.
4. I think there is material to write a more extensive paper after the ECFA report is out
5. Update of *htc* couplings limits probably compulsory then

Thank you



$$pp \rightarrow ttbb$$

$$Z \rightarrow bb\phi \rightarrow bbbb$$

$Z \to b\bar{b}b\bar{b}$ Decay Mode Summary PDGID:S044.73 INSPIRE

	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Conf. Level	P(MeV/c)
Γ_{13}	$Z \to b\bar{b}b\bar{b}$	$(3.6 \pm 1.3) \times 10^{-4}$		

The following data is related to the above value:

$\Gamma(Z \to b\bar{b}b\bar{b})/\Gamma(Z \to$ hadrons$)$ Γ_{13}/Γ_8 –

VALUE (10^{-4})	DOCUMENT ID		TECN	COMMENT
5.2 ± 1.9 OUR AVERAGE				
3.6 ±1.7 ±2.7	[1] ABBIENDI	2001G	OPAL	E^{ee}_{cm} = 88 – 94 GeV
6.0 ±1.9 ±1.4	[2] ABREU	1999U	DLPH	E^{ee}_{cm} = 88 – 94 GeV

[1] ABBIENDI 2001G use a sample of four-jet events from hadronic Z decays. To enhance the $b\bar{b}b\bar{b}$ signal, at least three of the four jets are required to have a significantly detached secondary vertex.

[2] ABREU 1999U force hadronic Z decays into 3 jets to use all the available phase space and require a b tag for every jet. This decay mode includes primary and secondary $4b$ production, $e.g$, from gluon splitting to $b\bar{b}$.

References

Direct Reach (HL-)LHC

Direct Searches for new Higgs doubles

Still to be incorporated

ATLAS PUB Note

ATL-PHYS-PUB-2024-008

28th May 2024

Summary plots for beyond Standard Model Higgs boson benchmarks for direct and indirect searches

The ATLAS Collaboration

This note presents an update of the plots that summarize the interpretations of various searches for additional Higgs bosons beyond the Standard Model, as well as the Higgs boson coupling combination, in the hMSSM and the 2HDM. This version supersedes ATL-PHYS-PUB-2022-043.