Rare top quark decays at the FCC-hh

Based on arXiv:1712.06332
[Published in Eur.Phys.J. C78 (2018) no.3, 214]

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&
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[FCC Week 2018, 9-13 April, Amsterdam, NL]

introduction

$$m_{\rm top} \sim \frac{v}{\sqrt{2}} \sim 174 \text{ GeV}$$

(or: $y_t \simeq 1$ **)**

$$\Rightarrow$$

the top quark is quite likely intimately linked to Electro-Weak Symmetry Breaking

introduction

the top quark carries <u>colour charge</u>

+ decays <u>before</u> hadronisation (mostly) through $t \rightarrow Wb$,

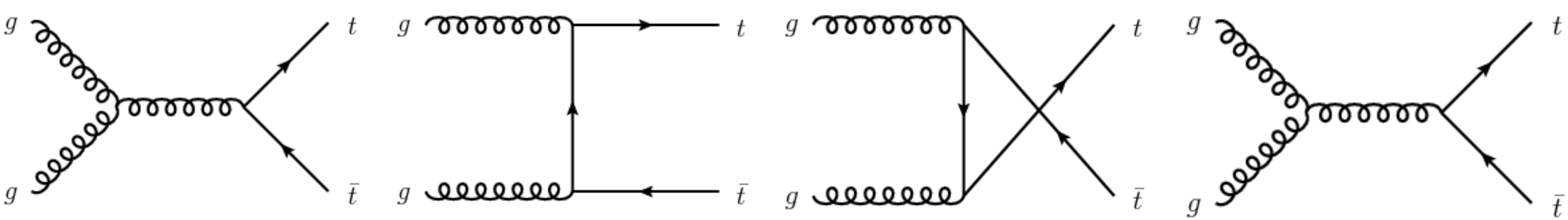
$$\Rightarrow$$

<u>unique</u> amongst quarks.

+ QCD pair production with <u>large cross sections</u>

@ hadron colliders:

(LO diags.)



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LHC exploration (ATLAS)

cross section: $\sigma(t\bar{t})_{\rm LHC} \sim \mathcal{O}(1~{\rm nb})$

Search for flavour-changing neutral current top quark decays t->qZ at 13 TeV NEW	Submitted to JHEP	26-MAR-18	13	36 fb^{-1}
Measurements of ttbar+njets differential cross-sections in the l+jets channel at 13 TeV	Submitted to JHEP	19-FEB-18	13	3.2 fb^{-1}
Differential ttbar cross-section all-hadronic boosted 13 TeV	Submitted to PRD	06-JAN-18	13	36 fb^{-1}
inclusive ttbar cross section in the lepton+jets channel at 8 TeV	Submitted to EPJC	19-DEC-17	8	20.3 fb^{-1}
Measurement of tW single top differential cross-sections at 13 TeV	Eur. Phys. J. C 78 (2018) 186	05-DEC-17	13	36 fb^{-1}
tZ cross section in the trilepton channel at 13 TeV	Submitted to PLB	10-OCT-17	13	36 fb^{-1}
Dilepton differential ttbar cross-sections at 8 TeV and pole mass determination	Eur. Phys. J. C 77 (2017) 804	27-SEP-17	8	20 fb^{-1}
ATLAS+CMS ttbar Charge asymmetry combination	Submitted to JHEP	15-SEP-17	7, 8	5 fb^{-1}, 20 fb^{-1}
Measurement of the top quark width at 8 TeV	Eur. Phys. J. C 78 (2018) 129	13-SEP-17	8	20.2 fb^{-1}
Measurement of the lepton+jets ttbar differential cross section at 13 TeV	JHEP 11 (2017) 191	02-AUG-17	13	3.2 fb^{-1}
Single top anomalous couplings 3 angle fit at 8 TeV	JHEP 12 (2017) 017	17-JUL-17	8	20 fb^{-1}
Search FCNC t->h(125) q, h(125)->gammagamma	JHEP 10 (2017) 129	05-JUL-17	13	36.1 fb^{-1}

[ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults]

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LHC exploration (CMS)

85	TOP-17-002	Measurement of differential cross sections for the production of top quark pairs and of additional jets in lepton+jets events from pp collisions at $\sqrt{s} = 13$ TeV
84	TOP-16-014	Measurements of differential cross sections of top quark pair production as a function of kinematic event variables in proton-proton collisions at $\sqrt{s} = 13$ TeV
83	TOP-16-020	Measurement of the associated production of a single top quark and a Z boson in pp collisions at $\sqrt{s} = 13$ TeV
82	TOP-17-003	Search for the flavor-changing neutral current interactions of the top quark and the Higgs boson which decays into a pair of b quarks at $\sqrt{s} = 13$ TeV
81	TOP-16-023	Measurement of the inclusive $t\bar{t}$ cross section in pp collisions at $\sqrt{s} = 5.02$ TeV using final states with at least one charged lepton
80	TOP-17-005	Measurement of the cross section for top quark pair production in association with a W or Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV
79	TOP-17-009	Search for standard model production of four top quarks with same-sign and multilepton final states in proton-proton collisions at $\sqrt{s} =$ 13 TeV
78	TOP-15-016	Combination of inclusive and differential $t\bar{t}$ charge asymmetry measurements using ATLAS and CMS data at $\sqrt{s} = 7$ and 8 TeV
77	TOP-16-007	Measurement of normalized differential $t\bar{t}$ cross sections in the dilepton channel from pp collisions at $\sqrt{s} = 13$ TeV
76	TOP-14-008	Measurement of the semileptonic $t\bar{t}+\gamma$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV
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[CMS: http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html]

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top quarks at pp@100 TeV

pp@100 TeV cross section: $\sigma(t\bar{t})_{\mathrm{FCC-hh}} \sim \mathcal{O}(35\ \mathrm{nb})$

⇒ ~10^{12} top quarks produced in *O*(10) ab^{-1} ,
⇒ excellent opportunity for:

- **tests of QCD: through production mechanism.**

- **+ electro-weak (or new) physics: through decays.**

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our focus in this talk

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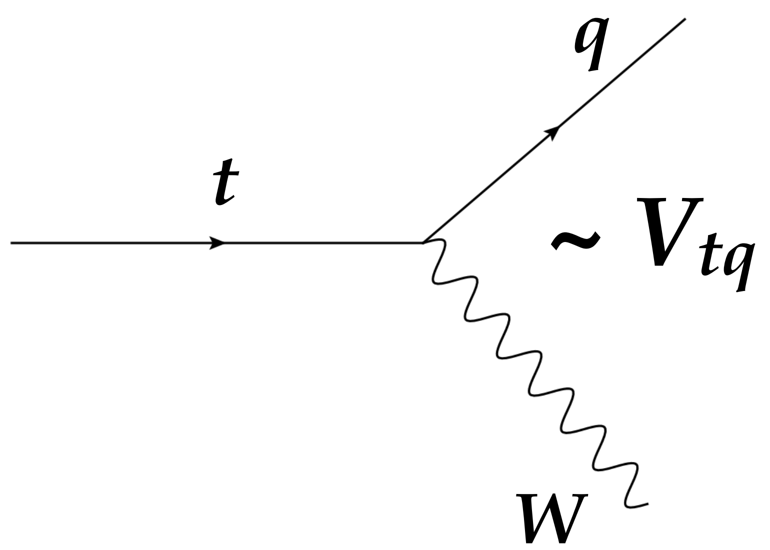
a survey of top quark decays

most top decays highly suppressed in SM:

⇒ an excellent window to probe new phenomena.

e.g.: "CKM" decays:



Channel	Br (SM)
$t \to bW$	~ 1
$t \to sW$	$1.6 \cdot 10^{-3}$
$t \to dW$	$\sim 10^{-4}$

a survey of top quark decays

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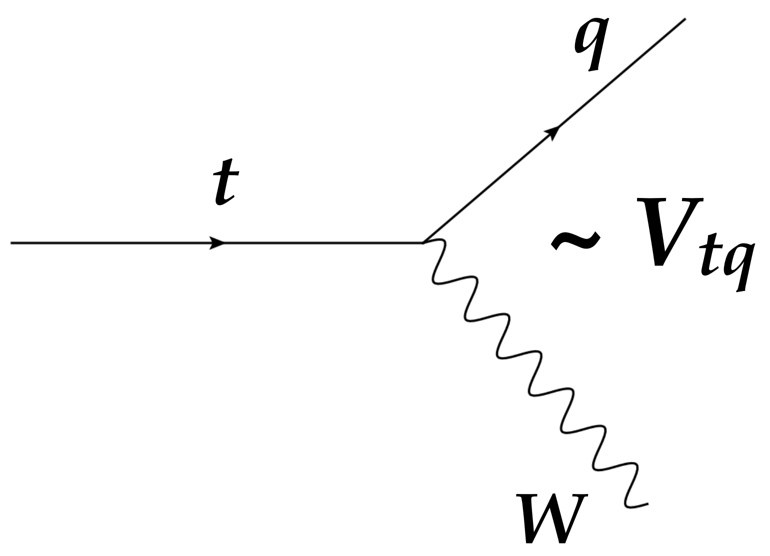

Channel	Br (SM)
$t \to bW$	~ 1
$t \to sW$	$1.6 \cdot 10^{-3}$
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e.g. in MSSM:
BR(t → sW) ~ 10^{-2}
[Diaz-Cruz, Gaitan-Lozano, Lopez-Castro, Pagliarone, 0712.3782]

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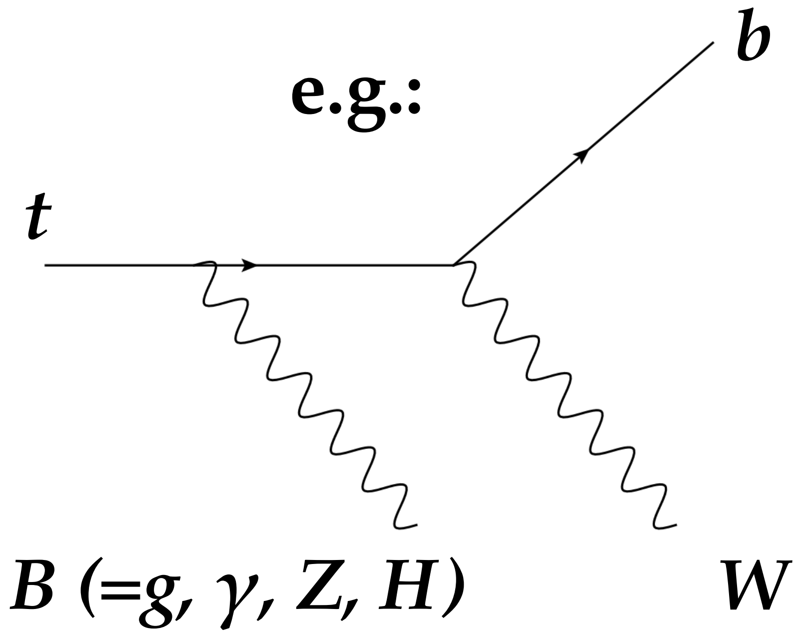
a survey of top quark decays

e.g.: "radiative" decays:



Channel	Br (SM)
$t \to bWg$	0.3 $(E_g > 10\ \text{GeV})$
$t \to bW\gamma$	$3.5 \cdot 10^{-3}$ $(E_\gamma > 10\ \text{GeV})$
$t \to bWZ$	$2 \cdot 10^{-6}$
$t \to bWH$	$1.8 \cdot 10^{-9}$

[Mele, hep-ph/0003064], [Mahlon, hep-ph/9810485], [Han, Ruiz, 1312.3324]

a survey of top quark decays

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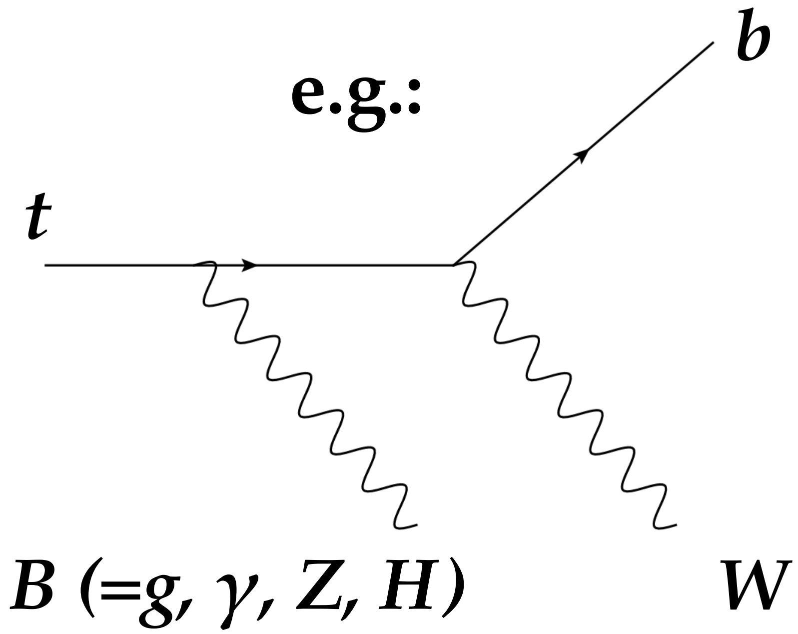

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a survey of top quark decays

e.g.: “exotic” decays:

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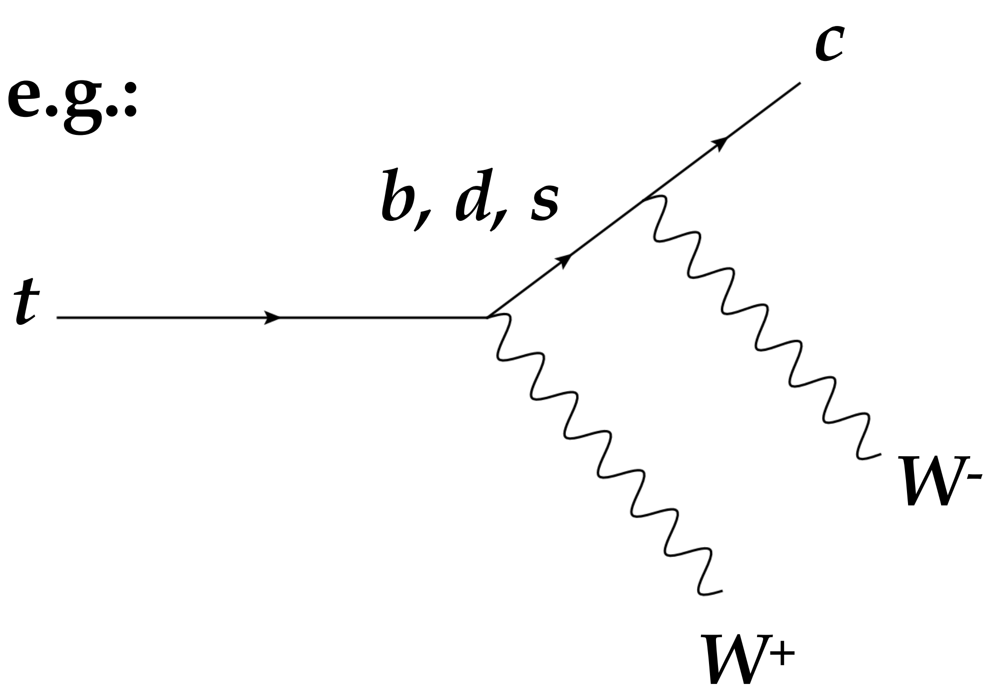

[see backup slides for references]

Channel	Br (SM)
cWW	$1.3 \cdot 10^{-13}$
$u\gamma$	$(3.7^{+2.7}_{-2.3}) \cdot 10^{-16}$
$c\gamma$	$5 \cdot 10^{-13}$ [7] $(4.6^{+2.0}_{-1.2}) \cdot 10^{-14}$ [6]
ug	$(3.7^{+2.8}_{-2.3}) \cdot 10^{-14}$ [6]
cg	$(4.6^{+2.4}_{-1.2}) \cdot 10^{-12}$ [6]
uZ	$8 \cdot 10^{-17}$[13]
cZ	$1.3 \cdot 10^{-13}$ [9, 2] 10^{-14} [13]
uH	$2.0 \cdot 10^{-17}$ [13]
cH	$0.4605 \cdot 10^{-13}$ $m_H = 120$ GeV [12] $0.3146 \cdot 10^{-13}$ $m_H = 130$ GeV [12]
$c\gamma\gamma$	$< 10^{-16}$ [2]

BRs ~
$10^{-12} - 10^{-17}$

a survey of top quark decays

e.g.: "exotic" decays:

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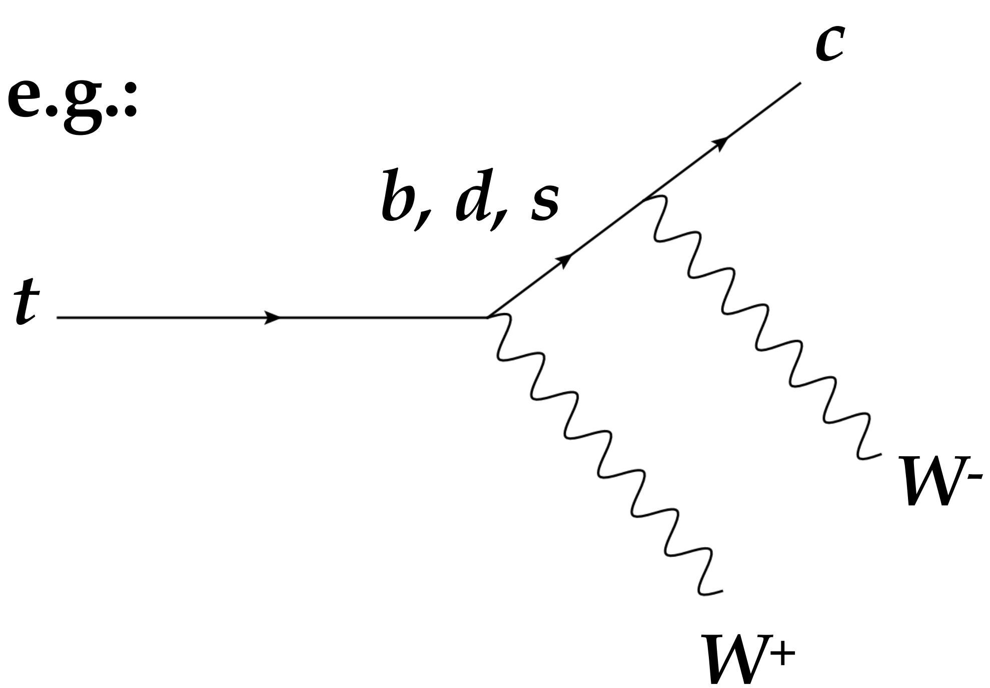

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BRs ~ $10^{-12} - 10^{-17}$

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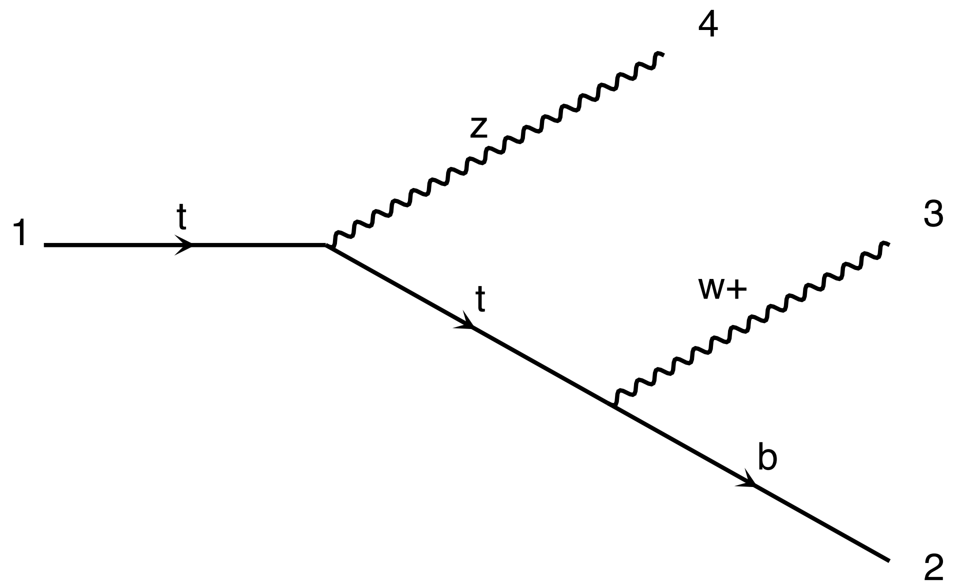
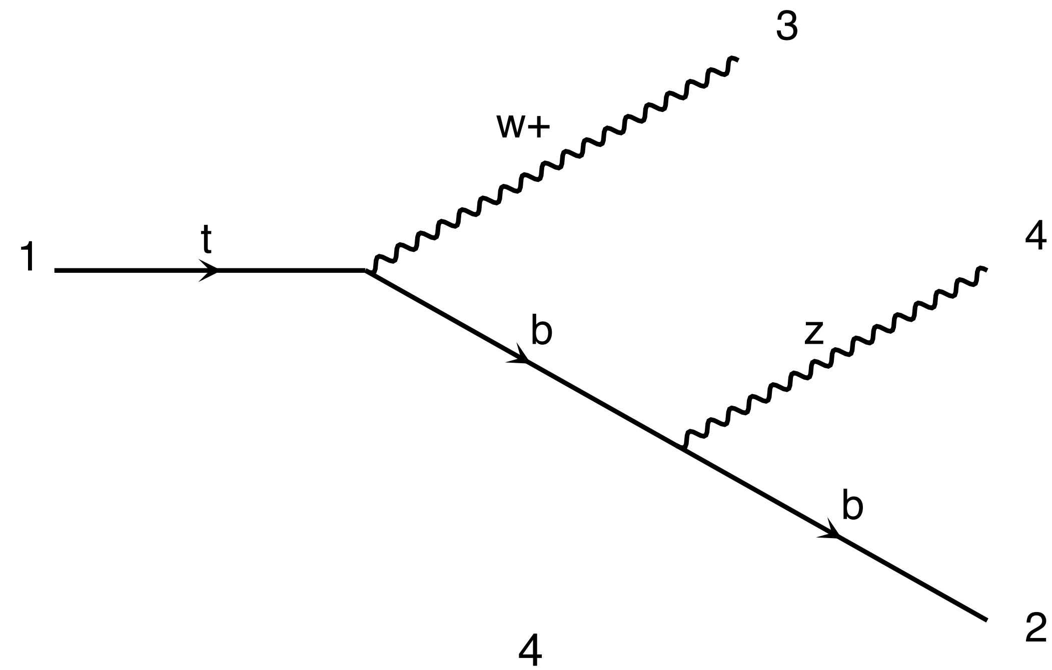
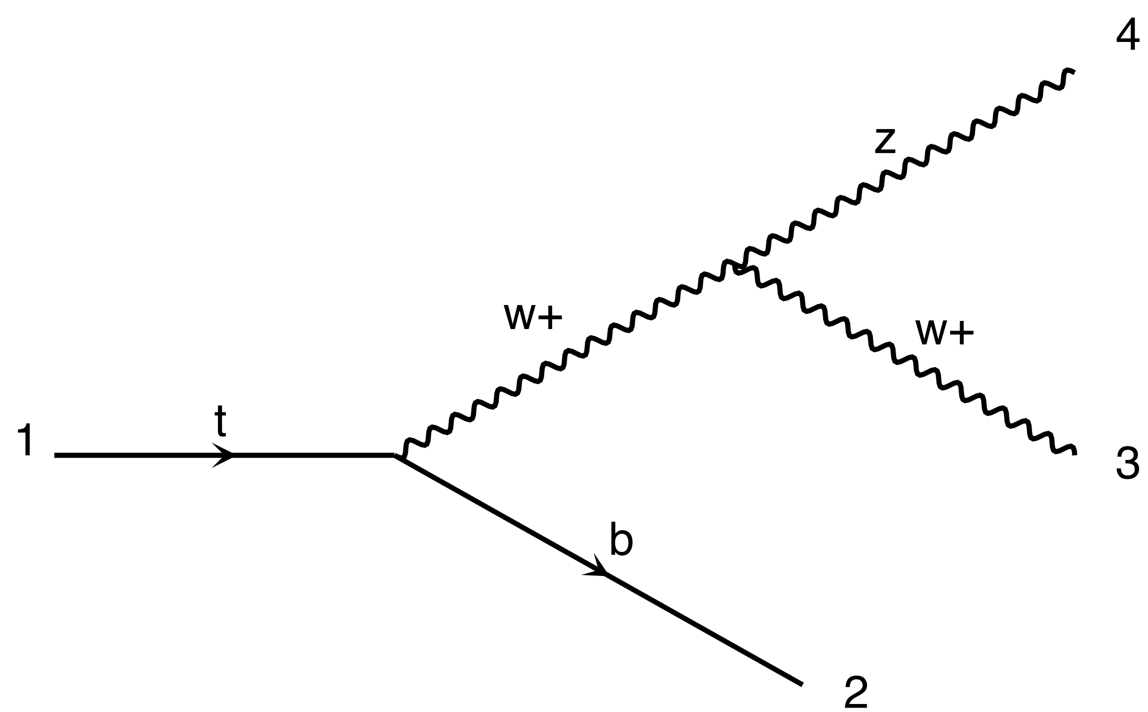
$$t \rightarrow bWZ$$

$$\text{BR(SM)} \sim 2 \times 10^{-6}$$

radiative decay with a Z boson: $t \to bWZ$

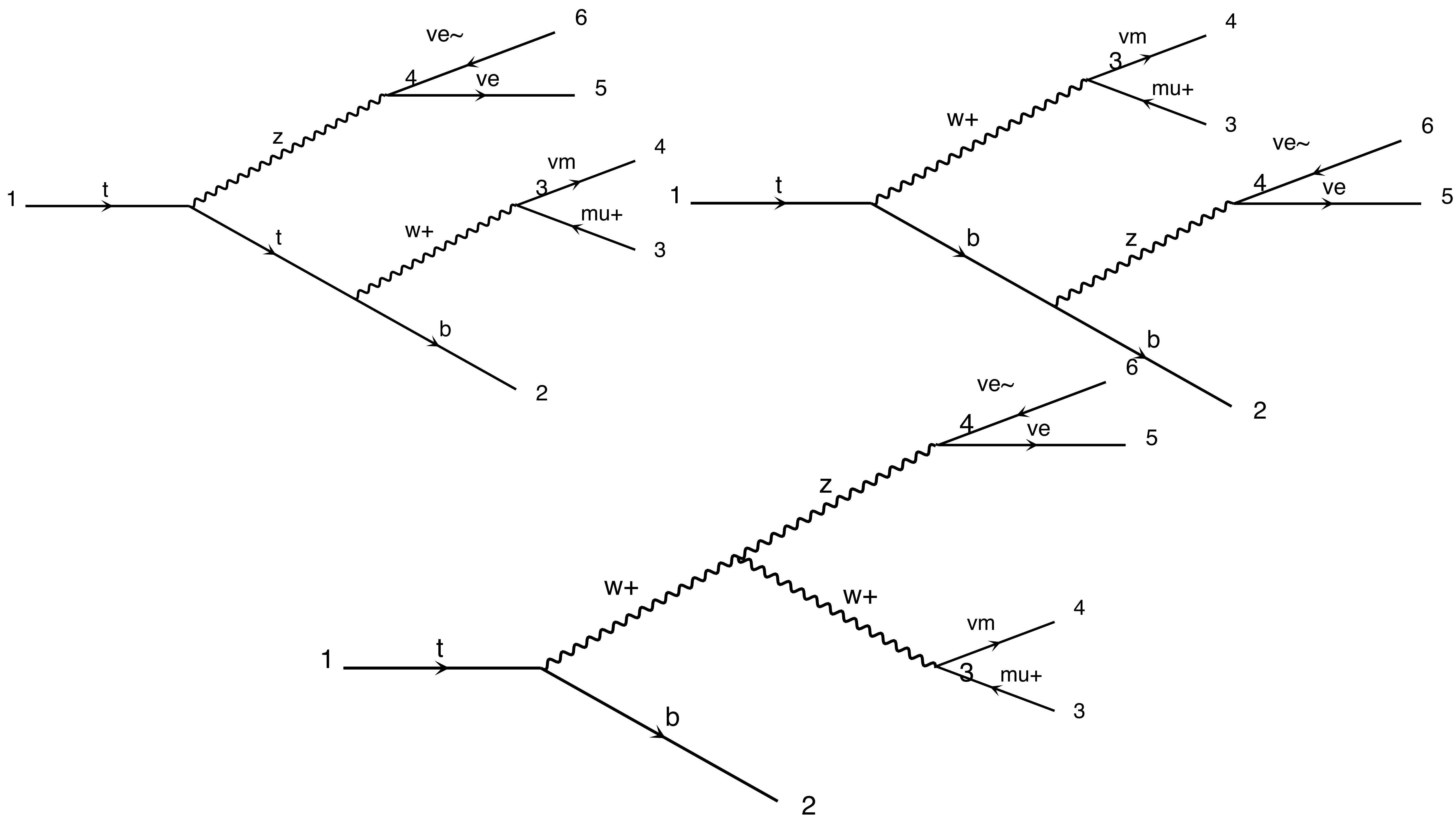






[MadGraph5_aMCatNLO]

radiative decay with a Z boson:
$t \to bWZ$



[MadGraph5_aMCatNLO]

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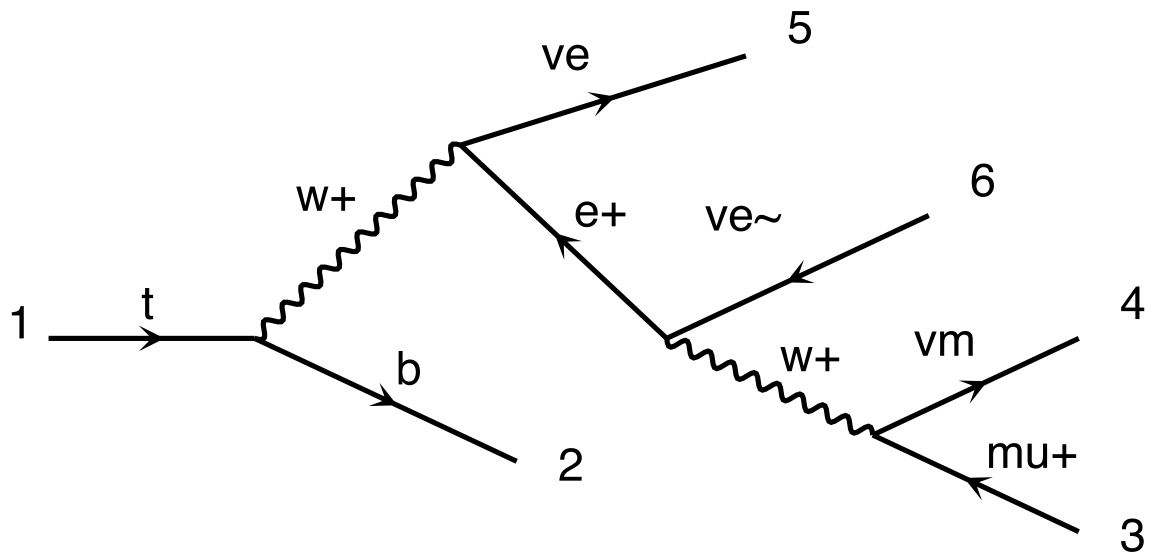
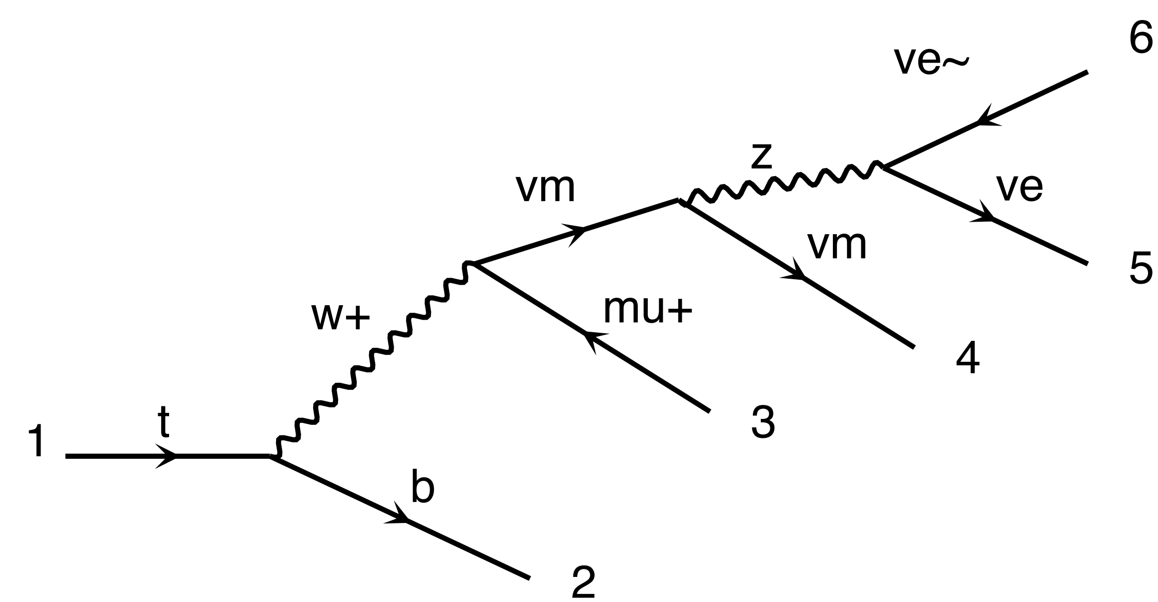
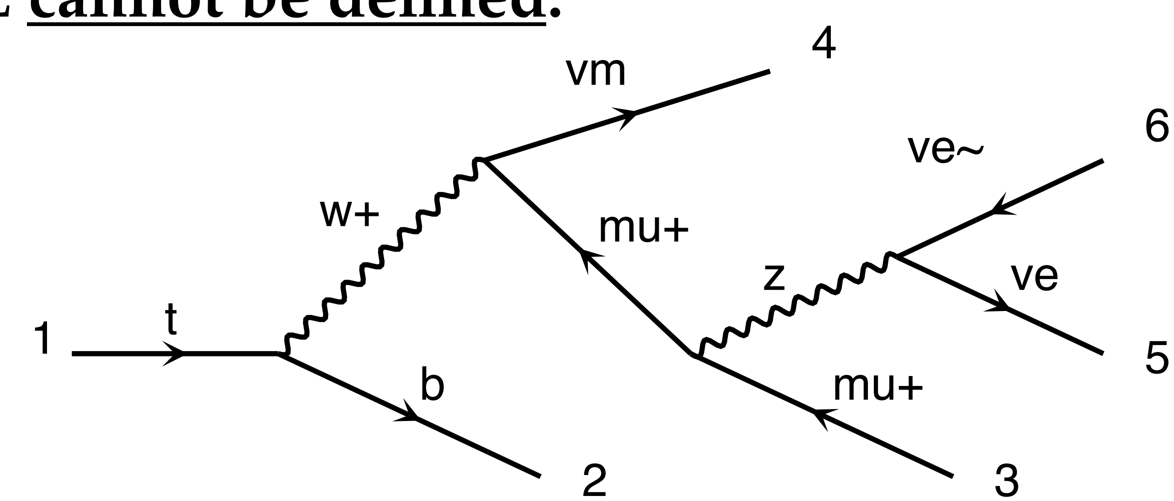
additional diagrams:
$t \rightarrow bWZ \rightarrow b(\mu^+\nu_\mu)(\nu\bar{\nu})$





(example) additional diagrams: pure $t \rightarrow bWZ$ <u>cannot be defined</u>.



[MadGraph5_aMCatNLO]

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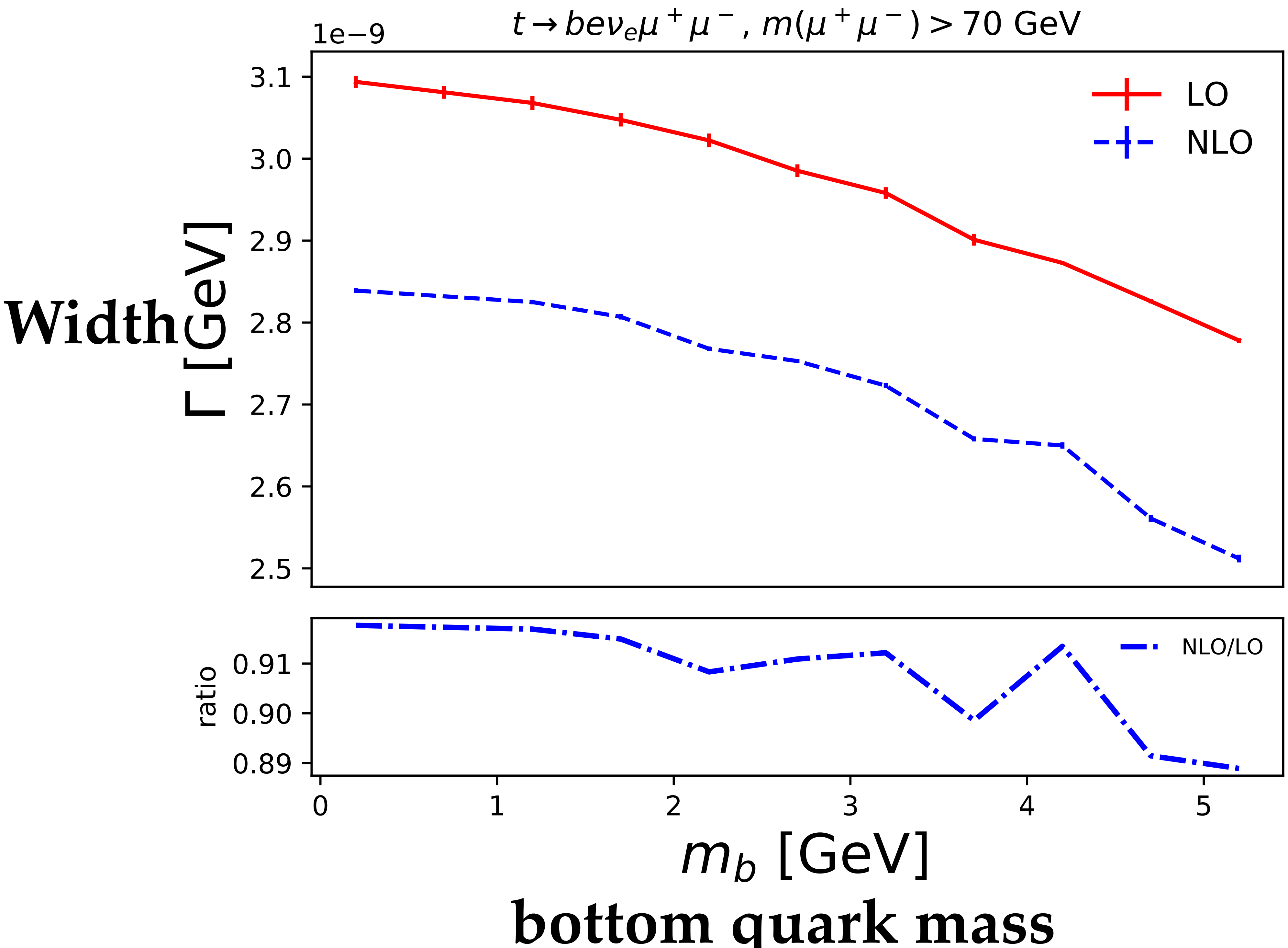
$t \rightarrow bWZ$, QCD corrections

[A.P., Tetlalmatzi-Xolocotzi, arXiv:1712.06332]



⇒

~10% reduction of BR at NLO QCD

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challenges for (SM) t → bWZ

[A.P., Tetlalmatzi-Xolocotzi, arXiv:1712.06332]

signal decay is very close to threshold!:

$$m_t(\sim 173.1 \text{ GeV}) \simeq m_b + m_W + m_Z(\sim 175.8 \text{ GeV})$$

$\Rightarrow$ only possible due to off-shell particles:
SM *BR* ~2×10^{-6}

$\Rightarrow$ b-jets are softer in signal than backgrounds.

analysis for (SM) $t \to bWZ$

[A.P., Tetlalmatzi-Xolocotzi, arXiv:1712.06332]

we looked at two final states:

$$pp \to t\bar{t} \to (b\ell'^{+}\nu_{\ell}\ell^{+}\ell^{-})(\bar{b}jj) \quad \textbf{(3-lepton)}$$

$$pp \to t\bar{t} \to (bjj\mu^{+}\mu^{-})(\bar{b}jj) \quad \textbf{(2-lepton)}$$

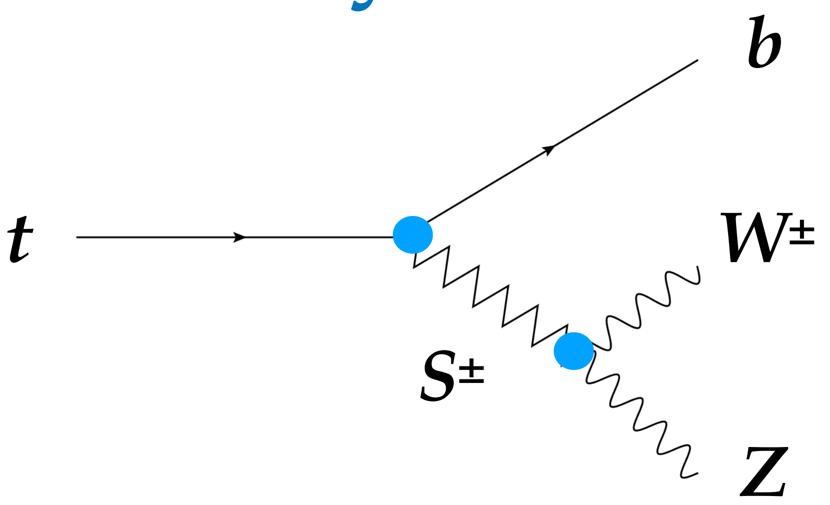
and only backgrounds arising from: $pp \to t\bar{t}Z$

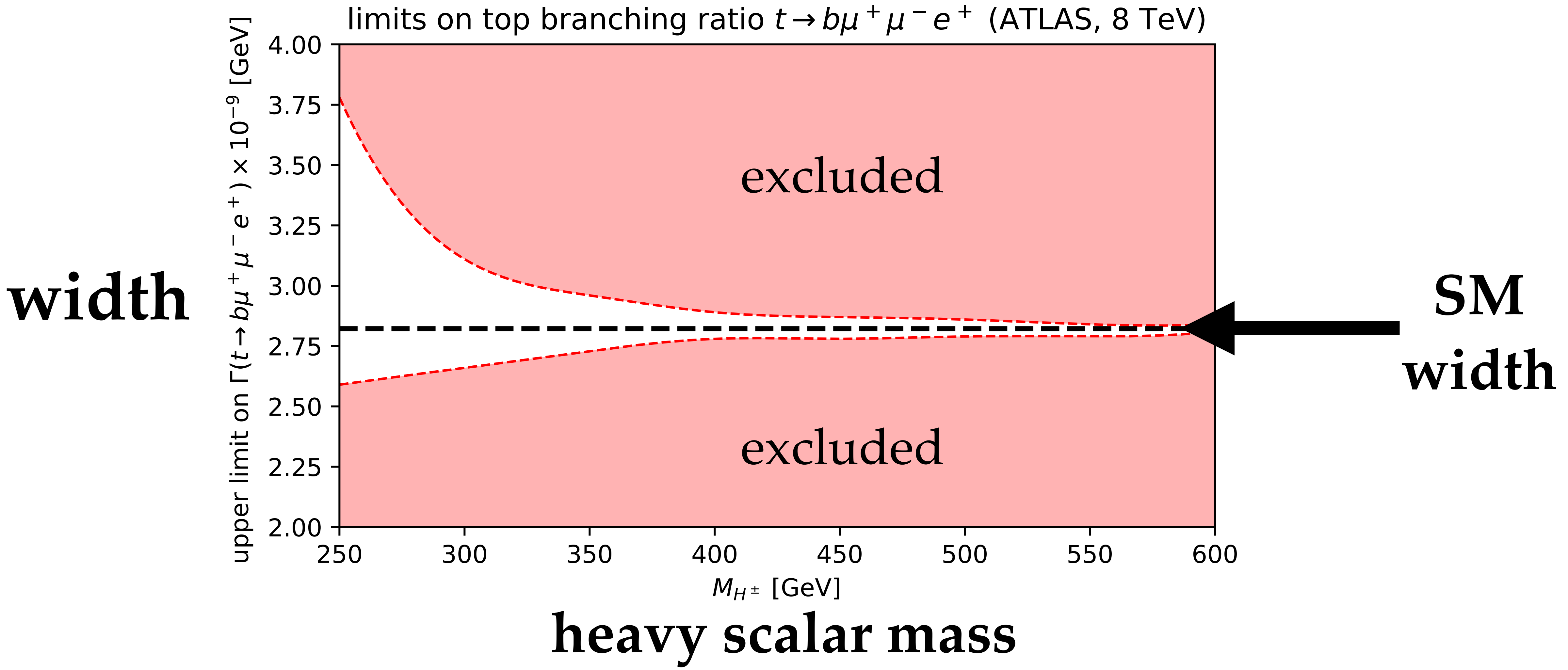
$\Rightarrow$ both analyses less than 1σ for SM@10/ab.

$\Rightarrow$ <u>challenging</u>, even at FCC-hh!

can a new charged heavy scalar enhance the BR?

i.e.:





$\Longrightarrow$ **<u>NO!</u>** only up to **BR ~ 2 x BR(SM).**

[A.P., Tetlalmatzi-Xolocotzi, arXiv:1712.06332]

$$t \to ch \quad / \quad \mathrm{BR(SM)} \sim 10^{-13}$$

[see appendix for diagrams]

FCNC decay to Higgs + charm

[A.P., Tetlalmatzi-Xolocotzi, arXiv:1712.06332]

- flavour-changing neutral current through:

$$\mathcal{L}_{thc} = \lambda^h_{ct} \bar{Q}_c H q_t + \text{h.c.}$$

[here: real & symmetric couplings]

- LHC: top pair production, current best constraints:

	ATLAS ($h \to \gamma\gamma$)	CMS ($h \to b\bar{b}$)
BR <	0.22%	0.47%

[13 TeV, ~36 fb^{-1}]

***note**: no c-tagging employed: constrain combination of $t \to hc$ and $t \to hu$.

- High-luminosity LHC projection: **BR < 0.02% ($h \to \gamma\gamma$)**.

$t \rightarrow hc$ @ FCC-hh

[A.P., Tetlalmatzi-Xolocotzi, arXiv:1712.06332]

- look at $pp \to t\bar{t} \to (hc)\bar{t}$. [and charge conjugate]

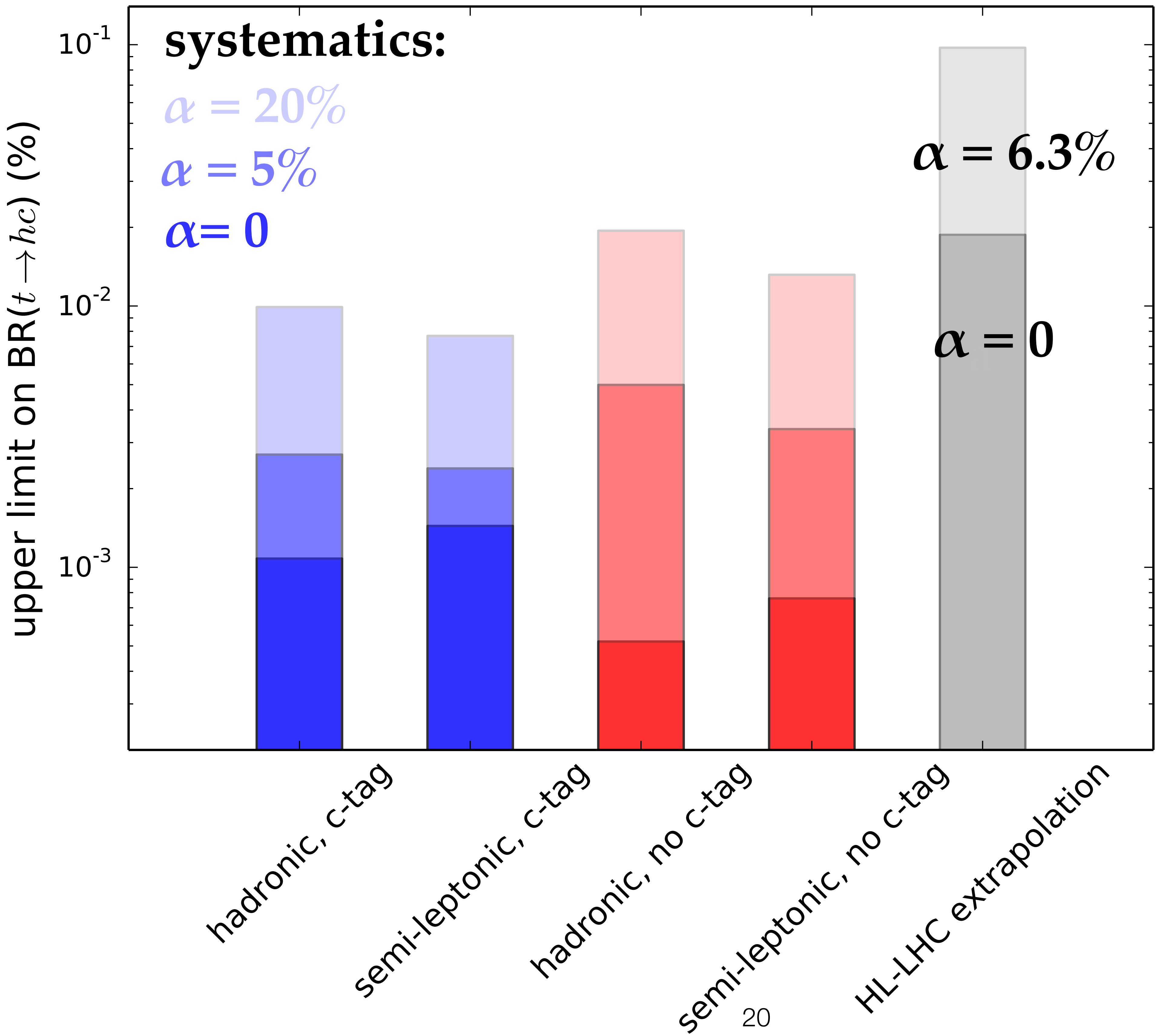
- **h ➞** γγ + two signal regions: (i) fully hadronic **or** (ii) semi-leptonic decays of the "non-signal" top.

- MG5_aMC@NLO [parton level] + HERWIG 7 [parton shower / non-pert. effects].

- two analyses: (i) with or (ii) without c-tagging. [see appendix for details]

- (very) rough estimates of systematics by rescaling backgrounds by a factor α.

constraints for BR(t → hc) @ FCC-hh



[A.P., Tetlalmatzi-Xolocotzi, arXiv:1712.06332]

⇒

FCC-hh better than HL-LHC by at least an order of magnitude.

[see appendix for numerical results]

conclusions

- ~10^{12} top quarks produced over the FCC-hh lifetime: an excellent opportunity to study its properties.
- in particular: **rare top decays**.
- we have examined **$t \to bWZ$** and **$t \to hc$** in our study.
- the SM radiative decay **$t \to bWZ$** will be difficult to observe and heavy scalars do not increase the rate enough.
- for **$t \to hc$**: FCC-hh better than HL-LHC by at least an order of magnitude.
- **<u>outlook</u>**: what can the FCC-hh deliver on **other** rare decays?

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Thanks!

appendix

analysis summary: t → hc @ FCC-hh

[A.P., Tetlalmatzi-Xolocotzi, arXiv:1712.06332]

- signal (λ=0.1) and background **initial** cross sections:

Process	$\sigma_{\rm gen}^{\rm had.}$ [pb]	$\sigma_{\rm gen}^{\rm s.l.}$ [pb]
$pp \to t\bar{t} \to (hc)\bar{t}+$ h.c.	0.332	0.122
$pp \to t\bar{t}h$	0.044	0.030
$pp \to hjjW^{\pm}$	0.022	0.070
$pp \to t\bar{t}\gamma\gamma$	0.042	0.028
$pp \to \gamma\gamma jjW^{\pm}$	1.294	0.424

↑ $\bar{t} \to \bar{b}jj$ ↑ $\bar{t} \to \bar{b}\ell\bar{\nu}_\ell$

analysis summary: t → hc @ FCC-hh

[A.P., Tetlalmatzi-Xolocotzi, arXiv:1712.06332]

- summary of analysis, "hadronic" or "semi-leptonic" analysis:

<table>
<tr><td colspan="2">exactly one b-jet, $p_T > 25$ GeV, $|\eta| < 2.5$,
$P_{b\to b} = 0.7$, $P_{c\to b} = 0.1$, $P_{l\to b} = 0.01$,
≥ 2 photons, $p_T > 25$ GeV, $|\eta| < 2.5$,</td></tr>
<tr><td>hadronic:
≥ 1 light jets,
top: combine b-jet + 1, 2 light jets.</td><td>semi-leptonic:
≥ 1 leptons, $p_T > 25$ GeV, $|\eta| < 2.5$,
solve for p^z_ν using mass constraint.</td></tr>
<tr><td>with c-tagging:
$P_{c\to c} = 0.2$, $P_{l\to c} = 0.005$,
$P_{b\to c} = 0.125$.</td><td>no c-tagging:
no charm jets.</td></tr>
<tr><td colspan="2">$m_{\text{top, reco}} \in [150, 200]$ GeV.
$m_{\gamma\gamma c} \in [160, 190]$ GeV,</td></tr>
</table>

analysis results: t → hc @ FCC-hh

[A.P., Tetlalmatzi-Xolocotzi, arXiv:1712.06332]

- summary of resulting cross sections, "hadronic" or "semi-leptonic" analysis:

$\mathscr{L} = 10$ ab^{-1}		
Process	$N^{\text{had.}}_{\text{c-tag}}$	$N^{\text{s.l.}}_{\text{c-tag}}$
$pp \to t\bar{t} \to (hc)\bar{t}+$ h.c.	22952	10260
$pp \to t\bar{t}h$	1816	689
$pp \to hjjW^{\pm}$	7	1
$pp \to \gamma\gamma jjW^{\pm}$	211	2
$pp \to t\bar{t}\gamma\gamma$	107	39

$\mathscr{L} = 10$ ab^{-1}		
Process	$N^{\text{had.}}_{\text{no c-tag}}$	$N^{\text{s.l.}}_{\text{no c-tag}}$
$pp \to t\bar{t} \to (hc)\bar{t}+$ h.c.	191871	61124
$pp \to t\bar{t}h$	26533	6962
$pp \to hjjW^{\pm}$	66	19
$pp \to \gamma\gamma jjW^{\pm}$	7130	164
$pp \to t\bar{t}\gamma\gamma$	1598	478

↑ $\bar{t} \to \bar{b}jj$

↑ $\bar{t} \to \bar{b}\ell\bar{\nu}_\ell$

constraints: $t \to hc$ @ FCC-hh

[A.P., Tetlalmatzi-Xolocotzi, arXiv:1712.06332]

- summary of resulting cross sections, "hadronic" or "semi-leptonic" analysis:

with c-tagging:

analysis:	hadr.,	semi-lept.
$\lambda_{ct}^{h} \times 10^{-3}$	(6.42, 10.15, 19.40)	(7.40, 9.52, 17.08)
BR in 10^{-3}%	(1.08, 2.70, 9.91)	(1.44, 2.39, 7.69)

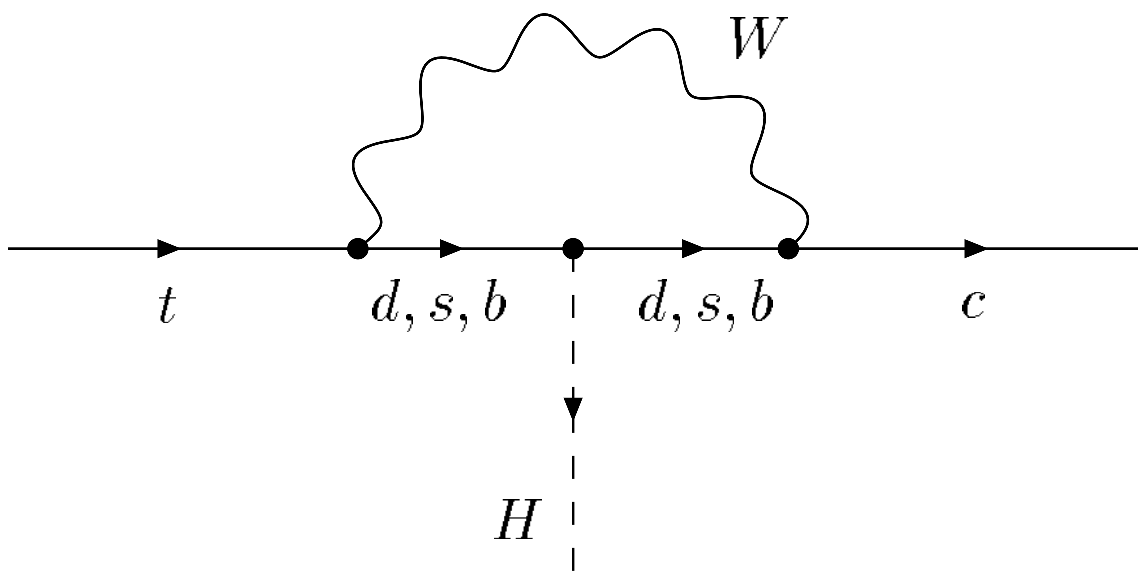
no c-tagging:

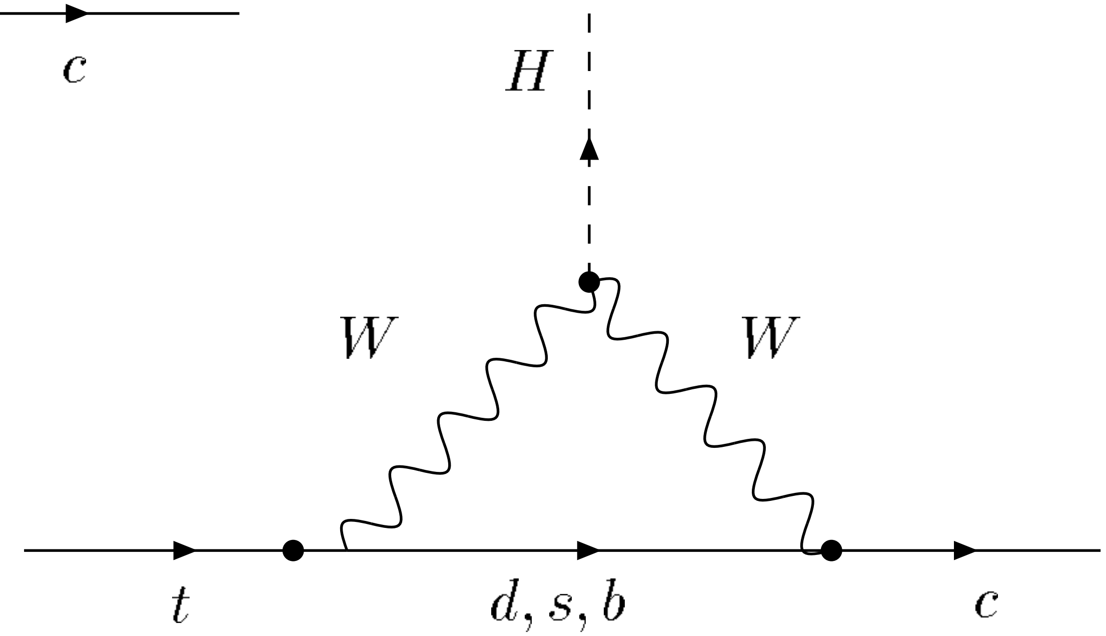
$\lambda_{ct}^{h} \times 10^{-3}$	(4.43, 13.61, 27.15)	(5.38, 11.32, 22.36)
BR in 10^{-3}%	(0.52, 4.99, 19.42)	(0.76, 3.38, 13.17)

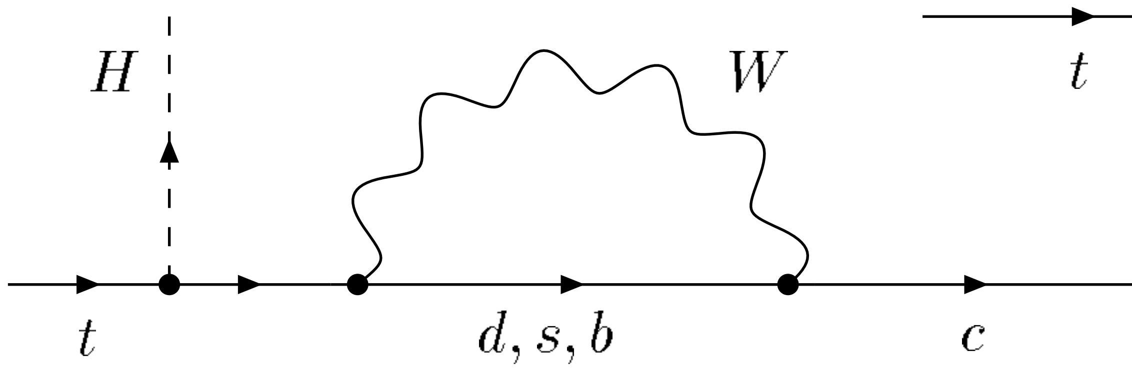
systematics: $\alpha = (0, 5\%, 20\%)$

Feynman graphs for t ➞ ch

[Mele, hep-ph/0003064]







(unitary gauge, assuming $m_c = 0$)

rare top decays summary

Input $\sigma = 35$ nb and $\int \mathcal{L}dt = 10^4$ fb^{-1}

Channel	Br (SM)	# events (SM)	Br (THDM)	# events (THDM)	Br (MSSM)	# events (MSSM)
bW	1	$35 \cdot 10^{10}$				
sW	$1.6 \cdot 10^{-3}$ [1]	$5.6 \cdot 10^8$	$\sim 10^{-3}$ [2]	$\sim 3.5 \cdot 10^8$	$10^{-3} - 10^{-2}$ [2]	$3.5 \cdot (10^8 - \cdot 10^9)$
dW	$\sim 10^{-4}$ [1] ($\sim 5.5 \cdot 10^{-5}$ [2])	$3.5 \cdot 10^7$ ($1.9 \cdot 10^7$)				
bWg	0.3 [1, 3]	$1.05 \cdot 10^{11}$				
$bW\gamma$	$3.5 \cdot 10^{-3}$ ($E_\gamma > 10$ GeV) [1]	$1.225 \cdot 10^9$				
bWZ	$2 \cdot 10^{-6}$ [1]	$7 \cdot 10^5$	$\simeq 10^{-4}$ [2]	$3.5 \cdot 10^7$		
bWH	$1.80 \cdot 10^{-9}$ [4]	630				
cWW	$1.3 \cdot 10^{-13}$ [5]	0.0455	$10^{-4} - 10^{-3}$	$3.5 \cdot (10^7 - 10^8)$ [2]		
$u\gamma$	$(3.7^{+2.7}_{-2.3}) \cdot 10^{-16}$ [6]	$1.295 \cdot 10^{-4}$			$2 \cdot 10^{-6}$ [13]	$7 \cdot 10^5$
$c\gamma$	$5 \cdot 10^{-13}$ [7] $(4.6^{+2.0}_{-1.2}) \cdot 10^{-14}$ [6]	0.175 0.0161	$\mathcal{O}(10^{-6})$ [8]	$\mathcal{O}(3.5 \cdot 10^5)$	$\mathcal{O}(10^{-7})$ [2]	$\mathcal{O}(3.5 \cdot 10^4)$
ug	$(3.7^{+2.8}_{-2.3}) \cdot 10^{-14}$ [6]	0.01295			$8 \cdot 10^{-5}$ [13]	$2.8 \cdot 10^7$
cg	$(4.6^{+2.4}_{-1.2}) \cdot 10^{-12}$ [6]	1.61	10^{-4} [13]	$3.5 \cdot 10^7$	$8.0 \cdot 10^{-5}$ [13]	$2.8 \cdot 10^7$
uZ	$8 \cdot 10^{-17}$[13]	$2.8 \cdot 10^{-5}$			$2.0 \cdot 10^{-6}$ [13]	$7.0 \cdot 10^5$
cZ	$1.3 \cdot 10^{-13}$ [9, 2] 10^{-14} [13]	0.0455 $3.5 \cdot 10^{-3}$	10^{-7} [13]	$3.5 \cdot 10^4$	$2 \cdot 10^{-6}$ [13]	$7.0 \cdot 10^5$
uH	$2.0 \cdot 10^{-17}$ [13]	$7.0 \cdot 10^{-6}$	$5.5 \cdot 10^{-6}$ [13]	$1.9 \cdot 10^6$	10^{-5} [13]	$3.5 \cdot 10^6$
cH	$0.4605 \cdot 10^{-13}$ $m_H = 120$ GeV [12] $0.3146 \cdot 10^{-13}$ $m_H = 130$ GeV [12]	0.01612 0.01101	$1.5 \cdot 10^{-5}$ [13]	$5.25 \cdot 10^6$	10^{-5} [13]	$3.5 \cdot 10^6$
$c\gamma\gamma$	$< 10^{-16}$ [2]	$3.5 \cdot 10^{-5}$	$\sim 10^{-4}$ [2]	$\sim 3.5 \cdot 10^7$	$< 10^{-8}$ [2]	$< 3.5 \cdot 10^3$
cZZ			$10^{-5} - 10^{-3}$[2]	$3.5 \cdot 10^6 - 3.5 \cdot 10^8$		

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rare top decays summary (notes)

- The determination of $Br(t \to bWH)$ shown in the Table was done considering a virtual W and $m_H = 125.5$ GeV.
- In models with extra $Q = 2/3$ singlets the following bound is obtained $Br(t \to ug) = 1.5 \cdot 10^{-7}$ [13], for this case # events = 52500.
- Other BSM bounds for $Br(t \to c\gamma)$: $\mathcal{O}(10^{-6})$ (Warped Extra Dimensions [10]).
- Current experimental bounds for $Br(t \to c\gamma)$ and $Br(t \to u\gamma)$ from CMS: $Br(t \to c\gamma) < 1.7 \cdot 10^{-3}$ and $Br(t \to u\gamma) < 1.3 \cdot 10^{-4}$ [11].
- In models with extra $Q = 2/3$ singlets $Br(t \to uZ) = 1.1 \cdot 10^{-4}$ [13], for this case # events = $3.85 \cdot 10^{7}$.
- In non minimal models with R parity violation it is possible to have $Br(t \to cZ) = 3 \cdot 10^{-5}$ and consequently # events = $1.05 \cdot 10^{7}$.
- Other reference for the SM calculation of $Br(t \to hc)$ commonly quoted in the literature is [13] $Br(t \to hc) = 3.5 \cdot 10^{-15}$. See also: [14].
- Current experimental (observed) bound for $Br(t \to hc)$ from Atlas: $Br(t \to hc) < 0.46\%$ [15].
- In models with extra $Q = 2/3$ singlets the following bound is obtained $Br(t \to hu) = 4.1 \cdot 10^{-5}$ [13] leading to # events = $1.435 \cdot 10^{7}$.
- Current experimental (observed) bound for $Br(t \to hu)$ from Atlas: $Br(t \to hu) < 0.45\%$ [15].

rare top decays summary (refs)

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