SECOND **ECFA** WORKSHOP on e^+e^- Higgs / Electroweak / Top Factories

Focus Topic "BSM Top (decay)"

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Oct 11th 2023, Paestum

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Top quark and BSM

why top is a necessary part of the future collider program(s)

- the top quark plays a role in all scenarios of physics beyond the SM that try to dynamically explain the size of the EW scale
- the top quark is an “outstanding” flavor, being the only quark with “regular” size Yukawa in the SM (and larger than the rest by more than one order of magnitude)
- as an outstanding flavor it could even be a “portal” to new physics, e.g. “*dark*” may be a *flavor* after all

The most obvious way to study the top quark is to produce it in large numbers

$\Rightarrow$ Make a Top factory

$\sigma_{pp \to t\bar{t}} \simeq 1$ nb at 14 TeV means 10^9 top quarks per ab^{-1} at HL-LHC

$\sigma_{e^+e^- \to t\bar{t}} \simeq 1$ pb at 0.365 TeV means 10^6 top quarks per ab^{-1} at the top factory

obvious complementarities,

- where the HL-LHC suffers too busy events the top factory can shine
- where the top factory lacks statistics the HL-LHC can supply

also "single" production modes can bring very useful info

$pp \to t + X$ e.g. can measure weak couplings

$e^+e^- \to tq$ can probe top quark contact interactions (even at energies below the top quark pair threshold)

also "boosted" production modes can bring very useful info

$pp \to tt$ still O(pb) for $p_{T,top} \geq 500$ GeV at LHC14

$pp \to ttj$ still O(pb) for $p_{T,jet} \geq 500$ GeV at LHC14

also "associated" production modes can bring very useful info

$pp \to ttZ, tth$ unique routes to access couplings weak and Yukawa couplings

very articulated field with lots of cross-talk between pp and e^+e^-

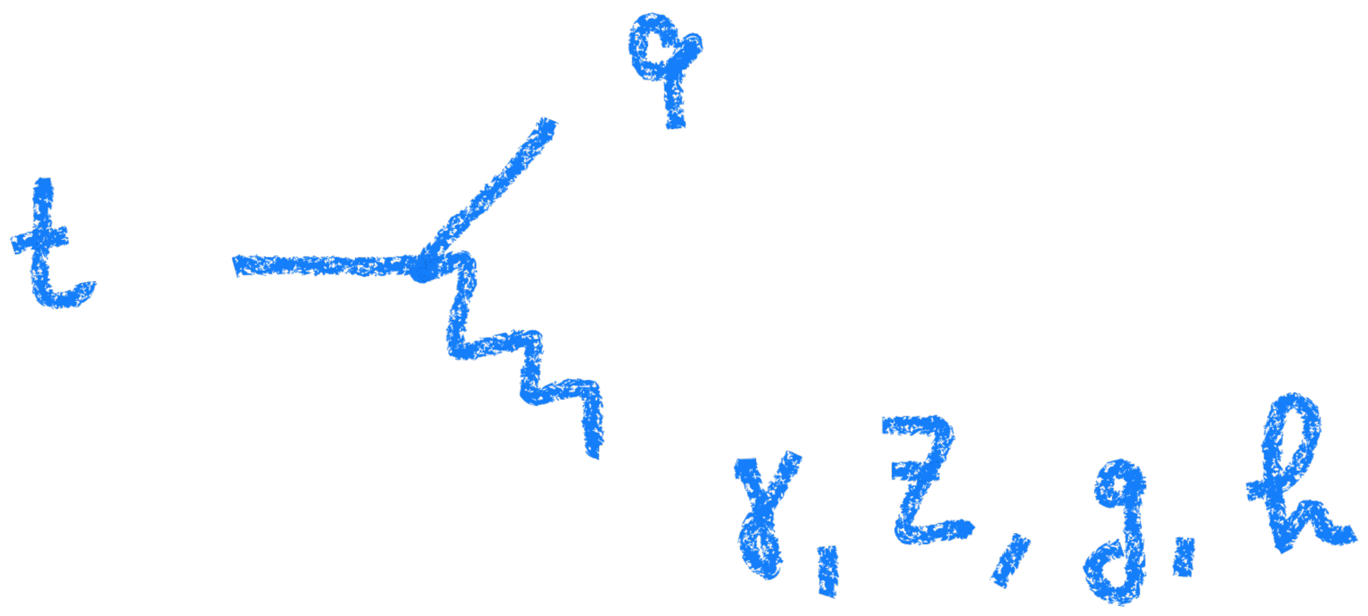
Top quark decay

Traditional topic for top factories is the possibility of BSM decays

Especially when the direct reach was limited (e.g. LEP and TeVatron times) the top quark might have been our “window” to new physics

e.g. $t \to H^+ b$ in MSSM or general 2HDM

e.g. $t \to Vq$ in MSSM or general 2HDM and many other models



Such light H^+ is hardly tenable* these days. The possibility of flavor violation, instead, is more subtle.

BSM decays of the top quark

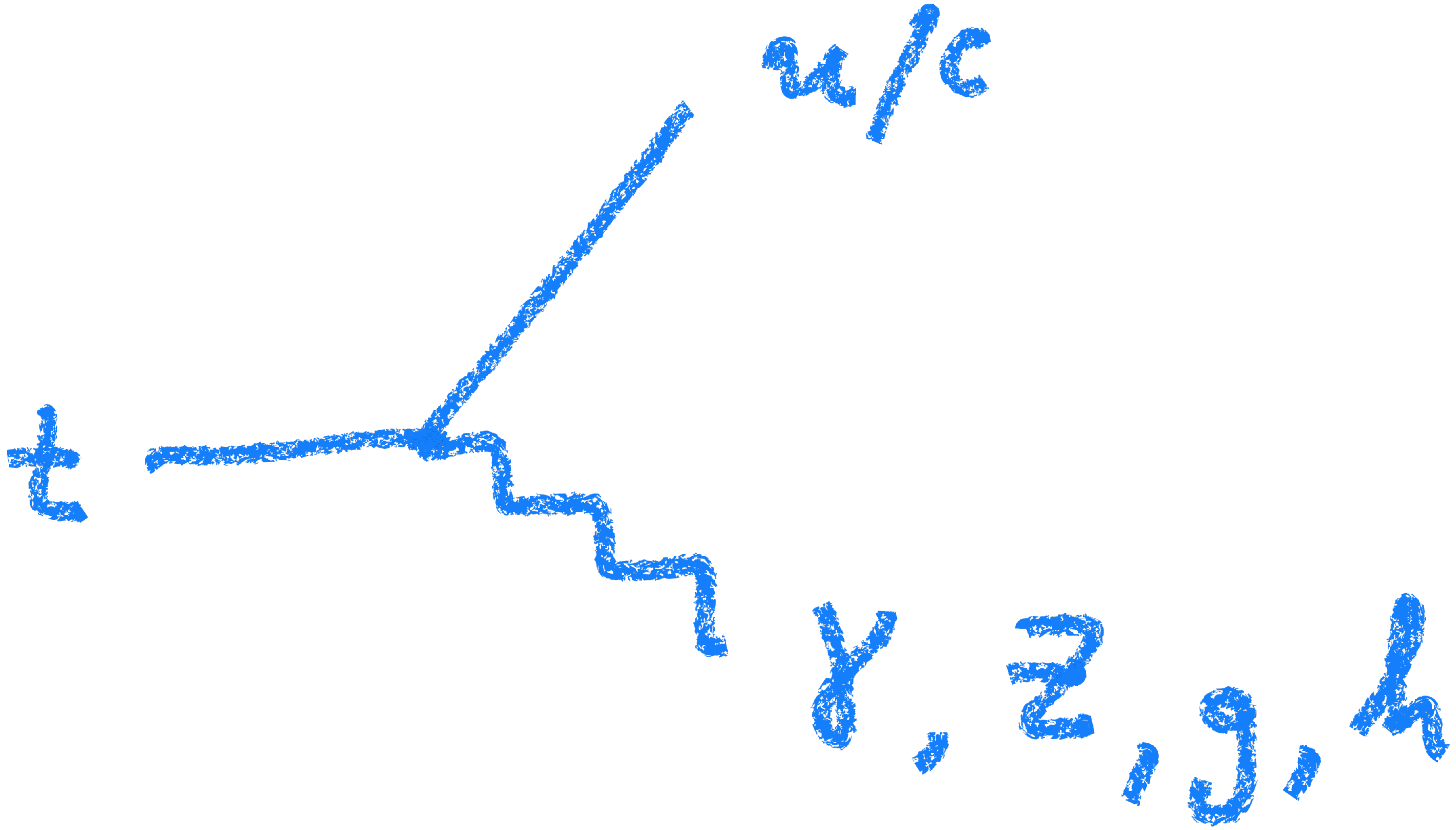
Focus Topic “*EXtt*”

- Update of the tenable FCNC BR incorporating direct searches for the microscopic BSM states that mediate flavor changing transitions, e.g. squarks
- Identification of more general patterns of BSM decay of the top quark in light of recent model building and of the new constraints
- Identification of blindspots for the LHC, ideally pursuing both signature-driven and model-driven routes
- Establishing the sensitivity of experiments at the top factory with realistic detector treatment (Delphes via KEY4HEP)
- Establishing connection with other stages of the HET program (e.g. single top production at 240 GeV)

Top quark decay at the Top Factory

$t \to BSM$

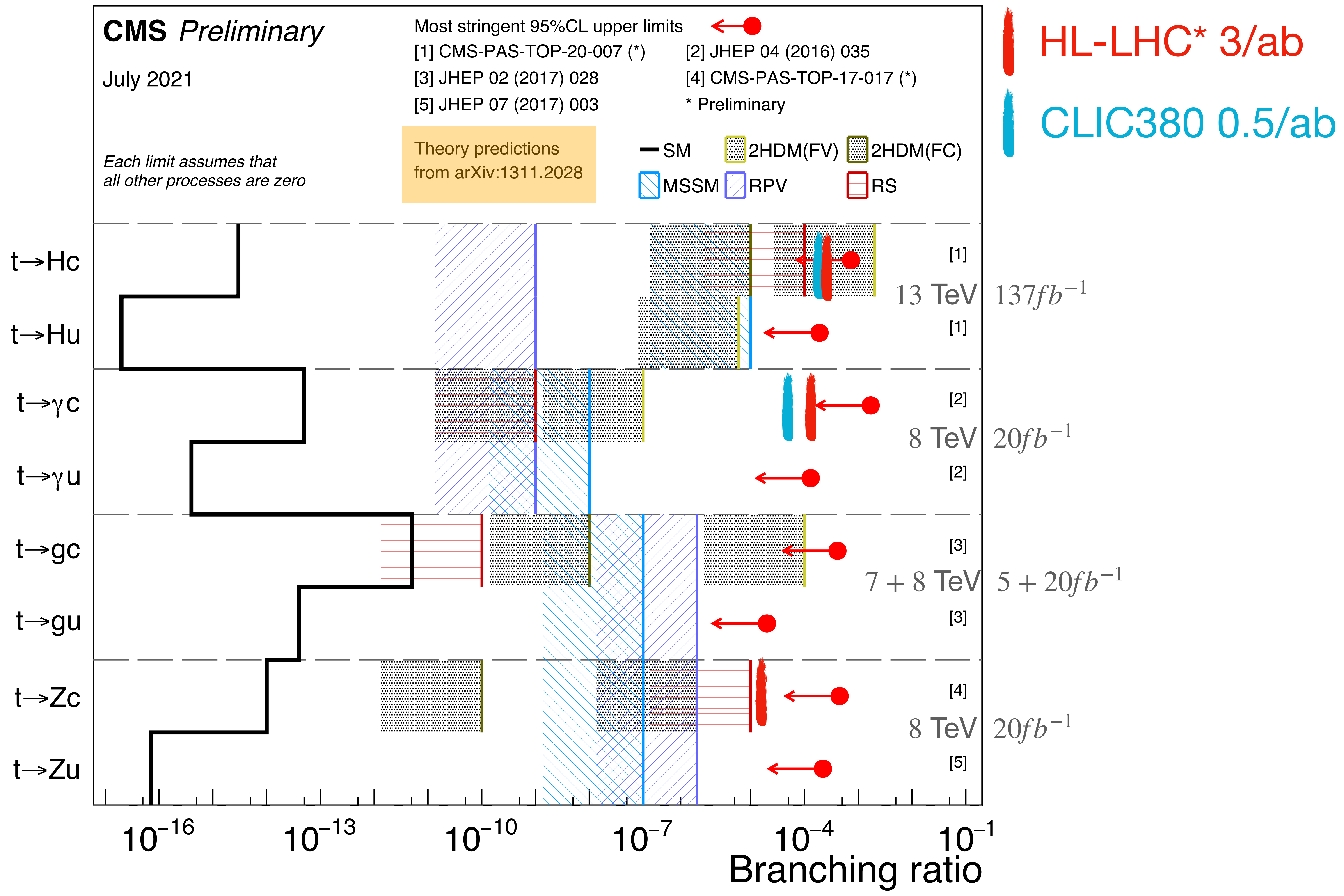
- BSM means SM EW final states



Top quark decay at the Top Factory

$t \to BSM$

Kaustubh Agashe and Sagar Airen at U. of Maryland agreed to help with the update

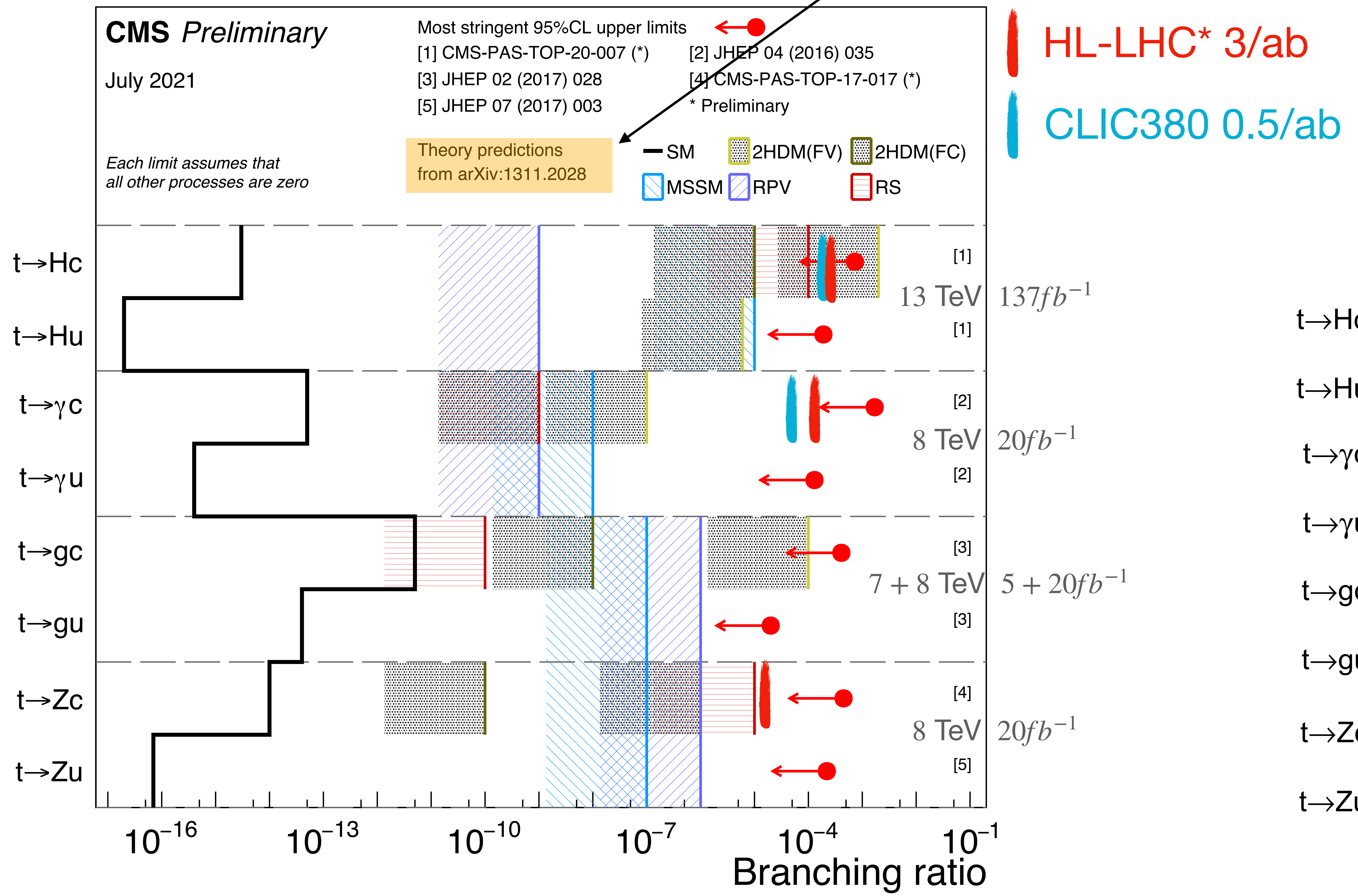


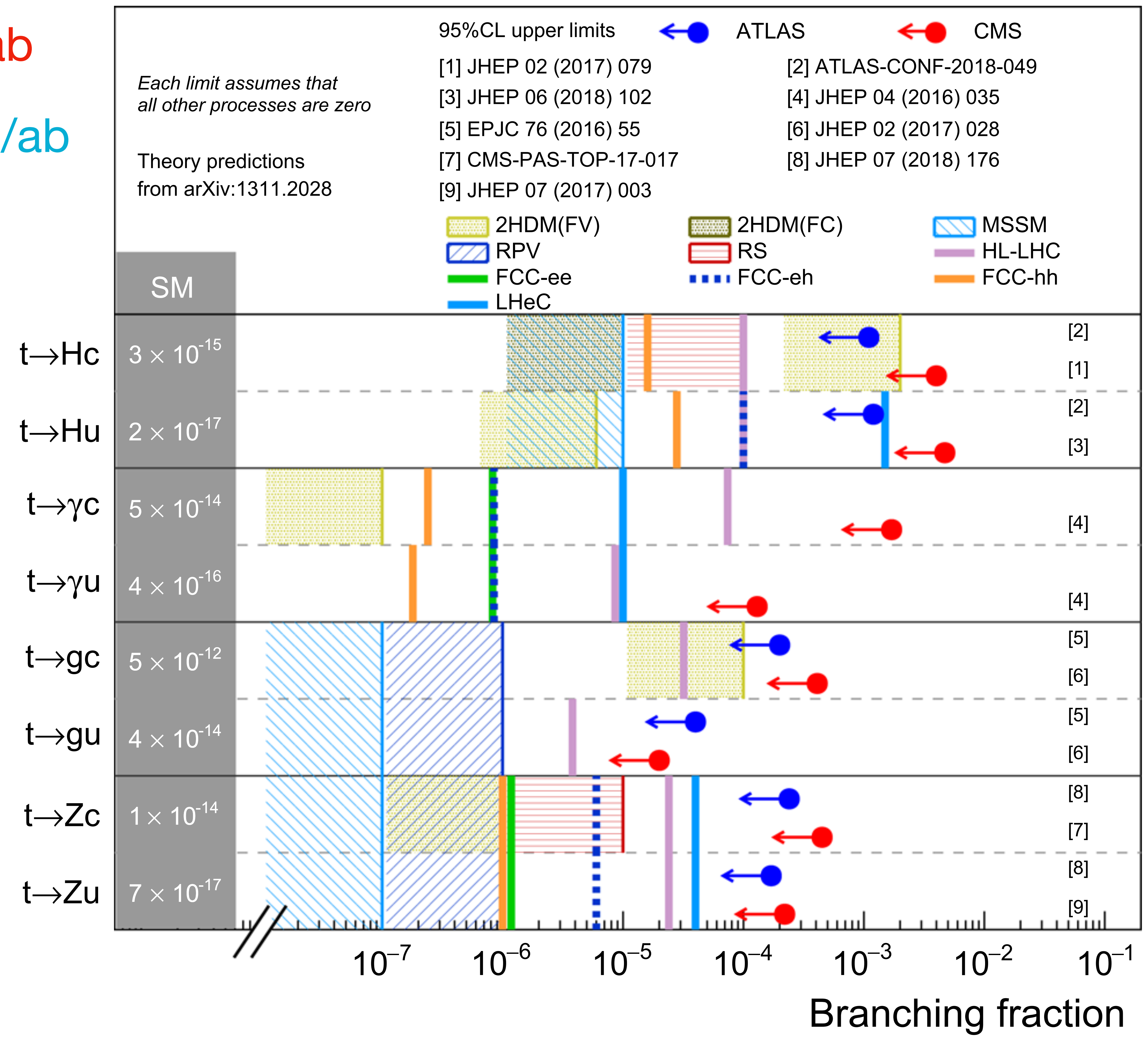
- Last refresh of BSM benchmark is quite old (2013)
- Regardless of the focus topics a refresh seems needed for the final report
- Quick assessment concluded that most results may need a retouch
- Inquiry for update/revalidation of the BSM benchmarks has started
- Relation to EFT to be investigated further

Top quark decay at the Top Factory

$t \to BSM$

1311.2028 - Agashe et al. - Snowmass 2013 Top quark working group report





Top quark decay at the Top Factory

$t \to BSM$

1311.2028 - Agashe et al. - Snowmass 2013 Top quark working group report

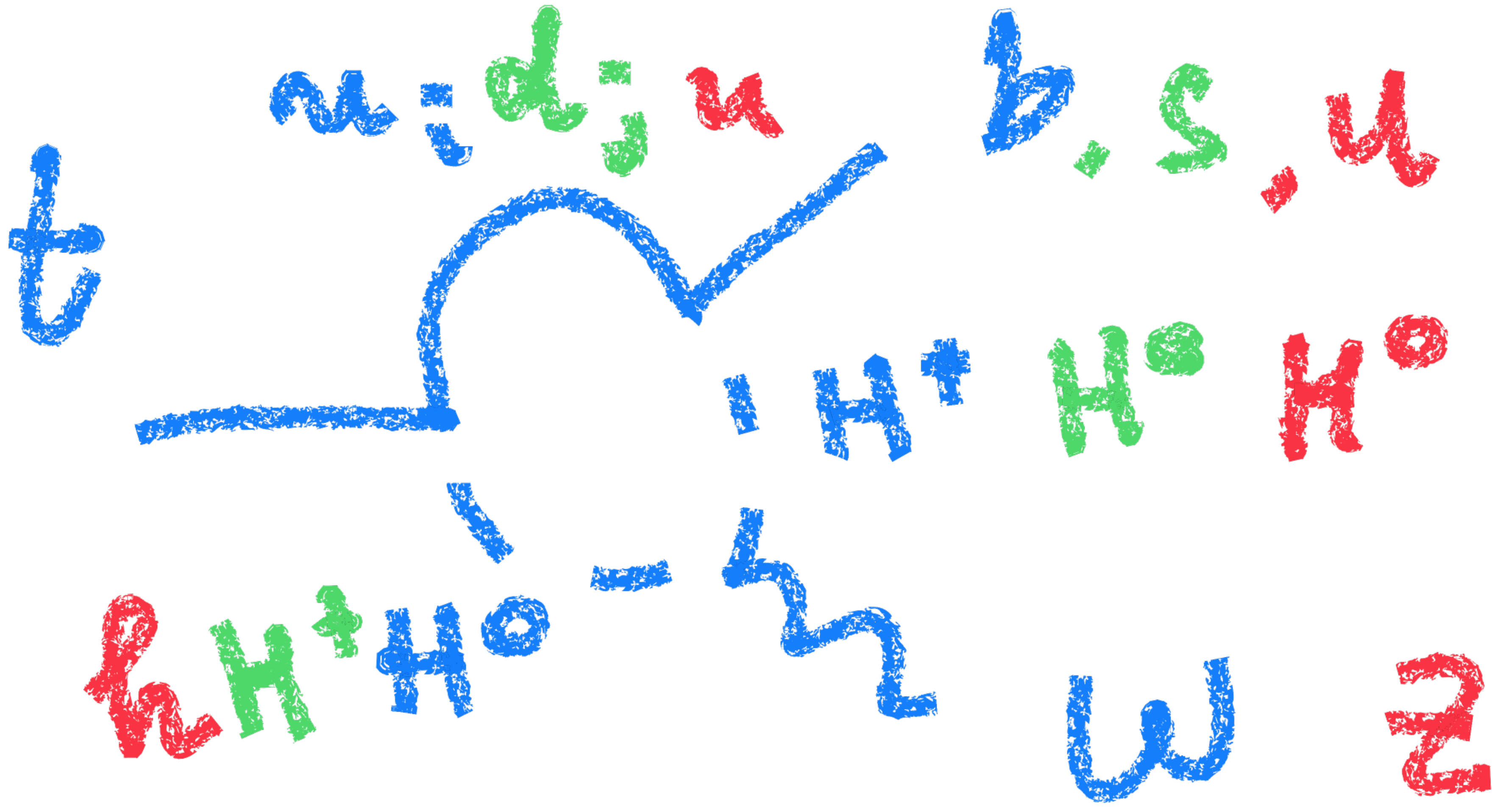
Table 1-7. *SM and new physics model predictions for branching ratios of top FCNC decays. The SM predictions are taken from [119], on 2HDM with flavor violating Yukawa couplings [119, 120] (2HDM (FV) column), the 2HDM flavor conserving (FC) case from [121], the MSSM with 1 TeV squarks and gluinos from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

Process	SM	2HDM(FV)	2HDM(FC)	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}	$\leq 10^{-5}$	$\leq 10^{-5}$	$\leq 10^{-9}$	$\leq 10^{-4}$

observable at top factory

not observable at top factory

Use MSSM instead



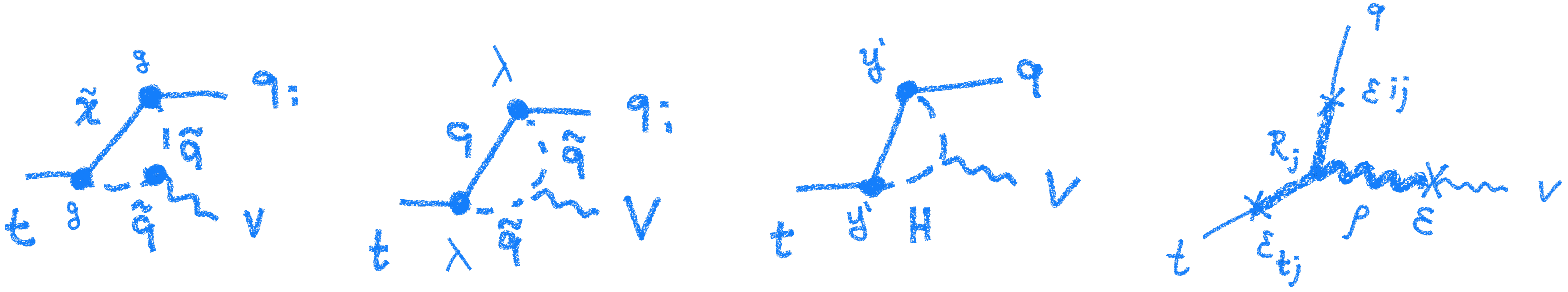
typical 2HDM contribution

$$BR \sim \left(1/M_{2HDM}\right)^4$$

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

$t \to BSM$



$$BR \sim \left(1/M_{NP}\right)^4$$

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$t \to gu$	4×10^{-14}	–	–	$\le 10^{-7}$	$\le 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\le 10^{-4}$	$\le 10^{-8}$	$\le 10^{-7}$	$\le 10^{-6}$	$\le 10^{-10}$
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$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\le 10^{-5}$	$\le 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\le 10^{-5}$	$\le 10^{-5}$	$\le 10^{-9}$	$\le 10^{-4}$

observable at top factory

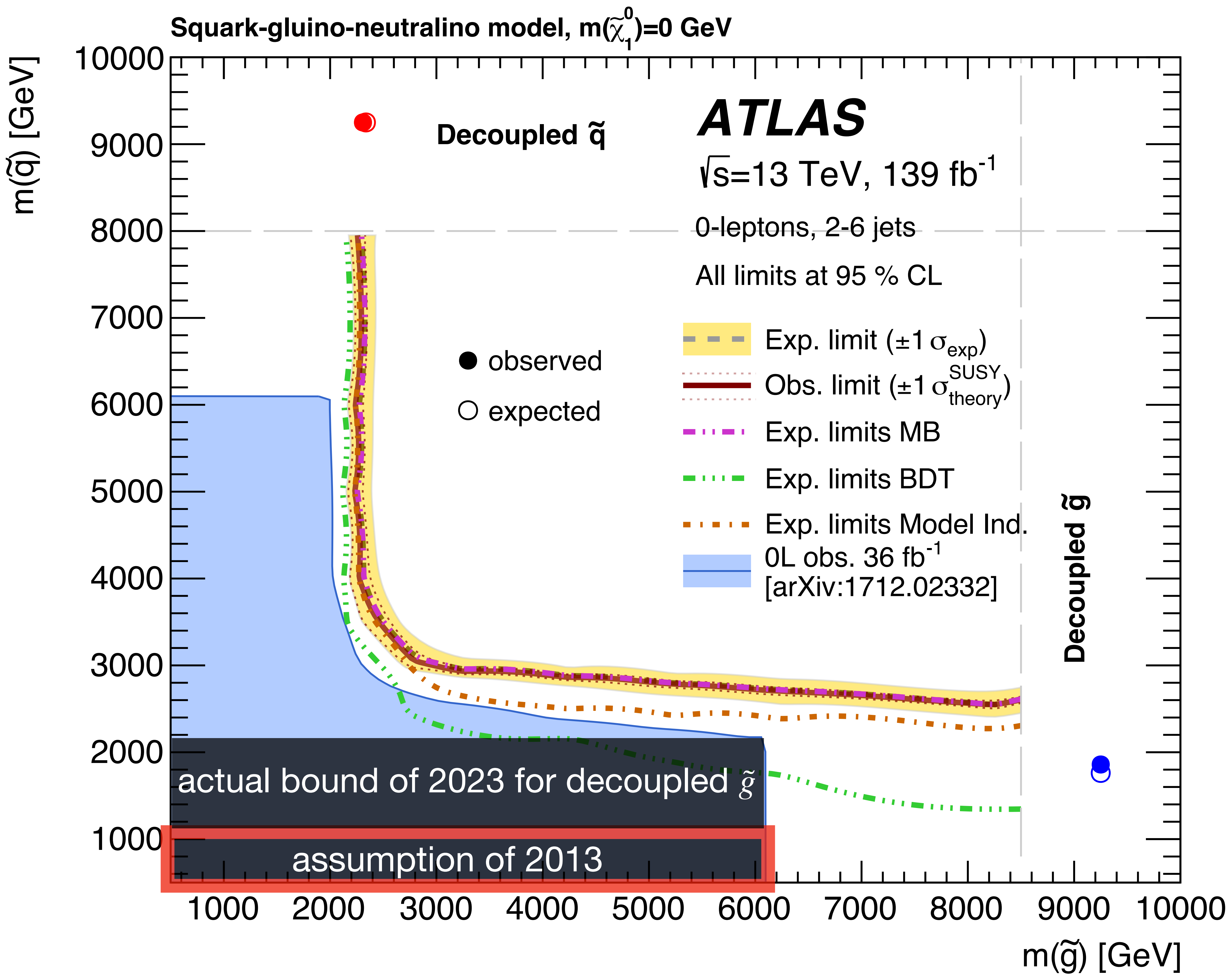
not observable at top factory

Use MSSM instead

- Most references are on complete models, some from 1990s
- Correct formulae do not expire.
- But phenomenological interpretations of correct formulae do expire when high energy (LHC) and high-intensity (flavor) experiments work hard to search NP!
- Most recent searches of NP express results in "*simplified models*", small brothers of the full microscopic models, used to can capture salient feature of a relatively broad class of models.
- Translation and merging of info is needed to really update these specific models

MSSM RPC squarks

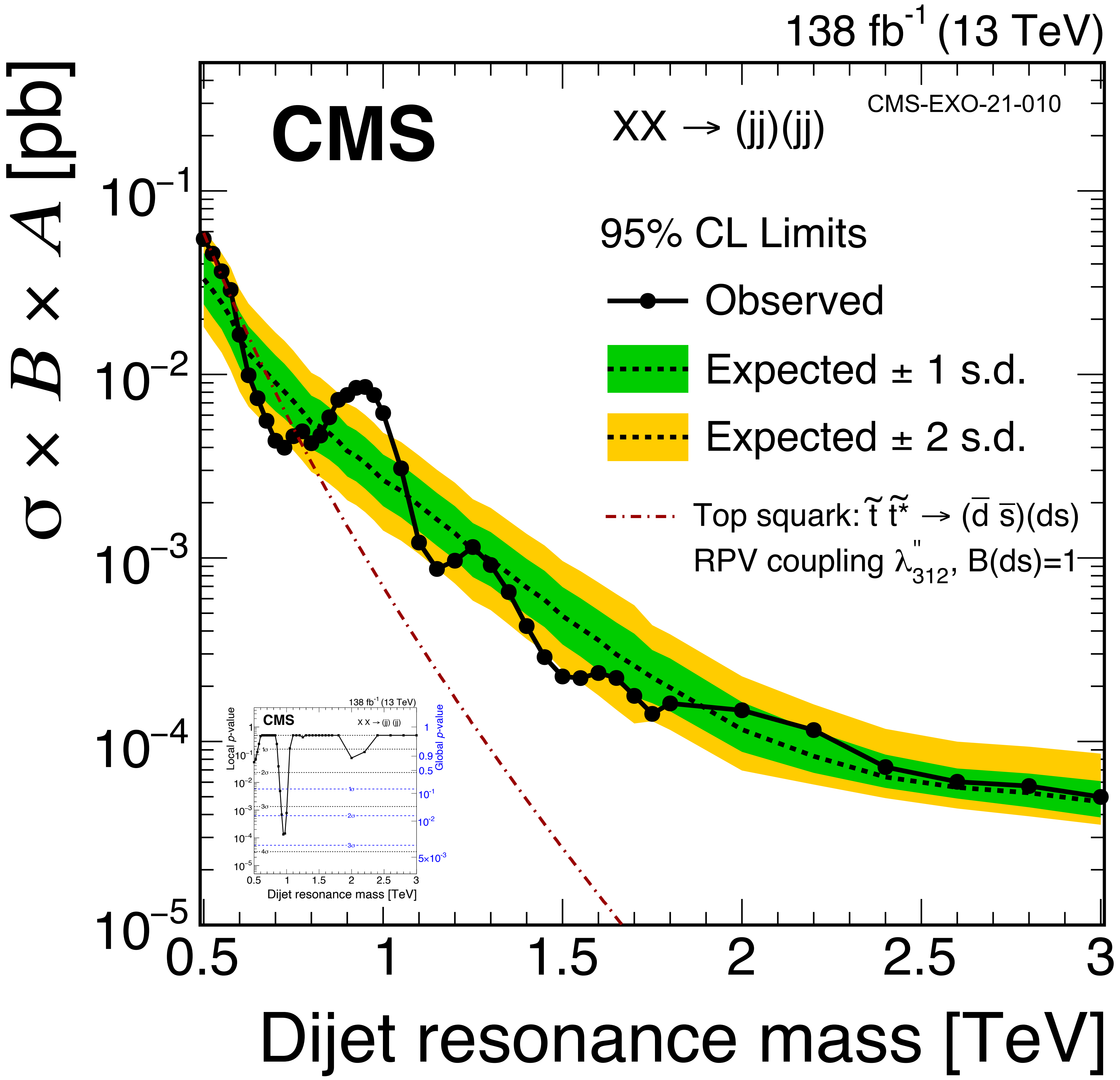
$\tilde{q} \to q$ **mET**



BRs in the MSSM may undergo a reduction due to squarks limits at 2+ TeV

MSSM-RPV squarks

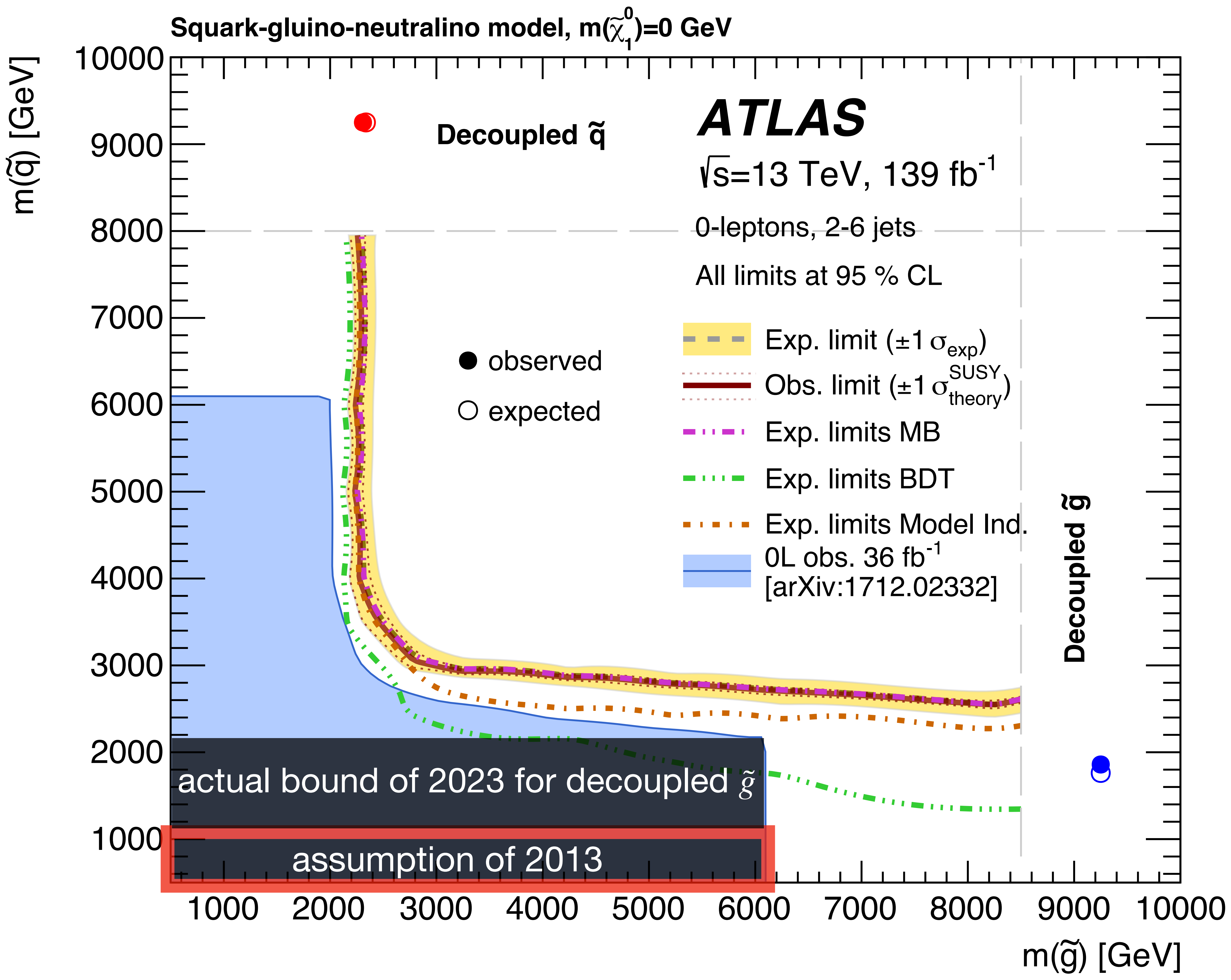
$\tilde{q} \to qq$



RPV MSSM seems to have less stringent bounds, so it might re-enable the MSSM (RPV columns untouched)

MSSM RPC squarks

$\tilde{q} \rightarrow q$ **mET**



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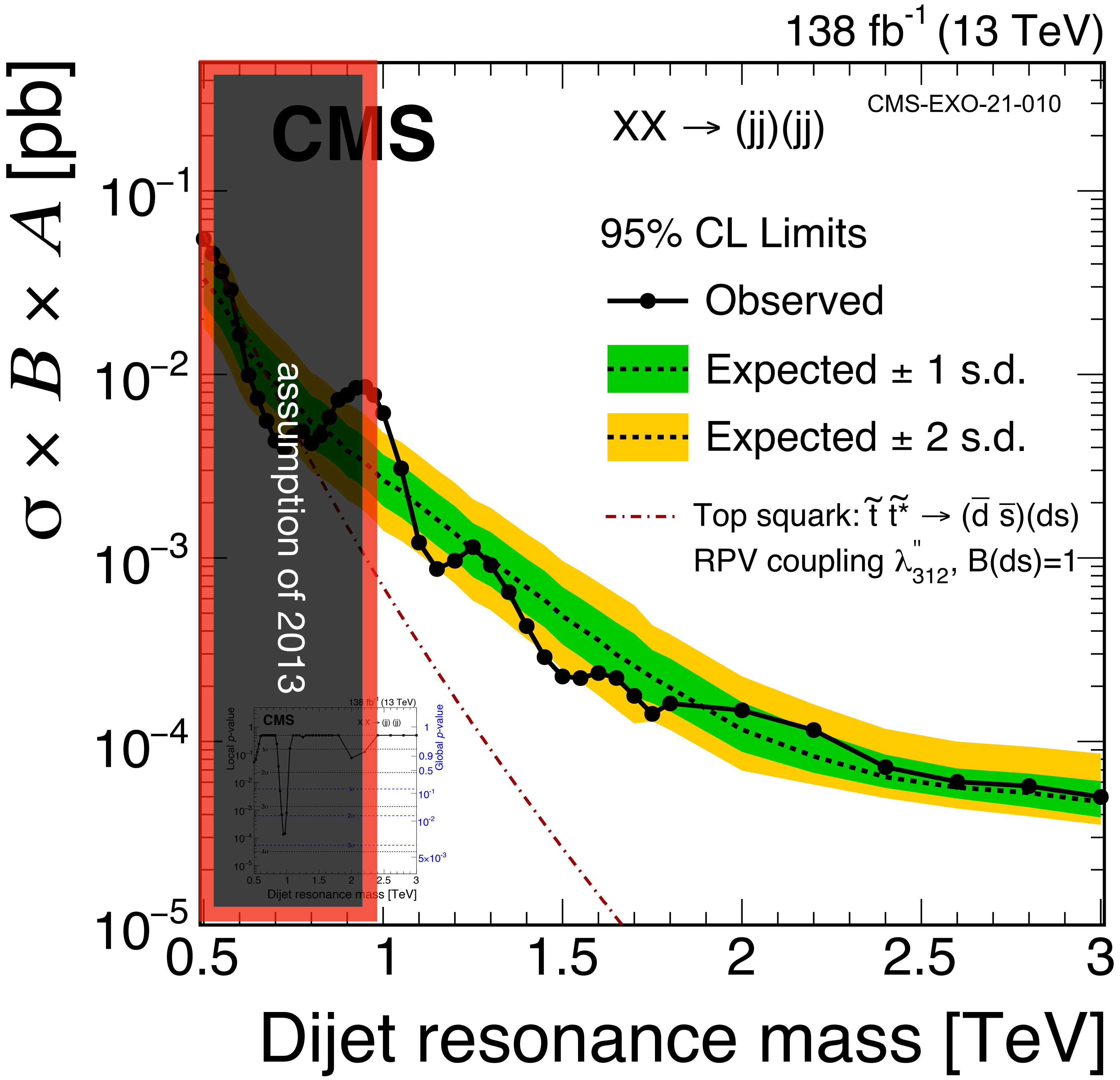


RPV MSSM seems to have less stringent bounds, so it might re-enable the MSSM (RPV columns untouched)

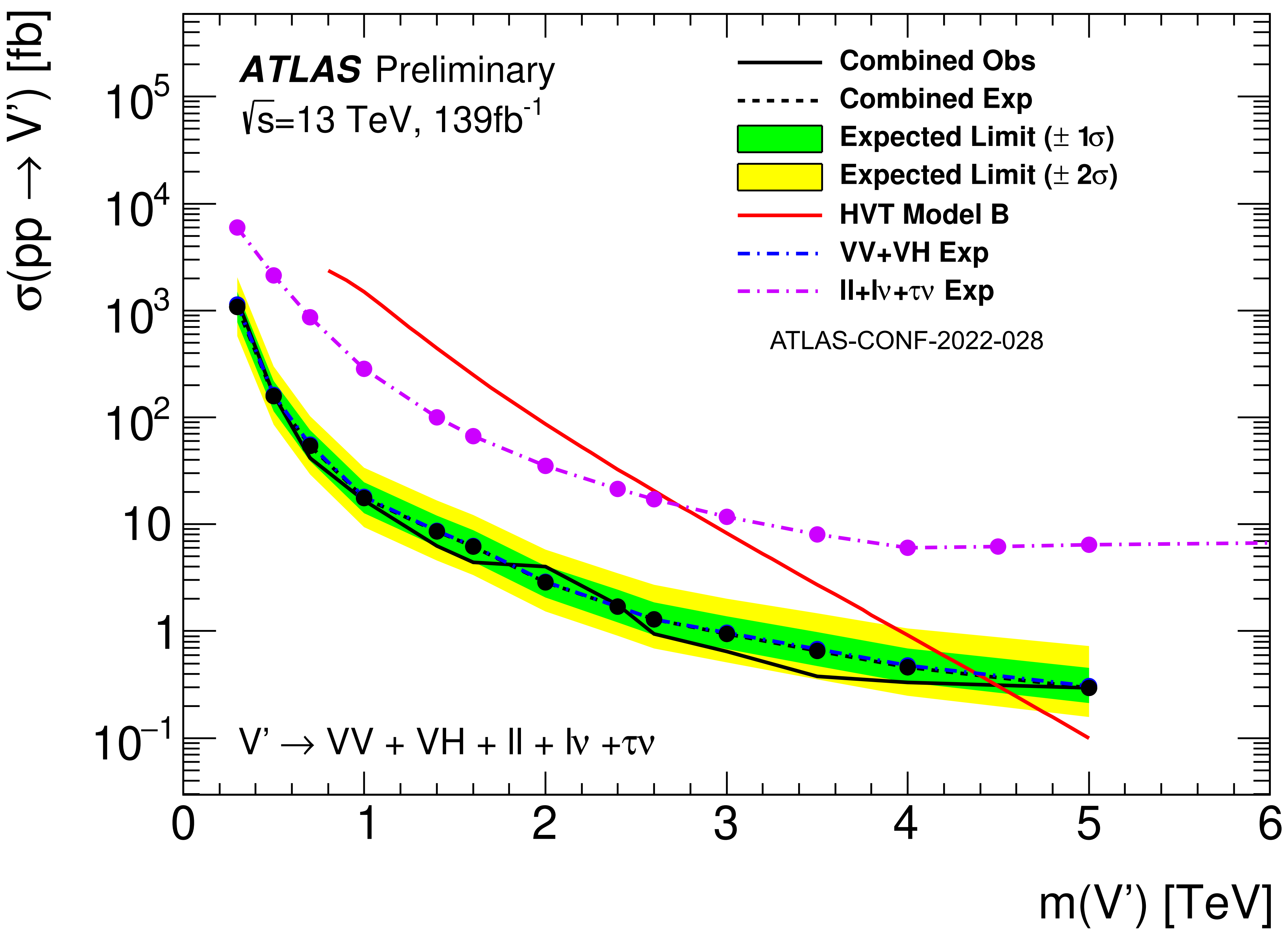
Randall-Sundrum →Heavy Vector Triplet scenario

$\rho \to VV$

hep-ph/0709.0007

	A_1		$\tilde{Z}_1$		$\tilde{Z}_{X1}$	
	Γ(GeV)	BR	Γ(GeV)	BR	Γ(GeV)	BR
$\bar{t}t$	55.8	0.54	18.3	0.16	55.6	0.41
$\bar{b}b$	0.9	8.7×10^{-3}	0.12	10^{-3}	28.5	0.21
$\bar{u}u$	0.28	2.7×10^{-3}	0.2	1.7×10^{-3}	0.05	4×10^{-4}
$\bar{d}d$	0.07	6.7×10^{-4}	0.25	2.2×10^{-3}	0.07	5.2×10^{-4}
$\ell^+\ell^-$	0.21	2×10^{-3}	0.06	5×10^{-4}	0.02	1.2×10^{-4}
$W_L^+W_L^-$	45.5	0.44	0.88	7.7×10^{-3}	50.2	0.37
Z_Lh	-	-	94	0.82	2.7	0.02
Total	103.3		114.6		135.6	

- RS FCNC computed for **3 TeV** new resonances in 2013
- Quite generous/safe assumption back then
- No specific RS searches found so far for the relevant color-singlet new resonances for the FCNC BR
- Closest searches expressed as “Heavy Vector Triplet” model B (established map between models and appropriate rescaling in progress)
- Limits potentially touching the 3+ TeV at 140/fb and may reach 6 TeV at HL-LHC (prelim. estimate)



Randall-Sundrum →beyond Heavy Vector Triplet scenario

$\rho \to t\bar{t}$

	A_1		$\tilde{Z}_1$		$\tilde{Z}_{X1}$	
	Γ(GeV)	BR	Γ(GeV)	BR	Γ(GeV)	BR
$\bar{t}t$	55.8	0.54	18.3	0.16	55.6	0.41
$\bar{b}b$	0.9	8.7×10^{-3}	0.12	10^{-3}	28.5	0.21
$\bar{u}u$	0.28	2.7×10^{-3}	0.2	1.7×10^{-3}	0.05	4×10^{-4}
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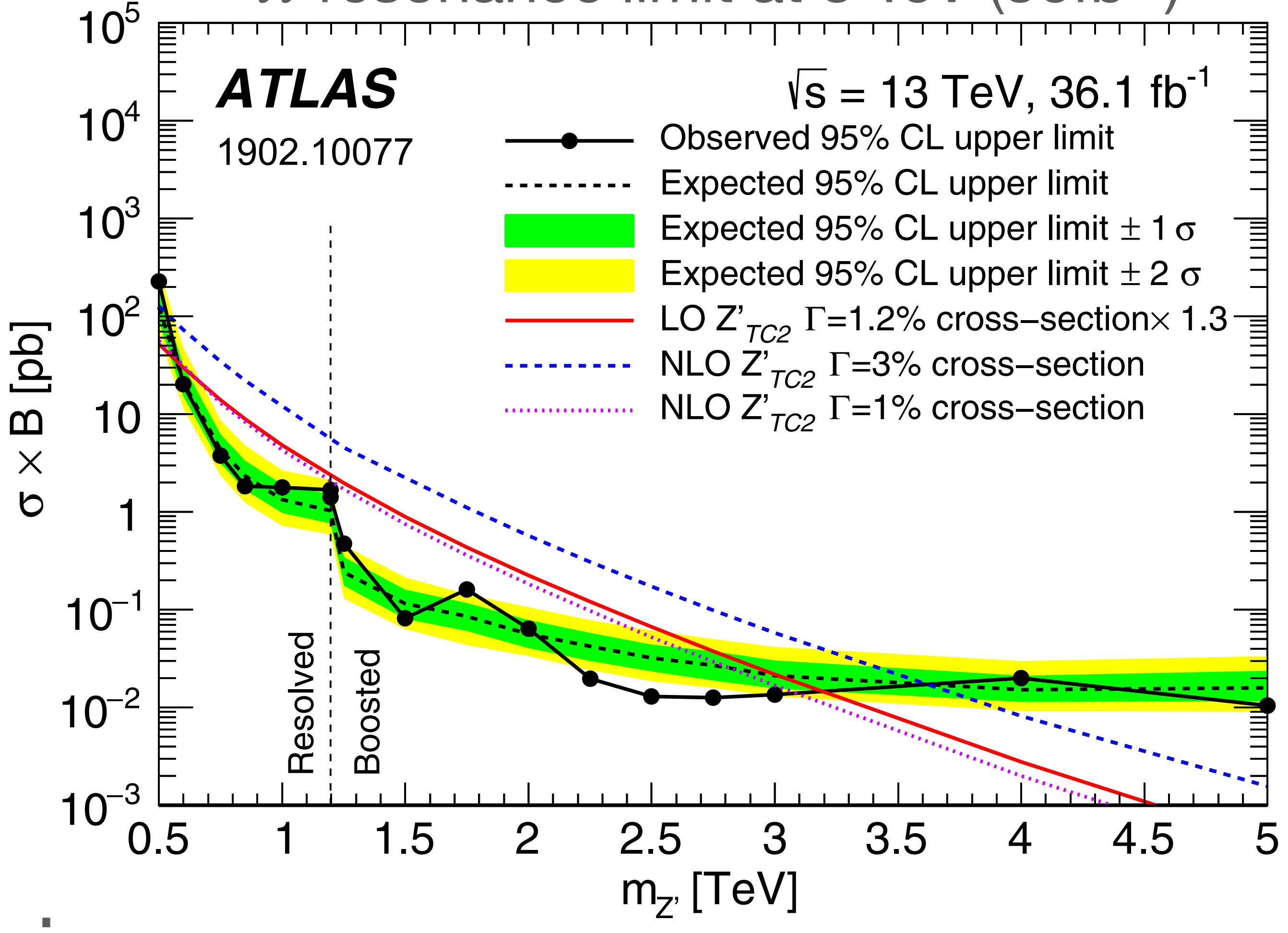
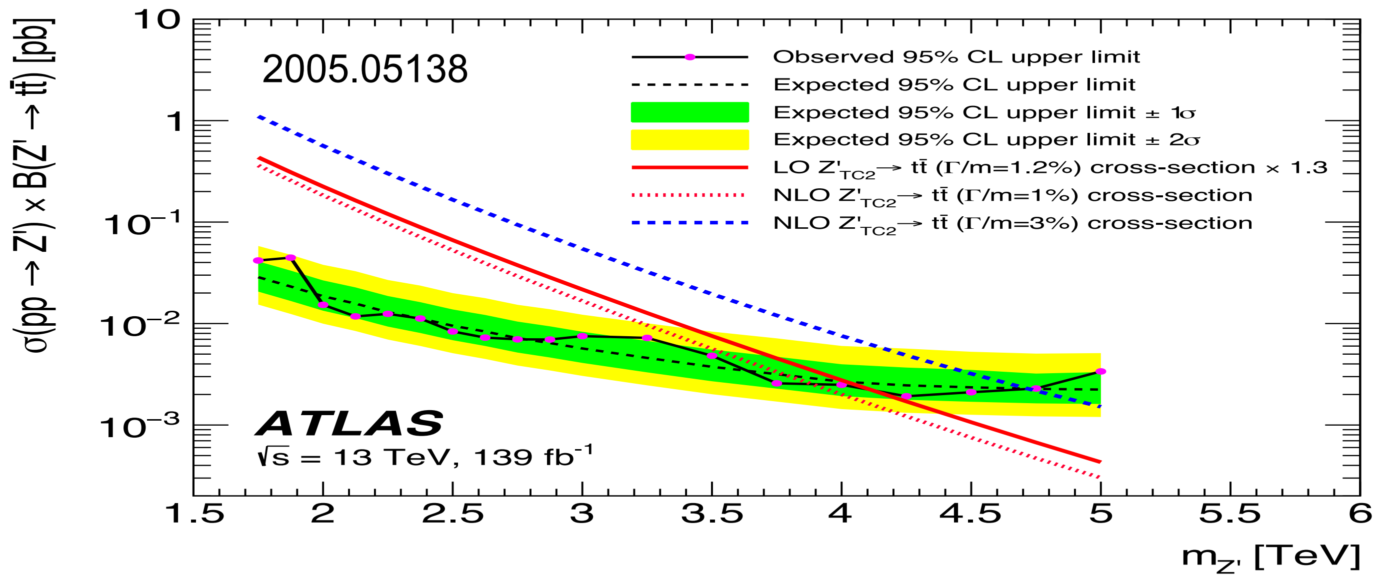
Total	103.3		114.6		135.6	

$t\bar{t}$ resonance limit at 3 TeV (36fb^{-1})



$t\bar{t}$ resonance limit at 4 TeV (136fb^{-1})



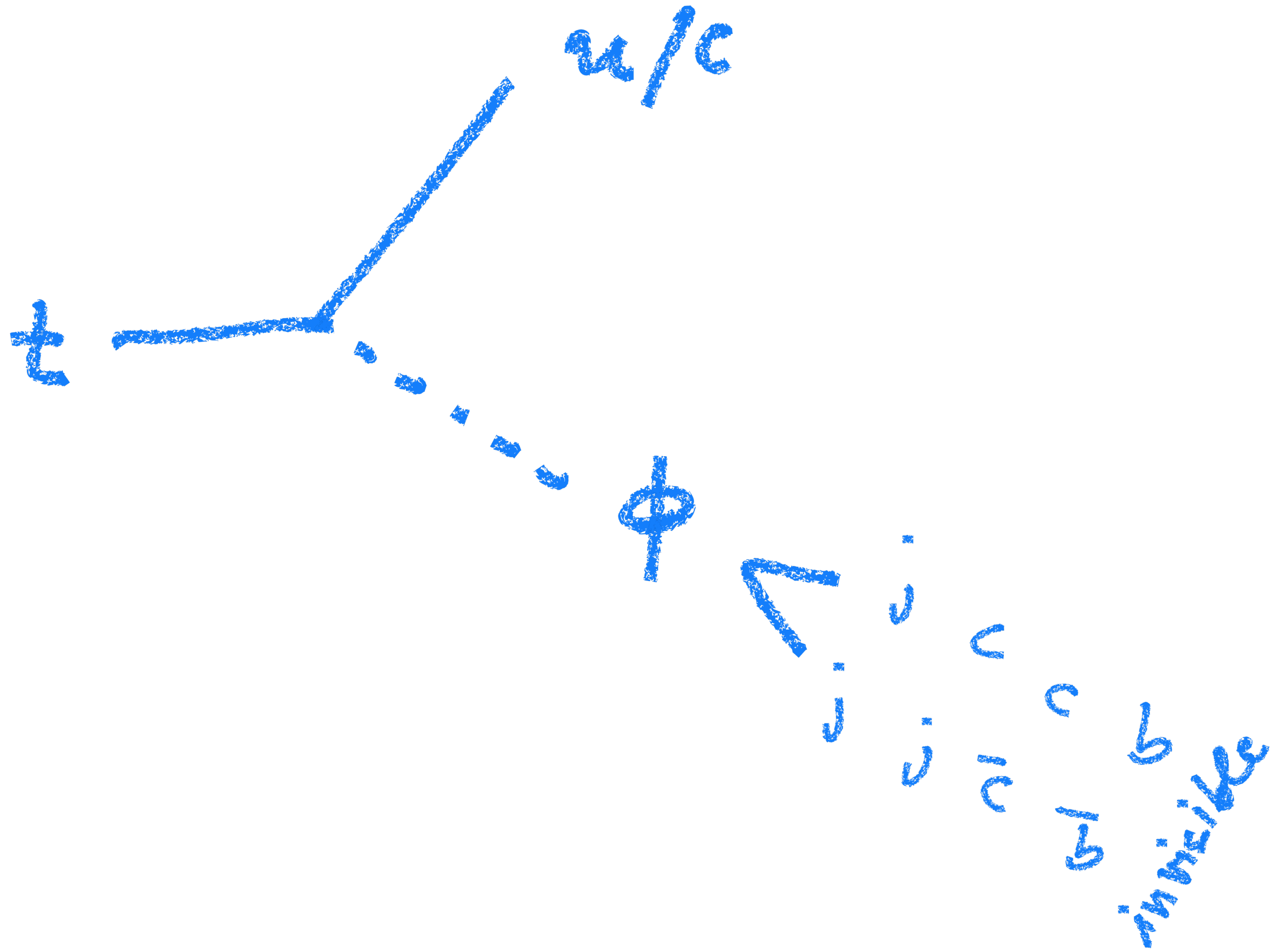
- RS FCNC computed for **3 TeV** new resonances in 2013
- Quite generous/safe assumption back then
- No specific RS searches found so far for the relevant color-singlet new resonances for the FCNC BR
- Closest searches expressed as Z'_{TC2} or dark matter mediator Z' (established map between models and appropriate rescaling in progress)
- Limits potentially touching the 3+ TeV at 140/fb and may reach 6 TeV at HL-LHC (prelim. estimate)

appropriate rescaling of couplings necessary, in progress

Top quark decay at the Top Factory

$t \to BSM$

- can we find a (light) state in the **mass range** not currently investigated by the LHC?
- can we find a new state in the **final states** not currently investigated by the LHC?



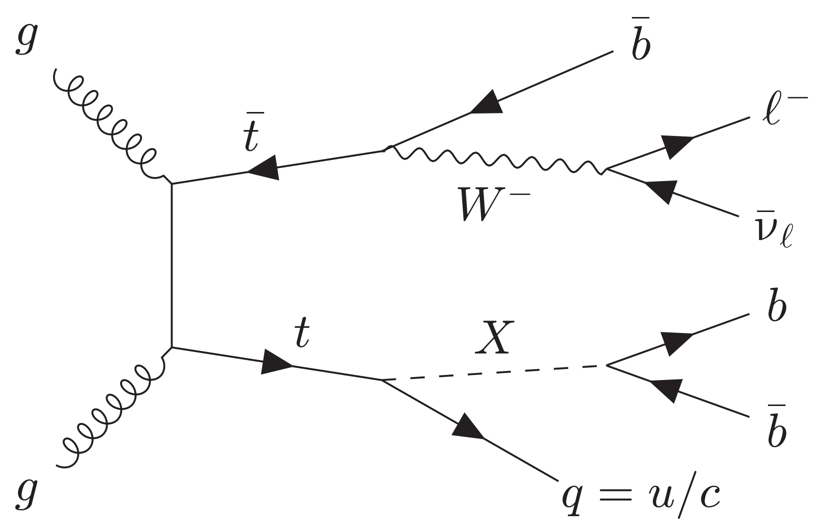
Top quark decay at the Top Factory

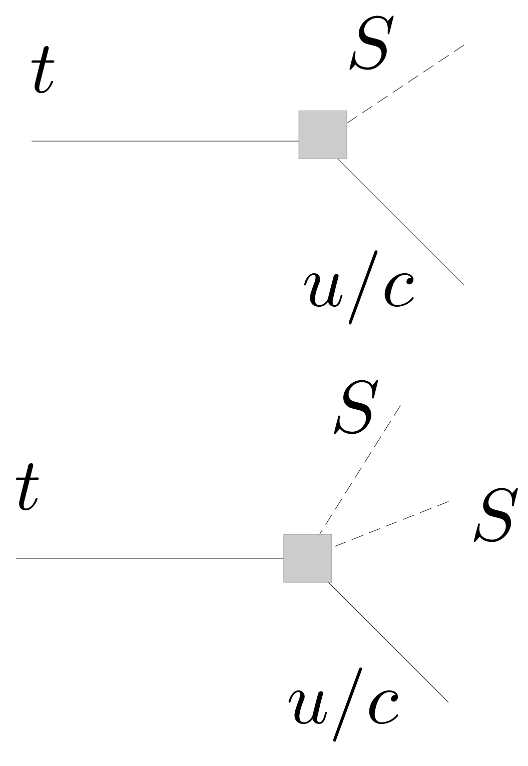
$t \to \phi q, \phi \to bb$

ATLAS 2301.03902, 1806.02836 Banerjee, Chala, Spannowsky,

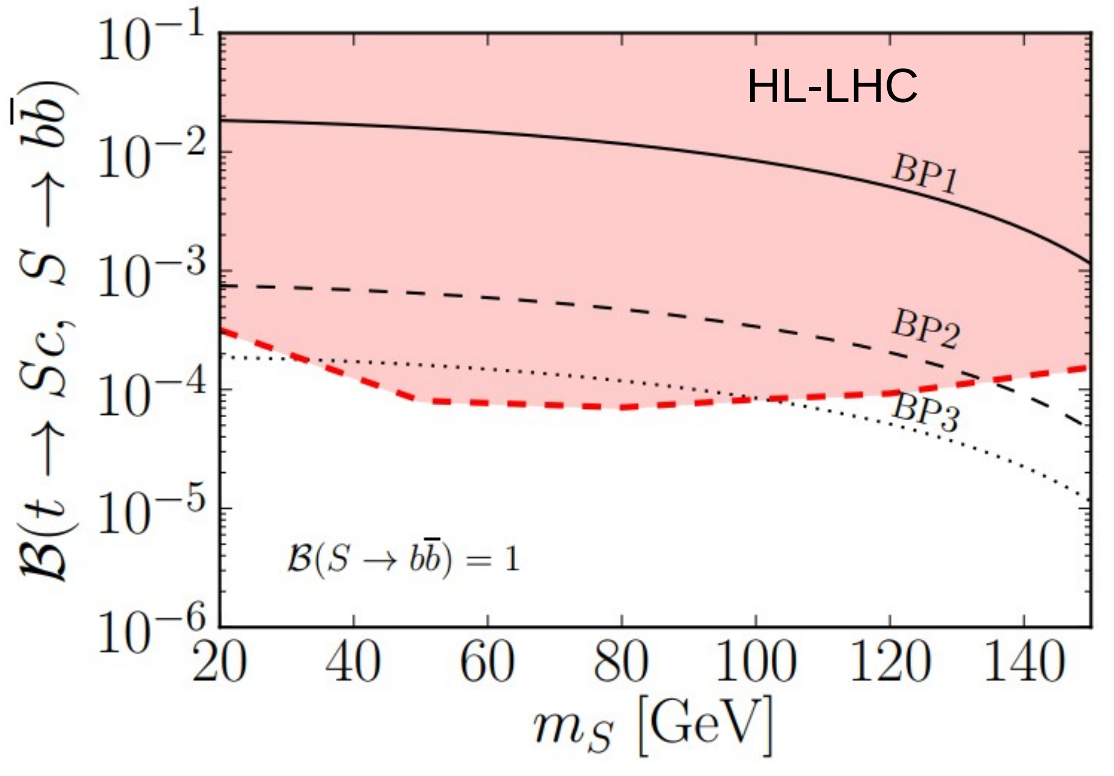
One extra singlet: SO(6)→ SO(5)

2. Rare top decays. About O(10^6) ttbar events at 350 GeV FCC-ee, ILC, ...

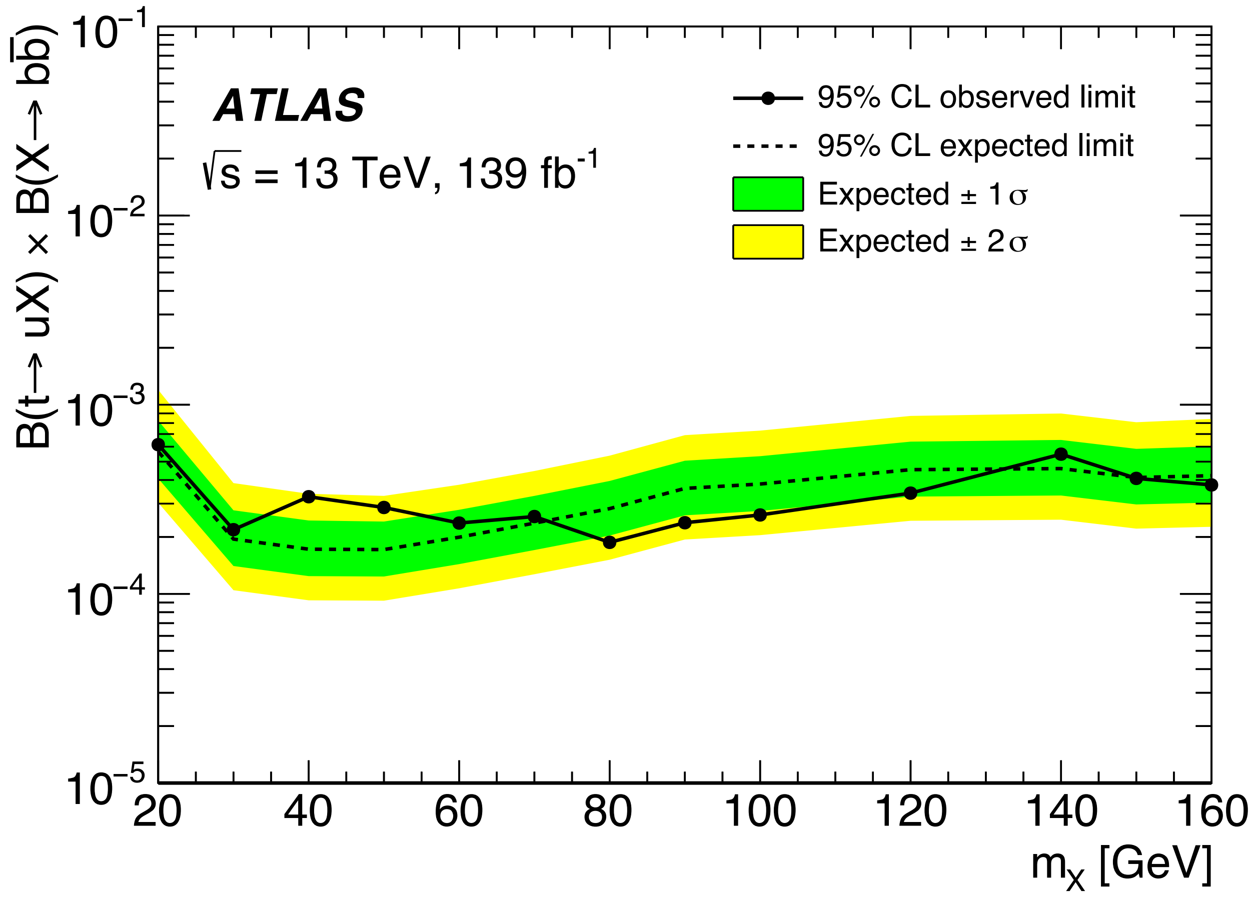




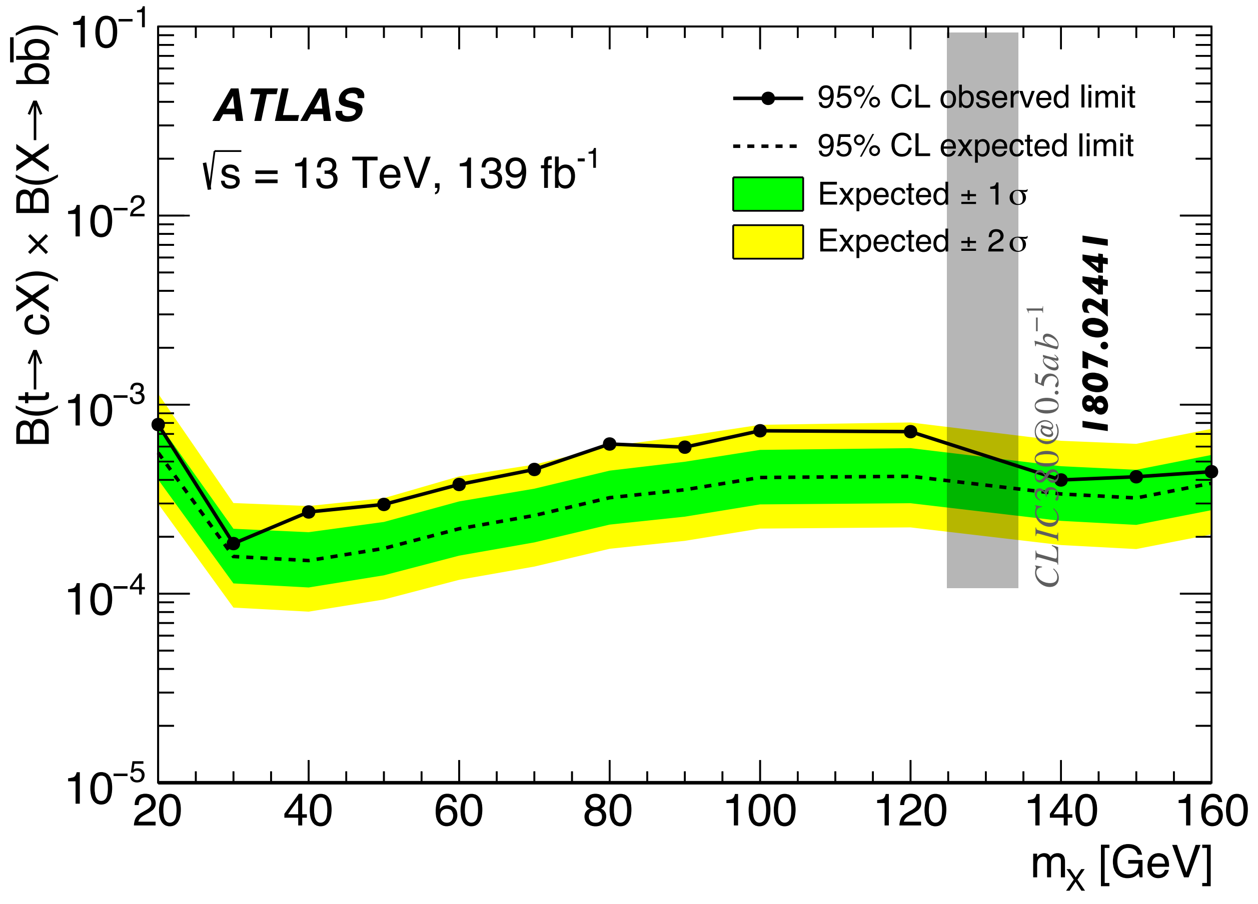
$f_{\max} \sim 100$ TeV



Banerjee, MC, Spannowsky '18



2301.03902



Ample room for improvement with top factory

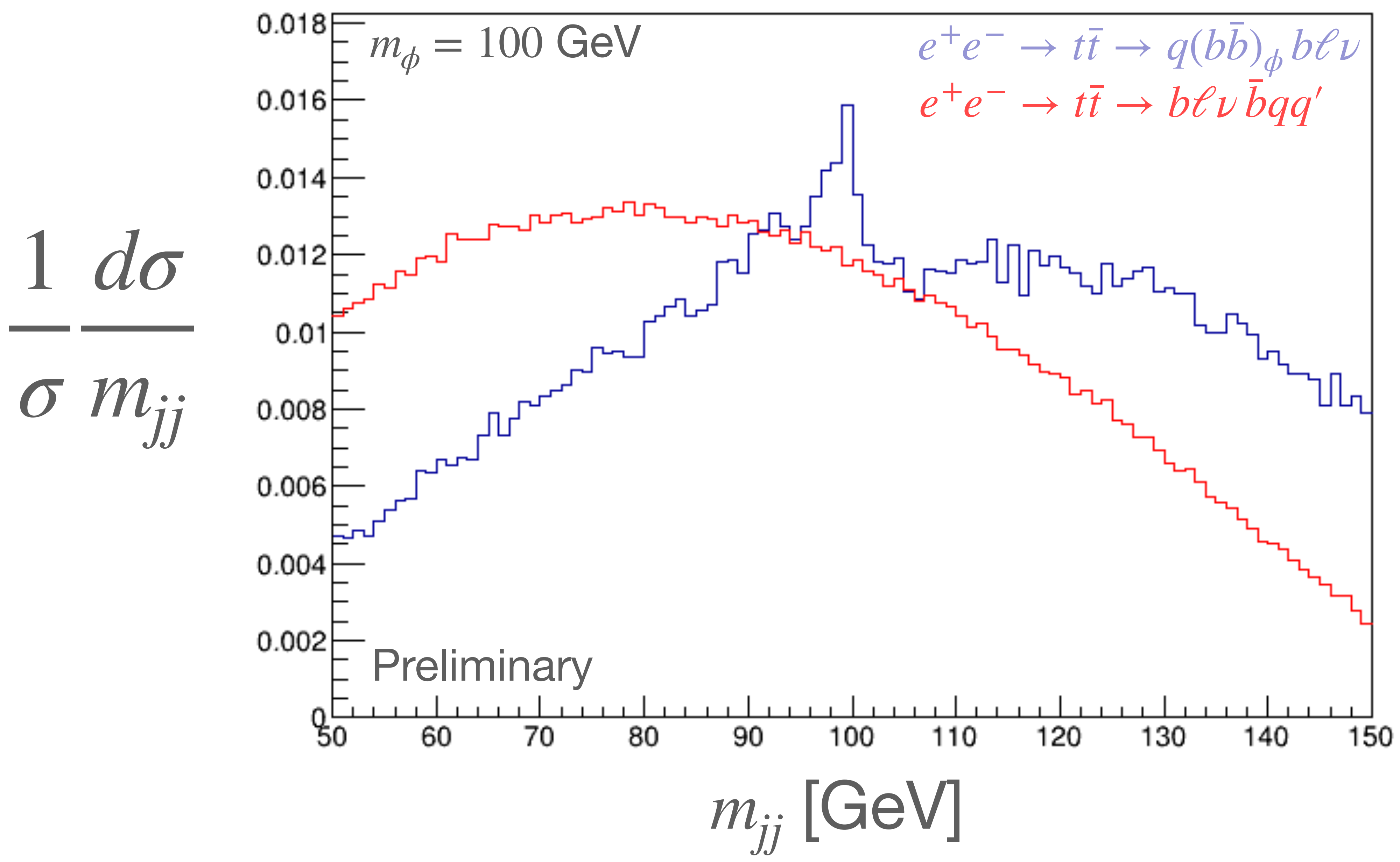
New terrain of search for m_X outside the range studied by LHC (e.g. $m_X \in [10,20]$ GeV)

Top quark decay at the Top Factory

$t \to \phi q, \phi \to b\bar{b}$

Kevin Mota and Kirill Skovpen started to work on IDEA projections for this decay

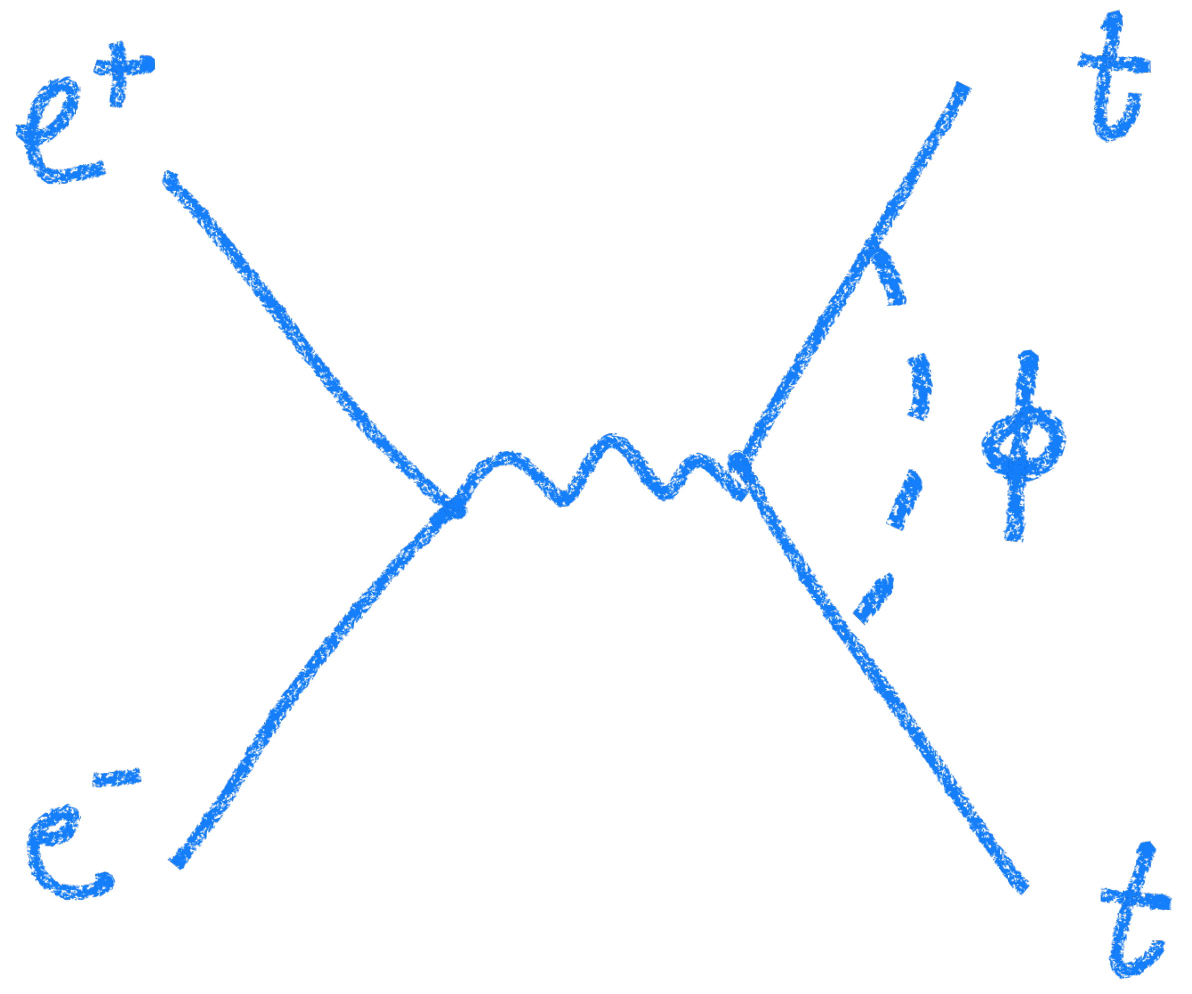
- Delphes simulation using **IDEA** detector card
- First look at semi-leptonic final states
- So far simple analysis pipeline already shows potential for signal-vs-background discrimination
- N=4 Durham exclusive jet clustering so far, other possibilities to be investigated
- Still can exploit jet flavor tagging, angular variables, …



NP in top quark production

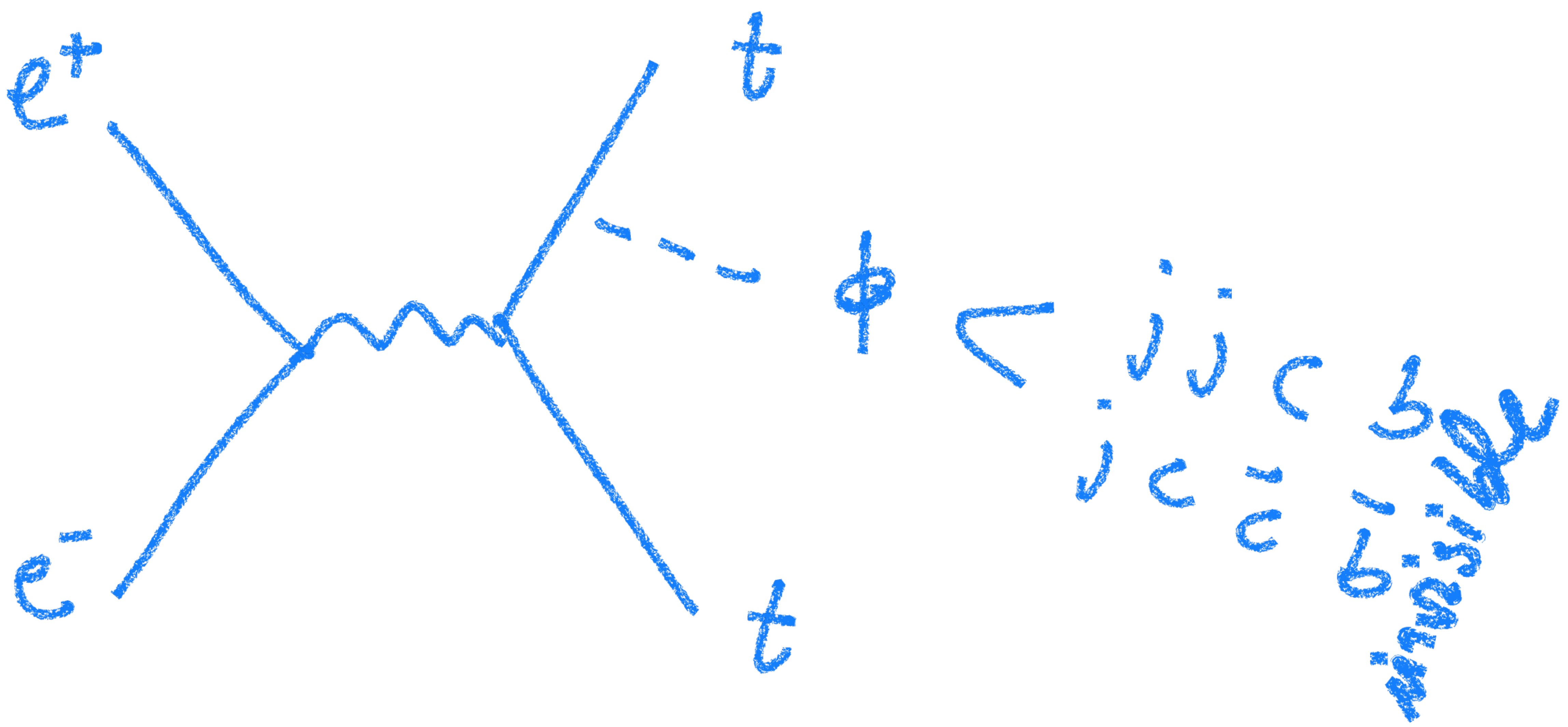
$e^+e^- \to tt\phi$

- can we find a light new state produced in association with $t\bar{t}$ during a **threshold scan** at $\sqrt{s} = 350$ GeV?



threshold studies with BSM

- can we find a a light new state in the **“above”** $t\bar{t}$ **threshold** operation of the top quark factory $\sqrt{s} =$ 365 or 380 GeV ?



Conclusions and Outlook

EXtt

- Top quark physics is a pillar of the future collider physics case
- Important interplay between pp and e^+e^- and between stages of HET
- Several possible contributions from Top Factory to aspects where HL-LHC cannot contribute easily or at all
    - we concentrated on exotic top quark hadronic final states mediated via new physics, which was studied very little at e^+e^- machines
    - first results on IDEA detector for $t \to \phi q \to (b\bar{b})_\phi q$
    - update in progress for BR of FCNC SM final states ($Zq, hq, \gamma q, gq$)
    - exploration of other models that can give large enough BR for observation at HET
- keen to see more people joining on this and other topics that can branch off this first effort (other decay modes, associated productions, …)

Thank you!

Decays

FCNC EW

2301.11605 - ATLAS

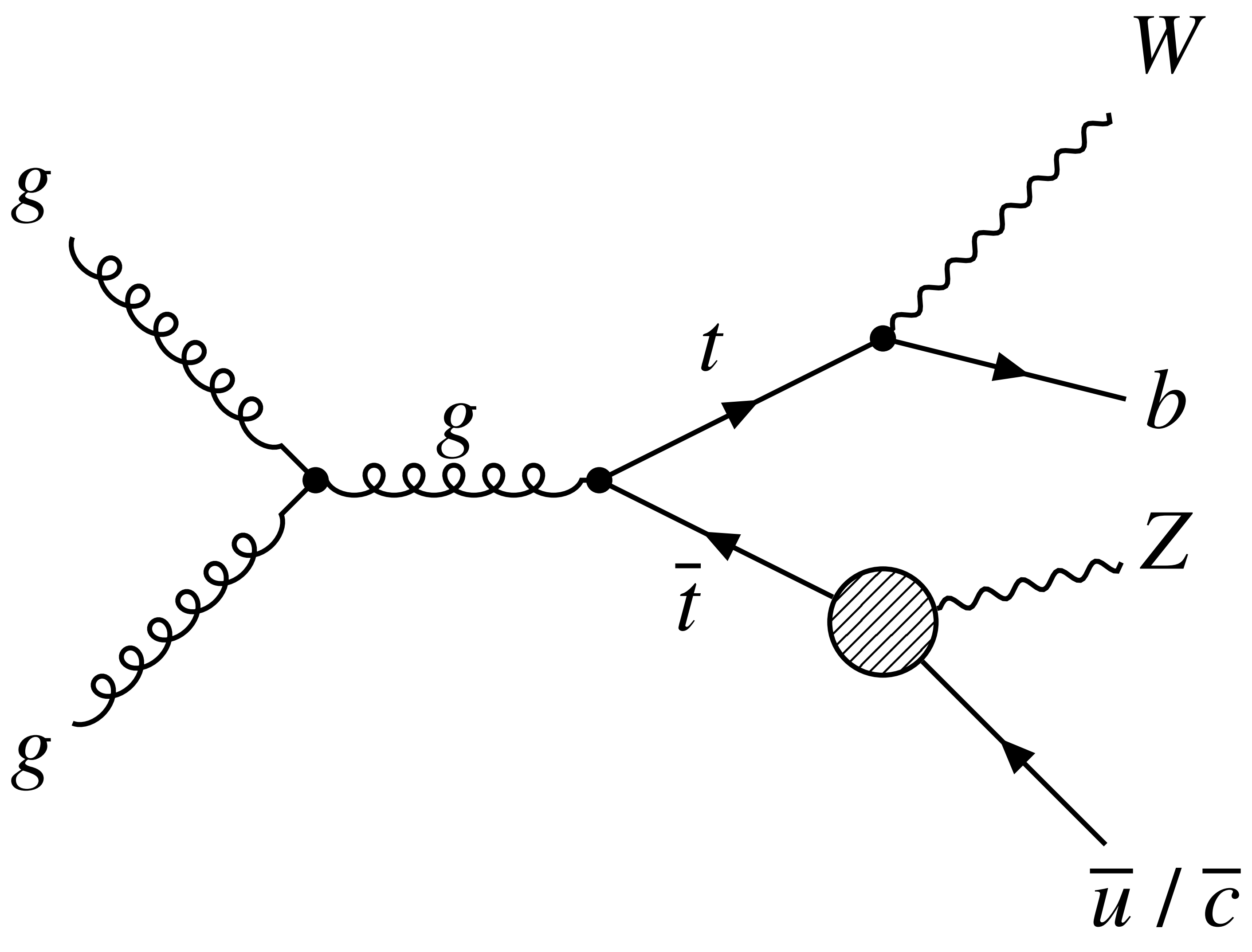


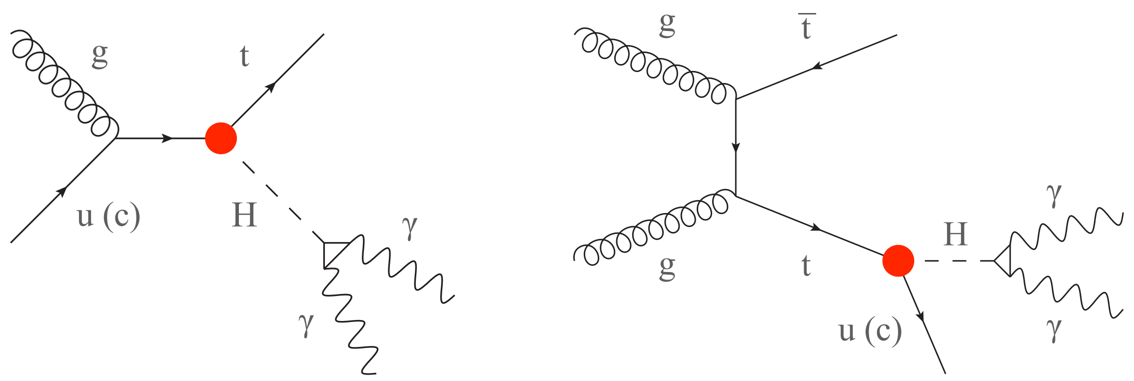
Table 8: Observed and expected 95% CL limits on the FCNC $t \to Zq$ branching ratios and the effective coupling strengths for different vertices and couplings (top eight rows). For the latter, the energy scale is assumed to be Λ_{NP} = 1 TeV. The bottom rows show, for the case of the FCNC $t \to Zu$ branching ratio, the observed and expected 95% CL limits when only one of the two SRs, either SR1 or SR2, and all CRs are included in the likelihood.

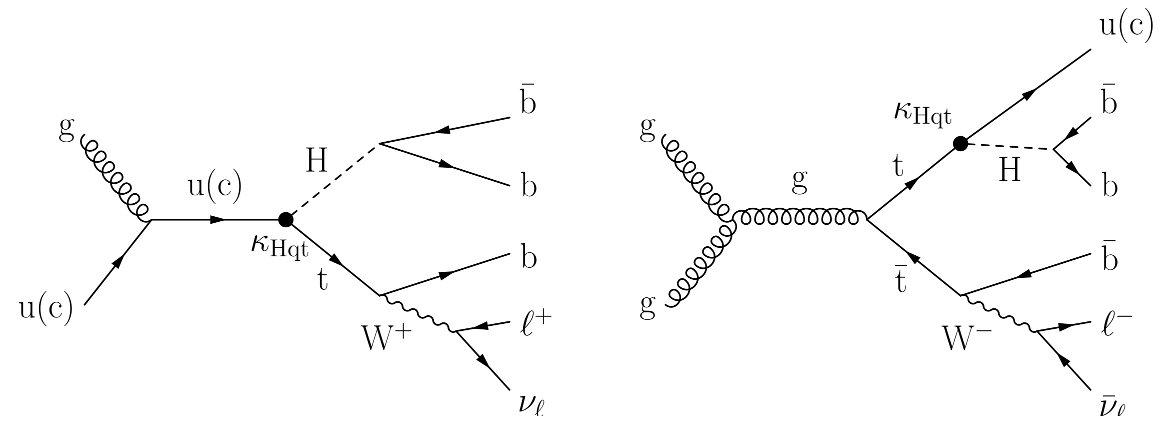
Observable	Vertex	Coupling	Observed	Expected
SRs+CRs				
$\mathcal{B}(t \to Zq)$	tZu	LH	6.2×10^{-5}	$4.9\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	6.6×10^{-5}	$5.1\,^{+2.1}_{-1.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	LH	13×10^{-5}	$11\,^{+5}_{-3}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZc	RH	12×10^{-5}	$10\,^{+4}_{-3}\times10^{-5}$
$\lvert C_{uW}^{(13)*}\rvert$ and $\lvert C_{uB}^{(13)*}\rvert$	tZu	LH	0.15	$0.13\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(31)}\rvert$ and $\lvert C_{uB}^{(31)}\rvert$	tZu	RH	0.16	$0.14\,^{+0.03}_{-0.02}$
$\lvert C_{uW}^{(23)*}\rvert$ and $\lvert C_{uB}^{(23)*}\rvert$	tZc	LH	0.22	$0.20\,^{+0.04}_{-0.03}$
$\lvert C_{uW}^{(32)}\rvert$ and $\lvert C_{uB}^{(32)}\rvert$	tZc	RH	0.21	$0.19\,^{+0.04}_{-0.03}$
SR1+CRs				
$\mathcal{B}(t \to Zq)$	tZu	LH	9.7×10^{-5}	$8.6\,^{+3.6}_{-2.4}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	9.5×10^{-5}	$8.2\,^{+3.4}_{-2.3}\times10^{-5}$
SR2+CRs				
$\mathcal{B}(t \to Zq)$	tZu	LH	7.8×10^{-5}	$6.1\,^{+2.7}_{-1.7}\times10^{-5}$
$\mathcal{B}(t \to Zq)$	tZu	RH	9.0×10^{-5}	$6.6\,^{+2.9}_{-1.8}\times10^{-5}$

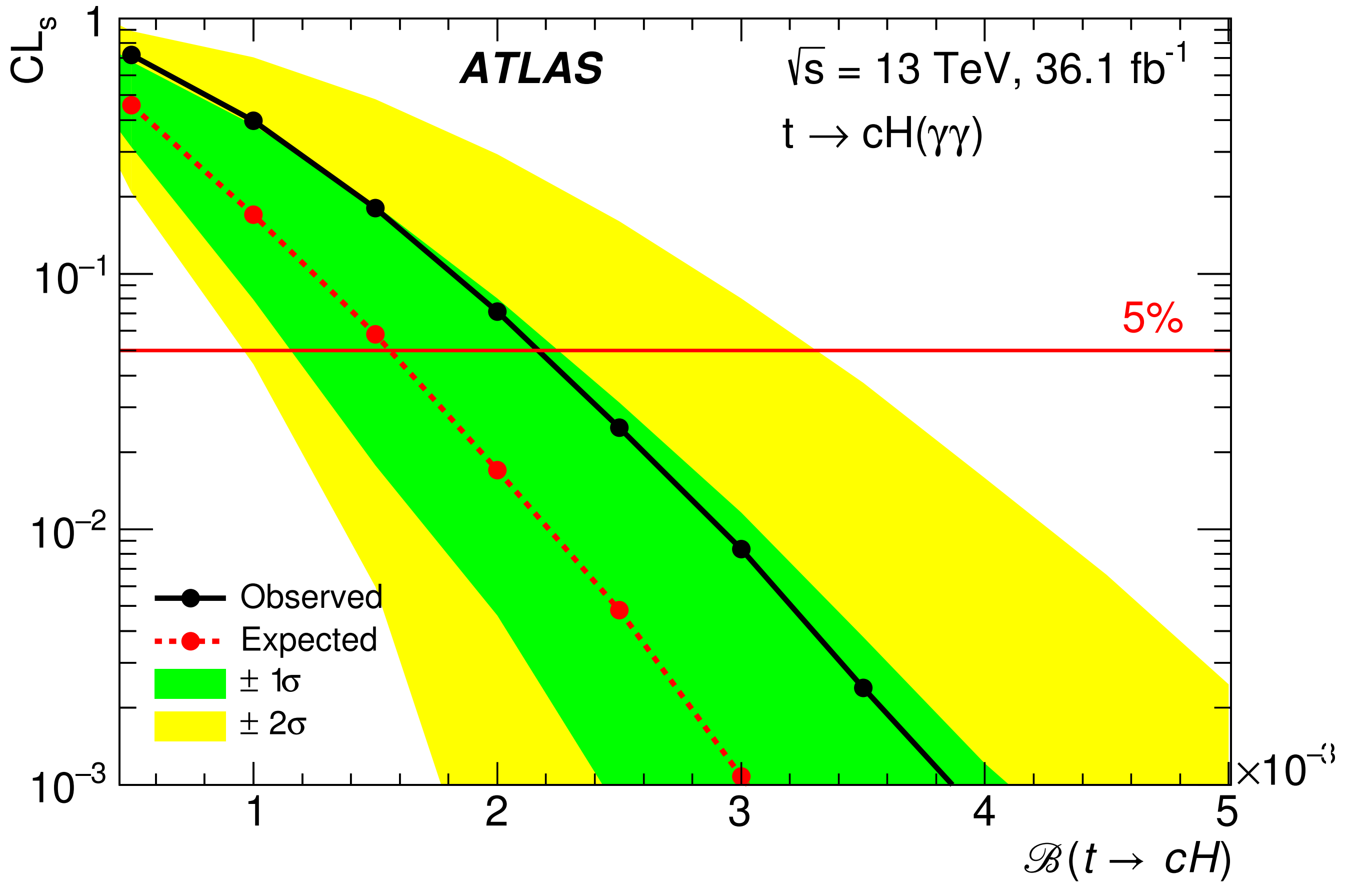
Present $BR < 10^{-4}$, HL-LHC might leave little room to improve (projection for HL-LHC should be around few 10^{-5} for $Z \to \ell\ell$ according to ATL-PHYS-PUB-2019-001)

FCNC Higgs

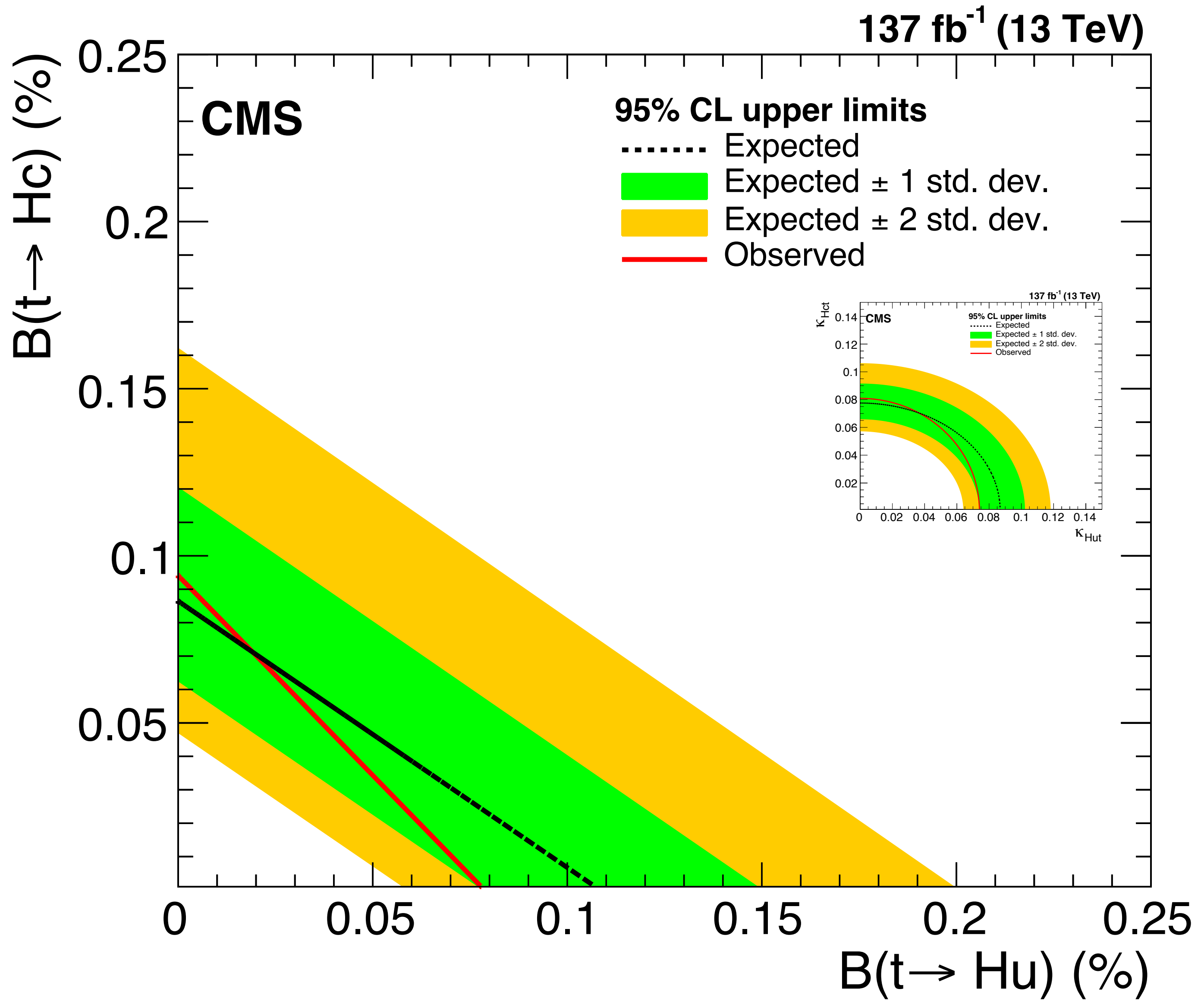
1707.01404 - ATLAS 2112.09734, 2111.02219 CMS

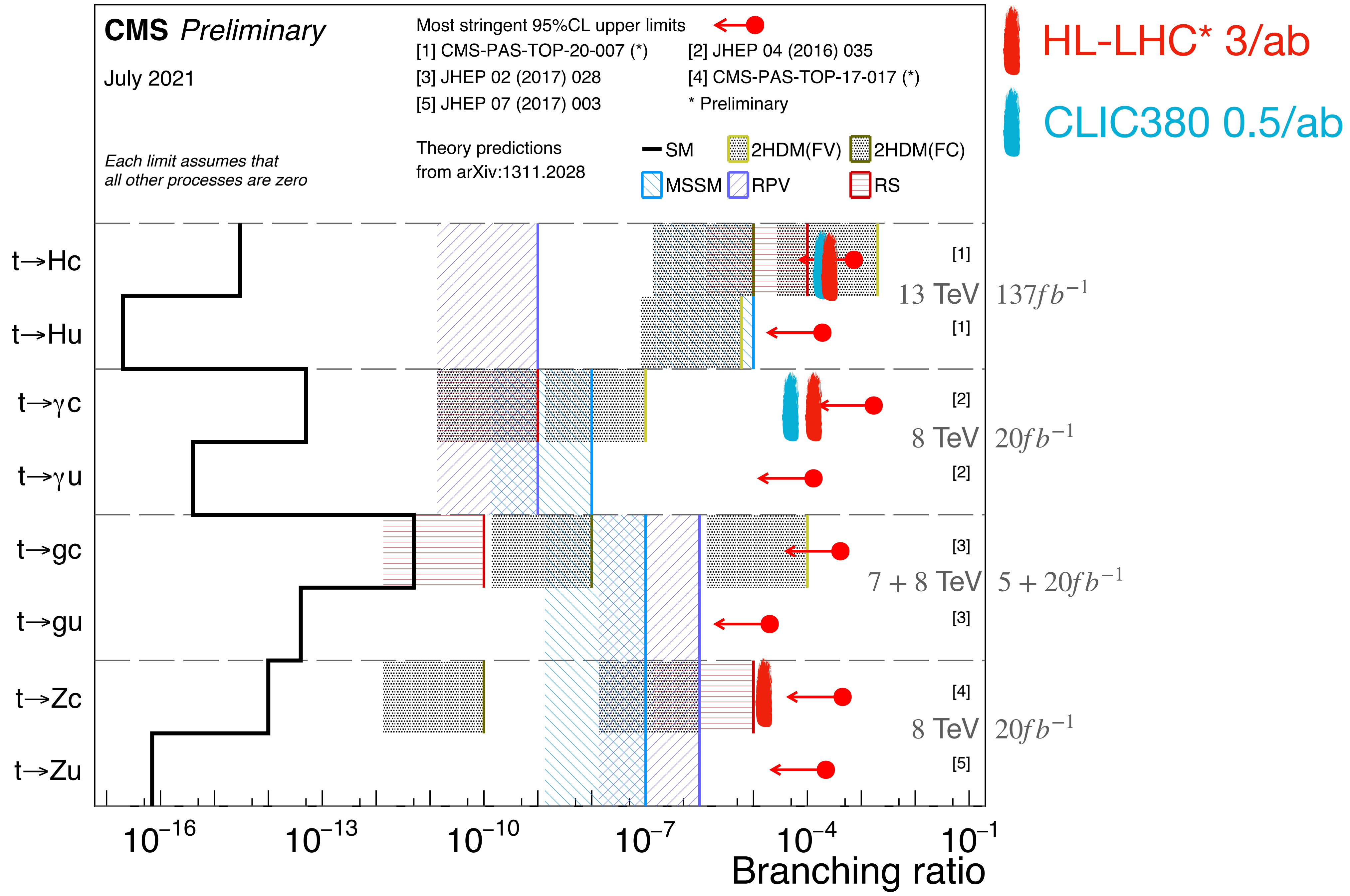






No significant excess is observed and an upper limit is set on the t → cH branching ratio of 2.2 × 10^{-3} at the 95% confidence level, while the expected limit in the absence of signal is 1.6 × 10^{-3}. The corresponding limit on the tcH coupling is 0.090 at the 95% confidence level. The observed upper limit on the t → uH branching ratio is 2.4 × 10^{-3}.



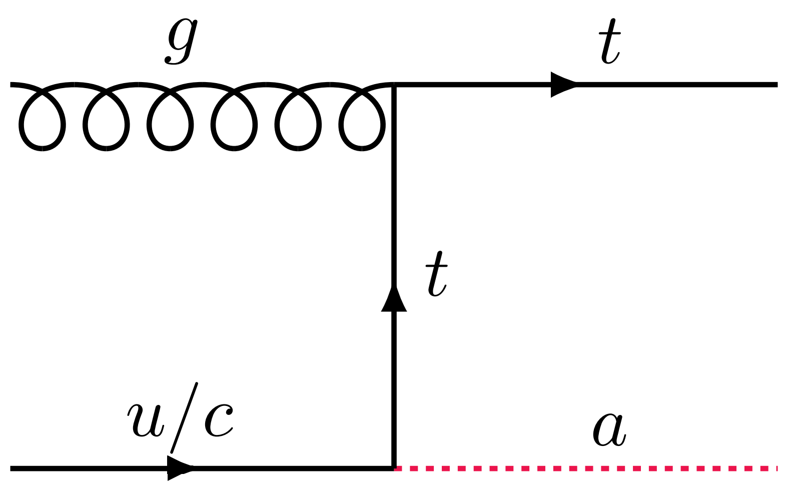


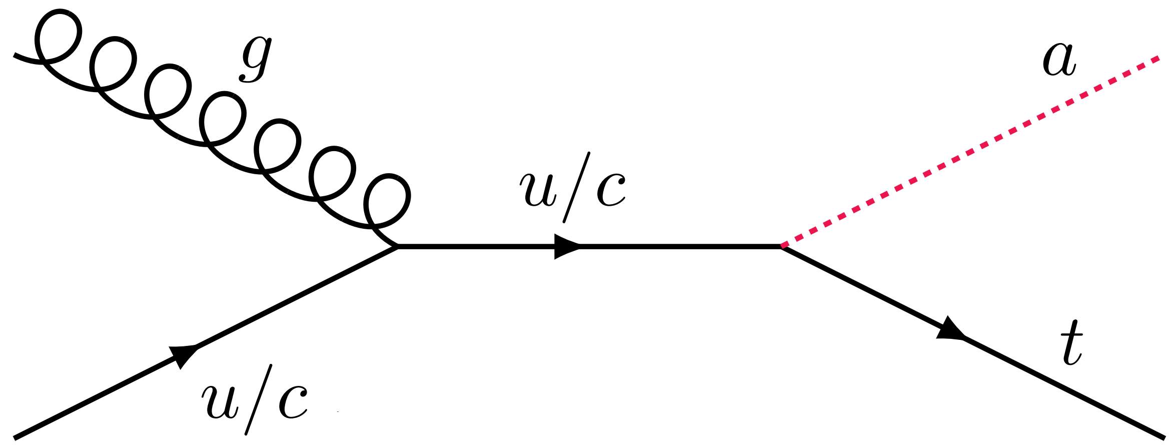
Present $BR(t \to cH) < 2.2 \cdot 10^{-3}$ @$36\ \text{fb}^{-1}$, $9.4 \cdot 10^{-4}$@137fb^{-1}, HL-LHC might go to $3 \cdot 10^{-4}$ (TBC), which leaves little room for the top factory, e.g. 500fb^{-1} at CLIC380 gives is BR<$2 \cdot 10^{-4}$

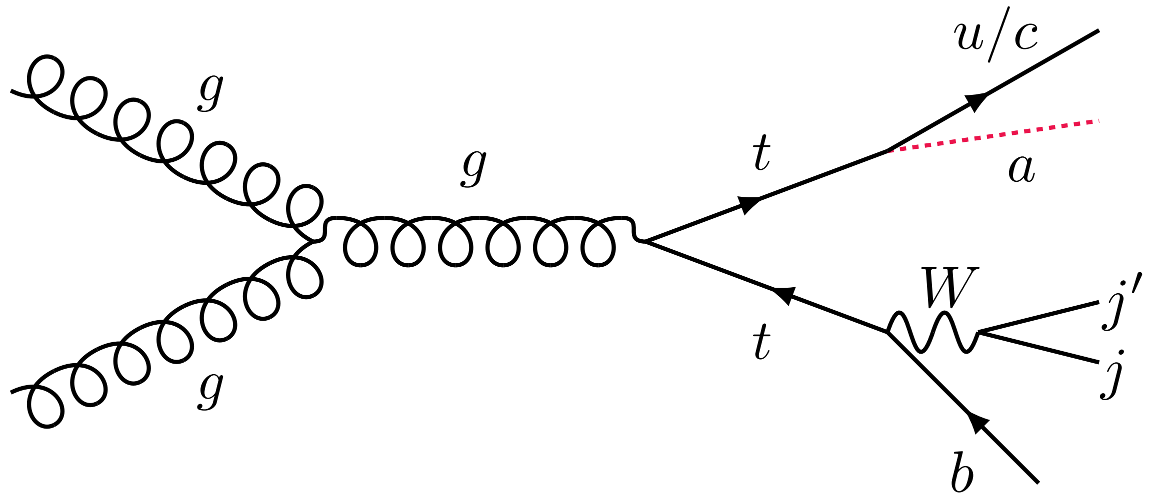
[1810.05487] Expected 95% C.L. limits for 500 fb−1 collected at 380 GeV CLIC are:
BR(t → cγ) < 4.7·10^{-5}, BR(t → cH)×BR(H → bb) < 1.2·10^{-4} and BR(t → cEmiss) < 1.2 – 4.1 · 10^{-4}.

$t \to a u_i, a \to uu, cc, uc$

2101.07803, 2202.09371 - Carmona, Elahi, Scherb, Schwaller

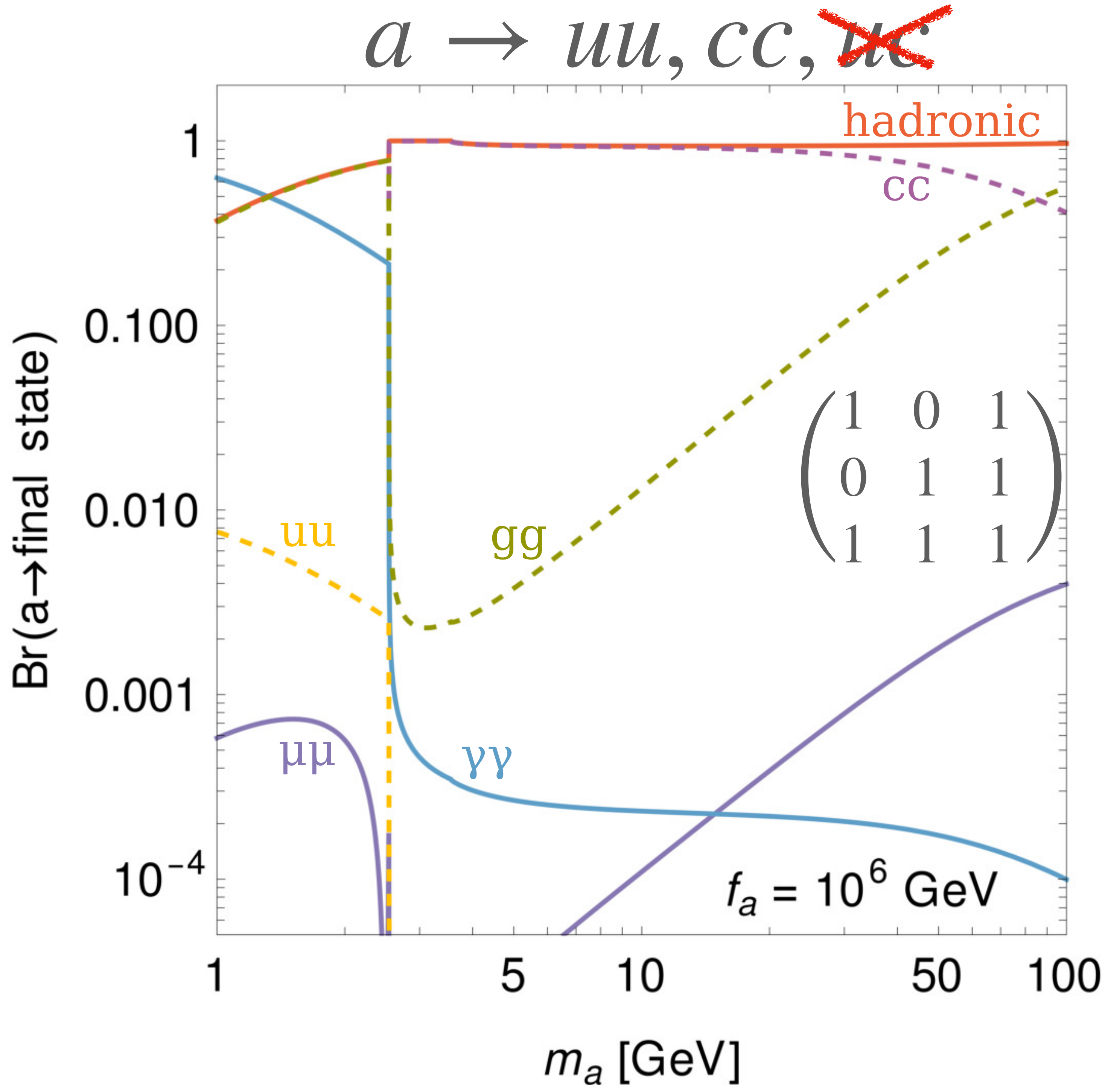


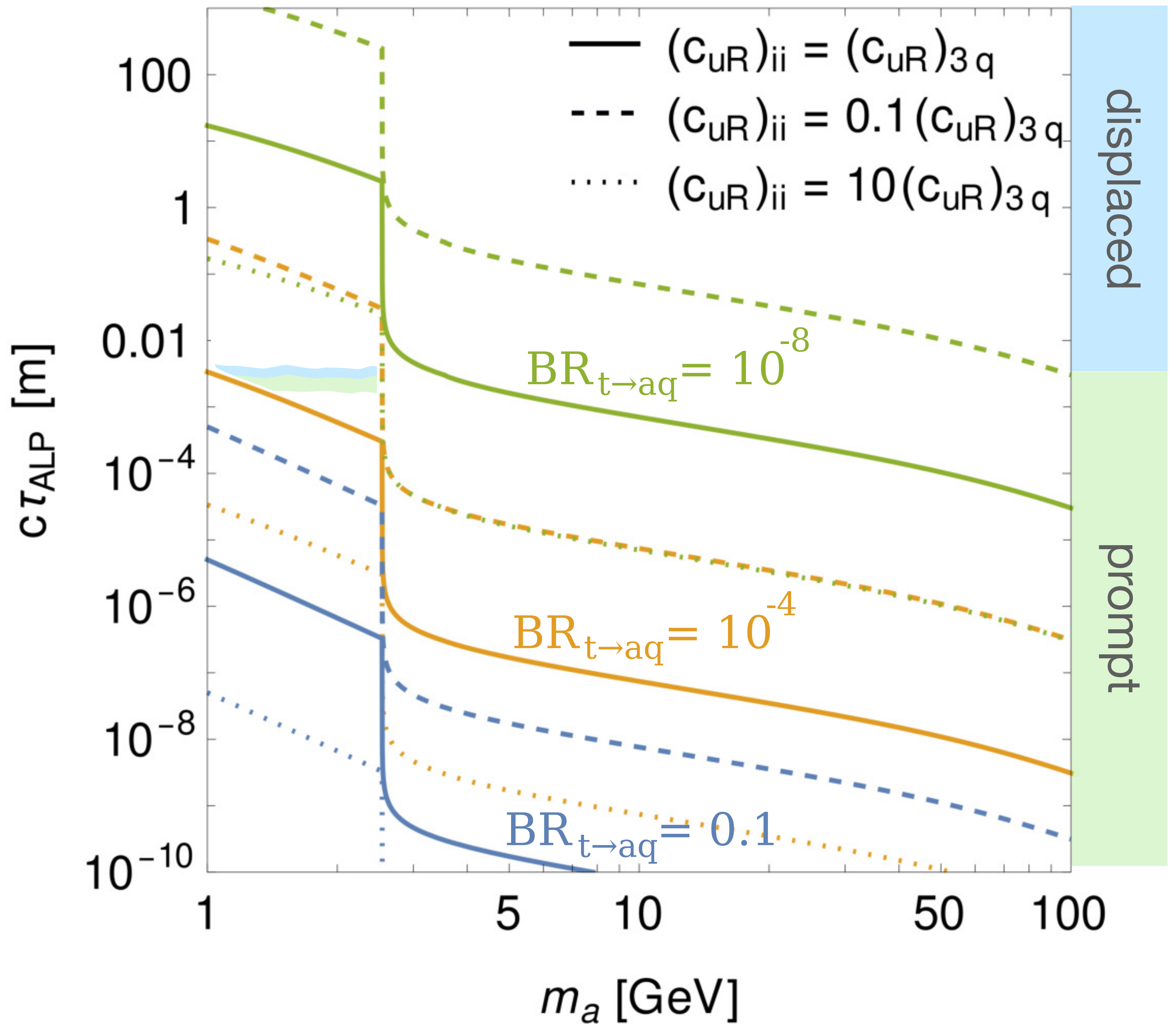


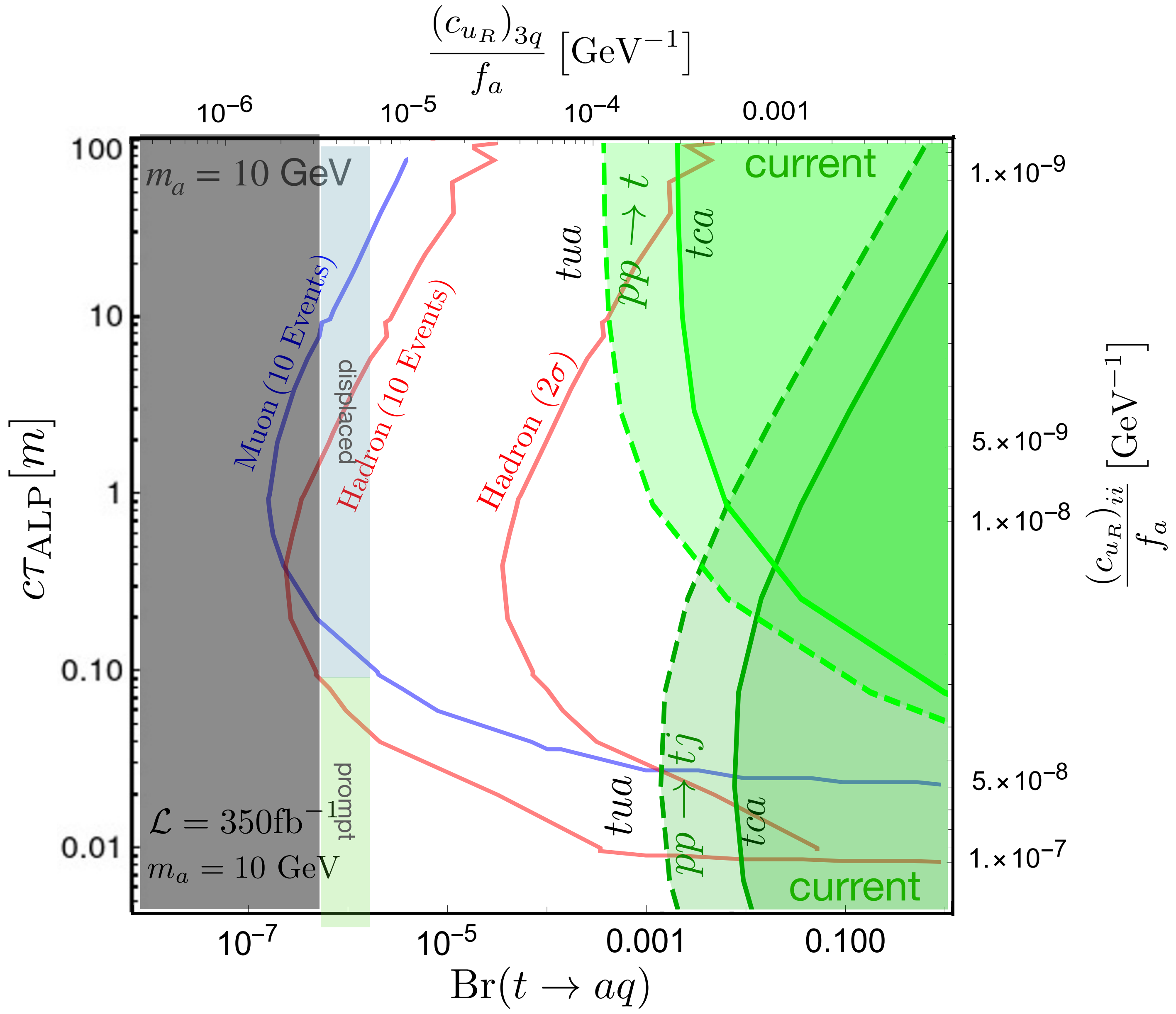


$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}\left[(c_{u_R})_{ij}\bar{u}_{Ri}\gamma^\mu u_{Rj}\right.$

$$c_{u_R} \sim \begin{pmatrix} 2 & 3\epsilon & 3\epsilon^2 \\ 3\epsilon & 1 & \epsilon \\ 3\epsilon^2 & \epsilon & \epsilon^2 \end{pmatrix}$$







focus on displaced flavor-conserving decay so far

Ample room for improvement with top factory studies for prompt decays $a \to jj, uc, cc$ and invisible

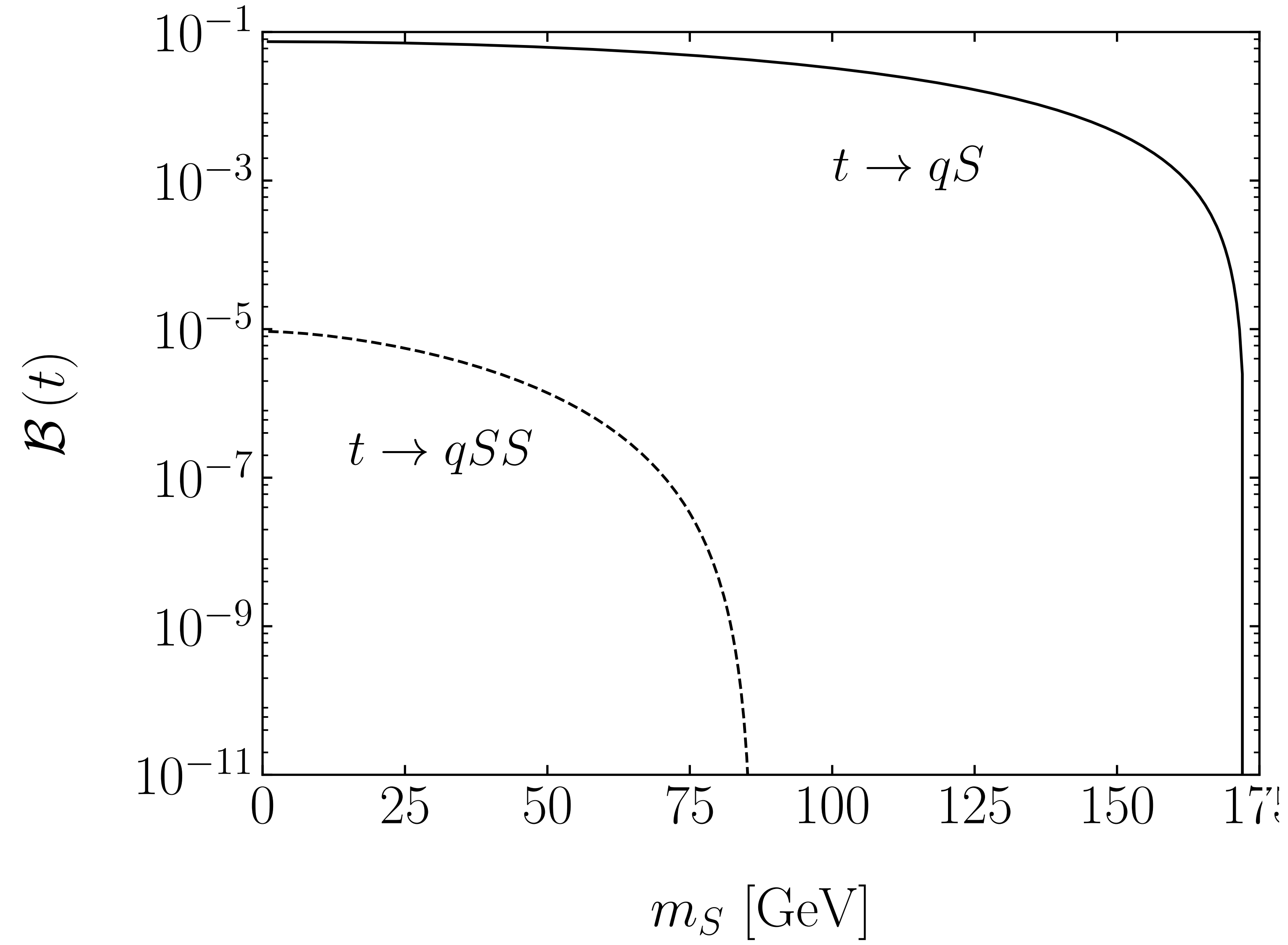
$t \to \phi q, \phi\phi q, \phi \to \ell\ell$

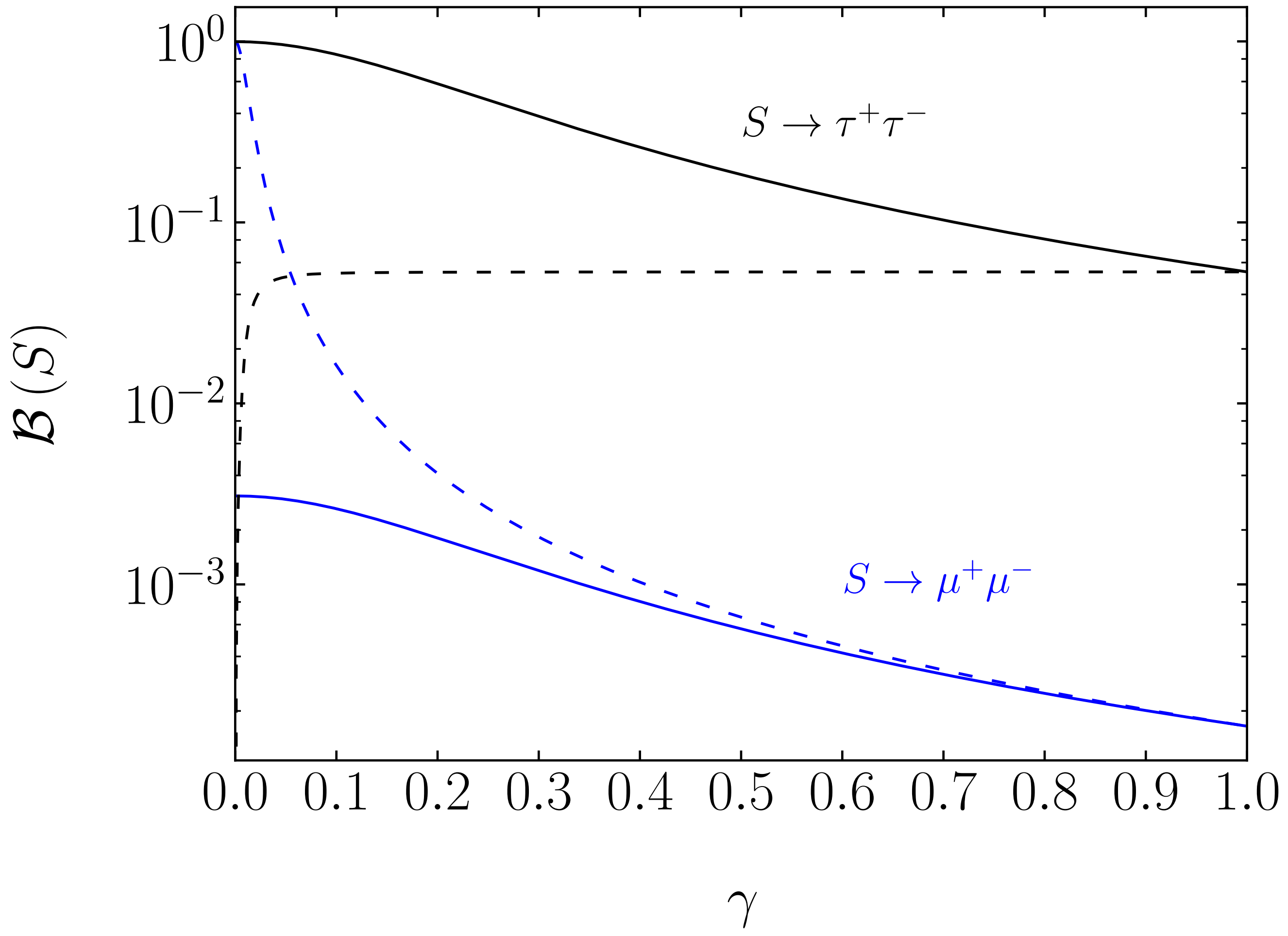
2005.09594 - Castro, Chala, Peixoto, Ramos

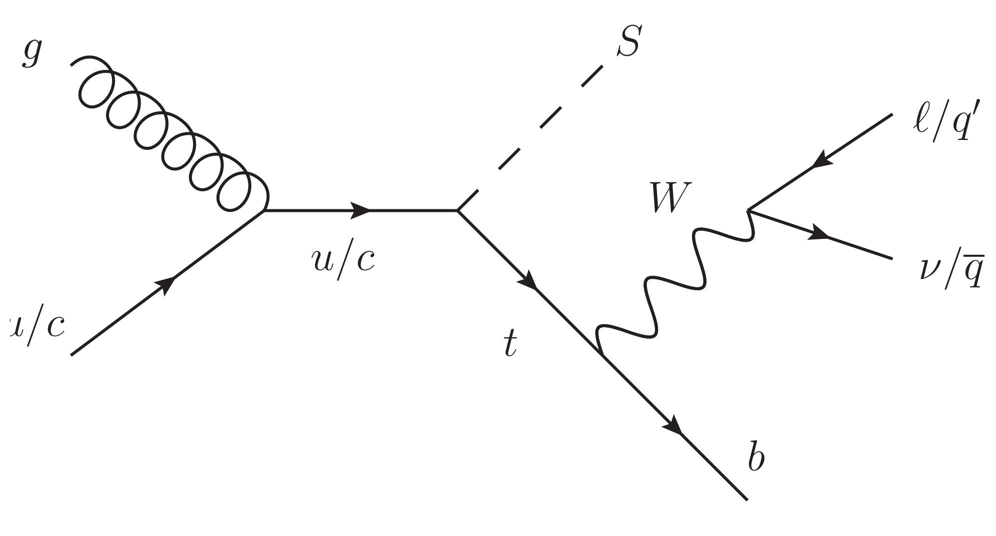
$$
\begin{aligned}
&\text{BP 1}: && \mathbf{Y^q}_{i3} = \mathbf{Y^q}_{3i} = 0.01\,, && \Lambda = 5\ \text{TeV} && \Longrightarrow && \mathcal{B}(t \to Sq) \sim 10^{-8} - 10^{-7}\,,\\
&\text{BP 2}: && \mathbf{Y^q}_{i3} = \mathbf{Y^q}_{3i} = 0.10\,, && \Lambda = 5\ \text{TeV} && \Longrightarrow && \mathcal{B}(t \to Sq) \sim 10^{-6} - 10^{-5}\,,\\
&\text{BP 3}: && \mathbf{Y^q}_{i3} = \mathbf{Y^q}_{3i} = 0.10\,, && \Lambda = 1\ \text{TeV} && \Longrightarrow && \mathcal{B}(t \to Sq) \sim 10^{-4} - 10^{-3}\,,\\
&\text{BP 4}: && \tilde{\mathbf{Y}}^{\mathbf{q}}_{i3} = \tilde{\mathbf{Y}}^{\mathbf{q}}_{3i} = 1.00\,, && \Lambda = 5\ \text{TeV} && \Longrightarrow && \mathcal{B}(t \to SSq) \sim 10^{-11} - 10^{-8}\,,\\
&\text{BP 5}: && \tilde{\mathbf{Y}}^{\mathbf{q}}_{i3} = \tilde{\mathbf{Y}}^{\mathbf{q}}_{3i} = 0.20\,, && \Lambda = 1\ \text{TeV} && \Longrightarrow && \mathcal{B}(t \to SSq) \sim 10^{-10} - 10^{-7}\,,\\
&\text{BP 6}: && \tilde{\mathbf{Y}}^{\mathbf{q}}_{i3} = \tilde{\mathbf{Y}}^{\mathbf{q}}_{3i} = 1.00\,, && \Lambda = 1\ \text{TeV} && \Longrightarrow && \mathcal{B}(t \to SSq) \sim 10^{-8} - 10^{-5}\,,
\end{aligned}
$$

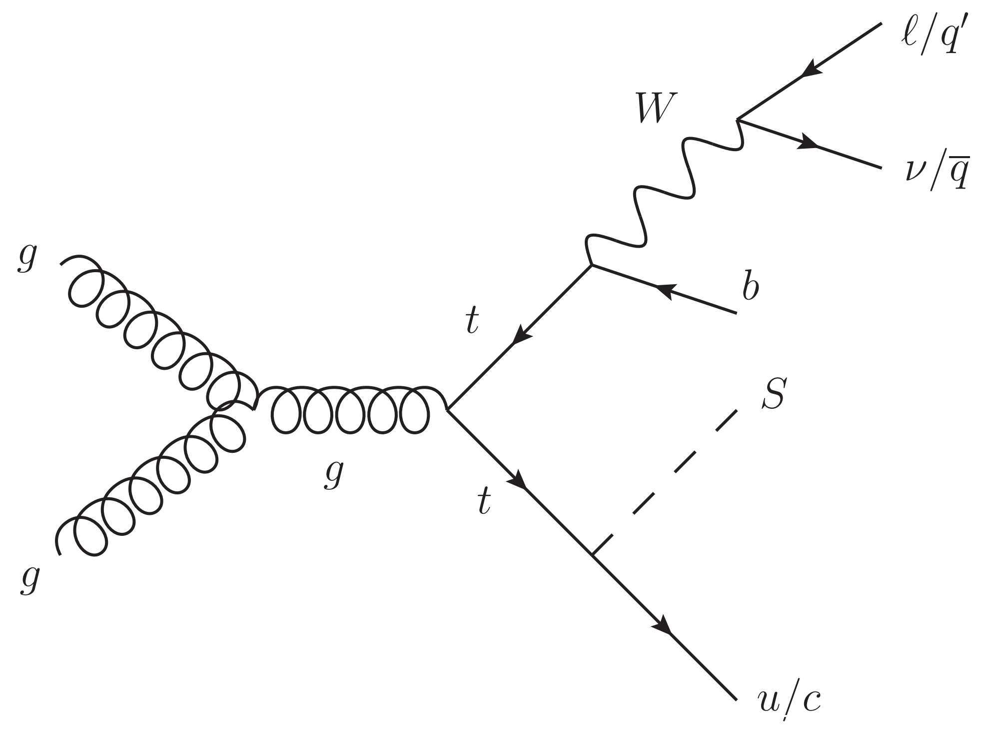
focus on lepto-philic so far

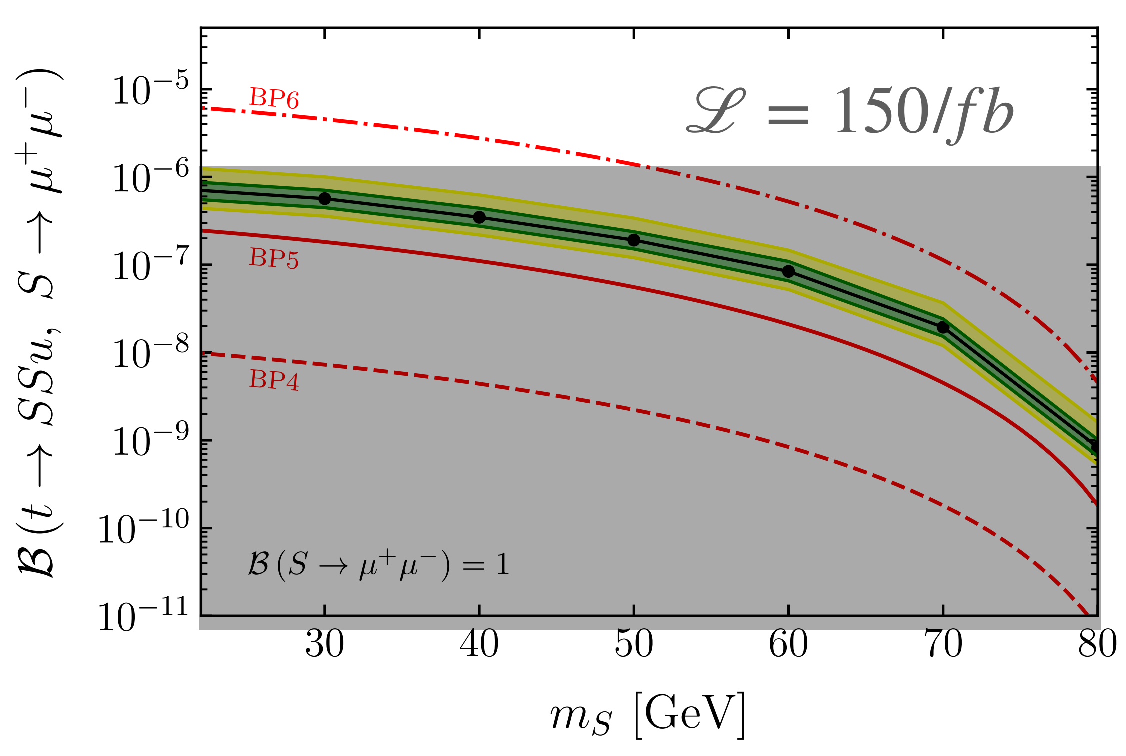
hadro-philic would require some model building

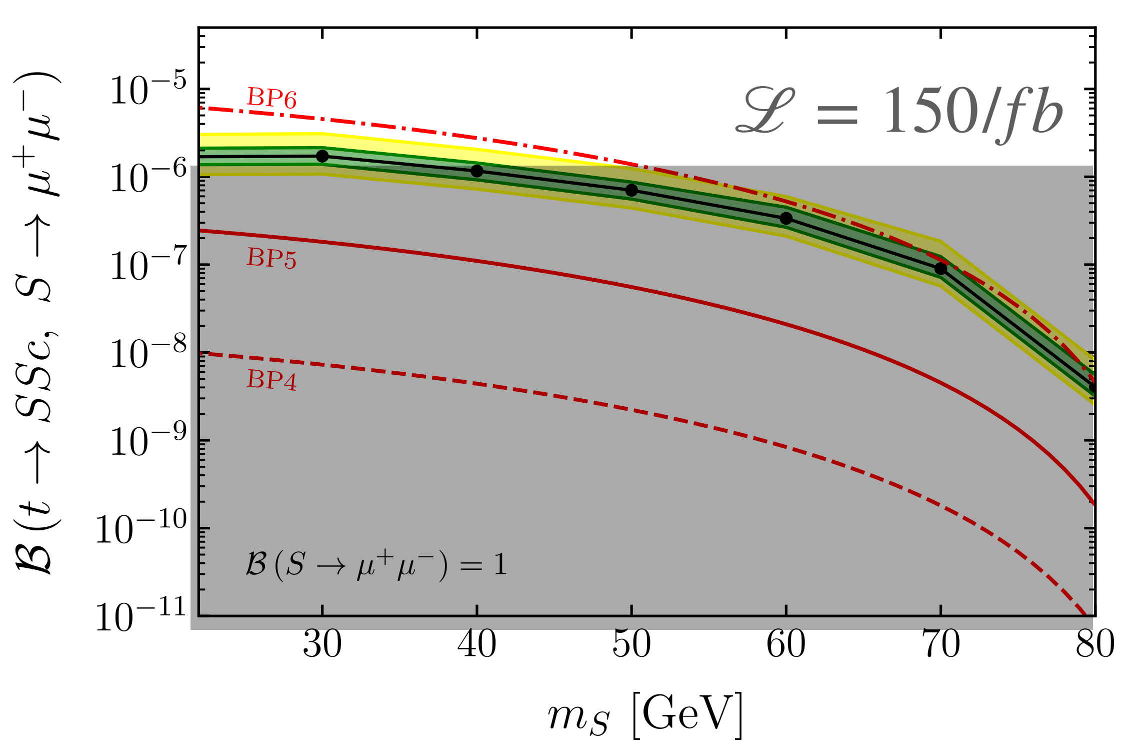


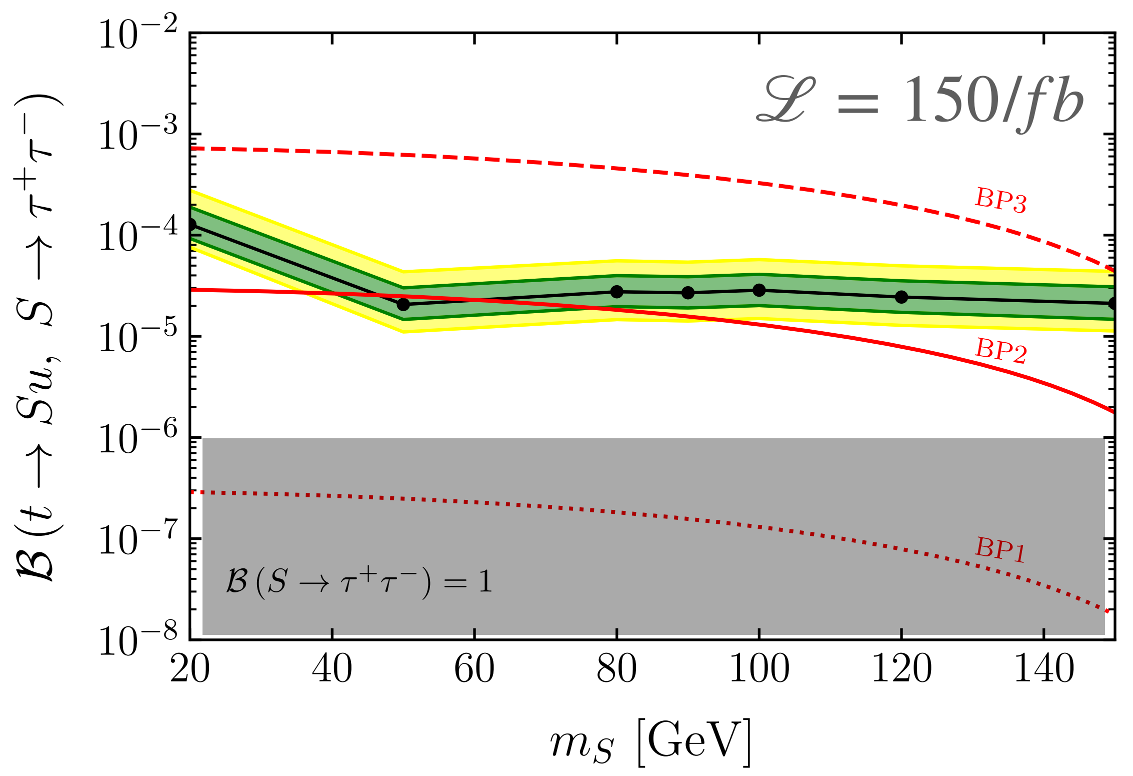


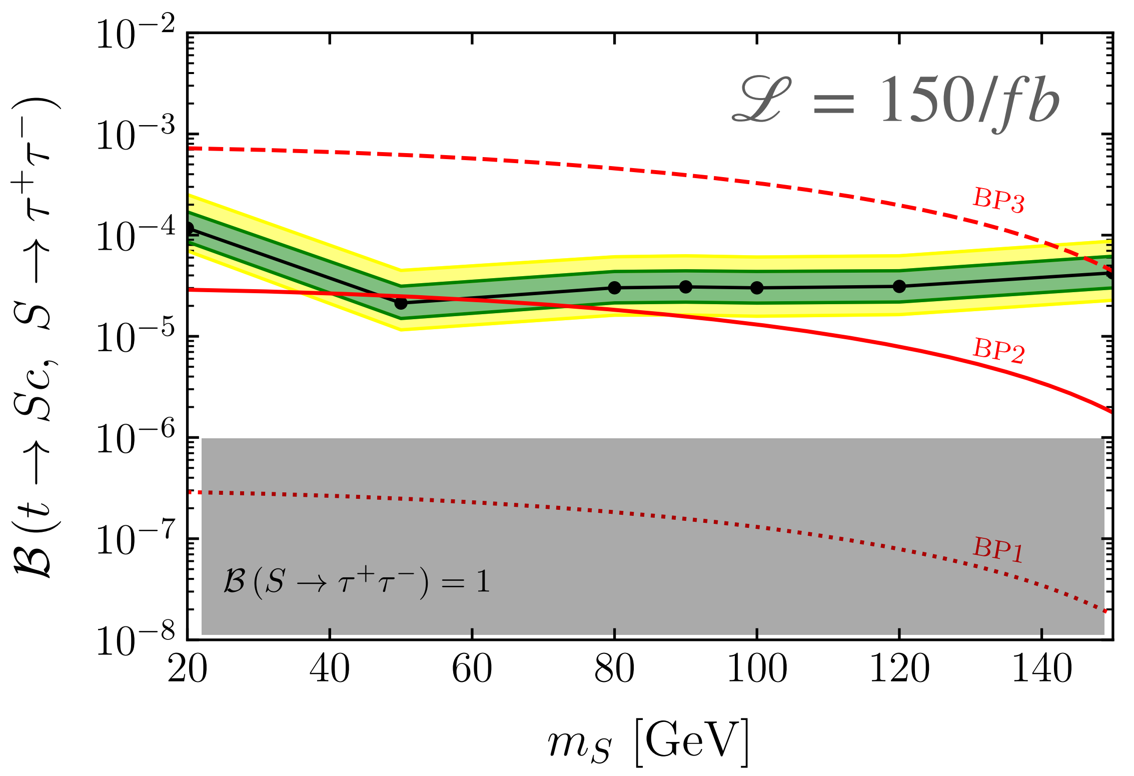












Run2 limits at 10^{-5} in $\tau\tau$, even stronger for $\mu\mu$. Little chance to improve at top factory even for $\tau\tau$

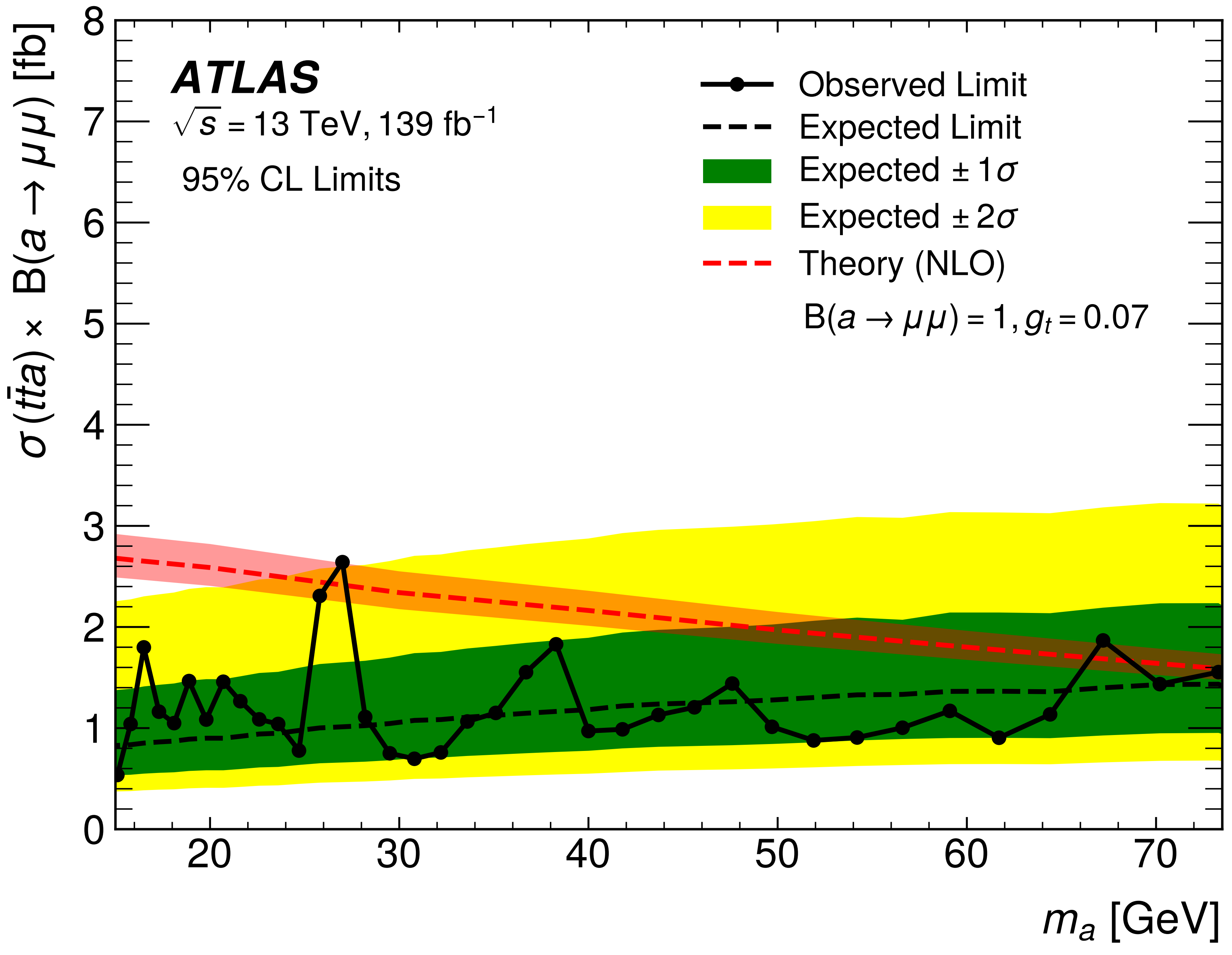
LHC

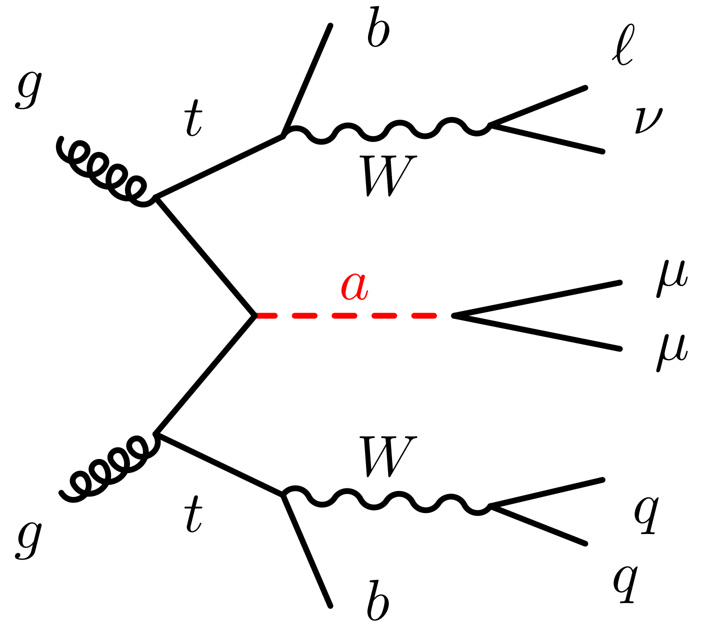
Associated productions

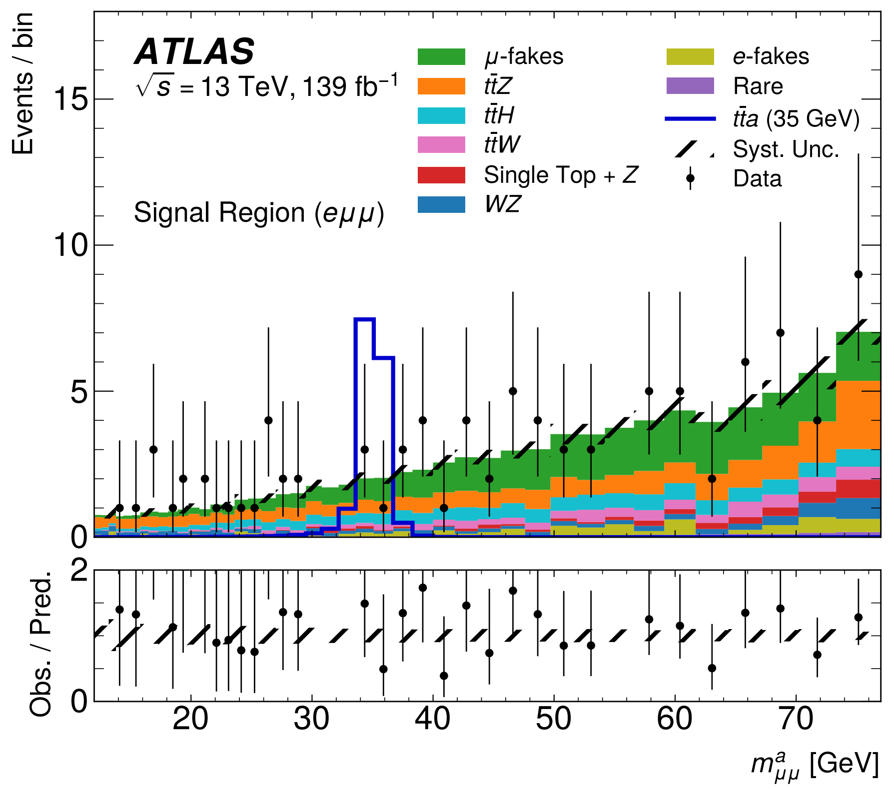
e^+e^- at $\sqrt{s} = 350, 365, 380$ GeV

Associated $tta, a \to \mu\mu$

2304.14247 - ATLAS







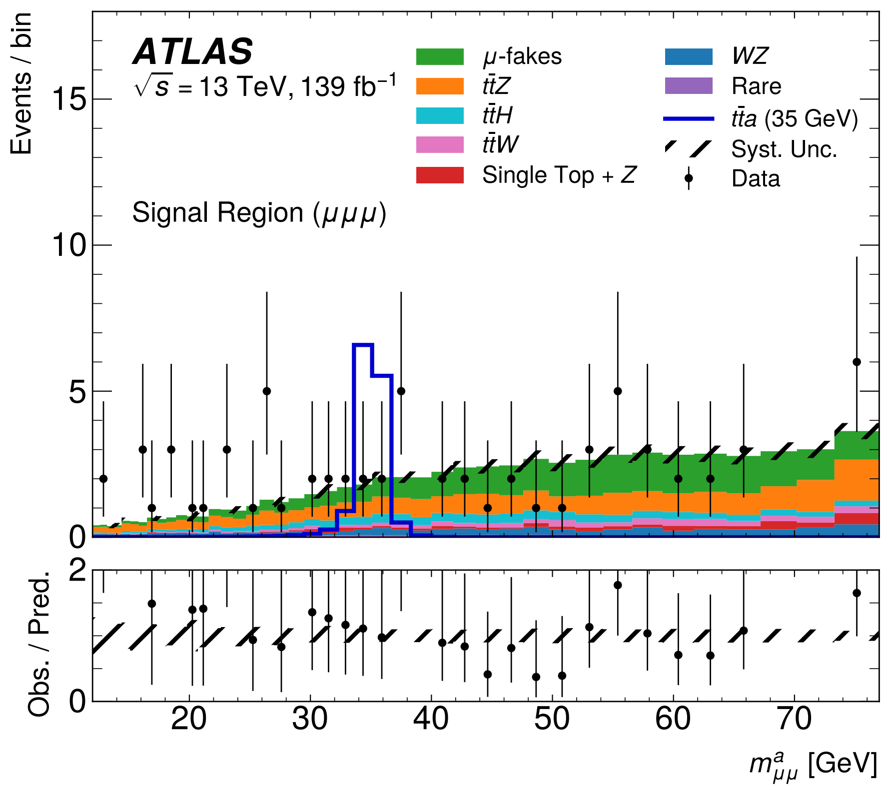


Table 2: Definition of the
mass requirements on m

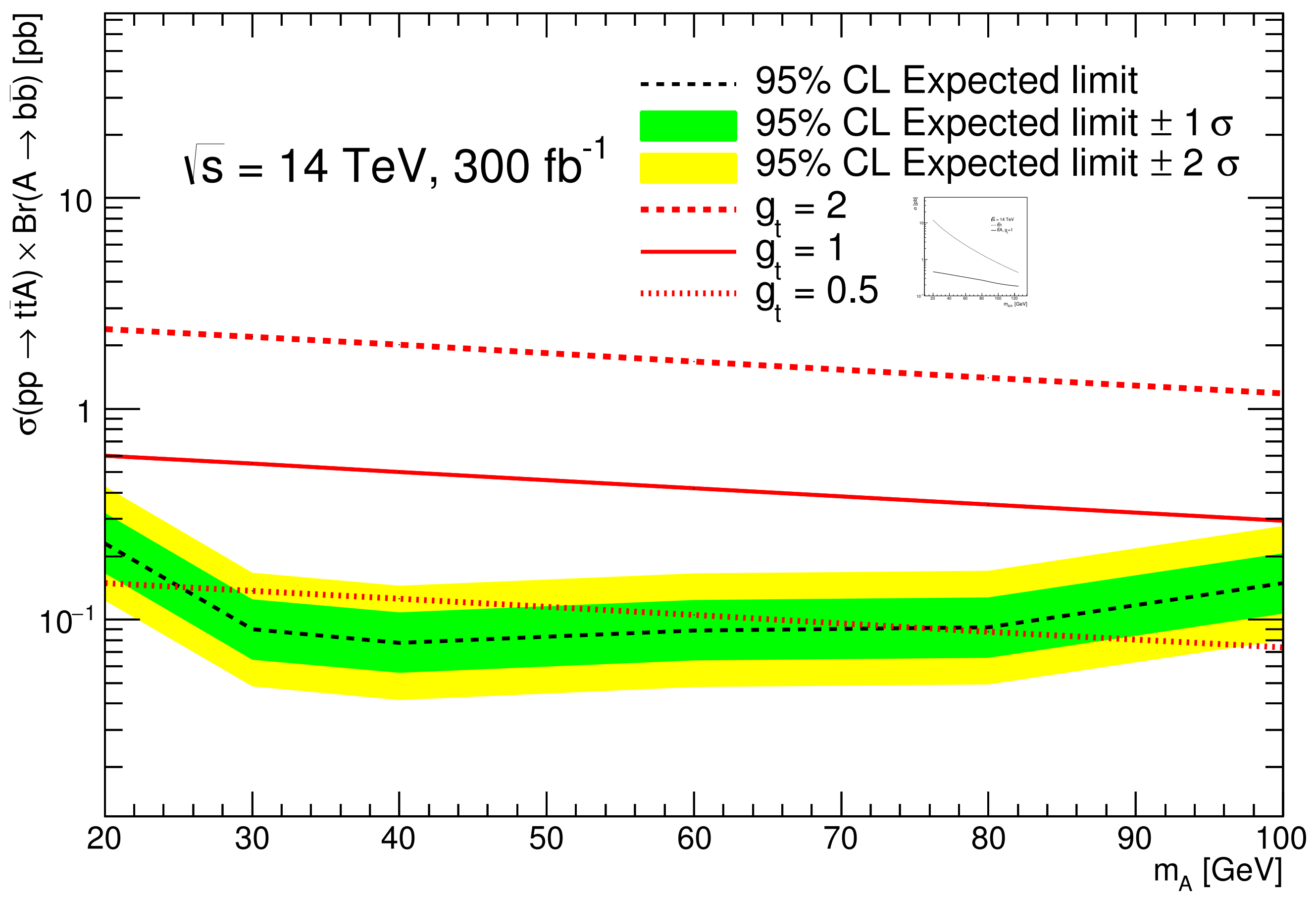
	Signal Regions		on-Z Control Region		$t\bar{t}$ Control Region
Channel	$e\mu\mu$	$\mu\mu\mu$	$e\mu\mu$	$\mu\mu\mu$	$e\mu\mu$
Binning	$m^a_{\mu\mu}$	$m^a_{\mu\mu}$	$n_{\text{jets}}, n_{b\text{-jets}}$	$n_{\text{jets}}, n_{b\text{-jets}}$	$p_T^{\mu,\text{fake}}$
$n_{\text{electrons}}$	1	0	1	0	1
n_{muons}	2	3	2	3	2
$m_{\mu\mu}$ [GeV]	$12 < m^a_{\mu\mu} < 77$	$12 < m^a_{\mu\mu} < 77$ and $m^{\text{other}}_{\mu\mu} < 77$ or > 107	$77 < m^a_{\mu\mu} < 107$	$77 < m^a_{\mu\mu} < 107$ or $77 < m^{\text{other}}_{\mu\mu} < 107$	$12 < m^a_{\mu\mu} < 77$
	-		-		-
n_{jets}	≥ 3				1 or 2
$n_{b\text{-jets}}$	≥ 1				1

so far limited to muon final states and moderate mass 12-77 GeV

ample room for improvement outside the probed mass range and in other a decay final states, e.g. hadrons

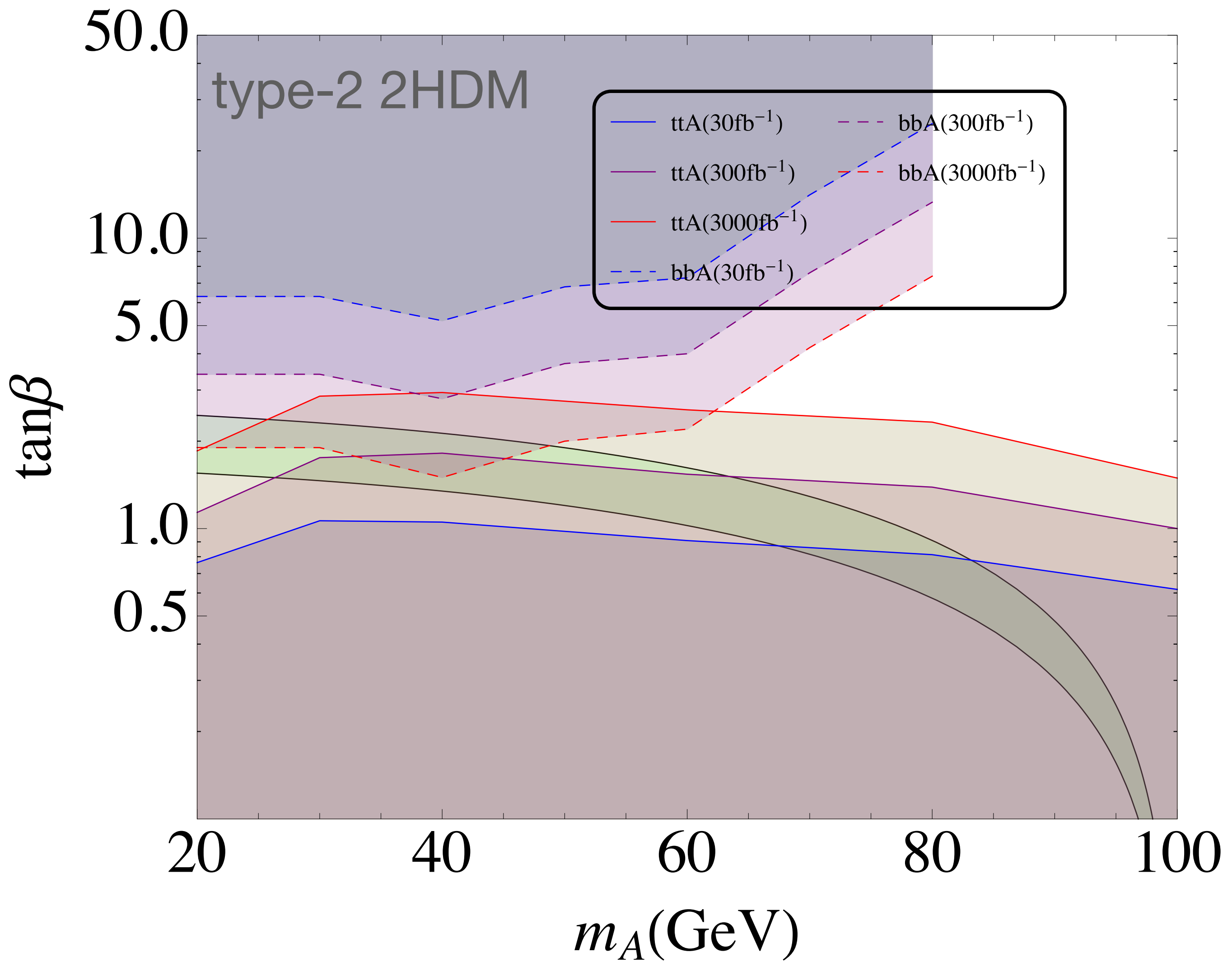
$tta, a \to bb$

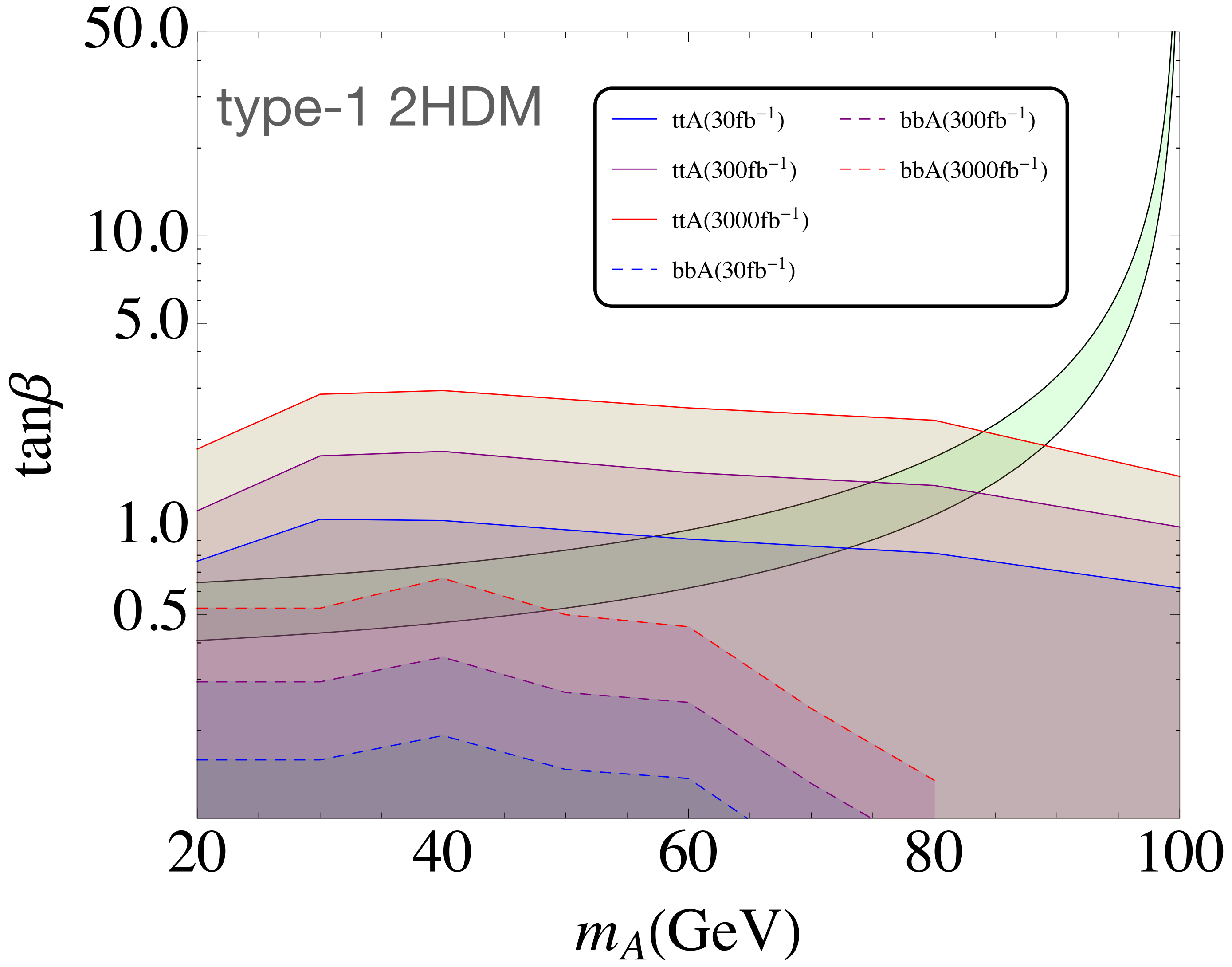
1507.07004 - Casolino, Farooque, Juste, Liu, Spannowsky



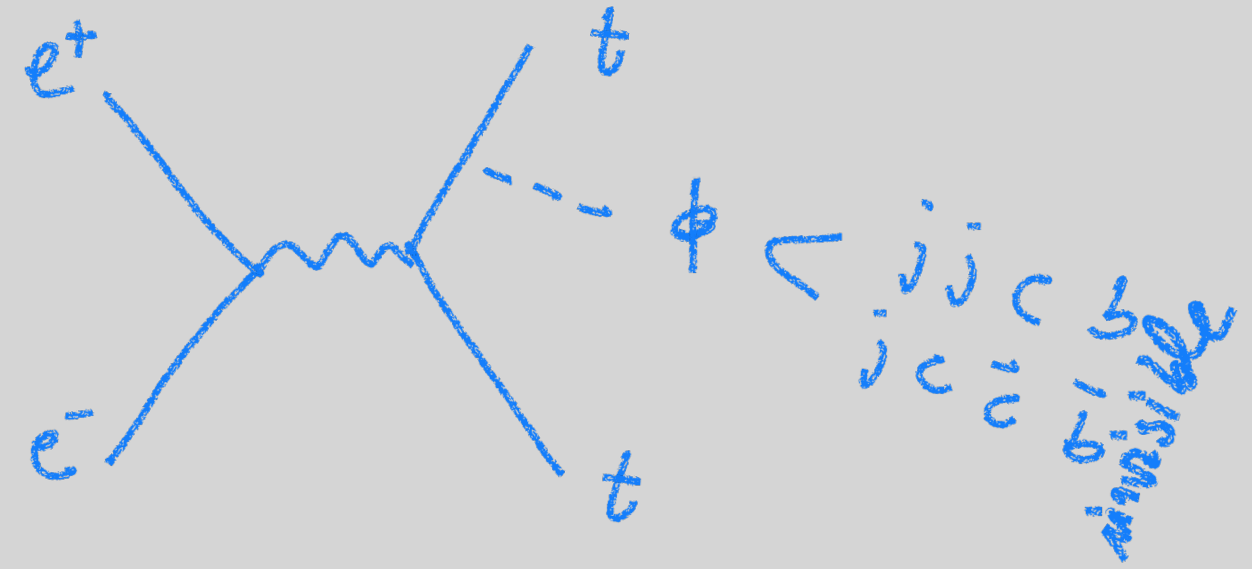
LHC bounds need to be interpreted

95 % CL limit on $\hat{g}_t$ assuming $BR(a \to bb) = 1$						
	m_A (GeV)					
$\mathcal{L}$ (fb^{-1})	20	30	40	60	80	100
1	2.73	2.14	2.18	2.48	2.82	3.65
30	1.31	0.94	0.95	1.10	1.23	1.62
100	1.06	0.72	0.71	0.83	0.93	1.25
300	0.88	0.57	0.55	0.65	0.72	1.00
3000	0.54	0.35	0.34	0.39	0.43	0.67





e^+e^- study missing



ample room for improvement outside the probed mass range and in other a decay final states, e.g. hadrons