Topportunities:
Rare top decays and interpretations

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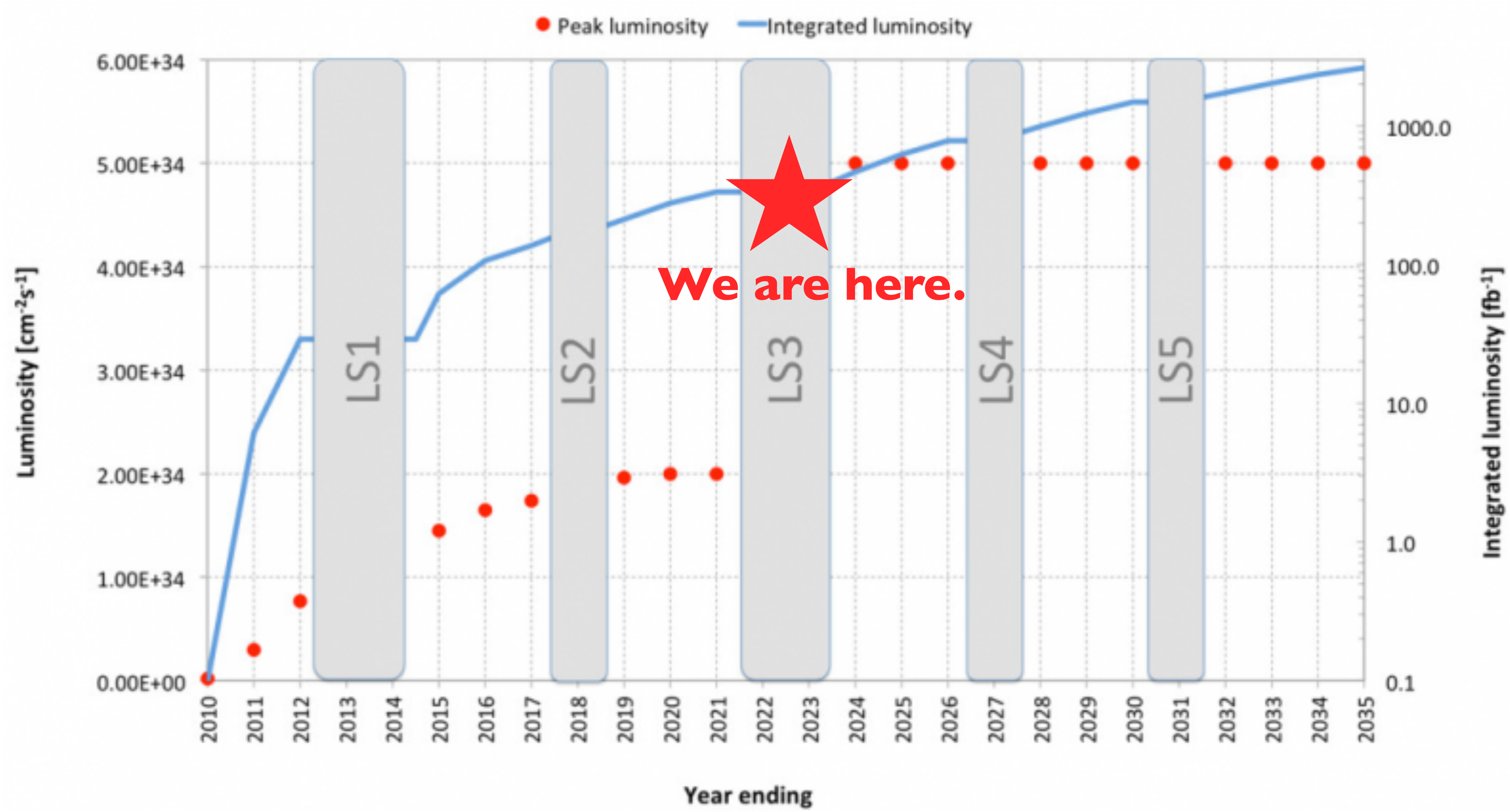
Based on H. Bahl, S. Koren, and LTW. 2307.11154

ECFA HTE Workshop. Sept 25, 2023

The focus of our paper

- HL-LHC.
- I will briefly comment on e^+e^-

Motivation



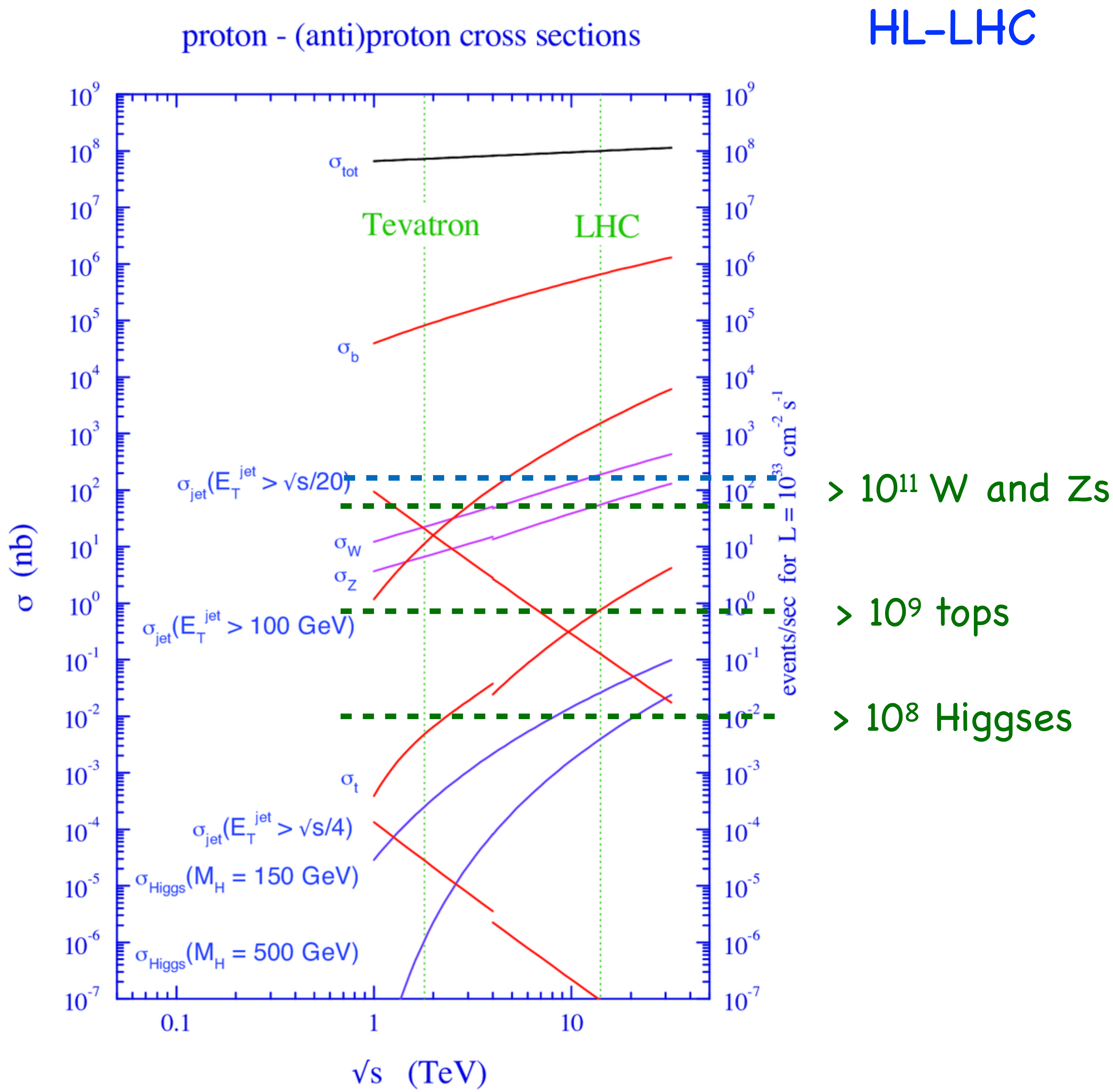
Still about 10 times amount of data to come.

Most immediate question:
How to fully realize the potential of the LHC?

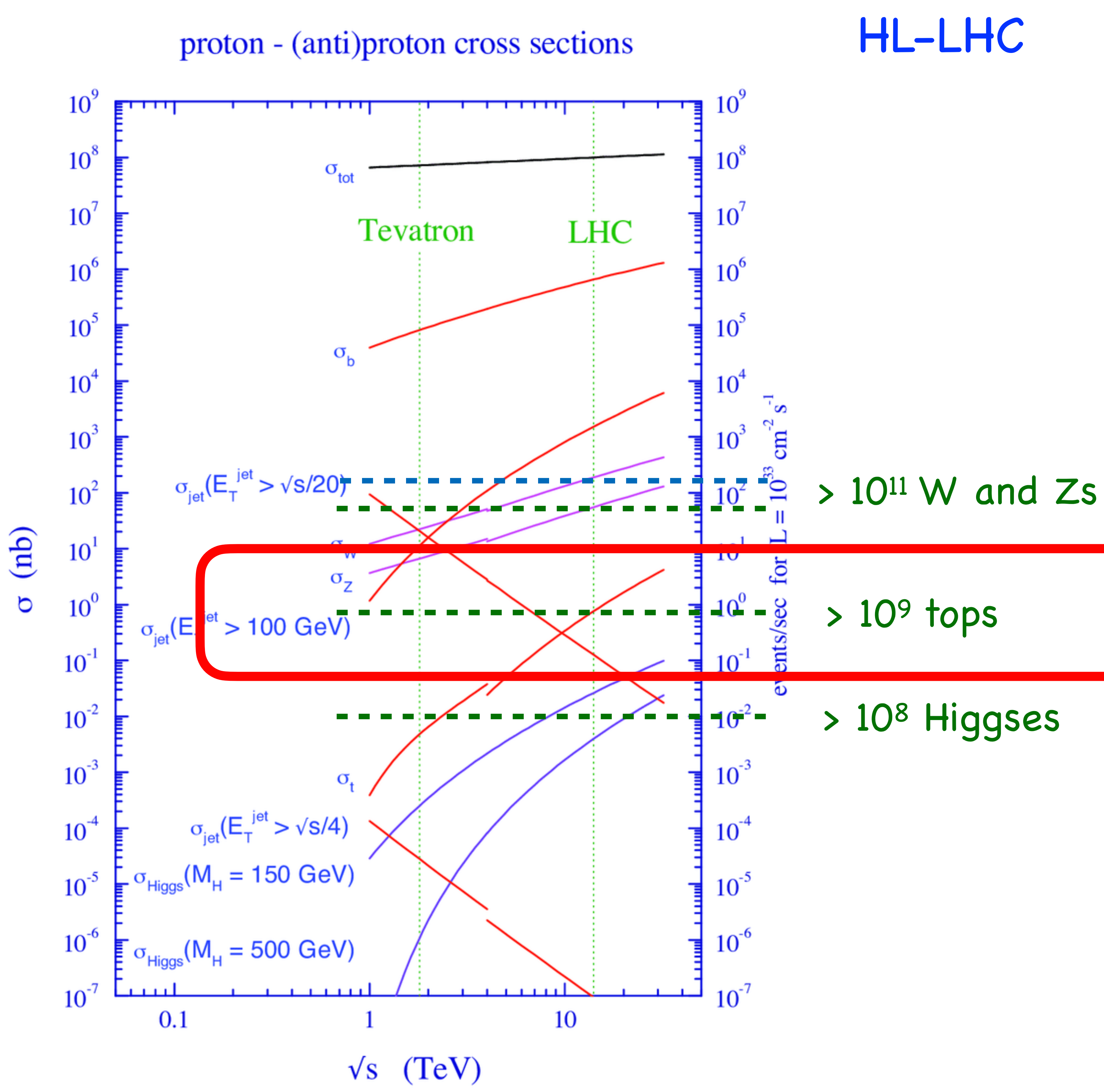
Rare processes

Unlikely, but seeing one can teach us a lot.

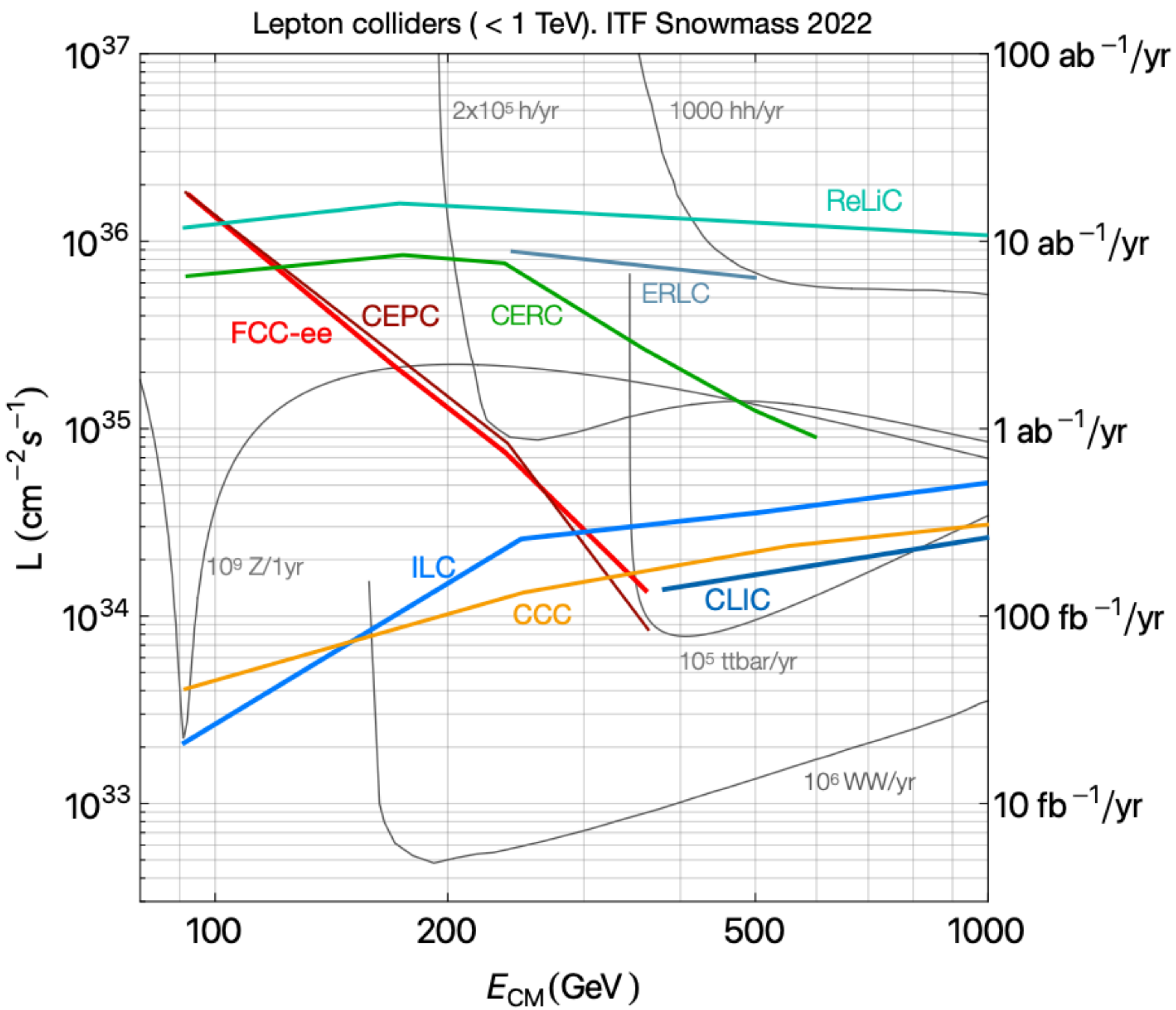
Particle factories



Particle factories



Top also a main output for e+e-



Main physics output:

10^6 Higgses

10^{12} Zs

10^6 WW

10^5 ttbar

Statistics = sensitivity to rare phenomena

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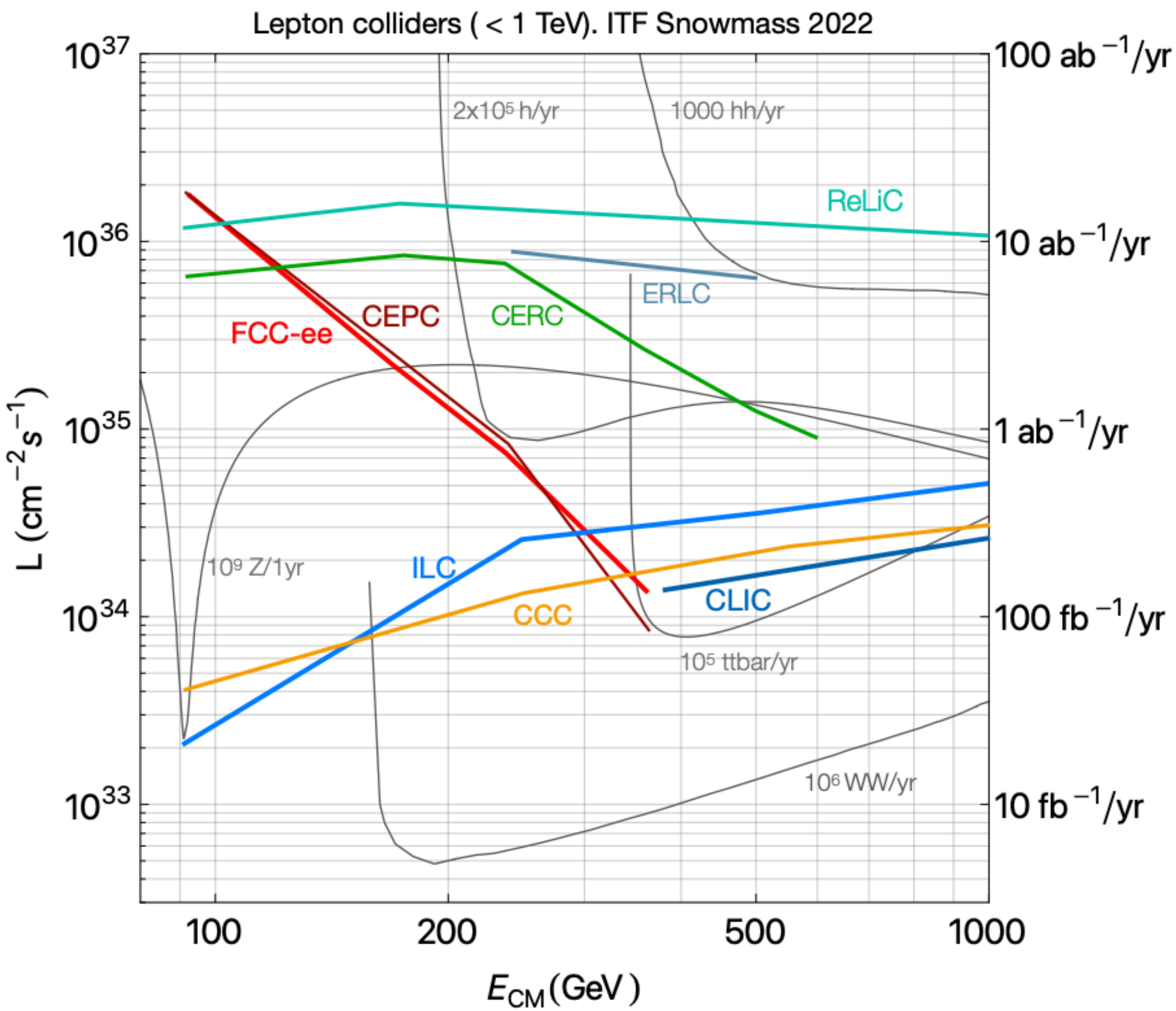

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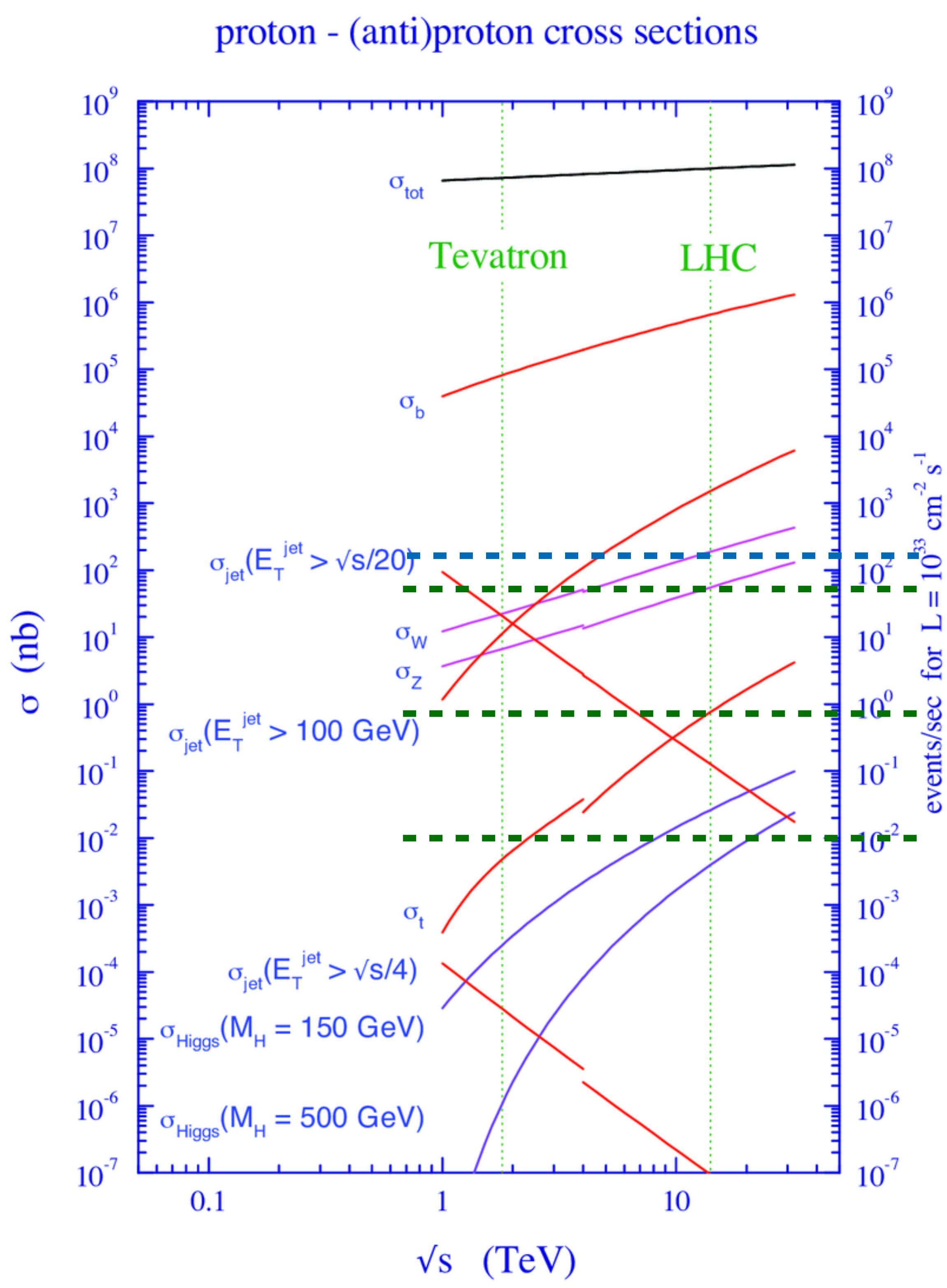
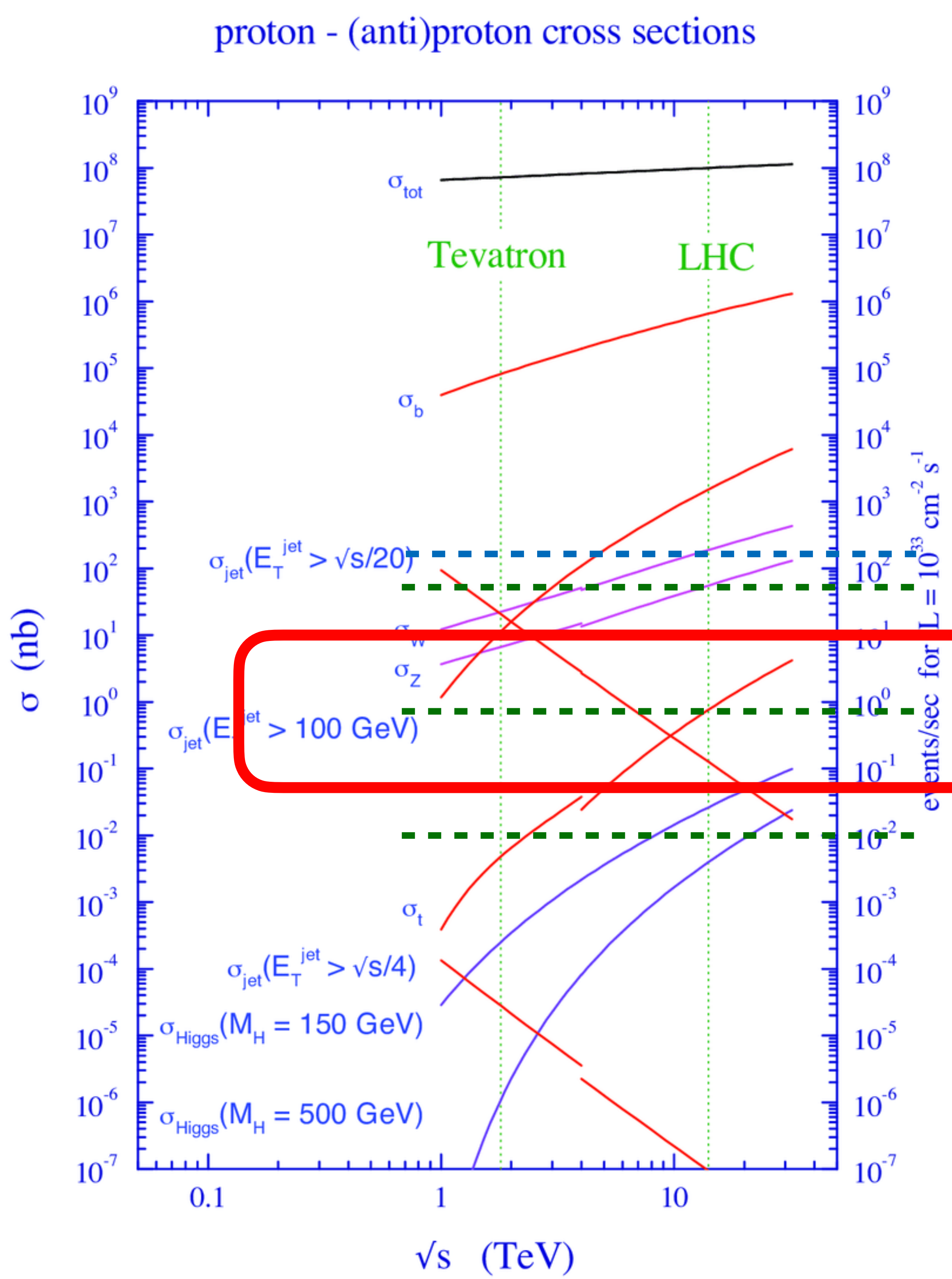


HL-LHC	e^+e^-
> 10^{11} W and Zs	10^8 W, 10^{12} Z
> 10^9 tops	10^5 tops
> 10^8 Higgses	10^6 Higgses

Particle factories



HL-LHC	e^+e^-
> 10^{11} W and Zs	10^8 W, 10^{12} Z
> 10^9 tops	10^5 tops
> 10^8 Higgses	10^6 Higgses

An EFT for top decays

SM dim 6	
$\mathcal{O}^6_{uqud}$	$(\bar{Q}_{Li}u_{Rj})\,(\bar{Q}_{Lk}d_{Rl})$
$\mathcal{O}^6_{qule}$	$(\bar{Q}_{Li}u_{Rj})\,(\bar{L}_{Lk}e_{Rl})$
$\mathcal{O}^6_{\Phi\Phi qu\Phi}$	$(\Phi^\dagger\Phi)(\bar{Q}_{Li}u_{Rj}\tilde{\Phi})$
$\mathcal{O}^6_{\Phi D\Phi qq}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{Q}_{Li}\gamma^\mu Q_{Lj})$
$\mathcal{O}^6_{qu\Phi G}$	$(\bar{Q}_{Li}\sigma^{\mu\nu}\tau^A u_{Rj})\widetilde{\Phi}G^A_{\mu\nu}$
$\mathcal{O}^6_{qu\Phi W}$	$(\bar{Q}_{Li}\sigma^{\mu\nu}\tau^I u_{Rj})\widetilde{\Phi}W^I_{\mu\nu}$
$\mathcal{O}^6_{qu\Phi B}$	$(\bar{Q}_{Li}\sigma^{\mu\nu}u_{Rj})\widetilde{\Phi}B_{\mu\nu}$

Φ : Higgs doublet

Q_L : 3rd gen doublet

BSM dim 5	
$\mathcal{O}^5_{SqDq}$	$S(\bar{Q}_{Li}\not{D}Q_{Lj})$
$\mathcal{O}^5_{SQu\Phi}$	$S(\bar{Q}_{Li}u_{Rj}\widetilde{\Phi})$
BSM dim 6	
$\mathcal{O}^6_{qdlN}$	$(\bar{Q}_{Li}d_{Rj})\,(\bar{L}_{Lk}N)$
$\mathcal{O}^6_{qulN}$	$(\bar{Q}_{Li}u_{Rj})\,(\bar{N}L_{Lk})$
$\mathcal{O}^6_{dueN}$	$(\bar{e}^c_{Rj}u_{Rj})\,(\bar{d}_{Rk}N)$
$\mathcal{O}^6_{qqNN}$	$(\bar{Q}_{Li}\gamma_\mu Q_{Lj})\,(\bar{N}\gamma^\mu N)$
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$\mathcal{O}^6_{SSqu\Phi}$	$S^2(\bar{Q}_{Li}u_{Rj}\widetilde{\Phi})$
$\mathcal{O}^6_{qu\Phi Z'}$	$(\bar{Q}_{Li}\sigma^{\mu\nu}u_{Rj})\widetilde{\Phi}F'_{\mu\nu}$

Light BSM singlets

S : scalar

N : Dirac fermion

Z', F' : $U(1)'$ gauge boson

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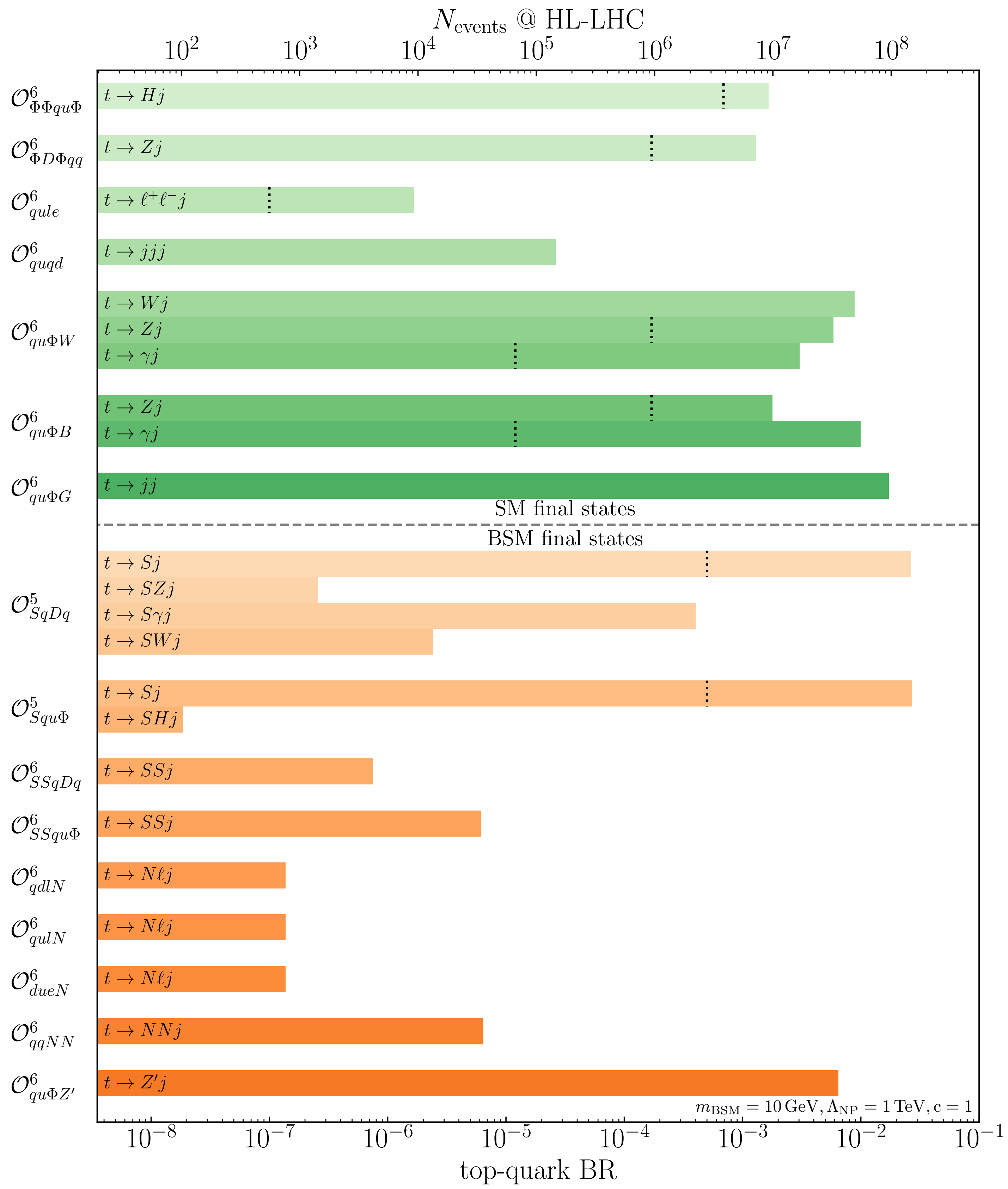
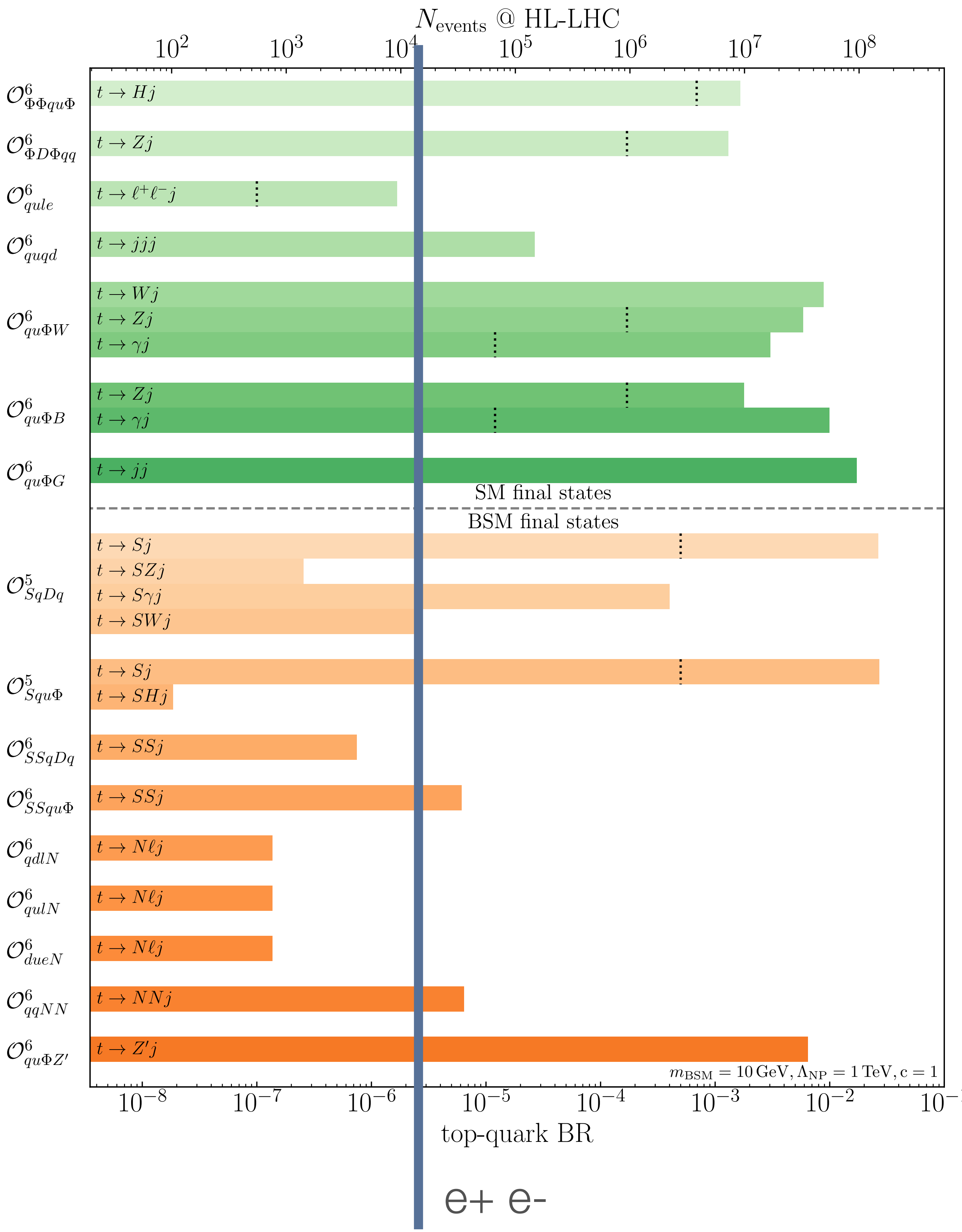
$\mathcal{O}^6_{qu\Phi Z'}$	$(\bar{Q}_{Li}\sigma^{\mu\nu}u_{Rj})\widetilde{\Phi}F'_{\mu\nu}$

These are generated by some unspecified heavy new physics with M_{NP}.
Stoped at dim-6 operators, with M_{NP} = 1 TeV, lead to interesting rates at HL-LHC
For dim-7 operators, M_{NP} would be too light, covered by direct searches.



N_{events} @ HL-LHC
10^2 10^3 10^4 10^5 10^6 10^7 10^8
$\mathcal{O}^6_{\Phi\Phi qu\Phi}$ $t \to Hj$
$\mathcal{O}^6_{\Phi D\Phi qq}$ $t \to Zj$
$\mathcal{O}^6_{qule}$ $t \to \ell^+\ell^- j$
$\mathcal{O}^6_{quqd}$ $t \to jjj$
$\mathcal{O}^6_{qu\Phi W}$ $t \to Wj$ $t \to Zj$ $t \to \gamma j$
$\mathcal{O}^6_{qu\Phi B}$ $t \to Zj$ $t \to \gamma j$
$\mathcal{O}^6_{qu\Phi G}$ $t \to jj$
SM final states
BSM final states
$\mathcal{O}^5_{SqDq}$ $t \to Sj$ $t \to SZj$ $t \to S\gamma j$ $t \to SWj$
$\mathcal{O}^5_{Squ\Phi}$ $t \to Sj$ $t \to SHj$
$\mathcal{O}^6_{SSqDq}$ $t \to SSj$
$\mathcal{O}^6_{SSqu\Phi}$ $t \to SSj$
$\mathcal{O}^6_{qdlN}$ $t \to N\ell j$
$\mathcal{O}^6_{qulN}$ $t \to N\ell j$
$\mathcal{O}^6_{dueN}$ $t \to N\ell j$
$\mathcal{O}^6_{qqNN}$ $t \to NNj$
$\mathcal{O}^6_{qu\Phi Z'}$ $t \to Z'j$
$m_{\text{BSM}} = 10\,\text{GeV}, \Lambda_{\text{NP}} = 1\,\text{TeV}, c = 1$
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
top-quark BR

Set M_{NP} = 1 TeV



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e+ e-

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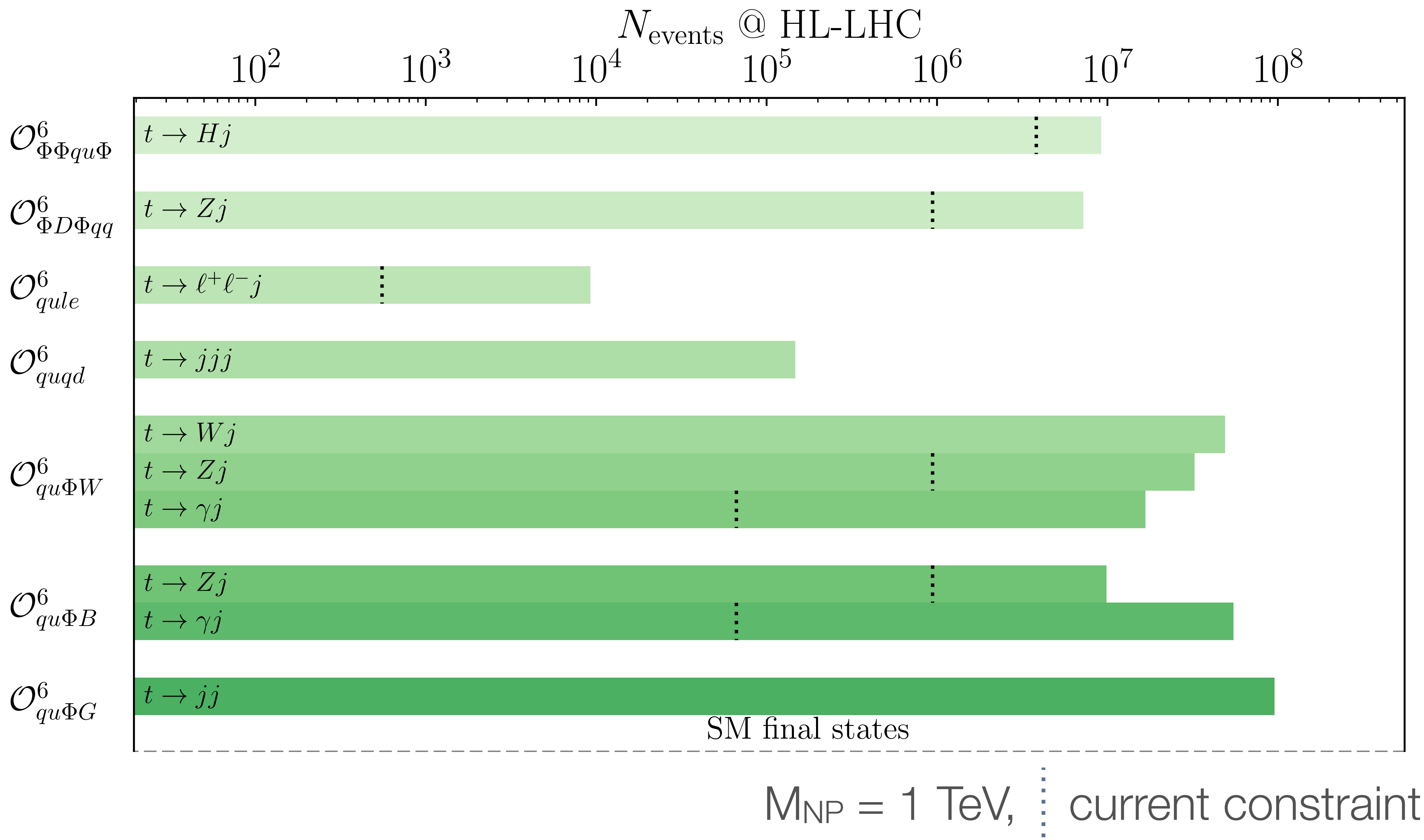
SM final state



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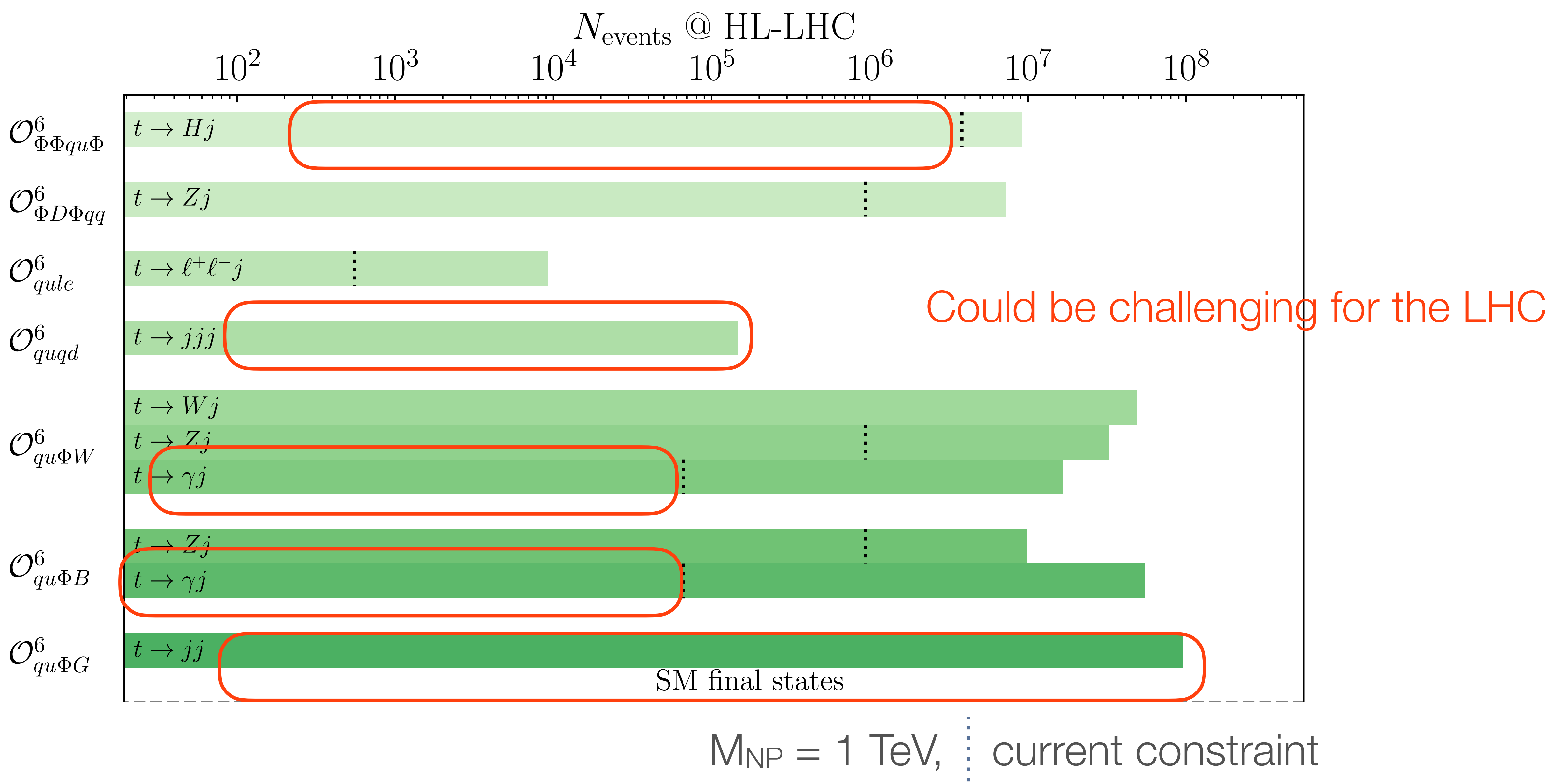

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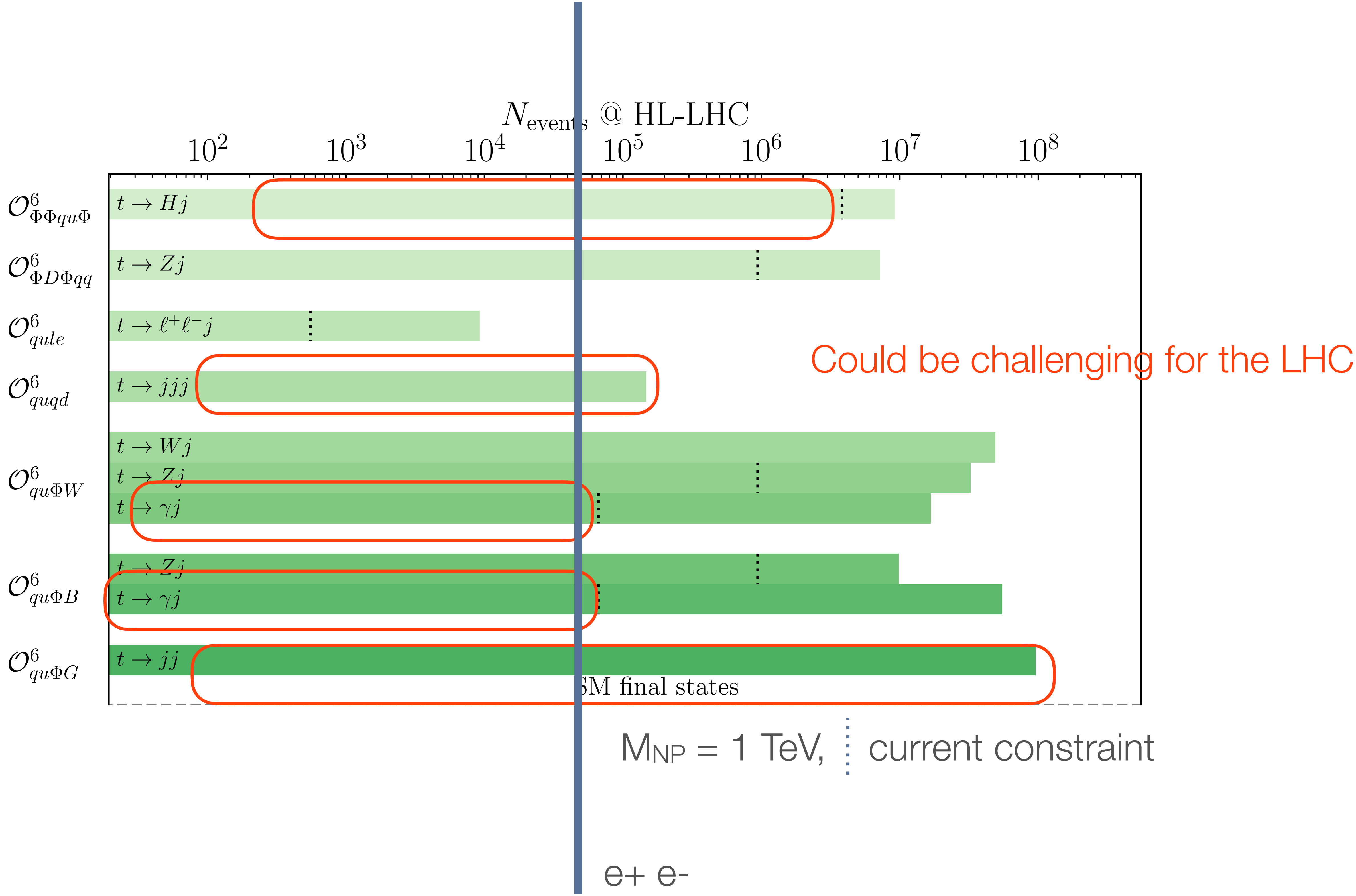
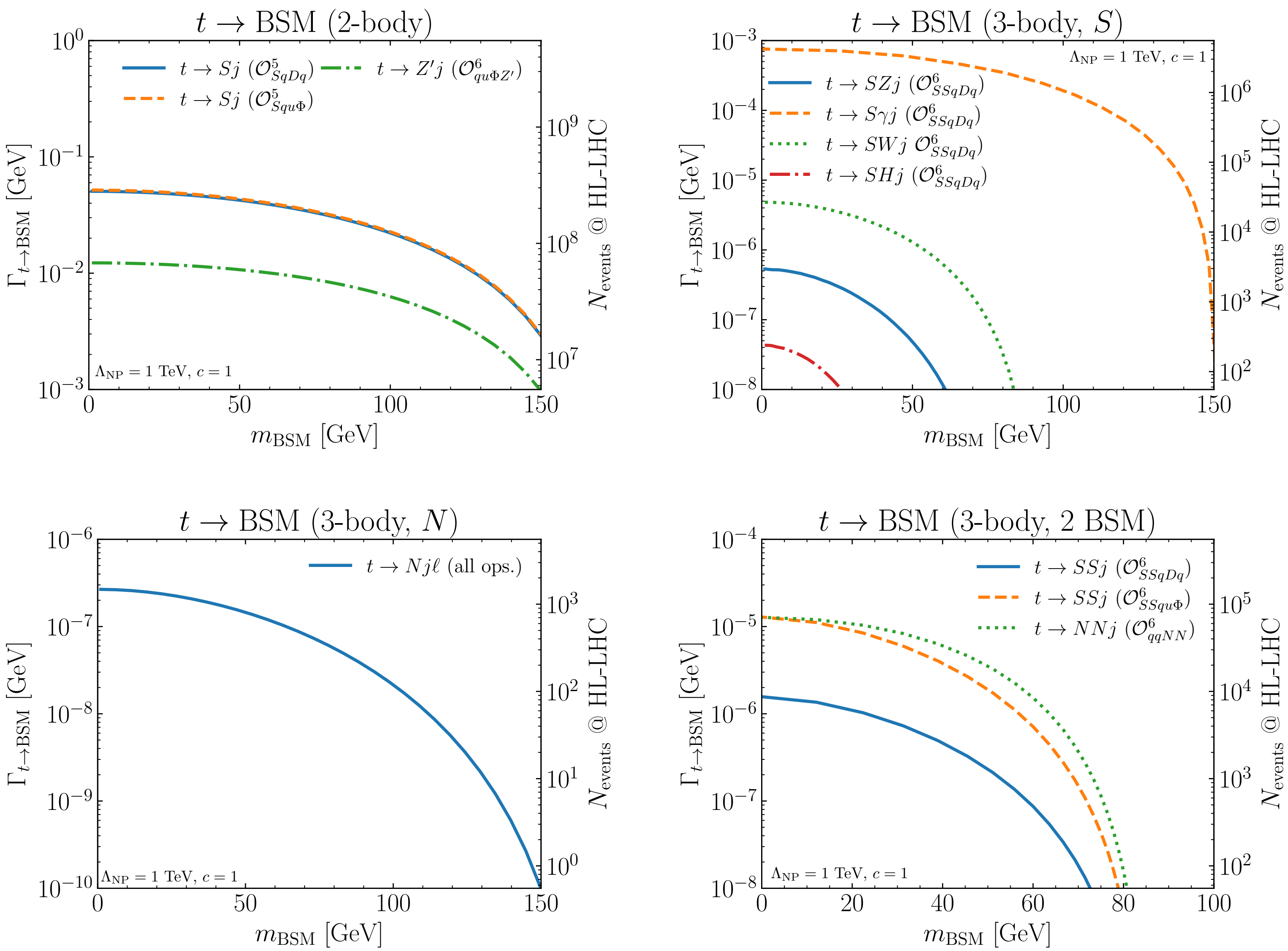


BSM decays.



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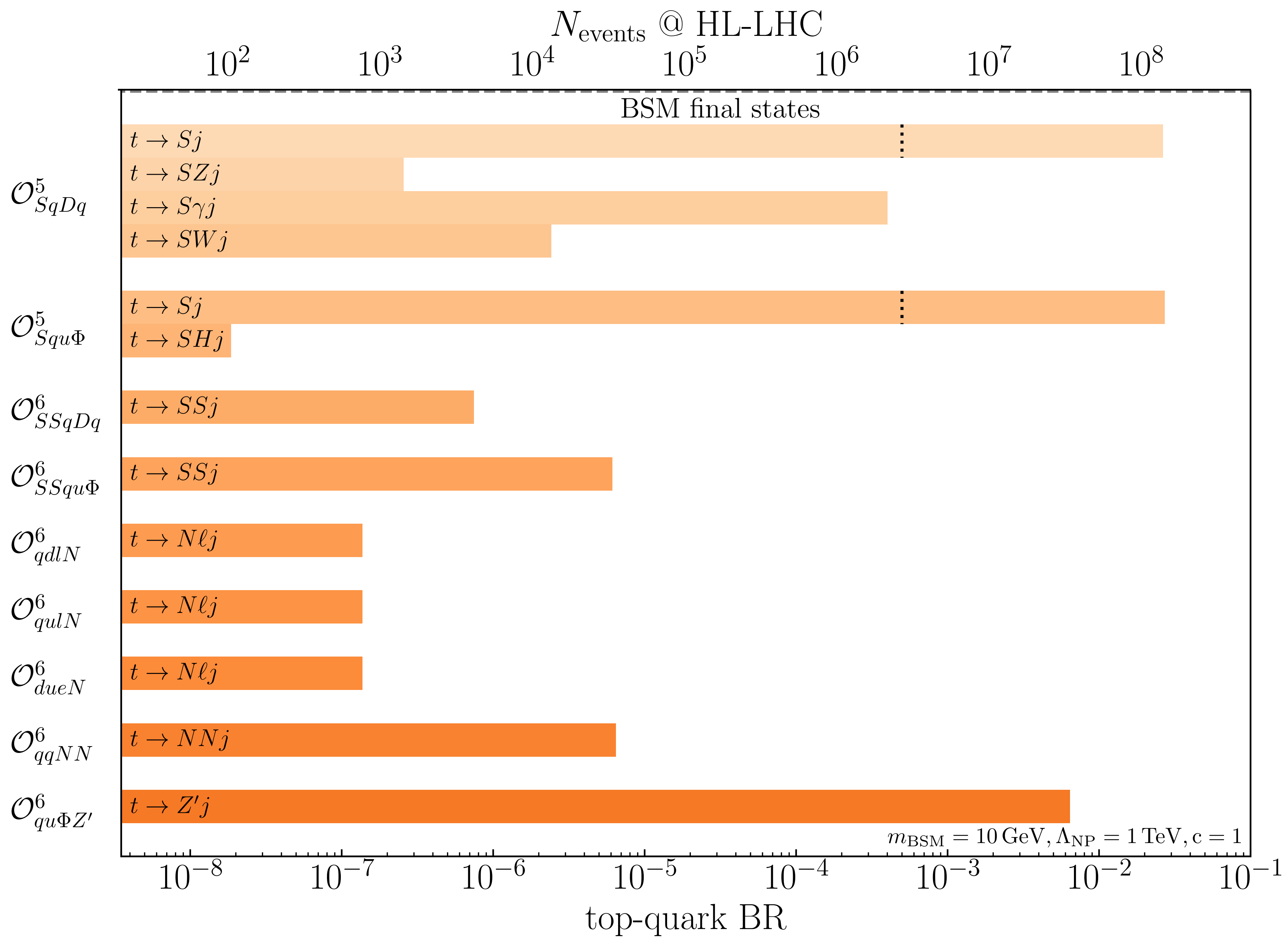
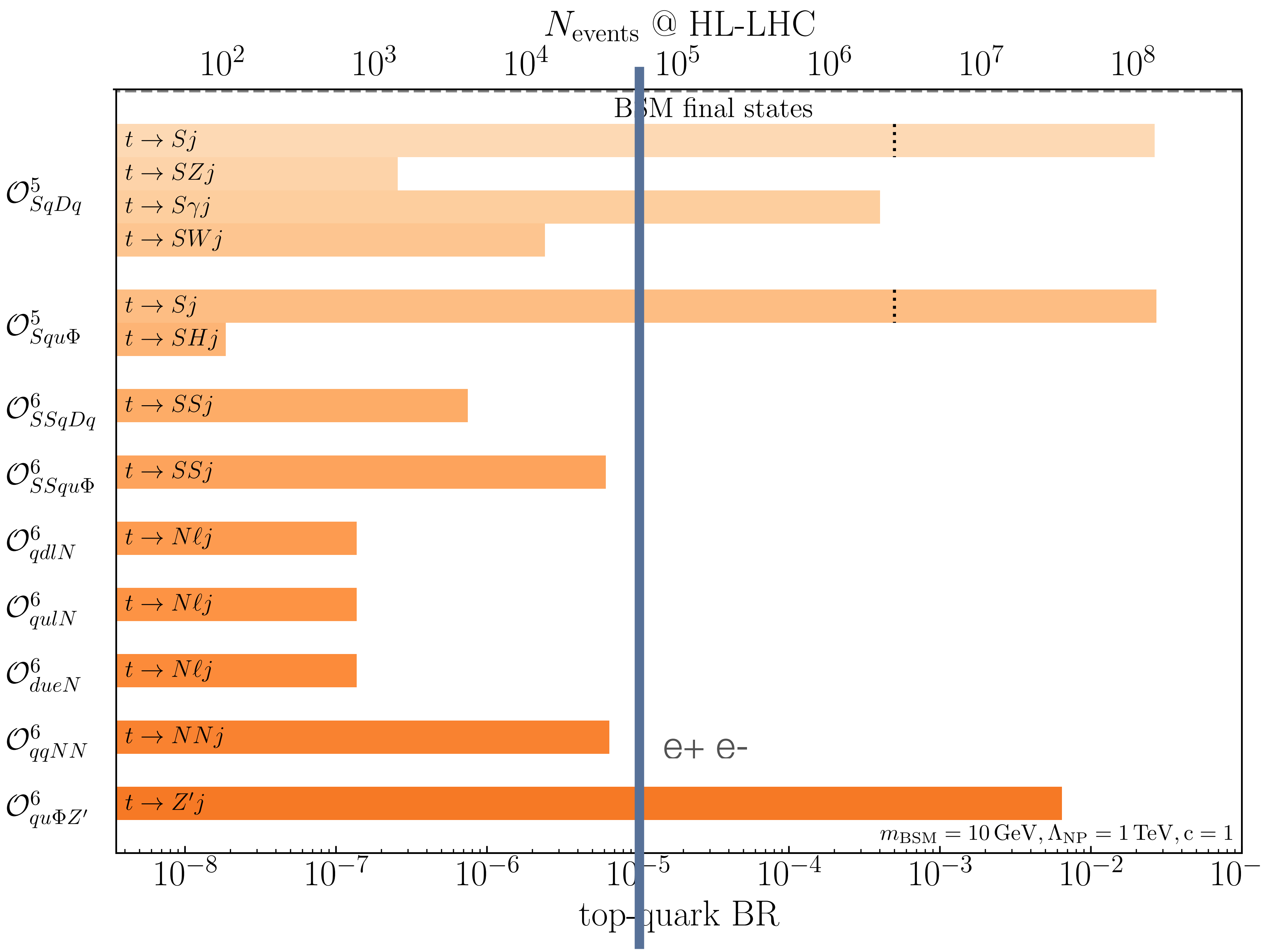
BSM final state



Signal depends on how the BSM states decays

BSM final state



Signal depends on how the BSM states decays

Possibility 1: NP stable

For example:

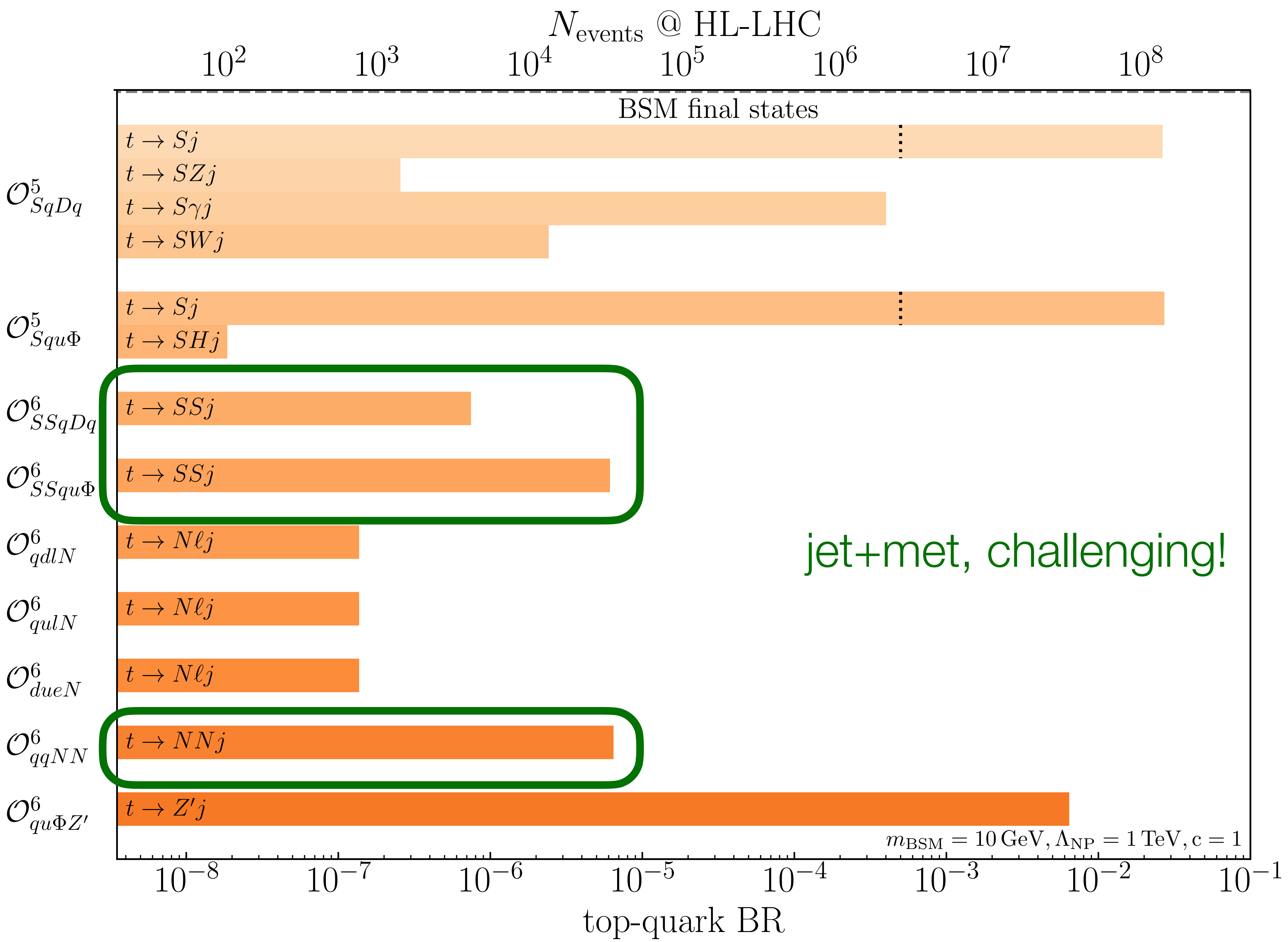
If the top decay is through operators:

$\mathcal{O}^6_{qqNN}$	$\left(\bar{Q}_{Li}\gamma_\mu Q_{Lj}\right)\left(\bar{N}\gamma^\mu N\right)$
$\mathcal{O}^6_{SSqDq}$	$S^2(\bar{Q}_{Li}\not{D}Q_{Lj})$
$\mathcal{O}^6_{SSqu\Phi}$	$S^2(\bar{Q}_{Li}u_{Rj}\widetilde{\Phi})$

It is consistent for the NP to have a Z_2 symmetry, hence stable.

Leads to missing energy.

MET



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$t \to N\ell j$
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$t \to N\ell j$
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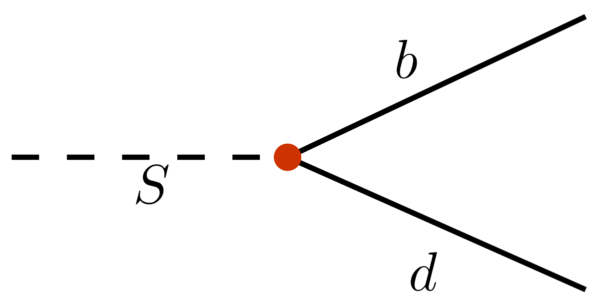
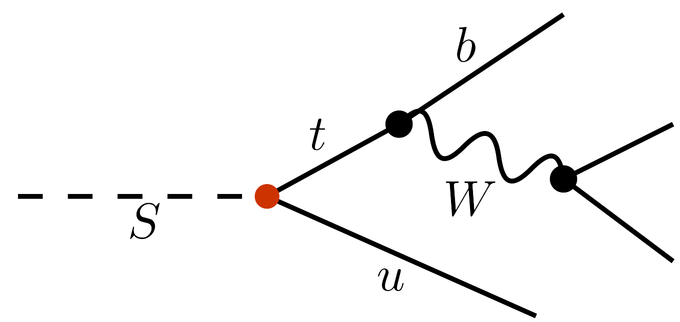
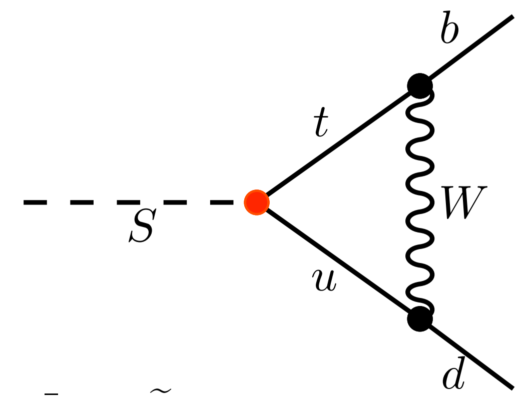
jet+met, challenging!
$m_{\text{BSM}} = 10\,\text{GeV}, \Lambda_{\text{NP}} = 1\,\text{TeV}, \text{c} = 1$
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
top-quark BR

NP (scalar singlet) decay







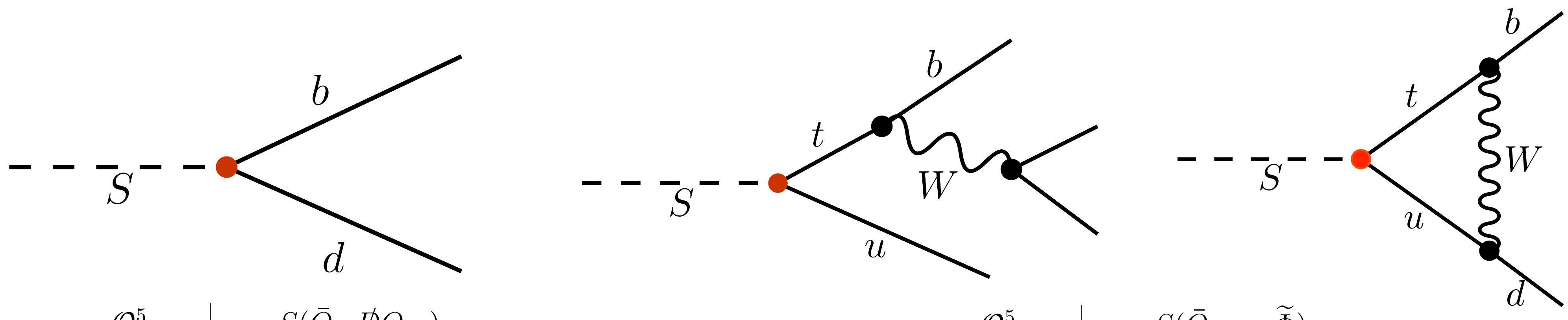
$\mathcal{O}^5_{SqDq}$ | $S(\bar{Q}_{Li} \not{D} Q_{Lj})$

$\mathcal{O}^5_{SQu\Phi}$ | $S(\bar{Q}_{Li} u_{Rj} \widetilde{\Phi})$

Minimal width

The operator mediate top decay also contribute to singlet decay

NP (scalar singlet) decay



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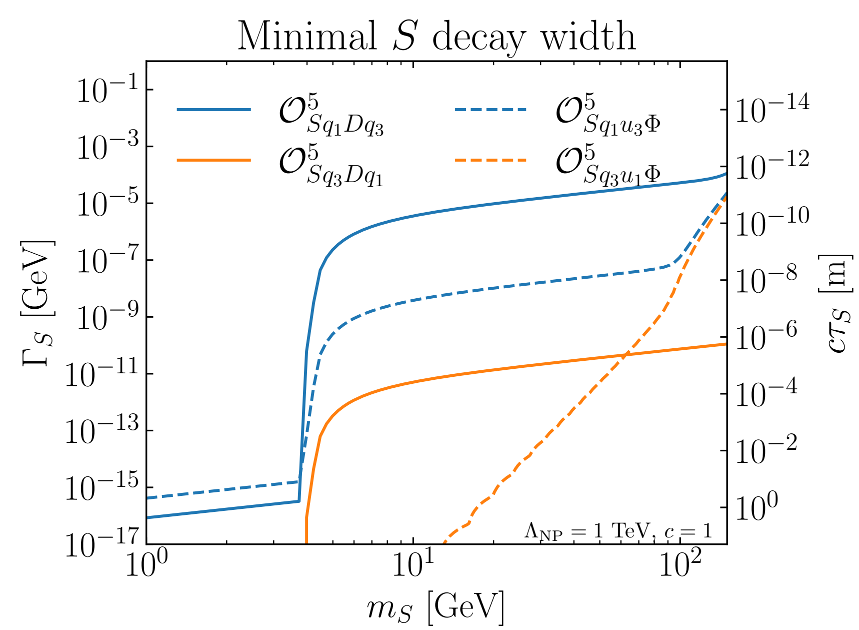
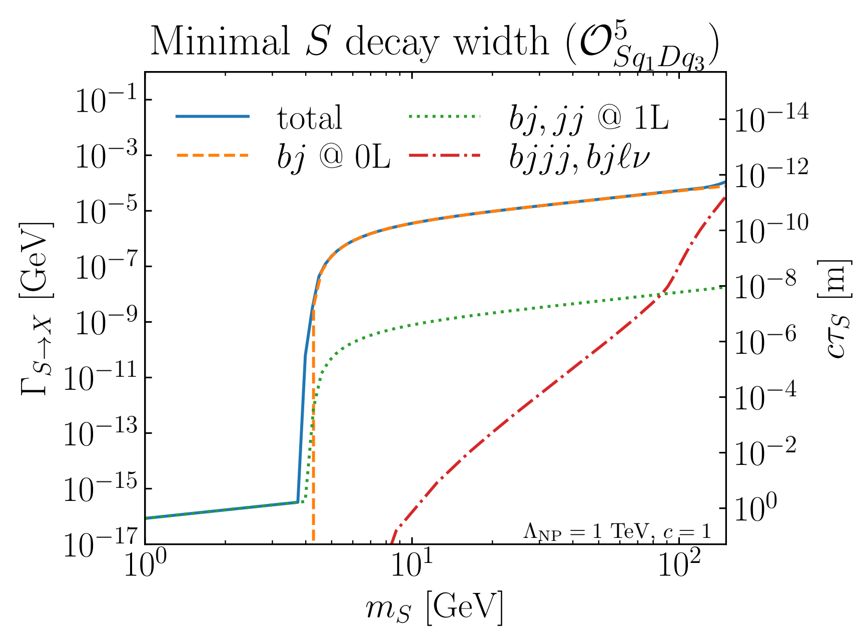
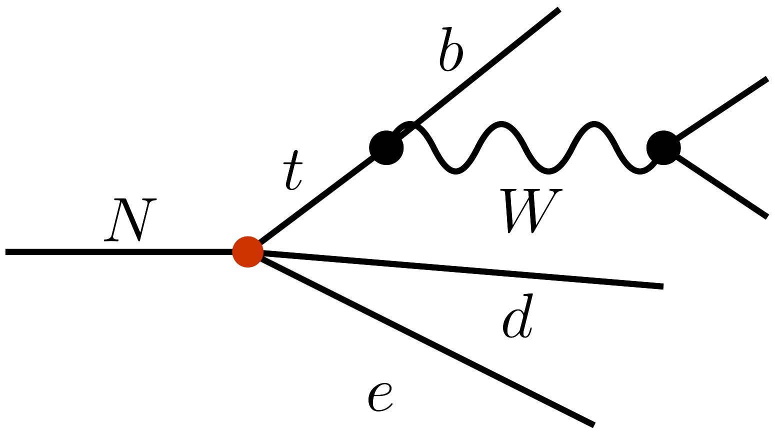
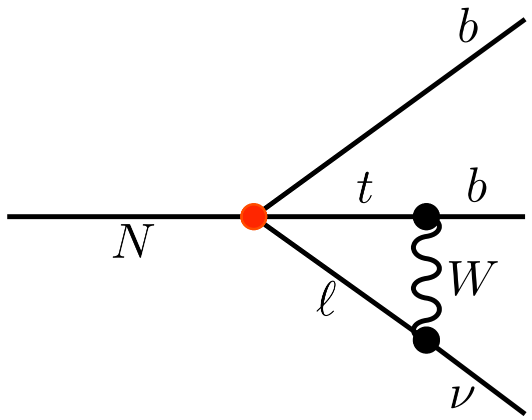


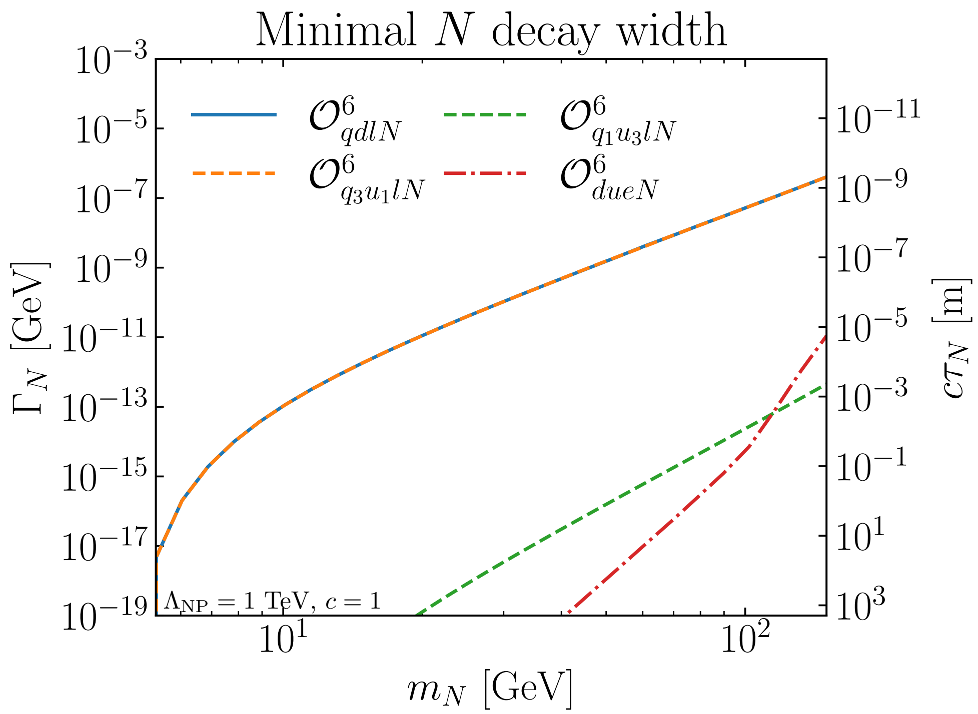


Loop with 1st generation suffer from further helicity suppression.

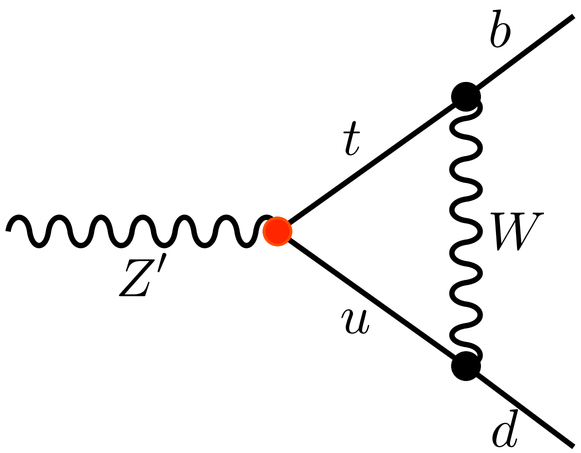
Dirac fermion singlet

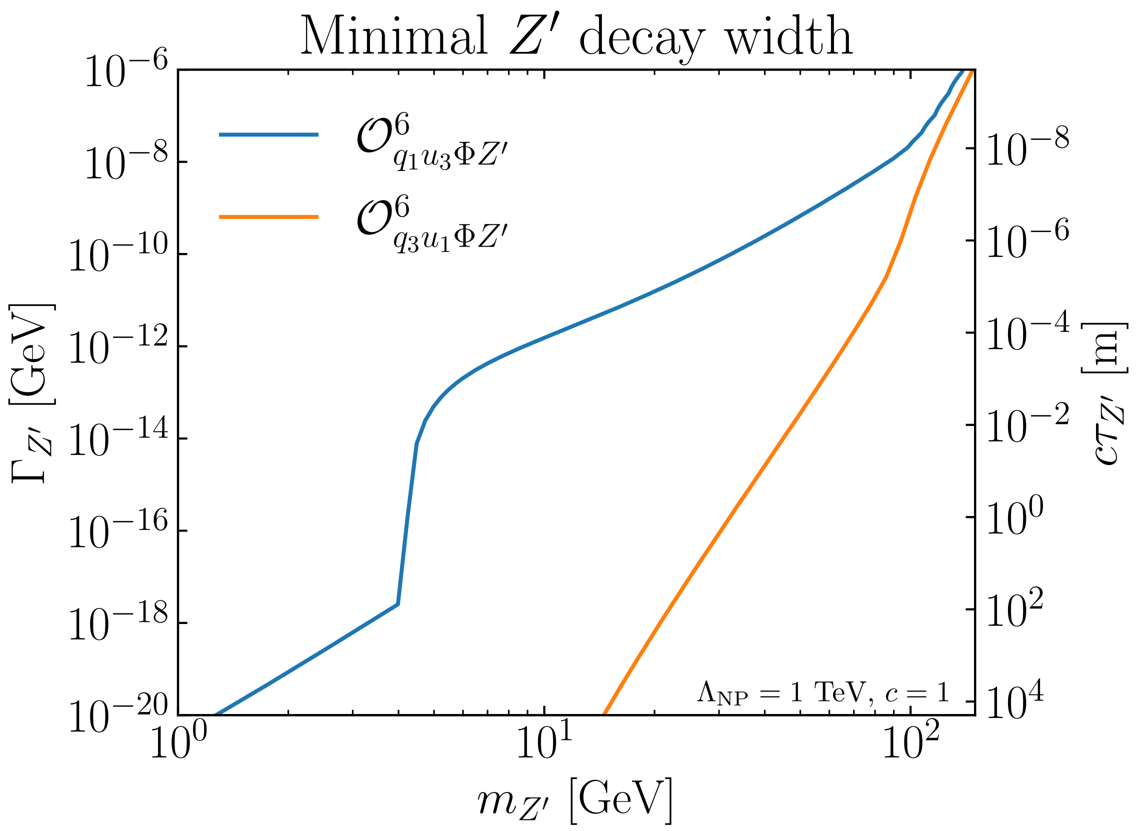






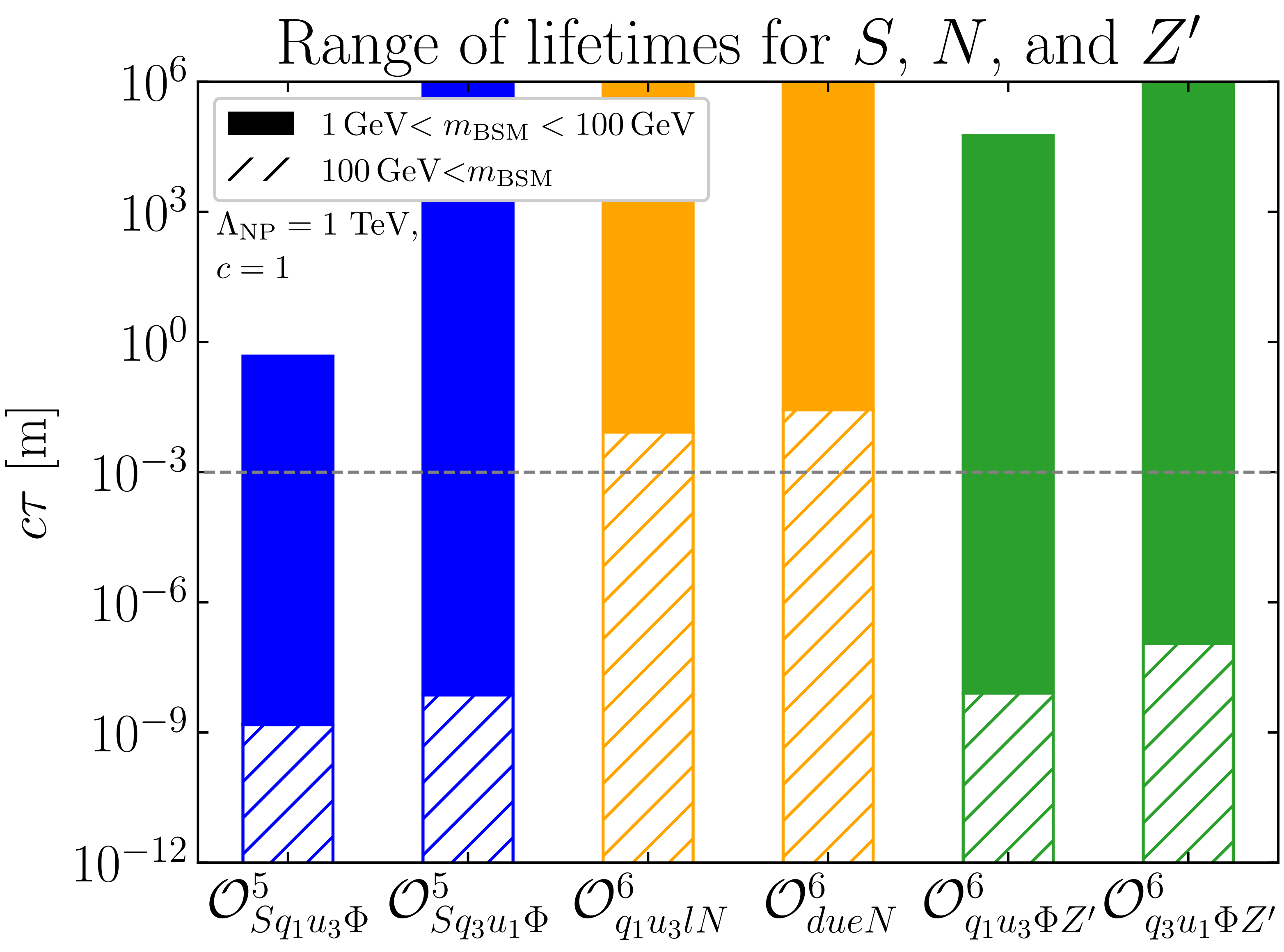
U(1)’ decay



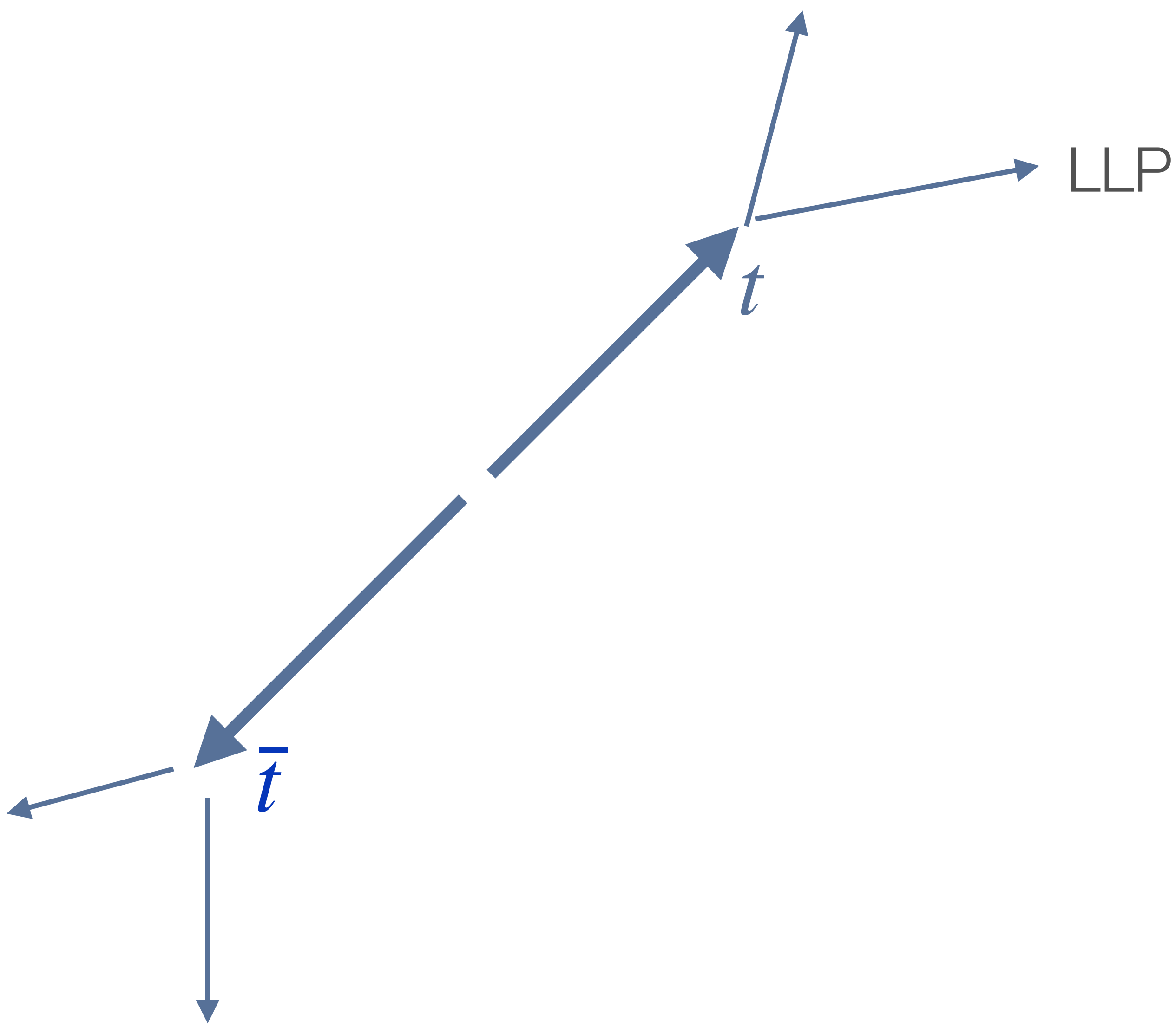


Loop with 1st generation suffer from further helicity suppression.

Long lived particles



LLP searches in ttbar



The rest of the event = “free” trigger.

Unlike higgs→ LLP, or disappearing track, need another radiation to trigger

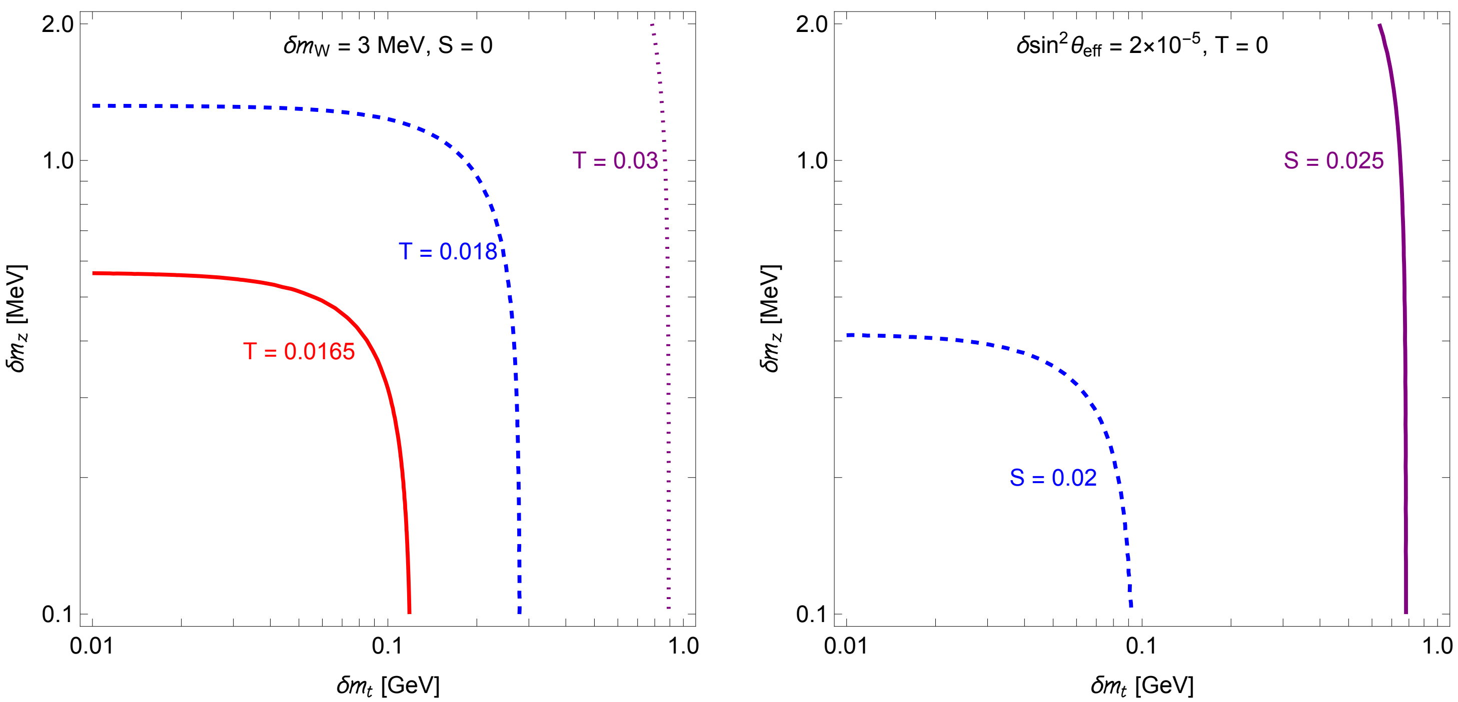
Conclusions

- HL-LHC is a top factory.
  - Great opportunity to go after top rare decays.
- Rich SM final states.
- NP final states, new opportunity for LLP searches.
- e+e- can be complementary in some channels.

Why 350?

Gains from run at ttbar

- Top mass a key input for electroweak precision.



Parameter	Current	CEPC baseline	Improved m_t
S	3.4×10^{-2}	8.1×10^{-3}	6.6×10^{-3}
T	2.8×10^{-2}	9.2×10^{-3}	6.5×10^{-3}

Beyond top mass

$$\mathcal{O}_{Hq}^{(1)} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu q_L),$$

$$\mathcal{O}_{Hq}^{(3)} = \frac{i}{\Lambda^2}(H^\dagger \tau^I \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu \tau^I q_L)$$

$$\mathcal{O}_{Ht} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R \gamma^\mu t_R),$$

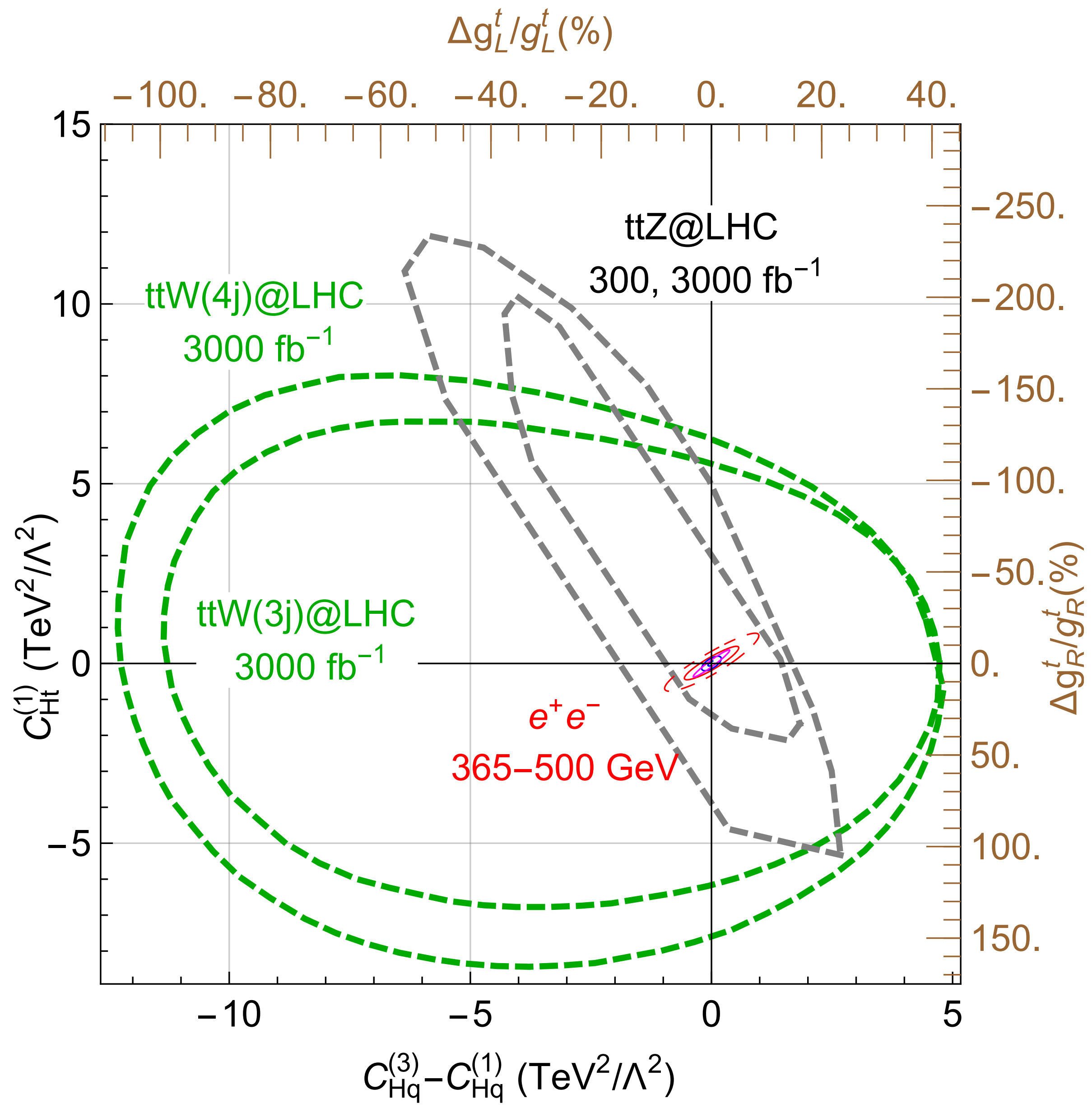
$$\mathcal{O}_{Hb} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{b}_R \gamma^\mu b_R),$$

Modifies Vqq couplings

Also qqVh, little impact on Higgs coupling fits

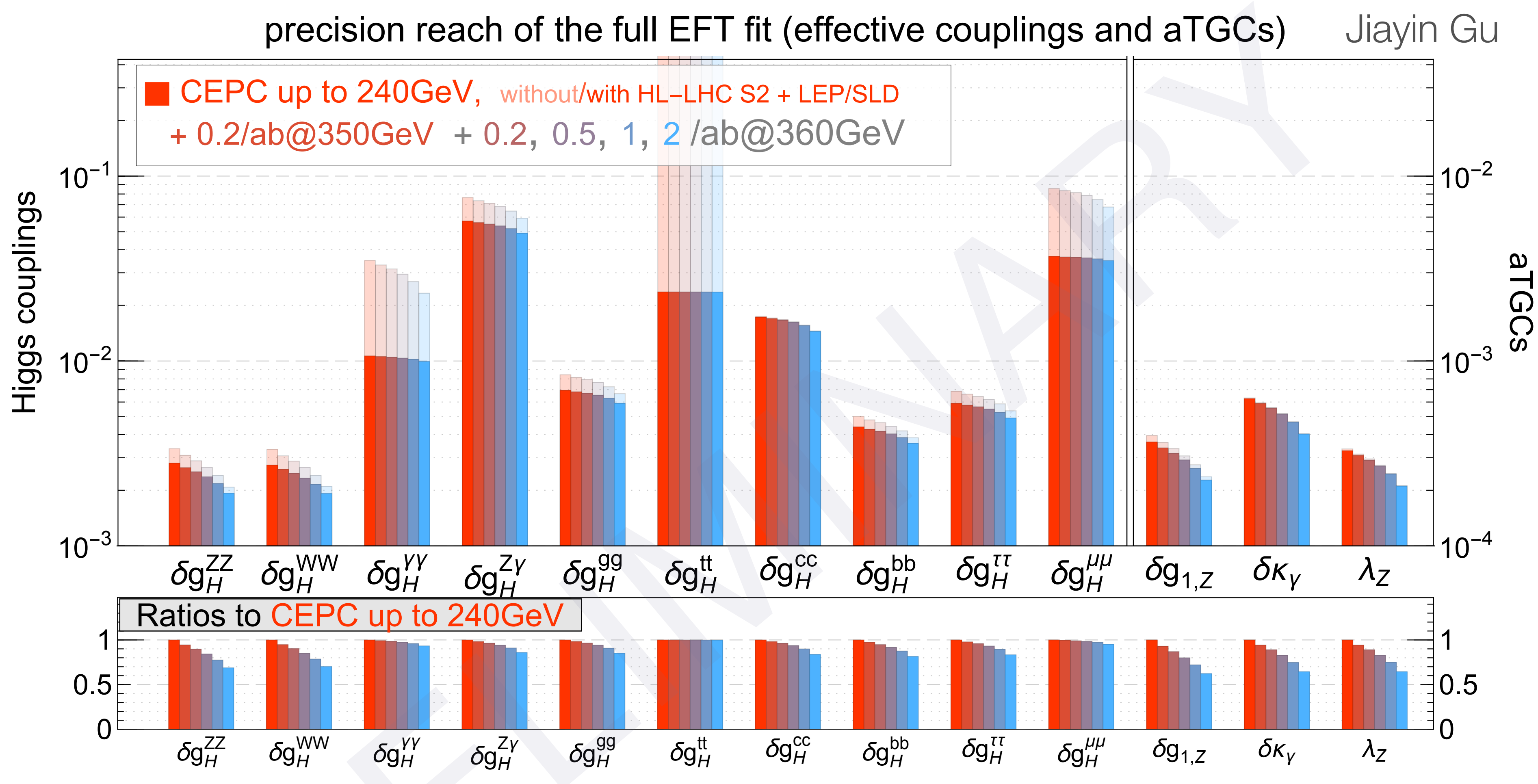
Better sensitivities to these running at the ttbar energies

Better sensitivities at ttbar



Probed by $e^+ e^- \rightarrow Z^* \rightarrow tt$

Better at higher energies



Gain up to a factor of a few

Even better if one can run at even higher energies.