Brookhaven Forum, 2017

Loop-induced Single Top Partner Production at the LHC

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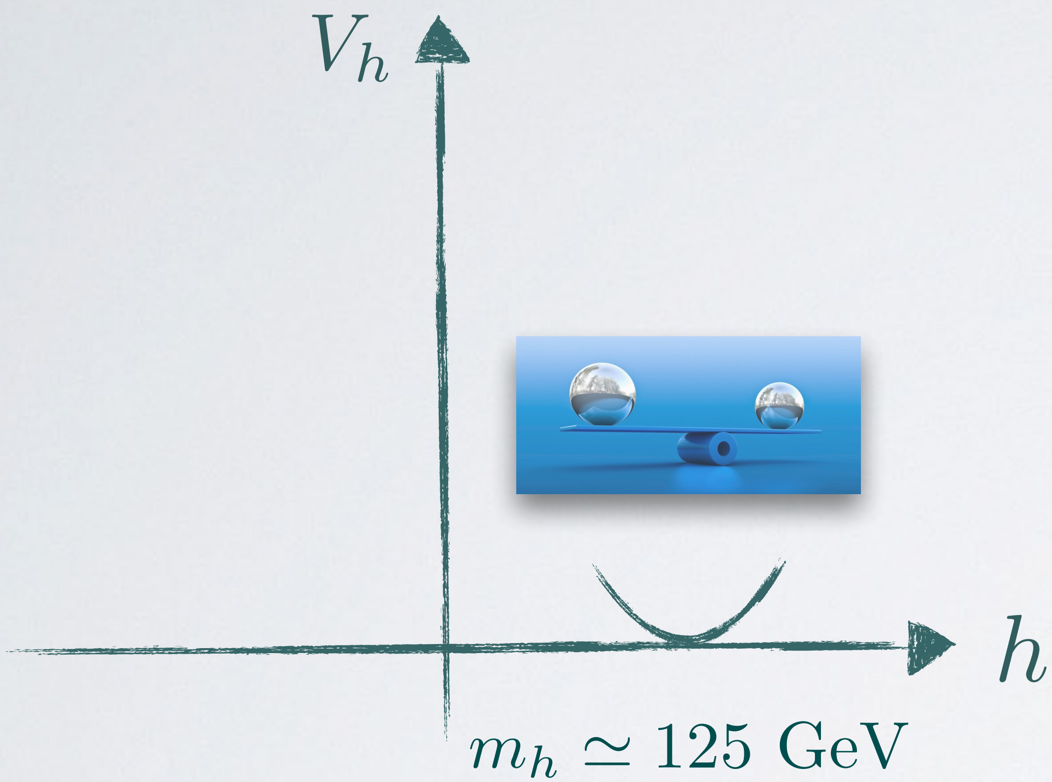
In collaboration with Ian Lewis

Motivation

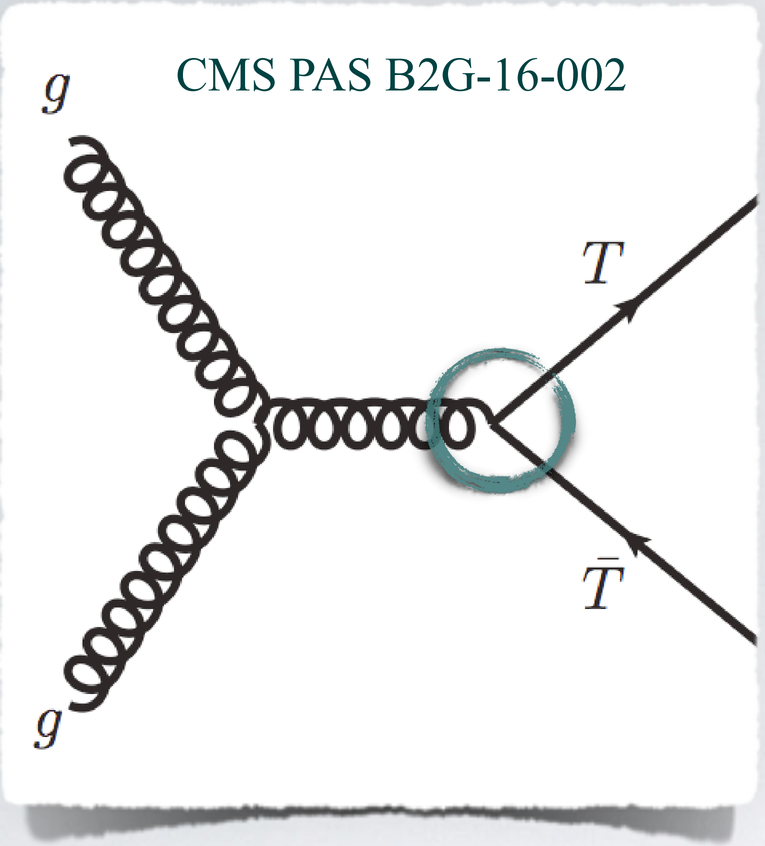


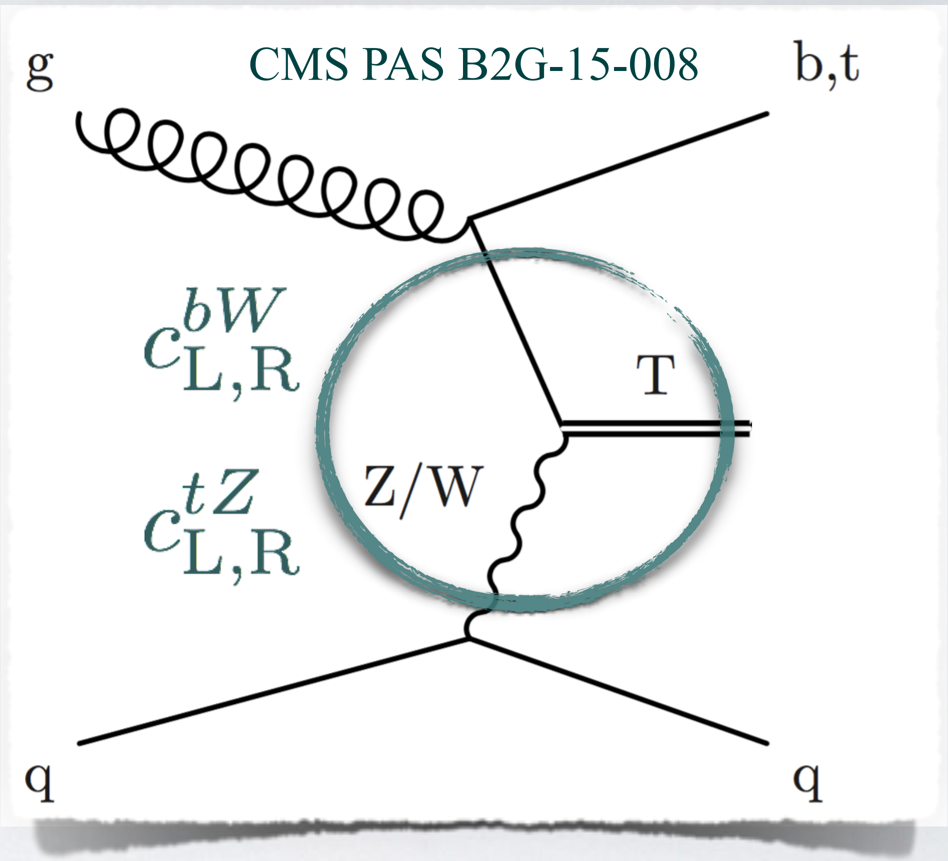
Radiative instability

Alternative theories of EWSB

- Radiative instability of the Higgs mass.
- Vector-like top partners (T') appear in many extensions of the SM to address the hierarchy problem.
- e.g. In composite Higgs models, the Higgs potential is radiatively generated by a top and T' loops.
- The interplay of T' is crucial to get the sensible Higgs mass.

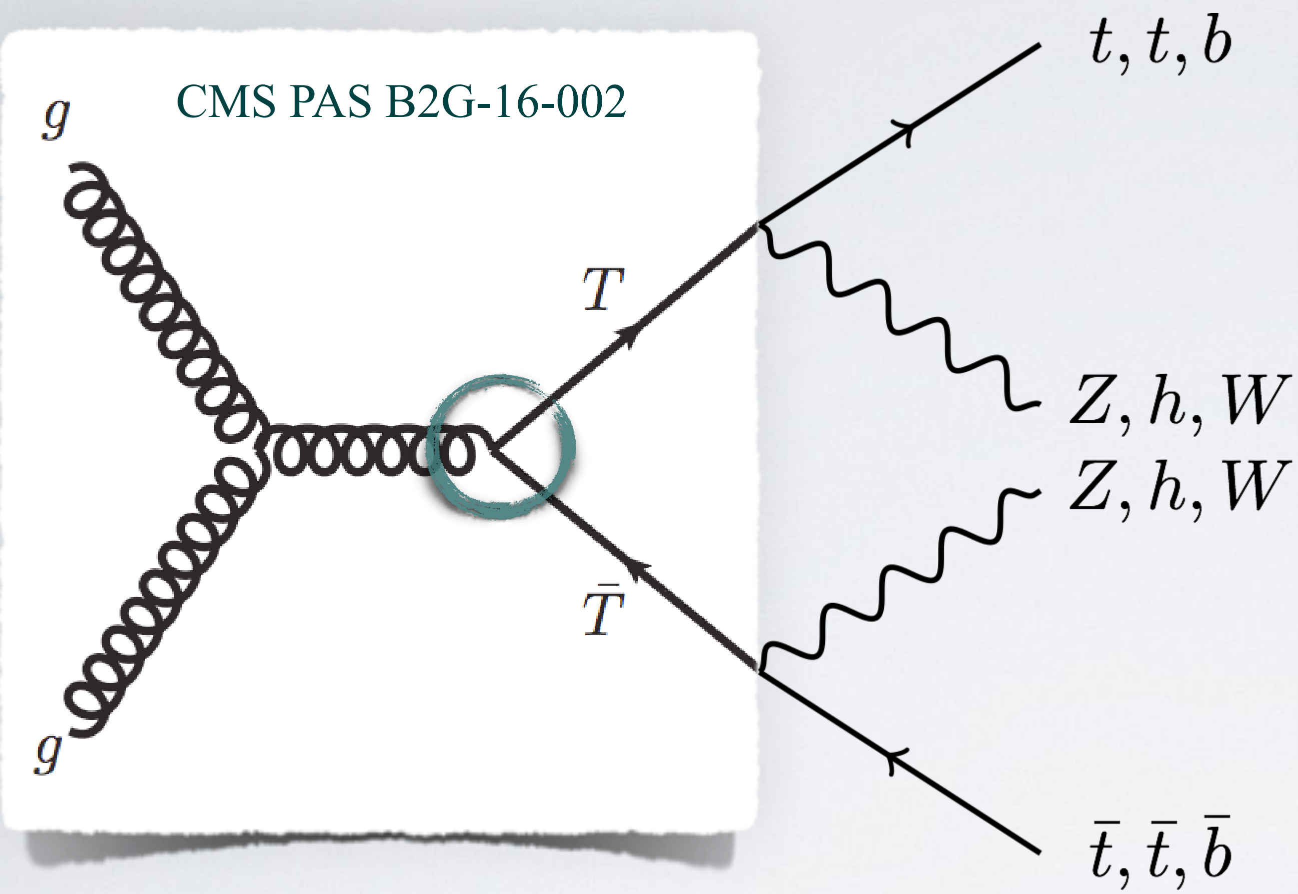
Productions of T' at the LHC

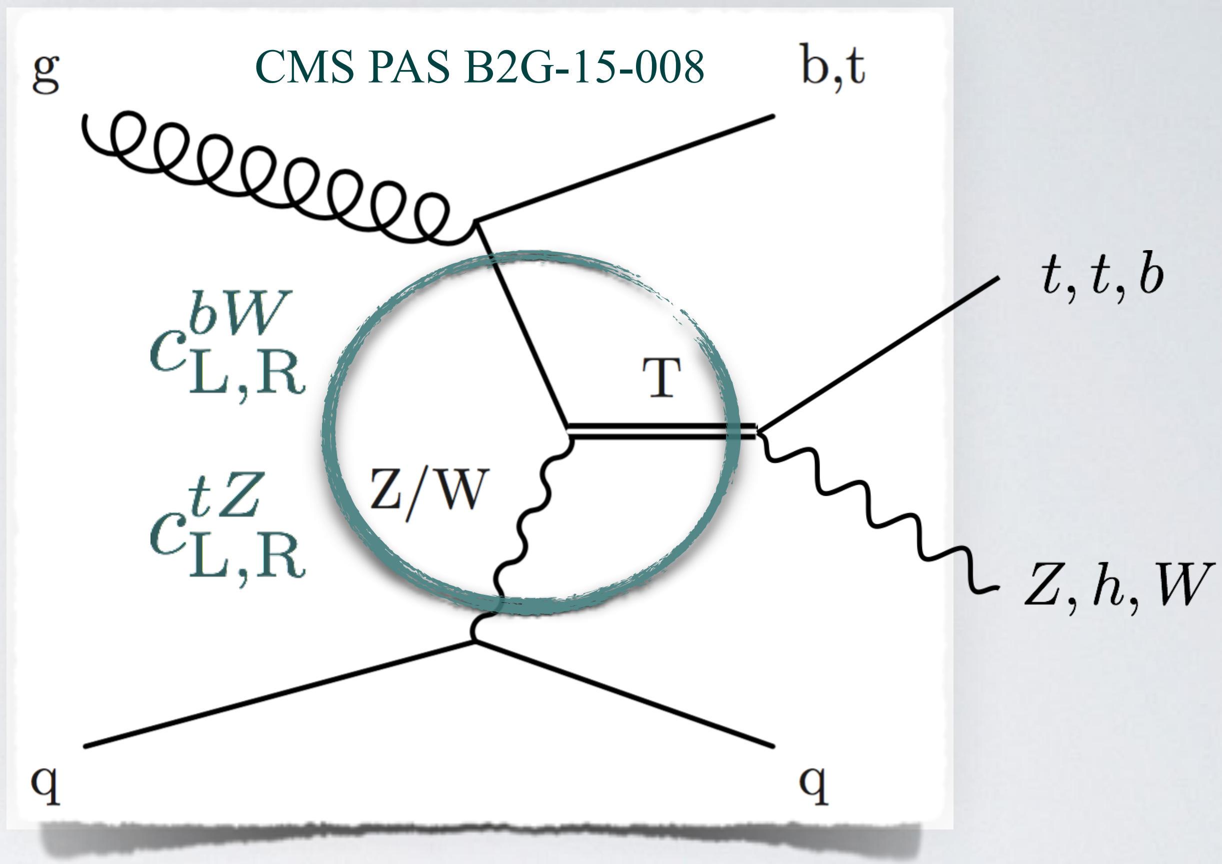




- Typically the T' can be produced in pair or in single.
- The vertex responsible to create T' in pair is the strong coupling.
- The single production is induced by EW coupings.
- Restricted to T' decays to *tZ*, *th* and *bW*.

Productions of T' at the LHC





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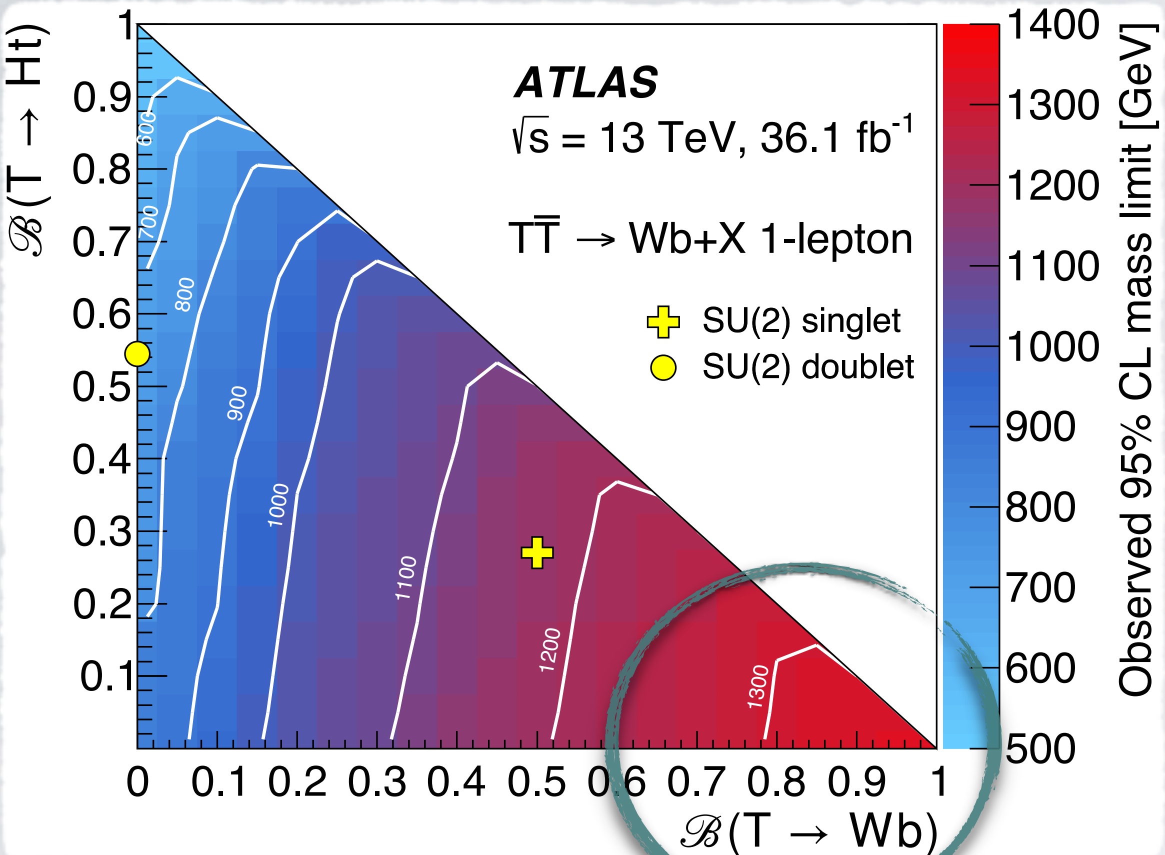
Bounds on T'

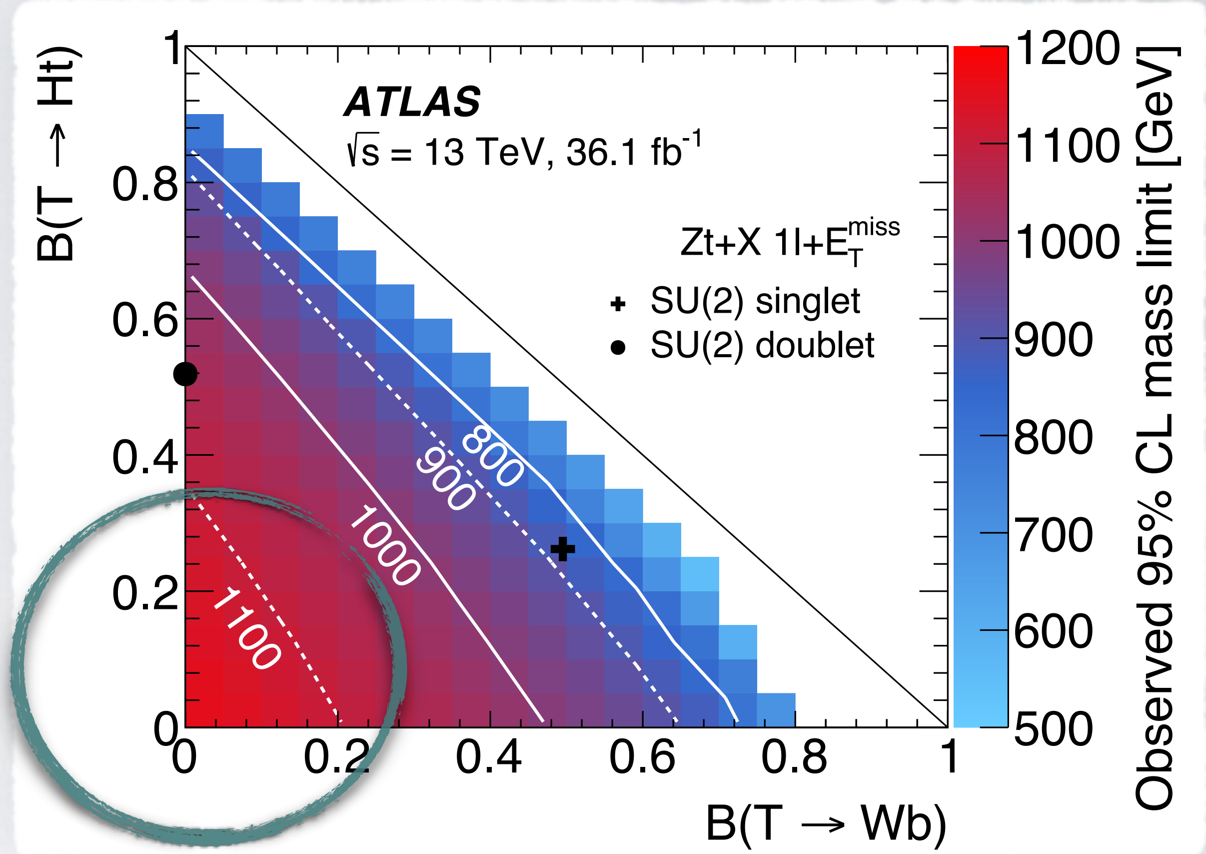
ATLAS, arXiv:1707.03347

$T'\bar{T}' \to W^+ b W^- \bar{b}$



$M_{T'} \gtrsim 1.3$ TeV

$T'\bar{T}' \to ZtZ\bar{t}$ ATLAS, arXiv:1705.10751

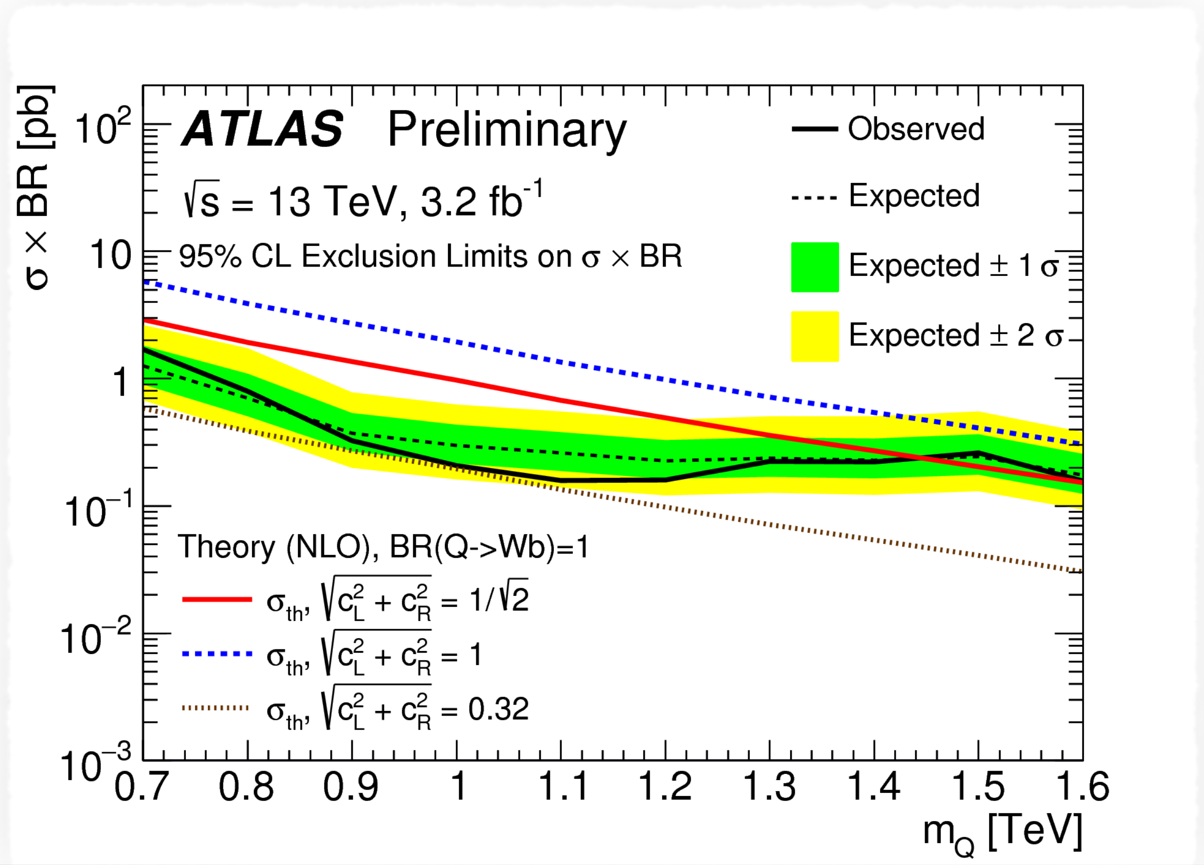


$M_{T'} \gtrsim 1.2$ TeV

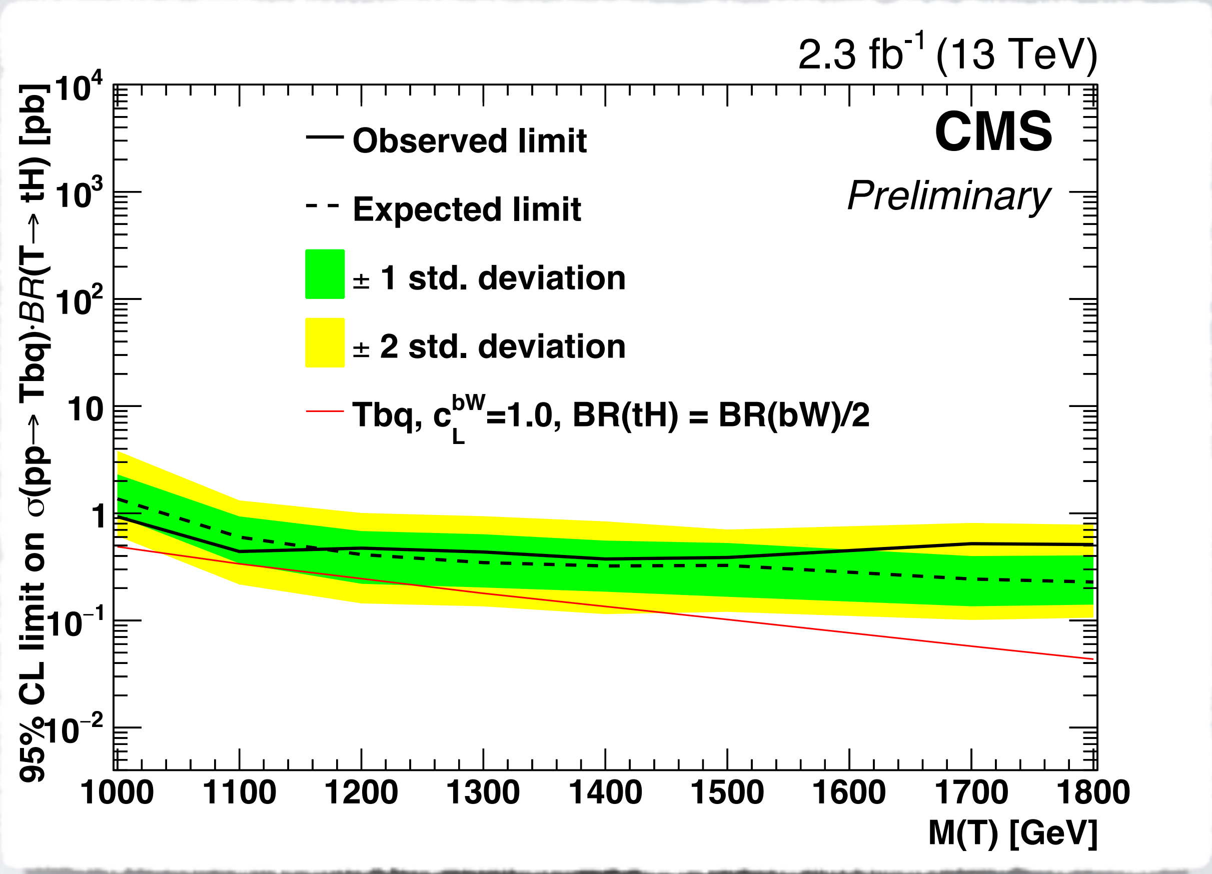
- Recent bounds on T' from the pair production.
- The bounds depend on the assumptions of its BR.

Bounds on T'

$T' \to W^+ b$ ATLAS-CONF-2016-072



$T' \to t\, h$ CMS PAS B2G-16-005



$$M_{T'} > 1 \sim 1.8 \text{ TeV}$$

- Recent bounds on T' from the single production.
- The bounds depend on the size of the EW vertices and BR.

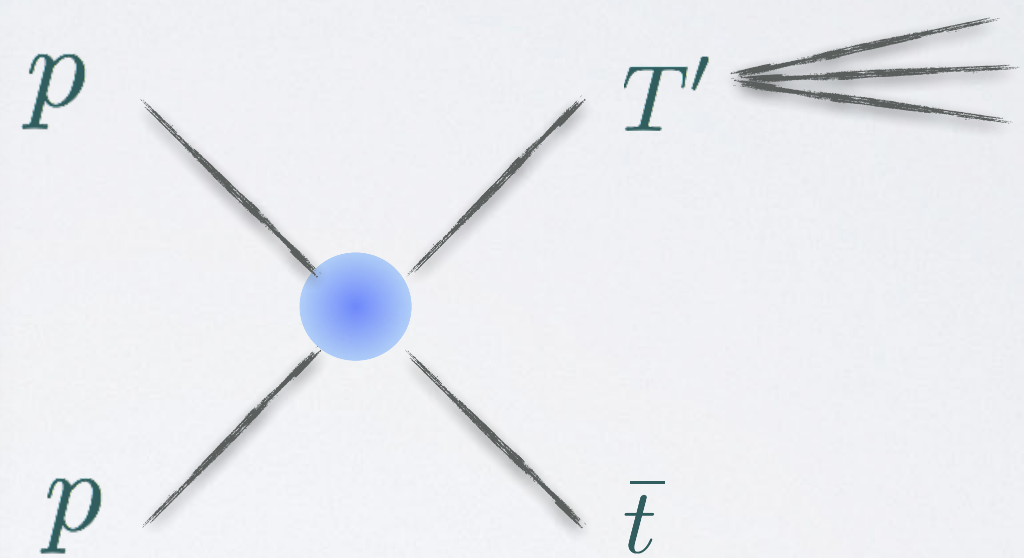
New productions and decays?

SAM & DAVE DIG A HOLE, Mac Barnett & Jon Klassen

So Dave went one way..

and Sam went another..

T' could be produced by new mechanisms and decay into new final states..



- First to write down renormalizable Lagrangian, which can guide us to a new path.

The Lagrangian

- Add two pieces of Lagrangians with a new singlet scalar (*S*) and SU(2)$_L$ singlet *T′*.

$$\mathcal{L}_{\rm NP} = \bar{T} i \not{D} T - M_2 \bar{T} T + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} M_S^2 S^2 + \left(-\lambda_2 S \bar{T}_L T_R + \text{h.c.}\right)$$

$$\mathcal{L}_{\rm mix} = -\left(\lambda_t \bar{Q}_L \tilde{\Phi} T_R + \lambda_1 S \bar{T}_L t_R + \text{h.c.}\right)$$

Mixing

$$\not{D} = \not{\partial} - i g' \frac{2}{3} \not{B} - i g_s \not{G}$$

$$\mathcal{L}_M = -\begin{bmatrix} \bar{t}_L & \bar{T}_L \end{bmatrix} \begin{bmatrix} \frac{y_t v}{\sqrt{2}} & \frac{\lambda_t}{\sqrt{2}} v \\ 0 & M_2 \end{bmatrix} \begin{bmatrix} t_R \\ T_R \end{bmatrix} + \text{h.c.}$$

$$\Phi = \begin{pmatrix} -i G_p \\ \frac{1}{\sqrt{2}}(v + h + i G_0) \end{pmatrix}$$

$$Q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

- *S* can talk in two ways.
- Allowing *T′* to mix with a top quark.

Mixing with T'

- We diagonalize the mass matrix by unitary transformations of the left- and right-handed fields.

$$M_D = \begin{bmatrix} \overset{173\text{GeV}}{M_t} & 0 \\ 0 & M_{T'} \end{bmatrix}$$

- The amount of mixings is dictated by $\sin\theta_L$

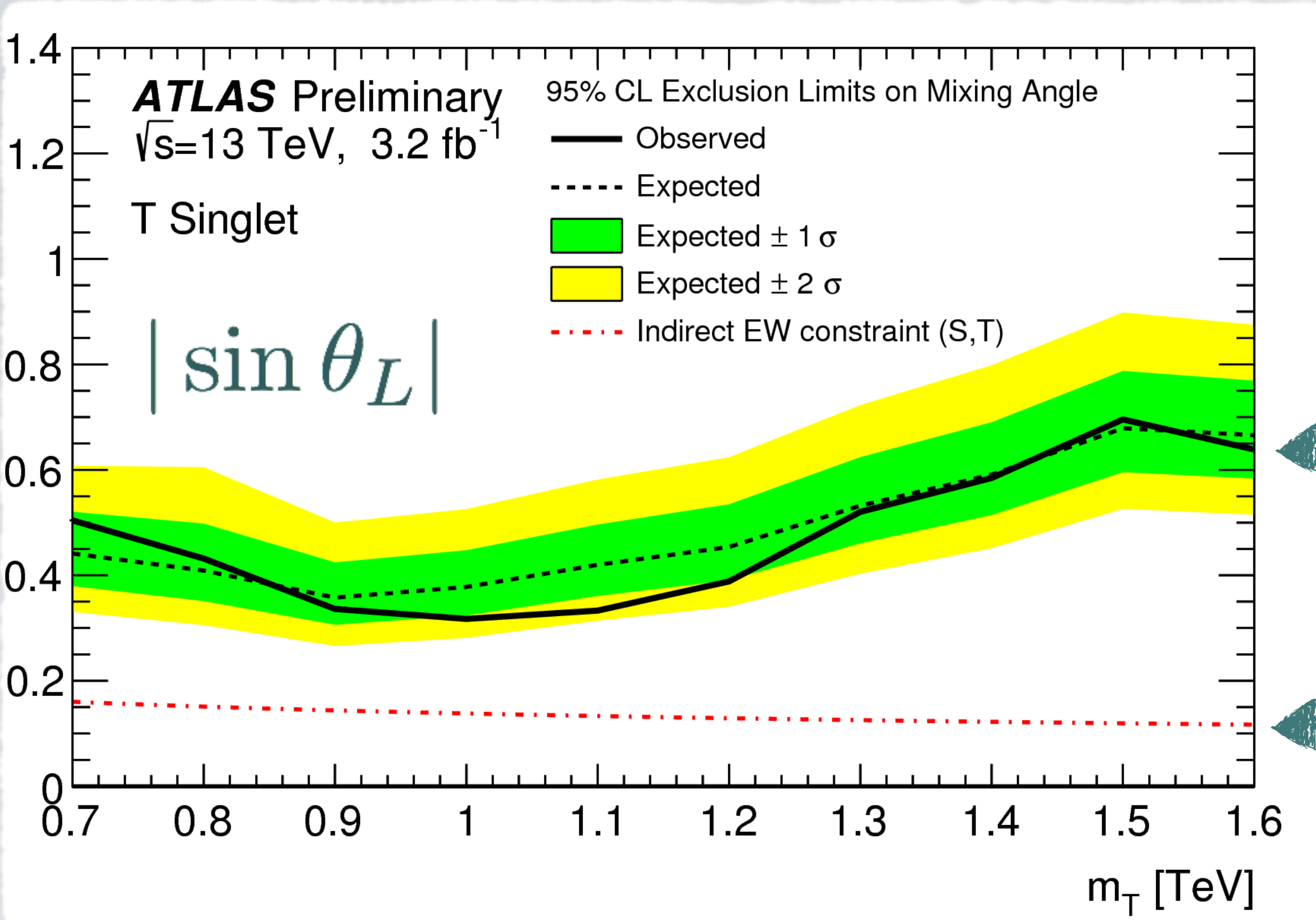
$$\begin{bmatrix} t'_L \\ T'_L \end{bmatrix} \equiv \begin{bmatrix} \cos\theta_L & -\sin\theta_L \\ \sin\theta_L & \cos\theta_L \end{bmatrix} \begin{bmatrix} t_L \\ T_L \end{bmatrix} \longrightarrow \sin\theta_L \sim \frac{v\lambda_t}{M_2\sqrt{2}}$$

$$\begin{bmatrix} t'_R \\ T'_R \end{bmatrix} \equiv \begin{bmatrix} \cos\theta_R & -\sin\theta_R \\ \sin\theta_R & \cos\theta_R \end{bmatrix} \begin{bmatrix} t_R \\ T_R \end{bmatrix} \longrightarrow \sin\theta_R \sim 0 \quad \left(\text{for } \frac{v^2}{M_2^2} \ll 1\right)$$

- Independent parameters: $\lambda_1 \quad \lambda_2 \quad \sin\theta_L \quad M_{T'} \quad M_S$

Limits on the mixing angle

$T' \to W^+ b$ ATLAS-CONF-2016-072



$$\sigma^{\text{limit}}(M_{T'}, \sin\theta_L)\, \text{BR}(T' \to Wb)\Big|_{0.5}$$

$M_{T'}^{\text{limit}}$ $\sin\theta_L^{\text{limit}}$

oblique parameters

- The strongest limit is obtained by oblique parameters.

$$\sin\theta_L \lesssim 0.16 \quad (\text{for } M_{T'} \sim 1\ \text{TeV})$$

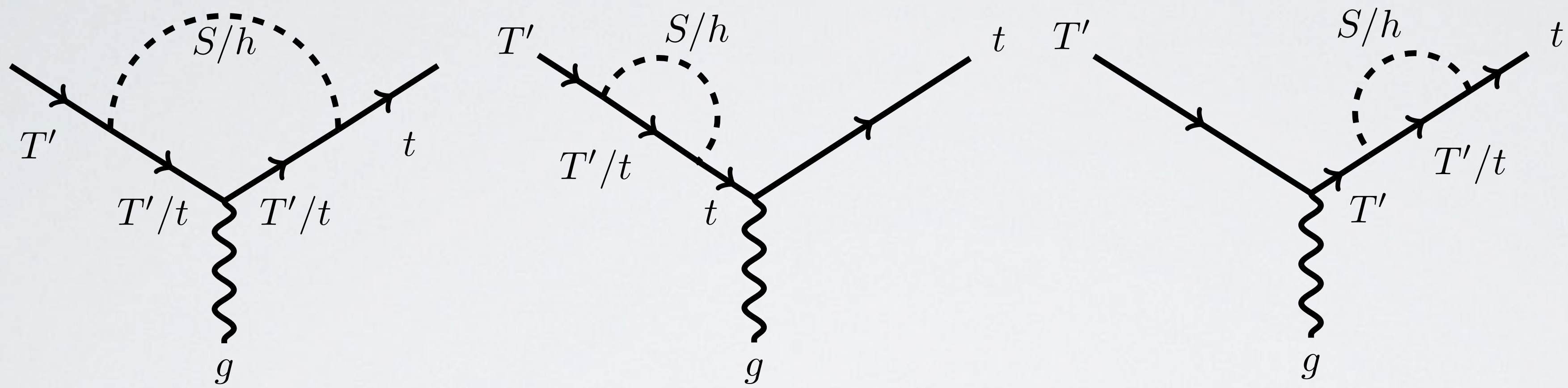
- So the small mixing is preferable..

Chien-Yi Chen, S. Dawson, I. M. Lewis [2014]

J. A. A. Saavedra, R. Benbrik, S. Heinemeyer, M. P. Victoria [2013]

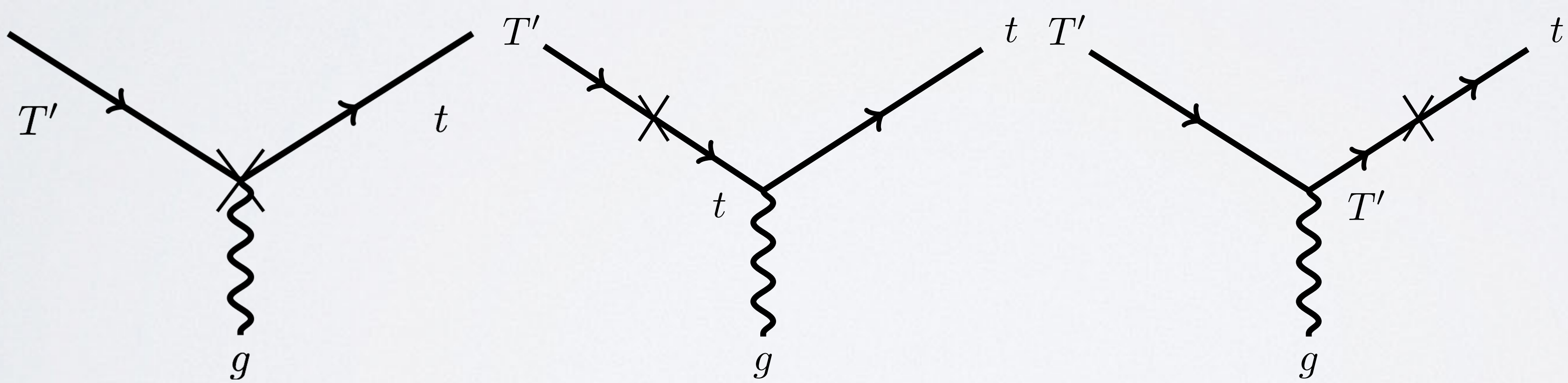
New T' decays

- First we're interested in the new decay $T' \rightarrow t\, g$ (divergent).



+ W, Z, Goldstone bosons loops ...

- We should renormalize the Lagrangian to get counter terms.



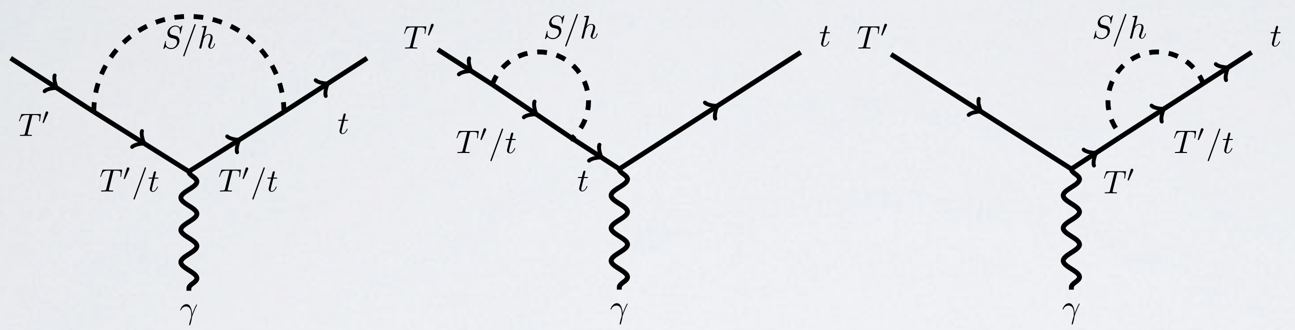
+

- Taken together, we get the finite piece of the amplitude.

New T' decays

- And then there’s another interesting decay mode $T' \rightarrow t\,\gamma$.

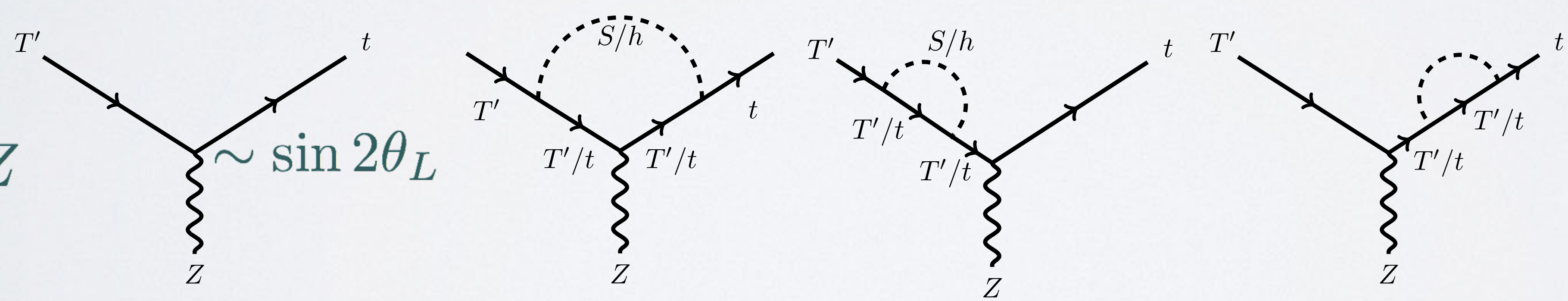
$T' \to t\gamma$



$+$ Counter terms, W, Z, Goldstone bosons loops ...

- The conventional decay mode $T' \rightarrow t\,Z$ acquires the tree-level contribution as long as the mixing is turned on.

$T' \to tZ$

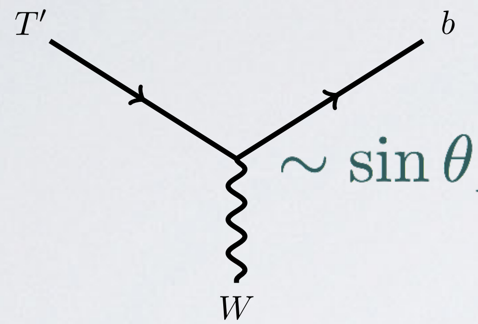


$+$ Counter terms, W, Z, Goldstone bosons loops ...

- If the mixing is off, then $T' \rightarrow t\,Z$ becomes match-fit with $T' \rightarrow t\,\gamma$.

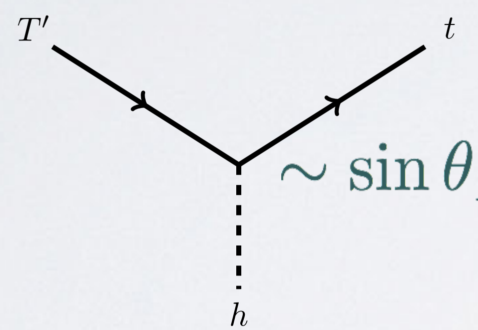
New *T′* decays

$T' \to bW$



$\sim \sin\theta_L \;+\;$ loops ...

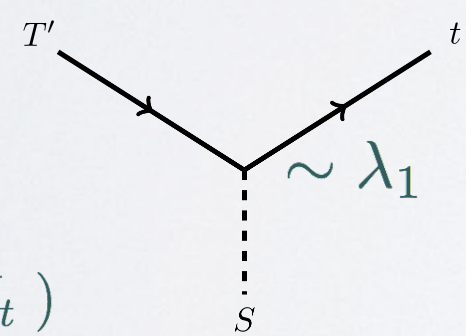
$T' \to th$



$\sim \sin\theta_L \;+\;$ loops ...

$T' \to tS$

$(M_{T'} > M_S + M_t)$

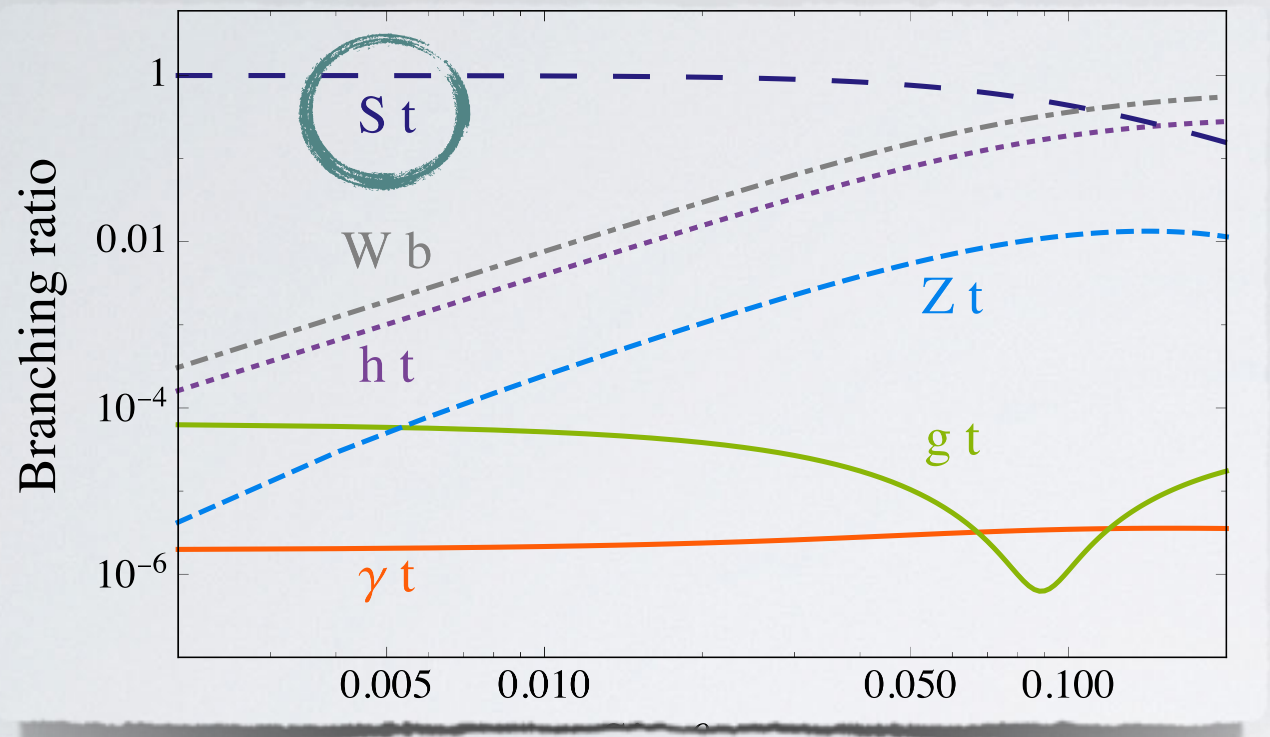


$\sim \lambda_1 \;+\;$ loops ...

- $T' \to b\,W$ and $T' \to t\,h$ receive the tree-level contributions (but suppressed as $\sin\theta_L \to 0$).
- The game changer is $T' \to t\,S$ decay, if it is kinematically allowed.
- It grows with λ_1 from the tree-level without $\sin\theta_L$ suppresssion.

T' branching ratios ($M_{T'} > M_S + M_t$)

$M_{T'} = 1.5$ TeV $M_S = 200$ GeV $\lambda_1 = \lambda_2 = 1$



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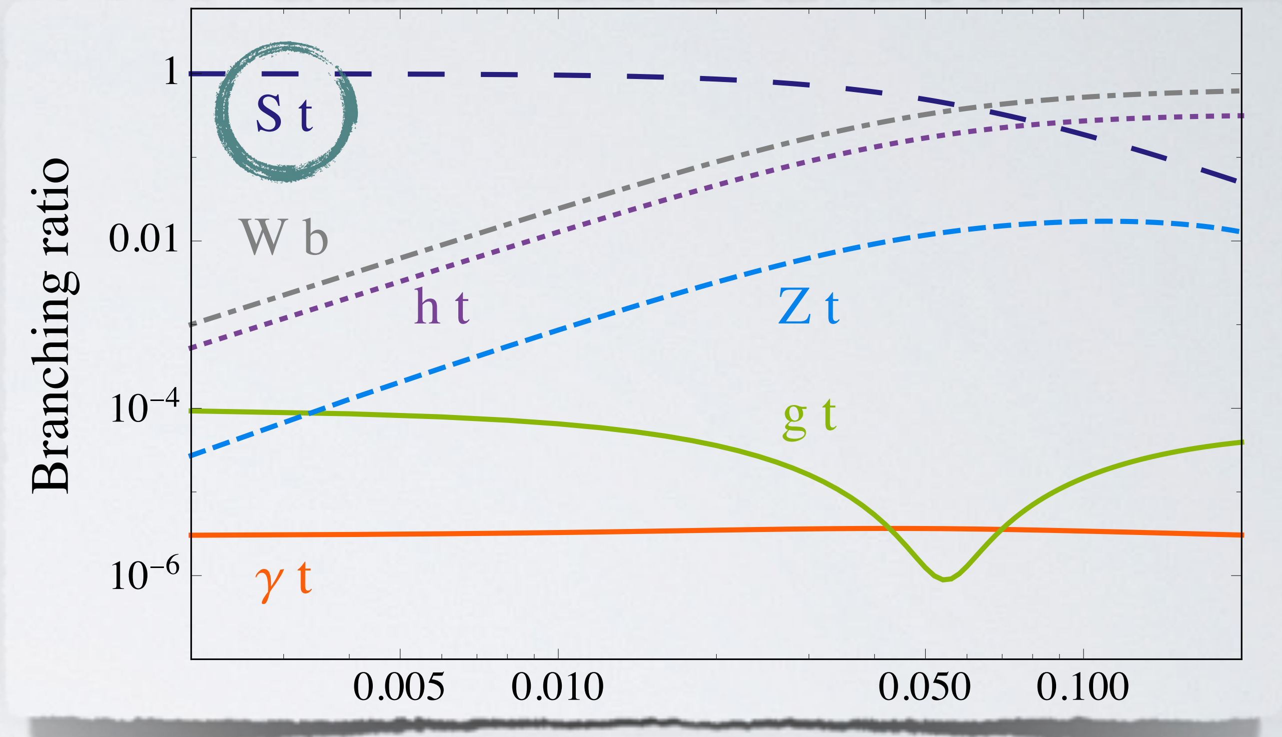


$\sin\theta_L$ 10^{-1}

$\sin\theta_L$ 10^{-1}

- When $M_{T'}$ is heavier than M_S
- $T' \rightarrow t\, S$ predominates throughout the ragne of $\sin\theta_L$.
- Other conventional decays are turned off, unless we have a sizable $\sin\theta_L$.

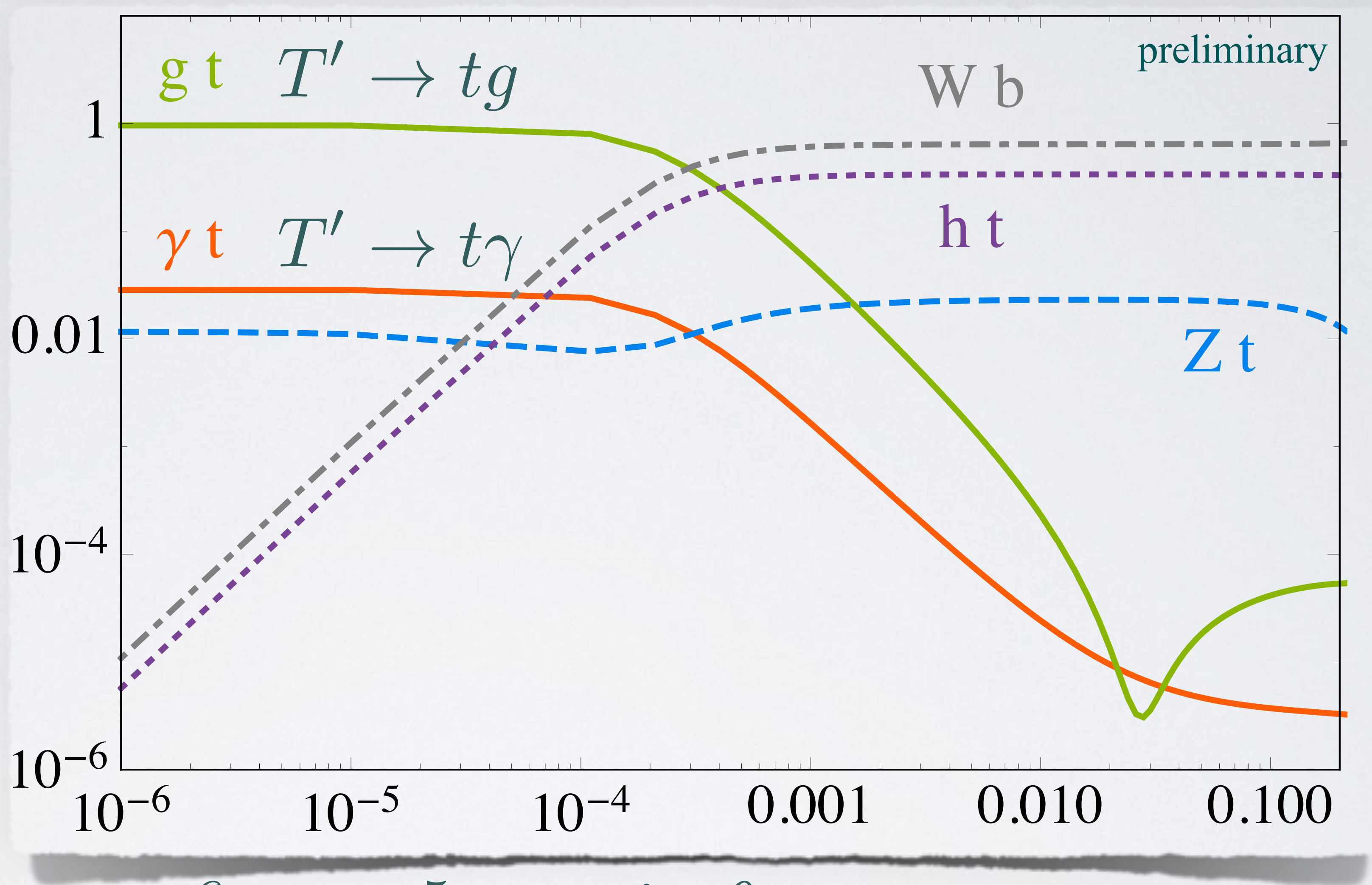
T' branching ratios ($M_{T'} < M_S + M_t$)

$M_{T'} = 1.5$ TeV $\quad M_S = 3$ TeV $\quad \lambda_1 = \lambda_2 = 1$

$\mathrm{BR}(T' \to tg) \sim 97\%$

$\mathrm{BR}(T' \to t\gamma) \sim 2\%$

Conventional decay modes are turned off..



10^{-6} $\quad 10^{-5}$ $\quad \sin\theta_L$

- But the tide changes, when $M_{T'}$ is lighter than M_S.
- There is a region of parameter space that T′ favourably decays into $t\,g$ or $t\,\gamma$.

T' branching ratios ($M_{T'} < M_S + M_t$)

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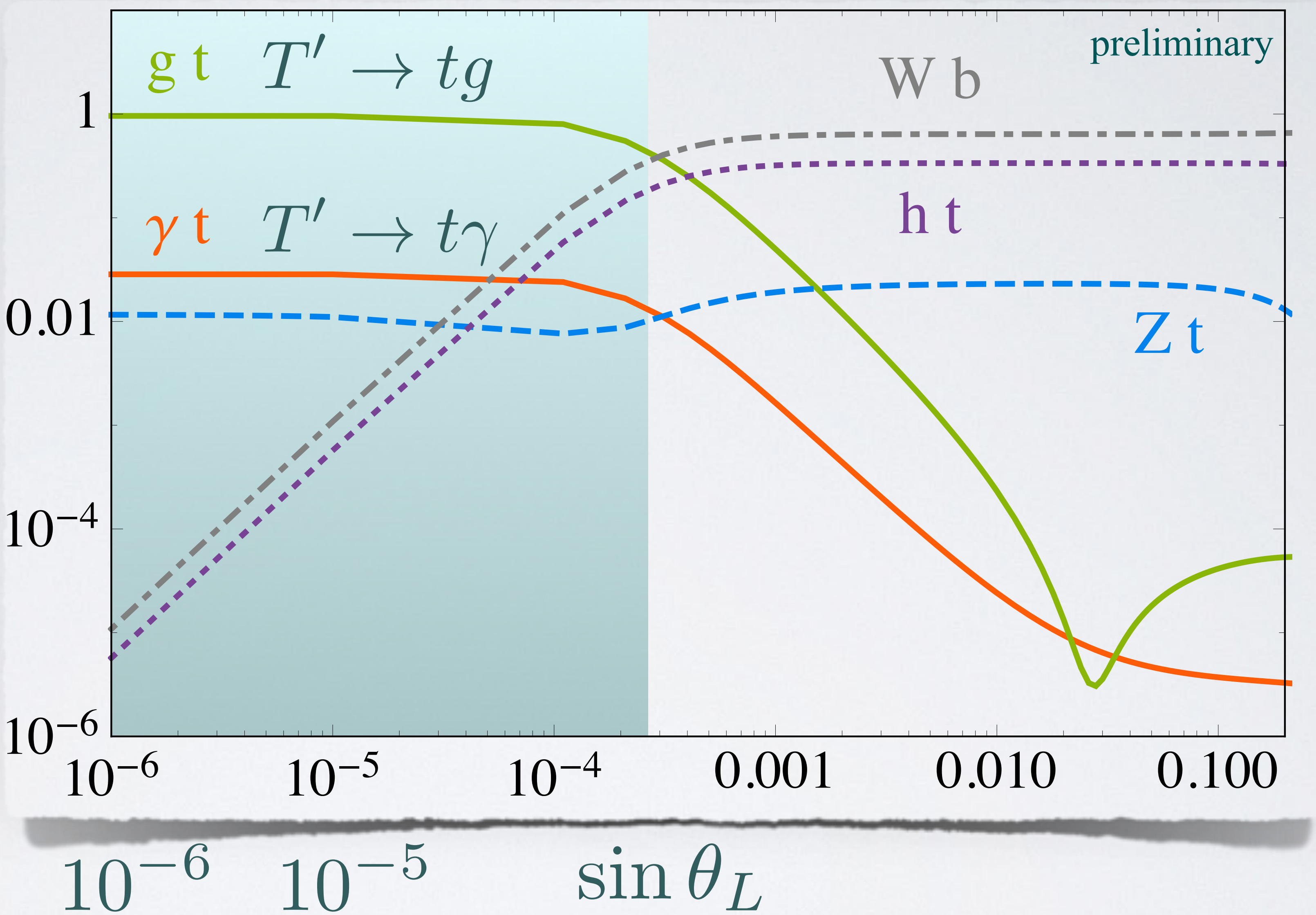
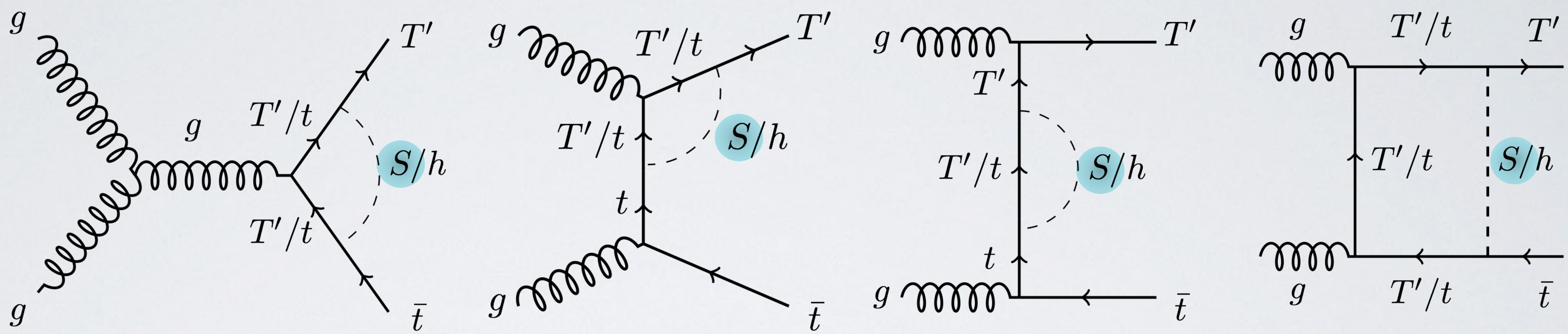
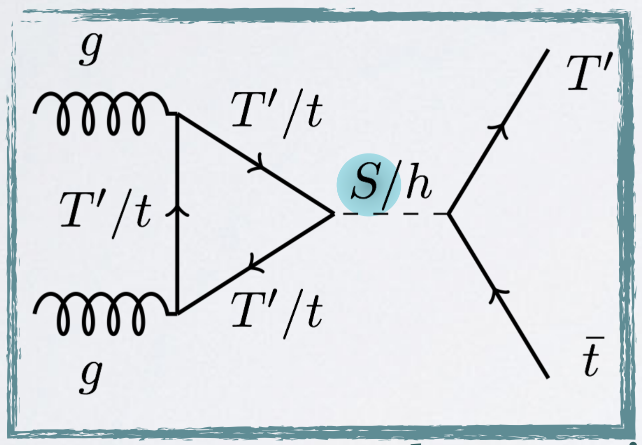


- But the tide changes, when $M_{T'}$ is lighter than M_S.
- There is a region of parameter space that T′ favourably decays into $t\,g$ or $t\,\gamma$.

New single *T′* productions

$gg \to T' \, \bar{t}$



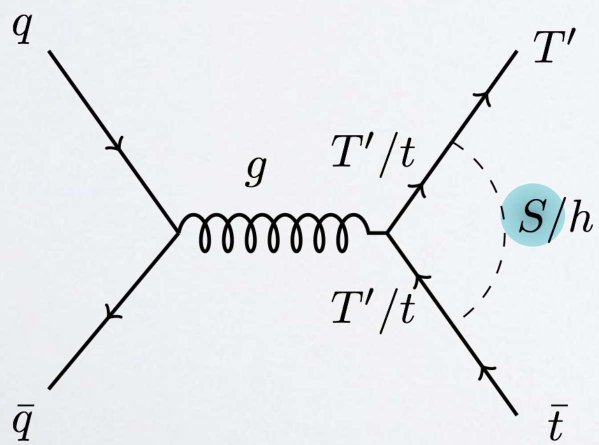


resonant production!

+ Counter terms, W, Z, Goldstone bosons loops ...

- There can be a new single *T′* production through loop processes.
- Including all *W, Z* and Goldstone bosons loops and counter terms.

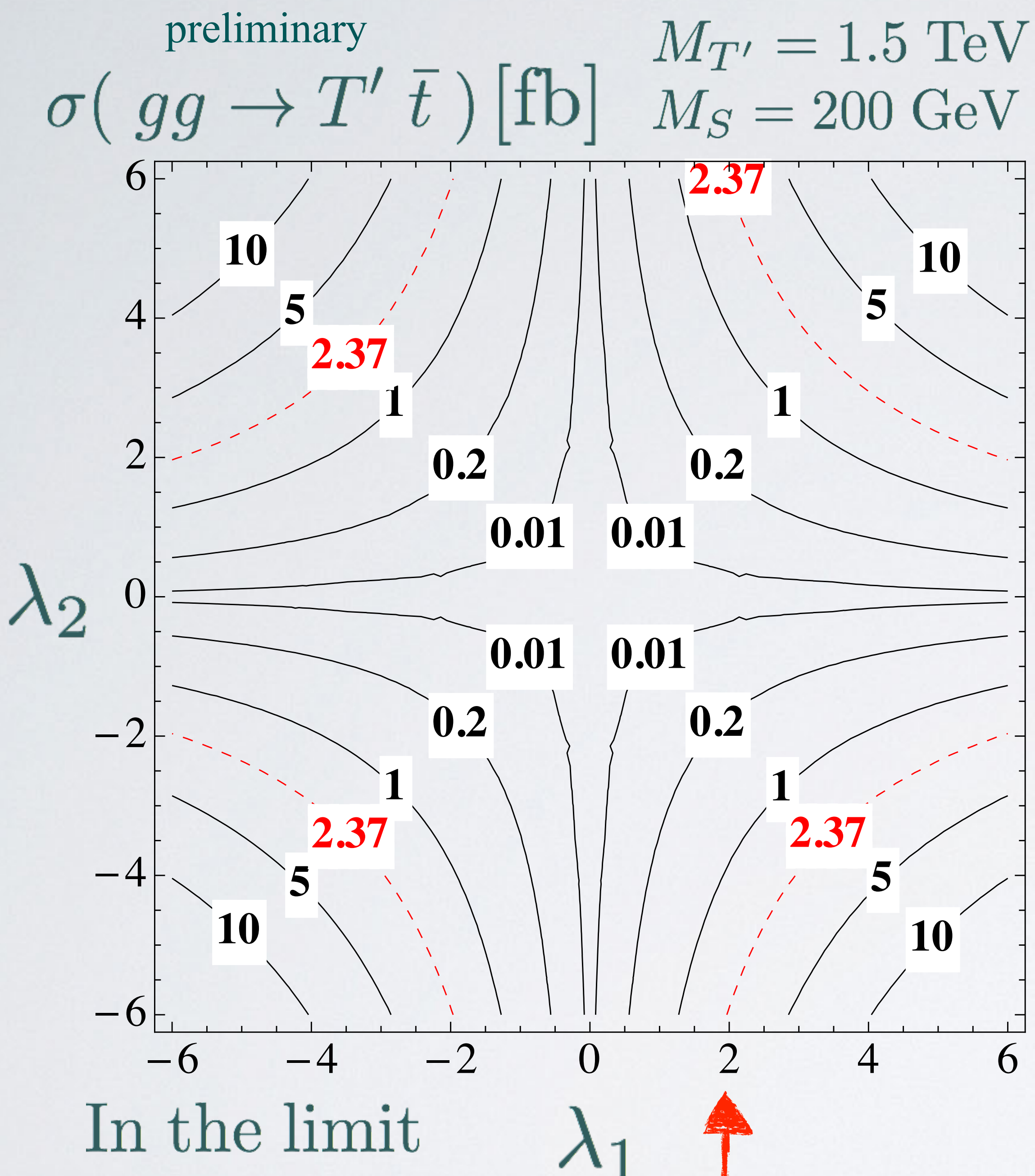
$q\bar{q} \to T' \, \bar{t}$



+ Counter terms, W, Z, Goldstone bosons loops ...

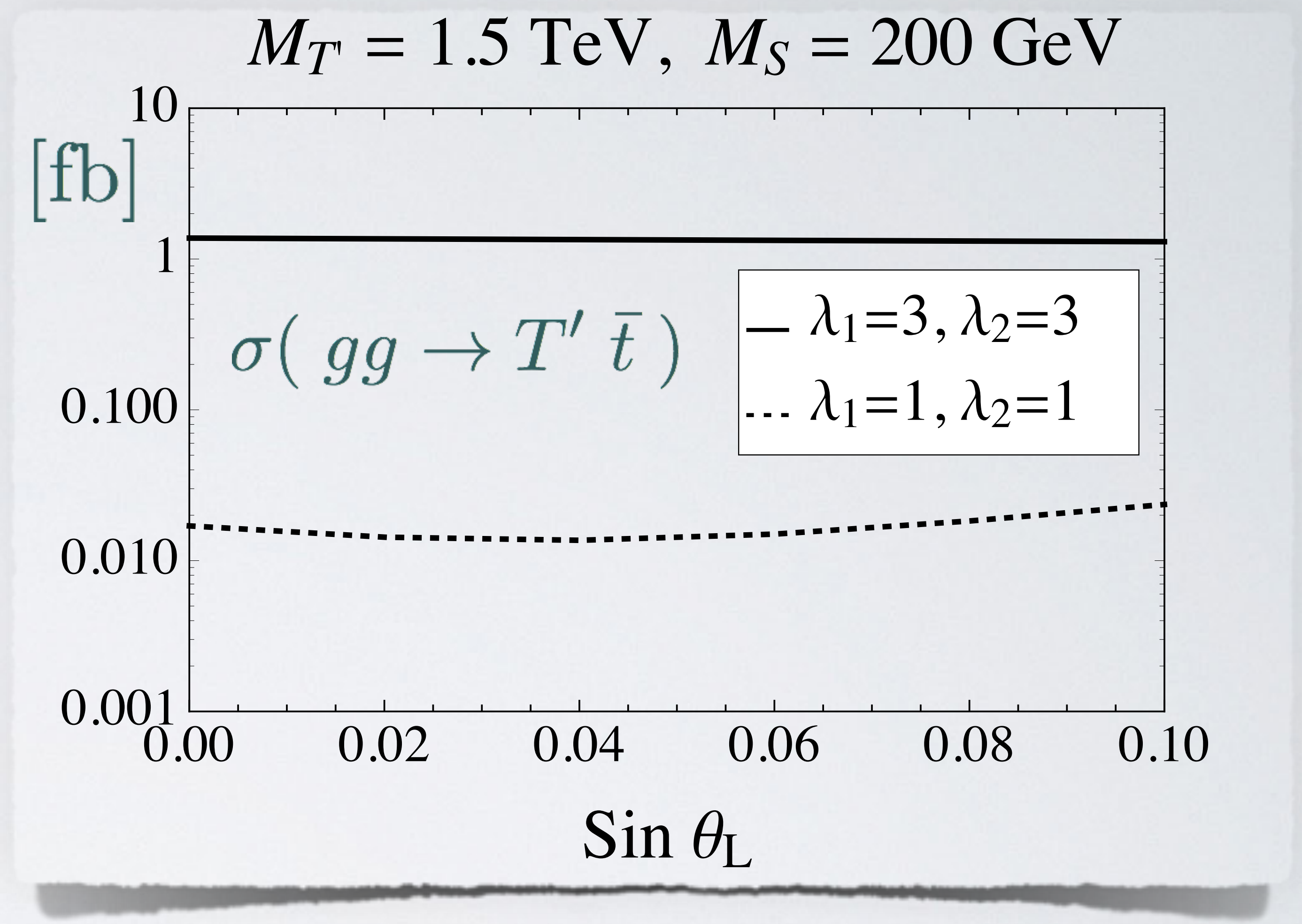
- For heavier *S*, there can be even a resonant production.

Non-resonant T' production cross section



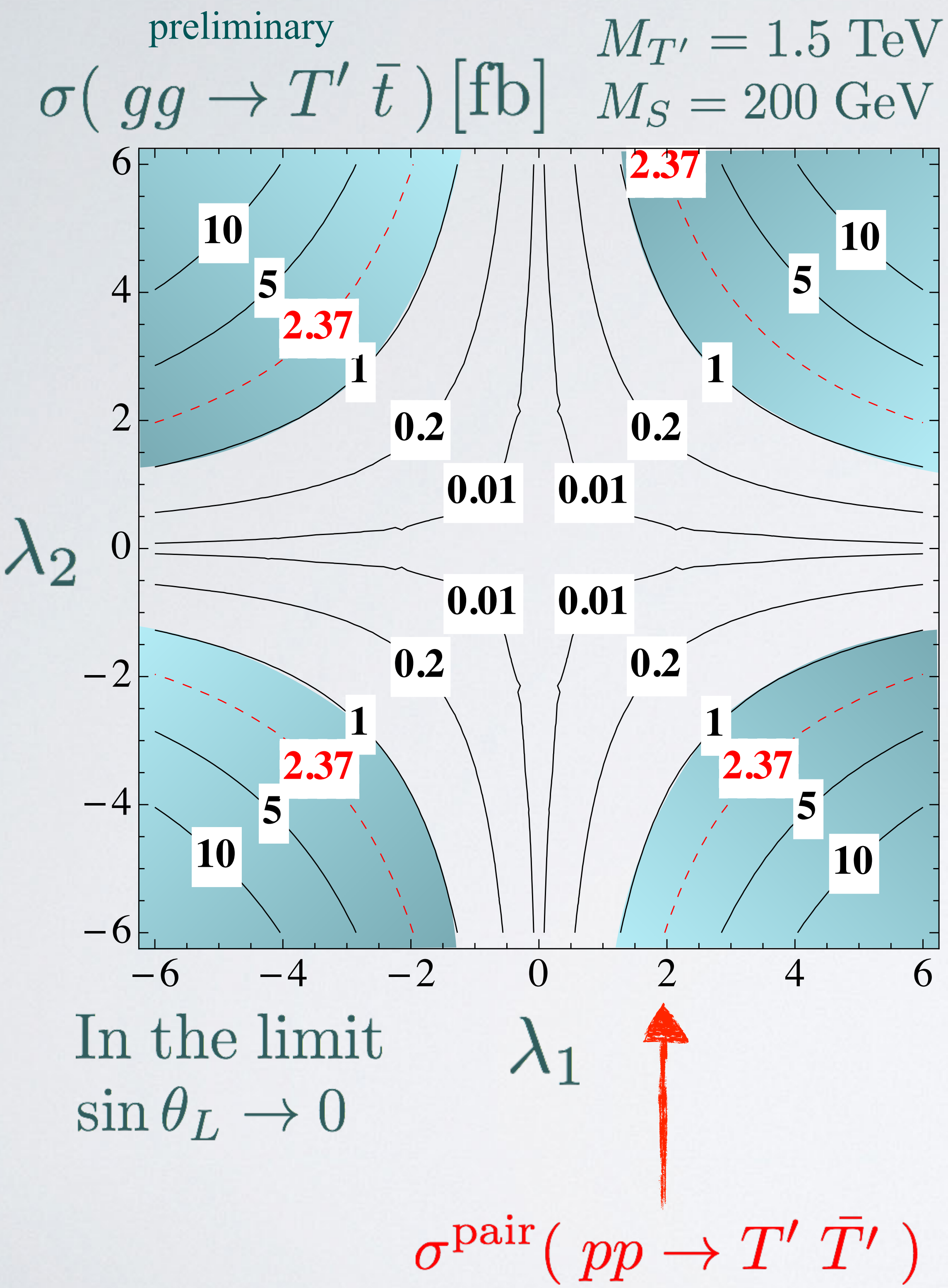
In the limit $\sin\theta_L \to 0$

$\sigma^{\text{pair}}(\,pp \to T'\,\bar{T}'\,)$

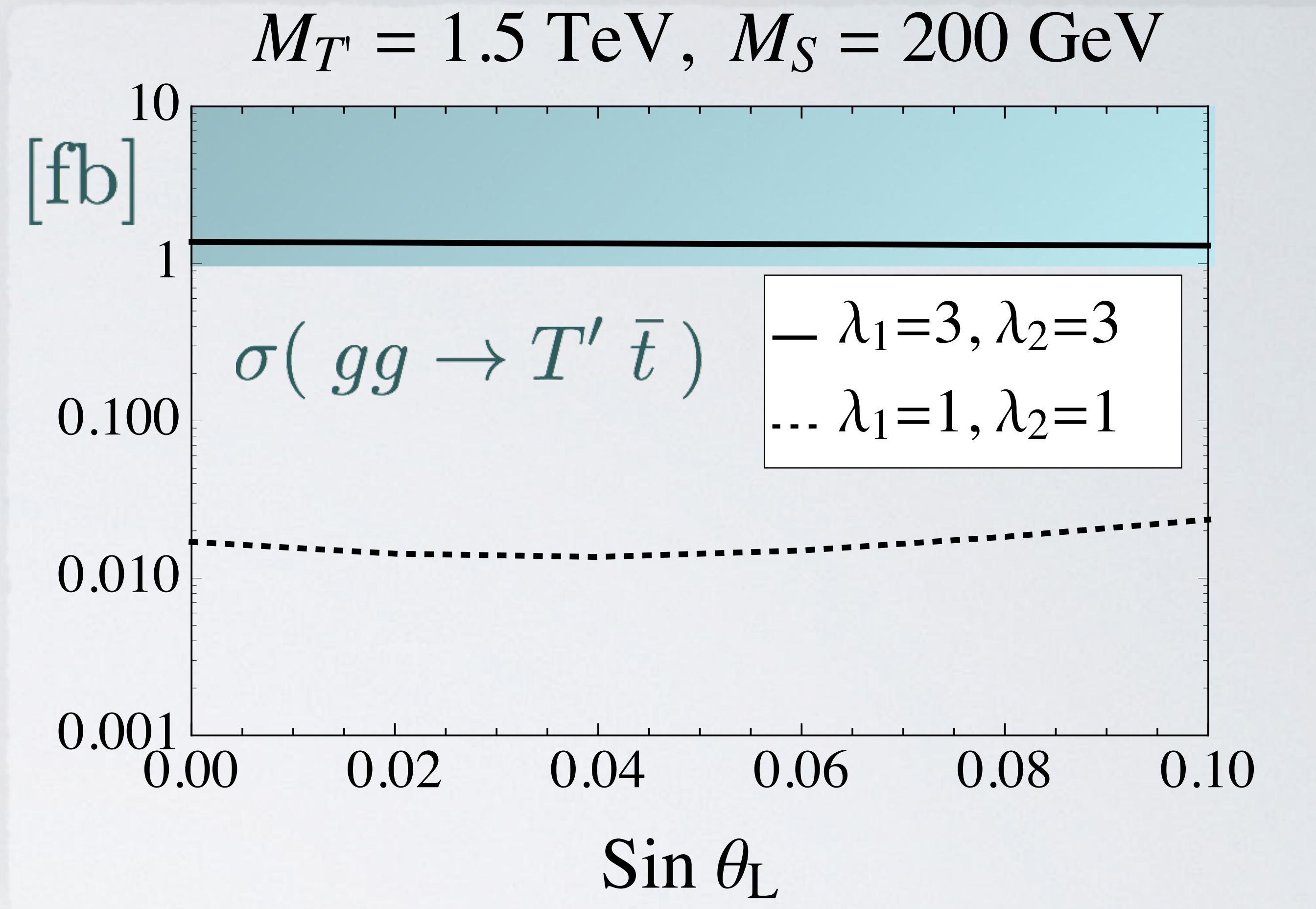


- There is a parameter space with cross sections of $\mathcal{O}(1\text{ fb})$
- It can compete with the pair production if we allow $\mathcal{O}(1)$ couplings for λ_1 and λ_2 .

Non-resonant T' production cross section



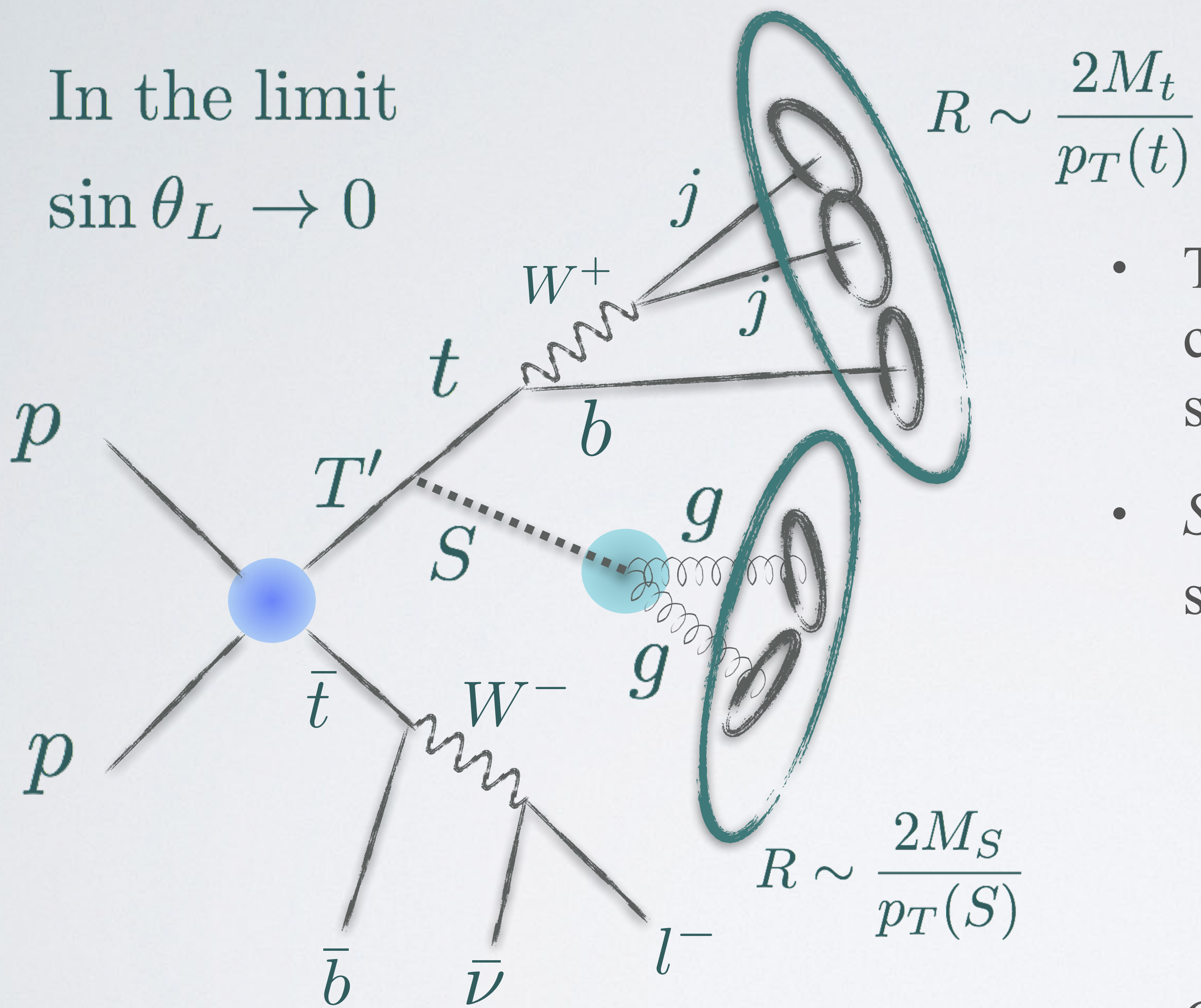
In the limit $\sin\theta_L \to 0$



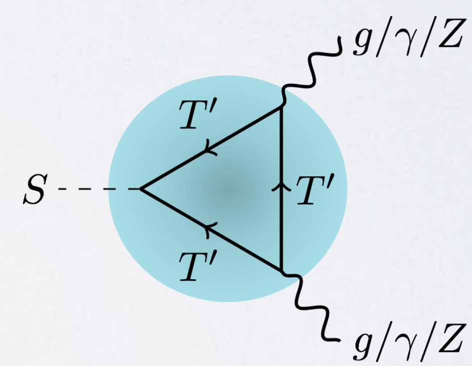
- There is a parameter space with cross sections of $\mathcal{O}(1\ \text{fb})$
- It can compete with the pair production if we allow $\mathcal{O}(1)$ couplings for λ_1 and λ_2 .

Searching for *T′* in new final states

In the limit $\sin\theta_L \to 0$



- The new productions and decays can give rise to new final states to search for.
- *S* exclusively decays into gg in the $\sin\theta_L \to 0$ limit.

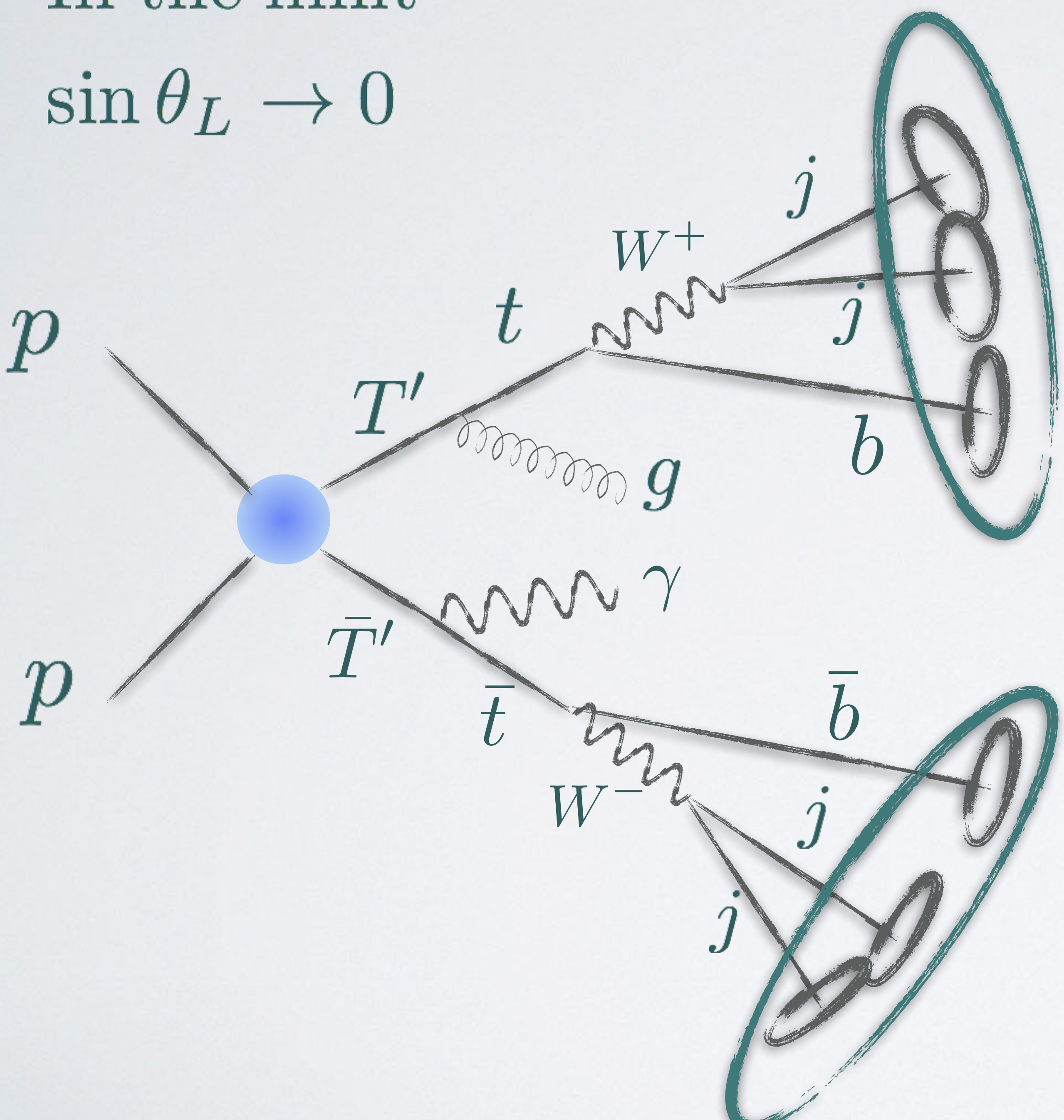


- One boosted top + one collimated dijet + one lepton + one b-jet + $\not{E}_T$

Searching for *T´* in new final states

In the limit

$\sin\theta_L \to 0$

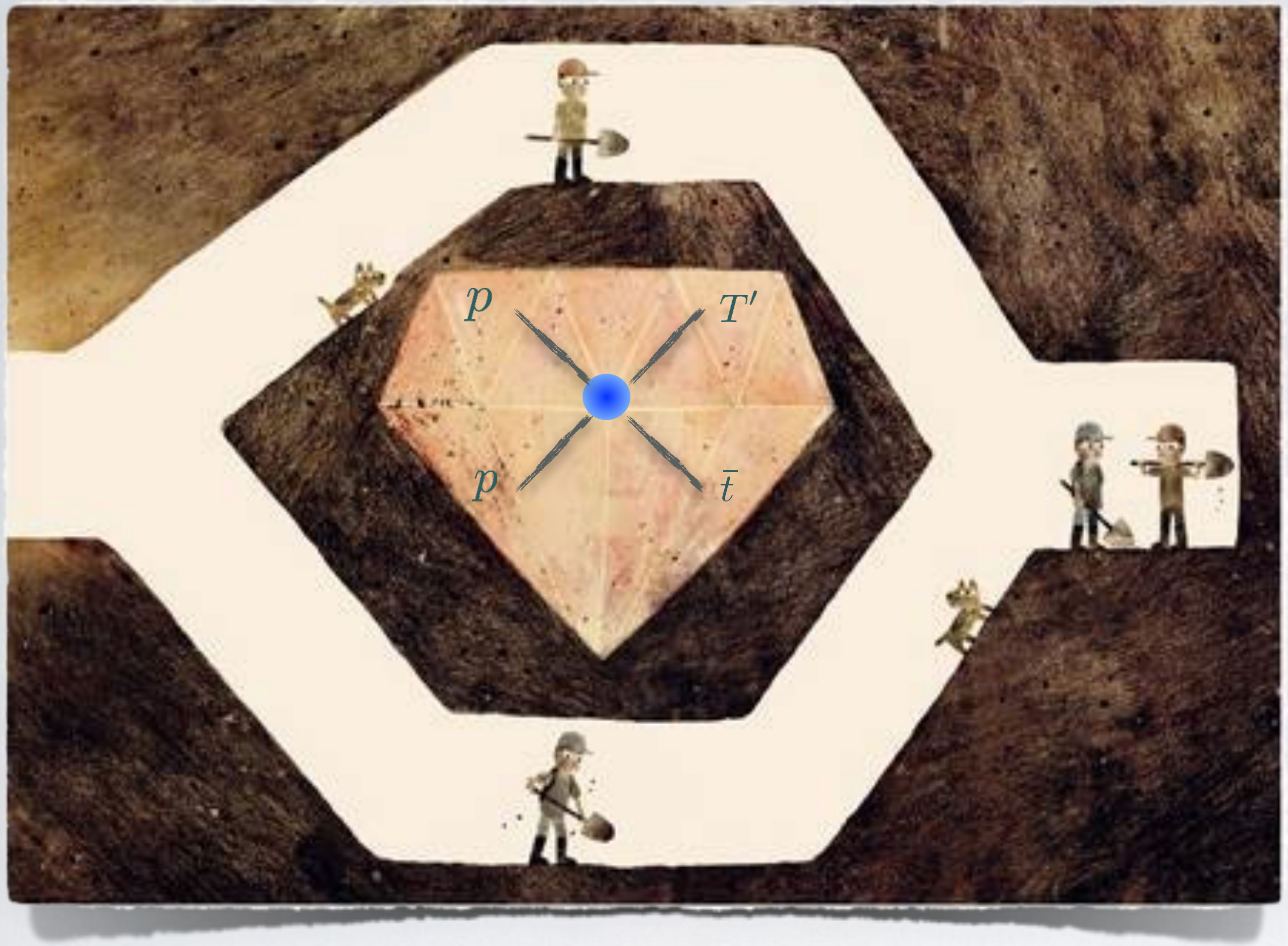


- Or we can think of the pair production where each *T´* decays to *t g* or *t γ*.
- It can give a rise to two boosted tops + one hard photon + one hard jet.
- There are more other interesting new final states that we haven't even looked at it…

Work in progress with H. Alhazmi K. Kong, I. Lewis

Summary

SAM & DAVE DIG A HOLE,
Mac Barnett & Jon Klassen



- There are new paths to search for T'.
- To understand the next layer of new physics.
- Thanks you very much for listening!

Back-up

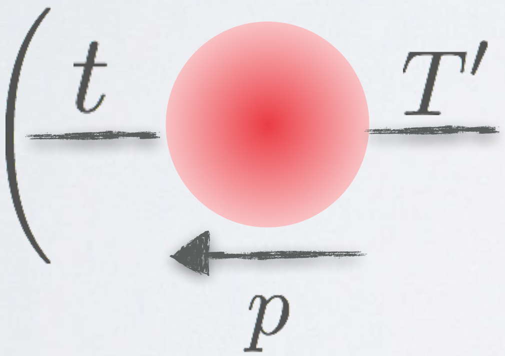
Renormalizing the Lagrangian

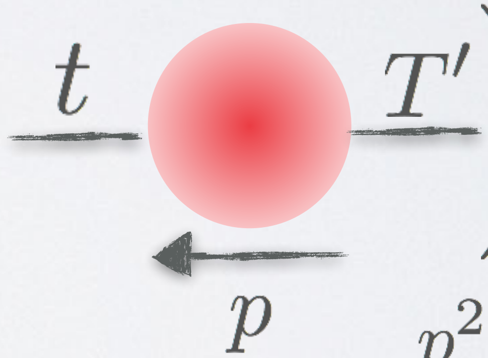
- Wave function renormalization constants (w.f.c.) for fermions

$$\begin{bmatrix} t_{L0} \\ T'_{L0} \end{bmatrix} \simeq \begin{bmatrix} 1+\frac{1}{2}\delta Z^L_{tt} & \frac{1}{2}\delta Z^L_{tT} \\ \frac{1}{2}\delta Z^L_{Tt} & 1+\frac{1}{2}\delta Z^L_{TT} \end{bmatrix} \begin{bmatrix} t_L \\ T'_L \end{bmatrix} \; , \; \begin{bmatrix} t_{R0} \\ T'_{R0} \end{bmatrix} \simeq \begin{bmatrix} 1+\frac{1}{2}\delta Z^R_{tt} & \frac{1}{2}\delta Z^R_{tT} \\ \frac{1}{2}\delta Z^R_{Tt} & 1+\frac{1}{2}\delta Z^R_{TT} \end{bmatrix} \begin{bmatrix} t_R \\ T'_R \end{bmatrix}$$

$$\begin{bmatrix} \bar{t}_{L0} \\ \bar{T}'_{L0} \end{bmatrix} \simeq \begin{bmatrix} 1+\frac{1}{2}\delta \bar{Z}^L_{tt} & \frac{1}{2}\delta \bar{Z}^L_{tT} \\ \frac{1}{2}\delta \bar{Z}^L_{Tt} & 1+\frac{1}{2}\delta \bar{Z}^L_{TT} \end{bmatrix} \begin{bmatrix} \bar{t}_L \\ \bar{T}'_L \end{bmatrix} \; , \; \begin{bmatrix} \bar{t}_{R0} \\ \bar{T}'_{R0} \end{bmatrix} \simeq \begin{bmatrix} 1+\frac{1}{2}\delta \bar{Z}^R_{tt} & \frac{1}{2}\delta \bar{Z}^R_{tT} \\ \frac{1}{2}\delta \bar{Z}^R_{Tt} & 1+\frac{1}{2}\delta \bar{Z}^R_{TT} \end{bmatrix} \begin{bmatrix} \bar{t}_R \\ \bar{T}'_R \end{bmatrix}$$

- For off-diagonal w.f.c. we use on-shell renormalization conditions:

$Re\Big($ 

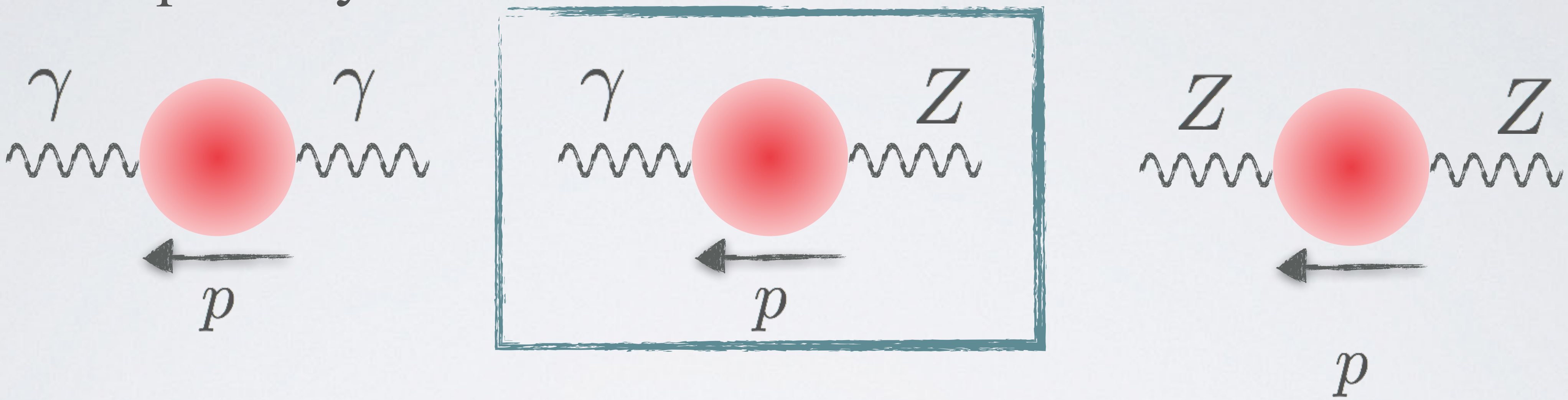
$u(p)\Big)\Big|_{p^2=M^2_{T'}} = 0$, $Re\Big(\bar{u}(p)$ 

$\Big)\Big|_{p^2=M^2_t} = 0$

- For diagonal w.f.c. use the mass pole and unite residue conditions.

Renormalizing the Lagrangian

- Due to mixing, we can't renormalize the photon and *Z* boson fields separately.



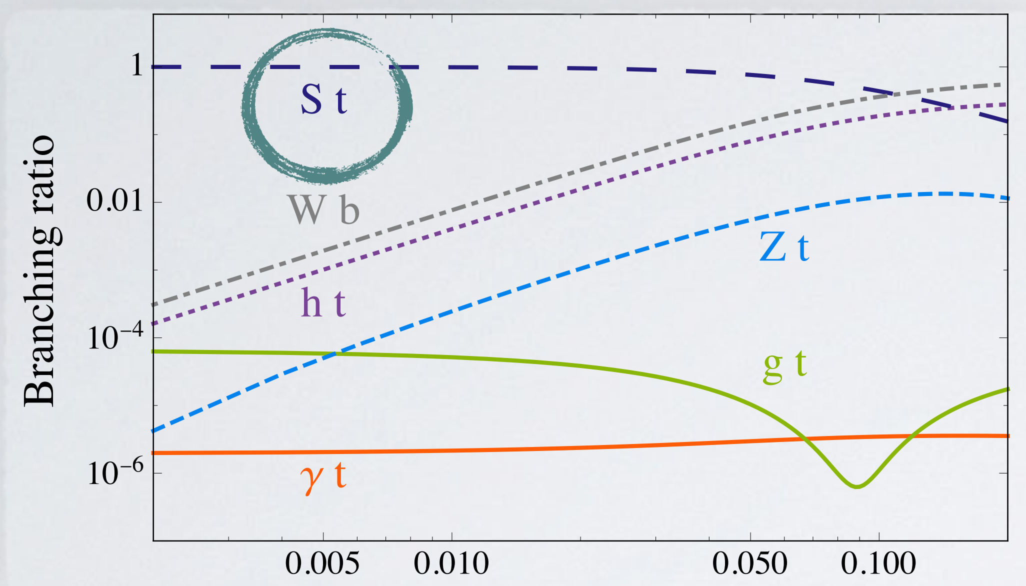
- Wave function renormalization constants (w.f.c.) for *A* and *Z* fields

$$\begin{bmatrix} A_0 \\ Z_0 \end{bmatrix} \simeq \begin{bmatrix} \sqrt{Z_\gamma} & -\Delta_Z - \Delta_0 \\ \Delta_0 & \sqrt{Z_Z} \end{bmatrix} \begin{bmatrix} A \\ Z \end{bmatrix}$$

$$\Delta_0 = \frac{\Pi_{\gamma Z}(0)}{M_Z^2} \qquad \Delta_Z = \frac{Re[\Pi_{\gamma Z}(M_Z^2)] - \Pi_{\gamma Z}(0)}{M_Z^2}$$

T' branching ratios ($M_{T'} > M_S + M_t$)

$M_{T'} = 1.5$ TeV
$M_S = 200$ GeV $\quad \lambda_1 = \lambda_2 = 1$



$\sin\theta_L \quad 10^{-1}$

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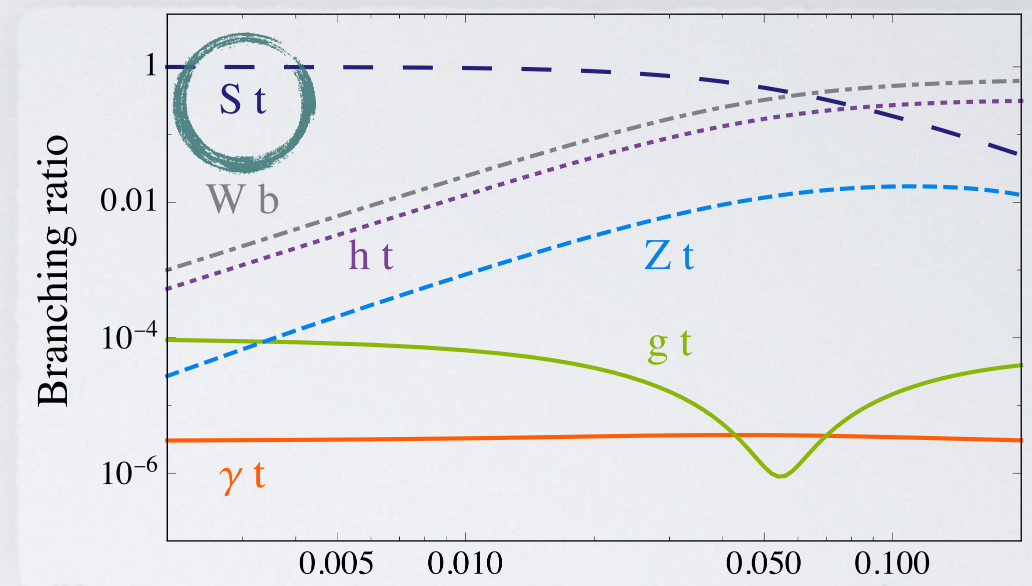
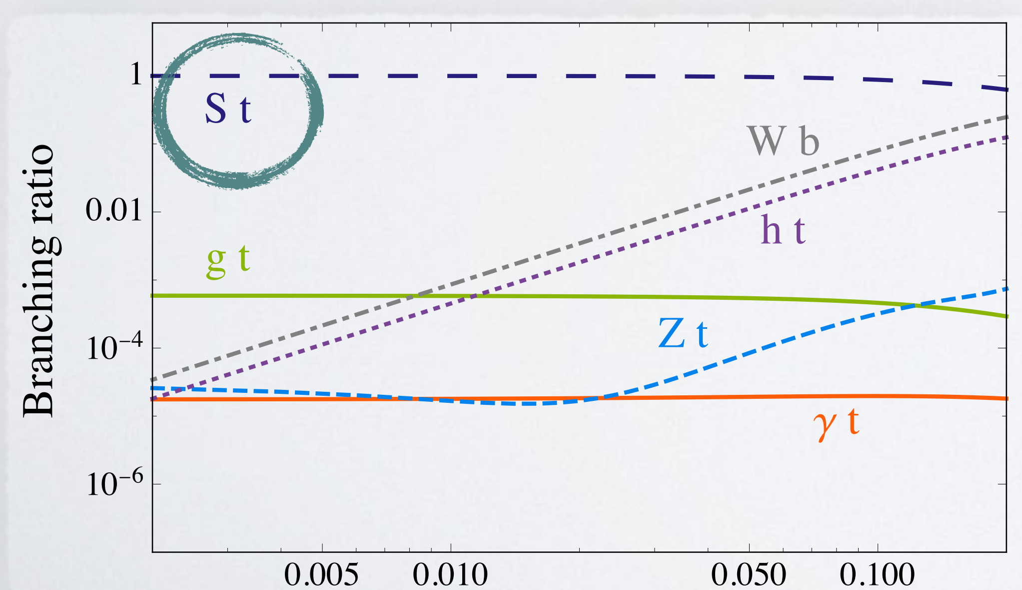


$\sin\theta_L \quad 10^{-1}$

$M_{T'} = 1.5$ TeV
$M_S = 200$ GeV $\quad \lambda_1 = \lambda_2 = 3$



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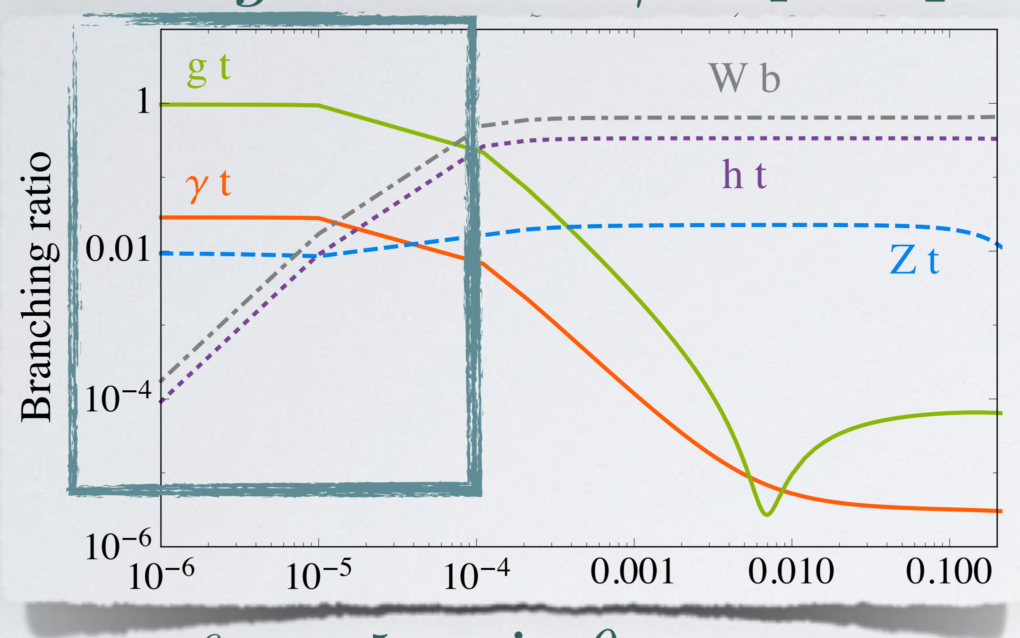
T' branching ratios ($M_{T'} < M_S + M_t$)

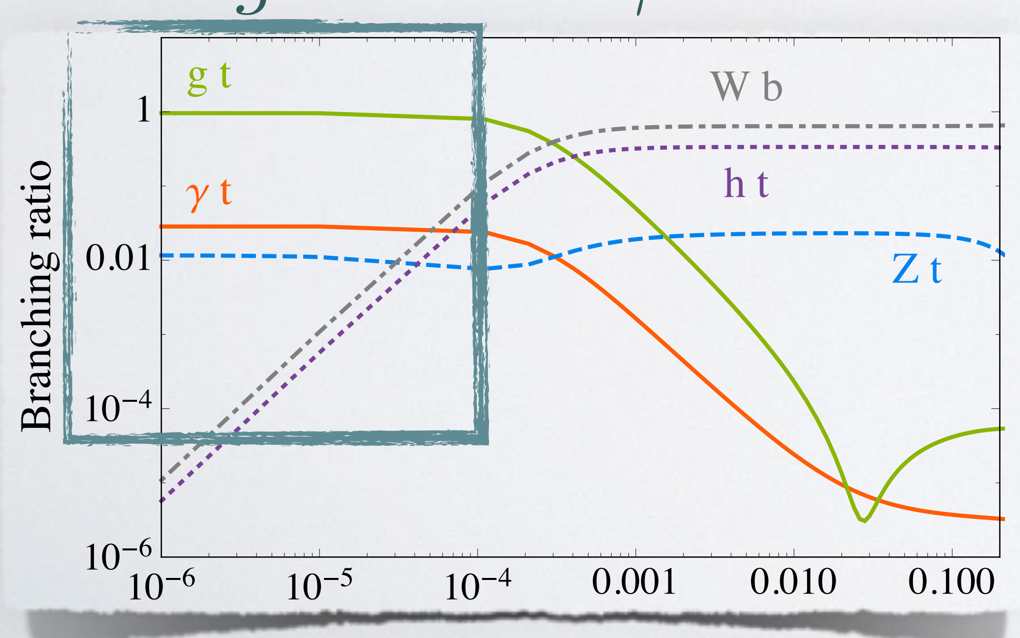
$M_{T'} = 1.5$ TeV
$M_S = 10$ TeV
$\lambda_1 = \lambda_2 = 1$

$T' \to tg$ $\quad T' \to t\gamma$



10^{-6} $\quad 10^{-5}$ $\quad \sin\theta_L$

$T' \to tg$ $\quad T' \to t\gamma$



10^{-6} $\quad 10^{-5}$ $\quad \sin\theta_L$

$M_{T'} = 1.5$ TeV
$M_S = 3$ TeV
$\lambda_1 = \lambda_2 = 1$

- But the tide changes, when $M_{T'}$ is lighter than M_S.
- There is a region of parameter space that T′ favourably decays into $t\,g$ or $t\,\gamma$.

$\mathrm{BR}(T' \to tg) \sim 97\%$

$\mathrm{BR}(T' \to t\gamma) \sim 2\%$

In the limit $\sin\theta_L \to 0$

- Conventional decay modes are off.