Maverick Vector Like Quarks
Loop Induced Decays

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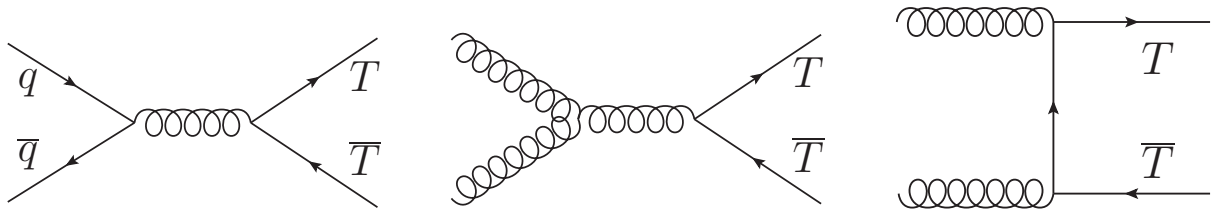
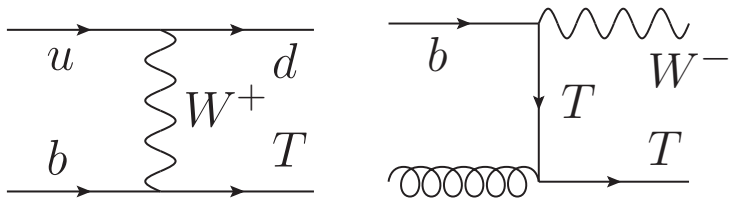
Traditional Searches

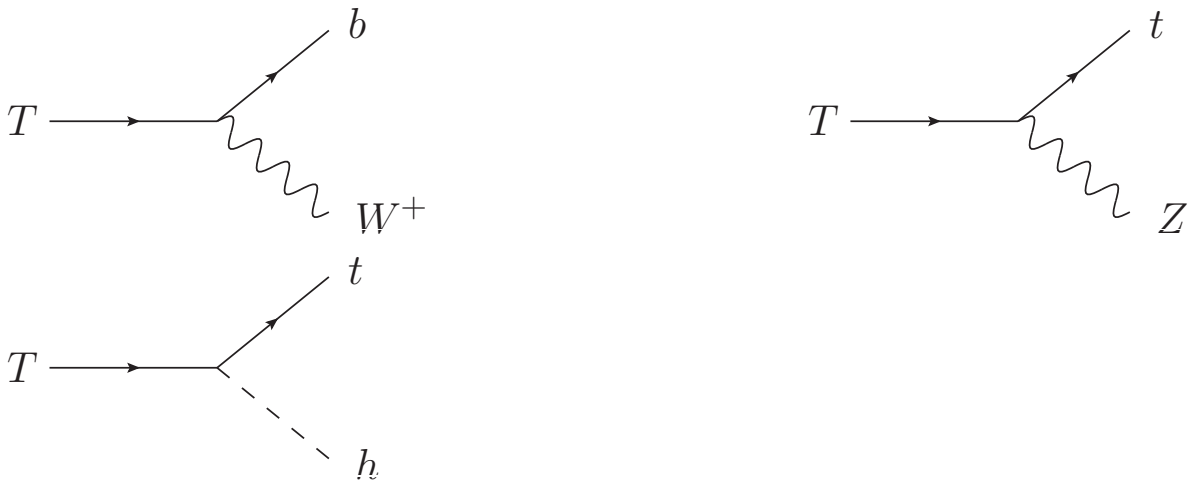
- By top partner we mean up-type vector-like quark. Not concerned with naturalness.
- Pair Production.:



  - Model independent but phase space limited at high masses.
- Single Production:

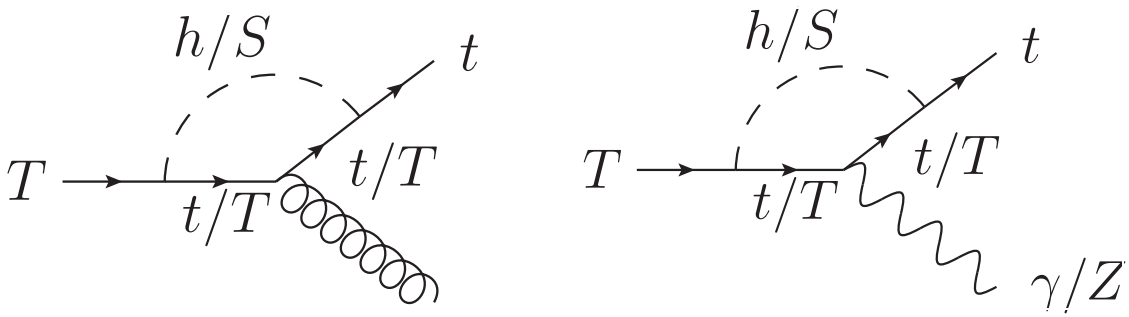


- Decays:



Maverick Top Partners

- "Maverick Top Partners"[1]: Vector-like quarks with non-traditional decays/production mechanisms.
- For example, scalar mediated loop induced decays:



[1] Name suggested by Doug McKay and KC Kong

Singlet Vector Like Quark+Singlet Scalar - Loop Induced decays

- Mass terms in usual simplified model:

$$-\mathcal{L}_{Yuk} = y_t \overline{Q}_L \widetilde{\Phi} t_{1R} + \lambda_t \overline{Q}_L \widetilde{\Phi} t_{2R} + M_2 \bar{t}_{2L} t_{2R} + \text{h.c.}$$

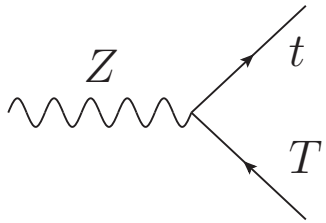
  - $\Phi = (0, (h+v)/\sqrt{2})^{\mathrm{T}}$ is the Higgs doublet.
  - 3^{rd} generation SM quarks: Q_L, t_{1R}
  - Vector-like $SU(2)_L$ singlet quark: t_2
- Add a scalar singlet S see also Dolan, Hewett, Krämer, Rizzo, JHEP 07 (2016) 039:

$$-\mathcal{L}_{Yuk} = \lambda_1 S \bar{t}_{2L} t_{1R} + \lambda_2 S \bar{t}_{2L} t_{2R} + h.c.$$

- Two off-diagonal terms: λ_t and λ_1
  - λ_t is responsible for mass mixing. Goes to zero as mixing angle vanishes.
  - λ_1 is independent of mixing, survives as mixing vanishes.

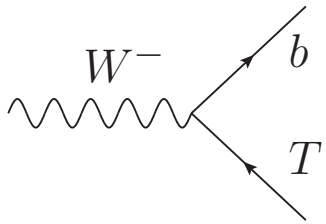
Off-Diagonal Feynman Rules

- $Z-t-T$:



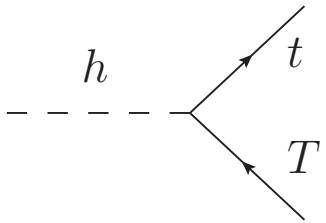
$$-i\frac{e}{2\cos\theta_W \sin\theta_W}\theta_L \gamma^\mu P_L + \mathcal{O}(\theta_L^2)$$

- $W-b-T$:



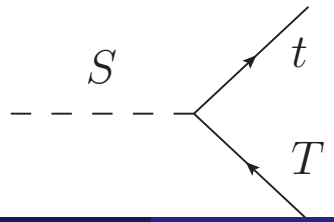
$$-i\frac{e}{\sin\theta_W}\sqrt{2}\theta_L \gamma^\mu P_L + \mathcal{O}(\theta_L^2)$$

- $h-t-T$:



$$i\sqrt{2}\theta_L \left(m_t P_L - m_T P_R\right) + \mathcal{O}(\theta_L^2)$$

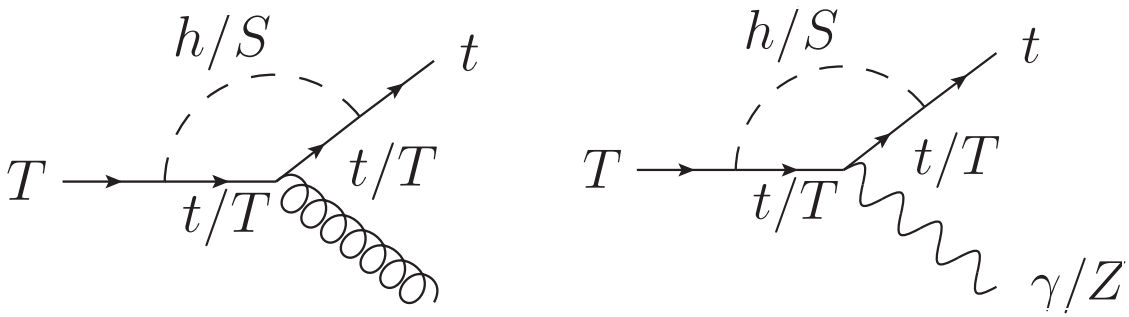
- $S-t-T$:



$$i\left(\lambda_1 P_L + \lambda_2 \theta_L \left(P_R - \frac{m_t}{m_T} P_L\right)\right) + \mathcal{O}(\theta_L^2)$$

Maverick Top Partners

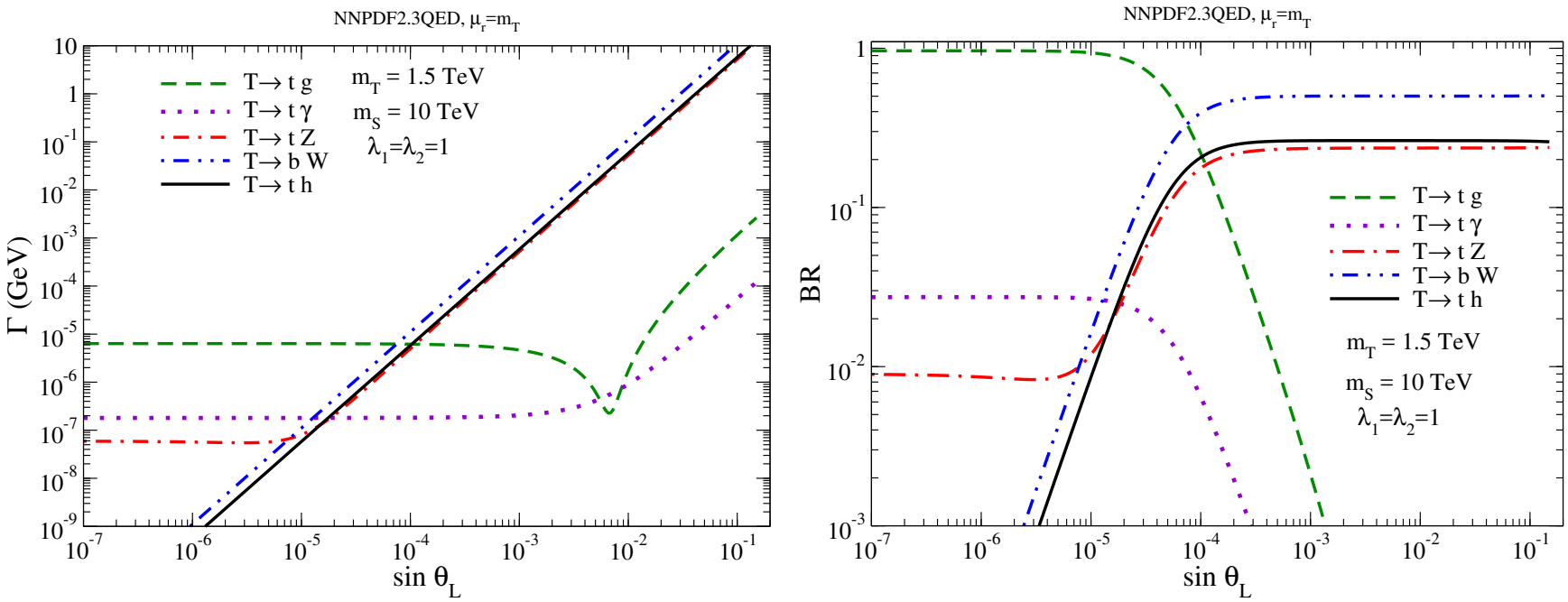
- "Maverick Top Partners"[2]: Vector-like quarks with non-traditional decays/production mechanisms.
- For example, scalar mediated loop induced decays:



[2]Name suggested by Doug McKay and KC Kong

Loop induced decays

- Loop induced decay $T \to tg$, $T \to t\gamma$ important as small angles:

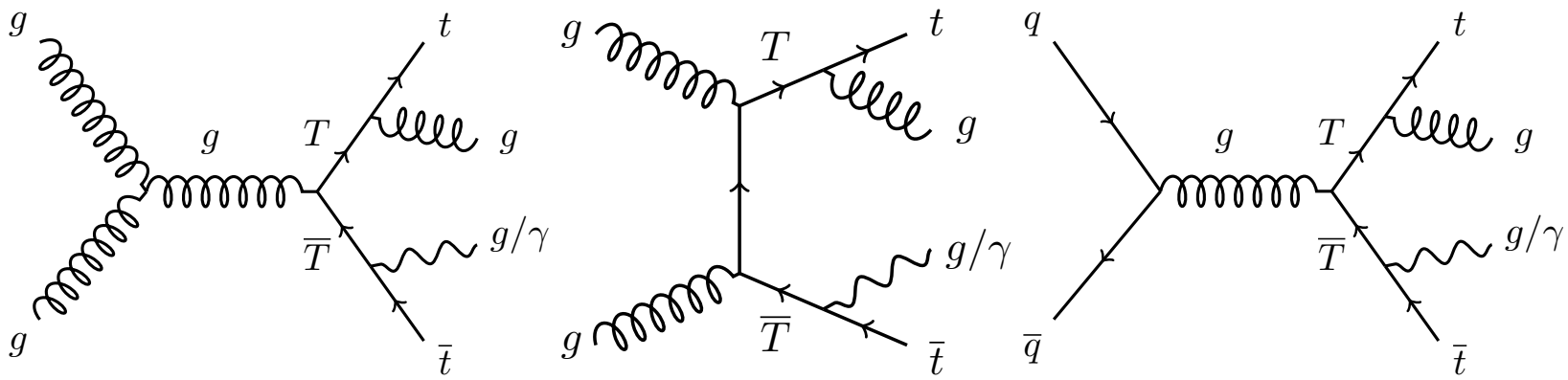


J.H. Kim, **I.M. Lewis**, JHEP 1805 (2018) 095

- At larger mixing angles: $\Gamma(T \to th) \sim \Gamma(T \to tZ) \sim \frac{1}{2}\Gamma(T \to bW)$
- These plots are assuming an $SU(2)$ singlet VLQ.

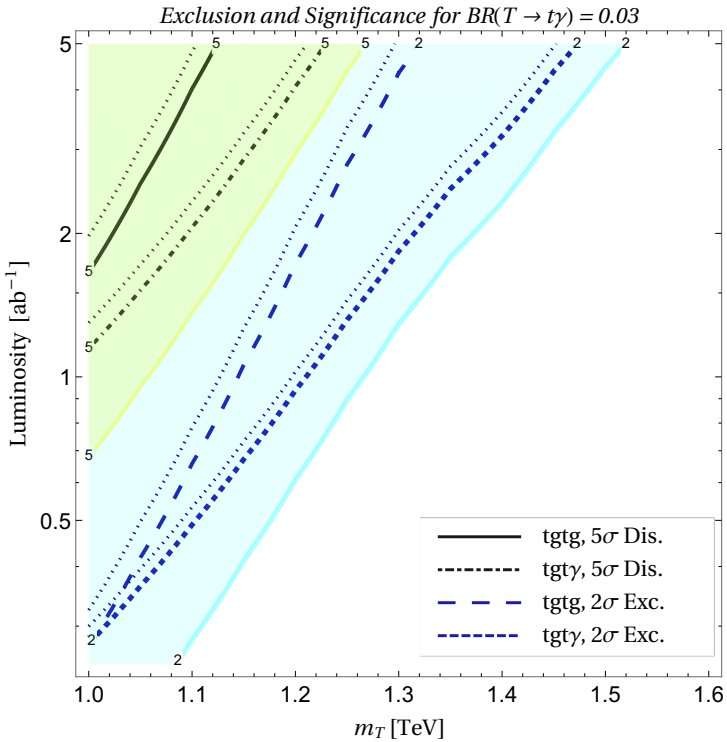
Collider Study for $m_S > m_T$

- CMS has a search for $pp \to T\overline{T} \to t\bar{t} + gg$ for spin-3/2 particle. Phys. Lett. B778 (2018) 349
- May also have $pp \to T\overline{T} \to t\bar{t} + g\gamma$:



- Even though BR$(T \to t\gamma) \sim 1\%$, signal is much cleaner.
- Additionally CMS did not consider boosted techniques.
- Study both $T\overline{T} \to t\bar{t} + gg$ and $T\overline{T} \to t\bar{t} + g\gamma$

Results for spin-1/2



$$\mathrm{BR}(T \to tg) = 0.97, \mathrm{BR}(T \to t\gamma) = 0.03$$

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- Blue: 2σ exclusion, Black: 5σ discovery
- Dotted: varying background by 20%.
- Blue shaded: combined 2σ exclusion
- Green shaded: combined 5σ discovery

Conclusions

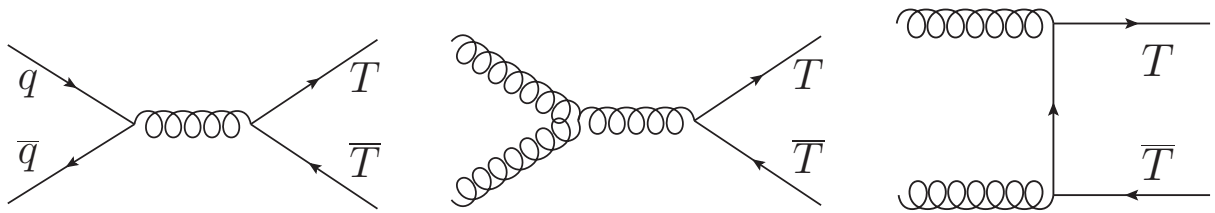
- Studied a model with a top partner and scalar singlet.
  - New loop induced decays $T \to tg$, $T \to t\gamma$, $T \to tZ$ are important.
  - Can also have new loop induced single production modes $pp \to Tt$
- Studied $T\overline{T} \to t\bar{t} + gg$ and $T\overline{T} \to t\bar{t} + g\gamma$ at the HL-LHC.
- We intend to update our studies for other possible future high energy colliders.

Thank You

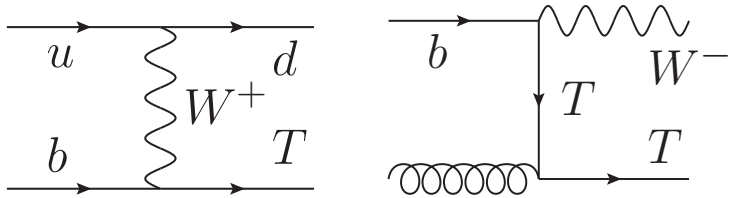
Backup Slides

New Single Production Modes for $SU(2)$ Singlet VLQ

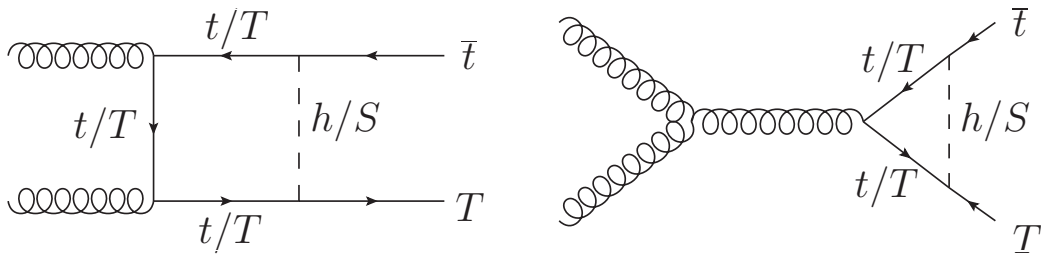
- Pair Production:



- Single Production:



- Scalar Mediated Loops:



  - Persists in the $\theta_L \to 0$ limit.

Collider Study for $m_S < m_T$

- We study loop induced single top partner production in association with a top partner:

$$pp \to T\bar{t} + t\overline{T}$$

- Considered zero-mixing scenario:

$$\theta_L = 0$$

- To maximize cross section, set

$$m_S = 110 \text{ GeV}$$

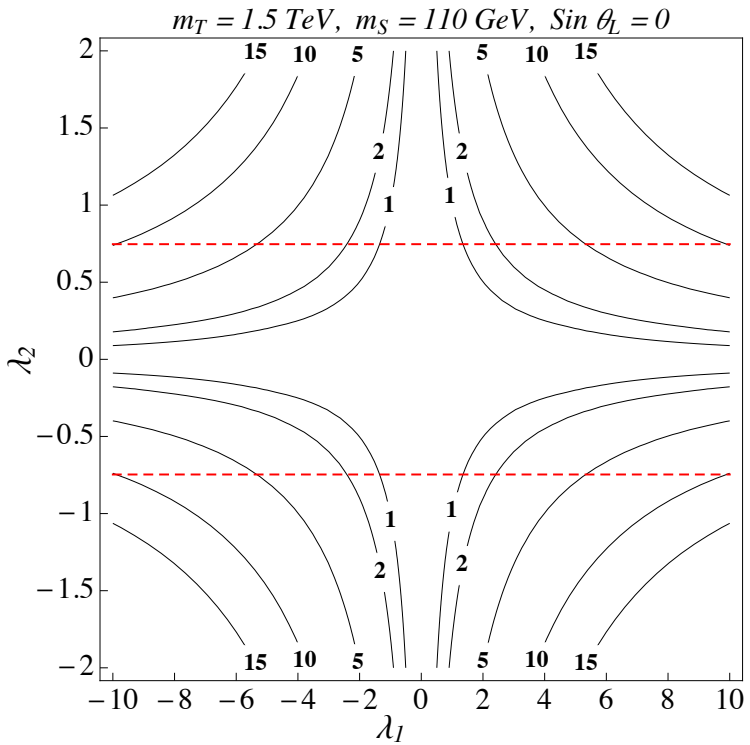
- Consider two benchmark mass:

$$m_T = 1.5 \text{ TeV} \quad \text{and} \quad m_T = 2 \text{ TeV}$$

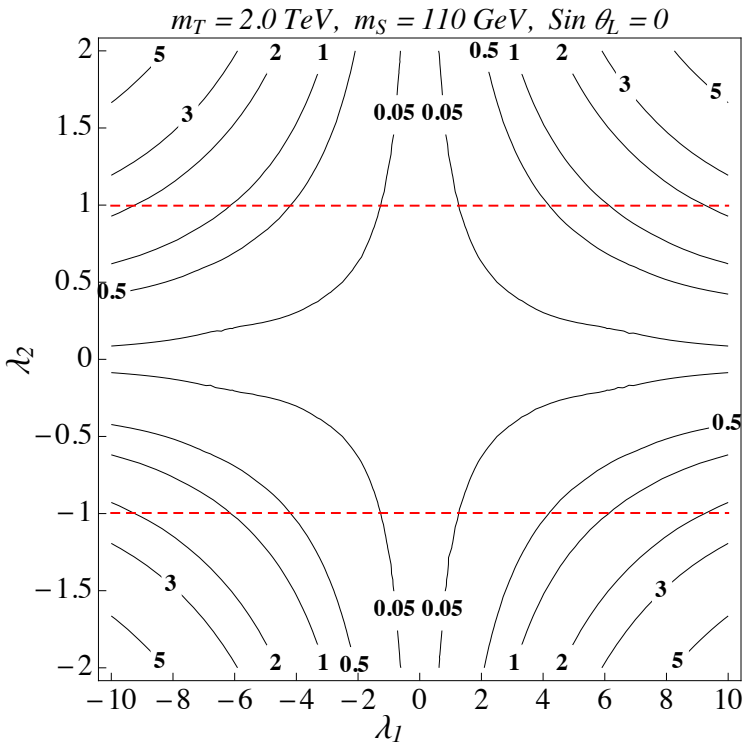
- In this case $T \to tS$ is by far the dominant decay mode.
  - S and at least one top quark are boosted.
- $S \to gg$ is by far the dominant decay mode.
- Signal considering semi-leptonic top decays:

$$pp \to T\bar{t} + t\overline{T} \to t\bar{t}S \to t\bar{t}gg \to \ell + 2b + 2q + gg + \not{E}_T$$

Results



$m_T = 1.5$ TeV



$m_T = 2$ TeV

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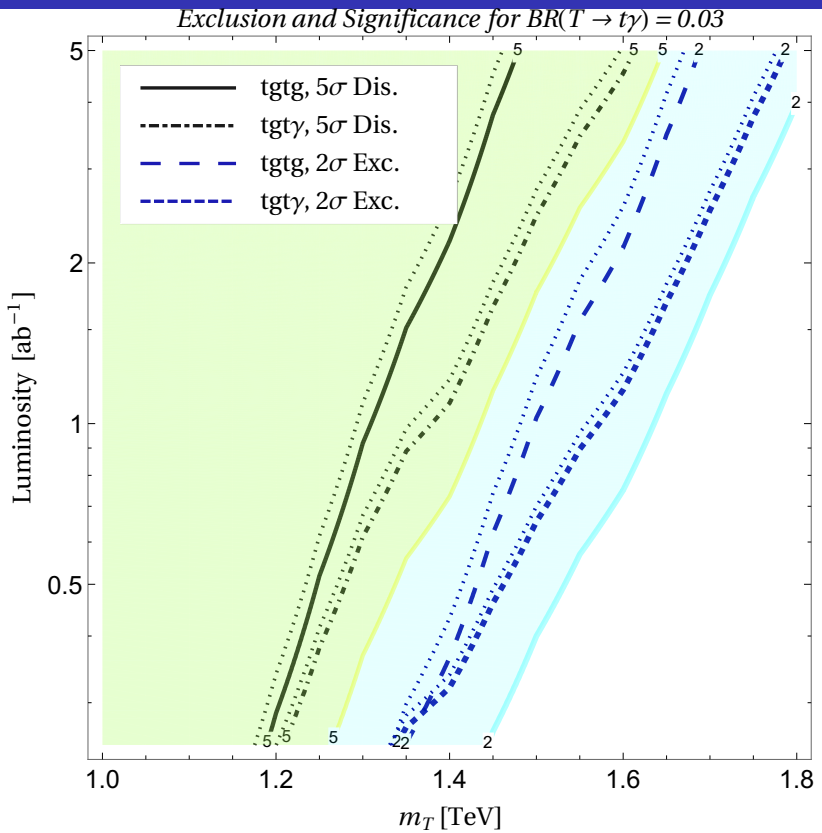
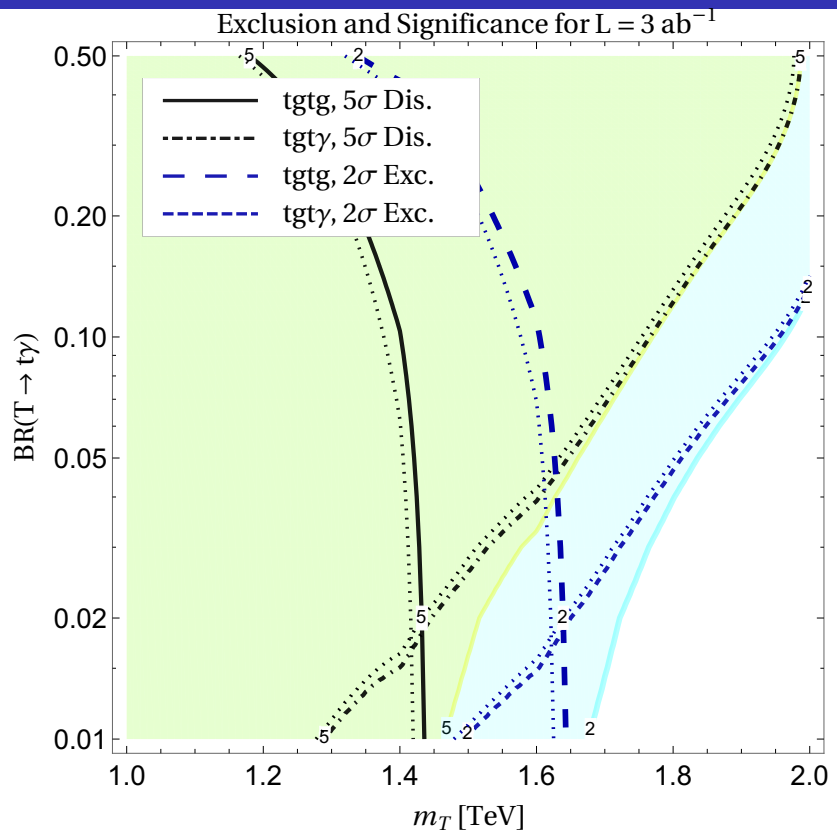
- Solid black lines: Contours of constant significance for $t\overline{T} + T\bar{t}$ at 3 ab^{-1}
- Dashed red lines: Expected limits from $S \to \gamma\gamma$ at 3 ab^{-1}.
- LHC can exclude:
  - $\sqrt{|\lambda_1\lambda_2|} \gtrsim 1.35$ for $m_T = 1.5$ TeV
  - $\sqrt{|\lambda_1\lambda_2|} \gtrsim 3.04$ for $m_T = 2$ TeV

Results for spin-3/2





$\mathrm{BR}(T \to tg) = 0.97, \mathrm{BR}(T \to t\gamma) = 0.03$

$\mathrm{BR}(T \to tg) = 1 - \mathrm{BR}(T \to t\gamma)$

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