Loop Induced Single Top Partner Production and Decay at the LHC

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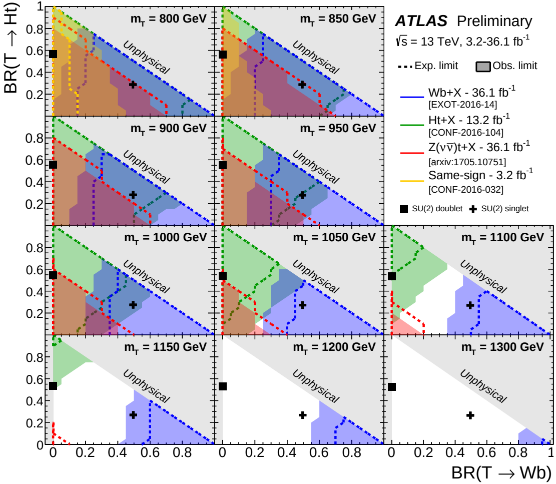
J.H. Kim, **I.M. Lewis** JHEP 1805 (2018) 095

July 5, 2018
ICHEP 2018
Seoul

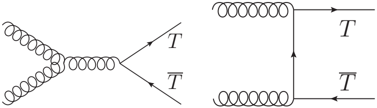
Top Partners

- Traditionally important because they help solve the naturalness problem of the SM.
- Many searches at LHC:



Traditional Searches

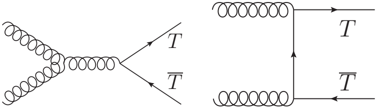
- Pair Production:



  - Model independent but phase space limited at high masses.

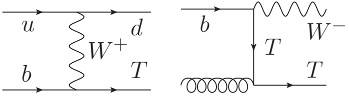
Traditional Searches

- Pair Production:

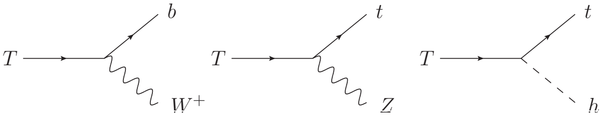


  - Model independent but phase space limited at high masses.

- Single Production:



- Decays:



  - Single production and decays limited by top-partner/top mixing angle.

The Model

- Introduce $SU(2)_L$ singlet vector-like top partner: t_2
- Introduce gauge singlet scalar S
- Only consider interactions with 3rd generation SM quarks:

$$Q_L = \begin{pmatrix} t_{1L} \\ b_L \end{pmatrix}, \quad t_{1R}, \quad b_R$$

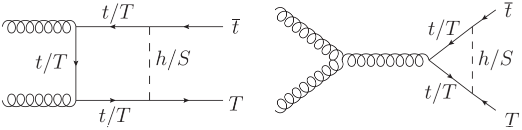
- Yukawa interactions:

$$\begin{aligned} -\mathcal{L}_{Yuk} &= y_b \overline{Q}_L \Phi b_R + y_t \overline{Q}_L \widetilde{\Phi} t_{1R} + \lambda_t \overline{Q}_L \widetilde{\Phi} t_{2R} + M_2 \bar{t}_{2L} t_{2R} \\ &\quad + \lambda_1 S \bar{t}_{2L} t_{1R} + \lambda_2 S \bar{t}_{2L} t_{2R} + h.c. \end{aligned}$$

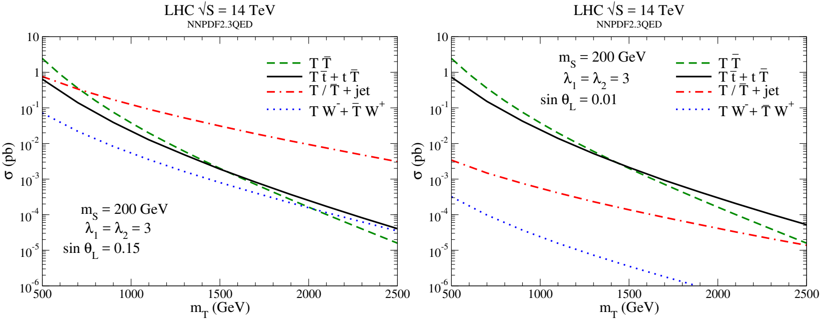
  - Two mass eigenstates t, T with masses $173 \text{ GeV} = m_t < m_T$.
  - One independent mixing angle between: θ_L
  - λ_t is source of mixing and goes to zero as mixing angle vanishes.
  - λ_1 unrelated to mixing, survives as $\theta_L \to 0$.
- We neglect scalar-Higgs mixing for simplicity. See Dolan, Hewett, Krämer, Rizzo, JHEP 07 (2016) 039 for tree level analysis with non-zero scalar-Higgs mixing.

New Single Production Modes

- Scalar mediated loops:

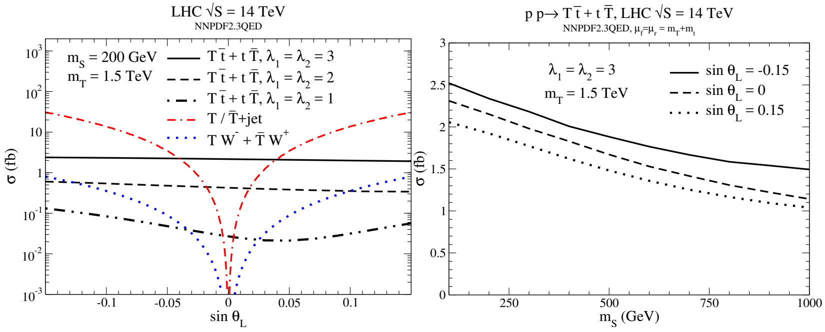


- Important at small mixing angles:



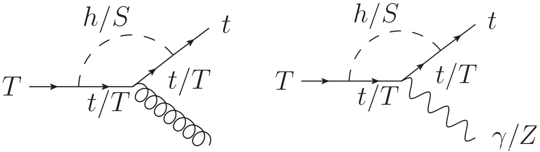
New Single Production Mode

- Important at small mixing angles and small scalar masses:

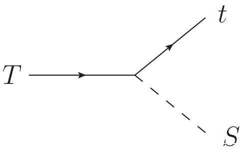


New Decay Modes

- Scalar mediated loops:

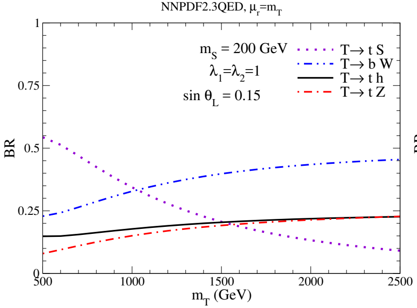


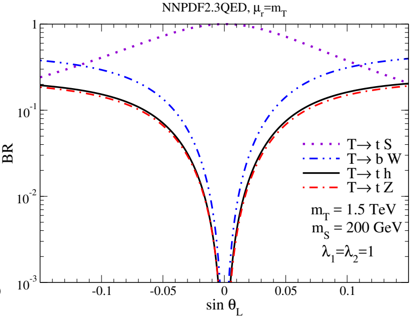
- New tree level decay:



$m_S < m_T$ and $T \to tS$ is allowed

- Important at small angles and small T mass.





- In limit $v, m_S \ll m_T$:

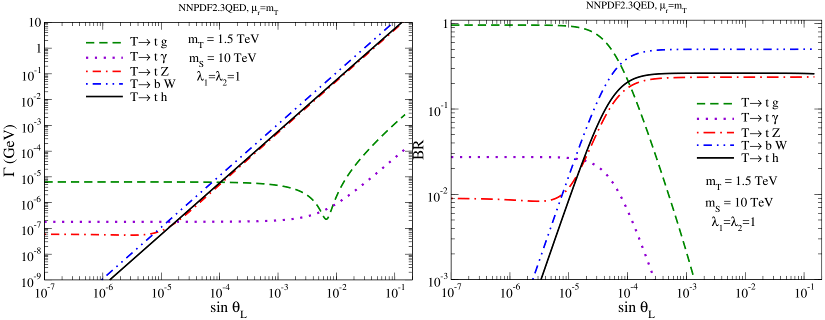
$$\Gamma(T \to th) \sim \Gamma(T \to tZ) \sim \frac{1}{2}\Gamma(T \to bW) \sim \frac{m_T^3 \sin^2\theta_L}{32\pi v^2}$$

$$\Gamma(T \to tS) \sim \frac{\lambda_1^2 m_T}{32\pi}$$

- Rates to SM final states suppressed by $\sin^2\theta_L$ and obey equivalence theorem.
- Rates to SM final states grow as m_T^3 while to S it grows as m_T.

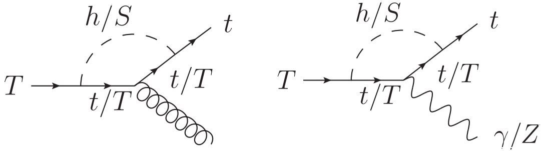
$m_S > m_T$ and $T \to tS$ is forbidden

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



- At larger mixing angles: $\Gamma(T \to th) \sim \Gamma(T \to tZ) \sim \frac{1}{2}\Gamma(T \to bW)$

- At smaller mixing angles, loop induced decays dominate:

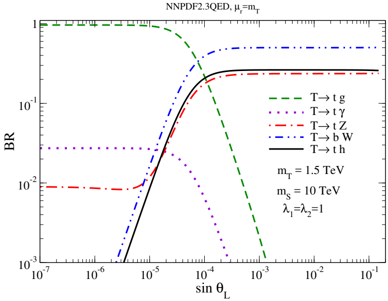


- Same couplings, except different gauge couplings:

$$\Gamma(T \to tg) : \Gamma(T \to t\gamma) : \Gamma(T \to tZ) = g_s^2 C_F : (eQ_t)^2 : (e\,Q_t \tan\theta_W)$$

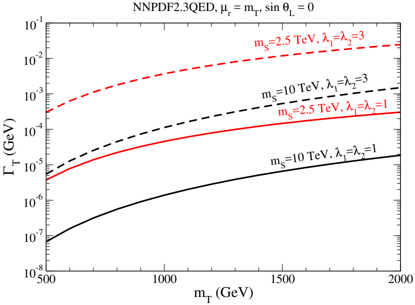
- This fixes the branching ratios:

$$\mathrm{BR}(T \to tg) = 0.9725, \mathrm{BR}(T \to t\gamma) = 0.021, \mathrm{BR}(T \to tZ) = 0.00601$$



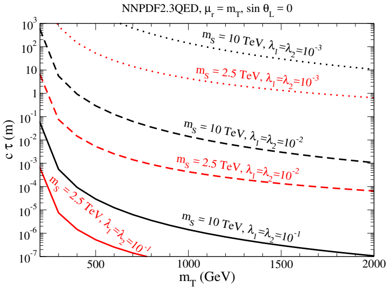
Width for $m_S > m_T$ and $\theta_L = 0$

- Due to loop induced decays at small mixing angles, the width of the top partner is small:



- Almost always hadronizes before it decays. See M. Buchkremer, A. Schmidt, Adv. High Energy Phys. (2013) 690354
- Can form heavy quarkonia if $\Gamma_T \lesssim \frac{C_F^2}{4}\alpha_s^2(m_T)m_T = 4\,\text{GeV}\left(\frac{\alpha_s(m_T)}{\alpha_s(1\,\text{TeV})}\right)^2\frac{m_T}{1\,\text{TeV}}$

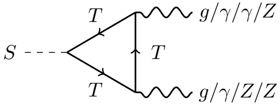
Decay length for $m_S > m_T$ and $\theta_L = 0$



- **Prompt decays**: Impact parameter $\lesssim 500\ \mu$m
- **Displaced vertices**: Reconstruct decay vertex for $c\tau \sim O(1\text{ mm}) - O(1\text{ m})$
- **"Stable" particles**: Escape detector for $c\tau \gtrsim O(1\text{ m})$
- **Stopped particles**: top inside hadronic calorimeter. Searched for as decays out of time with bunch crossings for $\tau \gtrsim O(100\text{ ns})$
- Very different phenomenology even for not too small couplings.

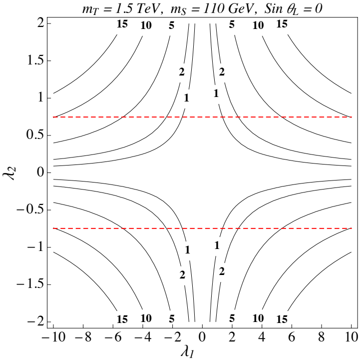
Collider Study

- We studied loop induced single top partner production in association with a top partner: $T\bar{t}+t\overline{T}$.
- Considered zero-mixing scenario: $\theta_L = 0$.
- To maximize cross section, set $m_S = 110$ GeV.
- In this case $T \to tS$ is by far the dominant decay mode.
- Without Higgs mixing, the possible scalar decays are loop induced through the top partner:

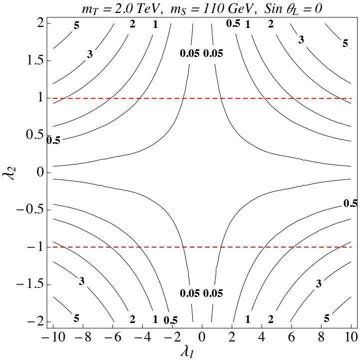


  - Branching ratios governed by gauge couplings.
  - $S \to gg$ is by far the dominant decay mode.
- Signal: $T\bar{t}+t\overline{T} \to t\bar{t}S \to t\bar{t}gg \to \ell + 2b + 2q + gg + \not{E}_T$
- Used boosted techniques to reconstruct tops and scalars. See J.H. Kim, **I.M. Lewis**, JHEP 1805 (2018) 095 for details.

Results



$m_T = 1.5$ TeV



$m_T = 2$ TeV

- Solid black lines: Contours of constant significance at 3 ab^{-1}
- Dashed red lines: Expected limits from production and decay of scalar S at 3 ab^{-1}.
- For reasonable coupling constant values start to be sensitive to new regions of parameter space.

Conclusions

- Studied a model with a top partner and scalar singlet.
  - Small extension of usual top partner simplified models.
  - May expect both in composite Higgs scenarios.
- For scalar mass larger than top partner mass:
  - New loop induced decays $T \to tg$, $T \to t\gamma$, $T \to tZ$ are important.
  - Top partner can be quite long lived. Qualitatively different phenomenology.
- For scalar masses less than top partner mass:
  - New loop induced production modes $gg \to T\bar{t} + t\overline{T}$ and $q\bar{q} \to T\bar{t} + t\overline{T}$ can be important at high m_T.
  - The new decay mode $T \to tS$ dominant at small mixing angles.
  - Studied $T\bar{t} + t\overline{T}$ with top partner decay $T \to tS \to tgg$
    - With 3 ab^{-1} LHC can be sensitive to new regions of parameter space.

Thank You