Vectorlike top production via a chromomagnetic moment at the LHC

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Context:

Dynamical or composite theories of the large top quark mass often include TeV-scale vectorlike top quark (T) and bottom quark (B) partner states accessible at the LHC. T and B can potentially lie in various electroweak representations and generally carry color charge.

LHC searches for T and B partner states have mainly focused on

- QCD-induced pair production of TT or BB (for lighter partner states)
- Electroweak production of a single T or B, decaying into a third-generation quark and an electroweak scalar or vector boson (for heavier partner states)

These searches produce lower bounds on T or B masses of 1-1.5 TeV; details depend on the assumed dominant decays of the partner state.

Scenarios with both B and T states offer discovery channels that cover higher masses and otherwise inaccessible areas of parameter space.

B partners

The strongest single-production limits on B states are from searches seeking "excited b quarks" produced through bg-fusion via a chromomagnetic moment operator

$$\frac{g_s}{\Lambda}\ \bar{b}_{R,L}\sigma^{\mu\nu}G_{\mu\nu}B_{L,R}$$

Such an interaction occurs naturally if ordinary quarks and their partners are composite states (arising from a dynamical theory of flavor and electroweak symmetry breaking) and share constituents.

Current LHC bounds from single production of an excited B decaying to tW or bg set limits of order $M_{B_1} > 1.2 - 1.6\ \mathrm{TeV}$

New possibilities arise if both T and B are present and form a single electroweak multiplet.

T and B in a single electroweak multiplet

In this context there are two ways to extend searches for T and B vectorlike partners by considering the effects of the (usually neglected) chromomagnetic interactions.

1. If B is heavier than T, then B will be produced via bg fusion through the operator above ($\frac{g_s}{\Lambda}\,\bar{b}_{R,L}\sigma^{\mu\nu}G_{\mu\nu}B_{L,R}$) and will decay to TW

2. Since T is also a color-triplet composite fermion, it will have its own chromomagnetic operator $$\frac{g_s}{\Lambda}\,\bar{t}_{R,L}\sigma^{\mu\nu}G_{\mu\nu}T_{L,R}$$

This enables associated single production of T via gg → Tt

Signal kinematics are distinctive

The kinematics of bg → B → TW and gg → tT are very similar: each yields a heavy T associated with a much lighter SM state (W or t). This provides a highly distinctive signature.

Consider, for instance, gg → **t**T → **t** **t** h

- The **t** is dominantly produced at threshold.
- The **t** and h produced from T → **t**h are each highly boosted "fat jets".

Combinatorial issues usually make tth events hard to reconstruct.

- Here, the different kinematics of **t** and **t** unambiguously distinguish them.
- One could therefore combine the fat **t** jet and fat h jet (if h → bb) to seek an invariant mass peak that would reveal the presence of the T state.

Background kinematics don’t resemble signal

- The **tt+jet background** would have the same composition as the signal and nominally has a large cross-section.
  - However, only radiation of an unusually hard gluon would enable one of the top quarks to be as near-threshold as in the signal case.
  - Moreover, the kinematics would not resemble the signal’s at all
    - Combining g + softer t should reveal reveal an invariant mass peak at mt
    - Combining g + harder t should not yield anything distinctive.
- The **ttW background** would be only electroweak in rate.
  - Again, its kinematics would differ from the signal’s; there would be no reason for one of the tops to be significantly boosted relative to the other.

tl;dr

For compositeness scales Λ in the few to tens of TeV regime, the two proposed channels

$$pp \to B_1 \to T_1 W \to (th)W$$

$$pp \to T_1 t \to (th)t$$

- complement conventional searches for a heavy vectorlike quark via either pair or single production, as well as those for single excited b quark production.
- extend the LHC's reach for vectorlike partner quarks at run III and HL-LHC into interesting regions of model parameter space

Simplified Model: gauge eigenstates

We consider a simple extension of the SM with new <u>composite</u> EW doublets and singlets of vector-like fields directly associated with generating the top-quark mass:

$$Q^0_{L,R} = \begin{pmatrix} T^0_{L,R} \\ B^0_{L,R} \end{pmatrix} \quad \text{and} \quad \tilde{T}^0_{L,R}$$

These new gauge eigenstates couple to their <u>elementary</u> SM top and bottom counterparts and the SM Higgs doublet via mass mixings

$$\mathcal{L}_{\text{mass}} = -M_Q \overline{Q^0_L} Q^0_R - M_{\tilde{T}} \overline{\widetilde{T}^0_L} \widetilde{T}^0_R - \left(y^* (\overline{Q^0_L} \cdot \Phi^\dagger) \widetilde{T^0_R} + \Delta_L \overline{q^0_L} Q^0_R + \Delta_R \overline{t^0_R} \widetilde{T}^0_L + \text{H.c.} \right).$$

We assume the Higgs is composite, so we neglect its direct couplings to elementary quarks.

Simplified Model: chromomagnetic couplings

The gauge eigenstates mix to form mass eigenstates t, T_1, T_2, b, B_1

Partial compositeness generally predicts d=5 chromomagnetic interactions at the EW scale [where $\mathcal{Q} = Q^0 \text{ or } \tilde{T}^0$]

$$\mathcal{L}_{\text{chromo}} = \frac{g_s}{\Lambda} \overline{\mathcal{Q}_L} \sigma^{\mu\nu} G_{\mu\nu} \mathcal{Q}_R + \text{H.c.}$$

The mixing of SM and partner gauge eigenstates yields off-diagonal chromomagnetic interactions between a single third-generation mass eigenstate and a single heavy partner eigenstate:

$$\frac{g_s}{\Lambda} G_{\mu\nu} \left[\mathcal{C}_1 \overline{T}_{1R} \sigma^{\mu\nu} t_L + \mathcal{C}_2 \overline{T}_{1L} \sigma^{\mu\nu} t_R + \mathcal{C}_3 \overline{T}_{2R} \sigma^{\mu\nu} t_L + \mathcal{C}_4 \overline{T}_{2L} \sigma^{\mu\nu} t_R + \mathcal{C}_5 \overline{B}_{1R} \sigma^{\mu\nu} b_L + \text{H.c.} \right]$$

Simplified Model: parameter space

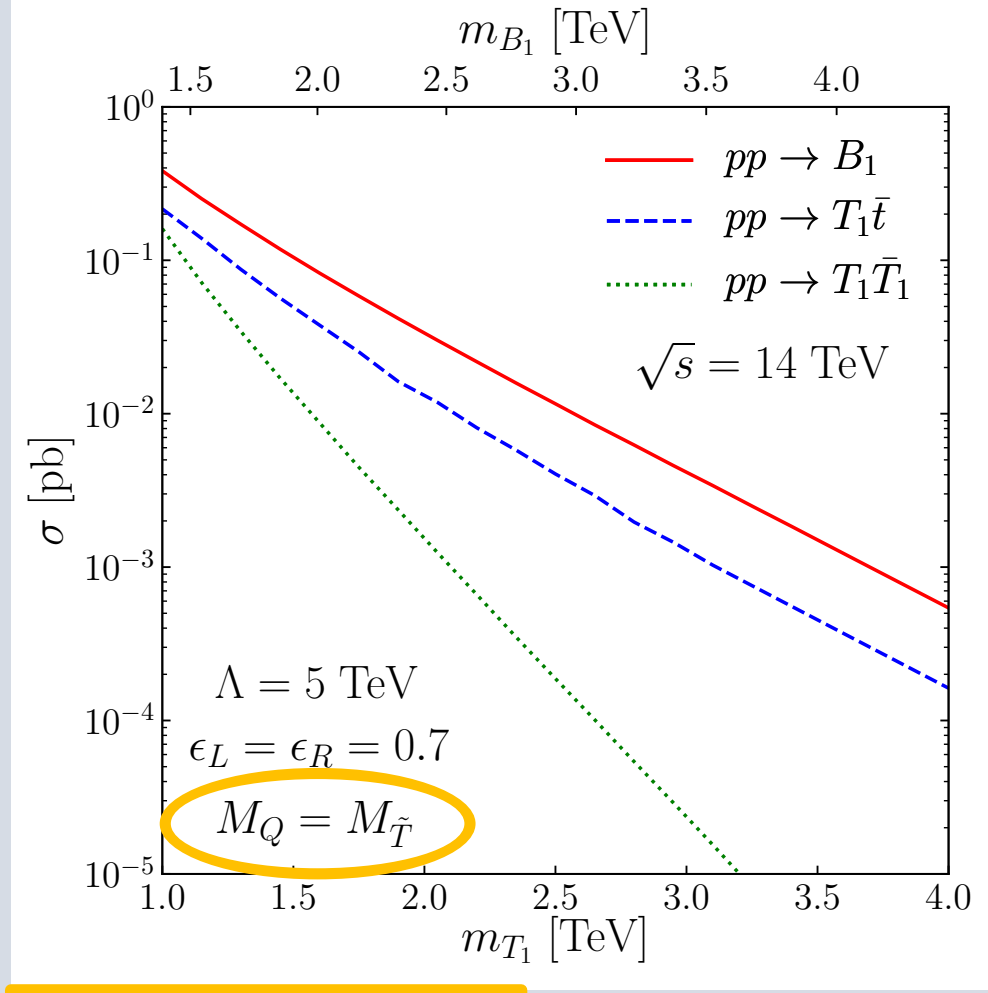
This model is determined by five independent mixing parameters and the compositeness scale. Fixing m_t at the SM value, we have the following five quantities to track:

$$\left\{ \epsilon_L = \frac{\Delta_L}{M_Q}, \quad \epsilon_R = \frac{\Delta_R}{M_{\tilde{T}}}, \quad m_{T_1}, \quad \frac{M_Q}{M_{\tilde{T}}} \quad , \quad \Lambda \right\}$$

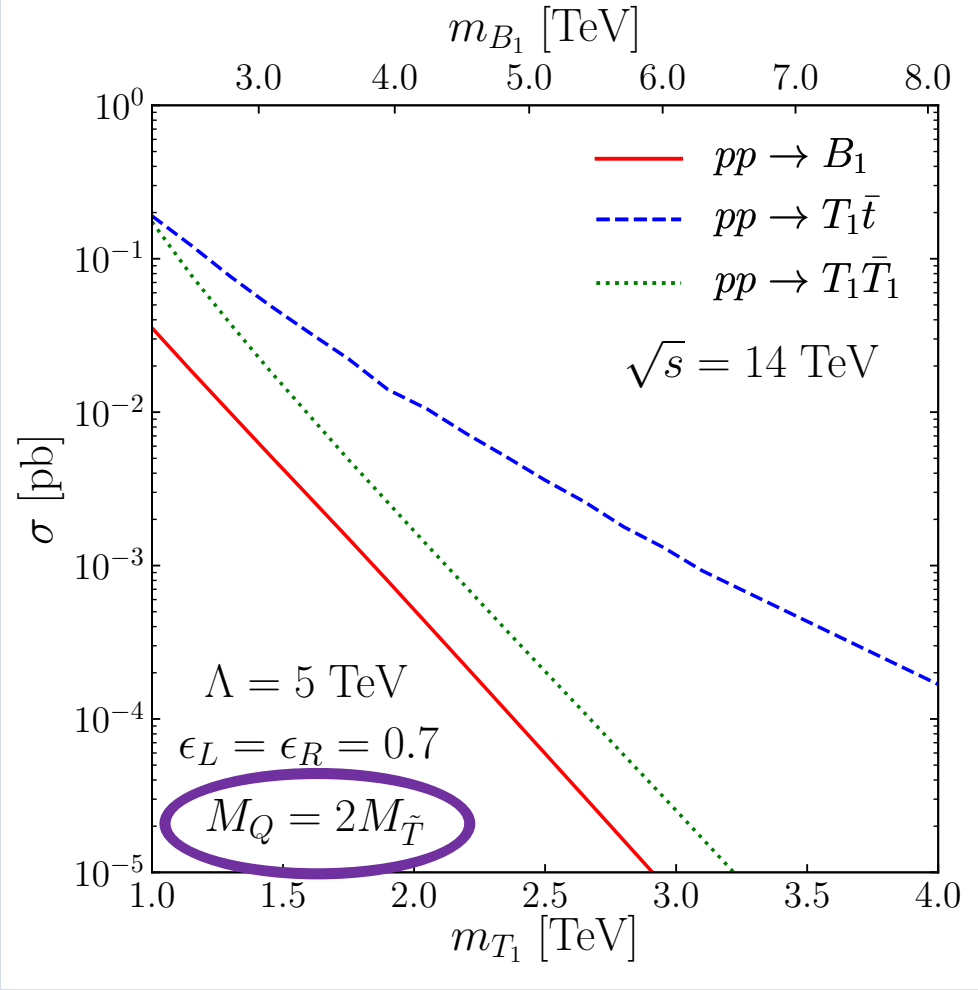
We explore variations in

- degrees of overall SM/partner mixing (scale of ϵ's)
- relative sizes of q^0_L and t^0_R mixing with partners ($\epsilon_L \ \mathrm{vs} \ \epsilon_R$)
- Doublet-to-singlet mass ratio, which controls decoupling of T_2 and singlet-vs-doublet nature of T_1 and T_2. ($M_Q/M_{\tilde{T}}$)

Production of B_1 and T_1 states at LHC

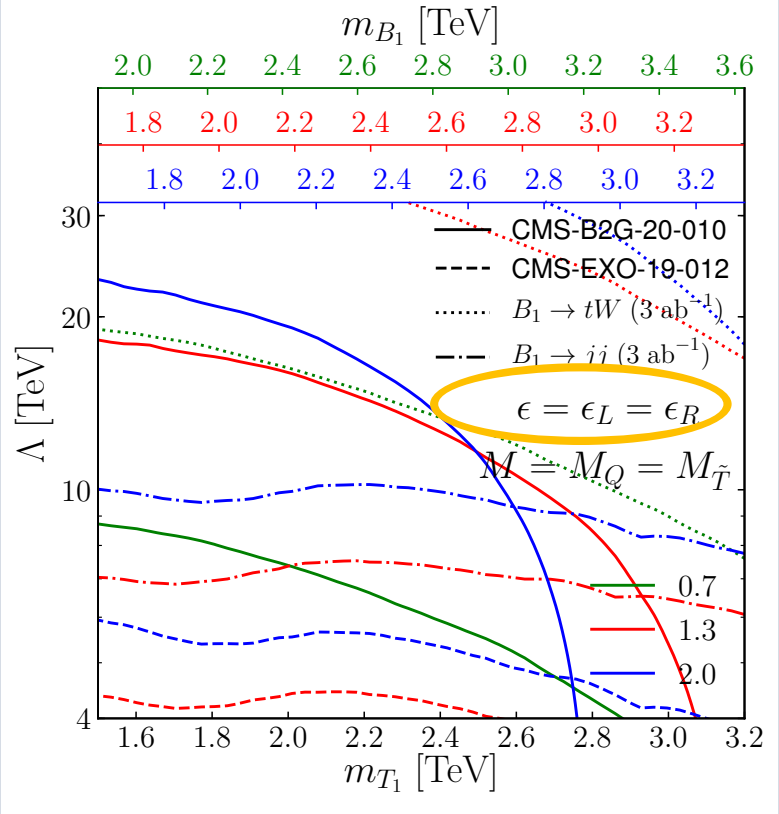


B_1 and T_1 masses similar

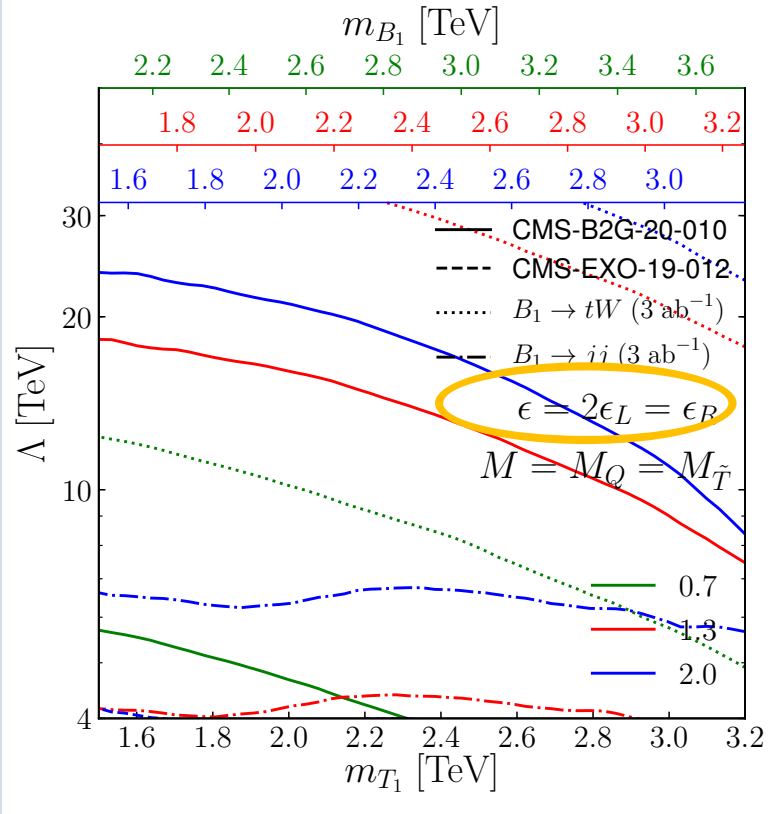


B_1 much heavier than T_1

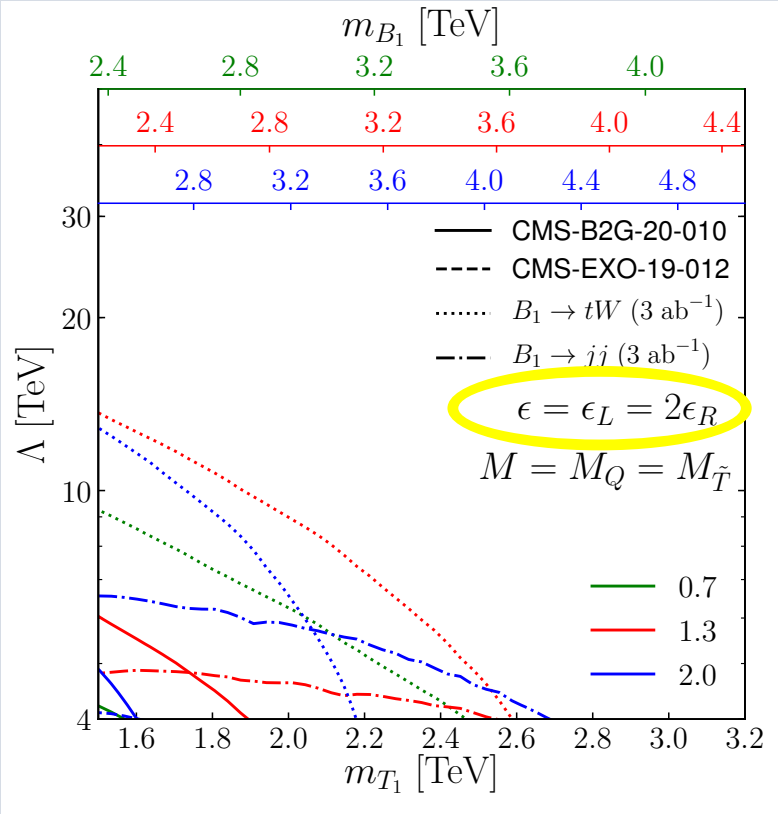
Recasting "excited b quark" searches



$B_1 \to bg, tW$ dominate



$B_1 \to tW$ dominates



$B_1 \to T_1 W$ dominates

Significant coverage of parameter space now [solid, dashed] and further reach projected for the HL-LHC era [dotted, dot-dashed]

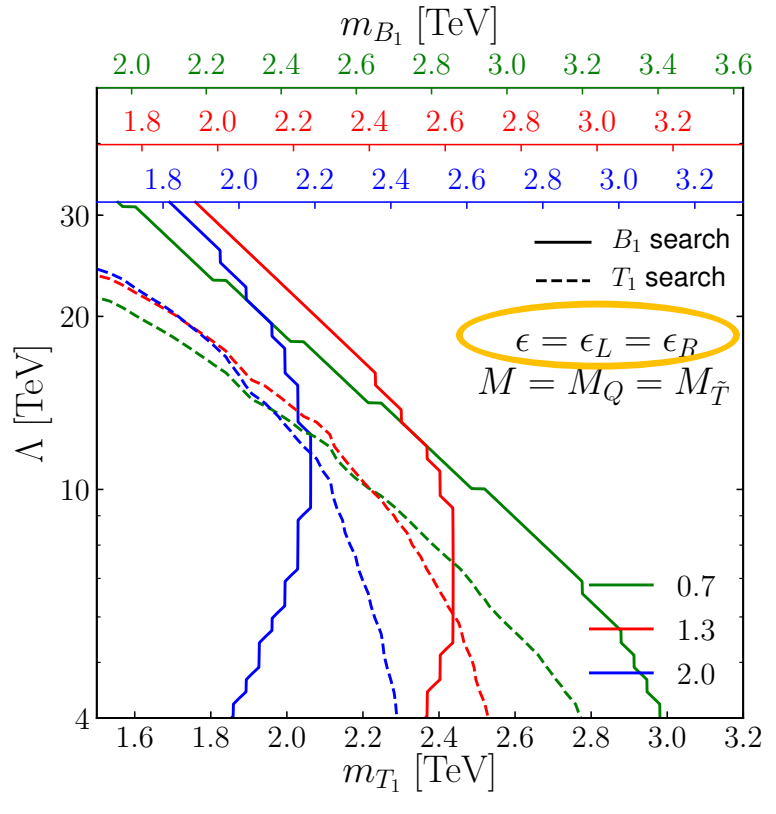
No coverage now and limited projected future coverage

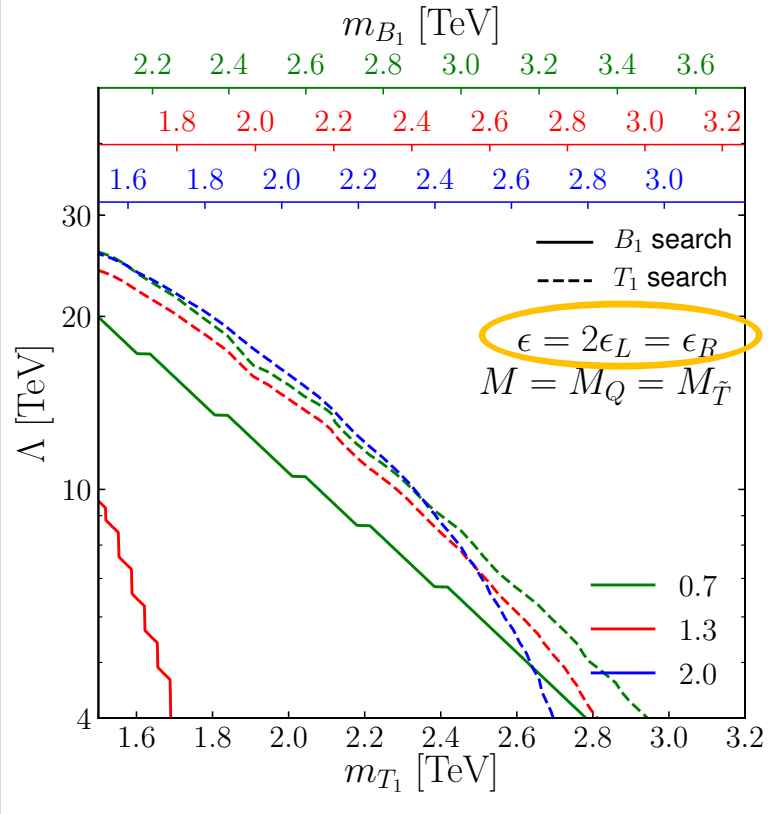
Proposed new searches: $pp \to B_1 \to T_1 W$ & $pp \to T_1 t$

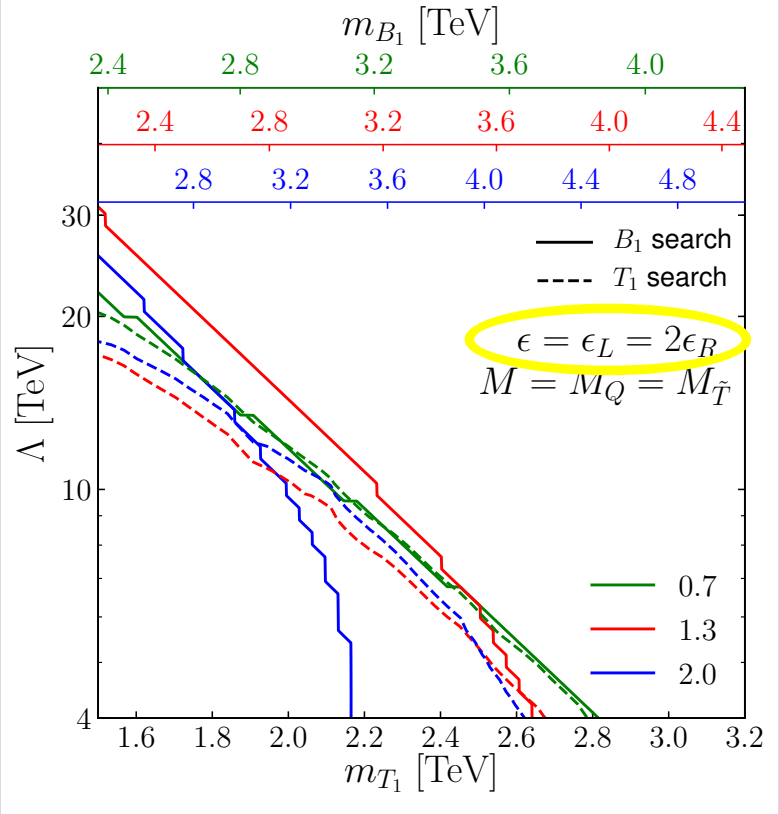
$$pp \to B_1 \to T_1 W \to (th)W \quad \mathrm{with} \quad h \to bb$$

$$pp \to T_1 t \to (th)t \quad \mathrm{with} \quad h \to bb$$

Proposed new searches when $M_{B1} \approx M_{T1}$



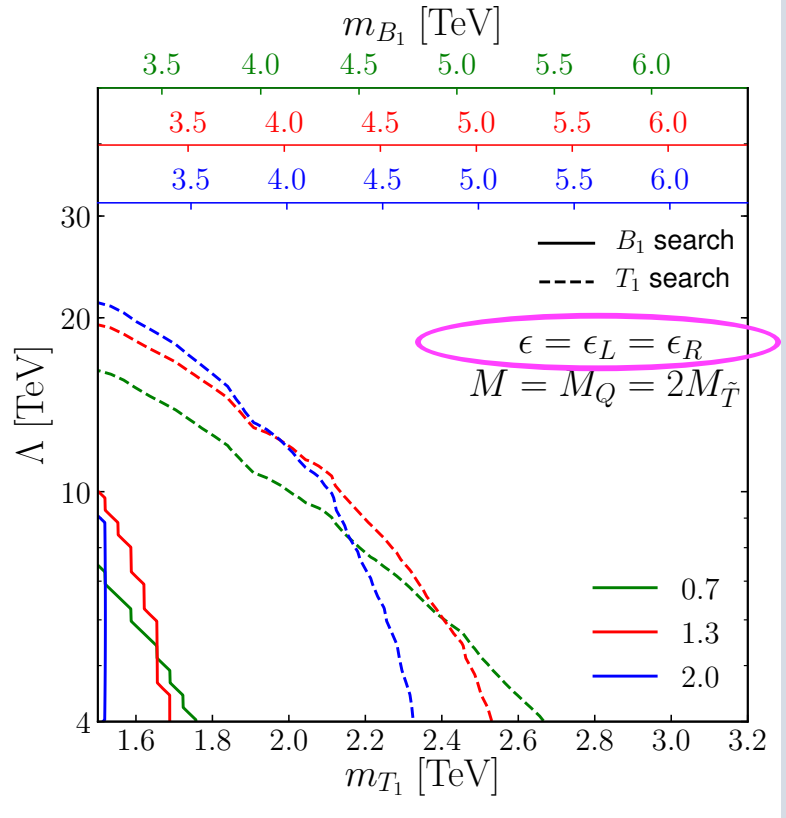


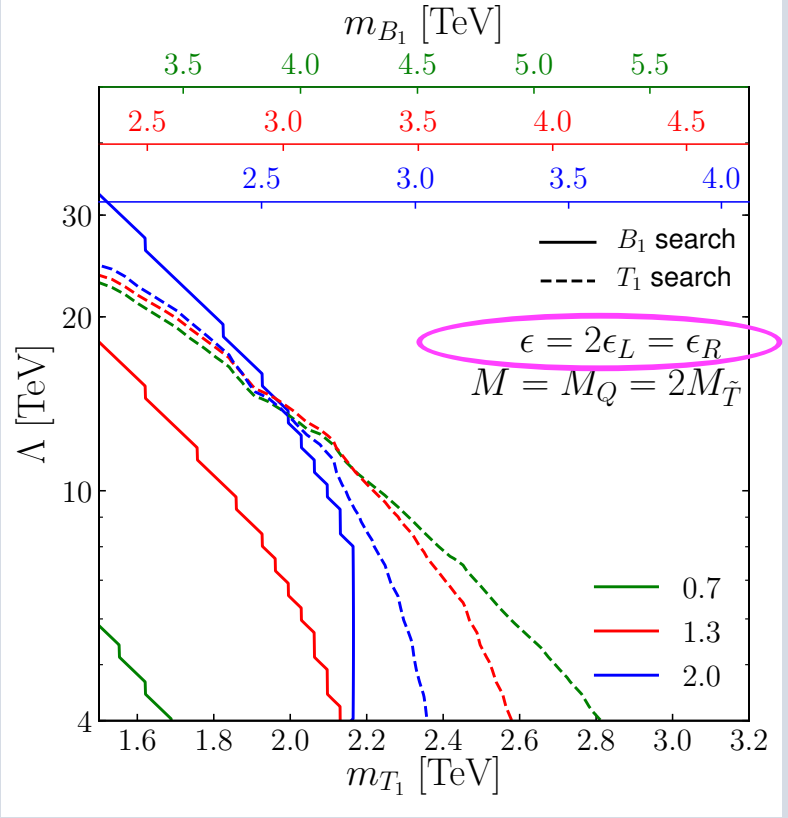


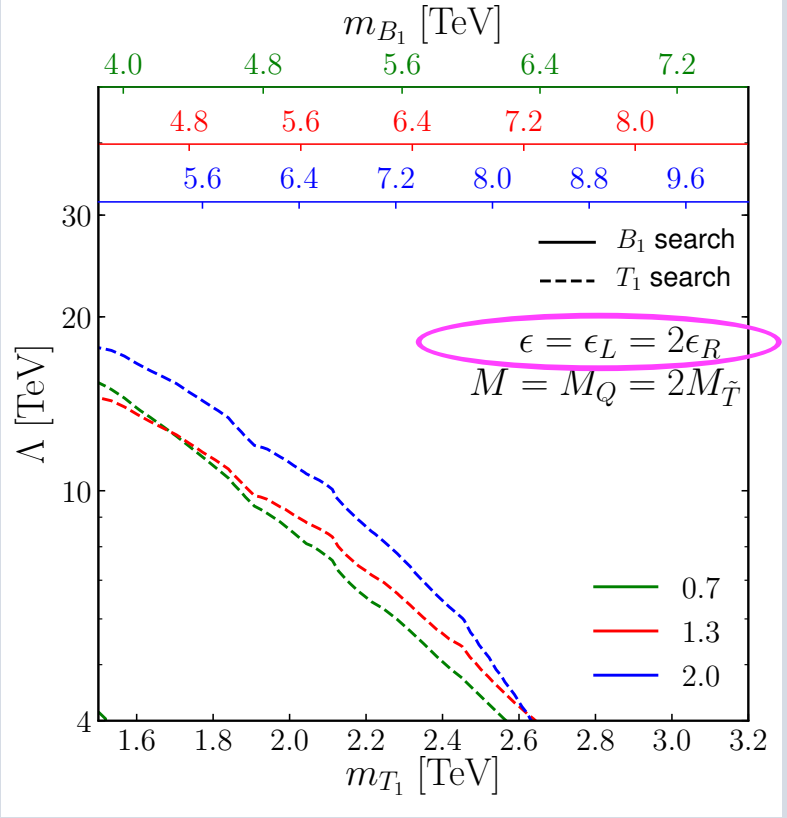
Significant reach for both B_1 and T_1
which complements conventional "excited b quark" searches for B_1.

Both B_1 and T_1 accessible,
in contrast to conventional
searches

Proposed new searches when $M_{B_1} > 2M_{T_1}$

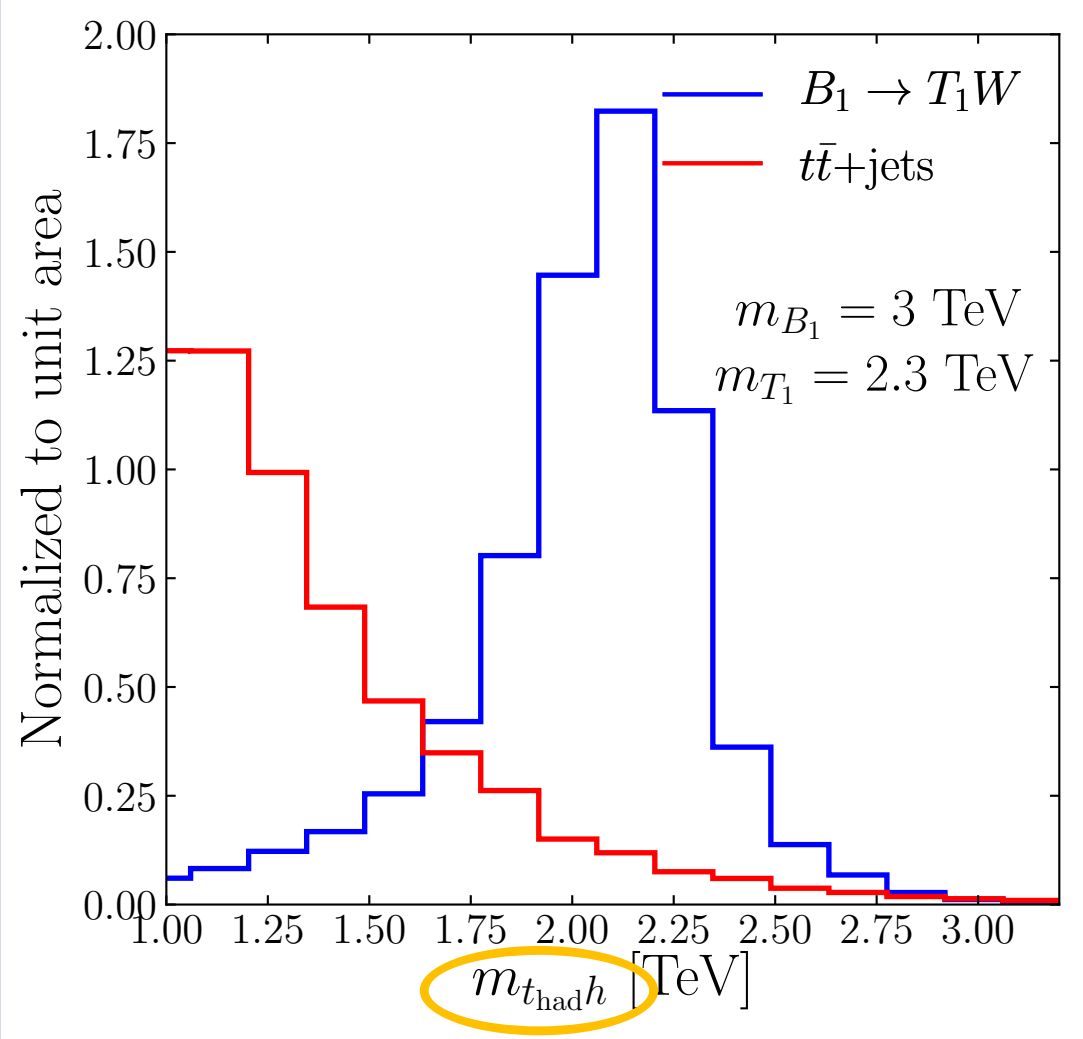




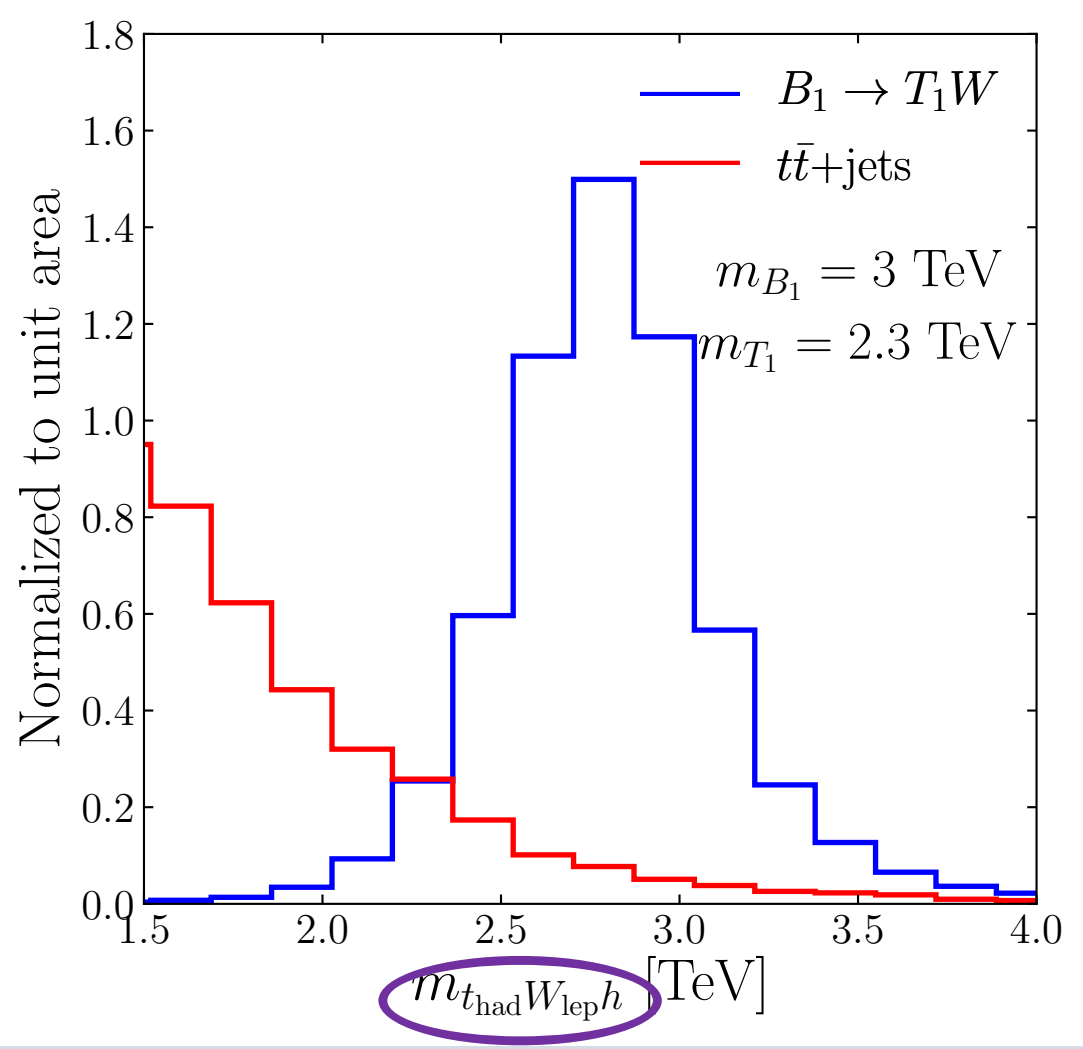


This is a part of parameter space the conventional "excited b quark" searches do not probe.
The $pp \to T_1 t \to tth$ channel is especially valuable.

Distinctive kinematics work as predicted



Two fat jets sum to T_1



Add the W to recover B_1

Summary

We have investigated the LHC's discovery reach for top partner states produced via their **chromomagnetic moment interaction**, using

$$pp \to B_1 \to T_1 W \to thW \quad \text{with } h \to b\bar{b}$$
$$pp \to T_1 t \to tth \quad \text{with } h \to b\bar{b}$$

These production mechanisms provide **greatly increased sensitivity** where traditional searches are relatively uninformative.

- Partner masses ~3 TeV can be reached in LHC run III or HL-LHC, substantially extending the expected mass reach for these new states.
- Where $M_Q = M_{\tilde{T}}$, the new search enables exploration of the case $\varepsilon=\varepsilon_L=2\varepsilon_R$ to which existing searches are insensitive.
- For $M_Q = 2M_{\tilde{T}}$, while conventional searches have very limited reach, the new searches allow a wide swath of parameter space to be explored.

Next Steps

In subsequent work, we have been extending the analyses presented here both theoretically and phenomenologically.

- On the theoretical side,
  - We are exploring a more realistic model with a custodial symmetry. *Coming to arXiv soon!*
- On the phenomenological side,
  - We have studied the reach of a FCC-hh/SppC 100 TeV collider. For top partners of a few TeV composite scales of 80–100 TeV should be accessible. (arXiv: 2209.03333)
  - We are considering additional decay modes for the heavy partners