New Limits on Coloured Three Jet Resonances

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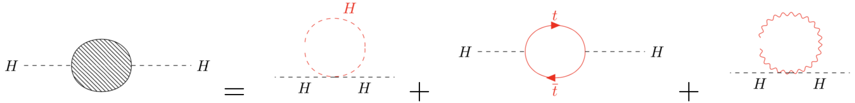
Based on work with Thomas Gregoire and Daniel Stolarski,

arXiv:2003.00014

Motivations

- Why is the the Higgs so much lighter than the other scales?? Such as $M_{Planck} \approx 10^{19}$ GeV $\gg m_H \approx 125.5$ GeV
- Higgs mass is unstable from Quantum corrections, at one loop the corrections are:

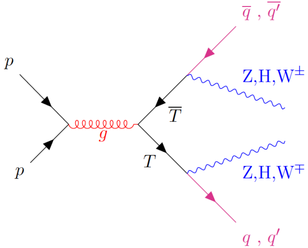


$$\delta m_H^2 = \frac{\Lambda^2}{16\pi^2}\left(6\lambda - y_t^2 + \frac{3}{4}(3g^2 + g'^2)\right) \quad (1)$$

- Proposed solution includes Supersymmetry (SUSY), composite Higgs, Little Higgs, extra dimensions, and NNaturalness models....

Current Status of Vector-Like Quark ...

- An up-type Vector-Like Quark (VLQs) dubbed Top partner (T) provides an intriguing avenues for experimental searches [1].
  - Left & right handed components transform the same way under SM gauge group.
- Current collider searches, for Top partner are carried out under the assumption: $T \longrightarrow tZ \quad , T \longrightarrow bW \quad , T \longrightarrow th$



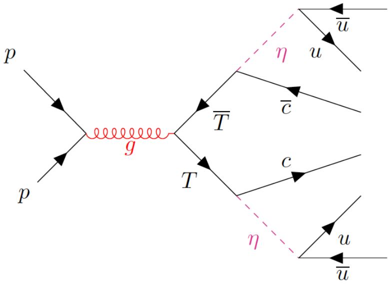
- However, there are stringent constraints on such models with $m_T \geq 1.3 - 1.66$ TeV from the current experimental searches[2].

[1] 1812.09768, 1805.04758, 1710.01539, 1808.02343

[2] arXiv:1808.02343 , arXiv:1806.10555, 1812.09768, 1805.04758, 1710.01539, ...

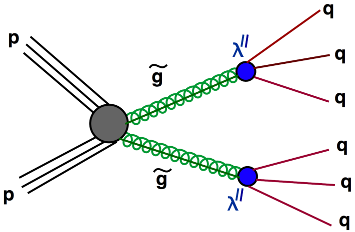
What to explore?

- We concentrate on two cases:
  1. Top partner decays primarily to three light jets
  2. Top partner decays to a light quark and two b-jets
- Large QCD background associated with the fully hadronic modes and there are no limits.
- Case I: The full process is, $pp \to T\bar{T} \to jj\eta\eta \to 6j$ (Not counting ISR/FSR)



LHC Benchmark Model Searches

- The analogue model with similar signatures are RPV SUSY with gluino pair production.



- Gluino is a colour octet while the Top Partner is a colour triplet $\Rightarrow$ Larger $\sigma(pp \rightarrow \tilde{g}\tilde{g})$
- On-shell scalar can change the kinematics relative to the gluino.

CMS three-jet resonance search at $\sqrt{s} = 13$ TeV

Table: The selection criteria for the CMS search arXiv:1810.10092.[3]

Gluino mass range [GeV]	Jet p_T [GeV]	H_T [GeV]	Sixth Jet p_T [GeV]	$D^2_{[(6,3)+(3,2)]}$	A_m	Δ [GeV]	$D^2_{[3,2]}$
200-400	> 30	> 650	> 40	< 1.25	< 0.25	> 250	< 0.05
400-700	> 30	> 650	> 50	< 1.00	< 0.175	> 180	< 0.175
700-1200	> 50	> 900	> 125	< 0.9	< 0.15	> 20	< 0.2
1200-2000	> 50	> 900	> 175	< 0.75	< 0.15	> -120	< 0.25

- The symmetry of the jet inside a triplet is defined as:

$$D^2_{[3,2]} = \sum_{i>j} \left(\hat{m}(3,2)_{ij} - \frac{1}{\sqrt{3}} \right)^2 , \tag{2}$$

where

$$\hat{m}(3,2)^2_{ij} = \frac{m^2_{ij}}{m^2_i + m^2_j + m^2_k + m^2_{ijk}} \quad \text{where } i,j,k \in \{1,2,3\} \tag{3}$$

[3]Gluino masses below 1500 GeV are excluded at 95% CL

Case I Constraints $T \longrightarrow j\eta \; (\eta \longrightarrow jj)$

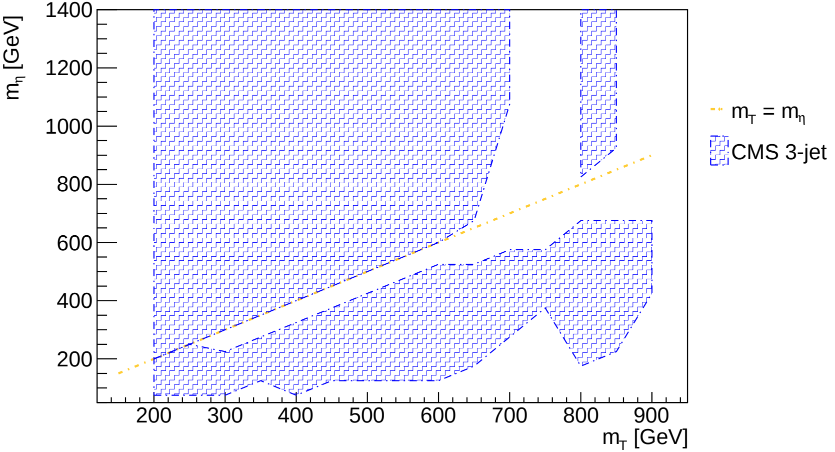
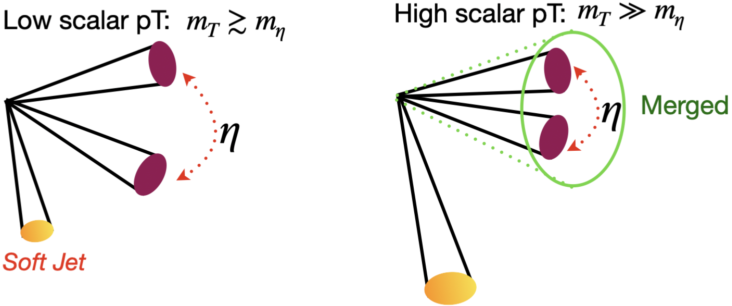


Figure: The *shaded region* is excluded by the CMS three-jet resonance search

Case I Constraints $T \longrightarrow j\eta \; (\eta \longrightarrow jj)$

- Three-jet resonances search loses sensitivity in two regions where a di-jet topology emerges.



ATLAS di-jet resonance search at $\sqrt{s} = 13$ TeV

Table: The selection criteria for the di-jet search (Plus a window cut on m_{avg}) [4].

Jet p_T [GeV]	A_m	$\lvert\cos(\theta^*)\rvert$	ΔR_{min}
> 120	< 0.05	< 0.3	$< -0.002 \cdot (\frac{m_{avg}}{GeV} - 225) + 0.72$, if $m_{avg} \leq 225$ GeV $< +0.0013 \cdot (\frac{m_{avg}}{GeV} - 225) + 0.72$, if $m_{avg} > 225$ GeV

- The mass asymmetry is defined as (arXiv:1710.07171):

$$A_m = \frac{|m_{ij} - m_{mn}|}{m_{ij} + m_{mn}} \tag{4}$$

- The angular distance is:

$$\Delta R_{min} = \min \left\{ \sum_{i=1}^{2} |\Delta R_i - 1| \right\} , \tag{5}$$

where $\Delta R_i = \sqrt{\Delta\phi_i^2 + \Delta\eta_i^2}$ is the distance between the two jets in i^{th} pair.

[4] Top squark mass in the range 100 GeV $< m_{\tilde{t}} <$410 GeV are excluded at 95% CL

Case I: Combined Constraints $T \longrightarrow j\eta \ (\eta \longrightarrow jj)$

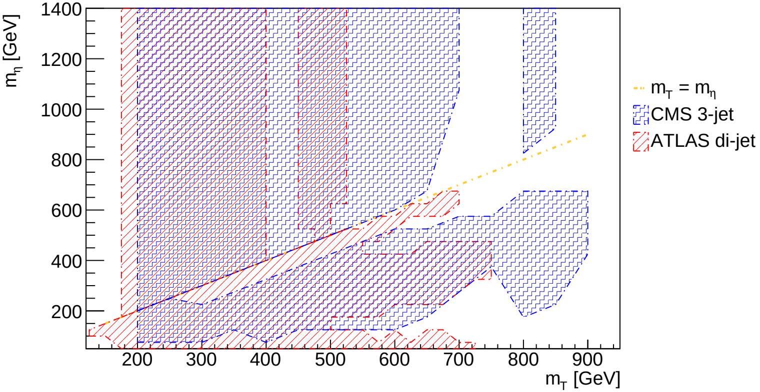
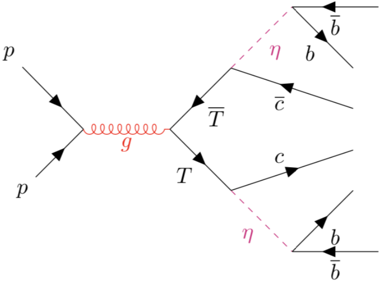


Figure: The *shaded regions* are excluded by the direct searches arXiv:1810.10092, arXiv:1710.07171.

- The di-jet search fills most of the holes left by the three-jet resonances.

LHC Phenomenology Case II

- Case II: The full process is, $pp \to T\bar{T} \to jj\eta\eta \to 2j4b$
  - Scalars tend to decay to heavy fermions
  - Possibly stronger limits



- One applicable search was performed by CMS at $\sqrt{s} = 8$ TeV [5].
- As well as the ATLAS di-jet search arXiv:1710.07171.

[5] arXiv:1311.1799

Case II: Combined Constraints $T \longrightarrow j\eta$ ($\eta \longrightarrow b\bar{b}$)

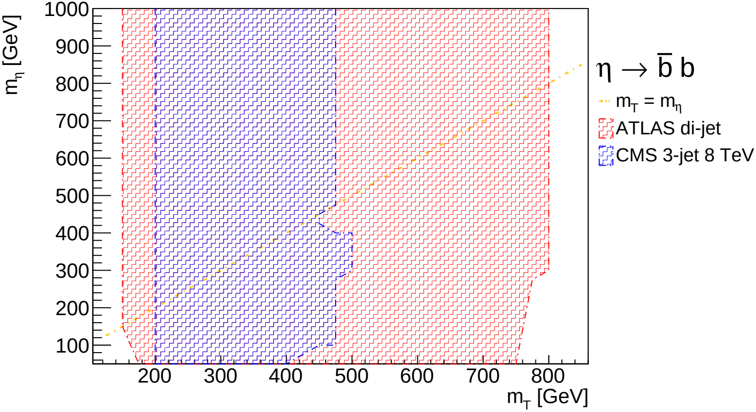


Figure: The *shaded regions* are excluded by the direct searches arXiv:1311.1799, arXiv:1710.07171[6].

[6] Limits obtained for the light case apply here as well

Case II: Possible Improvements ($\eta \longrightarrow b\bar{b}$)

Table: Imposing b-tagging requirements can improve the limits from the searches.

B-tagging requirement	$\frac{s}{\sqrt{b}}$	Improvement	Mass Sensitivity [GeV]
$N_b \geq 0$	0.31	-	900
$N_b \geq 1$	0.58	1.86	1000
$N_b \geq 2$	1.04	3.33	1050
$N_b \geq 3$	2.30	8.36	1200
$N_b \geq 4$	4.66	14.89	1300

Summary

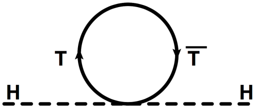
- The top partner provides a possible solution to the hierarchy problem.
- Studied the LHC signatures for previously unexplored decay modes of the Top Partner.
- For the light flavour search, the CMS and ATLAS searches have excluded the mass region of at most $m_T \approx 900 GeV$.
- For the Heavy flavour search (include the b-quark) limits are expected to be stronger due to the b-quarks but we have found that they are very similar to the light flavour scenario.
- Constraints are weaker in comparison to the *traditional* decay channels
  - However, searches designed specifically for final states containing b-jets could significantly constrain the parameter space.

Thank You!

Back Up

Motivation

- Option1: There is an incredible fine-tuning cancellation between the quadratic radiative corrections and the bare mass
- Options 2: New physics beyond the SM is introduced. As such, solutions such as Supersymmetry (SUSY), composite Higgs, Little Higgs, extra dimensions, and NNaturalness models has been proposed.
- Most of the BSM models predicts the existence of new particles expected to have masses near TeV scale.
- Top partner (T) provides a possible solution. Contribution to the Higgs mass is: $\delta m_H^2 \propto \frac{1}{16\pi^2}\lambda m_T^2$. [7]



[7] arXiv:1506.0513

- Further exotic decay modes studied are : $T \to t\ \gamma/g/\gamma_d$ arXiv:1808.03649, arXiv:1904.05893 , $T \to t\ \eta$ stable neutral Particles arXiv:1506.05130
- $T \to t\ S$ with $S \to \gamma\gamma,\ gg, WW, ZZ, t\bar{t}, b\bar{b}$ arXiv:1907.05929 , arXiv:1908.07524, arXiv:1705.03013
- Searches for most of these exotic decays considered in the literature are experimentally very clean.
- Due to the lack of evidence for new particles and many of the obvious possibilities constrained well above TeV, it is of paramount importance to explore new resonances
- As such, we consider the most constraining LHC searches for VLQs matching our topology for unexplored decay channels.

Dalitz variables ...

- The six jet distance measure is defined as:

$$D^2_{[(6,3)+(3,2)]} = \sum_{i<j<k} \left(\sqrt{\hat{m}(6,3)^2_{ijk} + D^2_{[3,2],ijk}} - \frac{1}{\sqrt{20}} \right)^2 \quad (6)$$

- Where $\hat{m}(6,3)^2_{ijk} = \frac{m^2_{ijk}}{4 \cdot m^2_{ijklmn} + 6 \sum_i m^2_i}$ with $i, j, k, l, m, n \in \{1, 2, ..., 6\}$ and m_{ijklmn} the invariant mass of the six highest p_T jets
- The "Delta cut" defined as:

$$M_{jjj} < \sum_{i=1}^{3} p^i_T - \Delta \quad (7)$$

where M_{jjj} is the invariant mass of the triplet and Δ is an adjustable parameter.
- The mass asymmetry is defined as:

$$A_m = \frac{|m_{ijk} - m_{lmn}|}{m_{ijk} + m_{lmn}} \quad (8)$$

CMS 8 TeV Three Jet Resonance Search

- Typically in the high mass region, the signal events have a more spherical shape than the background (which generally contain back to back jets thus more linear shape)
- Sphericity variable is defined as:

$$S = \frac{3}{2}(\lambda_2 + \lambda_3) \ , \quad \lambda_1 \geq \lambda_2 \geq \lambda_3 \ , \tag{9}$$

where λ's are the eigenvalues of the the sphericity tensor,

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |p_i|^2} \ , \quad \alpha \ , \ \beta = \ \mathrm{x} \ , \mathrm{y} \ , \mathrm{z} \ , \tag{10}$$

where α and β label separate jets, and the sphericity S is calculated using all jets in each event.

CMS three-jet resonance search at $\sqrt{s} = 8$ TeV

Table: The selection criteria for the 3-jet resonance search

Mass Range [GeV]	Δ [GeV]	$p_{T,j}^{4th}$ [GeV]	$p_{T,j}^{6th}$ [GeV]	Sphericity
200-600	> 110	> 80	> 60	—
600-1500	> 110	> 110	> 110	> 0.4

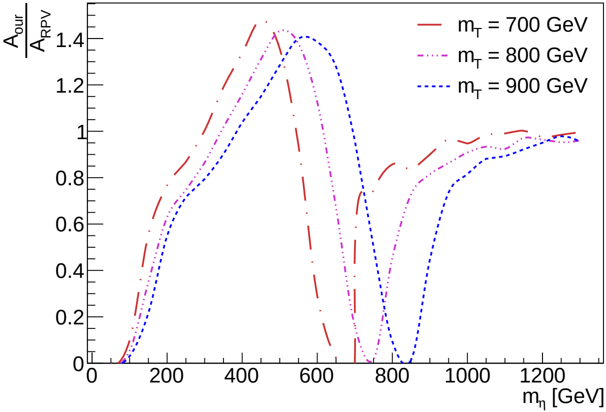
QCD multijet Cross Section

Table: Four partonic hard jets production production cross section using MadGraph5 at $\sqrt{s} = 13$ TeV.

$p_{T,min}(j)$ Generator Level [GeV]	σ_{4j} [pb]
20	1.79×10^7
60	7.64×10^4
100	4.68×10^3
200	7.216×10^1

Case I Constraints $T \longrightarrow j\eta \; (\eta \longrightarrow jj)$

Figure: The ratio of our model over the RPV benchmark model acceptance as a function of the scalar mass for a few top partner masses recasted for the CMS search



Case I Constraints $T \longrightarrow j\eta$ ($\eta \longrightarrow jj$)

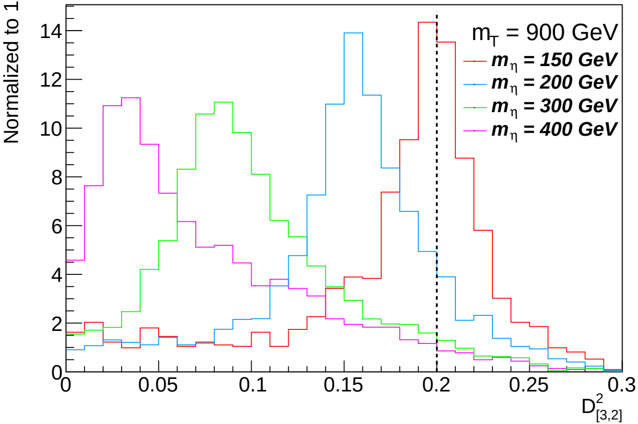
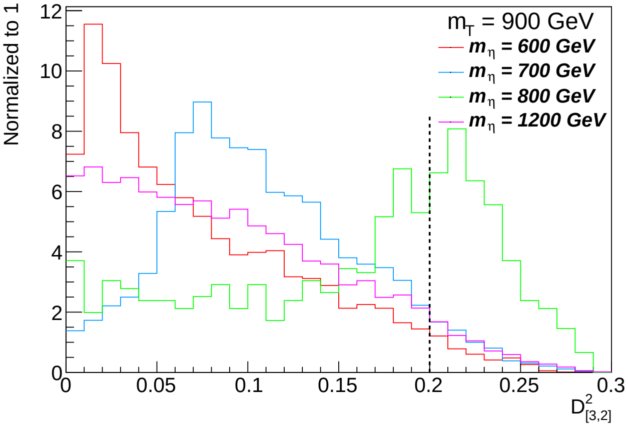


Figure: The $D^2_{[3,2]}$ variable distributions for signal triplets with top partner mass of 900 GeV and various scalar masses

Case I Constraints $T \longrightarrow j\eta\ (\eta \longrightarrow jj)$



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Pair Production Cross Section

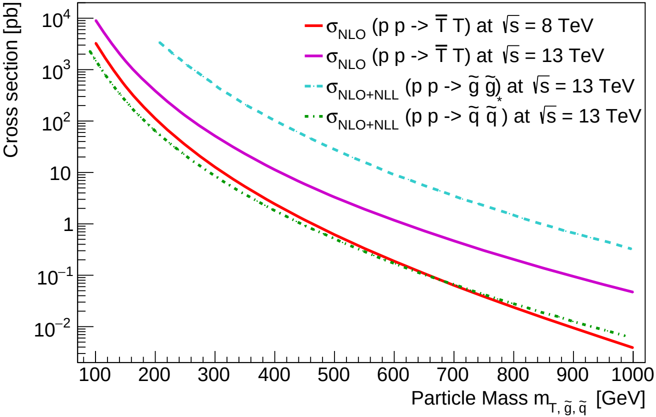

Figure: Next-to-leading order (+NLL) pair production cross section for the top partner, gluino and squarks as a function of $m_T/m_{\tilde{g}}/m_{\tilde{q}}$