Multi top quark production in composite Higgs models

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Why Composite Higgs?

Naturalness problem:

Elementary Higgs $\Rightarrow$ large radiative corrections to Higgs mass

$\Rightarrow$ massive cancellations necessary to obtain $m_h = 125$ GeV

Possible solution: Higgs as a pseudo Nambu-Goldstone (pNGB) bound state of two fermions:

$$h \sim \langle \Psi\Psi \rangle$$

CH model: hyperquarks Ψ charged under a new asymptotically free gauge group G_{HC} which induces a spontaneous $G \to H$ global symmetry breaking when it condenses

Features of composite Higgs models

"Minimal model" SO(5)/SO(4) cannot be realised with underlying fermionic description

Minimal breaking is SO(6)/SO(5) $\sim$ SU(4)/Sp(4): Higgs bidoublet + singlet scalar
$\Rightarrow$ CHMs contain further pNGBs besides the Higgs

Class of 12 promising models characterised by Ferretti et al [1610.06591]

Further bound states: QCD-coloured pNGBs, spin-1 mesons, baryons $\Psi\Psi\Psi$

Features of composite Higgs models

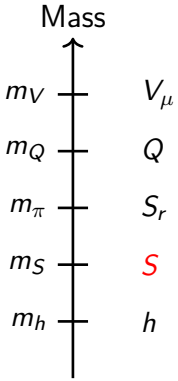
Further bound states: QCD-coloured pNGBs, spin-1 mesons, baryons $\Psi\Psi\Psi$

Baryons must contain *top partners* Q that mix with the elementary 3$^{\text{rd}}$ gen quarks q to generate a large top mass

Mixing terms contain couplings $\bar{Q}Sq$ (schematically) that induce

$$Q \to Sq, \qquad S \to q\bar{q}'$$

Typical spectrum



Colour-singlet pNGBs S

Universal:

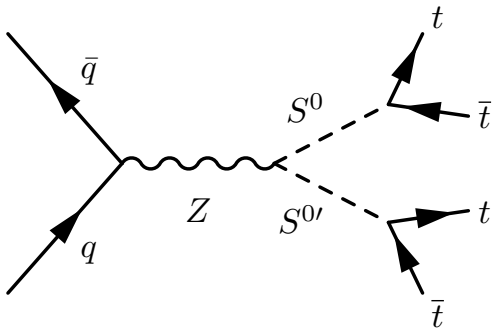
$$S^0 \to t\bar{t}$$

[Suppressed topological decays into dibosons, $S^0 \to \gamma\gamma, \gamma Z, ZZ, WW; gg$]

In some models:

$$S^+ \to t\bar{b}, \quad S^{++} \to W^+ t\bar{b}$$

Four tops: DY scalar production 2210.01826



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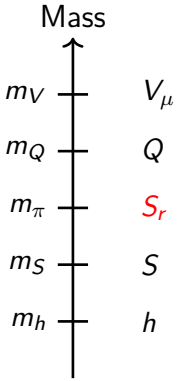


QCD-coloured pNGBs S_r

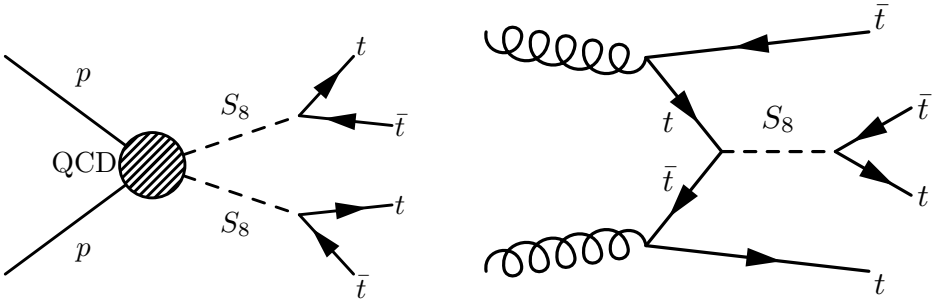
Universal:

$$S_8 \to t\bar{t}$$

Some models additionally have one of:

$$S_6^{4/3} \to tt, \quad S_6^{-2/3} \to bb, \quad S_3^{2/3} \to \bar{b}\bar{s}$$

Four tops: coloured scalar production



Four tops: coloured scalar production [ATLAS 2408.17164]

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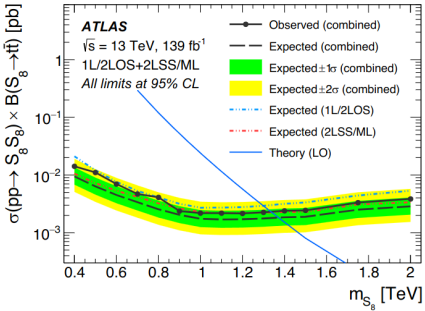
https://doi.org/10.1140/epjc/s10052-025-14041-z

THE EUROPEAN PHYSICAL JOURNAL C

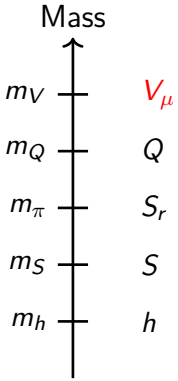
Regular Article - Experimental Physics

Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$ production in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration*
CERN, 1211 Geneva 23, Switzerland



Typical spectrum



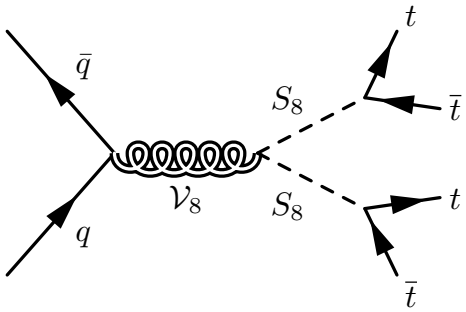
Spin-1 resonances V_μ, colour singlets and octet

Universal colour octet V_8 with coupling to all quarks
$\Rightarrow$ single production

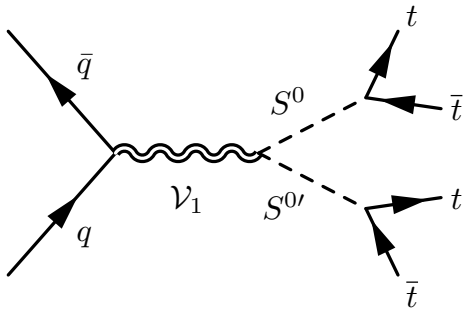
$$q\bar{q} \to V_8 \to q\bar{q},\ t\bar{t},\ SS$$

Some models additionally have sextet/triplet vectors

Four tops: resonant scalar production

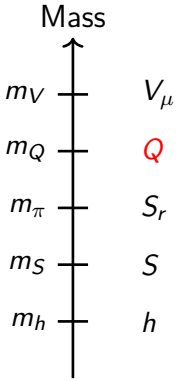


$\Rightarrow m_{V_8} \gtrsim 4.0$ TeV [2404.02198]



$\Rightarrow m_{V_1} \gtrsim 2.0$ TeV [2412.08720]

Typical spectrum



Baryonic resonances

Universal vector-like quarks $X_{5/3}, T, B$
with couplings to SM particles

$$T \to bW, tZ, th$$

and new scalars, such as

$$T \to tS^0 \to tt\bar{t}$$

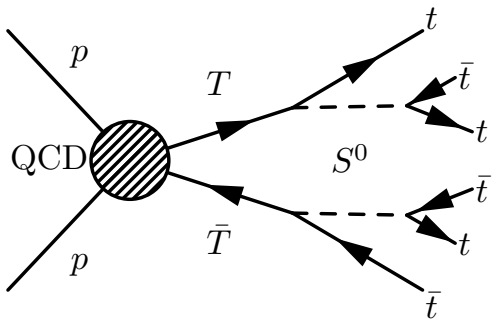
Bounds on exotic VLQ decays

CMS has searched for

- $T\bar{T} \to tS^0\bar{t}S^0$ with one $S^0 \to \gamma\gamma$ [CMS-PAS-B2G-24-016]
- $X_{5/3}\bar{X}_{5/3} \to tS^+\bar{t}S^-$ with $S^\pm \to tb$, excluding $m_Q \leq 1.7$ TeV [CMS-PAS-B2G-24-005]

Most channels remain unexplored $\to$ need recasting tools (MadAnalysis5, Rivet/Contur, CheckMATE) to set bounds

Six tops: top partner production [Flacke, MK 2606.xxxxx]



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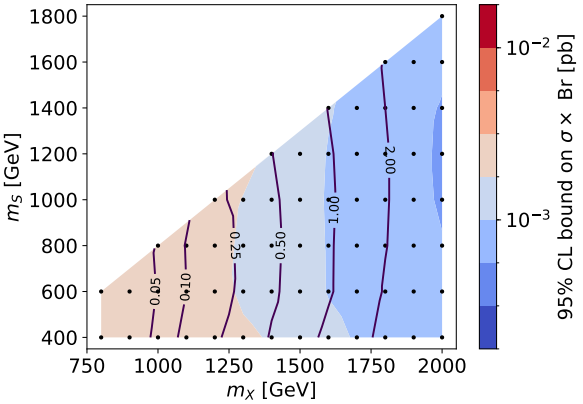
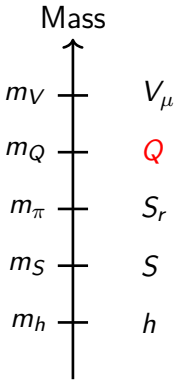


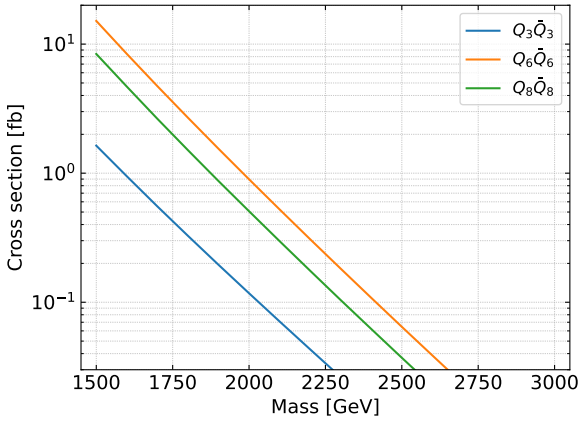
For 100% BR: $T\bar{T} \to 6t$ excluded up to 1.6 TeV just from recasts [ATLAS RPV SUSY 1706.03731, 1909.08457]

Typical spectrum



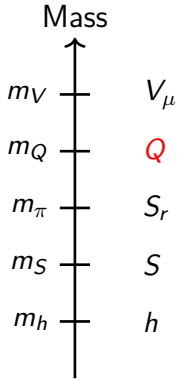
Besides VLQs: also exotic baryons possible: Q_1, Q_8, Q_6

Baryon pair production cross section [2605.04143]



LO cross section (no NLO available for sextets)

Typical spectrum [2605.04143]



The sextets come with different charges:

$$Q_6^{-5/3}, \quad 3 \times Q_6^{-2/3}, \quad Q_6^{1/3}$$

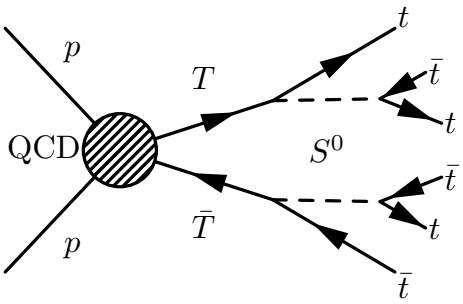
Generic coupling: $Q_6 \to Q_3^c S_8$

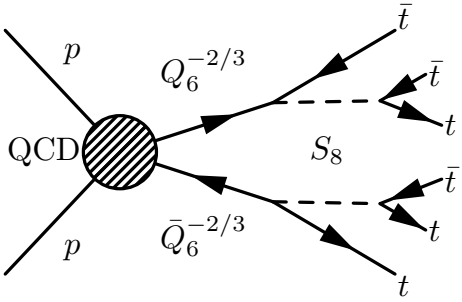
Charge $-2/3$:

$$Q_6^{-2/3} \to \bar{T} S_8 \xrightarrow{\text{mix}} \bar{t} S_8 \to \bar{t} t \bar{t}$$

$\Rightarrow 6t$ from pair production

Six tops: top partner production





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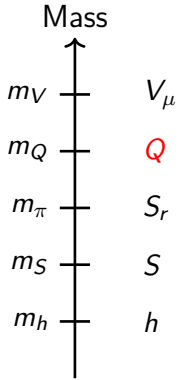

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$$Q_6^{-5/3}, \quad 3 \times Q_6^{-2/3}, \quad Q_6^{1/3}$$

Generic coupling: $Q_6 \to Q_3^c S_8$

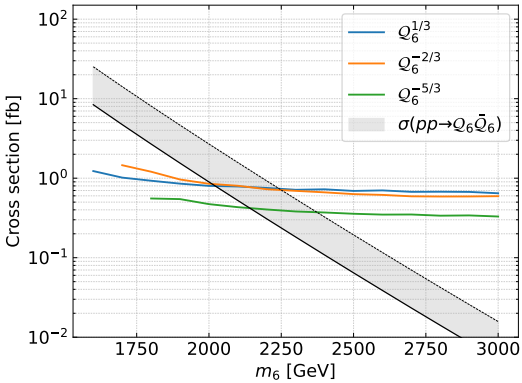
Charge $+1/3$:

$$Q_6^{1/3} \to \bar{B} S_8 \xrightarrow{\text{mix}} \bar{b} S_8 \to \bar{b} t \bar{t}$$

Charge $-5/3$: we have $X_{5/3} \to W^+ t$, $S^{++} b$, $S^+ t$, so for example

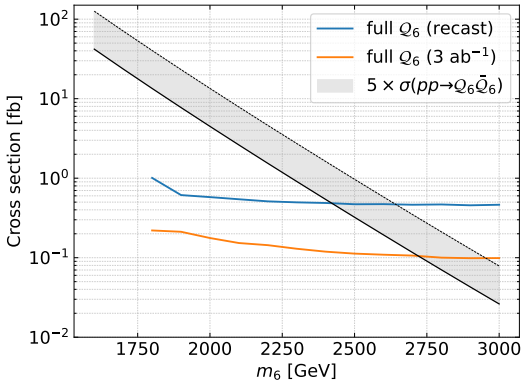
$$Q_6^{-5/3} \to \bar{X} S_8 \to W^- \bar{t} t \bar{t}$$

Bounds on $Q_6\bar{Q}_6$ production [2605.04143]



(Derived from surrogate model with triplet fermions due to colorflow issues)

Bounds on $Q_6\bar{Q}_6$ production [2605.04143]



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Conclusions

- Composite Higgs models predict many resonances with decays to third generation quarks
- Production of four and six top quarks are generic predictions
- Smoking gun processes are $S_8 S_8 \to 4t$ and $T\bar{T} \to tS^0\bar{t}S^0 \to 6t$
- (Recasting) bounds require quite high masses $\Rightarrow$ boosted decay products

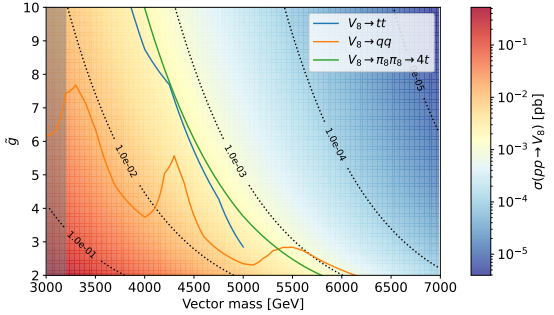
Backup

Ferretti models

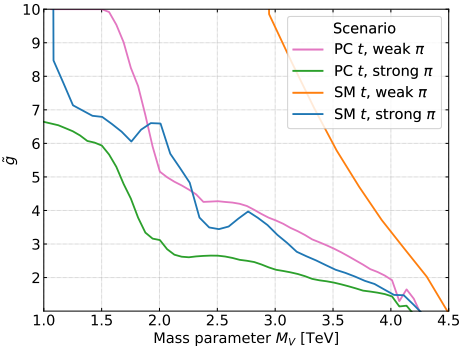
Name	G_{HC}	ψ	χ	Coset
M1	SO(7)	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$\frac{\text{SU}(5)}{\text{SO}(5)} \frac{\text{SU}(6)}{\text{SO}(6)}$
M2	SO(9)	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	$\frac{\text{SU}(5)}{\text{SO}(5)} \frac{\text{SU}(6)}{\text{SO}(6)}$
M3	SO(7)	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$\frac{\text{SU}(5)}{\text{SO}(5)} \frac{\text{SU}(6)}{\text{SO}(6)}$
M4	SO(9)	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	$\frac{\text{SU}(5)}{\text{SO}(5)} \frac{\text{SU}(6)}{\text{SO}(6)}$
M5	Sp(4)	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	$\frac{\text{SU}(5)}{\text{SO}(5)} \frac{\text{SU}(6)}{\text{Sp}(6)}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
M12	SU(5)	$4 \times (\mathbf{F}, \bar{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \bar{\mathbf{A}}_2)$	$\frac{\text{SU}(4)^2}{\text{SU}(4)} \frac{\text{SU}(3)^2}{\text{SU}(3)}$

Ferretti et al, 1312.5330, 1604.06467, 1610.06591

Four tops: resonant scalar production



(a) Coloured vectors [2404.02198]



(b) EW vectors [2412.08720]

$\tilde{g}$: gauge coupling in the composite sector; (b) includes all decays of $\mathcal{V}_1$