Searching for signs of composite Higgs models at LHC run II

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M. Backović, TF, S. J. Lee, G. Perez [JHEP 1509, 022]

M. Backović, TF, J. H. Kim, S. J. Lee [JHEP 1504, 082, Phys.Rev. D92 (2015) 011701, arXiv: 1507.06568]

A. Belyaev, G. Cacciapaglia, H. Cai, TF, A. Parolini, H. Serôdio [arXiv: 1512.07242]

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Outline

- Motivation for composite Higgs models
- A low-energy effective setup: minimal composite Higgs from $SO(5)/SO(4)$
- Prospects for composite top partners at LHC run II
- Potential composite Higgs UV embeddings, their Standard Model singlet pseudo Nambu-Goldstone boson and its collider phenomenology
- Conclusions and Outlook

Motivation

☺ Atlas and CMS found a Higgs-like resonance with a mass $m_h \sim 125$ GeV and couplings to $\gamma\gamma$, WW, ZZ, bb, and $\tau\tau$ compatible with the Standard Model (SM) Higgs.

☹ The Standard Model suffers from the hierarchy problem.

$\Rightarrow$ Search for an SM extension with a Higgs-like state which provides an explanation for why $m_h, v \ll M_{pl}$.

One possible solution: Composite Higgs Models (CHM)

- Consider a model which gets strongly coupled at a scale $f \sim \mathcal{O}(1\,\mathrm{TeV})$. $\rightarrow$ Naturally obtain $f \lll M_{pl}$.
- Assume a global symmetry which is spontaneously broken by dimensional transmutation $\rightarrow$ strongly coupled resonances at f and Goldstone bosons (to be identified with the Higgs sector).
- Assume that the only source of explicit symmetry breaking arises from gauging the SM subgroup and Yukawa-type interactions. $\rightarrow$ The Higgs-like particles become pseudo-Goldstone bosons $\Rightarrow$ Naturally generates a scale hierarchy $v \sim m_h < f \lll M_{pl}$.

Composite Higgs model: low energy effective theory approach

Simplest realization:
The minimal composite Higgs model (MCHM) Agashe, Contino, Pomarol [2004]
Effective field theory based on $SO(5) \to SO(4)$ global symmetry breaking.

- The Goldstone bosons live in $SO(5)/SO(4) \to$ 4 d.o.f.
- $SO(4) \simeq SU(2)_L \times SU(2)_R$
  Gauging $SU(2)_L$ and T_R^3 yields a Higgs-like Goldstone boson multiplet.
  Later: Include a global $U(1)_X$ and gauge $Y = T_R^3 + X$.

How to include quarks and quark masses?
One solution Kaplan [1991]: Include elementary fermions q as incomplete linear representations of $SO(5)$ which couple to the strong sector via

$$\mathcal{L}_{mix} = y\bar{q}f(U(\Pi))\mathcal{O}_{fermion} + \text{h.c.}\,,$$

where $U(\Pi)$ is the Goldstone matrix

$$U(\Pi) = \exp\left(\frac{i}{f}\Pi_i T^i\right) = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \cos \overline{h}/f & \sin \overline{h}/f \\ 0 & 0 & 0 & -\sin \overline{h}/f & \cos \overline{h}/f \end{pmatrix},$$

Simplest choice for quark embedding:

$$q_L^5 = \frac{1}{\sqrt{2}}\begin{pmatrix} ib_L \\ b_L \\ it_L \\ -t_L \\ 0 \end{pmatrix}, \quad t_R^5 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ t_R \end{pmatrix}, \quad \psi = \begin{pmatrix} Q \\ \tilde{T} \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} iB - iX_{5/3} \\ B + X_{5/3} \\ iT + iX_{2/3} \\ -T + X_{2/3} \\ \sqrt{2}\tilde{T} \end{pmatrix}.$$

BSM particle content (per u-type quark):

	T	$X_{2/3}$	B	$X_{5/3}$	$\tilde{T}$
$SO(4)$	**4**	**4**	**4**	**4**	**1**
$SU(3)_c$	**3**	**3**	**3**	**3**	**3**
$U(1)_X$ charge	$2/3$	$2/3$	$2/3$	$2/3$	$2/3$
EM charge	$2/3$	$2/3$	$-1/3$	$5/3$	$2/3$

Fermion Lagrangian:

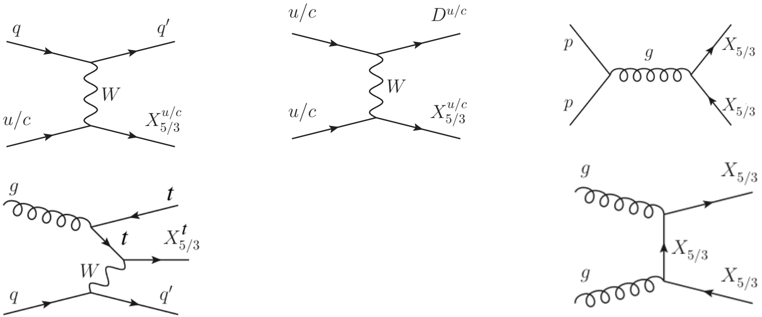
$$\mathcal{L}_{comp} = i\,\overline{Q}(D_\mu + ie_\mu)\gamma^\mu Q + i\bar{\tilde{T}}\not{D}\tilde{T} - M_4\overline{Q}Q - M_1\bar{\tilde{T}}\tilde{T} + \left(ic\overline{Q}^i\gamma^\mu d_\mu^i\tilde{T} + \text{h.c.}\right),$$

$$\mathcal{L}_{el,mix} = i\,\bar{q}_L\not{D}q_L + i\,\bar{t}_R\not{D}t_R - y_L f\bar{q}_L^5 U_{gs}\psi_R - y_R f\bar{t}_R^5 U_{gs}\psi_L + \text{h.c.}$$

where U_{gs} is the Goldstone boson matrix, and d_μ, e_μ are the Cartan-Maurer one-forms.

Production and decays

Production mechanisms (shown here: $X_{5/3}$ prod. for partners of up-type quarks)



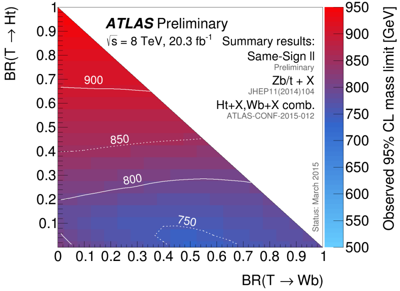
(a) EW single production (b) EW pair production (c) QCD pair production

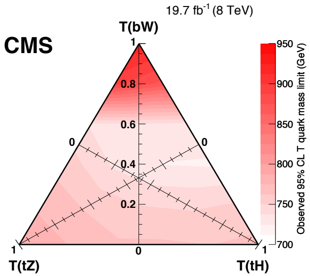
Decays:

- $X_{5/3} \to W^+ t$ (100%),
- $B \to W^- t$ ($\sim$ 100%),
- $T_{f1}, T_{f2}, T_s \to W^- b, Zt, ht$ (with parameter-dependent BRs)

Bounds on top partners from run I

- ATLAS and CMS determined bounds on (QCD) pair-produced top partners with charge $5/3$ (the $X_{5/3}$) in the same-sign di-lepton channel.
  $M_{X_{5/3}} > 770\,\mathrm{GeV}$ ATLAS [JHEP 1411 (2014) 104] , $M_{X_{5/3}} > 800\,\mathrm{GeV}$ CMS [PRL 112 (2014) 171801]
  Run II: $M_{X_{5/3}} > 940(960)\,\mathrm{GeV}$ CMS [B2G-15-006]
- ATLAS and CMS determined a bound on (QCD) pair-produced top partners with charge $2/3$ (applicable for the T_s, T_{f1}, T_{f2}). [Similar bounds for B]





CMS [hep-ex:1509.04177]

Prospects for composite quark partners at LHC run II

At run II, we have more energy
$\Rightarrow$ searches are sensitive to higher quark partner masses.

Further genuine aspects for composite quark partner searches at run II:

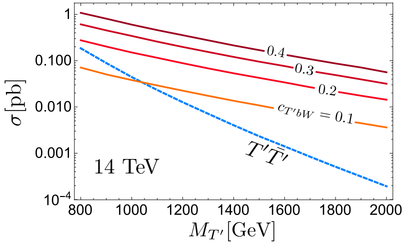
1. At higher masses, single-production channels become more important as compared to QCD pair production channels.
2. For heavier quark partners, their decay products become strongly boosted
$\Rightarrow$ requires dedicated for boosted tops, Higgses, EW gauge bosons.

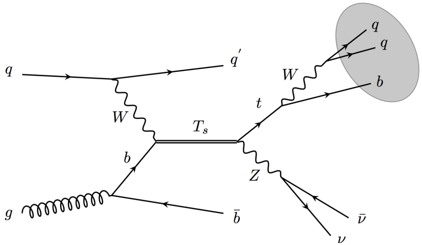
Examples:

- * Maximizing the sensitivity for charge 2/3 top partners:
A comprehensive survey on single produced T' and its decay channels.
M. Backović, TF, J. H. Kim, S. J. Lee [Phys.Rev. D92 (2015) 011701, arXiv: 1507.06568]
- Maximizing the sensitivity for the “most visible” quark partner:
An alternative search strategy for $X_{5/3}$.
M. Backović, TF, S. J. Lee, G. Perez [JHEP 1509, 022]
- Maximizing the sensitivity for “the illusive Q_h ” quark partner:
M. Backović, TF, J. H. Kim, S. J. Lee [JHEP 1504, 082]

Prospects for composite quark partners: charge 2/3 partner(s)

Search for top quark singlet partners in the $j\bar{b}tZ$ final state ($Z \to ll$ vs. $Z \to \nu\bar{\nu}$):





Cuts used in our simulation:

- high H_T-cut [500 (750) GeV for 1 (1.5) TeV search],
- Ov_3^t top-template with b tag,
- forward-jet-tag,
- for the $Z \to ll$ channel: $\Delta R_{ll} < 1.0$ and $|m_{ll} - m_Z| < 10\,\mathrm{GeV}$,
- for the $Z \to \nu\bar{\nu}$ channel: $\not{E}_T > 400\,(600)\,\mathrm{GeV}$.

Prospects for composite quark partners: charge 2/3 partner(s)

Search for top quark singlet partners in the $j\bar{b}tZ$ final state:

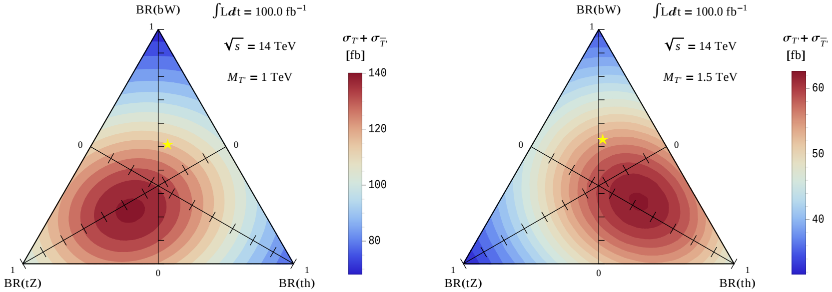
$T' \to Z_{\rm inv} t_{\rm had}$	$M_{T'} = 1.0$ TeV search						$M_{T'} = 1.5$ TeV search					
	signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}\,(100\,\text{fb}^{-1})$	signal	$t\bar{t}$	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}\,(100\,\text{fb}^{-1})$
preselection	4.9	26000	21000	44	0.00011	0.23	1.3	5200	5300	12	0.00012	0.12
Basic Cuts	3.5	900	6100	11	0.00050	0.42	1.0	140	1200	2.4	0.00074	0.27
$Ov_3^t > 0.6$	2.7	510	840	6.5	0.0020	0.75	0.87	81	230	1.6	0.0028	0.49
b-tag	1.8	300	28	4.1	0.0055	1.0	0.51	42	6.7	0.9	0.010	0.72
$\not{E}_T > 400\,(600)$ GeV	1.2	13	8.3	0.84	0.055	2.6	0.39	0.95	1.4	0.13	0.16	2.5
$N_{\rm fwd} \geq 1$	0.75	2.5	1.2	0.25	0.19	3.8	0.26	0.19	0.23	0.039	0.58	3.9
$\lvert\Delta\phi_{\not{E}_T,j}\rvert > 1.0$	0.62	0.89	0.91	0.21	0.31	4.4	0.21	0.072	0.17	0.031	0.78	4.1

$T' \to Z_{ll} t_{\rm had}$	$M_{T'} = 1.0$ TeV search					$M_{T'} = 1.5$ TeV search				
	signal	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}$	signal	$Z+X$	$Z+t$	S/B	$S/\sqrt{B}$
preselection	1.6	4800	13	3.3×10^{-4}	0.23	0.42	1300	3.5	3.3×10^{-4}	0.12
Basic Cuts	1.1	750	1.3	0.0014	0.39	0.30	170	0.36	0.0018	0.23
$Ov_3^t > 0.6$	0.71	71	0.61	0.010	0.85	0.24	19	0.14	0.012	0.54
b-tag	0.49	2.6	0.40	0.16	2.8	0.14	0.64	0.082	0.19	1.7
$\Delta R_{ll} < 1.0$	0.49	2.6	0.39	0.16	2.8	0.14	0.64	0.081	0.20	1.7
$\lvert m_{ll} - m_Z\rvert < 10$ GeV	0.44	2.4	0.35	0.16	2.7	0.13	0.58	0.074	0.19	1.6
$N_{\rm fwd} \geq 1$	0.28	0.38	0.10	0.58	4.0	0.084	0.098	0.018	0.72	2.5

Prospects for composite quark partners: charge 2/3 partner(s)

We also did detailed analyses of the $W_{\rm lep}b$, $W_{\rm had}b$, $h_{bb}t_{\rm had}$, and $h_{bb}t_{\rm lep}$ channels, and found best results for $Z_{\rm inv}t_{\rm had}$, $W_{\rm lep}b$ and $h_{bb}t_{\rm had}$.

M. Backović, TF, J. H. Kim, S. J. Lee [arXiv: 1507.06568]



Expected discovery reach for a T' with mass of 1 TeV (left) and 1.5 TeV (right) in terms of T' production cross section for the LHC at 14 TeV with 100 fb^{-1} of data. The yellow star marks the branching ratios at the sample model point used for simulation.

Towards a Composite Higgs UV embedding [arXiv:1512.07242]

The above approaches Composite Higgs models in terms of a low-energy EFT.

Are there candidates for a UV embeddings (and what is the confining group, what are the Higgs and quark partner constituents ("preons"))?

Ferretti, Karateev [JHEP 1403 (2014) 077] classified candidate models which

- contain no elementary scalars (to not re-introduce a hierarchy problem),
- have a simple hyper-color group G_{HC},
- have a Higgs candidate amongst its Goldstone bosons,
- have a top partner candidate amongst its bound states,
- satisfy other consistency conditions (asymptotic freedom, no anomalies, ...),
- (no SM gauge group Landau pole near the EW scale).

Upshot: The models satisfying this wish-list have minimal EW co-sets $SU(5)/SO(5)$ c.f. Ferretti [JHEP 1406 (2014) 142], $SU(4)/Sp(4)$ c.f. Barnard, Gherghetta, Ray [JHEP 1402 (2014) 002] or $SU(4) \times SU(4) \to SU(4)_D$ Vecchi [arXiv:1506.00623].
All models contain two types of preons χ, ψ. The Higgs is realized as a $\psi\psi$ bound state while top partners are $\psi\chi\chi$ or $\psi\psi\chi$ bound states.

Towards a composite Higgs UV embedding

G_{HC}	ψ	χ	EW	Colour	X
$Sp(2N_c)$, $2 \leq N_c \leq 18$	**F**	**A**	$\frac{SU(4)}{Sp(4)}$	$\frac{SU(6)}{SO(6)}$	2/3
SO(11), SO(13)	**Spin**	**F**			2/3
$Sp(2N_c)$, $N_c \geq 2$	**A**	**F**	$\frac{SU(5)}{SO(5)}$	$\frac{SU(6)}{Sp(6)}$	1/3
$Sp(2N_c)$, $N_c \geq 6$	**Adj**	**F**			1/3
SO(11), SO(13)	**F**	**Spin**			1/3
SO(7), SO(9)	**Spin**	**F**	$\frac{SU(5)}{SO(5)}$	$\frac{SU(6)}{SO(6)}$	2/3
SO(7), SO(9)	**F**	**Spin**			1/3
$SO(N_c)$, $N_c \geq 15$	**Adj**	**F**			1/3
$SO(N_c)$, $N_c \geq 55$	**S**	**F**			1/3
SU(4)	**A**	**F**	$\frac{SU(5)}{SO(5)}$	$\frac{SU(3)^2}{SU(3)}$	1/3
SO(10), SO(14)	**F**	**Spin**			1/3
SU(4)	**F**	**A**	$\frac{SU(4)^2}{SU(4)}$	$\frac{SU(6)}{SO(6)}$	2/3
SO(10)	**Spin**	**F**			2/3
SU(7)	**F**	$\mathbf{A_3}$	$\frac{SU(4)^2}{SU(4)}$	$\frac{SU(3)^2}{SU(3)}$	1/12
$SU(N_c)$, $N_c \geq 5$	**F**	**A**			2/3
$SU(N_c)$, $N_c \geq 5$	**F**	**S**			2/3
$SU(N_c)$, $N_c \geq 5$	**A**	**F**			1/12
$SU(N_c)$, $N_c \geq 8$	**S**	**F**			1/12

The complete list of theories. The HC representations are: **F**: fundamental, **S**: 2-index symmetric, **A**: 2-index anti-symmetric, $\mathbf{A_3}$: 3 index anti-symmetric, **Adj**: adjoint, **Spin**: spinorial of SO. The last column contains the $U(1)_X$ charge assignment. [arXiv:1512.07242]

Towards a composite Higgs UV embedding

Key-observations:

- The pNGB sector of these models is always larger than that of the minimal $SO(5)/SO(4)$ model. $\Rightarrow$ additional potentially light resonances.
- *ALL* models have a $U(1)_\chi \times U(1)_\psi$ global symmetry which is spontaneously broken by the condensates *and* a G_{HC} anomaly.
  $\Rightarrow$ The particle spectrum contains a SM singlet pNGB.
- The SM singlet pNGB is comprised of preons which carry SM charges.
  $\Rightarrow$ The SM singlet pNGB couples to SM gauge bosons via anomaly terms, (almost) fully determined by the preon quantum numbers.

Upshot: UV embeddings of composite Higgs models contain a SM singlet pNGB σ, fully described by

$$\mathcal{L} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{m_\sigma^2}{2}\sigma^2 + \frac{g_i^2}{32\pi^2}\frac{\kappa_i}{f_\sigma}\,\sigma\,\epsilon^{\mu\nu\alpha\beta}G^i_{\mu\nu}G^i_{\alpha\beta}\,,$$

where m_σ must arise from explicit breaking, f_σ should be determined from the G_{HC} dynamics, but all κ_i are model-specific and fixed. $\Rightarrow$ Highly predictive models.

Towards a composite Higgs UV embedding

Example: Lets assume that the recent 750 GeV di-photon access (of 10 fb (5 fb)) arises from this CHM σ.
"Under this assumption: which models are not yet excluded by current LHC run I and run II di-boson searches?"

		R_{WW}	R_{ZZ}	$R_{Z\gamma}$	R_{gg}	Γ_{tot}	f_σ
SU(7)	(**F**, **A$_3$**)	9.5	3.0	0.8	140	0.4	2900
SU(5)	(**A**, **F**)	10	3.2	0.9	1300	3.2	830
SO(11)	(**Spin**, **F**)	4.4	0.5	**3.5**	500	0.8	2330
SO(13)	(**Spin**, **F**)	2.6	0.2	**2.6**	400	1.0	4000
SU(4)	(**A**, **F**)	**23**	**6.6**	**3.4**	960	1.7	680
SO(7)	(**F**, **Spin**)	**20**	5.7	**2.7**	600	1.5	1300
SO(9)	(**F**, **Spin**)	16	4.8	2.0	300	0.8	2200
SO(10)	(**F**, **Spin**)	15	4.6	1.8	227	0.6	2500
SO(11)	(**F**, **Spin**)	15	4.3	1.7	180	0.4	2900
SO(13)	(**F**, **Spin**)	13	4.1	1.5	120	0.3	3500
SO(14)	(**F**, **Spin**)	13	4.0	1.4	99	0.2	3800

List of models that can explain the di-photon excess of 10 fb (5 fb) and are compatible with present "di-boson" searches. $R_{XX} \equiv \sigma_{XX}/\sigma_{\gamma\gamma}$.The models are grouped according to the Higgs coset: $SU(4)^2/SU(4)$ for the top block, $SU(4)/Sp(4)$ for the second block, and $SU(5)/SO(5)$ for the bottom one. Values for Γ_{tot} and f_σ are given in GeV. [arXiv:1512.07242]

Conclusions

- Composite Higgs models provide a viable solution to the hierarchy problem. Realizing quark masses via partial compositeness requires quark partners.
- Top partners (in the MCHM) are constraint from run I to $M_X \gtrsim 800\,\mathrm{GeV}$.
- For run II, single-production channels and strongly boosted top, W, Higgs, and Z searches become important.
  Examples:
  - For charge 2/3 top partners, we presented a comprehensive analysis of the most promising final states from T' decays.
    Shown here: $T' \to Z_{\mathrm{inv}}\, t_{\mathrm{had}}$. Please see [arXiv:1507.06568] for many other channels and simulation details.
  - For $X_{5/3}$, the semi-leptonic decay channel has good discovery reach.
- EFT descriptions of composite Higgs models are only a part of the story. UV embeddings need to be studied and will lead to novel (or already well-known) BSM LHC signatures.
- We showed that di-boson signatures are predicted in a large class of CH UV embeddings. The models are highly predictive because the branching ratios of the SM singlet pseudo-Goldstone boson are fully determined by the quantum numbers of the underlying fermion content.

Backup

Results for Wess-Zumino-Witten coefficients

G_{HC} anomaly free $U(1)$ combination: $q_\psi = N_\chi T_\chi$, $q_\chi = -N_\psi T_\psi$,
(T_x: Dynkin indices of the HC reps., N_x: fermion multiplicities.)

WZW coefficients of the $U(1)_\psi$ and $U(1)_\chi$ associated "Goldstones":

$$\kappa_W = \kappa_B = d_\psi, \quad \text{for} \quad SU(4)/Sp(4),$$
$$\kappa_W = \kappa_B = 2d_\psi, \quad \text{for} \quad SU(5)/SO(5) \text{ and } SU(4)^2/SU(4),$$
$$\begin{matrix} \kappa_g = 2d_\chi, \\ \kappa_B = 12X^2 d_\chi, \end{matrix} \quad \text{for} \quad \text{all color cosets},$$

where d_x is the dimension of the rep..

WZW coefficient of the G_{HC} anomaly-free combination: $\kappa_i = q_\psi \kappa_i^\psi + q_\chi \kappa_i^\chi$.

Diboson cross sections and bounds used

Run I di-boson bounds at $m_\sigma = 750\,\mathrm{GeV}$ used:

$\sigma(pp \to \sigma \to gg)$	$\lesssim$	$3\,\mathrm{pb}$	ATLAS [PRD 91 (2015), 5], CMS [PAS-EXO-14-005]
$\sigma(pp \to \sigma \to WW)$	$\lesssim$	$40\,\mathrm{fb}$	ATLAS [arXiv:1509.00389]
$\sigma(pp \to \sigma \to ZZ)$	$\lesssim$	$12\,\mathrm{fb}$	ATLAS [1507.05930]
$\sigma(pp \to \sigma \to Z\gamma)$	$\lesssim$	$4\,\mathrm{fb}$	ATLAS [PLB 738 (2014), 428]

Run II di-photon signal cross section assumed: $10\,\mathrm{fb}$ [ATLAS- CONF-2015-081]

Ratio of production cross sections :

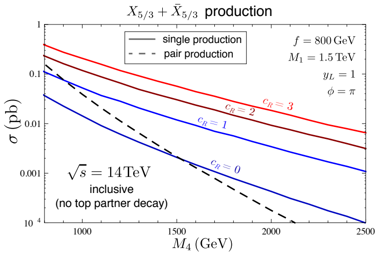
$$\xi = \frac{\sigma_{13}(gg \to \sigma)}{\sigma_8(gg \to \sigma)} \simeq 4.6$$

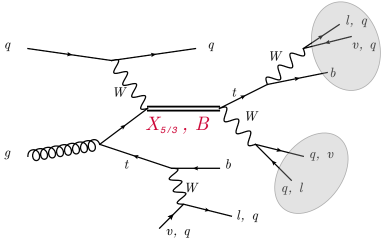
Resulting bound on $R_{XY} \equiv Br(\sigma \to XY)/Br(\sigma \to \gamma\gamma)$:

$$R_{gg} \lesssim 1400,\ \ R_{WW} \lesssim 19,\ \ R_{ZZ} \lesssim 6,\ \ R_{WW} \lesssim 2.$$

Prospects for composite quark partners at LHC run II

Search for top partners in the $q\bar{t}tW$ final state with semi-leptonic decay of tW.





The final state is characterized by		We use this by
- a high energy forward jet	$\rightarrow$	used as a tag
- two b's	$\Rightarrow$	demand two b-tags
- a highly boosted tW system with:		
– one hard lepton,	$\rightarrow$	$p_T^l > 100\,\mathrm{GeV}$ cut
– missing energy,		
– "fat jets",	$\rightarrow$	reconstruct boosted t/W using Template Overlap Method (TOM)

Prospects for composite quark partners at LHC run II

Search for top partners in the $q\bar{t}tW$ final state with semi-leptonic decay of tW.

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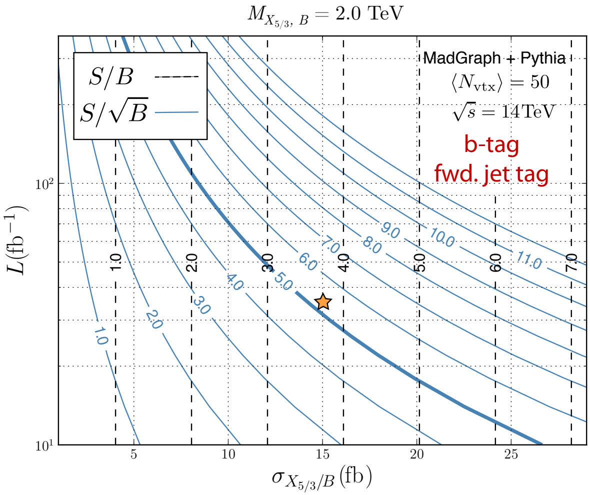
$M_{X_{5/3}/B} = 2.0$ TeV, $\sigma_{X_{5/3}+B} = 15\,\text{fb}$, $L = 35\,\text{fb}^{-1}$, $\langle N_{\text{vtx}} \rangle = 50$

$X_{5/3} + B$	σ_s [fb]		$\sigma_{t\bar{t}}$ [fb]		$\sigma_{W+\text{jets}}$ [fb]		ϵ_s		$\epsilon_{t\bar{t}}$		$\epsilon_{W+\text{jets}}$		S/B		$S/\sqrt{B}$	
Fat jet candidate	t	W	t	W	t	W	t	W	t	W	t	W	t	W	t	W
Basic Cuts	1.6	2.3	76.0	556.0	5921.0	3879.0	0.36	0.51	0.06	0.46	0.19	0.12	3×10^{-4}	4×10^{-4}	0.1	0.1
$p_T > 700$ GeV	1.3	2.0	60.0	506.0	1322.0	1082.0	0.28	0.45	0.05	0.42	0.04	0.04	9×10^{-4}	8×10^{-4}	0.2	0.2
$p_T^l > 100$ GeV	1.2	1.9	23.0	349.0	912.0	733.0	0.27	0.41	0.02	0.29	0.03	0.02	0.001	0.001	0.2	0.2
$Ov > 0.5$	1.0	1.3	12.0	170.0	354.0	254.0	0.23	0.30	0.01	0.14	0.01	0.008	0.003	0.002	0.3	0.3
$M_{X_{5/3}/B} > 1.5$ TeV	0.9	1.2	0.7	106.0	168.0	160.0	0.20	0.26	6×10^{-4}	0.09	0.006	0.005	0.005	0.003	0.4	0.3
$m_{jl} > 300$ GeV	0.8	0.4	0.5	12.0	111.0	27.0	0.17	0.08	4×10^{-4}	0.01	0.004	9×10^{-4}	0.007	0.02	0.4	0.7
b-tag & no fwd. tag	**0.3**	0.1	**0.08**	2.7	**0.2**	0.5	0.07	0.03	7×10^{-5}	0.002	5×10^{-6}	2×10^{-5}	**1.3**	0.09	**3.7**	1.0
fwd. tag & no b-tag	**0.5**	0.3	**0.2**	3.7	**32.0**	7.8	0.10	0.06	2×10^{-4}	0.003	0.001	3×10^{-4}	**0.02**	0.05	**0.6**	0.9
b-tag and fwd. tag	**0.2**	0.1	**0.03**	0.9	**0.03**	0.1	0.05	0.02	2×10^{-5}	7×10^{-4}	1×10^{-6}	4×10^{-6}	**3.7**	0.2	**5.3**	1.3

Table 5. Example cutflow for signal and background events **in the presence of** $\langle N_{\text{vtx}} \rangle = 50$ **interactions per bunch crossing**, for $M_{X_{5/3}/B} =$ 2.0 TeV and inclusive cross sections $\sigma_{X_{5/3}/B}$. No pileup subtraction/correction techniques have been applied to the samples. $\sigma_{s,t\bar{t},W+\text{jets}}$ are the signal/background cross sections including all branching ratios, whereas ϵ are the efficiencies of the cuts relative to the generator level cross sections. The results for $M_{X_{5/3}/B} = 2.0$ TeV assume both $X_{5/3}$ and B production.

Prospects for composite quark partners at LHC run II

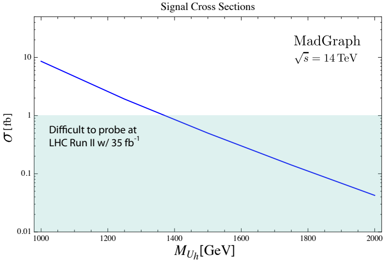


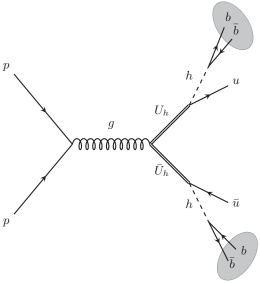
M. Backović, TF, S. J. Lee, G. Perez [JHEP 1509, 022]

Prospects for composite quark partners at LHC run II

Search for light quark singlet partners in the *hhjj* final state with $h \to b\bar{b}$ decays.

M. Backović, TF, J. H. Kim, S. J. Lee [JHEP 1504, 082]





Cut Scheme	Basic Cuts	Demand at least four fat jets ($R = 0.7$) with $p_T > 300$ GeV, $\lvert\eta\rvert < 2.5$
		Declare the two highest p_T fat jets satisfying $Ov_2^h > 0.4$ and $Ov_3^t < 0.4$ to be Higgs candidate jets. At least 1b-tag on both Higgs candidate jets.
		Select the two highest p_T light jets ($r = 0.4$), with $p_T > 25$ GeV to be the u quark candidates.
	Complex Cuts	$\lvert\Delta_h\rvert < 0.1$ $\lvert\Delta_{U_h}\rvert < 0.1$ $m_{U_{h1,2}} > 800$ GeV

Table III: Summary of the Event Selection Cut Scheme

Prospects for composite quark partners at LHC run II

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	σ_s [fb]	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{b\bar{b}}$ [fb]	$\sigma_{\text{multi-jet}}$ [fb]	S/B	$S/\sqrt{B}$
Preselection Cuts	6.8	4.6×10^{2}	8.4×10^{3}	2.8×10^{5}	2.4×10^{-5}	7.5×10^{-2}
Basic Cuts	1.2	4.6	16.0	6.8×10^{2}	1.7×10^{-3}	2.7×10^{-1}
$\lvert\Delta_{mh}\rvert < 0.1$	8.2×10^{-1}	1.7	6.5	2.8×10^{2}	2.9×10^{-3}	2.9×10^{-1}
$\lvert\Delta_{mU}\rvert < 0.1$	5.6×10^{-1}	5.5×10^{-1}	2.0	87.0	6.3×10^{-3}	3.5×10^{-1}
$m_{U_{h1,2}} > 800$ GeV	5.0×10^{-1}	3.6×10^{-1}	1.6	67.0	7.3×10^{-3}	3.6×10^{-1}
b-tag	3.4×10^{-1}	4.4×10^{-2}	1.1×10^{-2}	1.5×10^{-2}	**4.8**	**7.5**

Table IV: $M_{U_h} = 1$ TeV , $\sigma_s = 6.8$ fb , $\mathcal{L} = 35$ fb^{-1}

	σ_s [fb]	$\sigma_{t\bar{t}}$ [fb]	$\sigma_{b\bar{b}}$ [fb]	$\sigma_{\text{multi-jet}}$ [fb]	S/B	$S/\sqrt{B}$
Preselection Cuts	2.4	4.6×10^{2}	8.4×10^{3}	2.8×10^{5}	8.15×10^{-6}	2.6×10^{-2}
Basic Cuts	6.0×10^{-1}	4.6	16.0	6.8×10^{2}	8.6×10^{-4}	1.4×10^{-1}
$\lvert\Delta_{mh}\rvert < 0.1$	3.9×10^{-1}	1.7	6.5	2.8×10^{2}	1.4×10^{-3}	1.4×10^{-1}
$\lvert\Delta_{mU}\rvert < 0.1$	2.7×10^{-1}	5.5×10^{-1}	2.0	87.0	3.0×10^{-3}	1.7×10^{-1}
$m_{U_{h1,2}} > 1000$ GeV	2.2×10^{-1}	1.9×10^{-1}	1.0	45.0	4.8×10^{-3}	1.9×10^{-1}
b-tag	1.34×10^{-1}	2.2×10^{-2}	8.5×10^{-3}	1.2×10^{-2}	**3.1**	**3.8**

Table V: $M_{U_h} = 1.2$ TeV , $\sigma_s = 2.4$ fb , $\mathcal{L} = 35$ fb^{-1}