

Searching for composite quark partners at LHC run I and II



Thomas Flacke

KAIST

C. Delaunay, TF, J. Gonzales-Fraile,
S.J. Lee, G. Panico, G. Perez [JHEP 02 (2014) 055]

TF, Jeong Han Kim,
S. J. Lee, Sung Hak Lim [JHEP 1405 (2014) 123]

M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]

M. Backović, TF,
Jeong Han Kim, S. J. Lee [arXiv: 1410.xxxx]

4th KIAS Workshop on
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Outline

- Motivation
- The general setup: minimal composite Higgs from $SO(5)/SO(4)$ breaking
- Partially composite quarks
 - The Lagrangian
 - Overview on the phenomenology
- Constraints on composite quark partners from run I
- Prospects for composite quark partners at LHC run II
- 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.

⇒ 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 $f \sim \mathcal{O}(1 \text{ TeV})$.
→ Naturally obtain $f \lll M_{pl}$.
- Assume a global symmetry which is spontaneously broken by dimensional transmutation → 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 Yukawa-type interactions.
→ The Higgs-like particles become pseudo-Goldstone bosons
⇒ Naturally generates a scale hierarchy $v \sim m_h \ll f \lll M_{pl}$.

Composite Higgs model: general setup

Simplest realization:

The minimal composite Higgs model (MCHM) Agashe, Contino, Pomarol [2004]

Effective field theory based on $SO(5) \rightarrow SO(4)$ global symmetry breaking.

- The Goldstone bosons live in $SO(5)/SO(4) \rightarrow 4$ d.o.f.
- $SO(4) \simeq SU(2)_L \times SU(2)_R$

Gauging $SU(2)_L$ yields an $SU(2)_L$ Goldstone doublet.

Gauging T_R^3 assigns hyper charge to it. Later: Include a global $U(1)_X$ and gauge $Y = T_R^3 + X$.

\Rightarrow Correct quantum numbers for the Goldstone bosons

to be identified as a non-linear realization of the Higgs doublet.

We use the CCWZ construction to construct the low-energy EFT.

Coleman, Wess, Zumino [1969], Callan, Coleman [1969]

Central element: the Goldstone boson matrix

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

where $\Pi = (0, 0, 0, \bar{h})$ with $\bar{h} = \langle h \rangle + h$
and T^i are the broken $SO(5)$ generators.

From it, one can construct the CCWZ d_μ^i and e_μ^a symbols
E.g. kinetic term for the “Higgs”:

$$\mathcal{L}_\Pi = \frac{f^2}{4} d_\mu^i d^{i\mu} = \frac{1}{2} (\partial_\mu h)^2 + \frac{g^2}{4} f^2 \sin^2 \left(\frac{\bar{h}}{f} \right) \left(W_\mu W^\mu + \frac{1}{2c_w} Z_\mu Z^\mu \right)$$

$$\Rightarrow v = 246 \text{ GeV} = f \sin \left(\frac{\langle h \rangle}{f} \right) \equiv f \sin(\epsilon).$$

Note: In the above, the Higgs multiplet is parameterized as a Goldstone multiplet and it is *assumed* that a Higgs potential is induced which leads to EWSB.

Concrete realizations *c.f. e.g. Review by Contino [2010], Panico et al. [2012], ...*:

Couplings of the Higgs to the quark sector (most importantly to the top)*
 explicitly break the $SO(5)$ symmetry.

\Rightarrow Couplings to the top sector induce an effective potential for the Higgs
 which induces EWSB.

* *c.f. Delaunay, Grojean, Perez [2013] for the influence of other quark partners on Higgs physics*

How to include the quarks?

In the SM, the Higgs multiplet

- induces EWSB (✓ in CHM),
- provides a scalar degree of freedom (✓ in CHM),
- generates fermion masses via Yukawa terms (← implementation in CHM?).

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

$$\mathcal{L}_{mix} = y \bar{q}_{l_0} \mathcal{O}^{l_0} + \text{h.c.},$$

where \mathcal{O} is an operator of the strongly coupled theory in the representation l_0 .

Note: The Goldstone matrix $U(\Pi)$ transforms non-linearly under $SO(5)$, but linearly under the $SO(4)$ subgroup $\rightarrow \mathcal{O}^{l_0}$ has the form $f(U(\Pi))\mathcal{O}'_{fermion}$.

Simplest choice for quark embedding:

$$q_L^5 = \frac{1}{\sqrt{2}} \begin{pmatrix} id_L \\ d_L \\ iu_L \\ -u_L \\ 0 \end{pmatrix}, \quad u_R^5 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ u_R \end{pmatrix}, \quad \psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix}.$$

BSM particle content (per u -type quark):

	U	$X_{2/3}$	D	$X_{5/3}$	\tilde{U}
$SO(4)$	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:

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

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

Derivation of Feynman rules:

- expand d_μ , e_μ , U_{gs} around $\langle h \rangle$,
- diagonalize the mass matrices,
- match the lightest mass eigenvalue with the SM quark mass
→ this fixes y_L in terms of the other parameters
(light quarks: $m_q \ll v/\sqrt{2}$; if $y_R \sim 1 \Rightarrow y_L \ll 1$)
(top quark: $m_t \sim v/\sqrt{2}$; requires $y_R \sim 1$ and $y_L \sim 1$)
- calculate the couplings in the mass eigenbasis.

Masses and couplings

The SM like quark:

$$m_u = \frac{v}{\sqrt{2}} \frac{|M_1 - M_4|}{f} \frac{y_L f}{\sqrt{M_4 + y_L^2 f^2}} \frac{y_R f}{\sqrt{|M_1|^2 + y_R^2 f^2}} + \mathcal{O}(\epsilon^3)$$

Partners in the **4**:

$$M_{X_{5/3}} = M_4 = M_{U_{f1}} + \mathcal{O}(\epsilon^2)$$

$$M_D = \sqrt{M_4^2 + y_L^2 f^2} = M_{U_{f2}} + \mathcal{O}(\epsilon^2)$$

Singlet Partner:

$$M_{U_S} = \sqrt{|M_1|^2 + y_R^2 f^2} + \mathcal{O}(\epsilon^2)$$

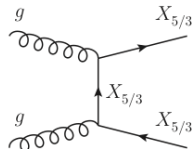
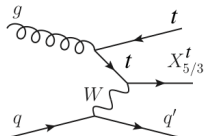
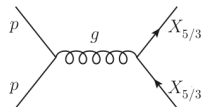
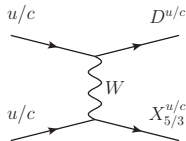
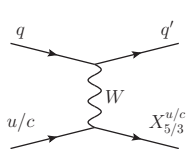
Couplings (examples):

$$|g_{XWu}^R| = \frac{g}{\sqrt{2}} \frac{\epsilon}{\sqrt{2}} \left| \frac{y_R f M_1}{M_4 M_{U_S}} - \sqrt{2} c_{CR} \frac{y_R f}{M_{U_S}} \right| + \mathcal{O}(\epsilon^3)$$

$$|g_{U_S W d}^L| = \frac{g}{\sqrt{2}} \frac{\epsilon}{\sqrt{2}} \left(\frac{y_L f (M_1 M_4 + y_R^2 f^2)}{M_{U_{f2}} M_{U_S}^2} - \frac{\sqrt{2} c_{LY} y_L f}{M_{U_{f2}}} \right) + \mathcal{O}(\epsilon^3)$$

Production and decays

Production mechanisms (shown here: $X_{5/3}$ production)



(a) EW single production

(b) EW pair production

(c) QCD pair production

Decays:

- $X_{5/3} \rightarrow W^+ u$ (100%),
- $D \rightarrow W^- u$ ($\sim 100\%$),
- $U_{f1} \rightarrow Zu$ (dominant),
- $U_{f2} \rightarrow hu$ (dominant),
- light quark partner: $U_s \rightarrow hu$, top partner: also $U_s \rightarrow Zu$, $U_{s.} \rightarrow Wb$

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.

$$M_{X_{5/3}} > 770 \text{ GeV} \text{ ATLAS [1409.5500]} \quad , \quad M_{X_{5/3}} > 800 \text{ GeV} \text{ CMS [PRL 112 (2014) 171801]}$$

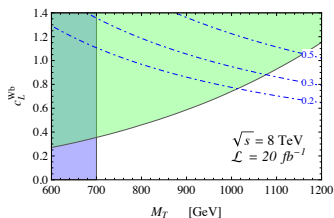
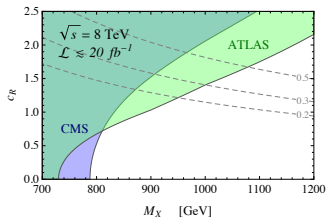
- ATLAS and CMS determined a bound on (QCD) pair-produced top partners with charge $2/3$ (applicable for the T_s, T_{f1}, T_{f2}). [Similar bounds for B]

$$M_{T_s} > \sim 350 \text{ (810) GeV} \text{ ATLAS [1409.5500]} \quad , \quad M_{T_s} > 687 \text{ (782) GeV} \text{ CMS [PLB 729, 149 (2014)]}$$

(the bound depends on the BRs assumed for $T_s \rightarrow th, tZ, Wb$)

- Bounds including single-production channels: Matsedonskyi, Panico, Wulzer [2014]

for earlier work, see also Li, Liu, Shu [2013]



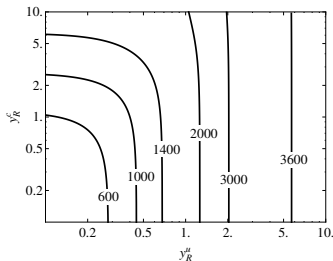
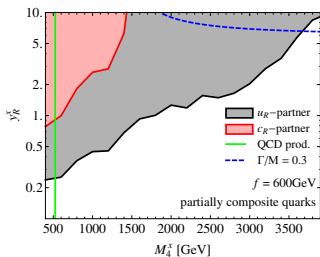
Note: In the above plots $c_R = 2g_{XWU}^R/g$ and $c_L^{Wb} = 2g_{UsWd}^L/g$ as compared to the coupling formulae given earlier.

Determining bounds on partners of light quarks from run I

• Bounds on partners of light quarks in the 4

Delaunay, TF, Gonzales-Fraile, S.J. Lee, Panico, Perez [JHEP 02 (2014) 055]

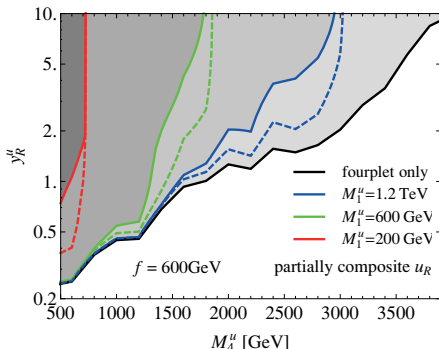
- From QCD pair production: $M_4^{u,d,s,c} > 530 \text{ GeV}$
(from ATLAS and CMS searches applicable to $WWjj, ZZjj$ final states)
- Single production:
(from ATLAS and CMS searches applicable to Wjj, Zjj final states)



Determining bounds on partners of light quarks from run I

The above results for light quark partners assumed absence of a singlet partner. In the presence of an $SO(4)$ singlet quark partner, bounds from single-production channels are relaxed:

Delaunay, TF, Gonzales-Fraile, S.J. Lee, Panico, Perez [JHEP 02 (2014) 055]



Limits on y_R^u as a function of M_4 for different values of M_1 .
 Solid: full limits. Dashed: limits ignoring signal loss due to cascade decays.

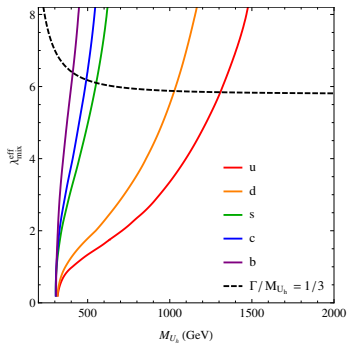
⇒ **Bounds on $SO(4)$ singlet partners are important!**

Determining bounds on partners of light quarks from run I

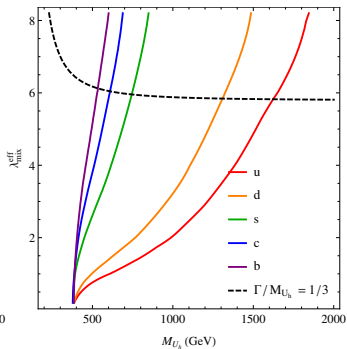
- Bounds on partners of light quarks in the singlet [TF, J. H. Kim, S. J. Lee, S. H. Lim \[JHEP 1405](#)

(2014) 123]

- From QCD pair production: $M_4^{u,d,s,c} > 310 \text{ GeV}$
(using $p_T^{\gamma\gamma}$, N_{jet} , p_T^{jet} from the $h \rightarrow \gamma\gamma$ search in [\[ATLAS-CONF-2013-072\]](#))
- Single production:



Constraints neglecting events with $p_T^{\gamma\gamma} > 200 \text{ GeV}$
(conservative; ignoring overflow bins)



Constraints including events with $p_T^{\gamma\gamma} > 200 \text{ GeV}$
(projection; including overflow bins)

Prospects for composite quark partners at LHC run II

At run II, we have more energy

⇒ searches are sensitive to higher quark partner masses.

However, for composite quark partners there are two additional genuine aspects:

1. Single-production channels (if present) will become more important as compared to QCD pair production channels.
2. For heavier quark partners, their decay products become strongly boosted ⇒ we need dedicated search strategies for boosted tops, Higgses, EW gauge bosons.

Two examples:

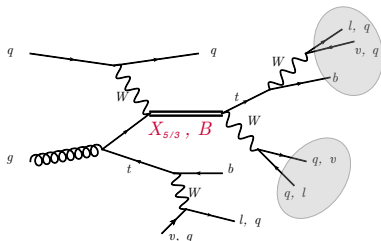
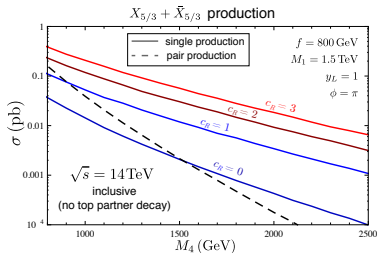
1. Maximizing the sensitivity for the “most visible” quark partner:
An optimized search strategy for top partners in the **4**.
2. Maximizing the sensitivity for the “least visible” quark partner:
An optimized search strategy for singlet partners of light quarks.

M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]

M. Backović, TF, J. H. Kim, S. J. Lee [arXiv: 1410.xxxx]; to appear this Friday

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

- a high energy forward jet
- two b 's
- a highly boosted tW system with:
 - one hard lepton,
 - missing energy,
 - "fat jets",

We use this by

- used as a tag
- ⇒ demand two b -tags
- $p_T^l > 100 \text{ GeV}$ cut
- 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 .

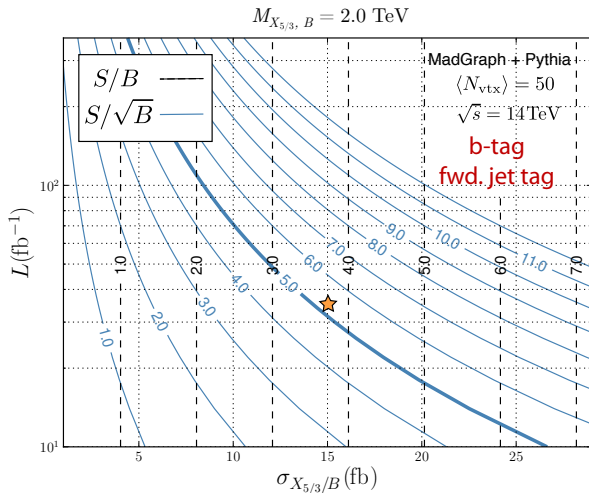
M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]

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

$X_{5/3} + B$	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}	
	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
$p_T > 700 \text{ GeV}$	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
$p_T^l > 100 \text{ GeV}$	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
$0v > 0.5$	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
$M_{X_{5/3}/B} > 1.5 \text{ TeV}$	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
$m_{jt} > 300 \text{ GeV}$	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 $M_{X_{5/3}/B} = 2.0 \text{ TeV}$ 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 $M_{X_{5/3}/B} = 2.0 \text{ TeV}$ assume both $X_{5/3}$ and B production.

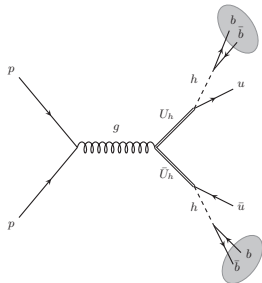
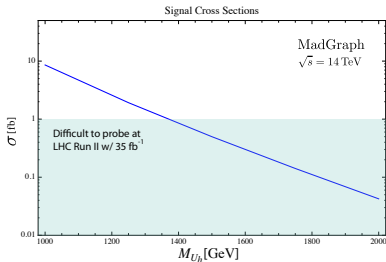
Prospects for composite quark partners at LHC run II



Prospects for composite quark partners at LHC run II

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

M. Backović, TF, J. H. Kim, S. J. Lee [arXiv: 1410.xxxx]



Cut Scheme	Basic Cuts	Demand at least four fat jets ($R = 0.7$) with $p_T > 300 \text{ GeV}$, $ \eta < 2.5$
		Declare the two highest p_T fat jets satisfying $0v_2^h > 0.4$ and $0v_3^h < 0.4$ to be Higgs candidate jets.
	Complex Cuts	At least 1b-tag on both Higgs candidate jets. Select the two highest p_T light jets ($r = 0.4$), with $p_T > 25 \text{ GeV}$ to be the u quark candidates.
		$ \Delta_h < 0.1$ $ \Delta_{U_h} < 0.1$ $m_{U_{h1,2}} > 800 \text{ GeV}$

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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}
$ \Delta_{mh} < 0.1$	8.2×10^{-1}	1.7	6.5	2.8×10^2	2.9×10^{-3}	2.9×10^{-1}
$ \Delta_{mU} < 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}
$ \Delta_{mh} < 0.1$	3.9×10^{-1}	1.7	6.5	2.8×10^2	1.4×10^{-3}	1.4×10^{-1}
$ \Delta_{mU} < 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 $^{-1}$

Conclusions and Outlook

- 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 $M_X \gtrsim 800 \text{ GeV}$.
- The phenomenology of light quark partners strongly differs from top-partner phenomenology.
 - For partially composite quarks with partners in the fourplet, we find a flavor and y_R independent bound of $M_4^{u/c} \gtrsim 525 \text{ GeV}$ as well as stronger flavor and y_R dependent bounds (e.g. $M_4^u \gtrsim 1.8 \text{ TeV}$, $M_4^c \gtrsim 610 \text{ GeV}$ for $y_R^{u/c} = 1$).
 - For partially composite quarks with partners in the singlet, we find a flavor- and $\lambda_{\text{mix}}^{\text{eff}}$ independent bound of $M_{U_h} > 310 \text{ GeV}$ as well as increased flavor- and $\lambda_{\text{mix}}^{\text{eff}}$ -dependent bounds.
- For run II, single-production channels and strongly boosted top and Higgs searches become important.
 - Performing dedicated searches for boosted tops, the $X_{5/3}$ can be discovered even at masses beyond 2 TeV .
 - Even the (currently weakest constraint) singlet partners of light quarks can be discovered at masses beyond 1 TeV .