Searching for composite quark partners at LHC run I and II

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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 *(in preparation)*

TF, SangEun Han,
Jeong Han Kim, S. J. Lee *(in preparation)*

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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.

$\Rightarrow$ 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 Yukawa-type interactions.
  $\rightarrow$ The Higgs-like particles become pseudo-Goldstone bosons
  $\Rightarrow$ 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 $SO(5) \to SO(4)$ 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 $SU(2)_L$ yields an $SU(2)_L$ Goldstone doublet.
  Gauging T^3_R assigns hyper charge to it. Later: Include a global $U(1)_X$ and gauge $Y = T^3_R + X$.
  $\Rightarrow$ 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

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

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

From it, one can construct the CCWZ d^i_μ and e^a_μ symbols
E.g. kinetic term for the “Higgs”:

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

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

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 ($\leftarrow$ 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

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

where $\mathcal{O}$ is an operator of the strongly coupled theory in the representation $I_{\mathcal{O}}$.
Note: The Goldstone matrix $U(\Pi)$ transforms non-linearly under $SO(5)$, but linearly under the $SO(4)$ subgroup $\to$ $\mathcal{O}^{I_{\mathcal{O}}}$ 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:

$$\begin{aligned}\mathcal{L}_{comp} &= i\,\overline{Q}(D_\mu + ie_\mu)\gamma^\mu Q + i\bar{\tilde{U}}\not{D}\tilde{U} - M_4\overline{Q}Q - M_1\bar{\tilde{U}}\tilde{U} + \left(ic\overline{Q}^i\gamma^\mu d^i_\mu \tilde{U} + \text{h.c.}\right),\\ \mathcal{L}_{el,mix} &= i\,\overline{q}_L\not{D}q_L + i\,\overline{u}_R\not{D}u_R - y_L f\overline{q}^5_L U_{gs}\psi_R - y_R f\overline{u}^5_R U_{gs}\psi_L + \text{h.c.}\end{aligned}$$

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
  $\rightarrow$ 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**:

$$\begin{aligned} M_{X5/3} = & \quad M_4 & = M_{Uf1} + \mathcal{O}(\epsilon^2) \\ M_D = & \sqrt{M_4^2 + y_L^2 f^2} & = M_{Uf2} + \mathcal{O}(\epsilon^2) \end{aligned}$$

Singlet Partner:

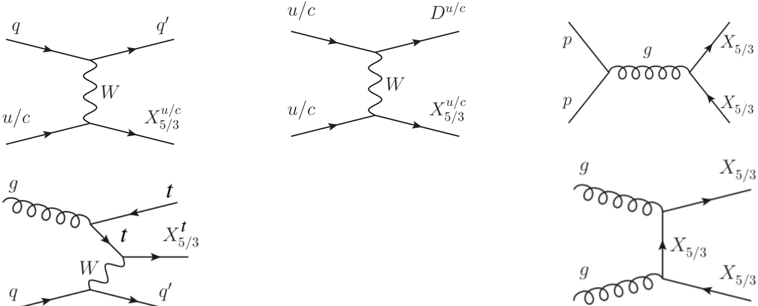
$$M_{Us} = \sqrt{|M_1|^2 + y_R^2 f^2} + \mathcal{O}(\epsilon^2)$$

Couplings (examples):

$$\begin{aligned} \left| g^R_{XWu} \right| &= \frac{g}{\sqrt{2}} \frac{\epsilon}{\sqrt{2}} \left| \frac{y_R f\, M_1}{M_4 M_{Us}} - \sqrt{2} c_R \frac{y_R f}{M_{Us}} \right| + \mathcal{O}(\epsilon^3) \\ \left| g^L_{UsWd} \right| &= \frac{g}{\sqrt{2}} \frac{\epsilon}{\sqrt{2}} \left(\frac{y_L f\, (M_1 M_4 + y_R^2 f^2)}{M_{Uf2} M_{Us}^2} - \frac{\sqrt{2} c_L y_L f}{M_{Uf2}} \right) + \mathcal{O}(\epsilon^3) \end{aligned}$$

Production and decays

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



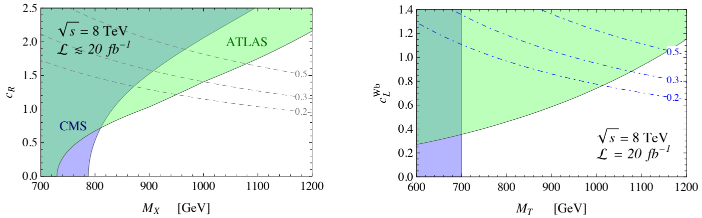
(a) EW single production (b) EW pair production (c) QCD pair production

Decays:

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

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.
  $M_{X_{5/3}} > 770\,\mathrm{GeV}$ [ATLAS-CONF-2013-051]
  $M_{X_{5/3}} > 800\,\mathrm{GeV}$ CMS [PRL 112 (2014) 171801]
- CMS determined a bound on (QCD) pair-produced top partners with charge $2/3$ (applicable for the T_s).
  $M_{T_s} > 687\,(782)\,\mathrm{GeV}$ CMS [PLB 729, 149 (2014)]
  (the bound depends on the BRs assumed for $T_s \to th,\ tZ,\ Wb$)
- Bounds including single-production channels: Matsedonskyi, Panico, Wulzer [2014]



Note: In the above plots $c_R = 2g^R_{XWu}/g$ and $c_L^{Wb} = 2g^L_{UsWd}/g$ as compared to the coupling formulae given earlier.

Determining bounds on partners of light quarks from run I

To determine the bounds from Tevatron, ATLAS and CMS searches we

- implemented the model [FeynRules2.0 $\rightarrow$ MadGraph5 (using CTEQ6L)],
- simulated the BSM signals on parton level,
- compared with the bounds established by the experimental searches.

  - Single production: *Wjj*, *Zjj*

    D0 Collaboration, [Phys. Rev. Lett. 106, 081801 (2011)]

    CDF Collaboration, [CDF/PUB/EXOTIC/PUBLIC/1026]

    ATLAS Collaboration, [ATLAS-CONF-2012-137] (4.64 fb^{-1} 7 TeV)

    CMS Collaboration, [CMS-PAS-EXO-12-024] (19.8 fb^{-1} 8 TeV)

  - Pair production: *WWjj*, *ZZjj*

    D0 Collaboration, [Phys. Rev. Lett. 107, 082001 (2011)]

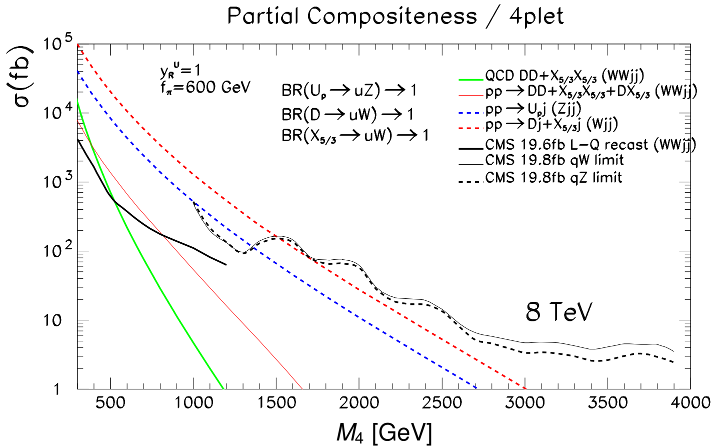
    CDF Collaboration, [Phys. Rev. Lett. 107, 261801 (2011)]

    ATLAS Collaboration, [Phys. Rev. D 86, 012007 (2012)] (1.04 fb^{-1} 7 TeV)

    CMS Collaboration, [CMS-PAS-EXO-12-042] (19.6 fb^{-1} 8 TeV; Leptoquark search, final state: $\mu\mu jj$)

Determining bounds on partners of light quarks from run I

Example



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

Determining bounds on partners of light quarks from run I

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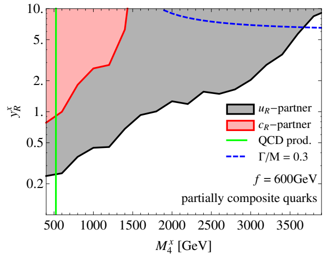
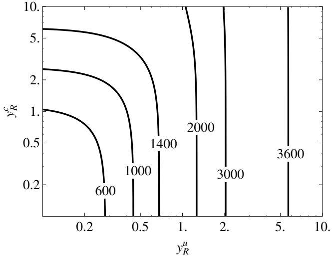




Bound from pair production ($y_R^{u,c}$-independent):

$$M_4^{u,c} > 530\,\mathrm{GeV}.$$

Bounds including single-production channels (for $y_R^{u,c} = 1$):

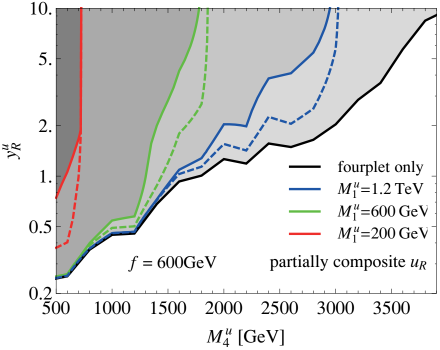
$$M_4^u > 1.8\,\mathrm{TeV}, \quad M_4^c > 610\,\mathrm{GeV}.$$

Not shown here: Bounds for down-type quark partners. For d, s partners bounds are be expected to lie in between the u, c partner bounds. b partners require a separate analysis. (TF, SangEun Han, Jeong Han Kim, S. J. Lee, (work in progress))

Determining bounds on partners of light quarks from run I

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

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 $g_1^* \equiv M_1/f$.
Solid: full limits. Dashed: limits ignoring signal loss due to cascade decays.

Determining bounds on the singlet partner of light quarks from run I

These bounds do not capture the singlet partner U_s. It is dominantly pair-produced and decays into hj.

$$\Rightarrow \text{Signal: } hhjj.$$

Two main possibilities:

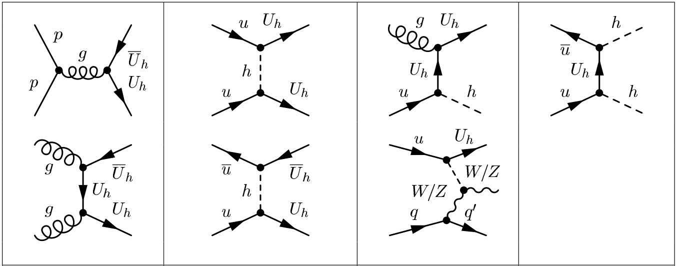
- Try using ATLAS and CMS di-Higgs searches
  By now CMS published di-Higgs search results in the $llll$ and $ll\gamma\gamma$ channel. [CMS PAS HIG-13-025]
  Naive matching of the hh cross section bound yields $m_{U_h} \gtrsim 300\,\mathrm{GeV}$.
  Problem: These searches assume a different event topology ($H \to hh$).
- *OR:* Consider the $hhjj$ channel as an additional source of Higgs production and use "standard" Higgs search data. TF, J.H. Kim, S.J. Lee, S.H. Lim, [JHEP 1405 (2014) 123]
  (Requires suitable observables which allow to discriminate between SM and BSM production of Higgses; *e.g.* $p_T^h \leftrightarrow$ boosted signals)

Effective Lagrangian for a composite quark partner in the $SO(4)$ singlet representation:

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \overline{U}_h \left(i\not{D} - M_{U_h}\right) U_h - \left[\lambda^{\mathrm{eff}}_{\mathrm{mix}} h \overline{U}_{h,L} u_{l,R} + \text{h.c.}\right].$$

Constraining Partners in the singlet

BSM production channels which yield Higgs bosons:



(a) QCD pair prod. | (b) non-QCD pair prod. | (c) single prod. | (d) t-channel

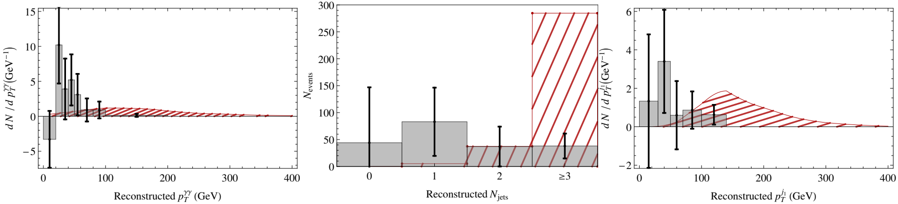
Note: Processes (a)-(c) produce one or two partner quarks which decay into a boosted Higgs (if $M_{U_h} > m_h$) and a light quark.

- Unlike SM produced Higgses, this typically yields high p_T Higgses.
- The BSM processes yield one (or more) high p_T jets in the final state.

Constraining the singlet partner

ATLAS provides measurements of differential cross sections of the Higgs di-photon decay, where bounds on the $p_T^{\gamma\gamma}$, N_{jets}, and p_T^{j1} distributions are given [ATLAS-CONF-2013-072].

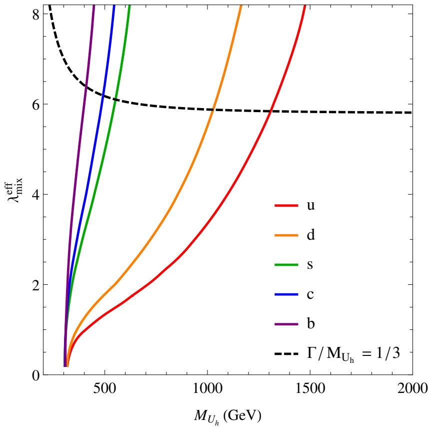
We simulate these distributions for BSM Higgs production and subsequent $H \to \gamma\gamma$ decay.



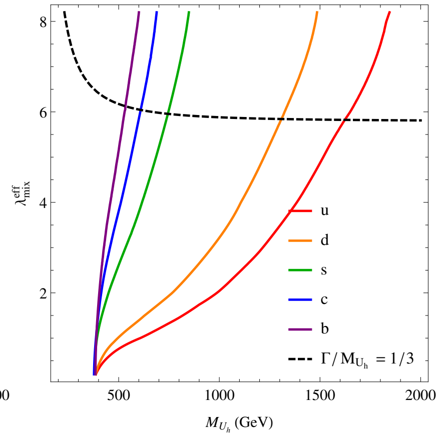
Example: $p_T^{\gamma\gamma}$, N_{jets}, and p_T^{j1} distributions for $M_{U_h} = 300\,\mathrm{GeV}$ and $y_R = 1.1$.

Constraining the singlet partner

Performing a bin-by-bin χ^2 test on the BSM distributions, we obtain a bound on the composite quark parameter space.



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



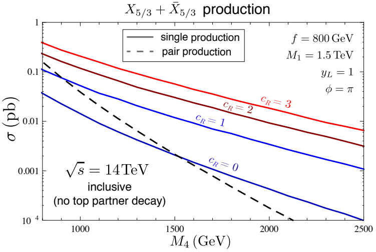
Constraints including events with $p_T^{\gamma\gamma} > 200$ GeV
(projection; including overflow bins)

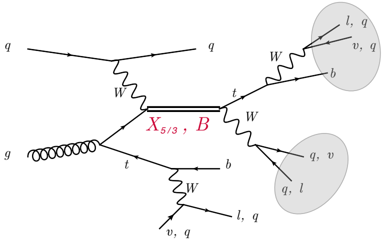
Prospects for composite quark partners at LHC run II

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

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

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





With search strategies for boosted tops, top partners can be discovered at run II even beyond masses of 2 *TeV*.
M. Backović, TF, S. J. Lee, G. Perez [arXiv: 1409.0409]

Conclusions and Outlook

- Composite Higgs models provide a viable solution to the hierarchy problem and generically predict partner states to the fermions.
- Top partners (in the MCHM) are constraint from run I to $M_X \gtrsim 800\,\mathrm{GeV}$.
- 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 $M_4^{u/c} \gtrsim 525$ GeV as well as stronger flavor and y_R dependent bounds (*e.g.* $M_4^u \gtrsim 1.8$ TeV, $M_4^c \gtrsim 610$ GeV for $y_R^{u/c} = 1$).
  - For partially composite quarks with partners in the singlet, we find a flavor- and $\lambda_{\mathrm{mix}}^{\mathrm{eff}}$ independent bound of $M_{U_h} > 310\,\mathrm{GeV}$ as well as increased flavor-and $\lambda_{\mathrm{mix}}^{\mathrm{eff}}$-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 $2\,\mathrm{TeV}$. ($\rightarrow$ Mihailo's talk)
  - A study for singlet partner quarks using boosted Higgs signals is under way.
    [M. Backović, TF, Jeong Han Kim, S. J. Lee (to appear)]

Backup

Definition of d and e symbols:

$$
\begin{aligned}
d_\mu^i &= \sqrt{2}\left(\frac{1}{f}-\frac{\sin\Pi/f}{\Pi}\right)\frac{\vec{\Pi}\cdot\nabla_\mu\vec{\Pi}}{\Pi^2}\Pi^i+\sqrt{2}\frac{\sin\Pi/f}{\Pi}\nabla_\mu\Pi^i \\
e_\mu^a &= -A_\mu^a+4\,i\,\frac{\sin^2\left(\Pi/2f\right)}{\Pi^2}\vec{\Pi}^t t^a\nabla_\mu\vec{\Pi}
\end{aligned}
$$

d_μ symbol transforms as a fourplet under the unbroken $SO(4)$ symmetry, while e_μ belongs to the adjoint representation.
$\nabla_\mu\Pi$ is the "covariant derivative" of the Goldstone field Π

$$
\nabla_\mu\Pi^i=\partial_\mu\Pi^i-iA_\mu^a\left(t^a\right)^i{}_j\,\Pi^j\,,
$$

A_μ: gauge fields of the gauged subgroup of $SO(4)\simeq SU(2)_L\times SU(2)_R$

$$
\begin{aligned}
A_\mu &= \frac{g}{\sqrt{2}}W_\mu^+\left(T_L^1+iT_L^2\right)+\frac{g}{\sqrt{2}}W_\mu^-\left(T_L^1-iT_L^2\right) \\
&\quad +g\left(c_w Z_\mu+s_w A_\mu\right)T_L^3+g'\left(c_w A_\mu-s_w Z_\mu\right)T_R^3\,.
\end{aligned}
$$

Explicit form in unitary gauge:

$$\begin{cases} e_L^{1,2} = -\cos^2\left(\frac{\overline{h}}{2f}\right) W_L^{1,2} \\ e_L^3 = -\cos^2\left(\frac{\overline{h}}{2f}\right) W^3 - \sin^2\left(\frac{\overline{h}}{2f}\right) B \end{cases}, \begin{cases} e_R^{1,2} = -\sin^2\left(\frac{\overline{h}}{2f}\right) W_L^{1,2} \\ e_R^3 = -\cos^2\left(\frac{\overline{h}}{2f}\right) B - \sin^2\left(\frac{\overline{h}}{2f}\right) W^3 \end{cases}$$

and

$$\begin{cases} d_\mu^{1,2} = -\sin(\overline{h}/f)\frac{W_\mu^{1,2}}{\sqrt{2}} \\ d_\mu^3 = \sin(\overline{h}/f)\frac{B_\mu - W_\mu^3}{\sqrt{2}} \\ d_\mu^4 = \frac{\sqrt{2}}{f}\partial_\mu h, \end{cases} .$$

General case: M_1 and M_4 finite.

We have obtained bounds on the fourplet partners with the singlet decoupled.

How are these bounds modified when the singlet is not decoupled?

BSM Particle content: $X_{5/3}$, D, U_p, U_1, U_2
Where $U_{1,2}$ are the mass eigenstates of $U_m - \tilde{U}$ mixing.

Masses: $m_{U_p} = m_D = m_{X_{5/3}} = M_4$, $m_{U_{1,2}} =$

$$\frac{1}{2}\left[{M_1}^2 + {M_4}^2 + {y_R}^2 f^2 \mp \sqrt{({M_1}^2 - {M_4}^2 + {y_R}^2 f^2)^2 - 4\sin^2\epsilon\,({M_1}^2 - {M_4}^2)\,{y_R}^2 f^2}\right].$$

"mixing" couplings with light quarks:

$$\begin{aligned}
\lambda_{huU_1} &\approx -y_R \cos\epsilon \cos\varphi_4 \cos\tilde{\varphi}_1\,,\\
\lambda_{huU_2} &\approx y_R \sin\epsilon \cos\varphi_4 \cos\tilde{\varphi}_1\,,\\
g_{WuD} = -g_{WuX} = -c_w\, g_{ZuU_p} &\approx \frac{g}{2} \cos\epsilon \sin\varphi_4 \cos\tilde{\varphi}_1\,,
\end{aligned}$$

where

$$\tan\tilde{\varphi}_1 \equiv \frac{y_R f \cos\epsilon / M_1}{1 + (y_R f \sin\epsilon)^2 / {M_4}^2}.$$

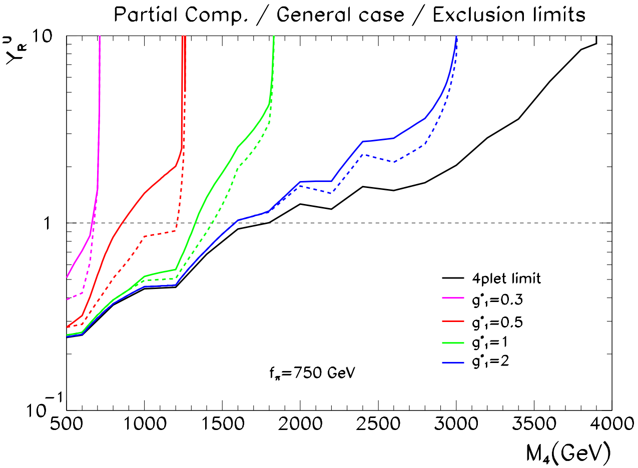
...also present: "Mixing" couplings amongst heavy quarks partners: $\lambda_{hU_1 U_2}$, $g_Z U_{1/2} U_p$, and analogous for charged couplings.

General case: M_1 and M_4 finite.

Consequences of finite M_1 for fourplet bounds:

- The single-production cross section of $X_{5/3}$, D, U_1 is reduced.
  Physical reason: The production arises due to mixing of u_R with the fourplet, but now, u_R also mixes with the singlet.
- If the lighter up-type mass eigenstate U_1 is mostly singlet (for $M_1 \lesssim M_4$):
  Fourplet states U_p, D, $X_{5/3}$ can also cascade decay via the U_1
  $\rightarrow$ The previously considered signal cross section gets reduced due to the BR into cascade decays.

General case: M_1 and M_4 finite, up-partners



Limits on y_R^u as a function of M_4 for different values of $g_1^* \equiv M_1/f$.
Solid: full limits. Dashed: limits ignoring signal loss due to cascade decays.