Searching for composite quark partners at the LHC

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

TF, Jeong Han Kim, Seung Joon Lee, Sung Hak Lim [arXiv:1312.5316]

TF, Sang Eun Han, Jeong Han Kim, Seung Joon Lee *in preparation*

SNU-KAIST-KASI-IBS Journal Club
2014/03/12

Outline

Motivation

- ☺ Atlas and CMS found a Higgs-like resonance with a mass $m_h \sim 126$ GeV and couplings to $\gamma\gamma$, WW, ZZ, bb, and $\tau\tau$ compatible with the standard model Higgs.
- ☹ The standard model suffers from the hierarchy problem.

$\Rightarrow$ We need to 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 spont. broken by dim. 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
(roughly speaking: connections corresponding to broken / unbroken generators).
E. g. kinetic term for the “Higgs”:

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

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

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.

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

Simplest choice for quark embedding:

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

How to include the quarks?

Remarks:

- Another "as minimal" embedding as considered here:
  embed q_L and ψ in the same way in the **5** and u_R as a chiral $SO(5)$ singlet.
  $\Rightarrow$ "(fully) composite right-handed quarks *c.f. e.g.* Rattazzi *et al.* [2012]
  (We studied this second case in detail, too. $\rightarrow$ backup slides)
- The choice of rep. for the light quarks and their partners is not unique.
  Other embeddings which are sometimes discussed:
  - $\mathbf{14} = \mathbf{1} \oplus \mathbf{4} \oplus \mathbf{9}$ *c.f. e.g.* Rattazzi *et al.* [2012], Panico *et al.* [2012], Torre *et al.* [2013]
    One qualitative new feature:
    The **9** contains additional partner particles with exotic charges.
  - $\mathbf{10} = \mathbf{4} \oplus \mathbf{6}$ *c.f. e.g.* Contino *et al.* [2006], Redi *et al.* [2008], Panico *et al.* [2010], Azatov *et al.* [2011], Mühlleitner *et al.* [2013]
    New features:
    New partners in the **6**.
    Quark partners in the **10** can serve as up- *and* down-type partners simultaneously.

Back to partially composite quarks in the **5**.
BSM particle content:

	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:

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

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

Derivation of Feynman rules:

- expand d_μ, e_μ, U_{gs} around $\langle h \rangle$,
- diagonalize the mass matrices,
- match the lightest up-type mass with the SM quark mass
  $\rightarrow$ this fixes y_L in terms of the other parameters ($y_R \sim 1 \Rightarrow y_L \ll 1$)
- calculate the couplings in the mass eigenbasis.

Partners in the fourplet

Lets first consider the limit $M_1 \to \infty$.
$\tilde{U}$ decouples, and the remaining quark partners form a **4** of $SO(4)$.

Mass eigenstates:
$U_{p/m} = (1/\sqrt{2})\left(U \pm X_{2/3}\right)$, D, $X_{5/3}$.

Masses:
$m_{U_p} = m_D = m_{X_{5/3}} = M_4$, $m_{U_m} = \sqrt{M_4^2 + (y_R f \sin(\epsilon))^2}$, with $\epsilon = \langle h \rangle / f$.

"Mixing" couplings:

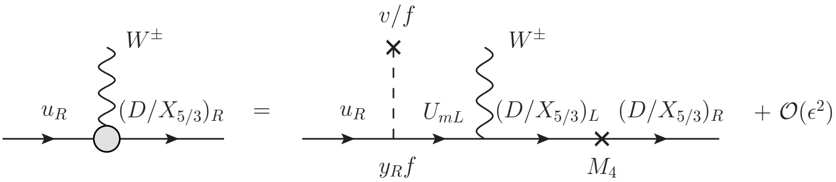
$$\begin{aligned} g_{WuX} = -g_{WuD} = -c_w\, g_{ZuU_p} &= \frac{g}{2} \cos\epsilon \sin\varphi_4 , \\ \lambda_{huU_m} &= y_R \cos\epsilon \cos\varphi_4 , \end{aligned}$$

with

$$\tan\varphi_4 \equiv \frac{y_R f \sin\epsilon}{M_4} .$$

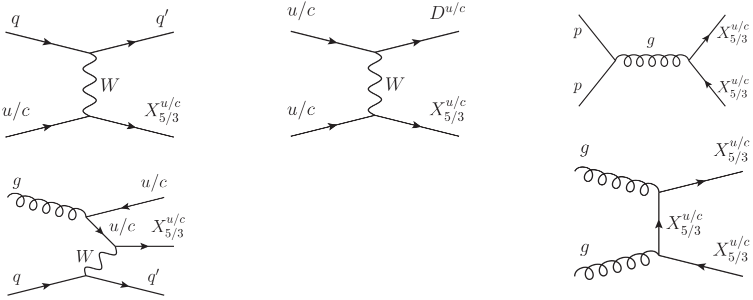
Partners in the fourplet

How to (qualitatively) understand the “mixing” couplings:



Partners in the fourplet

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%),
- $D \to W^- u$ (100%),
- $U_p \to Zu$ (100%),
- $U_m \to hu$ (100%).

NOTE:

- The EW production mechanisms strongly differs for 1st, 2nd, and 3rd generation partners due to the differing PDFs for u, c, t in the proton.
- The final states (search signatures) differ:
  - 1st generation partners: u, d quarks in the final state $\rightarrow$ jets.
  - 2nd generation partners: $c, s \rightarrow$ jets, potentially tagable c in the future
  - 3nd generation partners: $t, b \rightarrow$ well distinguishable from jets

We focus on 1st and 2nd family partners.

c.f. [Rattazzi *et al.* (2012)] for top partners.

c.f. [TF, S.E. Han, J.H. Kim, S.J. Lee, (to appear soon)] for bottom partners.

$\rightarrow$ relevant measured final states:

- 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: $WWjj$, $ZZjj$

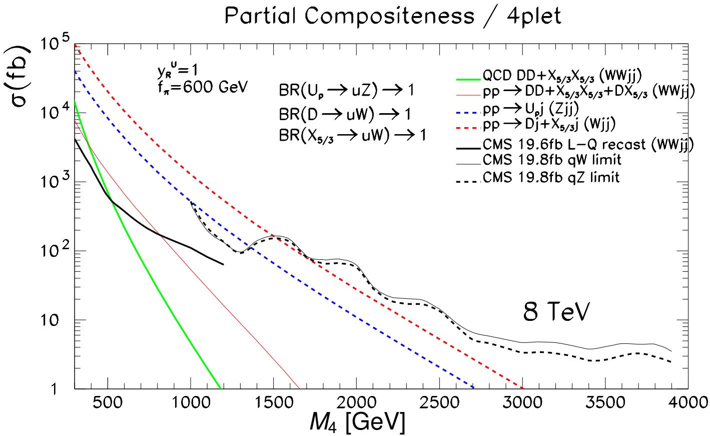
  [D0 Collaboration], Phys. Rev. Lett. 107, 082001 (2011)
  [CDF Collaboration], Phys. Rev. Lett. 107, 261801 (2011)
  [ATLAS Collaboration], Phys. Rev. D 86, 012007 (2012) (1.04 fb^{-1} 7 TeV)
  [CMS Collaboration], CMS-PAS-EXO-12-042 (19.6 fb^{-1} 8 TeV); Leptoquark search, final state: $\mu\mu jj$)

Determining bounds from searches

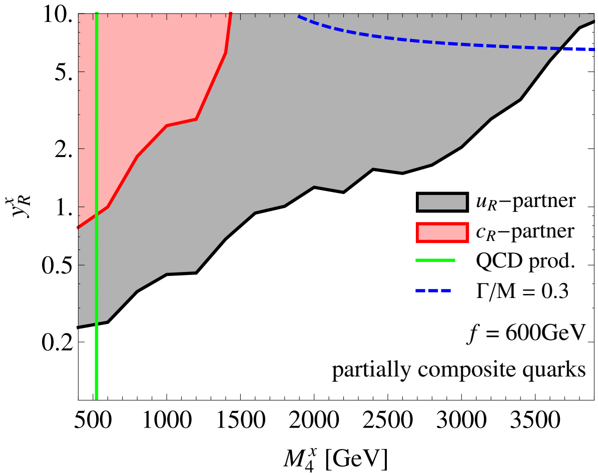
To determine the bounds from Tevatron, ATLAS and CMS searches we

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

E.g.



Determining bounds from searches



[JHEP 02 (2014) 055]. Analysis for bottom partners is under way

Partners in the singlet (qualitative discussion)

Now lets look at the opposite limit: M_1 finite and $M_4 \to \infty$.
Then, all fourplet states decouple, and the only remaining BSM state is $\tilde{U}$.

Mass: $m_{\tilde{U}} = \sqrt{{M_1}^2 + (y_R f \cos(\epsilon))^2}$

only "mixing" coupling:

$$\lambda_{hu\tilde{U}} = y_R \sin\epsilon \cos\varphi_1 , \qquad \text{with} \qquad \tan\varphi_1 \equiv \frac{y_R f \cos\epsilon}{M_1} .$$

Production: pair-production (QCD and EW)

Decay: $\tilde{U} \to hj$ (100%)

Signal: $pp \to hhjj$.
No data on the di-higgs channel was available at the time of our study.
$\Rightarrow$ Only "theory" bound: $m_{\tilde{U}} > m_h$ (otherwise Higgs BR are modified).

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: $m_{U_p} = m_D = m_{X_{5/3}} = M_4$, $m_{U_{1,2}} =$
$$\frac{1}{2}\left[{M_1}^2 + {M_4}^2 + {y_R}^2 f^2 \mp \sqrt{\left({M_1}^2 - {M_4}^2 + {y_R}^2 f^2\right)^2 - 4\sin^2\epsilon\,\left({M_1}^2 - {M_4}^2\right) {y_R}^2 f^2}\right].$$

“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

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

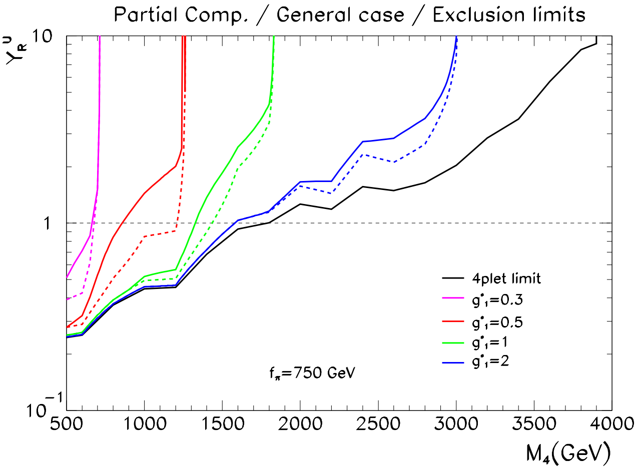
...also present: “Mixing” couplings amongst heavy quarks partners: $\lambda_{hU_1 U_2}$, $g_Z U_{1/2} U_p$, and analogous for charged couplings.

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.

Constraining Partners in the singlet

[TF, Jeong Han Kim, Seung Joon Lee, Sung Hak Lim, arXiv:1312.5316]

We see from the previous analysis:

- The "standard search channels" for quark partners do not yield a bound on the singlet partner because it couples to SM quarks only via the Higgs.
- A light singlet partner dilutes the bounds on the fourplet partners.

$\Rightarrow$ A bound on singlet partner from other search channels is required.

Two main possibilities:

- Consider the *hhjj* channel as an additional source of Higgs production and use "standard" Higgs search data.
  (Requires suitable observables which allow to discriminate between SM and BSM production of Higgses; *e.g.* $p_T^h \leftrightarrow$ boosted signals)
  Sung Hak Lim's talk tomorrow: $m_{U_h} > 310\,\mathrm{GeV}$ [TF, J.H. Kim, S.J. Lee, S.H. Lim, arXiv:1312.5316]
- Wait for 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]
  Matching the cross-section bounds to our previous CHM analysis yields the estimate: $m_{U_h} \gtrsim 300\,\mathrm{GeV}$.

Conclusions

- Composite Higgs models provide a viable solution to the hierarchy problem and generically predict partner states to the fermions.
- 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, $M_4^c \gtrsim 0.8$ TeV for $y_R^{u/c} = 1$).
- For partially composite quarks with partners in the singlet, we find a flavor- and y_R independent bound of $M_{U_h} > 310\,\mathrm{GeV}$ as well as increased flavor-and y_R-dependent bounds. (*c.f.* Sung Hak Lim's talk tomorrow:)
- We performed analogous analyses for fully composite right-handed light quarks, for which many of the aspects presented here apply as well.

Outlook / To do

- Our analysis focussed on light quarks. Top- and bottom partners are partially but not systematically discussed elsewhere. *c.f. e.g.* [Rattazzi *et al.* (2012), Mühlleitner *et al.* (2013)]
  A more comprehensive study of bottom partners is under way.
  [Jeong Han Kim, Seung Joon Lee (to appear soon)]
- Improve bounds by more detailed analysis (making use of boosted decays).
  [M. Backovic, TF, S.J. Lee, J. Juknevich, *(in progress)*]
- In the current analysis, we only considered a single flavor at a time.
  $\rightarrow$ Include full quark sector, consistent with bounds from flavor physics.
  [TF, S.J. Lee, G. Perez, Y. Soreq *(in progress)*]
- On a more general level:
  We only *parameterize* the lowest lying quark partner resonances.
  - UV completion?
  - Determination of parameters from the strong sector?
  - ...

Fully composite quarks

Fermion embedding

Like before:

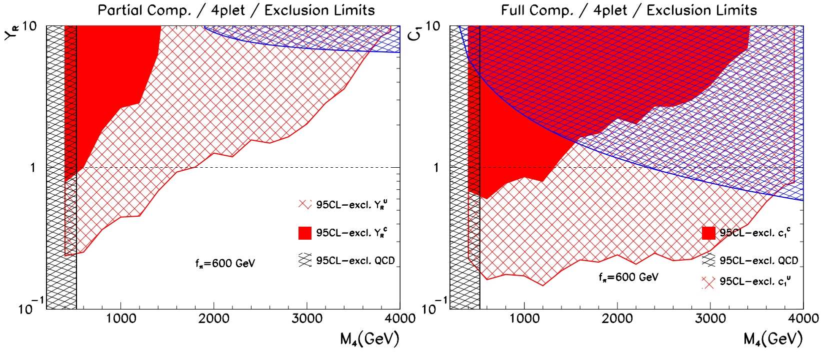
$$q_L^5 = \frac{1}{\sqrt{2}} \begin{pmatrix} i d_L \\ d_L \\ i u_L \\ -u_L \\ 0 \end{pmatrix}, \quad \psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix},$$

but now, embed u_R as a chiral composite $SO(5)$ singlet.

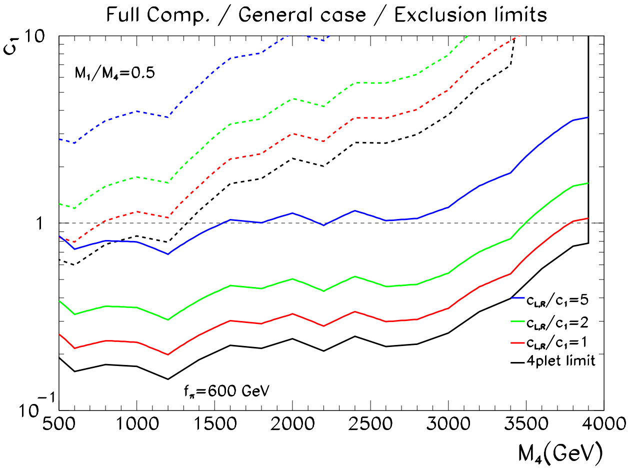
Fermion-Lagrangian

$$\begin{aligned} \mathcal{L}^f_{comp} &= i\,\overline{\psi}(D_\mu + i e_\mu)\gamma^\mu \psi + i\,\overline{u}_R \not{D} u_R - M_4 \overline{Q} Q - M_1 \overline{\tilde{U}} \tilde{U} \\ &\quad + \left[i c_L\, \overline{Q}^i_L d^i_\mu \gamma^\mu \tilde{U}_L + i c_R\, \overline{Q}^i_R d^i_\mu \gamma^\mu \tilde{U}_R + \text{h.c.} \right] + \left[i c_1\, \overline{Q}^i_R d^i_\mu \gamma^\mu u_R + \text{h.c.} \right], \\ \mathcal{L}^f_{el+mix} &= i\,\overline{q}_L \not{D} q_L - \left[y\, f \left(\overline{q}^5_L U_{gs} \right)_i Q^i_R + \right. \\ &\quad \left. + y\, c_2\, f \left(\overline{q}^5_L U_{gs} \right)_5 u_R + y\, c_3\, f \left(\overline{q}^5_L U_{gs} \right)_5 \tilde{U}_R + \text{h.c.} \right], \end{aligned}$$

Determining bounds from searches



General case: M_1 and M_4 finite, up-partners, fully composite



Limits on c_1^u (solid) and c_1^c (dashed) as a function of M_4 for different values of c_R/c_1 (with $c_L = c_R$).

Constraining partner quarks in the singlet

Main difference as compared to partially composite quarks:

- The "mixed" coupling to the Higgs is naturally small for light quark partners.
  $\Rightarrow$ QCD pair production is the dominant production process.
- The BR of U_h decays into W, Z, and h and a light quark are $\sim 50\%, \sim 25\%, \sim 25\%$.
  $\Rightarrow$ the "signal" from $U_h \to hj \to \gamma\gamma j$ is reduced.

With an analogous study as for the partially composite quarks, we find a a flavor and y_R independent bound of $M_{U_h} \gtrsim 212$ GeV.

Definition of d and e symbols:

$$d_\mu^i = \sqrt{2}\left(\frac{1}{f} - \frac{\sin \Pi/f}{\Pi}\right)\frac{\vec{\Pi}\cdot\nabla_\mu\vec{\Pi}}{\Pi^2}\Pi^i + \sqrt{2}\frac{\sin \Pi/f}{\Pi}\nabla_\mu\Pi^i$$

$$e_\mu^a = -A_\mu^a + 4\,i\,\frac{\sin^2(\Pi/2f)}{\Pi^2}\vec{\Pi}^t t^a \nabla_\mu\vec{\Pi}$$

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 $SO(4) \simeq SU(2)_L \times SU(2)_R$

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

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

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