Searching for composite quark partners at the LHC

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C. Delaunay, TF, J. Gonzales-Fraile, Seung Joon 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*

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Composite Higgs model

☺ 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 get 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_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 non-linear realizations 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 lepton masses via Yukawa terms ($\leftarrow$ implementation in CHM?).

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

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

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:

$$\begin{aligned}
\overline{q}^5_L &= \frac{1}{\sqrt{2}}\left(-i\overline{d}_L\,,\overline{d}_L\,,-i\overline{u}_L\,,-\overline{u}_L\,,0\right)\,,\\
\overline{u}^5_R &= (0\,,0\,,0\,,0\,,\overline{u}_R)\,,\\
\overline{\psi} = \left(\overline{Q},\overline{\tilde{U}}\right) &= \left(-i\overline{D}+i\overline{X}_{5/3},\overline{D}+\overline{X}_{5/3},-i\overline{U}-i\overline{X}_{2/3},-\overline{U}+\overline{X}_{2/3},\sqrt{2}\overline{\tilde{U}}\right)\,.
\end{aligned}$$

How to include the quarks?

Remarks:

- The choice of rep. for the LH quarks and its partners is not unique. Other embeddings which are sometimes discussed:
  - $\mathbf{14} = \mathbf{1} \oplus \mathbf{4} \oplus \mathbf{9}$
  - $\mathbf{10} = \mathbf{4} \oplus \mathbf{6}$

  Main qualitative new feature:
  Additional partner particles, some of which have exotic charges.
- Another "as minimal" embedding as considered here:
  embed q_L and ψ in the same way 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 $\rightarrow$ results in the backup)

Back to the partially composite quarks in the **5**.
BSM particle content: $\overline{\psi} = \left(\overline{Q}, \overline{\tilde{U}}\right)$.

	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:

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

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 (m_u or m_c)
  $\rightarrow$ 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:

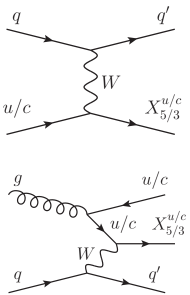
$$
\begin{aligned}
g_{WuX} = -g_{WuD} = -c_w \, g_{ZuU_p} &= \frac{g}{2} \cos\epsilon \sin\varphi_4 \,, \\
\lambda_{huU_m} &= y_R \cos\epsilon \cos\varphi_4 \,,
\end{aligned}
$$

with

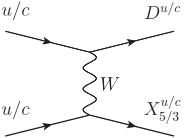
$$
\tan\varphi_4 \equiv \frac{y_R f \sin\epsilon}{M_4} .
$$

Partners in the fourplet

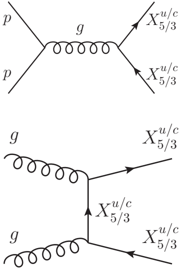
Production mechanisms (shown here: $X_{5/3}$ production)



(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 $\to$ jets.
  - 2nd generation partners: $c, s \to$ jets, potentially tagable c in the future
  - 3nd generation partners: $t, b \to$ well distinguishable from jets

We focus on 1st and 2nd family partners (*c.f.* Rattazzi *et al.* [2012] for 3rd family partners).
$\to$ 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: $WWjj$, $ZZjj$, $hhjj$

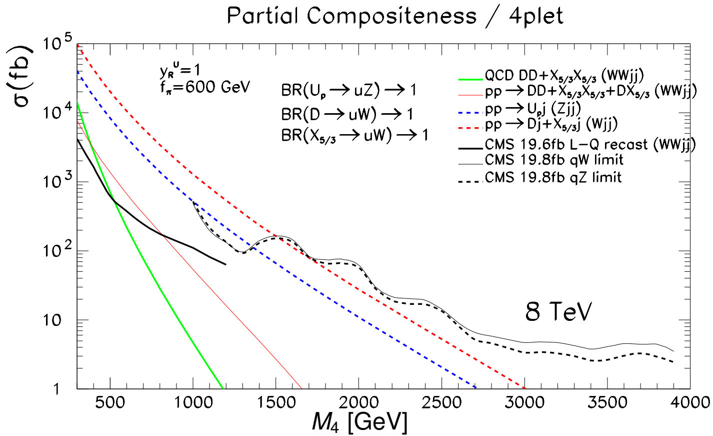
  [D0 Collaboration], Phys. Rev. Lett. 107, 082001 (2011)
  [CDF Collaboration], Phys. Rev. Lett. 107, 261801 (2011)
  [ATLAS Collaboration], Phys. Rev. D 86, 012007 (2012) (1.04 fb^{-1} 7 TeV)
  [CMS Collaboration], CMS-PAS-EXO-12-042 (19.6 fb^{-1} 8 TeV); Leptoquark search, final state: $\mu\mu jj$)

Determining bounds from searches

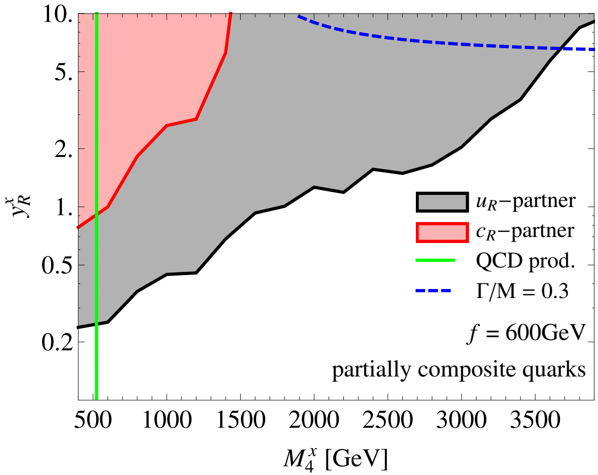
To determine the bounds from Tevatron, ATLAS and CMS searches we

- implement the model [FeynRules2 $\rightarrow$ 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 [TF, Sang Eun Han, Jeong Han Kim, Seung Joon Lee]

Partners in the singlet

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)

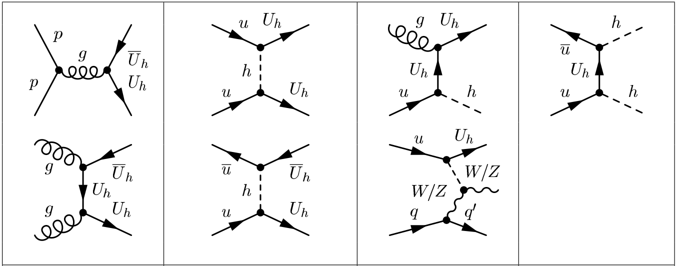
Decay: $\tilde{U} \to hj$ (100%)

Most promising signal: $pp \to hhjj$.
But there are no ATLAS or CMS searches for this channel, so far!
$\Rightarrow$ Only "theory" bound currently: $m_{\tilde{U}} > m_h$ (otherwise Higgs BR are modified)

Other option: Deviations in $pp \to h(hjj) \to \gamma\gamma X$ or $b\bar{b}X$
i.e. modifications to SM Higgs signals and their angular and p_T distributions.

Constraining Partners in the singlet [TF, J.H. Kim, S.J. Lee, S.H. Lim, arXiv:1312.5316]

BSM production channels which yield Higgs bosons:



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

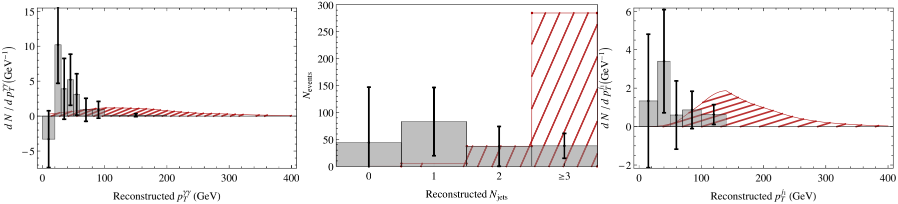
Note: Processes (a)-(c) produce one or two partner quarks which decay into a boosted Higgs (if $M_{U_h} > m_h$) and a light quark.

- 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 Partners in the singlet

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].

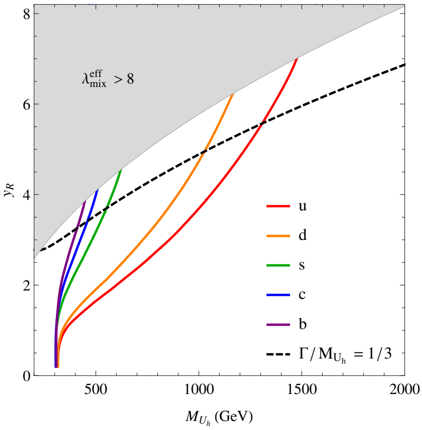
We simulate these distributions for BSM Higgs production and subsequent $H \to \gamma\gamma$ decay.



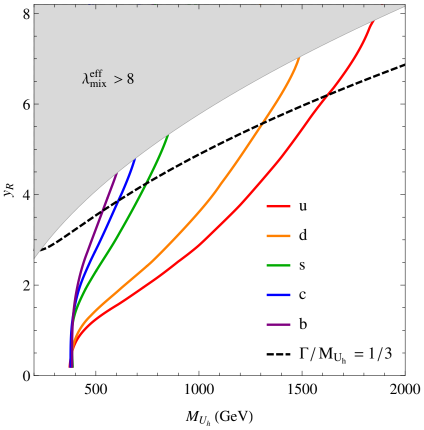
Example: $p_T^{\gamma\gamma}$, N_{jets}, and p_T^{j1} distributions for $M_{U_h} = 300\,\mathrm{GeV}$ and $y_R = 1.1$.

Constraining Partners in the singlet

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)

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 u (c) quarks with partners in the fourplet, we find $M_4^{u/c} \gtrsim 530$ GeV (from QCD pair production), as well as substantially (marginally) enhanced bounds for M_u (M_c) for large $y_R^{u/c}$.
- For partially composite quarks with partners in the singlet, we find $M_{U_h} > 310\,\mathrm{GeV}$ (from QCD pair production), as well as increased bounds for large y_R, depending on the quark flavor.
- We performed an analogous analyses for fully composite right-handed 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? *c.f.* [Serone *et al.* (2013)] for first approaches
  - Determination of parameters from the strong sector?
  - ...

Fully composite up- and charm quarks

Fermion embedding

Like before:

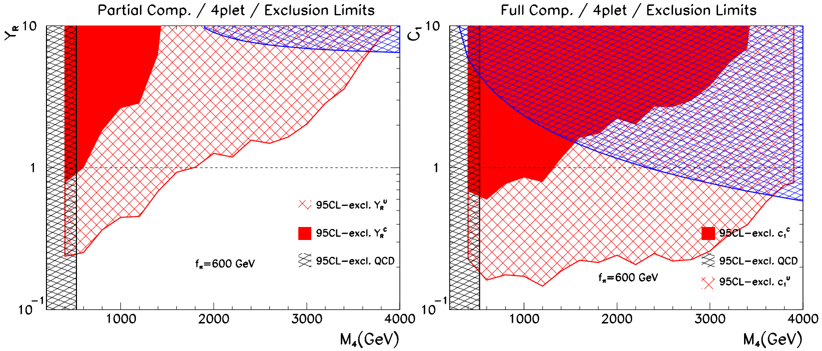
$$\overline{q}_L^5 = \frac{1}{\sqrt{2}}\left(-i\overline{d}_L\,,\overline{d}_L\,,-i\overline{u}_L\,,-\overline{u}_L\,,0\right) \quad , \quad \psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix},$$

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

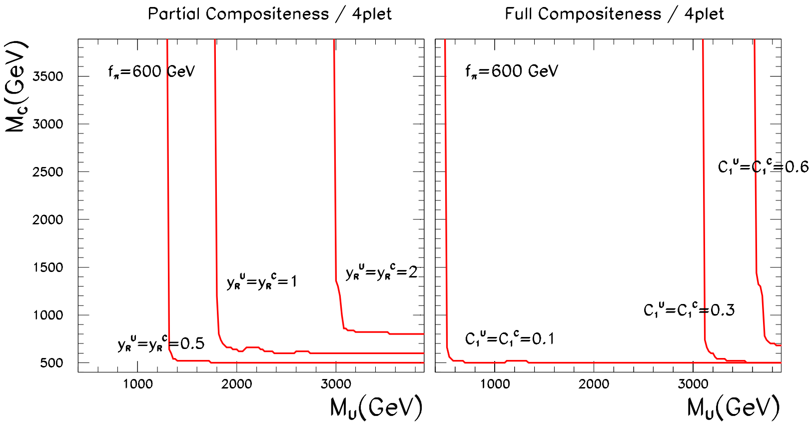
Fermion-Lagrangian

$$\begin{aligned} \mathcal{L}^f_{comp} &= i\,\overline{\psi}(D_\mu + ie_\mu)\gamma^\mu\psi + i\,\overline{u}_R \not{D} u_R - M_4 \overline{Q}Q - M_1 \overline{\tilde{U}}\tilde{U} \\ &\quad + \left[ic_L\,\overline{Q}^i_L d^i_\mu \gamma^\mu \tilde{U}_L + ic_R\,\overline{Q}^i_R d^i_\mu \gamma^\mu \tilde{U}_R + \text{h.c.}\right] + \left[ic_1\,\overline{Q}^i_R d^i_\mu \gamma^\mu u_R + \text{h.c.}\right], \\ \mathcal{L}^f_{el+mix} &= i\,\overline{q}_L \not{D} q_L - \left[y\,f\left(\overline{q}^5_L U_{gs}\right)_i Q^i_R + \right. \\ &\quad \left. + y\,c_2\,f\left(\overline{q}^5_L U_{gs}\right)_5 u_R + y\,c_3\,f\left(\overline{q}^5_L U_{gs}\right)_5 \tilde{U}_R + \text{h.c.}\right], \end{aligned}$$

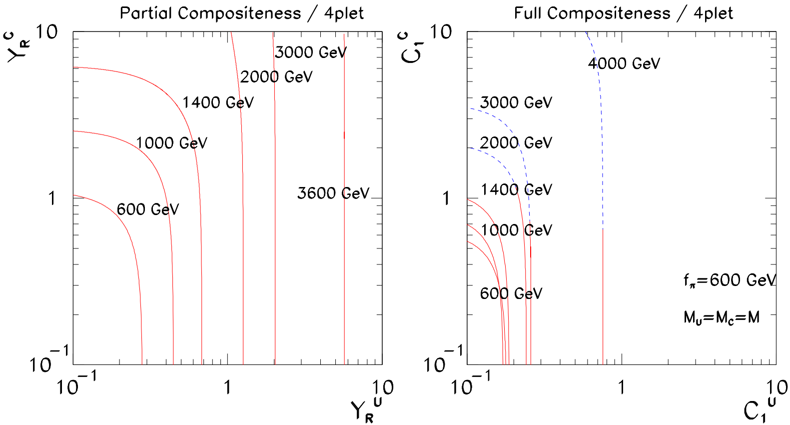
Determining bounds from searches



Determining bounds from searches



Determining bounds from searches



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

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

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

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

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

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