Composite quark partners in composite Higgs models at LHC

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C. Delaunay, TF, J. Gonzales-Fraile, S.J. Lee, G. Panico, G. Perez — *appearing tomorrow*

TF, J.H. Kim, S.J. Lee, S.H. Lim — *work in progress*

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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 $m_h, v \ll M_{pl}$.

Possible solution:
There is a symmetry which protects the quadratic terms in the Higgs potential from quadratically divergent loop corrections.

- classical scale invariance?
- supersymmetry?
- Higgs as a pseudo goldstone boson of a global symmetry.$\leftarrow$ todays topic

Motivation

The SM Higgs doublet fulfills several tasks:

- it generates of the W and Z masses via EWSB,
- it generates quark and lepton masses via Yukawa terms in the action,
- it provides a physical scalar degree of freedom and predicts its couplings (consistent with the newly observed 126 GeV particle).

$\Rightarrow$ In a composite Higgs setup, these beneficial features of the SM Higgs are most efficiently mimicked if the whole Higgs multiplet is realized as PGBs.

Simplest realization:
The minimal composite Higgs model (MCHM) Agashe, Contino, Pomarol [2004]
based on $SO(5)/SO(4)$.

Composite Higgs model: general setup

"Consider a strongly coupled theory with a global symmetry $SO(5)(\times U(1)_X)$ which at a scale f is spontaneously broken to $SO(4)(\times U(1)_X)$.

- The Goldstone bosons live in $SO(5)/SO(4) \to$ 4 d.o.f.
- $SO(4) \simeq SU(2)_L \times SU(2)_R \to$
  Gauging $SU(2)_L$ yields an $SU(2)_L$ goldstone doublet.
  (Later: Gauging $Y = T_R^3 + X$ allows for fermion embeddings with consistent $U(1)_Y$ charge.)

This choice already fixes the gauge and Higgs sector:
We use the CCWZ construction. 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":

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

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

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]:
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?

The model contains elementary fermions q and composite fermionic resonances of the strongly coupled theory, which mix via linear interactions

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

where $\mathcal{O}$ is an operator of the strongly coupled theory in the rep. $I_{\mathcal{O}}$, and $\overline{q}_{I_{\mathcal{O}}}$ is an (incomplete) embedding of the elementary q into $SO(5)$.

One common choice (partially composite quarks):

$$\begin{aligned} \overline{q}_L^5 &= \frac{1}{\sqrt{2}}\left(-i\overline{d}_L\,,\overline{d}_L\,,-i\overline{u}_L\,,-\overline{u}_L\,,0\right), \\ \overline{u}_R^5 &= (0\,,0\,,0\,,0\,,\overline{u}_R)\,, \end{aligned}$$

This fixes composite partner quarks to be embedded as **5** reps. of $SO(5)$:

$$\psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix}.$$

How to include the quarks?

Remarks:

- Another "as minimal" embedding as considered here:
  embed q_L and ψ in the same way 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)
- The choice of rep. for the LH quarks and its partners is not unique.
  Another embedding which is sometimes discussed: $\mathbf{14} = \mathbf{1} \oplus \mathbf{4} \oplus \mathbf{9}$
  Main qualitative new feature:
  The $\mathbf{9}$ contains additional partner particles with exotic charges.

Back to the 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 (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:

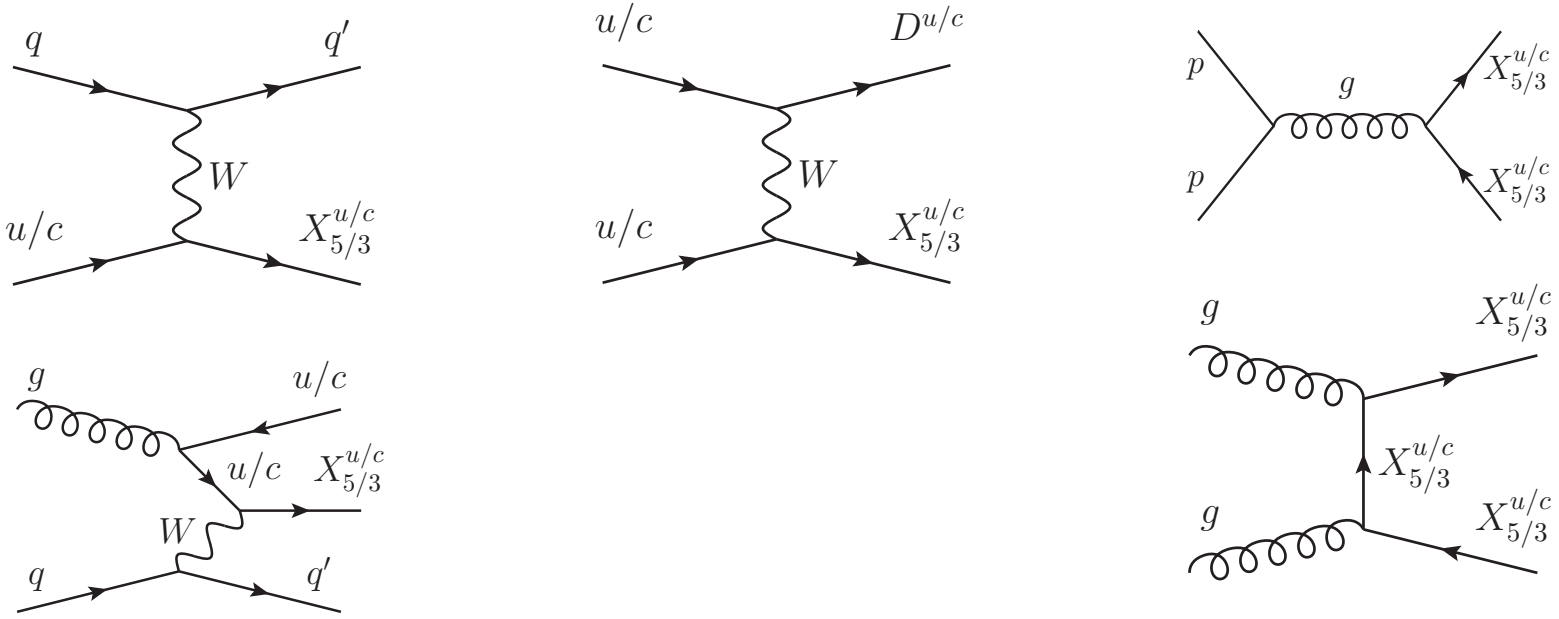
$$\begin{aligned} g_{WuX} = -g_{WuD} = -c_w\, g_{ZuU_p} &= \frac{g}{2}\cos\epsilon \sin\varphi_4, \\ \lambda_{huU_m} &= y_R \cos\epsilon \cos\varphi_4, \end{aligned}$$

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 $\rightarrow$ 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 3rd family 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: $WWjj$, $ZZjj$, $hhjj$

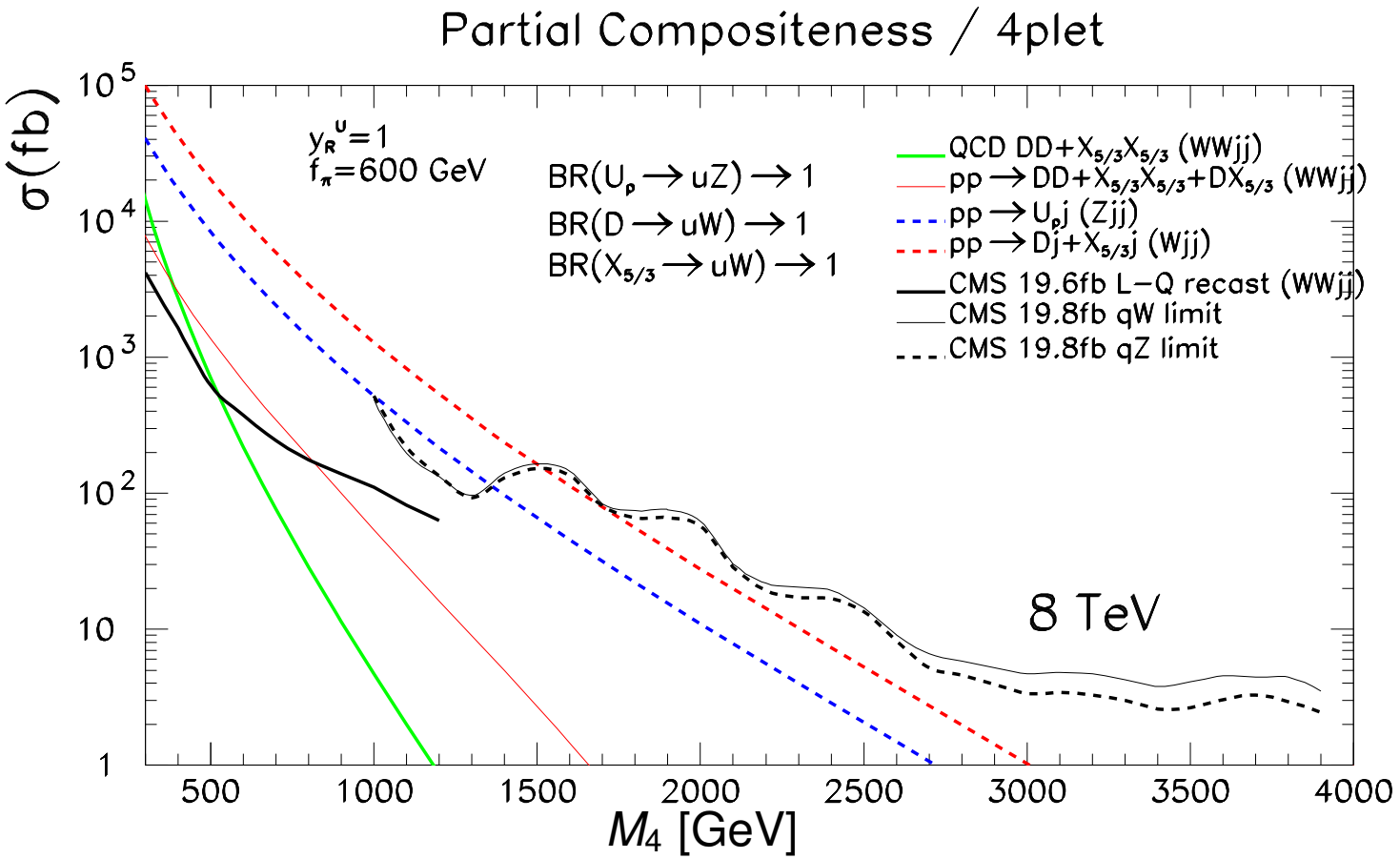
  [D0 Collaboration], Phys. Rev. Lett. 107, 082001 (2011)
  [CDF Collaboration], Phys. Rev. Lett. 107, 261801 (2011)
  [ATLAS Collaboration], Phys. Rev. D 86, 012007 (2012) (1.04 fb^{-1} 7 TeV)
  [CMS Collaboration], CMS-PAS-EXO-12-042 (19.6 fb^{-1} 8 TeV); Leptoquark search, final state: $\mu\mu jj$)

Determining bounds from searches

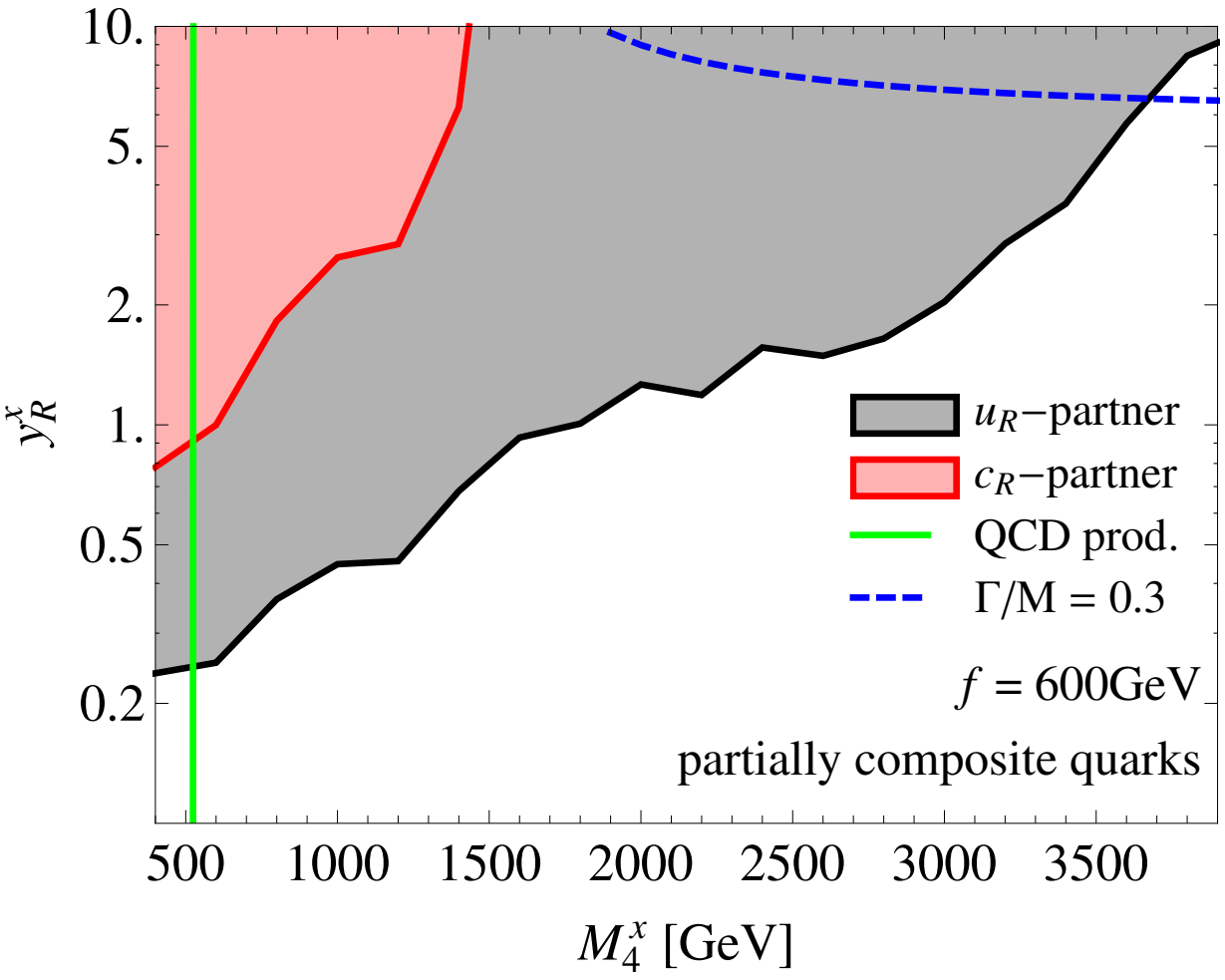
To determine the bounds from Tevatron, ATLAS and CMS searches we

- implement the model [FeynRules2 → 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



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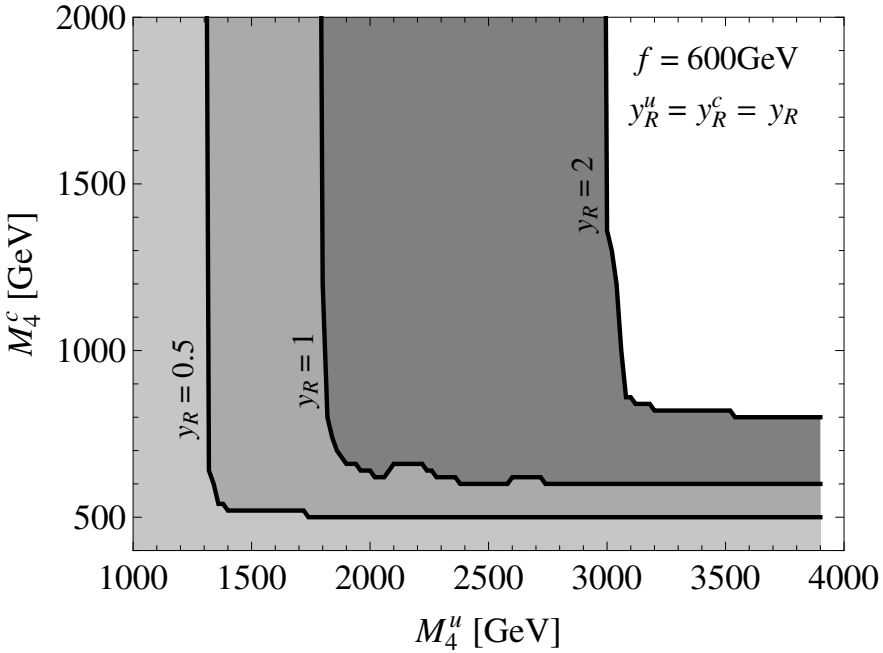
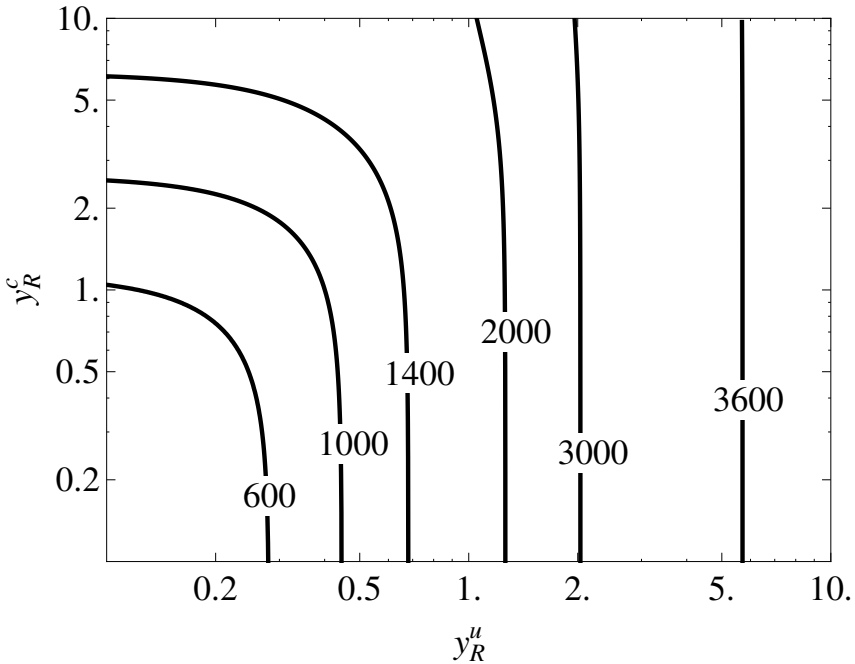




Partners in the singlet (qualitative discussion)

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%)

Most promising signal: $pp \to hhjj$.
We did not find any current 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.
[TF, J.H. Kim, S.J. Lee, S.H. Lim, *in preparation*]

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

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

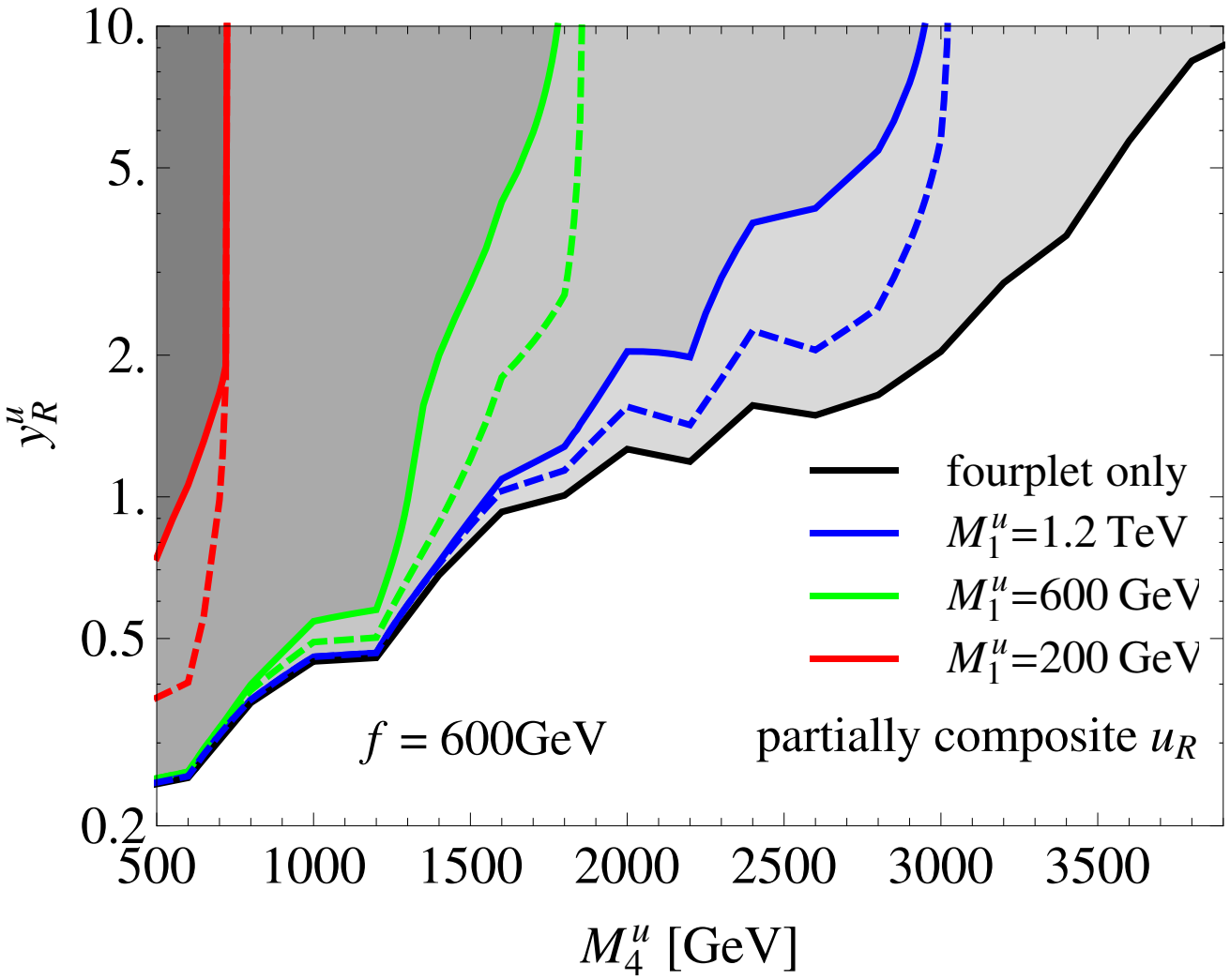
...also present: "Mixing" couplings amongst heavy quarks partners: $\lambda_{hU_1U_2}$, $g_Z U_{1/2} U_p$, and analogous for charged couplings.

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 M_1.
Solid: full limits. Dashed: limits ignoring signal loss due to cascade decays.

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 $M_4^u \gtrsim 1.8$ TeV, $M_4^c \gtrsim 610$ GeV (both for $y_R^X = 1$) and $M_4^{u/c} \gtrsim 530$ GeV (independent of y_R^u).
- For partially composite u (c) quarks with partners in the singlet, currently no bounds are available (only trivial bound: $m_{\tilde{U}} > m_h$). [work in progress at KAIST]
- The fourplet bounds can be substantially weakened when considering the generic case of fourplet and singlet partners being present.
- We performed an analogous analysis for fully composite right-handed light quarks, for which many of the aspects presented here apply as well.

Fully composite up- and charm quarks

Fermion embedding

Like before:

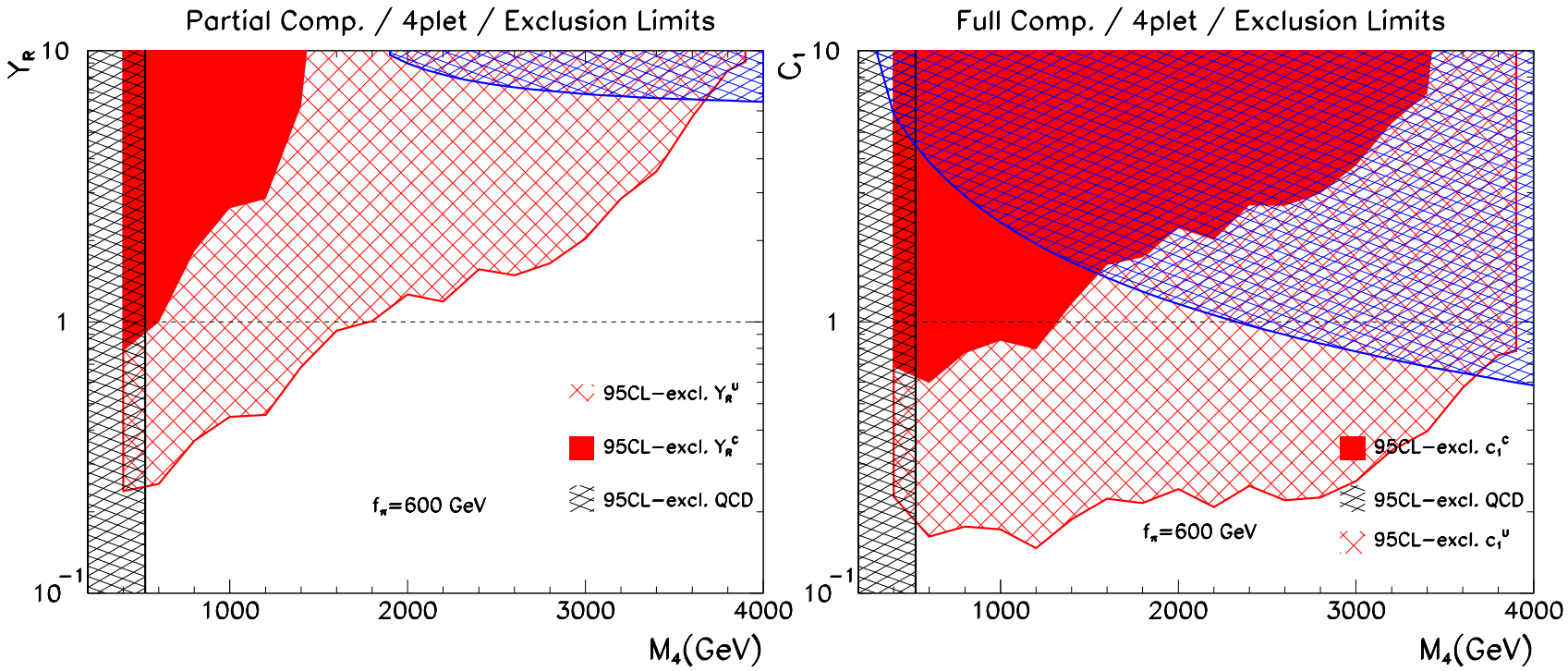
$$\overline{q}_L^5 = \frac{1}{\sqrt{2}}\left(-i\overline{d}_L\,,\overline{d}_L\,,-i\overline{u}_L\,,-\overline{u}_L\,,0\right) \quad , \quad \psi = \begin{pmatrix} Q \\ \tilde{U} \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} iD - iX_{5/3} \\ D + X_{5/3} \\ iU + iX_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U}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

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

Fermion-Lagrangian

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

Determining bounds from searches



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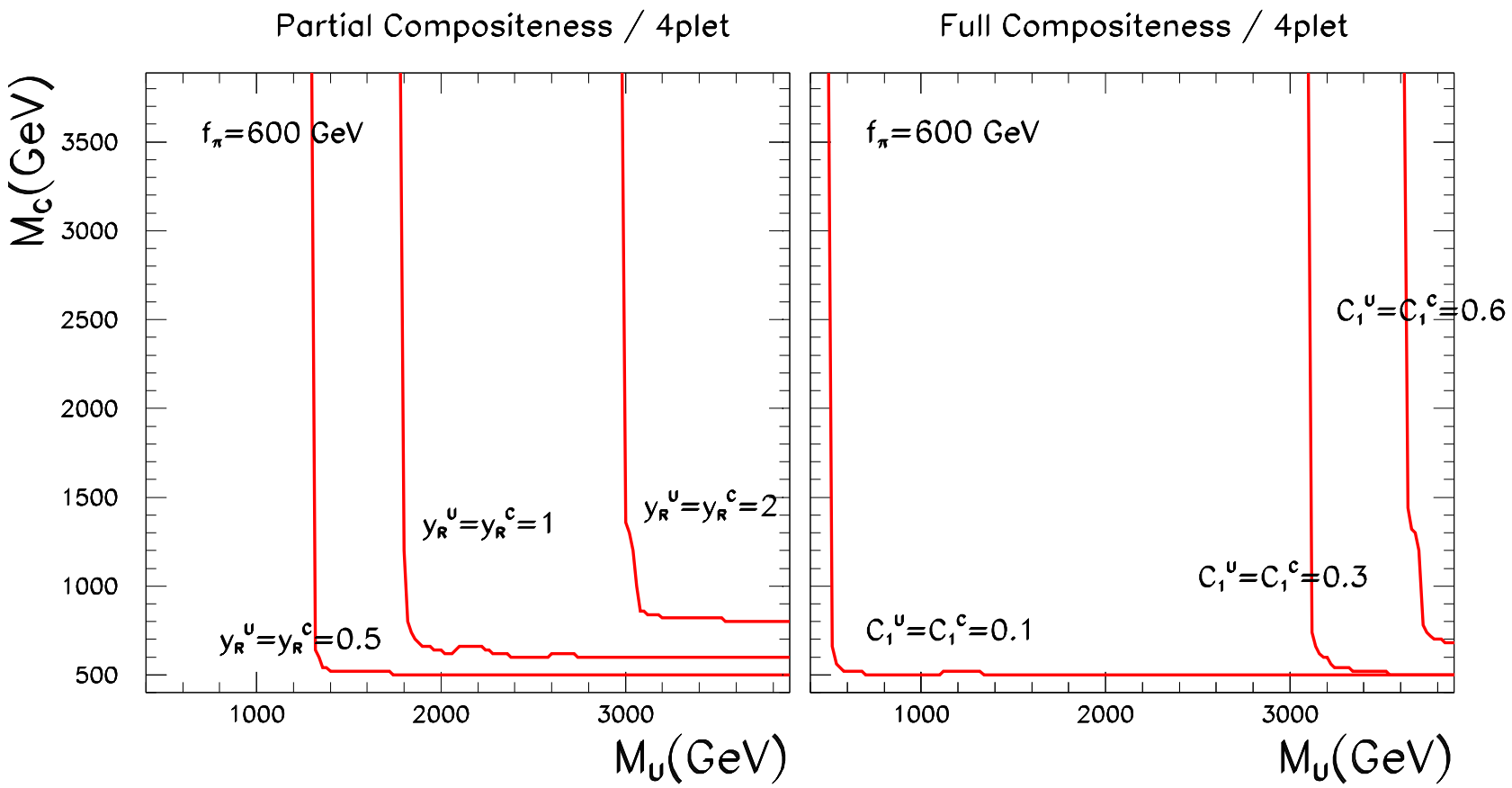

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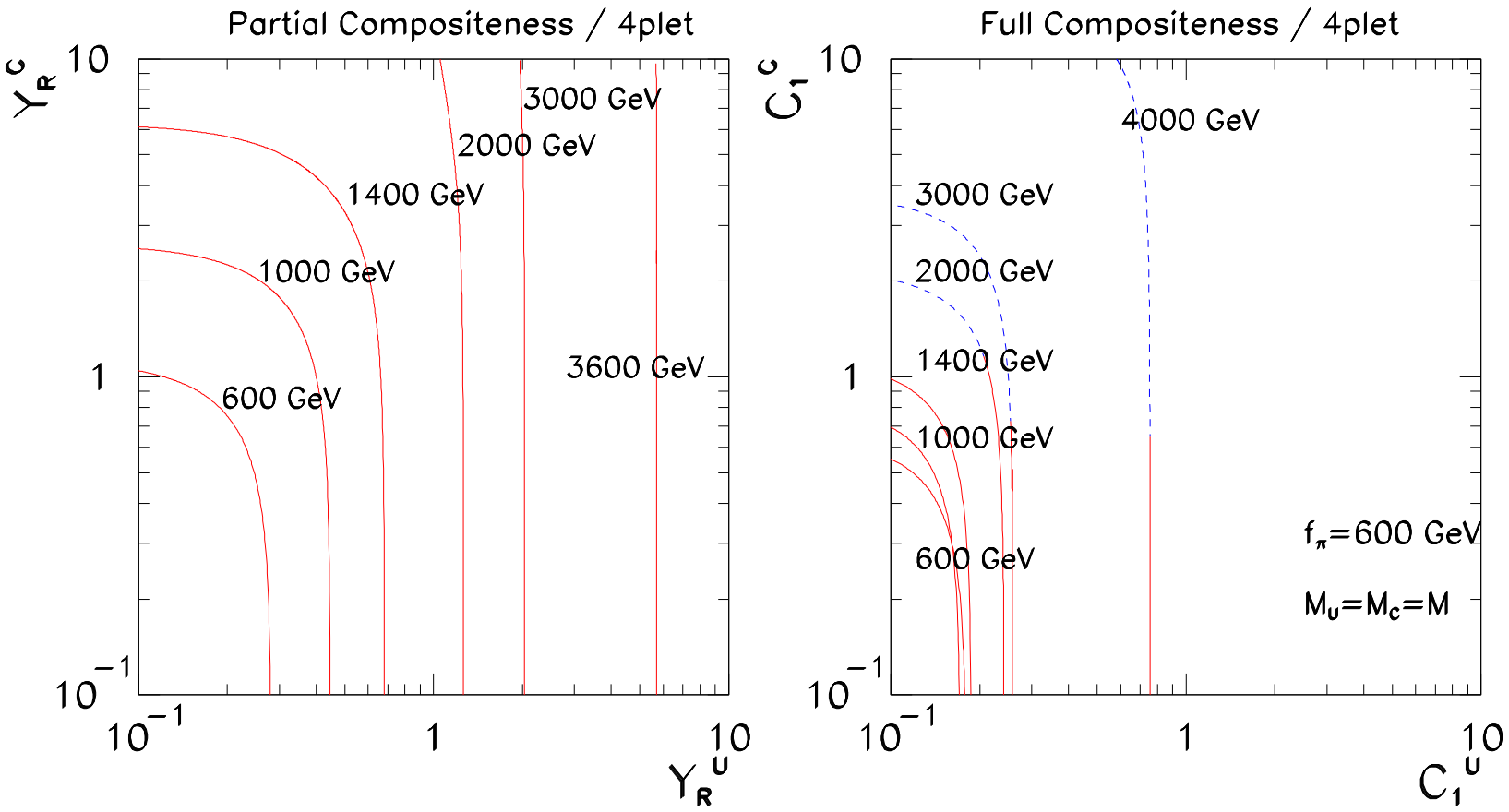
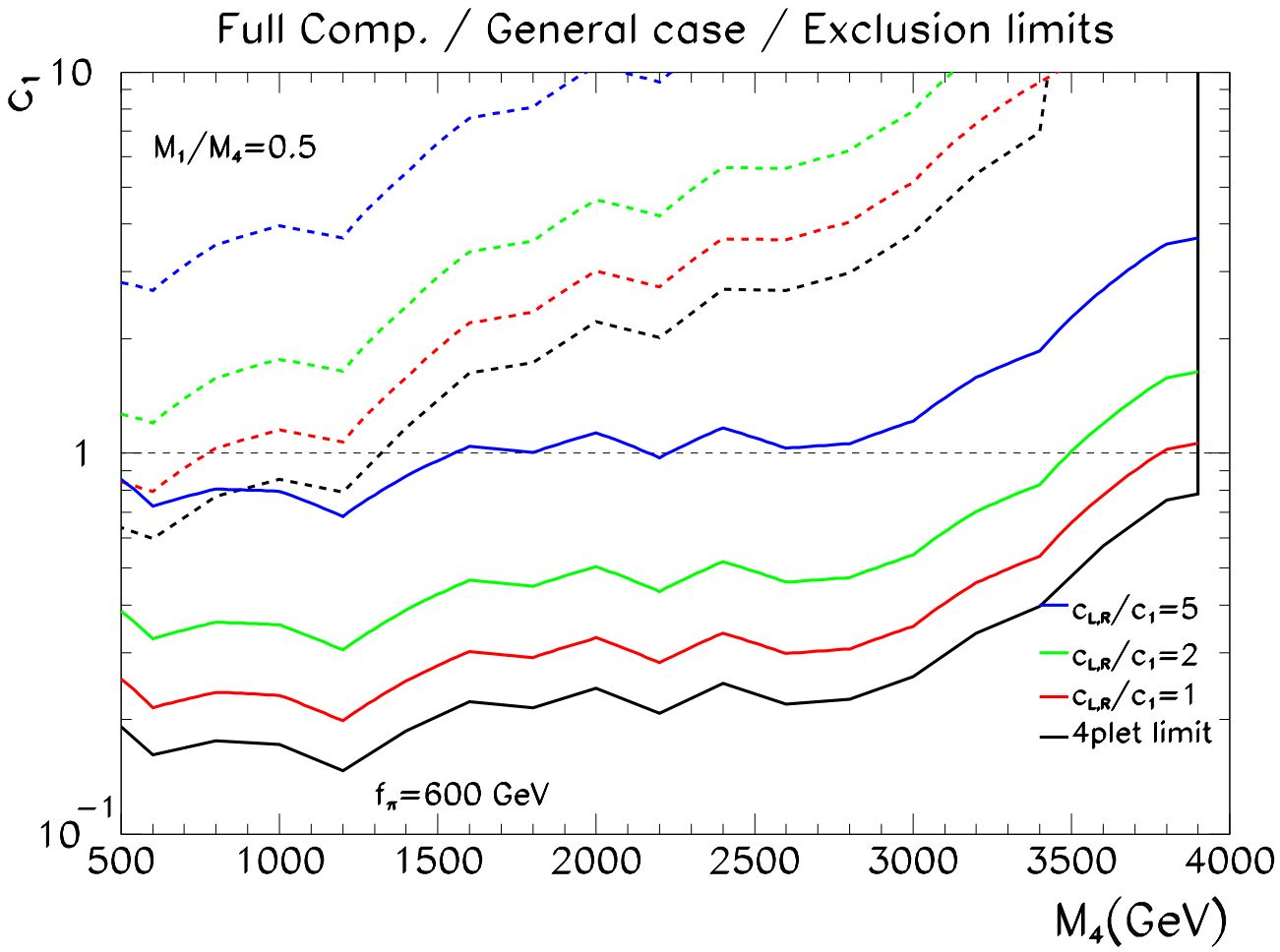


General case: M_1 and M_4 finite, up-partners, fully composite



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 $c_L = c_R$).

Definition of d and e symbols:

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

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

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

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

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

$$\begin{aligned} A_\mu &= \frac{g}{\sqrt{2}}W^+_\mu\left(T^1_L + iT^2_L\right) + \frac{g}{\sqrt{2}}W^-_\mu\left(T^1_L - iT^2_L\right) \\ &\quad + g\left(c_w Z_\mu + s_w A_\mu\right)T^3_L + g'\left(c_w A_\mu - s_w Z_\mu\right)T^3_R\,. \end{aligned}$$

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

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