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(Non-degenerate) light generation compositeness in composite Higgs models

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Outline

- Motivation
- General setup: Minimal Composite Higgs: Higgs as a PGB of extended gauge symmetry with SO(5)/SO(4) breaking
- Partial Composite quarks @ LHC
- Summary

Motivation

♦ The discovery of the Higgs boson at the LHC is a great victory for the SM.

♦ However, the fact that the Higgs mass is subject to additive renormalization implies that the EW scale is unnatural.

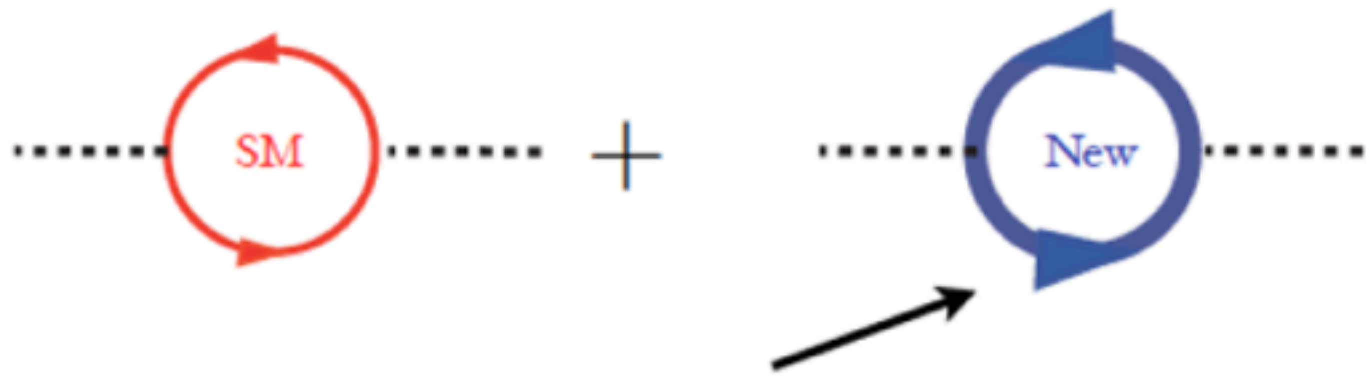
♦ The solution of this UV sensitivity problem requires new dynamics characterized by energy scale close to the weak scale.

Motivation

Two main naturalness roadmaps remain

Supersymmetry

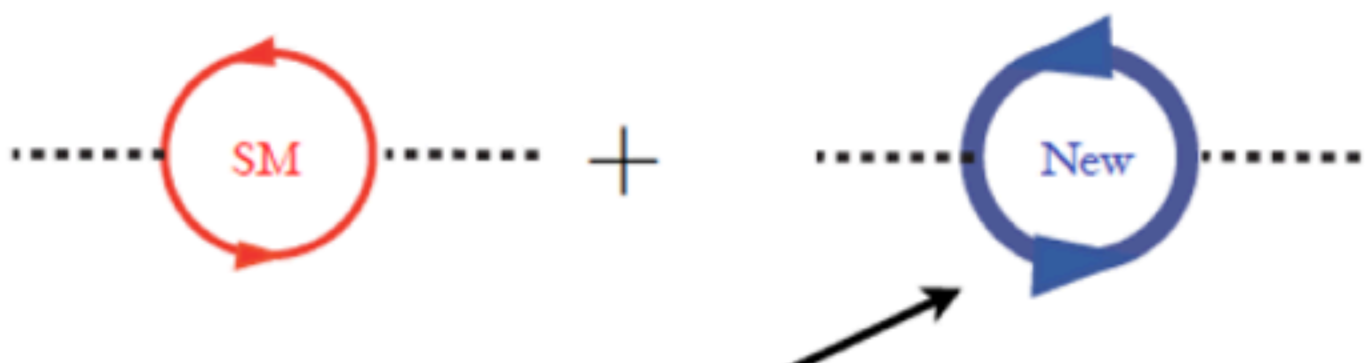
Barbieri
(via Altarelli's talk on Monday)

$\delta m_H^2 =$  ~ 0

s-particles (scalars)

The Higgs boson as a pseudoGolsdtone

(like the π in QCD)

$\delta m_H^2 =$  ~ 0

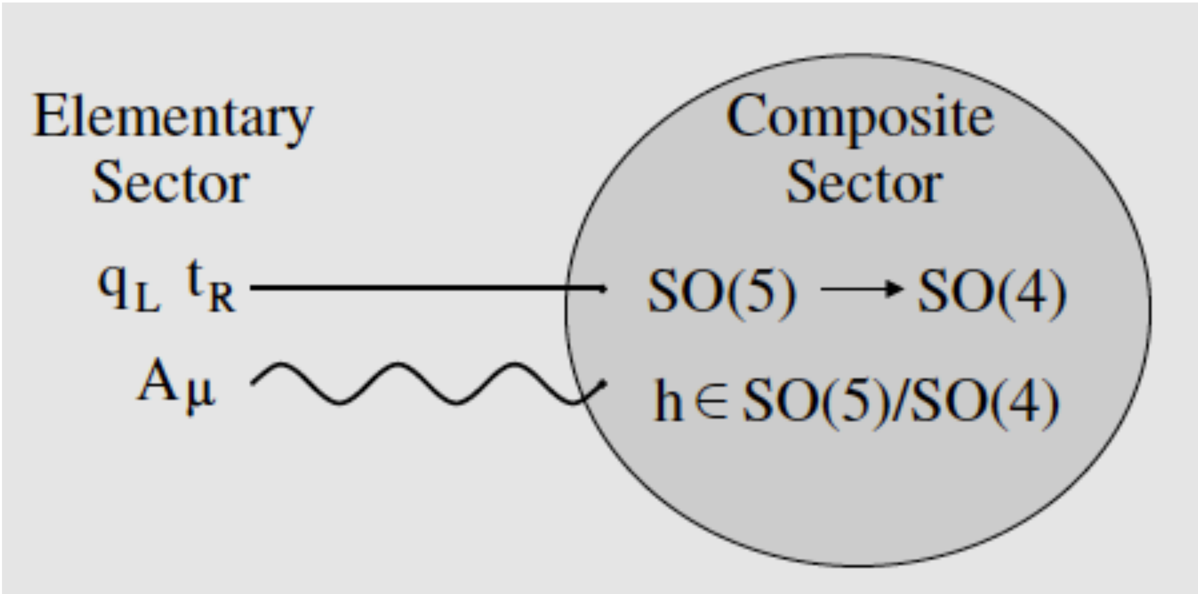
Heavy "composite" f (fermions)

Motivation

Composite Higgs

Georgi, Kaplan '84; Kaplan '91; Agashe, Contino, Pomarol '05; Agashe et al '06; Giudice et al '07; Contino et al '07; Csaki, Falkowski, Weiler '08; Contino, Servant '08; Mrazek, Wulzer '10; Panico, Wulzer '11; De Curtis, Redi, Tesi '11;Marzocca, Serone, Shu '12; Pomarol, Riva'12; De Simone et al '12.........

- Just as pion (PGB) is the lightest states in QCD, Higgs is a PGB of a new strong sector => Higgs is lighter than other resonances
- minimal model: SO(5)/SO(4) with 4 GBs => Higgs doublet



Motivation

- Higgs potential radiatively generated by resonances loops (top is the largest contribution)
- Top contribution to the Higgs potential:

Contino et. al,
Pomarol, Riva 12

$$m_h^2 \simeq \frac{N_c}{\pi^2}\left[\frac{m_t^2}{f^2}\frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2}\log\left(\frac{m_{Q_1}^2}{m_{Q_4}^2}\right)\right]$$

5 of SO(5) =4 + 1

with EM charge 5/3,2/3,-1/3,...

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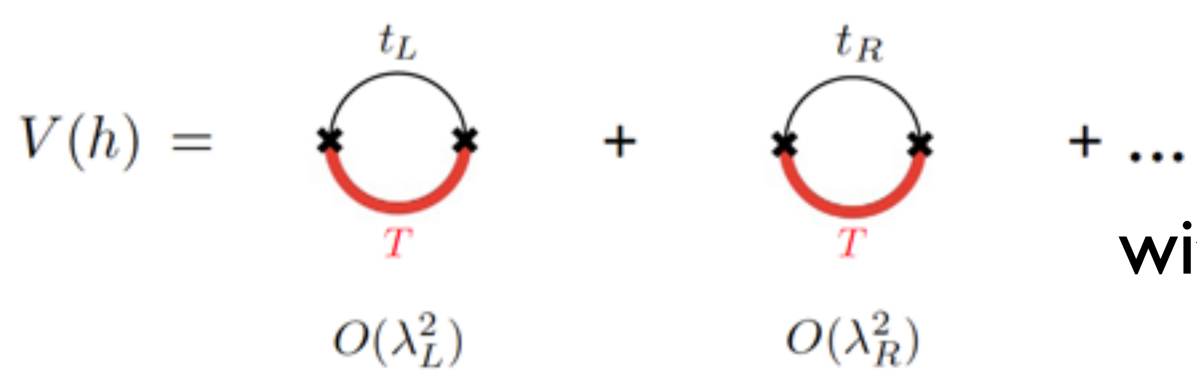
5 of SO(5) =4 + 1

=> light top partners (< 1 TeV) are required to obtain 125 GeV Higgs mass



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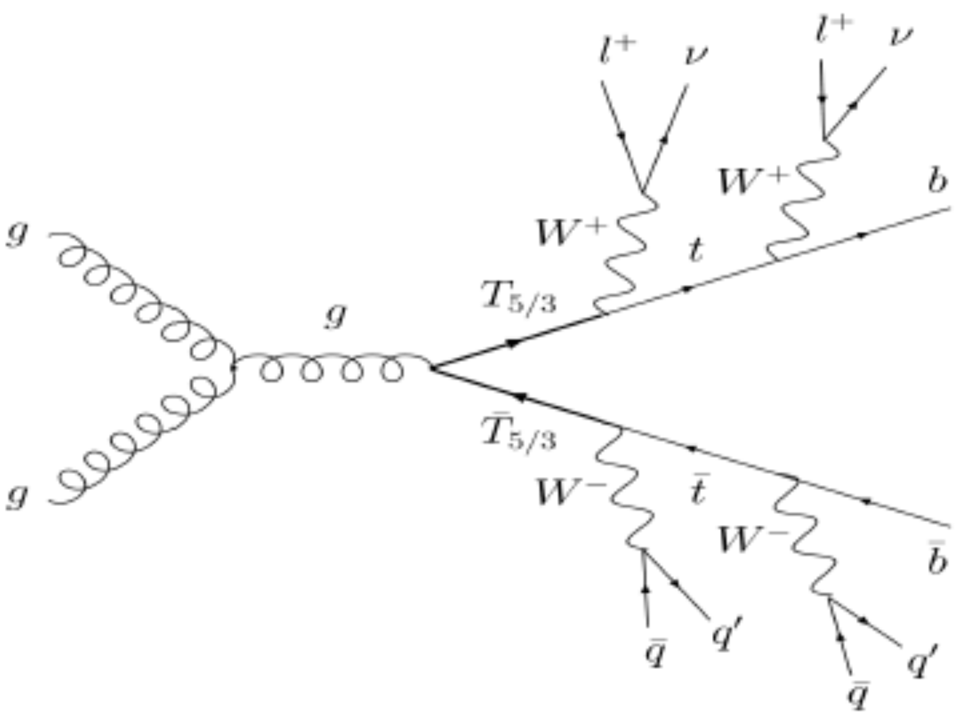
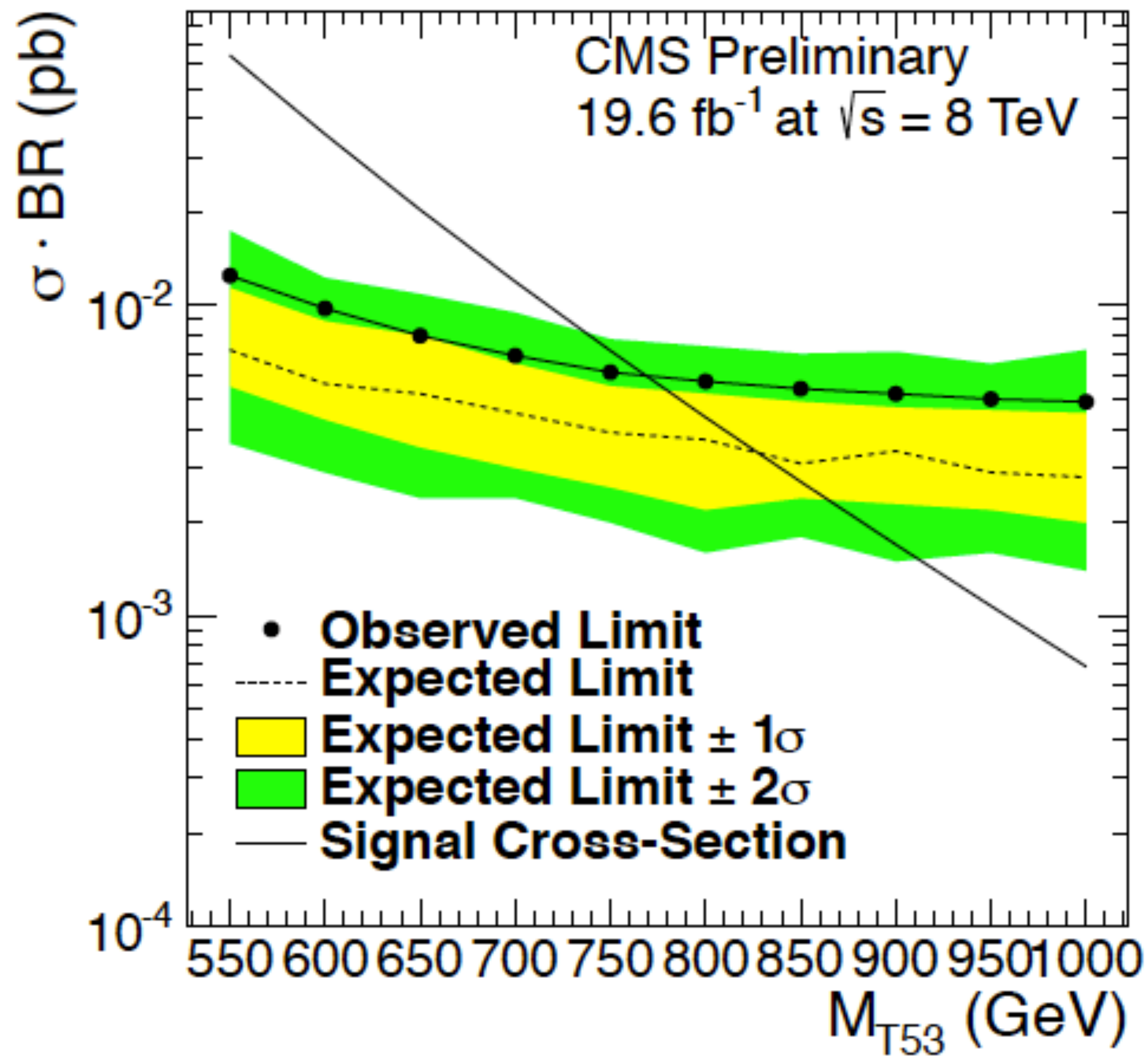
Motivation

But, top partner searches pushes the limit of t partner





- limit: expected 830, observed 770 GeV

Motivation

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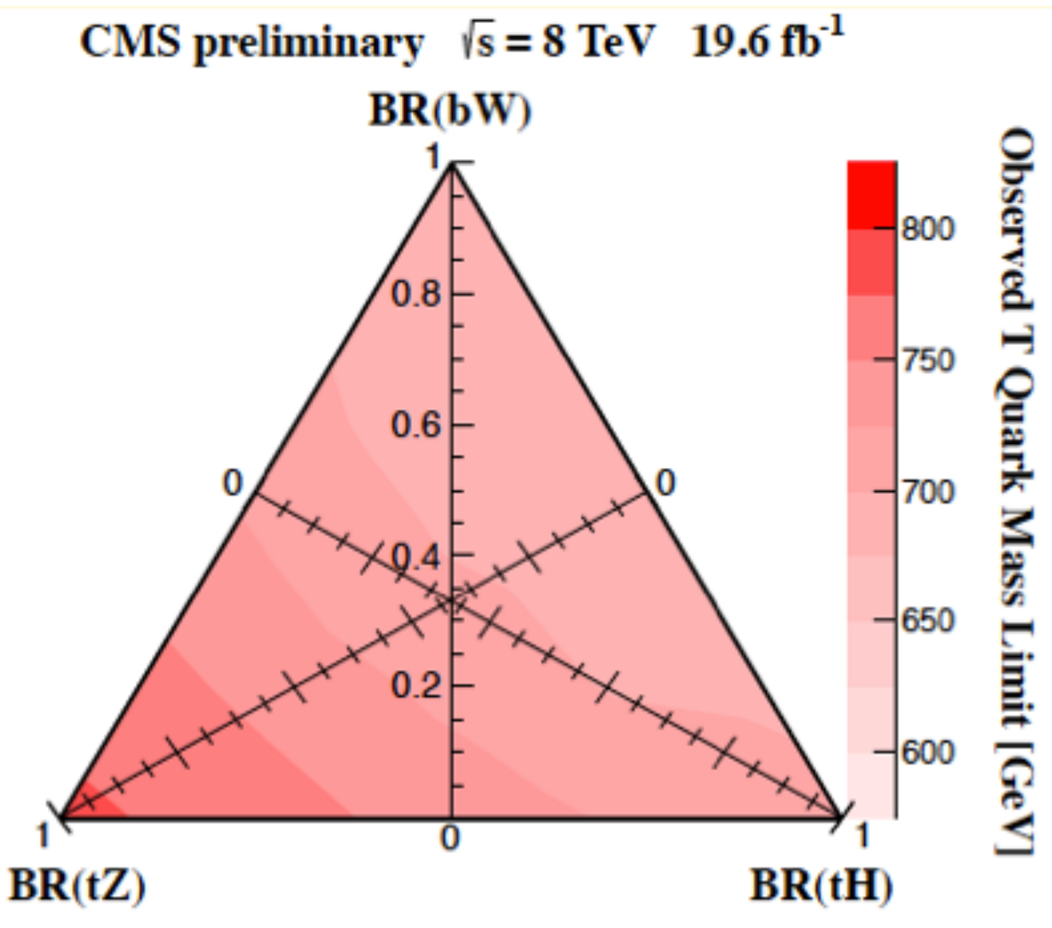

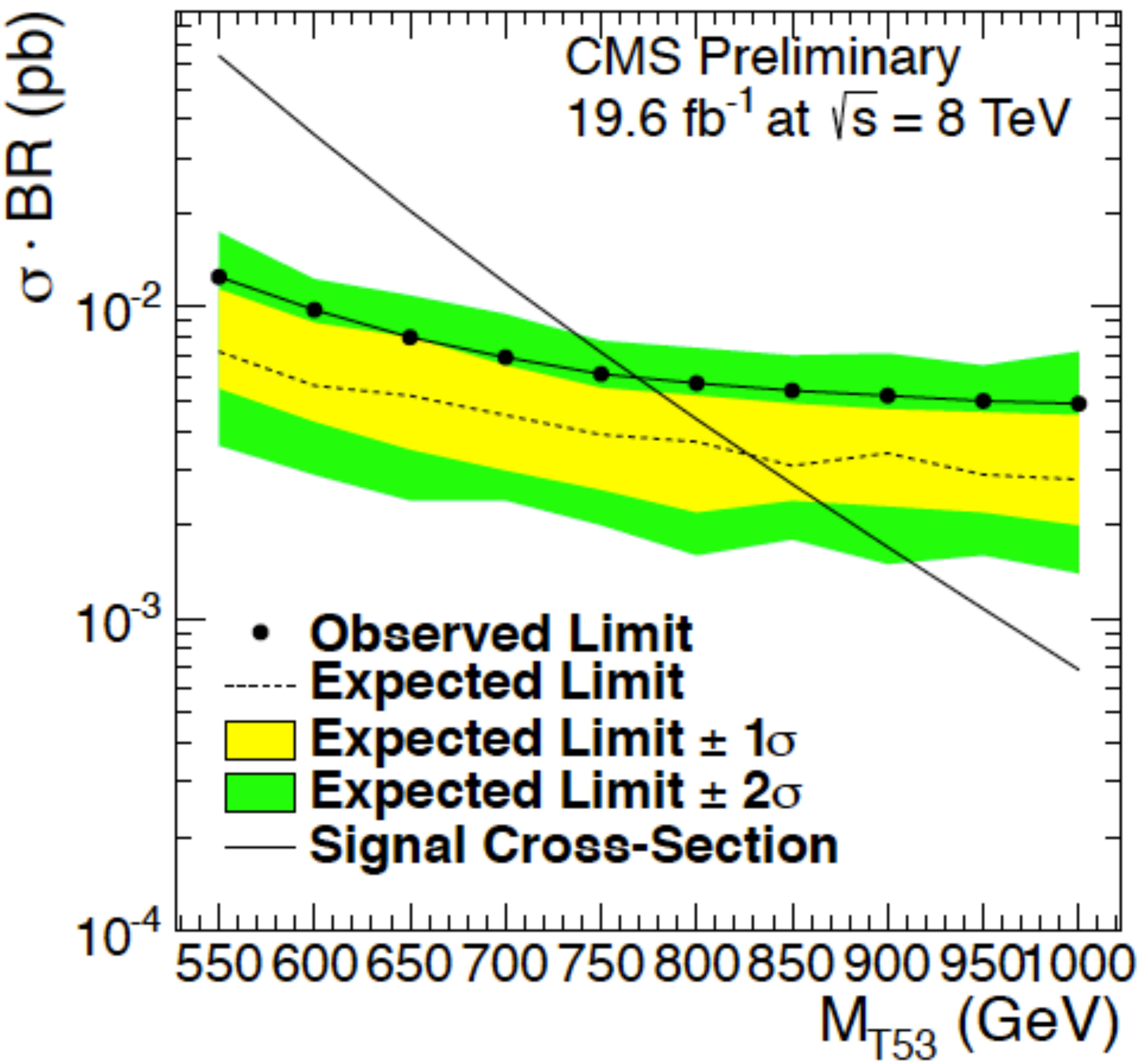

- limit: expected 830, observed 770 GeV

Motivation (light gen. compositeness)

♦ It was demonstrate that in SUSY, the top squark flavor eigenstate can consist of an admixture of would be stop-like and scharm-like mass eigenstate.

Mahbubani, Papucci, Perez, Ruderman, Weiler 12
Blanke, Giudice, Paradisi, Perez, Zupan 13

=> the bounds from direct bounds are somewhat relaxed as direct scharm searches are currently limited in reach

♦ Another motivation: MFV

Redi, Weiler 11
(RH-compositeness with vector resonance) Redi, Sanz, de Vries, Weiler 13

♦ or 5D flavor trivial model (alignment for right-handed up type quark compositeness) Delaunay, Gedalia, SL, Perez, Pondon 10

Motivation (light gen. compositeness)

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But what are the bounds on 1st and 2nd generation partners?

...And how much do *u* and *c* partner bounds differ?

General Set-up

♦ As a setup we choose the minimal composite Higgs model based on SO(5)/SO(4). We use the CCWZ construction. Coleman, Wess, Zumino 69, Callan, Coleman 69

Note: possible vector resonances are "integrated out" and do not appear directly in the effective description

- The Higgs is realized as the Goldstone Boson of $SO(5)/SO(4)$ breaking.
- Left-handed and right-handed chiral quarks (SM-like) are embedded as incomplete **5** reps. of $SO(5)$:

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

$$\overline{u}_R^5 = (0\,,0\,,0\,,0\,,\overline{u}_R)\,,$$

the strong sector resonances are classified in terms of irreducible representations of the unbroken global $SO(4)$

- Composite partner quarks are embedded as **5** reps. of $SO(5)$:

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

General Set-up

- BSM particle content: 5 = 4 + 1

	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**
EM charge	$2/3$	$2/3$	$-1/3$	$5/3$	$2/3$

- Two principal ways to embed the right-handed up-type quarks:
  - In the elementary sector, which mix with their partners, ($\rightarrow$ "partially composite quarks")
  - or as chiral composite states. ($\rightarrow$ "fully composite quarks")

Partial Composite quarks

- Fermion Lagrangian:

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

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

where d^i_μ, e_μ are the CCWZ "connections", and U_{gs} is the Goldstone matrix

$$U_{gs} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & \cos\overline{h}/f & \sin\overline{h}/f \\ 0 & 0 & 0 & -\sin\overline{h}/f & \cos\overline{h}/f \end{pmatrix},$$

with $\overline{h} = \langle h\rangle + h$.

- 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.

Partial Composite quarks

♦ Fermion Lagrangian:

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

$$\mathcal{L}_{el,mix} = \ldots U_{qs}\psi_L + \text{h.c.},$$

wh... Goldstone matrix

,

w...

♦ De...

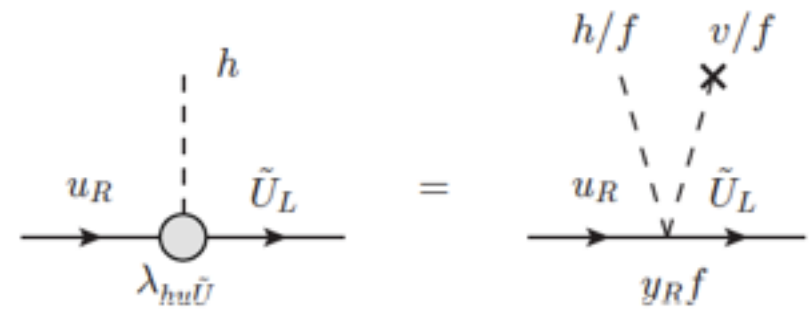
- e...
- diagonalize the mass matrices,
- match the lightest up-type mass with the SM quark mass (m_u or m_c) $\rightarrow$ this fixes y_L in terms of the other parameters ($y_R \sim 1 \Rightarrow y_L \ll 1$)
- calculate the couplings in the mass eigenbasis.

y_L<<1, the Lagrangian for the composite states and
the right-handed up quark becomes invariant under the custodial symmetry $SO(3)_c$

=> u_R, higgs, $\tilde{U}$, and one comb. of 4-plet are singlet,
while GB, and three comb. of 4-plet are triplet under $SO(3)_c$

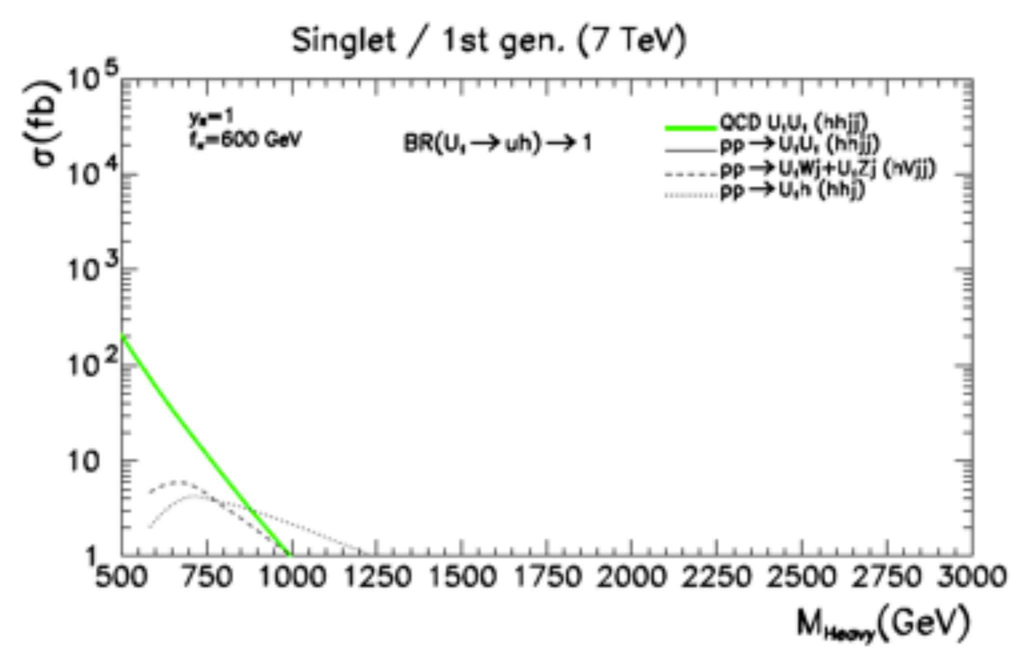
Partners in Singlet

- 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:



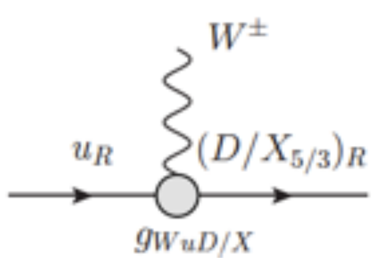
$$\lambda_{hu\tilde{U}} = y_R \sin\epsilon \cos\varphi_1 , \qquad \text{with} \qquad \tan\varphi_1 \equiv \frac{y_R f \cos\epsilon}{M_1} .$$

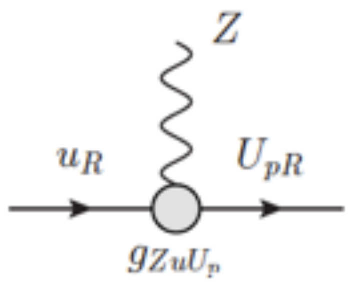
- Production: pair-production (QCD and EW)
- Decay: $\tilde{U} \to hj$ (100%)
- Signal: $pp \to hhjj$.
  What are the LHC bounds on this channel?



Partners in 4-plet

- 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:
  $U_{p/m} = (1/\sqrt{2})\,(U \pm X_{2/3})$, 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:



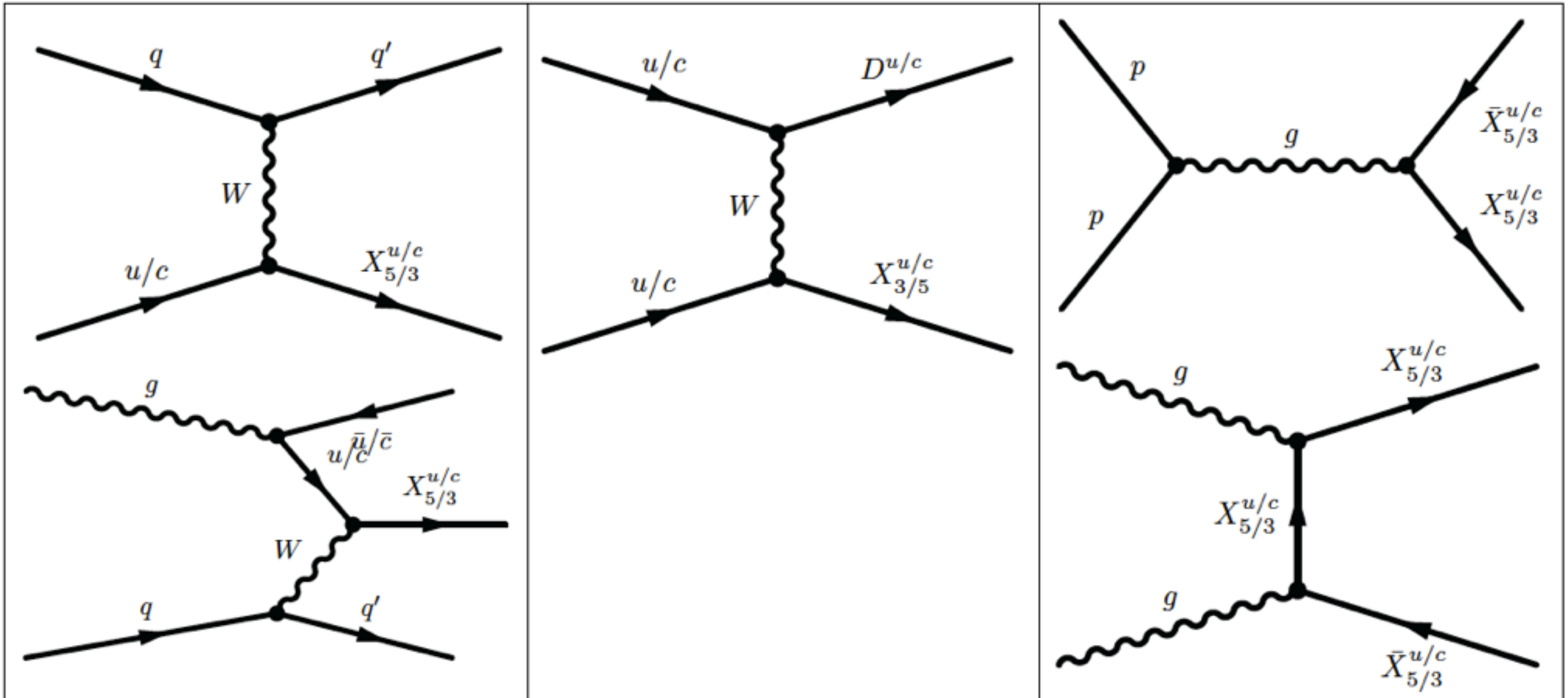


$$
\begin{aligned}
g_{WuX} = -g_{WuD} = -c_W\, g_{ZuU_p} &= \frac{g}{2} \cos\epsilon \sin\varphi_4 , \\
\lambda_{huU_m} &= y_R \cos\epsilon \cos\varphi_4 ,
\end{aligned}
$$

with

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

Partners in 4-plet



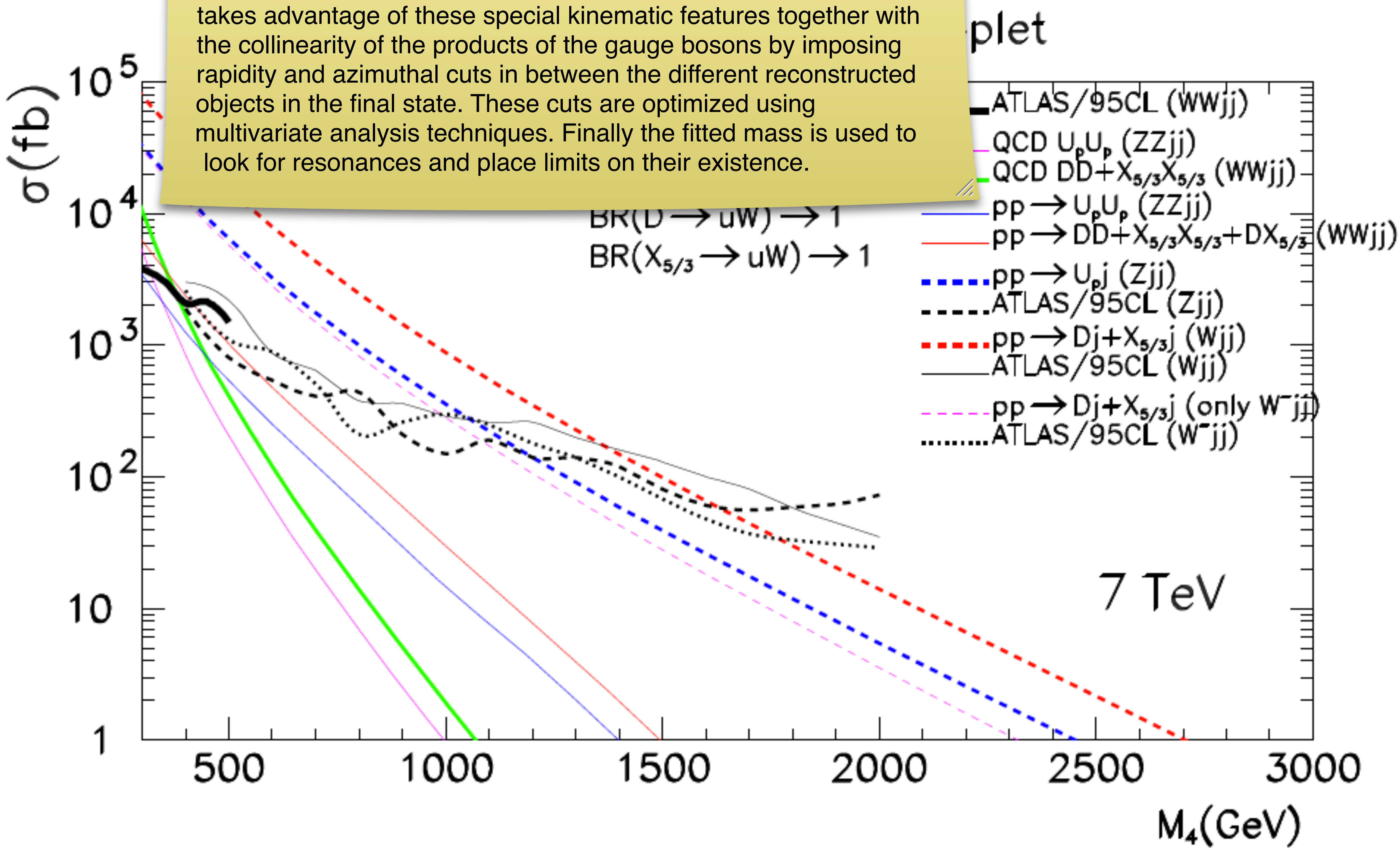
(a) electroweak single production | (b) electroweak pair production | (c) QCD pair production

NOTE: Production mechanism *and* final states for (formerly studied) 3rd family searches differ.

Bou… TeV LHC

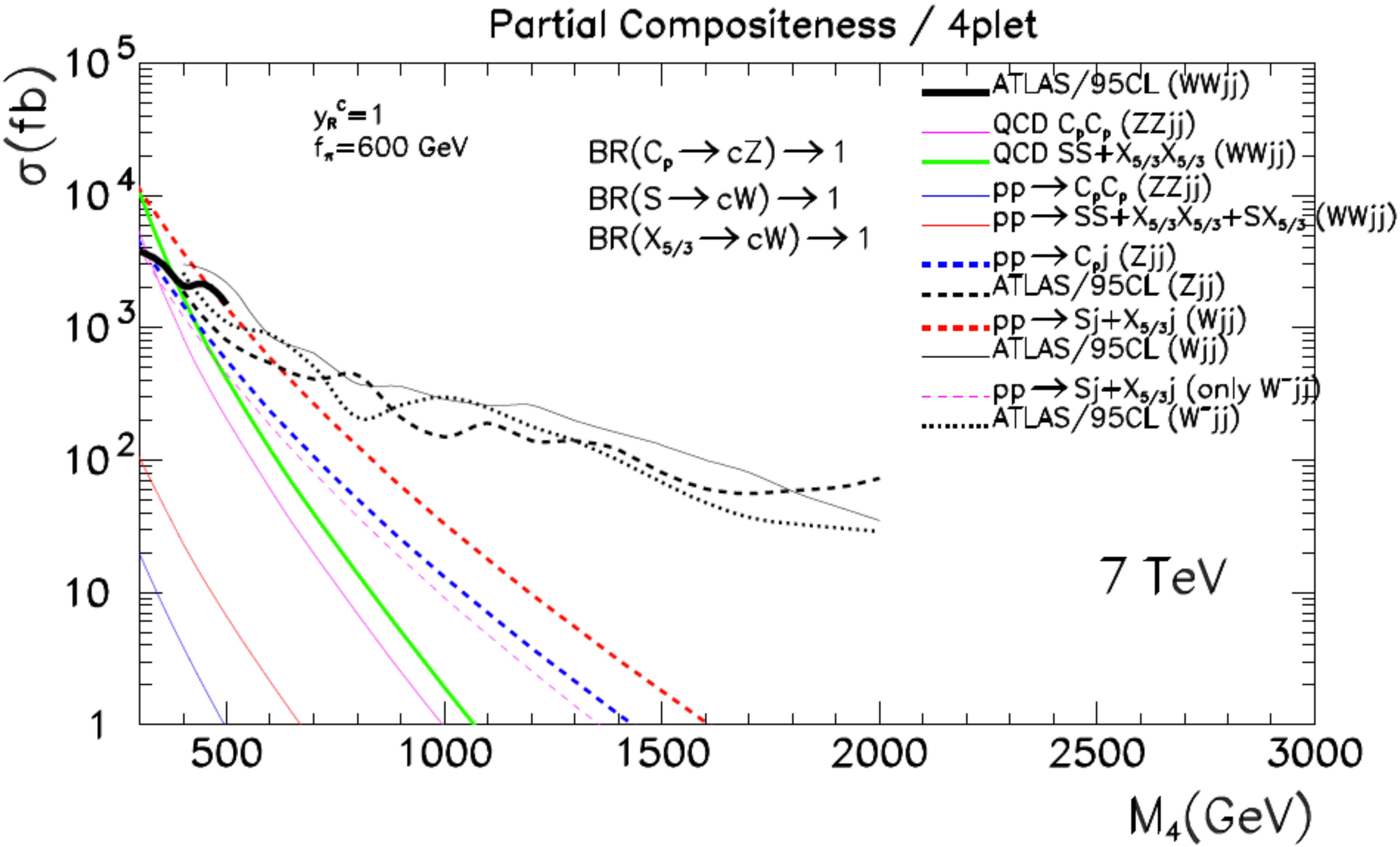
ATLAS analysis of *Zjj* and *Wjj* final states using 4.64 fb^{-1} of integrated luminosity of the 7 TeV run [11]:In this experimental analysis ATLAS searches for light family partners single produced by looking for final states with a jet with high transverse momentum, a sub-leading jet in the forward direction and an isolated hard lepton(s) coming from the decay of the W(Z) boson. In the case of just one lepton in the final state a large transverse missing energy is also required for the final state. The search takes advantage of these special kinematic features together with the collinearity of the products of the gauge bosons by imposing rapidity and azimuthal cuts in between the different reconstructed objects in the final state. These cuts are optimized using multivariate analysis techniques. Finally the fitted mass is used to look for resonances and place limits on their existence.

experimental bou… b^{-1} [ATLAS PRD 86, 012007 (2012)]



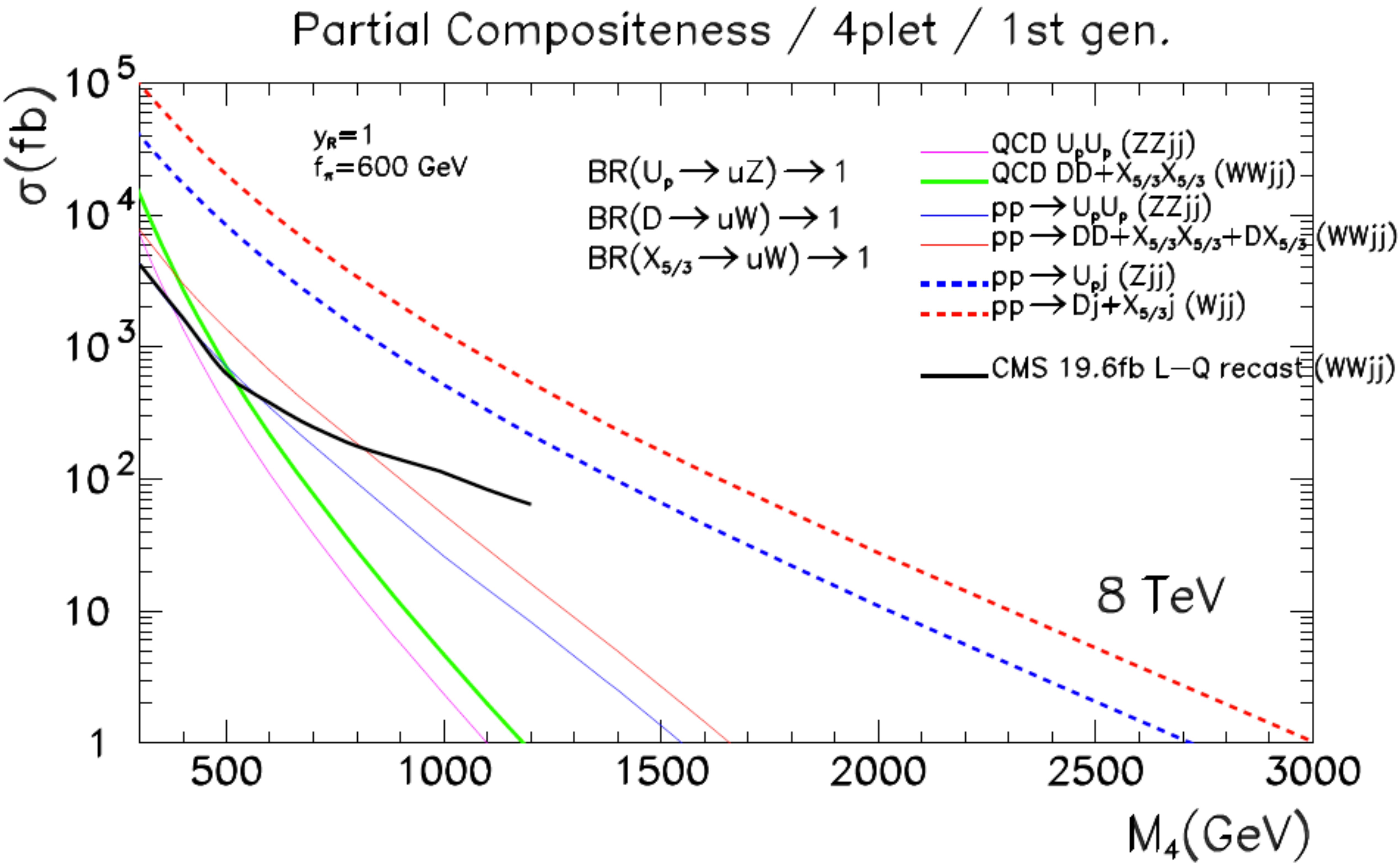
Bounds on c partner from 7TeV LHC

experimental bounds: *Wjj*, *Zjj* with 4.64 fb^{-1} [ATLAS-CONF-2012-137], *WWjj*, *ZZjj* with 1.04 fb^{-1} [ATLAS PRD 86, 012007 (2012)]

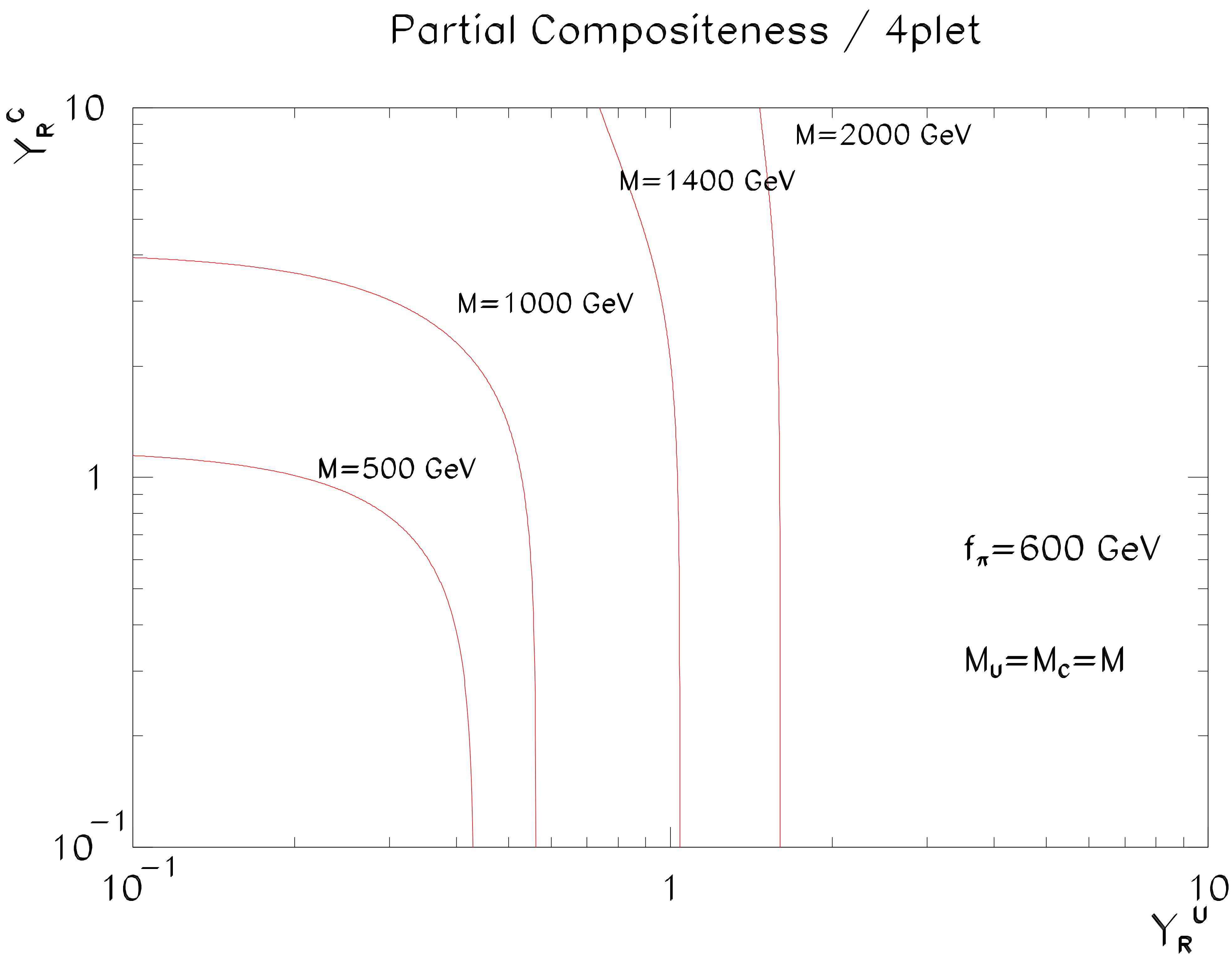


Bounds on u/c partner from 8TeV LHC

experimental bounds: scalar leptoquark search (final state: $\mu^+\mu^- jj$) with 19.6 fb^{-1} [CMS-PAS-EXO-12-042]

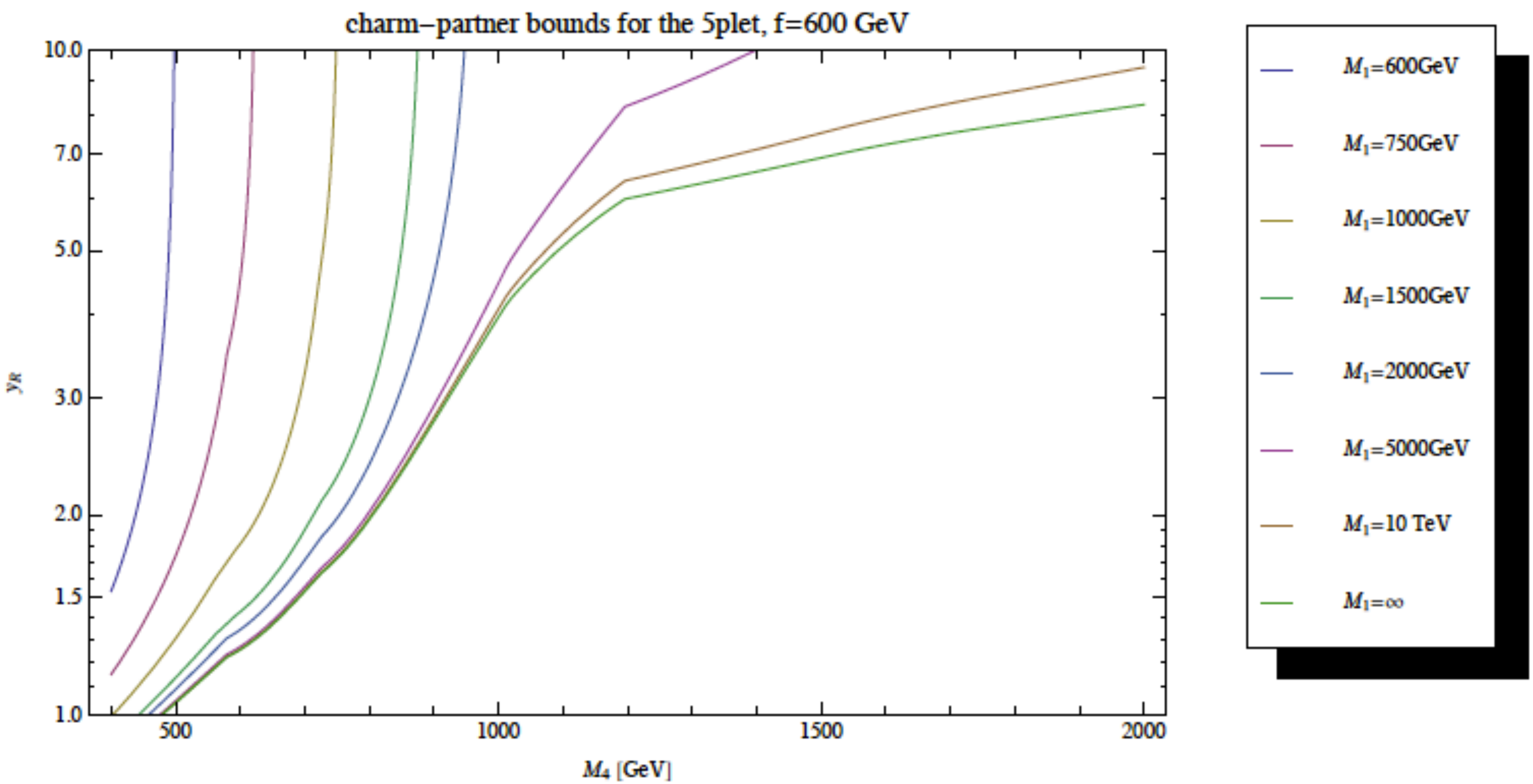


Partners in 4-plet

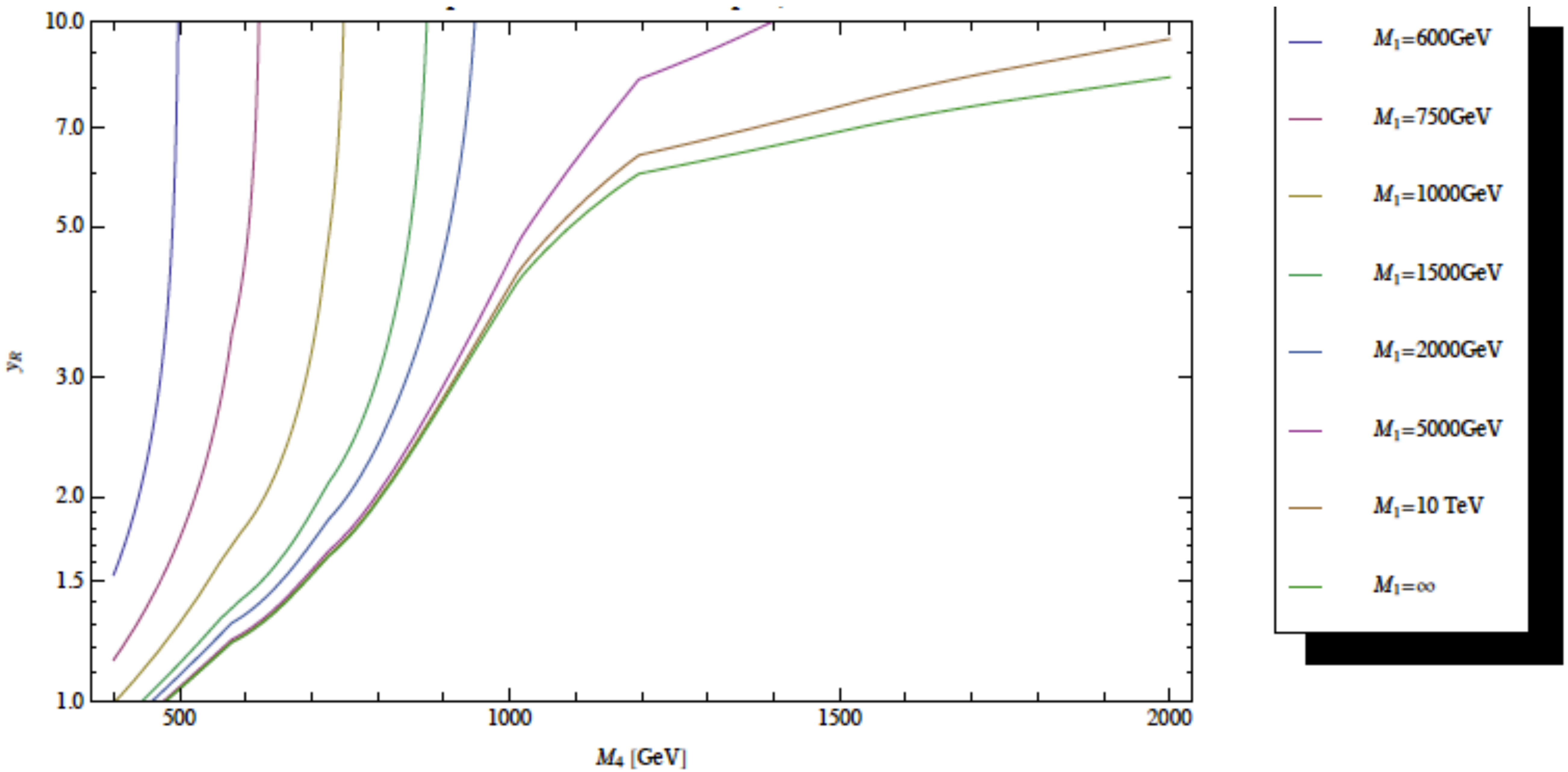


General 5-plet case: 4 + 1

♦ For M1 < M4, cascade decay of 4-plet into singlet can hide 4-plet partner searches (also applicable to top partner case)



- 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.



Summary

♦ Composite Higgs model (with H as PGB) provide a viable solution to the hierarchy problem and generically predict partner states to the fermion

♦ The phenomenology of light generation differs from top partner phenomenology

♦ Bound on charm partners bound is much weaker than that of up and top partners (charm tagging may help probing charm partners)

♦ 4-plet bound can be substantially weakened when considering the generic case where both 4-plet and singlet partners being present with M4>M1 (interesting implication for top partner searches as well).