Composite Light Quarks

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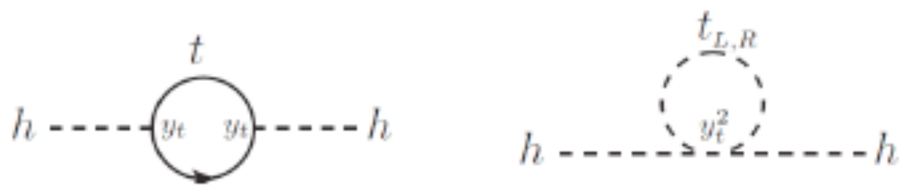
Aspen Winter Conference 2014
Frontiers in Particle Physics: From Dark Matter to the LHC and Beyond

Motivation

Joe Lyken &
Gilad Perez's talk on Sunday

Naturalness => new colored partners, potentially within the LHC reach.

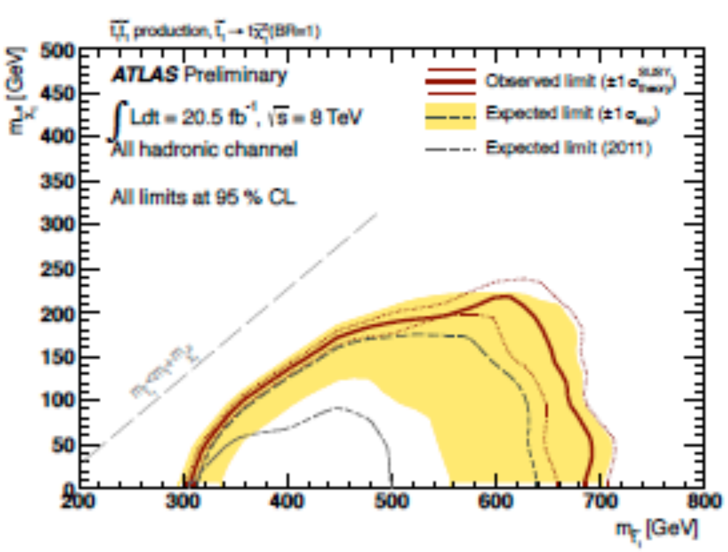


$$\frac{\delta m_h^2}{m_h^2} \sim \left(\frac{\tilde{m}_t}{400\,\mathrm{GeV}}\right)^2$$

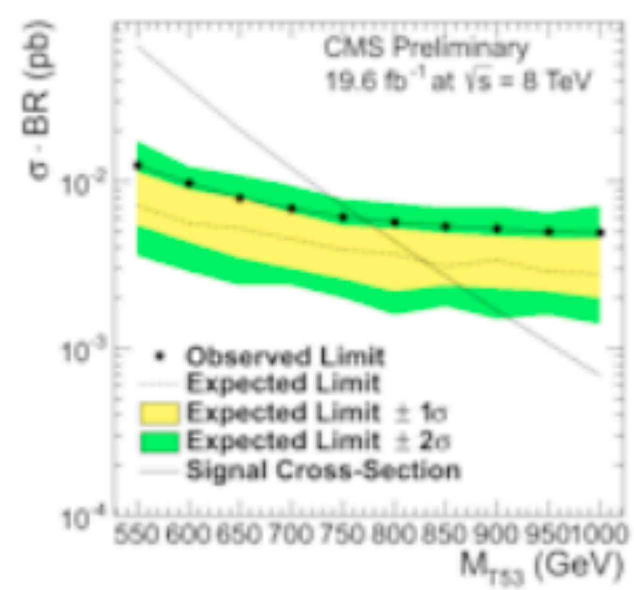
2 leading frameworks
of naturalness

SUSY

composite Higgs



$m_{\mathrm{stop}} \gtrsim 700\,\mathrm{GeV}$



$m_{T5/3} \gtrsim 800\,\mathrm{GeV}$

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; Contno, Servant '08; Mrazek, Wulzer '10; Panico, Wulzer '11; De Curtis, Redi, Tesi '11, Marzocca, Serone, Shu '12; Pomarol, Riva '12; Bellazini et al '12; De Simone et al '12, Grojean, Matsedonskyi, Panico ''13,...

- Just as pion (PGB) is the lightest states in QCD, Higgs is a PGB of a new strong sector (with symmetry breaking scale f) => Higgs is lighter than other resonances
  Georgi & Kaplan '84

- Warped XD models: 5D dual (AdS/CFT correspondence) of Composite Higgs: 5D model gives an explicit realization of the 4D
  Randall & Sundrum,... '90s
  GUT works just as good as in SUSY

- Little Higgs: collective symmetry breaking
  Two or more explicit symmetry breaking terms are needed to break all symmetries protecting the Higgs mass. No quadratic divergences at one-loop.
  Arkani-Hamed, Cohen, Georgi '00s

- Holographic Higgs: Higss as a component of GB (A5)
  Contino, Nomura, Pomarol; Agashe, Contino, Pomarol; Hosotani,...

- Simple 4D effective description (Strongly-Interacting Light Higgs)
  Giudice, Grojean, Pomarol, Rattazzi '07

NB: Higgs does not need to be a usual PGB and can arise from other mechanisms,i.e. it can be a light dilaton
Bellazzini, Csaki, Hubisz, Serra, Terning '12

Composite Higgs

- 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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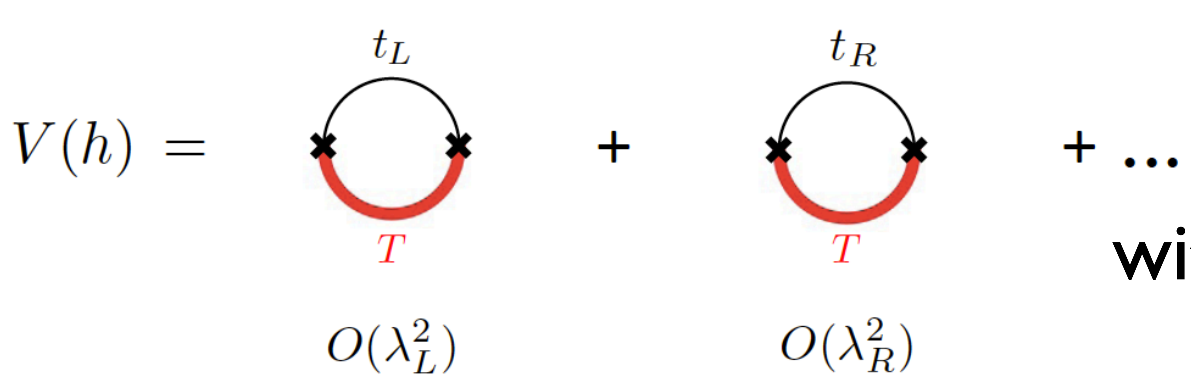
5 of SO(5) =4 + 1

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



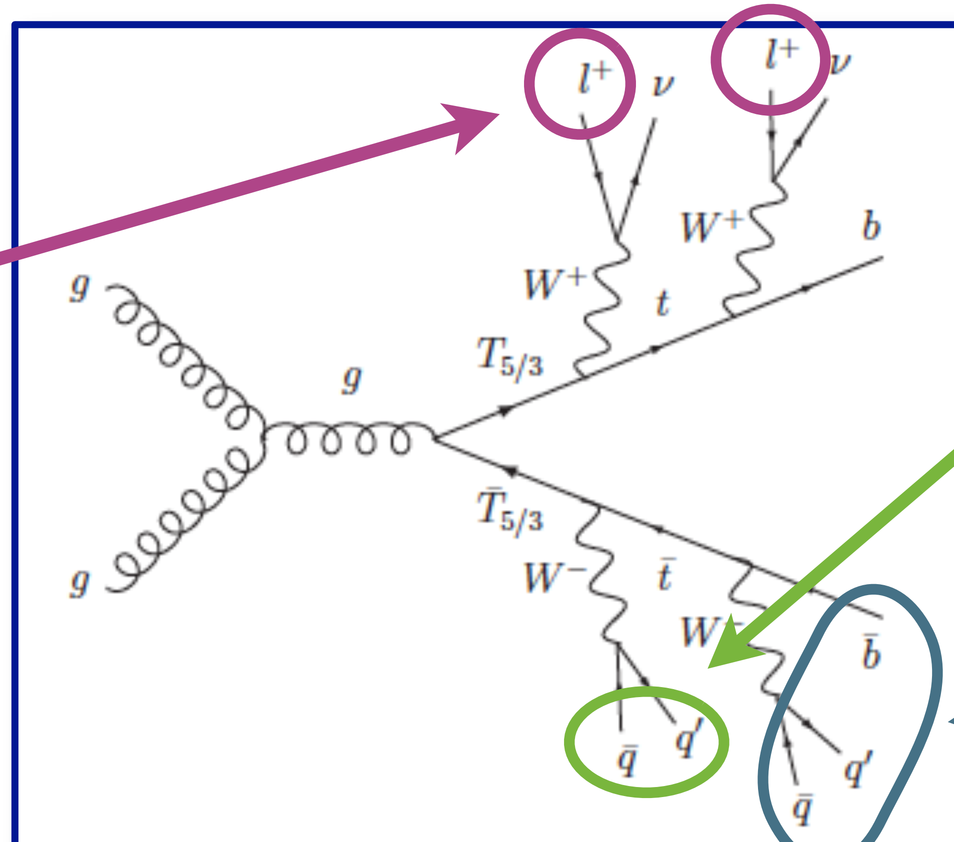
with EM charge 5/3,2/3,-1/3,...

Limit on composite Top partner

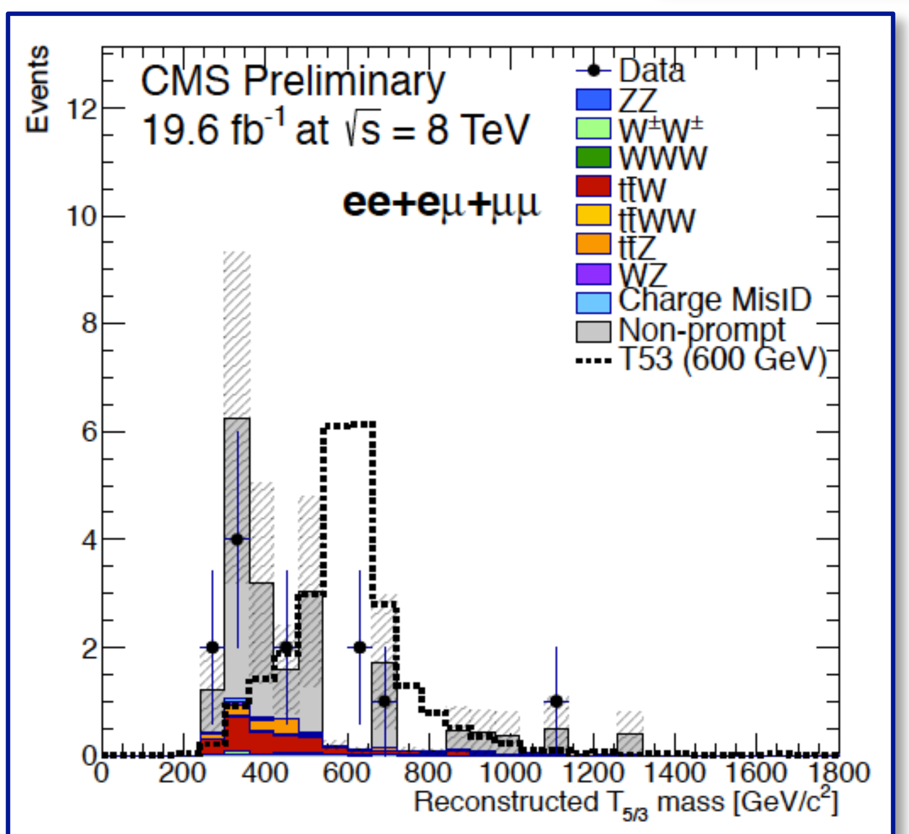
Robin Erbacher's talk on Sunday

- same-sign dileptons

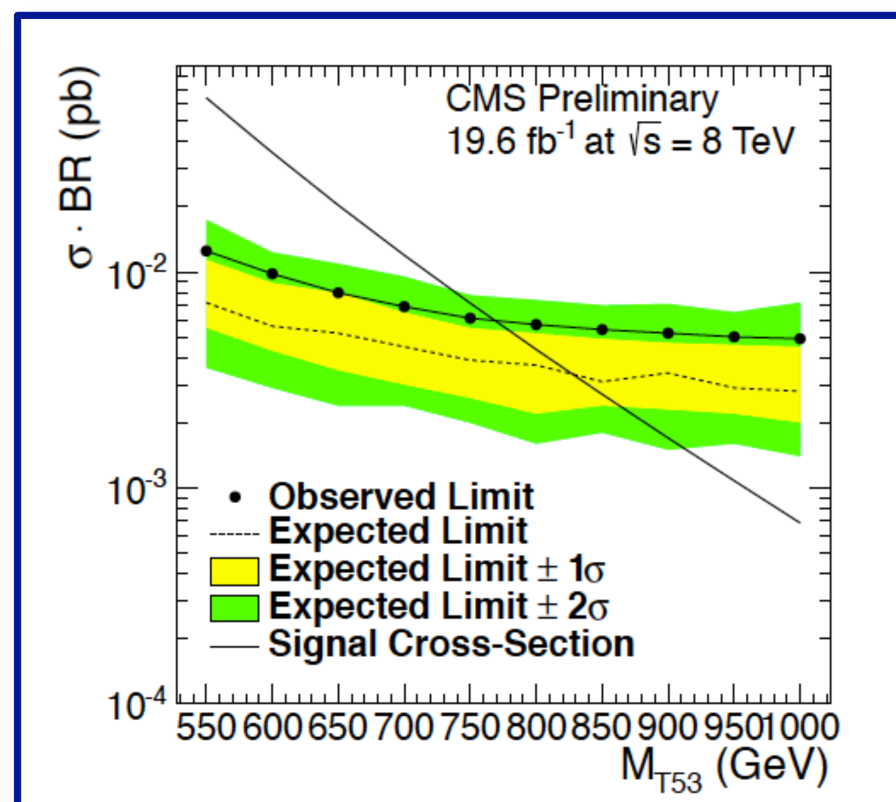
CMS-PAS-B2G-12-012



- W tag: 2 subjets, M_j [60,130]
- CMS top tag



$M_{T(5/3)} > 770$ GeV



Flavourful naturalness

Gilad Perez's talk on Sunday

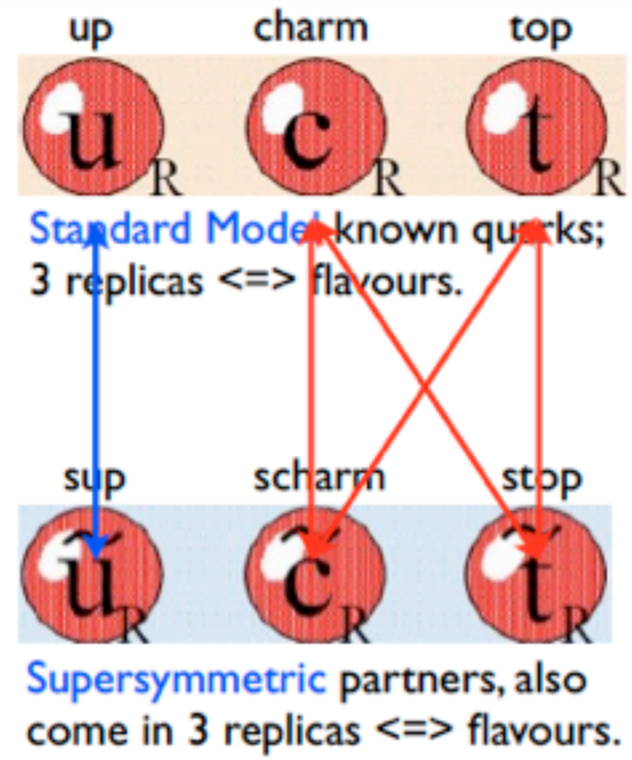
- Standard model: 3 copies (flavours) of quarks;

  same holds for new physics. (say supersymmetry)

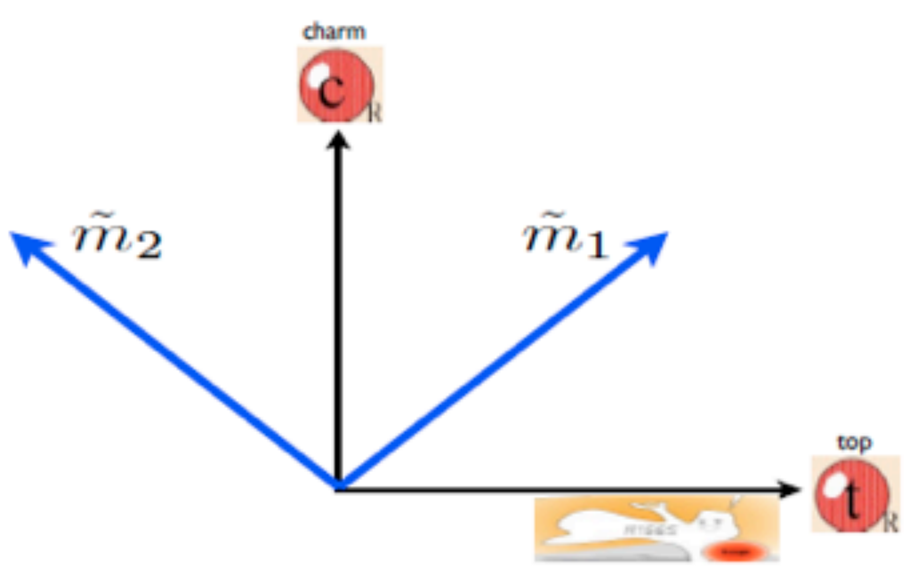
- "Hardwired" assumption:

  top partner (stop) is mass eigenstate.

  Dine, Leigh & Kagan, Phys.Rev. D48 (93); Dimopoulos & Giudice (95); Cohen, Kaplan & Nelson (96) > 1000 citations !



- This need not be the case, top-partner => "stop-scharm" admixture.



Composite Light Quark

- Custodial symmetry for Z->bb Agashe, Contino, Da Rold, Pomarol '12
  => allow for composite light quark without tension with precision tests Delaunay, Gedalia, SL, Perez, Ponton (x2) '10; Redi, Weiler '11 MFV

- Drastic change to phenology: large production rates, top forward-backward asymmetry, non-standard flavor signals ... Delaunay, Gedalia, SL, Perez, Ponton (x2) '10; Redi, Weiler '11; Redi, Sanz, de Vries, Weiler '13; Da Rold, Delaunay, Grojean, Perez '13; Atre, Chala, Santiago '13

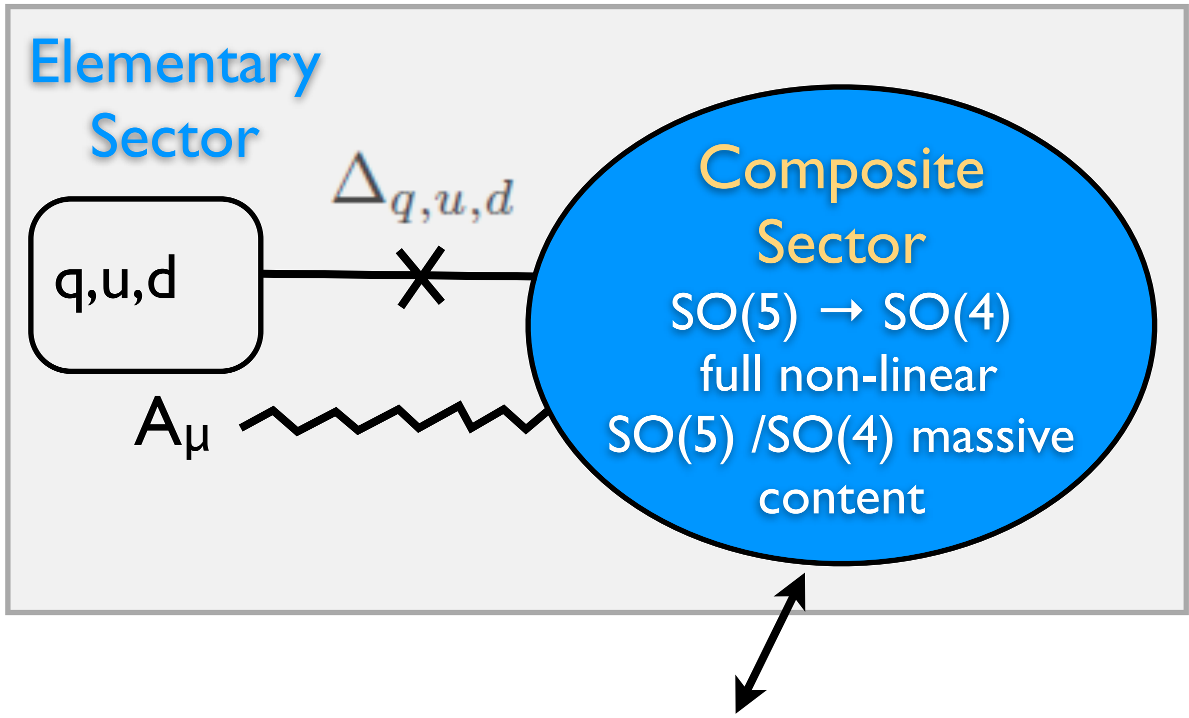
- And LHC implications for non-degenerate first 2-generation partners. Delaunay, Fraille, Flacke, SL, Panico, Perez `13 Kim, Flake, SL, Lim '13

Partial Compositeness

* Partial Compositeness: D.B. Kaplan; Gorssman & Neubert; Huber,...
  Elementary-composite states talk through linear couplings.

The flavor problem of TC theories can be improved if the Yukawa couplings arise through mixings of elementary quarks with fermionic operators of the strong sector

- minimal model: SO(5)/SO(4) with 4 GBs => Higgs doublet
  Agashe, Contino, Pomarol '05



$$y_{SM} \simeq \frac{y_L y_R}{g_\Psi}$$

$$m_\Psi \simeq g_\Psi f$$

Typically (anarchy): $\Delta_i \ll \Delta_{q3,u3} \sim M$, i = 1, 2 .

$\Delta_i = y_i f$ (f ⇔ decay constant for the SO(5)/SO(4) breaking)

Partial Compositeness

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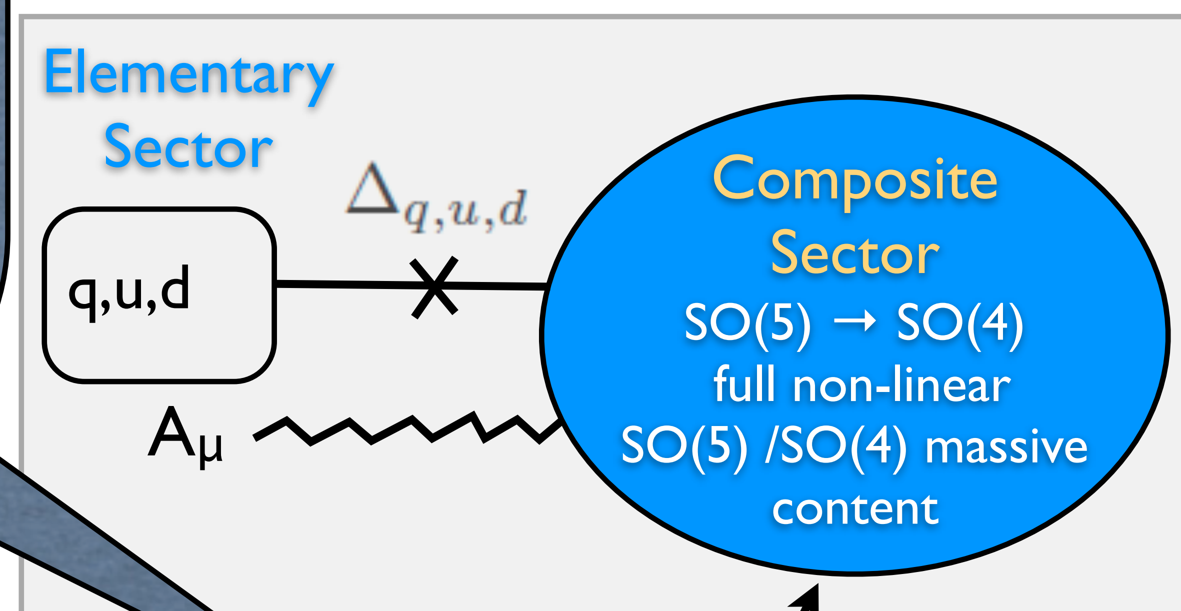
  Elementary-composite states talk through linear couplings.

... can be improved if the Yukawa ... lementary quarks with ... ctor

What if the first two generations of RH quarks are composite but not at the same level, for instance:

$$y_u \lesssim y_c \sim y_t \sim 1$$



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General Set-up

- As a setup we choose the minimal composite Higgs model based on SO(5)/SO(4). We use the CCWZ construction in order to write down $\mathcal{L}_{eff}$ in a nonlinearly invariant way under SO(5) Coleman, Wess, Zumino '69, Callan, Coleman '69
  Note: possible vector resonances are "integrated out" and do not appear directly in the effective description

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

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

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

- One common choice (partially composite quarks):

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

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

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

General Set-up

* BSM particle content: 5 = 4 + 1 $Y = T_R^3 + X$

	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")

General Set-up

- BSM particle conte… $T_R^3 + X$

$SO(4)$	
$SU(3)_c$	
EM charge	2/…

In this talk, I will focus on partially composite quarks scenario, while we did analysis for fully composite cases as well

- 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 light quarks

Delaunay, Fraille, Flacke, SL, Panico, Perez `13
Flacke, Kim, SL, Lim `13

- 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.

$$m_u \simeq \frac{v}{\sqrt{2}f} \times |M_1 - M_4| \times \frac{y_L f}{\sqrt{(M_4^2 + y_L^2 f^2)}} \times \frac{y_R f}{\sqrt{(M_1^2 + y_R^2 f^2)}}$$

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wh... tone matrix

$y_L \ll 1$, the Lagrangian for the composite states and the right-handed up quark becomes invariant under the custodial symmetry $SO(3)_c$ subgroup of SO(4)

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

w...

- De...
  - expand d_μ, e_μ, U_{gs} around $\langle h\rangle$,
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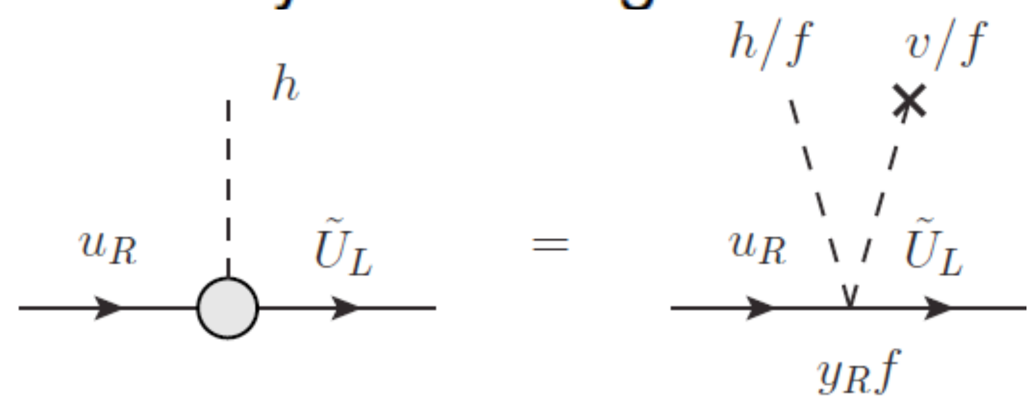
$$m_u \simeq \frac{v}{\sqrt{2}f} \times |M_1 \ldots| \times \frac{y_L f}{\sqrt{(M_4^2 + y_L^2 f^2)}} \times \frac{y_R f}{\sqrt{(M_1^2 + y_R^2 f^2)}}$$

Partners in Singlet

Delaunay, Fraille, Flacke, SL, Panico, Perez `13
Flacke, Kim, SL, Lim `13

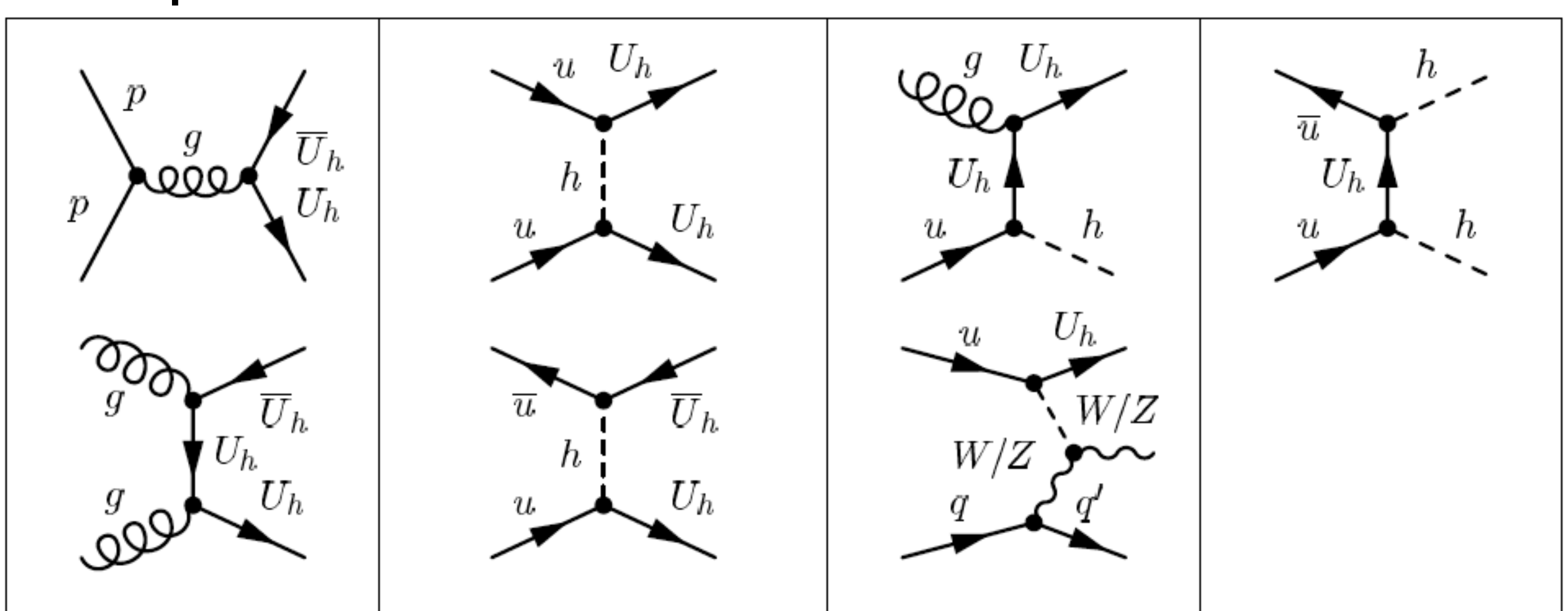
- Now lets look at the singlet limit: M_1 finite and $M_4 \to \infty$. Then, all fourplet states decouple, and the only remaining BSM state is $\tilde{U}$.
- Mass: $m_{\tilde{U}} = \sqrt{M_1^2 + (y_R f \cos(\epsilon))^2}$
- only "mixing" coupling:



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

- main production channels:

$$\epsilon \equiv \frac{v}{f}$$



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

Partners in Singlet

Flacke, Kim, SL, Lim `13

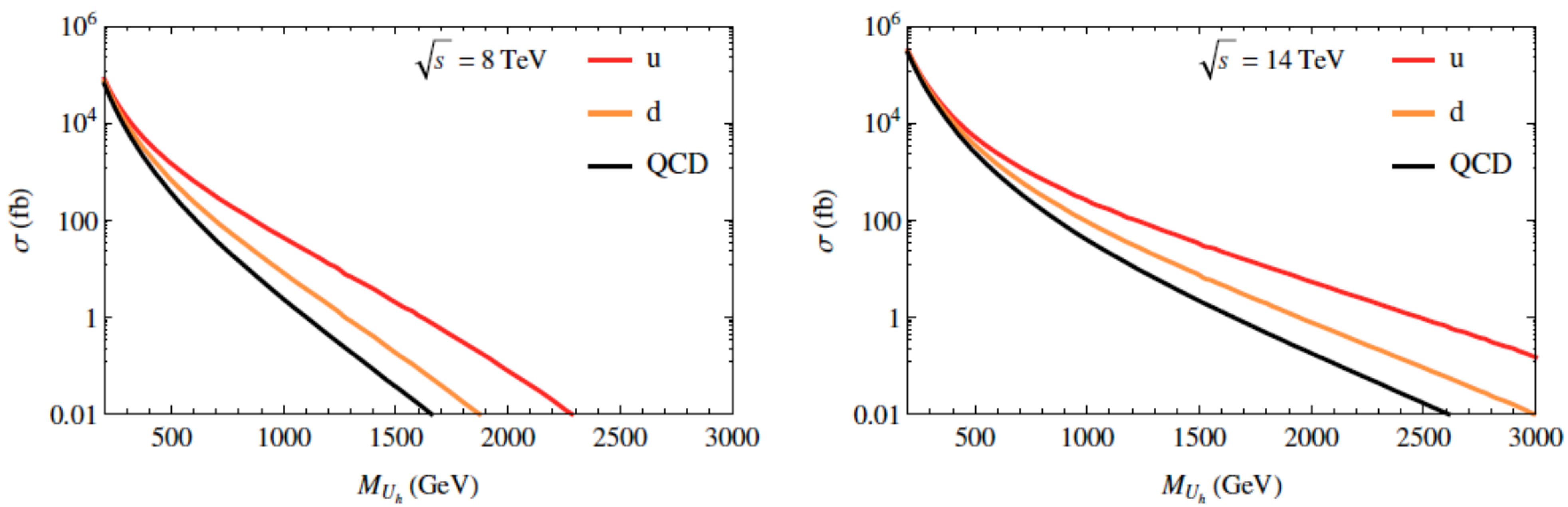
$$\mathcal{L} = i\overline{\tilde{U}}\not{D}\tilde{U} - M_1\overline{\tilde{U}}\tilde{U} + i\,\overline{q}_L\,\not{D}q_L + i\,\overline{u}_R\,\not{D}u_R$$
$$- \left[\frac{y_L}{\sqrt{2}} f\overline{u}_L F\left(\frac{h+v}{f}\right)\tilde{U}_R + y_R f\overline{\tilde{U}}_L G\left(\frac{h+v}{f}\right)u_R + \text{h.c.}\right]$$

5 rep'

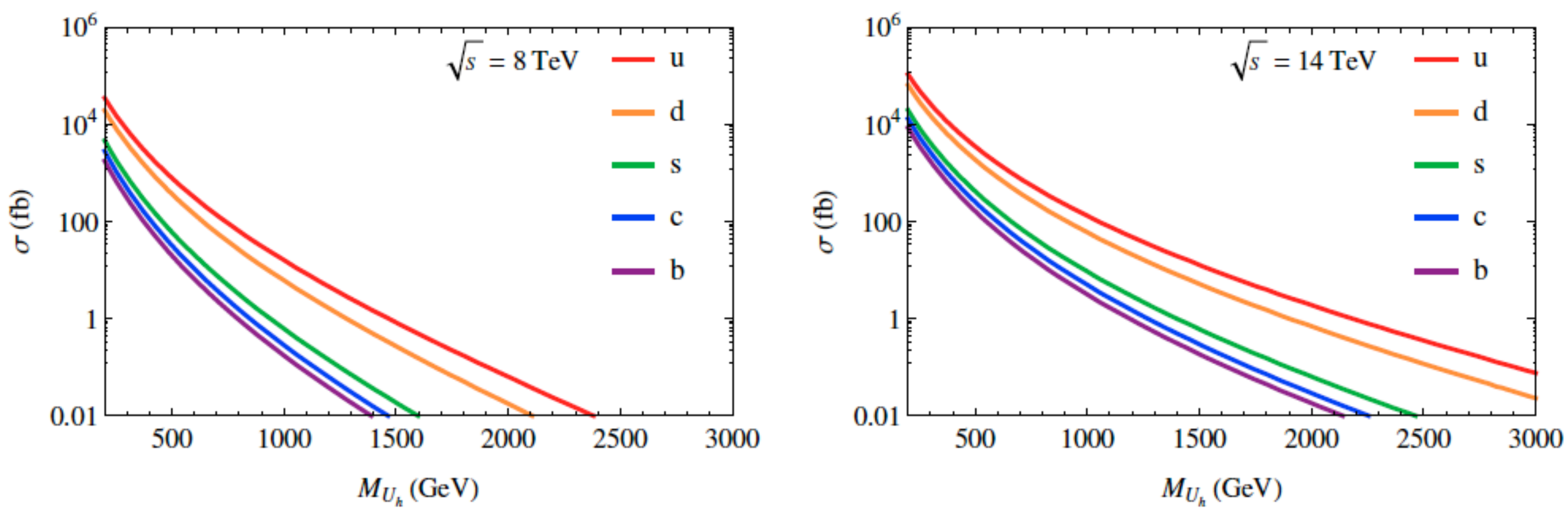
$$= i\overline{\tilde{U}}\not{D}\tilde{U} - M_1\overline{\tilde{U}}\tilde{U} + i\,\overline{q}_L\,\not{D}q_L + i\,\overline{u}_R\,\not{D}u_R$$
$$- \left[m_2\overline{u}_L\tilde{U}_R + m_3\overline{\tilde{U}}_L u_R + \lambda_2 h\overline{u}_L\tilde{U}_R + \lambda_3 h\overline{\tilde{U}}_L u_R + \text{h.c.} + \mathcal{O}(\epsilon^2)\right]$$

	$\mathcal{F}(U_{\rm gs})$	$\mathcal{G}(U_{\rm gs})$	$F(\frac{h+v}{f})$	$G(\frac{h+v}{f})$	$\lambda^{\rm eff}_{\rm mix}$
$q_L \in \mathbf{5}$ $\psi \in \mathbf{5}$	$U^{i5}_{\rm gs}$	$U^{i5}_{\rm gs}$	$-\sin(\frac{h+v}{f})$	$\cos(\frac{h+v}{f})$	$-\frac{y_R^2}{2}\sin(2\epsilon)\frac{f}{M_{U_h}}$ $= -y_R^2\frac{v}{M_{U_h}}[1+\mathcal{O}(\epsilon^2)]$
$q_L \in \mathbf{14}$ $\psi \in \mathbf{5}$	$U^{i5}_{\rm gs}U^{j5}_{\rm gs}$	$U^{i5}_{\rm gs}U^{j5}_{\rm gs}$	$\frac{1}{\sqrt{2}}\sin(2\frac{h+v}{f})$	$\frac{1}{\sqrt{2}}\sin(2\frac{h+v}{f})$	$-\frac{y_R^2}{2}\sin(4\epsilon)\frac{f}{M_{U_h}}$ $= 2y_R^2\frac{v}{M_{U_h}}[1+\mathcal{O}(\epsilon^2)]$

pair production



single production



Singlet

Flacke, Kim, SL, Lim `13

Decay: U → hj (100%)

Most promising signal: pp → hhjj

boosted analysis needed (no LHC bounds yet)

$\mathcal{L} = i$ … c.]

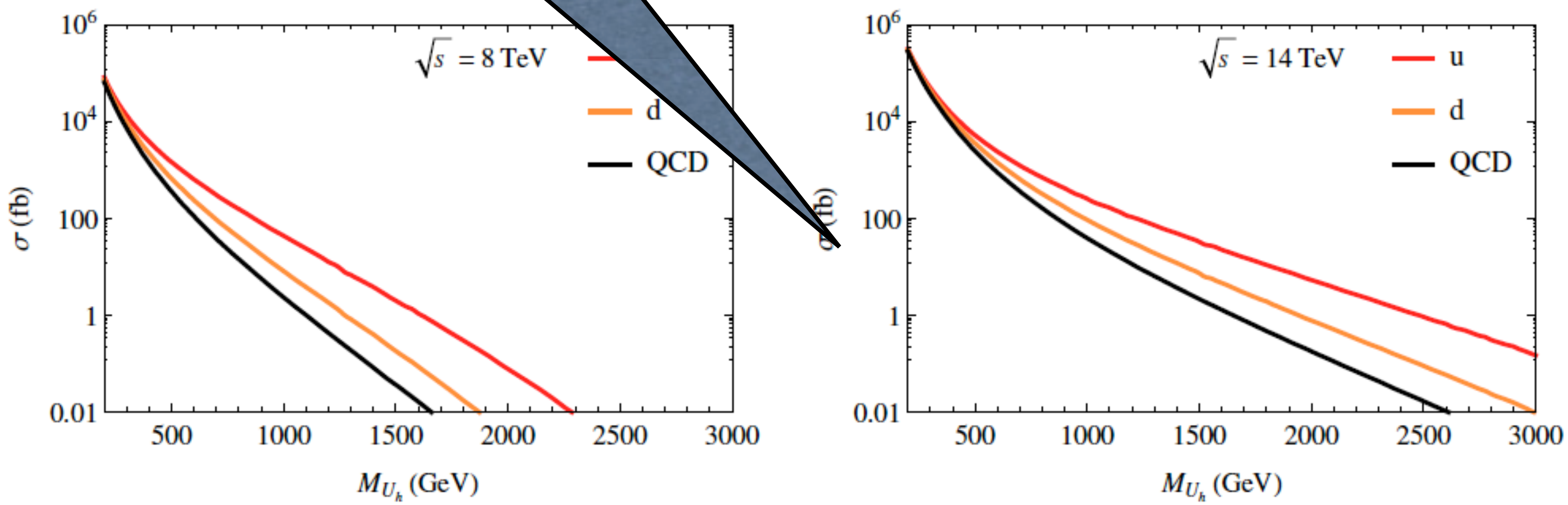
5 rep'

$= i$

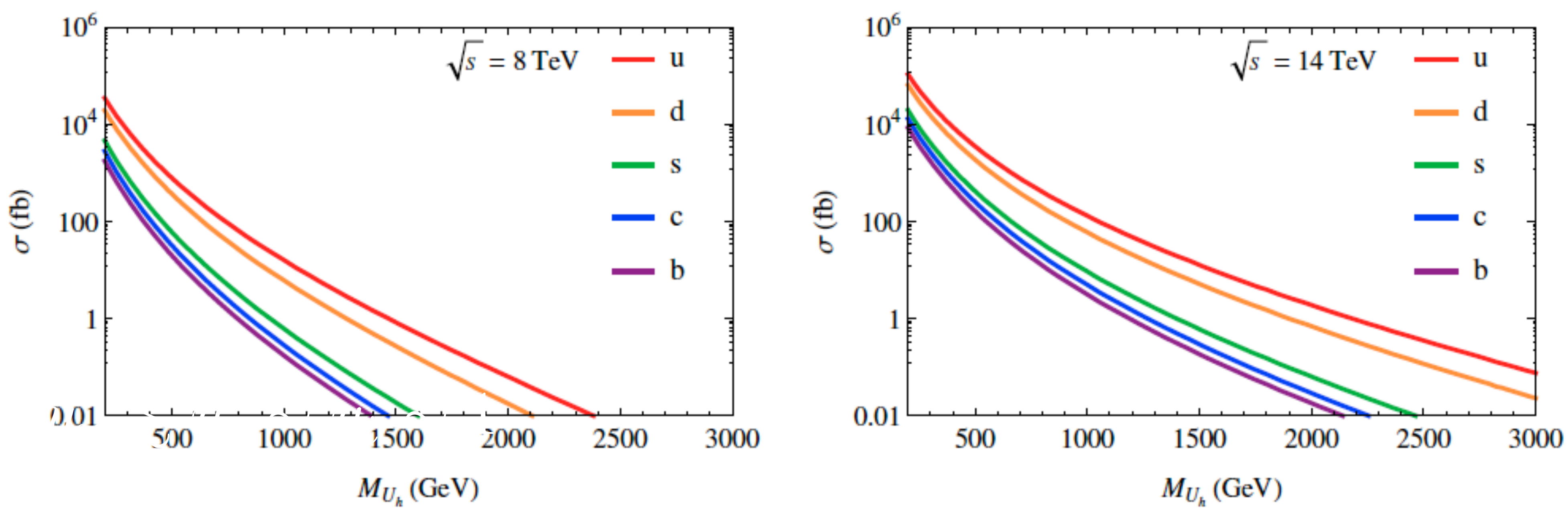
$-[$ … $\text{c.} + \mathcal{O}(\epsilon^2)]$

	$\mathcal{F}(U_{\text{gs}})$	$\mathcal{G}(U_{\text{gs}})$	$F(\frac{h+v}{f})$	$G(\frac{h+v}{f})$	$\lambda^{\text{eff}}_{\text{mix}}$
$q_L \in \mathbf{5}$ $\psi \in \mathbf{5}$	U^{i5}_{gs}	U^{i5}_{gs}	$-\sin(\frac{h+v}{f})$	$\cos(\frac{h+v}{f})$	$-\frac{y_R^2}{2}\sin(2\epsilon)\frac{f}{M_{U_h}}$ $= -y_R^2\frac{v}{M_{U_h}}[1+\mathcal{O}(\epsilon^2)]$
$q_L \in \mathbf{14}$ $\psi \in \mathbf{5}$	$U^{i5}_{\text{gs}}U^{j5}_{\text{gs}}$	$U^{i5}_{\text{gs}}U^{j5}_{\text{gs}}$	$\frac{1}{\sqrt{2}}\sin(2\frac{h+v}{f})$	$\frac{1}{\sqrt{2}}\sin(2\frac{h+v}{f})$	$-\frac{y_R^2}{2}\sin(4\epsilon)\frac{f}{M_{U_h}}$ $= 2y_R^2\frac{v}{M_{U_h}}[1+\mathcal{O}(\epsilon^2)]$

pair production



single production



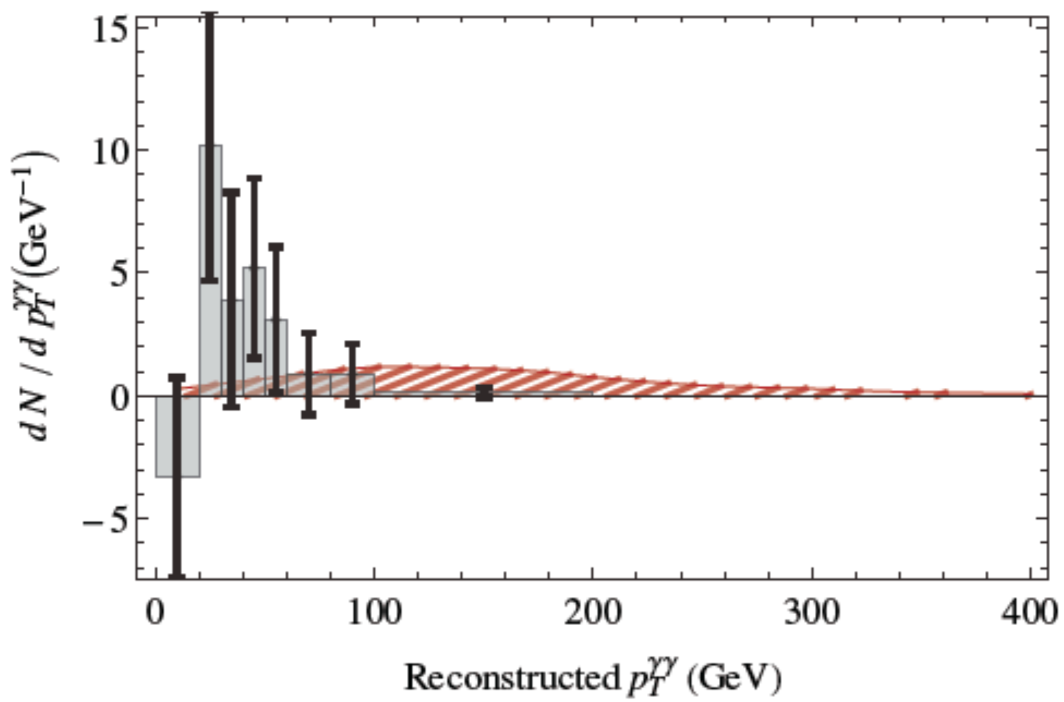
Partners in Singlet

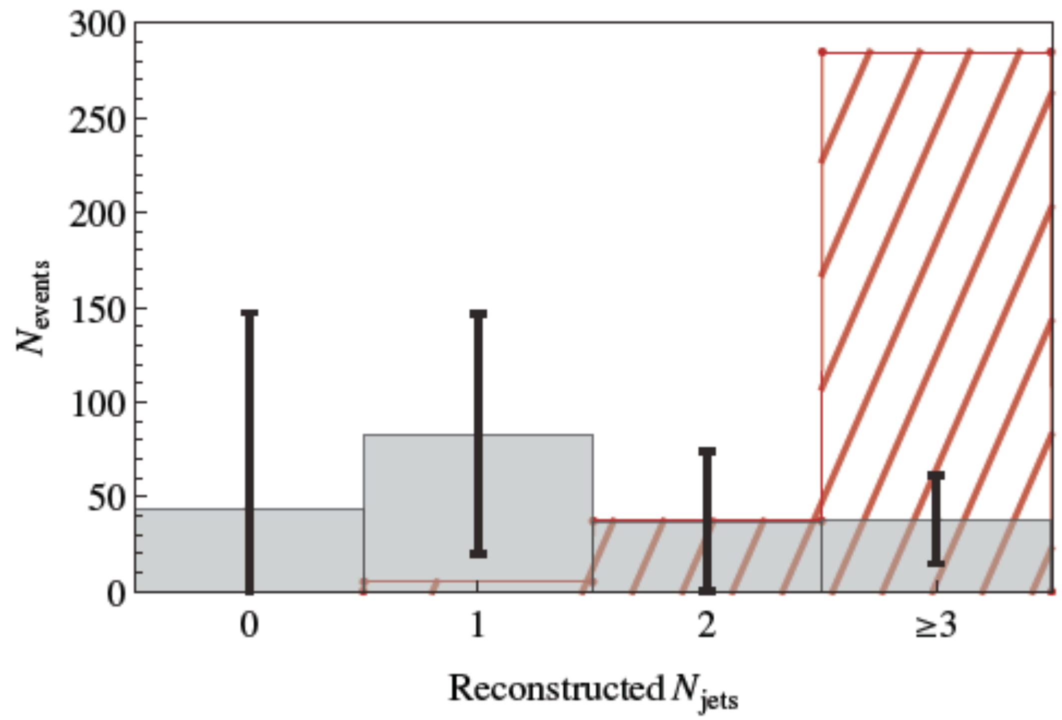
Flacke, Kim, SL, Lim `13

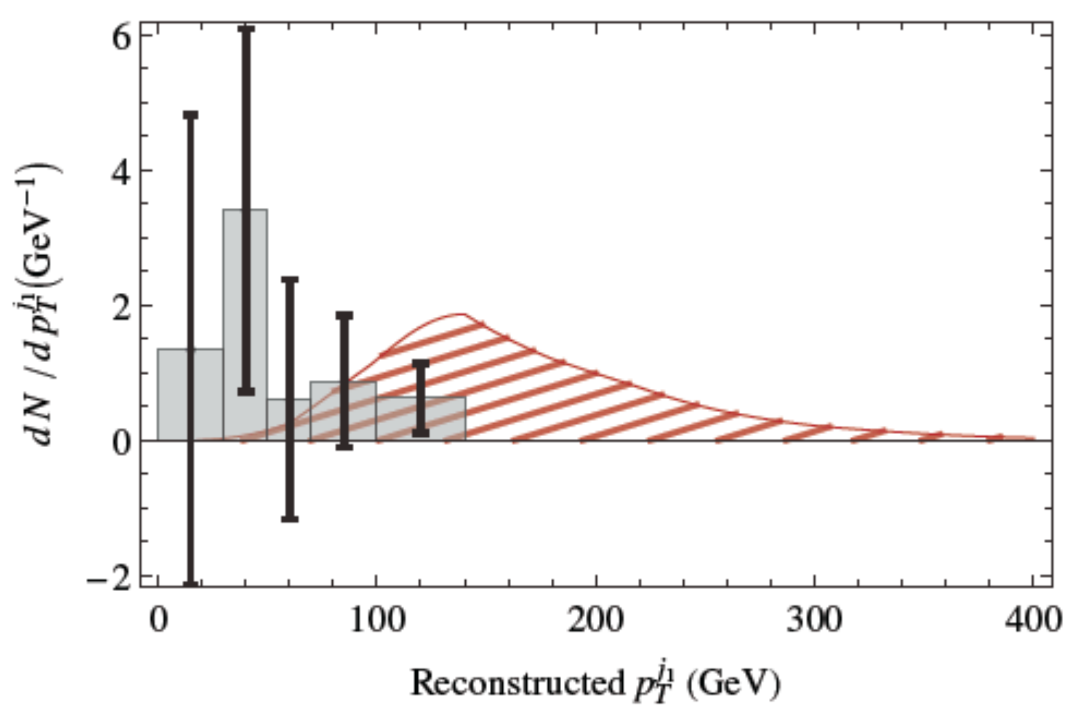
- LHC bounds comes mostly from $h \to \gamma\gamma$ ATLAS-CONF-2013-072

Look for a deviations in pp → h(hjj) → $\gamma\gamma$ X or bbX

i.e. modifications to SM Higgs signals and their angular and p_T distributions







The distributions shown result from a partially composite down-quark model with a partner mass of M_{Uh} = 300 GeV and effective coupling =1(red striped region).

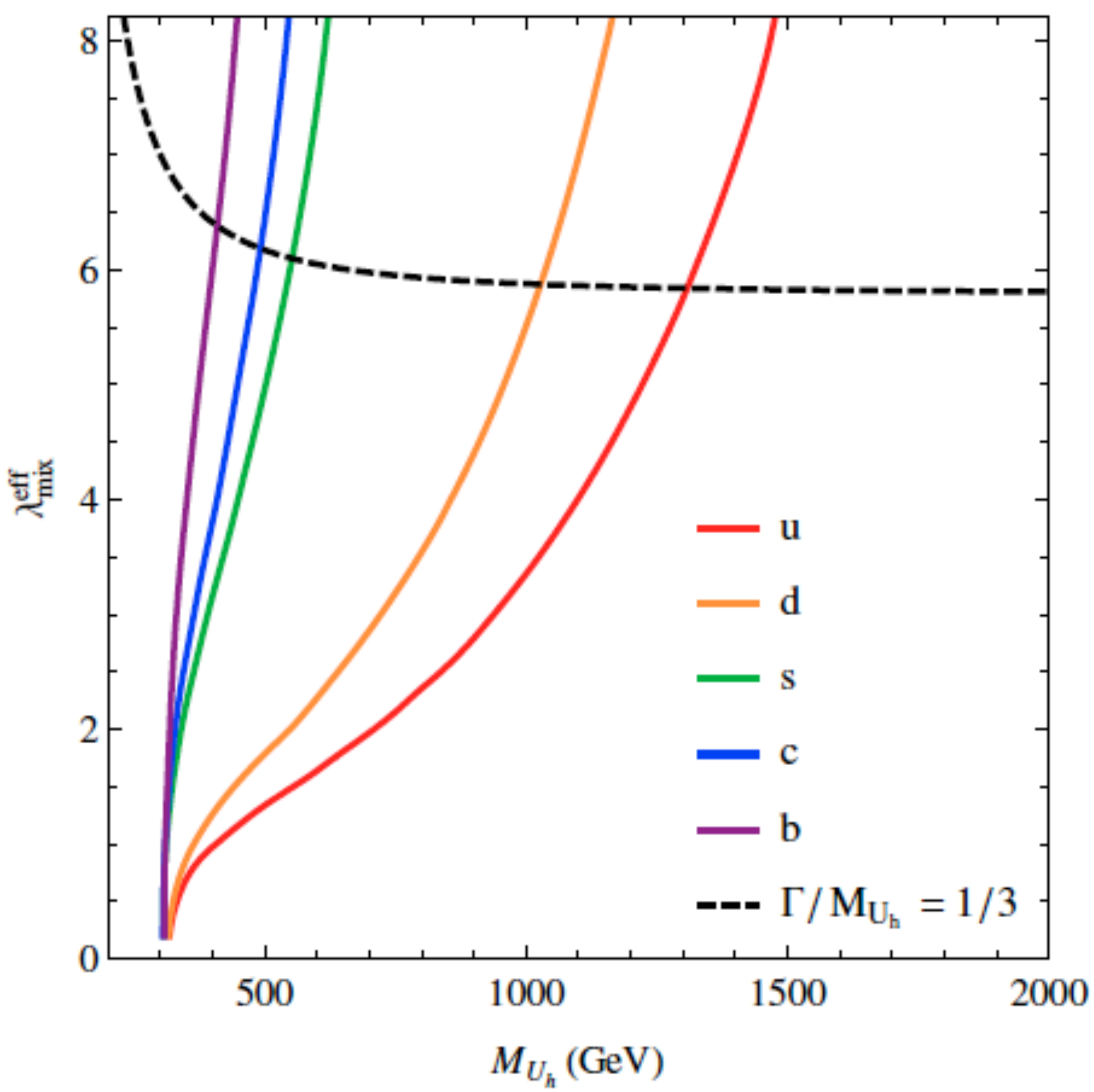
Partners in Singlet

Flacke, Kim, SL, Lim `13

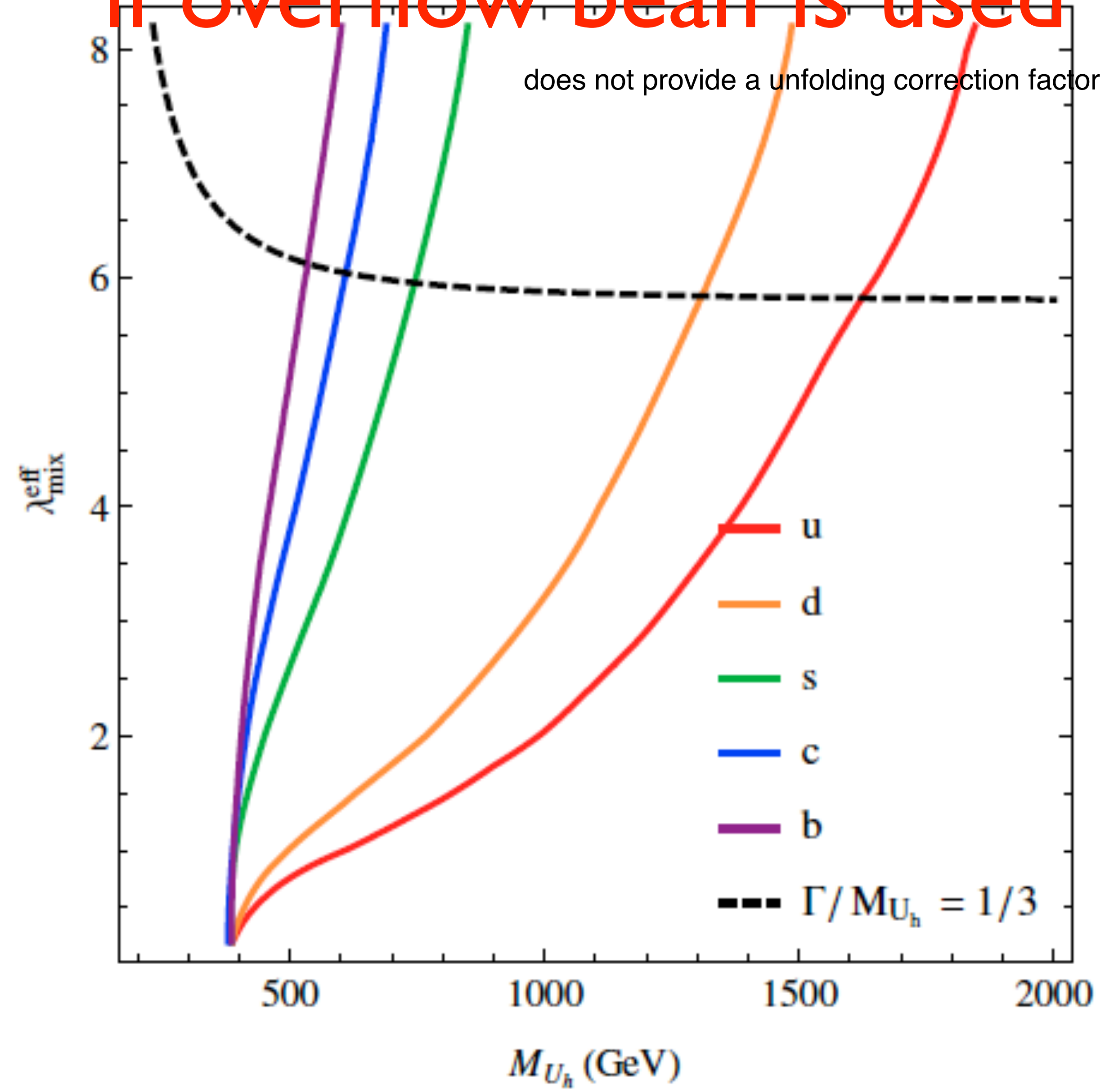
- LHC bounds comes from QCD pair production:

partially composite: $M_{U_h} \gtrsim 310\ \mathrm{GeV}$ fully composite: $M_{U_h} \gtrsim 212\ \mathrm{GeV}$

- LHC bounds for single production (partially composite):



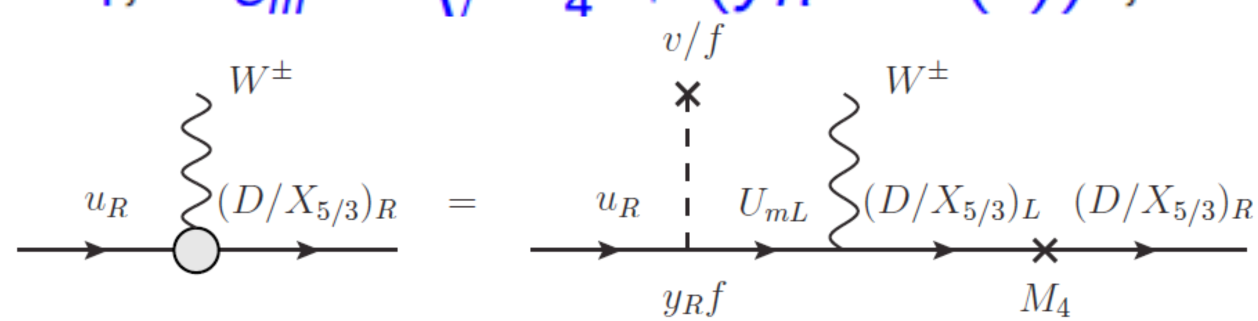
if overflow bean is used



Partners in 4-plet

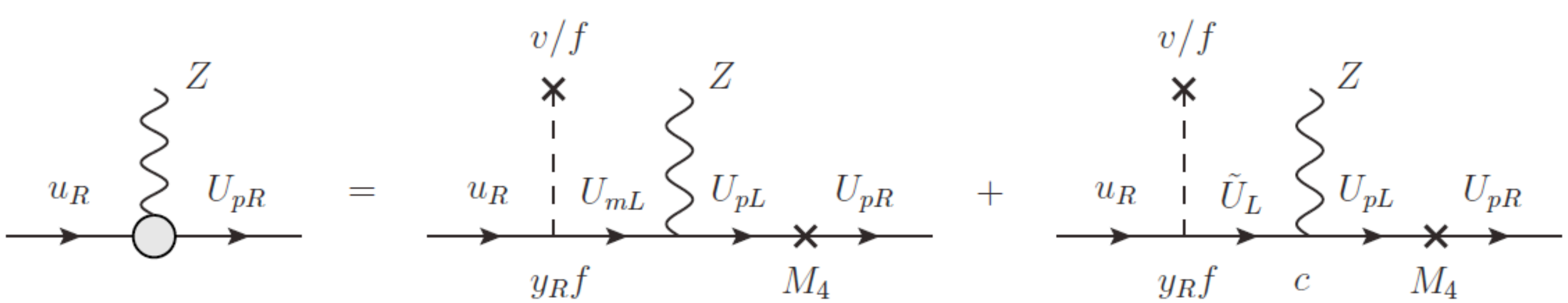
Delaunay, Fraille, Flacke, SL, Panico, Perez `13

- Let's now 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:



$$g_{WuX} = -g_{WuD} = -c_w\, g_{ZuU_p} = \frac{g}{2} \cos\epsilon \sin\varphi_4 ,$$

$$\lambda_{huU_m} = y_R \cos\epsilon \cos\varphi_4 ,$$

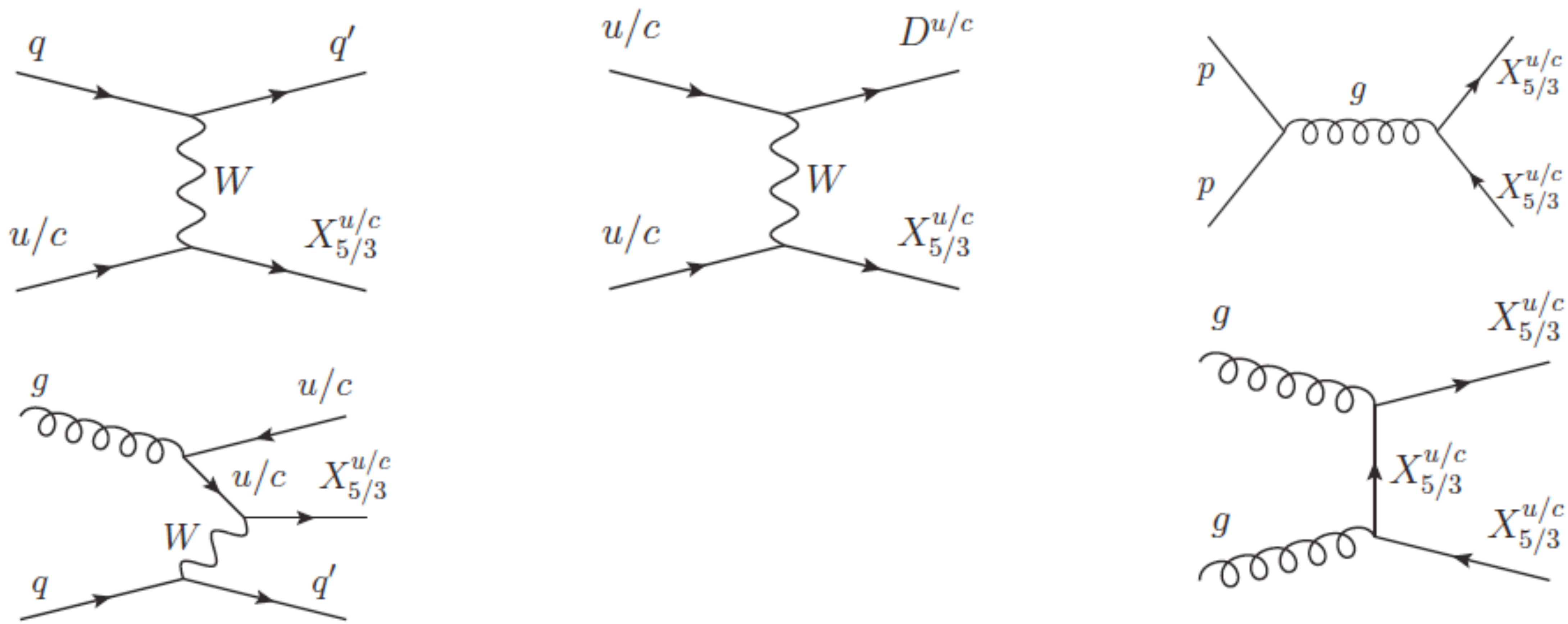


$$\tan\varphi_4 \equiv \frac{y_R f \sin\epsilon}{M_4} .$$

Partners in 4-plet

Delaunay, Fraille, Flacke, SL, Panico, Perez `13

- 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%).

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)

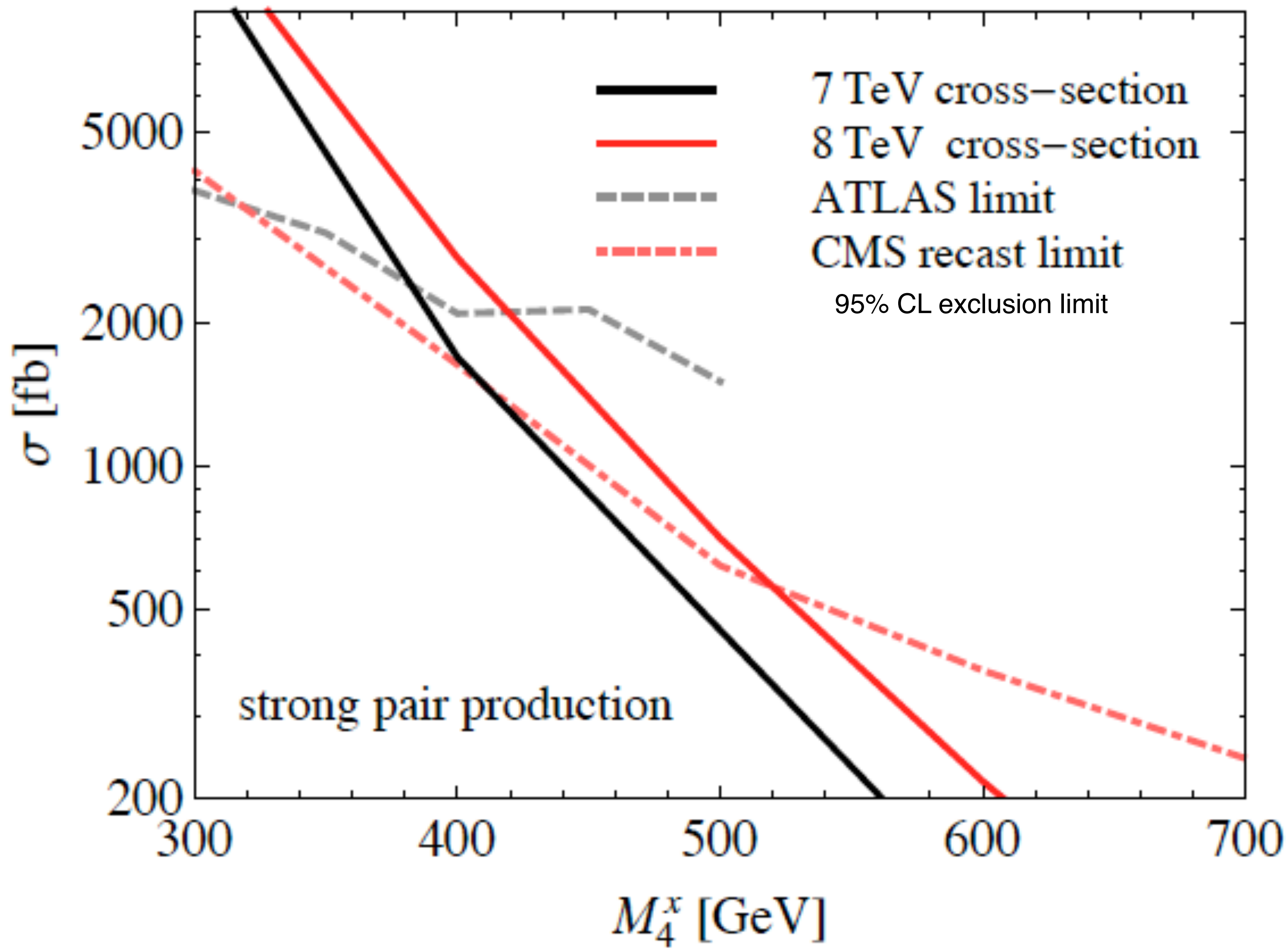
[CDF Collaboration], Phys. Rev. Lett. 107, 261801 (2011)

[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: μμjj)

Bounds on u/c partner from 7TeV LHC

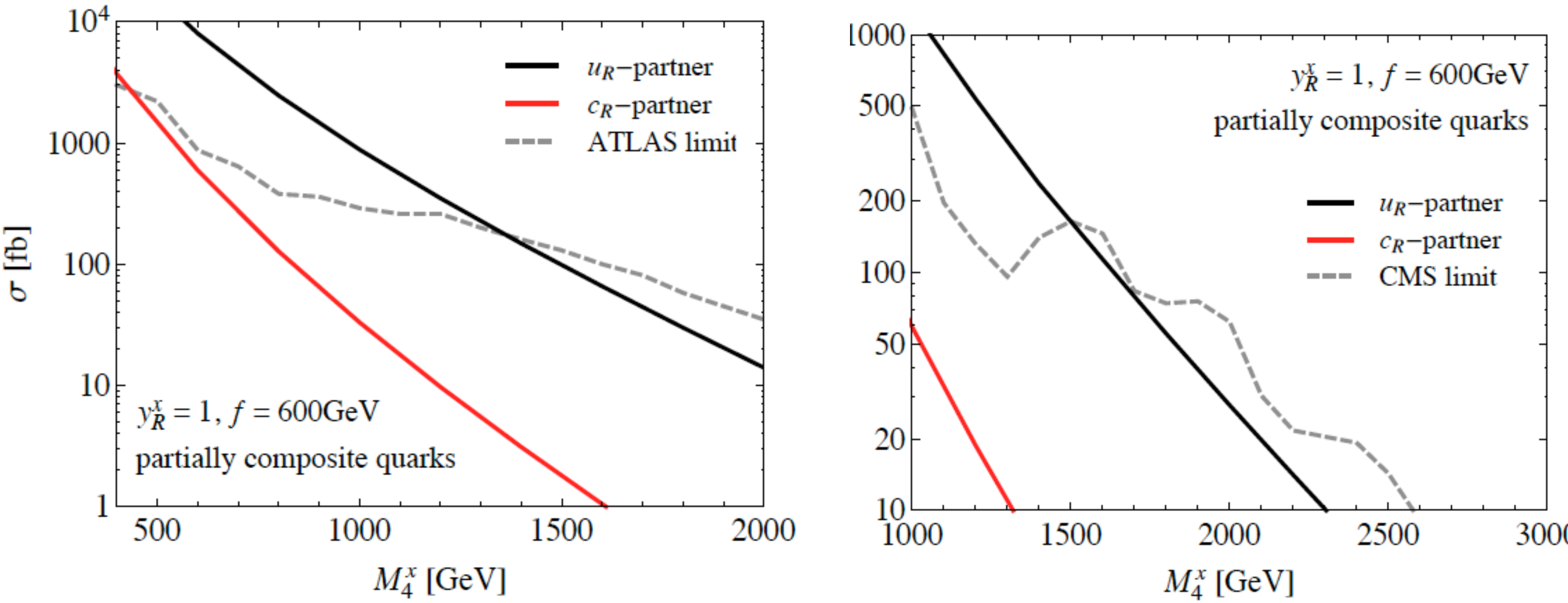
Delaunay, Fraille, Flacke, SL, Panico, Perez `13



Model Independent predictions for WWjj cross sections through QCD pair production of –1/3 and 5/3 charge partners of the composite right-handed up and charm quarks. The solid black (red) line stands for the 7TeV (8TeV) cross section. They are the same for the first two generations and in both partially and fully quark scenarios.

Bounds on u/c partner from 7TeV LHC

Delaunay, Fraille, Flacke, SL, Panico, Perez `13

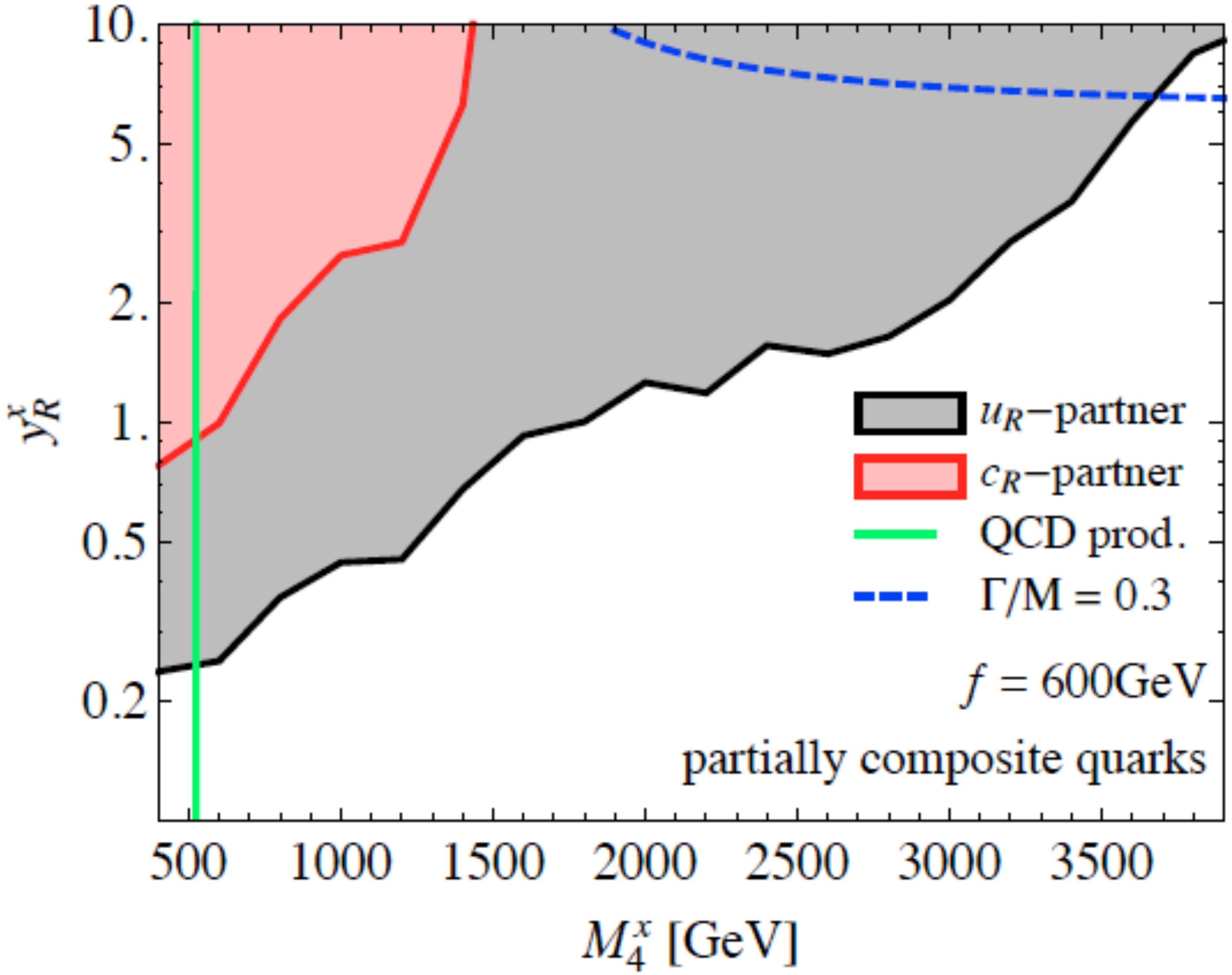


Predictions for Wjj cross sections of function of the fourplet partner mass M_4^x ,x = u, c, in the partially composite right-handed for two generation quarks. dashed curve is the 95% CL exclusion limit from the ATLAS and CMS searches at the 7TeV LHC run

Partners in 4-plet

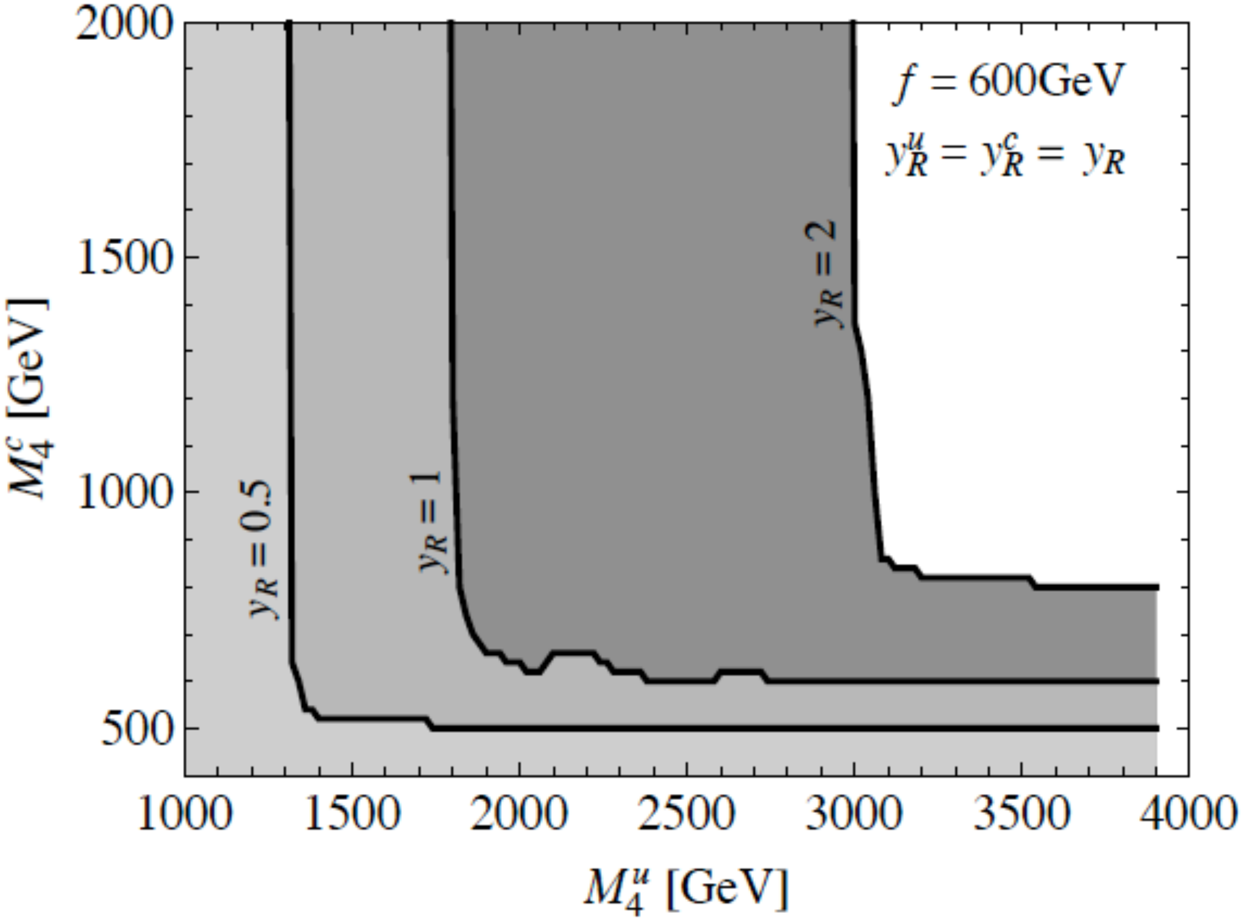
Delaunay, Fraille, Flacke, SL, Panico, Perez `13

95% CL exclusion limits



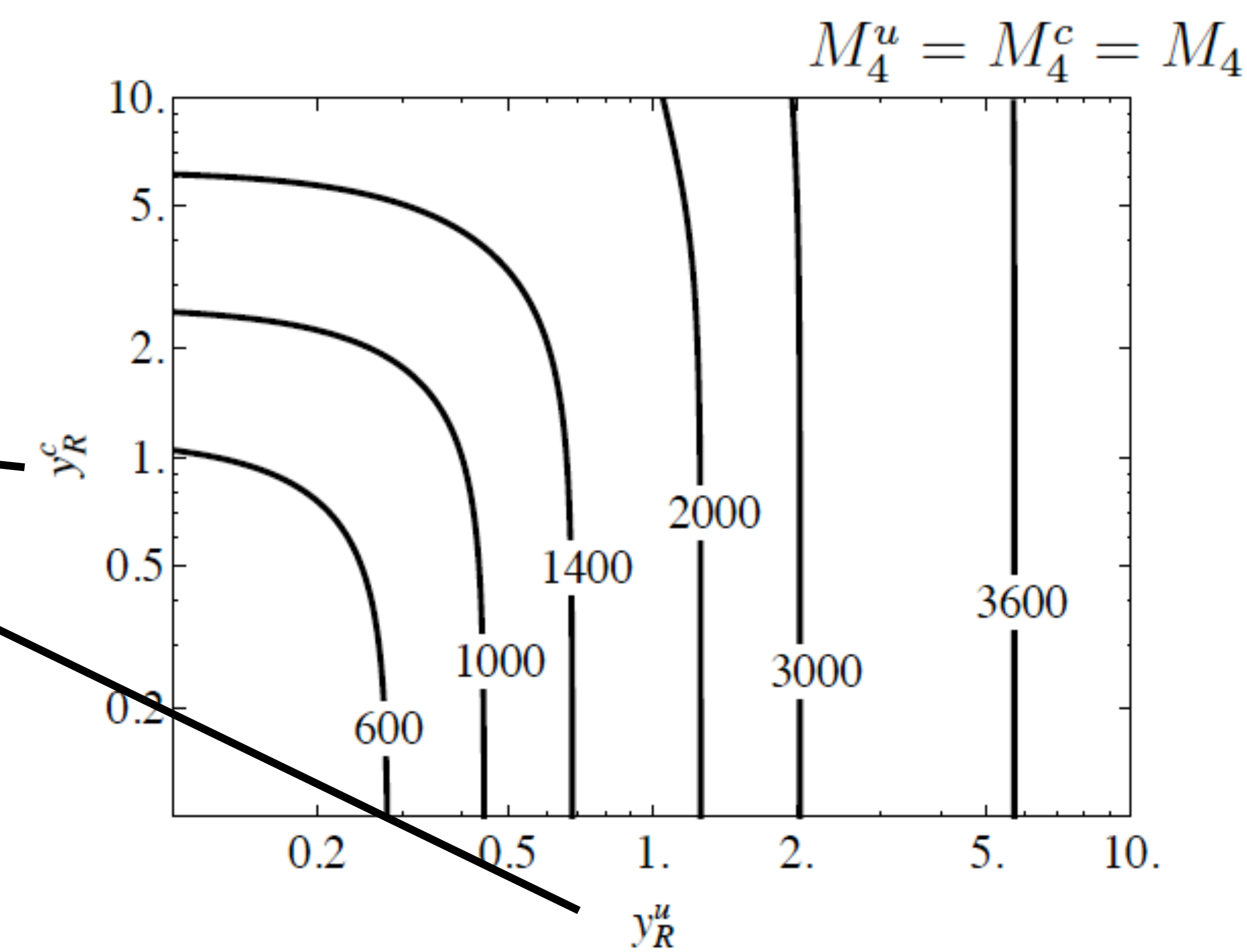
Collider implications for split 2 generations (similar to SUSY case)

Delaunay, Fraille, Flacke, SL, Panico, Perez `13



$$M_c \ll M_U$$

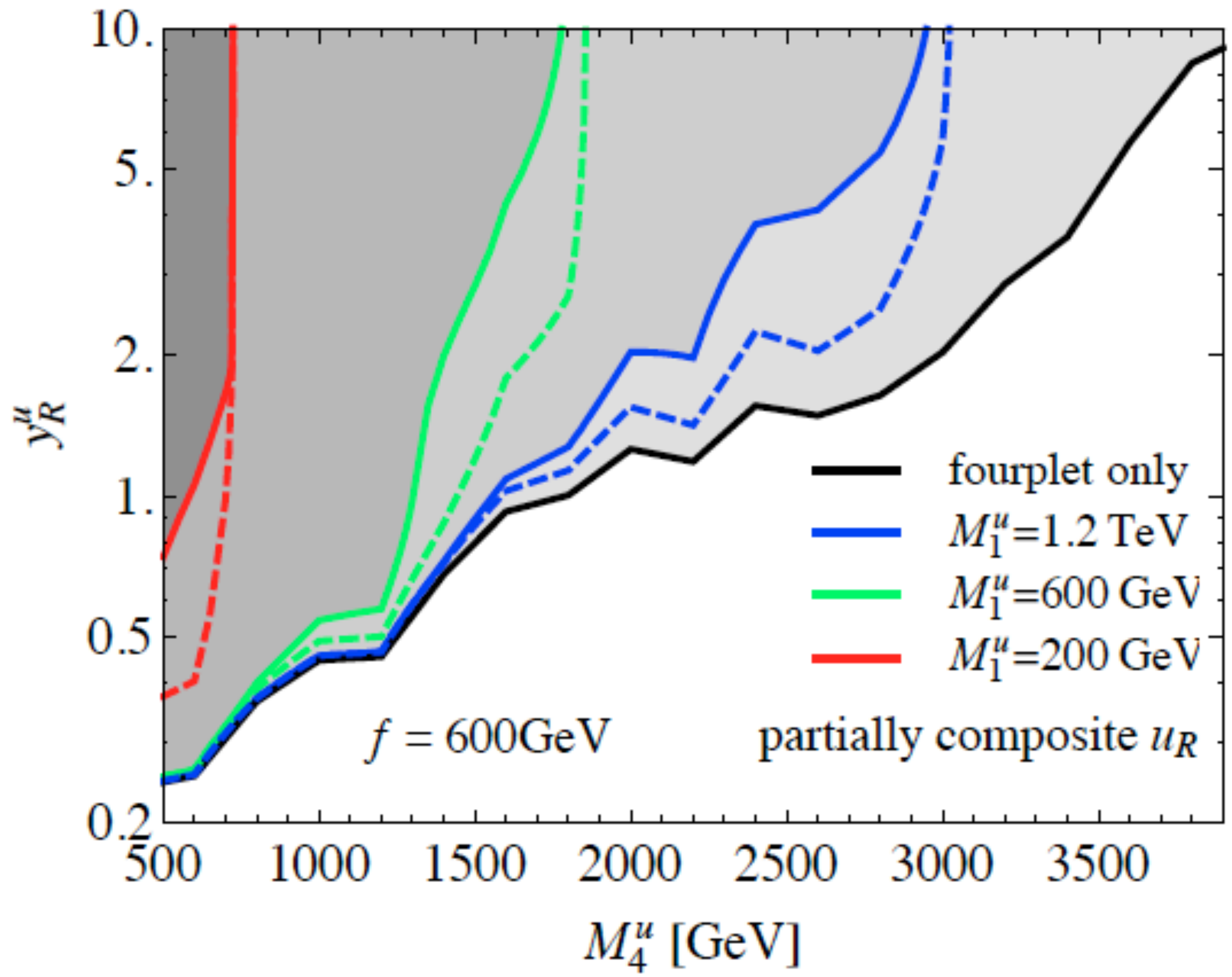
$$y_c \gg y_u$$



General 5-plet case: 4 + 1

Delaunay, Fraille, Flacke, SL, Panico, Perez `13

- 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.

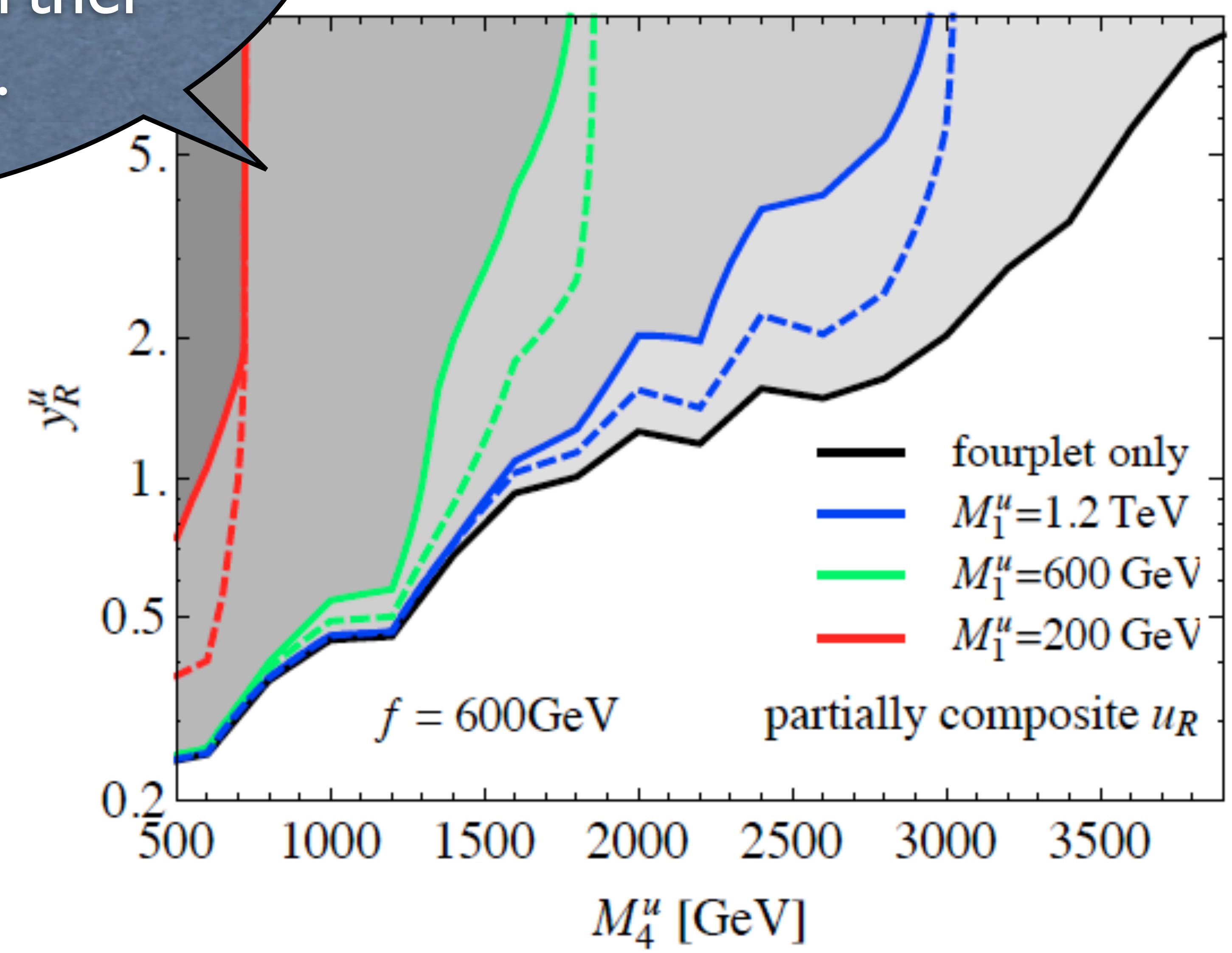


General 5-plet case: 4 + 1

Delaunay, Fraille, Flacke, SL, Panico, Perez `13

* Th... ...tion of $X_{5/3}$, D, U_1 is reduced.
...ises due to mixing of u_R with the fourplet,
...t.
...$_1$ is mostly singlet (for $M_1 \lesssim M_4$):
...scade decay via the U_1
...oss section gets reduced due to the

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).



Indirect constraints from dijet production Strong dynamics

Delaunay, Fraille, Flacke, SL, Panico, Perez `13

- new physics dijet sources are generically induced by unknown physics at the cut-off scale $\Lambda \sim 4\pi f$.

$$\frac{1}{2f^2}\left[(\bar{Q}\gamma_\mu Q)^2 + (\bar{\tilde{U}}\gamma_\mu \tilde{U})^2 + (\bar{u}_R\gamma_\mu u_R)^2\right]$$

- In the presence of mixings between the chiral quarks and the vector-like heavy resonances

$$\mathcal{L}_{4f} = \frac{c_{uu}}{2}\left(\bar{u}_R^{SM}\gamma_\mu u_R^{SM}\right)^2 + \frac{c_{cc}}{2}\left(\bar{c}_R^{SM}\gamma_\mu c_R^{SM}\right)^2 + c_{uc}\left(\bar{u}_R^{SM}\gamma^\mu u_R^{SM}\right)\left(\bar{c}_R^{SM}\gamma_\mu c_R^{SM}\right)$$

$\chi_j \equiv e^{2y_j}$ uniform for QCD background, while it's peacked at lower value for above operators

$\lvert c_{qq}\rvert^{-1/2} \gtrsim 2.2\,\text{TeV}$	for	$c_{qq} > 0$	from ATLAS
$\lvert c_{qq}\rvert^{-1/2} \gtrsim 2.1\,(3.0)\,\text{TeV}$	for	$c_{qq} > 0\,(c_{qq} < 0)$	from CMS

Indirect constraints from dijet production Strong dynamics

Fraille, Flacke, SL, Panico, Perez `13

* new phys ... ced by
unknown

* In th ... ks
and the

Neither ATLAS nor CMS has looked at this:
require it does not deviate
from SM expectations more than in the presence of

$$c_{qq}/2 \times (\bar{q}_L^{\rm SM}\gamma_\mu q_L^{\rm SM})^2,\ \text{with}\ |c_{qq}|^{-1/2} = 3\,\text{TeV}$$

=> indirect bound is not strong, smaller than
direct bound!

$$\mathcal{L}_{4f} = \frac{c_{uu}}{2}\left(\bar{u}_R^{\rm SM}\gamma_\mu u_R \ldots\right) \ldots \left(\bar{c}_R^{\rm SM}\gamma_\mu c_R^{\rm SM}\right)$$

$$\chi_j \equiv e^{2y_j}$$

uniform for QC... peacked
at lower value for above operators

$$|c_{qq}|^{-1/2} \gtrsim 2.2\,\text{TeV} \quad \text{for} \quad c_{qq} > 0$$ from ATLAS

$$|c_{qq}|^{-1/2} \gtrsim 2.1\,(3.0)\,\text{TeV} \quad \text{for} \quad c_{qq} > 0\,(c_{qq} < 0)$$ from CMS

Summary

- Composite Higgs model (with H as PGB) provides a viable solution to the hierarchy problem and generically predict partner states to the fermions

- The phenomenology of composite light quarks differs from top partner phenomenology

- Bound on charm partners is much weaker than that of up and top partners (charm tagging may help probing charm partners) => Flavorful Naturalness

- Dedicated analysis for boosted jets/VB/top is required

- Work in progress: Flavor physics and EWPT

Da Rold, Flacke, SL, Perez, Soreq, Weiler

Delaunay, Flacke, Han, Kim, SL

Backup Slide

CCWZ

Coleman, Wess, Zumino 69,
Callan, Coleman 69

- a prescription on how to express low energy L_{eff} for theories with SSB (G/H)
- classified all possible nonlinear transformation laws of fields in a neighborhood of the VEV
- every element of G can be expressed as $e^{\pi^{\hat{a}}T^{\hat{a}}}h'$

  broken generator of G ($T^{\hat{a}}$)

  unbroken element of H (h')

  => for any group element g of G, we can write $g\, e^{\pi^{\hat{a}}T^{\hat{a}}} = e^{\pi'^{\hat{a}}T^{\hat{a}}}h$

  with $\pi'^{\hat{a}}$ and $h \in H$
- with a field redefinition, one can find a "standard parametrization" $(\pi^{\hat{a}}, \psi^i)$ with the transformation law under $g \in G$

$$\pi^{\hat{a}} \to \pi'^{\hat{a}}, \qquad \psi^i \to D(h)^i_j \psi^j$$

linear representation of H ($D(h)$)

CCWZ

Coleman, Wess, Zumino 69,
Callan, Coleman 69

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...oken element of H

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... $\pi'^{\hat{a}}$ and $h \in H$

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$$\pi^{\hat{a}} \to \pi'^{\hat{a}}, \qquad \psi^{i} \to D(h)^{i}_{j}\psi^{j}$$

linear representation of H

span all possible nonlinear realizations of the group G: CCWZ classified all G-invariant Lagrangians constructed out of them (and their derivatives)

CCWZ

Coleman, Wess, Zumino 69,
Callan, Coleman 69

- Standard form of derivatives can be given in terms of d and e symbol:

$$U^{-1}\partial_\mu U = d_\mu^{\hat{a}} T^{\hat{a}} + e_\mu^a T^a$$

$U \equiv \exp(\pi^{\hat{a}} T^{\hat{a}})$

T^a → unbroken generator

generalized to continuous G transformation:

$$A_\mu = A_\mu^{\hat{a}} T^{\hat{a}} + A_\mu^a T^a \qquad U^{-1}(\partial_\mu - A_\mu)U = d_\mu^{\hat{a}} T^{\hat{a}} + e_\mu^a T^a$$

and $\nabla_\mu \psi^i \equiv \partial_\mu \psi^i + e_\mu^a \rho(T^a)^i_j \psi^j$ such that $\nabla_\mu \psi^i \to D(h)^i_j \nabla_\mu \psi^j$

- G invariant Lagrangian constructed out of $(\pi^{\hat{a}}, \psi^i)$, and their derivatives is equivalent to the one constructed out of $U,\ \psi^i,\ d_\mu,\ and\, \nabla_\mu \psi^i$

- For example, in SO(5)/SO(4),

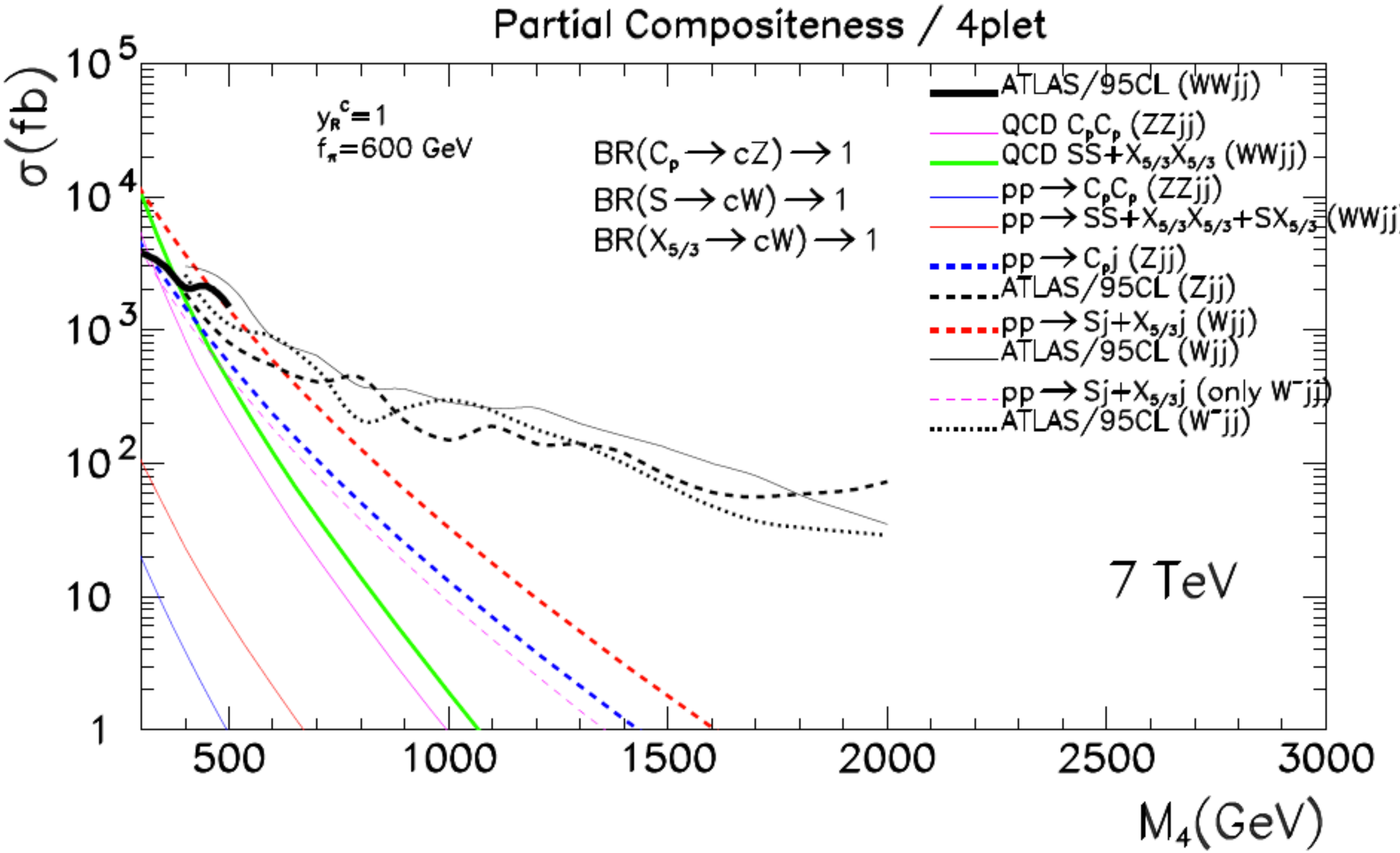
$$e_\mu^{1,2} = -\cos^2\left(\frac{\bar{h}}{2f}\right) g W_\mu^{1,2}, \quad e_\mu^3 = -\cos^2\left(\frac{\bar{h}}{2f}\right) g W_\mu^3 - \sin^2\left(\frac{\bar{h}}{2f}\right) g' B_\mu$$

$$e_\mu^{4,5} = -\sin^2\left(\frac{\bar{h}}{2f}\right) g W_\mu^{1,2}, \quad e_\mu^6 = -\cos^2\left(\frac{\bar{h}}{2f}\right) g' B_\mu - \sin^2\left(\frac{\bar{h}}{2f}\right) g W_\mu^3$$

$$d_\mu^{1,2} = -\sin(\bar{h}/f)\frac{g W_\mu^{1,2}}{\sqrt{2}}, \quad d_\mu^3 = \sin(\bar{h}/f)\frac{g' B_\mu - g W_\mu^3}{\sqrt{2}}, \quad d_\mu^4 = \frac{\sqrt{2}}{f}\partial_\mu h$$

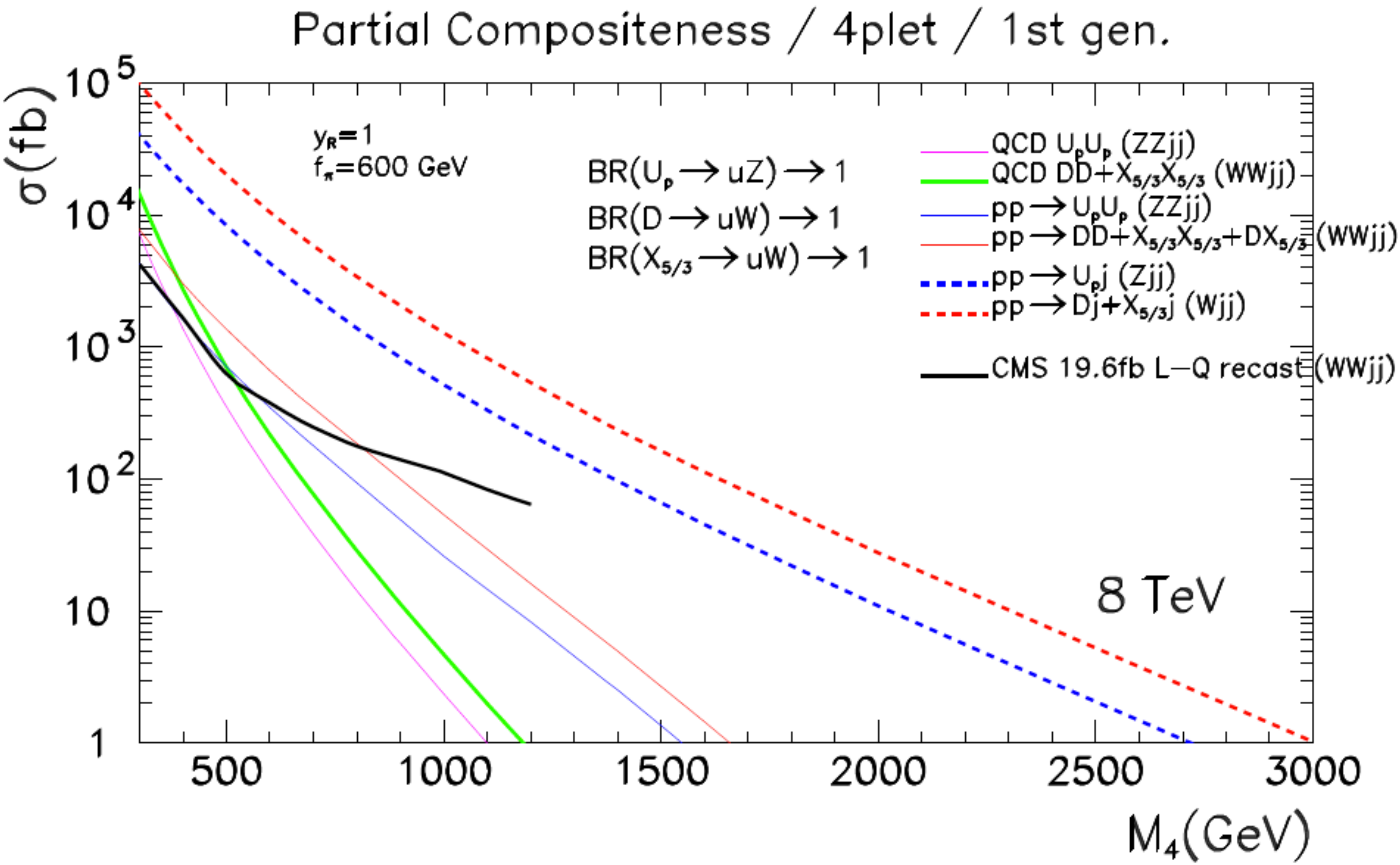
Bounds on c partner from 7TeV LHC

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]



✱ Fermion Lagrangian (with both up and down sector combined)

$$\mathcal{L} = \mathcal{L}_{comp} + \mathcal{L}_{el} + \mathcal{L}_{mix},$$

with

$$\begin{aligned}
\mathcal{L}_{comp} &= i\,\overline{Q^u}(D_\mu + ie_\mu)\gamma^\mu Q^u + i\,\overline{Q^d}(D_\mu + ie_\mu)\gamma^\mu Q^d + i\overline{\tilde{U}}\not{D}\tilde{U} + i\overline{\tilde{D}}\not{D}\tilde{D} \\
&\quad - M_4^u \overline{Q^u} Q^u - M_4^d \overline{Q^d} Q^d - M_1^u \overline{\tilde{U}}\tilde{U} - M_1^d \overline{\tilde{D}}\tilde{D} \\
&\quad + \left(ic^u \overline{Q^u}^i \gamma^\mu d^i_\mu \tilde{U} + ic^d \overline{Q^d}^i \gamma^\mu d^i_\mu \tilde{D} + \text{h.c.} \right), \\
\mathcal{L}_{el} &= i\,\overline{q}_L \not{D} q_L + i\,\overline{u}_R \not{D} u_R + i\,\overline{d}_R \not{D} d_R \\
\mathcal{L}_{mix} &= -y_L^u f \overline{q}^5_{L1} U_{gs} \psi^u_R - y_L^d f \overline{q}^5_{L2} U_{gs} \psi^d_R - y_R^u f \overline{u}^5_R U_{gs} \psi^u_L - y_R^d f \overline{d}^5_R U_{gs} \psi^d_L + \text{h.c.},
\end{aligned}$$

			$SO(5)$	$SO(4)$	$SU(2)_L$	$SU(2)_R$	$U(1)_X$	$U(1)_Y$	$U(1)_{em}$
q^5_{L1}			$\mathbf{5'}$	$\mathbf{4'}$	$\mathbf{2}$	**2'**	$2/3$	$1/6$	
		u_L					$2/3$	$1/6$	$2/3$
		d_L					$2/3$	$1/6$	$-1/3$
q^5_{L2}			$\mathbf{5'}$	$\mathbf{4'}$	$\mathbf{2}$	**2'**	$-1/3$	$1/6$	
		u_L					$-1/3$	$1/6$	$2/3$
		d_L					$-1/3$	$1/6$	$-1/3$
u_R			$\mathbf{5'}$	$\mathbf{1}$	-	-	$2/3$	$2/3$	$2/3$
d_R			$\mathbf{5'}$	$\mathbf{1}$	-	-	$-1/3$	$-1/3$	$-1/3$
ψ^U			$\mathbf{5}$				$2/3$		
	$\tilde{U}$			$\mathbf{1}$	-	-	$2/3$	$2/3$	$2/3$
	Q^u			$\mathbf{4}$			$2/3$		
		U^u					$2/3$	$1/6$	$2/3$
		D^u					$2/3$	$1/6$	$-1/3$
		$X^u_{5/3}$					$2/3$	$7/6$	$5/3$
		$X^u_{2/3}$					$2/3$	$7/6$	$2/3$
ψ^D			$\mathbf{5}$				$-1/3$		
	$\tilde{D}$			$\mathbf{1}$	-	-	$-1/3$	$-1/3$	$-1/3$
	Q^d			$\mathbf{4}$			$-1/3$		
		$X^d_{-1/3}$					$-1/3$	$-5/6$	$-1/3$
		$X^d_{-4/3}$					$-1/3$	$-5/6$	$-4/3$
		U^d					$-1/3$	$1/6$	$2/3$
		D^d					$-1/3$	$1/6$	$-1/3$