“Elusive” Compositeness

Giuliano Panico

IFAE, Barcelona

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Introduction

Introduction

Apart from the Higgs, no clear new physics effect has been discovered so far at the LHC

Is it possible that we missed something?

Consider this question in the context
of **“minimal” composite Higgs scenarios**

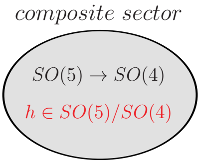
- for possible alternative constructions see talk by Chacko

Introduction: The general structure

Higgs as a Goldstone boson of a spontaneously broken symmetry

Minimal realizations:

$$SO(5) \to SO(4)$$



Introduction: The general structure

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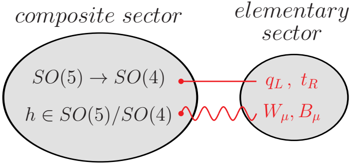


The other **SM states are external "elementary" fields** weakly coupled to the composite dynamics

The **coupling** is an essential ingredient:

- ➢ generates the couplings to the Higgs
- ➢ induces a small breaking of the Goldstone symmetry
  - ➠ generation of the Higgs potential

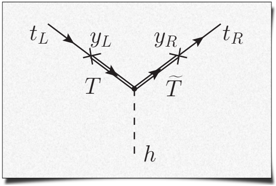
Introduction: Partial compositeness

The largest mixing comes from the top sector

$$\mathcal{L}_{mix} = y_L\, f\, \overline{q}_L \psi_R + y_R\, f\, \bar{t}_R \psi_L + \text{h.c.}$$

The mass eigenstates are an admixture of elementary and composite states

$$|SM_n\rangle = \cos\phi_n |elem_n\rangle + \sin\phi_n |comp_n\rangle$$



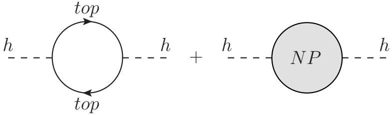
The **top partners** control the Higgs dynamics:

- ➢ generate the dominant contribution to the Higgs potential
- ➢ stabilize the Higgs mass

Introduction: A lesson from naturalness

The Hierarchy problem gives us an estimate of the scale at which top partners should appear

$$\delta m_h^2\big|_{1-loop} \sim$$



$$\sim -\frac{y_{top}^2}{8\pi^2} M_T^2 \lesssim \text{TeV}$$

minimizing the amount of tuning requires **light states**

$$\Delta \gtrsim \left(\frac{M_T}{400\ \text{GeV}}\right)^2$$

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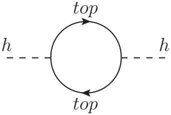

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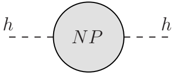

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Natural SUSY:	$\Leftrightarrow$	**Natural Composite Higgs**:
light stops		light top partners

Introduction: Top partners phenomenology

Top partners are a perfect target to probe natural composite Higgs scenarios

- ➢ naturally light
- ➢ charged under QCD ➠ large cross section
- ➢ large mixing with top quark ➠ distinctive signals

Introduction: Top partners phenomenology

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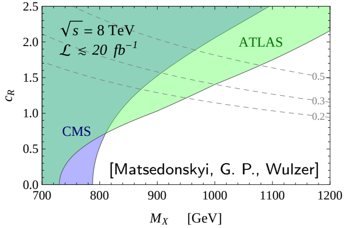
Top partners are **non-elusive!**

Introduction: Top partners phenomenology

Top partners are a perfe
Higgs scenarios

- ➢ naturally light
- ➢ charged under QCD
- ➢ large mixing with top

Already some bounds: $M \gtrsim 800$ GeV



Top partners are **non-elusive!**

Introduction

The composite Higgs scenario predicts many other BSM states

Is it possible that we **missed**
some other (relatively) **light resonance**?

Explore more carefully the dynamics of the composite sector

- Flavor structure
- Vector resonances

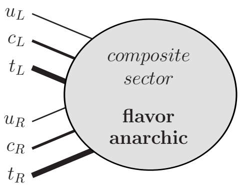
The flavor structure

Flavor anarchy

Anarchic scenarios

[Grossmann, Neubert; Gergetta, Pomarol; Huber, Shafi]

- flavor **anarchic** strong dynamics
- **hierarchical** elementary–composite mixings



Large mixing **only** with third generation

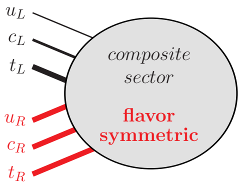
➢ light quarks are almost elementary
(small impact on collider phenomenology)

➢ **all fermionic resonances** are analogous to **top partners**

Flavor universal scenarios

[Cacciapaglia et al.; Barbieri et al.; Delaunay et al.; Redi, Weiler]

- **flavor symmetric** strong dynamics (or alignment)
- large **universal** mixing for right-handed quarks
- **hierarchical** mixing for left-handed quarks



Resonances are mixed with **only one generation**

➢ each generation is associated to a set of partners

➢ **light-generations partners** have a peculiar phenomenology

Phenomenology of light-generation partners

- Light-generations partners have sizable mixing only with the right-handed quarks
- The mixing with the left-handed quarks is negligible

Custodial symmetry is (nearly) **unbroken** for the light-generations partners and determines their properties

[Delaunay, Flacke, Gonzales, Lee, G. P., Perez]

Common multiplets:

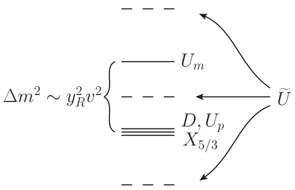
$$Q = \begin{bmatrix} U & X_{5/3} \\ D & X_{2/3} \end{bmatrix} \in \mathbf{4}_{SO(4)} \quad \Rightarrow \quad \begin{cases} \{D, U_p, X_{5/3}\} & \textit{triplet} \\ \qquad U_m & \textit{singlet} \end{cases}$$

$$\widetilde{U} \in \mathbf{1}_{SO(4)} \qquad\qquad \textit{singlet}$$

(where $U_{p,m} \equiv (U \pm X_{2/3})/\sqrt{2}$)

Phenomenology of light-generation partners

The mass spectrum and the couplings of the partners are fixed by the symmetry structure



- **triplet** coupled to the SM quarks through the **gauge bosons**

$$\mathcal{L}_{triplet} \simeq \frac{g}{2}\frac{y_R v}{M_4}\left(\overline{D}\,\not{W}^- - \overline{X}_{5/3}\not{W}^+ + \frac{1}{c_w}\overline{U}_p\,\not{Z}\right)u_R + h.c.$$

- **singlets** coupled to the SM quarks through the **Higgs**

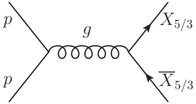
$$\mathcal{L}_{sing} \simeq y_R\,\overline{U}_m\,h\,u_R + h.c.$$

$$\mathcal{L}_{sing} \simeq y_R\frac{v}{f}\,\overline{\widetilde{U}}\,h\,u_R + h.c.$$

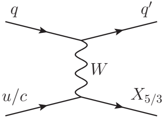
Triplet phenomenology

Production:

- pair production (mainly QCD)

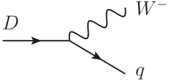


- EW single production (additional forward jet)

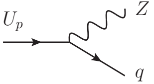


Decay:

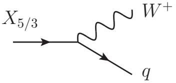
- two-body decays into **EW boson plus jet**



$D \to W^- j$



$U_p \to Zj$



$X_{5/3} \to W^+ j$

Triplet phenomenology

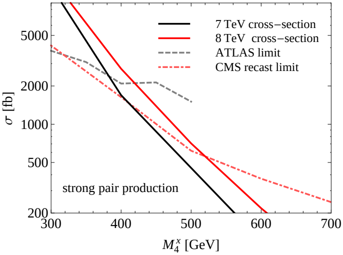
QCD pair production can be used to derive **model-independent bounds** on the triplet states

- bounds valid for first and second generation partners

Strongest bounds from recast of leptoquark CMS search

- final state: $\mu^+\mu^- + jets$
- bound: $\mathbf{M_4 \gtrsim 530}$ **GeV**
- not optimized for partners, improvement possible

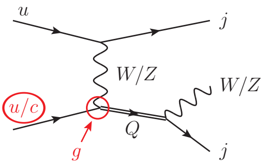
[Delaunay, Flacke, et al.]



Triplet phenomenology

Single production can lead
to large cross sections

$$pp \to Qj \to W/Zjj$$



Important features:

- Cross section crucially depends on the gauge coupling with SM fermions

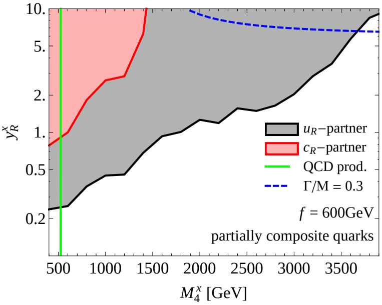
$$g_{WuX} = -g_{WuD} = -c_w\, g_{ZuU_p} \simeq \frac{g}{2}\frac{y_R v}{M_4}$$

  - in flavor-universal models $y_R \gtrsim 1$ needed for top Yukawa

- Big difference between first and second generation
  - large cross section for up partners
  - suppression for charm partners (from c PDF)

Triplet phenomenology

Strong bounds for the first-generation partners

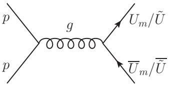


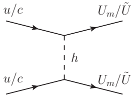
- In universal models with $SU(3)$ flavor symmetry the partners are excluded up to $\mathbf{M}_\psi \simeq \mathbf{1.7\ TeV}$
- If universality is relaxed (eg. with alignment) **light partners for the second generation** are still allowed

Singlet phenomenology

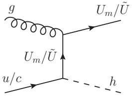
Production:

- pair production (mainly QCD)



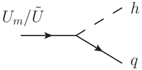


- single production in association with the Higgs



Decay:

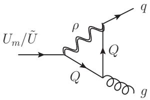
- **main decay** into **Higgs and jet**



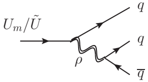
$$\widetilde{U} \to hj$$

- subleading channels into multi-jets

[Redi, Sanz, De Vries, Weiler]



$$\widetilde{U} \to jj$$



$$\widetilde{U} \to jjj$$

Singlet phenomenology

Best channels to look for singlets:

$$hhj, \quad hWjj, \quad hZjj, \quad hhjj$$

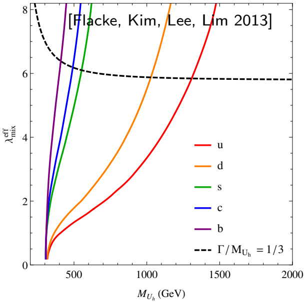
➢ so far no dedicated experimental analysis

Searches into multi-jets are difficult and disfavored by the small branching fractions

Singlet phenomenology

Bounds on the singlets can be derived by a recast of ATLAS **single Higgs search** in the $h \to \gamma\gamma$ channel.

[Flacke, Kim, Lee, Lim 2013]



- Universal bound from QCD pair production: $\mathbf{M_1 \gtrsim 310}$ **GeV**
- For large compositeness ($y_R \gtrsim 1$) stronger bounds for first generation partners due to enhanced EW production

Light partners are still **allowed!**

Phenomenology of vector resonances

Phenomenology of vector resonances

Vector resonances with SM quantum numbers are an essential part of the composite Higgs scenarios

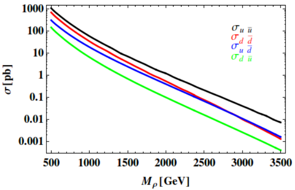
- only mild naturalness pressure
- EW precision data disfavor light EW resonances

Mass gap expected between the fermionic and vector states

$$M_\rho \sim 2 \text{ TeV} \quad > \quad M_\psi \sim 1 \text{ TeV}$$

Phenomenology of vector resonances

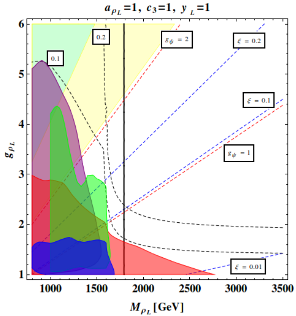
Vector resonances are usually produced in DY with sizable cross section



Already important bounds from the 8 TeV LHC

[Pappadopulo, Thamm et al.; Greco, Liu]

$$\rho^+ \to t\bar{b}$$
$$\rho^+ \to \bar{l}\nu$$
$$\rho^+ \to WZ$$



[Greco, Liu]

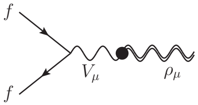
Phenomenology of vector resonances

Several effects can make the vector resonances **“elusive”**

- ❖ reduction of the couplings to quarks
- ❖ presence of light fermionic resonances

Phenomenology of vector resonances

The coupling to the light SM fermions is mainly generated by the mixing of the vector resonance with the SM gauge fields



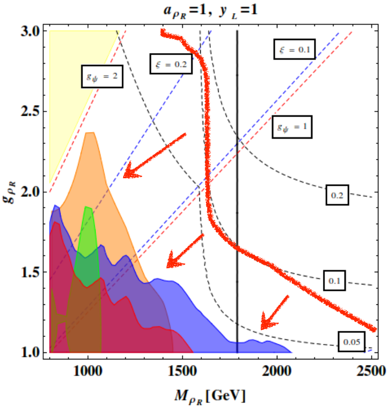
The size of the mixing depends on the resonance quantum numbers

$\rho_{SU(2)_L}$	$g_{\rho ff} \sim g^2/g_\rho$	$\rho^+_{(2,2)}$	$g_{\rho ff} \sim g^2/g_\rho\,(v/f)$
$\rho^0_{SU(2)_R}$	$g_{\rho ff} \sim g'^2/g_\rho$	$\rho_{U(1)_X}$	$g_{\rho ff} \sim g'^2/g_\rho$
$\rho^+_{SU(2)_R}$	$g_{\rho ff} \sim g'^2/g_\rho\,(v/f)^2$		

- sizable reductions are present for some states

Phenomenology of vector resonances

The reduction in the DY production cross section strongly affects the bounds

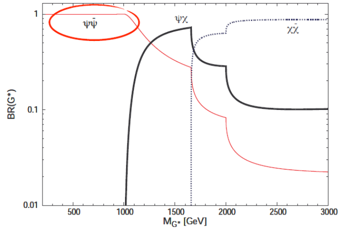


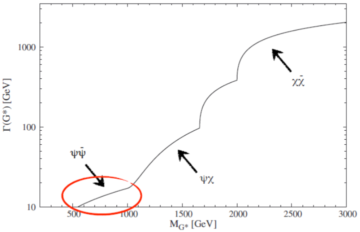
[Greco, Liu]

Phenomenology of vector resonances

The vector resonances have **large couplings** to the composite fermions

➢ decay into composite states is favored (if kinematically allowed) [Bini, Contino, Vignaroli; Chala, Juknevich et al.]





- if the fermionic states are "heavy" the direct decay into SM states has a sizable BR (eg. $\rho \to t\bar{t}$)
- the vector resonance is narrow

Phenomenology of vector resonances

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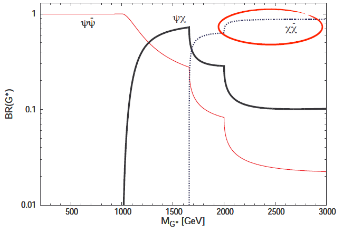
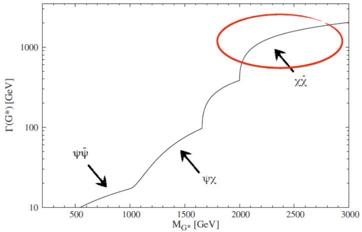
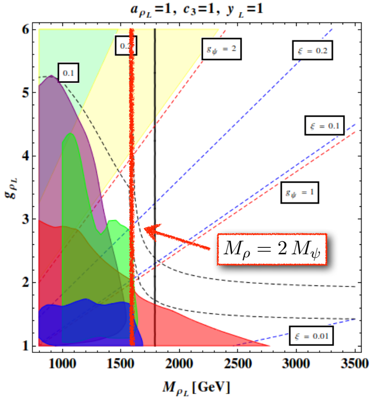




- light partners allow the decay into pairs of resonances
  ➠ direct decay into SM suppressed
- the vector resonance is broad

Phenomenology of vector resonances

Search much harder if decay into pair of composite states is allowed



[Greco, Liu]

- Improvement possible if the presence of fermionic resonances is taken into account [Chala, Juknevich et al.]

Conclusions

Conclusions

In "minimal" composite Higgs scenarios **light top partners** are needed for naturalness

➢ Perfect target for LHC searches

- large production cross section
- "easy" signatures (strong mixing to the top)

Already some non-trivial bounds from the $8\ \mathrm{TeV}$ LHC:

$$M_\psi \gtrsim 800\ \mathrm{GeV}$$

Conclusions

Many other composite states are also present that could be **more difficult to detect**

❖ **Partners of the light-generations quarks**

- predicted in models with flavor symmetries
- small production cross section (eg. charm partners)
- peculiar collider signatures (eg. $SO(4)$ singlets decaying through the Higgs)

❖ **Vector resonances**

- can be heavier than top partners (less naturalness pressure)
- can have suppressed DY production
- escape present searches if decay into pairs of fermion resonances is allowed