Collider phenomenology of Composite Higgs models

Giuliano Panico

IFAE, Barcelona

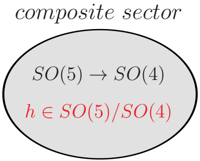
‘The Zurich Phenomenology Workshop 2015’

Zurich University – 9 January 2015

Introduction

Introduction: The general structure

Higgs as a Goldstone boson of
a spontaneously broken symmetry

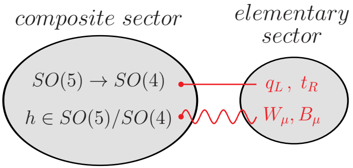


Minimal realizations:

$$\mathrm{SO}(5) \to \mathrm{SO}(4)$$

Introduction: The general structure

Higgs as a Goldstone boson of a spontaneously broken symmetry



Minimal realizations:

$$\mathrm{SO}(5) \to \mathrm{SO}(4)$$

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

The **mixing** 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

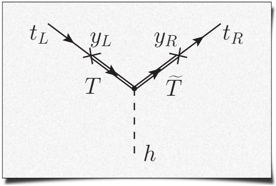
The largest mixing comes from the top sector

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

(f denotes the scale of spontaneous $\mathrm{SO}(5)$ breaking)

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:

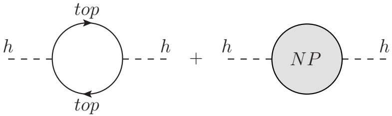
➢ generate the dominant contribution to the Higgs potential

➢ 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

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



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

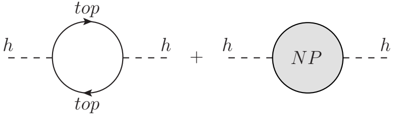
minimizing the amount of tuning requires **light states**

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

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**

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

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

The composite Higgs scenario predicts many other BSM states

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

Introduction

The composite Higgs scenario predicts many other BSM states

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

- In this talk: focus on the **flavor structure**
  - discuss possible set-ups
  - analyze collider phenomenology

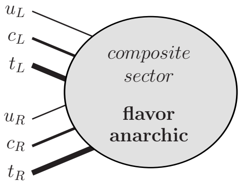
The flavor structure

Flavor anarchy

Anarchic scenarios

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

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



Large mixing **only** with third generation

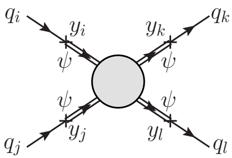
➢ light quarks are almost elementary
(small impact on collider phenomenology)

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

Flavor anarchy

FCNC among light quarks are **naturally suppressed** by the small compositeness (RS-GIM mechanism)

$$c^{ijkl} \sim \frac{1}{f^2}\frac{y_i}{M_\psi}\frac{y_j}{M_\psi}\frac{y_k}{M_\psi}\frac{y_l}{M_\psi}$$



Residual tension with data:

- Kaon system (ϵ_k): $M_\psi \gtrsim 10\ \mathrm{TeV}$
- Neutron EDM: $M_\psi \gtrsim 4\ \mathrm{TeV}$

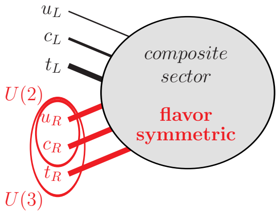
➢ Some protection mechanism or accidental cancellations seem necessary

Flavor universality

Flavor universal scenarios

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

- **flavor symmetric** strong dynamics (or alignment)
- large **universal** mixing with one quark chirality
- **hierarchical** mixing with the other chirality



The dominant mixings are flavor diagonal

➢ each generation is associated to a set of partners

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

Flavor universality

Models with $\mathrm{U}(3)$ symmetry **naturally implement MFV**

A **strong suppression of flavor-violation** for the light quarks is still present in the $\mathrm{U}(2)$ models

Bounds are somewhat milder than in the anarchic case

[Barbieri, Buttazzo et al. '12]

$\mathrm{U}(3)_L$	$M_\psi \gtrsim 5$ TeV
$\mathrm{U}(3)_R$	$M_\psi \gtrsim 3$ TeV
$\mathrm{U}(2)_L$	$M_\psi \gtrsim 0.6$ TeV
$\mathrm{U}(2)_R$	$M_\psi \gtrsim 1$ TeV

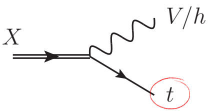
Collider phenomenology:

Top partners

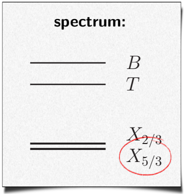
Top Partners phenomenology

Top partners fill **extended multiplets** as a consequence of the custodial invariance $\mathrm{SO}(4) \simeq \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$

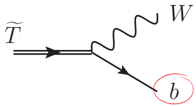
- **Fourplet** of custodial $\mathrm{SO}(4)$: $\begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix}$



  - sizable coupling to the **top**
  - **light exotic** state

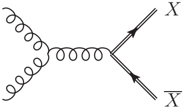


- **Singlet** of custodial $\mathrm{SO}(4)$: $\widetilde{T}$



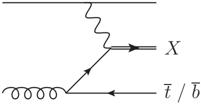
  - sizable coupling to the **bottom**

Top Partners phenomenology



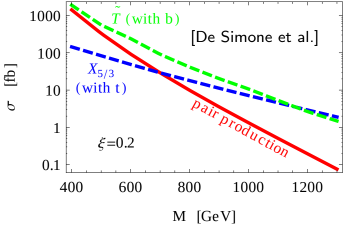
QCD **pair production**

- model independent
- relevant at low mass



Single production with t or b

- model dependent
- potentially relevant at high masses
- production with b dominant when allowed



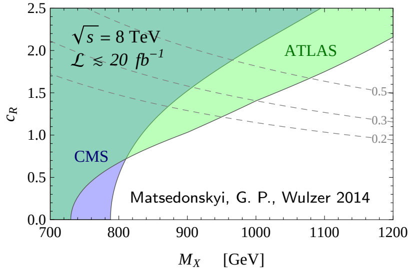
Top Partners phenomenology: the $X_{5/3}$

Current bounds on the **fourplet** are based on **pair production**
[CMS-B2G-12-012, ATLAS-CONF-2013-051]

➢ **model-independent** bound: $M_X \gtrsim 770\ \mathrm{GeV}$

Including **single production** can improve the bounds

➢ depends on single-production coupling: $c_R \frac{g_w}{2} \overline{X}_{5/3} \not{W} t_R$



Top Partners phenomenology: the $\widetilde{T}$

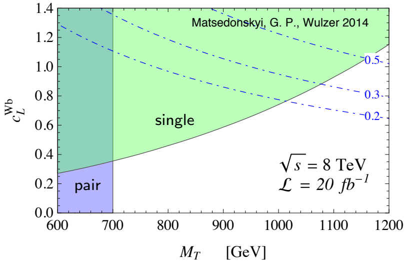
Similar bounds for the **singlet**

[ATLAS-CONF-2013-051, ATLAS-CONF-2014-036, CMS B2G-12-015]

➢ **model-independent** bound: $M_{\widetilde{T}} \gtrsim 700 \text{ GeV}$

Only estimate of the impact of single production

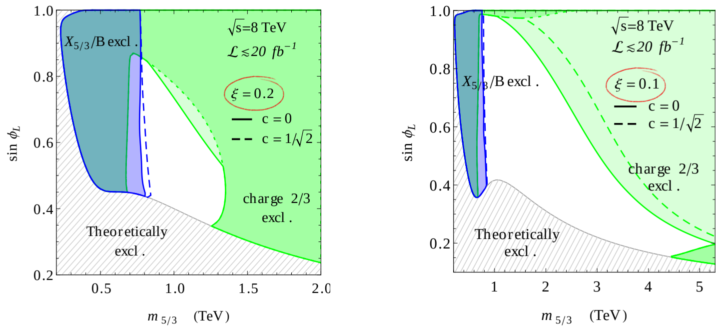
[Ortiz, Ferrando, Kar, Spannowsky 2014]



Top Partners phenomenology

The **direct bounds** are still **mild** in explicit models

- ➢ the configurations favored by the indirect bounds ($\xi \equiv v^2/f^2 \lesssim 0.1$) are only marginally tested
- ➢ no strong bound on minimal fine-tuning

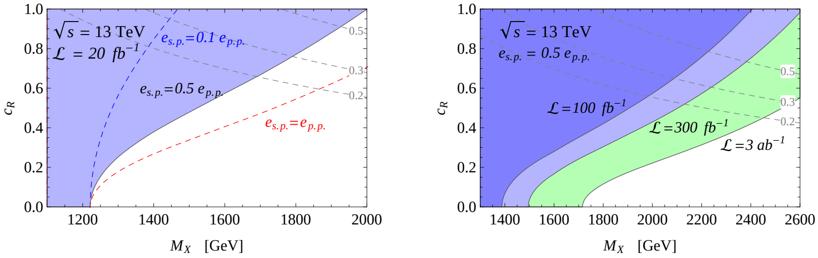


Top Partners phenomenology

Significant improvement in the next runs

At the end of the LHC we can test a minimal tuning

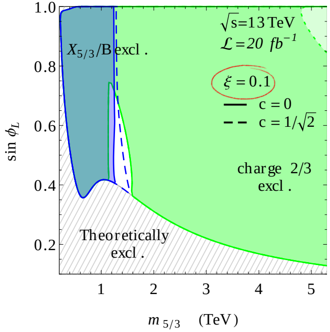
$$\frac{1}{\Delta} \lesssim \left(\frac{400 \text{ GeV}}{M_\psi \sim 2 \text{ TeV}} \right)^2 \sim 4\%$$



Top Partners phenomenology

The bounds in explicit models become better than the LEP one

➢ we can probe $\xi \simeq 0.05$



Collider phenomenology:

Light-generation partners

Phenomenology of light-generation partners

Common features:

- ➢ large mixing with light quarks
- ➢ single production enhanced by light-quark pdf's
- ➢ final states with gauge bosons/Higgs and jets

Two main classes of models:

- L-handed compositeness
- R-handed compositeness

Phenomenology of light-generation partners

Common features:

- ➢ large mixing with light quarks
- ➢ single production enhanced by light-quark pdf's
- ➢ final states with gauge bosons/Higgs and jets

Two main classes of models:

- L-handed compositeness
- R-handed compositeness

Light-generation partners: R-handed compositeness

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

Custodial symmetry $\mathrm{SO}(3)_c$ is (nearly) **unbroken** for the light-generations partners and determines their properties

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

Common multiplets:

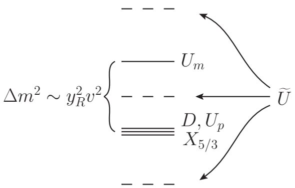
$$Q = \begin{bmatrix} U & X_{5/3} \\ D & X_{2/3} \end{bmatrix} \in \mathbf{4}_{SO(4)} \;\Rightarrow\; \begin{cases} \{D, U_p, X_{5/3}\} & \textit{triplet} \\ U_m & \textit{singlet} \end{cases}$$

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

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

Light-generation partners: R-handed compositeness

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**

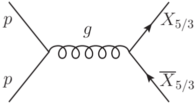
$$\mathcal{L}_{sing} \simeq y_R\,\overline{U}_m\,h\,u_R + h.c.$$

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

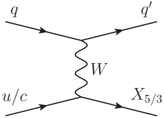
Triplet phenomenology

Production:

- pair production (mainly QCD)

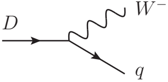


- EW single production (additional forward jet)

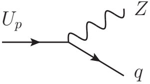


Decay:

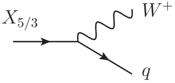
- two-body decays into **EW boson plus jet**



$$D \to W^- j$$

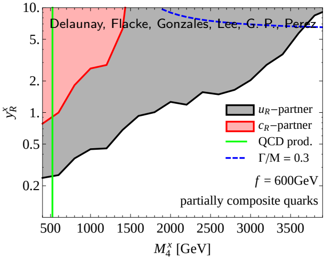


$$U_p \to Z j$$



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

Triplet phenomenology



Mild model-independent bound from **QCD pair production**:

$$M_\psi \gtrsim 530 \text{ GeV}$$

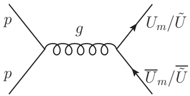
Stronger bounds from **single production**:

- In universal $\mathrm{U}(3)_R$ models a large compositeness is required to reproduce the top mass ($y_R \gtrsim 1$)
  - all partners excluded up to $M_\psi \simeq 2 \text{ TeV}$
- In universal $\mathrm{U}(2)_R$ models mild bounds if $y_R \lesssim 0.3$
- If universality is relaxed (eg. with alignment) **light charm partners** are allowed even for large compositeness

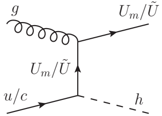
Singlet phenomenology

Production:

- pair production (mainly QCD)

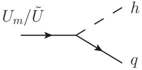


- single production in association with the Higgs



Decay:

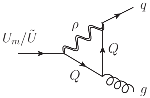
- **main decay** into **Higgs and jet**



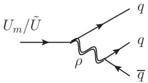
$$\widetilde{U} \to hj$$

- 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:

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

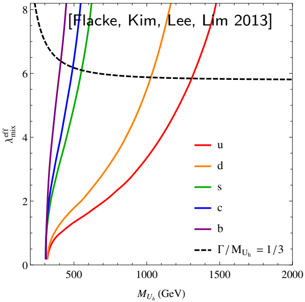
➢ so far no dedicated experimental analysis

- 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: $M_\psi \gtrsim 310$ GeV
- For large compositeness ($y_R \gtrsim 1$) stronger bounds for first generation partners due to enhanced EW production

Light partners are still **allowed!**

Conclusions

Conclusions

In **“minimal” composite Higgs scenarios** different realizations of the flavor structure are possible:

- flavor anarchy
- flavor universality (flavor-symmetric composite sector)

Light top partners are needed in all **natural** models

➢ Perfect target for LHC searches

- can test amount of tuning
- “easy” signatures (strong mixing to the top)
- mild bound so far, final reach $M_\psi \sim 2\ \mathrm{TeV}$

Conclusions

In models bases on flavor symmetries the **partners of the light-generation quarks** have a peculiar phenomenology

- large couplings only to the light quarks
- in some scenarios very light partners ($M_\psi \sim 300\ \mathrm{GeV}$) are still allowed