EFT for a Composite Goldstone Higgs

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Introduction

Introduction

In the quest for a fundamental description of the EW dynamics we have to cope with a serious obstruction: the **Naturalness Problem**

The LHC will finally tell us if the EW symmetry breaking dynamics is "Natural" or fine-tuned.

In this talk: focus on a class of **Natural** BSM theories, the **composite Higgs** scenarios

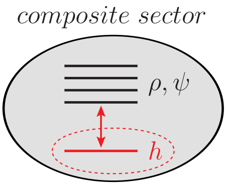
- ❖ general structure of the models
- ❖ description in the EFT framework
- ❖ impact of the LHC searches

Introduction: Composite Higgs in a nutshell

In composite Higgs models the EW dynamics is linked to a **new strongly-coupled sector**

[Georgi, Kaplan; . . . ; Contino, Nomura, Pomarol;
Agashe, Contino, Pomarol; Contino, Da Rold, Pomarol; . . .]
[For reviews see: Contino, 1005.4269; G. P., Wulzer, 1506.01961]

Main features:



❖ resonances at the TeV scale

- Fermionic resonances
- Spin-1 resonances
  (KK-gluons and EW resonances)

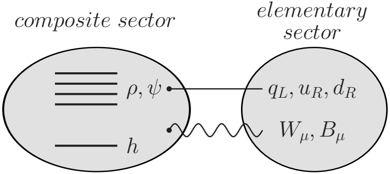
❖ Higgs doublet as a composite Goldstone

- symmetry structure ensures a mass gap
  between the resonances and the Higgs

Introduction: Composite Higgs in a nutshell

Elementary sector:

- SM states: gauge fields, elementary fermions



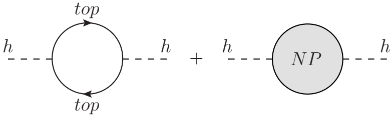
The SM states are **coupled** to the composite dynamics

- small (explicit) breaking of the Goldstone symmetry
  - ➢ the Higgs gets a potential and a mass
  - ➢ EW symmetry breaking is triggered

Introduction

The top sector and the "**top partners**" control the generation of the Higgs potential and the stability of the Higgs mass

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



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

➢ **Light top partners** are required to minimize the fine-tuning ($M_\psi \lesssim 1$ TeV)

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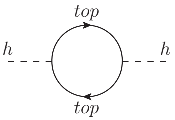

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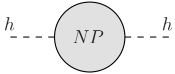


$\sim -\frac{y_{top}^2}{8\pi^2} M_\psi^2 \lesssim \mathrm{TeV}$

➢ **Light top partners** are required to minimize the fine-tuning ($M_\psi \lesssim 1$ TeV)

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

Introduction: Main phenomenological features

Several features can be used to probe the composite Higgs scenario at hadron colliders

- Modifications of the **Higgs couplings**
  - induced by the non-linear Goldstone structure
- **Fermionic resonances** (in particular top partners)
- **Vector resonances**

How to describe a composite Higgs: The EFT approach

General parametrizations can be obtained using an **effective field theory approach** [G. P., Wulzer; Matsedonskyi, G. P., Wulzer]

Basic assumptions:

- **Goldstone structure** giving rise to the Higgs doublet
- **calculability** of the main observables
  (eg. Higgs potential, EW parameters)

This minimal set of assumptions ensures that the effective theory describes a **generic composite Higgs scenario**

How to describe a composite Higgs: The EFT approach

Main **advantages** of the effective theory approach:

- simplicity
- model independence
  (useful to derive robust predictions)
- important tool for collider phenomenology
  (only relevant resonances are included, easy to implement in an event generator)

Applications of the EFT formalism

- Higgs couplings

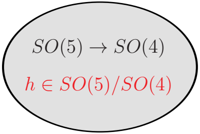
The Higgs sector

To generate the Higgs we assume that the composite dynamics has a spontaneously broken global invariance

Minimal models are based on the symmetry breaking pattern

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

composite sector



- The Higgs is described by a **non-linear σ-model**

$$\mathcal{L} = \frac{f^2}{2} \sum_i \partial_\mu U^t_{5i} \, \partial^\mu U_{i5} \qquad\qquad U = \exp\left[i \, h_i T^i\right]$$

- one free parameter: $f \equiv$ Goldstone decay constant

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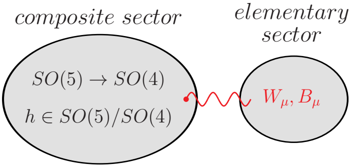

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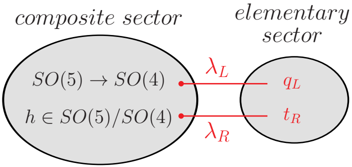
- **SM gauge fields** coupled by gauging $SU(2)_L \times U(1)_Y \subset SO(5)$

$$\partial_\mu U \rightsquigarrow D_\mu U = \partial_\mu U - i\, g\, A_\mu U$$

The SM fermions

Following the **Partial Compositeness** assumption the **SM fermions** are **linearly** coupled to the composite dynamics

$$\mathcal{L} \supset \lambda_L \bar{q}_L \mathcal{O}_L + \lambda_R \bar{t}_R \mathcal{O}_R + \text{h.c.}$$



The Yukawa couplings are fixed by the representation of the composite operators

- eg. in the MCHM_5 set-up $\mathcal{O}_{L,R} \in \mathbf{5}$ of $\mathrm{SO}(5)$

$$\mathcal{L}_{\text{Yuk}} = c_t \lambda_L \lambda_R (\bar{q}_L^{\mathbf{5}} U)_5 (U^t t_R^{\mathbf{5}})_5 \quad \Rightarrow \quad c_t \lambda_L \lambda_R \sin\left(\frac{2h}{f}\right) \bar{t}_L t_R$$

Higgs couplings

The effective formalism allows the direct extraction of the **modifications** of the Higgs couplings

$$\mathcal{L} = m_W^2 W_\mu^+ W^{-\mu} \left(1 + 2\, k_V \frac{h}{v}\right) - \sum_\psi m_\psi \overline{\psi}\psi \left(1 + k_F \frac{h}{v}\right) + h.c.$$

Higgs couplings

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❖ The size of the corrections controlled by $\xi \equiv v^2/f^2$

- The couplings to the gauge fields only depend on the Goldstone structure

$$\text{MCHM}_4,\ \text{MCHM}_5 \qquad \kappa_V = \sqrt{1-\xi}$$

- The couplings to the fermions have more model dependence

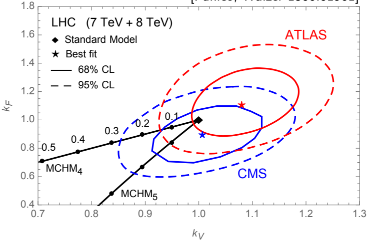
$$\text{MCHM}_4 \qquad k_F = \sqrt{1-\xi}$$

$$\text{MCHM}_5 \qquad k_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$

Higgs couplings

Measuring κ_V gives a **model-independent** bound on ξ

[Panico, Wulzer 1506.01961]



➢ Current bound driven by ATLAS [ATLAS Collab. 1509.00672]

MCHM$_5$	$\xi < 0.1$	$(\xi < 0.17$ exp.$)$	@ 95% C.L.
MCHM$_4$	$\xi < 0.12$	$(\xi < 0.23$ exp.$)$	

- Note: much stronger than expected due to shift in central value $(\kappa_V \simeq 1.08)$

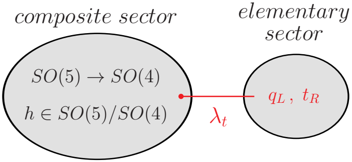
➢ Next runs not expected to improve significantly the bound
(unless the central value will still be shifted)

Applications of the EFT formalism

- Top partners

Top partners and Naturalness

Main breaking of the Goldstone symmetry from the mixing of the top to the composite sector



Due to the mixing the SM fields are an admixture of elementary states and **composite partners**

$$|\mathrm{SM}_n\rangle = \cos\varphi_n\ \ |elem_n\rangle + \sin\varphi_n\ \ |comp_n\rangle$$

The **top partners** control the Higgs dynamics

- ➢ generate the dominant contribution to the Higgs potential
- ➢ stabilize the Higgs mass and the EW scale

Top partners and Naturalness

The general form of the Higgs potential is

$$V[h] = -\alpha f^2 \sin^2(h/f) + \beta f^2 \sin^4(h/f)$$

Conditions from the Higgs mass and f

$$\alpha = \alpha_{needed} \simeq \frac{m_h^2}{4} \qquad \beta = \beta_{needed} = \frac{\alpha_{needed}}{2\xi} \gg \alpha_{needed}$$

Largest cancellation in α ➠ **estimate of the tuning**

$$\Delta \sim \frac{\alpha_{expected}}{\alpha_{needed}} \sim \lambda_t^2 \left(\frac{M_\psi}{450\ \mathrm{GeV}}\right)^2$$

Top partners at the LHC

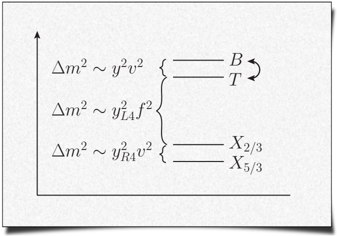
The effective field theory approach is useful to parametrize the **phenomenology of top partners** [De Simone, Matsedonskyi, Rattazzi, Wulzer; Matsedonskyi, G. P., Wulzer]

The **spectrum** and the **couplings** of the resonances are fixed by the Goldstone symmetry

❖ A typical example:

$$\psi_4 = (\mathbf{2},\mathbf{2})_{\mathrm{SO}(4)} = \begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix} \qquad \psi_1 = (\mathbf{1},\mathbf{1})_{\mathrm{SO}(4)} = \begin{pmatrix} \widetilde{T} \end{pmatrix}$$

- The partners fill complete $\mathrm{SO}(4)$ multiplets
- New colored fermions strongly coupled to the top
- Exotic resonances ($X_{5/3}$) give distinctive signals



Top partners at the LHC: Current bounds

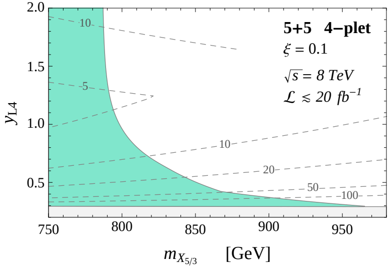
Current exclusions are mainly based on **pair production**

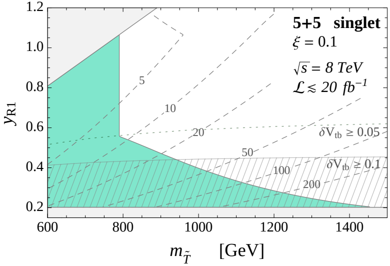
[CMS-B2G-12-012, ATLAS Coll. 1505.04306]

- **model-independent** bound $M_\psi \gtrsim 800$ GeV

Including **single production** can improve the bounds

[Matsedonskyi, G. P., Wulzer in preparation]



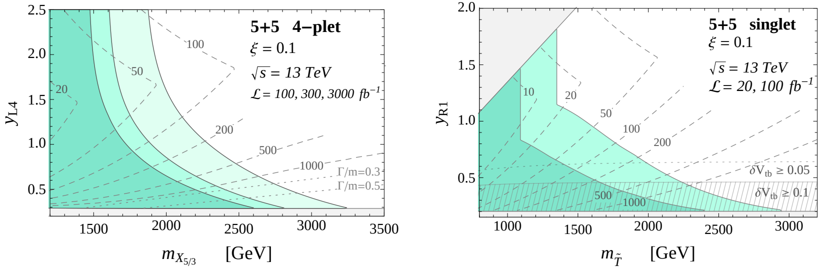


regions with **minimal tuning** $\Delta \sim 1/\xi \sim 10$ are **still allowed**

Top partners at the LHC: High-luminosity LHC

Top partners up to $M_\psi \simeq 3\ \mathrm{TeV}$ testable at the high-luminosity LHC

[Matsedonskyi, G. P., Wulzer in preparation]



➢ completely probing parameter space with $\Delta \lesssim 50$

Top partners at the LHC: Minimal models

In a large class of minimal models (eg. $\mathrm{MCHM}_{4,5,10}$) the mass of the lightest top partner is connected to the compositeness scale

[Matsedonskyi, G. P., Wulzer; Marzocca, Serone, Shu; Pomarol, Riva]

$$\frac{m_H}{m_{top}} \gtrsim \frac{\sqrt{3}}{\pi}\frac{M_\psi}{f} \quad \Rightarrow \quad \xi \lesssim \left(\frac{500\ \mathrm{GeV}}{M_\psi}\right)^2$$

➢ convert constraints on top partners into bounds on ξ

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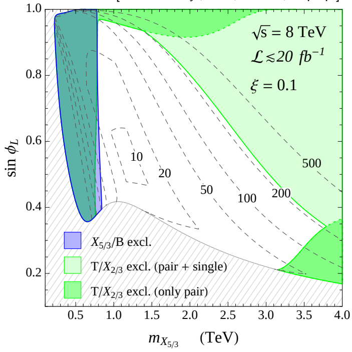
➢ convert constraints on top partners into bounds on ξ

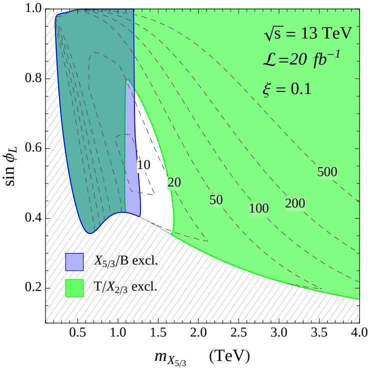
Current exclusions:

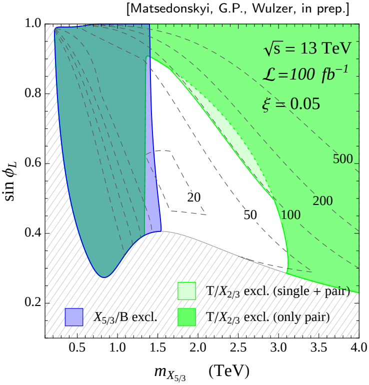
- large part of the parameter space still viable
- natural configurations ($\Delta \sim 10$) not yet tested
- single production can improve significantly the bounds

[Matsedonskyi, G.P., Wulzer, in prep.]



Top partners at the LHC: Minimal models





- models with $\xi = 0.1$ will be completely tested in the first stages of LHC Run 2
- **final reach** with high-luminosity upgrade $\boldsymbol{\xi \simeq 0.05}$

Conclusions

Conclusions

❖ The **EFT framework** offers a simple way to parametrize a composite Goldstone Higgs

➢ model-independent

➢ useful to compare with the experiments

❖ General predictions can be easily tested at the **LHC**

- precision **Higgs coupling** measurements
- searches for **resonances**

➢ current bounds: $\xi = v^2/f^2 \lesssim 0.1 \qquad M_\psi \gtrsim 800\ \mathrm{GeV}$

➢ **natural** configurations with minimal tuning ($\Delta \sim 10$) **still viable**

➢ future runs will probe configurations up to a $few\,\%$ tuning

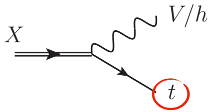
Backup material

Top partners

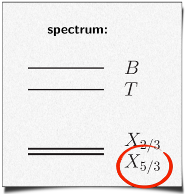
Top Partners phenomenology

Main couplings of the top parters (relevant for single production and decays)

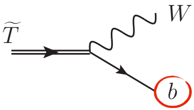
- **Fourplet** of custodial $\mathrm{SO}(4)$: $\begin{pmatrix} T & X_{5/3} \\ B & X_{2/3} \end{pmatrix}$



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

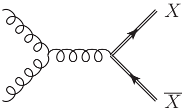


- **Singlet** of custodial $\mathrm{SO}(4)$: $\widetilde{T}$



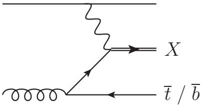
  - sizable coupling to the **bottom**

Top Partners phenomenology



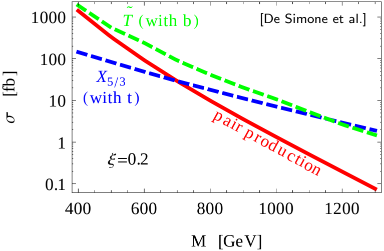
QCD **pair production**

- 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



Vector resonances

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:

$$\widehat{S} \simeq \frac{m_W^2}{M_\rho^2} \lesssim 2.5 \times 10^{-3} \quad \Rightarrow \quad M_\rho \gtrsim 1.6 \text{ TeV}$$

⬇

Mass gap expected between the fermionic and vector states

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

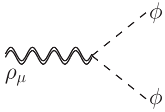
EW vector resonances: Phenomenology

Phenomenology mainly controlled by three couplings:

- coupling to **longitudinal EW bosons**

$$g_{\rho VV} \sim g_\rho$$

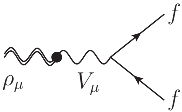
➠ relevant at **large** strong-sector coupling



- coupling to **SM fermions**

$$g_{\rho ff} \sim g^2/g_\rho$$

➠ relevant at **small** strong-sector coupling

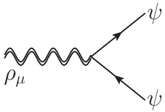


- coupling to **composite fermions**

$$g_{\rho\psi\psi} \sim g_\rho$$

➠ relevant at **large** strong-sector coupling

➠ important if decay channel is open ($M_\rho > 2M_\psi$)

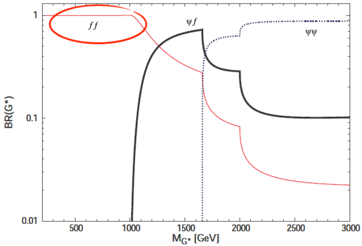


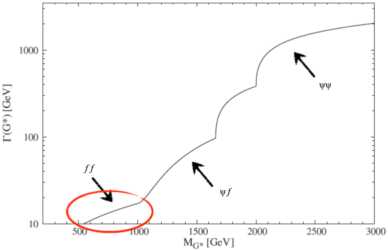
EW vector resonances: Phenomenology

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" $(M_\psi > M_\rho/2)$ the direct decay into SM states has a sizable BR
- the vector resonance is **narrow**

EW vector resonances: Phenomenology

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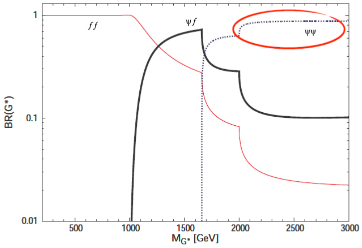
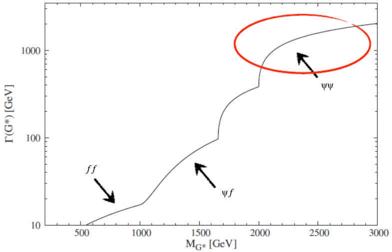




- light partners allow the decay into pairs of resonances

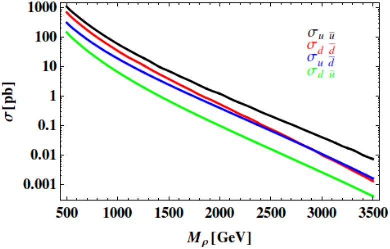
  ➠ direct decay into SM suppressed

- the vector resonance is **broad**

EW vector resonances: Current bounds

Sizable DY production

[Greco, Liu]



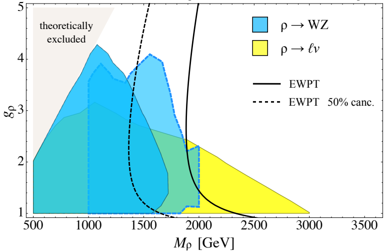
Exclusions from the 8 TeV LHC

$$\rho^+ \to l\nu$$

$$\rho^+ \to WZ$$

- ➢ current bounds comparable with constraints from EW data

[Pappadopulo, Thamm et al.]



EW vector resonances: Full LHC reach

- The high-luminosity LHC program can reach masses $M_\rho \lesssim 7 \text{ TeV}$
- Complementary bounds from precision Higgs measurements:

$$M_\rho \simeq g_\rho f$$

➢ constraints on ξ translate into constraints on the vector resonances

[Thamm, Torre, Wulzer]