"Higgs and Beyond" – PITT-PACC, Pittsburgh – 5 December 2015

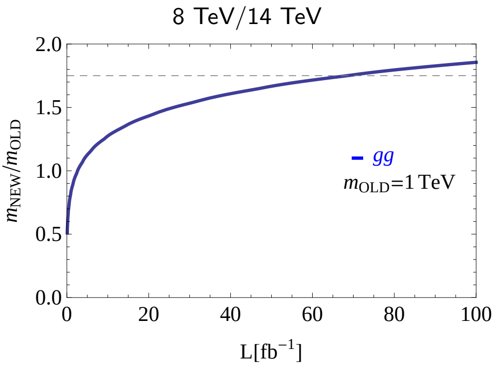
Composite Higgs "Signatures"

Andrea Tesi
University of Chicago

What Next?

Fingers crossed!

Early stages of Run2 crucial for direct searches



Slower improvements after 20-30/fb

Many motivated “benchmarks”

A long wish list, especially colored* particles

- Stops
- Gluinos
- Top partners
- Vector resonances

  ...

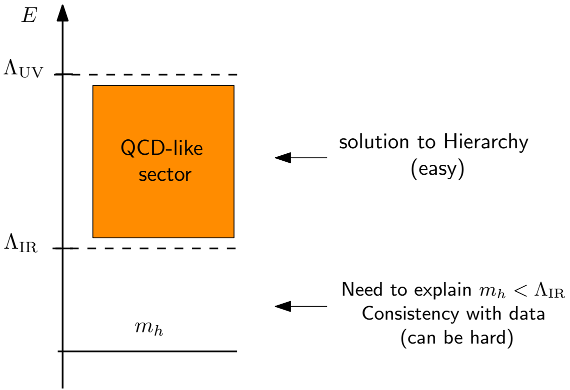
  ...

Motivated by
the Hierarchy Problem

Composite Higgs: generalities

Agashe, Contino, Pomarol
Giudice, Grojean, Pomarol, Rattazzi
Panico, Wulzer

Compositeness as a solution



Composite Higgs

Higgs doublet is an approximate Goldstone Boson

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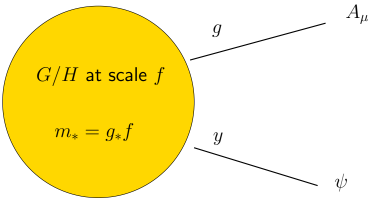

Higgs (and W/Z goldstones) are part of the strong sector

The external fields are the SM quarks and (transverse) gauge bosons

SO(5)/SO(4)$\supset$ **4** minimal case

Agashe, Contino, Pomarol

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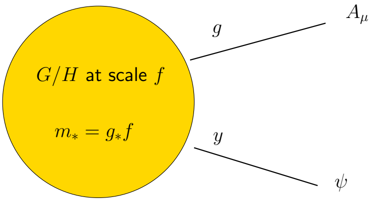

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Agashe, Contino, Pomarol

Challenges

- Achieve correct EWSB (g, y break the shift symmetry)
- Consistency with low energy data (Higgs couplings, EWPO)
- Find the resonances!

Partial compositeness

Composite sector has resonances coupled to SM
Spectrum is SO(4) invariant

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Vector resonances — ρ
Coupled to SM mostly via a universal $W - \rho$ mixing*

photon-rho mixing in QCD

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Fermion resonances — Ψ
Assume linear mixing of SM fields to composite fermions

$$y_L f \bar{q}_L \Psi_q + y_R f \bar{u}_R \Psi_u + h.c.$$

Kaplan '90

- Ψ are colored, $m_\psi \sim g_\psi f$
- SM Yukawas are $y \sim \sin_L g_\psi \sin_R$

A very rich phenomenology (maybe too rich)

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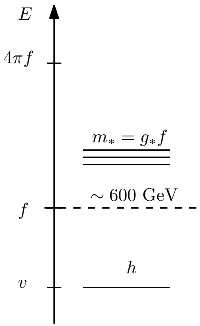
A light Higgs

- Loop induced EWSB

$$\mu^2 \simeq \frac{1}{16\pi^2}(\frac{9}{4}g^2 - N_c y_t^2)m_*^2$$



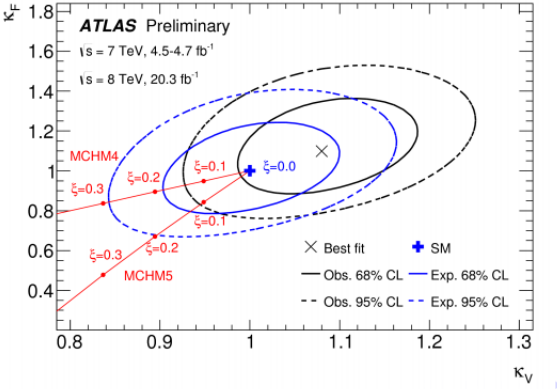
Higgs couplings modification

- Sizeable deviations v^2/f^2
  - mostly set by SO(5)/SO(4) structure
  - non-universal shift in fermions

New particles nearby

- Weakly coupled to elementary particles
- Sizeable coupling to W_L, Z_L, h, t

Higgs couplings

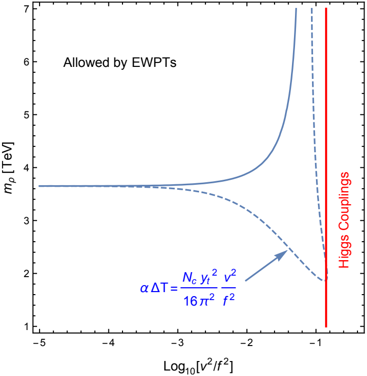


- $f \gtrsim 600\,\mathrm{GeV}$. Strongest bound from ATLAS (shifted best fit).
- Other indirect bounds on f (model dependent and avoidable)

Electroweak data

Beware of tree-level and log-enhanced contributions

- $\hat{S} \sim m_W^2/m_\rho^2$ (exchange of vector resonances)
- $\hat{S}, \hat{T} \sim \alpha v^2/f^2 \log$ (modified Higgs couplings)



It is possible to relax the bounds with "UV" corrections

Grojean, Matsedonskyi, Panico; Contino, Salvarezza

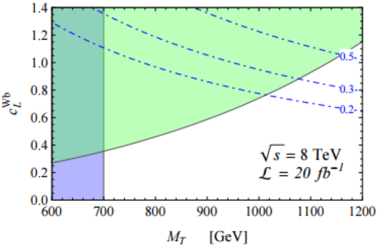
Top partners

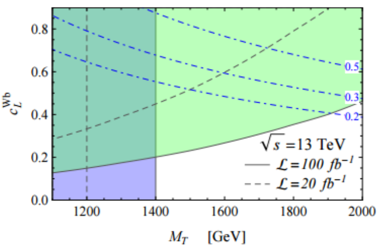
Production modes

- QCD, pair production
- $Vb(t)$ fusion, single production

Decay modes

- Depend on the EW charges
- $th, V_L b, V_L t$



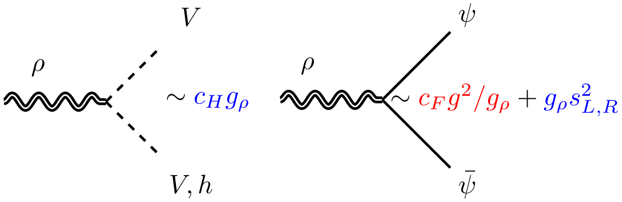


Matsedonskyi, Panico, Wulzer

Spin-1 resonances

In SO(5)/SO(4) we expect a **6** of SO(4)

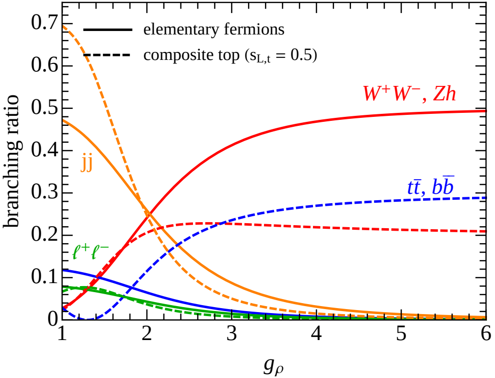
$$\mathbf{6} \rightarrow \mathbf{3}_0 + \mathbf{1}_0 + \mathbf{1}_\pm$$



Strong coupling to diboson — Weak coupling to light fermions

Production rate is model-independent $\sim g^2/g_\rho^4$

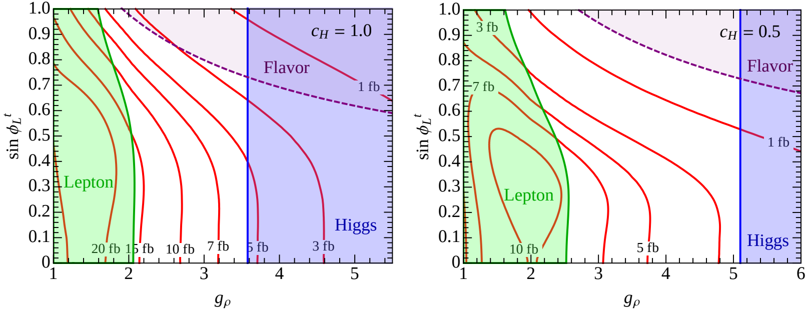
Spin-1 resonances: decay modes



- $V_L V_L$ and $V_L h$ related by eq. theorem
- Branching ratios of ρ^0 and $\rho^\pm$ correlated
- Interplay between s_L^t and g_ρ

Spin-1 resonances: the ATLAS diboson excess

$2\,\mathrm{TeV} \simeq g_\rho f$ in $VV(JJ)$, requires $\sigma \times \mathrm{BR} \simeq 5 - 10$ fb



[Low, T, Wang; arXiv:1507.07557]

- Natural explanation in composite higgs model
- $g_\rho \simeq 3$ fits the excess

Dobrescu, Liu; Franzosi, Sannino; Thamm, Torre, Wulzer; Lane Prichett; Kim, Kong, Lee, Park; Bian, Liu , Shu; Anchordoqui, Antoniadis, Goldberg, Huang; Lust, Taylor; Chao; Omura, Tobe, Tsumura; Sanz; Fukano, Matsuzaki , Yamawaki; Allanach, Gripaios, Sutherland; Carmona, Delgado, Quiros , Santiago...

Higgs mass and tuning

Higgs Potential

$$y_L f \bar{q}_L U \Psi_q + y_R f \bar{u}_R U \Psi_u + \mathcal{L}_{\rm comp}(\Psi, U, m_\psi, g_\psi), \quad U = \exp(ih/fT^4)$$

$$V(h) \simeq \frac{N_c}{16\pi^2}\left[a(yf)^2 m_\psi^2 F_1(h/f) + b(yf)^4 F_2(h/f)\right]$$

Giudice, Grojean, Pomarol, Rattazzi

- $F_{1,2}$ trigonometric function
- a, b O(1) coefficients

Focussing on top sector $y_t \sim y^2 \frac{f}{m_\psi}$

$$V \simeq \frac{N_c}{16\pi^2} m_\Psi^4 \left[a \frac{y_t f}{m_\Psi} F_1 + b(\frac{y_t f}{m_\Psi})^2 F_2\right]$$

$V(h)$ highly sensitive to m_ψ

Higgs mass and tuning

$$m_h^2 \simeq b\,\frac{N_c y_t^2 v^2}{2\pi^2}\,\frac{m_\Psi^2}{f^2}, \qquad \Delta \simeq \frac{m_\Psi^2}{m_t^2} = \frac{f^2}{v^2}\,\frac{m_\Psi^2}{y_t^2 f^2}$$

- Light top partners for the Higgs mass

  [Contino, Da Rold, Pomarol; Matsedonsky, Panico, Wulzer; Pomarol, Riva; Marzocca, Serone, Shu; Redi, T;...]

- Tuning grows with m_Ψ^2

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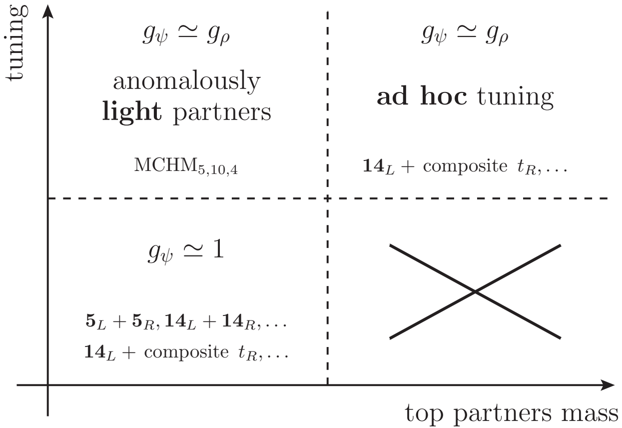
Within minimal models tuning always larger than f^2/v^2
if top partners are not found

Can we have heavy top partners and small tuning?

Panico, Redi, T, Wulzer



What if LHC14 finds nothing?

Twin Higgs mechanism

Chacko, Goh, Harnik '05

Lots of recent activity
Craig, Howe
Burdman et al
Geller, Telem
Craig, Katz, Strassler, Sundrum
Barbieri, Greco, Rattazzi, Wulzer

see Curtin, Strassler

The basic idea

The cancellation of the quadratic divergence can be achieved without colored particles

Chacko, Goh, Harnik

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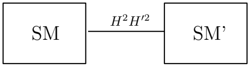
The cancellation of the quadratic divergence can be achieved
without colored particles

Chacko, Goh, Harnik

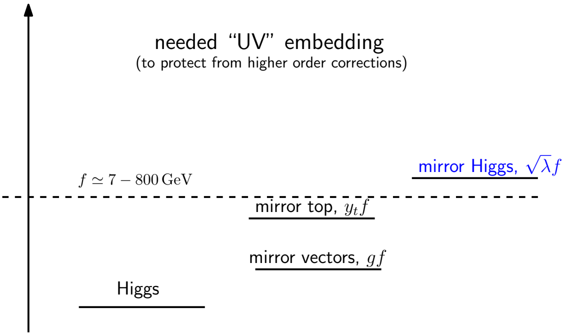
The actual realization

- Mirror copy of SM
- Assume an SO(8)/SO(7) accidental symmetry
- $\lambda(H^2 + H'^2 - f^2)^2$
- 7GBs - 3W - 3W' $=$ one physical pGB, h
- A radial mode $m_\sigma \sim \sqrt{\lambda} f$
- Gauge and Yukawas break global symmetry
- Add source of Z_2 breaking

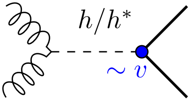


Chacko, Goh, Harnik

The low energy spectrum



All the partners are total singlets: difficult to produce and detect. Twin mechanism makes the naturalness-partners invisible.



pair production

The size of λ distinguishes between two scenarios

$$\lambda$$

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If $\lambda \sim O(1)$

radial mode close to f

look for the singlet!

w/ Dario Buttazzo and Filippo Sala

see also **[Craig, Katz, Strassler, Sundrum]**

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If $\lambda \sim O(16\pi^2)$
radial mode decoupled
Composite Twin Higgs
w/ Matthew Low and LianTao Wang
[Geller, Telem; Barbieri, Greco, Rattazzi, Wulzer]

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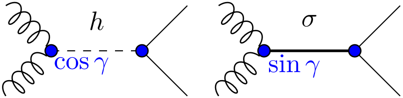
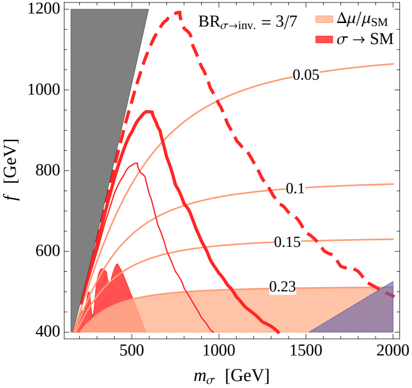
Look for the twin Higgs!

$$\sin^2\gamma \simeq \frac{v^2}{f^2} + O(1/m_\sigma^2)$$

Higgs couplings & Direct Searches



[Buttazzo, Sala, T; arXiv:1505.05488]



If Twin Higgs is weakly coupled, the twin Higgs (singlet) could be visible

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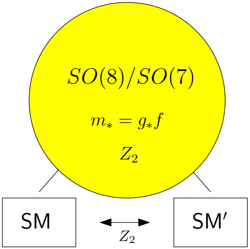
Natural embedding in the Composite Higgs

see also Geller, Telem; Barbieri, Greco, Rattazzi, Wulzer



In the gauge sector

$$A_\mu = \left(\begin{array}{c|c} g \cdot SO(4) & 0 \\ \hline 0 & g' \cdot SO(4)' \end{array} \right)$$

$$\Sigma = \left(0, 0, 0, s_h, 0, 0, 0, c_h \right)$$

- Inside SO(8) gauge two copies of SM
- Add mirror QCD

Three "sectors"

elementary fields — ele. mirror fields — composite resonances (Z_2)

Z_2 breaking and minimal tuning

Let us suppose that exists a model with Z_2-breaking

$$\underbrace{\frac{N_c y_t^4 f^4}{64\pi^2}\left[c_h^4 \log\left(\frac{2\Lambda^2}{y_t^2 f^2 c_h^2}\right) + s_h^4 \log\left(\frac{2\Lambda^2}{y_t^2 f^2 s_h^2}\right)\right]}_{Z_2-\text{symmetric, no quadratic corrections}} + \underbrace{\frac{N_c y_t^4 f^4}{32\pi^2} b\, s_h^2}_{\text{usually quadratic corrections}}$$

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Then we have

- Minimal tuning f^2/v^2 (for $b \sim O(1)$)
- Higgs mass in the right ballpark

$$m_h^2 \simeq \frac{N_c}{\pi^2}\frac{m_t^2 m_{t'}^2}{f^2}\left[\log\left(\frac{\Lambda^2}{m_{t'} m_t}\right) + \cdots\right]$$

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need a model where (numerically) Z_2- breaking is not too large

Z_2 breaking in the gauge sector

$$V(h) \simeq -\frac{N_c}{16\pi^2} a y_t^4 f^4 s_h^2 c_h^2 + b\, \frac{9(g^2 - g'^2)}{64\pi^2} f^2 m_\rho^2 s_h^2$$

- Breaking from $g \neq g'$
- Only log-sensitivity to m_ψ
- Power sensitivity to m_ρ

$$m_h^2 \simeq a \frac{N_c y_t^4}{2\pi^2} v^2, \qquad \Delta \simeq \frac{f^2}{v^2} \left(\frac{g_\rho}{4}\right)^2$$

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Vector resonances below the cutoff $g_\rho \sim 4$

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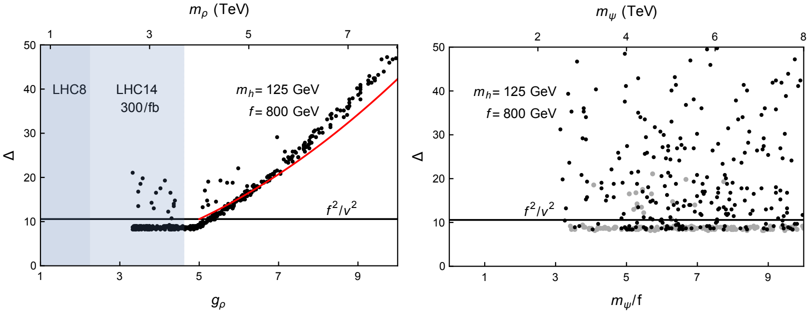
Vector resonances below the cutoff $g_\rho \sim 4$
Breaking in hyper-charge sector, $g_\rho \to 8 - 10$

see also Barbieri, Greco, Rattazzi, Wulzer

Higgs mass

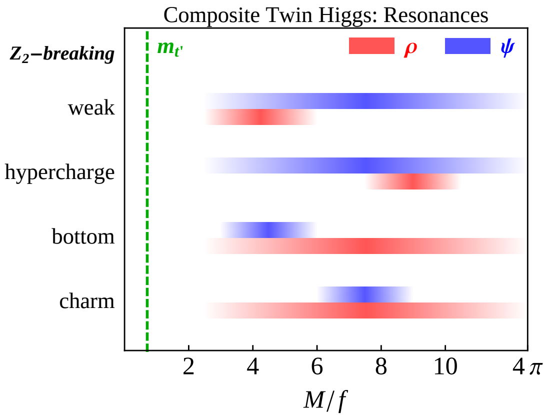
$$m_h^2 \simeq \frac{N_c y_t^4 v^2}{4\pi^2}\left[\log\left(\frac{m_1^2}{m_{t'} m_t}\right) + F(\{m_\Psi\})\right]$$



- Tuning grows with $g_\rho \gtrsim 5$ (red line)
- No evident correlation with m_ψ (average of mass parameters)
- Some "natural" regions will remain unexplored

There are scenarios where colored resonances can remain hidden at LHC

[Low, T, Wang; arXiv:1501.07890]



With tuning just driven by Higgs coupling measurements, f^2/v^2

Conclusions

At LHC

Composite Higgs offers a rich pheno

At LHC

Composite Higgs offers a rich pheno

After LHC

Composite Twin Higgs can come to rescue