Gearing up for LHC13 – GGI, Firenze – 24 September 2015

(Composite) Twin Higgs

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Thanks to

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(UChicago / IAS)

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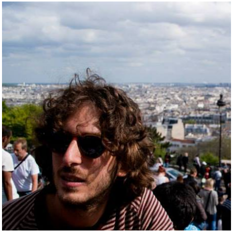
Thanks to



Dario Buttazzo

(TUM Munich)

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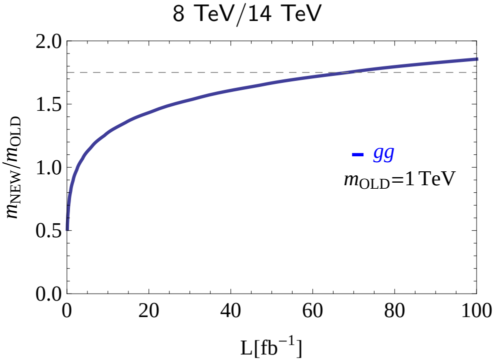
(Paris, Saclay)

What Next?

Look for new states!

Early stages of the LHC Run-II crucial for direct searches



Slower improvements after 20-30/fb

Many motivated "benchmarks"

A long wish list, especially colored particles

- Stops
- Gluinos
- Top partners

  ...

  ...

What if LHC14 finds nothing?

The usual story

If new symmetries stabilize the weak scale

$$\delta m_h^2 \simeq C \frac{g_{SM}^2}{16\pi^2} M_{NP}^2 + \cdots$$

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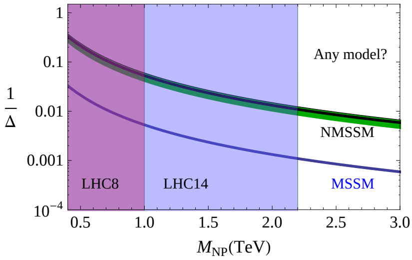
LHC8 measured a lot of tuning



The "problem" is that M_{NP} is "colored"

Twin Higgs mechanism

The basic idea

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

Chacko, Goh, Harnik

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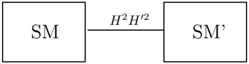
The actual realization

- Mirror copy of SM
- Assume a 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



Chacko, Goh, Harnik

Cancellation of quadratic corrections

Thanks to Z_2, accidental SO(8)-invariance at $O(g_{\rm SM}^2)$

$$V \supset C\frac{g_{SM}^2}{32\pi^2}\Lambda^2(H^2 + H'^2)$$

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Higher corrections in $g_{\rm SM}$ break SO(8)

$$V_{O(g_{\rm SM}^4)} \supset C'\frac{g_{\rm SM}^4}{32\pi^2}(H^4\log\frac{\Lambda^2}{g_{\rm SM}^2|H|^2}+H'^4\log\frac{\Lambda^2}{g_{\rm SM}^2|H'|^2})$$

Putting all together

$$V(H,H') = \lambda(H^2 + H'^2 - f^2)^2 + \delta(H^4 + H'^4)$$

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$$\langle H \rangle = v \ll \langle H' \rangle \sim f$$

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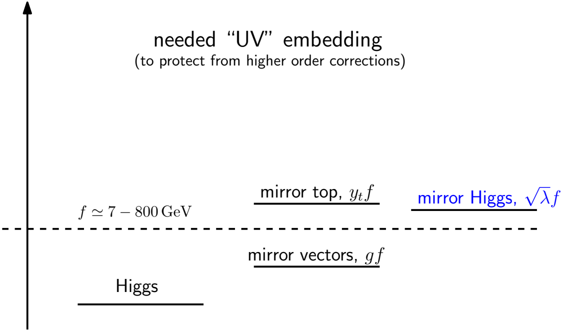
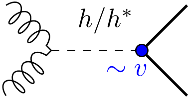
Now the model is phenomenologically viable

- Higgs coupling deviations measured by v^2/f^2
- Mirror sector is heavier by a factor f/v

The low energy spectrum



All the light new states 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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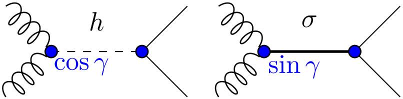
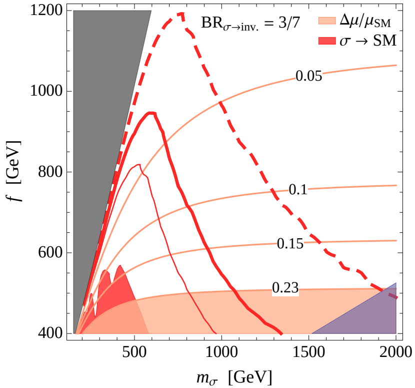
Look for the twin Higgs!

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

Higgs couplings & Direct Searches





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

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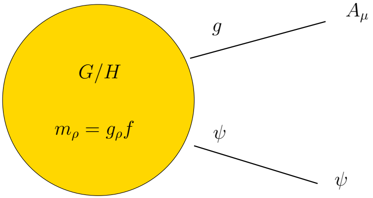
Composite (Twin) Higgs

Composite Higgs



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

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

1-loop potential breaks EWSB. The scale of the potential is set by the mass of the resonances: both vectors and fermions

$$m_* = g_* f$$

SO(5)/SO(4) minimal case

Agashe, Contino, Pomarol

Crucial role of fermions

Gauge sector does not break EW, other contributions needed
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 $y \sim \dfrac{y_L y_R}{g_\psi}$

 ...

 ...

Partial compositeness

The SM quarks are a combination of elementary and composite fields

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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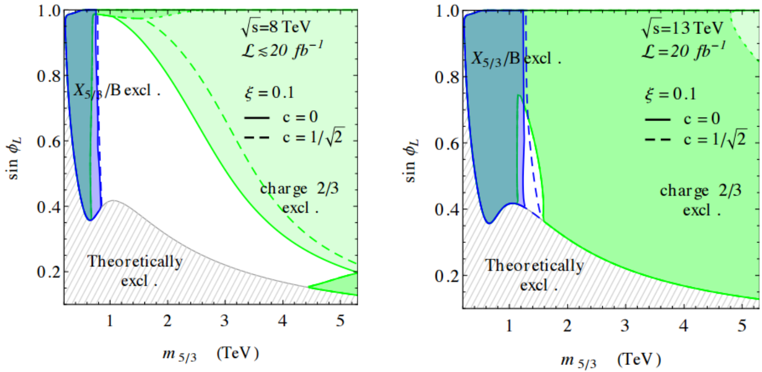
- Tuning grows with m_Ψ^2

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

A real problem?

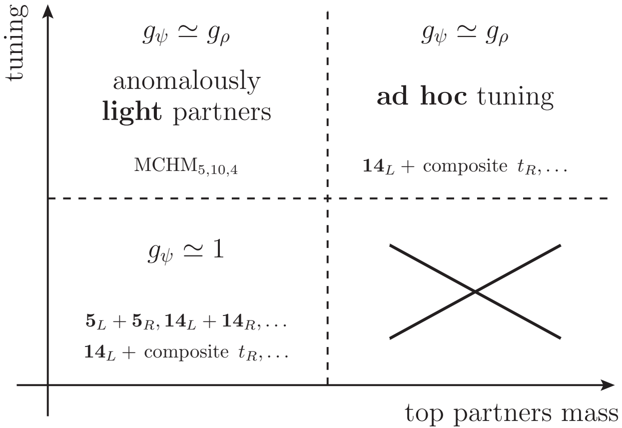
Not now, but we will know soon



taken from A. Wulzer's talk at Neutral Naturalness workshop

Can we have heavy top partners and small tuning?

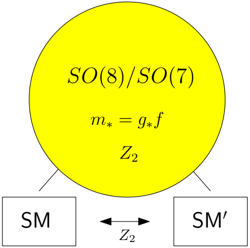
Panico, Redi, T, Wulzer



Composite Twin Higgs

Natural embedding in the Composite Higgs

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



In the gauge sector

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

$$\Sigma = \Big(0, 0, 0, s_h, 0, 0, 0, c_h \Big)$$

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

Three "sectors"
elementary fields — ele. mirror fields — composite resonances (Z_2)

Effect of the mirror top

$$\mathcal{L} = \bar{q}_L i \not{D} q_L + \bar{u}_R i \not{D} u_R + y_t f (\bar{q}_L^{\mathbf{8}})^i \Sigma_i u_R^{\mathbf{1}} + (\text{mirror})$$

- q_L in **8** of SO(8), $\quad (q_L^{\mathbf{8}})^i = \frac{1}{\sqrt{2}} \left(ib_L, b_L, it_L, -t_L, 0, 0, 0, 0\right)^i$
- Top and mirror top mass

$$m_t = \frac{y_t f s_h}{\sqrt{2}}, \qquad m_{t'} = \frac{y_t f c_h}{\sqrt{2}}$$

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$$m_t = \frac{y_t f s_h}{\sqrt{2}}, \qquad m_{t'} = \frac{y_t f c_h}{\sqrt{2}}$$

The potential is not sensitive to quadratic "divergences"

$$V = \frac{N_c y_t^4 f^4}{64\pi^2} \left[c_h^4 \log\left(\frac{2\Lambda^2}{y_t^2 f^2 c_h^2}\right) + s_h^4 \log\left(\frac{2\Lambda^2}{y_t^2 f^2 s_h^2}\right)\right] - \frac{N_c y_t^2 f^2 \Lambda^2}{16\pi^2}(s_h^2 + c_h^2)$$

Need a breaking of Z_2 to have $f > v$

Z_2 breaking and minimal tuning

Let us suppose that exists a model with Z_2-breaking

$$\frac{N_c y_t^4 f^4}{64\pi^2}\left[c_h^4 \log\left(\frac{2\Lambda^2}{y_t^2 f^2 c_h^2}\right) + s_h^4 \log\left(\frac{2\Lambda^2}{y_t^2 f^2 s_h^2}\right)\right] + \frac{N_c y_t^4 f^4}{32\pi^2} b\, s_h^2$$

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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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Z_2- breaking in top sector $\leftrightarrow$ standard Composite Higgs

Resonances and Z_2

At the level of the composite sector

- Automatic Z_2 in the gauge sector
- Need to impose Z_2 among composite and composite mirror fermions

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Resonances	SO(8)	SO(7)	SO(4) × SO(4)′	$SU(3)_c \times SU(3)'_c \times Z_2$
Ψ_L	$\mathbf{8}$	$\mathbf{7} \oplus \mathbf{1}$	$(\mathbf{4},\mathbf{1}) \oplus (\mathbf{1},\mathbf{4})$	$(\mathbf{3},\mathbf{1}) \oplus (\mathbf{1},\mathbf{3})$
Ψ_R	$\mathbf{1}$	$\mathbf{1}$	$(\mathbf{1},\mathbf{1})$	$(\mathbf{3},\mathbf{1}) \oplus (\mathbf{1},\mathbf{3})$
Ψ_R	$\mathbf{35}$	$\mathbf{27} \oplus \mathbf{7} \oplus \mathbf{1}$	$(\mathbf{9},\mathbf{1}) \oplus (\mathbf{1},\mathbf{9}) \oplus (\mathbf{4},\mathbf{4}) \oplus (\mathbf{1},\mathbf{1})$	$(\mathbf{3},\mathbf{1}) \oplus (\mathbf{1},\mathbf{3})$
Ψ_R	$\mathbf{28}$	$\mathbf{21} \oplus \mathbf{7}$	$(\mathbf{6},\mathbf{1}) \oplus (\mathbf{1},\mathbf{6}) \oplus (\mathbf{4},\mathbf{4})$	$(\mathbf{3},\mathbf{1}) \oplus (\mathbf{1},\mathbf{3})$
ρ	$\mathbf{28}$	$\mathbf{21} \oplus \mathbf{7}$	$(\mathbf{6},\mathbf{1}) \oplus (\mathbf{1},\mathbf{6}) \oplus (\mathbf{4},\mathbf{4})$	$(\mathbf{1},\mathbf{1})$

Z_2 on the Higgs: $h \to -h + \frac{\pi}{2} f$

$$s_h \leftrightarrow c_h$$

General potential

Largest Z_2-invariant contribution from top-sector

- Preserve Z_2 in the top sector
- Z_2-breaking in other sectors via elementary-composite couplings
- Dependence on fermion reps

$$V(h) \simeq \frac{N_c}{16\pi^2}(yf)^{2n} m_\Psi^{2(2-n)} \left[- a s_h^2 c_h^2 + b\chi\, s_h^2 \right] \quad n = 1, 2$$

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χ parametrizes deviation from O(1)

Ingredients unrelated to Twin Mechanism

- Need to $n = 2$
- t_R mostly composite, $y_L \sim y_t$
- Breaking should come from y_L

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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m_ψ heavy, q_L mostly elementary
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

Z_2 breaking in lighter quarks

If we do not mirror lighter generations (fraternal, Craig, Katz, Strassler, Sundrum)
(or we just break Z_2 there)

$$V(h)_{\rm TH} \simeq \frac{N_c}{16\pi^2}\left[-a y_t^4 f^4 s_h^2 c_h^2 + b\, y^2 f^2 m_\Psi^2 s_h^2\right]$$

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- Power sensitivity to m_ψ

$$m_h^2 \simeq \frac{a N_c y_t^4 v^2}{2\pi^2}, \qquad \Delta\big|_{\rm charm} \sim \frac{f^2}{v^2}\left(\frac{m_\Psi}{7f}\right)^3$$

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m_ψ practically heavy, q_L mostly elementary

An example

Let us consider the Z2-breaking in the gauge sector

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- Fermionic lagrangian (top-sector), Z_2-invariant

$$\mathcal{L} = y_L f (\bar{q}_L^{\mathbf{8}})^i (U_{iJ} \Psi_7^J + U_{i8} \Psi_1) + \text{h.c.}$$
$$+ \bar{\Psi} i \not{D} \Psi - m_1 \bar{\Psi}_1 \Psi_1 - m_7 \bar{\Psi}_7 \Psi_7 - m_R (\bar{\Psi}_1)_L u_R^{\mathbf{1}} + (\text{mirror})$$

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- Gauge sector with Z_2 breaking

$$\mathcal{L} = -\frac{1}{4}(F_{\mu\nu}^2 + \text{mirror}, \text{g}') - \frac{1}{4}\rho_{\mu\nu}^2 + \frac{f^2}{4}\text{Tr}[(D_\mu U)^t D_\mu U]$$

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$$V(h) = -\alpha s_h^2 c_h^2 + \beta s_h^2, \quad m_h^2 \simeq \frac{8\alpha}{f^2} v^2$$

Computation of the Higgs mass

Expanding in large m_ψ, first contribution at $O(y_L^4)$

$$\alpha = N_c y_L^4 f^4 \int \frac{d^4p}{(2\pi)^4} \frac{\left(m_1^2 p^2 + m_7^2(m_R^2 - p^2)\right)^2}{2p^4(m_7^2 - p^2)^4 \left(m_1^2 + m_R^2 - p^2\right)^2},$$

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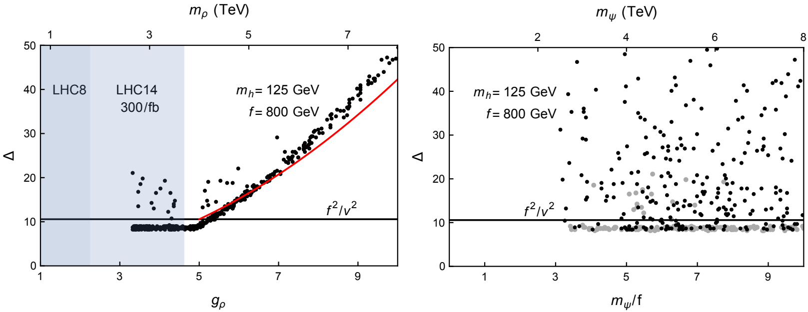
Higgs mass

$$m_h^2 \simeq \frac{N_c y_t^4 v^2}{4\pi^2} \left[\log\left(\frac{m_1^2}{m_{t'} m_t}\right) + F(m_R, m_1, m_7)\right]$$

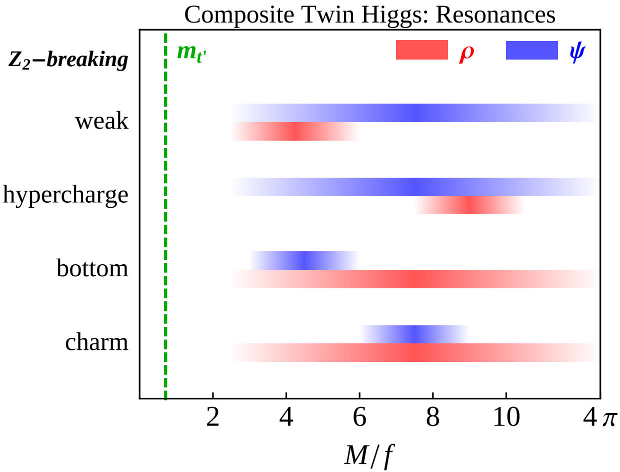
Rough verification of the estimates



- 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

Even better hiding with just unmirrored hyper-charged, $\sim \sqrt{3} g_Y / g$

There are scenarios where colored resonances can remain hidden at LHC



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

After LHC

Composite Twin Higgs can come to rescue