TH - Neutral Naturalness, 22/04/2015

Twin Higgs mechanism and Composite Higgs

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Apologies for a twin talk

Outline

- Why Twin Higgs?
- Why Composite Higgs?
- Why Composite Twin Higgs?

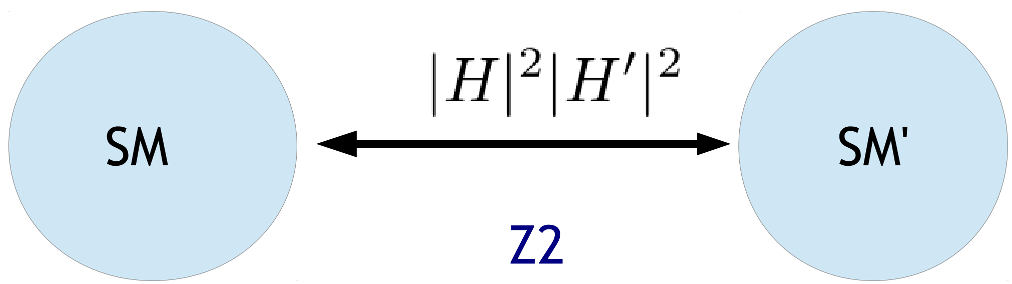
Twin Higgs

The Twin Higgs idea

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

Chacko, Goh, Harnik '05

Use a mirror copy of the SM, SM'



Assume that the potential is dominated by a SO(8)-invariant term

$$\lambda(H^2 + H'^2 - f^2)^2 \qquad \frac{SO(8)}{SO(7)} = 7\,\mathrm{GBs}$$

7 Gbs - (3 W/Z) -(3 W'/Z') = 1 physical scalar, h $\quad m_h = 0$

+1 “radial mode”, σ $\quad m_\sigma \sim \sqrt{\lambda} f$

Radiative contributions are SO(8)-invariant at the leading order

$$V \supset -N_c \frac{y_t^2}{32\pi^2}\Lambda^2(H^2 + H'^2) \longrightarrow m_h^2 = 0$$

While at O(g^4) we have contributions that break SO(8)

$$V_{O(y_t^4)} \supset N_c \frac{y_t^4}{32\pi^2}(H^4 \log \frac{\Lambda^2}{y_t^2|H|^2} + H'^4 \log \frac{\Lambda^2}{y_t^2|H'|^2})$$

$$m_h^2 \sim g_{SM}^4 v^2$$

At 1-loop there is no sensitivity to Λ^2 thanks to the additional Z2
Higgs mass proportional to O(g^4)

The potential is then of the form

$$V(H,H') = \lambda(H^2 + H'^2 - f_0^2)^2 + \delta(H^4 + H'^4)$$

The model is clearly ruled out

Need to break the Z2 symmetry

$$V(H,H') = \lambda(H^2 + H'^2 - f_0^2)^2 + \delta(H^4 + H'^4) + m^2(H^2 - H'^2)$$

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

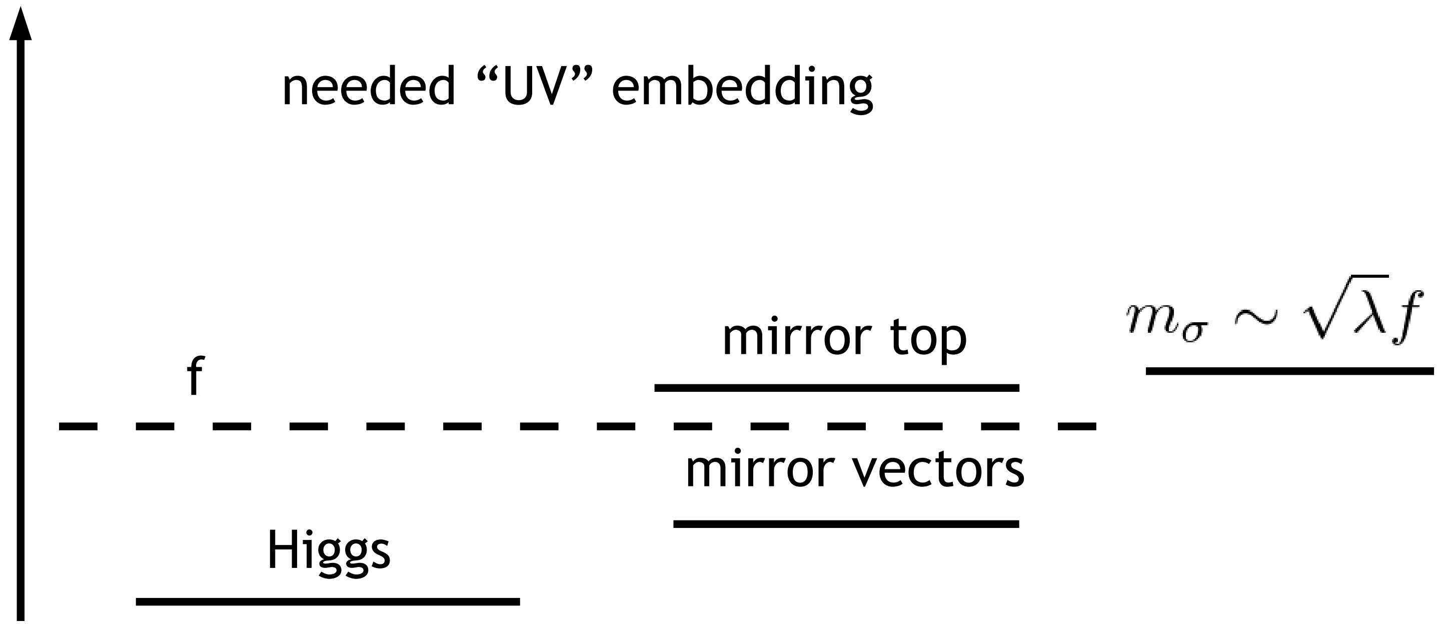
Now the model is phenomenologically viable

$$\sin^2\gamma = \frac{f^2 m_h^2 - \left(m_h^2 + m_\sigma^2\right) v^2}{f^2\left(m_h^2 - m_\sigma^2\right)}$$

mixing angle between h and σ
deviation in h-couplings

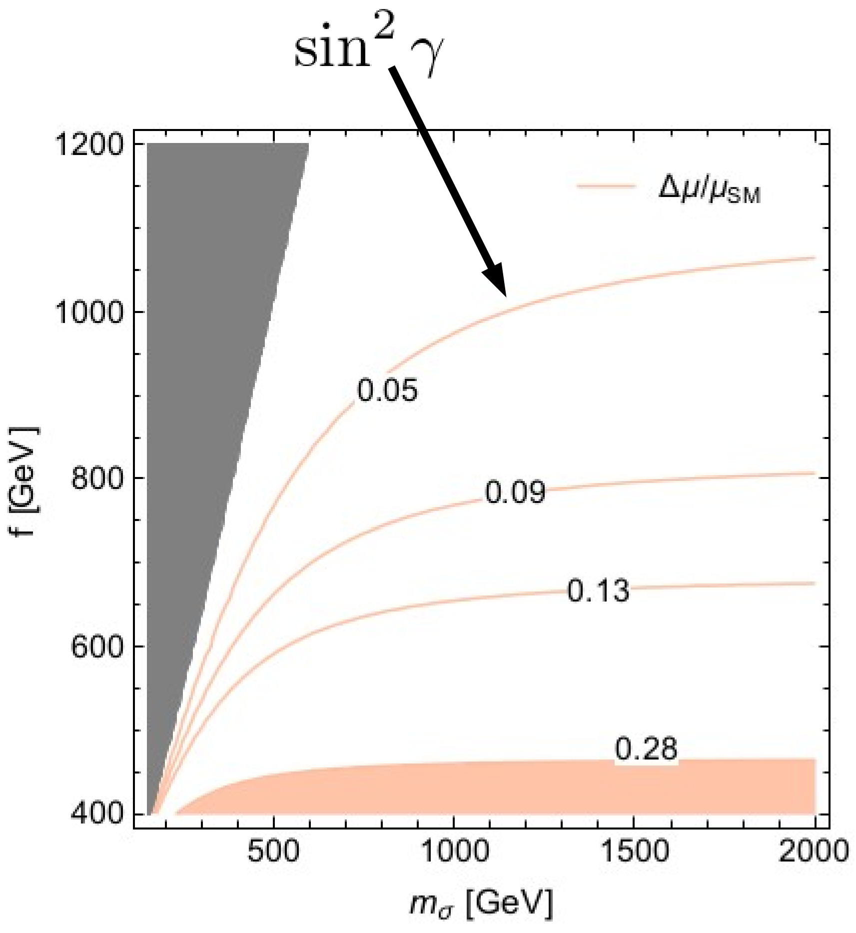
The low energy spectrum

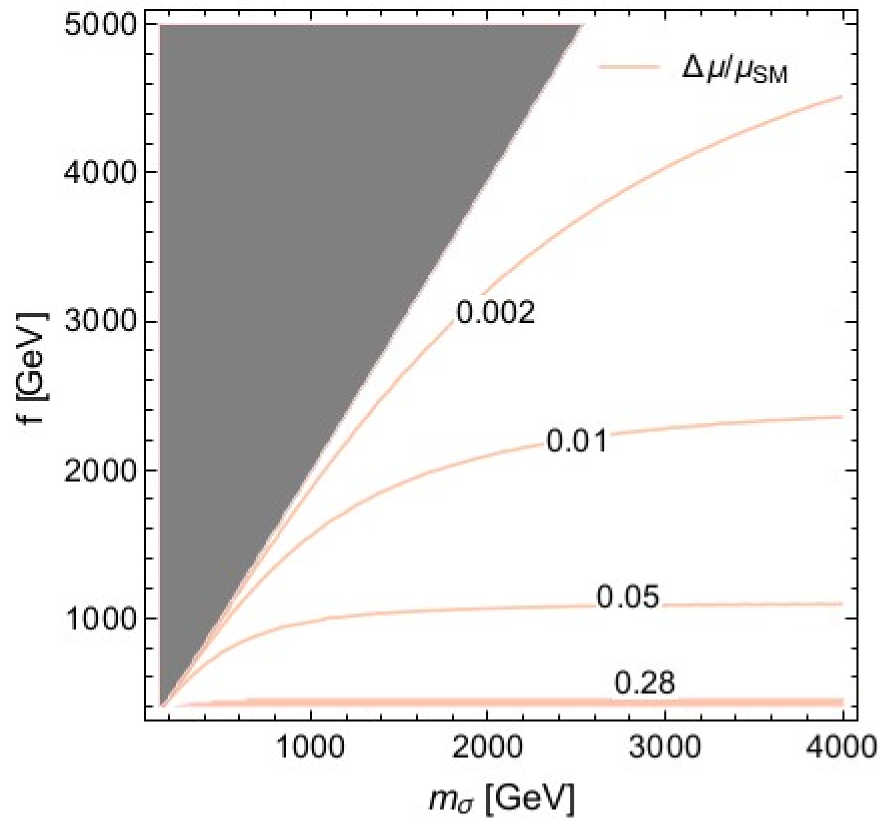
Upon EWSB (and Z2-breaking) the mirror spectrum is lifted by f/v



Depending on the size of λ, the radial mode can be close to f

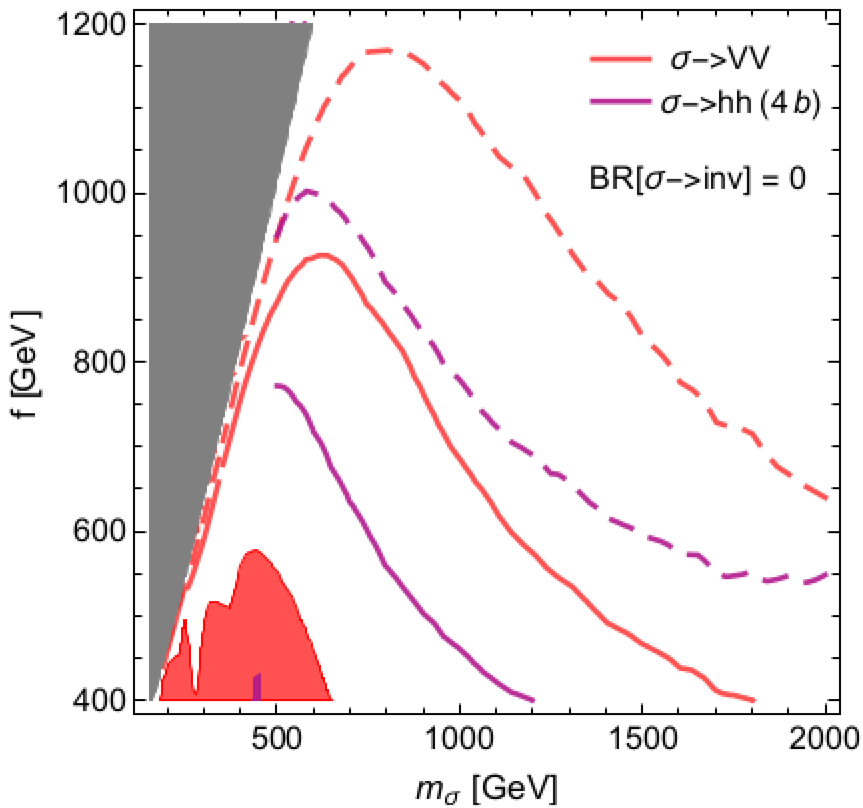
The scale f and the mass mσ control the phenomenology

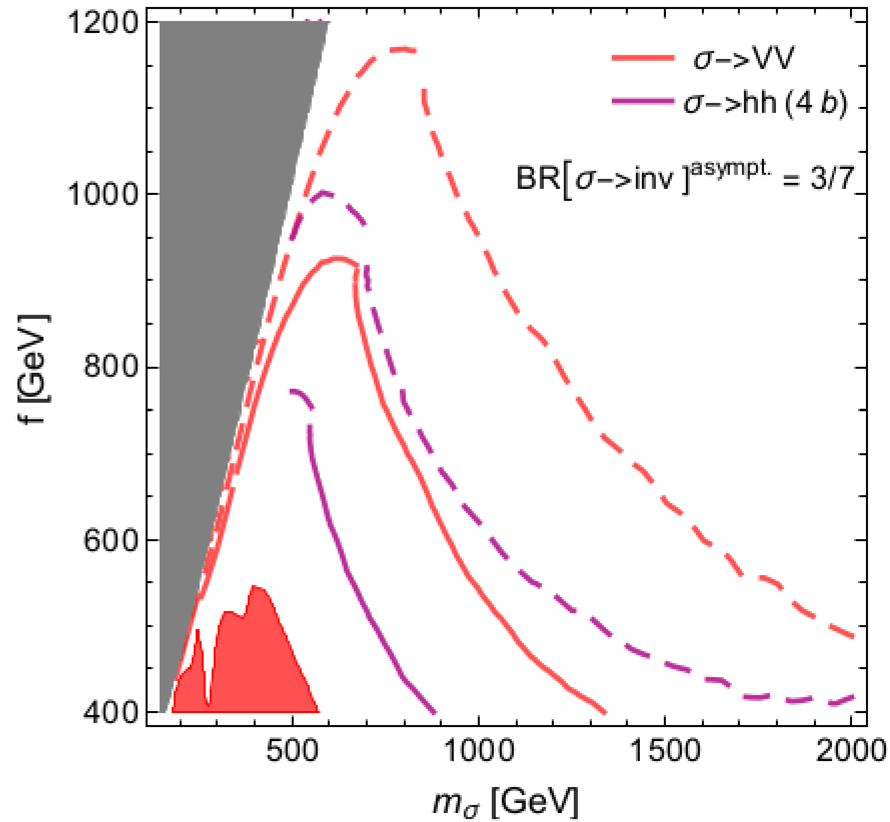




Relevance of Higgs physics
EWPT equally important

If the needed UV completion is weakly coupled, σ is expected close to f.
The model can be mainly studied by looking for the extra scalar





single production

w/ Dario Buttazzo and Filippo Sala

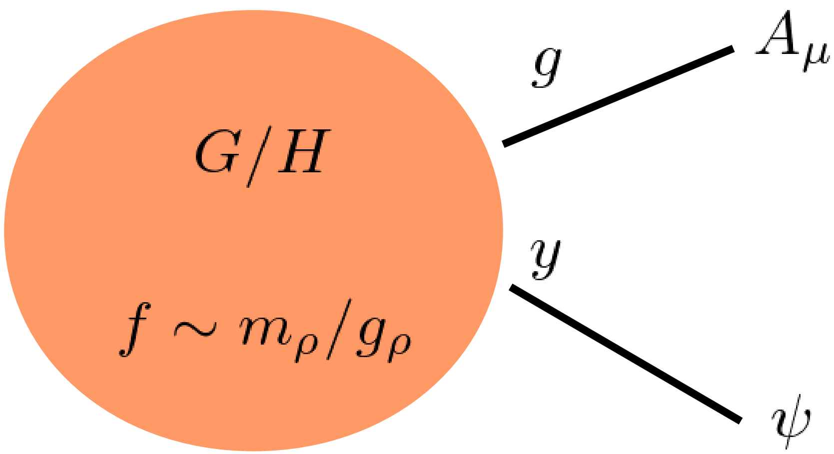
anyhow, I will focus on strongly coupled scenarios

Composite Higgs

Composite Higgs models

Georgi Kaplan '80s
...
Agashe, Contino, Pomarol

In presence of an approximate global symmetry the Higgs is a pseudo-GB



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

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

The couplings to the SM sector break the shift symmetry and generate a potential at 1-loop.

- Generate EWSB radiatively and achieve a Higgs boson of 125 GeV
- Consistency with precision data
- Minimize the fine-tuning

Crucial role of the fermions

The gauge sector alone does not generate the EWSB
However the inclusion of the fermion sector is **model dependent**

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

In order to avoid the usual flavor problems of TC we rely on a linear mixing

- The SM Yukawa couplings are given by $$y_{SM} \simeq y_L y_R \frac{f}{m_\Psi}$$
- The composite fermions are coloured

Kaplan '91

The above linear coupling is called partial compositeness mechanism.
The SM quarks are a combination of elementary and composite fields.

Higgs potential

In the limit where g=0, the potential is entirely due to the top sector

$$\mathcal{L} = y_L f \bar{q}_L U \Psi + y_R f \bar{u}_R U \Psi + \mathcal{L}_{\rm comp}(\Psi, U, m_\psi)$$

At 1-loop, the mixing between q and u with Ψ generates non-vanishing contributions

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

Giudice, Grojean, Pomarol , Rattazzi

- Fx is a sum of trigonometric functions of h/f
- a, b are model-dependent coefficients

Remember that $y_{SM} \simeq y^2 \frac{f}{m_\Psi}$ $\longrightarrow$ $V \simeq \frac{N_c}{16\pi^2} m_\Psi^4 \left[a \frac{y_t f}{m_\Psi} F_a + b(\frac{y_t f}{m_\Psi})^2 F_b\right]$

Composite Higgs potential is highly sensitive to the fermionic scale

m_ψ is the physical threshold

Higgs mass and tuning

In most of the models we have the following predictions

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

Tuning larger than naïve v^2/f^2

- 125 GeV requires light composite fermions*
- Light means mΨ/f ~ 1 (not 4π)
- Tuning is minimized when the overall scale mΨ is light
- Need to look for colored fermionic top-partners

$$m_\Psi\Big|_{m_h} \sim 800\,\mathrm{GeV}\left(\frac{f}{600GeV}\right)$$

*different from SUSY

Can we disentangle the relation mΨ ~ mh?

In standard Composite models we can only play with:

- representations of Ψ
- size of the elementary-composite mixings

Two main possibilities within SO(5)/SO(4)

- tR, fully composite (aka total singlet)

$$y_{SM} \simeq y^2 \frac{f}{m_\Psi} \xrightarrow{y_R \to m_\Psi / f} y_{SM} \simeq y \qquad m_h^2 \simeq b\, \frac{N_c y_t^4 v^2}{2\pi^2} \qquad \Delta \simeq \frac{m_\Psi^2}{m_t^2}$$

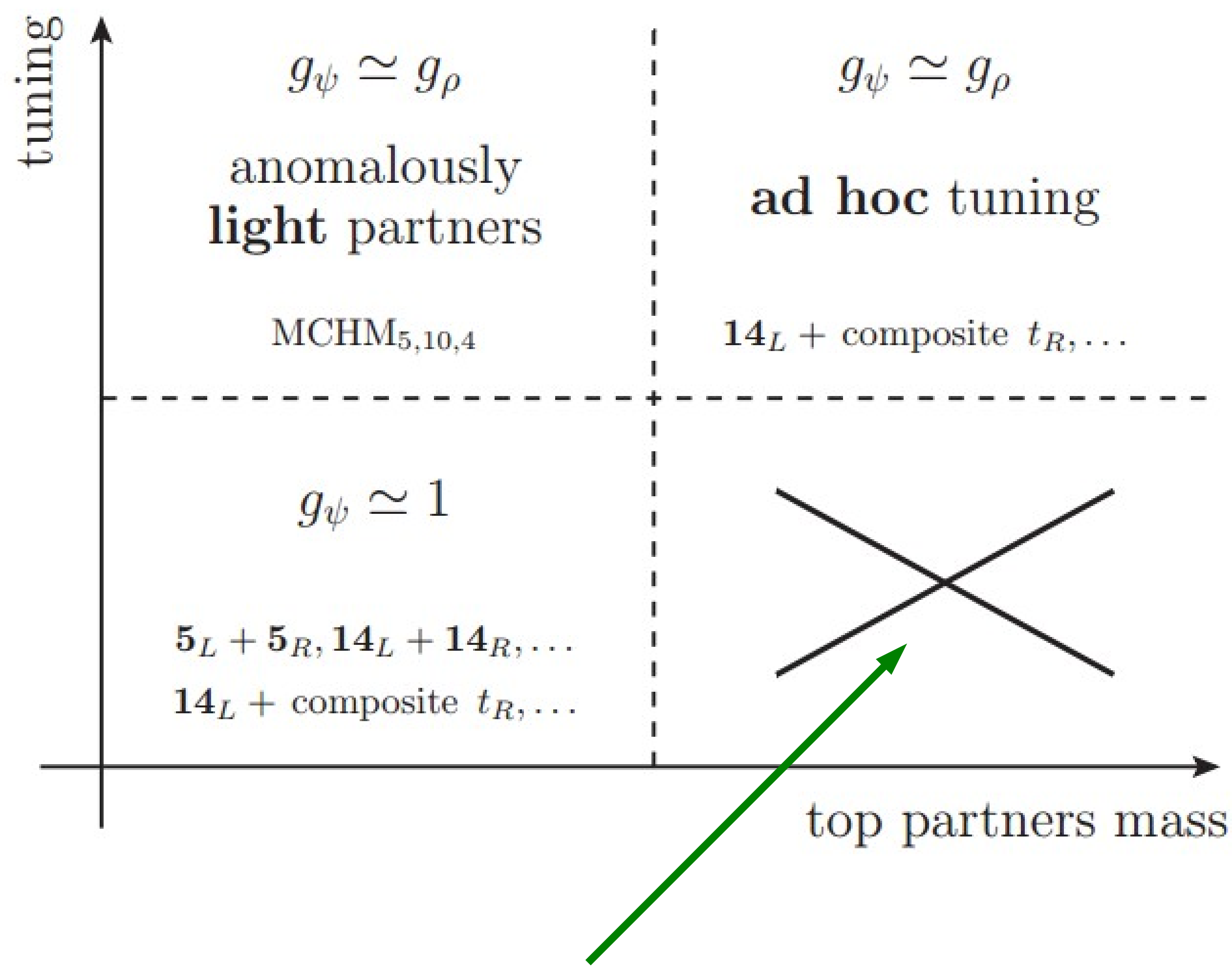
no light fermions, but large tuning

- qL in the **14**

$$m_h^2 \simeq b\, \frac{N_c y_t^2 v^2}{2\pi^2} \left(\frac{m_\Psi}{f}\right)^{2-3} \qquad \Delta \simeq \frac{f^2}{v^2}$$

mΨ not in VEV, but in mh

An open question:



Is it really impossible to fill in that region?

Twin Higgs and Composite Higgs

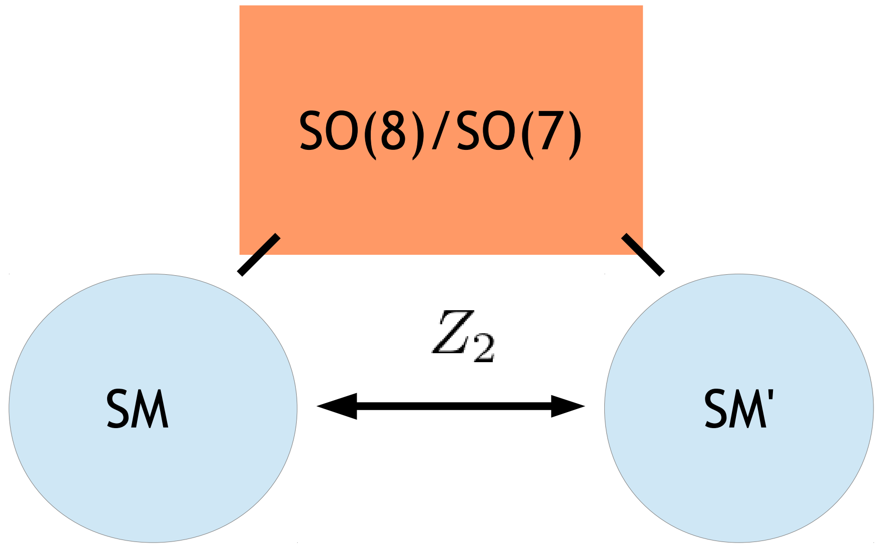
with M. Low and L.T Wang
arXiv:1501.07890

see also
Geller, Telem
Craig, Sundrum, Katz, Strassler,
Barbieri, Greco, Rattazzi, Wulzer

Composite Twin Higgs

The minimal option is offered by SO(8)/SO(7)

composite sector; resonances



elementary sector;

$$U = \exp\left(i\sqrt{2}\frac{\pi^a}{f}T^a\right) \quad T^a = \begin{pmatrix} 0 & X_a \\ -X_a & 0 \end{pmatrix} \quad \Sigma_i = U_{i8}$$

The gauging of the EW part of SM and SM' is given by

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

Need to gauge also the mirror SU(3)'

Composite Twin Higgs - 2

- The vector resonances are in the **21** + **7**, Z2 is automatic
- Need to double the composite fermions in a Z2-fashion

Resonances	SO(8)	SO(7)	$SO(4) \times SO(4)'$	$SU(3)_c \times SU(3)'_c \times Z_2$
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	$\mathbf{28}$	$\mathbf{21} \oplus \mathbf{7}$	$(\mathbf{6},\mathbf{1}) \oplus (\mathbf{1},\mathbf{6}) \oplus (\mathbf{4},\mathbf{4})$	$(\mathbf{1},\mathbf{1})$

The Gbs can be cast into a 8-plet

$$\Sigma = (0,0,0,\sin\frac{h}{f},0,0,0,\cos\frac{h}{f})$$

$$v = f \sin h/f$$

Under the action of Z2

$$h \to -h + \frac{\pi}{2} f$$

V(h) from the top-sector

We can focus on the nlσ-model with just SM and its mirror copy

$$\mathcal{L} = \bar{q}_L i D q_L + \bar{u}_R i D u_R + y_t f (\bar{q}_L^{\mathbf{8}})^i \Sigma_i u_R^{\mathbf{1}} + (\mathrm{mirror}).$$

SO(8) requires qL in a **8** of SO(8)

$$(q_L^{\mathbf{8}})^i = \frac{1}{\sqrt{2}} (i b_L, b_L, i t_L, -t_L, 0, 0, 0, 0)^i \qquad m_t = \frac{y_t f s_h}{\sqrt{2}}, \quad m_{t'} = \frac{y_t f c_h}{\sqrt{2}}$$

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

- No power sensitivity to the mass thresholds Λ
- IR-effects due to top and mirror top masses
- Potential breaks SO(8), but not Z2

same mechanism for gauge bosons...

Z2 breaking - minimal tuning

Suppose that we add a Z2 breaking term

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

If b~O(1), we achieve the correct electro-weak vacuum with a tuning

$$\Delta \simeq \frac{f^2}{v^2}$$ minimal tuning

the Higgs mass is of the right size

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

If such Z2 breaking term exists we have no power sensitivity to Λ~ mΨ and the tuning is minimal (in the sense above)

General expression for V(h)

- Focus on the top-sector: largest Z2-even contribution
- Allow for Z2-odd terms
- Let me forget about the logs (for the moment)

model dependent deviation from O(1)

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

$$y_{\rm SM} \simeq y^k \frac{f^{k-1}}{m_\Psi^{k-1}} \qquad k = 1, 2.$$

		n	k	$V(h)_{\rm TH}$	$y_{\rm SM}$
$q_L^{\mathbf{8}}$	$u_R^{\mathbf{1}}$	2	1	$\sim y^4 f^4$	y
$q_L^{\mathbf{8}}$	$u_R^{\mathbf{28}}$	2	2	$\sim y^4 f^4$	$y^2(f/m_\Psi)$
$q_L^{\mathbf{8}}$	$u_R^{\mathbf{35}}$	1	2	$\sim y^2 f^2 m_\Psi^2$	$y^2(f/m_\Psi)$

To get an interesting result we shall focus only on tR as a total singlet
(this has nothing to do with the twin mechanism)

Possibilities for the Z2-breaking

Z2 breaking in the top sector

Suppose we break Z2 in the elementary-composite mixing

$$y_L f \bar{q}_L U \Psi + y_L' f \bar{q}_L' U \Psi' + \mathcal{L}_{\rm comp}(Z_2)$$

notice that tR does not break SO(8)

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

Z2 ~~Z2~~

yL~yL'~y

$$m_h^2 \simeq a \frac{N_c y_t^4 v^2}{2\pi^2} \qquad \Delta \simeq \frac{m_\Psi^2}{m_t^2}$$

same as in Composite Higgs

We also discussed a soft breaking mψ≠mψ', w/ large masses and small splitting

$$\Delta \sim \frac{f^2}{v^2} \frac{m_\Psi^2 - m_{\Psi'}^2}{y_t^2 f^2} \quad \overset{\text{almost } Z_2}{\sim} \quad \frac{f^2}{v^2}$$

Z2 breaking in the ligther quarks

If the breaking originates in the lighter quarks

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

$$y^2 \sim y_q^{\rm SM}\frac{m_\Psi}{f}$$

Higgs mass is OK and the VEV is *mildly* sensitive to composite fermions

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

- > The prediction is mψ ~ 4-7 f
- > Vector resonances are “unconstrained”

Z2 breaking in the gauge sector

Another possibility can be offered by breaking Z2 in the gauge sector

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

Higgs mass is OK and the VEV is not sensitive to composite fermions

$$m_h^2 \simeq a \frac{N_c y_t^4}{2\pi^2} v^2, \qquad \Delta \simeq \frac{f^2}{v^2}\left(\frac{g_\rho}{5}\right)^2$$

- The prediction is mρ ~ 4-5 f
- And composite fermions can be really at 4π f
- Even better when only the mirror hypercharge is un-mirrored (see Barbieri et al)

Z2 breaking at 2 loops

The Z2 breaking in SU(2) sector will affect the running of yt and yt' (equal at 4pi f)

$$\Delta V(h)_{2-loop} \simeq \tilde{b}\frac{N_c}{16\pi^2} f^2 m_\Psi^2 s_h^2 \frac{y_t^2}{16\pi^2}\frac{9}{4}(g^2 - g'^2)\log\frac{m_\Psi}{m_t}$$

The relative size is sufficiently small in the relevant regions

$$\frac{\Delta V(h)}{V(h)_{gauge}} = \left(\frac{m_\Psi}{4\pi f}\right)^2 \frac{N_c y_t^2}{g_\rho^2}\frac{\tilde{b}\log(4\pi f/m_t)}{b}$$

An example

An explicit computation

Let us consider the Z2-breaking in the gauge sector

$$\mathcal{L} = y_L f (\bar{q}_L^{\mathbf{8}})^i (U_{iJ}\Psi_7^J + U_{i8}\Psi_1) + \text{h.c.}$$
$$+ \bar{\Psi} i D \Psi - m_1 \bar{\Psi}_1 \Psi_1 - m_7 \bar{\Psi}_7 \Psi_7 - m_R (\bar{\Psi}_1)_L u_R^{\mathbf{1}} + (\text{mirror})$$

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

$$m_\rho = g_\rho f$$

From the previous discussion

$$V(h) = -\alpha s_h^2 c_h^2 + \beta s_h^2 \qquad v = \sqrt{\frac{\alpha - \beta}{2\alpha}} f, \quad m_h^2 = \frac{8\alpha}{f^4} v^2 \left(1 - \frac{v^2}{f^2}\right)$$

α: from top sector (also the log)

β: $b\,\dfrac{9(g^2 - g'^2)}{64\pi^2} f^2 m_\rho^2$

Computation of the Higgs mass

Expanding in yL*f/m, the first contribution arises at O(yL^4)

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

UV-convergent (a spurious IR-divergence: just the log-running of CW)

The prediction for the Higgs mass:

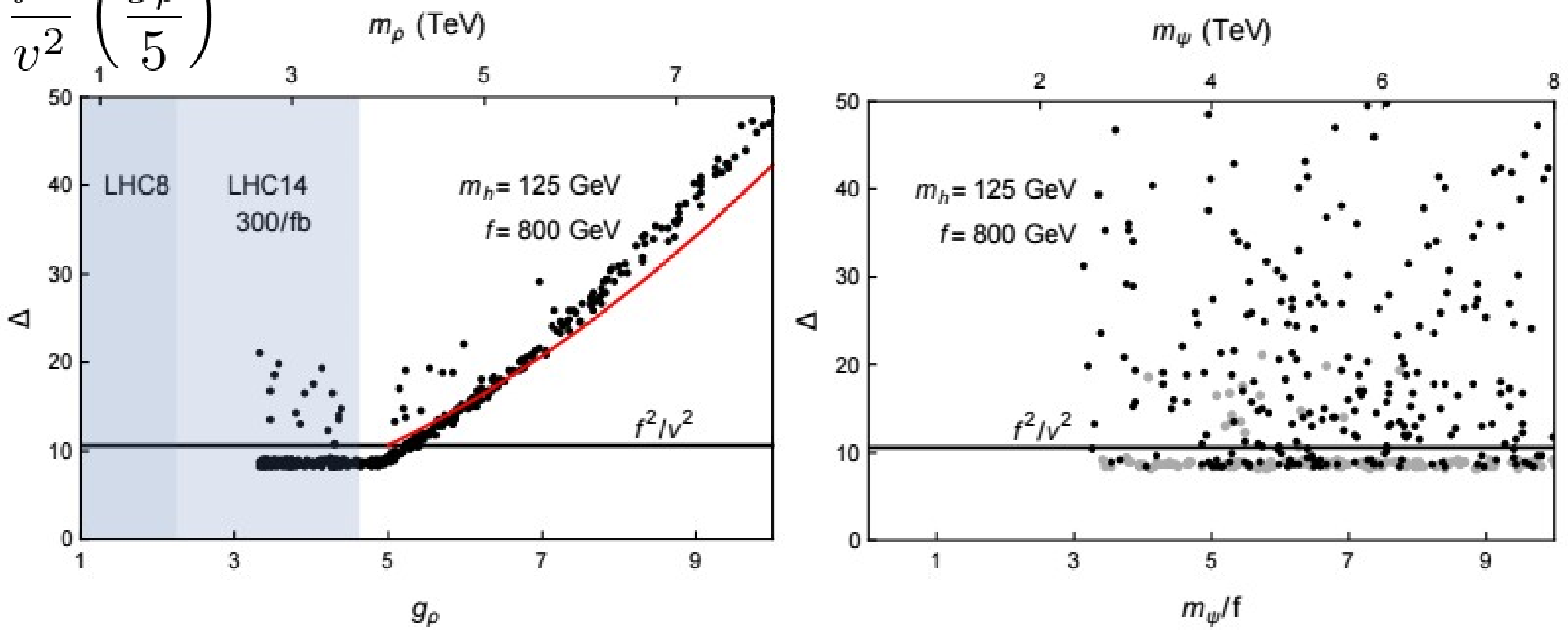
$$m_h^2 \simeq \frac{N_c y_t^4 v^2}{4\pi^2} \left[\log\left(\frac{\bar{m}_{\mathbf{1}}^2}{m_{t'} m_t}\right) - 5\left(1 - \frac{4}{5}\frac{\bar{m}_{\mathbf{7}}^2}{\bar{m}_{\mathbf{7}}^2 - \bar{m}_{\mathbf{1}}^2} \log\left(\frac{\bar{m}_{\mathbf{7}}^2}{\bar{m}_{\mathbf{1}}^2}\right)\right)\right]$$

$$\bar{m}_{\mathbf{7}}, \bar{m}_{\mathbf{1}} \gg y_L f,\; m_1/m_R \simeq 1 + O(y_L^2)$$

The value of β needed for EWSB/Higgs mass corresponds to gρ~4-5

Sensitivity to parameters

$$\Delta \simeq \frac{f^2}{v^2}\left(\frac{g_\rho}{5}\right)^2$$

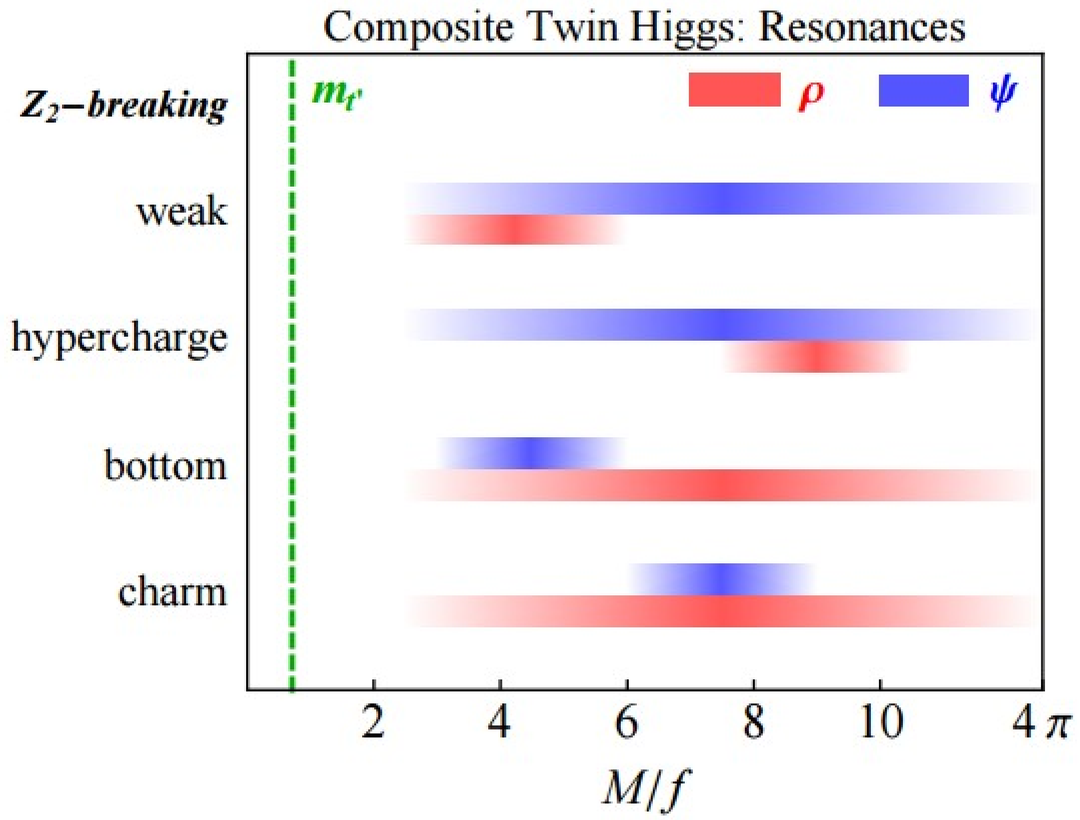


- dependence on grho above 4-5
- No correlation with the fermionic parameters
- O(1) estimates respected

the same can be applied to hypercharge effects
a translation of ~ g/gy

Generic phenomenology

"Colored" resonances can remain hidden during the second run of LHC



the phenomenology is governed by precision measurements once again

Higgs couplings in Twin Higgs

In SO(8)/SO(7) there is a universal rescaling of all the tree-level Higgs couplings

$$c_{hVV} = \sqrt{1 - v^2/f^2}, \qquad c_{hff} = \sqrt{1 - v^2/f^2},$$

$$c_{hV'V'} = -\sqrt{1 - v^2/f^2}(g'^2/g^2), \qquad c_{hf'f'} = -(v/f)(y'/y),$$

On top of the usual shift, there is a potentially large invisible decay width

$$\mu = (1 - \frac{v^2}{f^2})(1 - \mathrm{BR}_{\mathrm{inv}})$$

This suggests that constraints on f are stronger than in the standard Composite Higgs case

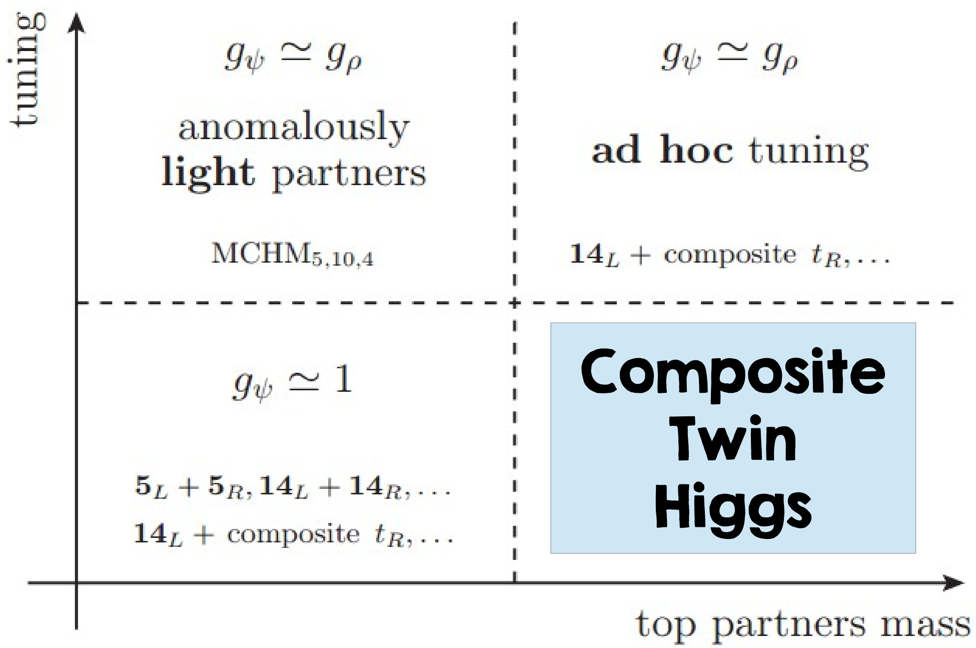
$$\Gamma_{b'b'} \sim \frac{v^2}{f^2}\Gamma_{bb}^{SM}$$

more details in Burdman et al
Craig, Katz, Strassler, Sundrum

Conclusions

Composite Higgs models will be crucially tested at LHC14.
A null result will disfavor the existing models,
unless the overall scale f is raised (above the exp. lower bound)

However, Composite Twin Higgs can come to rescue



beware of EWPTs...

Thank you!