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Twin Higgs mechanism and Composite Higgs

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Disclaimer

In this talk many O(1) estimates

- Composite models are not really calculable
- I will focus more on the proposal of a scenario than an actual model
- I think that this approach catches the relevant physics

Outline

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

Again on the Hierarchy Problem

Not a problem of quadratic “divergences”, but a matter of thresholds

$$\mathcal{L}_{UV} = \frac{1}{2}(\partial\varphi)^2 - \frac{1}{2}m^2\varphi^2 + \bar{\psi}i\partial\psi - M_\psi\bar{\psi}\psi - y\varphi\bar{\psi}\psi$$

Suppose m << mΨ and integrate out the fermion
The boundary condition has to be known with accuracy (aka tuning)

$$\Delta = \frac{y^2}{4\pi^2}\frac{M_\psi^2}{m^2}$$

If new particles are coupled to the Higgs they induce a tuning if they're heavy.
Many phenomena point to the existence of new particles/scales
(Dark Matter, Baryogenesis, Neutrino Physics, …)

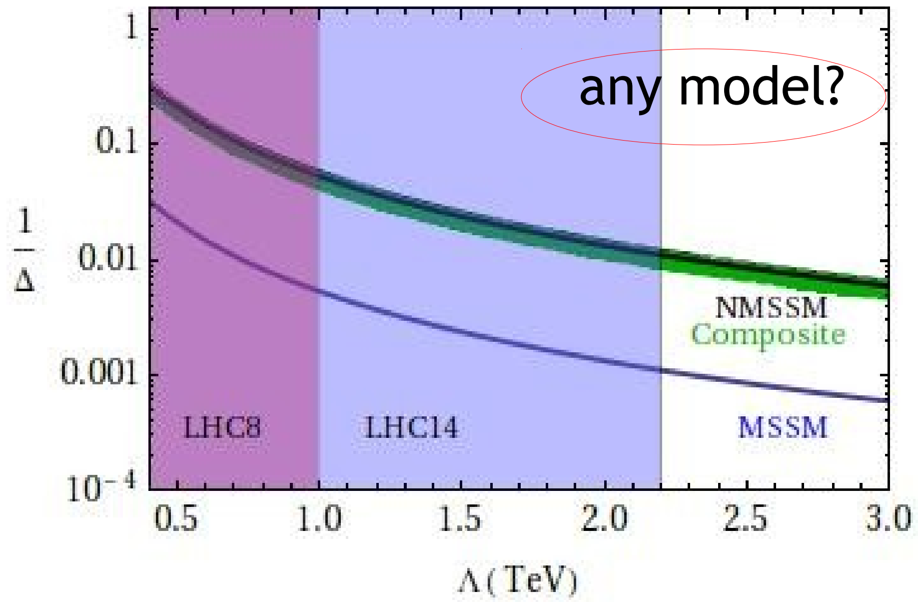
A conservative approach is to screen these UV effects already at the weak scale
(Even a ‰ tuning is nothing compare to what we gain by screening the UV)

The top-sector and the tuning

If new symmetries stabilize the weak scale, the top-loop becomes important (Supersymmetry, Composite Higgs)

$$|\delta m_h^2| = \frac{3}{8\pi^2} y_t^2 \Lambda^2_{\text{colored}} + \cdots$$

LHC measured a lot of tuning, despite it is not an observable



After two years of the run II we might be in an unpleasant situation

Twin Higgs

Chacko, Goh, Harnik '05

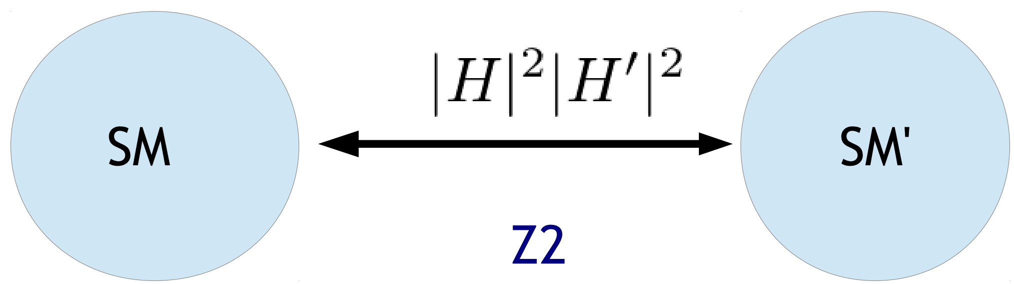
The Twin Higgs idea

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

Chacko, Goh, Harnik '05

How?

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

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

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

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

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

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

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

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

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

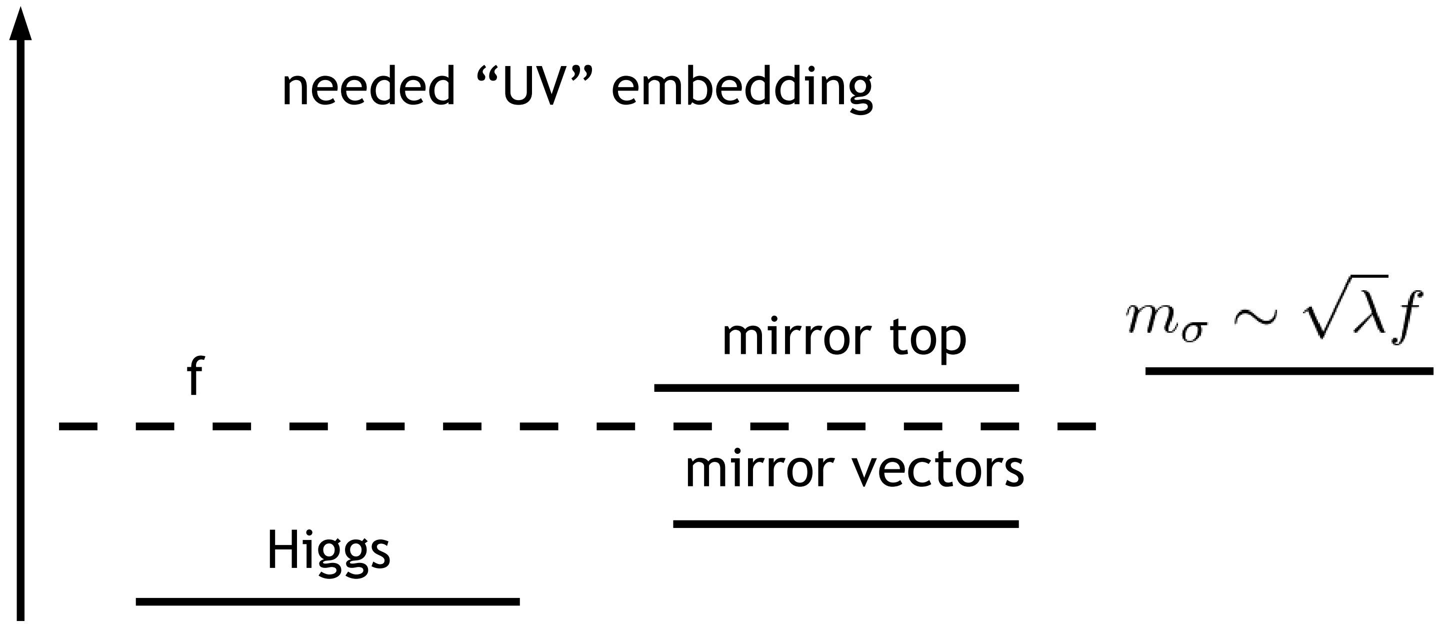
Now the model is phenomenologically viable

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

mixing angle between h and σ
deviation in h-couplings

The low energy spectrum

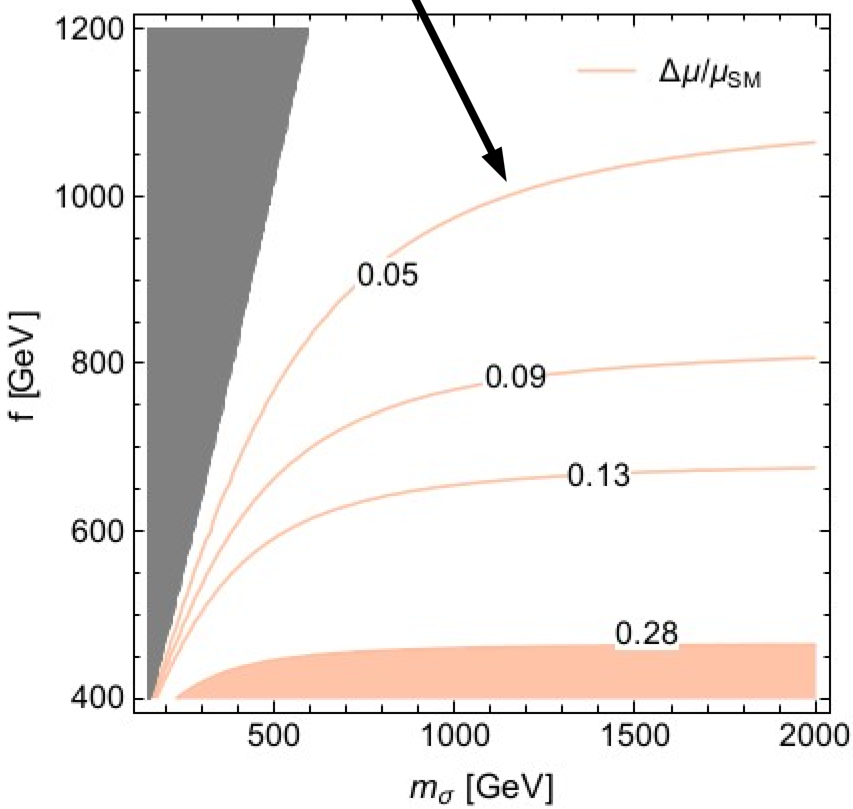
Upon EWSB (and Z2-breaking) the mirror spectrum is lifted by f/v
(by the amount of Z2 breaking)

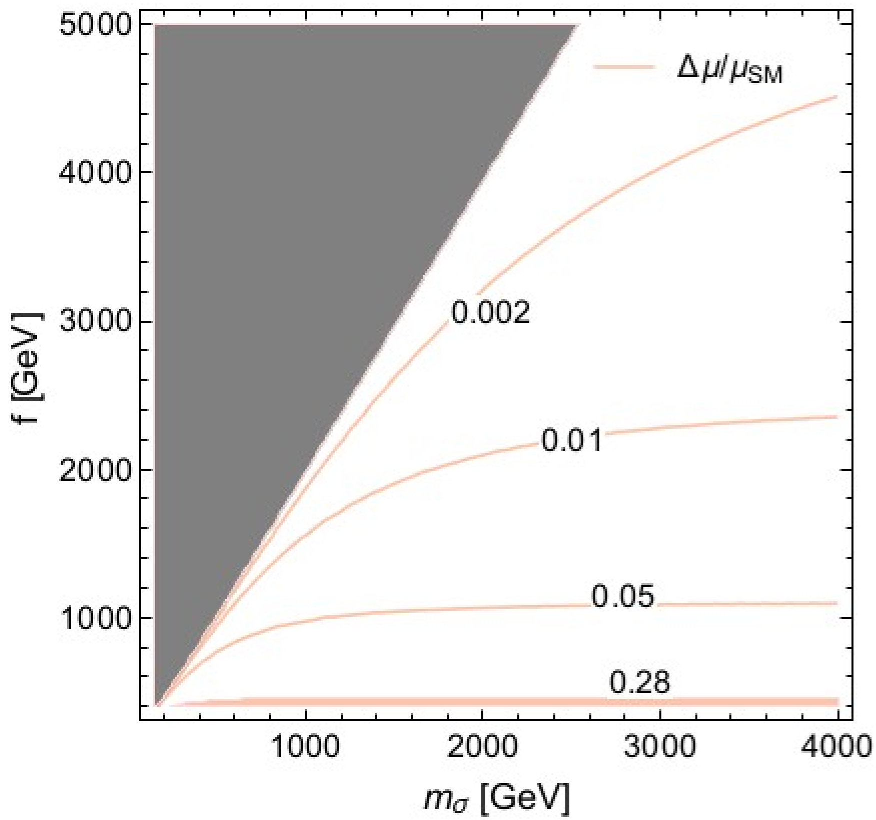


Depending on the size of λ, the radial mode can be close to f

The scale f and the mass mσ control the phenomenology

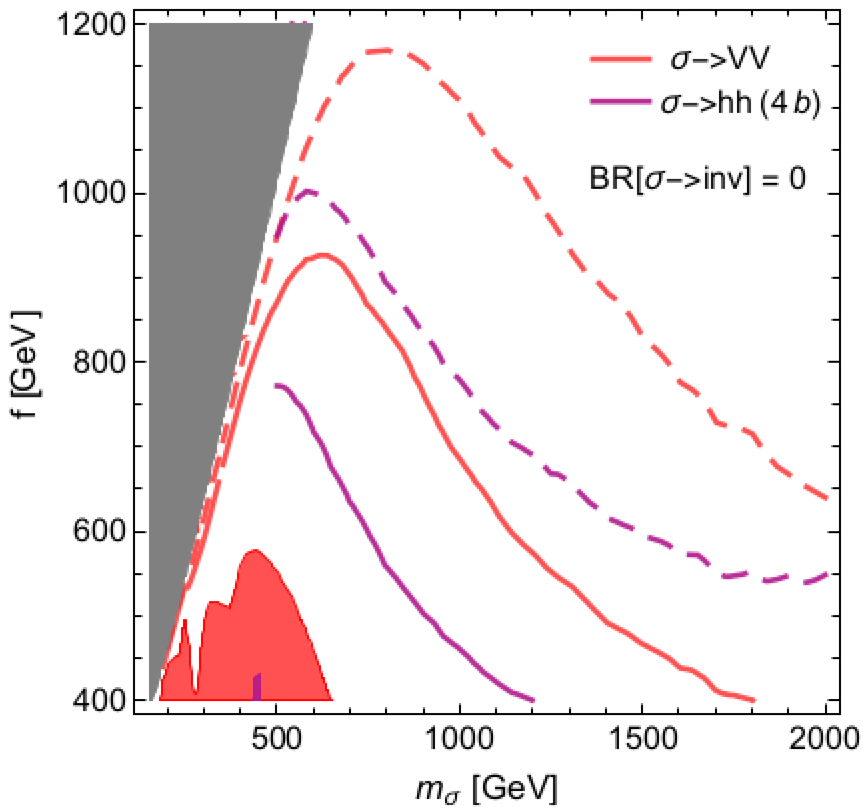
$\sin^2\gamma$

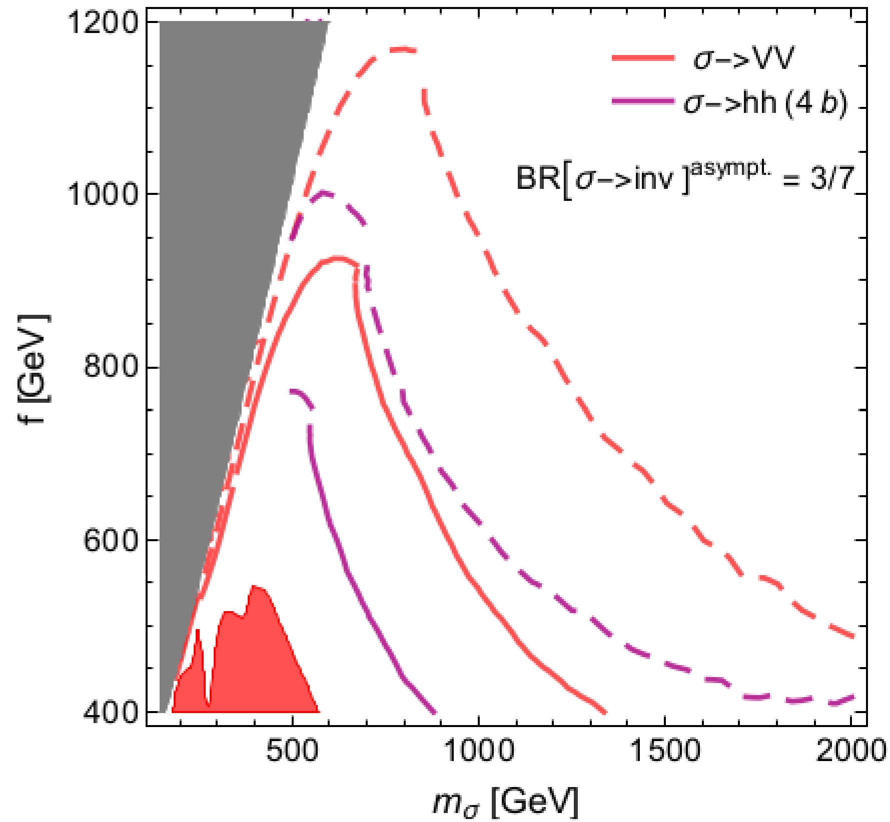




Relevance of Higgs physics
EWPT equally important

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

The Twin Higgs mechanism is a symmetry argument to protect the Higgs potential

Question:

Can we combine it with models that already address the Hierarchy problem?

- > check if the scale of colored partners can be "decoupled"
- > check what is the advantage of the whole picture

Two main paradigms on the market:

SUSY + twin *

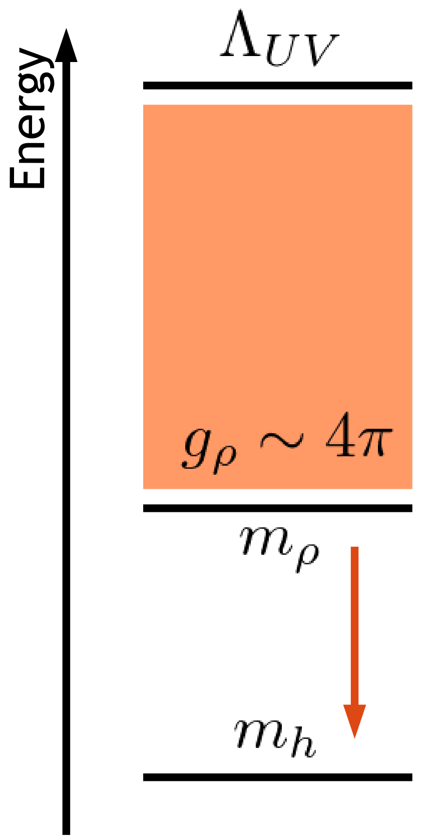
see Craig, Howe

Composite + twin

this talk

Composite Higgs

The compositeness "paradigm"



Easy piece:
UV – IR link achieved via a QCD-like dynamics

Difficult piece:
A light Higgs from the strong sector and be consistent with data

This scenario offers a solution to the previous problem if

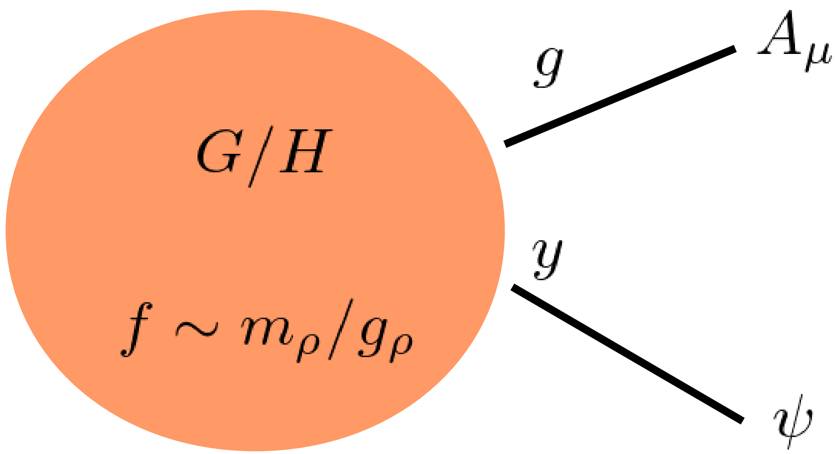
$$m_\rho \sim 500\,\mathrm{GeV}\sqrt{\Delta}$$

In technicolor-like theory a light Higgs is not expected,
need some other ingredients

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

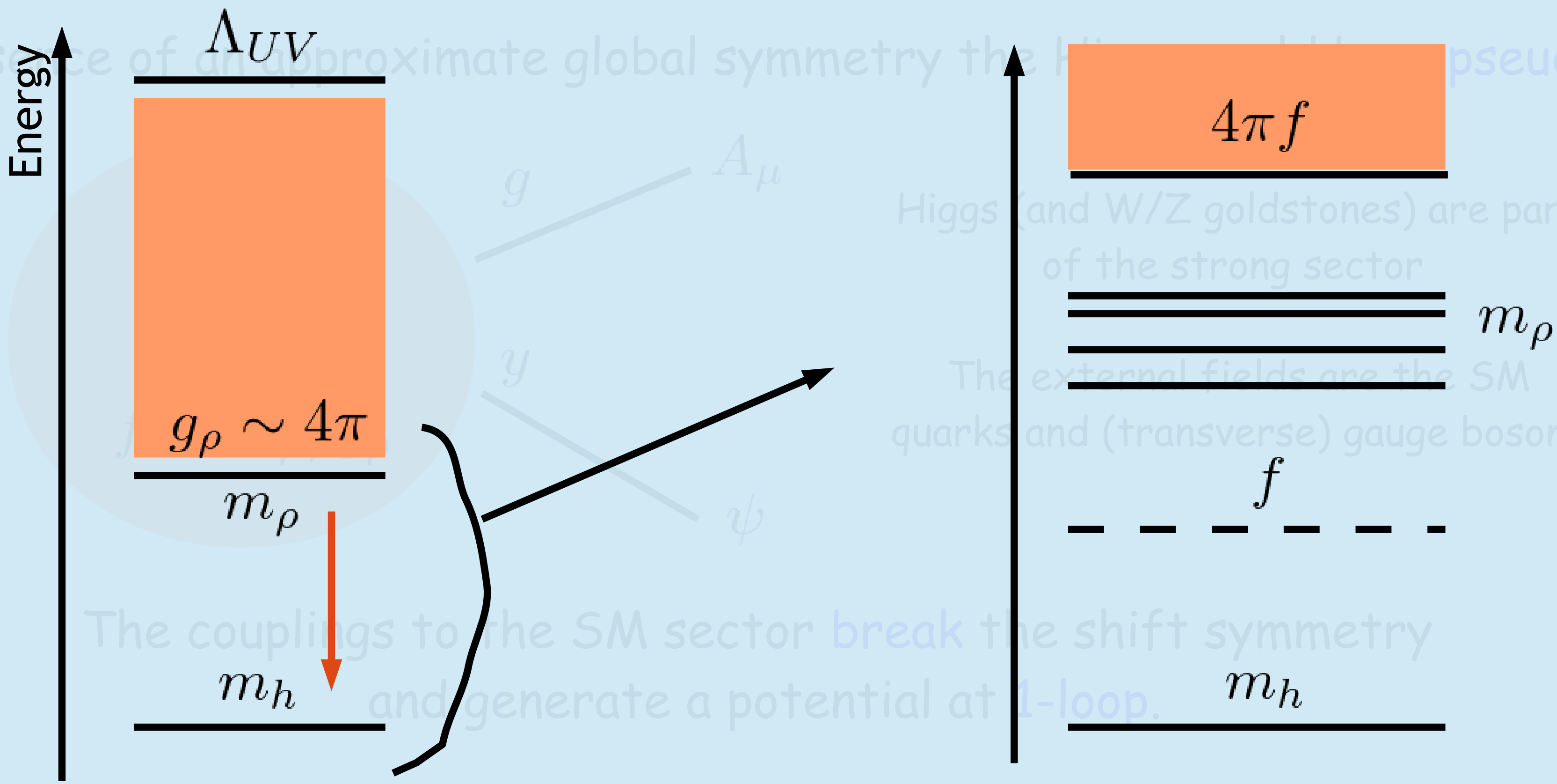
The external fields are the SM quarks and (transverse) gauge bosons

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

(Ambitious) task

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

Let me zoom in the low-energy region



Below 4πf it makes sense to talk about resonances and to describe them according to the symmetries at the scale f

I am not going to argue anything about what is above 4πf
(same as in low-energy QCD)

The Minimal Composite Higgs

Agashe, Contino, Pomarol

$$SO(5)/SO(4) \to 4\,\mathrm{GBs}$$

$$U = \exp\left(i\sqrt{2}\frac{\pi^a}{f}T^a\right) \quad T^a = \begin{pmatrix} 0 & X_a \\ -X_a & 0 \end{pmatrix} \quad \Sigma_i = U_{i5}$$

The lowest-energy lagrangian (below mρ) is highly constrained by G/H

Writing the pion lagrangian and introducing the gauging with minimal substitution we get,

$$\frac{1}{2}(D_\mu \Sigma)^2 \supset \frac{1}{2}(\partial h)^2 + \frac{1}{2}m_V^2 V_\mu^2 \left(1 + 2\sqrt{1 - \frac{v^2}{f^2}}\frac{h}{v} + \cdots\right) \qquad \begin{array}{l} h = \pi^4 - \theta \\ v \equiv f \sin\theta \end{array}$$

The first **prediction** is a shift in the Higgs couplings

$M_W = (g\, f/2) \sin\theta$

- Large f, SM-limit
- f=v, Technicolor-limit

LHC data suggest
f>5-600 GeV

$\Sigma = (0,0,0,\mathrm{Sin}(h/f),\mathrm{Cos}(h/f))$

θ is determined dynamically

Indirect effects in Composite Higgs

SO(4) avoids large custodial breaking: after EWSB there is a residual SO(3)

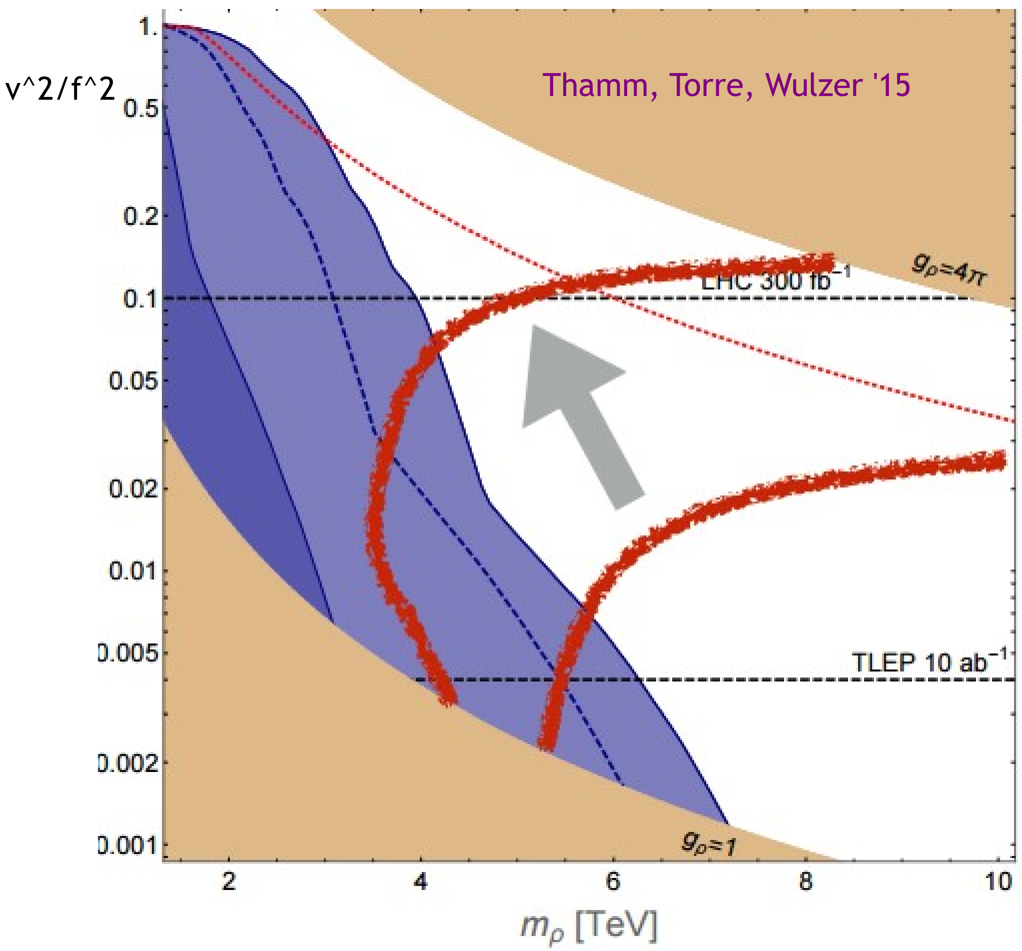
- T-parameter: zero at tree-level
- S-parameter: generated at tree-level by resonances $\simeq m_W^2/m_\rho^2$
- Modified Higgs couplings generate a contribution to S and T via running

$$S \simeq +\frac{1}{12\pi t_w^2}\frac{v^2}{f^2}\log\frac{m_\rho^2}{m_h^2}$$

$$T \simeq -\frac{3}{16\pi c_w^2}\frac{v^2}{f^2}\log\frac{m_\rho^2}{m_h^2}$$

Strict EWPTs require f > TeV.

It is easy to find UV contributions from fermions and relax this bound at a level comparable with Higgs couplings constraints



Matsedonskyi et al, Contino et al '13

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

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

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

mψ 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

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

*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)

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

no light fermions, but large tuning

- qL in the **14**

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

mΨ not in VEV, but in mh

The search for top partners

Given that the Higgs mass requires mΨ ~ f,
direct searches are more powerful than precision constraints*

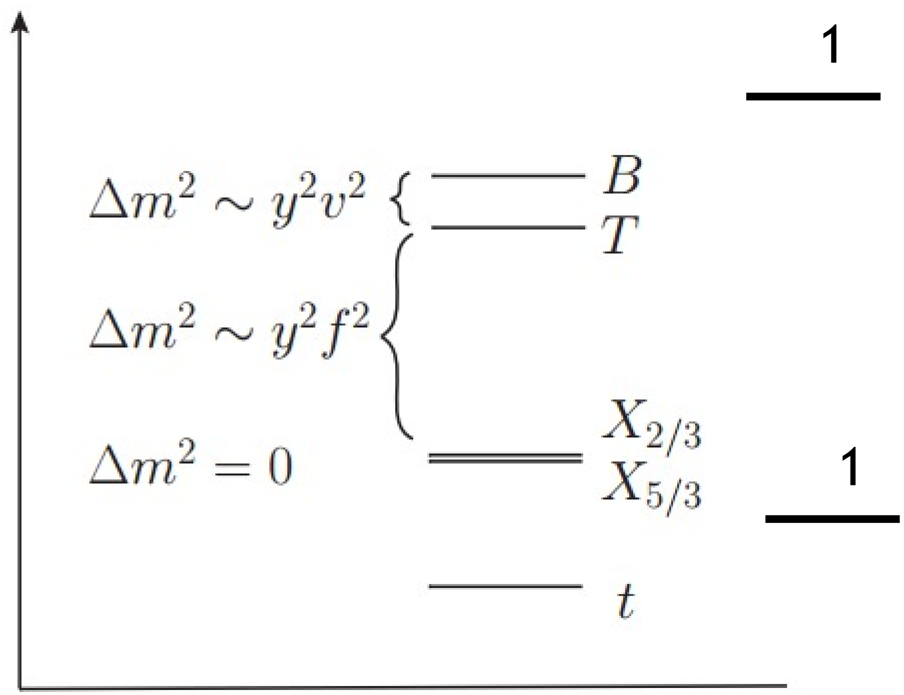
Ψ is a complete multiplet of SO(5), usually a **5=4+1** of SO(5)

$$\Psi = \frac{1}{\sqrt{2}} \underbrace{\begin{pmatrix} iB - iX_{5/3} \\ B + X_{5/3} \\ iT + iX_{2/3} \\ -T + X_{2/3} \end{pmatrix}}_{\mathbf{4}} + \mathbf{1}$$

Lightest state has 5/3 e-charge,
X5/3 → W + top

mΨ > 800 GeV

pair produced



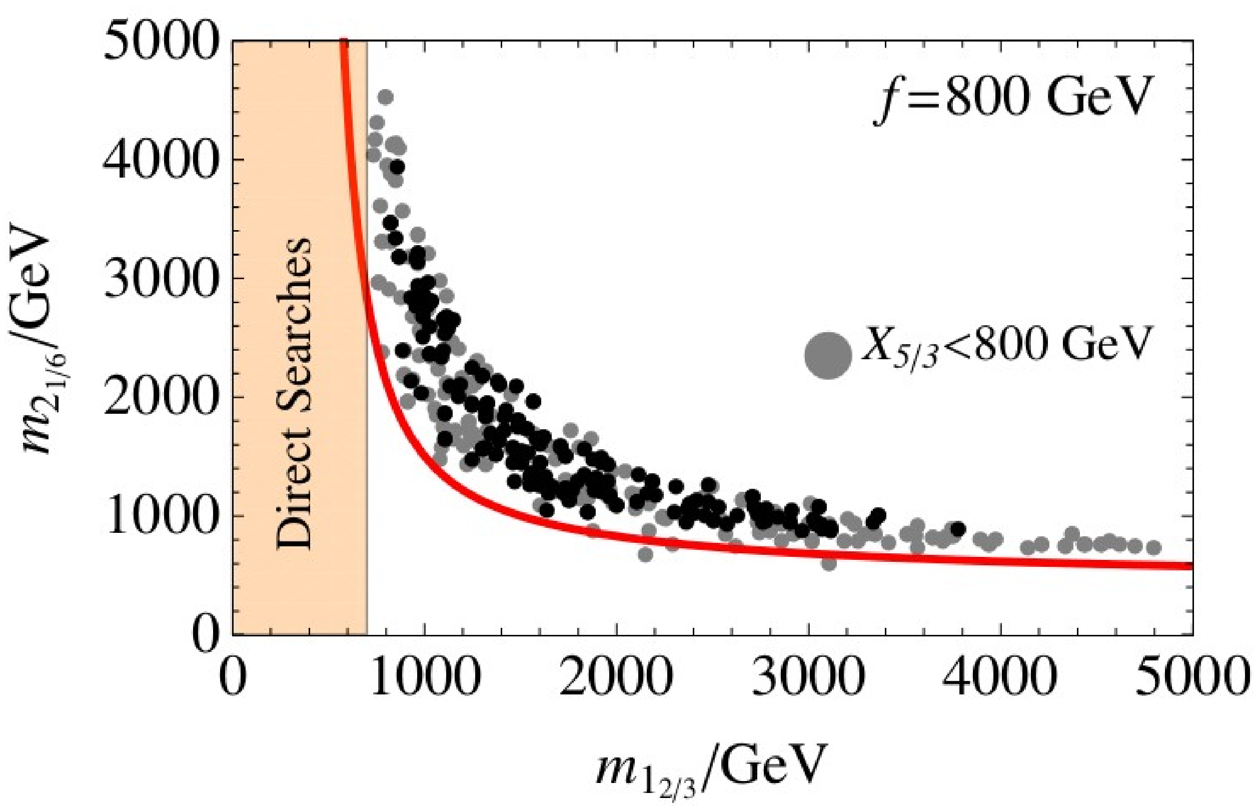
De Simone, Matsedonskyi, Rattazzi, Wulzer

An explicit model

Using a 3-site model we can compute the Higgs potential (at 1-loop)
The finiteness of the potential depends on the number of resonances below $4\pi f$

When we focus on the 2 lightest top-partners

$$m_h^2 \simeq \frac{N_c}{\pi^2}\frac{m_t^2}{f^2}\frac{m^2_{\mathbf{2}_{1/6}}\, m^2_{\mathbf{1}_{2/3}}}{m^2_{\mathbf{2}_{1/6}} - m^2_{\mathbf{1}_{2/3}}}\log\frac{m^2_{\mathbf{2}_{1/6}}}{m^2_{\mathbf{1}_{2/3}}}$$



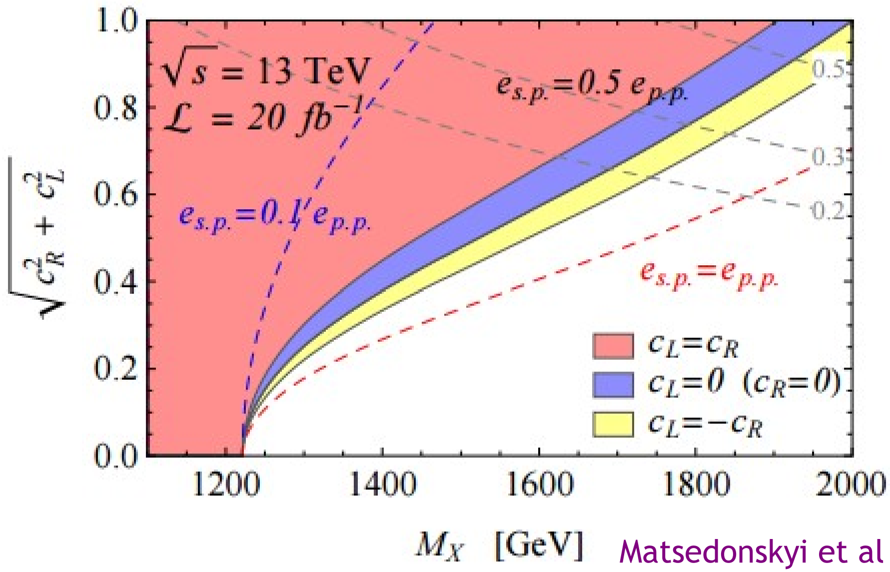
- LHC14 will explore the relevant regions
- Here f is fixed at the target value of LHC14
- Raising f does not change the Higgs mass (only v^2/f^2 corrections)

Summary of Composite Higgs

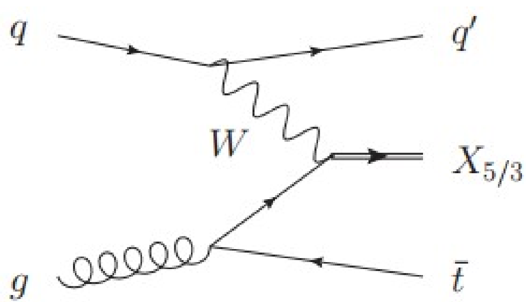
Composite Higgs models at LHC14

Composite Fermions

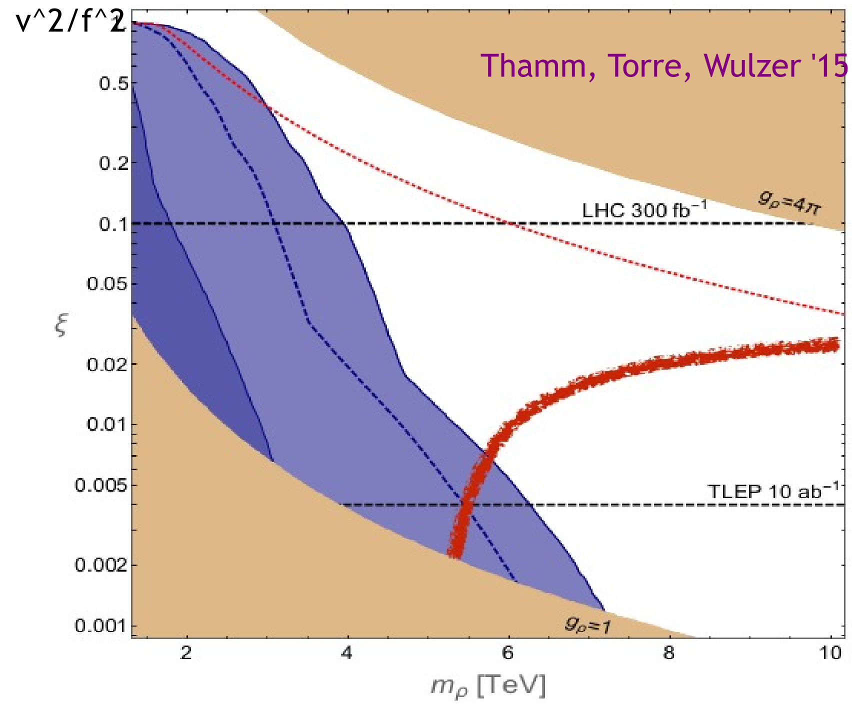
Single production might be relevant



Matsedonskyi et al '14

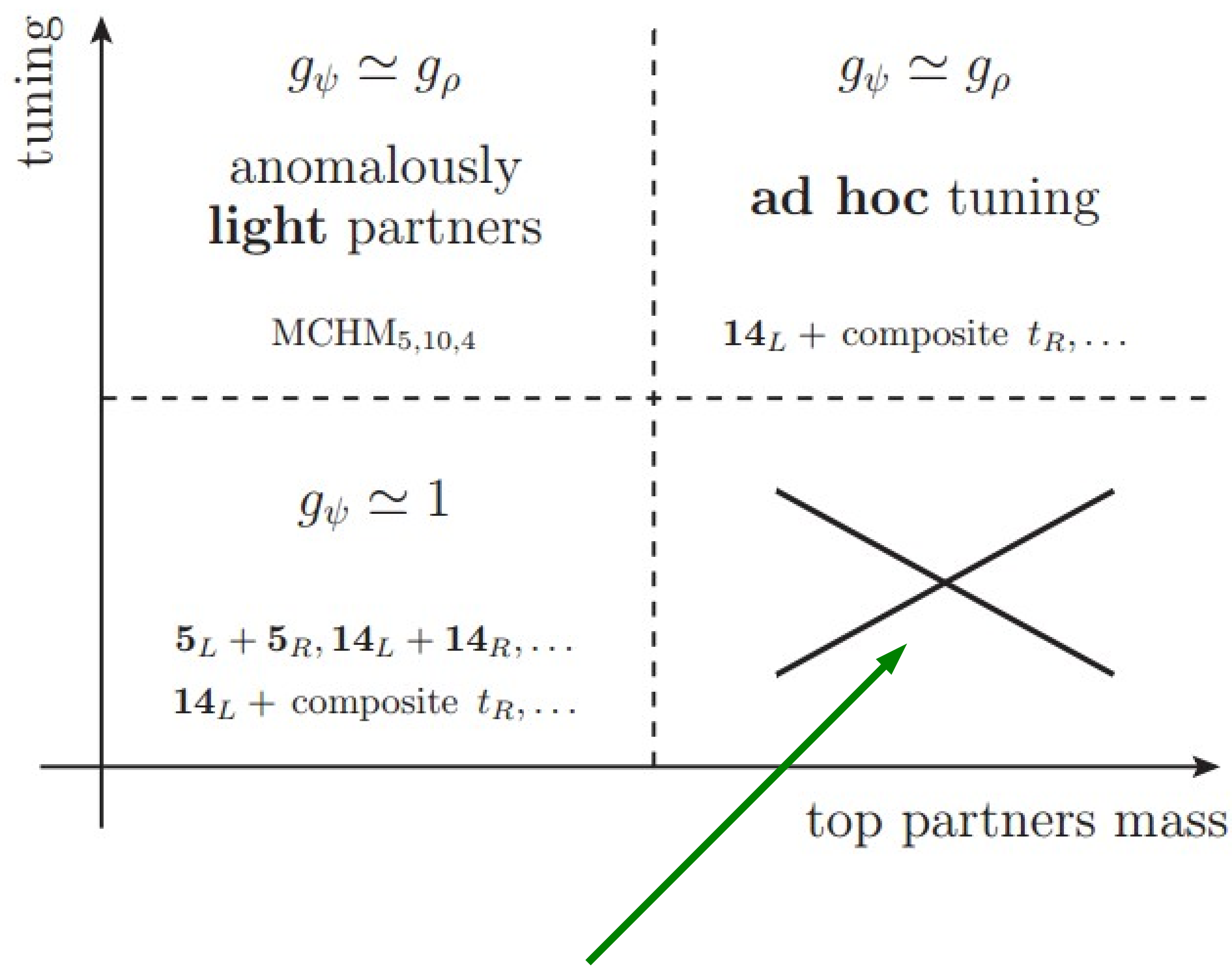


Composite Vectors



“trivial” phenomenology

An open question:



Is it really impossible to fill in that region?

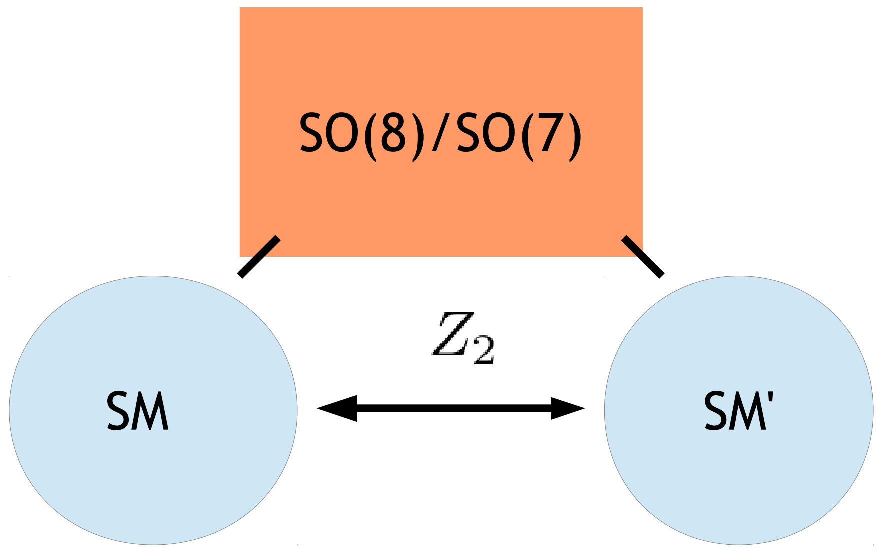
Twin Higgs and Composite Higgs

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)'

Resonances in the model

- 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

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

Under the action of Z2

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

Why not SU(4)/SU(3) ?

SU(4)/SU(3) describes the same 7 GBs

However the twin mechanism fails in the gauge sector

$$a|D_\mu\Sigma|^2 + b(\Sigma^\dagger D_\mu\Sigma)^2 + (\text{mirror})$$

Barbieri, Greco, Rattazzi, Wulzer

$$V(h) \sim ag^4 f^4 s_h^2 c_h^2 + bg^2 g_\rho^2 s_{2h}^2 \sim O(g^2) \quad \text{not } O(g^4)$$

The second invariant breaks also the custodial symmetry

Chacko, Goh, Harnik '05

Maybe this is only a problem of strongly coupled theories,
where anything that is not forbidden by some symmetry it will happen

V(h) from the top-sector

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

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

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

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

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

> 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)

$$V(h)_{\rm TH} \simeq \frac{N_c}{16\pi^2}\Big[-\underbrace{a y^4 f^4 s_h^2 c_h^2}_{Z2} + \underbrace{b\, y^2 f^2 m_\Psi^2 s_h^2}_{\cancel{Z2}} \Big].$$

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 $m_\psi \neq m_{\psi'}$, 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

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

> 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 m_ρ ~ 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)

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

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

from top sector
(also the log)

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

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:

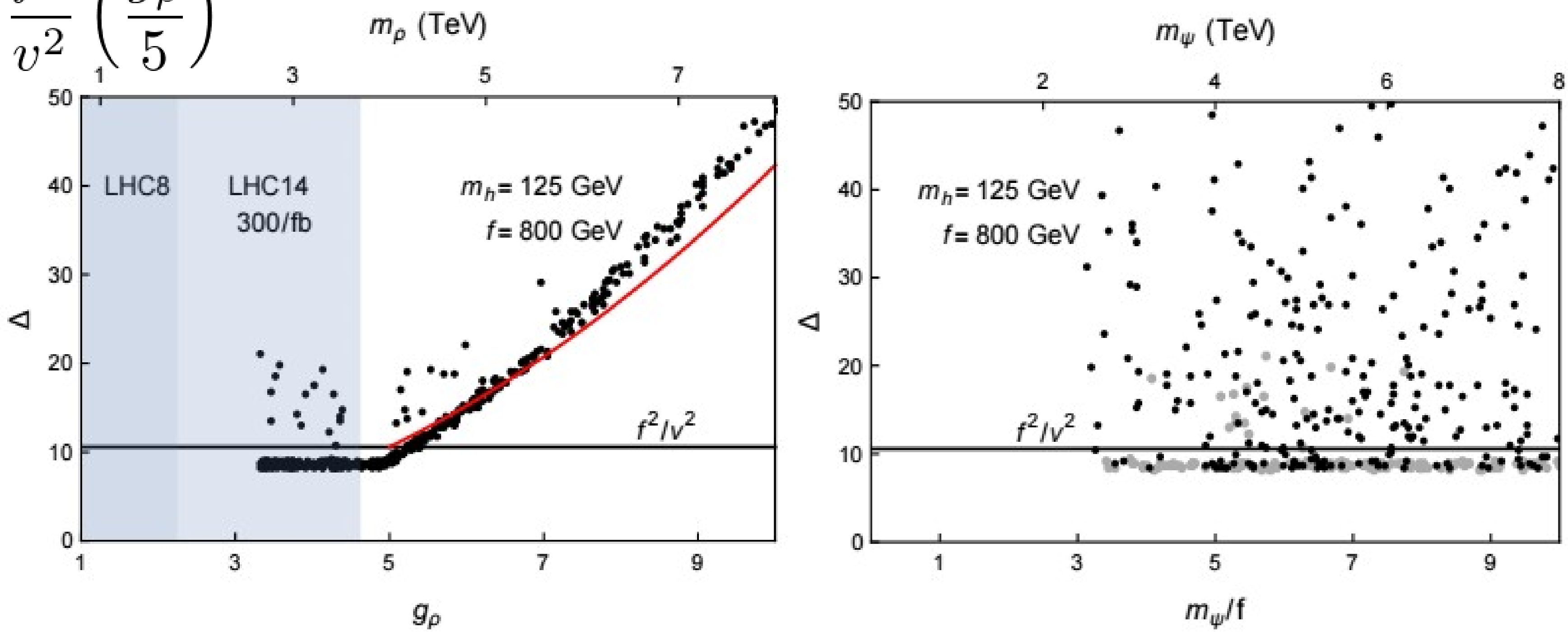
$$m_h^2 \simeq \frac{N_c y_t^4 v^2}{4\pi^2} \left[\log\left(\frac{\bar{m}_{\mathbf{1}}^2}{m_{t'} m_t}\right) - 5\left(1 - \frac{4}{5}\frac{\bar{m}_{\mathbf{7}}^2}{\bar{m}_{\mathbf{7}}^2 - \bar{m}_{\mathbf{1}}^2} \log\left(\frac{\bar{m}_{\mathbf{7}}^2}{\bar{m}_{\mathbf{1}}^2}\right)\right)\right]$$

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

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

Sensitivity to parameters

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

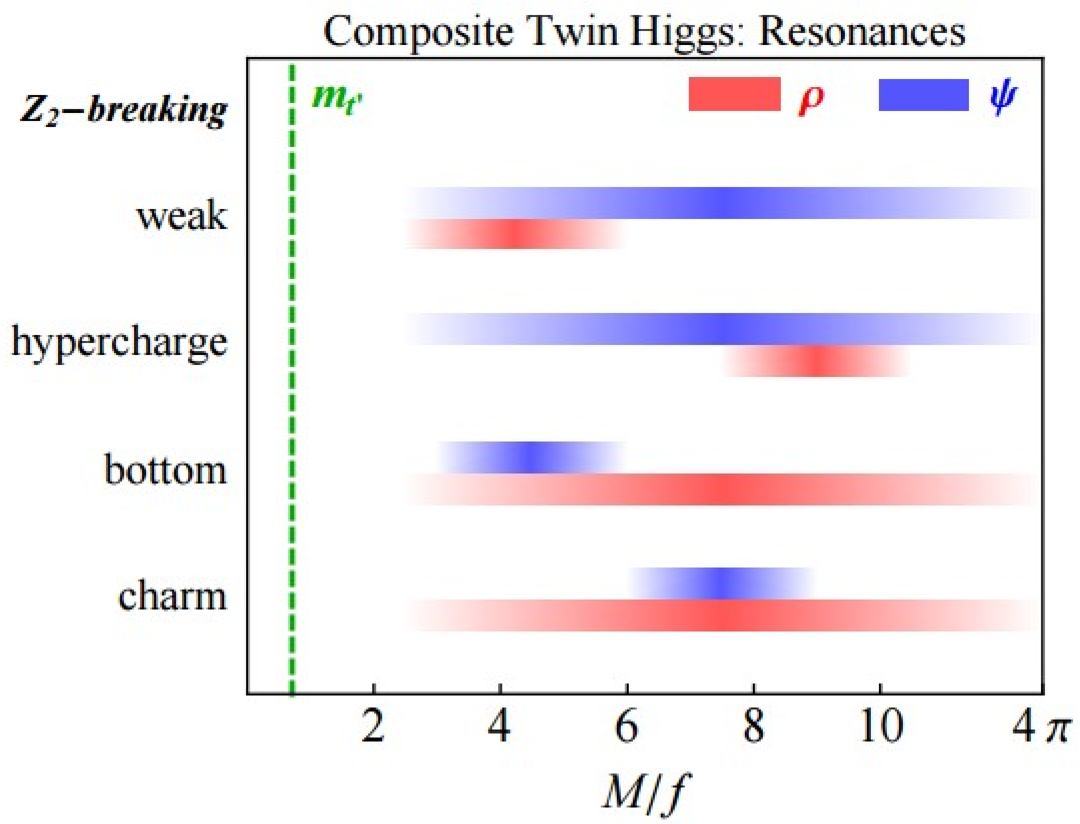


- > dependence on grho above 4-5
- > No correlation with the fermionic parameters
- > O(1) estimates respected

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

Phenomenology of the mirror sector

It is highly model dependent

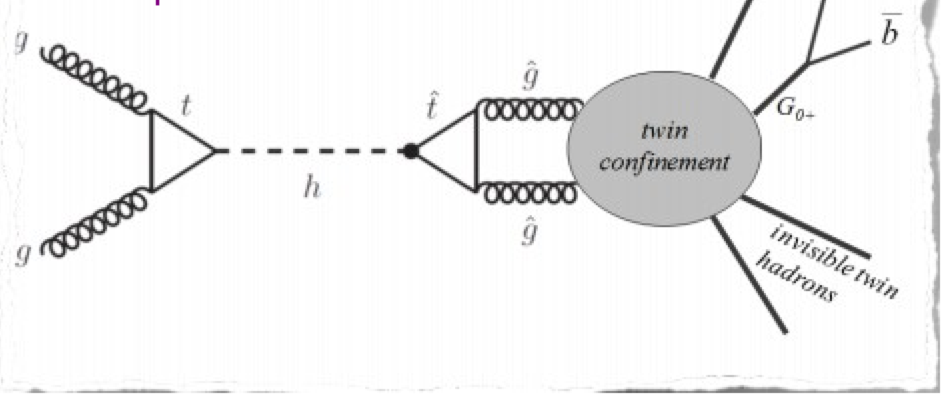
The mirror particles can be produced through the Higgs

$$y_b' \frac{v}{f} h \bar{b}' b', \qquad \frac{\alpha_S'}{4\pi} \frac{v}{f} \frac{h}{f} {G'_{\mu\nu}}^2$$

Do they decay back to us?

They can decay back to the Higgs (if sufficiently light)
mirror glueballs and bottomonium decays

A. Katz at CERN workshop



Challenging at the LHC

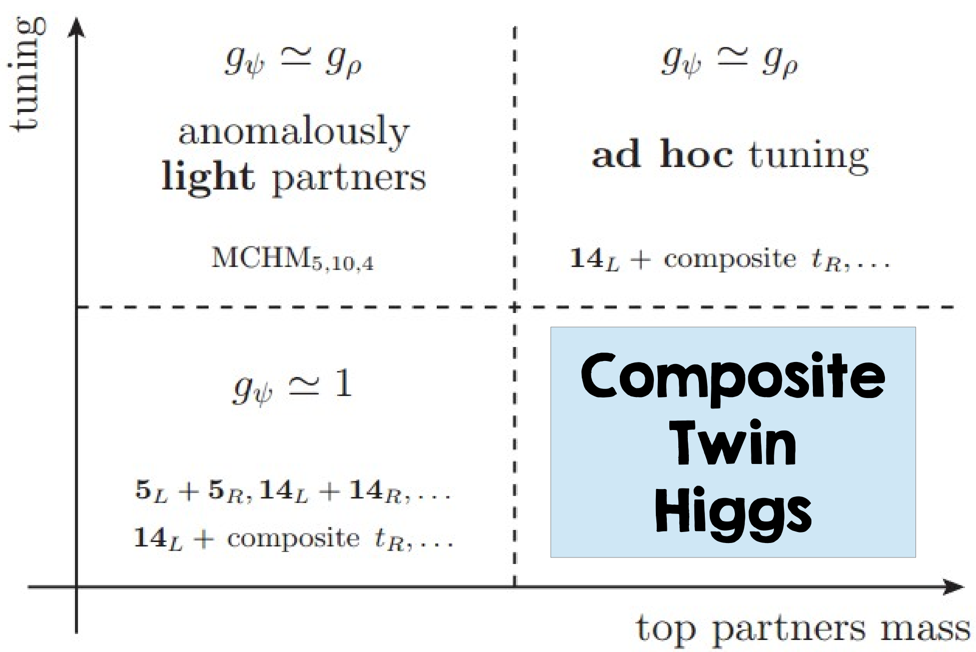
look for displaced b's

D.Curtin at CERN workshop

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



Thank you!