IVICFA **Friday's Miniworkshops**

Theoretical Physics II

November 23, 2012

Strong EWSB at the LHC Era

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Strong EWSB at the LHC Era

A journey to the composite world
(with selected stops)

Outline

- What's wrong with the SM (Higgs)?
- A cuter version: composite Higgs
- How to survive the (killer) LHC (in a natural way)
- Weak vs strong coupling
- Strongly interacting light Higgs
- Selected topics in CHM phenomenology
- Summary

What's wrong with the SM (Higgs)

- It is not natural:
  - The mass of an elementary scalar is sensitive to any UV scale in the theory (it would be the first elementary scalar found in Nature)
- Does not EXPLAIN many features, like flavor (mass hierarchies and mixing angles, number of generations, neutrino masses, …)
- Cannot even ACCOMMODATE some observations: Dark Matter, ...

A cuter version: composite Higgs

- Can we make it natural? Make it composite!
  - We have observed many light composite scalars
- The mass is protected by its finite size
  - Above the compositeness scale new dynamics appears without light elementary scalars
- New ingredient: new (nearly conformal) sector that becomes strongly coupled and condenses around the TeV scale
  - The Higgs is a resonance of the strong sector

Low energy QCD: an excellent analogy!

How to Survive the Killer LHC

- New Strong sector with largish coupling to some SM particles (top, W, Z)
  - Relatively heavy resonances: $m_\rho \gtrsim 2.5 \text{ TeV } (\hat{S})$
  - Custodial symmetry: strong sector has an unbroken O(4) global symmetry
    - $\hat{T}$ parameter
    - $Z b_L \bar{b}_L$ coupling
  - Partial compositeness: SM sector (minus the Higgs) is external to the Strong sector. The two sectors talk through linear couplings
    - SM (and new) particles are an admixture of elementary and composite states

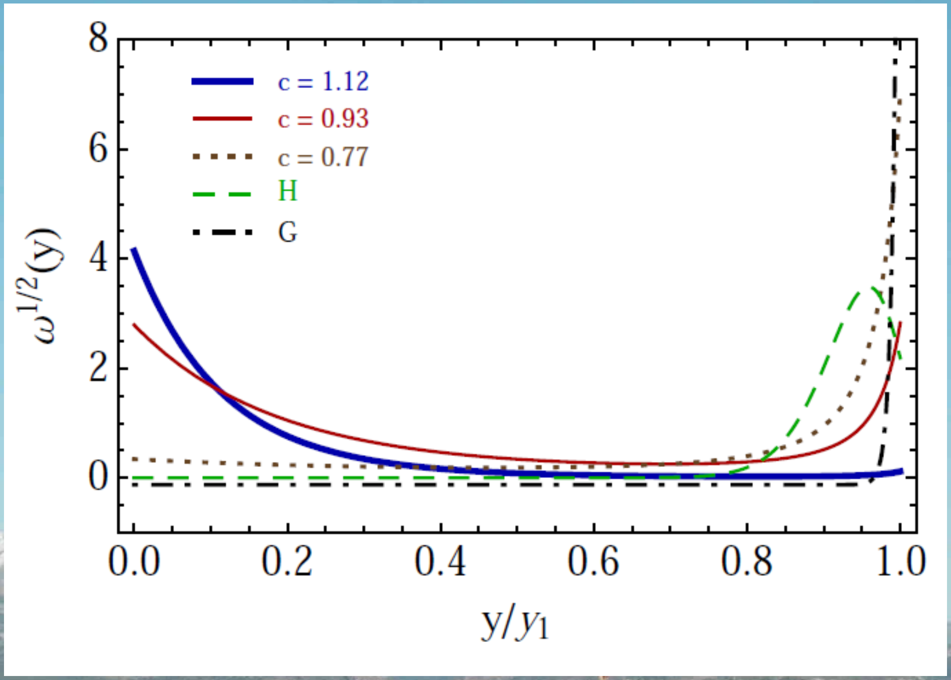
Is custodial symmetry necessary?

- Departure from conformal invariance at ~ TeV could avoid the need of custodial symmetry

Cabrer, Gersdorff, Quirós '10-'11

- Detailed analyses in 5D dual models give a bound $m_\rho \gtrsim 2.3\ \mathrm{TeV}$

Carmona, Pontón, Santiago '11



  - What is the natural cut-off for the Higgs mass?

    This can only be answered if the Higgs is a pNGB

    Perez-Victoria, Santiago, Setzer in progress

How to Survive the Killer LHC (in a natural way)

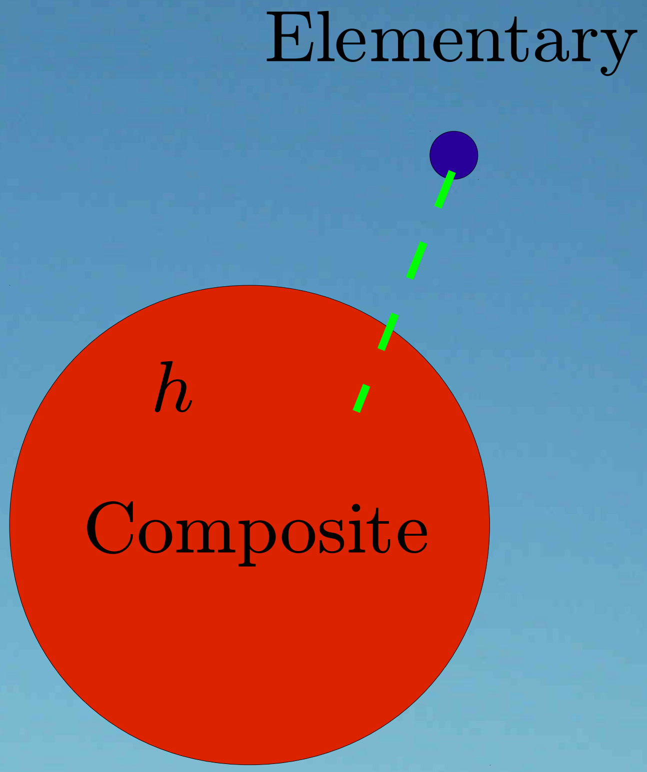
- We can solve the little hierarchy problem if the Higgs is a pNGB
  - Strong sector: exact global symmetry G spontaneously broken to H
  - Elementary sector explicitly breaks the symmetry

$$m_h^2 \sim \frac{g^2}{16\pi^2} m_\rho^2 \ll \text{ TeV}^2 \text{ (despite } m_\rho \gtrsim 2.5 \text{ TeV)}$$

Weak coupling!

Higgs as a composite pNGB

- Two-scale breaking:
  - G (global symmetry of the strong sector) spontaneously broken to H at a scale f~TeV
    - SM $\subset$ H unbroken
    - Higgs is a NGB in G/H
  - G explicitly broken by the elementary sector
    - Higgs potential generated at one loop (v=246 GeV)
    - $\xi = v^2/f^2$ suppression of EWPO (and measure of fine-tuning)



How do we compute?

Weak vs Strong EWSB

- Assume SO(4)/SO(3) custodial pattern

$$\Sigma = \exp(i\sigma^I \chi^I(x)/v) \qquad v = 246 \text{ GeV}$$

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left[1 + 2\underline{a}\,\frac{h}{v} + b\,\frac{h^2}{v^2} + \ldots\right]$$

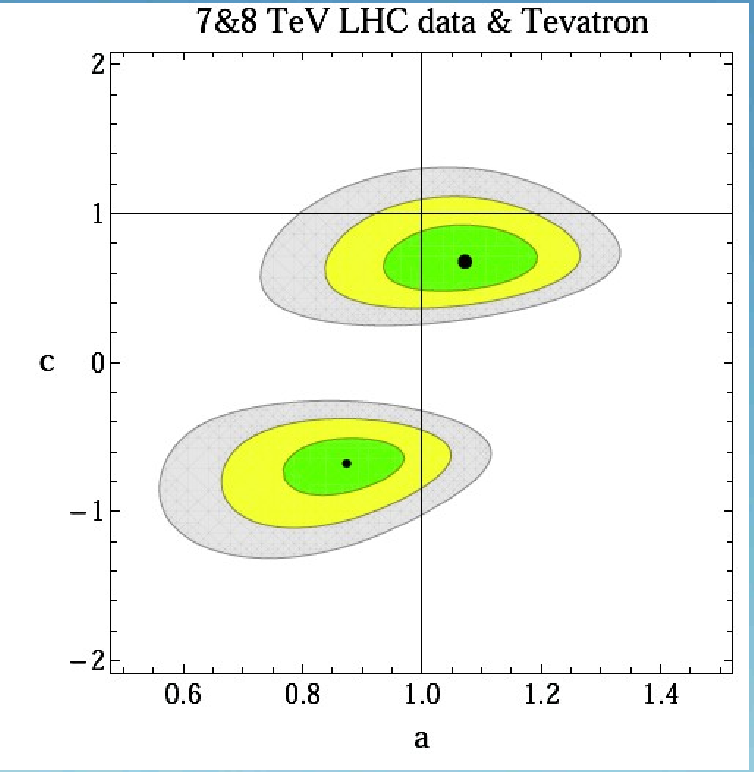
$$- m_i\,\bar{\psi}_{Li}\,\Sigma\left(1 + \underline{c}\,\frac{h}{v} + \ldots\right)\psi_{Ri} + \text{h.c.}\,,$$

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\,\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots$$

- SM (weak EWSB) $a = b = c = d_3 = d_4 = 1, \quad \ldots = 0$
- Otherwise strong EWSB

Weak vs Strong EWSB

- Higgs data starting to put constraints

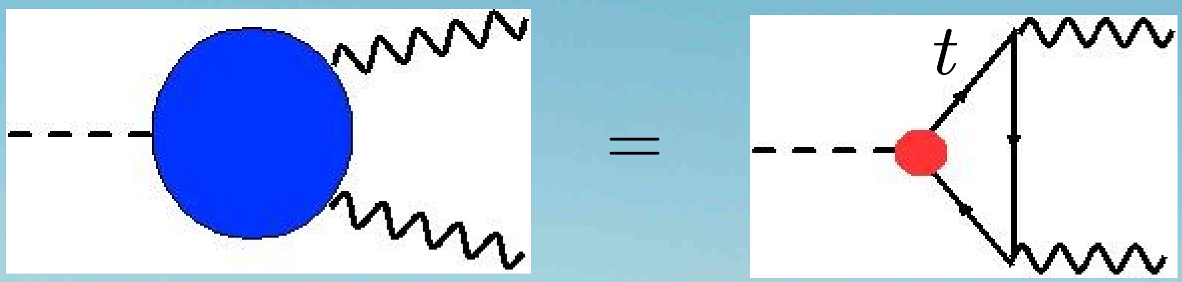


  - Effective negative top Yukawa driven (partly) by $\gamma\gamma$ excess
  - Degeneracy could be lifted through the process $pp \to thj(b)$
  - But things might be more interesting: two types of top Yukawa couplings
    - “Tree level” λ_t
    - “Loop level” λ_t

Azatov, Contino, Galloway '12; Corbett, Eboli, González-Fraile, González-García '07; Giardino, Kannike, Raidal, Strumia '12; Montull, Riva '12; Espinosa, Grojean, Muhlleitner, Trott '12; Carmi, Falkowski, Kuflik, Volansky, Zupan '12

Effective top Yukawa coupling

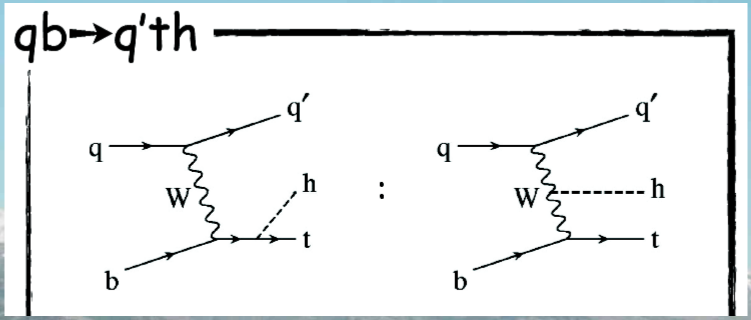
- Top Yukawa receives corrections from two sources:
  - Non-linear Higgs effects: fixed by symmetry
  - From mixing with top partners: spectrum dependent
- In some cases, symmetry guarantees that only the first one contributes to $H \to gg, \gamma\gamma$



Azatov, Galloway '11

Effective top Yukawa coupling

- Interesting situation
  - $\lambda_t \sim -1$ as effectively measured from $H \to gg, \gamma\gamma$ and determined purely from symmetry
  - Real λ_t can be quite different from -1, with the differences giving information on the spectrum
- $pp \to Hqt$: sensitive to the sign of λ_t
  - Some info at LHC8, sign determined at LHC14



Farina, Grojean, Maltoni, Salvioni, Thamm, '12

Not necessarily the same coupling!

Chala, Santiago in progress

One step further: SILH

- Strongly interacting light Higgs (SILH)
  - H is the only pNGB
  - Unique scale in the strong sector $m_\rho = g_\rho f$
  - Global symmetry explicitly broken by elementary sector with coupling $g \ll g_\rho \lesssim 4\pi$

Giudice, Grojean, Pomarol, Rattazzi '07

$$\mathcal{L}_{\rm SILH} = \frac{c_H}{2f^2}[\partial_\mu(H^\dagger H)]^2 + \frac{c_T}{2f^2}[H^\dagger \overleftrightarrow{D}_\mu H]^2$$

$$-\frac{c_6\lambda}{f^2}[H^\dagger H]^3 + \left[\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right]$$

$$+\frac{\mathrm{i}c_W g}{2m_\rho^2}[H^\dagger \sigma^I \overleftrightarrow{D}_\mu H][D_\nu W^{\mu\nu}]^I + \frac{\mathrm{i}c_B g'}{2m_\rho^2}[H^\dagger \overleftrightarrow{D}_\mu H][\partial_\nu B^{\mu\nu}]$$

One step further: SILH

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$$\hat{T} = c_T \xi$$

$$\hat{S} = (c_W + c_B)\frac{m_W^2}{m_\rho^2}$$

$$c_T = 0 \ (\mathrm{custodial\ symm.})$$

$$m_\rho \gtrsim 1.6 - 2.5\sqrt{c_W + c_B}\ \mathrm{TeV}$$

One step further: SILH

- Back to non-custodial symmetry

Perez-Victoria, Santiago, Setzer in progress

- SU(2)xU(1) with Higgs as a pNGB

$$SU(3) \times U(1)_X \to SU(2) \times U(1) \times U(1)$$

- $c_T = 1/4$ fixed by the symmetry breaking pattern (independent of conformal symmetry breaking)
- T receives contribution from excitations of B and Z', the two combine in a spectrum independent value

Custodial symmetry seems necessary in natural models

Building specific CHMs

- Further progress can be made specifying the symmetry breaking pattern

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
$\mathrm{SO}(5)$	$\mathrm{SO}(4)$	4	$\mathbf{4} = (\mathbf{2},\mathbf{2})$
$\mathrm{SO}(6)$	$\mathrm{SO}(5)$	5	$\mathbf{5} = (\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
$\mathrm{SO}(6)$	$\mathrm{SO}(4)\times\mathrm{SO}(2)$	8	$\mathbf{4}_{+\mathbf{2}} + \bar{\mathbf{4}}_{-\mathbf{2}} = 2\times(\mathbf{2},\mathbf{2})$
$\mathrm{SO}(7)$	$\mathrm{SO}(6)$	6	$\mathbf{6} = 2\times(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$
$\mathrm{SO}(7)$	G_2	7	$\mathbf{7} = (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
$\mathrm{SO}(7)$	$\mathrm{SO}(5)\times\mathrm{SO}(2)$	10	$\mathbf{10}_{\mathbf{0}} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
$\mathrm{SO}(7)$	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3}) = 3\times(\mathbf{2},\mathbf{2})$
$\mathrm{Sp}(6)$	$\mathrm{Sp}(4)\times\mathrm{SU}(2)$	8	$(\mathbf{4},\mathbf{2}) = 2\times(\mathbf{2},\mathbf{2}), (\mathbf{2},\mathbf{2}) + 2\times(\mathbf{2},\mathbf{1})$
$\mathrm{SU}(5)$	$\mathrm{SU}(4)\times\mathrm{U}(1)$	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{+\mathbf{5}} = 2\times(\mathbf{2},\mathbf{2})$
$\mathrm{SU}(5)$	$\mathrm{SO}(5)$	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

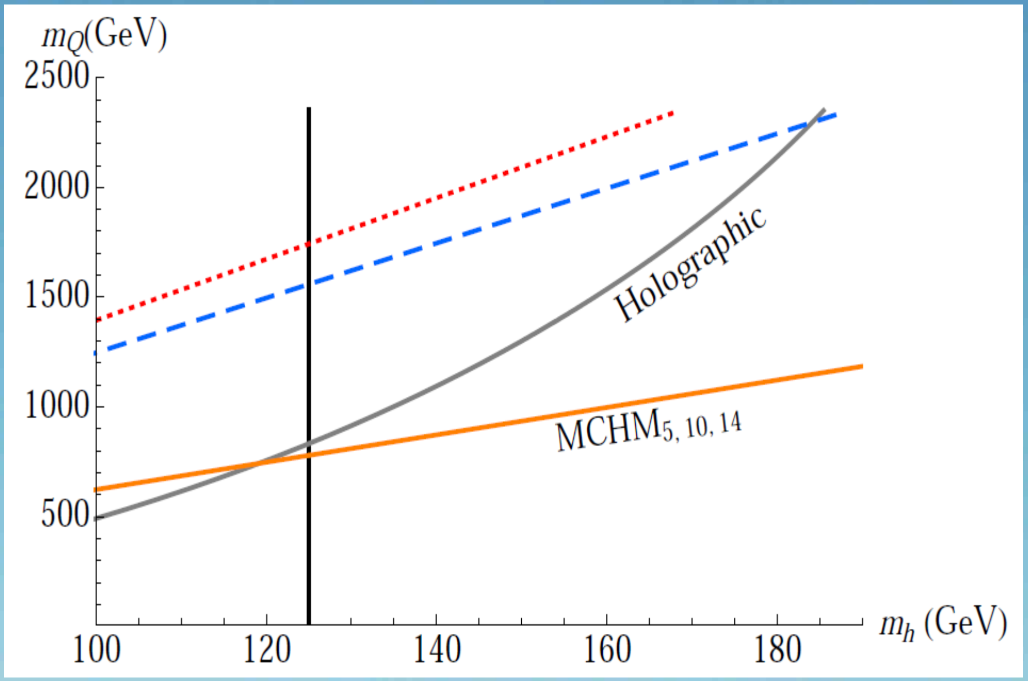
Building specific CHMs

- Further progress can be made specifying the symmetry breaking pattern
- The only extra ingredient is the quantum numbers of the fermions (resonances that mix with the elementary fields)
- Minimal Composite Higgs Model: SO(5)/SO(4)
  - Custodial symmetry
  - Just 4 Goldstones transforming in the (2,2)
  - Excellent playground
  - Fermion representations: 4, 5, 10, ...

Agashe, Contino, Da Rold, Pomarol '04-'06

MCHM

- 125 GeV Higgs introduces new constraints
  - Light top partners (custodians) in natural models



Top partners: New vector-like quarks related to the top by the symmetries of the strong sector

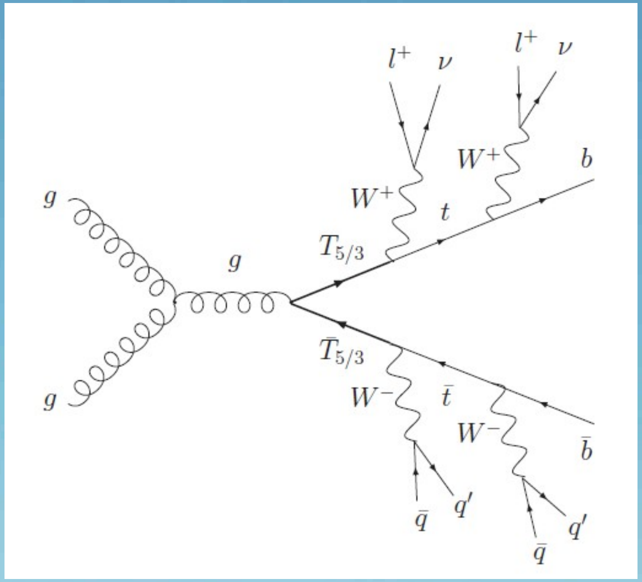
Hipothesis on form factors: Weinberg sum rules, holographic models

Pomarol, Riva '12; Matsedonskyi, Panico, Wulzer '12; Redi, Tesi '12; Marzocca, Serone, Shu '12; Panico, Redi, Tesi, Wulzer '12

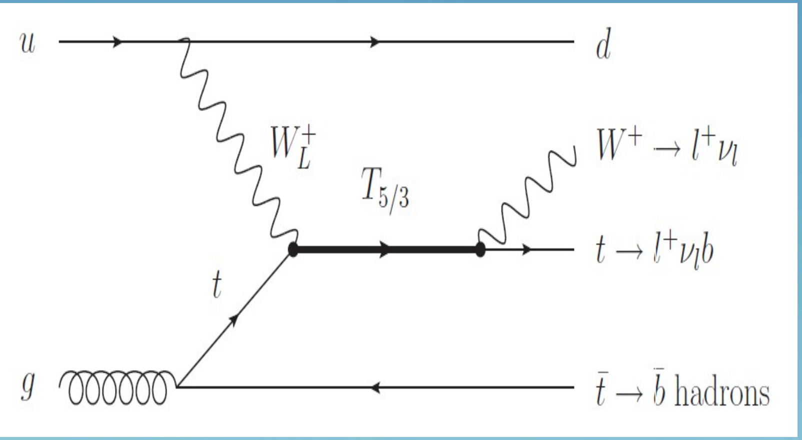
MCHM

- 125 GeV Higgs introduces new constraints
  - Light top partners (custodians) in natural models

Contino, Servant '08



Mrazek, Wulzer '09

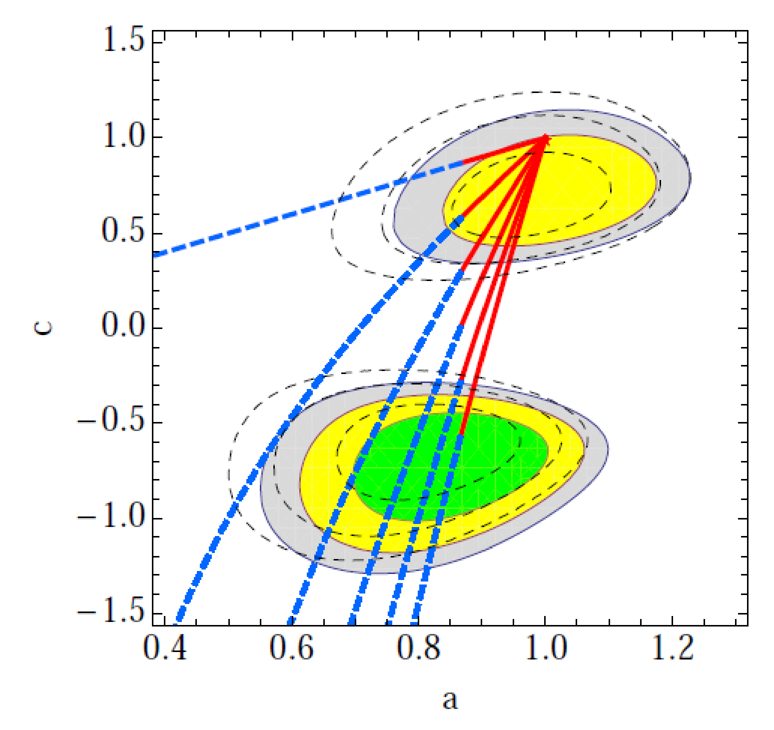


- Excellent reach if light, can be tested up to $M \sim 1.5$ TeV

Aguilar-Saavedra '09
Dissertori, Furlan, Moorgat, Nef '10

MCHM

- Can we also fit the Higgs rates?



- Yes … in non-minimal models
  - Larger fermion representations in MCHM   Pomarol, Riva '12
  - Go beyond MCHM: SO(6)/SO(5) has an extra singlet
    - Can help with Higgs fits

      Gripaios, Pomarol, Riva, Serra '09
      Montull, Riva '12
      Chala, Grojean, Santiago in progress

    - Can serve as DM

      Frigerio, Pomarol, Riva, Urbano '12

Light quark custodians

- Flavor constraints in CHM can be avoided by imposing MFV

Redi, Weiler '11

- u_R can be very composite: light up custodians with a large mixing to u_R

Atre, Carena, Han, Santiago '08

Atre, Azuelos, Carena, Han, Ozcan, Santiago, Unel '11

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\psi}^{(i)} \not{D} \psi^{(i)} - M \bar{\psi}^{(i)} \psi^{(i)}$$

$$-\lambda' [\bar{\psi}^{(1)} \tilde{\phi} + \bar{\psi}^{(2)} \phi] u_R + \text{h.c.}$$

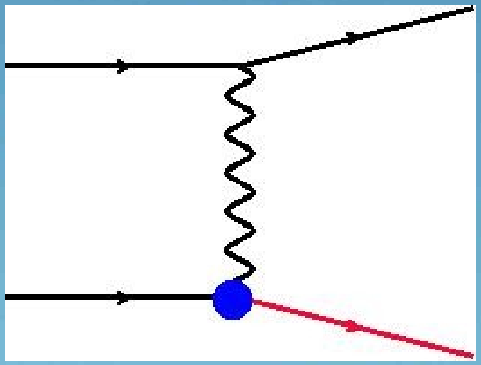
Atre, Chala, Santiago in progress

$$\psi^{(1)} = \begin{pmatrix} U \\ D \end{pmatrix} \qquad \psi^{(2)} = \begin{pmatrix} X \\ U \end{pmatrix}$$

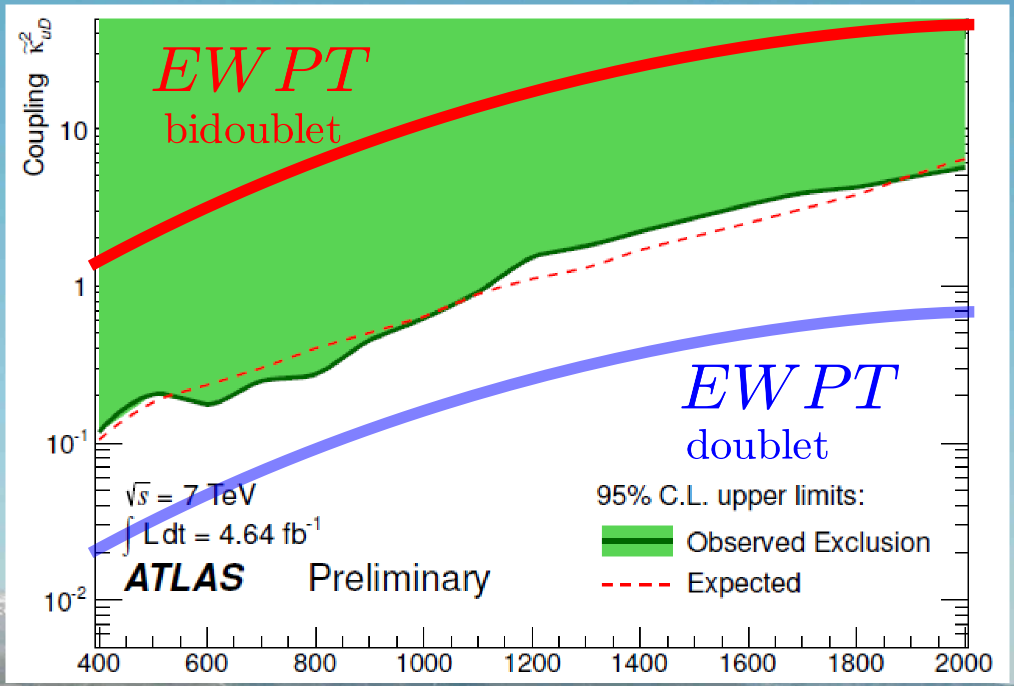
- No indirect constraints even for large λ'

Light quark custodians

- u (or d) custodians can be ideally searched for in single production



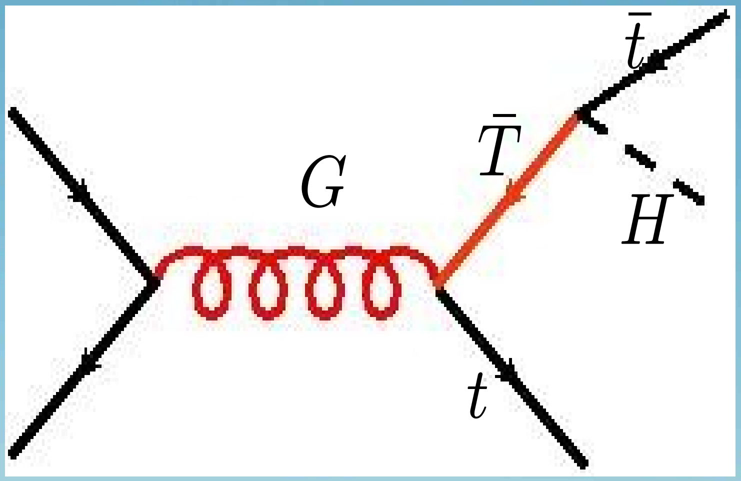
Atre, Carena, Han, Santiago '08
Atre, Azuelos, Carena, Han, Ozcan, Santiago, Unel '11
ATLAS PLB (12)
ATLAS-CONF-2012-137



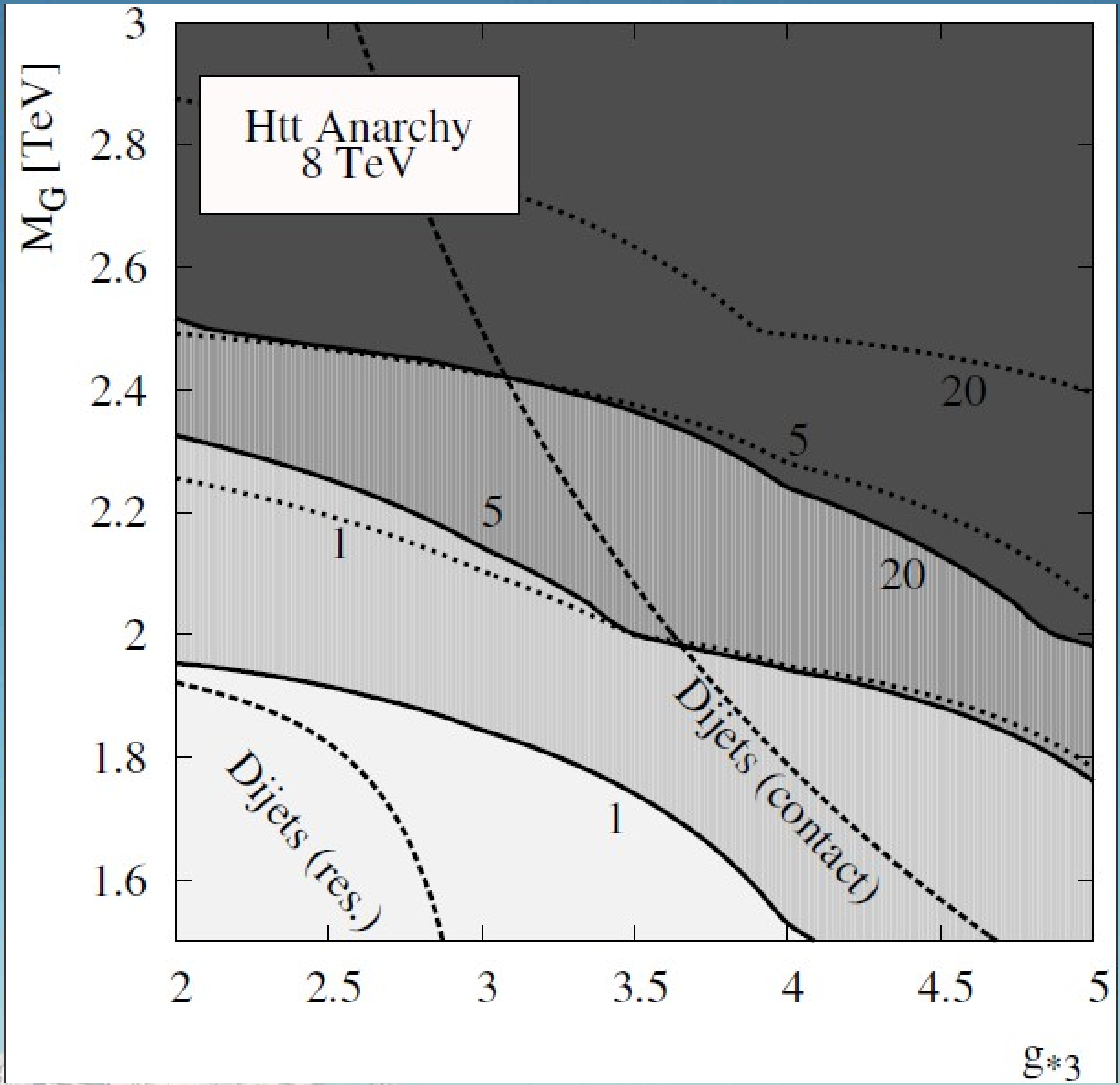
New Production Mechanisms

- Other (heavier) resonances also predicted in models of strong EWSB
- Heavy gluons can mediate new (Higgs) production mechanisms

Carmona, Chala, Santiago '12



  - Sizeable cross section and distinctive kinematics
  - Independent of top Yukawa coupling (not the standard Htt)
  - Can also use u custodians: Hjj with two hard (as opposed to forward) jets



Htt Anarchy
8 TeV
M_G [TeV]
3
2.8
2.6
2.4
2.2
2
1.8
1.6
2
2.5
3
3.5
4
4.5
5
g_{*3}
20
5
20
5
1
1
Dijets (contact)
Dijets (res.)

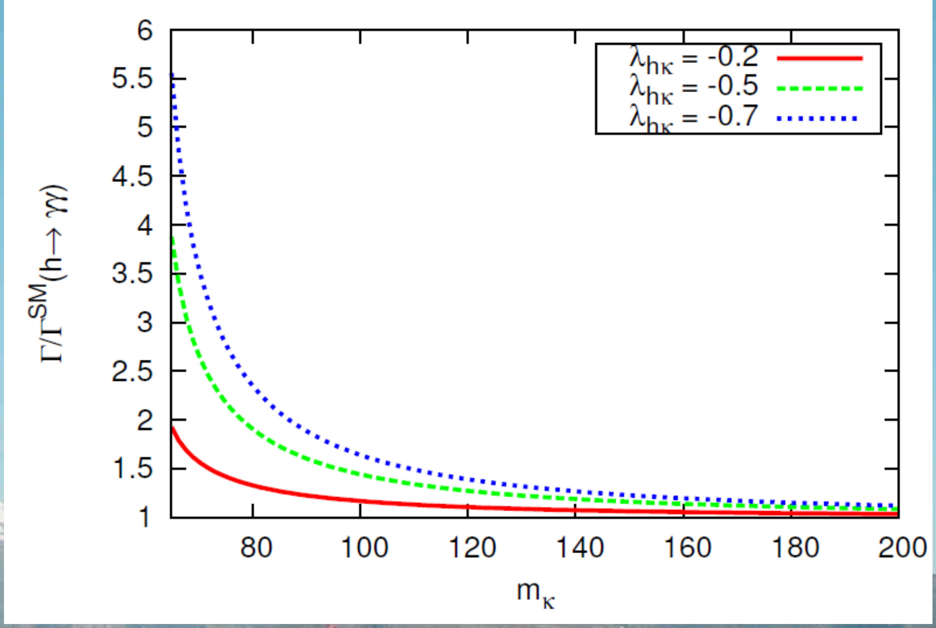
New Production Mechanisms

- Other (heavier) resonances also predicted in models of strong EWSB
- Heavy gluons can mediate new (Higgs) production mechanisms
- EW decays also interesting (might be relevant for the tt forward-backward asymmetry)

Barcelo, Carmona, Chala, Masip, Santiago '11
Bini, Contino, Bignaroli '11

SO(7)/G2: di-photons and DM

- Minimal models don't explain the diphoton excess or dark matter — Chala '12
- SO(7)/G2 has 7 NGB: $\phi, \eta, \kappa^{\pm}$
  - η can be stable: dark matter candidate
  - $\kappa^{\pm}$ contributes to $H \to \gamma\gamma$



One final thought

- How do we know H is composite?
  - Compositeness scale is likely beyond the LHC reach
  - Difficult to measure form factors beyond the leading terms in the expansion (could be compositeness or anything else)

$$\mathcal{L}_{\mathrm{SILH}} = \frac{c_H}{2f^2}[\partial_\mu(H^\dagger H)]^2 + \frac{c_T}{2f^2}[H^\dagger \overleftrightarrow{D}_\mu H]^2 - \frac{c_6\lambda}{f^2}[H^\dagger H]^3 + \left[\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \mathrm{h.c.}\right] + \frac{\mathrm{i}c_W g}{2m_\rho^2}[H^\dagger \sigma^I \overleftrightarrow{D}_\mu H][D_\nu W^{\mu\nu}]^I + \frac{\mathrm{i}c_B g'}{2m_\rho^2}[H^\dagger \overleftrightarrow{D}_\mu H][\partial_\nu B^{\mu\nu}]$$

Summary

- Higgs as a composite pNGB with partial compositeness: appealing realization of EWSB
- Natural models require light custodians
  - Top partners and effective top yukawa
  - u, d partners and single production
  - New production mechanisms in association with other resonances
- Non-minimal models can reproduce Higgs data, DM, …