New Production Mechanism for Composite Higgs at the LHC

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Outline

Higgs as a pseudo-Goldstone boson

Light custodians

Two-site model

New composite Higgs production mechanism

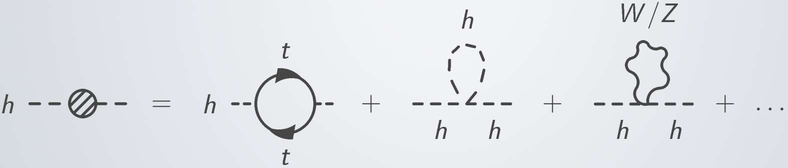
Conclusions

Higgs discovery

CMS and ATLAS have observed a 126 GeV boson

Is it the Higgs boson? Is it a fundamental scalar like in the SM?

In that case there is a hierarchy problem

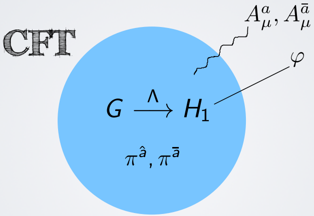


$$\delta m_H^2 = \left(2M_W^2 + M_Z^2 + m_H^2 - 4m_t^2\right)\frac{3G_F\Lambda^2}{16\sqrt{2}\pi^2}$$

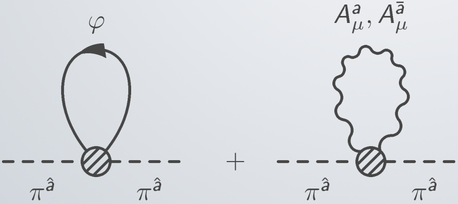
One interesting possibility is that the Higgs is composite, the remnant of some new strong dynamics [Kaplan, Georgi '85]

Composite pseudo-Goldstone bosons

It is particularly compelling when the Higgs is the PGB of some new strong interaction. Something like pions in QCD.



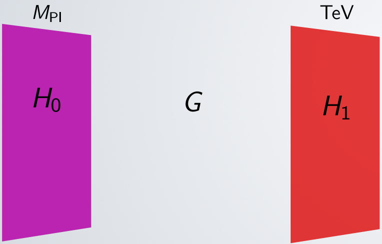
$$\mathcal{L} = \mathcal{L}_{\mathsf{CFT}} - \frac{1}{4} F^{\alpha}_{\mu\nu} F^{\mu\nu\alpha} + A^{\alpha}_{\mu} J^{\mu\alpha} + \varphi \cdot \mathcal{O}_{\varphi}, \quad \alpha = a, \bar{a},$$



$$m_\pi^2 = m_H^2 \sim \frac{g_{\mathrm{el}}^2}{16\pi^2} \Lambda^2$$

AdS/CFT correspondance

Models with warped extra dimensions are weakly coupled duals to strongly coupled 4D conformal theories [Maldacena '98]



$$ds^2 = \left(\frac{R}{z}\right)^2 \left[\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right]$$

$A_\mu^{\hat{a}}(-,-) \quad T^{\hat{a}} \in \mathrm{Alg}\{G/(H_0 \cup H_1)\}$

Model of gauge-Higgs unification

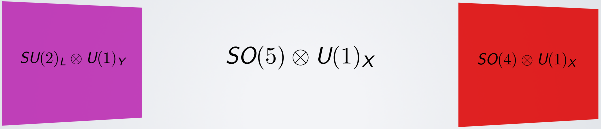
$$A_5^{(0)\hat{a}} \sim H^{\hat{a}}$$

The Higgs is massless at tree-level due to the 5D gauge symmetry, its mass arises radiatively at one-loop. These corrections are finite and UV insensitive.

Minimal Composite Higgs Model

[Agashe,Contino,Pomarol, '04]

We choose $G = SO(5) \otimes U(1)_X$



$SU(2)_L \otimes U(1)_Y$

$SO(5) \otimes U(1)_X$

$SO(4) \otimes U(1)_X$

The minimal group that

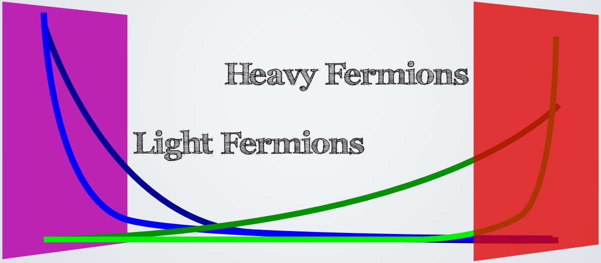
contains the EW group : $SU(2)_L \times U(1)_Y \subset G$

contains the custodial group : $SU(2)_L \times SU(2)_R \sim SO(4) \subset G$

Fermions can transform in the fundamental ($\mathbf{MCHM}_5$) or in the adjoint representation ($\mathbf{MCHM}_{10}$)

Partial compositeness

Fermion masses are given by the overlaps with the Higgs boson, which is peaked towards the IR brane. KK excitations are IR localized too



- The top quark is, due to its large mass, the more composite fermion
- Larger representations required by GHU models can lead to new light resonances, the custodial partners of the top quark

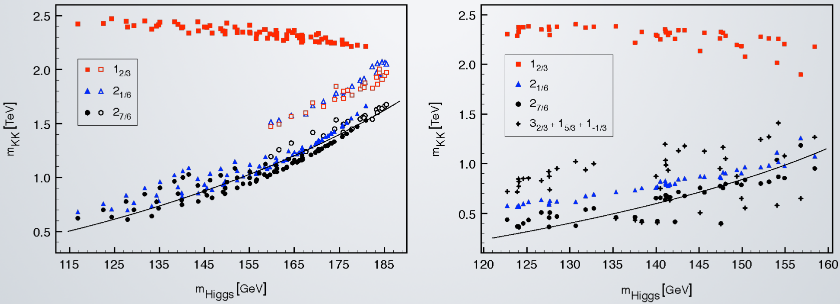
Top Custodians

[Contino,da Rold,Pomarol, '06]

Top quark also responsible for triggering the EWSB

$$V(h) \cong \frac{9}{2} \int \frac{d^4 p}{(2\pi)^4} \log \Pi_W - 2N_c \int \frac{d^4 p}{(2\pi)^4} \log \left(p^2 \Pi_{t_L} \Pi_{t_R} - \Pi^2_{t_L t_R} \right)$$

$$m_h \approx \sqrt{\frac{N_c}{2} \frac{y_t}{\pi} \frac{m_q^*}{f_\pi}}\, v$$



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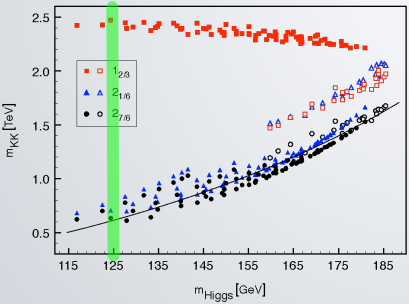
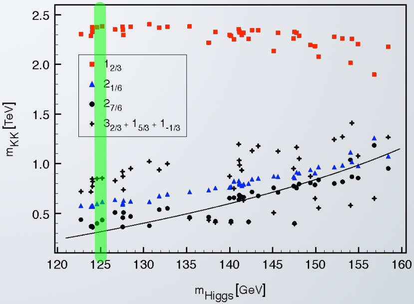




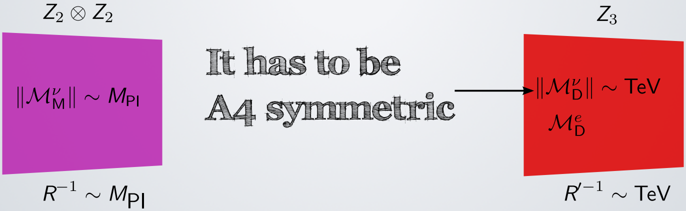
Light resonances at the reach of the LHC!

Tau Custodians

[del Águila,Carmona,Santiago, **arXiv:1001.5151**]

What about leptons?

- Looking at the lepton masses we would say that leptons are mostly elementary
- However, it was shown that it is no necessary the case when we try to explain the non-hierarchical mixing angles in A_4 models



$Z_2 \otimes Z_2$

$\|\mathcal{M}_{\mathrm{M}}^{\nu}\| \sim M_{\mathrm{Pl}}$

$R^{-1} \sim M_{\mathrm{Pl}}$

It has to be A4 symmetric

Z_3

$\|\mathcal{M}_{\mathrm{D}}^{\nu}\| \sim \mathrm{TeV}$

$\mathcal{M}_{\mathrm{D}}^{e}$

$R'^{-1} \sim \mathrm{TeV}$

In A_4 models tau can be more composite than expected $\Rightarrow$ τ-custodians

Tau Custodians

[del Águila,Carmona,Santiago, **arXiv:1007.4206**]

$$\zeta_\tau = \underbrace{\begin{pmatrix} \nu_\tau[+-] & \tilde{e}_\tau[+-] \\ e_\tau[+-] & \widetilde{Y}_\tau[+-] \end{pmatrix}} \oplus e'_\tau[--], \qquad c_\tau \sim 0.5$$

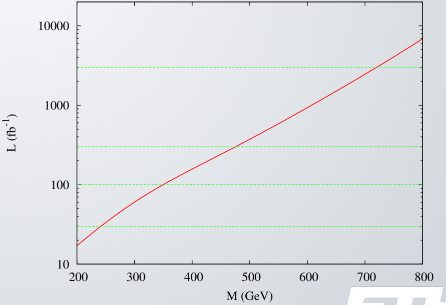
The bidoublet has, for $c_\tau \sim 0.5$, an ultra-light KK mode with almost degenerate leptons E_1, E_2, Y and N, with masses ~ 0.5 TeV and large couplings to τ

[*del Águila, Santiago, '02*] [*Atre, Carena, Han, Santiago, '08*]

We studied pair production of τ custodians at the LHC with

- all leptonic τ's (fully collimated)
- one leptonic Z

$$pp \to \bar{\tau}\tau ZZ/W/H$$
$$\to l^+ l^- l'^+ l''^- jj\not{E}_T$$



Tau Custodians

Originally considered in MCHM$_5$ [del Águila,AC,Santiago, arXiv:1007.4206]

$$L^{(0)}_{1L,R} = \begin{pmatrix} N^{(0)}_{L,R} \\ E^{(0)}_{1L,R} \end{pmatrix} \sim (2)_{-\frac{1}{2}} \quad L^{(0)}_{2L,R} = \begin{pmatrix} E^{(0)}_{2L,R} \\ Y^{(0)}_{L,R} \end{pmatrix} \sim (2)_{-\frac{3}{2}}$$

$$vY^{(-1)} = \begin{pmatrix} c_R^2 m_\tau & 0 & s_R c_R m_\tau \\ 0 & 0 & 0 \\ s_R c_R m_{E_2} & 0 & s_R^2 m_{E_2} \end{pmatrix}$$

They lead to

- Suppression of $H \to \tau\bar{\tau}$
- Suppression of $H \to \gamma\gamma$

$$c_R^2 A_{1/2}(\tau_\tau) + s_R^2 A_{1/2}(\tau_{E_2}) \approx c_R^2 A_{1/2}(\tau_\tau) + s_R^2$$

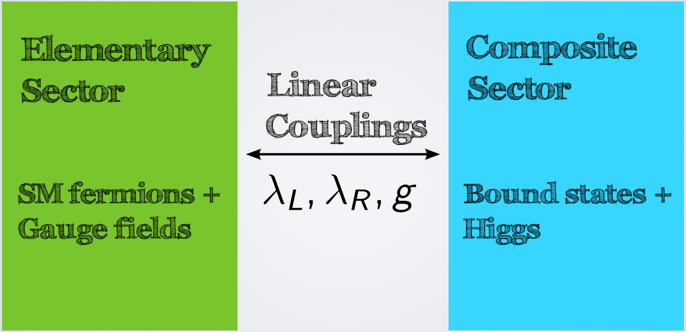
They are also present in MCHM$_{10}$ [AC, Goertz, In preparation] with a quite different phenomenology

Stay tuned!

Two-site model

[Contino,Krame,Son,Sundrum, 06]

Simplifed model useful for collider phenomenology



Elementary Sector

SM fermions + Gauge fields

Linear Couplings

λ_L, λ_R, g

Composite Sector

Bound states + Higgs

- Fully composite Higgs
- Linear couplings of the elementary sector to composite operators

$$\bar{q}_L i\not{D} q_L + \bar{t}_R i\not{D} t_R + \mathrm{Tr}\{\bar{\mathcal{Q}}\left(i\not{D}_* - \bar{m}_Q\right)\mathcal{Q}\} + \bar{\tilde{T}}\left(i\not{D}_* - \bar{m}_T\right)\tilde{T}$$

$$-\lambda_L \bar{q}_L Q_R - \lambda_R \bar{\tilde{T}}_L t_R - Y_{*U}\mathrm{Tr}\{\bar{\mathcal{Q}}\mathcal{H}\}\tilde{T}$$

Two-site MCHM$_5$

We consider one $\mathbf{5} = (\mathbf{2},\mathbf{2}) \oplus \mathbf{1}$ per family

$$\mathcal{Q}^{(i)} = (\mathbf{3},\mathbf{2},\mathbf{2})_{2/3} = \begin{pmatrix} T^{(i)} & T^{(i)}_{5/3} \\ B^{(i)} & T^{(i)}_{2/3} \end{pmatrix} \qquad \tilde{T}^{(i)} = (\mathbf{3},\mathbf{1},\mathbf{1})_{2/3}$$

The masses of the light quarks are given by the mixing with the strong sector

$$m_{u^{(i)}} \approx \frac{v}{\sqrt{2}} Y_{*U} \sin\phi_q^{(i)} \sin\phi_u^{(i)} \qquad m_{d^{(i)}} \approx \frac{v}{\sqrt{2}} Y_{*D} \sin\phi_2^{(i)} \sin\phi_d^{(i)}$$

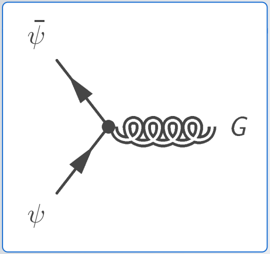
There are massive excitations of the SM gauge bosons, in particular a color octet resonance

$$-\frac{1}{4g_{\mathrm{el}}^2} g_{\mu\nu} g^{\mu\nu} - \frac{1}{4g_*^2} G_{\mu\nu} G^{\mu\nu} + \frac{1}{2} \frac{\bar{m}_G^2}{g_*^2} \left(g_\mu - G_\mu\right)^2$$

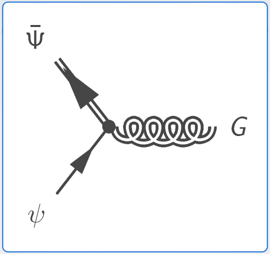
with the SM QCD coupling

$$g_3 = g_* \sin\theta_3$$

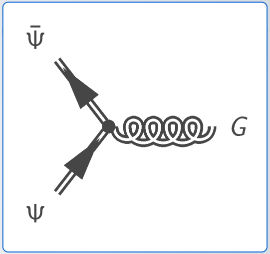
Two-site MCHM$_5$



$$g_3\left(s^2_{\phi_\psi}\cot\theta_3 - c^2_{\phi_\psi}\tan\theta_3\right)$$



$$g_3\,\frac{s_{\phi_\psi}c_{\phi_\psi}}{\sin\theta_3\cos\theta_3}$$



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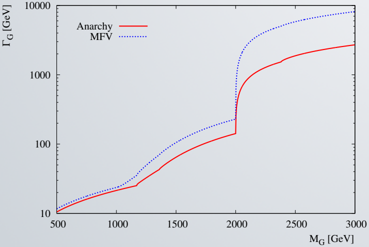

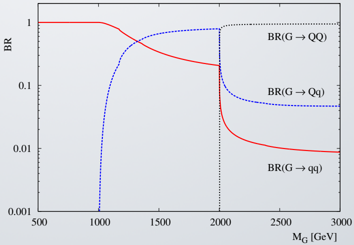

Too large width!!

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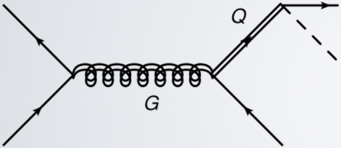
MQ=MG/2

New Composite Higgs production mechanism

arXiv:1205.2378

The Composite Higgs can be produced through a color octet resonance leading to single production of the new quark resonances



The final state is $H\bar{t}t$ or Hjj (just in MFV)

$$M_Q = M_G/2, \quad s_u = 0.6, \quad g_{*3} = Y_* = 3, \quad s_2 = 0.1$$

$$\text{Anarchy} \quad s_u^{(1)} \ll s_u^{(2)} \ll s_u^{(3)} \approx 1$$

$$\text{MFV} \quad s_u^{(1)} = s_u^{(2)} = s_u^{(3)} \approx 1$$

Use MadGraph (signal), Alpgen ($t\bar{t}, t\bar{t}b\bar{b}, W, Z, WW, \dots, +$ jets), Pythia and Delphes

Higgs couplings in MCHM$_5$

When the composite states are heavy enough

- the structure of the coset $SO(5)/SO(4)$

and

- the fermion quantum numbers

fix the Higgs couplings with the SM in terms of

$$\xi = \frac{v^2}{f_\pi^2}$$

$$R_{HVV} \equiv \frac{g_{HVV}}{g_{HVV}^{\mathrm{SM}}} = \sqrt{1-\xi} \qquad R_{Hff} \equiv \frac{g_{Hff}}{g_{Hff}^{\mathrm{SM}}} = \frac{1-2\xi}{\sqrt{1-\xi}}$$

$$\Gamma(H \to \gamma\gamma) = \frac{(R_{Hff} I_\gamma + R_{HVV} J_\gamma)^2}{(I_\gamma + J_\gamma)^2} \Gamma^{\mathrm{SM}}(H \to \gamma\gamma)$$

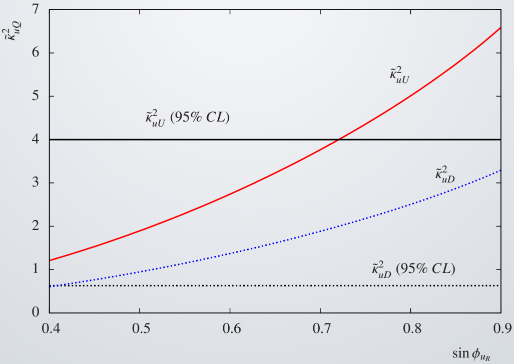
Experimental constraints

- Higgs searches

$$0 \leq \xi \leq 0.4 \qquad \xi = v^2/f_\pi^2 \qquad \text{for } m_H = 125 \text{ GeV}$$

- Vector-like quark searches (MFV)

$$\frac{g}{2c_W}\tilde{\kappa}_{uU}\frac{v}{m_U}Z_\mu \bar{u}_R\gamma^\mu U_R + \frac{g}{\sqrt{2}}\tilde{\kappa}_{uD}\frac{v}{m_D}W_\mu^+\bar{u}_R\gamma^\mu D_R + \text{h.c.},$$



Experimental constraints

- Top-antitop resonance searches. Traditionally considered the golden channel for G but it can change
  - if the top quark is not fully composite
  - if other quarks can be as composite as the top
  - if new decay channels involving fermion composite states are open

- Di-jet searches
  - Contact interactions

$$G_\mu^A \left[g_{q_L} \bar{q}_L \gamma^\mu T^A q_L + g_{u_R} \bar{u}_R \gamma^\mu T^A u_R + g_{d_R} \bar{d}_R \gamma^\mu T^A d_R \right] \Rightarrow$$

$$\mathcal{L} = \frac{c_{uu}^{(1)}}{M^2} \mathcal{O}_{uu}^{(1)} + \frac{c_{dd}^{(1)}}{M^2} \mathcal{O}_{dd}^{(1)} + \frac{c_{ud}^{(8)}}{M^2} \mathcal{O}_{ud}^{(8)} + \frac{c_{qq}^{(8)}}{M^2} \mathcal{O}_{qq}^{(8)} + \frac{c_{qu}^{(8)}}{M^2} \mathcal{O}_{qu}^{(8)} + \frac{c_{qd}^{(8)}}{M^2} \mathcal{O}_{qd}^{(8)}$$

  - Direct searches

$Ht\bar{t}$

Single production of top partners trough $s-$channel exchange of G

$$pp \to G \to T\bar{t} + \bar{T}t \to Ht\bar{t}$$

Strategy

- Use the leading $H \to b\bar{b}$ decay and semileptonic top decays

$$H\bar{t}t \to 4b + 2j + l + \not{E}_T$$

- Use b-tags and S_T as main discriminating variables

$$S_T \equiv \sum_{j=1}^{n_j} p_T(j) + \sum_{l=1}^{n_l} p_T(l) + \not{E}_T$$

- Use boosted top and Higgs techniques for larger masses

$Ht\bar{t}$ cuts

Low energy phase:

- At least 4 jets, of which at least 3 must be tagged as b-jets
- At least 1 isolated charged lepton
- A cut on S_T (in this case we have $n_j = 4$ and $n_l = 1$) that depends on the test M_G we are considering

$$S_T > 0.9,\ 1.1,\ 1.5 \text{ TeV for } M_G = 1.5,\ 2,\ 2.5 \text{ TeV}$$

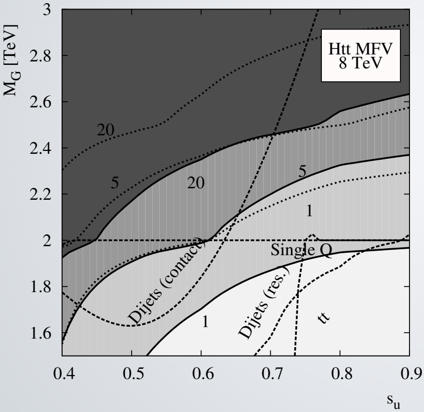
High energy phase:

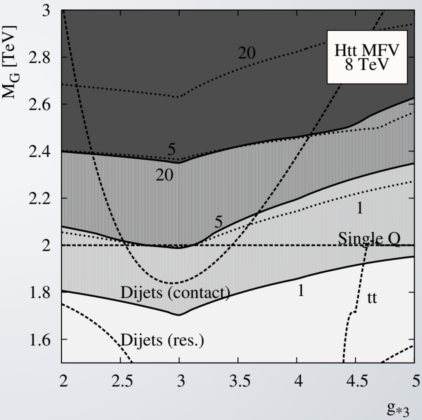
- At least 3 jets, with a minimum of 2 b tags
- At least 1 isolated charged lepton
- Two hardest jets required to have invariant masses close to the top and Higgs mass, $|m_{j_1} - m_t| \leq 40$ GeV and $|m_{j_2} - m_H| \leq 40$ GeV
- A cut on S_T that depends on the test M_G we are considering

$$S_T > 1.2,\ 1.5,\ 1.7,\ 2 \text{ TeV for } M_G = 2,\ 2.5,\ 3, \geq 3.5 \text{ TeV}$$

$Ht\bar{t}$ results

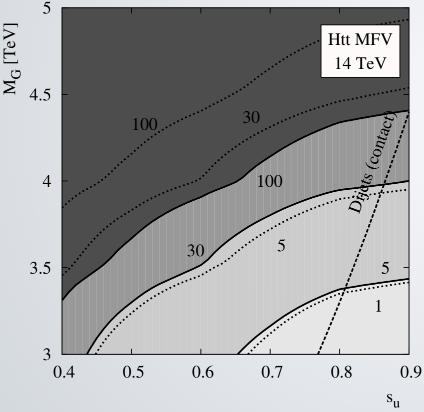
MFV

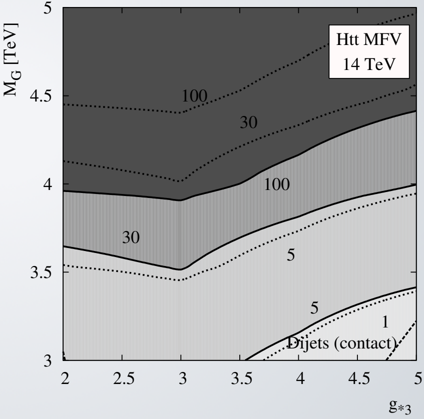




$Ht\bar{t}$ results

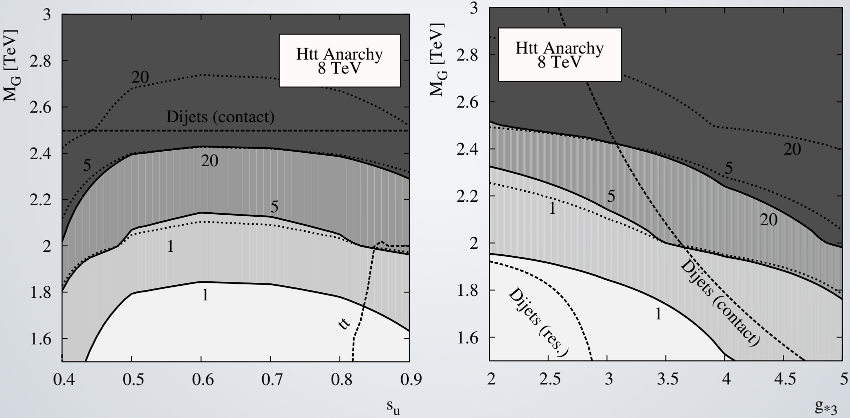
MFV





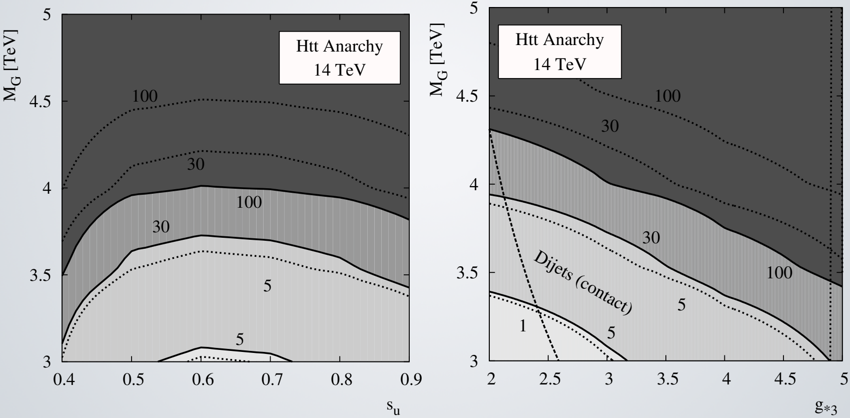
$Ht\bar{t}$ results

Anarchy



$Ht\bar{t}$ results

Anarchy



Hjj

Single production of up partners trough s and $t-$channel exchange of G

$$pp \to G \to U\bar{u} + \bar{U}u \to Hu\bar{u} \to 2j + 2l + \not{E}_T$$

- To avoid be swamped by background we impose $H \to W^* W$, with

  $$BR(H \to W^* W) = 0.33 \quad \text{in our benchmark model}$$

- Due to the relatively low cross sections and the huge $W + j$ background we look in the dilepton channel

- Just $\sqrt{s} = 14$ TeV

Hjj cuts

- At least 2 and no more than 6 jets
- Exactly 2 charged leptons, both with

$$p_T(l) \geq 50 \text{ GeV} \quad \text{and} \quad |\Delta\phi(l_1, l_2)| \leq 0.5$$

- A veto on b-tagged jets (no jet should be tagged as a b-jet).
- A cut on the two hardest jets

$$p_T(j_1) > 400 \text{ GeV} \quad p_T(j_2) > 200 \text{ GeV}$$

- A cut on the invariant mass of the two charged leptons

$$15 \text{ GeV} \leq m_{ll} \leq 70 \text{ GeV}$$

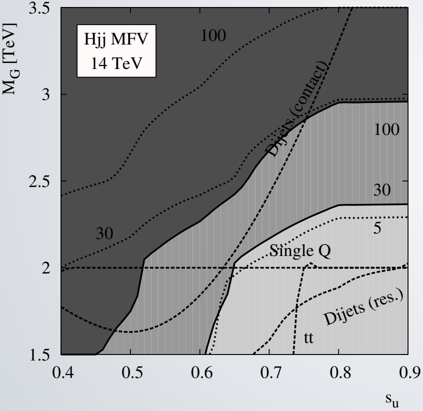
- A cut on the transverse mass of the Higgs decay products

$$m_T(l, l, \not{E}_T) < 120 \text{ GeV}$$

- A cut on S_T function of the test M_G

$$S_T > 1.5,\ 2.1\ , 2.3 \text{ TeV for } M_G = 2,\ 2.5, \geq 3 \text{ TeV}$$

Hjj results


Hjj MFV
14 TeV
M_G [TeV]
s_u
3.5
3
2.5
2
1.5
0.4
0.5
0.6
0.7
0.8
0.9
100
30
100
30
5
Dijets (contact)
Single Q
Dijets (res.)
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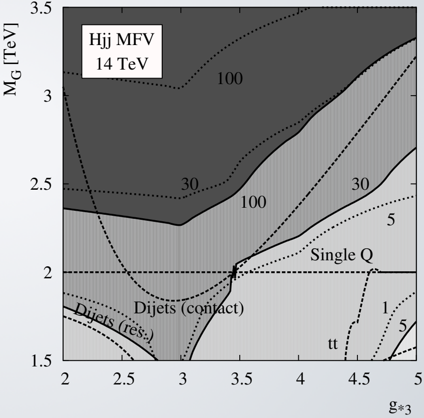
Hjj MFV
14 TeV
M_G [TeV]
g_{*3}
3.5
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3.5
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4.5
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100
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100
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Single Q
Dijets (contact)
Dijets (res.)
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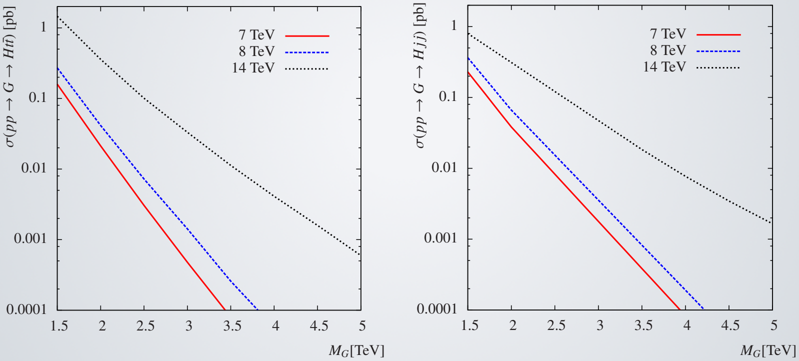
Conclusions

- Composite Higgs is a nice example of BSM solving the hierarchy problem
- There are new light excitations coupling mostly to the RH top
- It can happen also in the lepton sector (τ custodians)
- The strong sector can be probed through Higgs production mediated by color octet and fermion resonances

Backup Slides

Production cross sections



Some numbers

Process	LHC7 σ [pb]	LHC8 σ [pb]	LHC14 σ [pb]
$Ht\bar{t}$ ($M_G = 2$ TeV, MFV)	0.0213	0.0414	0.358
$Ht\bar{t}$ ($M_G = 3$ TeV, MFV)	0.000478	0.00142	0.0332
$Ht\bar{t}$ ($M_G = 3$ TeV, Anarchy)	0.0013	0.0037	0.084
Hjj ($M_G = 2$ TeV, MFV)	0.04	0.07	0.44
$t\bar{t}$+0-4 jets (semileptonic+leptonic)	47.9	70.47	268.55
$t\bar{t}b\bar{b}$	0.09	0.15	0.85
Z+1-4 jets (leptonic)	530.5	641	1423
WW + 0-2 jets (semileptonic+leptonic)	15	22.6	49
W+1-2 jets ($p_T > 150$ GeV, leptonic)	–	–	84.9
W+1-4 jets (leptonic)	5133	6489	–

Details on the analysis

In our analyses we define

- jets with a cone size $\Delta R = 0.7$, $p_T(j) > 30$ GeV and $|\eta_j| < 5$.
- isolated charged leptons (e or μ) when $p_T(l) > 20$ GeV and $|\eta_l| < 2.5$

We have assumed a b-tagging efficiency of 0.7 in our analyses. Finally, we use as discriminating variable

$$S_T \equiv \sum_{j=1}^{n_j} p_T(j) + \sum_{l=1}^{n_l} p_T(l) + \not{E}_T$$

where $n_{j,l}$ is the relevant number of jets or leptons.

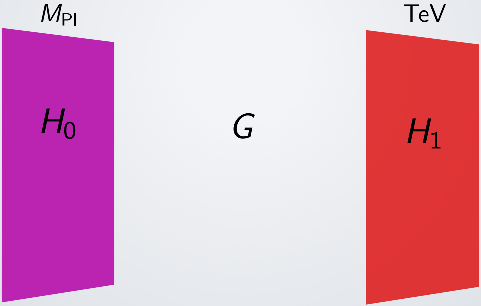
Given a number of signal (s) and background (b) events after the corresponding cuts, we compute the statistical significance of the signal from

$$\mathcal{S}(s,b) = \sqrt{2 \times \left[(s+b)\ln\left(1+\frac{s}{b}\right) - s\right]}$$

Models with Warped Extra Dimensions

Hierarchy Problem

In WED, the fundamental scale of the theory $\mathcal{O}(M_{\rm Pl})$ is redshifted by the warp factor to a few TeV on the IR brane, where the Higgs is localized [*Randall, Sundrum '99*]



$$ds^2 = \left(\frac{R}{z}\right)^2 \left[\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right]$$

Fermions and gauge bosons can propagate in the bulk

Bulk Fermions

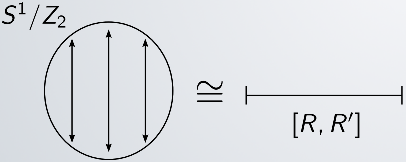
The smallest irrep of the 5D Clifford algebra

$$\{\Gamma^M, \Gamma^N\} = 2g^{MN} \qquad M, N = \mu, 5$$

is four-dimensional

$$\Gamma^5 = \pm\Gamma^0\Gamma^1\Gamma^2\Gamma^3 \;\Rightarrow\; \bar{\Gamma} \propto \mathbf{1}$$

1. 5D fermions $\psi(x,z)$ are vector-like and a bulk mass $c = MR$ is allowed
2. We can still get a 4D chiral spectrum



$$\psi_L(x,-\phi) = Z\psi_L(x,\phi) \qquad Z^2 = 1$$

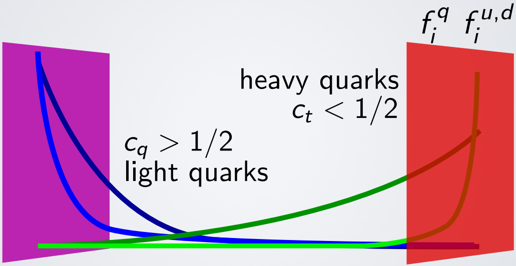
$$\psi_L(x,R^{(\prime)}) = 0 \quad \partial_z\psi_L(x,R^{(\prime)}) = 0$$

After Kaluza-Klein decomposition, we can have a chiral massless state

$$\psi_L(x,z) = f_L^{(0)}(z)\psi_L^{(0)}(x) + \sum_{n=1}^{\infty} f_L^{(n)}(z)\psi_L^{(n)}(x)$$

Bulk Fermions

- It turns out that we can explain the huge hierarchy existing between the different fermion masses



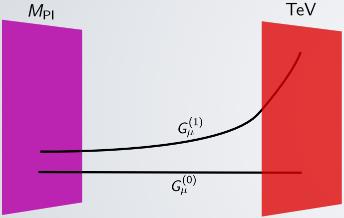
$$(m_{u,d})_{ij} \quad \sim \quad \frac{v}{\sqrt{2}} Y_* f_i^q f_j^{u,d}$$

- We obtain naturally also a hierarchical mixing in the quark sector

$$\left| U_L^{u,d} \right|_{ij} \quad \sim \quad f_i^q / f_j^q \qquad \left| U_R^{u,d} \right|_{ij} \sim f_i^{u,d} / f_j^{u,d} \qquad i \leq j$$

Flavor

Different fermion localizations lead to family dependent couplings to massive KK gauge bosons, which are IR localized



$$g_\alpha^{(1)} \approx g_{5D} R^{-1/2} \left(-\frac{1}{L} + f_\alpha^2 \gamma(c_\alpha) \right)$$

$$L = \log R/R' \approx 35 \quad \gamma(c_\alpha) \sim \mathcal{O}(1)$$

We have FCNC both in the quark and in the lepton sector

RS-GIM Mechanism

Off-diagonal couplings are suppressed by CKM entries and by ratios of CKM matrix elements and masses. Still, Δm_K and ϵ_K impose some tunning.

Lepton Masses and Mixings

- Fermion splitting seems to naturally lead to hierarchical masses and mixing angles, as the ones observed in the quark sector
- However, unlike the quark case, lepton mixing angles are not hierarchical. A good starting point is the tri-bimaximal mixing

$$|U_{\mathrm{PMNS}}| \sim |U_{\mathrm{TBM}}| = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

- Despite the RS-GIM mechanism, flavor constraints are quite strict

One possible solution is to assume a discrete symmetry acting on this sector

A_4 Symmetry

A_4 is the the group of even permutations of four elements. We can use two generators, S and T, satisfying

$$S^2 = T^3 = (ST)^3 = 1$$

It has 3 inequivalent one-dimensional representations

$$\begin{aligned} \mathbf{1}: &\quad S = 1, \quad T = 1, \\ \mathbf{1}': &\quad S = 1, \quad T = e^{i2\pi/3} = \omega, \\ \mathbf{1}'': &\quad S = 1, \quad T = e^{i4\pi/3} = \omega^2, \end{aligned}$$

and one three-dimensional irreducible representation, **3**

$$\mathbf{3} \otimes \mathbf{3} = \mathbf{3}_1 \oplus \mathbf{3}_2 \oplus \mathbf{1} \oplus \mathbf{1}' \oplus \mathbf{1}''$$

There are two important subgroups:

$$Z_2 \cong \{1, S\} \subset A_4 \qquad\qquad Z_3 \cong \left\{1, T, T^2\right\} \subset A_4$$

Tau custodian analysis

We are interested in the following signature at LHC with $\sqrt{s} = 14$ TeV

$$pp \to l^+ l^- l'^+ l''^- jj \not{E}_T \quad \text{with } l, l', l'' = e, \mu$$

The background we have considered are

$$\begin{array}{llll} Zt\bar{t} + n \text{ jets} & \sigma = 39.6 \text{ fb}, & Zb\bar{b} + n \text{ jets} & \sigma = 5.85 \text{ pb}, \\ ZZ + n \text{ jets} & \sigma = 2.35 \text{ pb}, & ZW + n \text{ jets} & \sigma = 1.76 \text{ pb}, \\ t\bar{t} + n \text{ jets} & \sigma = 55 \text{ pb}, & ZWW + n \text{ jets} & \sigma = 1.9 \text{ fb}, \end{array}$$

with one Z and both tops decaying leptonically.

- Signal generated with MadGraph/MadEvent v4 and τ decayed with Tauola
- Background events generated with Alpgen v2.13
- In both cases, we have used Pythia for hadronization and showering and PGS4 for detector simulation

Tau custodians results

14 TeV	$M = 200$ GeV	$M = 400$ GeV	$Zt\bar{t}$		ZZ	
Basic	0.85	0.14	0.49		0.44	
Leptons	0.68	0.11	0.41		0.41	
M_{jj}	0.49	0.063	0.15		0.13	
Tau rec.	0.42	0.057	0.039		0.052	
Pair prod.	0.39	0.045	0.017		0.032	
Mass rec.	0.37	0.041	0.008	0.0016	0.016	0.0018

- **Basic cuts**

$$p_T(l) \geq 10 \text{ GeV}, \quad p_T(j) \geq 20 \text{ GeV}, \quad \not{E}_T \geq 20 \text{ GeV},$$
$$|\eta_l| \leq 2.5, \quad |\eta_j| \leq 5, \quad \Delta R_{jj} \geq 0.5 \quad \Delta R_{jl} \geq 0.5$$

- **Leptons** $|M_{l^+l^-} - M_Z| \leq 10$ GeV and $\cos(\phi_{l'^+l''^-}) \geq -0.95$
- **M$_{jj}$** 50 GeV $\leq M_{jj} \leq$ 150 GeV
- **Tau reconstruction** We assume fully collimation
- **Pair production** $|M_{L_1} - M_{L_2}| \leq 50$ GeV
- **Mass reconstruction** $|M_{\tau l^+l^-} - M_L^{\text{test}}| \leq 50$ GeV