Tau Custodians and Higgs Decays

Scalars 2013, Warsaw

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JHEP 04 (2013) 163
AC, Goertz

ETH zürich

Composite Higgs

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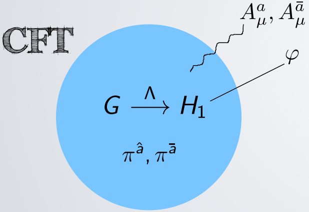
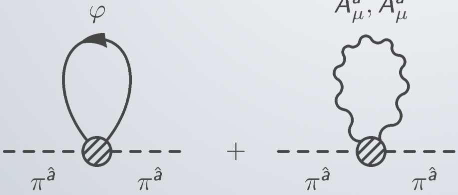
- One interesting possibility is that the Higgs is composite, the remnant of some new strong dynamics [Kaplan, Georgi '84] [Agashe, Contino, Pomarol '04]
- It is particularly compelling when the Higgs is the PGB of some new strong interaction. Something like pions in QCD.



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



$$m_\pi^2 = m_h^2 \sim \frac{g_{\rm el}^2}{16\pi^2} \Lambda^2$$

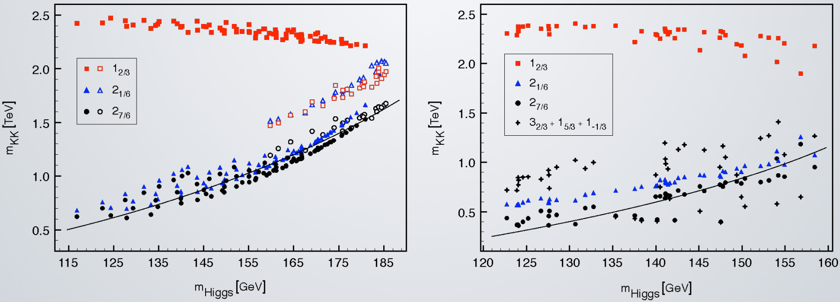
Top Custodians

Top quark also responsible for triggering the EWSB

[Contino,da Rold,Pomarol, '06]

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

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



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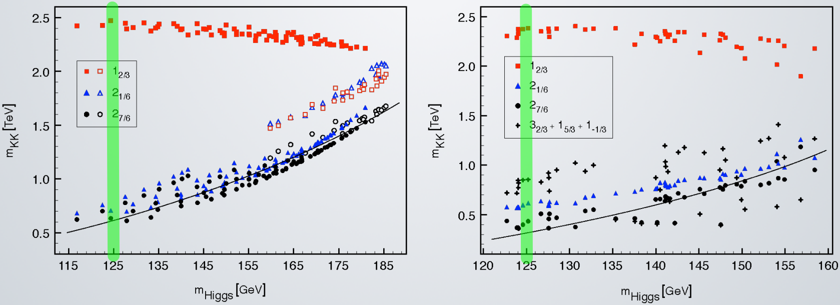

Light resonances at the reach of the LHC!

Top Custodians

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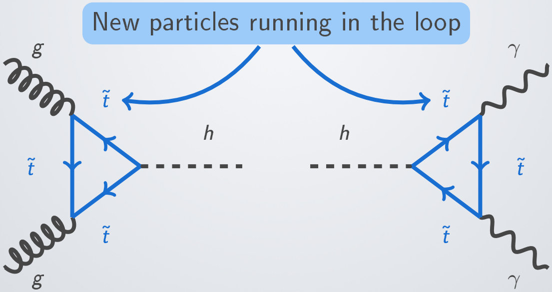
Regarding Higgs production and decays, there are mainly two effects

- Shift in SM couplings (mixing with NP and non-linear effects coming from the PGB nature of the Higgs)
- New particles enter in the loops



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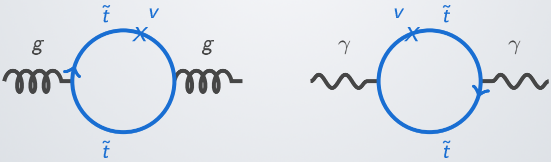
If $m_t, m_{\tilde{t}} \gg m_h$



$$\mathcal{L}_{hgg} = \frac{g_S^2}{96\pi^2} G^a_{\mu\nu} G^{\mu\nu a} h A_1 \qquad \mathcal{L}_{h\gamma\gamma} = \frac{e^2}{16\pi^2} F_{\mu\nu} F^{\mu\nu} h \left(Q_t^2 A_1 + \ldots \right)$$

$$A_1 = \frac{\partial}{\partial v} \log \det \mathcal{M}^2(v) \qquad \det \mathcal{M}(v) \propto F(v/f_\pi) \times P(\lambda_i, M_i, f_\pi)$$

Top Custodians

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- Shift in SM couplings (mixing with NP and non-linear effects coming from the PGB nature of the Higgs)
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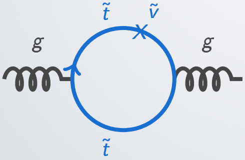
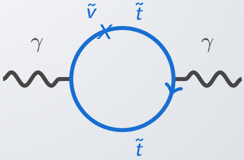
Cancel each other [Falkowski, '07]

If $m_t, m_{\tilde{t}} \gg m_H$





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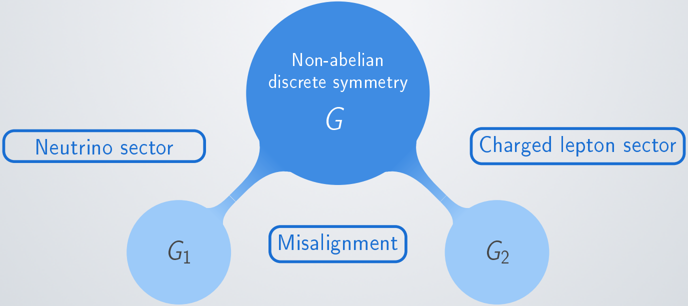
Tau Custodians

What about leptons?

- Looking at the lepton masses we would say that leptons are mostly elementary
- However, it is no necessary the case when we try to explain the PMNS matrix with non-abelian discrete symmetries



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

[del Águila,AC,Santiago, **JHEP** 1008 (2010) 127]

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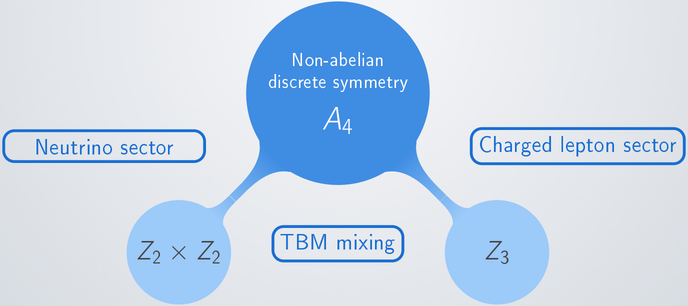

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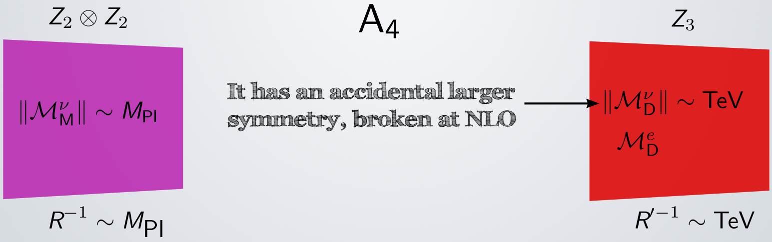

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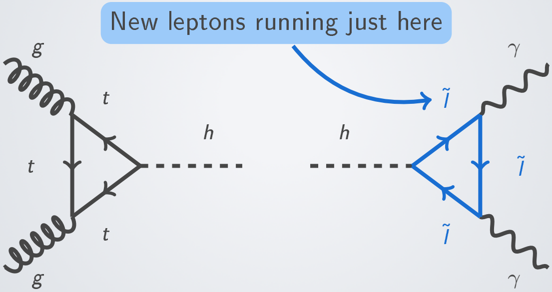
Tau Custodians

- Normally, light quark and lepton resonances were neglected due to their small degree of compositeness (except maybe the bottom)
- Otherwise, we're in business ... [AC, Goertz, '13, **JHEP** 04 (2013) 163]



The top KK tower contribution cancel with the shift in the $ht\bar{t}$ coupling produced by the mixing with the NP

$$A_q^h(\tau_t)(\mathrm{SM} + \mathrm{shift}) + \mathrm{NP} \approx \mathrm{SM} + \mathrm{shift} + \mathrm{NP} = \mathrm{SM}$$

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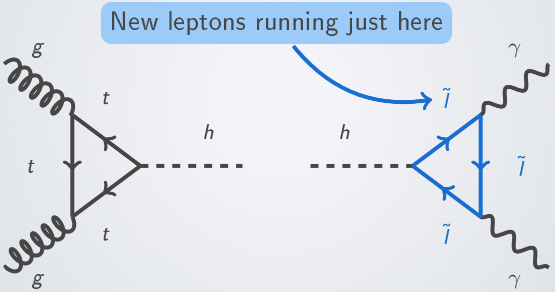

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Not true for the τ tower

$$A_q^h(\tau_t)(\text{SM} + \text{shift}) + \text{NP} \approx \text{SM} + \text{shift} + \text{NP} = \text{SM}$$

Light Custodians in $MCHM_5$

- It is possible to describe the effects of the NP in a transparent way by only considering the

SM + light custodians

- In this case the new spectrum is made of two degenerate $SU(2)$ doublets in both the lepton and the quark sectors

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

$$Q^{(0)}_{1L,R} = \begin{pmatrix} \Lambda^{(0)}_{1L,R} \\ T^{(0)}_{1L,R} \end{pmatrix} \sim \mathbf{2}_{+\frac{7}{6}}, \quad Q^{(0)}_{2L,R} = \begin{pmatrix} T^{(0)}_{2L,R} \\ B^{(0)}_{2L,R} \end{pmatrix} \sim \mathbf{2}_{+\frac{1}{6}}$$

Light Custodians in $MCHM_5$

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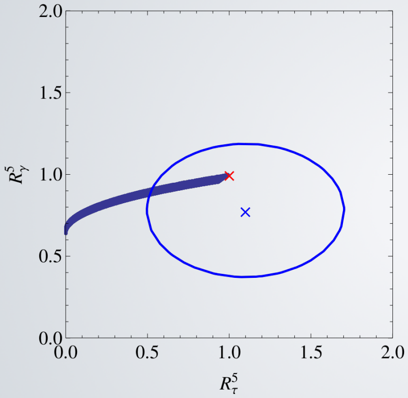
$$\mathcal{L}_L^m = -y\, \bar{l}_L^{(0)} H \tau_R^{(0)} - y' \left[\bar{L}_{1L}^{(0)} H + \bar{L}_{2L}^{(0)} \tilde{H} \right] \tau_R^{(0)} - M \left[\bar{L}_{1L}^{(0)} L_{1R}^{(0)} + \bar{L}_{2L}^{(0)} L_{2R}^{(0)} \right] + \text{h.c.}$$

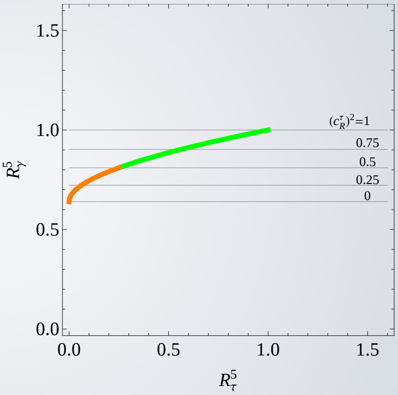
Mixing with composite resonances $\Rightarrow$ angle s_R

- Everything described by 3 parameters m_τ, s_R, M, with $v \ll M \ll \mathcal{O}(\text{TeV})$
- First two generations, ν and b behave SM-like
- Study change of Higgs production times branching

$$R_f^5 \equiv \frac{[\sigma(pp \to h)\text{Br}(h \to ff)]_{\text{MCHM}_5}}{[\sigma(pp \to h)\text{Br}(h \to ff)]_{\text{SM}}}$$

Light Custodians in MCHM$_5$





- Strong correlation allows to easily test the model

$$R_\gamma^5 \approx \frac{[\Gamma(h\to\gamma\gamma)]_{\mathrm{MCHM}_5}}{[\Gamma(h\to\gamma\gamma)]_{\mathrm{SM}}} \approx \left(1-\frac{(s_R^\tau)^2}{5}\right)^2 \qquad R_\tau^5 \approx \frac{[\Gamma(h\to\tau\tau)]_{\mathrm{MCHM}_5}}{[\Gamma(h\to\tau\tau)]_{\mathrm{SM}}} = (c_R^\tau)^4$$

Light Custodians in MCHM_{5+10}

- Going to larger representations, we can have a richer phenomenology

We put the τ_R in a $\mathbf{10}$ of $SO(5)$ and the others in $\mathbf{5}$'s

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

$$L^{(0)}_{3L,R} = \begin{pmatrix} N^{(0)}_{3L,R} \\ E^{(0)}_{3L,R} \\ Y^{(0)}_{3L,R} \end{pmatrix} \sim \mathbf{3}_{-1}, \quad N^{(0)}_{2L,R} \sim \mathbf{1}_0, \quad Y^{(0)}_{1L,R} \sim \mathbf{1}_{-2}$$

- Top custodians same as before, as we don't change the quark sector
- Relevant mass matrices

$$\mathcal{M}_E = \frac{v}{\sqrt{2}} \begin{pmatrix} y & 0 & 0 & -\tilde{y} \\ y' & \frac{\sqrt{2}}{v}M & 0 & -\hat{y} \\ y' & 0 & \frac{\sqrt{2}}{v}M & -\hat{y} \\ 0 & \bar{y} & \bar{y} & \frac{\sqrt{2}}{v}\tilde{M} \end{pmatrix} \quad \mathcal{M}_Y = v \begin{pmatrix} \frac{1}{v}\tilde{M} & -\bar{y} & 0 \\ \hat{y} & \frac{1}{v}M & -\hat{y} \\ 0 & \bar{y} & \frac{1}{v}\tilde{M} \end{pmatrix}$$

Light Custodians in MCHM_{5+10}

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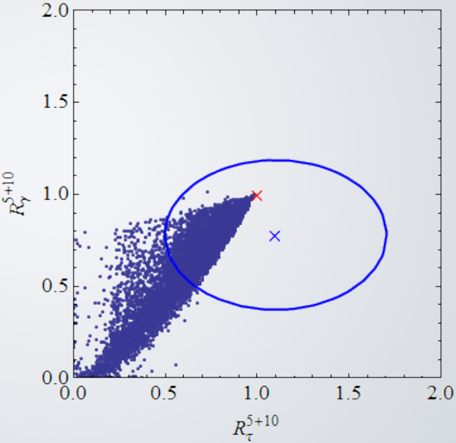
$$R_\gamma^{5+10} \approx \frac{\left[\Gamma(h \to \gamma\gamma)\right]_{\mathrm{MCHM}_{5+10}}}{\left[\Gamma(h \to \gamma\gamma)\right]_{\mathrm{SM}}}$$

$$R_\tau^{5+10} \approx \frac{\left[\Gamma(h \to \tau\tau)\right]_{\mathrm{MCHM}_{5+10}}}{\left[\Gamma(h \to \tau\tau)\right]_{\mathrm{SM}}}$$



PGB nature of the Higgs

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We consider now the effects coming from the non-linearity of the Higgs

- The rescaling of hVV couplings is fixed by the breaking $SO(5) \to SO(4)$

$$\kappa_W = \kappa_Z = \cos\left(\frac{v}{f_\pi}\right) \approx \sqrt{1-\xi} \quad \text{with} \quad \xi = v^2/f_\pi^2$$

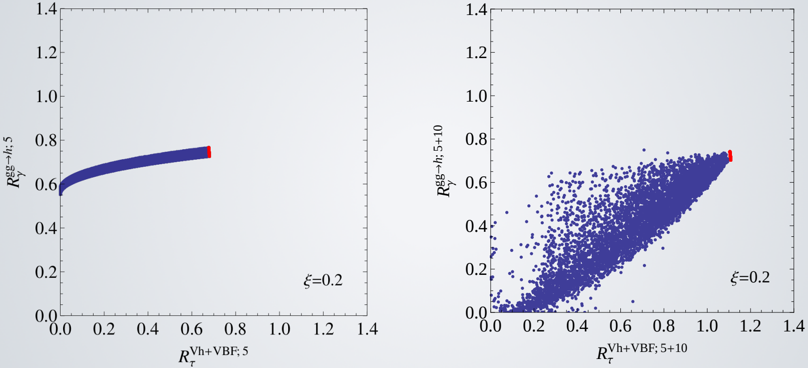
- The rescaling of the different fermion couplings are model dependent

$$\kappa_f^5 \quad \to \quad \kappa_f^5 \cos\left(\frac{2v}{f_\pi}\right) \approx \kappa_f^5 \frac{1-2\xi}{\sqrt{1-\xi}}$$

$$\kappa_g \quad \approx \quad \cos\left(\frac{2v}{f_\pi}\right) / \cos\left(\frac{v}{f_\pi}\right) \approx \kappa_f^5 (1-2\xi)/\sqrt{1-\xi}$$

$$\kappa_\tau^{5+10} \quad \to \quad \kappa_\tau^{5+10} \cos\left(\frac{v}{f_\pi}\right) \approx \kappa_\tau^{5+10} \sqrt{1-\xi}$$

PGB nature of the Higgs



where

$$R_f^{i;\,5,5+10} \equiv \frac{[\sigma(i)\mathrm{Br}(h\to ff)]_{\mathrm{MCHM}_{\mathbf{5},\mathbf{5}+\mathbf{10}}}}{[\sigma(i)\mathrm{Br}(h\to ff)]_{\mathrm{SM}}}, \qquad i = gg\to h,\, VBF,\, Vh$$

Conclusions

- Composite Higgs and light custodians are well known partners
- Light custodians can also happen in the lepton sector (τ custodians)
- They can lead to a distinct phenomenology with respect to previous studies of composite models
- Complementarity between direct searches for fermion partners and looking for indirect effects
- Precise measurement of Higgs couplings desirable

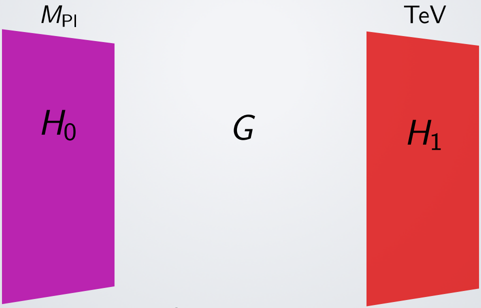
Backup Slides

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

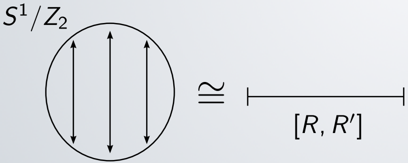
The smallest irrep of the 5D Clifford algebra

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

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



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

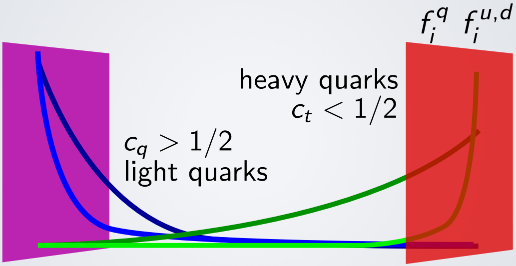
$$\psi_L(x, R^{(\prime)}) = 0 \quad \partial_z\psi_L(x, R^{(\prime)}) = 0$$

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



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

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

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

Flavor

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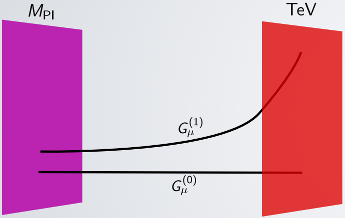
Different fermion localizations lead to family dependent couplings to massive KK gauge bosons, which are IR localized



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

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

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

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- 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

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

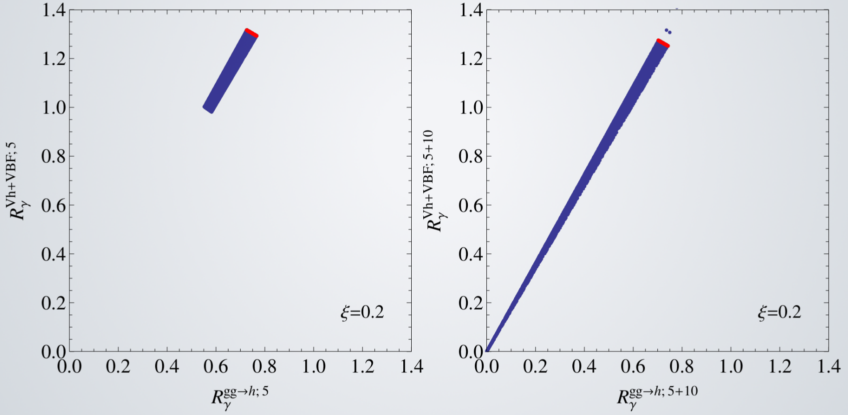
and one three-dimensional irreducible representation, $\mathbf{3}$

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

There are two important subgroups:

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

PGB nature of the Higgs



Tau Custodians

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

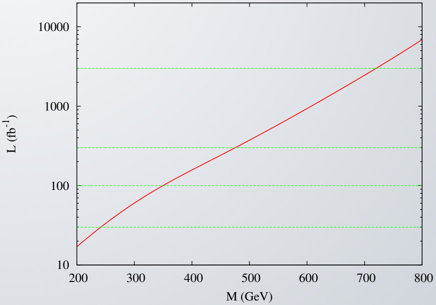
$$\zeta_\tau = \underbrace{\begin{pmatrix} \nu_\tau[+-] & \tilde{e}_\tau[+-] \\ e_\tau[+-] & \widetilde{Y}_\tau[+-] \end{pmatrix}} \oplus e'_\tau[--], \qquad c_\tau \sim 0.5$$

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

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



Single or pair production?

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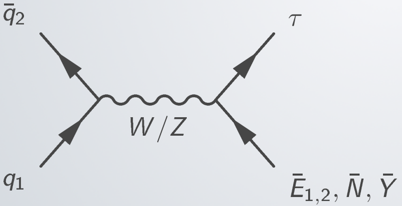
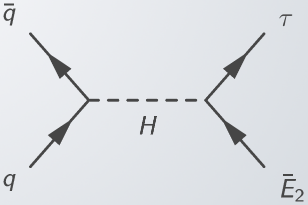
All relevant physics can be parametrized in terms of m_τ, s_R and M

$$s_L = s_R \frac{m_\tau}{M} \qquad m_N = m_{E_1} = m_Y = M \qquad m_{E_2} = \frac{M}{c_R}\sqrt{1 - s_R^2 \frac{m_\tau^2}{M^2}}$$

For $M \geq 100$ GeV we have $0 \approx s_L \leq 0.018 \quad 1 \approx c_L \geq 0.9998$

Single production





is proportional to $s_L \approx 0$ or s_R. Pair production is proportional to $c_L \approx 1$ or to $c_R \approx 1 - s_R^2 \quad \Rightarrow \quad$ Less sensitive to s_R for not big values

Decay channels

The leptons with mass M always decay into a tau lepton an a SM gauge boson

$$N \to \tau W^+ \qquad E_1 \to \tau Z \qquad Y \to \tau W^-$$

The heavier one decays to a tau and a Higgs

$$E_2 \to \tau H \qquad \text{if } c_R \geq (1 + m_W/M)^{-1}$$

We consider therefore the following channels (and the conjugated ones)

$$pp \to \bar{E}_1 E_1 \to ZZ\bar{\tau}\tau \qquad pp \to \bar{E}_1 Y \to ZW^-\bar{\tau}\tau$$
$$pp \to \bar{E}_1 E_2 \to ZH\bar{\tau}\tau \qquad pp \to \bar{E}_1 N \to ZW^+\bar{\tau}\tau$$

with fully leptonic tau decays and one Z decaying into leptons, i.e.

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

Tau custodian analysis

ETH zürich

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

ETH zürich

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