VIOLATION OF LEPTON FLAVOR UNIVERSALITY AND DARK MATTER FROM COMPOSITE HIGGS MODELS

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CERN - TH PARTICLE AND ASTRO - PARTICLE PHYSICS SEMINAR

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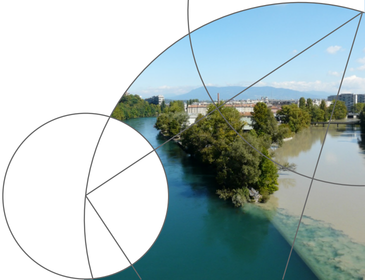


OUTLINE

1. Introduction

2. Violation of Lepton Flavor Universality in Composite Higgs Models

   AC, GOERTZ: PRL 116 2016 NO.25, 251801; ARXIV:1706.XXXXX

3. Composite Dark Matter

   BALLESTEROS, AC, CHALA, ARXIV:1704.07388

4. Conclusions

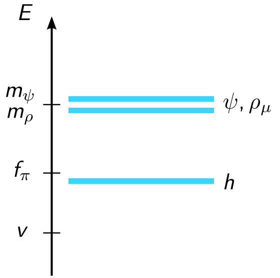
COMPOSITE HIGGS

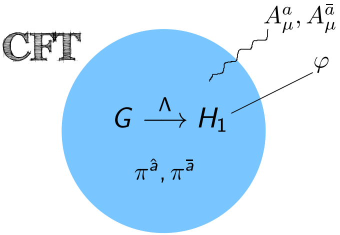
- One interesting solution to the hierarchy problem is making the Higgs composite, the remnant of some new strong dynamics

  KAPLAN,GEORGI '84

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

  AGASHE,CONTINO,POMAROL '04





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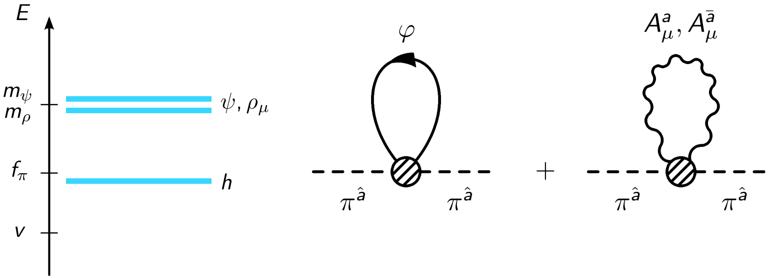

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TALKING TO FERMIONS

A priori, we have two different ways of introducing the mixing with the elementary fermions:

1. Quadratically, à la Technicolor

$$\frac{\lambda}{\Lambda^\gamma}\bar{q}_L t_R \mathcal{O}(x), \quad [\mathcal{O}(x)] = 1+\gamma \Longrightarrow m_q \sim f\frac{4\pi}{\sqrt{N}}\left(\frac{\mu}{\Lambda}\right)^\gamma, \qquad \gamma > 0$$

2. Linearly, via partial compositeness KAPLAN '91

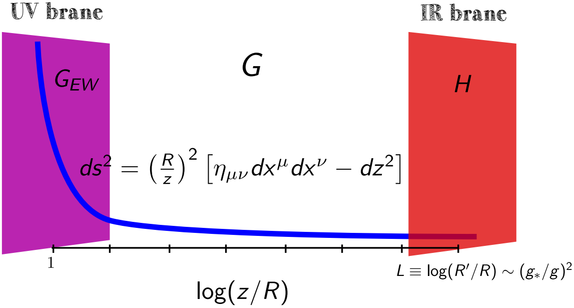
$$\frac{\lambda_L}{\Lambda^{\gamma_L}} q_L \mathcal{O}_L(x), \quad \frac{\lambda_R}{\Lambda^{\gamma_R}} t_R \mathcal{O}_R(x), \quad [\mathcal{O}_{L,R}(x)] = 5/2+\gamma_{L,R}, \qquad \gamma_{L,R} > -1$$

$$\Rightarrow m_q \sim v\frac{\sqrt{N}}{4\pi}\left(\frac{\mu}{\Lambda}\right)^{\gamma_L+\gamma_R} \quad \text{or} \quad m_q \sim v\frac{4\pi}{\sqrt{N}}\sqrt{\gamma_L\gamma_R}$$

Very well mimicked by Randal-Sundrum models!

ADS/CFT CORRESPONDENCE

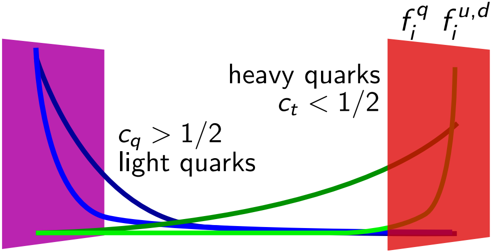
- Models with warped extra dimensions are weakly duals to strongly coupled 4D theories MALDACENA '98
- They provide a calculable framework for composite Higgs models



- The 5D realizations of models where the Higgs is a pNGB are models of gauge-Higgs unification (GHU), $\pi^{\hat{a}}(x) \sim A_5^{\hat{a}}(x)$

ADS/CFT CORRESPONDENCE

We can explain the huge hierarchy existing between the different fermion masses



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

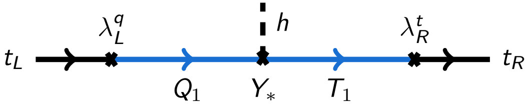
We also obtain naturally the hierarchical mixing observed in the quark sector

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

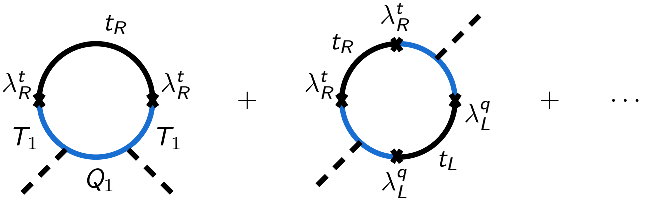
HIGGS POTENTIAL

- The gauge contribution is aligned in the direction that preserves the gauge symmetry WITTEN '83

- However, the linear mixings $\mathcal{L}_{\text{mix}} = \lambda_L^q \bar{q}_L \mathcal{O}_L^q + \lambda_R^t \bar{t}_R \mathcal{O}_R^t + \text{h.c.}$ needed to generate the fermion masses



break the NGB symmetry and will be also responsible for EWSB



HIGGS POTENTIAL

The fermion contribution will depend in general of the specific G-irrep of the composite operators $\mathcal{O}$

$$\mathcal{L}_{\rm mix} \sim \lambda_q \bar{q}_{\alpha L} (\Delta_q^\alpha)^I (\mathcal{O}_q)_I + \lambda_u \bar{u}_R (\Delta_u)^I (\mathcal{O}_u)_I + \lambda_d \bar{d}_R (\Delta_d)^I (\mathcal{O}_d)_I + \text{h.c.}\ .$$

One can promote Δ to spurions of G and expand in powers of λ

$$V \sim m_*^4 \frac{N_c}{16\pi^2} \left[\left(\frac{\lambda}{g_*}\right)^2 V_2(h/f) + \left(\frac{\lambda}{g_*}\right)^4 V_4(h/f) + \dots \right] \qquad m_* = g_* f$$

where

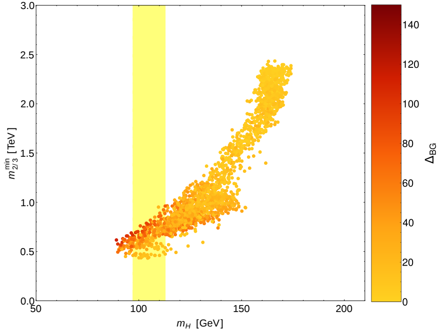
$$V_2(h/f) = c_1 V_2^{(1)}(h/f) + c_2 V_2^{(2)}(h/f) + \dots, \quad \dots$$

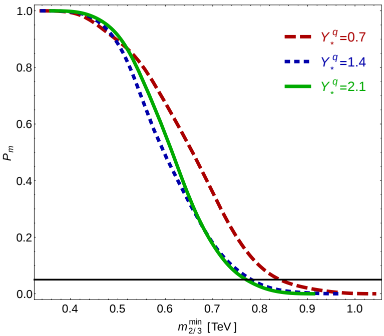
The large value of the top mass makes the top contribution (typically) responsible for triggering EWSB and since

$$y_{\rm top} \sim Y_* \frac{\lambda_q f}{M_Q} \frac{\lambda_t f}{M_T} \quad \text{and} \quad m_H \propto |\lambda|^2/g_*^2 \qquad \Rightarrow \qquad M_\Psi \ll m_*$$

LIGHT TOP PARTNERS AT THE LHC

We can see e.g. the MCHM$_5$, AC, GOERTZ, JHEP 1505 2015 002





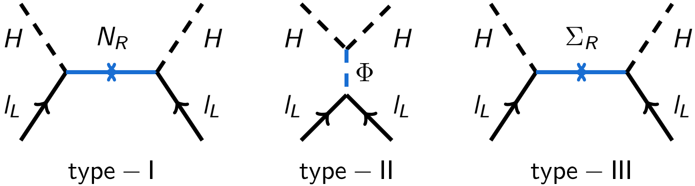
$f = 0.8$ TeV, $g_* \sim 4.4$. $Y^q_* = 0.7$ is the maximum allowed "Yukawa"

VIOLATION OF LFU IN CHMS

LEPTONS CAN PLAY A ROLE

Leptons are typically disregarded since one could naively expect $\lambda_\ell/g_* \ll 1$. However,

- They are not just a scaled version of the quark sector
- The mixing angles in the lepton sector are highly non-hierarchical
- Neutrinos could have Majorana masses!



Leptons can play a role

1. A 'normal' lepton sector will look like

$$\mathcal{L} \supset \frac{\lambda_\ell}{\Lambda^{\gamma_\ell}} \bar{\ell}_L \mathcal{O}_\ell + \frac{\lambda_e}{\Lambda^{\gamma_e}} \bar{e}_R \mathcal{O}_e + \frac{\lambda_\Sigma}{\Lambda^{\gamma_\Sigma}} \bar{\Sigma}_R \mathcal{O}_\Sigma - \frac{1}{2} M_\Sigma \mathrm{Tr}\left(\bar{\Sigma}_R^c \Sigma_R\right) + \mathrm{h.c.}$$

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2. Since $\|M_\Sigma\| \sim \Lambda \sim M_{\mathrm{Pl}}$, avoiding too small neutrino masses

$$(\mathcal{M}_\nu)_{\mathrm{light}} \sim v^2 \epsilon_\ell^2 \epsilon_\Sigma^2 \left(M_\Sigma\right)^{-1}, \quad \epsilon_{\ell,\Sigma} \sim \lambda_{\ell,\Sigma} \left(\frac{\mu}{\Lambda}\right)^{\gamma_{\ell,\Sigma}}$$

requires $0 \ll \epsilon_\Sigma$

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3. The $\mathbf{14} = (\mathbf{1},\mathbf{1}) \oplus (\mathbf{2},\mathbf{2}) \oplus (\mathbf{3},\mathbf{3})$ of $SO(5)$ makes possible to unify all the RH leptons in only one multiplet!

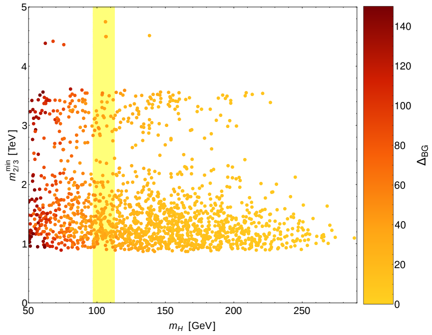
$$\mathcal{L} \supset \frac{\lambda_L^\ell}{\Lambda^{\gamma_\ell}} \bar{\ell}_L \mathcal{O}_\ell + \frac{\lambda_R}{\Lambda^{\gamma_R}} \bar{\Psi}_R \mathcal{O}_R - \frac{1}{2} M_\Sigma \mathrm{Tr}\left(\bar{\Sigma}_R^c \Sigma_R\right) + \text{h.c.}$$

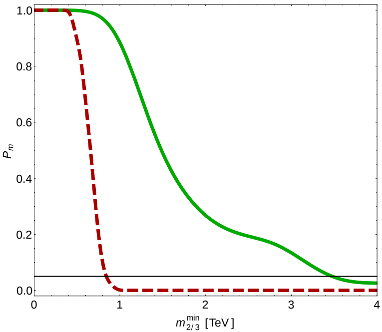
with $\Psi_R \supset e_R, \Sigma_R$, $\quad \mathcal{O}_\ell \sim \mathbf{5}$ and $\mathcal{O}_R \sim \mathbf{14}$

LIFTING THE TOP PARTNERS

This is really interesting since

- Since the contribution to the Higgs quartic from the $\mathbf{14}$ arises at $\mathcal{O}(\lambda_R^2/g_*^2)$, moderate values of λ_R can have an impact
- The three charged lepton RH fields will contribute to the potential





VIOLATION OF LFU

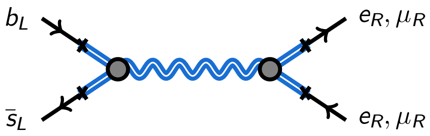
Since

$$\mathcal{M}_e \sim v\epsilon_\ell \qquad \text{and} \qquad (\mathcal{M}_\nu)_{\text{light}} \sim v^2 \epsilon_\ell^2 \epsilon_R^2 M_\Sigma^{-1},$$

having hierarchical charged lepton masses and anarchical neutrino masses leads to

$$0 \ll \epsilon_R^\tau \ll \epsilon_R^\mu \ll \epsilon_R^e$$

and to a violation of LFU



$$\sim g_*^2/m_*^2 \; (\epsilon_{s_L} \epsilon_{b_L} \epsilon_R^2)$$

THE CASE FOR RK

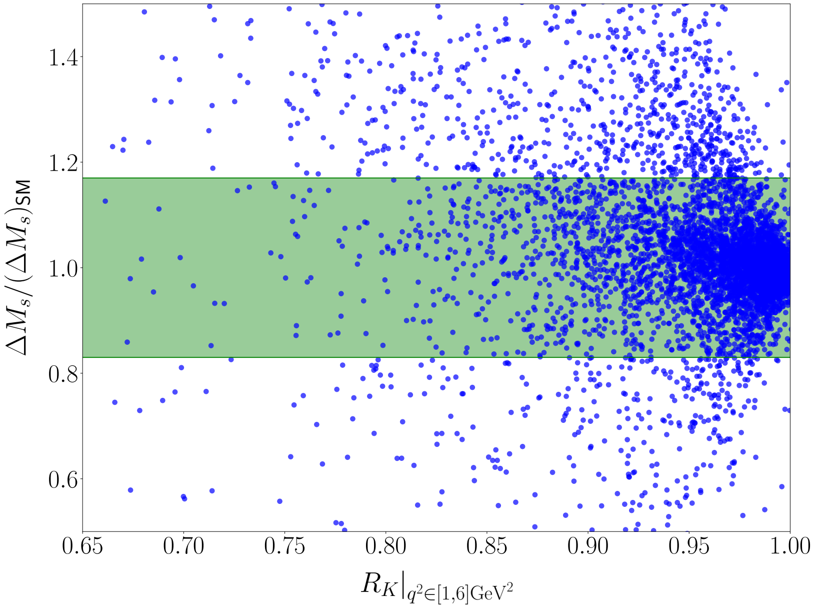
From the NP point of view,

$$R_{K^{(*)}}\Big|_{q^2\in[1.1,6]\ \mathrm{GeV}^2} = \frac{\Gamma(\bar{B}\to\bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B}\to\bar{K}^{(*)}e^+e^-)}\Bigg|_{q^2\in[1.1,6]\ \mathrm{GeV}^2}$$

stands out for several reasons

1. It is a very clean observable!
   - Perturbative and non-perturbative QCD contributions cancel
   - $\log(m_\ell)$ enhanced QED corrections are at the $\mathcal{O}(1\%)$ level BORDONE, ISIDORI, PATTORI, 16
2. It is a loop level effect in the SM
3. It probes a somehow fundamental feature of the SM: lepton flavor universality!

VIOLATION OF LFU



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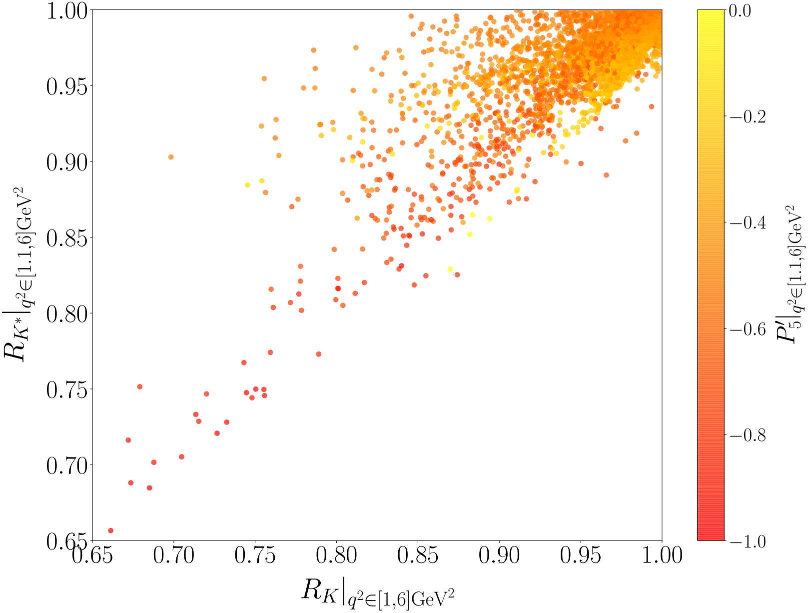
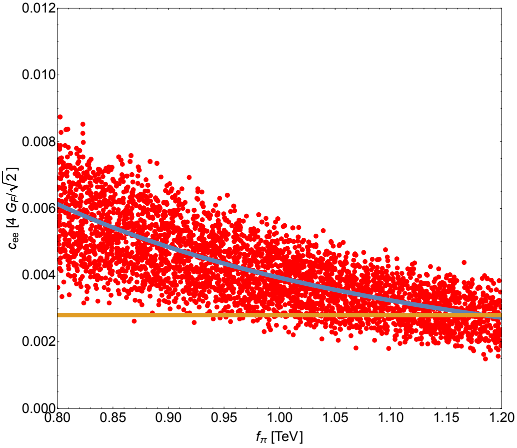


EWPD

One of the biggest tensions arises from EWPD on four-fermion interactions

$$(e_R \gamma_\mu e_R)(e_R \gamma^\mu e_R) \sim \frac{g_*^2}{m_*^2}(\epsilon_{e_R})^4$$

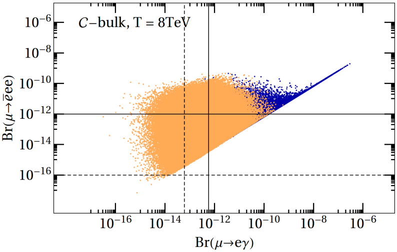


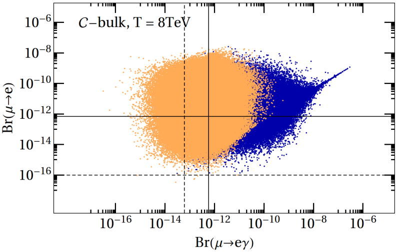
WHAT ABOUT LFV?

In principle, one expects to generate dangerous FCNCs leading to extremely constrained lepton flavor violating processes

$$\mu \to e\gamma, \quad \mu \to 3e, \quad \mu - e \text{ conv}, \quad \tau \to \mu\gamma, \quad \ldots$$

Some of them are an issue even for elementary leptons!



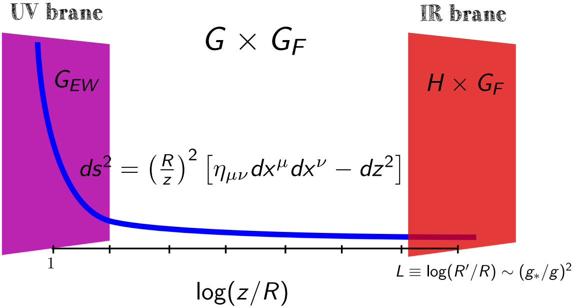


BENEKE, MOCH, ROHRWILD, '15

A FLAVOR PROTECTION

We would like to have a global flavor symmetry in the Composite Sector
$\Longleftrightarrow$ gauge symmetry in the bulk and the IR brane

5DMFV: FITZPATRICK,PEREZ,RANDALL, 07 , PEREZ,RANDALL, 08 , CSAKI,PEREZ,SURUJON,WEILER, 09



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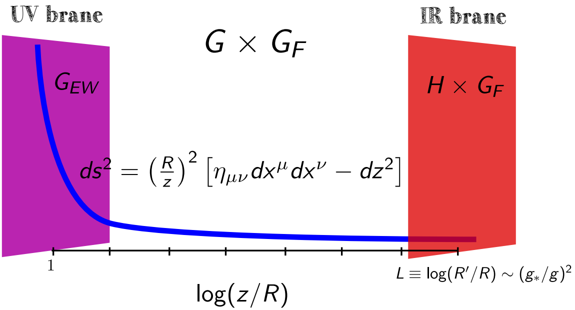

Since we only have two 5D multiplets: $\zeta_{\ell L} \sim \mathbf{5}$ and $\zeta_{\ell R} \sim \mathbf{14}$, we make them triplets of $G_F = SU(3)_L \times SU(3)_R$

$$\zeta_L \sim (\mathbf{3}, \mathbf{1}) \qquad \zeta_R \sim (\mathbf{1}, \mathbf{3})$$

A FLAVOR PROTECTION

We can then assume that all the breaking of G_F comes from one spurion

$$\mathcal{Y} \sim (\mathbf{3}, \bar{\mathbf{3}})$$

such that

$$c_L \equiv M_L R \sim \mathbf{1} + \mathcal{Y}\mathcal{Y}^\dagger \qquad c_R \equiv M_R R \sim \mathbf{1} + \mathcal{Y}^\dagger\mathcal{Y}$$

and

$$m_S \sim \mathcal{Y} \qquad m_B \sim \mathcal{Y}$$

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- By unifying all RH fields we sit in the 'alignment' limit of 5DMFV
- Then, all the flavor mixing comes via the Majorana masses!

COMPOSITE DARK MATTER

THE QUESTION OF DM

- In order to have a DM candidate one needs to go beyond the minimal model

  GRIPAIOS,POMAROL,RIVA,SERRA, '09, MRAZEK,POMAROL,RATTAZZI,REDI,SERRA, '11,

  FRIGERIO,POMAROL,RIVA,URBANO '12, BARNARD,GHETHETTA,RAY, '14, CHALA,NARDINI,SOBOLEV '16, ...

- One uses the fact that for a symmetric coset, $[X^a, X^b] = if_{abk}T^k$ and therefore, if $U = \exp(i\Pi^a X^a/f)$ and $-iU^{-1}\partial_\mu U = d^a_\mu X^a + E^i_\mu T^i$,

$$d_\mu = \frac{1}{f}\partial_\mu\Pi - \frac{i}{2f^2}[\Pi, \partial_\mu\Pi]_X - \frac{1}{6f^3}[\Pi,[\Pi,\partial_\mu\Pi]]_X + \frac{1}{24f^4}[\Pi,[\Pi,[\Pi,\partial_\mu\Pi]]]_X + \ldots,$$

and

$$\mathcal{L}_\sigma = \frac{1}{2}f^2\,\mathrm{Tr}\,(d_\mu d^\mu) + \mathcal{O}(\partial^4) \sim 1 + \frac{1}{f^2} + \frac{1}{f^4} + \ldots + \mathcal{O}(\partial^4)$$

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THE QUESTION OF DM

- We can then promote the accidental $\mathbb{Z}_2$ symmetry of $\mathrm{Tr}(d_\mu d^\mu)$ to a symmetry of the strong sector under which some pNGBs will be odd

$$H \to H \qquad \Phi \to -\Phi$$

- One needs to be sure that this symmetry is respected by the fermion linear mixings $\lambda \bar{q} \mathcal{O}$ and is therefore respected by the scalar potential

$$V(\Pi) \sim m_*^4 \frac{N_c}{16\pi^2} \left[\left(\frac{\lambda}{g_*} \right)^2 V_2(\Pi/f) + \left(\frac{\lambda}{g_*} \right)^4 V_4(\Pi/f) \right] + \dots$$

- Then the lightest $\mathbb{Z}_2$-odd scalar will be a DM candidate!

THE CASE OF SO7/G2

FIRST CONSIDERED IN 1210.6208

- It delivers a $\mathbf{7}$ of G_2, that decomposes under $SU(2) \times SU(2) \subset G_2$ as

$$\mathbf{7} = (\mathbf{2}, \mathbf{2}) \oplus (\mathbf{3}, \mathbf{1})$$

- Depending on which $SU(2)$ is weakly gauged, it means that

$$\mathbf{7} = \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 \quad \text{or} \quad \mathbf{7} = \mathbf{2}_{\pm 1/2} + \mathbf{1}_{\pm 1} + \mathbf{1}_0$$

  under the EW group

- If the $\mathbb{Z}_2$ is succesfully enforced it will provide a natural version of Higgs portal DM or the Inert Triplet Model

- The group is non-anomalous but $SO(7)/G_2$ is not symmetric!

THE CASE OF SO7/G2

Even though the coset is not symmetric, $f^2\mathrm{Tr}(d_\mu d^\mu)$ only features even powers of $1/f$

$$
\begin{aligned}
d_\mu = \frac{1}{f}\partial_\mu \Pi - \frac{i}{2f^2}\left[\Pi, \partial_\mu \Pi\right]_X - \frac{1}{6f^3}\left[\Pi, \left[\Pi, \partial_\mu \Pi\right]\right]_X \\
+ \frac{1}{24f^4}\left[\Pi, \left[\Pi, \left[\Pi, \partial_\mu \Pi\right]\right]\right]_X + \dots
\end{aligned}
$$

We make

$$q_L \sim \mathbf{35} = \mathbf{1} \oplus \mathbf{7} \oplus \mathbf{27}, \quad t_R \sim \mathbf{1}$$

leading to

$$V(\Pi) \approx m_*^2 f^2 \frac{N_c}{16\pi^2} y_t^2 \left[c_1 V_1(\Pi) + c_2 V_2(\Pi)\right],$$

with $c_{1,2} \lesssim 1$ numbers encoding the details of the UV dynamics

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$$d_\mu = \underbrace{\frac{1}{f}\partial_\mu \Pi + \frac{1}{f^2} g(\Pi/f)\,[\Pi, \partial_\mu \Pi]_X}_{\mathrm{Tr}=0} + \frac{1}{f^3} h(\Pi/f)\,[\Pi, [\Pi, \partial_\mu \Pi]]_X$$

We make

$$q_L \sim \mathbf{35} = \mathbf{1} \oplus \mathbf{7} \oplus \mathbf{27}, \quad t_R \sim \mathbf{1}$$

leading to

$$V(\Pi) \approx m_*^2 f^2 \frac{N_c}{16\pi^2} y_t^2 \left[c_1 V_1(\Pi) + c_2 V_2(\Pi)\right],$$

with $c_{1,2} \lesssim 1$ numbers encoding the details of the UV dynamics

THE CASE OF SO7/G2

Even though the coset is not symmetric, $f^2\,\mathrm{Tr}(d_\mu d^\mu)$ only features even powers of $1/f$

$$d_\mu = \frac{1}{f}\,\partial_\mu \Pi + \frac{1}{f^2} g(\Pi/f)\,[\Pi,\partial_\mu\Pi]_X + \underbrace{\frac{1}{f^3} h(\Pi/f)\,[\Pi,[\Pi,\partial_\mu\Pi]]_X}_{\mathrm{Tr}=0}$$

We make

$$q_L \sim \mathbf{35} = \mathbf{1}\oplus\mathbf{7}\oplus\mathbf{27}, \quad t_R \sim \mathbf{1}$$

leading to

$$V(\Pi) \approx m_*^2 f^2 \frac{N_c}{16\pi^2} y_t^2 \left[c_1 V_1(\Pi) + c_2 V_2(\Pi)\right],$$

with $c_{1,2} \lesssim 1$ numbers encoding the details of the UV dynamics

A NATURAL INERT TRIPLET MODEL

- We consider first the case where the additional pNGBs span a triplet
- At the renormalizable level

$$V(H,\Phi) = \mu_H^2|H|^2 + \lambda_H|H|^4 + \frac{1}{2}\mu_\Phi^2|\Phi|^2 + \frac{1}{4}\lambda_\Phi|\Phi|^4 + \lambda_{H\Phi}|H|^2|\Phi|^2$$

with $H \sim \mathbf{2}_{1/2}$ and $\Phi \sim \mathbf{3}_0$ and

μ_H^2	μ_Φ^2	λ_Φ	$\lambda_{H\Phi}$
$-v^2\lambda_H$	$\frac{2}{3}f^2\lambda_H\left(1-\frac{8}{3}\frac{v^2}{f^2}\right)$	$-\frac{4}{9}\lambda_H\left(1-\frac{8}{3}\frac{v^2}{f^2}\right)$	$\frac{5}{18}\lambda_H\left(1+\frac{32}{15}\frac{v^2}{f^2}\right)$

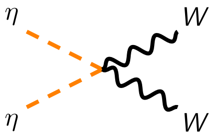
- Extremely predictive, only one free parameter f !
- $\mu_\Phi^2 > 0$ as well as $m_\Phi^2 = \mu_\Phi^2 + \lambda_{H\Phi}v^2 > 0$ so $\langle\Phi\rangle = 0$

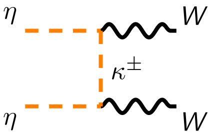
COANNIHILATIONS

- EW gauge bosons induce a radiative splitting between the neutral and the charged components

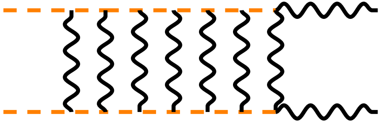
$$\Delta m_\Phi = g m_W \sin^2\theta_W/2 \sim 166\,\text{MeV}$$

- The coannihilation is dominated by gauge interactions



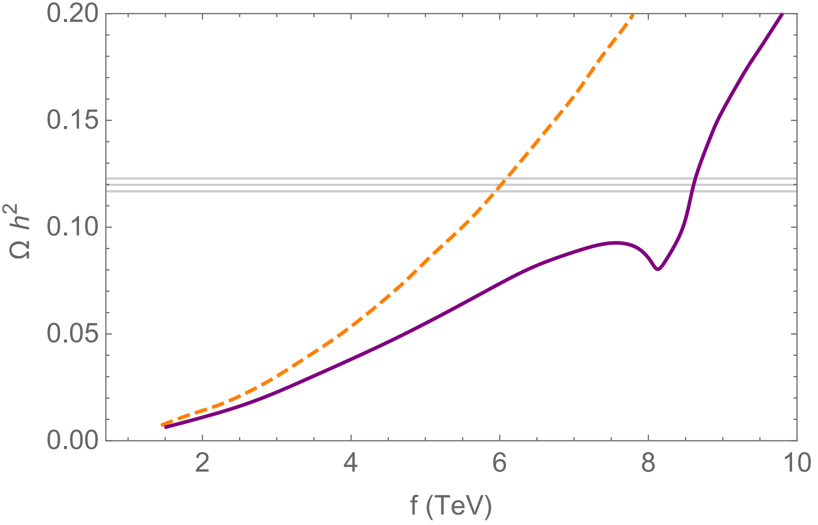


- Sommerfeld enhancement and bound state production are important! $g m_\Phi/m_W \gg 1$ CIRELLI,STRUMIA,TAMBURINI '07



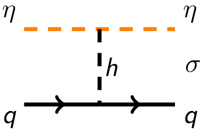
RELIC ABUNDANCE

RECAST OF 0706.4071



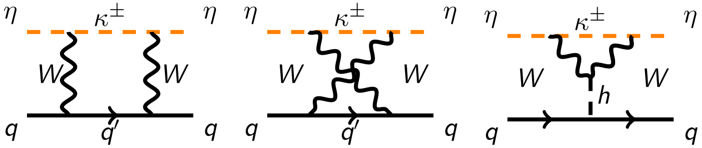
DIRECT DETECTION

- There is a m_Φ^2-suppressed tree-level contribution proportional to $\lambda_{H\Phi}$



$$\sigma = \lambda_{H\Phi}^2 m_N^4 f_N^2/(\pi m_h^4 m_\Phi^2), \quad f_N = \sum_q \langle N|\bar{q}q|N\rangle \approx 0.3$$

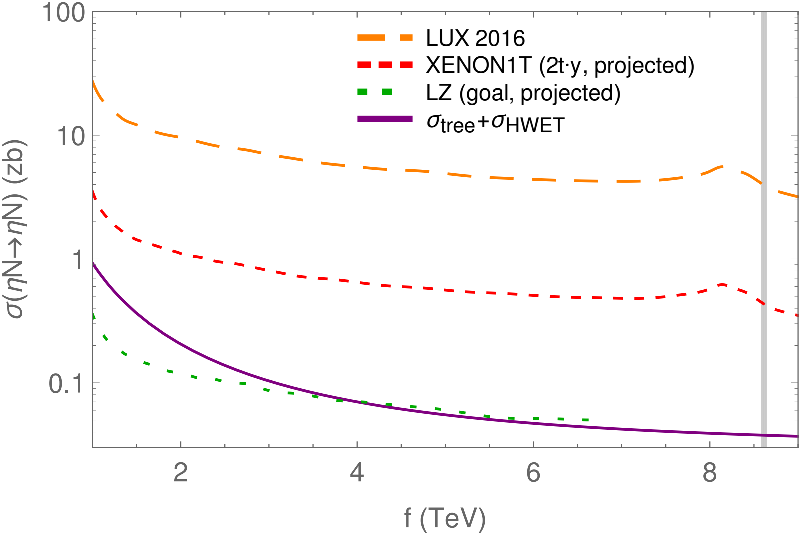
- But there are also m_Φ-independent loop induced contributions



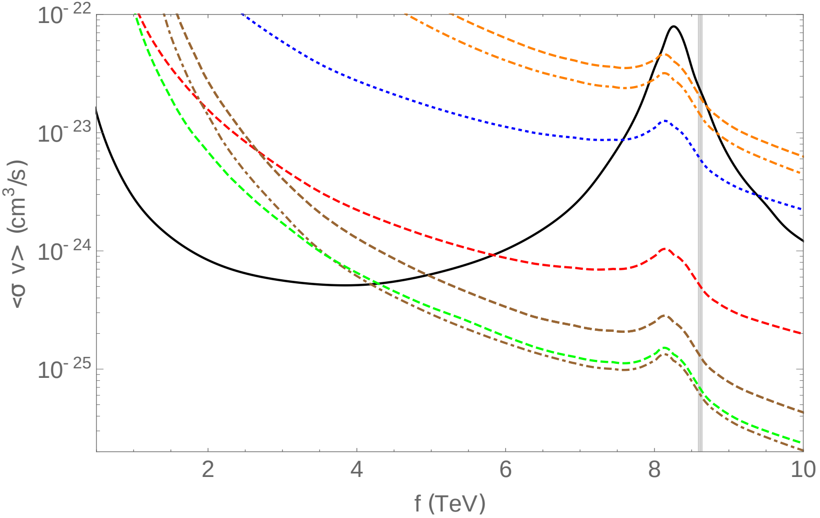
It has been computed in the heavy WIMP effective theory HILL,SOLON, '13

$$\sigma(\eta N \to \eta N)_{\mathrm{HWET}} = 1.3^{+0.4+0.4}_{-0.5-0.3} \times 10^{-2}\,\mathrm{zb}$$

DIRECT DETECTION



INDIRECT DETECTION



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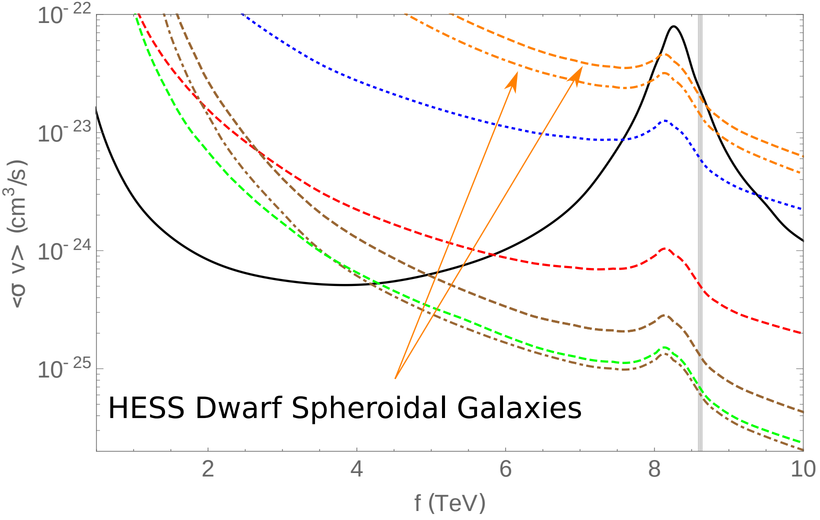

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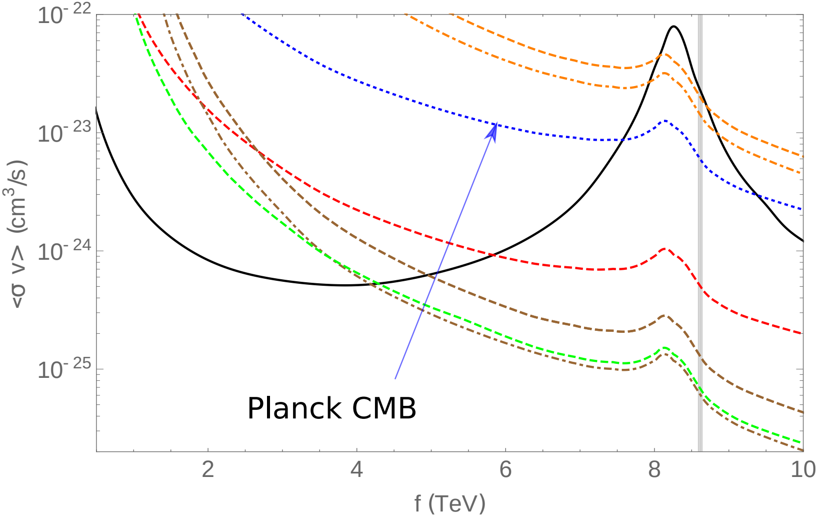

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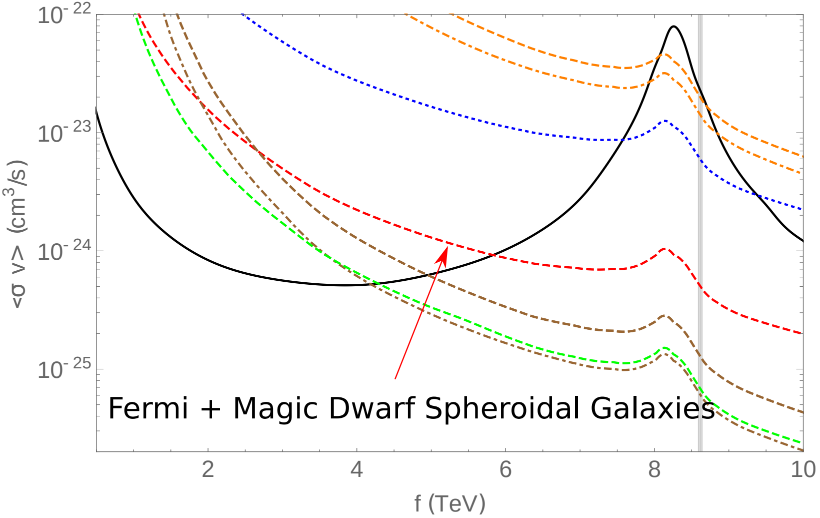
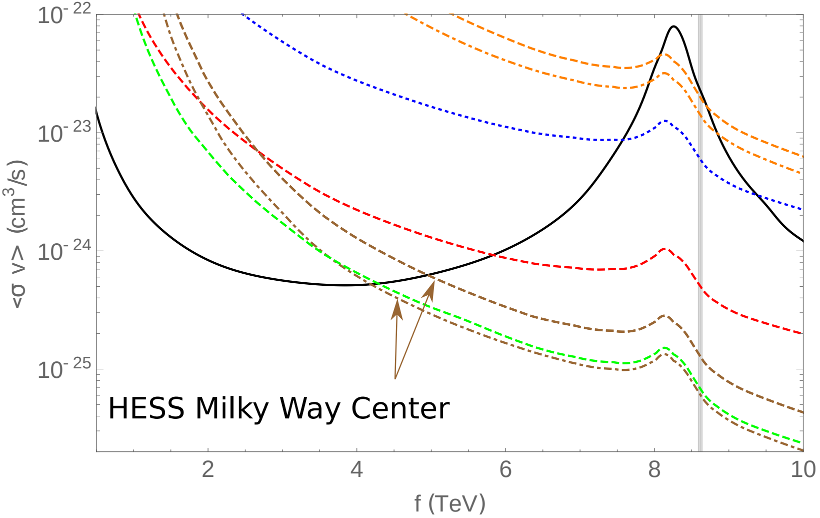
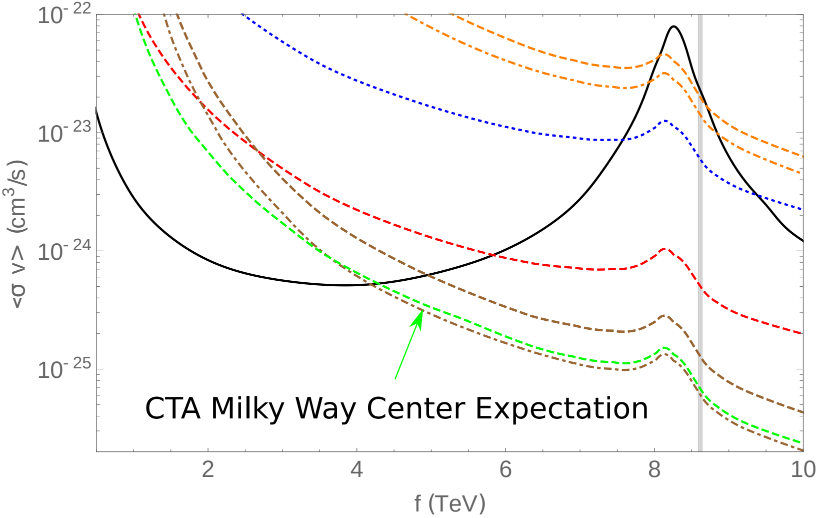


INDIRECT DETECTION



INDIRECT DETECTION



COLLIDER SIGNATURES AND OTHER CONSTRAINTS

- EWPT: modification of hVV coupling $\Rightarrow f \gtrsim 900$ GeV 1511.08235
- Modification of Higgs production and decay

$$R_\gamma = \frac{\sigma(gg \to h) \times BR(h \to \gamma\gamma)}{\sigma_{SM}(gg \to h) \times BR_{SM}(h \to \gamma\gamma)} \sim 1 + \mathcal{O}\left(\frac{v^2}{f^2}\right) \Rightarrow f \gtrsim 800 \text{ GeV}$$

- Searches for dissapearing tracks: κ^+ has a decay length of a few cm

$f \gtrsim 650$ GeV RECAST OF AN ATLAS 8 TEV ANALYSIS 1310.3675

- Monojet searches are not competitive to the previous ones

THE SINGLET CASE

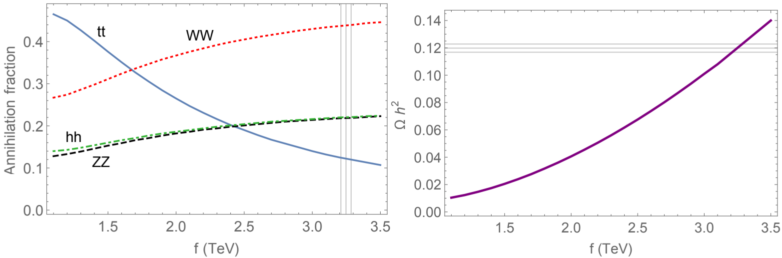
THE SCALAR POTENTIAL

The leading contribution to the scalar potential remains the same but there are subleading contributions

- Breaking the degeneracy of κ^+ and η (coming mostly from B_μ)
- Making $\kappa^\pm$ decay into $t_L b_R$ (coming from the b_R)

RELIC ABUNDANCE

- Sommerfeld effects and bound state production no longer relevant
- $|H|^2(\partial_\mu \eta)^2/f^2$ dominates over $\lambda_{H\Phi}|H|^2\eta^2$



THE SINGLET CASE

DIRECT DETECTION

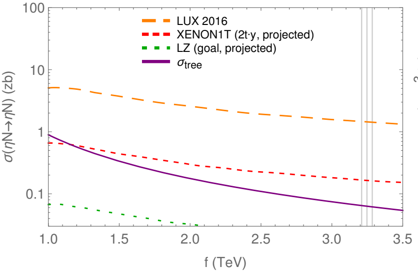
- No m_Φ-independent contribution but the bounds rescale differently

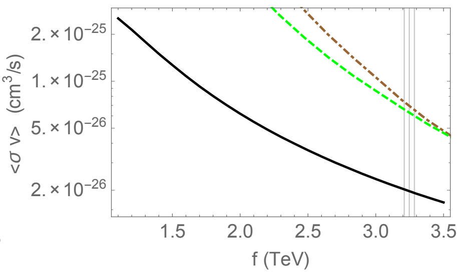
INDIRECT DETECTION

- Now it is possible to accommodate the whole DM abundance

COLLIDER SEARCHES

- Dissapearing tracks are no longer relevant





Conclusions

- In CHMs, the absence of top partners can be translated into ~~LFU~~!
- Therefore, $R_K < 1$ and $R_{K^*} < 1$ could be the first probe of the dynamics of EWSB
- Scalar WIMPs can naturally arise in non-minimal composite Higgs models.
- In particular, the coset $SO(7)/G_2$ leads to natural versions of Higgs portal DM and the Inert Triplet Model
- In general, NP could be probed first via non-resonant searches!

THANKS!

BACK - UP SLIDES

COMPOSITE RH NEUTRINOS

When the operator

$$\frac{\lambda_R}{\Lambda^{\gamma_R}}\bar{\Psi}_R\mathcal{O}_R$$

is relevant, i.e., $\gamma_R < 0$, a very large kinetic term is induced

$$\frac{\lambda_R^2}{\Lambda^{2\gamma_R}}\int \mathrm{d}^4p\,\mathrm{d}^4q\;\bar{\Psi}_R(-p)\langle\mathcal{O}_R(p)\bar{\mathcal{O}}_R(-q)\rangle\Psi_R(q)$$
$$\sim \lambda_R^2\left(\frac{\mu}{\Lambda}\right)^{2\gamma_R}\int \mathrm{d}^4x\;\bar{\Psi}_R(x)i\partial\!\!\!/\Psi_R(x)$$

Canonically normalizing Ψ_R requires

$$\Psi_R \to \frac{1}{\lambda_R}\left(\frac{\mu}{\Lambda}\right)^{-\gamma_R}\Psi_R$$

and leads to $M_\Sigma \to M_\Sigma\lambda_R^{-2}(\mu/\Lambda)^{-2\gamma_R}$ and

$$M_D \sim v\lambda_\ell\left(\frac{\mu}{\Lambda}\right)^{\gamma_L}$$

EWPD

For elementary fermions and a composite Higgs,

$$\hat{T} \sim [\hat{\alpha} - 2\hat{\beta} + \hat{\gamma}], \qquad \hat{S} \sim [-\hat{\beta} + \hat{\gamma}], \qquad W = Y \sim \hat{\gamma}$$

where

$\hat{\alpha}$ $\hat{\beta}$ $\hat{\gamma}$

and ■ $\sim \sqrt{L}$, ● $\sim 1/\sqrt{L}$, $\sqrt{L} \sim g_* / g_{\text{el}}$. Thus,

$$\hat{T} \sim L, \qquad \hat{S} \sim 1, \qquad W = Y \sim 1/L$$

$\hat{T} \gg \hat{S} \gg W, Y$

We can make $\hat{T}$ and $\delta Z \bar{\ell}_R \ell_R$ small enough thanks to our custodial setup

Agashe, Delgado, May, Sundrum, '03 Agashe, Contino, Da Rold, Pomarol, '06