RECENT B PHYSICS ANOMALIES
A FIRST HINT FOR COMPOSITENESS?

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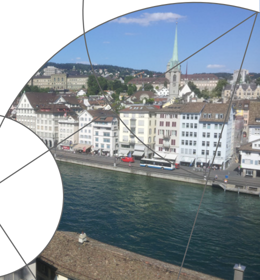


April 10, 2018

OUTLINE

1. Recent B-physics anomalies

2. Violation of Lepton Flavor Universality in Composite Higgs Models

   AC, GOERTZ: PRL 116 2016 NO.25, 251801; ARXIV:1510.07658;

   AC, GOERTZ: ARXIV:1712.02536

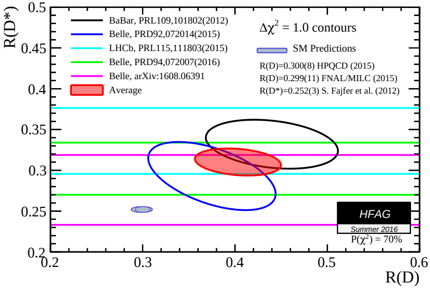
3. Conclusions

FLAVOR ANOMALIES

CHARGED CURRENTS

✓ A combined $\sim 4\,\sigma$ anomaly on charged current semileptonic $\bar{B} \to D^{(*)}$ decays

$$R_D^{(*)} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}; \quad R_D/R_D^{\mathsf{SM}} = 1.37 \pm 0.17 \quad R_{D^*}/R_{D^*}^{\mathsf{SM}} = 1.28 \pm 0.08$$



! Requires very light NP, since it has to compete with the SM tree-level prediction

FLAVOR ANOMALIES

NEUTRAL CURRENTS

✓ There are several prominent deviations in $b \to s\ell\ell$ transitions

Observable	Experiment	SM prediction	pull
$\langle P_5' \rangle_{[4,6]}$	-0.30 ± 0.16	-0.82 ± 0.08	-2.9
$\langle P_5' \rangle_{[6,8]}$	-0.51 ± 0.12	-0.94 ± 0.08	-2.9
$R_K^{[1,6]}$	$0.745^{+0.090}_{-0.074} \pm 0.036$	1.00 ± 0.01	+2.6
$R_{K^*}^{[0.045,1.1]}$	$0.66^{+0.11}_{-0.07} \pm 0.03$	0.92 ± 0.02	+2.2
$R_{K^*}^{[1.1,6]}$	$0.69^{+0.11}_{-0.07} \pm 0.05$	1.00 ± 0.01	+2.5
$\ldots$			

where

$$R_K^{[q_0^2,q_1^2]} \equiv \left. \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} \right|_{[q_0^2,q_1^2]} , \quad R_{K^*}^{[q_0^2,q_1^2]} \equiv \left. \frac{\mathcal{B}(B^0 \to K^* \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^* e^+ e^-)} \right|_{[q_0^2,q_1^2]}$$

and P_5' is some 'complicated' angular observable in $B \to K^* \mu\mu$.

THE CASE FOR RK$^{(*)}$

From the NP point of view, R_K and R_{K^*} stand out for several reasons

1. They are very clean observables!

   For R_K

   - Perturbative and non-perturbative QCD contributions cancel
   - $\log(m_\ell)$ enhanced QED corrections are at the $\mathcal{O}(1\%)$ level BORDONE, ISIDORI, PATTORI, 16

   For R_{K^*}, QCD contributions cancel within the SM

2. It is a loop level effect in the SM

3. They probe a somehow fundamental feature of the SM: lepton flavor universality!

EFT APPROACH

In order to compute the NP effects in $b \to s\ell\ell$ we use the following effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}(V_{ts}^* V_{tb}) \sum_i \hat{C}_i^\ell \mathcal{O}_i^\ell(\mu),$$

with the relevant operators being

$$\begin{aligned}
\mathcal{O}_7 &= \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\alpha\beta} P_R b\right) F^{\alpha\beta}, & \mathcal{O}_7' &= \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\alpha\beta} P_L b\right) F^{\alpha\beta}, \\
\mathcal{O}_9^\ell &= \frac{\alpha}{4\pi} \left(\bar{s}\gamma_\alpha P_L b\right)\left(\bar{\ell}\gamma^\alpha \ell\right), & \mathcal{O}_9^{\ell\prime} &= \frac{\alpha}{4\pi} \left(\bar{s}\gamma_\alpha P_R b\right)\left(\bar{\ell}\gamma^\alpha \ell\right), \\
\mathcal{O}_{10}^\ell &= \frac{\alpha}{4\pi} \left(\bar{s}\gamma_\alpha P_L b\right)\left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right), & \mathcal{O}_{10}^{\ell\prime} &= \frac{\alpha}{4\pi} \left(\bar{s}\gamma_\alpha P_R b\right)\left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right),
\end{aligned}$$

and $\hat{C}_i = C_i^{\text{SM}} + C_i^{\text{NP}}$. We have

$$C_9^{\ell\,\text{SM}} = 4.07\,,\;\; C_{10}^{\ell\,\text{SM}} = -4.31\,,\;\; C_7^{\text{SM}} = -0.29\,.$$

and $C_{7,9,10}^{\ell\prime\text{SM}} = 0$.

EFT APPROACH

There are also (pseudo)scalar operators

$$\mathcal{O}_S^{(\prime)} = \frac{\alpha}{4\pi}(\bar{s}P_{R,L}b)(\bar{\ell}\ell), \quad \mathcal{O}_P^{(\prime)} = \frac{\alpha}{4\pi}(\bar{s}P_{R,L}b)(\bar{\ell}\gamma_5\ell),$$

as well as tensor ones

$$\mathcal{O}_{T(5)} = \frac{\alpha}{4\pi}(\bar{s}\sigma^{\mu\nu}b)(\bar{\ell}\sigma_{\mu\nu}(\gamma_5)\ell).$$

However, only $\mathcal{O}_S - \mathcal{O}_P$ and $\mathcal{O}'_S + \mathcal{O}'_P$ are non zero when one goes from the dim-6 SM EFT to $\mathcal{H}_{\text{eff}}$

ALONSO, GRINSTEIN, MARTIN - CAMALICH '14

$\mathcal{B}(B_s^0 \to \ell^+\ell^-)$ very sensitive to (pseudo)scalar operators $\Rightarrow$ NP contributions there have to be small $\Rightarrow$ NP in $b \to s\ell\ell$ transitions can be very well parametrized by $\mathcal{O}_{9,10,7}^{(\prime)}$

EFT APPROACH

We can also use for convenience the chiral basis,

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}(V_{ts}^* V_{tb})\frac{\alpha}{4\pi}\left(\mathcal{O}_7 + \mathcal{O}_7' + \sum_{\substack{X,Y=L,R\\ \ell=e,\mu,\tau}} C_{bs_X\ell_Y}\mathcal{O}_{bs_X\ell_Y}\right) + \text{h.c.}\,,$$

with

$$\mathcal{O}_{bs_X\ell_Y} = (\bar{s}\gamma_\mu P_X b)(\bar{\ell}\gamma^\mu P_Y \ell)\,,$$

since often NP models treat a certain chirality in a special way and one can take advantage of the hierarchy of SM contributions

$$C^{\text{SM}}_{bs_L\ell_L} = 8.38 \gg -C^{\text{SM}}_{bs_L\ell_R} = 0.24.$$

In this basis

$$R_K = \frac{|C_{bs_L\mu_L} + C_{bs_R\mu_L}|^2 + |C_{bs_L\mu_R} + C_{bs_R\mu_R}|^2}{|C_{bs_Le_L} + C_{bs_Re_L}|^2 + |C_{bs_Le_R} + C_{bs_Re_R}|^2}$$

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$$C^{\text{SM}}_{bs_L\ell_L} = 8.38 \gg -C^{\text{SM}}_{bs_L\ell_R} = 0.24.$$

In this basis

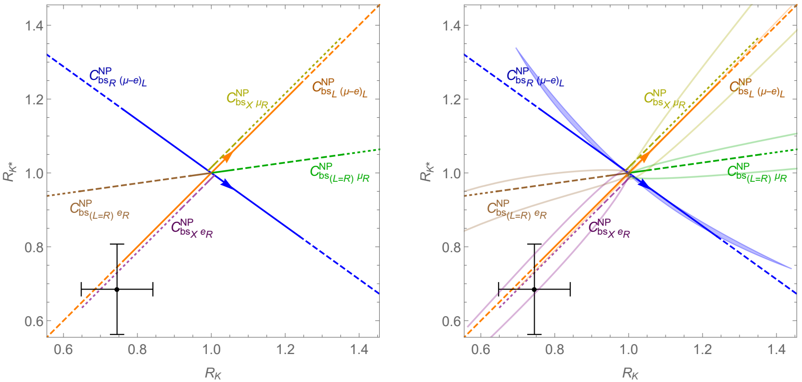
$$R_K \simeq 1 + 2\frac{\text{Re}[C^{\text{SM}*}_{bs_L\ell_L}(C^{\text{NP}}_{bs_L\mu_L} + C^{\text{NP}}_{bs_R\mu_L} - C^{\text{NP}}_{bs_L e_L} - C^{\text{NP}}_{bs_R e_L})]}{|C^{\text{SM}}_{bs_L\ell_L}|^2}$$
$$+\frac{|C^{\text{NP}}_{bs_L\mu_R} + C^{\text{NP}}_{bs_R\mu_R}|^2 - |C^{\text{NP}}_{bs_L e_R} + C^{\text{NP}}_{bs_R e_R}|^2}{|C^{\text{SM}}_{bs_L\ell_L}|^2}$$

EFT APPROACH

Analogously,

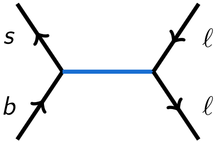
$$R_{K^*} \simeq R_K - 4p\frac{\mathrm{Re}[C^{\mathrm{SM}*}_{bs_L\ell_L}(C^{\mathrm{NP}}_{bs_R\mu_L} - C^{\mathrm{NP}}_{bs_Re_L})]}{|C^{\mathrm{SM}}_{bs_L\ell_L}|^2}$$

$$-4p\frac{\mathrm{Re}[C^{\mathrm{NP}}_{bs_L\mu_R}C^{\mathrm{NP}\,*}_{bs_R\mu_R} - C^{\mathrm{NP}}_{bs_Le_R}C^{\mathrm{NP}\,*}_{bs_Re_R}]}{|C^{\mathrm{SM}}_{bs_L\ell_L}|^2} \quad \text{where } p \approx 0.86$$

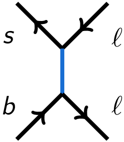


MODEL BUILDING

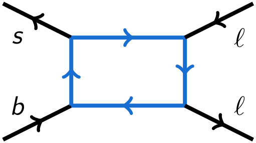
Three main possibilities:



Z' resonance



spin 0/1 leptoquark



loop stuff

- Most of the models are ad-hoc solutions to the flavor anomalies
- The connection with naturalness was largely unexplored
- Can it be the first hint of a bigger picture?

VIOLATION OF LFU IN CHMS

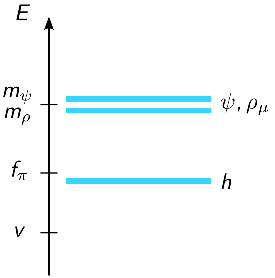
Composite Higgs

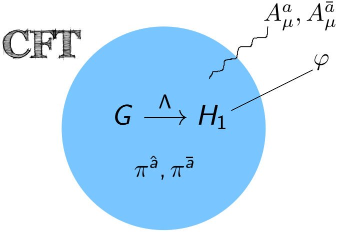
- One interesting solution to the hierarchy problem is making the Higgs composite, the remnant of some new strong dynamics

  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





They can naturally lead to a light Higgs $\quad m_\pi^2 = m_h^2 \sim g_{\mathrm{el}}^2 \mu^2 / 16\pi^2$

COMPOSITE HIGGS

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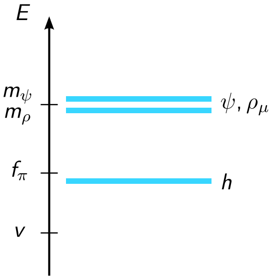

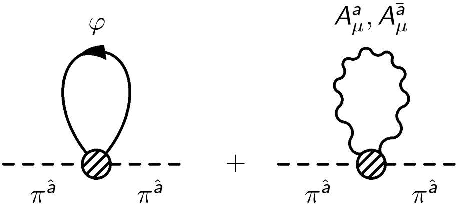

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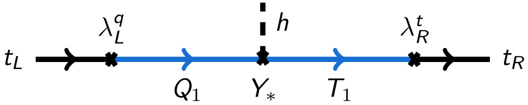
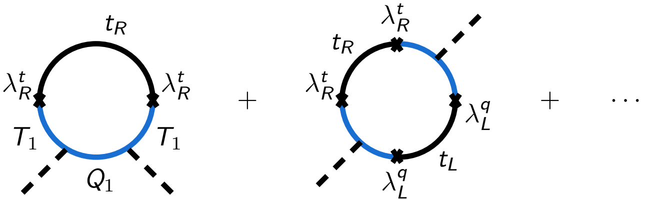
HIGGS POTENTIAL

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

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



break the NGB symmetry and will be also responsible for EWSB



HIGGS POTENTIAL

One can promote the linear mixings to spurions of G and expand in powers of λ/g_*

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

The large value of the top yukawa

$$y_{\mathrm{top}} \sim Y_* \frac{\lambda_q f}{M_Q} \frac{\lambda_t f}{M_T} \sim 1$$

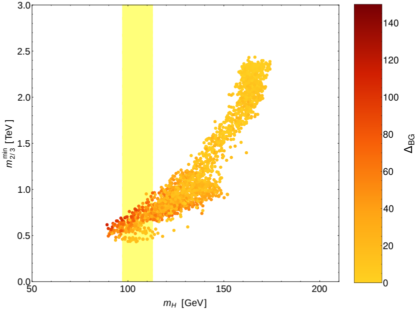
makes the top contribution (typically) responsible for triggering EWSB
CONTINO, DA ROLD, POMAROL, '06 and since

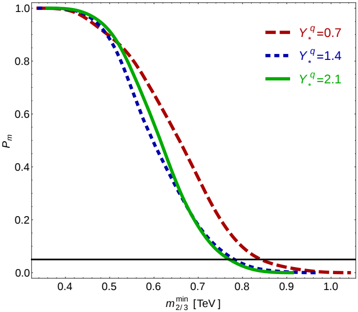
$$m_H^2 \propto |\lambda|^4 / g_*^4$$

We expect to have anomalously light top partners $M_\Psi \ll m_*$

LIGHT TOP PARTNERS AT THE LHC

We can see e.g. the MCHM_5, AC, GOERTZ, JHEP 1505 2015 002



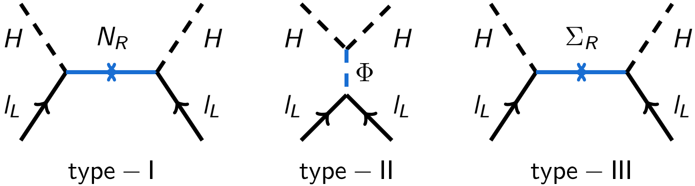


$f = 0.8$ TeV, $g_* \sim 4.4$. $Y_*^q = 0.7$ is the maximum allowed "Yukawa"

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

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

Leptons can play a role

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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!

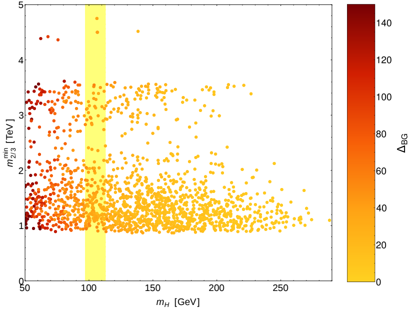
$$\mathcal{L} \supset \frac{\lambda_L^\ell}{\Lambda^{\gamma_\ell}} \bar{\ell}_L \mathcal{O}_\ell + \frac{\lambda_R}{\Lambda^{\gamma_R}} \bar{\Psi}_R \mathcal{O}_R - \frac{1}{2} M_\Sigma \mathrm{Tr}\left(\bar{\Sigma}_R^c \Sigma_R\right) + \text{h.c.}$$

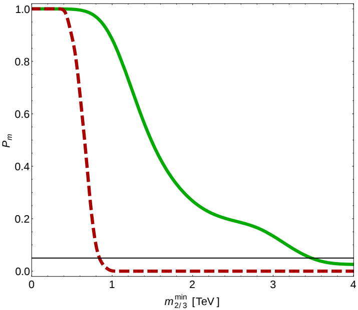
with $\Psi_R \supset e_R, \Sigma_R$, $\quad \mathcal{O}_\ell \sim \mathbf{5}$ $\quad$ and $\quad \mathcal{O}_R \sim \mathbf{14}$

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





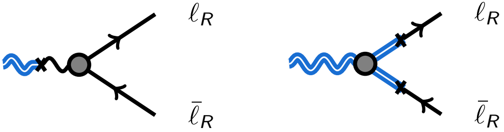
VIOLATION OF LFU

Vector resonances are ubiquitous in CHMs. In the particular case of

$$SO(5) \times U(1)_X / [SO(4) \times U(1)_X]$$

one gets

$$\mathbf{10} = (\mathbf{3}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{3}) \oplus (\mathbf{2}, \mathbf{2}), \qquad \mathbf{1} = (\mathbf{1}, \mathbf{1})$$



$\sim g^2/g_*$ $\qquad$ $\sim g_*(\epsilon_R^\ell)^2$

RH leptons are custodially symmetric and transform as $(\mathbf{1}, \mathbf{1})$ so they only couple (beforew EWSB) to the 'hypercharge' $(\mathbf{1}, \mathbf{1})$

VIOLATION OF LFU

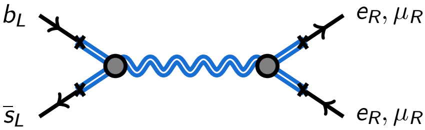
Since

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

having hierarchical charged lepton masses and anarchical neutrino masses leads to

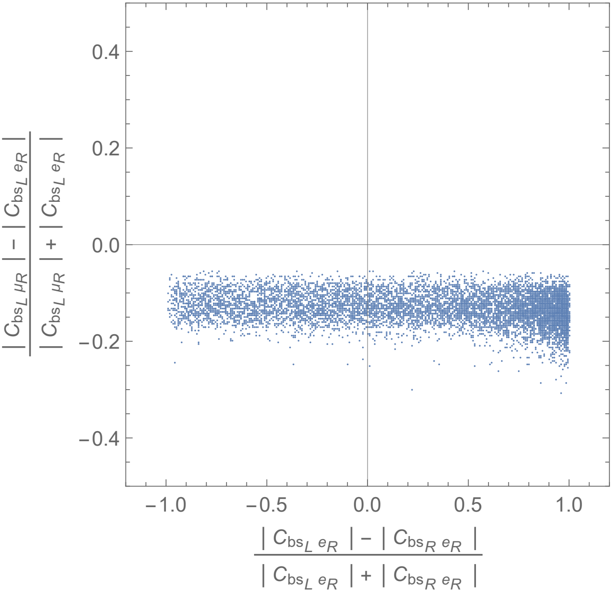
$$0 \ll \epsilon_R^\tau \ll \epsilon_R^\mu \ll \epsilon_R^e$$

and to a violation of LFU

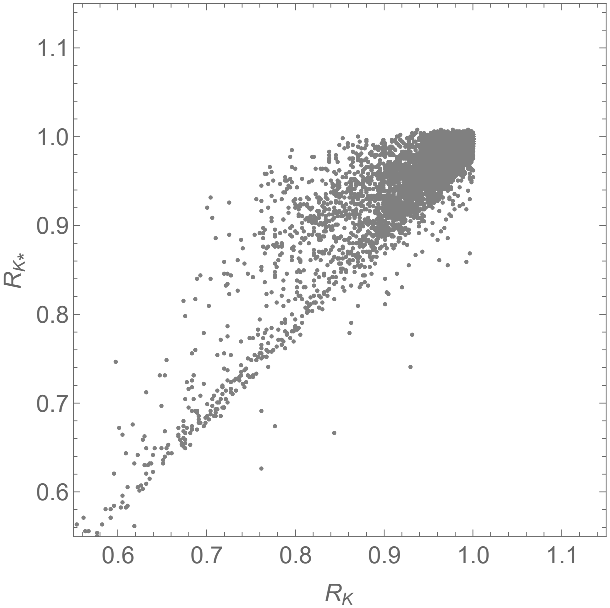


$$\sim g_*^2/m_*^2\ (\epsilon_{s_L}\epsilon_{b_L}\epsilon_R^2)$$

VIOLATION OF LFU



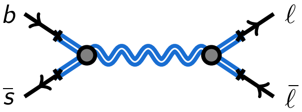
VIOLATION OF LFU



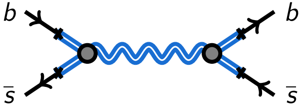
CONSTRAINTS

There are four irreducible constraints

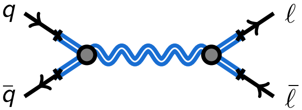
1. $B_s \to \ell\ell$



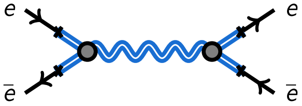
2. $B_s - \bar{B}_s$ mixing



3. $pp \to \ell\ell$

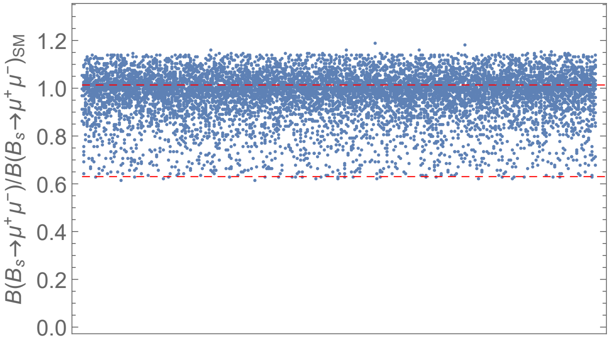


4. EWPD



1. $B_s \to \ell\ell$

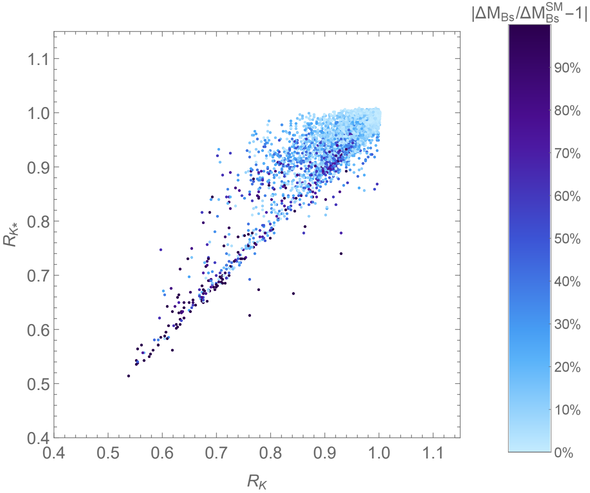
$$\frac{\mathcal{B}(B_s \to \ell^+\ell^-)}{\mathcal{B}(B_s \to \ell^+\ell^-)_{\mathrm{SM}}} = \left| 1 + \frac{C^{\mathrm{NP}}_{bs_L\ell_R} - C^{\mathrm{NP}}_{bs_L\ell_L} - C^{\mathrm{NP}}_{bs_R\ell_R} + C^{\mathrm{NP}}_{bs_R\ell_L}}{C^{\mathrm{SM}}_{bs_L\ell_R} - C^{\mathrm{SM}}_{bs_L\ell_L}} \right|^2$$



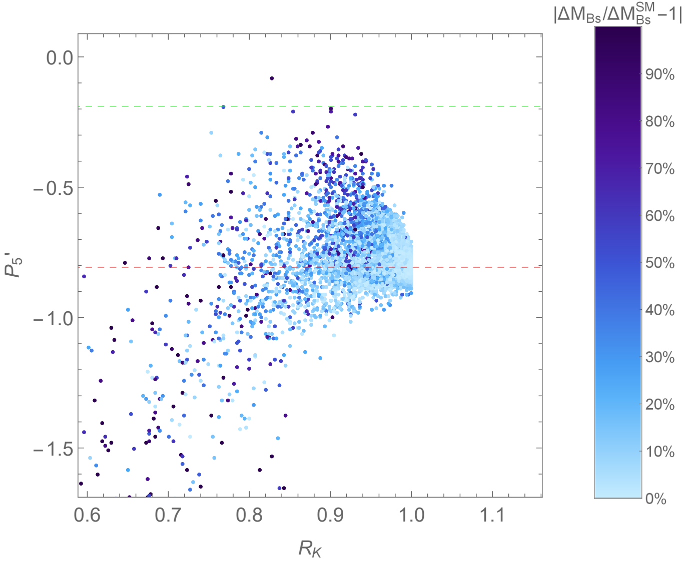
2. $B_s - \bar{B}_s$ MIXING

$$\frac{\Delta M_{B_s}}{\Delta M_{B_s}^{\rm SM}} \simeq 1 + \left(35.380\, \mathrm{Re}\, C_V^{LR} - 10.530\, \mathrm{Re}[C_V^{LL} + C_V^{RR}]\right)\, \mathrm{TeV}^2$$

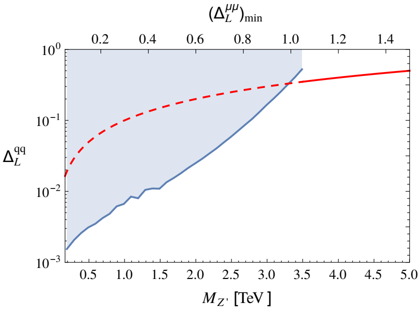
$$\mathcal{O}_V^{XY} = (\bar{s}\gamma_\mu P_X b)(\bar{s}\gamma^\mu P_Y b)$$



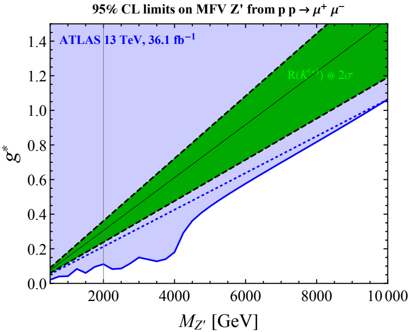
2. $B_s - \bar{B}_s$ MIXING AND $P'_{5[4.3,8.68]}$



3. DILEPTON SEARCHES



ALTMANNSHOFER, STRAUB, '14



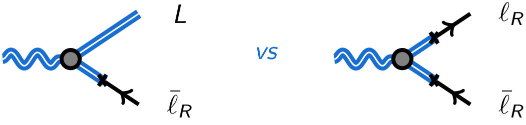
GRELJO, MARZOCCA, '17

- For $M_{Z'} \lesssim 3$ TeV, couplings to first generation quarks have to be small
- MFV-like couplings to quarks is already excluded!

✓ We have ~ 4 TeV Z's with very small couplings to light quarks

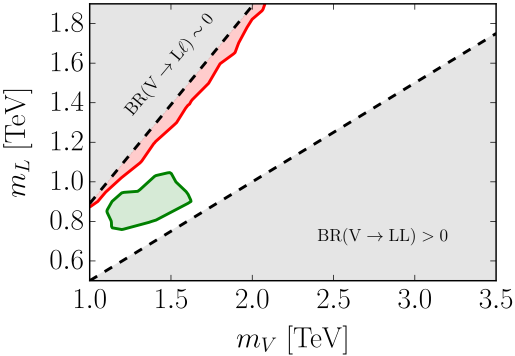
3. DILEPTON SEARCHES

Moreover, by naturalness, one expects the channel $Z' \to L\ell$ to be open and dominate the branching ratio



$\sim g_* \epsilon^{\ell}_{R}$ $\qquad$ $\sim g_* (\epsilon^{\ell}_{R})^2$

CHALA, SPANNOWSKY '18



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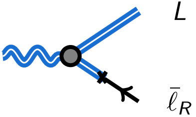

$\sim g_* \epsilon^\ell_R$

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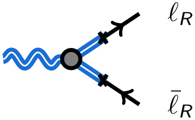

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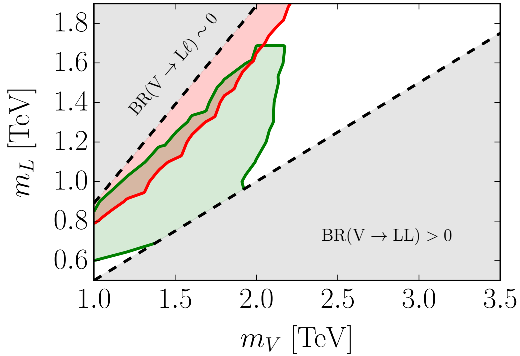
CHALA, SPANNOWSKY '18



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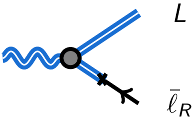

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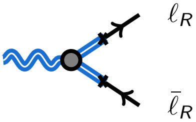

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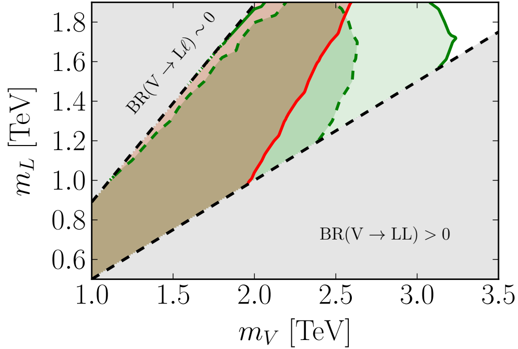
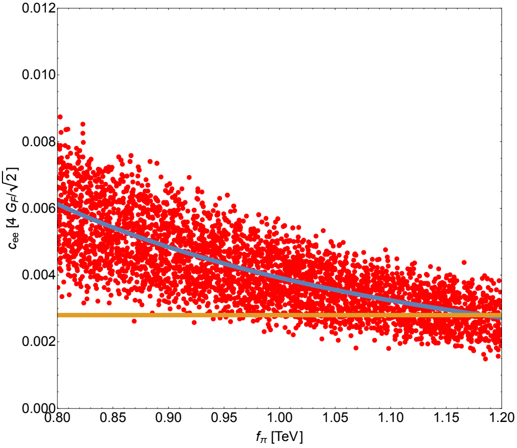
CHALA, SPANNOWSKY '18



4. EWPD

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

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

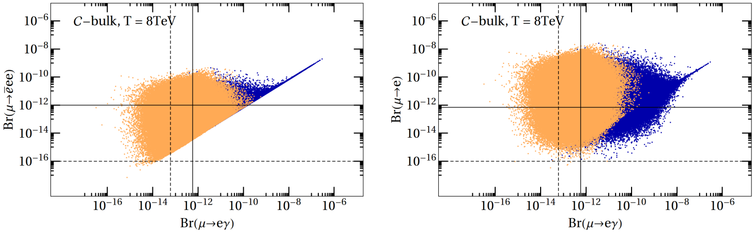


What about LFV?

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!

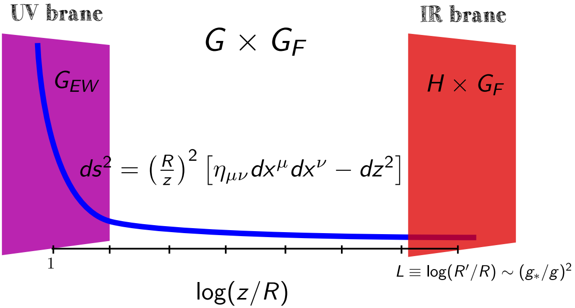


Beneke, Moch, Rohrwild, '15

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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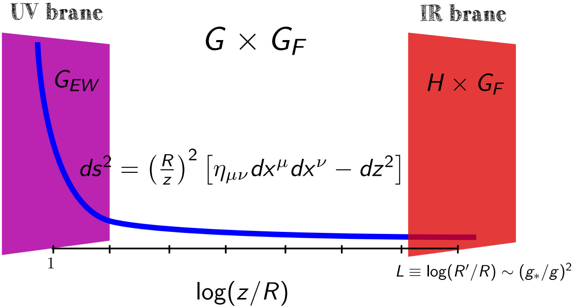

Since we only have two 5D multiplets: $\zeta_{\ell L} \sim \mathbf{5}$ and $\zeta_{\ell R} \sim \mathbf{14}$, we make them triplets of $G_F = SU(3)_L \times SU(3)_R$

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

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!

CONCLUSIONS

- R_K and R_{K^*} provide very clean probes of higher energies
- Both R_K and R_{K^*} anomalies can be succesfuly addresed with NP in the RH electron sector
- This can happen naturally in CHMs with a 'minimal' type-III seesaw
- In this setup, the absence of top partners can be translated into ~~LFU~~!
- Observed values in other observables like $B_s \to \mu^+\mu^-, \Delta M_{B_s}$ or P_5' can be reproduced
- Therefore, $R_K < 1$ and $R_{K^*} < 1$ could be the first probe of the dynamics of EWSB

THANKS!

BACK-UP SLIDES

$B \to K\ell^+\ell^-$

The individual branching fractions are given by

$$\frac{d\mathcal{B}(B \to K\ell^+\ell^-)}{dq^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{(4\pi)^5 m_B^3}([m_{B-K^*}^2]^2 - 2m_{B+K^*}^2 q^2 + q^4)^{\frac{3}{2}} (|F_V|^2 + |F_A|^2)$$

where

$$\begin{aligned} F_V(q^2) =& (C_{bs_R\ell_R} + C_{bs_L\ell_L} + C_{bs_R\ell_L} + C_{bs_L\ell_R})/2\, f_+(q^2) \\ &+ \frac{2m_b}{m_B + m_K}(C_7 + C_7')f_T(q^2) + h_K(q^2) \\ F_A(q^2) =& (C_{bs_R\ell_R} - C_{bs_L\ell_L} - C_{bs_R\ell_L} + C_{bs_L\ell_R})/2\, f_+(q^2) \end{aligned}$$

$m_{A\pm B}^2 \equiv m_A^2 \pm m_B^2$, and we neglected lepton masses, CP violation, and higher order corrections

$B^0 \to K^* \ell^+ \ell^-$

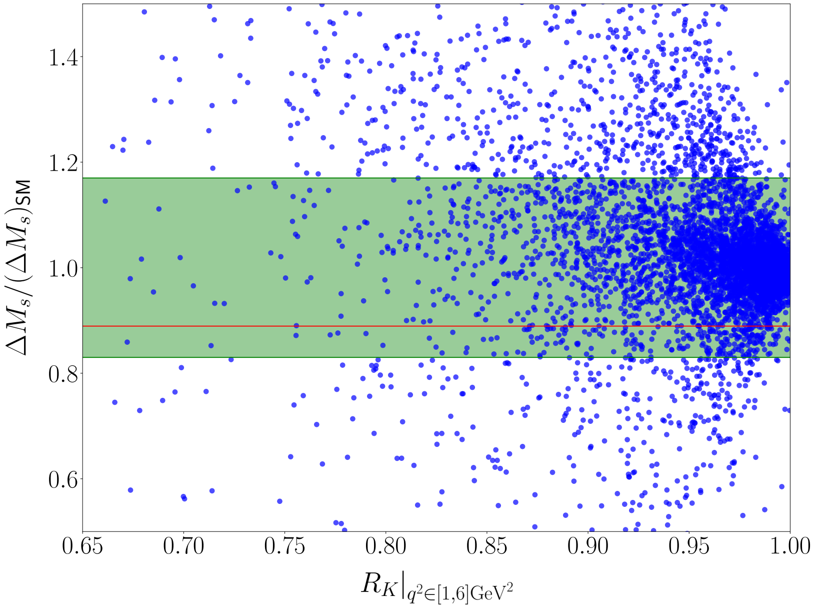
$$\frac{d\mathcal{B}(B^0 \to K^* \ell^+ \ell^-)}{dq^2} \simeq \tau_{B^0} \frac{G_F^2 \alpha^2 |V_{tb} V_{ts}^*|^2}{3 \cdot (4\pi)^5 m_B^3} ([m^2_{B-K^*}]^2 - 2 m^2_{B+K^*} q^2 + q^4)^{\frac{1}{2}} \, q^2$$
$$(|A_\perp^{\ell L}|^2 + |A_\parallel^L|^2 + |A_0^L|^2 + L \to R)$$

$$A_\perp^{\ell L,R} = +\sqrt{2} m_B (1 - q^2/m_B^2) \left[C_{bs_L \ell_{L,R}} + C_{bs_R \ell_{L,R}} \right] \xi_\perp$$
$$A_\parallel^{\ell L,R} = -\sqrt{2} m_B (1 - q^2/m_B^2) \left[C_{bs_L \ell_{L,R}} - C_{bs_R \ell_{L,R}} \right] \xi_\perp$$
$$A_0^{\ell L,R} = -\frac{m_B^3 (1 - q^2/m_B^2)^2}{2|q| m_{K^*}} \left[C_{bs_L \ell_{L,R}} - C_{bs_R \ell_{L,R}} \right] \xi_\parallel$$

Defining the integrated form factors

$$g_{\perp,\parallel,0}^{[q^2_{\rm min}, q^2_{\rm max}]} = \int_{q^2_{\rm min}}^{q^2_{\rm max}} dq^2 \, ([m^2_{B-K^*}]^2 - 2 m^2_{B+K^*} q^2 + q^4)^{\frac{1}{2}} \, \frac{2(q^3 - m_B^2 q)^2}{m_B^2}$$
$$\times \left\{ |\xi_\perp|^2, \, |\xi_\perp|^2, \, \frac{(m_B^2 - q^2)^2}{8 q^2 m_{K^*}^2} |\xi_\parallel|^2 \right\}, \quad p \equiv \frac{g_0 + g_\parallel}{g_0 + g_\parallel + g_\perp}$$

$B_s - \bar{B}_s$ MIXING



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

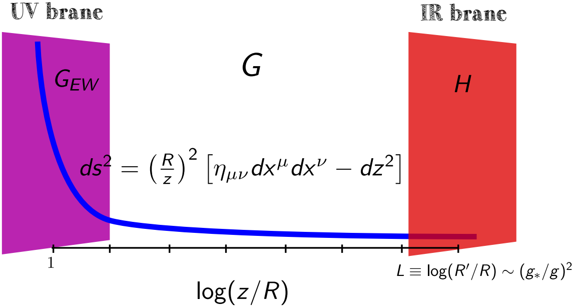
$$\frac{\lambda_L}{\Lambda^{\gamma_L}} q_L \mathcal{O}_L(x), \quad \frac{\lambda_R}{\Lambda^{\gamma_R}} t_R \mathcal{O}_R(x), \quad [\mathcal{O}_{L,R}(x)] = 5/2+\gamma_{L,R}, \qquad \gamma_{L,R} > -1$$

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

Very well mimicked by Randal-Sundrum models!

AdS/CFT correspondence

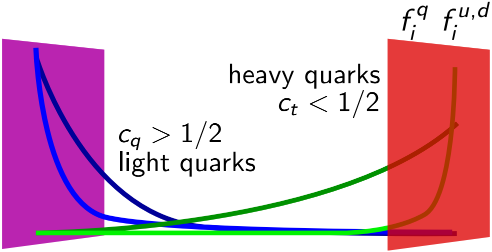
- Models with warped extra dimensions are weakly duals to strongly coupled 4D theories MALDACENA '98
- They provide a calculable framework for composite Higgs models



- 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



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

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

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

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

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

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