$R_{D^{(*)}}$ in warped space

CERN-TH Institute: From flavor anomalies to direct discoveries of New Physics

October 25, 2018

Mariano Quirós (IFAE, Bellaterra, Spain)

Outline

- Partial conclusion from previous workshop
- The (custodial) model
- The $R_{D^{(*)}}$ anomaly
- Constraints
- Model predictions
- Concluding remarks

Based on:
E. Megias, G. Panico, O. Pujolas, MQ, 1608.02362
E. Megias, MQ, L. Salas, 1703.06019; 1707.08014
M. Carena, E. Megias, MQ, C. Wagner, 1809.01107

Disclaimer: I won't be able to quote talks in "Workshop on high-energy implications of flavor anomalies" (CERN, 22-24 October 2018)

Some partial conclusions from the workshop

- $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies (if confirmed) would imply New Physics w/

  Lepton Flavor Universality (LFU) violation

  as the production of different lepton flavors is flavor sensitive

- In particular $R_{D^{(*)}}$ anomalies imply New Physics w/

  Strong dynamics

  as New Physics effects have to compete with tree-level EW physics

- $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies do not necesssarily imply New Physics w/

  Lepton Flavor Violation (LFV)

  which is strongly constrained by processes as $\mu \to e\gamma$. Still it is true

  $LFV \Rightarrow LFU$ violation

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$$\mathit{LFV} \Rightarrow \mathit{LFU}\ \text{violation}$$

An observation

- Both phenomena strong dynamics and LFU violation do appear in theories where the naturalness problem is solved in the context of

Composite Higgs Theories ⇔ Theories with Warped X-dimensions

- This is independent on whether

- The Higgs is a generic *mesonic* state: a SM composite $SU(2)$ doublet

  or...

- The Higgs is a (pseudo)-Nambu-Goldstone boson: gauge-Higgs unification with extended group

- The theory is AdS_5 (RS) with gauge custodial symmetry in the bulk

  or...

- The theory is a deformed AdS_5 in the IR brane: Asymptotically AdS_5

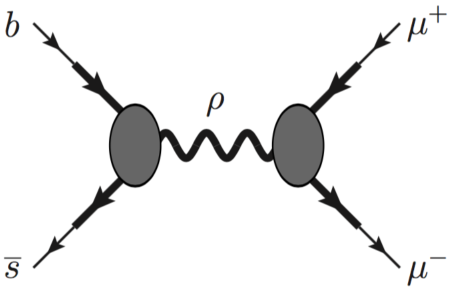


Diagram generating $R_{K^{(*)}}$ in the dual 4D CFT theory. Partly composite fermions mix with CFT fermionic operators which strongly interact with the ρ resonances.

Instead we will work in the dual warped 5D theory

There are many works on the subject. A sample of them:

- Using a warped extra dimension conformally deformed at the IR [1]
- Using warped custodial models [2]
- Using composite Higgs models [3]

I will present a simple 5D phenomenological model with *mesonic* Higgs and $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ with custodial invariance on the IR brane

[1] E. Megias, G. Panico, O. Pujolas, MQ, arXiv:1608.02362 [hep-ph]; E. Megias, MQ, L. Salas, arXiv:1703.06019 [hep-ph]; arXiv:1707.08014 [hep-ph]

[2] G. D'Ambrosio and A. M. Iyer, arXiv:1712.08122 [hep-ph]

[3] C. Niehoff, P. Stangl and D. M. Straub, arXiv:1503.03865 [hep-ph]; A. Carmona and F. Goertz, arXiv:1510.07658 [hep-ph]; B. Gripaios, M. Nardecchia and S. A. Renner, arXiv:1412.1791 [hep-ph]; A. Carmona and F. Goertz, arXiv:1610.05766 [hep-ph]; A. Carmona and F. Goertz, arXiv:1712.02536 [hep-ph]; F. Sannino, P. Stangl, D. M. Straub and A. E. Thomsen, arXiv:1712.07646 [hep-ph]

The (custodial) model

- I will present a warped model where those ideas can be realized
- A 5D model with two branes at $y = 0$ (UV) and $y = y_1$ (IR), and metric $A(y) = ky$ such that

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2, \quad ky_1 \simeq 35 \text{ (hierarchy problem)}$$

- The model is based on the bulk gauge group [4] with couplings

$$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \qquad (g_c, g_L, g_R, g_X)$$

Broken by UV brane BC's

$$SU(2)_R \otimes U(1)_{B-L} \to U(1)_Y \; [@UV]$$

[4] K. Agashe, A. Delgado, M. J. May and R. Sundrum, hep-ph/0308036

KK content

$$W_L^\pm, W_L^3\,, \qquad (+,+) \qquad (n = 0, 1, ...)$$

$$B = \frac{g_X W_R^3 + g_R X}{\sqrt{g_R^2 + g_X^2}}, \qquad (+,+) \qquad (n = 0, 1, ...)$$

$$W_R^\pm, \qquad (-,+) \qquad (n = 1, ...)$$

$$Z_R = \frac{g_R W_R^3 - g_X X}{\sqrt{g_R^2 + g_X^2}} \qquad (-,+) \qquad (n = 1, ...)$$

- Only the $(+,+)$ 5D fields have zero modes (SM gauge bosons).
- $(-,+)$ 5D fields only have heavy KK modes
- W_R^n modes will mediate in processes contributing to $R_{D^{(*)}}$
- Z_L^n, A^n, Z_R^n will mediate in processes contributing to $R_{K^{(*)}}$

- The model can have an "explanation" of the flavor problem
- The SM fermion $f_{L,R}$ is the zero mode of the 5D fermion $\Psi(x,y)$ with appropriate boundary conditions and a Dirac mass term

$$\mathcal{L}_5 = M_{f_{L,R}}(y)\bar{\Psi}\Psi, \quad M_{f_{L,R}}(y) = \mp c_{f_{L,R}} k$$

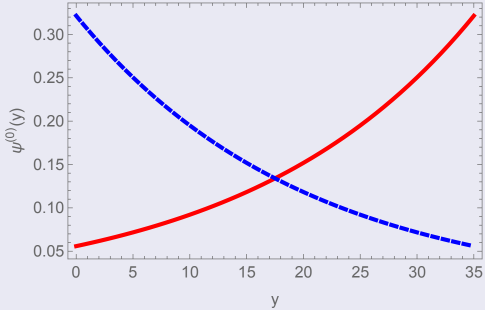
- Explicitely the zero modes (in flat coordinates) are given by

$$\psi^{(0)}_{L,R}(y,x) = \frac{e^{(1/2-c_{L,R})ky}}{\sqrt{e^{(1-2c_{L,R})ky}-1}} f_{L,R}(x)$$

where $f_{L,R}(x)$ are 4D SM fermions

- Fermions with $c < 0.5$ ($c > 0.5$) are localized towards the IR (UV) brane.

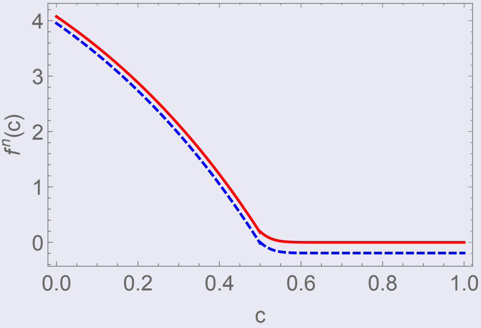
- For example the profile of fermions with $c = 0.45$ (solid red) and $c = 0.55$ (dashed blue) are



- Fermions with $c < 0.5$ ($c > 0.5$) are interpreted as partly composite (elementary) in the dual holographic theory

- As the KK modes are localized toward the IR brane, their coupling to fermions is enhanced by a factor $f^n(c)$ which depends on the fermion localization, i.e. on the fermion characteristic constant $c_{L,R}$

Dashed: (+,+), Solid: (-,+)



- Fermions localized on the IR brane can be considered as the limiting case where $c \to -\infty$ and $|f^n(-\infty)| = \sqrt{ky_1}$

LH Fermion content: bulk $SU(2)_L$ doublets

$$Q_L^i = \begin{pmatrix} u_L \\ d_L \end{pmatrix}^i, \quad L_L^i = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}^i, \; (i = 1, 2, 3)$$

RH Fermion content: 1st and 2nd generation bulk $SU(2)_R$ doublets

$$U_R^I = \begin{pmatrix} u_R \\ d_R' \end{pmatrix}^I, \; D_R^I = \begin{pmatrix} u_R' \\ d_R \end{pmatrix}^I, \; E_R^I = \begin{pmatrix} \nu_R' \\ e_R \end{pmatrix}^I, \; N_R^I = \begin{pmatrix} \nu_R \\ e_R' \end{pmatrix}^I$$

RH Fermion content: 3rd generation IR brane $SU(2)_R$ doublets

$$Q_R^3 = \begin{pmatrix} t_R \\ b_R \end{pmatrix}, \quad L_R^3 = \begin{pmatrix} \nu_R \\ \tau_R \end{pmatrix}$$

- Only unprimed fields have zero modes
- The electric charge is: $Q = T_L^3 + T_R^3 + \frac{1}{2}(B - L)$

Higgs content

$$\mathcal{H} = \begin{pmatrix} H_2^0 & H_1^+ \\ H_2^- & H_1^0 \end{pmatrix}, \quad B - L = 0$$

$$\Sigma = \begin{pmatrix} \Sigma^-/\sqrt{2} & \Sigma^0 \\ \Sigma^{--} & -\Sigma^-/\sqrt{2} \end{pmatrix}, \quad (B-L)/2 = -1$$

$$H_R = (H_R^0, H_R^-), \quad (B-L)/2 = -1/2$$

- Only $\mathcal{H}$ can give mass to fermions: $\tan\beta = v_2/v_1$
- Σ also breaks spontaneously $SU(2)_L \otimes U(1)_Y$ on the IR brane mixing with the Higgs $\mathcal{H}$ with an angle: $\sin\theta_\Sigma = v_\Sigma/v$
- $\langle H_R^0 \rangle = v_R$ breaks spontaneously $SU(2)_R \otimes U(1)_{B-L} \to U(1)_Y$ and is responsible for giving a mass to neutrinos by double seesaw

Free parameters (angles)

$$\tan\beta, \ \sin\theta_R \equiv \frac{g_Y}{g_R}, \ \sin\theta_\Sigma$$

The 5D Yukawa coupling terms for quarks and leptons localized on the IR brane and on the bulk are

Third generation RH fermions (IR brane)

$$Y_Q^{i3}\bar{Q}_{L\,i}\mathcal{H}Q_{R\,3}+\widetilde{Y}_Q^{i3}\bar{Q}_{L\,i}\widetilde{\mathcal{H}}Q_{R\,3}+Y_L^{i3}\bar{L}_{L\,i}\mathcal{H}L_{R\,3}+\widetilde{Y}_L^{i3}\bar{L}_{L\,i}\widetilde{\mathcal{H}}L_{R\,3}+h.c.$$

First and second geration RH fermions (bulk)

$$Y_Q^{il}\bar{Q}_{L\,i}\mathcal{H}U_{R_l}+\hat{Y}_Q^{il}\bar{Q}_{L\,i}\mathcal{H}D_{R_l}+\widetilde{Y}_Q^{il}\bar{Q}_{L\,i}\widetilde{\mathcal{H}}U_{R_l}+\hat{\widetilde{Y}}_Q^{il}\bar{Q}_{L\,i}\widetilde{\mathcal{H}}D_{R_l}+h.c.$$

$$Y_L^{il}\bar{L}_L^i\mathcal{H}N_R^l+\hat{Y}_L^{il}\bar{L}_L^i\mathcal{H}E_R^l+\widetilde{Y}_L^{il}\bar{L}_L^i\widetilde{\mathcal{H}}N_R^l+\hat{\widetilde{Y}}_L^{\prime\,il}\bar{L}_L^i\widetilde{\mathcal{H}}E_R^l,+h.c.$$

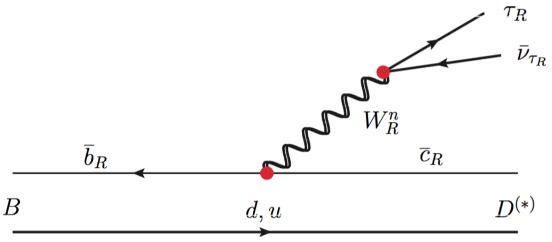
The top/bottom Yukawa couplings

$$Y^t=\left(\sin\beta\,Y_Q-\cos\beta\,\widetilde{Y}_Q\right)F(c_{b_L});\;\;Y^b=\left(\cos\beta\,Y_Q-\sin\beta\,\widetilde{Y}_Q\right)F(c_{b_L})$$

$$F(c)=\sqrt{2(1-2c},\quad (\text{for } c<1/2)$$

The $R_{D^{(*)}}$ anomaly

- The SM departure for $R_{D^{(*)}}$ is generated by the diagram



- We can write the 4D charged current Lagrangian in the mass eigenstate fermion basis as

$$\mathcal{L} = \frac{g_R}{\sqrt{2}} \sum_{n=1}^{\infty} \left\{ \bar{u}_R (V_{u_R}^{\dagger} G^n \, V_{d_R}) \not{W}_R^n d_R + \bar{\tau}_R \not{W}_R^n G^n \nu_{\tau_R} \right\}$$

- The coupling matrix G^n can be approximated by

$$G^n \equiv \text{diag}\,(G_1^n, G_2^n, G_3^n)$$

where $G_{1,2}^n \ll G_3^n = f_{W_R}^n(y_1)$

- After integration of the KK modes we can write down the effective Lagrangian

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb} C_\tau (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_R \gamma_\mu \nu_{\tau R})$$

- The Wilson coefficient is given by [5]

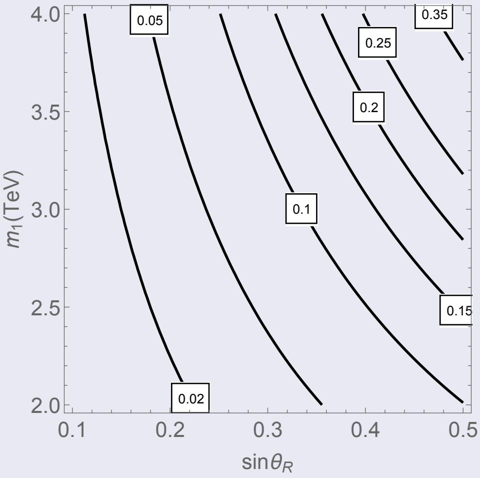
$$C_\tau = \sum_n \left(\frac{g_R}{2}\, G_3^n \frac{v}{m_n} \right)^2 \frac{\left(V_{u_R}^\dagger\right)_{23}}{V_{cb}}$$

[5] Similar to: P. Asadi et al., 1804.04135; A. Greljo et al., 1804.04642

The Wilson coefficient C_τ contributes (incoherently) to the ratio

$$R_{D^{(*)}}/R_{D^{(*)}}^{SM} = 1 + |C_\tau|^2$$

Contour lines of constant $(V_{u_R}^\dagger)_{23}$



- In principle the anomaly in the branching ratio $\mathcal{B}(B \to D^{(*)}\tau_R\bar{\nu}_R)$ might give rise to a large contribution to

$$\mathcal{B}(D_s \to \tau\bar{\nu}) \simeq 0.05$$

from the process $\bar{s}c \to \tau_R^+\nu_R$, which is mediated by W_R^n:

However c_R and s_R couple to W_R^n only via mixing with the third generation

- Similarly, in this model one would also expect an excess in

$$R(J/\Psi) = \left.\frac{\mathcal{B}(B_c^+ \to J/\Psi\ \tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\Psi\ \mu^+\nu_\mu)}\right|_{exp} = 0.71 \pm 0.25$$

while LHCb experiment has reported an excess of order 2σ above the SM value $R(J/\Psi)_{SM} \simeq 0.25 - 0.28$: We predict

$$\frac{R(J/\Psi)}{R(J/\Psi)_{\rm SM}} = 1 + |C_\tau|^2 \simeq 1.25$$

Constraints

They come from:

- Tree-level effects: mixing between gauge bosons and KK modes:

$$\frac{v^2}{4} G_3^n r_h(\alpha) \left\{ g_L^2 (W_L W_L^n + h.c.) - \frac{2 v_1 v_2}{v^2} g_L g_R (W_L W_R^n + h.c.) \right\}$$
$$+ \frac{v^2}{4} G_3^n r_h(\alpha) \left\{ \frac{g_L^2}{\cos^2\theta_L} Z_L Z_L^n + \frac{g_L g_R}{\cos\theta_L \cos\theta_R} \left[2\sin^2\theta_\Sigma - \cos^2\theta_R \right] Z_L Z_R^n \right\}$$

- Loop effects: Integrating out KK modes, Z_L^n, Z_R^n, A^n gives rise to operators

$$(\bar{f}\gamma^\mu f)(\bar{t}_R\gamma_\mu t_R), \quad (H^\dagger D_\mu H)(\bar{t}_R\gamma^\mu t_R), \quad (H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

When t_R propagates in loops, it couples strongly to the Higgs and can emit a gauge boson [6]

The considered constraints affect mainly:

- The coupling $Z\bar{f}f$
- The oblique observables
- The flavor observables
- LHC bounds

[6] F. Feruglio, P. Paradisi, A. Pattori, 1705.00929

$Z\tau_R\tau_R$ coupling

As the τ_R lepton is localized on the IR brane, and it couples strongly to the KK modes, the main constraint will be the modification of the coupling $Z_L\tau_R\tau_R$, defined as [7]

$$\mathcal{L}_{Z\tau_R\tau_R} = \frac{g_L}{\cos\theta_L}\bar{\tau}_R \not{Z}_L (g^{SM}_{Z_L\tau_R\tau_R} + \delta g_{Z_L\tau_R\tau_R})\tau_R$$

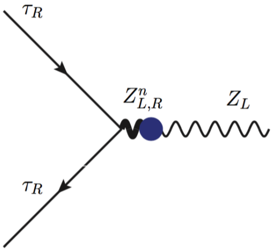
where the global fit provides

$$\delta g_{Z_L\tau_R\tau_R} = (0.42 \pm 0.62) \times 10^{-3}$$

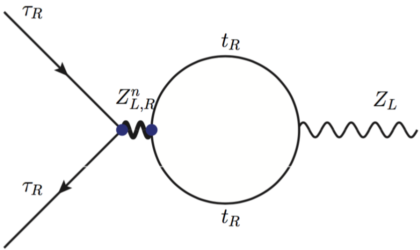
[7] A. Falkowski et al., 1706.03783

The leading contributions to $\delta g_{Z_L\tau_R\tau_R}$ come from:

Tree-level diagrams, from the mixing of Z with the KK modes

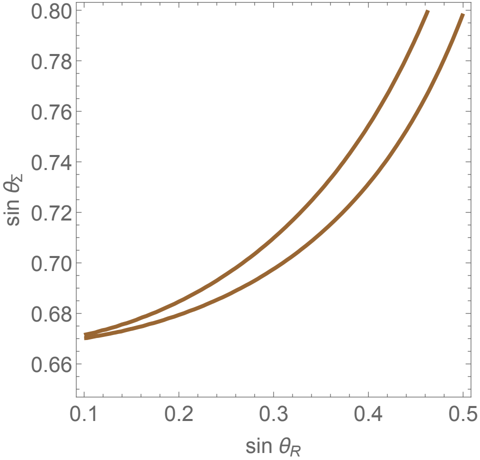


Loop diagrams where the strongly coupled top t_R propagates in loops



where the result depends on the mixing angles.

The available parameter space is given in the plot



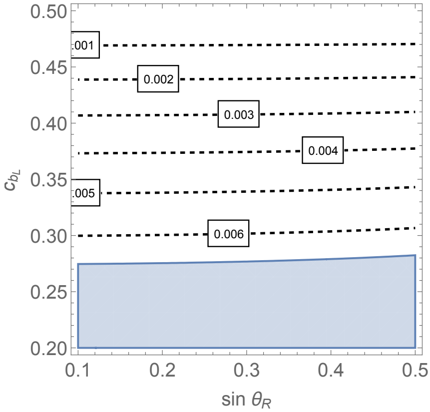
Which imposes a constraint as

$$\sin\theta_\Sigma = v_\Sigma/v \gtrsim 0.67$$

$Zb_L b_L$ coupling

From the bound

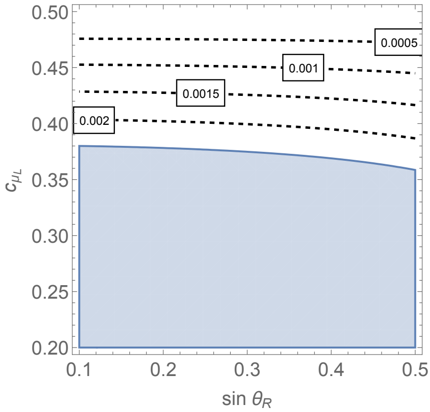
$$\delta g_{Z_L b_L b_L} = (3.3 \pm 1.7) \times 10^{-3}$$



$Z\mu_L\mu_L$ coupling

From the bound

$$\delta g_{Z_L\mu_L\mu_L} = (0.1 \pm 1.2) \times 10^{-3}$$



Oblique observables

The T parameter defined as

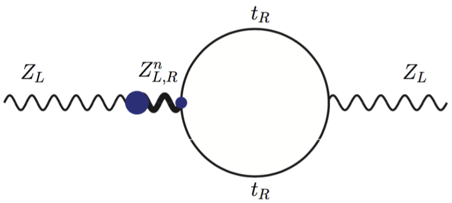
$$\alpha_{EM}(m_Z)T = \left[\frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2}\right]$$

is contributed by the diagrams

Tree-level diagrams

where the result depends on the mixing angles.

Loop diagrams



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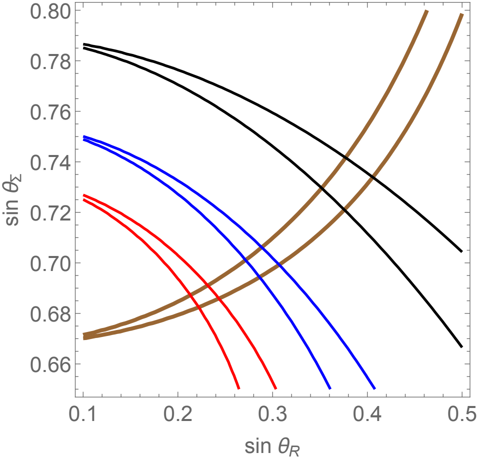


For

$$\tan\beta = \ (1\ \text{black}),\ (3\ \text{blue}),\ (5\ \text{red})$$

LHC bounds

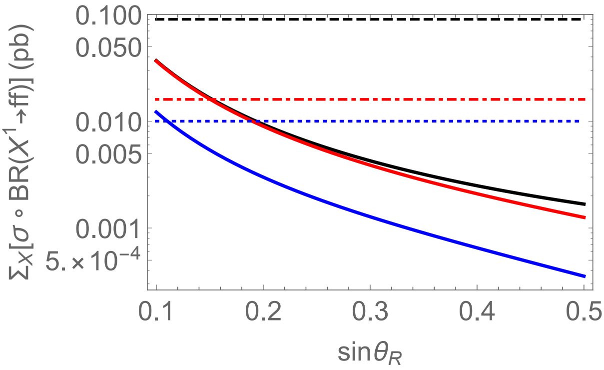
The first neutral KK resonance X^1 ($X = Z_L$, Z_R, A) can be produced on-shell at LHC in Drell-Yan processes $\sigma(b\bar{b} \to X^1)$, followed by decays $X^1 \to f\bar{f}$ where $f = \tau_R, b_R, t_R$. The production cross-section times branching ratio can be written as

$$\sum_X \sigma(pp \to X^1) \times \mathcal{B}(X^1 \to f\bar{f}) =$$

$$\frac{1}{9} g_R^2\, 2ky_1 f(m_1) \Big[\sin^2\theta_R \sin^2\theta_L \mathcal{B}(Z_L^1 \to f\bar{f})$$

$$+ \frac{1}{\cos^2\theta_R} (3/2 - \sin^2\theta_R)^2 \mathcal{B}(Z_R^1 \to f\bar{f}) + \sin^2\theta_R \cos^2\theta_L \mathcal{B}(A^1 \to f\bar{f}) \Big]$$

where $f(m_1)$ is the production cross-section for unit coupling obtained by `MadGraph v5`



For $m_1 = 3$ TeV and b_R (upper black solid), t_R (middle red solid) and τ_R (lower blue solid). Horizontal lines are corresponding bounds from ATLAS

$$\sin\theta_R \gtrsim 0.15$$

Flavor constraints

- New physics contribution to $\Delta F = 2$ observables appears mainly from exchange of KK gluons
- The leading flavor violating couplings of the KK gluons $\mathcal{G}_\mu^n$ involving RH down and up quarks is given by

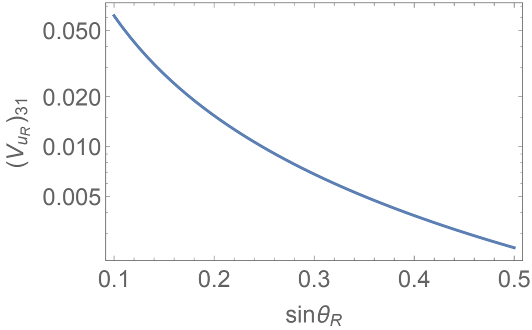
$$\mathcal{L}_s = g_s (V_{u_R}^\dagger)_{i3} (V_{u_R})_{3j} \bar{u}_R^i \not{\mathcal{G}}^n G_3^n u_R^j + g_s (V_{d_R}^\dagger)_{i3} (V_{d_R})_{3j} \bar{d}_R^i \not{\mathcal{G}}^n G_3^n d_R^j$$

- After integrating out the gluon KK modes we obtain a set of $\Delta F = 2$ dimension six operators. In particular, the most constrained operators are those given by

$$\mathcal{L}_{eff} = C_{sd} (\bar{s}_R \gamma^\mu d_R)^2 + C_{cu} (\bar{c}_R \gamma^\mu u_R)^2 + C_{bd} (\bar{b}_R \gamma^\mu d_R)^2 + C_{bs} (\bar{b}_R \gamma^\mu s_R)^2$$

Experimental data imply the bounds on RH angles

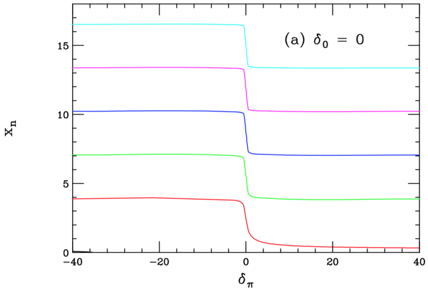
$$|(V^\dagger_{d_R})_{13}| \lesssim 1.1 \times 10^{-3} \left(\frac{m_1}{3\ \mathrm{TeV}}\right), \quad |(V^\dagger_{d_R})_{23}| \lesssim 5.2 \times 10^{-3} \left(\frac{m_1}{3\ \mathrm{TeV}}\right).$$

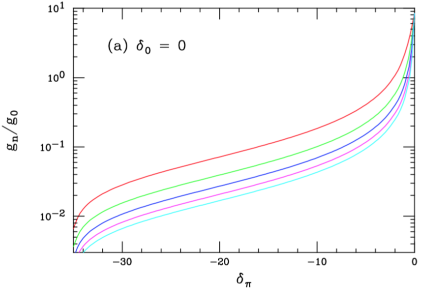


A way out for constraints from KK gluons is introducing a localized KT [8],

$$\delta S = \frac{\delta_1}{y_1} \int d^5 x \mathcal{G}_{\mu\nu} \mathcal{G}^{\mu\nu} \delta(y - y_1)$$

The KK modes $\mathcal{G}^n$ can be heavier than the EW ones and their couplings smaller





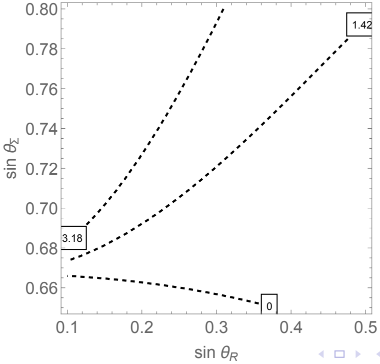
[8] H. Davoudiasl et al. hep-th/0212279; M. Carena et al. hep-ph/0212307

Predictions: A^b_{FB}

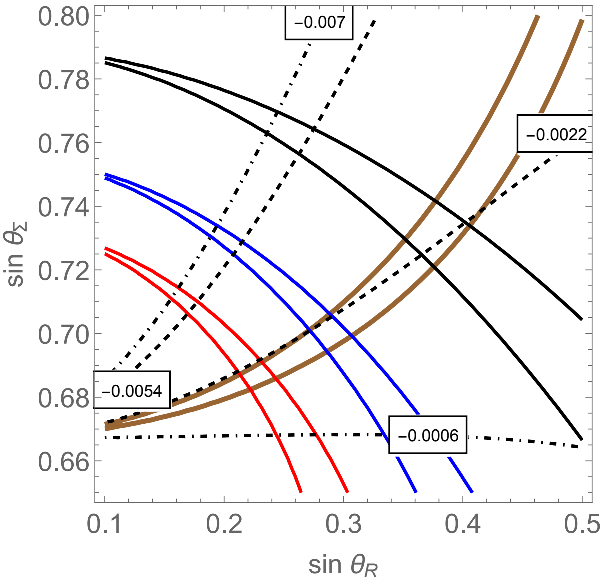
- On top of the correction $\delta g_{Z_L b_L b_L}$ there is a similar correction to $\delta g_{Z_L b_R b_R}$ compared with the anomalously large value

$$\delta g_{Z_L b_R b_R} = (2.3 \pm 0.88) \times 10^{-2}$$

- The calculation of $\delta g_{Z_L b_R b_R}$ departs from the SM prediction



The anomaly in $\delta g_{Z_L b_R b_R}$ leads to an anomaly in δA_{FB}^b as



The processes $B \to K\nu\nu$ and $B^+ \to K^+\tau^+\tau^-$

- The $R_{D^{(*)}}$ anomaly can in principle induce a large production in the process $B \to K\bar{\nu}\nu$
- Now we can write the ratio

$$R_K^{\nu\nu} = \frac{\mathcal{B}(B \to K\nu\nu)}{\mathcal{B}(B \to K\nu\nu)_{SM}}$$

- It depends on the angle $(V_{d_R}^\dagger)_{23}$ which is constrained by flavor observables to

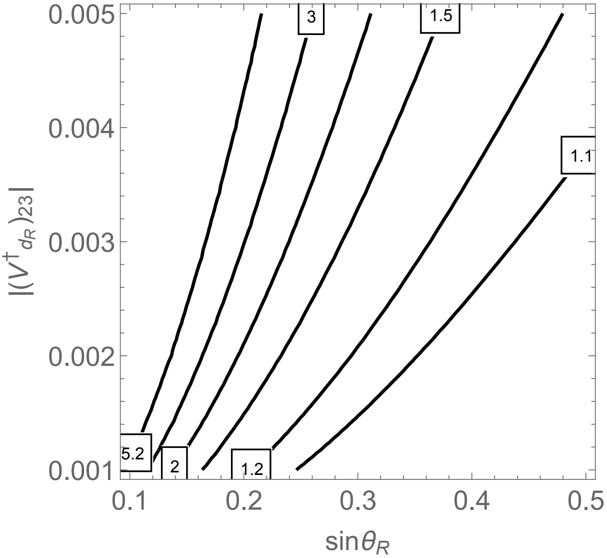
$$|(V_{d_R}^\dagger)_{23}| \lesssim 5.2 \times 10^{-3} \left(\frac{m_1}{3\ \mathrm{TeV}}\right)$$

- The actual experimental bound is [9]

$$(R_K^{\nu\nu})_{exp} < 5.2 \text{ at the 95\% CL}$$

[9] BELLE collaboration, 1702.03224

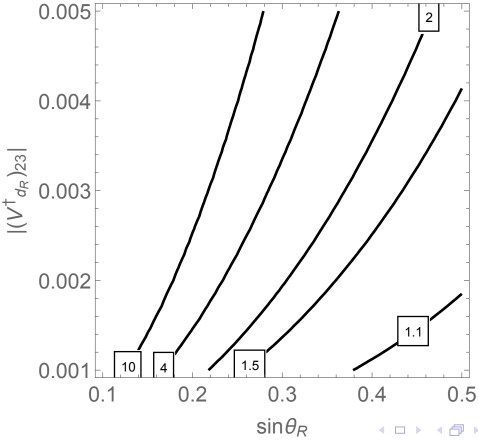
The model prediction for $R_K^{\nu\nu}$ is, for $m_1 = 3$ TeV



This model also predicts a strong $\tau\tau$ production in the observable

$$R_K^{\tau\tau} = \frac{\mathcal{B}(B^+ \to K^+\tau\tau)}{\mathcal{B}(B^+ \to K^+\tau\tau)_{SM}}, \quad (R_K^{\tau\tau})_{exp} < 10^4$$

The model prediction for $R_K^{\tau\tau}$ is, for $m_1 = 3$ TeV

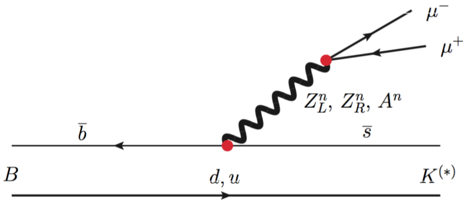


$R_{K^{(*)}}$

- In the chiral basis for the operators $\mathcal{O}_i$

$$\sum_{\chi,\chi'=L,R} C_{\chi\chi'}(\bar{s}\gamma^\mu P_\chi b)(\bar{\ell}\gamma_\mu P_{\chi'}\ell), \quad C_{LL}^{SM} \simeq 8.4, \quad C_{LR,RL,RR}^{SM} \simeq 0$$

- The contributions to the Wilson coefficients are generated by the diagrams



- In fact, in our model, for

$$c_{e_{L,R}} \gtrsim 1/2, \quad c_{\mu_R} \gtrsim 1/2$$

it turns out that

$$C^{e}_{\chi\chi'} \simeq C^{SM}_{\chi\chi'} \text{ and } \Delta C^{\mu}_{LR} \simeq \Delta C^{\mu}_{RR} \simeq 0$$

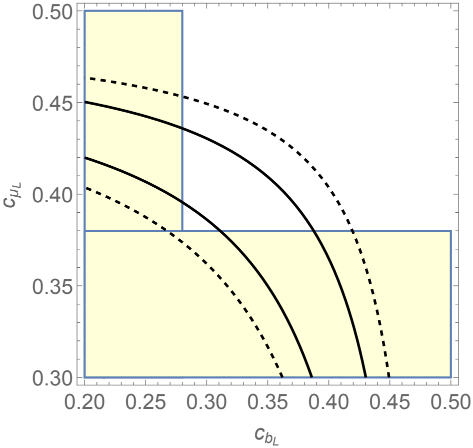
- Global fits yield [10]

$$\Delta C^{\mu}_{LL} \subset [-1.66, -1.04]_{1\sigma},\ [-1.98, -0.76]_{2\sigma}$$
$$\Delta C^{\mu}_{RL} \subset [-0.04, 0.36]_{1\sigma},\ [-0.24, 0.56]_{2\sigma}$$

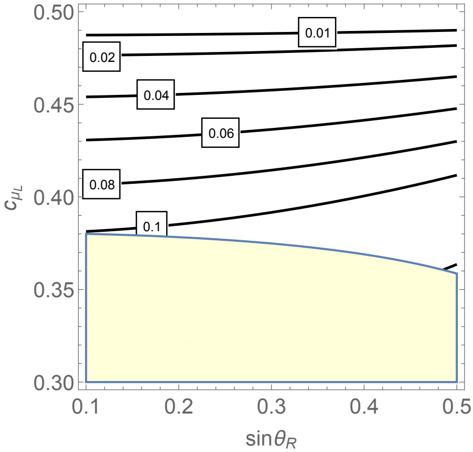
- Which constitutes a $\sim 4.8\sigma$ deviation with respect to the SM prediction

[10] W. Altmannshofer, C. Niehoff, P. Stangl, D.M. Straub, 1703.09189 [hep-ph]; B. Capdevila, A. Crivellin, S. Descotes-Genon, J. Matias, J. Virto, 1704.05340 [hep-ph]

Contour lines of constant ΔC_{LL}^{μ} using $V_{d_L} \simeq V$, $V_{u_L} \simeq 1$ and $\sin\theta_R = 0.35$, at 1 σ (solid lines) and 2 σ (dashed lines) level



Contour lines of constant ΔC_{RL}^{μ} after selecting the upper bound on $|(V_{d_R}^{\dagger})_{23}| \simeq 0.005$ from flavor observables



Conclusion

- The experimental measurements of $R_{D^{(*)}}$ show significant deviations from the SM values, a surprising result (for non-believers=everybody) due to their tree-level nature
- Possible resolutions of this anomaly face significant constraints from flavor physics and electroweak observables
- We have discussed an explicit realization of the solution to the $R_{D^{(*)}}$ anomaly based on the contribution of right-handed currents of quarks and leptons to this process
- The model is based on the embedding of the SM in warped space, with a bulk gauge symmetry $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$, with third-generation right-handed quarks and leptons localized on the IR-brane, ensuring a strong coupling to KK modes

- The right-handed $SU(2)_R$ gauge boson KK-modes provide the necessary contribution to $R_{D^{(*)}}$, due to appropriate mixing parameters in the right-handed up-quark sector
- This may be done without inducing large contributions to

$$B \to K\nu\nu$$

  or the B-meson mixings, since these observables strongly depend on the down-quark right handed mixing angles, which do not affect $R_{D^{(*)}}$
- The mass of the lightest KK-mode tends to be of about a few TeV, at reach of LHC in DY bb processes
- The model can accommodate the bottom forward-backward anomaly

$$\delta A_{FB}^{b} = (-3.8 \pm 1.6) \times 10^{-3}$$

- The model can also explain observables in the

$$b \to s\ell\ell$$

  channel, as e.g. the $R_{K^{(*)}}$ anomaly

Finally...

- To prevent strong bounds from

$$\mu \to e\gamma,\ \tau \to \mu\gamma, \ldots$$

  we have assumed no Lepton Flavor Violation (LFV)
- We are assuming that the 5D Yukawa couplings are such that the charged leptons are diagonal in the weak basis, so that $V_{\ell_{L,R}} \simeq 1$
- The required alignment in the lepton sector depends on the UV completion of the theory.
- This can be obtained e.g. by imposing a

$$U(1)^3$$

  flavor symmetry in the lepton sector broken only by the tiny effects due to the neutrino masses.... much more to do!