Uncovering extra dimensions at LHC

Spanish LHC network meeting
IFT/UAM, Madrid, 8-9 May 2017

Mariano Quirós

IFAE

Outline

- The model of a warped extra dimension
- Direct searches of EW KK modes
- Direct searches of gluon KK modes
- Back-ups: Indirect effect of KK modes: B-anomalies (if time permits)

The model of a warped extra dimension

- We will consider a model where the hierarchy problem is solved by a warped extra dimension y with general metric $A(y)$, and two branes, at the UV ($y = 0$) and at the IR ($y = y_1$)

$$ds^2 = e^{-2A(y)}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2, \quad A(y_1) \simeq 35 \text{ (to solve the hierarchy)}$$

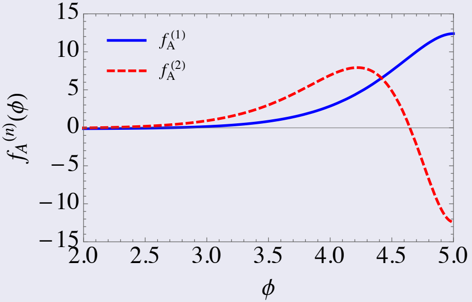
- The metric is fixed by the stabilizing bulk field ϕ, through the 5D Einstein equation or, equivalently, by the "superpotential" $W(\phi)$
- Our superpotential choice is

$$W(\phi) = 6k\left(1 + e^{a_0\phi}\right)^{b_0}, \quad b_0 = 2, a_0 = 0.15 \; (b_0 = 0 \; is \; RS)$$

- Extra dimension is close to AdS_5 near the UV, whereas the conformal invariance is broken by a deformation of the metric only near the IR

- All SM fields propagate in the bulk: gauge vectors, Higgs, fermions
- Every field has the zero mode and the Kaluza-Klein (KK) excitations
- The Higgs zero mode is localized towards the IR to solve the hierarchy problem
- KK excitations are localized towards the IR brane

For instance, $n = 1, 2$, KK modes of gauge bosons:



- KK modes of gauge bosons interact strongly (weakly) with IR (UV) localized fields

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

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

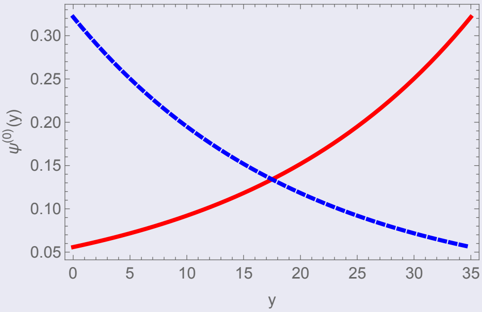
- Explicitely the zero mode profile (in flat coordinates) is given by

$$\psi^{(0)}_{L,R}(y,x) = \frac{e^{(1/2-c_{L,R})A(y)}}{\left(\int dy\, e^{A(1-2c_{L,R})}\right)^{1/2}} f_{L,R}(x)$$

where $f_{L,R}(x)$ are the SM fermion wave-functions

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

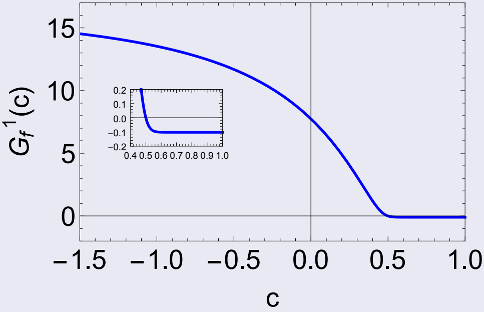
- For example the profile of fermions with $c = 0.45$ (solid red) and $c = 0.55$ (dashed blue) are



- Fermions with $c < 0.5$ ($c > 0.5$) are composite (elementary)
- The coupling of KK gauge bosons with fermions is

$$G^n_{f_{L,R}}(c_{L,R})\, g^{SM}_{f_{L,R}} \;\left(A^n_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}\right)$$

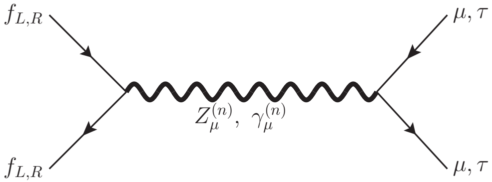
- In particular the interaction of gauge KK modes with fermions is Flavor Non-Universal, depending on the values of $c_{f_{L,R}}$: they couple differently to different fermions



- The coupling with IR localized fermions is stronger than the coupling with UV localized fermions
- For $c = 0.5$ the coupling is zero and for $c \gtrsim 0.5$ ($c \lesssim 0.5$) the coupling is tiny (large)

Direct searches of $Z^{(n)}$ and $\gamma^{(n)}$

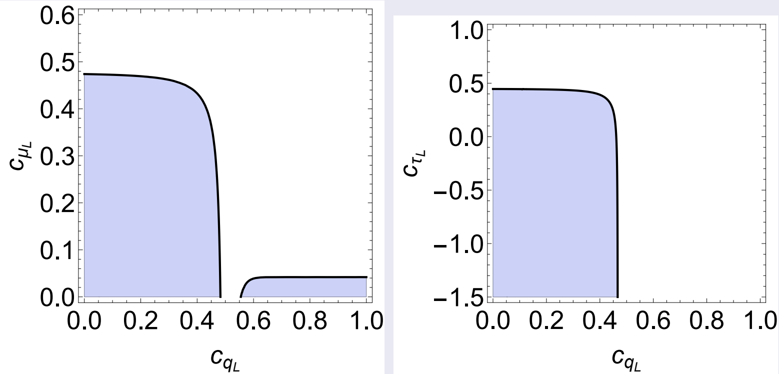
- The resonances Z_μ^n and γ_μ^n ($n=1$) can be produced by Drell-Yan processes and decay into a pair of leptons as in the figure
- The best bounds on dimuon resonances have been given by the ATLAS Collaboration based on 3.2 fb^{-1} data at $\sqrt{s}=13$ TeV. ATLAS obtained a 95% CL bound on the sequential Standard Model (SSM) Z'_{SSM} gauge boson mass, as $M_{Z'_{SSM}} \gtrsim 3.36$ TeV.
- Similarly the strongest bounds on ditau resonances have been obtained by the CMS Collaboration based on 2.2 fb^{-1} data at $\sqrt{s}=13$ TeV. CMS got the 95% CL bound $M_{Z'_{SSM}} \gtrsim 2.1$ TeV.



Dileptons searches in DY

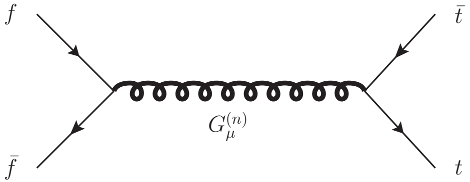
A 2 TeV resonance (or even lighter) should not have been discovered yet for the white region of parameter space (result slightly model dependent)

Di-muons $(c_u = c_d = c_c = c_s \equiv c_q)$ Di-taus



Direct searches of $G^{(n)}$

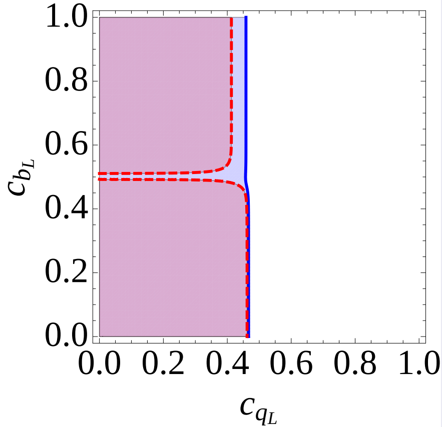
- Single KK gluons G_μ^n ($n = 1$) can be produced at LHC by Drell-Yan processes and decay into top quarks as in figure
- ATLAS uses $G^1_{q_{L,R}} \simeq -0.2$, for $(q = u, d, c, s)$, $G^1_{b_R} \simeq -0.2$, $G^1_{t_L} \simeq 0.95$ and $G^1_{t_R} \simeq 1.98$. From data at $\sqrt{s} = 8$ TeV corresponding to 20.3 fb^{-1} they obtain the 95% CL lower bound $M_1^{ATLAS} \gtrsim 2.2$ TeV
- CMS uses data at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 19.7 fb^{-1}. Using $G^1_{q_{L,R}} \simeq -0.2$, for $(q = u, d, c, s)$, $G^1_{b_R} \simeq -0.2$, $G^1_{t_L} \simeq 1$ and $G^1_{t_R} \simeq 5$, they obtain the 95% CL lower bound $M_1^{CMS} \gtrsim 2.5$ TeV



Ditop searches in DY

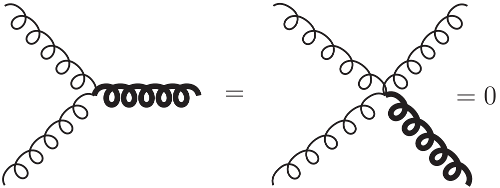
A 2 TeV resonance (or even lighter) should not have been discovered yet for the white region of parameter space (result slightly model dependent)

Di-top searches ($c_{t_R} = 0.45,\ c_{t_L} = c_{b_L}$)

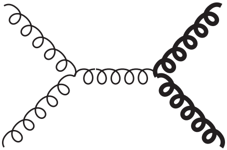


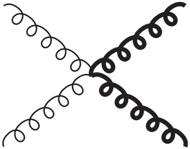
Four-top searches in DY

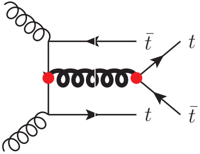
- The DY production of KK gluons decaying into two tops can be easily evaded by the localization of the first and second family quarks
- The alternative is to produce KK gluons by gluon fusion
- In this case the production of a simple KK gluon decaying into two tops is zero (by orthonormality of wave functions)



- KK gluons can be produced in pairs or in association with $t\bar{t}$ as in the figure
- Undotted vertices are SM couplings
- Red dotted vertices are strong (non SM) couplings
- All this processes would lead to four-top production





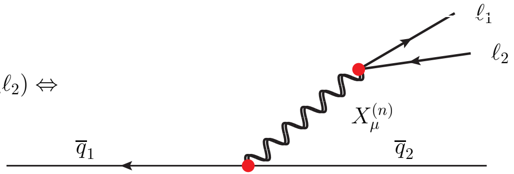


BACK
UP
TRANSPARENCIES

Accommodating the B-anomalies

- The warped model we have described contains the required ingredients to solve the anomalies
- Quark and leptons $f_{L,R}$ have a certain degree of compositeness, which depends on the value of $c_{f_{L,R}}$, and determines the strength of interaction with KK modes [the red dots]
- KK modes $X_\mu^{(n)} = Z_\mu^{(n)}, \gamma_\mu^{(n)}, W_\mu^{(n)}$ generate the effective operators via the tree level diagrams

$$\mathcal{O}^{\ell_1\ell_2}_{q_1q_2} = (\bar{q}_1\gamma^\mu q_2)(\bar{\ell}_1\gamma_\mu\ell_2) \Leftrightarrow$$



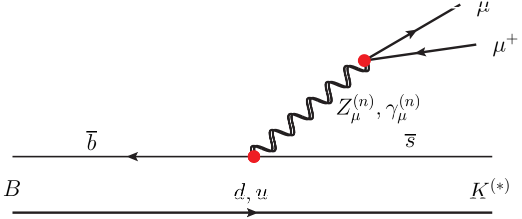
The $R_{K^{(*)}}$ anomalies

- The SM departure for $R_{K^{(*)}}$ is generated by the diagram
- The FCNC current $(\bar{b}\gamma^\mu s)$ is generated from

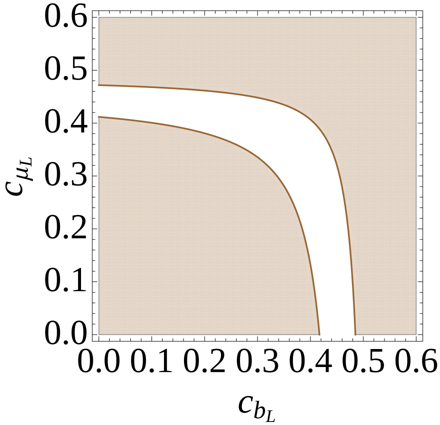
$$\left(V_d^\dagger G_d^n V_d\right)_{32}$$

$$G_d^n = \mathrm{diag}(G_d^n(c_d), G_s^n(c_s), G_b^n(c_b))$$

- Where $V_{d_{L,R}}$ are unitary matrices diagonalizing the *down* mass matrix
- We have considered Wolfenstein-like parametrizations for $V_{d_{L,R}}$, $V_{u_{L,R}}$



- The region allowed by $R_{K^{(*)}}$ data is the white region



- b_L and μ_L have a certain (correlated) degree of compositeness

$$c_{\mu_L} < 0.46, \quad c_{b_L} < 0.48$$

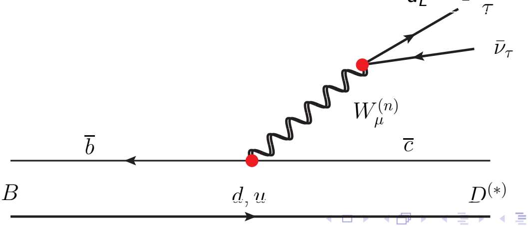
The $R_{D^{(*)}}$ anomalies

- The SM departure for $R_{D^{(*)}}$ is generated by the diagram
- The FC charged current $(\bar{b}_L \gamma^\mu c_L)$ is generated from

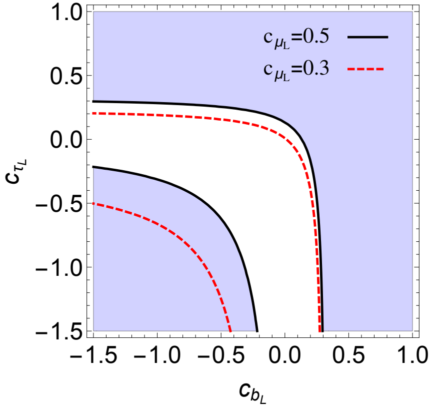
$$\left(V_{d_L}^\dagger G_{d_L}^n V_{u_L} \right)_{32}$$

$$G_{d_L}^n = \text{diag}(G_{d_L}^n(c_{d_L}), G_{s_L}^n(c_{s_L}), G_{b_L}^n(c_{b_L})), \quad c_{u_L} = c_{d_L}$$

- Where $V_{u_{L,R}}$ are unitary matrices diagonalizing the *up* mass matrix
- We have considered a parametrization such that $V_{d_L}^\dagger V_{u_L} = V_{CKM}$



- The relevant parameters here are c_{b_L}, c_{τ_L}
- The region allowed by $R_{D(*)}$ data is the white region



- b_L and τ_L have a certain (correlated) degree of compositeness

$$c_{\tau_L} \lesssim 0.3, \quad c_{b_L} \lesssim 0.3$$

The $R_{K^{(*)}}$ and $R_{D^{(*)}}$ anomalies

- The LHCb Collaboration has determined the ratios for $\bar{B} \to \bar{K}\ell\ell$ ($\ell = \mu, e$) for muons over electrons for $1 < q^2/GeV^2 < 6$ yielding

$$R_K = \frac{\mathcal{B}(\bar{B} \to \bar{K}\mu\mu)}{\mathcal{B}(\bar{B} \to \bar{K}ee)} = 0.745^{+0.090}_{-0.074} \pm 0.032$$

- As the SM result is

$$R_K^{\rm SM} \simeq 1$$

this result departs from the SM prediction by ~ 2.6

- This suggests a Lepton Flavor Universality Violation in the process

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

- Very recently the same tendency has been shown for the ratios

$$R_{K^*} = \frac{\mathcal{B}(\bar{B} \to \bar{K}^* \mu\mu)}{\mathcal{B}(\bar{B} \to \bar{K}^* ee)} = \begin{cases} 0.660^{+0.110}_{-0.070} \pm 0.024, & 0.045 < q^2/GeV^2 < 1.1 \\ 0.685^{+0.113}_{-0.069} \pm 0.047, & 1.1 < q^2/GeV^2 < 6 \end{cases}$$

which depart from the SM prediction $\sim 2.5\sigma$ and also suggests Lepton Flavor Universality Violation in the process

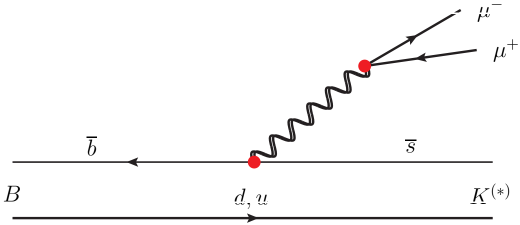
$$b \to s\ell\ell$$

- As in the Standard Model $R_K \simeq 1$ and $R_{K^*} \simeq 1$, this would suggest

New Physics coupled to the μ (not *electron*) sector

- A solution to this problem can be provided by vector bosons which couple to muons much more strongly than to electrons
- A typical new physics diagram which gives rise to effective operators

$$\mathcal{O}_9^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}_{10}^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,,$$
$$\mathcal{O}_9^{\prime\ell} = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}_{10}^{\prime\ell} = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,.$$



- The charged current decays $\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell$ have been measured by the BaBar, Belle and LHCb Collaborations which measure

$$R_{D^{(*)}} \equiv R^{\tau/\mu}_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell)}, \quad (\ell = \mu \text{ or } e)$$

- The averaged experimental results

$$R_D = 0.403 \pm 0.047, \quad R_{D^*} = 0.310 \pm 0.017$$

again depart from the Standard Model predictions

$$R_D^{\rm SM} = 0.300 \pm 0.011, \quad R_{D^*}^{\rm SM} = 0.254 \pm 0.004$$

by $\sim 2.2\sigma$ and 3.3σ, although the combined deviation is $\sim 4\sigma$

- This suggests Lepton Flavor Universality Violation in the process

$$b \to c\tau\bar{\nu}_\tau$$

- This would lead to

New Physics mainly coupled to the tau sector

- A solution to this problem can be given by charged vector bosons which couple to taus much more strongly than to muons and electrons
- A new physics diagram which gives rise to the effective operator

$$(\bar{c}\gamma^n u P_L b)\bar{\tau}\gamma_\nu (U\nu)_\tau$$