Bounds on Fermion–bulk masses in models with universal extra dimension

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based on
also 1204.4764 by CMS collaboration
contents

- Motivation: why UED? what is UED??
- mUED and its natural extensions
- The most updated bounds on bulk masses
- Conclusion/discussion
Motivation

- RS provides a possible (natural?) understanding of the big hierarchy in terms of geometry
- also provides an interesting (best to date?) framework to understand the flavor structure of the SM
- theoretically profound (AdS/CFT) and phenomenologically rich
- but...
• does not have a DM candidate without extending the particle contents..

• and rather hard to analyze due to the non-trivial AdS background.
WIMP DM = a massive stable particle

A parity (e.g. $Z_2$) could make the lightest $Z_2$ odd particle stable (like R-parity in SUSY)

If an extra dimension is symmetric about the middle point (invariant under the inversion), a natural geometric parity (KK-parity) could be imposed for all the bulk fields.
• glue two “same” spaces together

• then the resultant space is symmetric by construction
• glue two AdS ‘throats’ together

• RS + KK-parity

• A good theoretical model for the big hierarchy as well as DM :-)

RS

IR
UV
IR
Q. what is the low energy effective theory?
UED as an effective theory of RS

Csaki, Heinonen, Hubisz, Park, Shu, JHEP 1101 (2011) 089
BONUS

: A strict Flavor bound could be avoided in RS-limit where RS-GIM mechanism works..
RS-GIM

UV brane

IR brane

Kaluza-Klein (KK) modes

light quarks

heavy quarks
How to write a realistic model?

- Assume geometry is given (after moduli stabilization .. volume as well as shape)
- Gauge symmetry includes SU(3)XSU(2)XU(1)
- Matter includes Q,U,D,L,E
- ..all 5D, Dirac
- 5D Lorentz invariant in the bulk (far from the boundary)
- at the boundary 4D Lorentz invariant
5D Lorentz invariant
G-covariant Kinetic term + Mass term

\[ S = \int d^4x \mathcal{L}_5 + \delta(y - L)\mathcal{L}_L + \delta(y + L)\mathcal{L}_{-L} \]

4D Lorentz invariant
BLKT, BLMT

\textquote{minimal UED}
mUED

- An effective description of RS on "flat" $S^1/Z_2$
- Provides an interesting (and unified) framework for studying Collider physics (bosonic SUSY)
- Also Dark matter cosmology (LKP dark matter)
• all the SM particles are promoted to live in an 5D with ‘proper’ boundary conditions

• \{zero modes : Neumann BC\} = the SM (chiral)

• \{KK-towers\} (vector-like)

• LKP = B_1 (WIMP)
**KK decomposition**

*(an example)*

\[ E(x^\mu, y) = \sum e_L^{(n)}(x) f_L^{(n)} + e_R^{(n)}(x) f_R^{(n)} \]

\[ = e_R^{(0)} f_R^{(0)} + e_L^{(0)} f_L^{(0)} \]

\[ + e_R^{(1)} f_R^{(1)} + e_L^{(1)} f_L^{(1)} \]

\[ + e_R^{(2)} f_R^{(2)} + e_L^{(2)} f_L^{(2)} \]

\[ + \cdots \]

5D field ("electron")

\((1,1)\)-1

a smooth function on an interval \((S^1/Z_2)\)

\(=\) could be expanded by a complete set of functions

\[ \{ f_L^{(n)}(y), f_R^{(n)}(y) \} \]
Similar for $u_R, d_R$
similar for $Q_L$
Gauge boson?

\[ A^M(x, y) = (A^\mu, A^5) \]

\[ UA^M U^\dagger = (\pm A^\mu(-y), \mp A^5(-y)) \]

opposite parity under reflection

The zero mode of \( A^\mu \) needed => Neuman BC
\( A^5 \) is projected away by Dirichlet BC
lower bounds on $1/R$ in mUED

- $1/R > 600$ GeV (flavor bound .. loose bound due to KK-parity)
- $1/R > 700$ GeV (LHC7)
- $1/R > 750$ (300) GeV (EWPT for $m_{Higgs}=115$ (750)GeV)
upper bound from Dark Matter

\[ \sigma_{\text{tree}} v = a + b v^2 + \mathcal{O}(v^4) \]

\[
\begin{align*}
        a &= \sum_f \frac{32\pi\alpha_i^2 N_c m_{\tau_1}^2}{9} \left( \frac{Y_{fL}^4}{(m_{\tau_1}^2 + m_{fL}^2)^2} + \frac{Y_{fR}^4}{(m_{\tau_1}^2 + m_{fR1}^2)^2} \right), \\
        b &= -\sum_f \frac{4\pi\alpha_i^2 N_c m_{\tau_1}^2}{27} \left( Y_{fL}^4 \frac{11m_{\tau_1}^4 + 14m_{fL}^2m_{fR1}^2 - 13m_{fL1}^4}{(m_{\tau_1}^2 + m_{fR1}^2)^4} \\ &\hspace{1cm} + Y_{fR}^4 \frac{11m_{\tau_1}^4 + 14m_{fL}^2m_{fR1}^2 - 13m_{fL1}^4}{(m_{\tau_1}^2 + m_{fR1}^2)^4} \right),
\end{align*}
\]

larger \( M_{f1} \)  
⇒ smaller cross section  
⇒ larger Relic abundance  
⇒ set “upper bound” on KK-scale
Upper bound on $1/R$
set by DM relic abundance

Belanger, Kakizaki, Pukhov (2011)
A “tension” started to appear in MUED mainly by the LHC data & DM relic abundance

needs extension of the minimal model?
Three extensions without extending field contents

- Boundary localized mass & kinetic terms: dimension-5 operators
- Bulk or boundary localized interactions: dimension-6 or higher
- Bulk masses for fermions: dimension 4 operators $\Rightarrow$ This talk
A vector like mass

\[ S = - \int d^5 x M_\Psi \overline{\Psi} \Psi \]

the plane mass term is generically allowed
(but breaks KK-parity)
Kink Mass for UED keeps KK–parity

“split-UED”


The lowest energy configuration:

\[ M_\Psi(y) = \mu_\Psi \tanh \mu y \]

\[ \frac{\mu}{m \to \infty} \mu_\Psi \text{sgn}(y) = \begin{cases} 
-\mu_\Psi & \text{if } y < 0 \\
+\mu_\Psi & \text{if } y > 0 
\end{cases} . \]

Georgi, Hailu (2001)

Mass can have an internal parity
Wave function with Kink–Mass

\[ f_{R/L}^0(y) \sim e^{\mp \int_{-L}^{y} m_5(y') dy'} \rightarrow f_{R/L}^0(y) = N_{R/L} e^{\mp \mu |y|} \]

\[ M_\psi(y) = \mu_\psi \tanh m y \]

\[ m \to \infty \Rightarrow \mu_\psi \text{sgn}(y) = \begin{cases} -\mu_\psi & \text{if } y < 0 \\ +\mu_\psi & \text{if } y > 0 \end{cases} \]

KK–parity conserved! 
(LKP DM) 
(bonus) 
Room for Flavor physics

“split-UED”
model parameters

\[
\frac{g_5^2}{24\pi^3} \sim \frac{g_4^2 R}{24\pi^2} \sim \frac{1}{\Lambda}
\]

NDA:

\[
\Lambda R \sim \frac{24\pi^2}{g_4^2} \sim O(20)
\]
15 (18) bulk masses

\[ M_{Q3}, M_{Q2}, M_{Q1} \]

\[ M_{u3}, M_{u2}, M_{u1} \]

\[ M_{d3}, M_{d2}, M_{d1} \]

\[ M_{L3}, M_{L2}, M_{L1} \]

\[ M_{e3}, M_{e2}, M_{e1} \]

\[ M_{N3}, M_{N2}, M_{N1} \]

\[ M_Q \] (no flavor)

[Insert mathematical expressions]

\[ M_{\Psi} = M \] (safe)

\[ \rightarrow 0(\text{mUED}) \]
“running coupling constant”

\[ g_{m\ell n} = \frac{g_5}{\sqrt{L}} \int_{-L}^{L} dy \psi_m(y) \psi_\ell^*(y) f_Y^n(y) \]

\[ = g_{SM} F_{m\ell}^n (m_\Psi L) \]
“running coupling constant”

Kong, Park, Rizzo JHEP 1004 (2010) 081

$(-1)^n \sqrt{2}$

for $0 - 0 - 2n$

0–0–(2n) couplings can be sizable!
\[ m_{\Psi(n)}^2 = \begin{cases} \lambda_{\Psi}^2 v^2 & \text{if } n = 0 \\ \mu^2 + k_n^2 + \lambda_{\Psi}^2 v^2 & \text{if } n \geq 1 \end{cases} \]

\text{‘momentum’ (EOM + BC)}

\[ k_n = \begin{cases} \begin{align*} i\kappa_1 & : \kappa_1 = \kappa \in \{0 < \kappa \mid \mu = -\kappa \coth \kappa L, \mu L < -1\} \\ k_1 & : k_1 = k \in \{0 \leq k \leq \frac{\pi}{L} \mid \mu = -k \cot kL, \mu L \geq -1\} \end{align*} & \text{for } n = 1 \end{cases} \]

\[ \frac{n}{R} = \frac{n\pi}{2L} \]

\[ k_n = k \in \left\{ \frac{(n-2)\pi}{L} < k < \frac{(n-1)\pi}{L} \mid \mu = -k \cot kL \right\} \text{ for } n = 3, 5, 7, \cdots \]
"running KK-mass"

degeneracy is not a genuine feature of UED but a consequence of fine-tuning.

Kong, Park, Rizzo JHEP 1004 (2010) 081

Kong, Park, Rizzo JHEP 1007 (2010) 059
Q. What is the most preferred parameter space for $(1/R, M)$?
Theoretically

- “Natural” choice is $M \sim 1/R$ (the only scale in the theory)
- Any value of $M$ is allowed: $|M| \in (0, \Lambda)$
experimentally

- If $1/R \gg \text{TeV}$, theory decouples (hard to get tested ..)

- If $1/R \sim \text{TeV}$, theory can get constrained by EWPD(S,T,U), 4Fermi, g−2 , LHC, Dark matter..
The 1\textsuperscript{st} official LHC bound on split-UED from $W^{\prime} = W_2$

CMS collaboration
arXiv:1204.4764
for universal mass

Huang, Kong, SCP (2012)
for Non-Universal Masses

Huang, Kong, SCP (2012)

** Contours for $\Omega h^2 = 0.1123$
summary

- UED+bulk mass as an effective theory of RS
- KK-dark matter
- (universal, non-universal cases) is checked by the LHC7+ EWPD + DM
• A large portion of the model parameter is already probed by the LHC7

• if the universal mass is assumed: $m < (0.3-0.5)/L$ for $1/R=650-900$ GeV

• Non-universal case is slightly less constrained: $m_L < 1.7/L$ or $m_Q < 0.7/L$

• LHC8 will play even more important role to discover/disprove the model, which is good.
Discussion-1

- In effective theory point of view, Dim-5 terms (ex) BLKT could be important
- change the KK spectrum (make KK-bosons lighter) and interaction rates (weaker coupling)
- phenomenology (work in progress with T. Flacke and K.C.Kong)
125 Higgs ??

- KK-tops (and other particle too) can contribute to 1-loop induced gluon fusion process .. increase the production rate.. how much?)

- decay to photons ..(decrease the decay rate .. how much?)

- will show you next time! Thanks!
back up slides
contents

- UED model: brief reminder
- Effects of Bulk masses of fermion
- Summary
• 3 large (infinite ?) dimensions are responsible for everyday life, planetary motion, cosmology ..

• But, there can be additional dimensions, which can be fermionic (in SUSY models) or bosonic (this talk)

• XDs may be responsible for “not-so-well-understood-in-the-SM problems” ..

• notably including the big hierarchy problem, dark matter problem, flavor (hierarchy) problem, etc.
In particular, if XD is responsible for the Big hierarchy, we may be able to see the presence of it at the LHC.

..by observing the Kaluza-Klein states of particles having the momentum to the “y” direction (e.g., in RS and UED models.. $P_5 = n/R \sim \text{TeV}$

or seeing the low scale strong gravity (e.g., in RS and ADD models therein gravity becomes strong at $M_G \sim \text{TeV}$) .. KK gravitons and Black holes..

The details of the LHC signature depend on the particular realization .. geometry of XD and location of particles ..
• In principle, we may be able to learn the size of extra dimension and the shape of the extra dimension..

• we need to have a big energy to go over the large mass gap ($\sim E_{\text{CM}} > 2/R$ for pair production of the KK states),

• also have to have a large luminosity for precise determination of the spectrum.

• In reality, we are limited so that we can set the bounds on the size (and the shape) in a model dependent way
There are **MANY interesting models** of extra dimensions..

- ADD, RS, UED, GHU, 5DGUT, etc...

- Some of them are tightly constrained by the LHC
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<thead>
<tr>
<th></th>
<th>UED</th>
<th>RS</th>
<th>ADD</th>
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</thead>
<tbody>
<tr>
<td>$M_{KK}$</td>
<td>$\sim$TeV</td>
<td>$\sim$TeV</td>
<td>(too low to be seen)</td>
</tr>
<tr>
<td>$M_G$</td>
<td>(too high to be seen)</td>
<td>$\sim$TeV</td>
<td>$\sim$TeV</td>
</tr>
<tr>
<td><strong>LHC</strong></td>
<td><strong>Phenomenology</strong></td>
<td></td>
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<td></td>
<td>MET(LKP) pairs of 1st KK peak of 2nd KK</td>
<td>$G_{kk}$ resonance jet+MET $g_{kk}\rightarrow$ttbar.. $BH$(tops, Higgs..)</td>
<td>jet+$G_{kk}$ photon+$G_{kk}$ $BH$(jets)</td>
</tr>
<tr>
<td>Models/Experiment</td>
<td>mUED</td>
<td>RS</td>
<td>ADD</td>
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<td>LHC7 (Moriond 2012 March)</td>
<td>only poorly constrained with 1-loop induced interactions</td>
<td>$M_{Gk} \geq 1.8 \ (2.1) \ TeV$ with $k/M=0.05 \ (0.1)$</td>
<td>(Mass gap is too small to be directly seen)</td>
</tr>
<tr>
<td>Strong Gravity (BH)</td>
<td>(too high to be seen)</td>
<td>N/A</td>
<td>$&gt;3.8-5.2 \ TeV$</td>
</tr>
</tbody>
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**should be careful in interpretation**
Caution!

The CMS collaboration
arXiv:1202.6396

For a specific subset of the black hole models [7] that are being probed, we also set dedicated limits on semiclassical and quantum black hole and string-ball production performing counting experiments using optimized $S_T$ and $N$ selections. It should be noted that the semiclassical approximation used for deriving the cross section within respective benchmark scenarios is expected to break down for many of the points probed, a point emphasized in a recent critique [43]. Thus, these limits should be treated as indicative, rather than precise.

The 1st official LHC bound on split-UED from W’ search

CMS collaboration
arXiv:1204.4764