IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
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How large can UED be?

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IPMU, The University of Tokyo
Kobe, Jan 7, 2011

Csaki, Hubisz, Heinonen, SCP, Shu , arXiv:1007.0025

Contents

- UED and its extensions
- UED Flavor model
- Bound on the size of XD
- Conclusion

UED

- Universal Extra Dimension
  - All the SM fields are (universally) in 5D
  - $S^1/Z_2 \sim [-L/2, L/2]$ for chiral theory
  - Low energy effective theory = the SM + KK excited states

UED Lagrangian

$$S = \int d^4x \int_{-L/2}^{L/2} dy \left[\mathcal{L}_5 + \delta(y + L/2)\mathcal{L}_{-L/2} + \delta(y - L/2)\mathcal{L}_{L/2}\right]$$

orbifold

Bulk Action : respects 5D Lorentz

Boundary localized Action : respect 4D Lorentz

Bulk Lagrangian

$$G = SU(3)_c \times SU(2)_w \times U(1)_Y$$

$$\Psi_i(x^\mu, y) = (Q, U^c, D^c, L, E^c)_i$$
$$= ((3,2)_{1/6}, (\bar{3},1)_{-2/3}, (\bar{3},1)_{1/6}, (2,1)_{-1/2}, (1,1)_1)_i$$

$$\mathcal{L}_5^{gauge} = -\frac{1}{4g_{1,5}^2} B^{MN} B_{MN} - \frac{1}{2g_{2,5}^2} tr\left[W^{MN} W_{MN}\right] - \frac{1}{2g_{3,5}^2} tr\left[G^{MN} G_{MN}\right]$$

$$\mathcal{L}_5^{fermi} = \sum_{\Psi_i, \Psi_j} \frac{1}{2}\left(D_M \bar{\Psi}_i \Gamma^M \Psi_j - \bar{\Psi}_i D_M \Gamma^M \Psi_j\right) - m_{ij}(y) \bar{\Psi}_i \Psi_i$$

$$\Gamma^M = (\gamma^\mu, -i\gamma^5)$$

$$D_M = \partial_M - i\frac{\lambda_\alpha}{2} G_M^\alpha - i\frac{\tau^a}{2} W_M^a - i\frac{Y}{2} B_M$$

Orbifold BCs

- No need to reduce the rank of gauge group
  - $A_5(y=L)=0=A_5(y=-L)$
- ‘odd’ condition (or Dirichilet condition) for unwanted chiral states
  - $Q=Q_L+Q_R$: $Q^{(0)}{}_R=0$
  - $U=U_L+U_R$: $U^{(0)}{}_L=0$
  - $D=D_L+D_R$: $D^{(0)}{}_L=0$

Minimal UED

- Assume that No BLKT, No bulk mass
- The tree level KK spectrum is degenerate: 1/R, 2/R, 3/R ...
- Small separation (~O(10)% for colored particles, ~O(1)% for non-colored particles) due to RG running from 'cut-off'.
- Naive dimensional analysis suggests that 'cut-off' scale is around O(100/R).

$$\frac{g_5^2 \Lambda}{24\pi^3} = \frac{g_4^2 R\Lambda}{24\pi^2} \sim 1$$

UED good

- KK number conservation
    - No brane localized term assumed
    - No bulk mass for fermions assumed
  - The wave functions for zero modes are all flat
  - No direct contribution to S, T, U parameters
  - Low compactification scale (sub TeV) is allowed

UED phenomenology

- Pretty much parallel to MSSM with R-parity
- Each particle has its KK-partners (same spin, bosonic supersymmetry)
- Odd KK-particles produced in pairs
- In a minimal model, LKP is shown to be the first KK-photon ~ 1^{st} KK $U(1)_Y$ gauge boson, which is a perfect DM candidate

A ‘bench mark’ model

- Since low scale compactification is allowed (1/R<TeV), the model can be interesting at the LHC
- Collider study for spin-measurements, model discrimination (...compare to the MSSM ..)
- Vector-type Dark Matter candidate .. having different features from scalar or fermion type DM models
- MSSM like collider phenomenology for chains of heavy particle decay => used for studying kinematic observables which can be useful for the LHC

UED bad

- No hierarchy problem addressed .. (what's the use of a model which does not solve any problem?)
- With flavor asymmetric counter terms on branes, UED is NOT automatically MFV
- Also higher dimensional operators which can contribute to FCNC can be significant

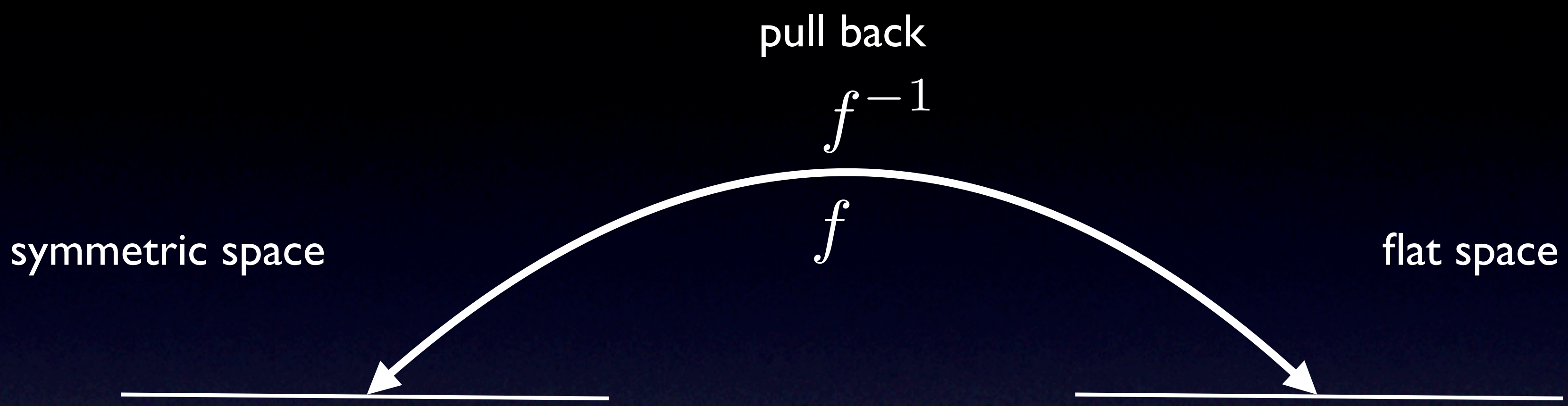
So..

- We tried to consider more generic situation.
- Make a UED flavor model which produces flavor hierarchy via wave function localization , then see how large extra dimension is allowed
- “KK-parity” and “bulk mass" are essential

KK-parity

- Z_2 reflection about the middle point of extra dimension.
- A remnant symmetry of 5D translational invariance, which is broken by end points (or fixed points in orbifold language).
- It is often claimed that KK-parity requires flat geometry like in UED. But, it is not true.

Indeed, KK-parity can be defined on any "symmetric" space.



$$g(y) = g(-y) \qquad\qquad g = 1$$

$$\{e^e, e^o\} \qquad\qquad \{\cos(ny/L), \sin(ny/L)\}$$

$$P_{KK} : \begin{cases} e^e \to +e^e, & even \\ e^o \to -e^o, & odd \end{cases} \qquad : \begin{cases} \cos \to +\cos, & even \\ \sin \to -\sin, & odd \end{cases}$$

reflection
about the middle point

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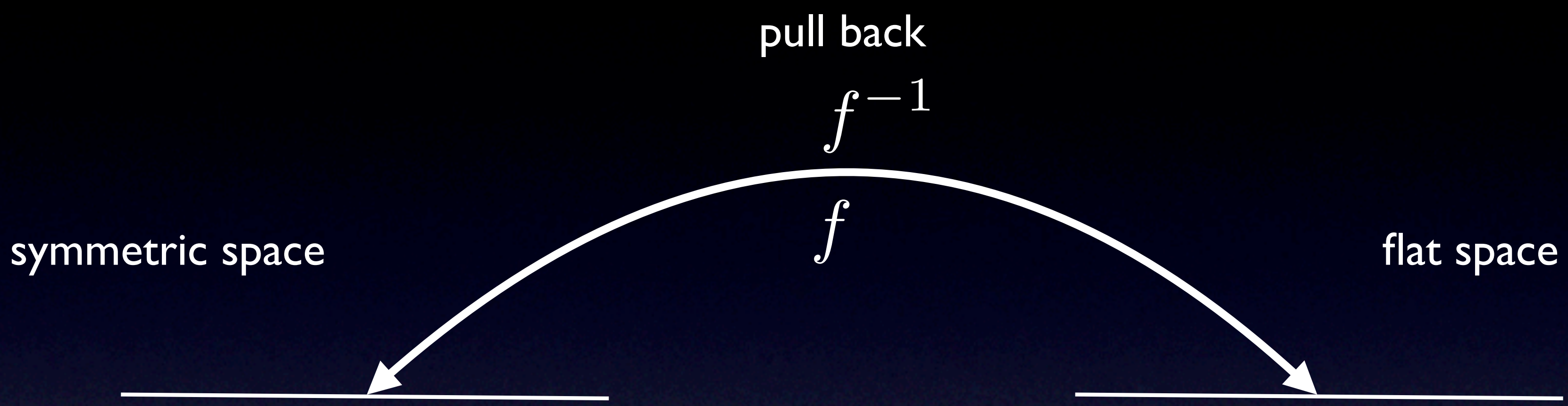

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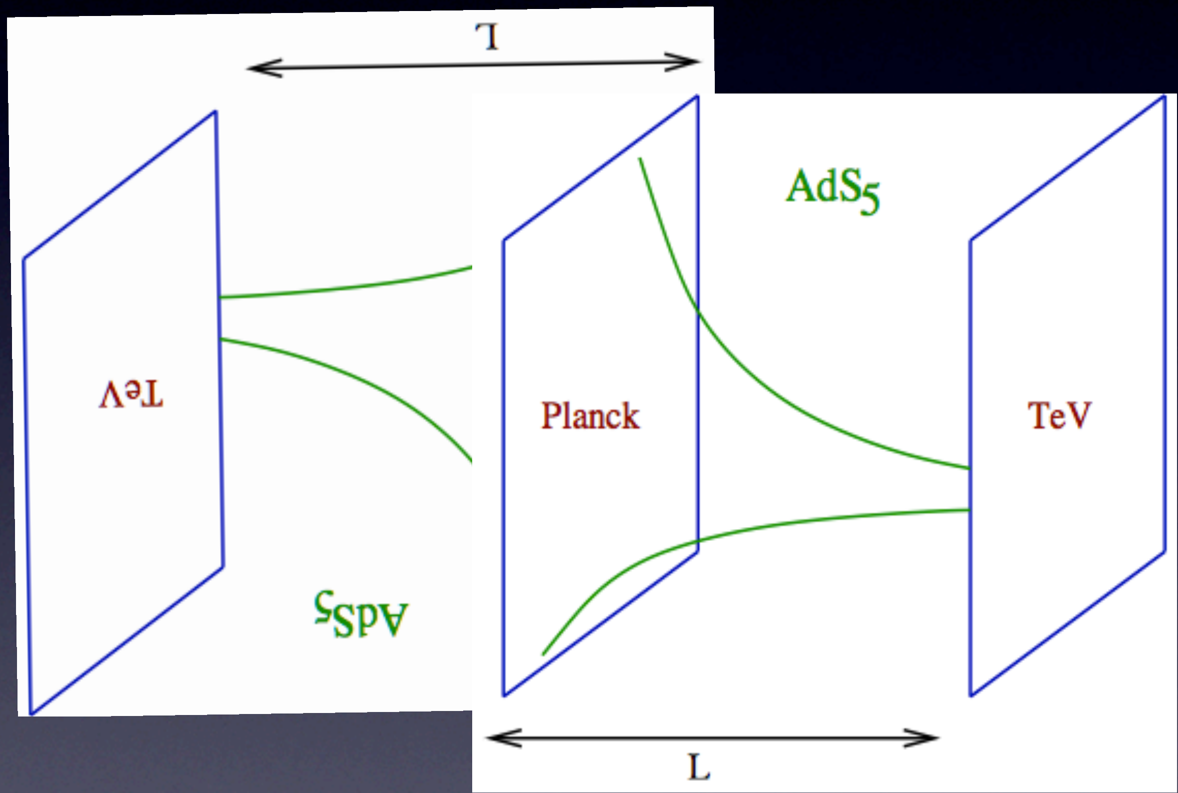
reflection
about the middle point

for a massive field

$$\{\cosh(ky), \sinh(ky)\}$$

Two throat warped geometry



[Agashe, Falkowski, Low, Servant, JHEP 0804(2008)027]

Interaction allowed/forbidden

$$g \propto \int_{-L}^{L} dy \psi_{even}\psi_{even}\psi_{even} \neq 0$$

Allowed

$$g \propto \int_{-L}^{L} dy \psi_{odd}\psi_{even}\psi_{even} = 0$$

Forbidden

Interaction allowed/forbidden

$$g \propto \int_{-L}^{L} dy \psi_{even} \psi_{even} \psi_{even} \neq 0$$

Allowed

$= 0$

Underlying Math for LKP DM

An odd function cannot be decomposed into finite number of even functions

Minimal Extensions

Without introducing additional field contents to UED, we can extend the model by introducing following terms:

- Brane localized terms (Dim=5, 6)
- Bulk mass for fermion (Dim=4)

Bulk Mass

- $M_{gauge}=0$: gauge symmetry.
- $M_{fermi} \neq 0$:Vectorlike Dirac mass term for fermion is not forbidden by 5D Lorentz symmetry and gauge symmetry. Thus, this term should be included in the effective theory point of view.
- To keep KK-parity, the mass term should be odd.

Dirac Bilinear is odd under the reflection thus KK parity forbids KK-even mass allows KK-odd mass.

$$y \to -y$$

$$\Psi(x^\mu, y) \to \pm\gamma_5 \Psi(x^\mu, y)$$

$$m_5(y) \to m_5(-y) = -m_5(y)$$

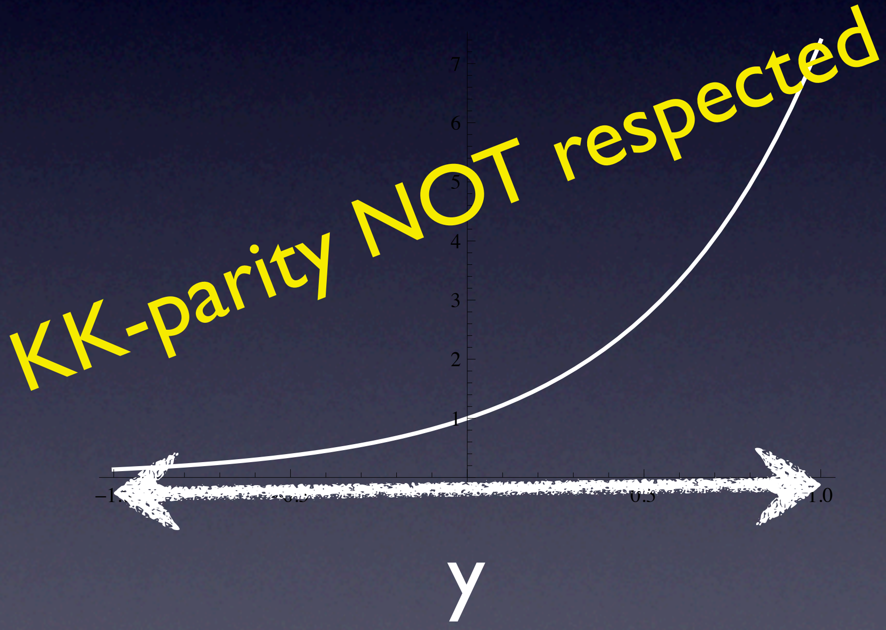
$m_5 \bar{\Psi}\Psi$ is invariant

(proof)

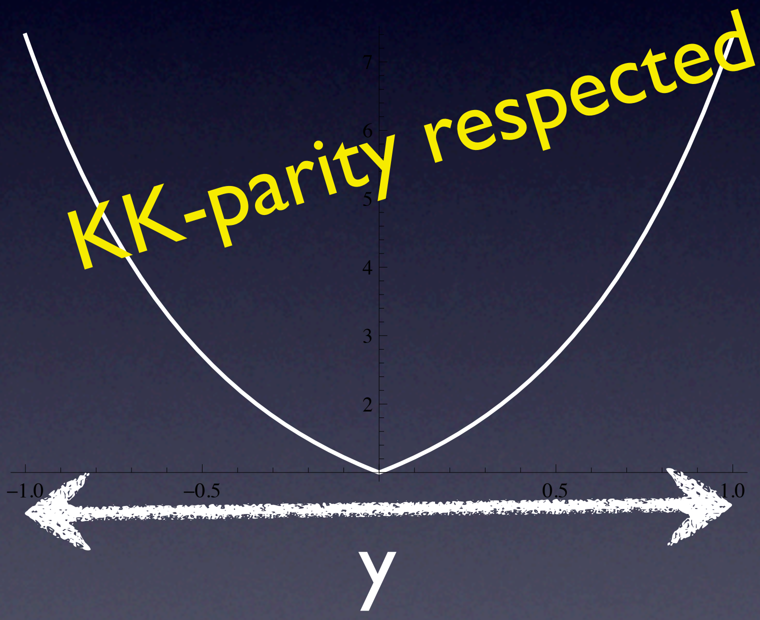
$$\begin{aligned}\bar{\Psi}\Psi \to (\gamma_5 \Psi)^\dagger \gamma^0 (\gamma_5 \Psi) \\ = \Psi^\dagger \gamma_5 \gamma^0 \gamma_5 \Psi \\ = -\Psi^\dagger \gamma^0 \Psi \\ = -\bar{\Psi}\Psi\end{aligned}$$

$$(\partial_y \pm m) f^{(0)}_{R/L} = 0$$

with “even mass”
m(-y)=m(y)

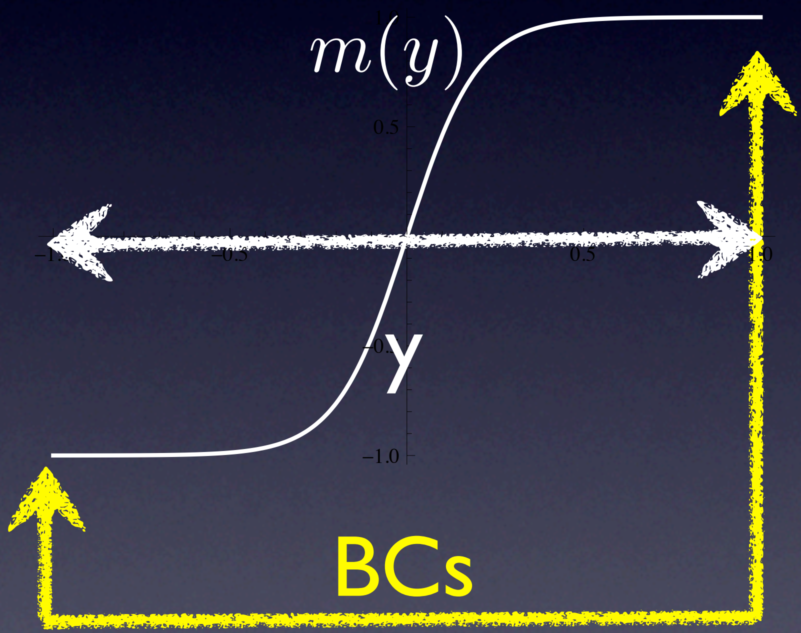


with “odd mass”
m(-y)=-m(y)



Odd mass on orbifold

$$M_5(y) \to M_5(-y) = -M_5(y)$$



The lowest energy configuration
interpolating boundary values:+M,-M

$$M \tanh \mu y \to M\theta(y)$$

Georgi, Grant, Hailu (2001)

kink-mass

$$S = \int d^4x \int_{-L/2}^{+L/2} dy \left[\frac{i}{2} \bar{\Psi}\, \Gamma^M \overleftrightarrow{\partial}_M \Psi - m_5(y) \bar{\Psi}\Psi \right]$$

$$\Psi = \begin{pmatrix} \chi_\alpha \\ \bar{\psi}^{\dot{\alpha}} \end{pmatrix}$$

$$m_5(y) = \mu\, \epsilon(y) = \begin{cases} -\mu, & y < 0 \\ +\mu, & y > 0 \end{cases}$$

EOM:

$$\begin{aligned} -i\bar{\sigma}^\mu \partial_\mu \chi + \partial_5 \bar{\psi} + m\bar{\psi} &= 0 \\ -i\sigma^\mu \partial_\mu \bar{\psi} - \partial_5 \chi + m\chi &= 0 \end{aligned}$$

KK-decomposition:

$$\Psi_n = \begin{pmatrix} g_n(y)\chi_n(x) \\ f_n(y)\bar{\psi}_n(x) \end{pmatrix} : \qquad \begin{aligned} -m_n g_n + \partial_5 f_n + m f_n &= 0 \\ -m_n f_n - \partial_5 g_n + m g_n &= 0 \end{aligned}$$

Zero mode solutions

RH LH

$$f_0(y) = \sqrt{\frac{+\mu}{1-e^{-\mu L}}}e^{-\mu|y|}, \qquad g_0(y) = \sqrt{\frac{-\mu}{1-e^{+\mu L}}}e^{+\mu|y|},$$

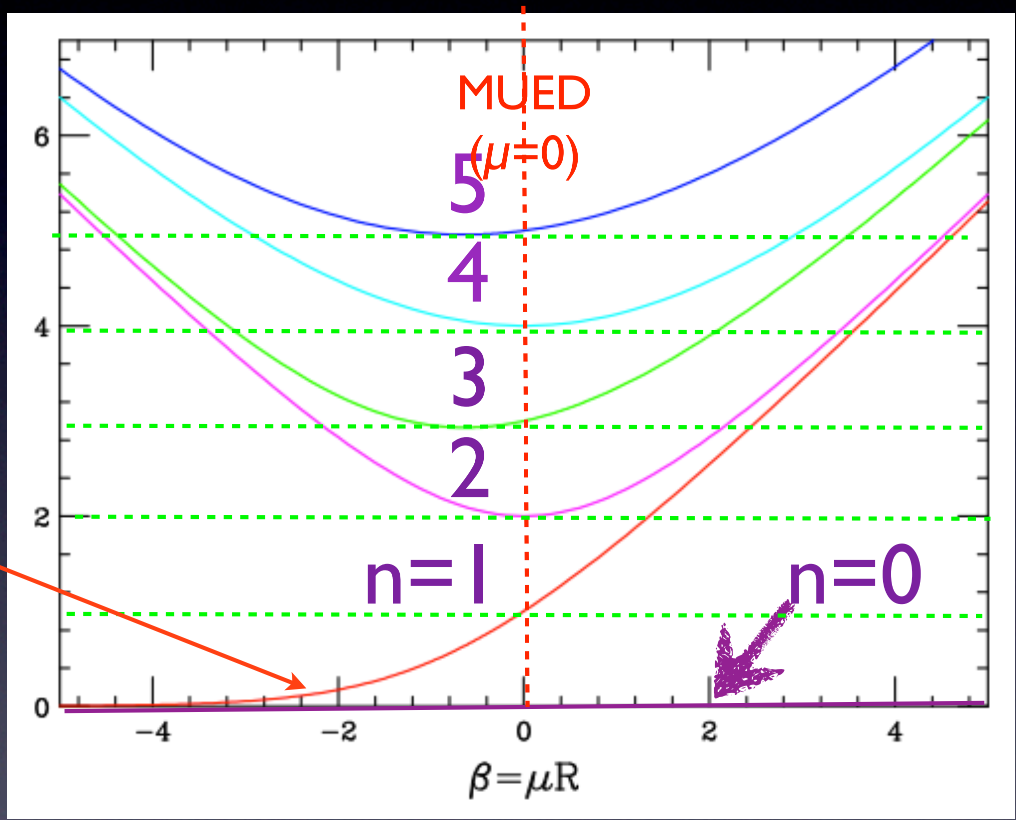
sign(μ)	Chirality	Localization	Ultralight KK-Mode
$\mu > 0$	RH	Midpoint	No
$\mu < 0$	RH	Endpoints	Yes
$\mu > 0$	LH	Endpoints	Yes
$\mu < 0$	LH	Midpoint	No

Ultra-light mode??

Full KK spectra, DL

$m_5(y) = \mu\theta(y)$

ultralight mode

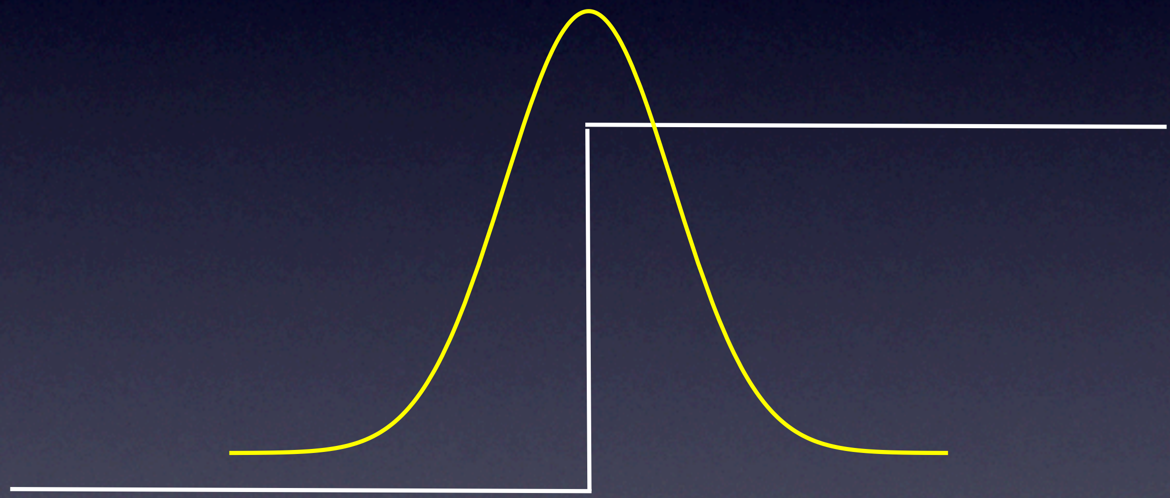


- M_5=0 corresponds to mUED.
- Chiral zero mode remains massless (n=0).
- KK mass spectrum of boson(fermion) is (not) equally spaced.
- n=1 mode can be degenerate with the zero mode (ultra light mode) when mu is negative. If positive, it will be heavy and approaches to n=2.

Domain wall fermion

$[-\infty, +\infty]$

- A `trapped fermion' exists in the presence of domain wall in infinite extra dimension. It is chiral (=massless). [domain wall fermion]



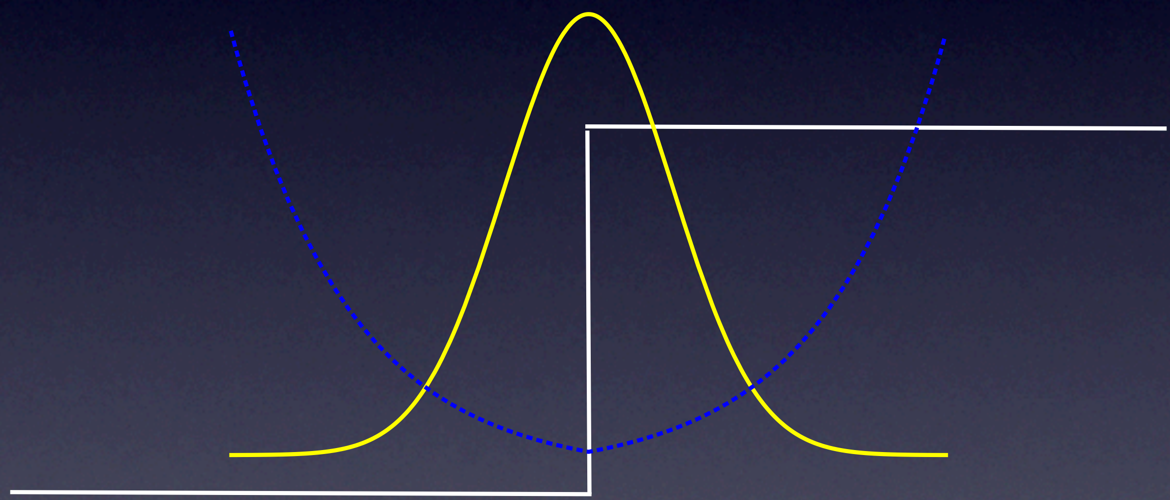
- The other chiral state is exponentially diverging (non-normalizable mode), which is not physical mode.

Only domain wall fermion is physical.

Domain wall fermion

[-L,+L]

- A `trapped fermion' still exists in the presence of domain wall in finite extra dimension. It is chiral (=massless). [domain wall fermion]



- The other chiral state is exponentially growing but normalizable since the extra dimension is finite. This mode is also physical.

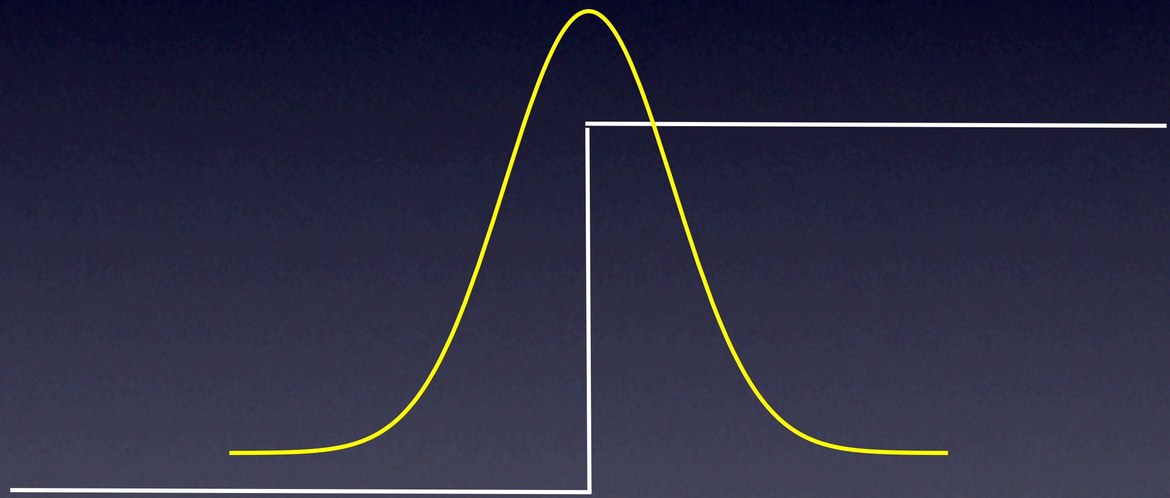
Both [can be] physical

Domain wall fermion

[-L,+L]

- There are two choices of BCs on orbifold.

(i) Dirichlet BC for growing mode.=> Domain wall fermion is physical zero mode



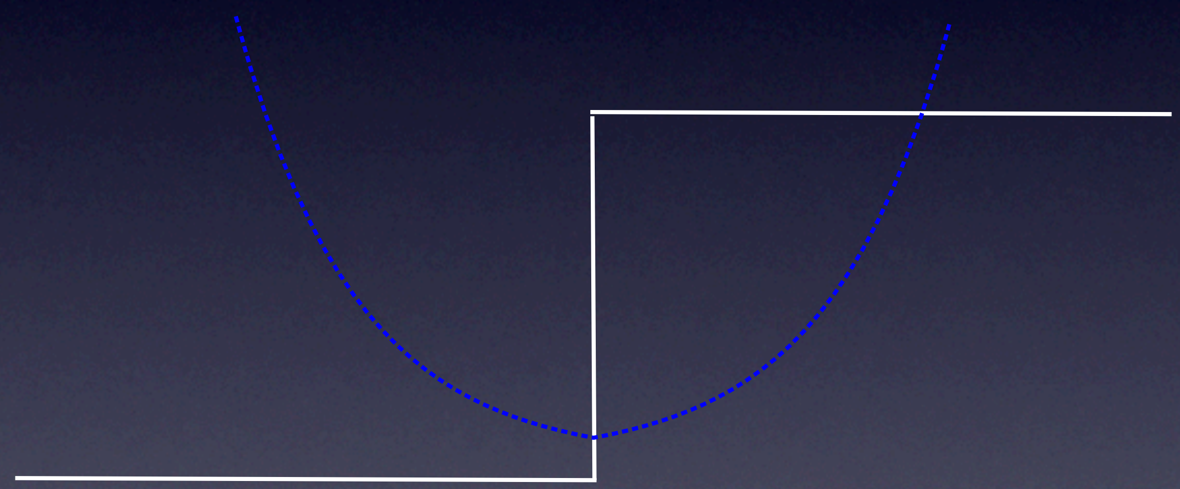
This case is totally OK as the domain wall fermion is a natural chiral zero mode

ultra-light mode

[-L,+L]

- There are two choices of BCs orbifold.

(ii) Dirichlet BC for Domain wall mode.=> Growing mode is physical zero mode

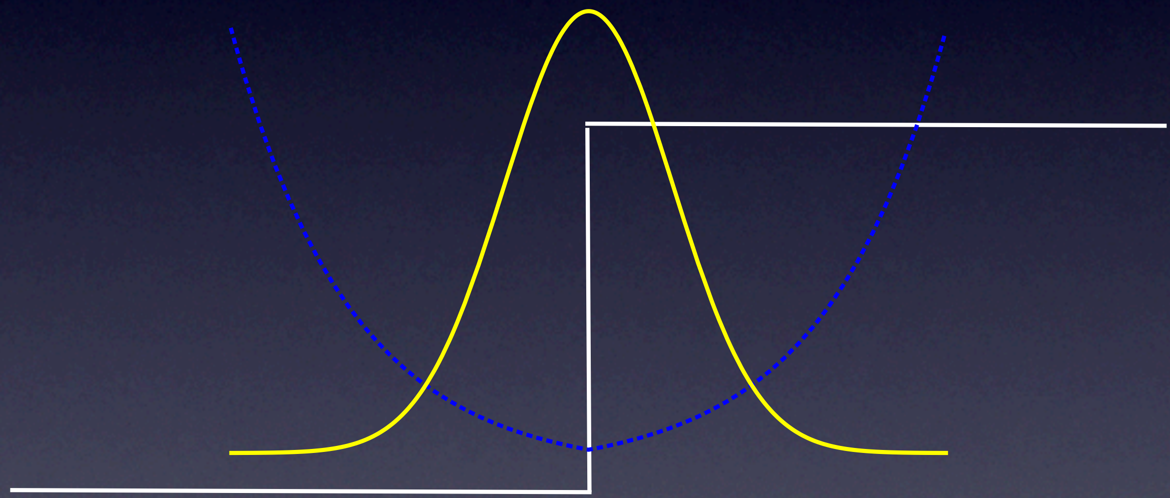


ultra-light mode

[-L,+L]

- There are two choices of BCs orbifold.

(ii) Dirichlet BC for Domain wall mode.=> Growing mode is physical zero mode

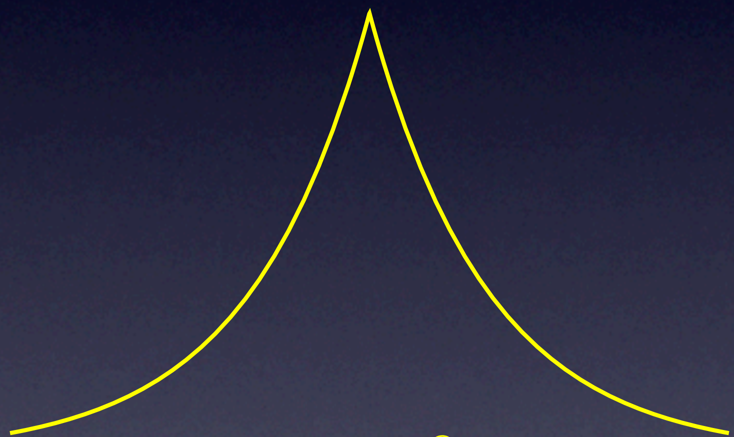


In this case, actually, 1st excited KK mode will become the `would-be' domain wall fermion', which is very light. $m_1 = 2|\mu|e^{-\mu L}$

Imposing DL

When Dirichlet BC is imposed to L-handed chirality (DL), R-handed chiral zero mode is the solution:

$$f_R^{(0)} = \sqrt{\frac{\mu}{1 - e^{-2\mu L}}} e^{-\mu|y|}$$



$\mu > 0$

no ultralight mode

$\mu < 0$

+ultralight mode

4 cases

RH LH

$$f_0(y) = \sqrt{\frac{+\mu}{1-e^{-\mu L}}} e^{-\mu|y|}, \qquad g_0(y) = \sqrt{\frac{-\mu}{1-e^{+\mu L}}} e^{+\mu|y|},$$

sign(μ)	Chirality	Localization	Ultralight KK-Mode
$\mu > 0$	RH	Midpoint	No
$\mu < 0$	RH	Endpoints	Yes
$\mu > 0$	LH	Endpoints	Yes
$\mu < 0$	LH	Midpoint	No

To avoid unwanted ultralight mode, we are enforced to have the localization of fermions in the midpoint.

Flavor hierarchy in Kink mass + Localized Higgs

Csaki, Hubisz, Heinonen, SCP, Shu (arXiv:1007.0025)

- As the localization of fermion wave function can be realized with bulk mass, one may address flavor hierarchy problem.
- The Higgs profile should be localized toward the end points.
- We still want to keep the KK-parity.

Higgs sector

[Haba, Oda, Takahashi, NPB 821, 74 (2009)]

$$S = \int d^5x |D_M H|^2 - m_H^2 |H|^2 - \delta(y+L) V_{-L}(H) - \delta(y-L) V_L(H)$$

$$V_L(H) = V_{-L}(H) = \lambda(|H|^2 - v^2)^2$$

- Because of the KK-parity, the form of the potential is identical
- We take the bulk potential to consist of a positive mass^2 term,
- while assume negative masses on boundaries which lead to the development of a VEV.

Higgs

$$S = \int d^4x \int_{-L/2}^{L/2} dy \left[\frac{1}{L} |D_M \Phi|^2 - \frac{1}{L} \mathcal{V}(\Phi) - \delta(y - L/2) V_{\frac{L}{2}}(\Phi) - \delta(y + L/2) V_{-\frac{L}{2}}(\Phi) \right]$$

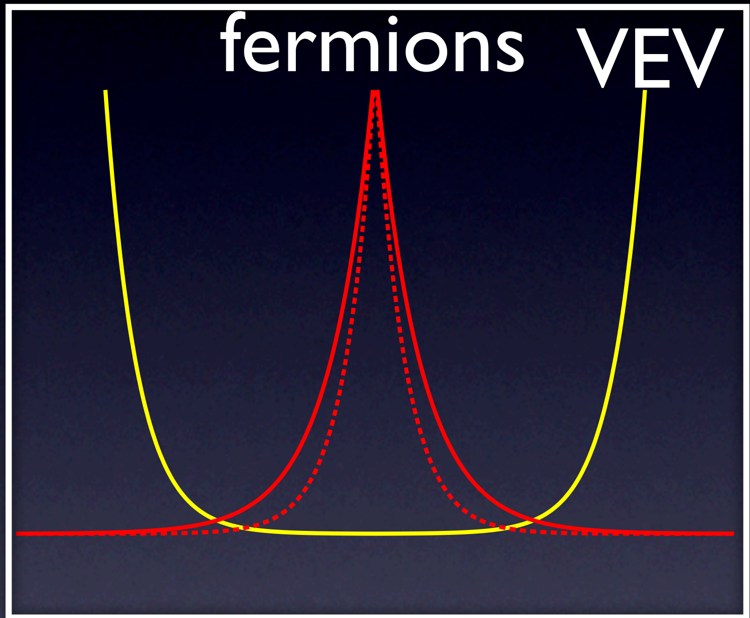
$$\begin{aligned} \mathcal{V}(\Phi) &= m^2 |\Phi|^2, \\ V_{-\frac{L}{2}}(\Phi) = V_{\frac{L}{2}}(\Phi) &= \frac{\lambda}{4} \left(|\Phi|^2 - \frac{v_0^2}{2} \right)^2 . \end{aligned}$$

$$\langle H_0 \rangle = v(y)/\sqrt{2} = A \cosh(my) + B \sinh(my),$$

$$A = \sqrt{\frac{\lambda L v_0^2 c_h - 4 m s_h}{\lambda L {c_h}^3}} \quad \text{and} \quad B = 0,$$

The lowest energy configuration

VEV profile



$$v(y) = A\cosh(m_H y)$$

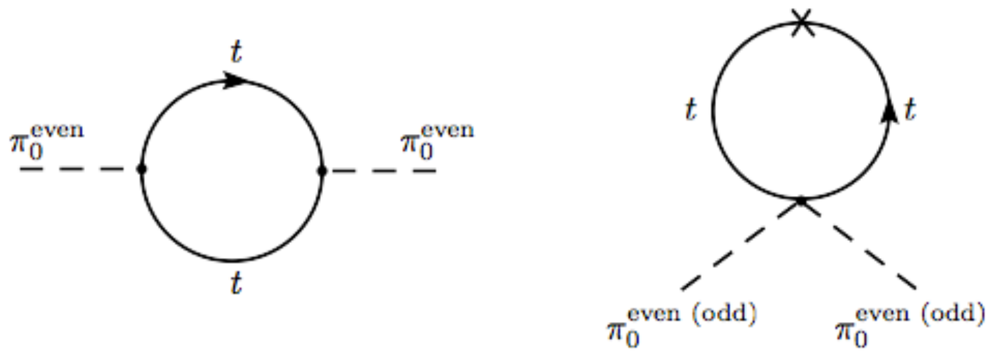
- The lowest energy VEV profile is indeed localized toward end points: a perfect situation for generating hierarchy.

KK Higgses

$$h_0^{(n)}(y) = A\cosh(k_n y) + B\sinh(k_n y),$$

$$k_0 \tanh(k_0 L/2) = 3m \tanh mL/2 - \frac{\lambda L v_0^2}{2} \qquad \text{(KK-even SM Higgs)}$$

$$\frac{k_1}{\tanh(k_1 L/2)} = 3m \tanh mL/2 - \frac{\lambda L v_0^2}{2} \qquad \text{(KK-odd partner).}$$



$$m_{\rm odd}^2 = \frac{3\lambda_t^2}{16\pi^2}\frac{6\zeta(3)}{L^2} \approx (400\ \text{GeV})^2 \times \left(\frac{1\ \text{TeV}^{-1}}{L}\right)^2$$

Other possibility with U(1)x

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X.$$

X(H)=1
X(femion)=0

Yukawa coupling is forbidden by U(1)x

$$B_\mu(z = \pm\tfrac{L}{2}) = 0 \qquad \text{and} \qquad \partial_5 B_5(z = \pm\tfrac{L}{2}) = 0.$$

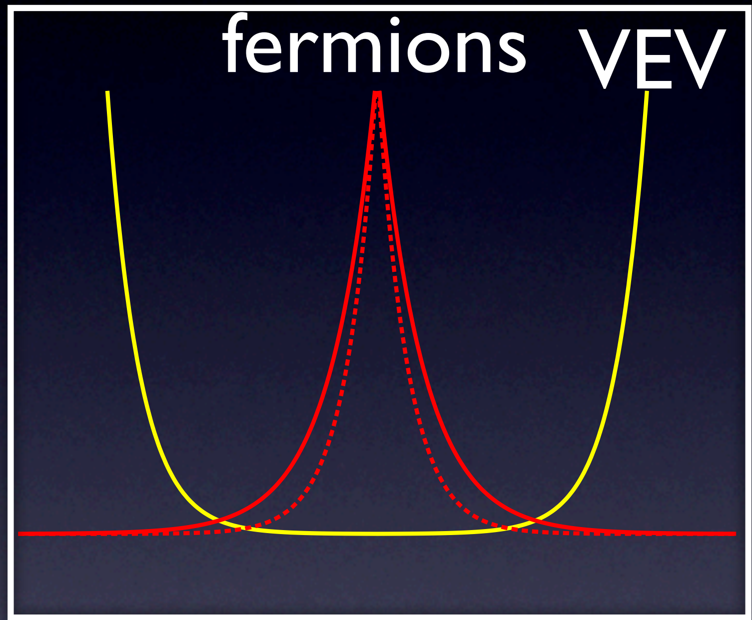
X is broken at the end point!

$$\mathcal{L}_Y = \left[H\bar{\Psi}_q Y_u \Psi_u + H^* \bar{\Psi}_q Y_d \Psi_d\right]_{y=\pm L/2} + h.c.$$

Yukawas allowed only at boundaries

The flat Higgs profile helps EWPT

Flavor hierarchy



Engineer bulk masses to generate proper Yukawa hierarchy & CKM

Fermion wave functions

$$\Psi_Q = (Q_1, Q_2, Q_3) \quad \Psi_u = (u_1, u_2, u_3) \quad \Psi_d = (d_1, d_2, d_3)$$

BCs are chosen such that Q contains LH zero modes,
and u, d contain RH zero modes.

$$f_R^{(0)}(y) = \sqrt{\frac{1}{L}} e^{-c_R(|y|/L-1/2)} f(c_R)$$

$$f_L^{(0)}(y) = \sqrt{\frac{1}{L}} e^{c_L(|y|/L-1/2)} f(c_L)$$

$$f(c) = \left(\frac{c}{e^c - 1}\right)^{1/2}$$

$$\tilde{c} = (2c-1)k\pi r_c$$

$$f_{RS}(c) = \left(\frac{1-2c_{RS}}{1-e^{(2c_{RS}-1)k\pi r_c}}\right)^{1/2} = \frac{1}{\sqrt{k\pi r_c}} f(\tilde{c}) \sim \frac{1}{\sqrt{30}} f(\tilde{c})$$

Effective Yukawa

$$\mathcal{L}_Y = \frac{1}{2}\int dy(\langle H\rangle \bar{\Psi}_q Y_u \Psi_u + \langle H^*\rangle \bar{\Psi}_q Y_d \Psi_d + h.c.)(\delta(y+L/2)+\delta(y-L/2))$$

$$M_u = \frac{v}{\sqrt{2}} f_q Y_u f_{u^c}$$

$$M_d = \frac{v}{\sqrt{2}} f_q Y_d f_{d^c}$$

$$f_q = \mathrm{diag}\left(f(-c_{q1}), f(-c_{q2}), f(-c_{q3})\right)$$

for fermions in the middle

CKM

diagonalize by unitary rotations $$M_{u,d} = U_{Lu,d} m_{u,d}^{SM} U_{Lu,d}^{\dagger}$$

$$V_{CKM} = U_{Lu}^{\dagger} U_{Ld}$$

$$(m_{u,d}^{SM})_{ii} \sim \frac{v}{2} (Y_{u,d})_{ii} f_{qi} f_{ui,di}$$

CKM fitting

$$|(U_L)_{ij}| \sim \frac{f_{q_i}}{f_{q_j}} \quad \text{and} \quad |(U_R)_{ij}| \sim \frac{f_{u_i,d_i}}{f_{u_j,d_j}}, \quad \text{for } i \le j.$$

$$|(V_{CKM})_{ij}| \sim f_{q_i}/f_{q_j} \qquad \frac{f_{q_2}}{f_{q_3}} \sim \lambda^2, \quad \frac{f_{q_1}}{f_{q_3}} \sim \lambda^3$$

$$\frac{f_{u_1}}{f_{u_3}} \sim \frac{m_u}{m_t}\frac{1}{\lambda^3} = 6.88 \times 10^{-4} \quad \frac{f_{u_2}}{f_{u_3}} \sim \frac{m_c}{m_t}\frac{1}{\lambda^2} = 1.02 \times 10^{-1} \tag{4.26}$$

$$\frac{f_{d_1}}{f_{u_3}} \sim \frac{m_d}{m_t}\frac{1}{\lambda^3} = 1.84 \times 10^{-3} \quad \frac{f_{d_2}}{f_{u_3}} \sim \frac{m_s}{m_t}\frac{1}{\lambda^2} = 8.63 \times 10^{-3} \quad \frac{f_{d_3}}{f_{u_3}} \sim \frac{m_b}{m_t} = 1.76 \times 10^{-2}.$$

$$f_{l_3^c} \sim \frac{m_\tau}{m_t} = 1.3 \times 10^{-2} \quad f_{l_2^c} \sim \frac{m_\mu}{m_t} = 7.75 \times 10^{-4} \quad f_{l_1^c} \sim \frac{m_e}{m_t} = 3.74 \times 10^{-6}.$$

FC couplings with KK-states

$$g_s^{(2n)}(c) = g^{4D}\sqrt{2}\left[1 - f_c^2\,\gamma_c^{(2n)}\right]$$

$$\gamma_c^{(2n)} = \frac{(-1)^n - 1 + \left(\frac{\pi}{c}\right)^2 (e^c - 1)}{c(1 + \left(\frac{\pi}{c}\right)^2)}.$$

$$g_{L\,u,d}^{(2n)} \to U_{L\,u,d}^\dagger g_q^{(2n)} U_{L\,u,d} \qquad \text{and} \qquad g_{R\,u,d}^{(2n)} \to U_{R\,u,d}^\dagger g_{u,d}^{(2n)} U_{R\,u,d}.$$

$$(g_{L\,u,d})_{ij} \sim \sqrt{2} g_s \sum_k f_k^2\,\gamma_k \left(\frac{f_{q_i}}{f_{q_k}}\right)^{\lambda_{ik}} \left(\frac{f_{q_j}}{f_{q_k}}\right)^{\lambda_{jk}} \quad \text{with} \quad \lambda_{nk} = \begin{cases} +1 & n < k \\ -1 & n > k \end{cases},$$

$$\begin{aligned}\mathcal{H} &= \frac{1}{M_G^2}\left[\frac{1}{6} g_L^{ij} g_L^{kl} (\bar{q}_L^{i\alpha}\gamma_\mu q_{L\alpha}^j)\,(\bar{q}_L^{k\beta}\gamma^\mu q_{L\beta}^l) - g_R^{ij} g_L^{kl}\left((\bar{q}_R^{i\alpha} q_{L\alpha}^k)\,(\bar{q}_L^{l\beta} q_{R\beta}^j) - \frac{1}{3}(\bar{q}_R^{i\alpha} q_{L\beta}^l)\,(\bar{q}_L^{k\beta} q_{R\alpha}^j)\right)\right] \\ &= C^1(M_G)(\bar{q}_L^{i\alpha}\gamma_\mu q_{L\alpha}^j)\,(\bar{q}_L^{k\beta}\gamma^\mu q_{L\beta}^l) + C^4(M_G)(\bar{q}_R^{i\alpha} q_{L\alpha}^k)\,(\bar{q}_L^{l\beta} q_{R\beta}^j) + C^5(M_G)(\bar{q}_R^{i\alpha} q_{L\beta}^l)\,(\bar{q}_L^{k\beta} q_{R\alpha}^j),\end{aligned}$$

$$\begin{aligned}C_K^4 &\sim \frac{2g_s^2}{(M_G^{(2n)})^2}\left[\Delta g_{q_1,q_2}^{(2n)} \cdot \Delta g_{d_1^c,d_2^c}^{(2n)}\right]\frac{f_{q_1}}{f_{q_2}}\frac{f_{d_1^c}}{f_{d_2^c}} \\ &\sim \frac{2g_s^2}{(M_G^{(2n)})^2}\left[\Delta g_{q_1,q_2}^{(2)} \cdot \Delta g_{d_1^c,d_2^c}^{(2n)}\right]\frac{m_d}{m_s} \\ &\equiv \left(\frac{g_s}{M_G^{(2n)}}\xi\right)^2\end{aligned}$$

Bound from K-$\bar{\text{K}}$ mixing

- No RS-GIM like mechanism works in UED so that flavor bound is severe as we can expect.

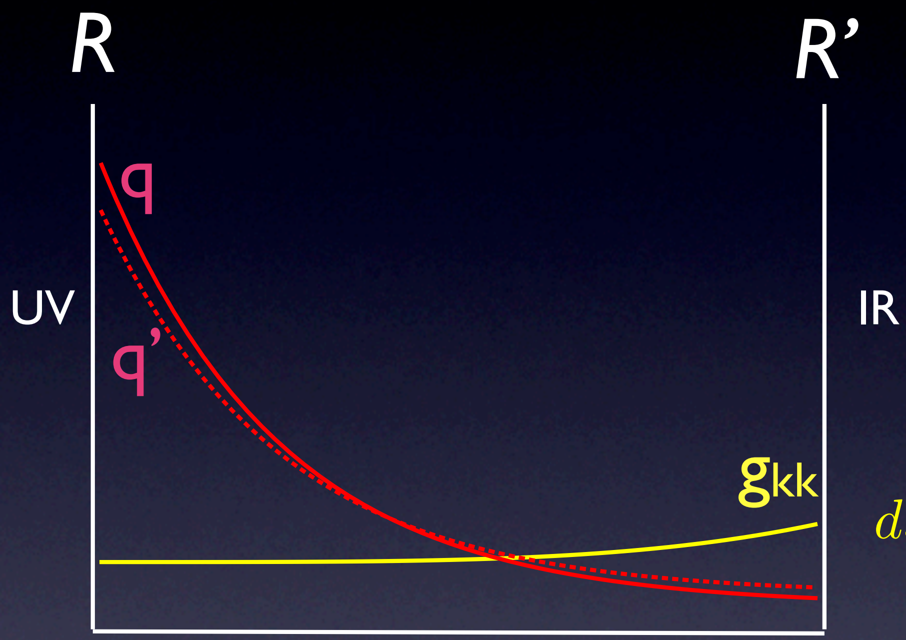
$$C_K^4 \approx [\frac{L \cdot 500\text{GeV}}{1000\text{TeV}}]^2$$ induced by flavor changing KK gluon exchanges

$$Re[C_K^4] \leq (10^4\text{TeV})^{-2}$$
$$Im[C_K^4] \leq (10^5\text{TeV})^{-2}$$
$$\Rightarrow \quad L^{-1} \geq 500\text{TeV}$$

Disappointingly large KK scale is required to fit flavor bound
Q. How to make KK-scale low so that the model remains interesting for the LHC search?

A Hint

RS-GIM



$$R'/R \sim 10^{16}$$

$$ds^2 = \left(\frac{R}{z}\right)^2 (dx^2 - dz^2)$$

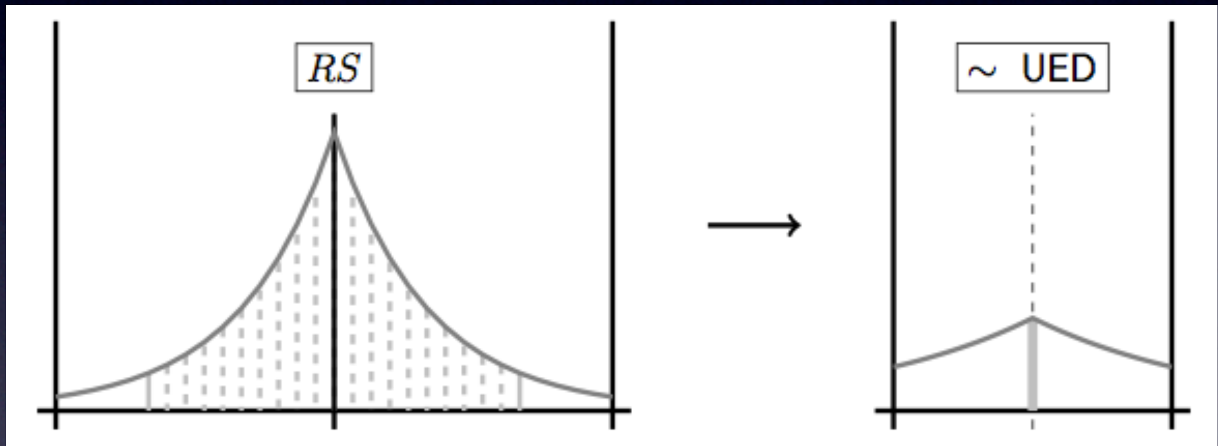
- In RS, the gauge boson KK-modes are basically flat throughout most of the bulk of the XD, varying mainly in the region of IR brane.
- Integrating out the region in the vicinity of the UV brane creates (after canonical normalization of the zero mode) flavor universal BLKT.

$$S_{\rm fermion} = \int d^5x \left\{ \frac{i}{2} \bar{\Psi} \Gamma^\mu \overleftrightarrow{\partial}_\mu \Psi \right\} \kappa_f L \delta(y).$$

- The remaining non-universal pieces arise only near the IR brane, where the fermion wave functions are exponentially suppressed~RS-GIM!

RS to UED

Interpret UED as an effective description of RS with two throats



- It is possible to reduce a warped geometry to an approximately flat XD by integrating our a large slice of the warped XD. A new BLKO induced.

$$S_{\text{fermion}} = \int d^5x \left\{ \frac{i}{2} \bar{\Psi}\, \Gamma^{\mu} \overleftrightarrow{\partial}_{\mu} \Psi \right\} \kappa_f L \delta(y).$$

- The remaining warping is minimal and it is clear that this model will describe exactly the same physics as the complete warped XD, encapsulating RS-GIM mechanism.

Allowed

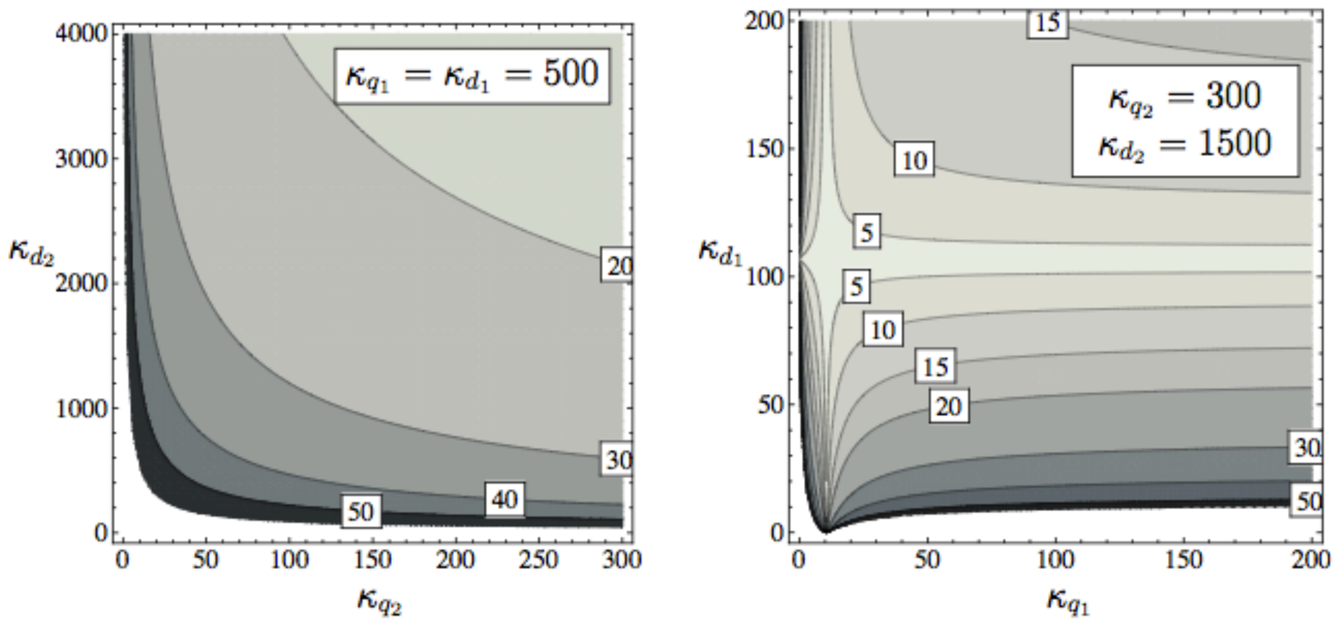


Figure 5: Bounds on KK-scale in the presence of brane localized kinetic terms for the fermions. The strengths of two of these are kept fixed, while we scan over the other two. Left: for $\kappa_{q_1} = \kappa_{d_1} = 500$, right: for $\kappa_{q_2} = 300$ and $\kappa_{d_2} = 1500$

Other constraints

EWPT

$$\Delta\rho = \alpha T = \frac{4}{v_0^2}(\Pi_{11} - \Pi_{33}) = \frac{g'^2 L^2 v_0^2}{48} \approx 0.1 \cdot 10^{-3} \times \left(\frac{L}{1\ \mathrm{TeV}^{-1}}\right)^2 .$$

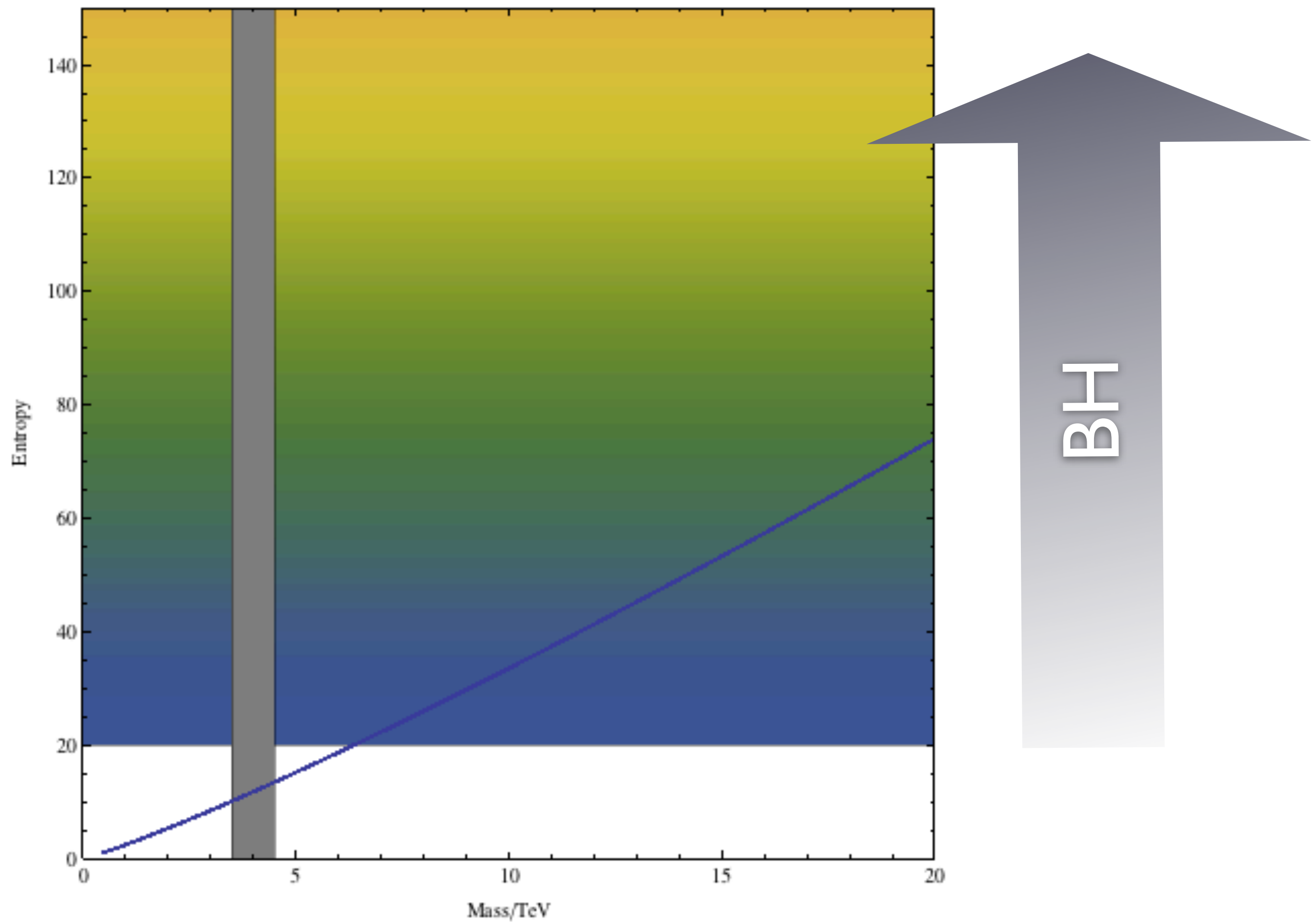
Four fermi

$$\mathcal{L}_{\mathrm{eff}} = \frac{4\pi}{\Lambda^2} \sum_{i,j=L,R} \eta_{ij} \bar{e}_i \gamma_\mu e_i \bar{q}_j \gamma^\mu q_j \,,$$

$L < (530\ \mathrm{GeV})^{-1}$

Conclusion

- We have explored the potential of a 5D flat geometry model with all SM fields propagating in the bulk for generating the observed fermion mass hierarchy while respecting low energy flavor physics bounds and preserving KK-parity.
- This is non-trivial, as standard UED is not automatically minimally flavor violating, as has been claimed in earlier literature.
- While it is not very difficult to generate the fermion mass hierarchy utilizing wave-function localization in the extra dimension, the resulting tension from flavor physics bounds renders the model rather implausible.
- The effects of the Randall-Sundrum GIM mechanism can be mimicked in this construction, but at the price of reintroducing what is essentially the same tuning that is required in the original UED models.
- While UED remains an interesting “straw man” from the perspective of model discrimination at the LHC, it has so far resisted implementation as a theoretically well-motivated competitor with TeV scale supersymmetry, strongly coupled theories of electroweak symmetry breaking, or warped extra dimensions.



140
120
100
80
60
40
20
0
Entropy
0
5
10
15
20
Mass/TeV
BH