

SPLIT UED

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SCP, Shu, Phys.Rev.D79 (Rapid):091702,2009
Chen, Nojiri, SCP, Shu,Takeuchi, JHEP 0909:078,2009
Chen, Nojiri, SCP, Shu, arXiv:0909:078,2009
K. Kong, SCP, T. Rizzo , JHEP 1004:081, 2010
K. Kong, SCP, T. Rizzo , arXiv:1004.4635,2010
Csaki, Hubisz, Heinonen, SCP, Shu (coming soon)

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- model: split-UED
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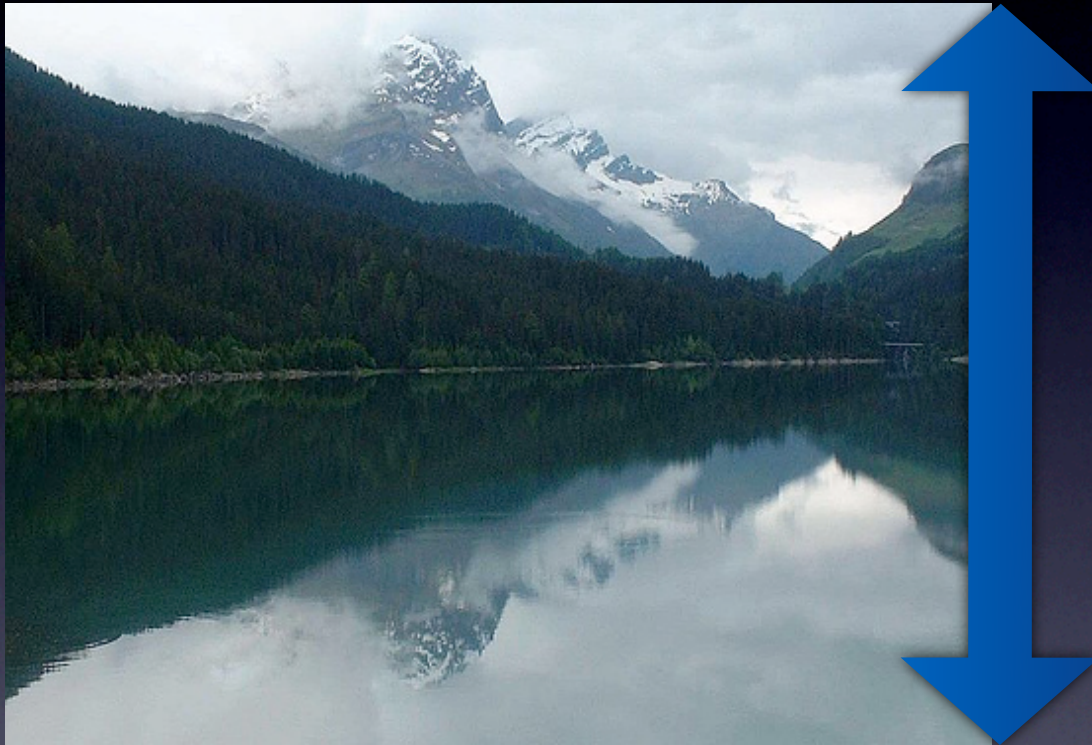
UED

Appelquist, Cheng, Dobrescu 2001

5D S_1/Z_2
 $SU(3) \times SU(2) \times U(1)$
 $\Psi(x,y) = \{Q, U, D, L, E, N\}$
“bulk mass=0”

- 4D SM + KK-excitations
- Flat profiles for zero modes
- KK-parity conserved

KK parity



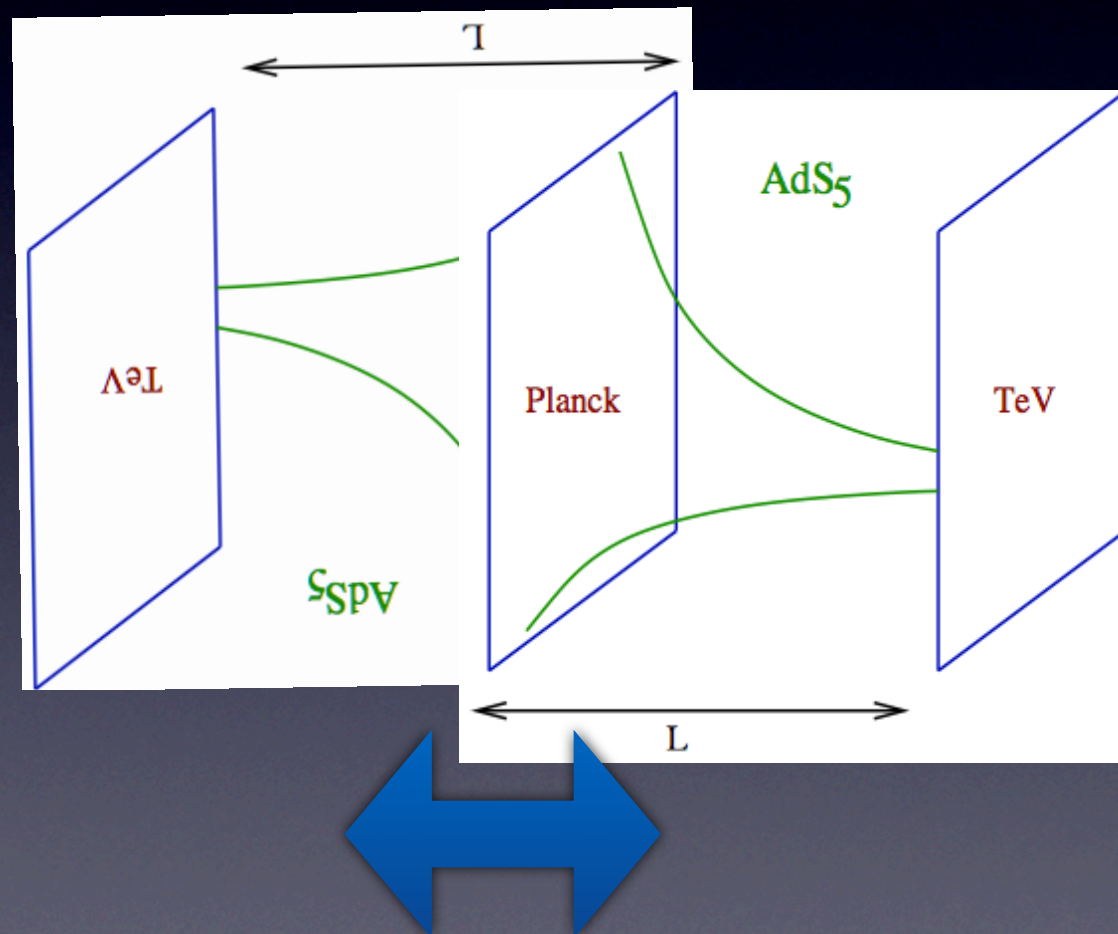
- Z_2 Reflection around the midpoint of extra dimension
- A remnant of 5D translational invariance which is broken by the end points of the interval (or fixed points in orbifold language).

KK parity

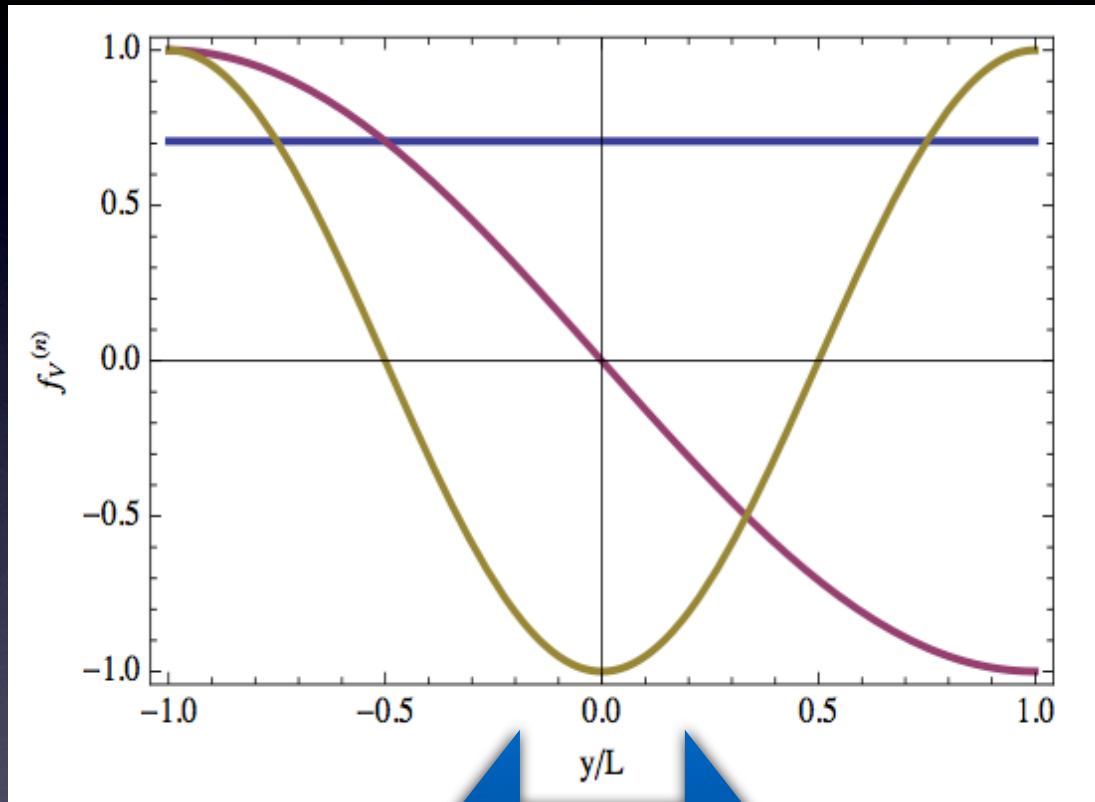
- found rather generic concept which can be widely used.
- In a symmetric space (flat, warped, twisted, ..whatever) which is invariant under the reflection, **KK basis functions are either even or odd functions**: (Odd/Even) parity for (Odd/Even) function, respectively.
- ★ (ex) { $\sin(n y/L)$, $\cos(n y/L)$ } for $m=0$ scalar in flat 5D

Two throats glued together

Agashe, Falkowski, Low, Servant (2008)



Flat



$n=0, 2$: even

$n=1$: odd

$$P_{kk} = (-1)^n$$

Interaction allowed/forbidden



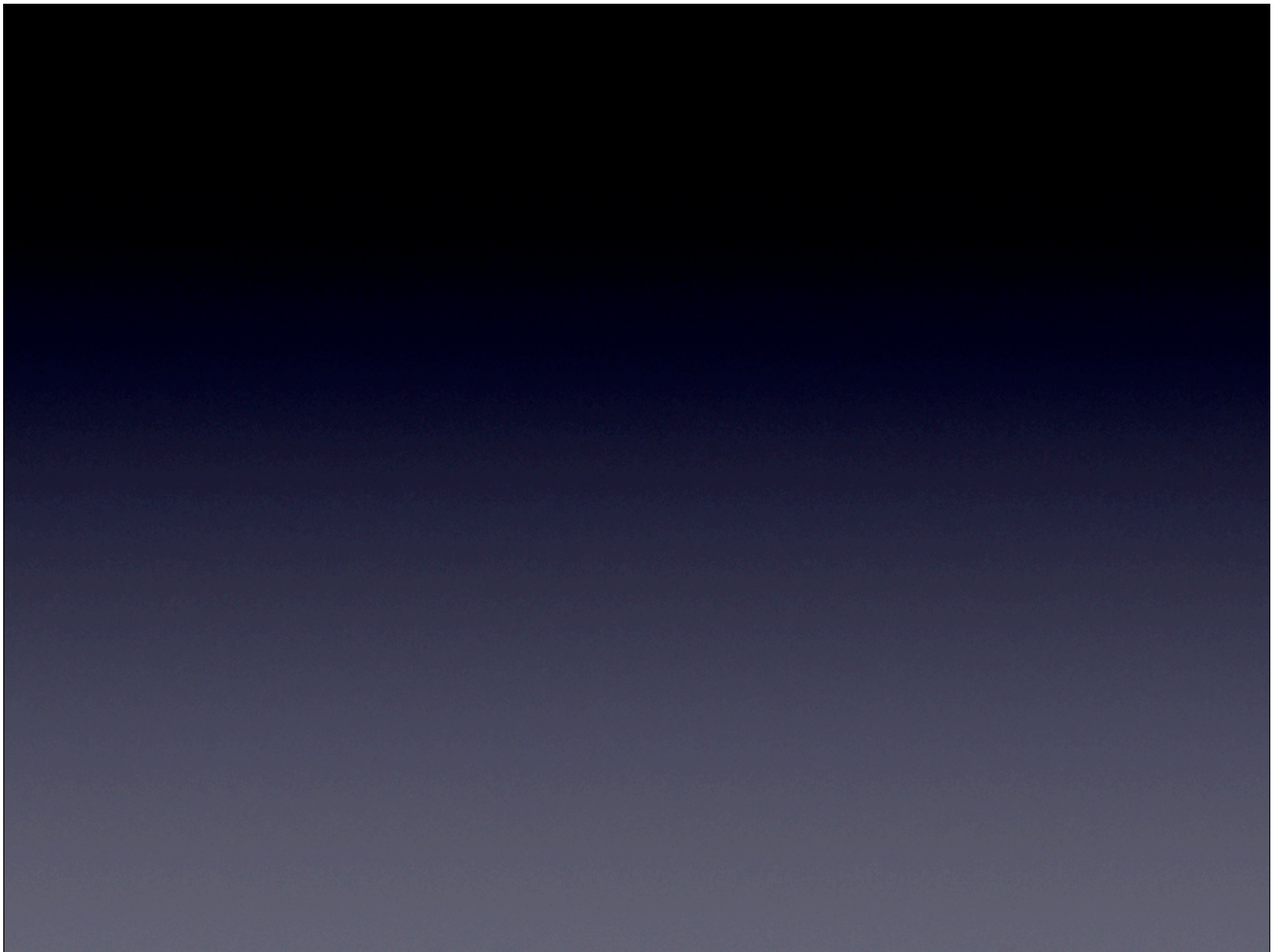
$$g \propto \int_{-L}^L dy \psi_{\text{even}} \psi_{\text{even}} \psi_{\text{even}} \neq 0$$

Allowed



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

Forbidden



Underlying Math:

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

Bulk Mass term=0 ? why??

- $M_{\text{gauge}}=0$: gauge symmetry.
- $M_{\text{fermi}} \neq 0$: Vectorlike mass term for fermion is not forbidden by 5D Lorentz symmetry, gauge symmetry. In principle, we should take this into account.
- Often it is claimed that KK-parity forbids the bulk mass. Is it really right?

5D Mass

Dirac Bilinear is odd under the reflection

$$y \rightarrow -y$$

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

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

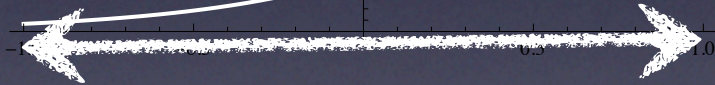
Thus, KK-even mass is forbidden by KK-parity.

Wave function

with “even mass”

$$m(-y) = m(y)$$

KK-parity NOT respected

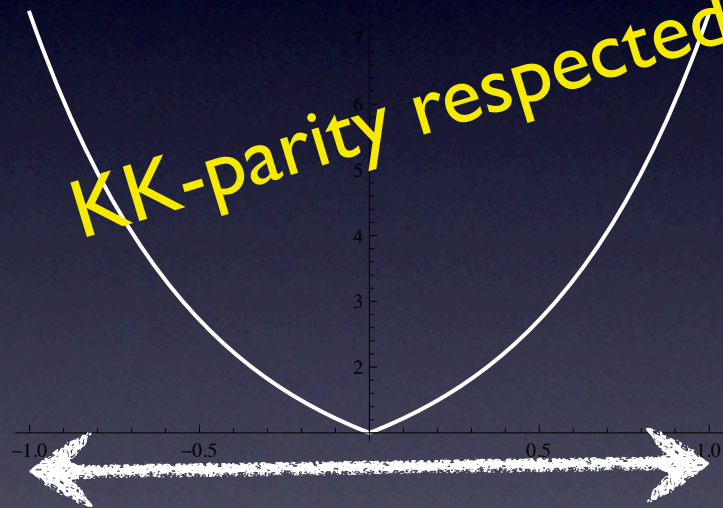


y

with “odd mass”

$$m(-y) = -m(y)$$

KK-parity respected

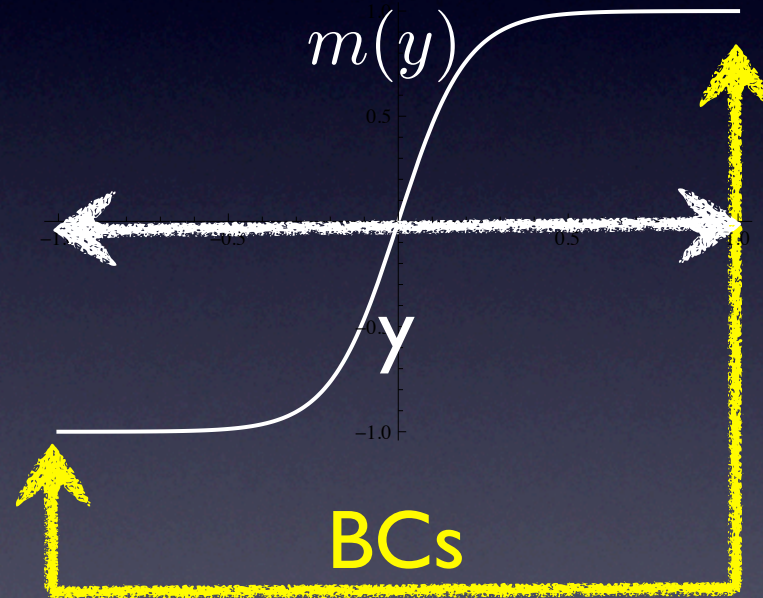


y

Odd mass on orbifold

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

$$\bar{\psi}\psi \rightarrow -\bar{\psi}\psi$$



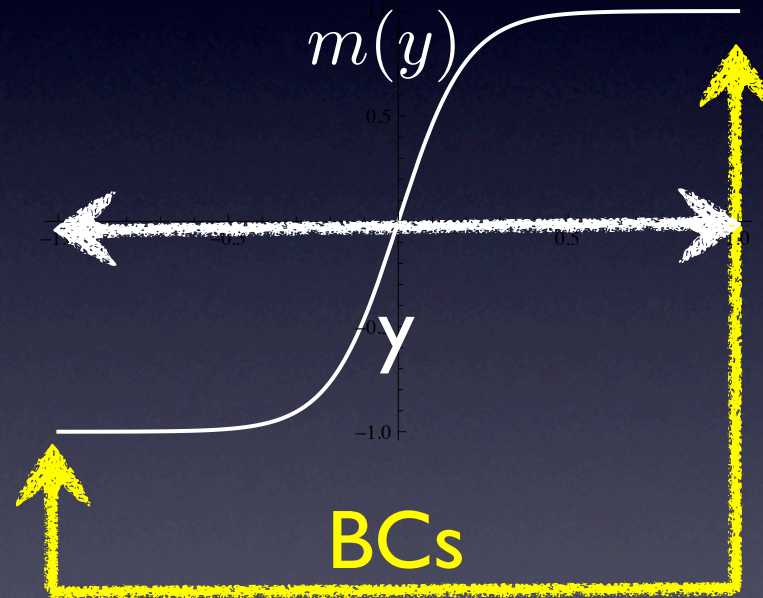
The lowest energy configuration interpolating boundary values: $+M, -M$

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

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split-UED
SCP, Shu 2009

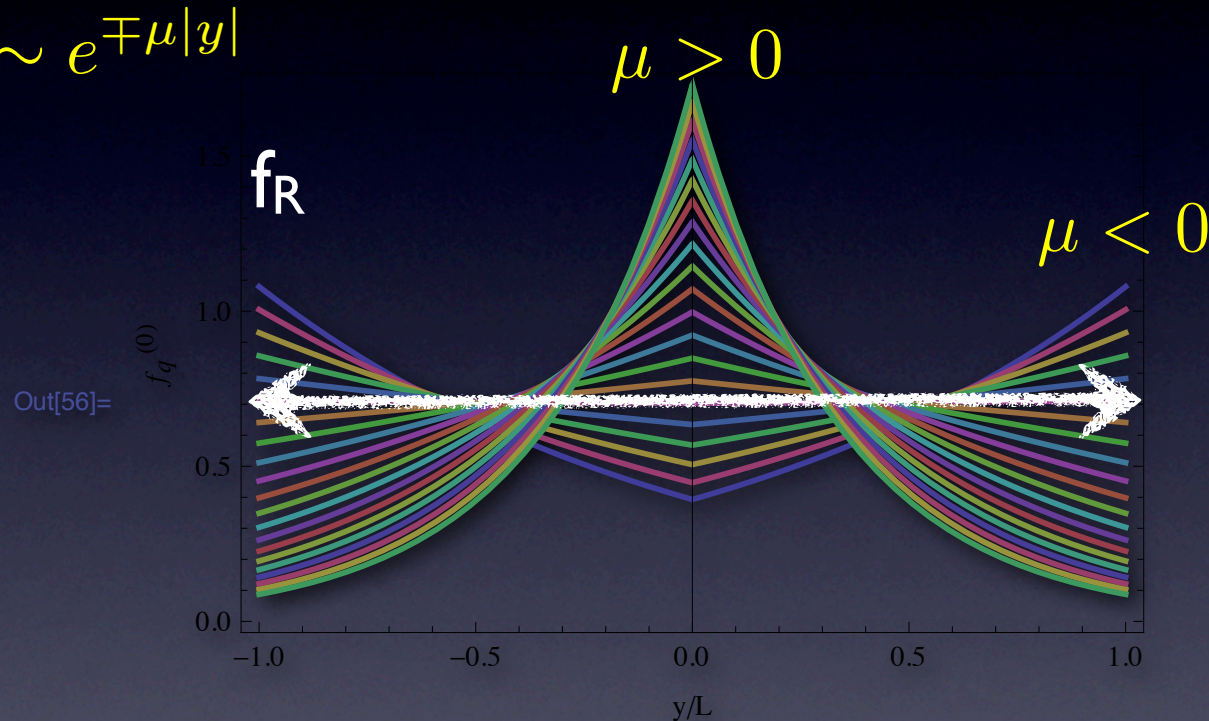
Split UED

SCP, Shu, 2009

- The 'odd' bulk masses for fermions are introduced
- KK-parity conserved (KK-number not conserved, in general)
- Rich phenomenology with more parameters. KK-spectra/profiles/coupling constants all depend on bulk masses.

KK profile

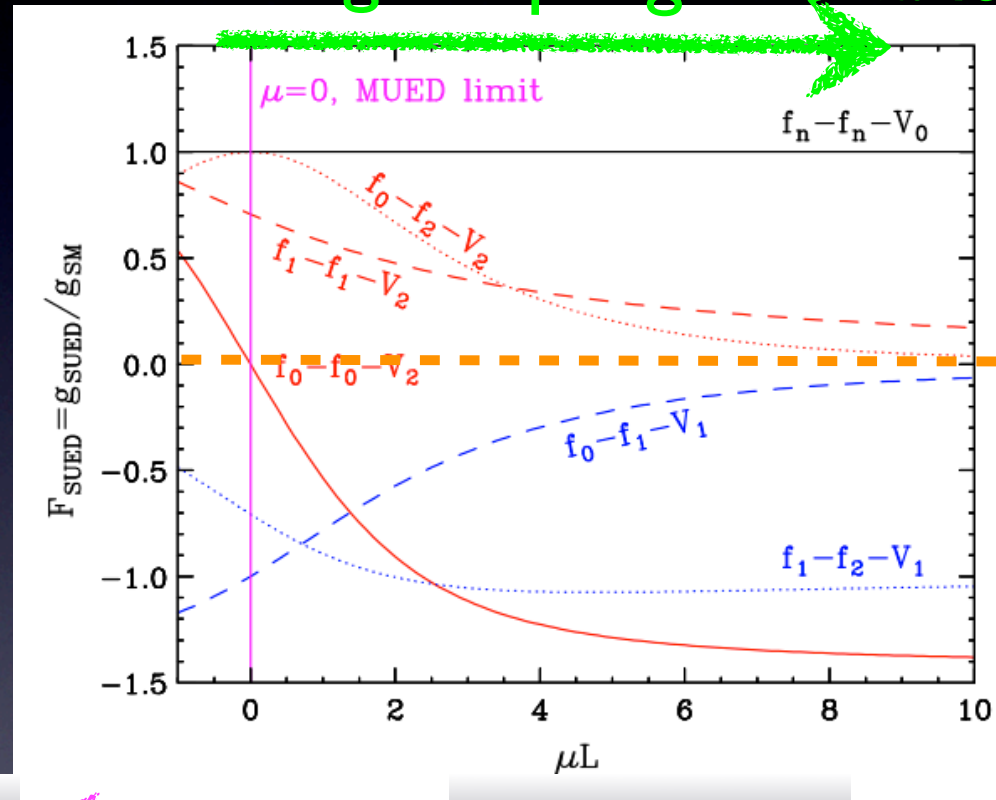
$$f_{L/R}^0 \sim e^{\mp\mu|y|}$$



- KK-parity respected.
- Profile is controlled by μ .
- Zero modes are massless regardless the 5D masses. Fermion masses are generated by SSB.

Coupling constant

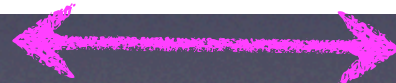
Running coupling constant



0-0-odd
“KK-parity
conservation”

0-0-2
“KK-number
violation”

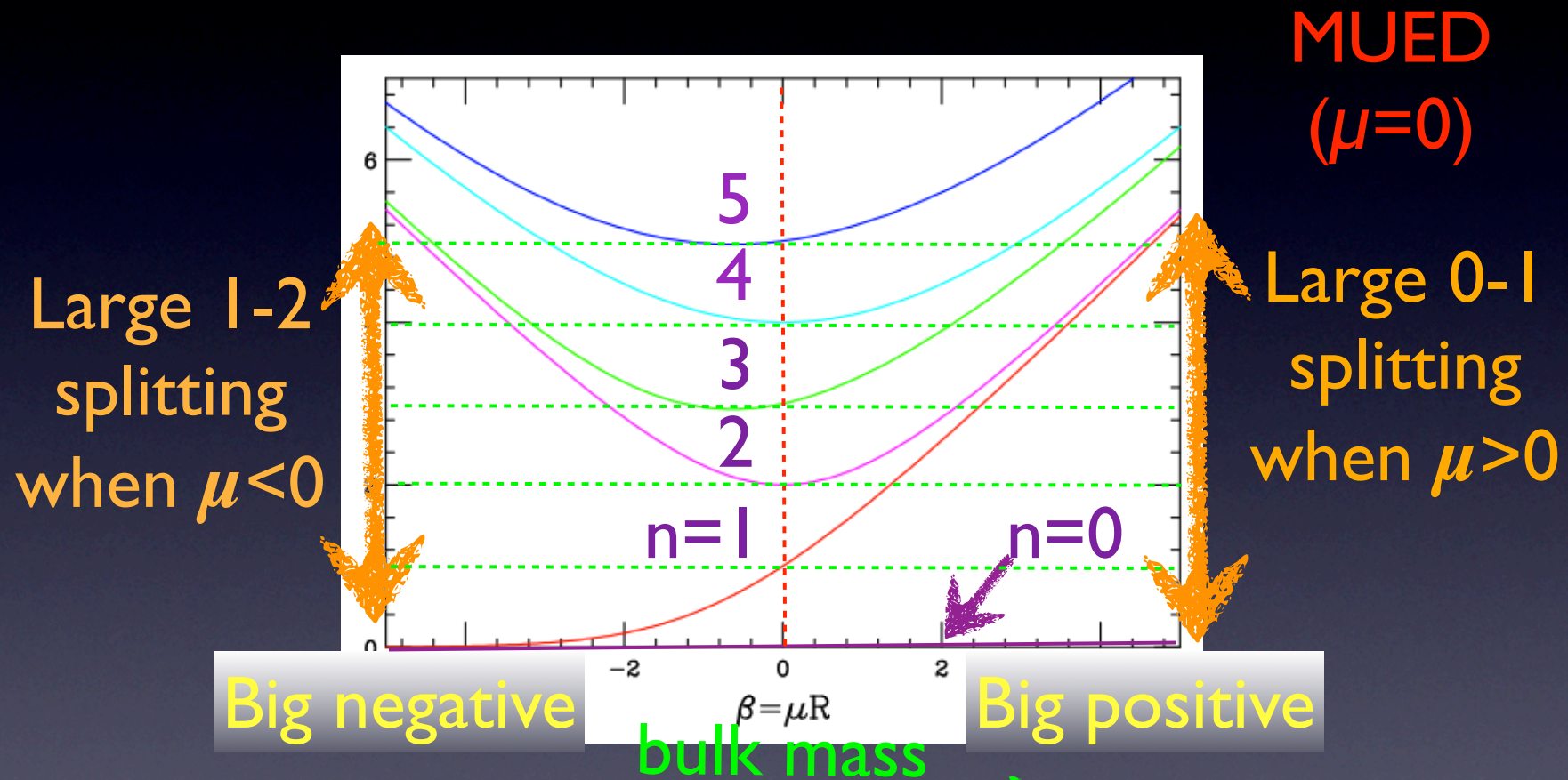
Big negative



Bulk Mass

Big positive

KK spectra

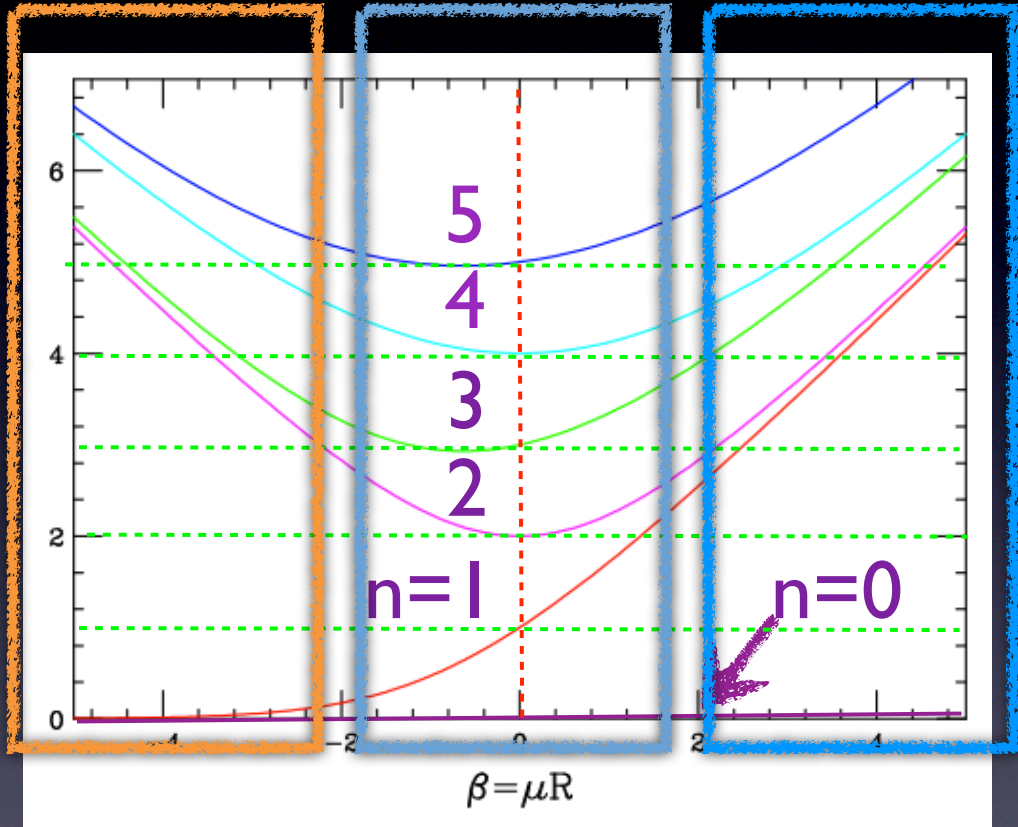


- Mass for the gauge boson stays (gauge symmetry forbids bulk mass)
- Fermion mass runs with bulk mass.
- LKP is the one of KK fermions when $\mu < 0$, Gauge boson when $\mu > 0$

ii

i

iii



$$m_{\text{fermi}}^1 \sim m_{\text{gauge}}^1$$

- Similar to the conventional UED but details depend on the bulk masses

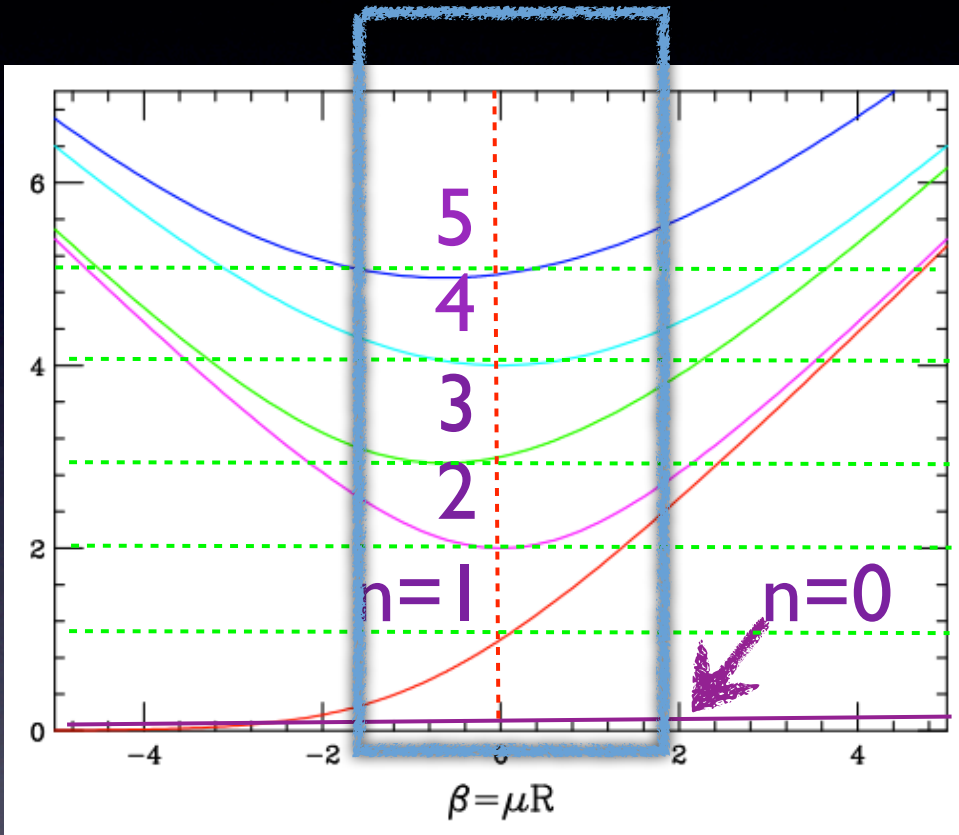
- Fermion spectrum changes
- If $\mu > 0$, LKP is the 1st KK boson

- $\text{Br}(B_1 B_1 \rightarrow f_0 \bar{f}_0)$ depends on m_{f1} : **Leptophilicness** can be easily realized

- LHC signatures if $1/R \sim \text{TeV}$

Chen, Nojiri, SCP, Shu (2009, 2009)

Kong, SCP, Rizzo (2010)

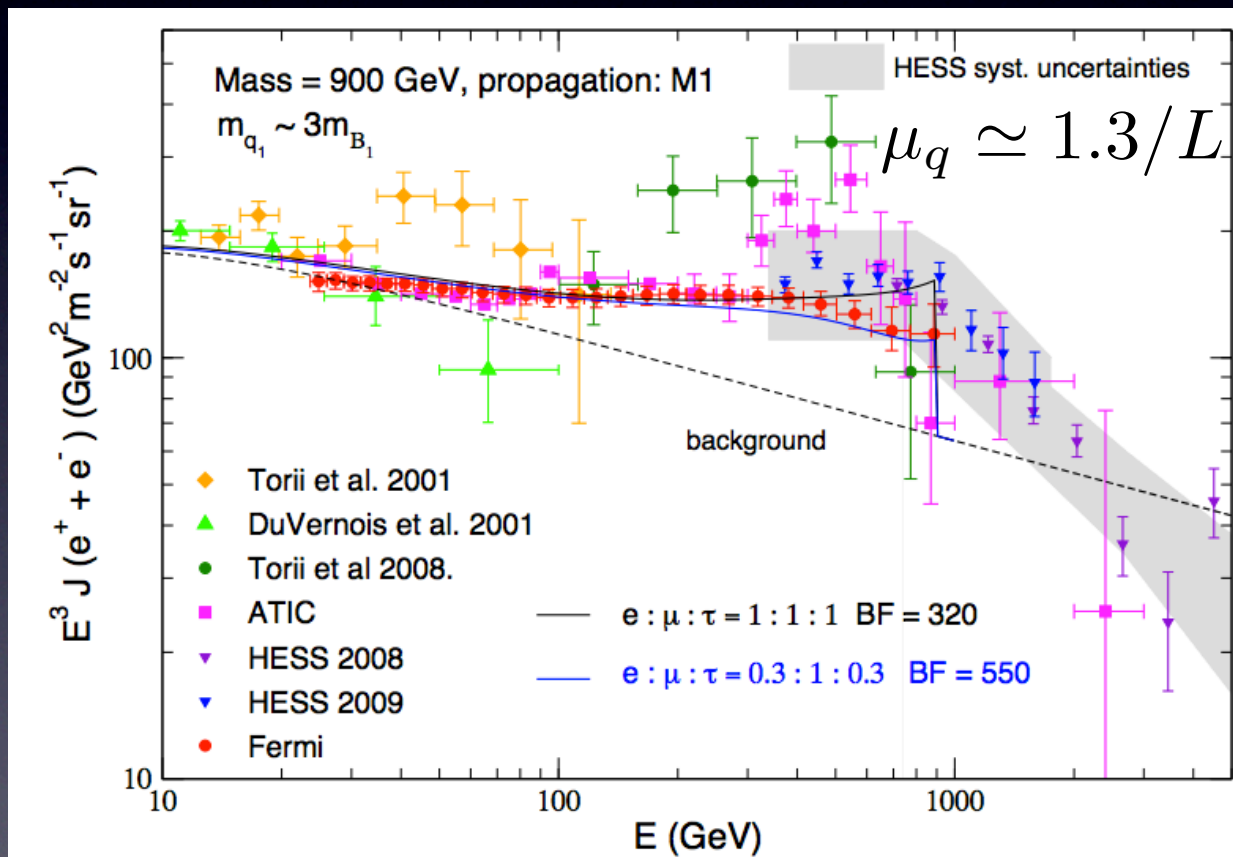


Split-UED fits

Pamela, ATIC, Fermi

Chen, Nojiri, SCP, Shu, 2009

BI μ
 BI μ
 μ



Leptophilic KK photon in split-UED fit
 (KK quarks are heavy here)

LHC signatures-i

Two resonances in dilepton channel

K. Kong, SCP, T. Rizzo, JHEP 1004:081, 2010

$$pp \rightarrow Z_2, \gamma_2 \rightarrow l\bar{l}$$

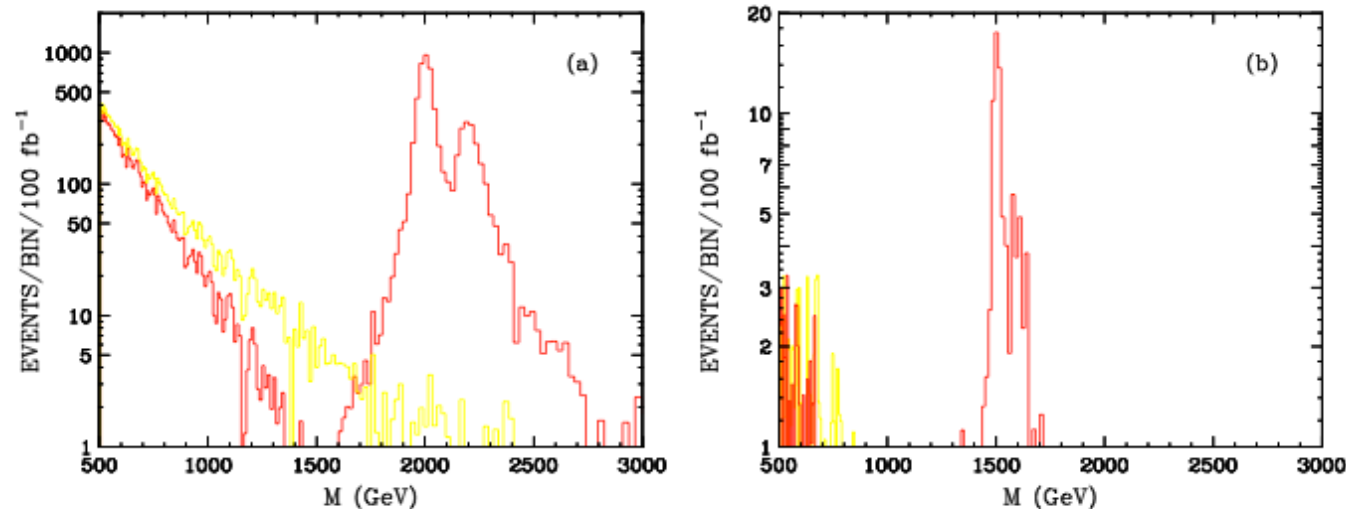
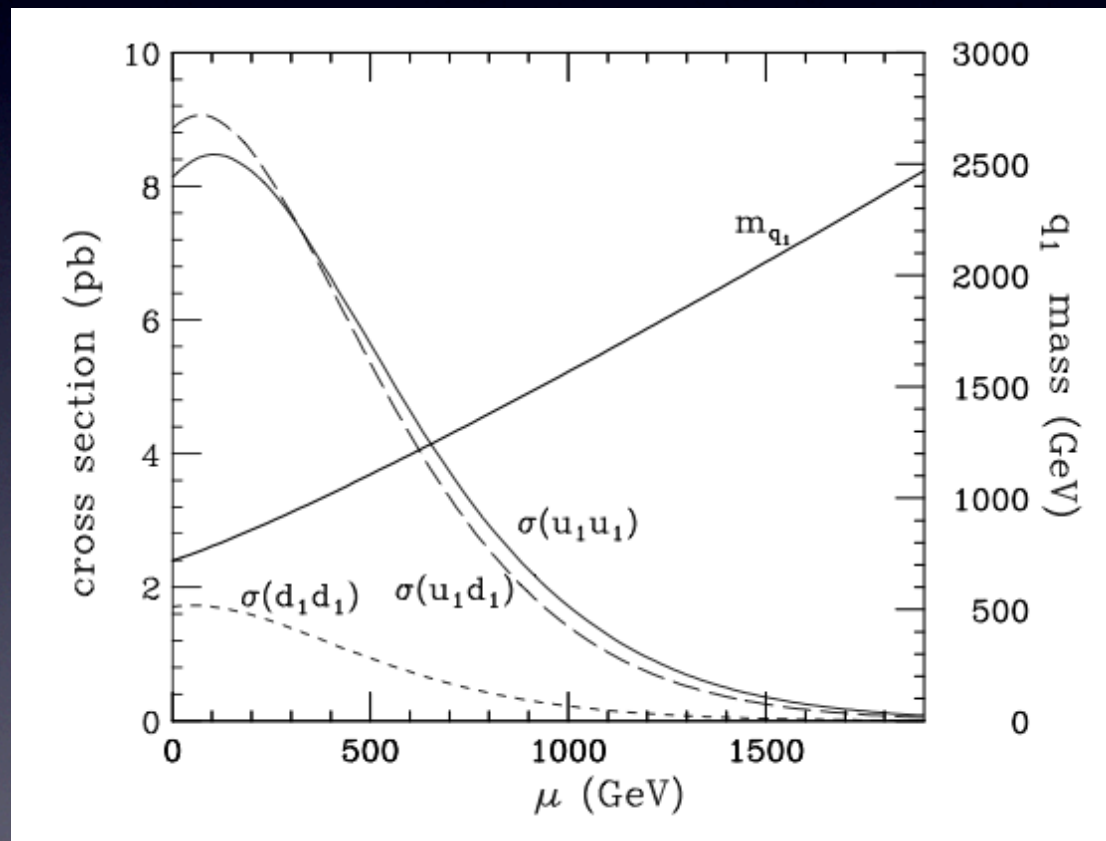


Figure 6: Invariant mass distributions at the LHC for (a) $R^{-1} = 1 \text{ TeV}$, $\sqrt{s} = 14 \text{ TeV}$ and $\mathcal{L} = 100 \text{ fb}^{-1}$ and (b) $R^{-1} = 0.75 \text{ TeV}$, $\sqrt{s} = 10 \text{ TeV}$ and $\mathcal{L} = 1 \text{ fb}^{-1}$. The yellow histogram is the SM background while the red histogram includes both signal and backgrounds.

LHC signatures-ii

Chen, Nojiri, SCP, Shu, Takeuchi, JHEP 0909:078, 2009,

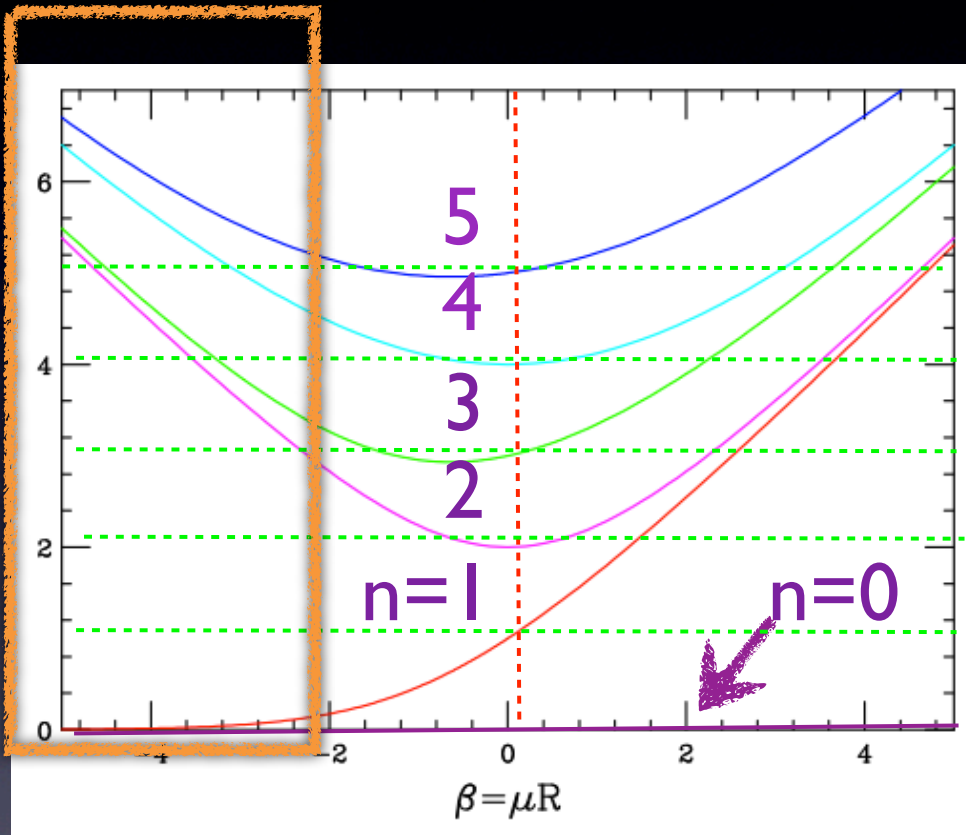
$$pp(q\bar{q}, gg) \rightarrow g \rightarrow q_1\bar{q}_1$$



The cross section is bigger than the cross section of squark pair production with the same masses

$$m_{\text{fermi}}^0 \lesssim m_{\text{fermi}}^1 \ll m_{\text{gauge}}^1 \ll m_{\text{fermi}}^2$$

- The “superlight modes” (it looks like the vectorlike 4th generation)
- Typically long lived. decay via KK gauge bosons which are much heavier than fermions.
- KK tower is not seen at low energy. Not quite looks like extra dimension..



$$L^{-1} = 10^2 \text{TeV}, \mu = 7.3 L^{-1}$$

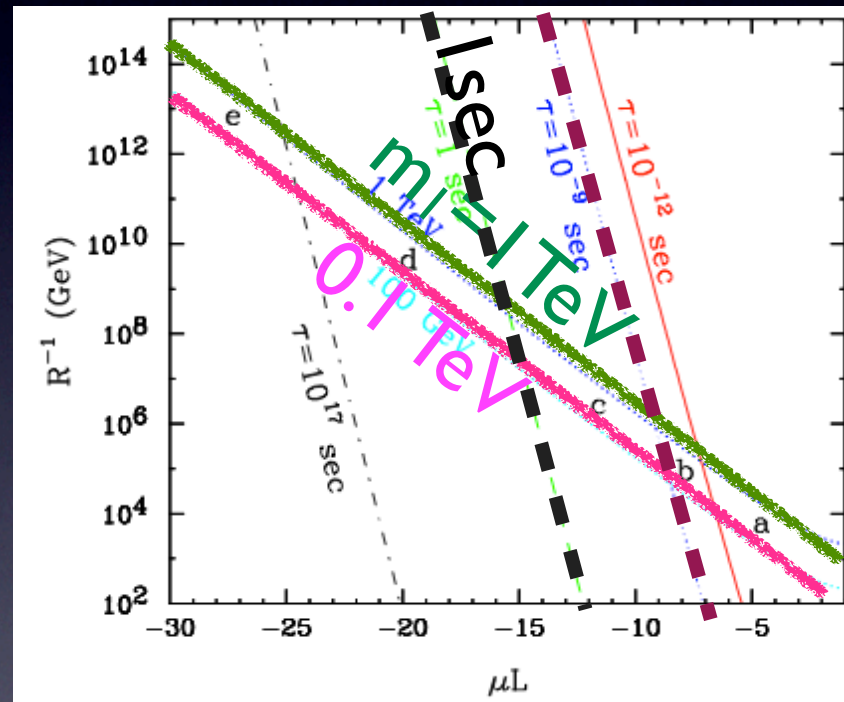
$$L^{-1} = 10^{11} \text{TeV}, \mu = 29 L^{-1}$$



$$m_1 = 1 \text{TeV}$$

Life time

$$1/\Gamma(e_R^1 \rightarrow e_R^0 B_1^* \rightarrow e_R^0 \nu_1 \nu_0)$$



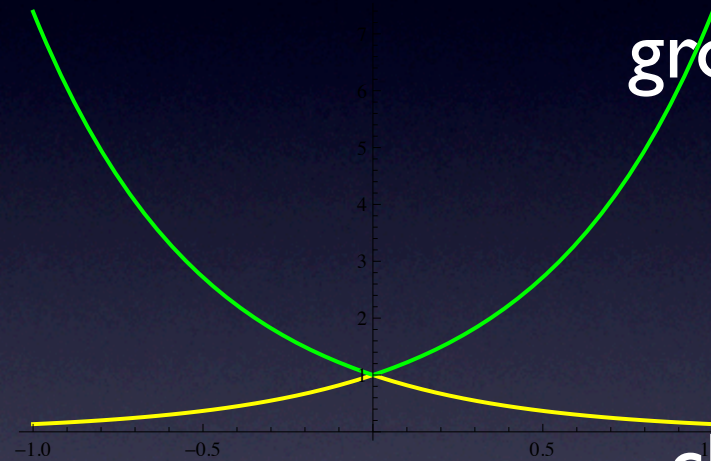
KK lepton decay
K.C.Kong, SCP, T.G.Rizzo (2010)

The superlight mode

$$m_1 = 2|\mu|e^{-\mu L}$$

In the presence of kink,

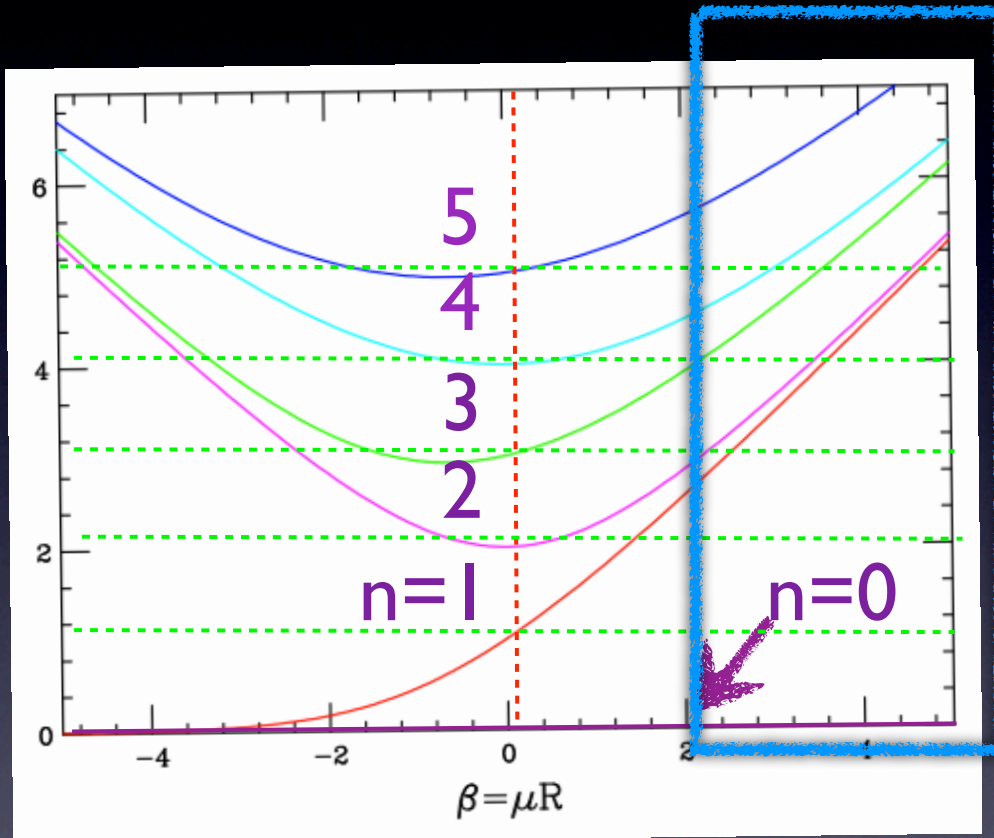
(non-)normalizable
growing mode (L/R)



normalizable
chiral mode(R/L)

Dirichlet BC	zero mode	superlight
localized	growing	localized
growing	localized	no

$$m_{\text{fermi}}^0 \ll m_{\text{gauge}}^1 \ll m_{\text{fermi}}^1 \sim m_{\text{fermi}}^2$$



- Tower of KK-gauge bosons appears well before touching the first KK-fermion
- similar to the case where only bosons are in the bulk

LHC physics



Flavor hierarchy

Csaki, Hubisz, Heinonen, SCP, Shu (in progress)

- Similar to the RS case with two throats. Hierarchy is due to the relative wave function overlaps
- No RS-GIM like mechanism works so that flavor bound is rather severe : $1/R > 5 \times 10^{3-4} \text{ TeV}$ (can be lower by a factor of 250 by localized kinetic term for gluon at the center) (cf) RS, $M_{kk} > 20 \text{ TeV}$
- $1/R \sim \text{TeV}$ UED is flavorless and requires flavor alignment

Summary

- Split-UED allows 5D masses in a way of keeping KK-parity
- Spectrum/Profile/coupling constant depends on bulk mass. Phenomenology looks different in the different parameter space.
- Flavor hierarchy may be due to the non-flat profiles but stringently constrained because of lack of RS-GIM like mechanism
- Distinctive LHC signals: double resonances in dimuon channel, KK-quark pair production, Vectorlike 4th generation ...