UED:

1. an effective theory of RS

based on

C, Csaki, J. Heinonen, J. Hubisz, SCP, J.Shu JHEP01(2011)089

2. updated experimental status

based on

G.-Y. Huang, K. Kong, SCP, JHEP06(2012)099

also 1204.4764 by CMS

Park, Seong Chan (SKKU)

Santa Fe Summer workshop

"LHC NOW"

June 13, 2012

Sungkyunkwan University (SKKU)

1398

founded as the highest educational institution in Chosun dynasty

1443

Korean Alphabet (Hangul) invented

Michael Graesser=마이클 그래서
Arvind Rajaraman=아빈드 라자라만

1996

"renew" by Samsung

-strong and well-known in nano-physics so far
-has vision for fundamental science (particle/astro/bio)

SKKU


Fengcheng
Chagang
South Hamyŏng
Kimch'aek
NORTH KOREA
Dandong
North P'yŏngan
Anju
Korea
Bay
P'yŏngyang
South P'yŏngan
Wonsan
Namp'o
North Hwanghae
Kangwŏn
Gangwon
Kaesong
Pocheon
South Hwanghae
Seoul
Gangneung
Songnam
Inch'on
Taebaek
Suwon
Chech'on
Sosan
Yesan
SOUTH KOREA
North Jeolla
Iksan
Yellow Sea
Jeonju
Ulsan
Gwangju
CH'Angwon
Chinju
Busan
Shimane
Okayama
Mokp'o
Sunch'on
Yosu
Hiroshima
bing
South Jeolla
Kohung
Terms of use

RS

- RS provides a possible 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

- The LHC is limited .. can probe the IR side of RS

- Near IR, the curvature is relatively small that the LHC may not see the actual AdS geometry

- but rather flat geometry..

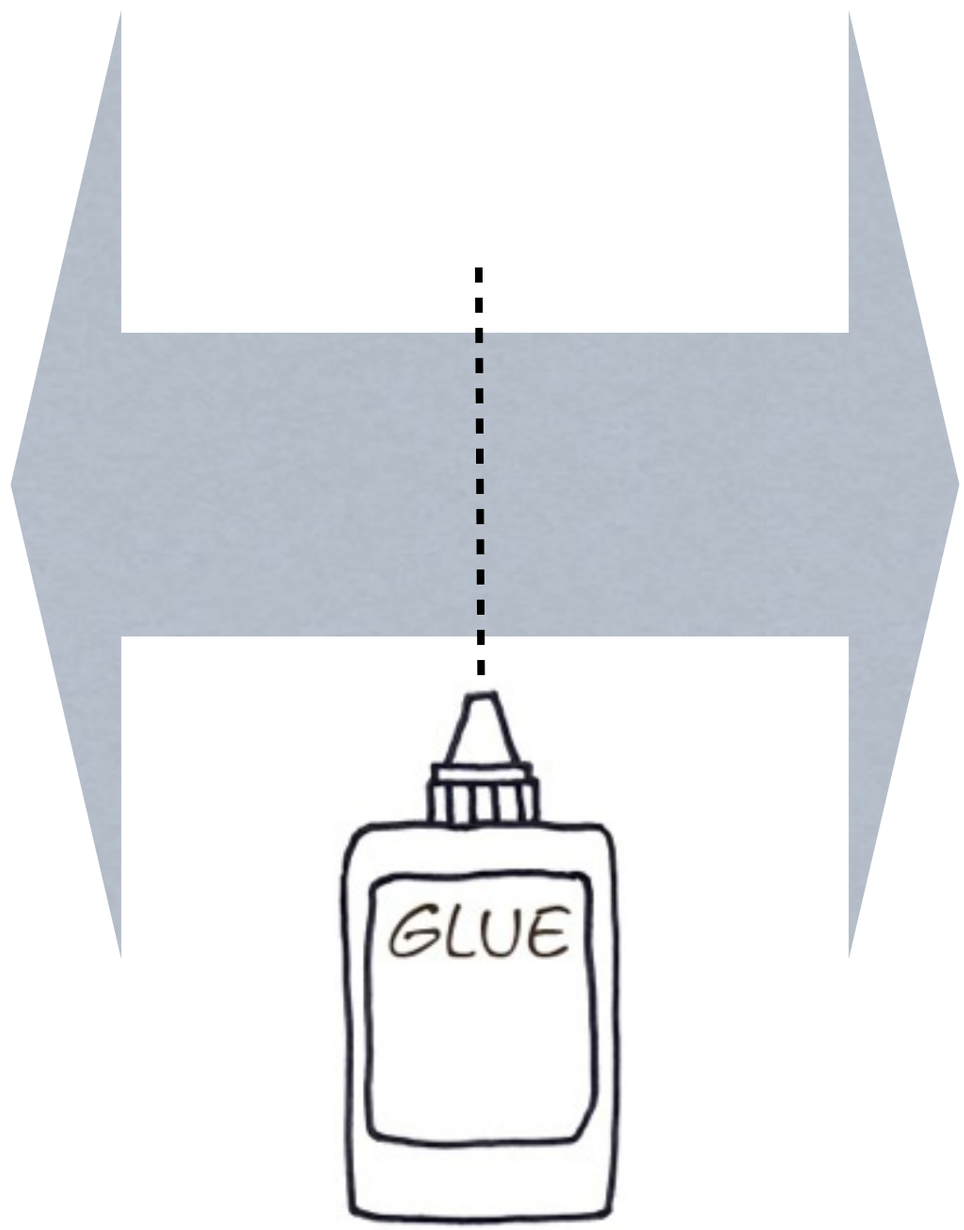
- just like in the conventional "UED models"

UED

- 5D model with all SM in the bulk
- UED is known as a model of DM thanks to the KK-parity
- .. the remnant Z_2 symmetry of the translational symmetry/orbifolding..
- The Z_2 could make the lightest Z_2 odd particle stable (like the LSP in SUSY/w R-parity)

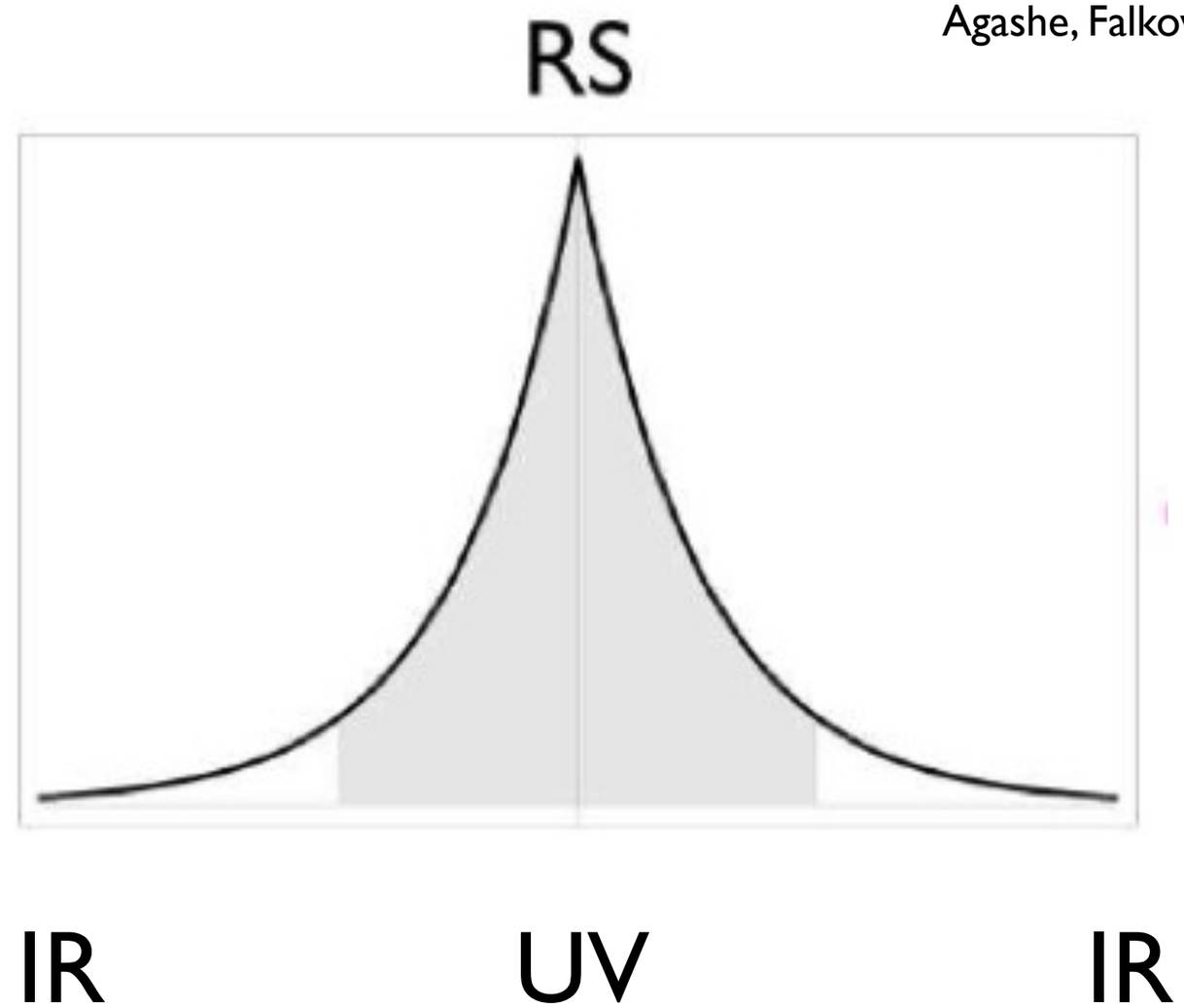
- If an extra dimension is symmetric, a geometric symmetry (KK-parity) could be imposed for all bulk fields and the LKP can be a good DM candidate.

It is easy to make a symmetric space!



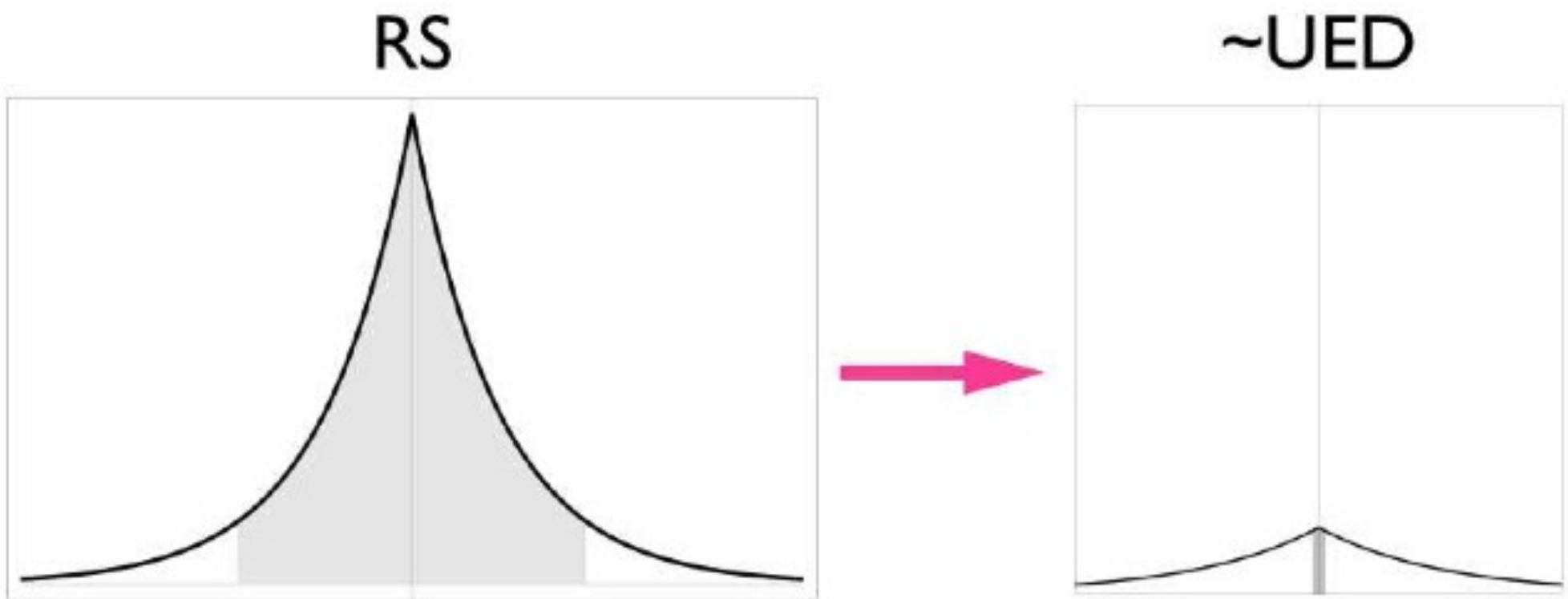
Two throats RS model with KK-parity

Agashe, Falkowski,Low, Servant 2008



- glue two AdS 'throats' together
- A model for the big hierarchy + DM

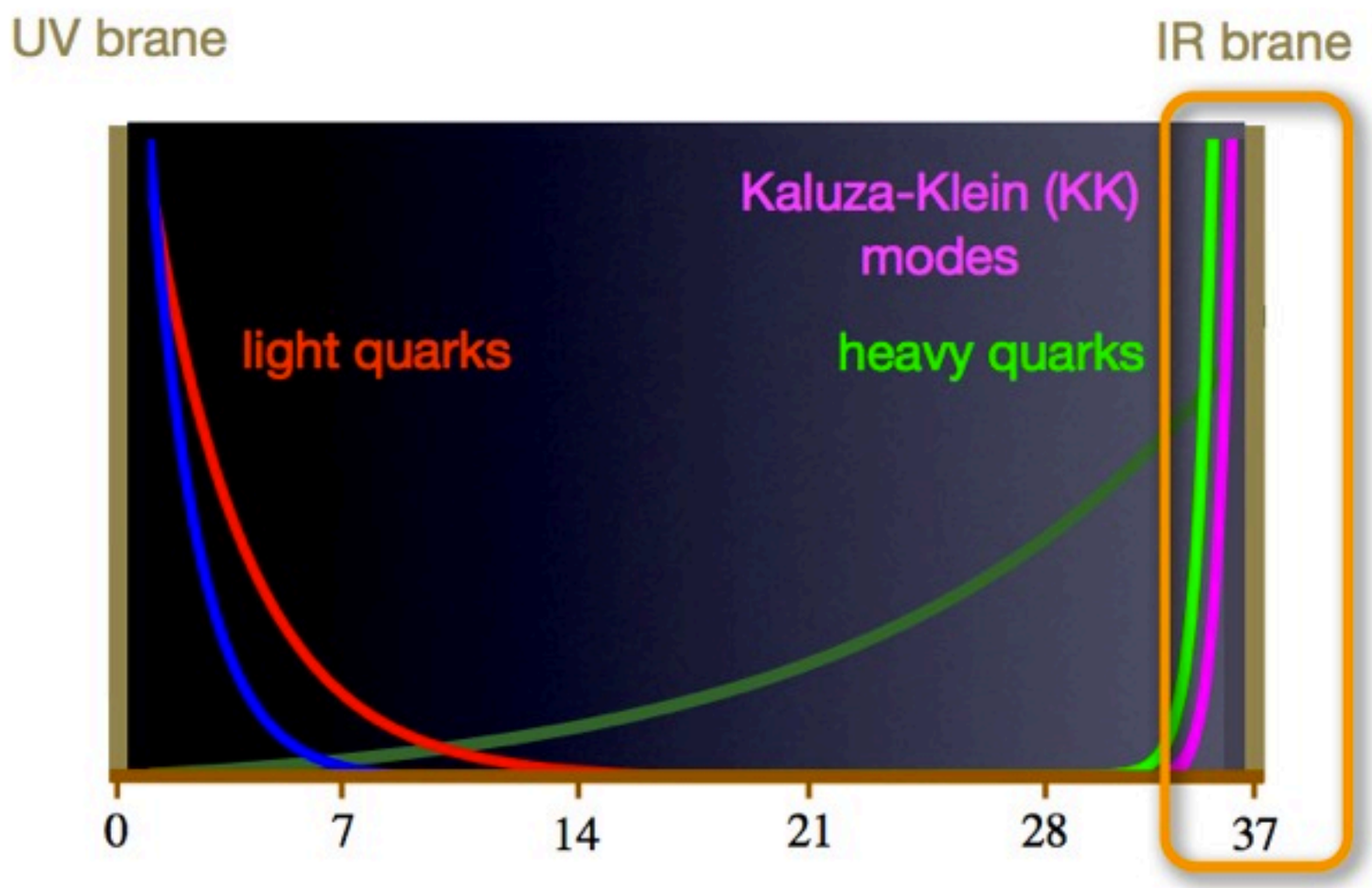
UED as an effective theory of RS



Csaki, Heinonen, Hubisz, SCP, Shu, JHEP 1101 (2011) 089

BONUS

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



How to write a realistic model on a symmetric space ?

- 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 in 5D, Dirac
- Require 5D Lorentz invariance in the bulk (far from the boundary)
- Require 4D Lorentz invariance at the boundary

5D Lorentz invariant
Gauge covariant Kinetic terms + ~~Mass terms~~

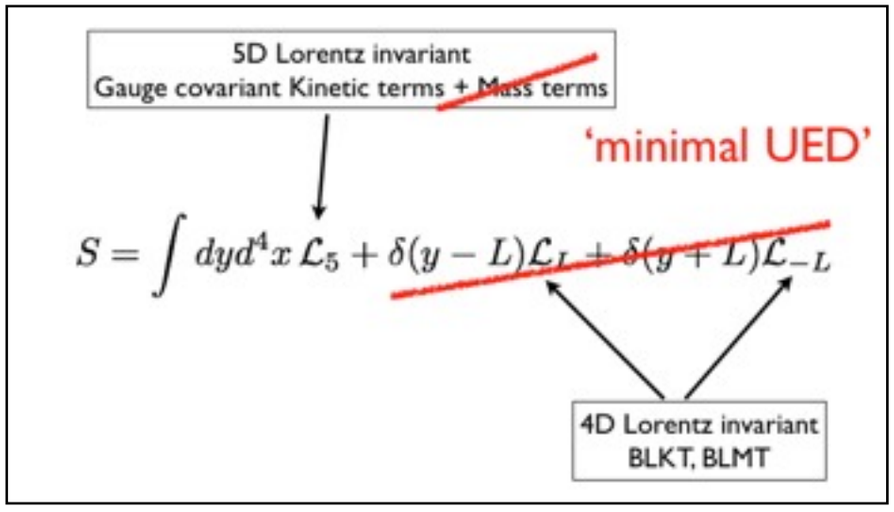
'minimal UED'

$$S = \int dy d^4x \, \mathcal{L}_5 + \cancel{\delta(y-L)\mathcal{L}_L + \delta(y+L)\mathcal{L}_{-L}}$$

Flat geometry assumed

4D Lorentz invariant
BLKT, BLMT

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)

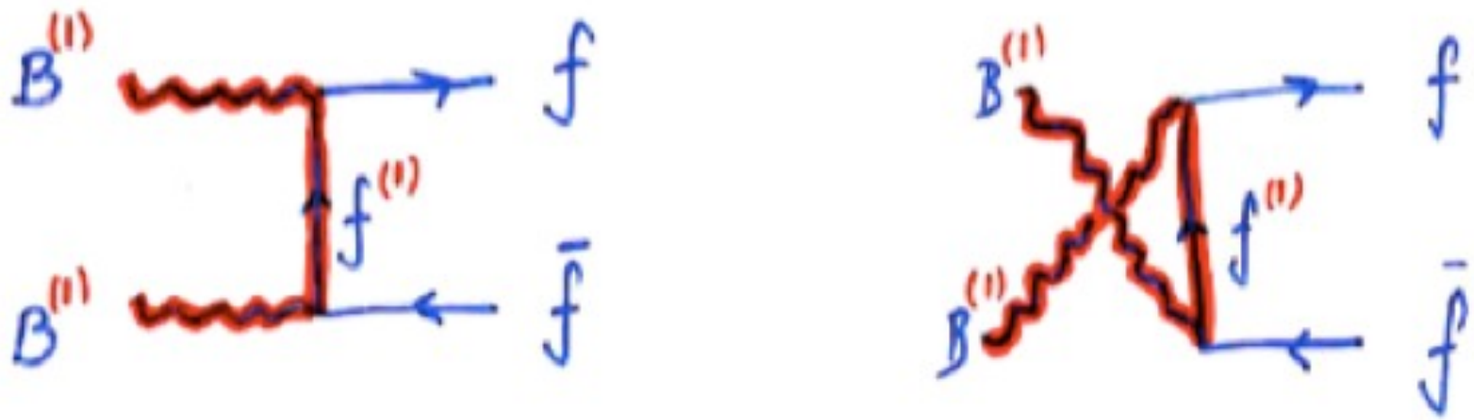
- {KK-towers} (vector-like)

- LKP = B_1 (WIMP)

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



$$\sigma_{tree} v = a + b v^2 + \mathcal{O}\left(v^4\right)$$

$$a = \sum_f \frac{32\pi\alpha_1^2 N_c m_{\gamma_1}^2}{9} \left(\frac{Y_{f_L}^4}{(m_{\gamma_1}^2 + m_{f_{L1}}^2)^2} + \frac{Y_{f_R}^4}{(m_{\gamma_1}^2 + m_{f_{R1}}^2)^2} \right),$$

$$b = -\sum_f \frac{4\pi\alpha_1^2 N_c m_{\gamma_1}^2}{27} \left(Y_{f_L}^4 \frac{11 m_{\gamma_1}^4 + 14 m^2 m_{f_{L1}}^2 - 13 m_{f_{L1}}^4}{(m_{\gamma_1}^2 + m_{f_{R1}}^2)^4} + Y_{f_R}^4 \frac{11 m_{\gamma_1}^4 + 14 m_{\gamma_1}^2 m_{f_{L1}}^2 - 13 m_{f_{L1}}^4}{(m_{\gamma_1}^2 + m_{f_{R1}}^2)^4} \right),$$

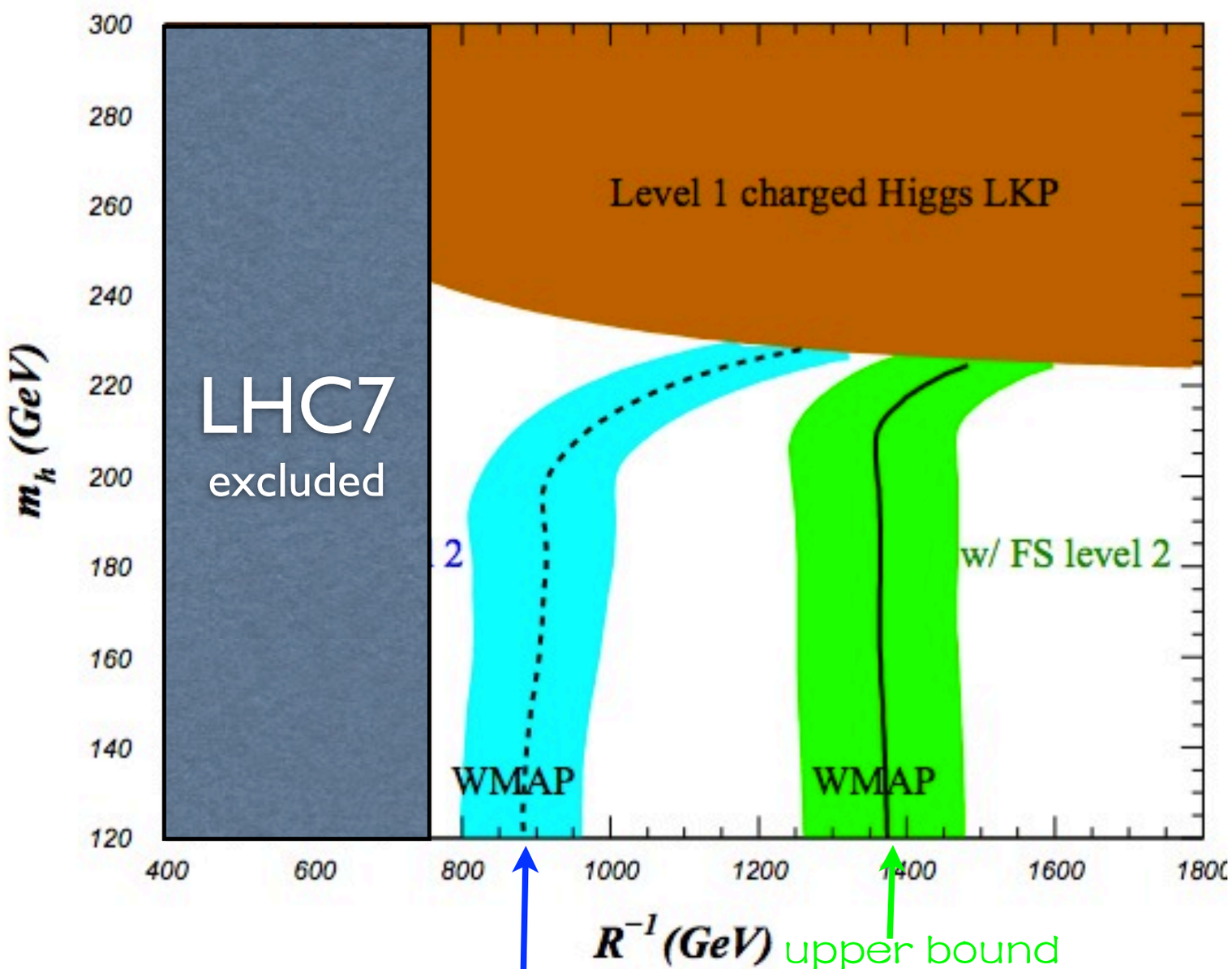
larger M_{f1}

$\Rightarrow$smaller cross section

$\Rightarrow$larger Relic abundance

$\Rightarrow$ set "upper bound" on KK-scale

Upper bound on 1/R set by DM relic abundance



upper bound w/o fine-tuning

upper bound w/ fine-tuning

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 : Dim−5 operators
- Bulk or boundary localized interactions : Dim−6 or higher
- Bulk masses for fermions : Dim−4 operators => This talk

A vector like mass

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

the plane mass term is generically allowed
(but breaks KK-parity)

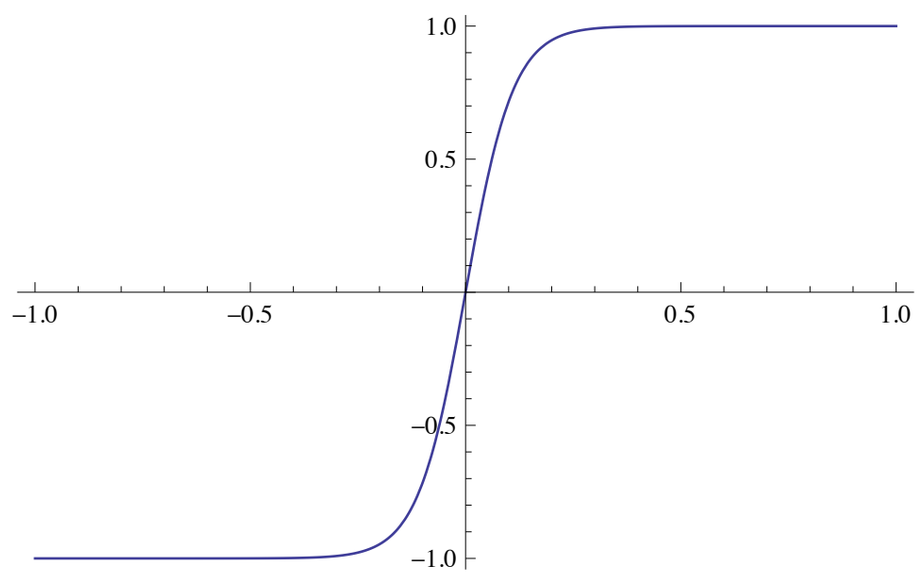
Kink Mass for UED keeps KK-parity

"split-UED"

SCP, Shu Phys.Rev. D79 (2009) 091702

$$M_\Psi(y) = \mu_\Psi \tanh my$$

$$\xrightarrow{m\to\infty} \mu_\Psi \mathrm{sgn}(y) = \begin{cases} -\mu_\Psi & \text{if } y < 0 \\ +\mu_\Psi & \text{if } y > 0 \end{cases}.$$



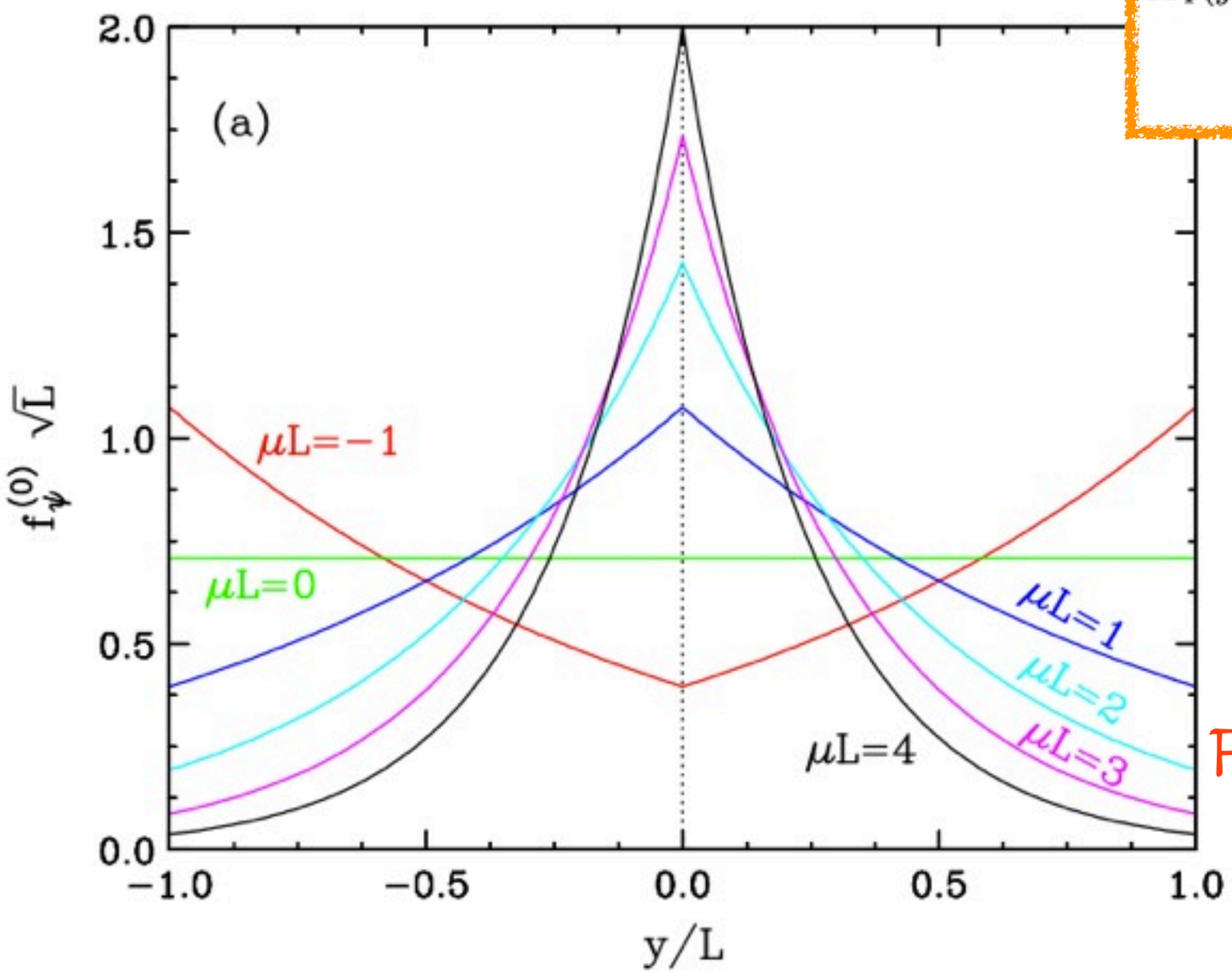
Georgi, Hailu (2001)

Wave function with Kink-Mass

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

$$M_\Psi(y) = \mu_\Psi \tanh my$$

$$\xrightarrow{m\to\infty} \mu_\Psi \mathrm{sgn}(y) = \begin{cases} -\mu_\Psi & \text{if } y < 0 \\ +\mu_\Psi & \text{if } y > 0 \end{cases}$$



KK-parity conserved!

(bonus) Room for Flavor physics

"split-UED"

Park, Shu Phys.Rev. D79 (2009) 091702

The model parameters

$$1/R, (\Lambda), m_\Psi$$

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

NDA:

$$\Lambda R \sim \frac{24\pi^2}{g_4^2} \sim O(20)$$

15 (18) bulk masses

$M_{Q_3}, M_{Q_2}, M_{Q_1}$

$M_{u_3}, M_{u_2}, M_{u_1}$

$M_{d_3}, M_{d_2}, M_{d_1}$

M_Q

(no flavor)

$M_\Psi = M$

(safe)

$\to 0(\mathrm{mUED})$

$M_{L_3}, M_{L_2}, M_{L_1}$

$M_{e_3}, M_{e_2}, M_{e_1}$

$M_{N_3}, M_{N_2}, M_{N_1}$

M_L

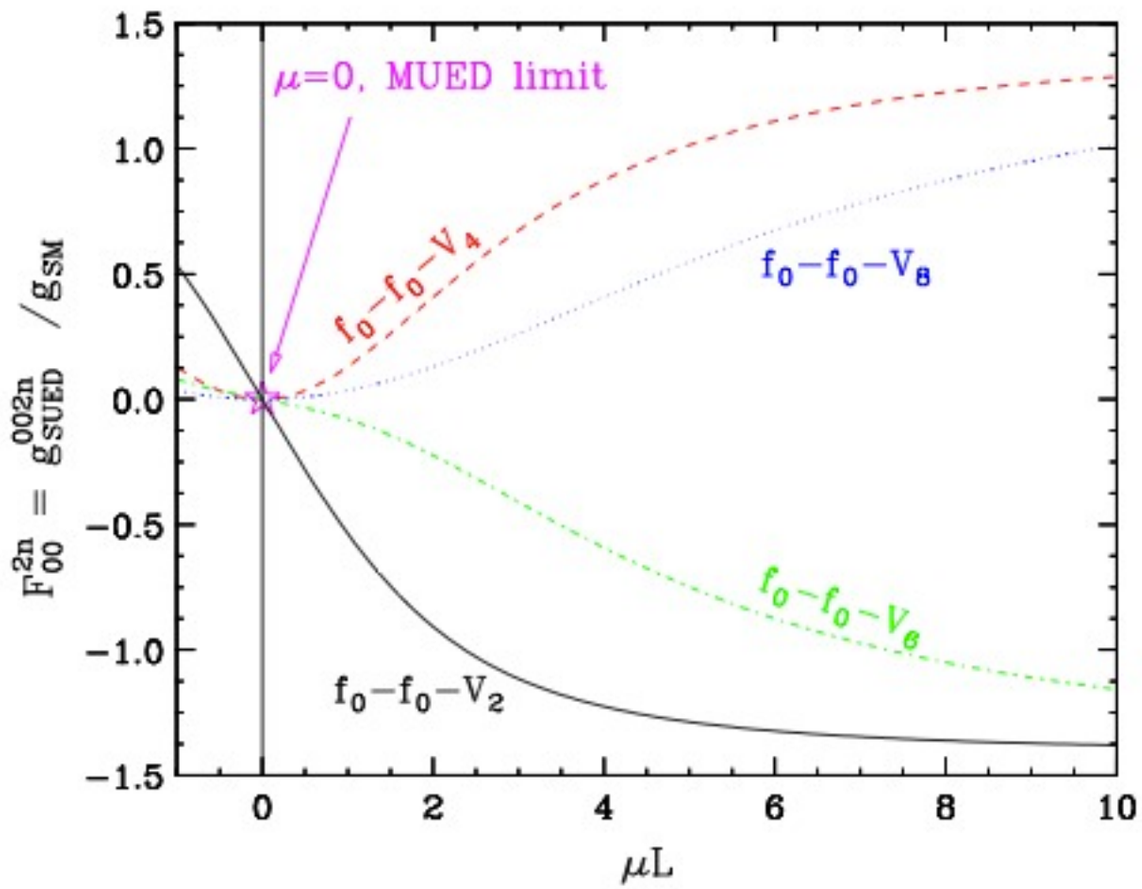
"running coupling constant"

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

$$= g_{\rm SM} \mathcal{F}_{m\ell}^n(m_\Psi L)$$

"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!

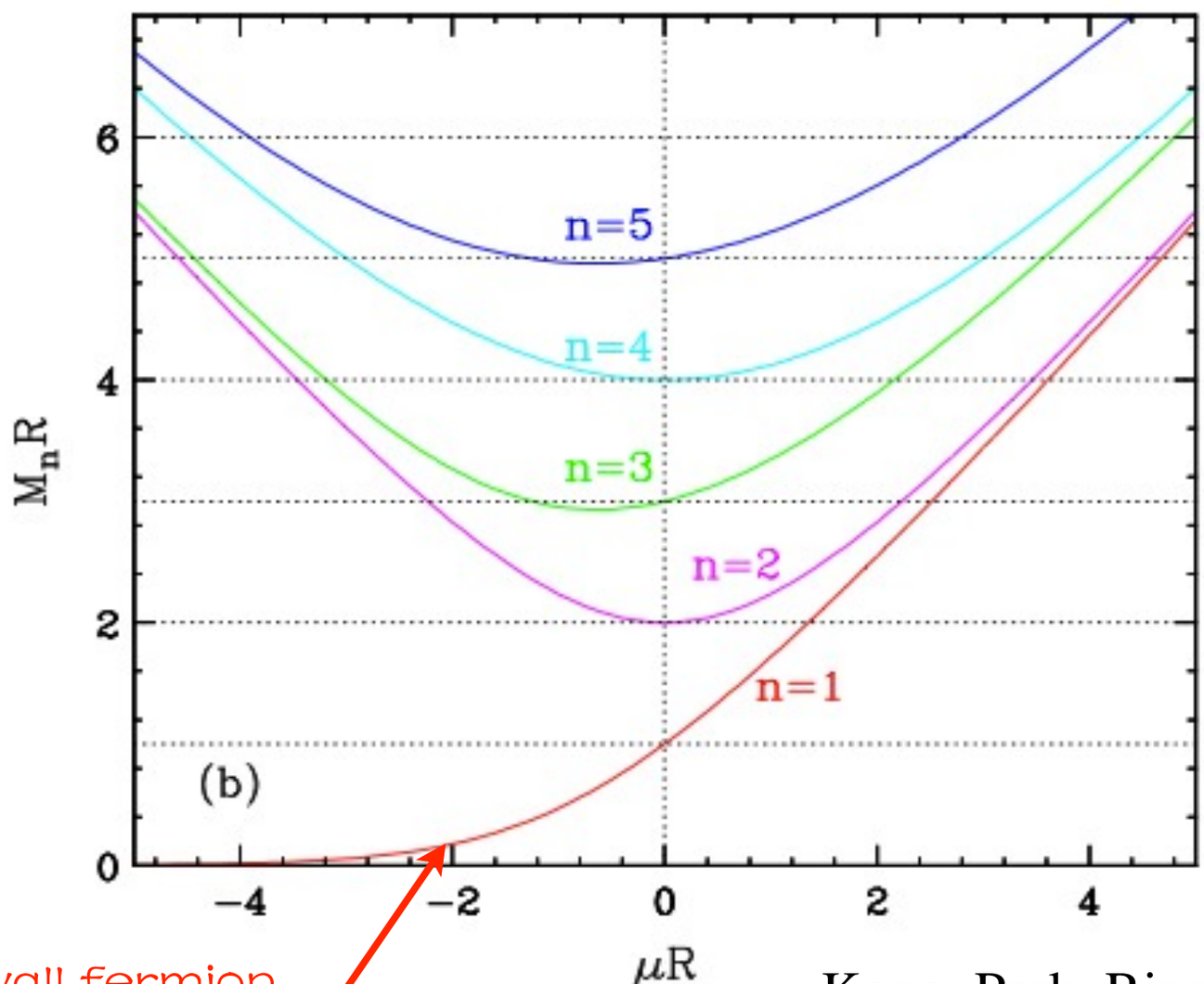
KK-mass

$$m^2_{\Psi(n)} = \begin{cases} \lambda^2_\Psi v^2 & \text{if } n = 0 \\ \mu^2 + k_n^2 + \lambda^2_\Psi v^2 & \text{if } n \geq 1 \end{cases},$$

'momentum' (EOM + BC)

$$k_n = \begin{cases} \begin{cases} i\kappa_1 & : \kappa_1 = \kappa \in \{0 < \kappa \mid \mu = -\kappa \coth \kappa L,\ \mu L < -1\} \\ k_1 & : k_1 = k \in \left\{0 \leq k \leq \frac{\pi}{L} \mid \mu = -k \cot kL,\ \mu L \geq -1\right\} \end{cases} & \text{for } n = 1 \\ \frac{n}{R} = \frac{n\pi}{2L} & \text{for } n = 2, 4, 6, \cdots \\ k_n = k \in \left\{ \frac{(n-2)\pi}{L} < k < \frac{(n-1)\pi}{L} \mid \mu = -k \cot kL \right\} & \text{for } n = 3, 5, 7, \cdots \end{cases}$$

"running KK-mass"



a domain wall fermion
(an origin of 4th generation)

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

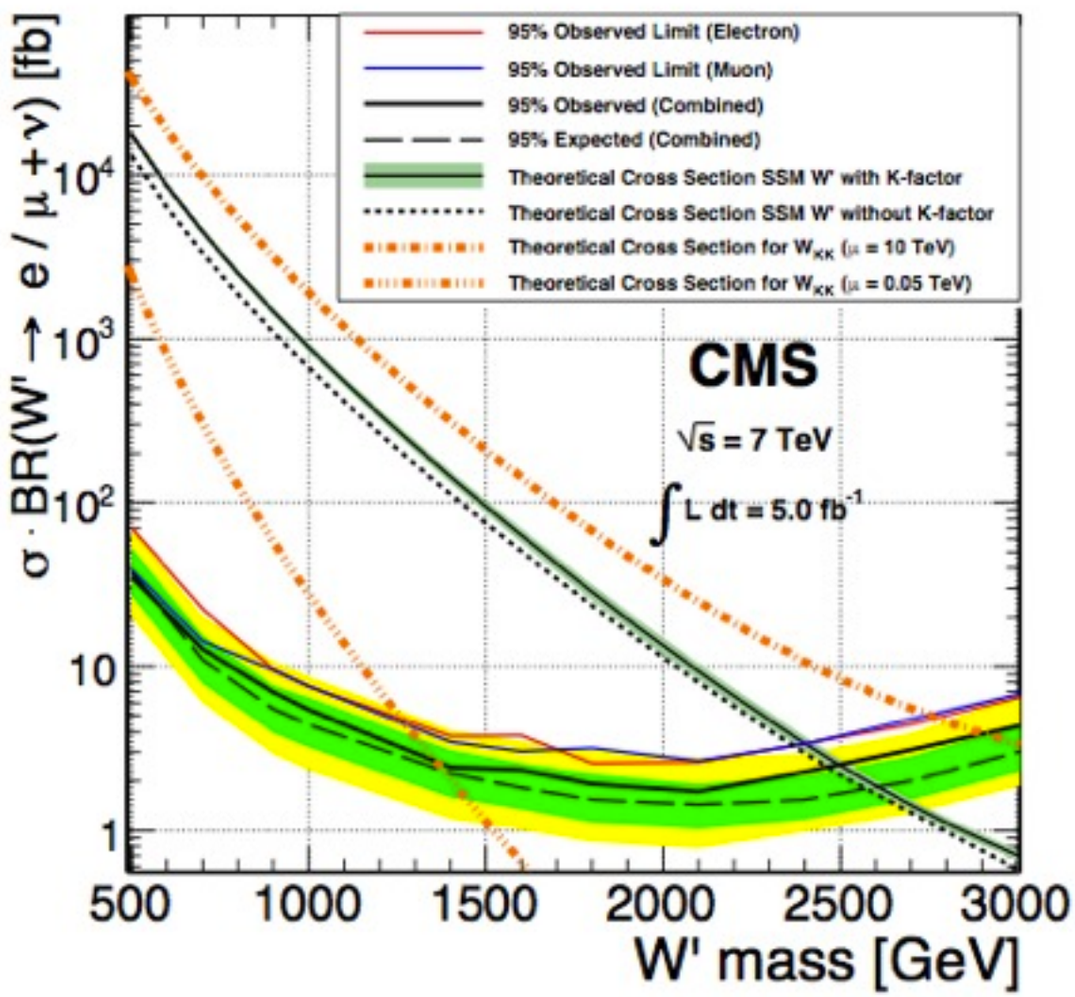
- "Natural" choice is $M \sim 1/R$ (the only scale in the theory)
- Any value of M is allowed : $|M| \in (0, \Lambda)$

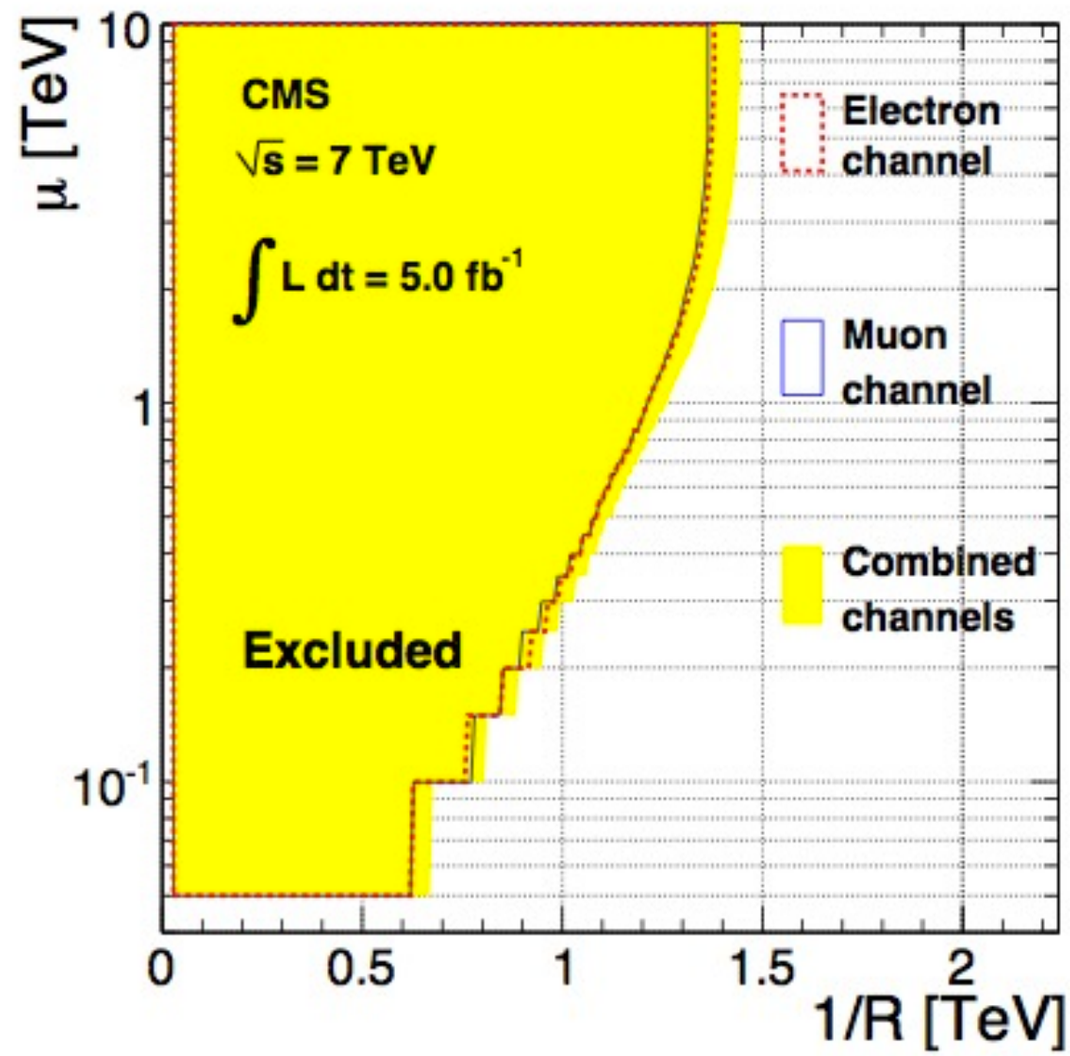
experimentally

- If $1/R \gg$ TeV, theory decouples (hard to get tested ..)
- If $1/R \sim$ TeV, theory can get constrained by EWPD(S,T,U), 4Fermi, g−2 , LHC, Dark matter..

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

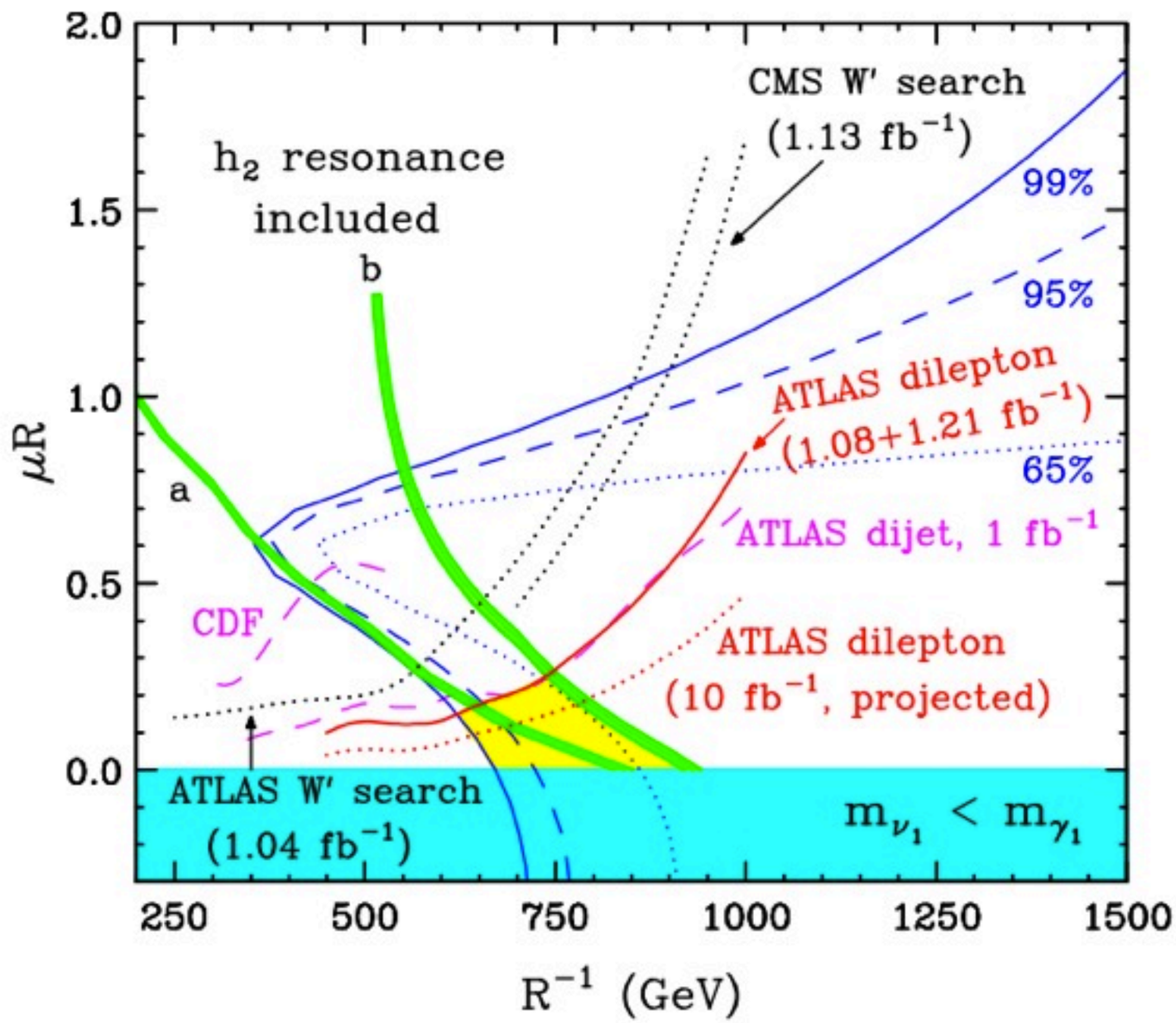
CMS collaboration (2012)





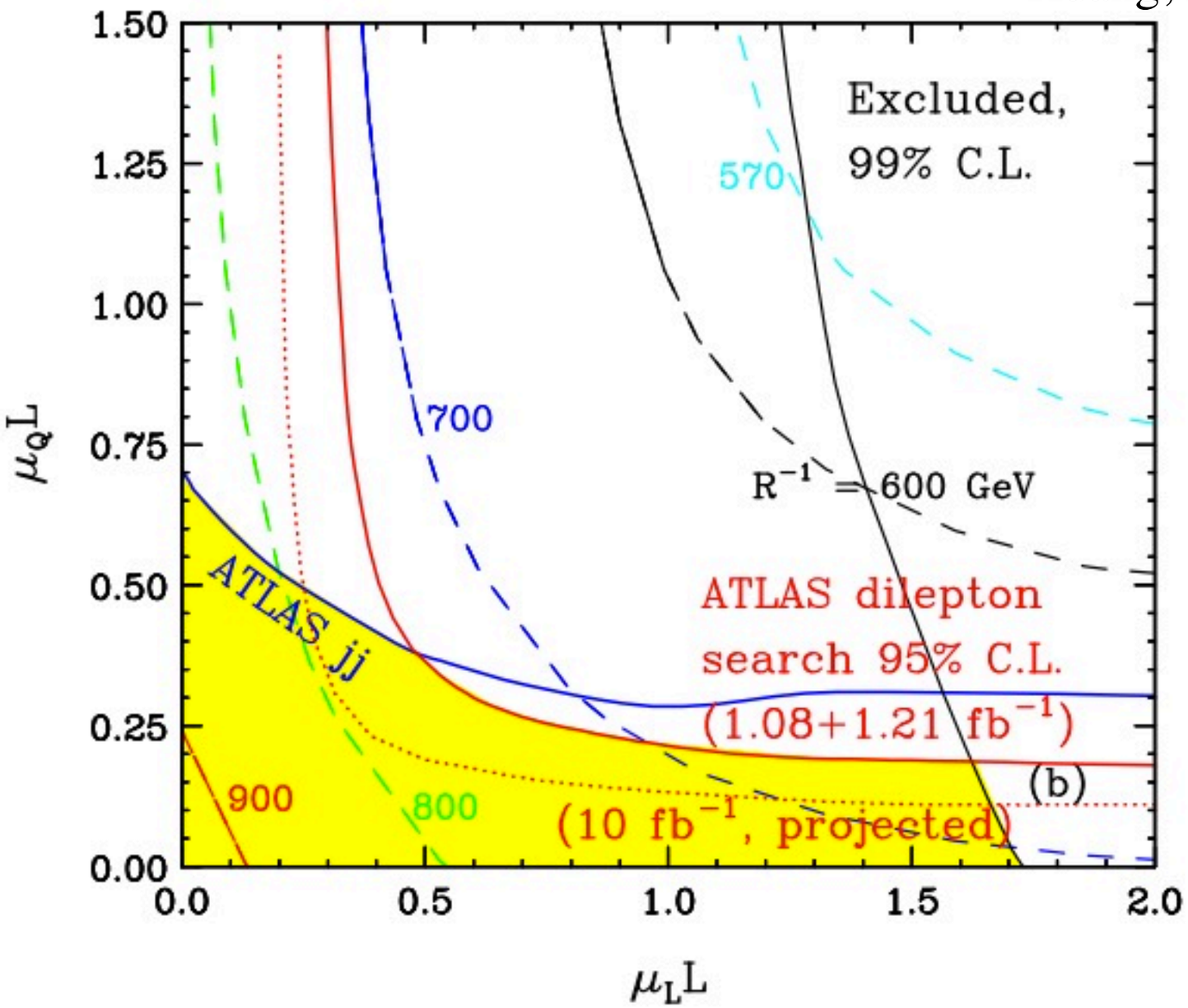
for universal mass

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.
- Thanks!