Non-minimal Universal Extra Dimension: the strongly interacting sector at the LHC

Kenji Nishiwaki

(Harish-Chandra Research Institute)

In collaboration with

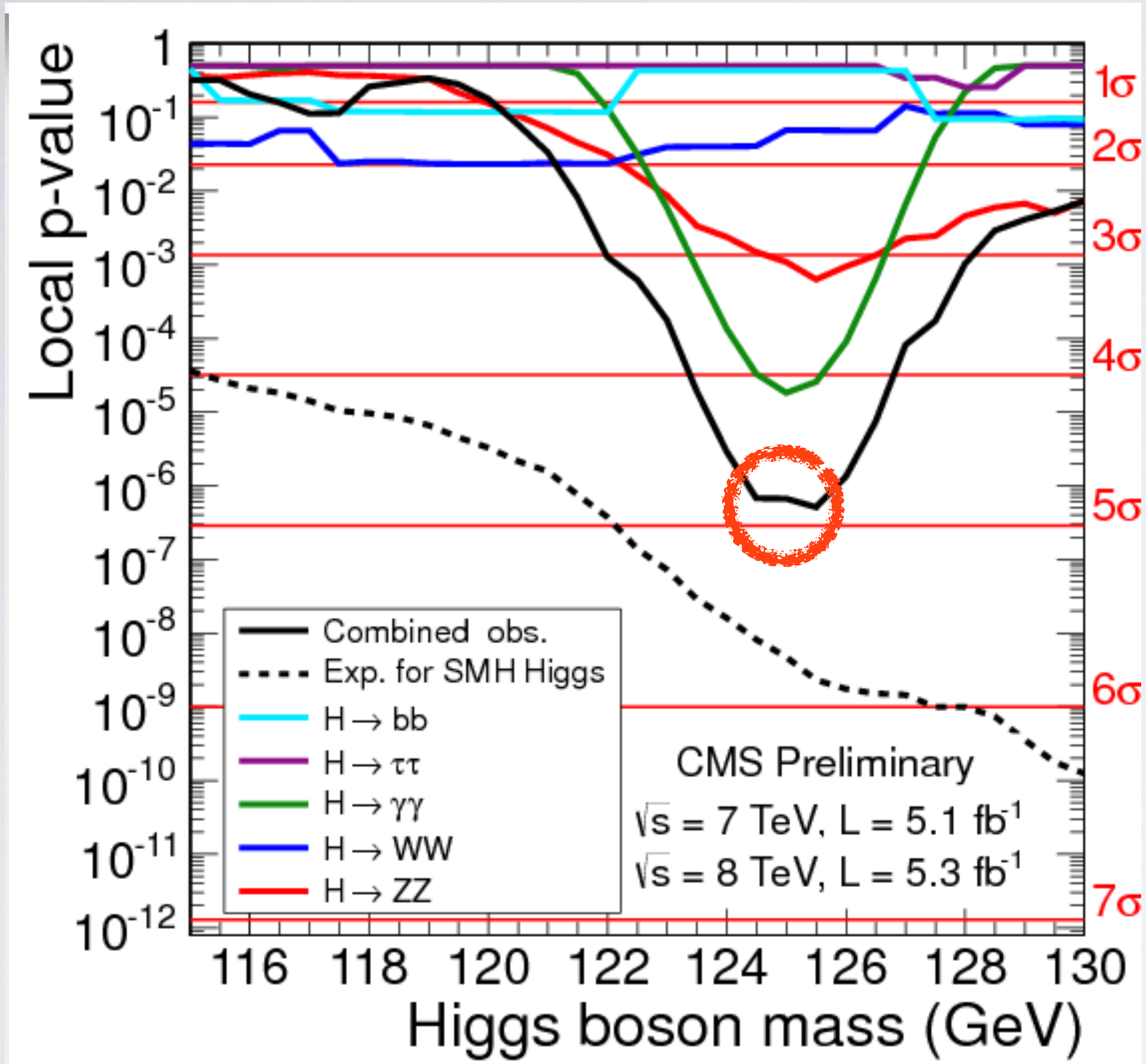
Aseshkrishna Datta (Harish-Chandra Research Institute)
Saurabh Niyogi (Harish-Chandra Research Institute)

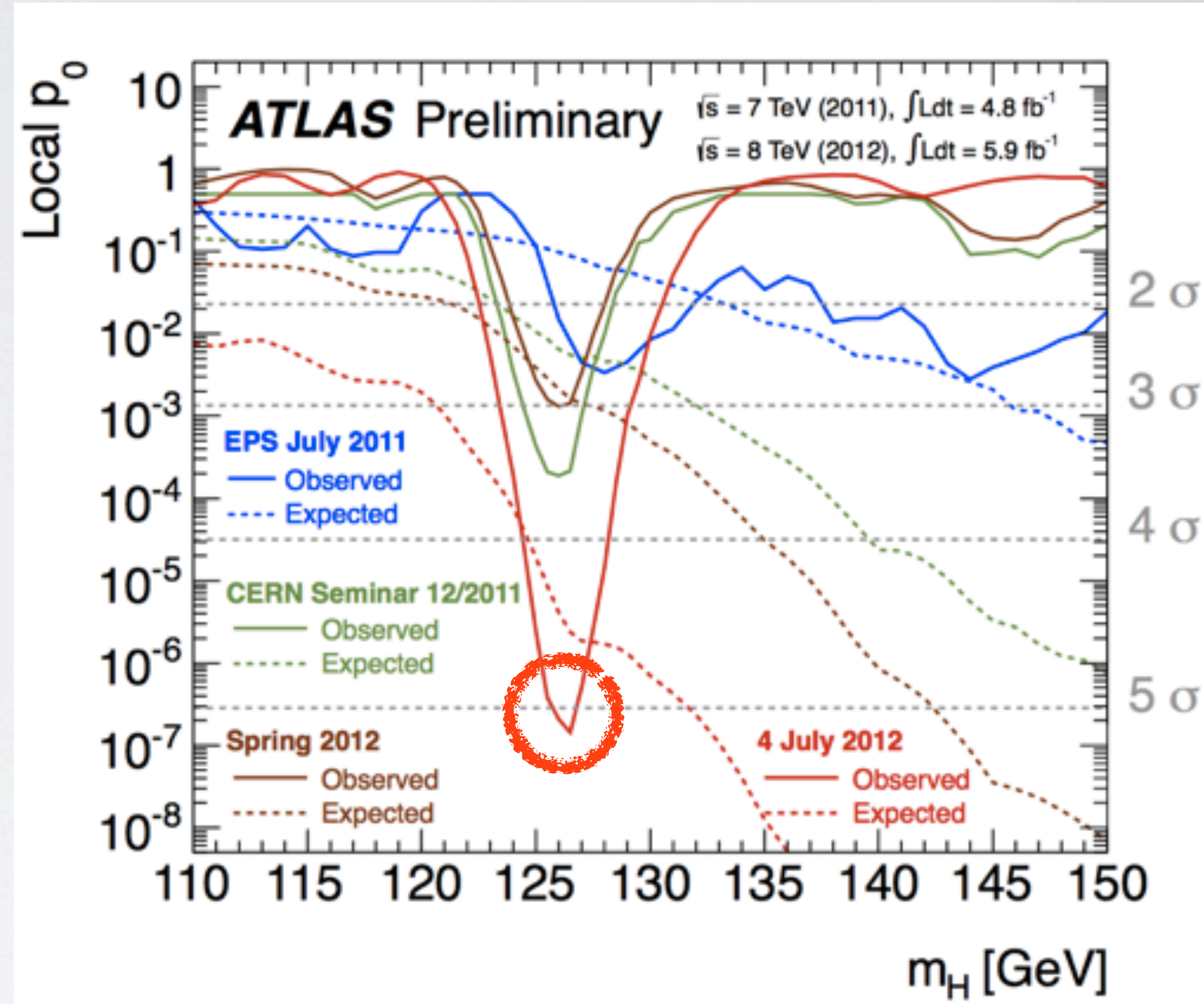
Yukihiro Fujimoto (Kobe Univ.)
Tomoaki Nagasawa (Tomakomai National College of Tech.)
Satoshi Ohya (Harish-Chandra Research Inst.)
Makoto Sakamoto (Kobe Univ.)

Takuya Kakuda (Niigata Univ.)
Kin-ya Oda (Kyoto Univ.)
Naoya Okuda (Osaka Univ.)
Ryoutaro Watanabe (Osaka Univ.)

Seminar @ Osaka University
2012/07/31

A historical observation





We find a new particle consistent with the SM Higgs boson!!

But there still some issues exist.

- The theory behind this is the SM?
- Origins of phenomena hard to be explained by the SM.
  - dark matter candidate
  - deviation in muon g-2
  - baryon asymmetry
  - number of generations
  - mass hierarchy in quarks/leptons
  - flavor mixing
  - top quark forward-backward asymmetry
  - ATIC anomaly
  - and so on...

minimal Universal Extra Dimension (UED) model has nice features.

- The theory behind this is the minimal UED?
  → The current LHC results are consistent with the model.
- Rich collider signatures
- Can minimal UED explain origins of the phenomena?
  - dark matter candidate (explained)
  - deviation in muon g-2
  - baryon asymmetry
  - number of generations
  - mass hierarchy in quarks/leptons
  - flavor mixing
  - top quark forward-backward asymmetry
  - ATIC anomaly

minimal Universal Extra Dimension (UED) model has nice features.

- The theory behind this is the minimal UED?
  $\rightarrow$ The current LHC results are consistent with the model.
- Rich collider signatures

- Can minimal UED explain origins of the phenomena?

  - dark matter candidate (explained)
  - deviation in muon g-2
  - baryon asymmetry
  - number of generations
  - mass hierarchy in quarks/leptons
  - flavor mixing
  - top quark forward-backward asymmetry
  - ATIC anomaly

It is hard to explain the issues in minimal UED.

Purpose of this talk

We consider three ways of extending minimal UED.

We also discuss associated interesting topics.

- UED on 6D geometry.
- UED with junction points(additional boundary).
- UED with tree-level brane-localized terms.

Purpose of this talk

We consider three ways of extending minimal UED.

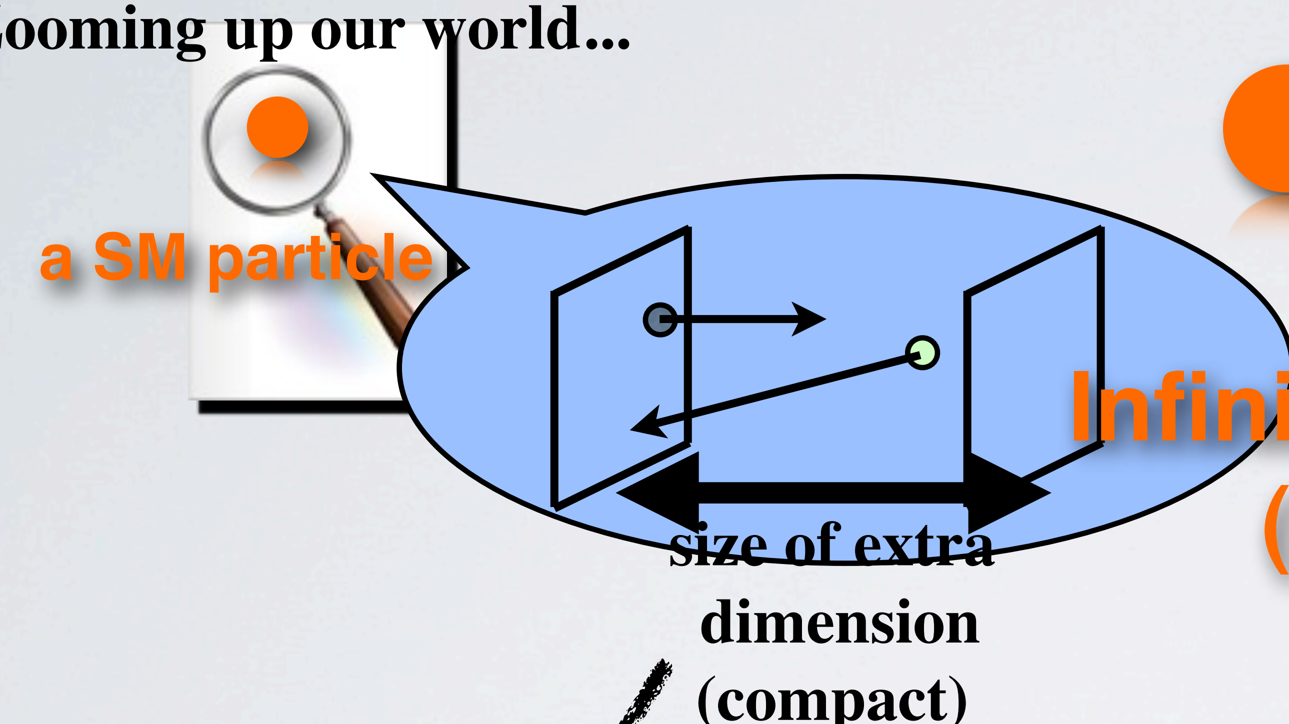
We also discuss associated interesting topics.

- **UED on 6D geometry.**
  - ■ **Retest LHC results prefer (6D) UEDs.**
- **UED with junction points(additional boundary).**
  - ■ **Generations, mass hierarchy, CKM matrix are explained simultaneously via geometry.**
- **UED with tree-level brane-localized terms.**
  - ■ **In lower R^{-1} case, anomalous strong coupling region emerges.**

minimal Universal Extra Dimension on S^1/Z_2

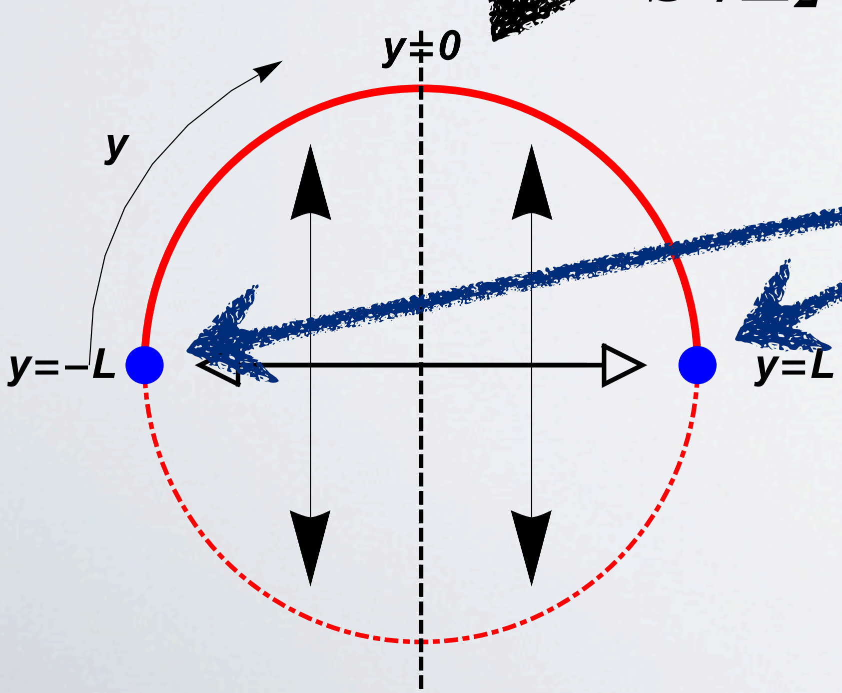
We consider the SM in higher dimension.

Zooming up our world...



Infinite # of heavy copies occur.
(Kaluza-Klein Particles)

simplest case:
S^1/Z_2 orbifold (with vertical identification)

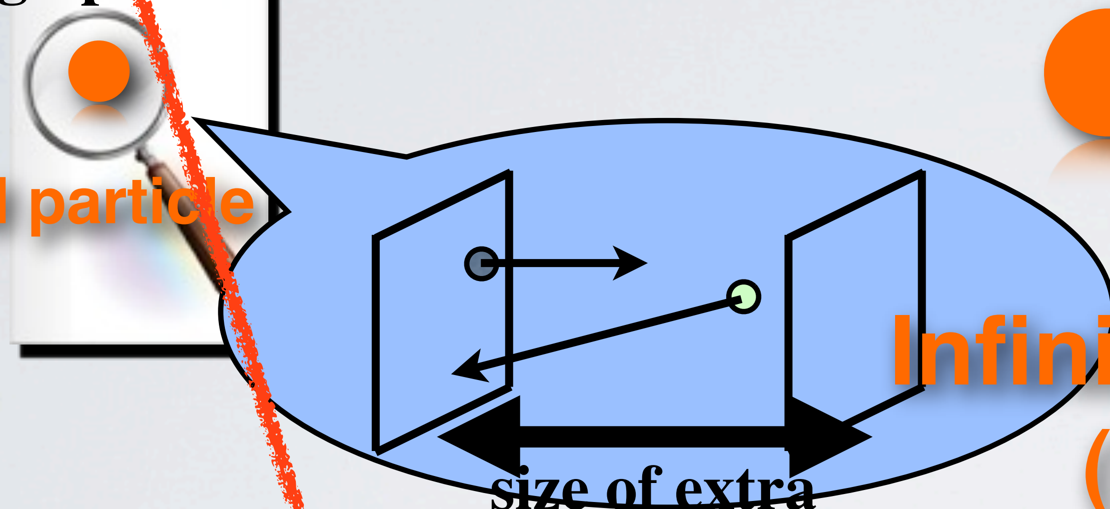


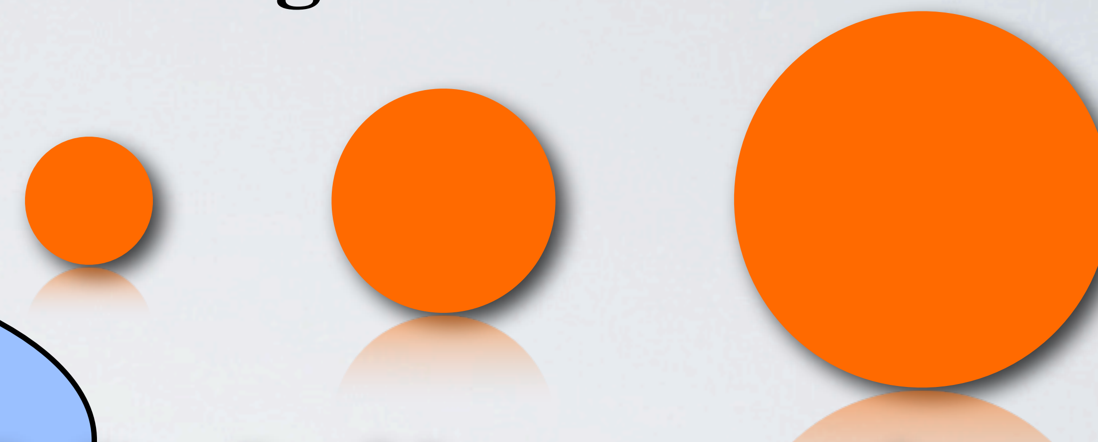
Two fixed points:
needed for realizing 4D Weyl fermion
(No 5D Weyl fermion)

minimal Universal Extra Dimension on S^1/Z_2

We consider the SM in higher dimension.

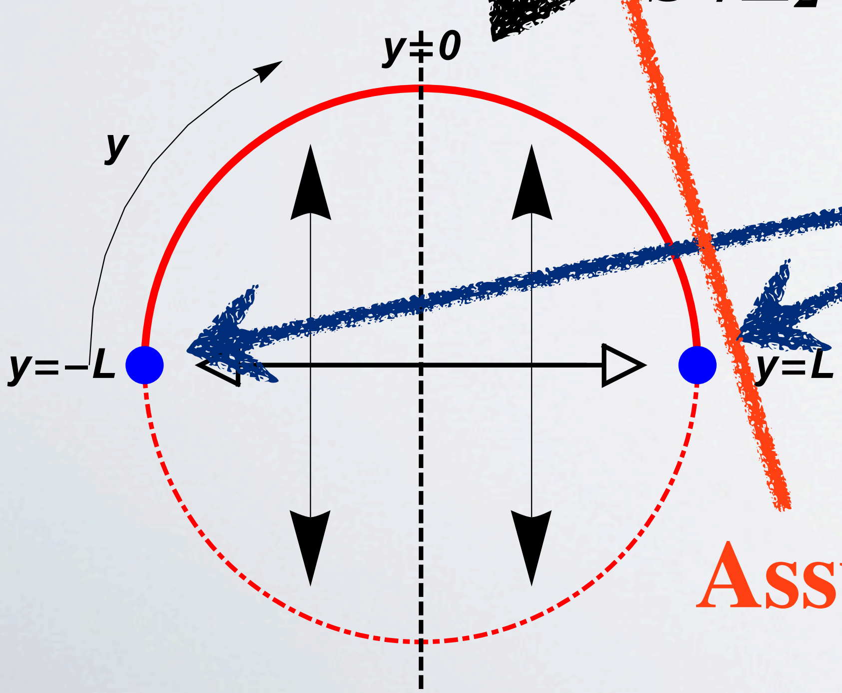
Zooming up our world...





Infinite # of heavy copies occur.
(Kaluza-Klein Particles)

simplest case:
S^1/Z_2 orbifold (with vertical identification)



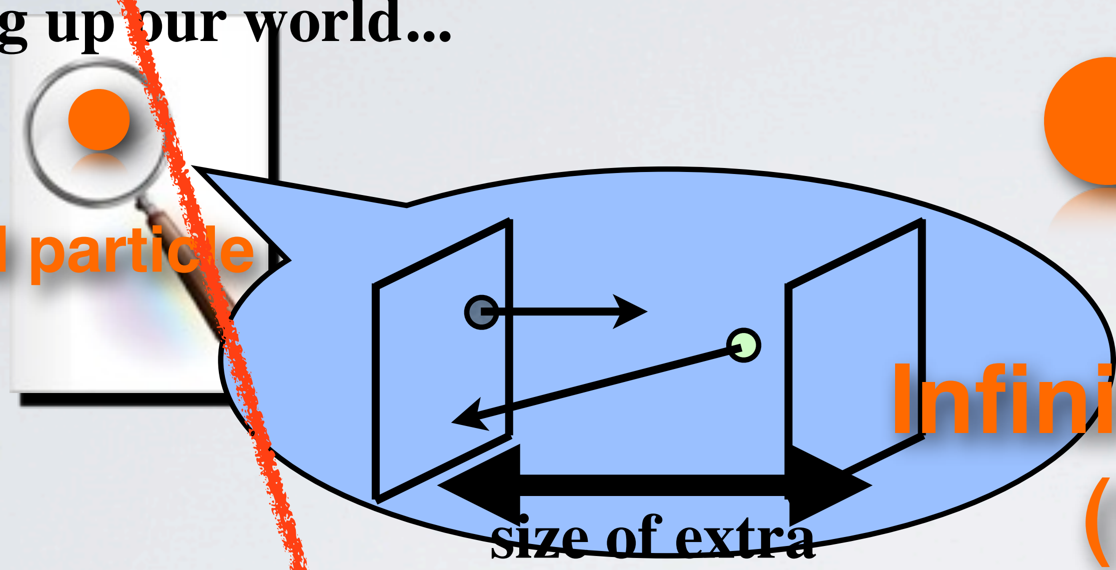
Two fixed points:
needed for realizing 4D Weyl fermion
(No 5D Weyl fermion)

Assumption: no tree-level brane-localized terms

minimal Universal Extra Dimension on S^1/Z_2

We consider the SM in higher dimension.

Zooming up our world...



Infinite # of heavy copies occur.
(Kaluza-Klein Particles)

Interesting points

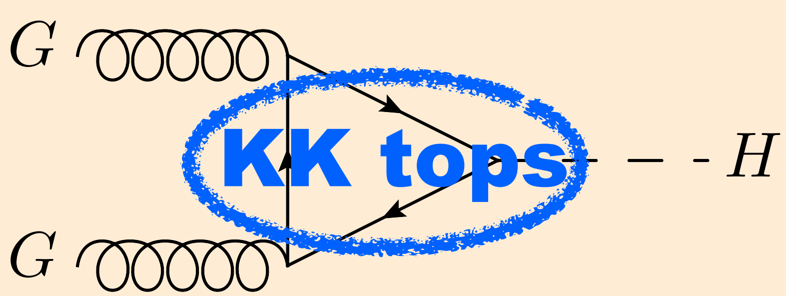
- Dark matter candidate = Lightest KK particle
- 125GeV Higgs is possible
- Loose constraint on m_{KK} ←Possibly detectable at the LHC

Issues after "Higgs" discovery

1. Enhancement of Higgs signal @ LHC:

[F.Petriello] (2002)

[GG -> H (via gluon fusion)]

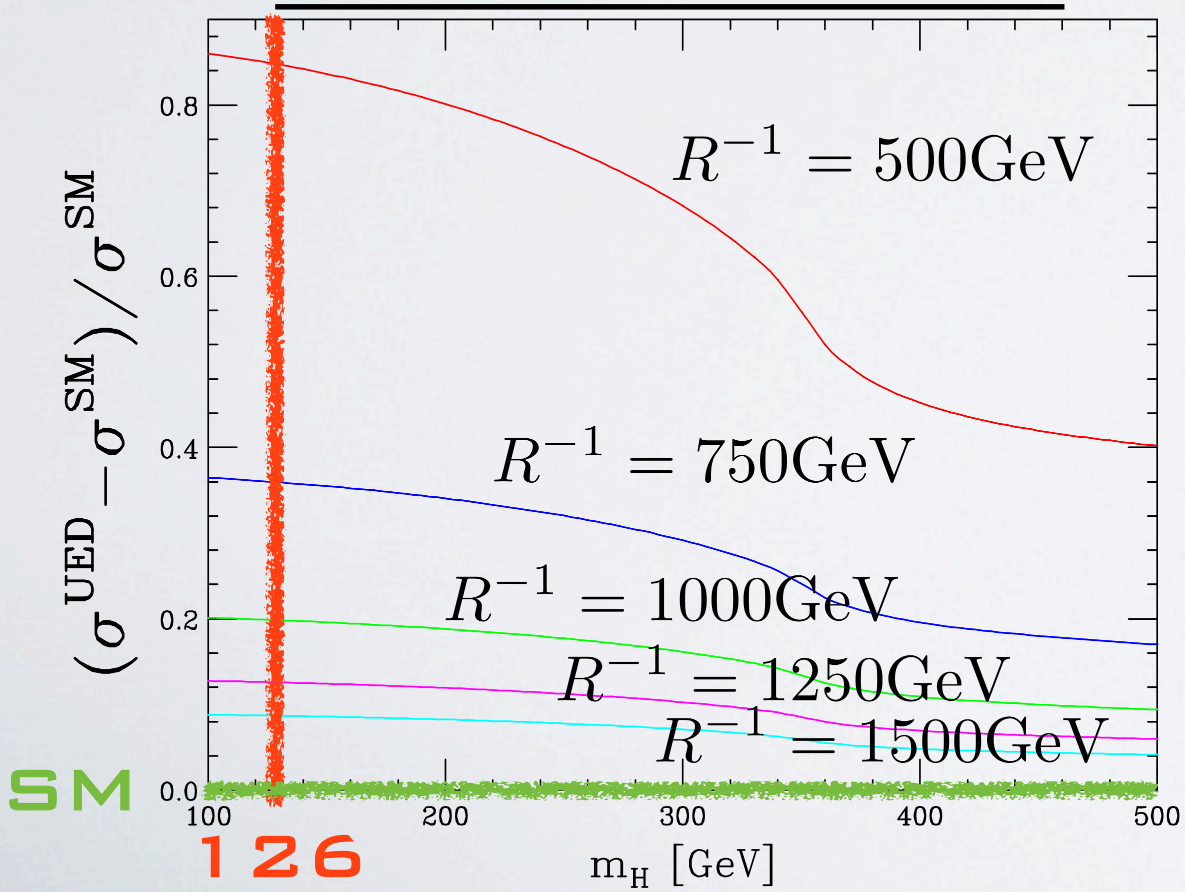


enhanced

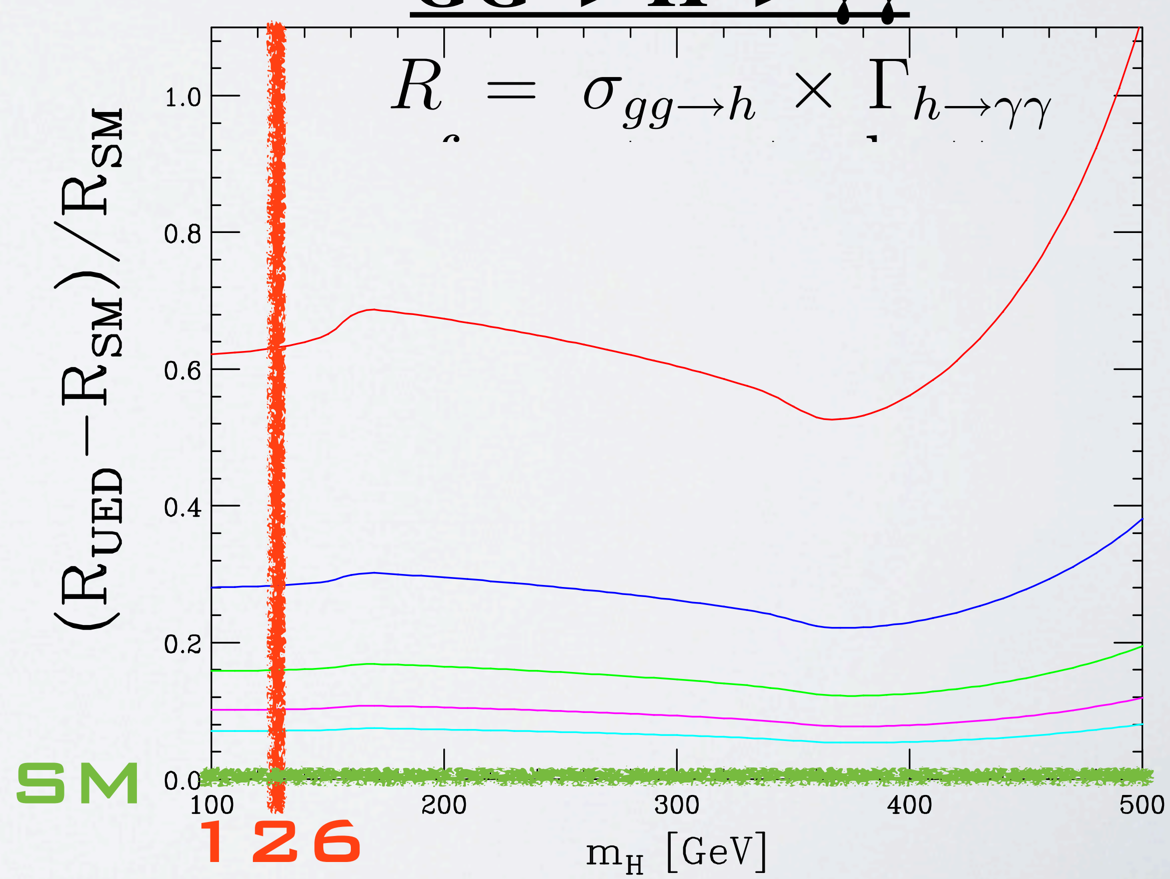
[H -> γγ]

suppressed

GG -> H -> WW or ZZ



GG -> H -> γγ

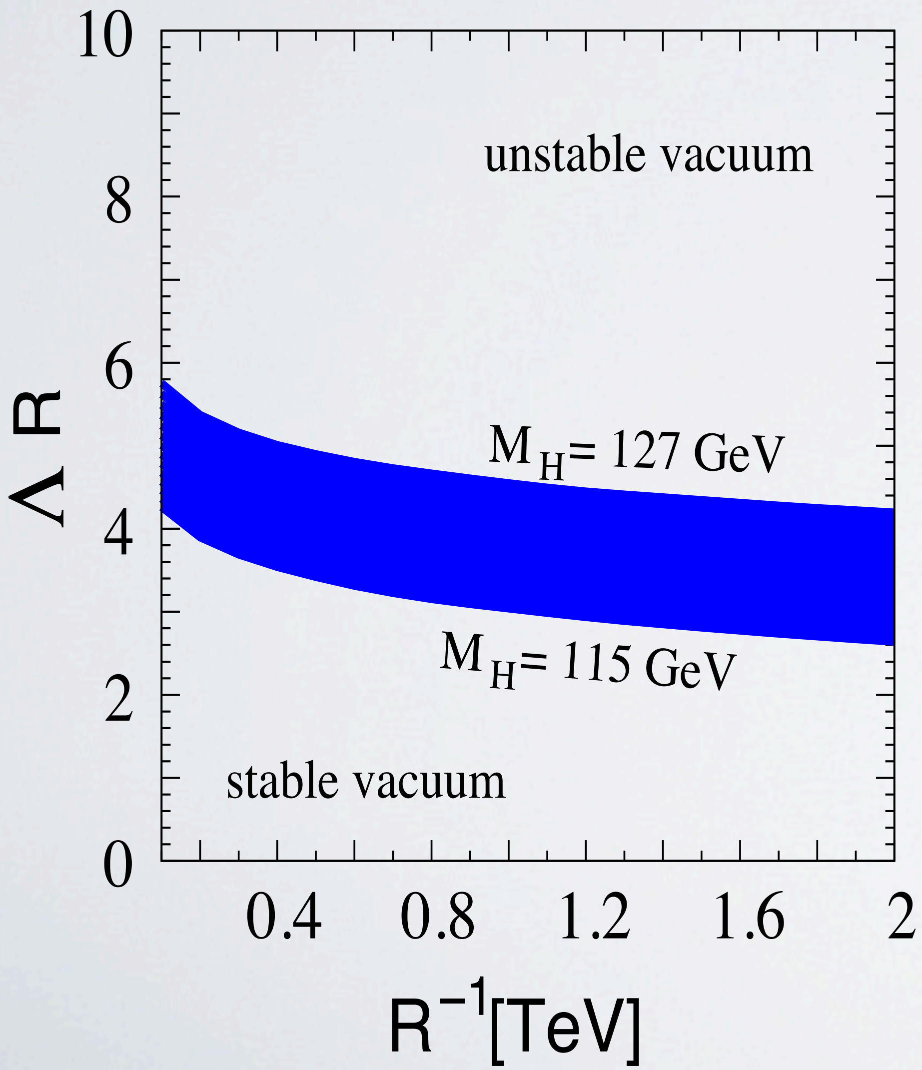


2. Constraint on cutoff scale from Higgs vacuum stability:

[G.Bhattacharyya et al.] (2007)
[A.Datta,S.Raychaudhuri] (2012)

Higgs (126 GeV) < top quark (173.2 GeV)

(stabilizing vacuum) (destabilizing vacuum)



- **RGE in 5D: power running**
- **Severe constraint on upper bound of UED cutoff scale**
- **Only small mass splits is allowed (hard to be detected @ LHC)**

UED on 6D geometry

- dark matter candidate
- number of generations

In collaboration with

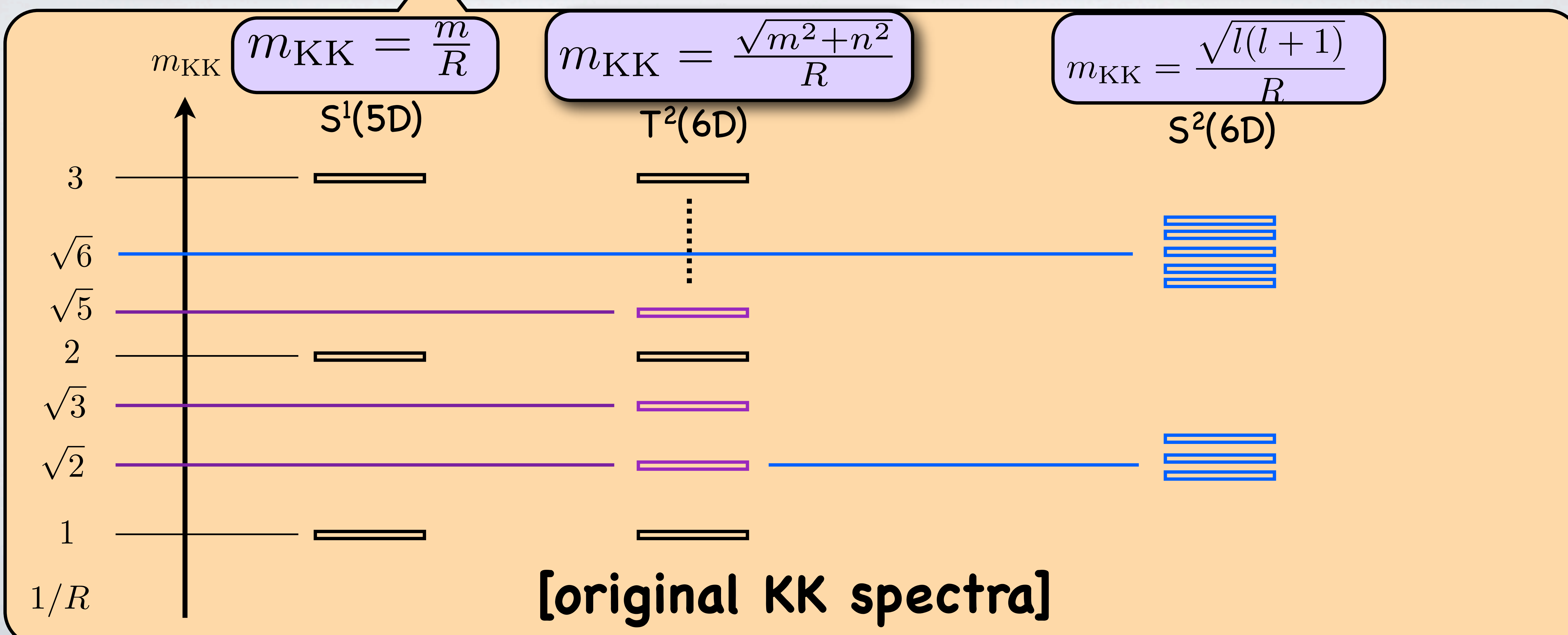
Takuya Kakuda (Niigata Univ.)
Kin-ya Oda (Kyoto Univ.)
Naoya Okuda (Osaka Univ.)
Ryoutaro Watanabe (Osaka Univ.)

work will be completed

New aspects in 6D

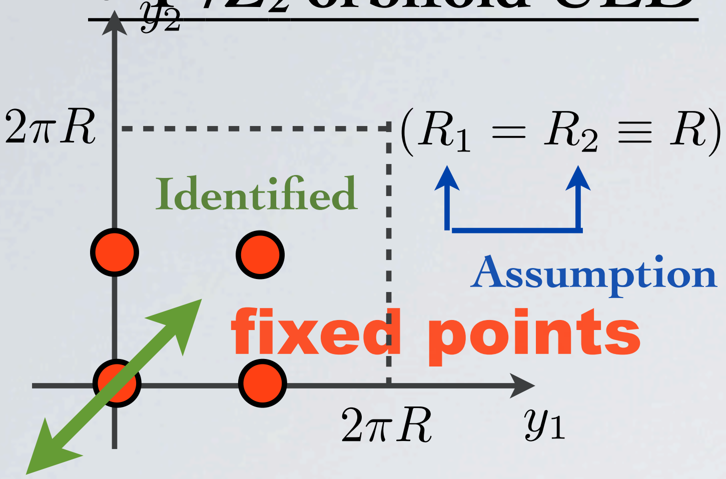
[B.A.Dobrescu,E.Poppitz] (2001)

- Cancellation of global SU(2) anomaly
  ← # of generation is three (mod 3)
- New type of scalar particles appear
  ← ~(6th components of 6D gauge bosons)
- Many possibilities of background geometry
- Unequally-spaced KK mass spectrum(@ tree-level)



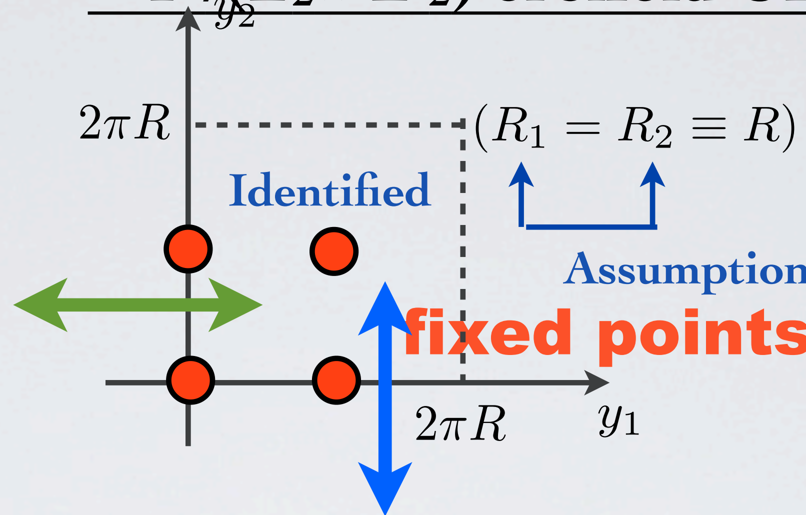
T^2-based

- T^2/Z_2 orbifold UED



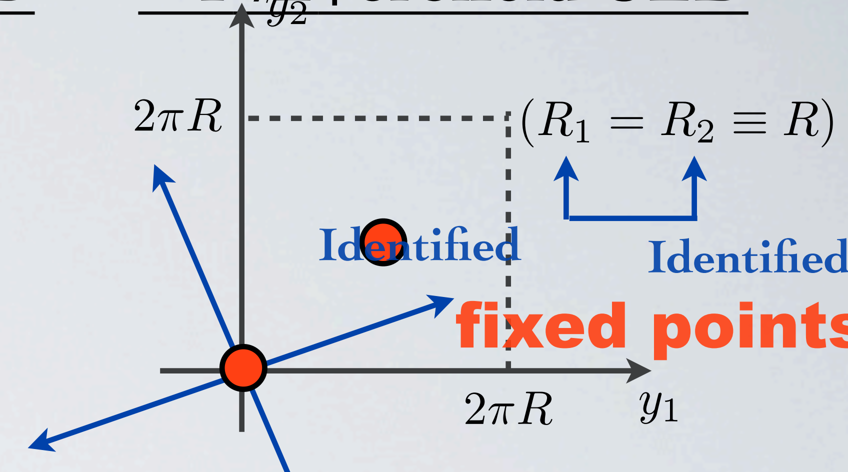
[T.Appelquist, H-C.Cheng, B.A.Dobrescu] (2001)

- $T^2/(Z_2\times Z'_2)$ orbifold UED



[R.N.Mohapatra, A.Perez-Lorenzana] (2003)

- T^2/Z_4 orbifold UED

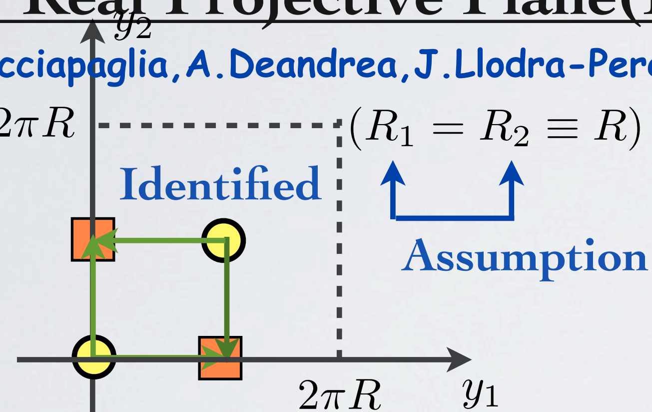


[B.A.Dobrescu,E.Ponton] (2004)

[G.Burdman,B.A.Dobrescu,E.Ponton] (2006)

- Real Projective Plane(RP^2) UED

[G.Cacciapaglia,A.Deandrea,J.Llodra-Perez] (2010)

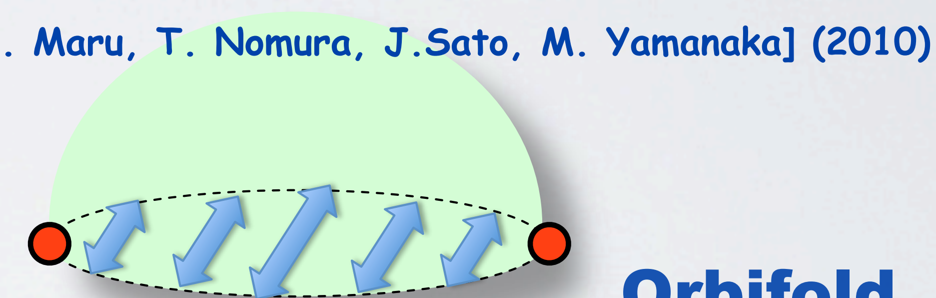


No fixed point globally **Unorientable Manifold**

S^2-based

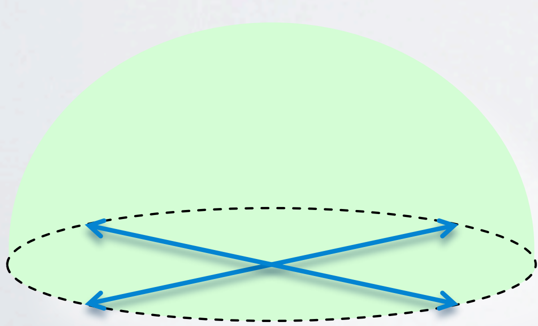
- S^2/Z_2 orbifold UED

[N. Maru, T. Nomura, J.Sato, M. Yamanaka] (2010)



fixed points **Orbifold**

- Projective sphere(PS) UED

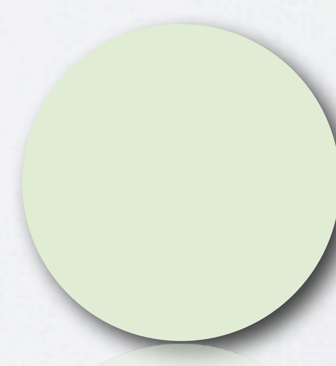


No fixed point

Unorientable Manifold

[H. Dohi, K-y.Oda] (2010)

- S^2 UED with a Stueckelberg field(S^2)

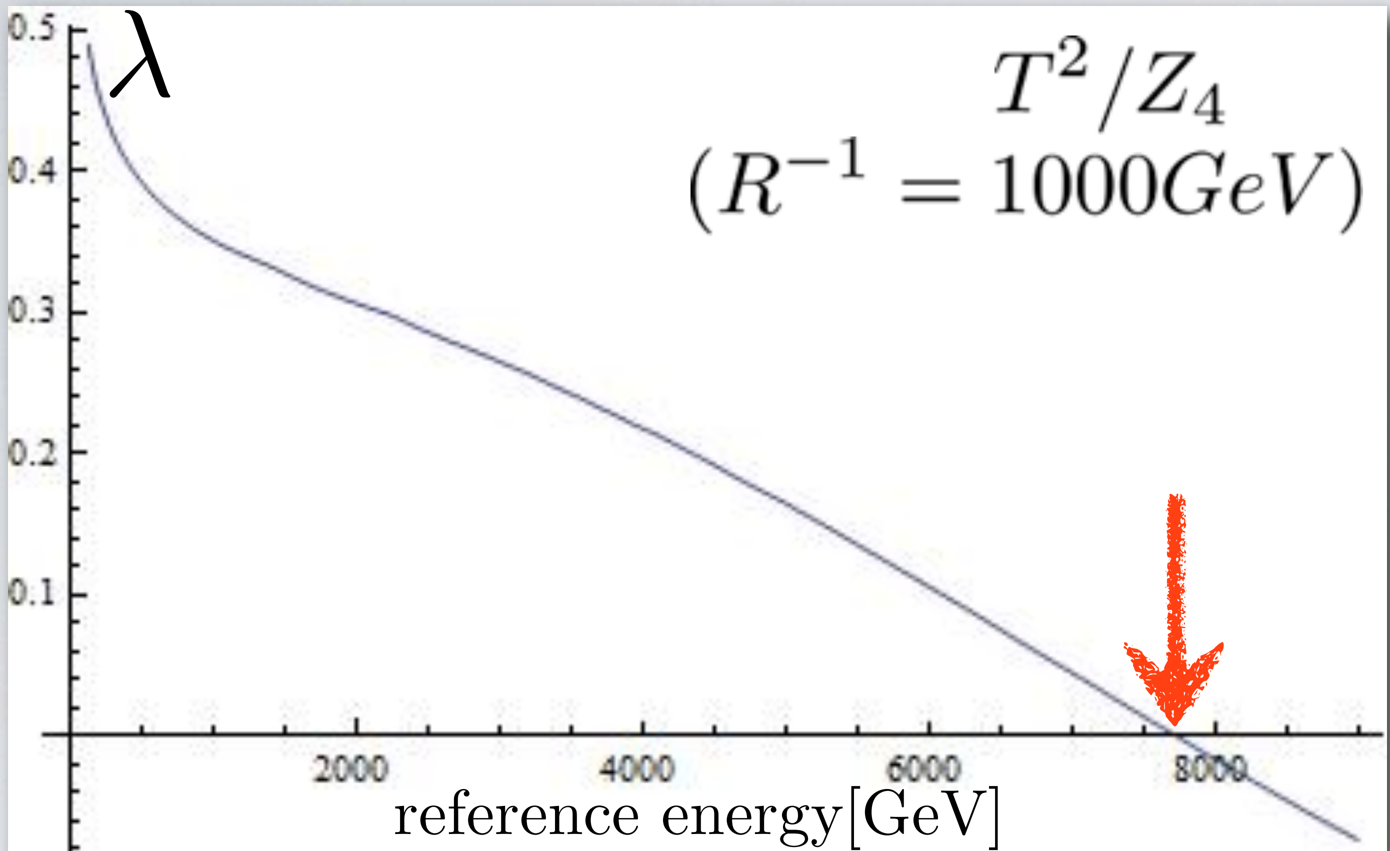


No fixed point

Manifold

[H. Dohi, K.N, K-y.Oda, N.Okuda, R.Watanabe] (in progress)

Higgs vacuum stability bound in 6D UED



- RGE in 6D: putting a stringent constraint on Λ. (larger # of KK states)
- using MS-bar m_{top} = 160GeV.

[Maximal cutoff scales of 6D UEDs]

Preliminary

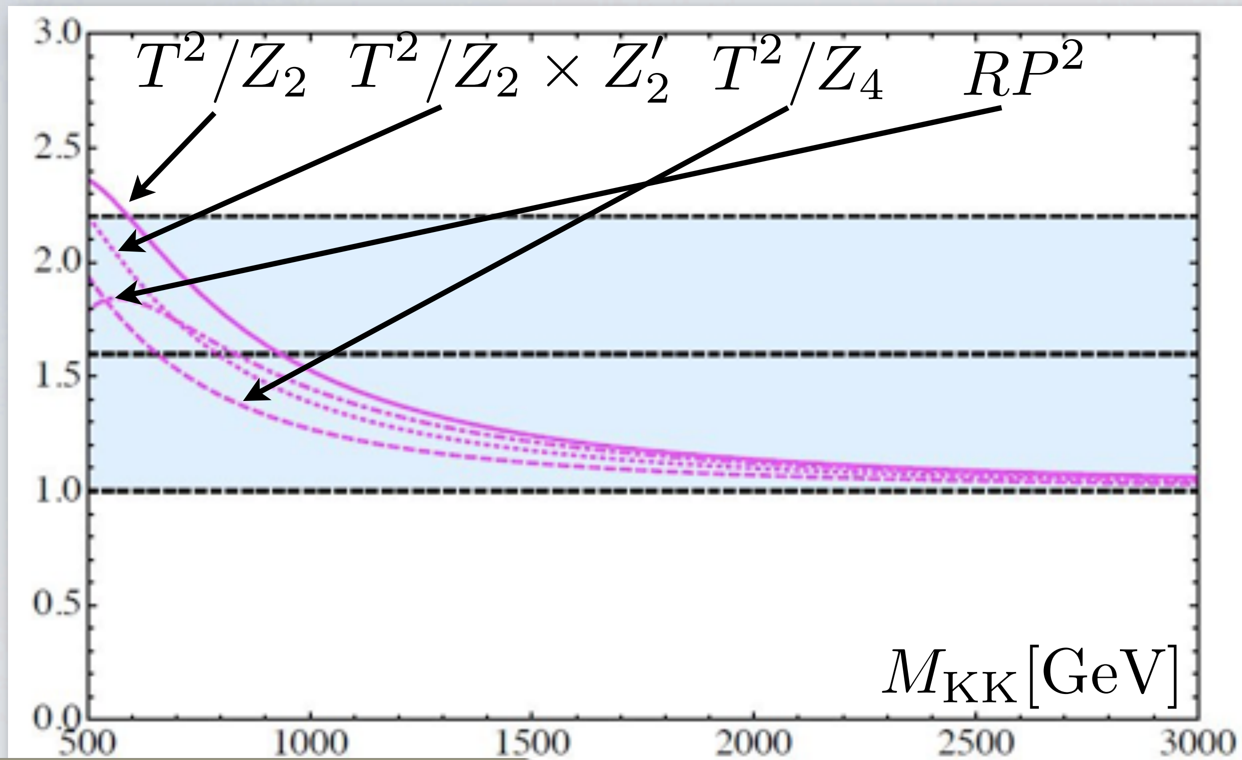
S^2 , PS	$l = 1$, 2 , 3
S^2/Z_2	$l = 1$, 2 , 3 , 4
T^2/Z_2 , RP^2	$m^2 + n^2 < 5.8^2$
T^2/Z_4 , $T^2/Z_2 \times Z^{2\prime}$	$m^2 + n^2 < 7.7^2$

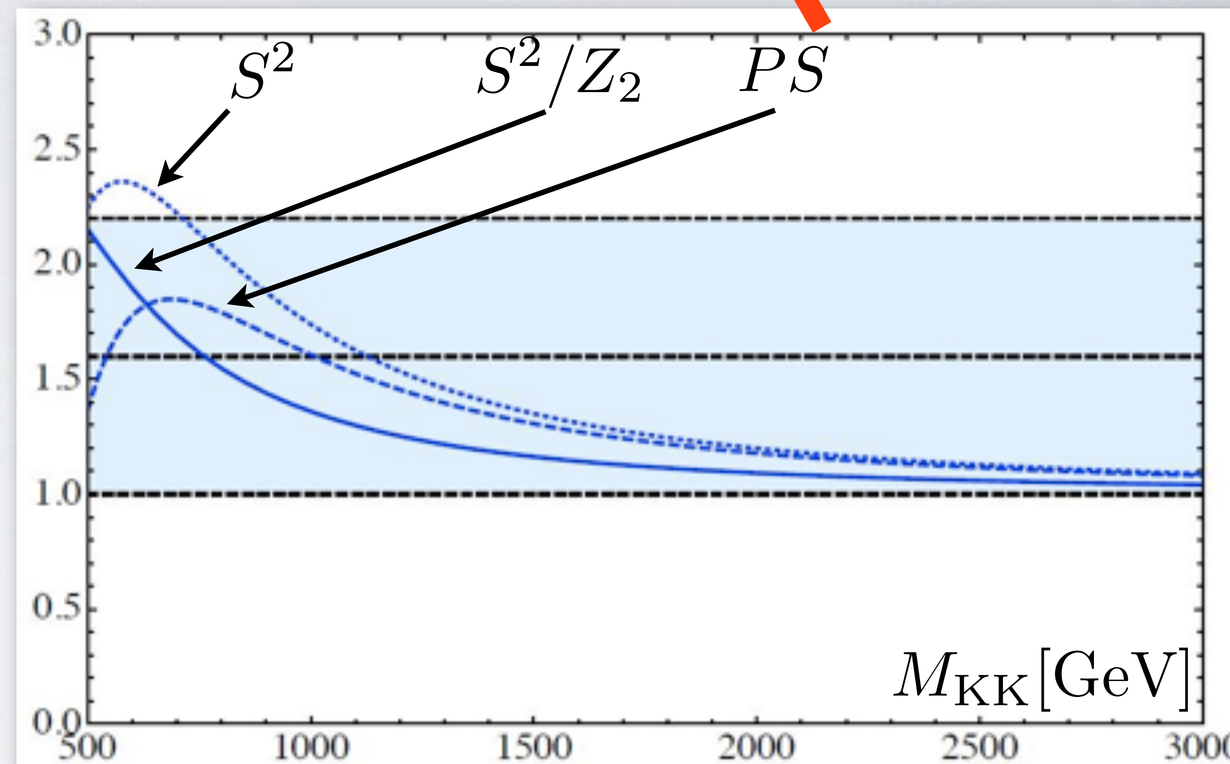
Higgs Signal strength @ LHC

$H \to \gamma\gamma$

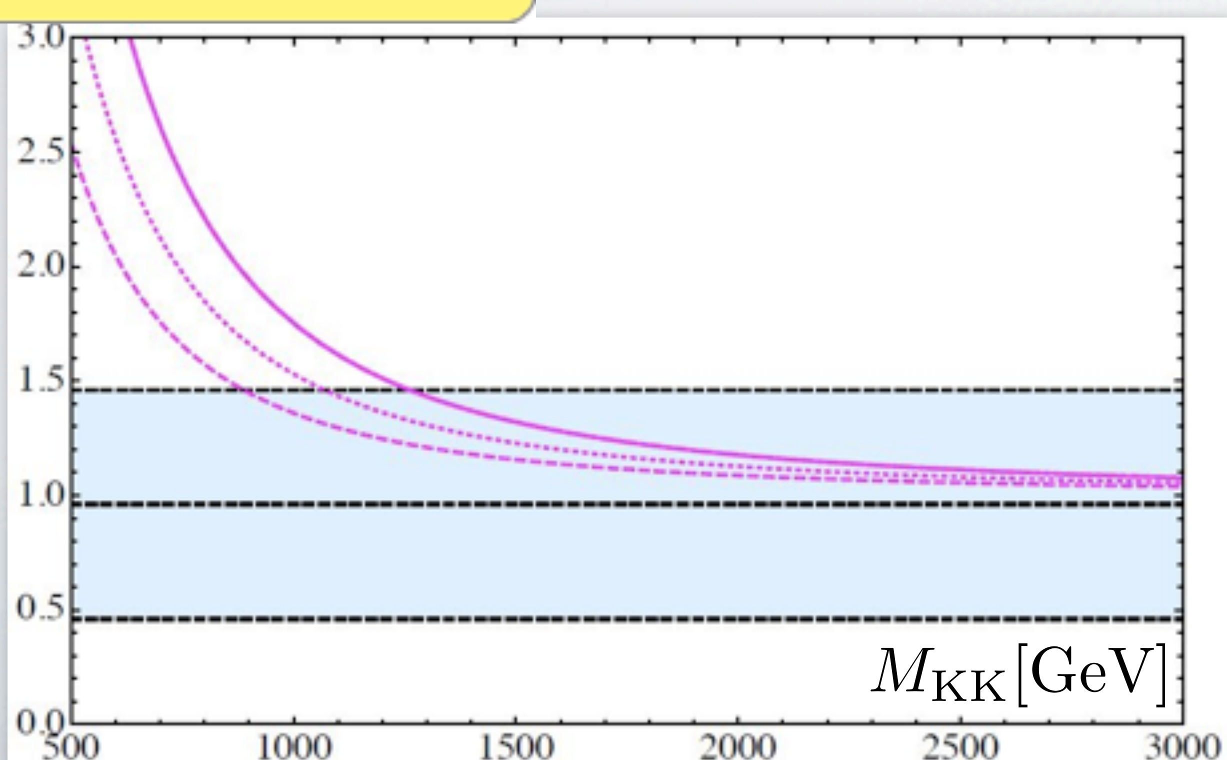
Blue zones: combined 2σ allowed regions

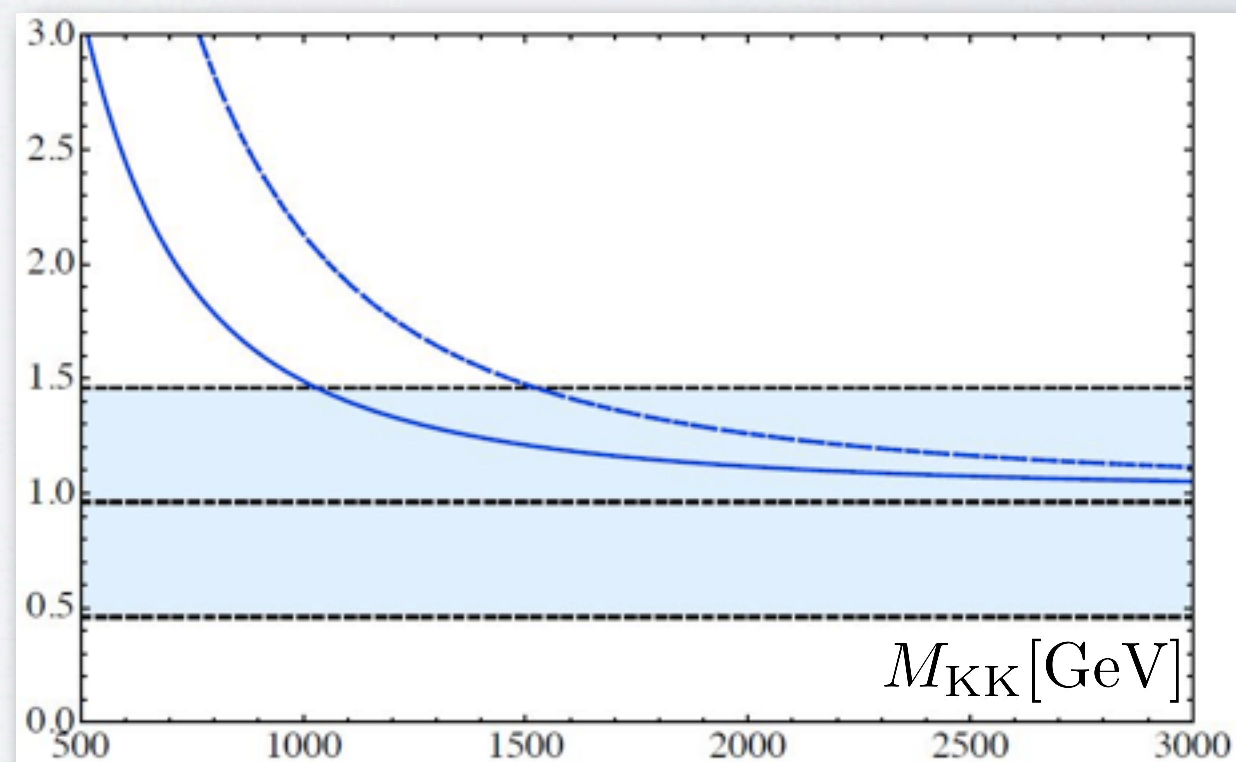
Preliminary



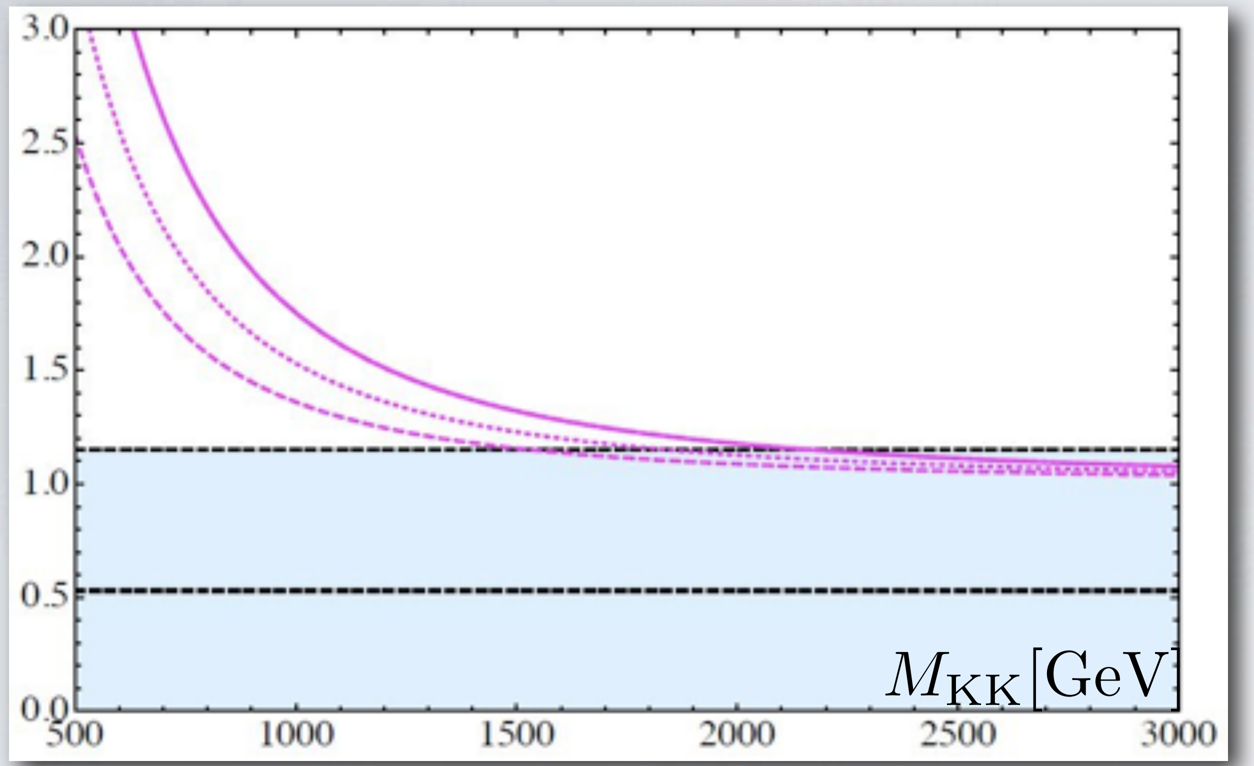


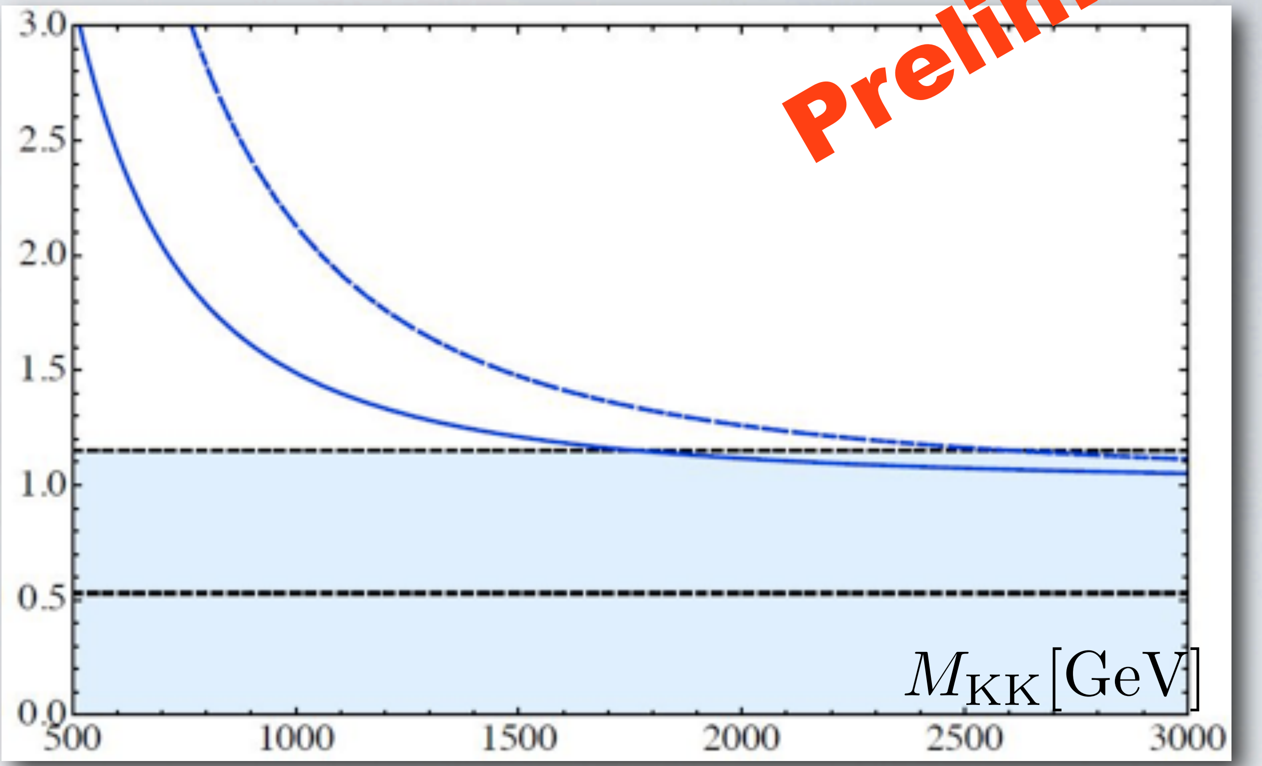
$H \to ZZ$





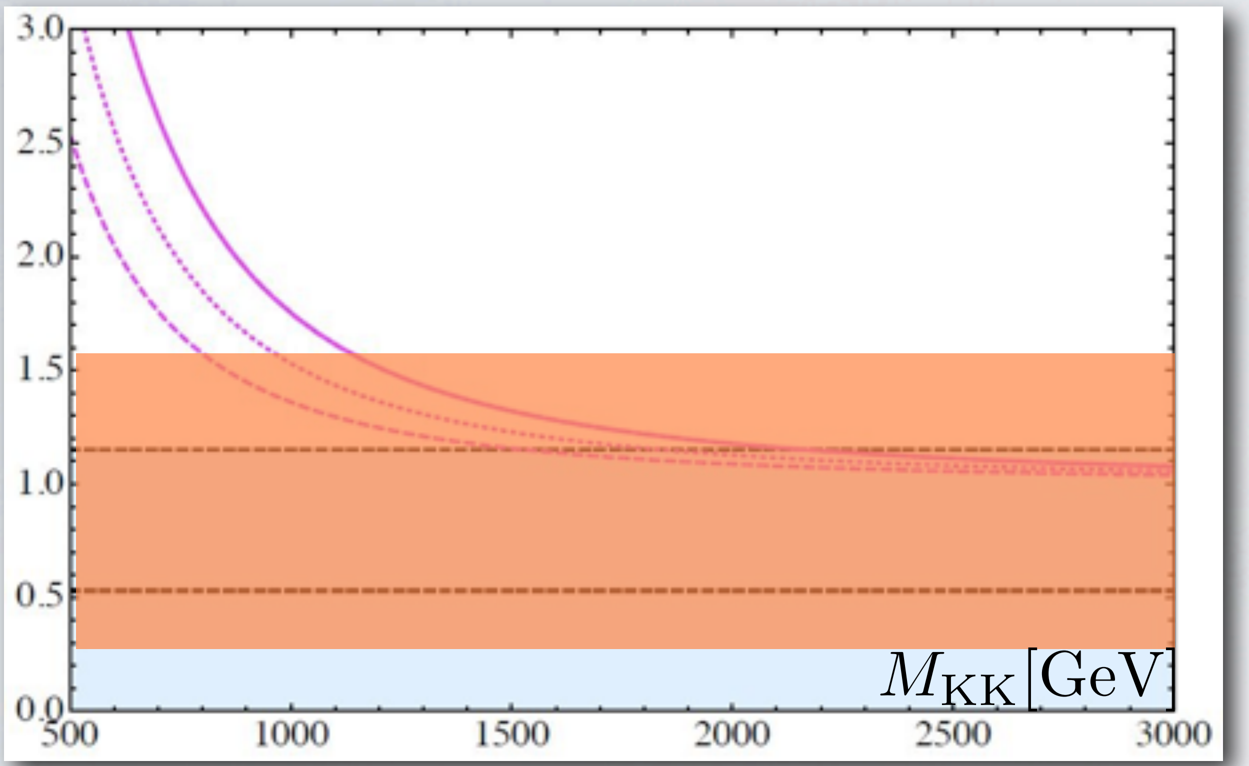
$H \to WW$



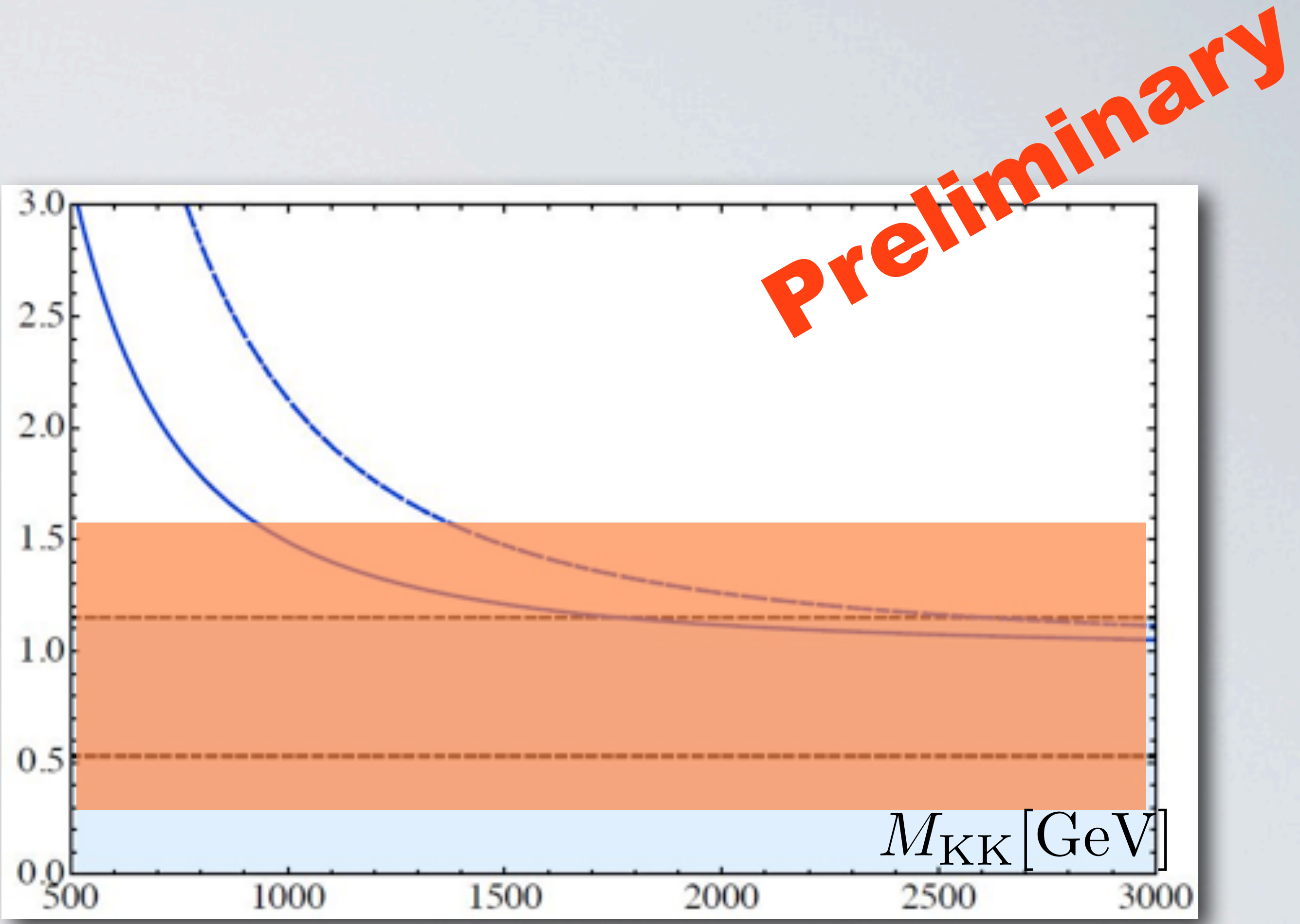


Preliminary

$H \to WW$



3.0
2.5
2.0
1.5
1.0
0.5
0.0
500
1000
1500
2000
2500
3000
M_{KK}[GeV]



Preliminary
3.0
2.5
2.0
1.5
1.0
0.5
0.0
500
1000
1500
2000
2500
3000
M_{KK}[GeV]

S,T parameters estimation

Preliminary

	Lower values of R^{-1}(2σ)
T^2/Z_2	$2.9TeV$
T^2/Z_4	$2.0TeV$
$T^2/Z_2 \times Z_2'$	$2.5TeV$
RP^2	$2.9TeV$
S^2/Z_2	$2.0TeV$
S^2	$2.7TeV$
PS	$2.7TeV$

UED with junction points (additional boundary)

- number of generations
- mass hierarchy in quarks/leptons
- flavor mixing

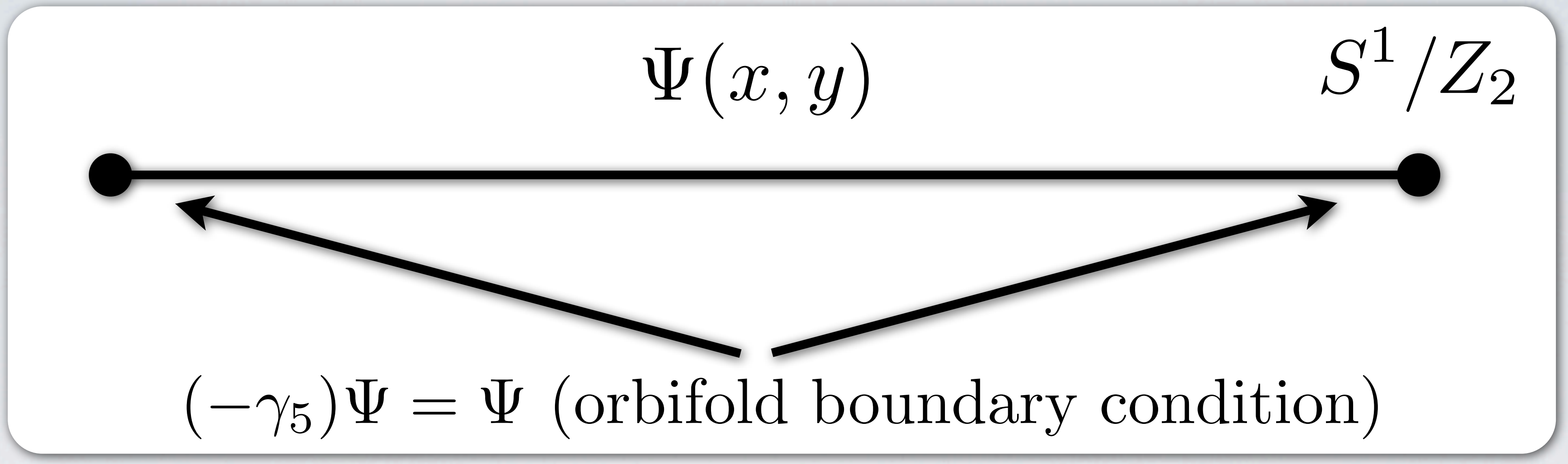
In collaboration with

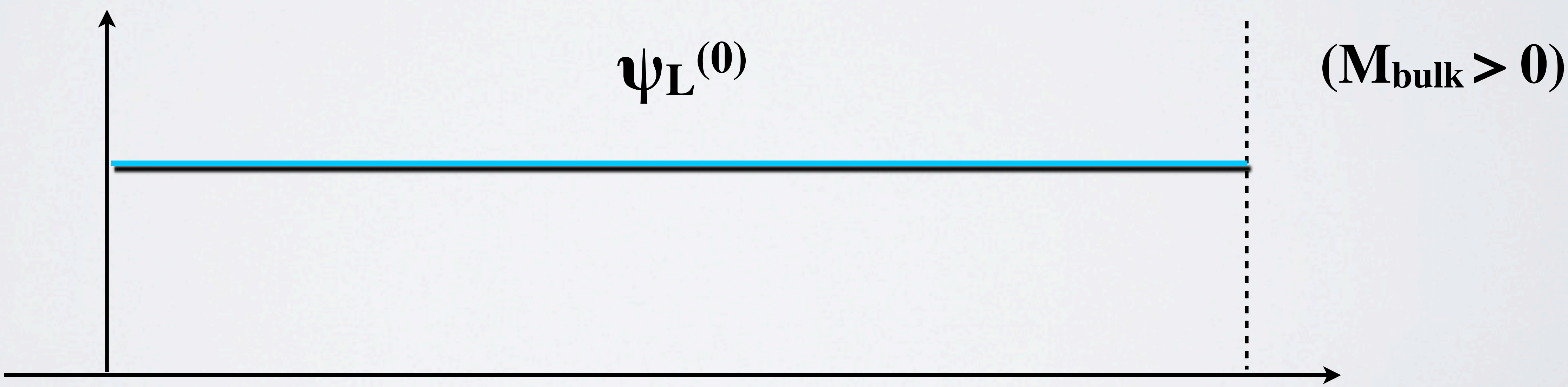
Yukihiro Fujimoto (Kobe Univ.)
Tomoaki Nagasawa (Tomakomai National College of Tech.)
Satoshi Ohya (Harish-Chandra Research Inst.)
Makoto Sakamoto (Kobe Univ.)

paper in preparation

Split chiral zero modes

In mUED, chiral fermion is realized by orbifold.

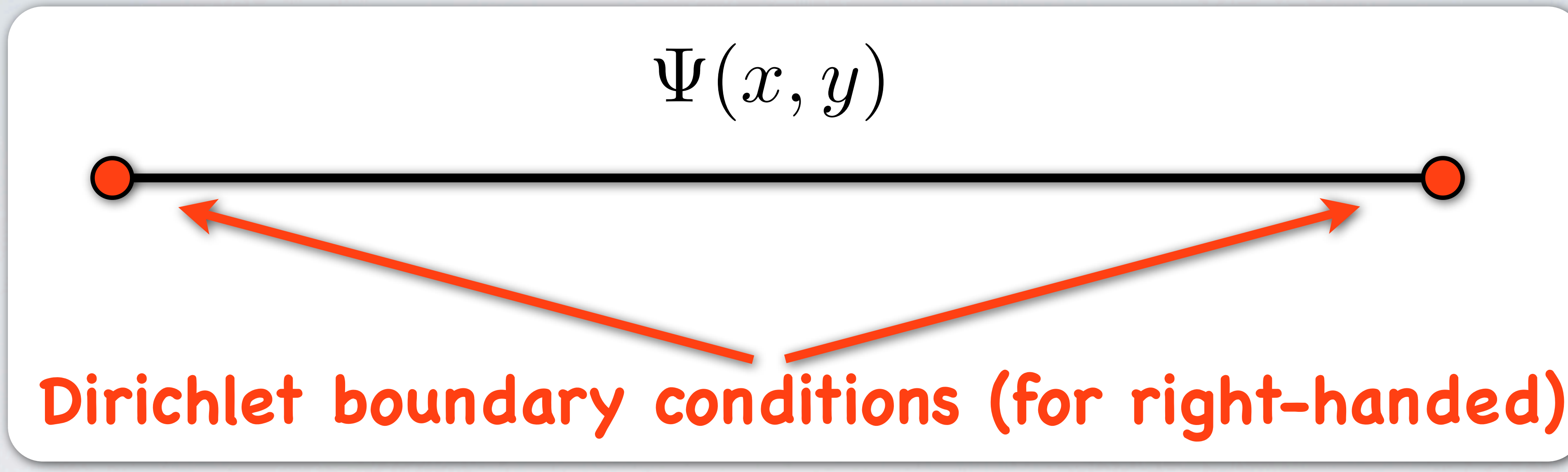


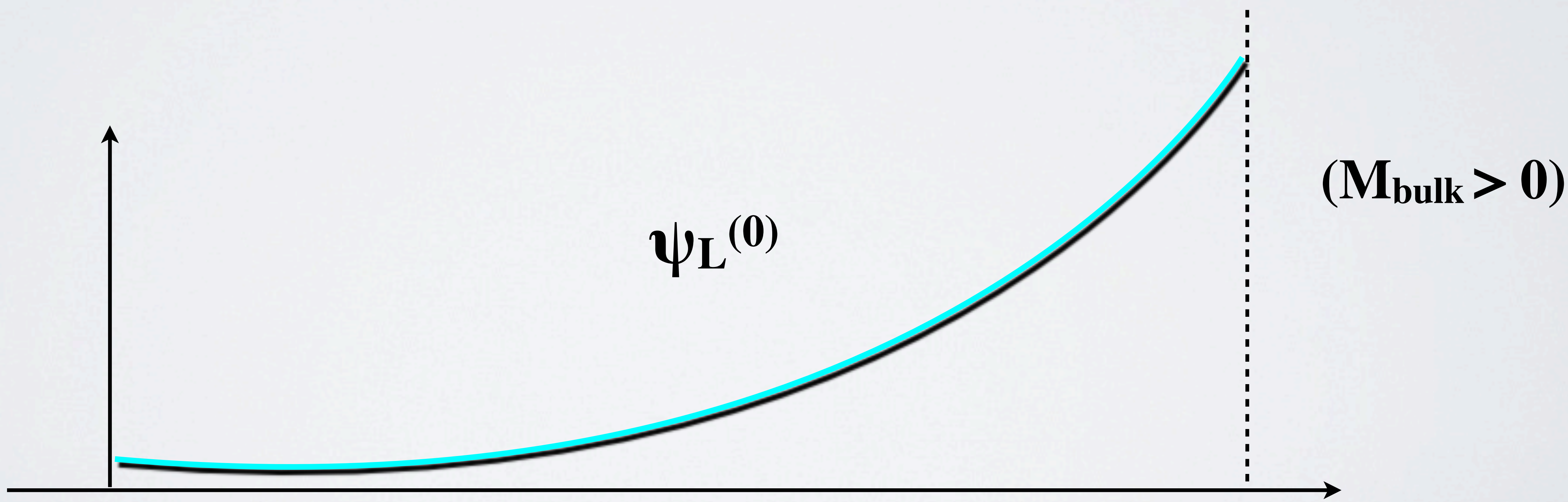


One flat zero mode appears.

Split chiral zero modes

We go for an interval with fermion bulk mass (M_{bulk}).

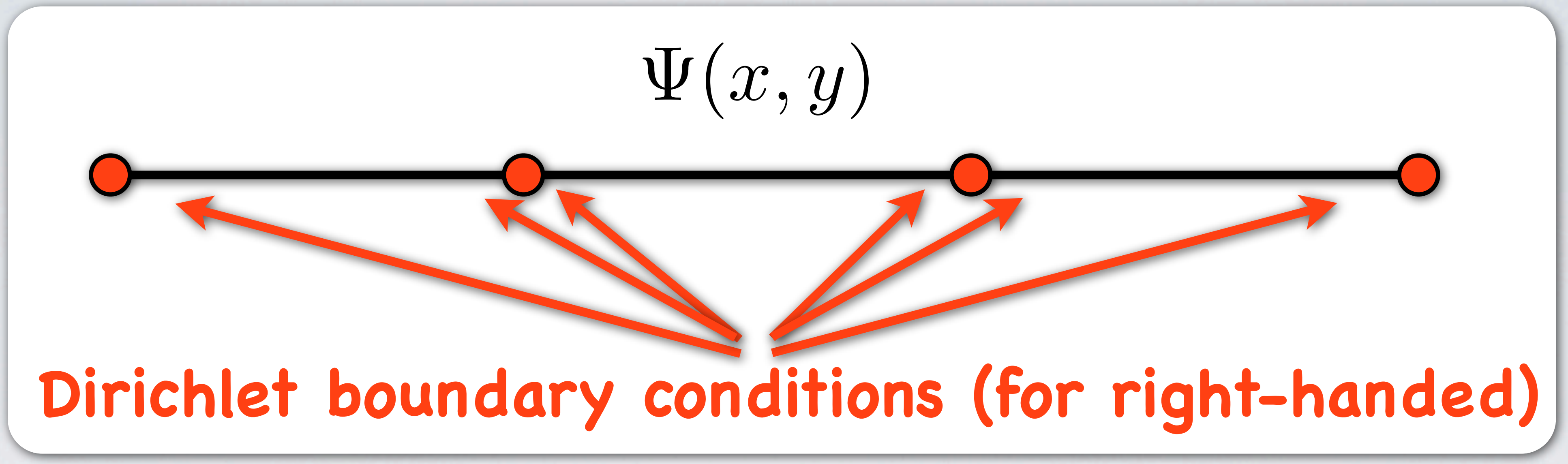




Curved profile can be obtained.

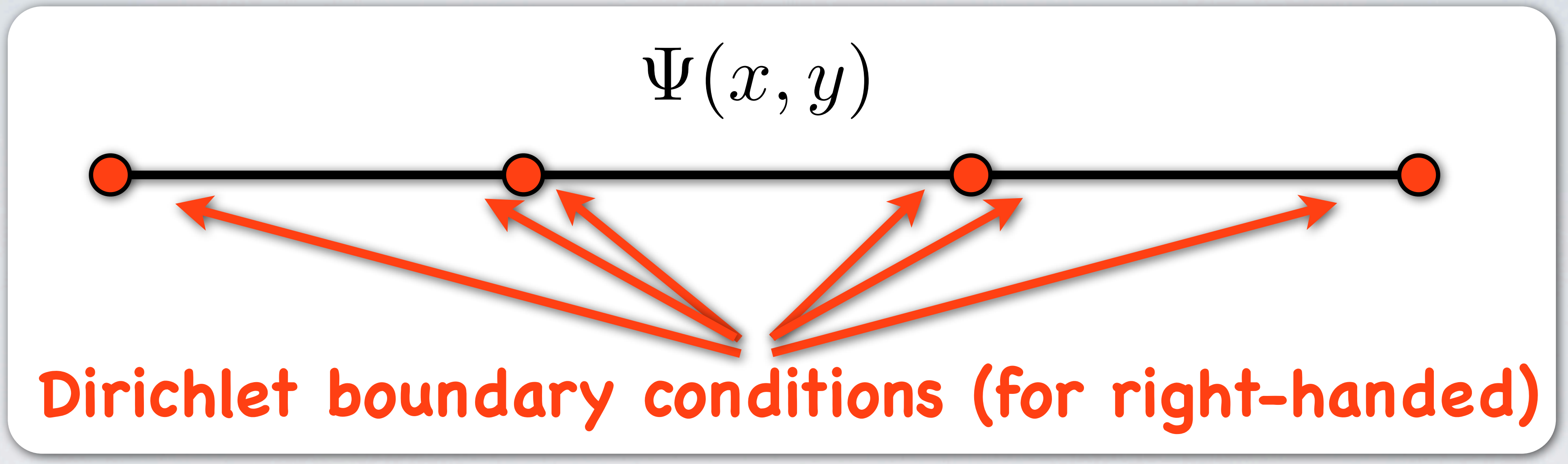
Split chiral zero modes

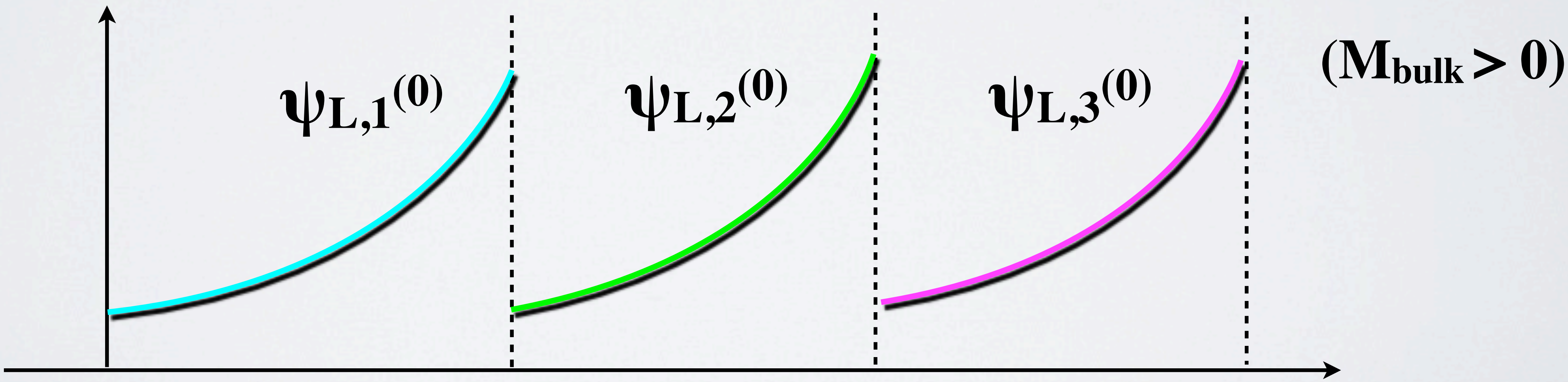
Besides, we add two junction points.



Split chiral zero modes

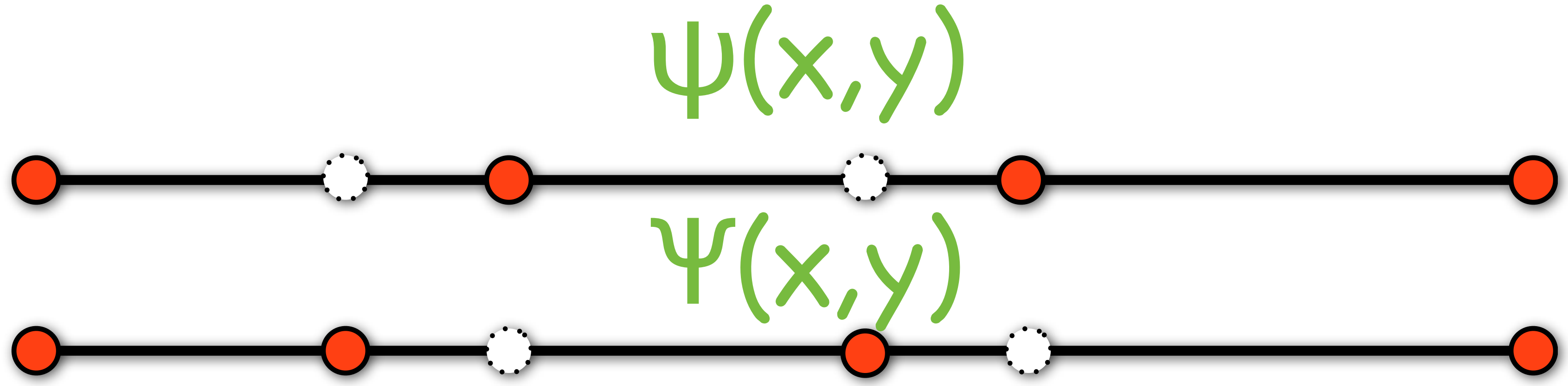
Besides, we add two junction points.





Three-generation structure is realized.

More one step in fermion

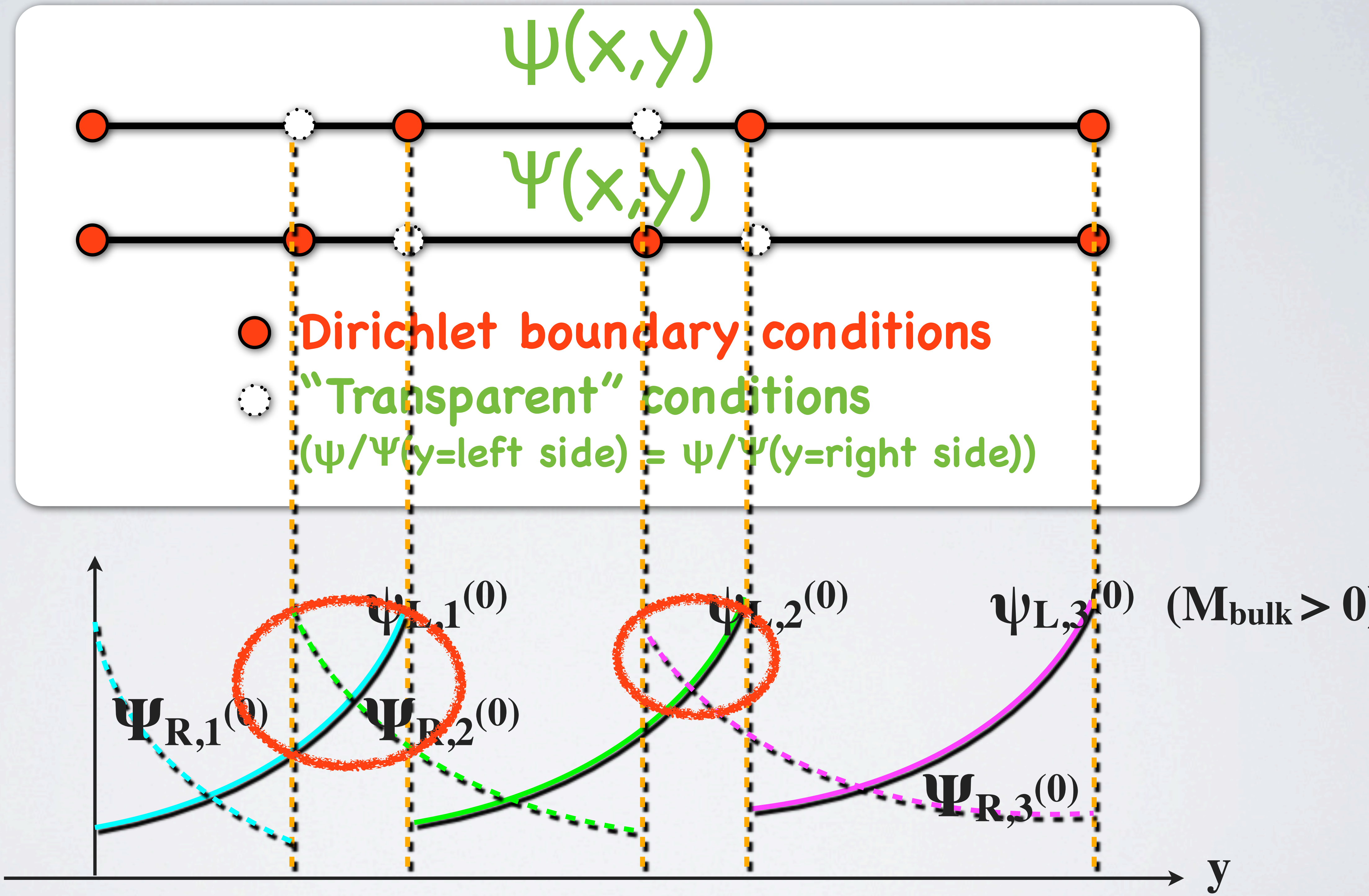


Dirichlet boundary conditions

"Transparent" conditions

(ψ/Ψ(y=left side) = ψ/Ψ(y=right side))

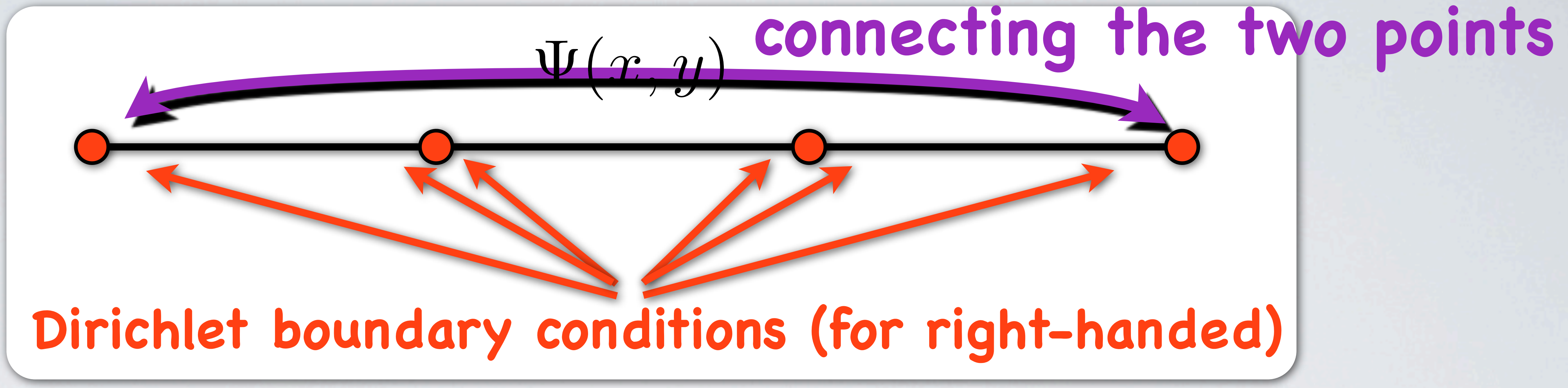
More one step in fermion



Flavor mixing structure appear naturally.

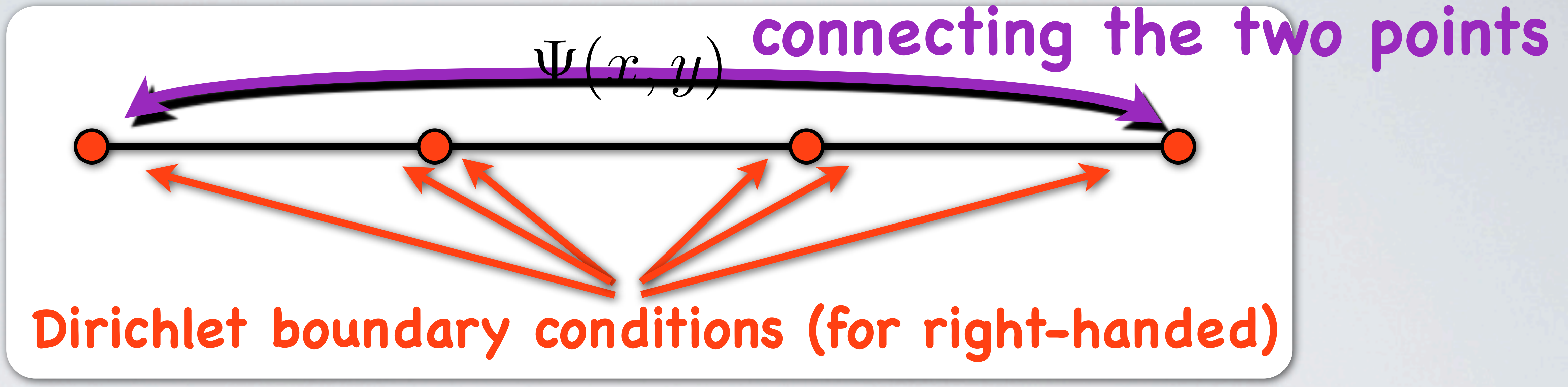
Split chiral zero modes

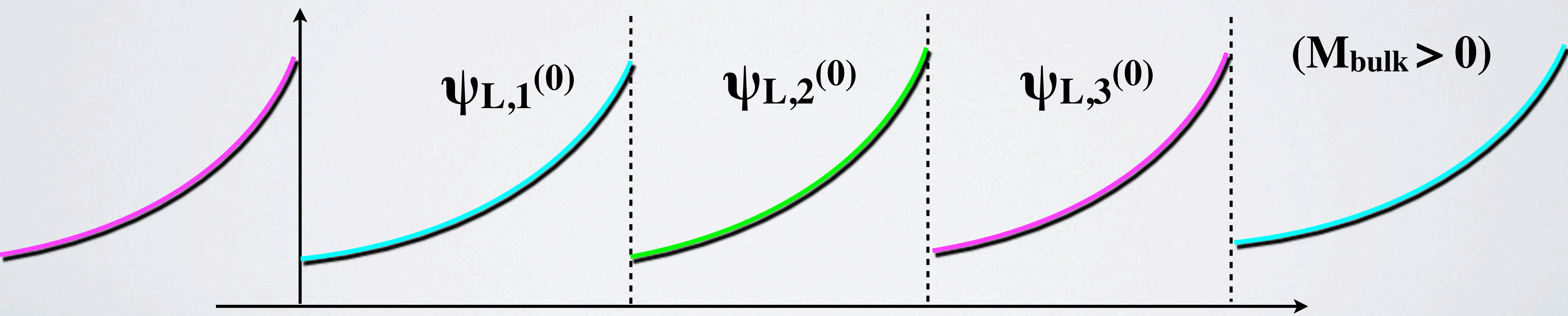
We can connect the two end points for a fermion.



Split chiral zero modes

We can connect the two end points for a fermion.

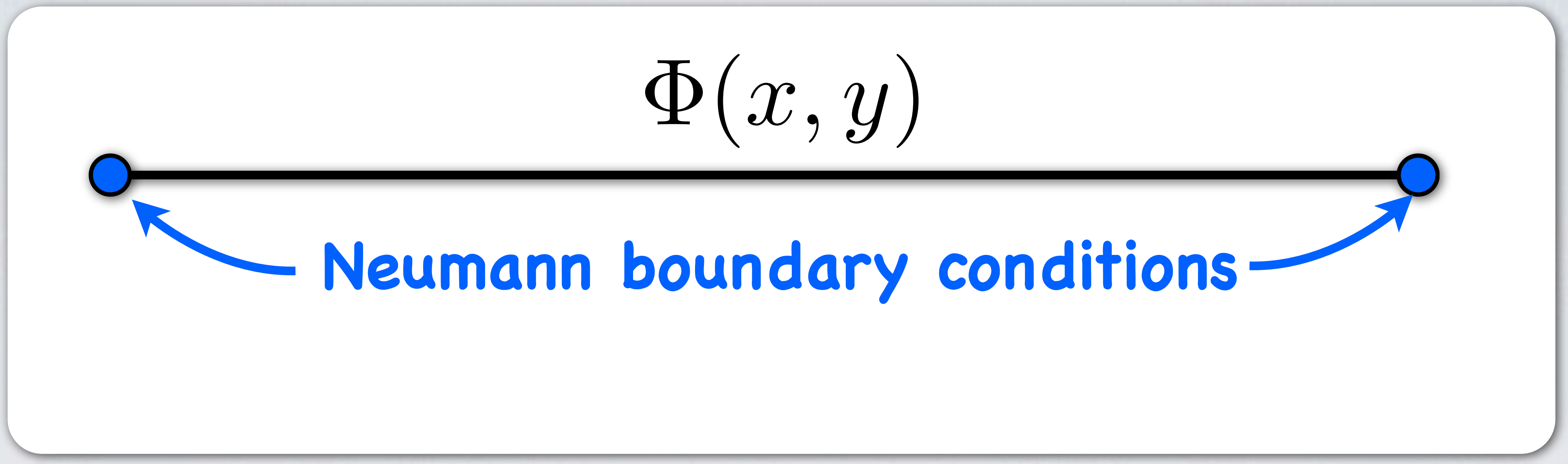


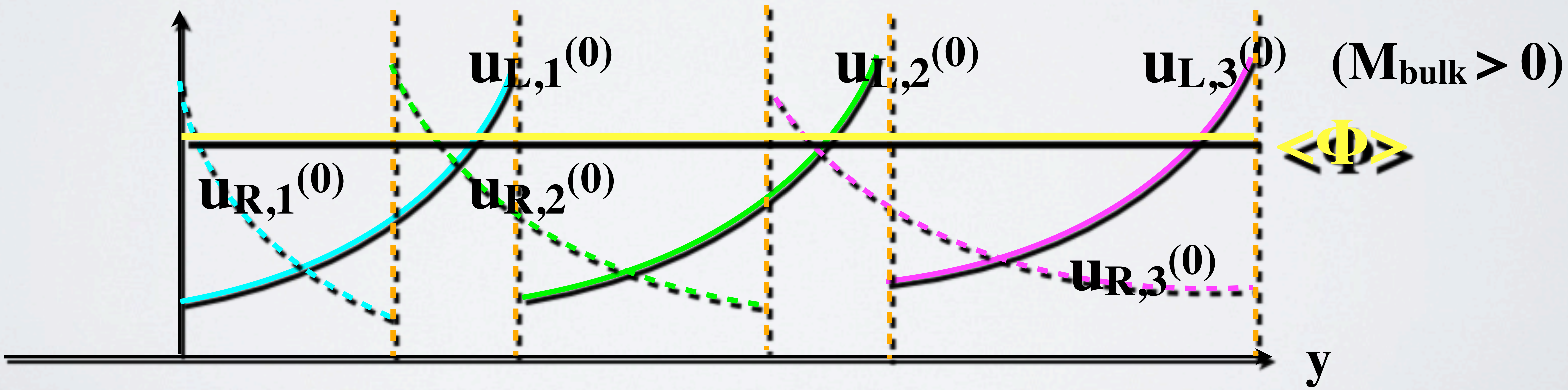


The system becomes periodic.

ordinary Higgs boundary condition

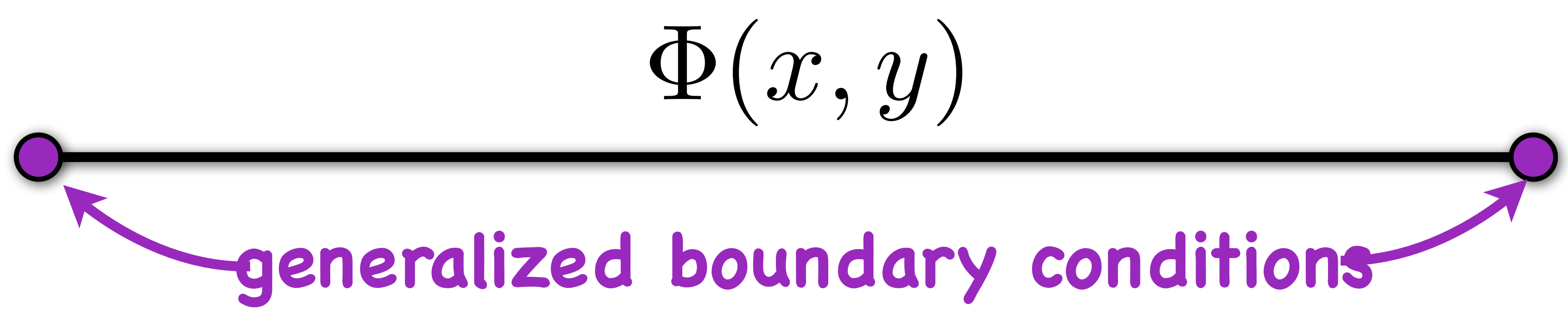
- Like minimal UED case:





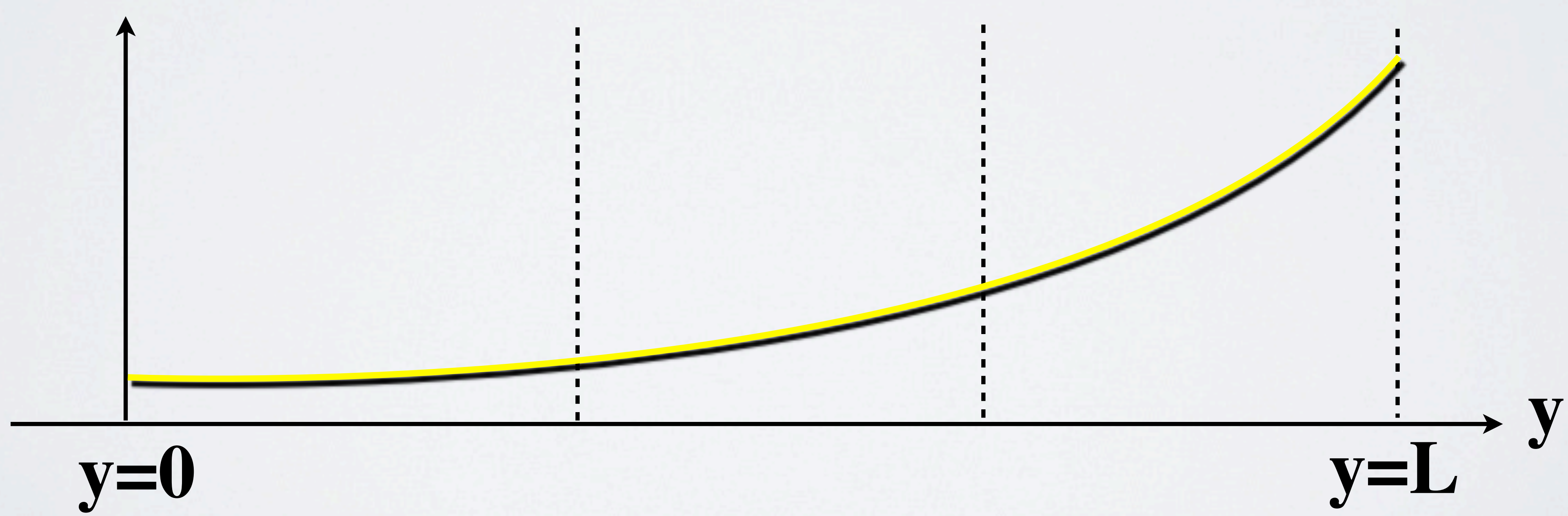
- At this stage, it is hard to generate large hierarchy.

generalized Higgs boundary condition



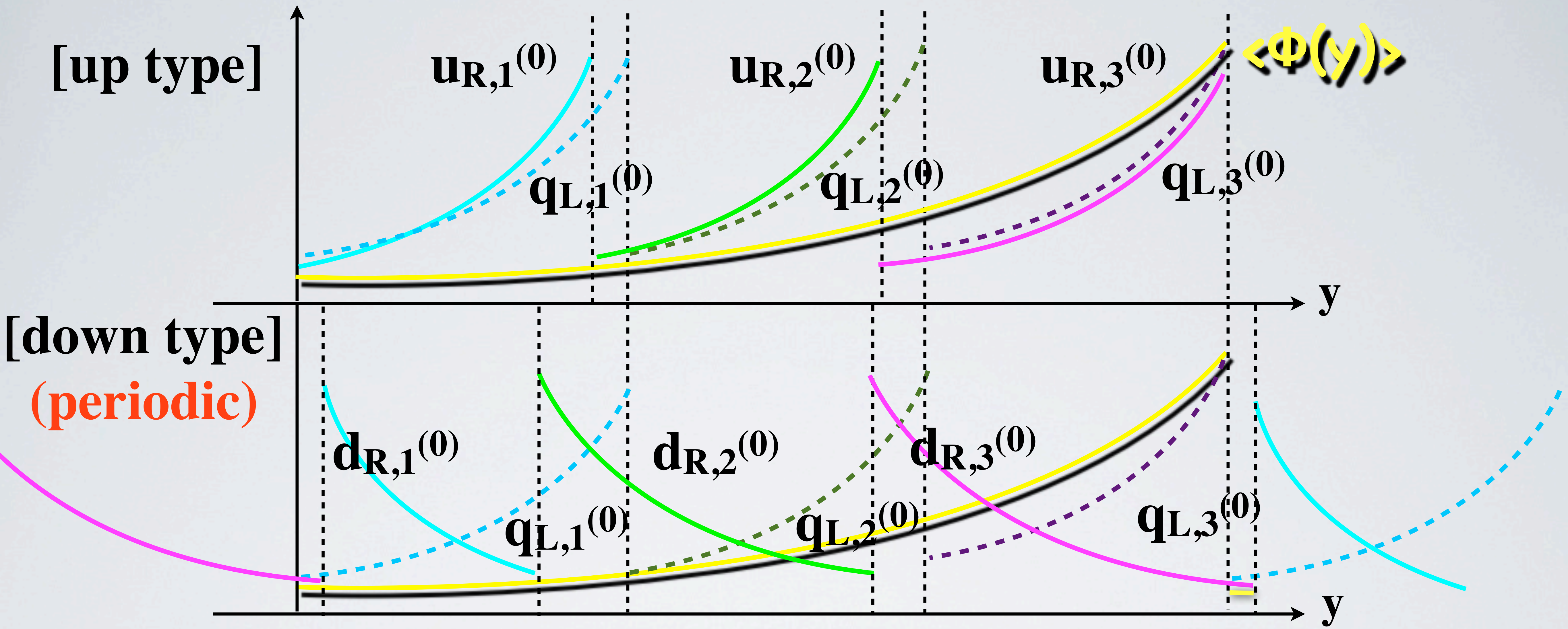
$$\Phi(0) + L_{+}\partial_y \Phi(0) = 0$$

$$\Phi(L) - L_{-}\partial_y \Phi(L) = 0 \quad (-\infty \leq L_{\pm} \leq \infty)$$

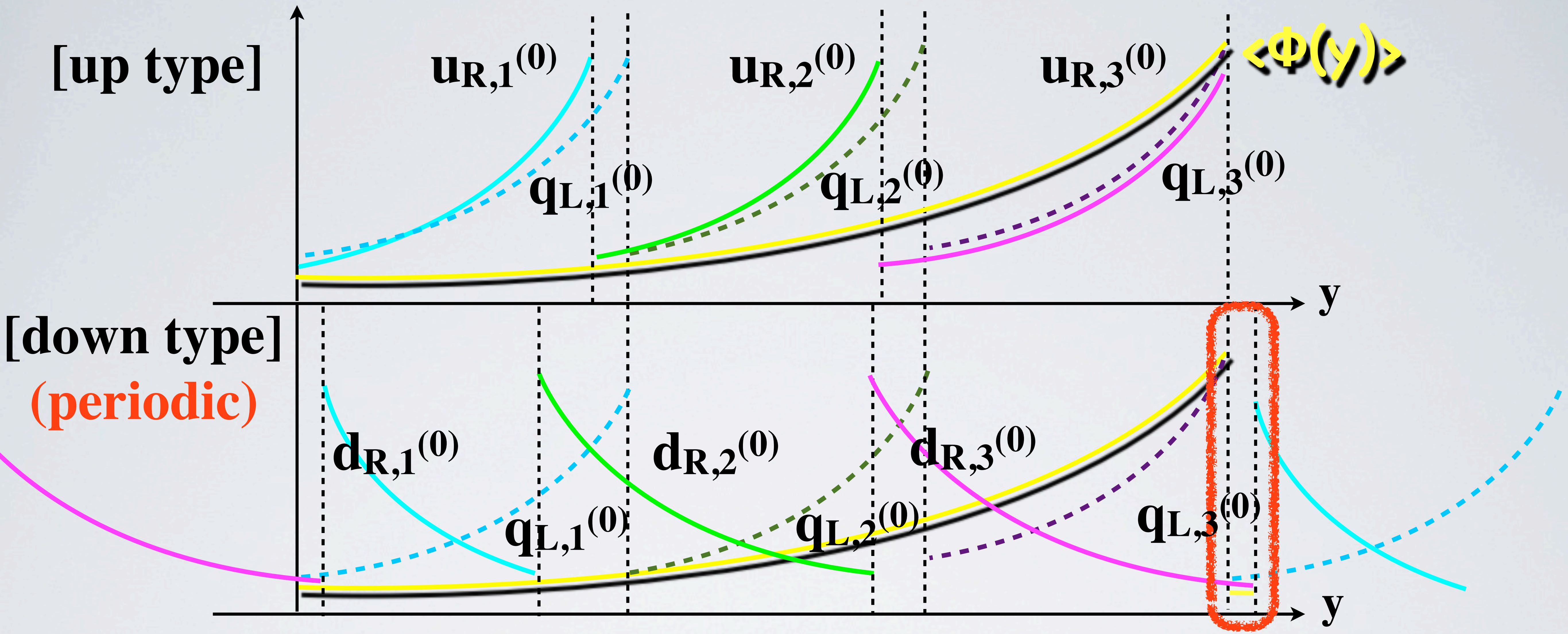


- We can find the “warped” Higgs VEV form.

up & down quark mass matrix



up & down quark mass matrix



1-3 mixing occurs due to the periodic profile

$$\mathcal{M}^{(u)} = \begin{bmatrix} m_{11}^{(u)} & m_{12}^{(u)} & 0 \\ 0 & m_{22}^{(u)} & m_{21}^{(u)} \\ 0 & 0 & m_{33}^{(u)} \end{bmatrix}, \quad \mathcal{M}^{(d)} = \begin{bmatrix} m_{11}^{(d)} & m_{12}^{(d)} & m_{13}^{(d)} \\ 0 & m_{22}^{(d)} & m_{21}^{(d)} \\ 0 & 0 & m_{33}^{(d)} \end{bmatrix}$$

Obtained CKM matrix

with good precision

$$|V_{\rm CKM}| = \begin{pmatrix} 0.976 & 0.216 & 0.00313 \\ 0.216 & 0.975 & 0.0498 \\ 0.0138 & 0.0480 & 0.999 \end{pmatrix}.$$

~60% larger than exp. value

Obtained CKM matrix

with good precision

$$|V_{\rm CKM}| = \begin{pmatrix} 0.976 & 0.216 & 0.00313 \\ 0.216 & 0.975 & 0.0498 \\ 0.0138 & 0.0480 & 0.999 \end{pmatrix}.$$

~60% larger than exp. value

We can (almost) explain the three issues of

- generations
- large mass hierarchy
- CKM (small) mixing

simultaneously via geometry.

Obtained CKM matrix

with good precision

$$|V_{\rm CKM}| = \begin{pmatrix} 0.976 & 0.216 & 0.00313 \\ 0.216 & 0.975 & 0.0498 \\ 0.0138 & 0.0480 & 0.999 \end{pmatrix}.$$

~60% larger than exp. value

We can (almost) explain the three issues of

- generations
- large mass hierarchy
- CKM (small) mixing

simultaneously via geometry.

→ Next theme: deriving leptons' large mixing

UED with tree-level brane-localized terms

- dark matter candidate
- top quark forward-backward asymmetry(?)
- ATIC anomaly(?)

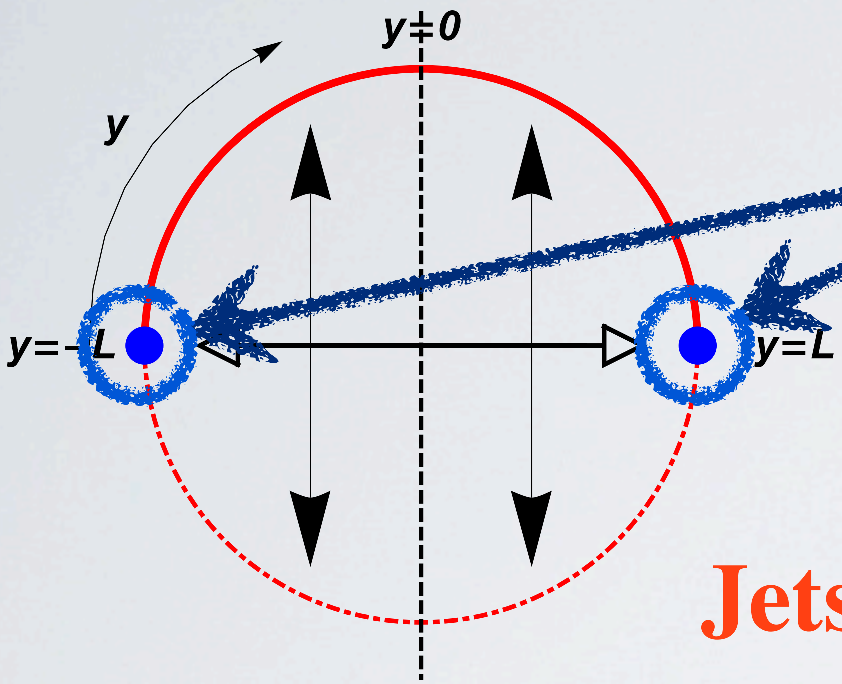
In collaboration with

Aseshkrishna Datta (Harish-Chandra Research Institute)
Saurabh Niyogi (Harish-Chandra Research Institute)

arXiv:1206.3987

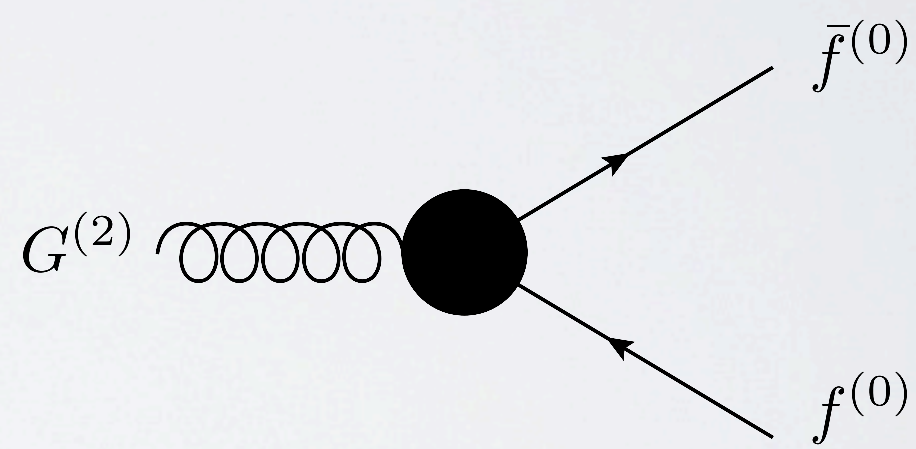
deforming minimal UED

We can consider a extended model without losing existence of dark matter candidate.



Introducing (tree-level) brane-localized terms

Jets are hard.



tree-level KK momentum violating interactions exist.

!?

- top quark forward-backward asymmetry
- ATIC anomaly

non-minimal "QCD"

[F.del Aguila,M.Perez-Victoria,J.Santiago] (2003,2004)
[T.Flacke,A.Menon.D.J.Phalen] (2009)

- **[Gluon part]**

$$S_{\text{gluon}} = \int d^4x \int_{-L}^{L} dy \left\{ -\frac{1}{4} G^a_{MN} G^{aMN} + \Big(\delta(y-L) + \delta(y+L)\Big) \left[-\frac{r_G}{4} G^a_{\mu\nu} G^{a\mu\nu} \right] \right\}$$

$$S_{\text{gluon,gf}} = \int d^4x \int_{-L}^{L} dy \left\{ -\frac{1}{2\xi_G} \left(\partial_\mu G^{a\mu} - \xi_G \partial_y G^a_y\right)^2 - \frac{1}{2\xi_{G,b}} \left[\left(\partial_\mu G^{a\mu} + \xi_{G,b} G^a_y\right)^2 \delta(y-L) + \left(\partial_\mu G^{a\mu} - \xi_{G,b} G^a_y\right)^2 \delta(y+L) \right] \right\},$$

- **[Qaurk part]**

Brane terms are 4D gauge invariant.

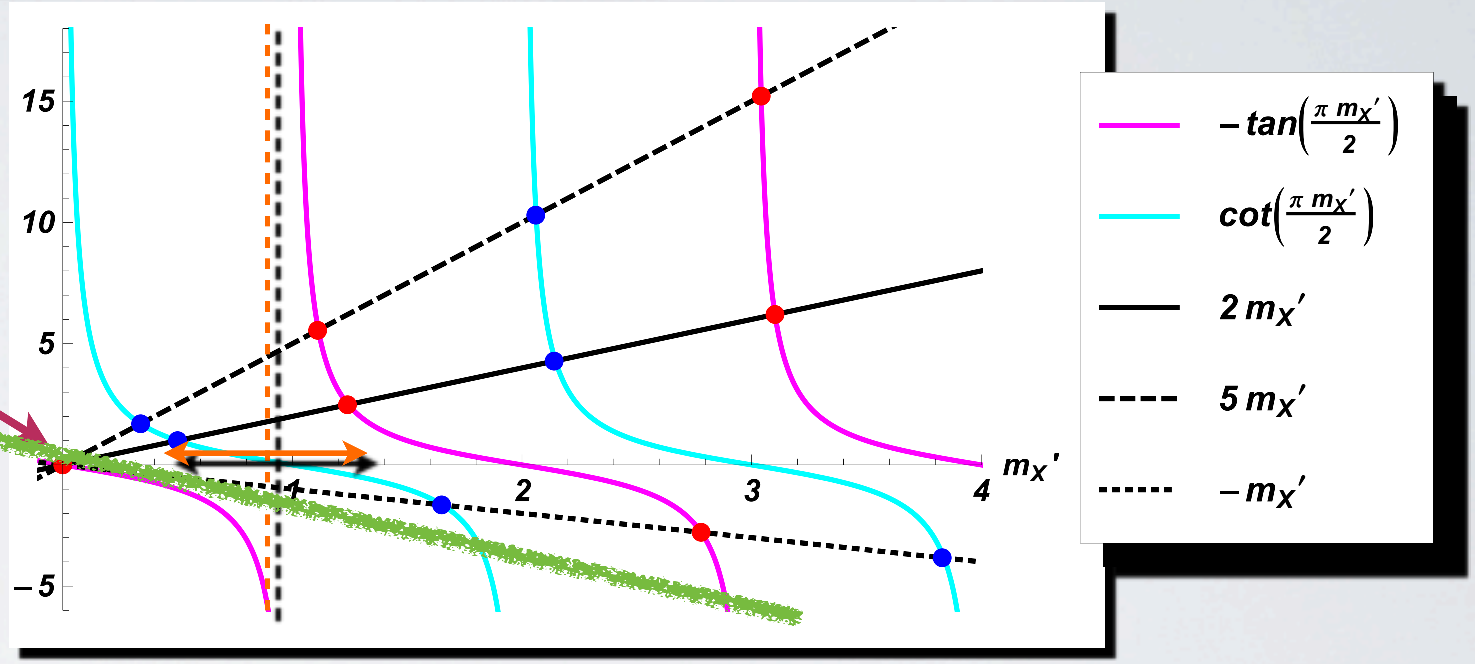
$$\begin{aligned} S_{\text{quark}} = \int d^4x \int_{-L}^{L} dy \sum_{i=1}^{3} \Big\{ & i\overline{U}_i \Gamma^M \mathcal{D}_M U_i + r_Q \Big(\delta(y-L) + \delta(y+L)\Big) \left[i\overline{U}_i \gamma^\mu \mathcal{D}_\mu P_L U_i \right] \\ & + i\overline{D}_i \Gamma^M \mathcal{D}_M D_i + r_Q \Big(\delta(y-L) + \delta(y+L)\Big) \left[i\overline{D}_i \gamma^\mu \mathcal{D}_\mu P_L D_i \right] \\ & + i\overline{u}_i \Gamma^M \mathcal{D}_M u_i + r_Q \Big(\delta(y-L) + \delta(y+L)\Big) \left[i\overline{u}_i \gamma^\mu \mathcal{D}_\mu P_R u_i \right] \\ & + i\overline{d}_i \Gamma^M \mathcal{D}_M d_i + r_Q \Big(\delta(y-L) + \delta(y+L)\Big) \left[i\overline{d}_i \gamma^\mu \mathcal{D}_\mu P_R d_i \right] \Big\}, \end{aligned}$$

KK Mass spectrum

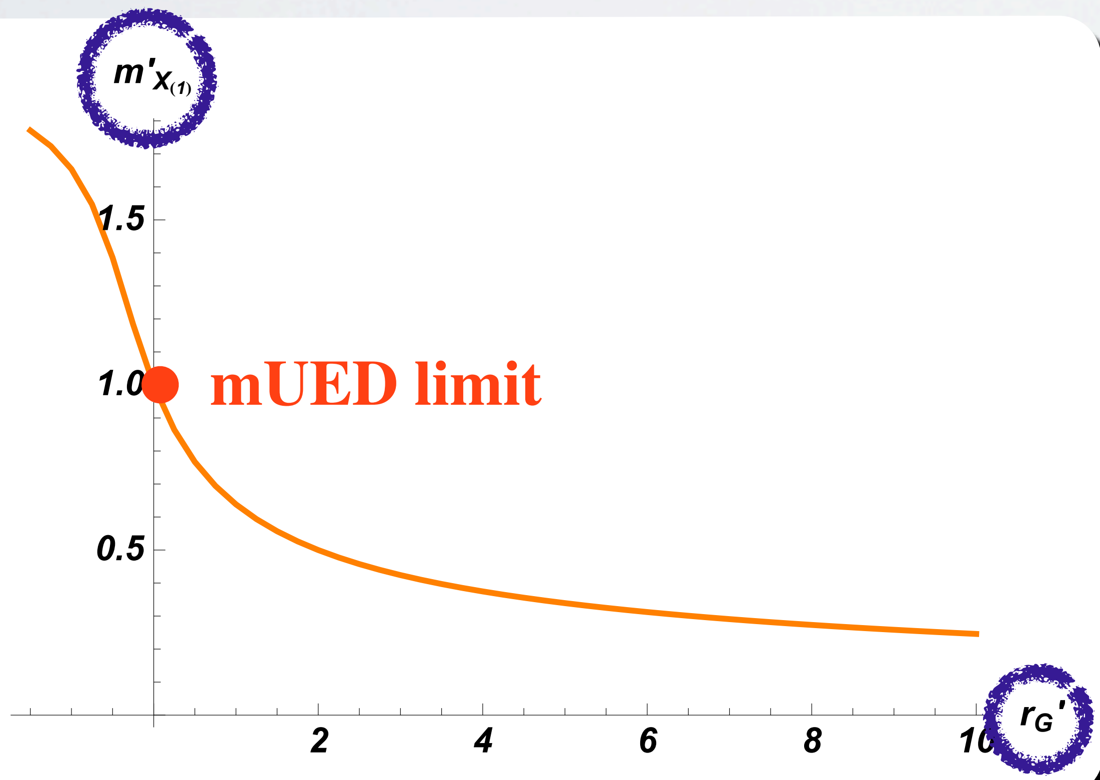
$$r_G m_{G_{(n)}} = \begin{cases} -T_{G_{(n)}} & \text{for } n \text{ even} \\ 1/T_{G_{(n)}} & \text{for } n \text{ odd} \end{cases}$$

value of KK mass is changed

massless mode exists irrespective of r_G



$-\pi/2\ m'_X$



mUED limit

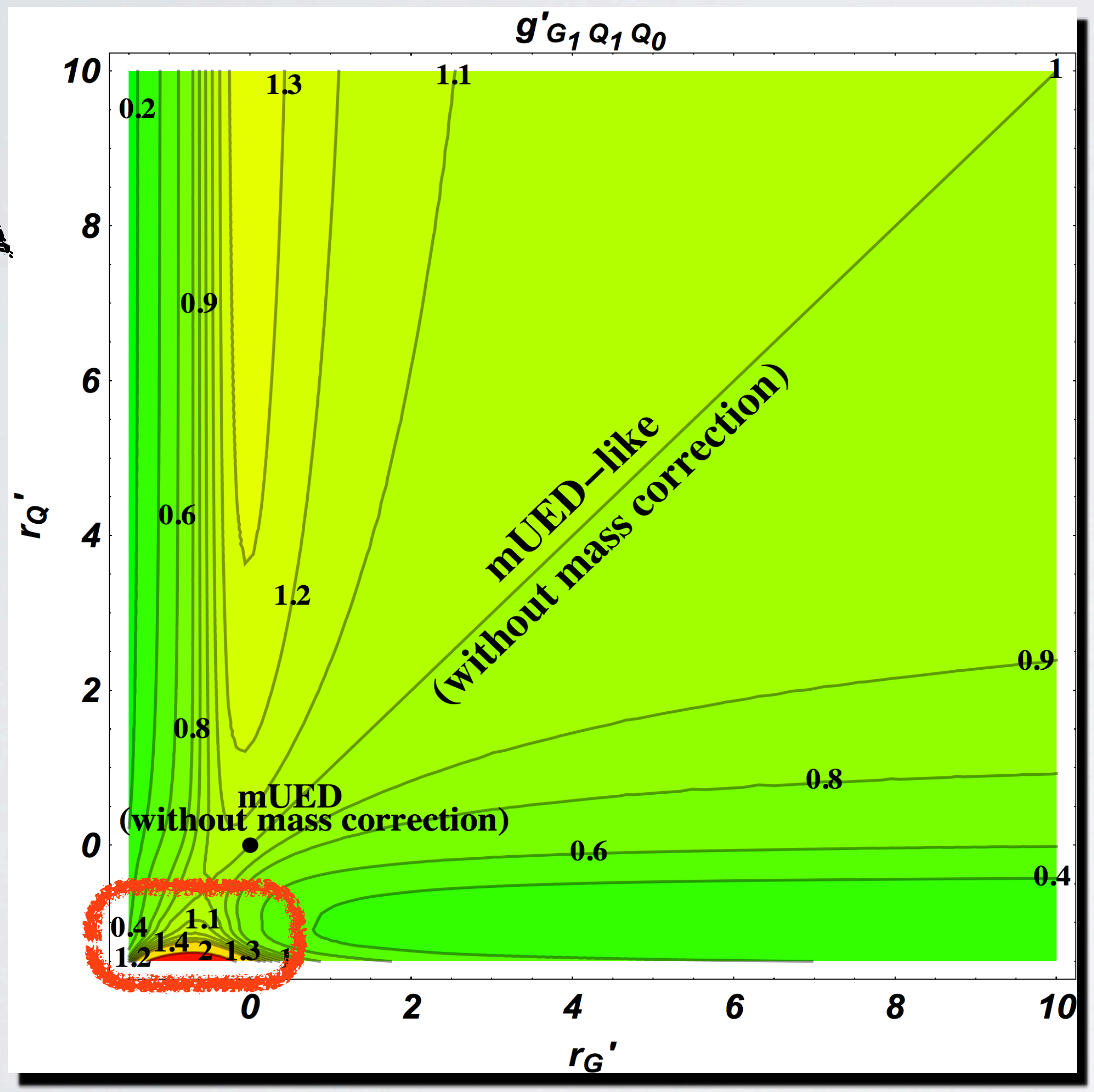
$$r_X m_{X_{(1)}} = 1/T_{X_{(1)}} = r'_X m'_{X_{(1)}}$$

$$(r_X \equiv r'_X R,\ m_{X_{(1)}} \equiv m'_{X_{(1)}}/R)$$

scaled values

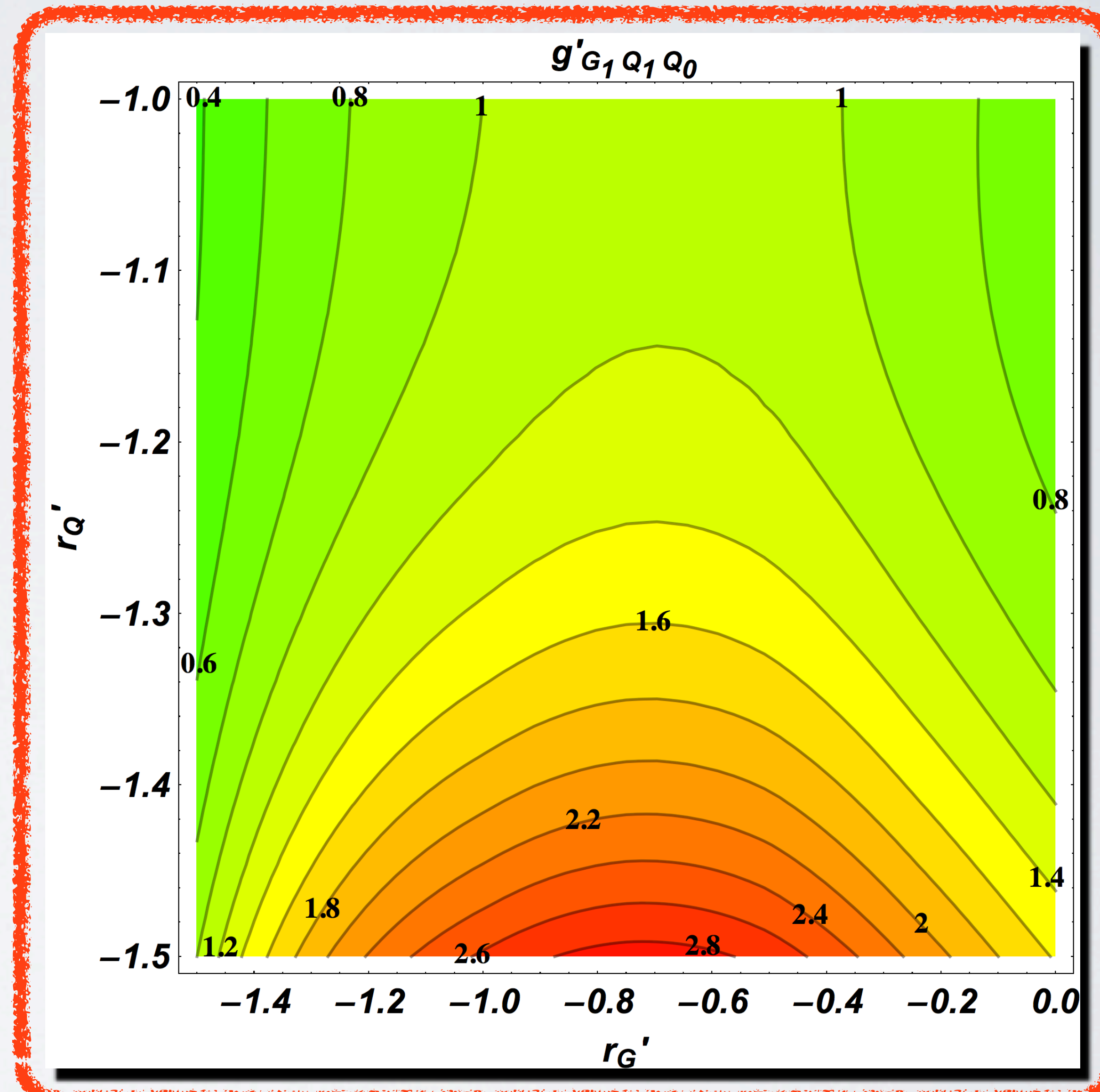
G_1-Q_1-Q_0 gauge coupling

Nontrivial interference occurs between mode functions of 1st KK quark & gluon.

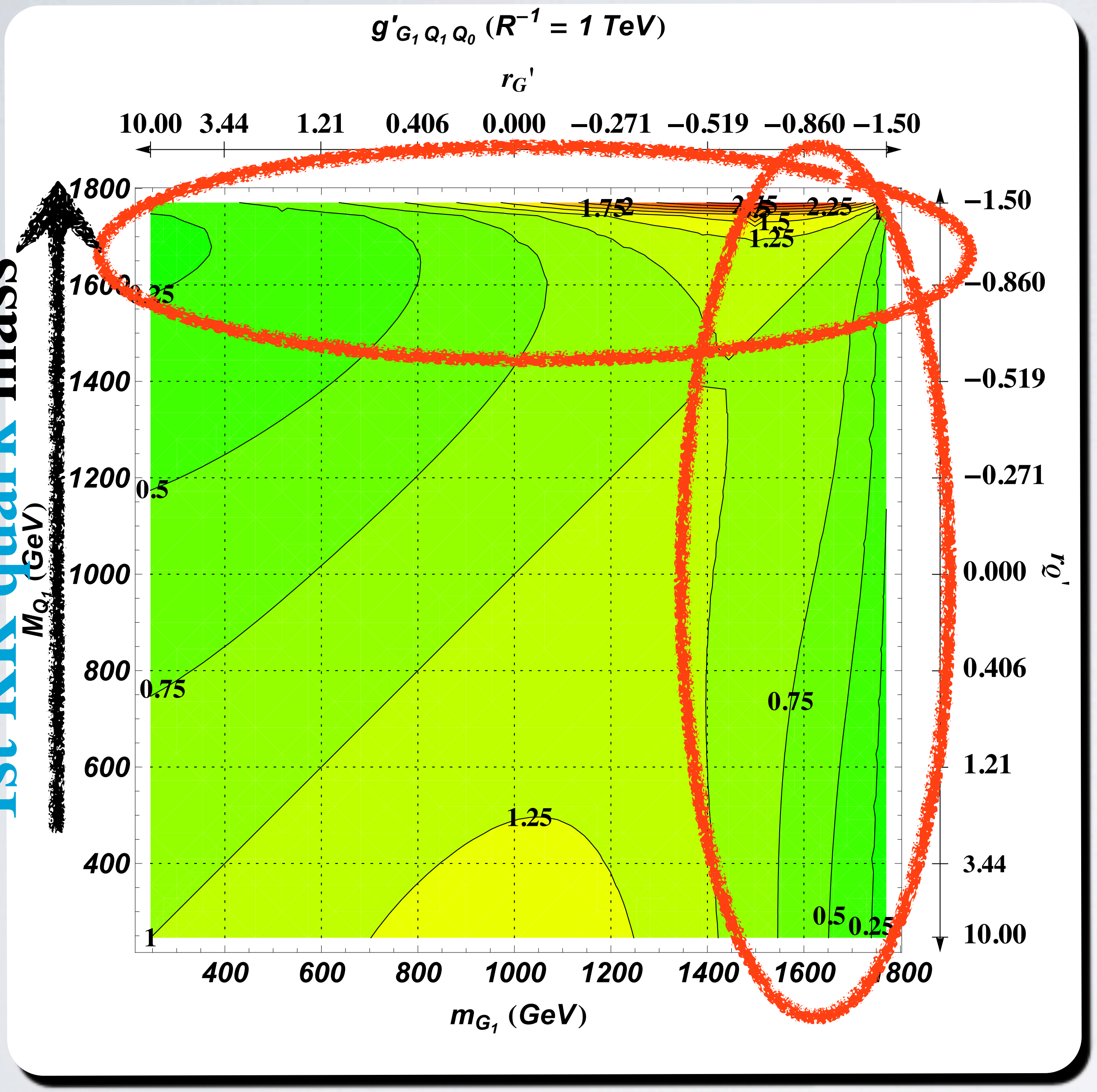


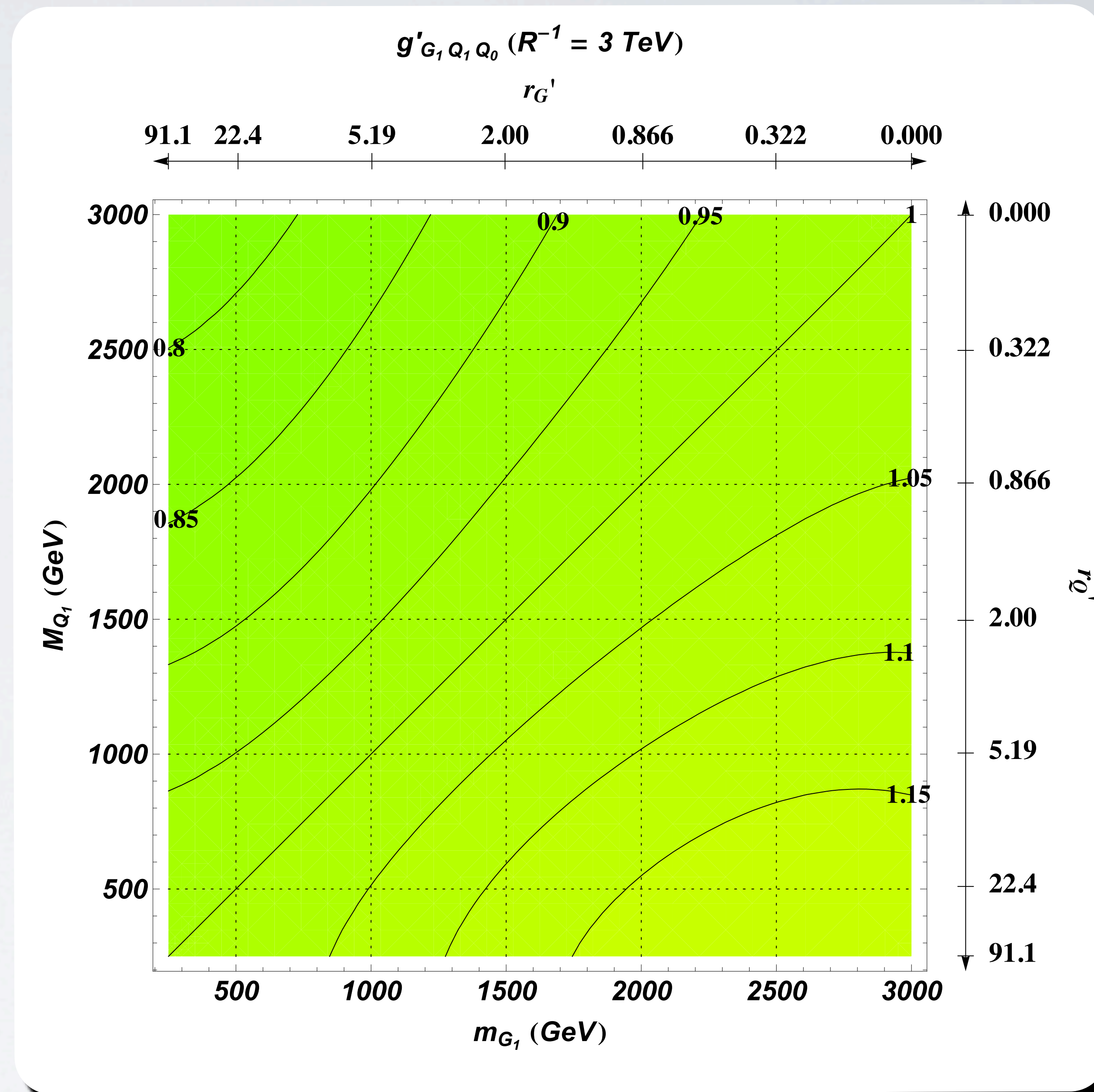
quark coefficient

gluon coefficient



After choosing R-1, the coupling becomes a function of 1st KK masses.

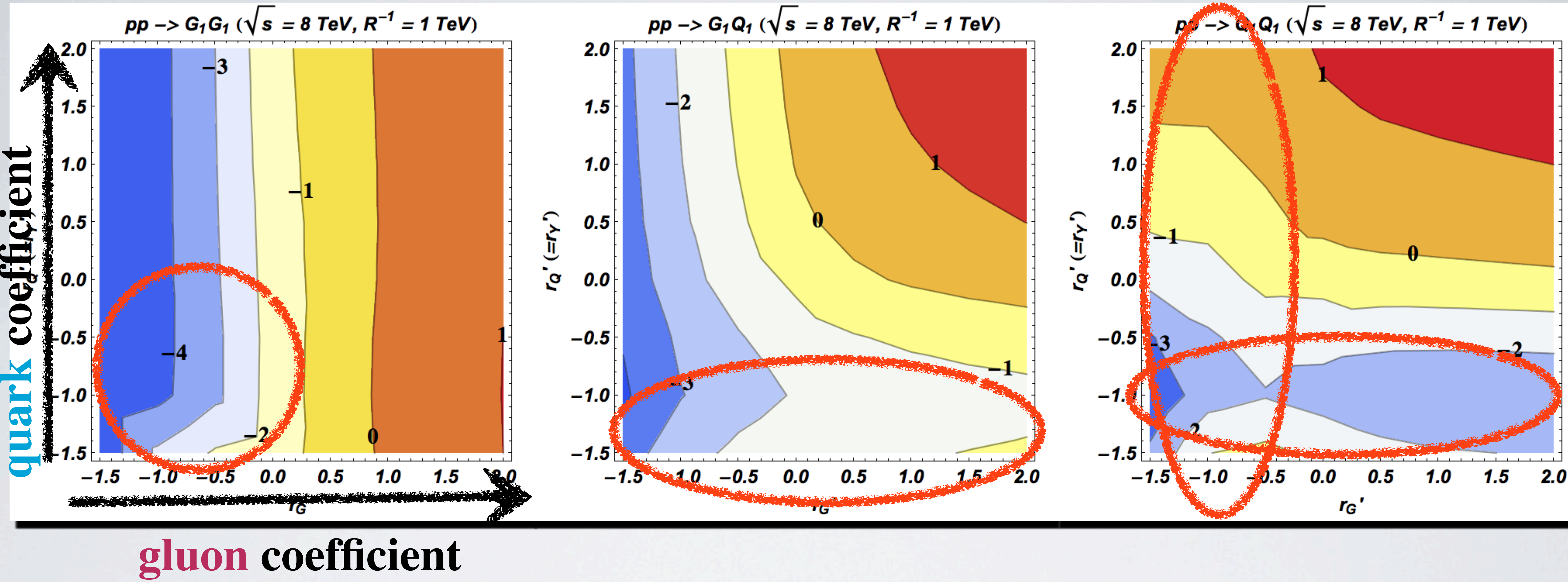




1st KK quark mass

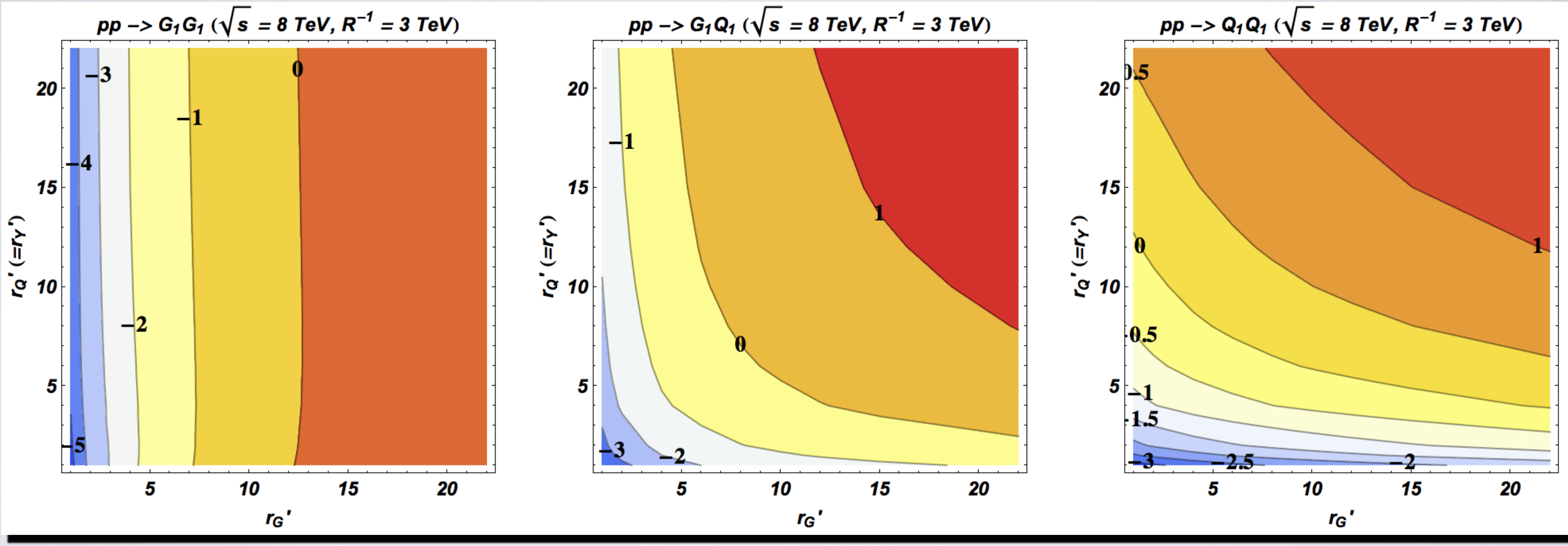
1st KK gluon mass

8TeV run with R^{-1} = 1 TeV



There are anomalous regions.

8TeV run with R^{-1} = 3 TeV



No anomalous region.

Summary

- **UED on 6D geometry.**
  - ■ Retest LHC results prefer (6D) UEDs.
- **UED with junction points(additional boundary).**
  - ■ Generations, mass hierarchy, CKM matrix are explained simultaneously via geometry.
- **UED with tree-level brane-localized terms.**
  - ■ In lower R^{-1} case, anomalous strong coupling region emerges.

Summary

- UED on 6D geometry.
  - Retest LHC results prefer (6D) UEDs.
- UED with junction points(additional boundary).
  - Generations, mass hierarchy, CKM matrix are explained simultaneously via geometry.
- UED with tree-level brane-localized terms.
  - In lower R^{-1} case, anomalous strong coupling region emerges.
    - deviation in muon g-2
    - baryon asymmetry

Summary

- **UED on 6D geometry.**
  - ■ Retest LHC results prefer (6D) UEDs.
- **UED with junction points(additional boundary).**
  - ■ Generations, mass hierarchy, CKM matrix are explained simultaneously via geometry.
- **UED with tree-level brane-localized terms.**
  - ■ In lower R^{-1} case, anomalous strong coupling region emerges.
    - deviation in muon g-2
    - baryon asymmetry
  - ■ Adding new particle.

Thank

you

for

your attention