EXTRA DIMENSIONS

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東北大学
TOHOKU UNIVERSITY

OUTLINE

- XD models: RS, UED, ADD
- Experimental status
- Black hole ?
- Higgs on XD

SM AND BSM

SM

$$D = 4$$

$$G_{SM} = SU(3) \times SU(2) \times U(1)$$

$$\Psi = (Q_L, u_R, d_R, L_L, e_R)_{g=1,2,3}$$

$$H$$

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(Ψ, Ψ_n)

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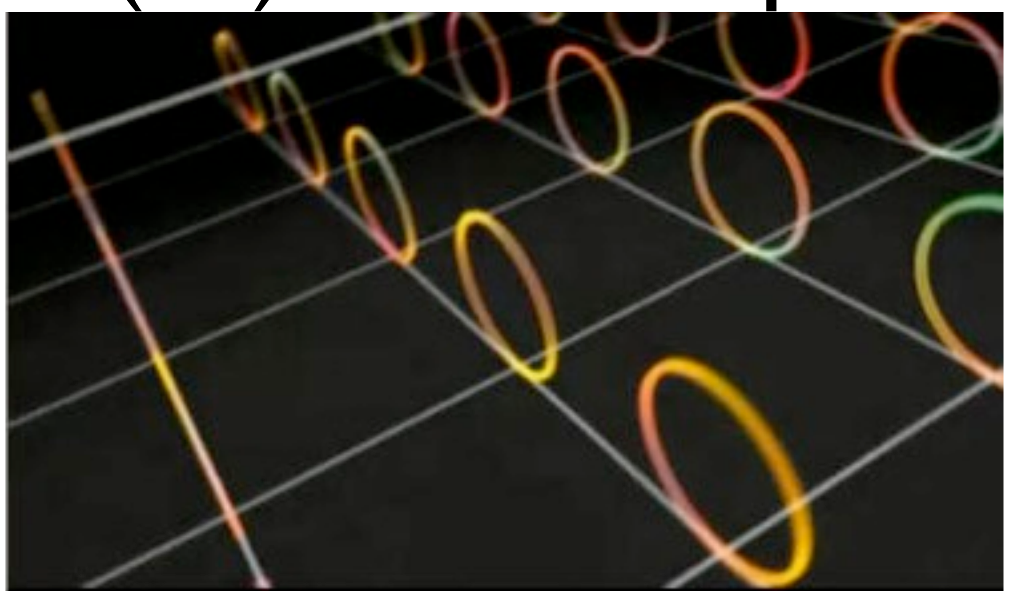
XD= BOSONIC SUSY

Kaluza-Klein states

D=4+1 :

(ex)circle compactification



$$\partial^2 = \partial_0^2 - \partial_i^2 \; - \partial_{new}^2$$

$$p^2 = E^2 - p_i^2 \; - p_{new}^2 \quad = m^2$$

$$E^2 = p_i^2 + m^2 + p_{new}^2$$

$$m_n^2 = m^2 + n^2/R^2$$

$$p_{new} = n/R$$

(momentum quantization)

(Kaluza-Klein spectrum)

KALUZA-KLEIN STATES

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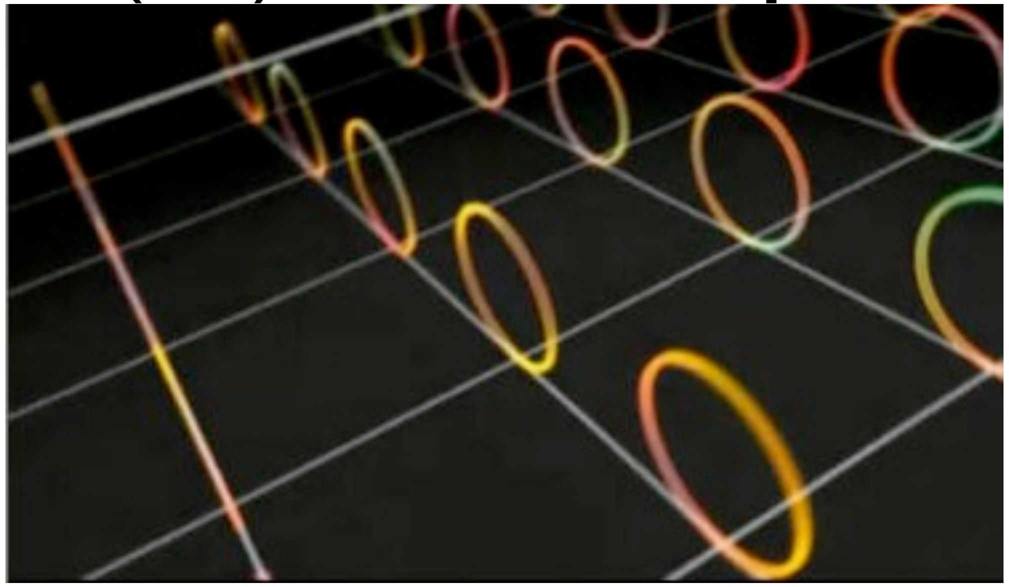
SEARCHING FOR XD =FINDING KK MODES



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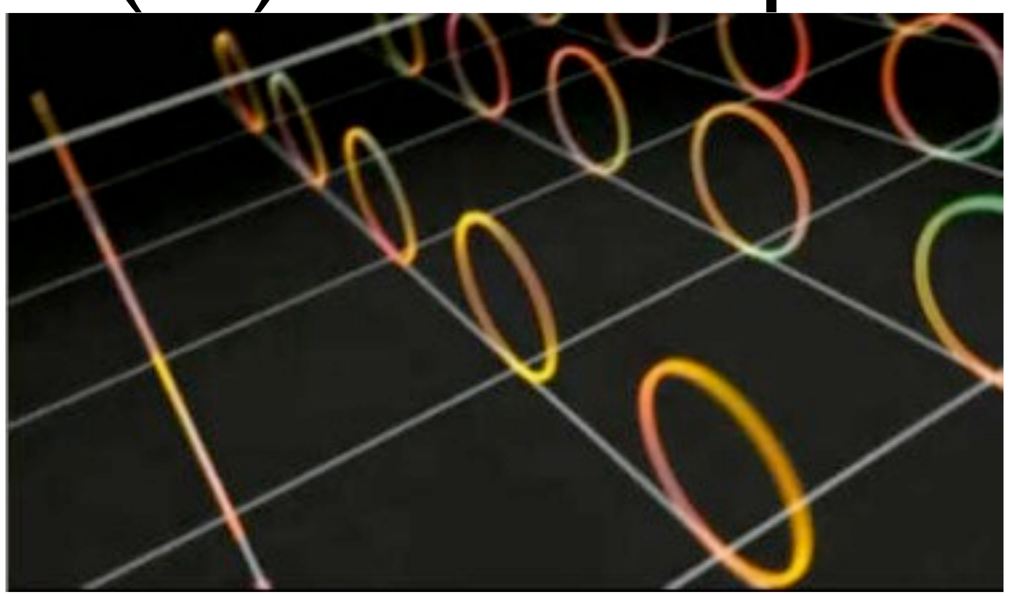

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Searching for XD =Finding KK modes

t',W',Z', g' ....
:heavy partners of SM particles

$$+ p_{new}^2$$

$$m^2 + n^2/R^2$$

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KALUZA-KLEIN STATES

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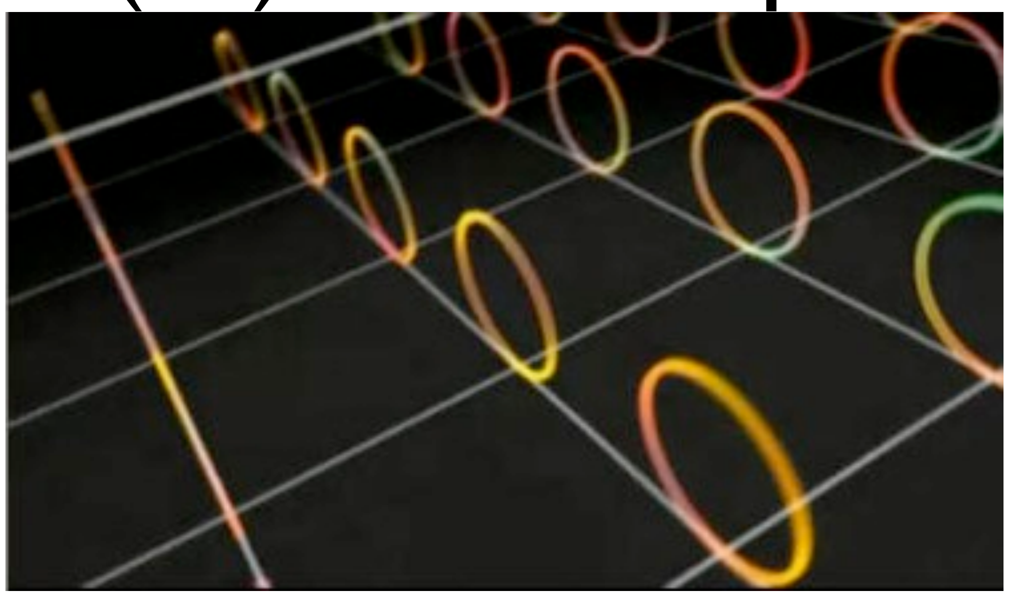

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...a-Klein spectrum)

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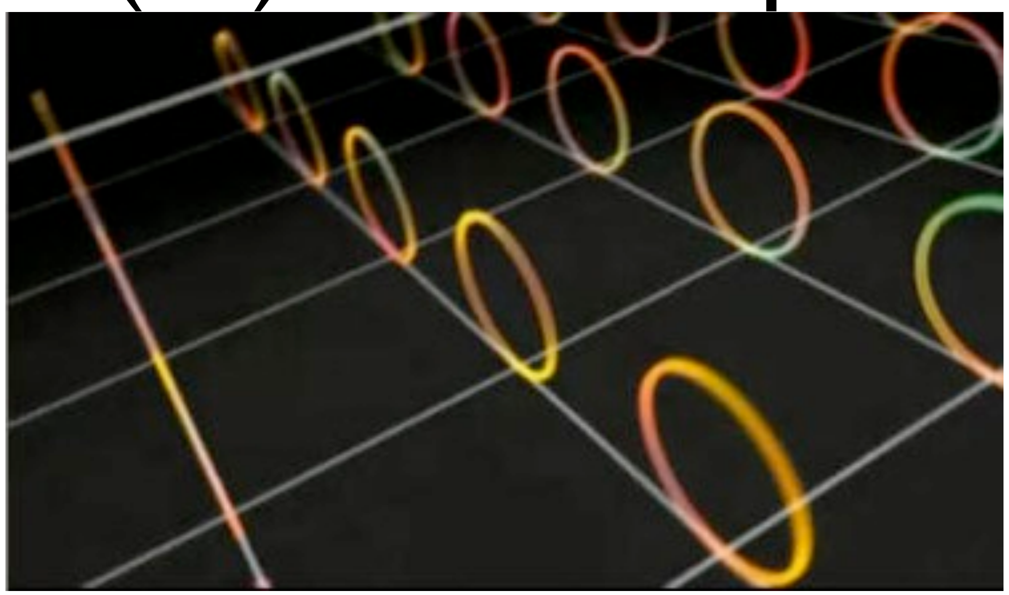

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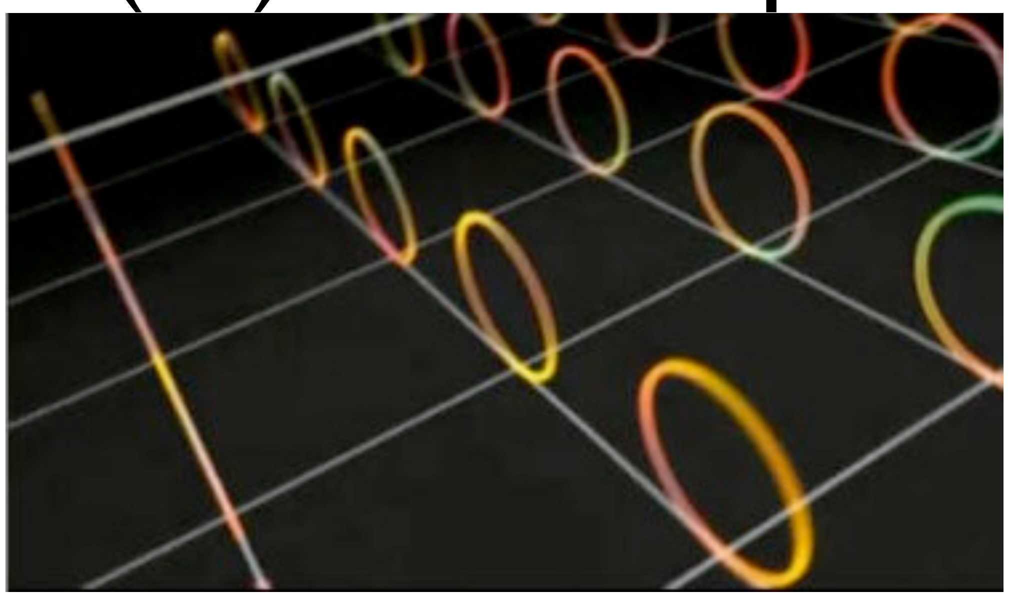

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SEARCHING FOR XD =FINDING KK MODES

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:heavy partners of SM particles

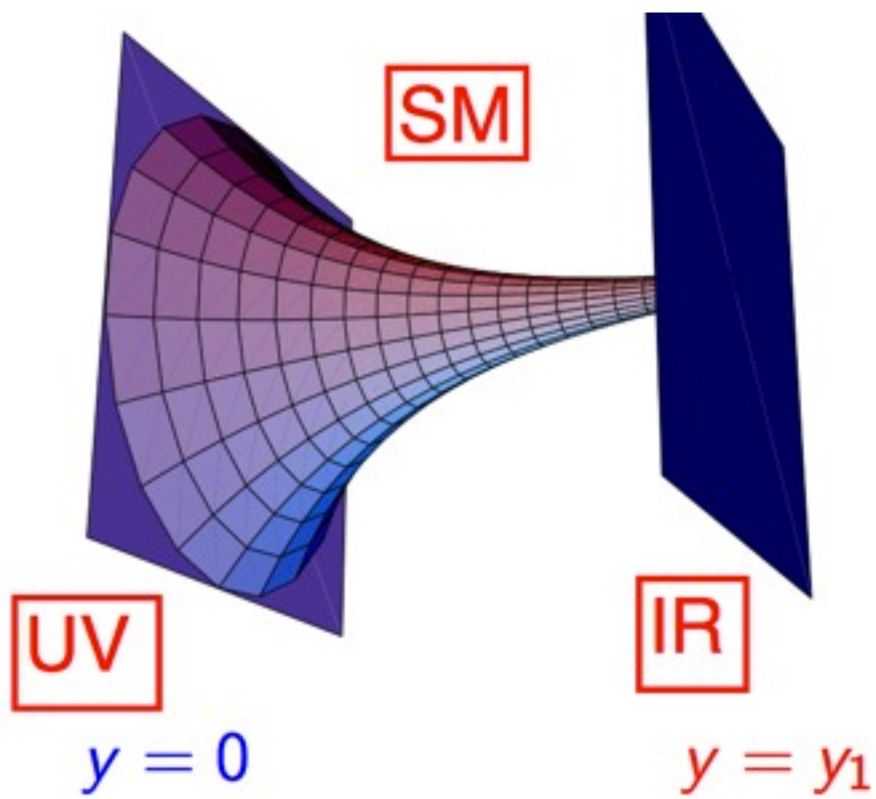
- How heavy? How to interact with SM?
- Depends on "volume" and "shape"
- +locations of each particle in XD

"VOLUME" AND "SHAPE"

- In principle, we can learn the size and shape of XD by measuring enough number of KK-particles and their interactions.
- we need big energy to go over the mass gap ($\sim E_{CM} > 2/R$ 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 ..
- ..today, I only cover the three models, namely UED, RS and ADD models, which can get directly checked by the LHC

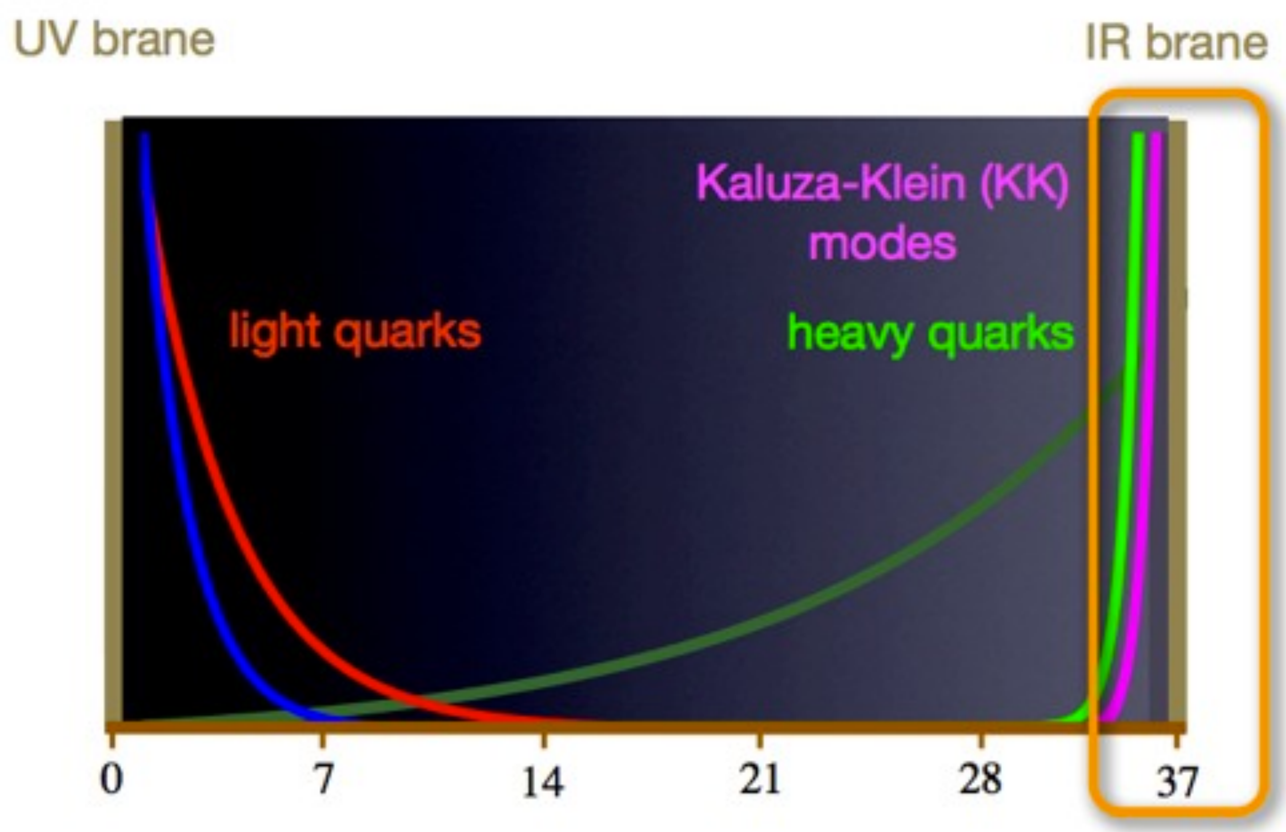
RS

Randall,Sundrum (1999)



$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - y^2$$

- The bulk has a sizable (negative) cosmological constant .. AdS_5
- Warped geometry in an interval $(y_{UV}, y_{IR}) \sim (0, y_1)$
- The hierarchy problem is solved by the large warping: $\Lambda(y) = \Lambda_{UV}\, e^{-k\, y} \sim$ TeV at IR boundary
- In the original version, all particles except gravitons are on the IR boundary... they all feel the low scale gravity
- Later, it is realized that all the particles except the Higgs can live in the bulk.

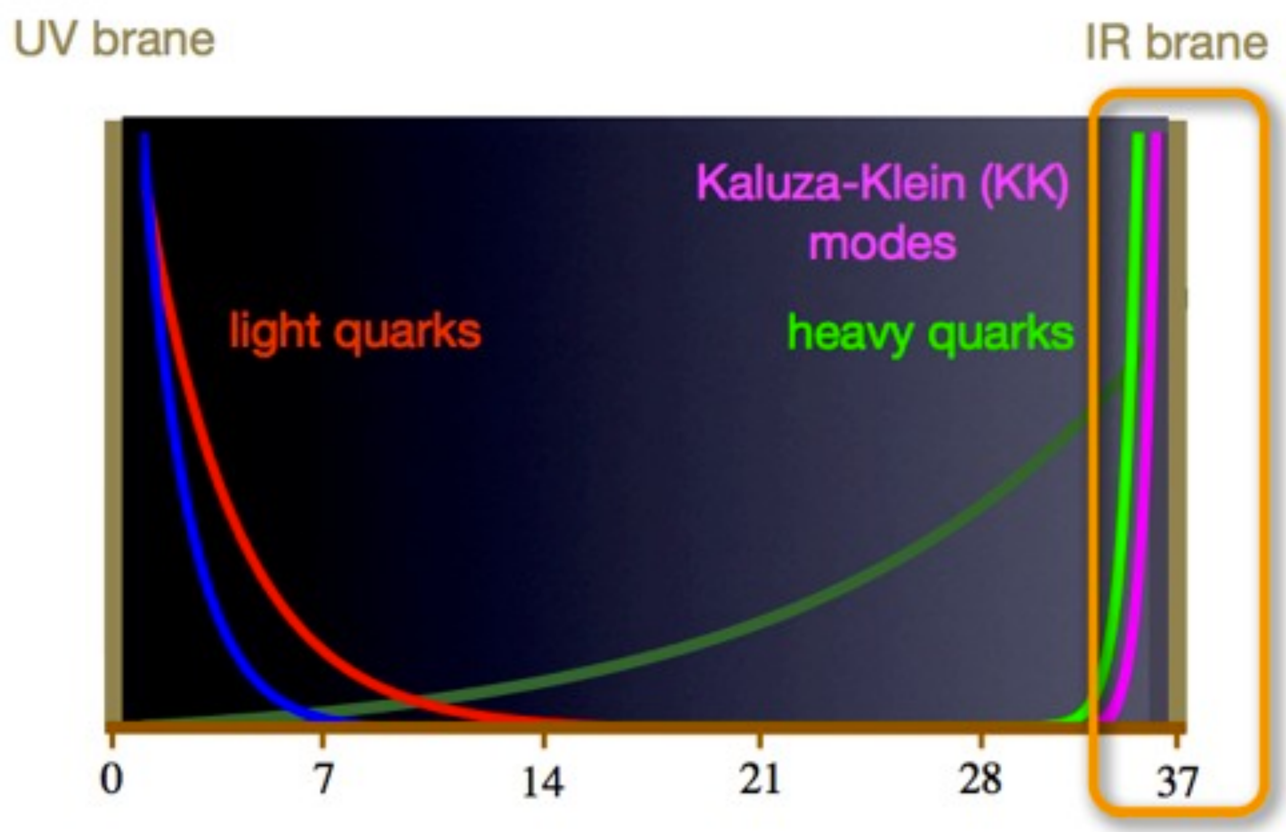


- By putting all the particles in the bulk, the model can be a beautiful model of flavor hierarchy : top has a large overlap with the higgs boson so has a large Yukawa coupling..light quarks small overlap.

- RS-GIM mechanism protects severe FCNC problems.

- KK-gluon, W,Z could be produced (signatures depends where the light fermions locate..)

- Microscopic black holes may also be produced and decays to multi-tops, Higgses, gluon jets



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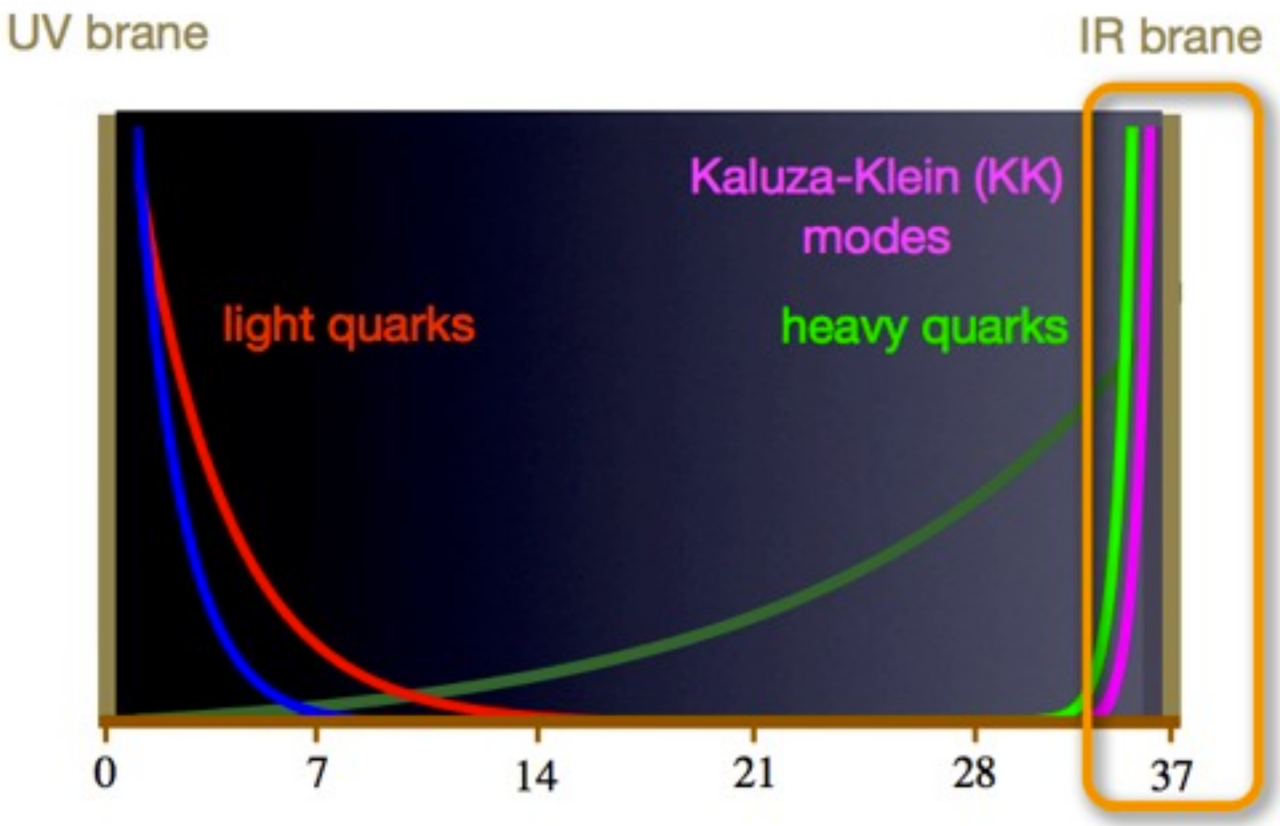

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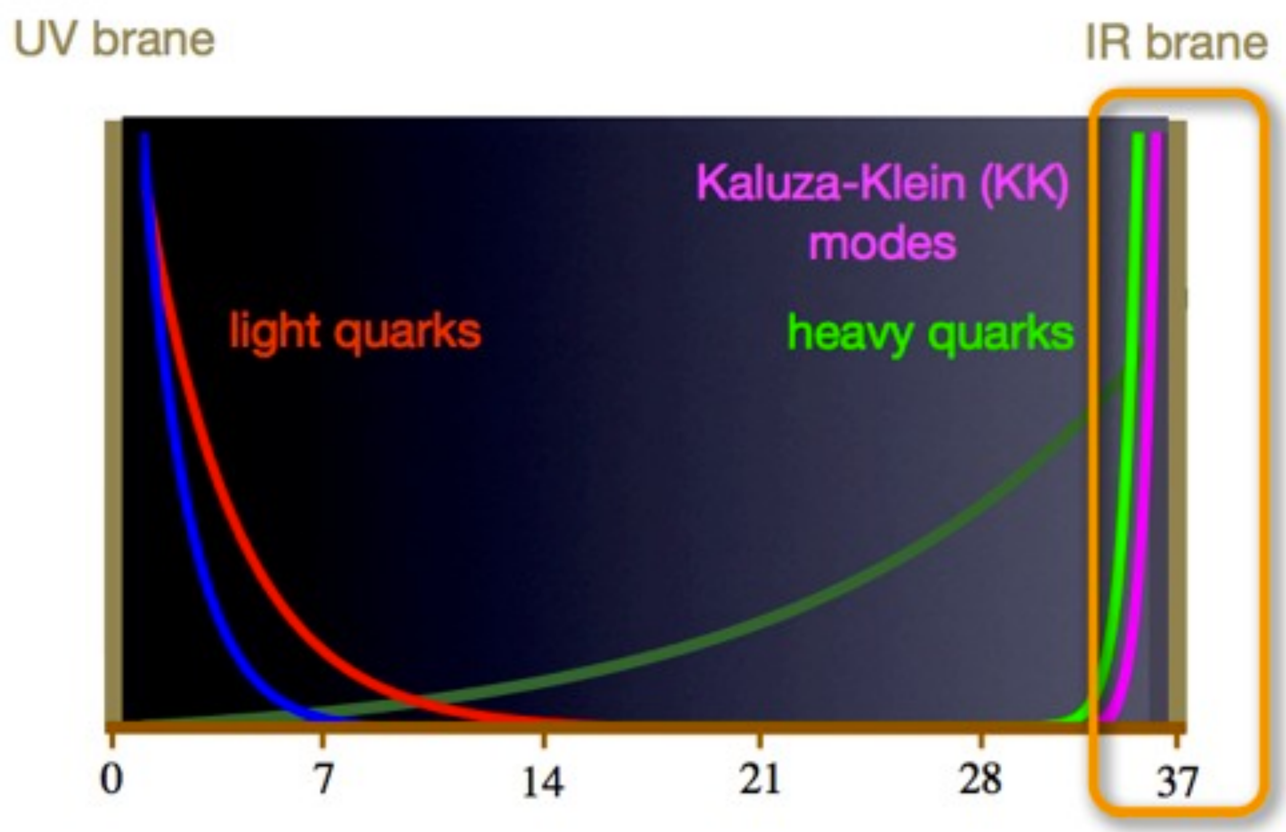

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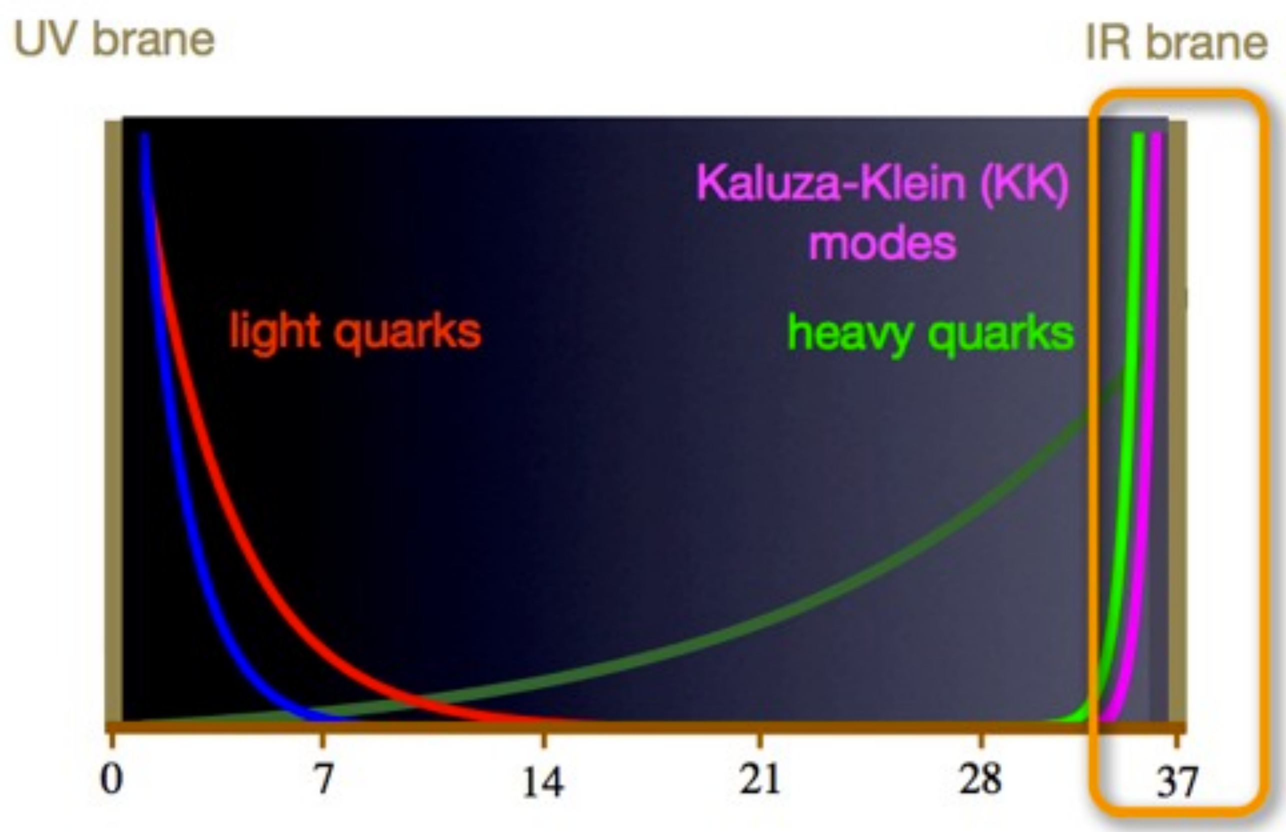

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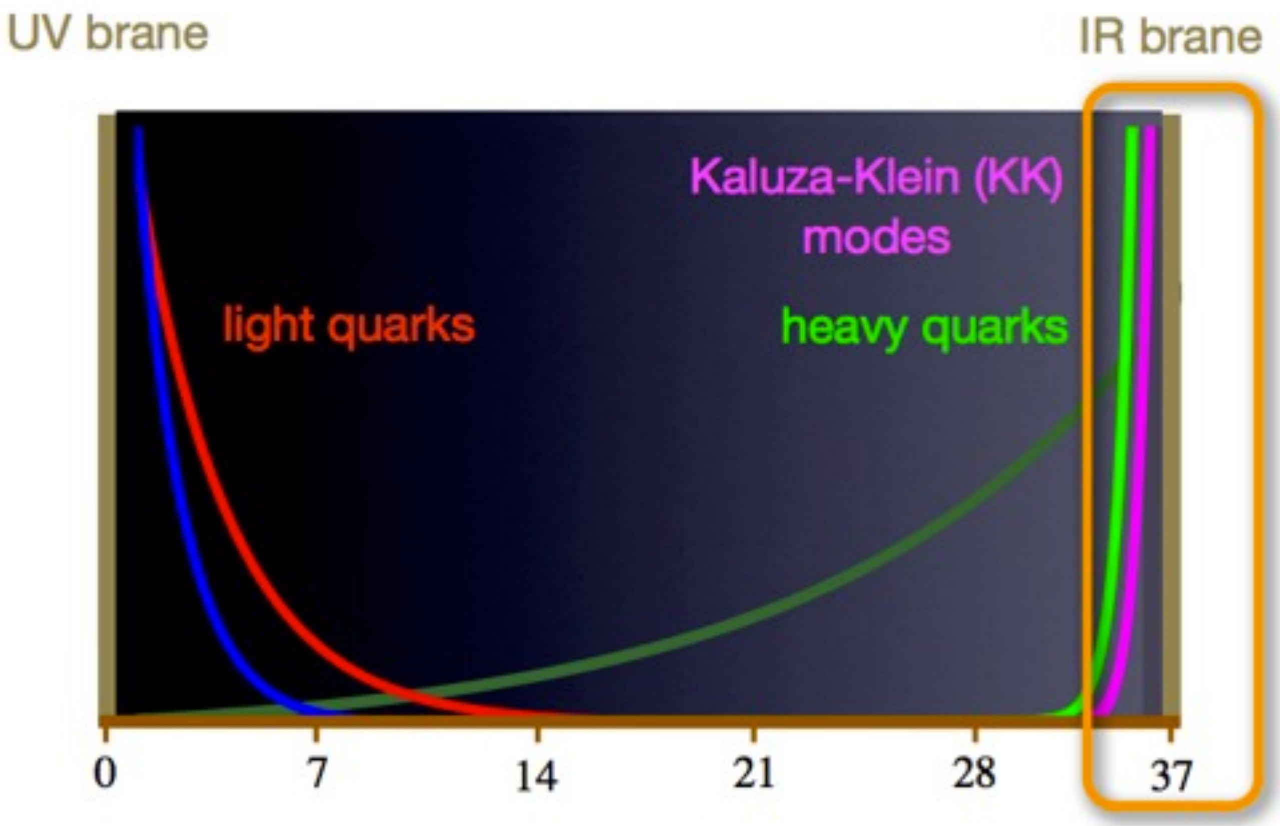

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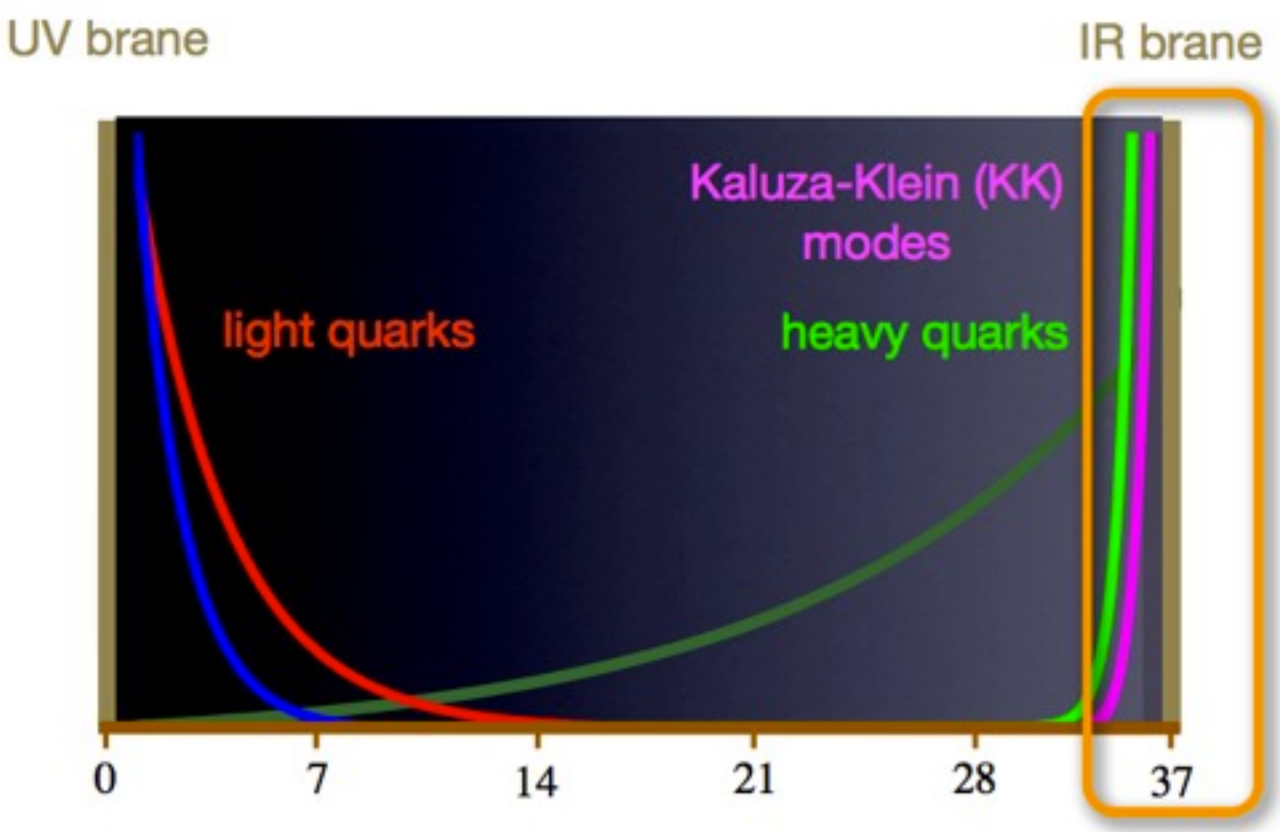

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Q.Where's DM?

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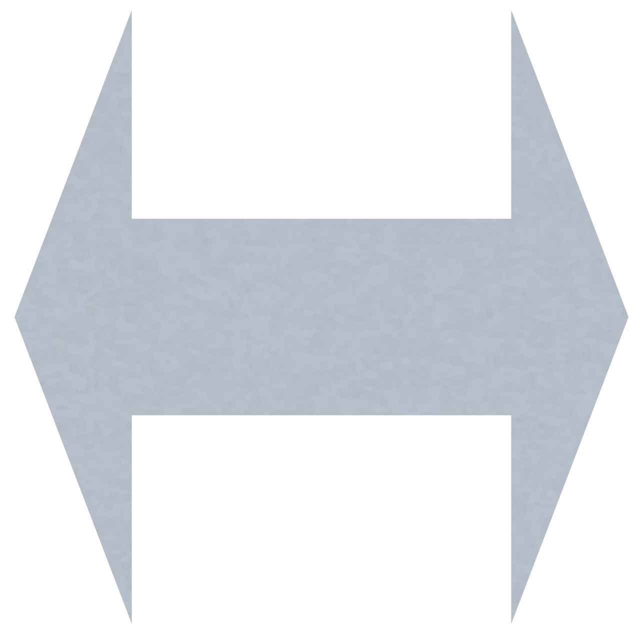
IN GENERAL...



In 'symmetric' extra dimension, we can immediately find a good geometric $\mathbb{Z}_2$ symmetry: the reflection about the middle point:

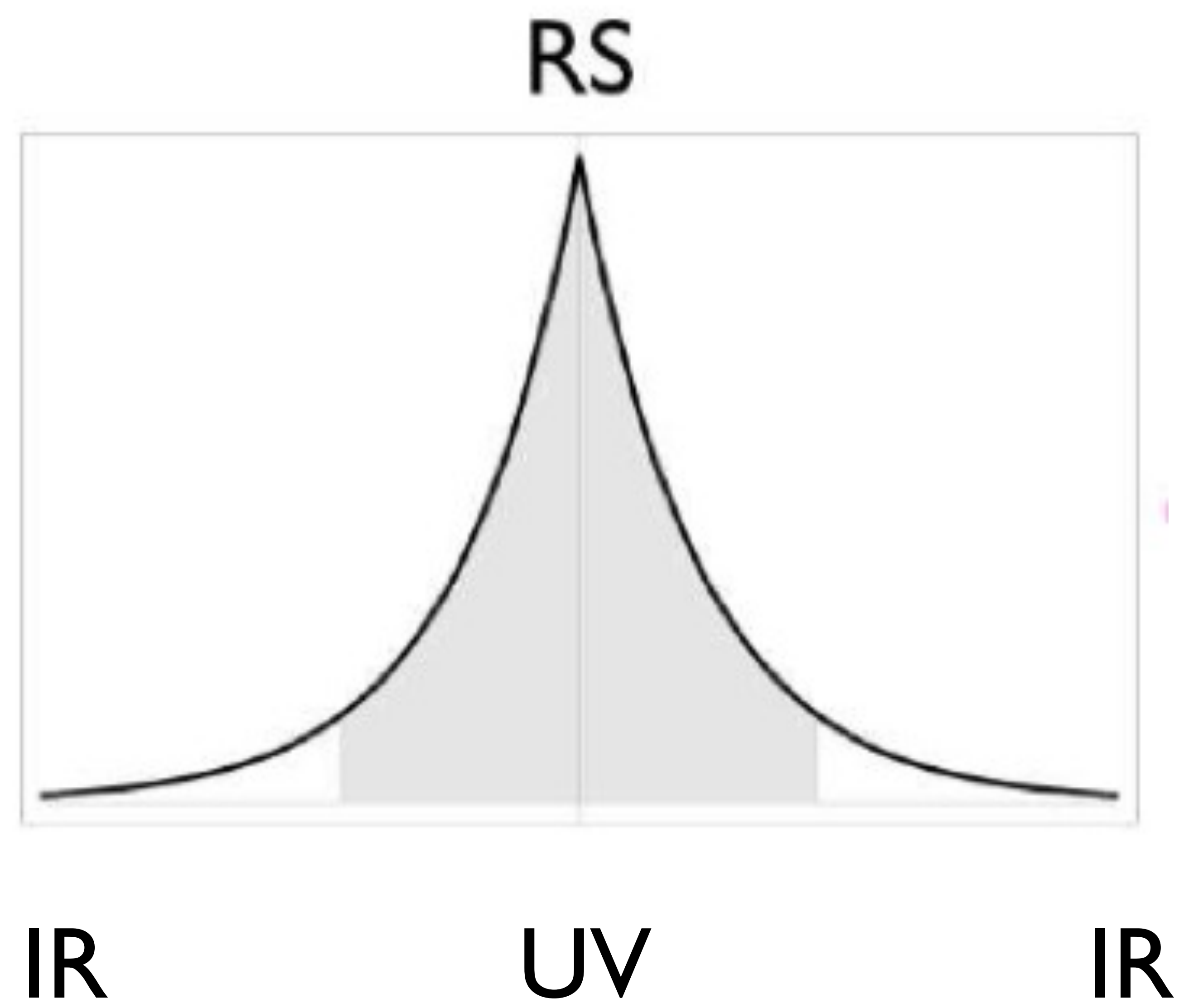
KK-PARITY

KK PARITY

- n-th KK excitation $\sim(-1)^n$
- The lightest KK-odd particle (**LKP**) is protected by KK-parity so that stable. LKP can be a good dark matter candidate (e.g, KK photon, KK Z, KK neutrino .. (cf) neutralino or sneutrino LSP)
  - ✶ KK-odd particle produced only in pairs (0-1-1)
  - ✶ KK-even states can be seen in resonances (0-0-2)
- The phenomenology shares many common features with the MSSM+Rp (a.k.a. Bosonic supersymmetry)

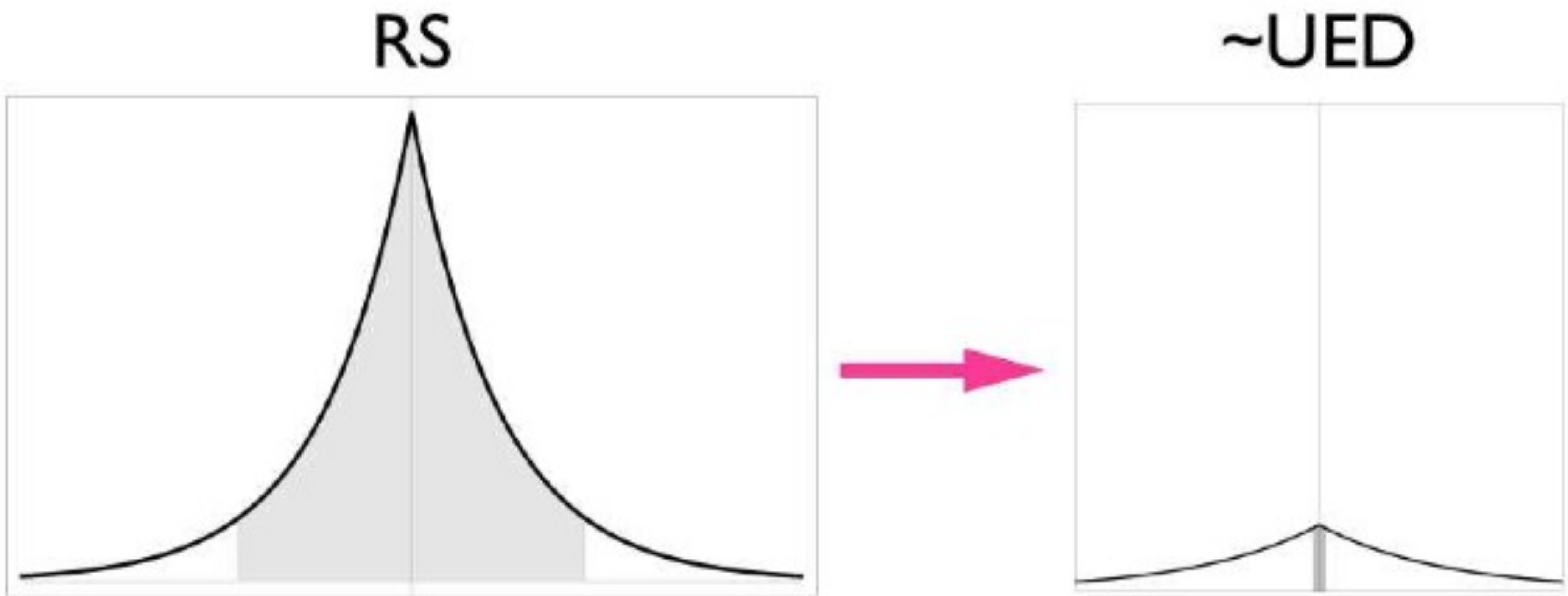
GLUE TWO THROATS

Agashe, Falkowski,Low, Servant 2008



Effectively RS looks like UED!

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



- Putting two throats together, the geometry becomes symmetric (Z_2 : **KK-PARITY**)
- After integrating out the large region in UV, the IR geometry is rather flat in an interval

UED

5D Lorentz invariant
Gauge covariant Kinetic terms + Mass terms

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

4D Lorentz invariant
BLKT

- Universal Extra Dimension: All Particles are in D>4 ..not a single model but a family of models..
- KK-parity (inversion symmetry about the middle point of XD) is a good symmetry by construction => KK DM
- minimal UED model (mUED) is based on S^1/Z_2 orbifold ≃ (-pi R/2, pi R/2).
- For proper effective field theory description, one may include 5D masses for fermions (Dirac mass) and boundary localized parameters (4D Lorentz invariant) : Model parameters

(1/R, r, m)

some technical details

5D Lorentz invariant
Gauge covariant Kinetic terms + Mass terms

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$M_\psi \bar{\psi}\psi$

SCP, Shu (2009)

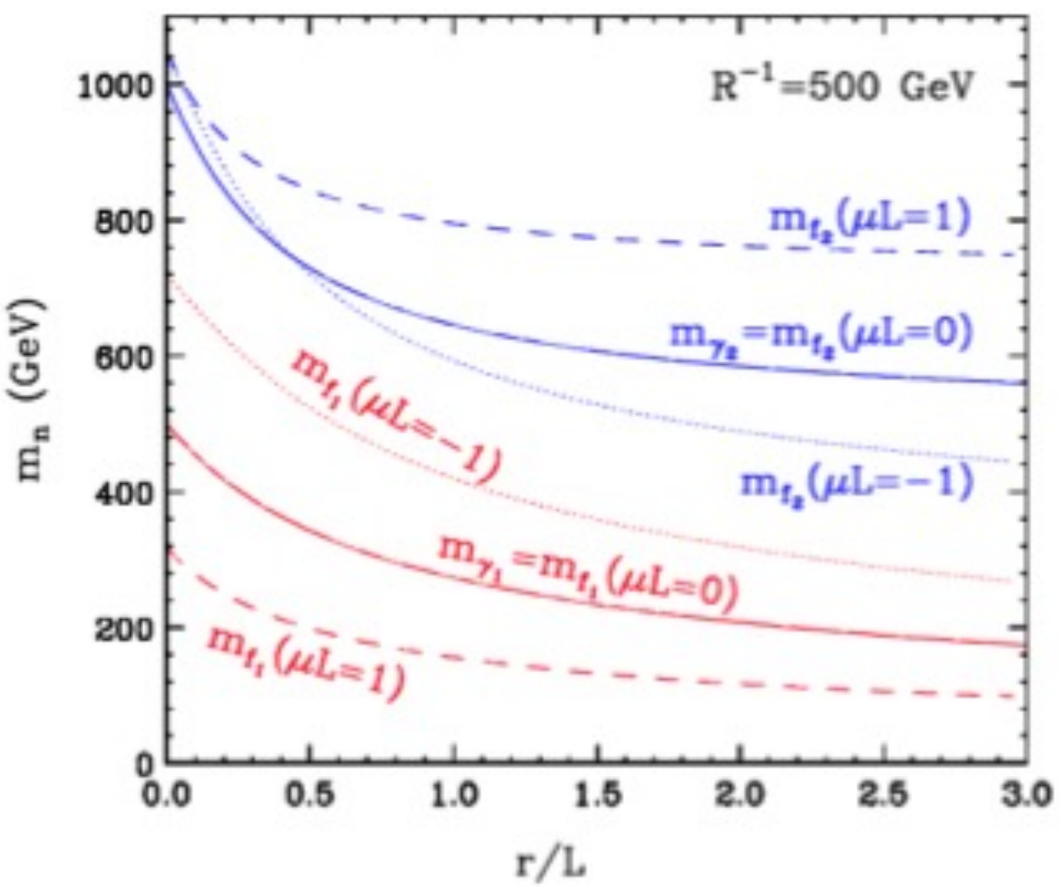
4D Lorentz invariant
BLKT $r\mathcal{L}_4$

Carena, Ponton, Tait, Wagner (2003)

- Any theory in odd dimension is vectorlike (non−chiral).
- In 5D, the minimal spinor representation is Dirac thus includes both chiralities and has Dirac mass.
- Chiral theory is obtained by boundary conditions.

KK-MASSES

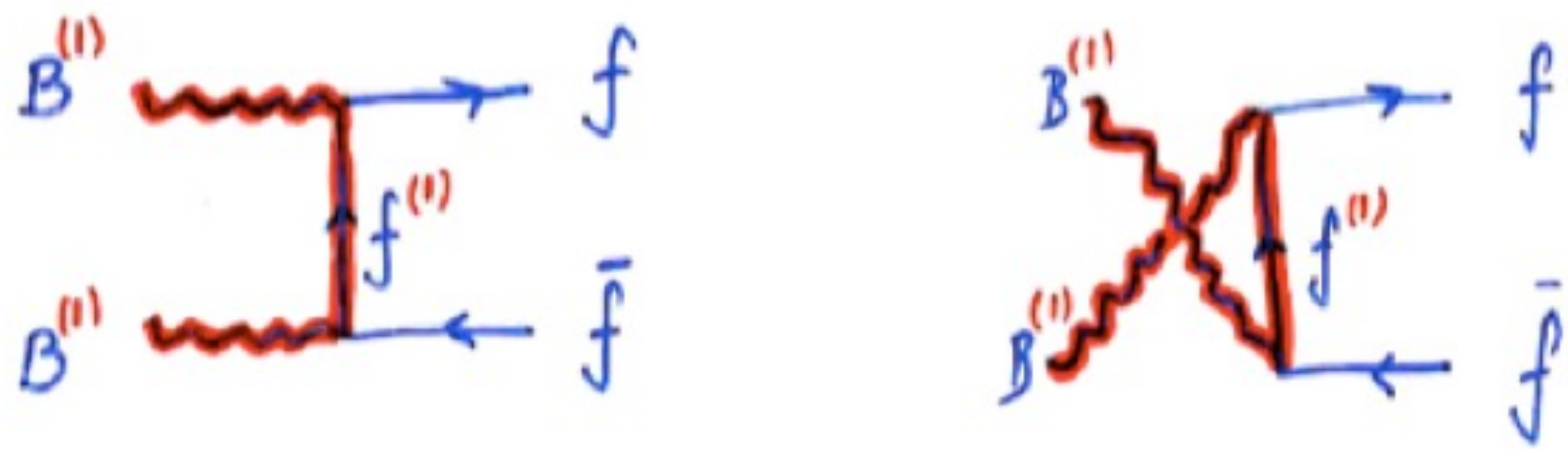
vs (r,mu)



Flacke, Kong, SCP(2013)

- large r => lighter KK mass
- large mu => heavier KK mass for level-1

UPPER BOUND ON 1/R BY KK-DM



$$\Omega h^2 = \frac{0.1\text{pb}}{\langle \sigma v \rangle}$$

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

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

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

larger KK−mass for fermion

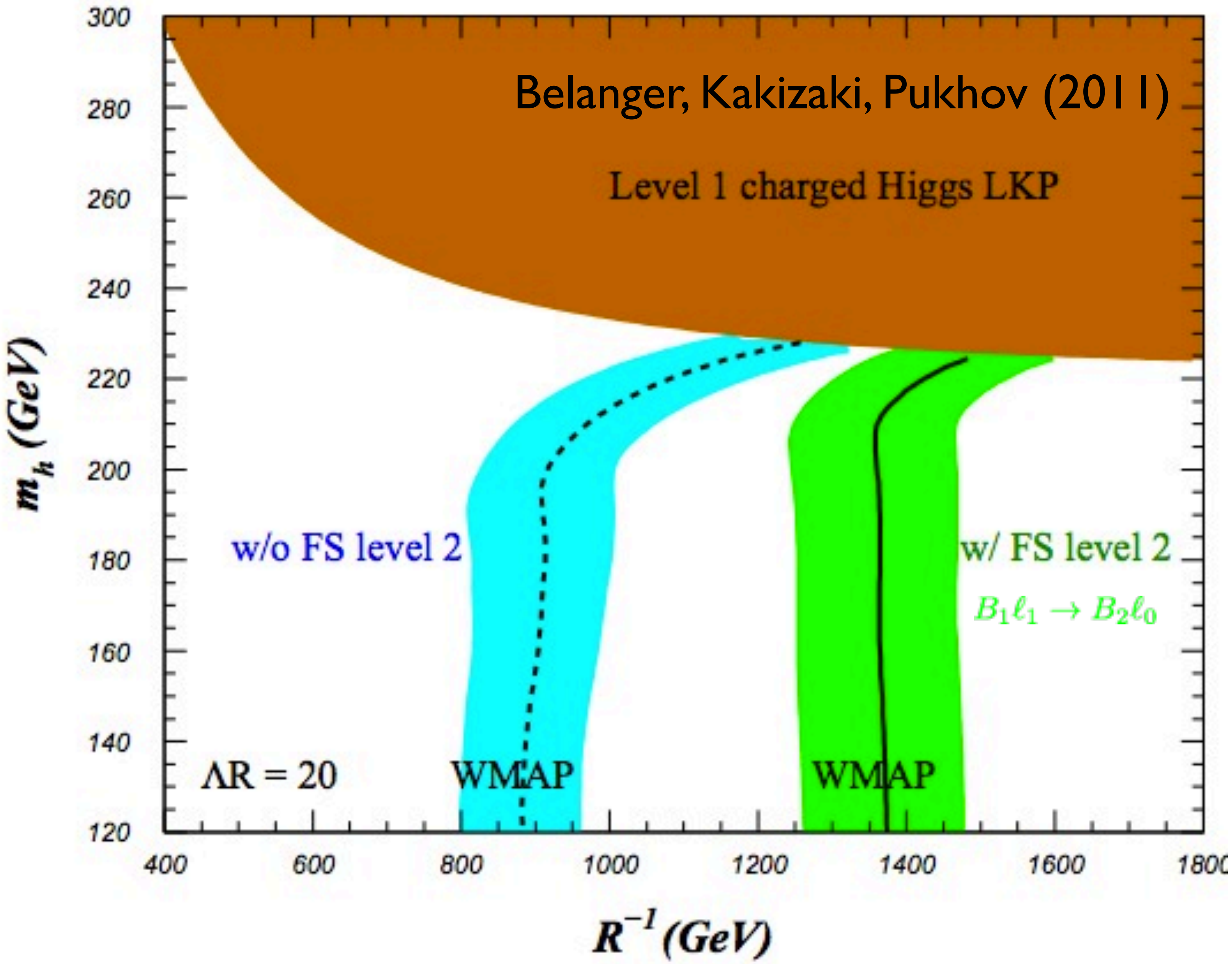
⇒smaller cross section

⇒larger Relic abundance

⇒ too big abundance not allowed and set upper bound on KK−scale

UPPER BOUND ON 1/R

(SET IN MUED +ALLOWING TUNING IN KK-MASS(SUED)



1/R<1.5 TeV

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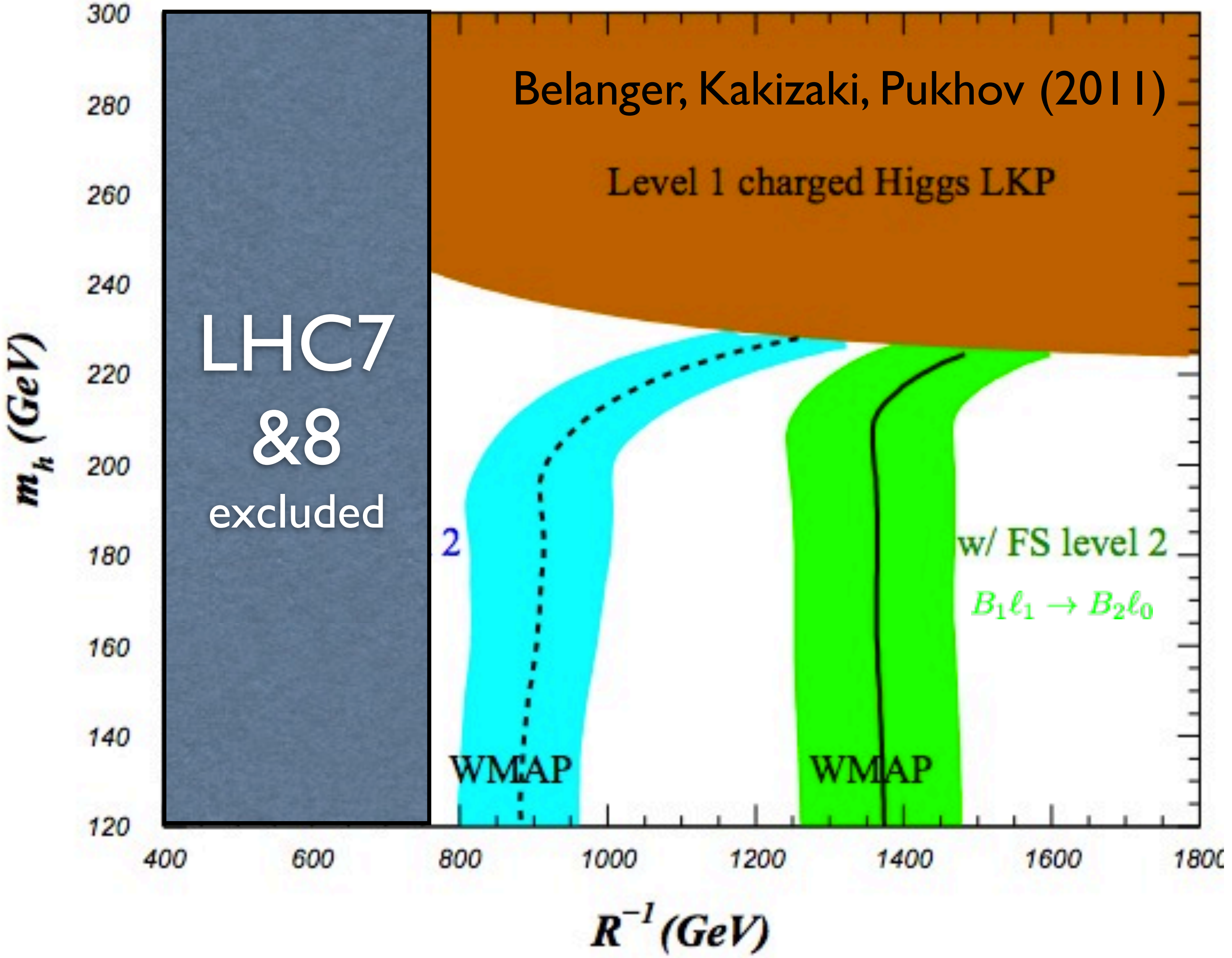
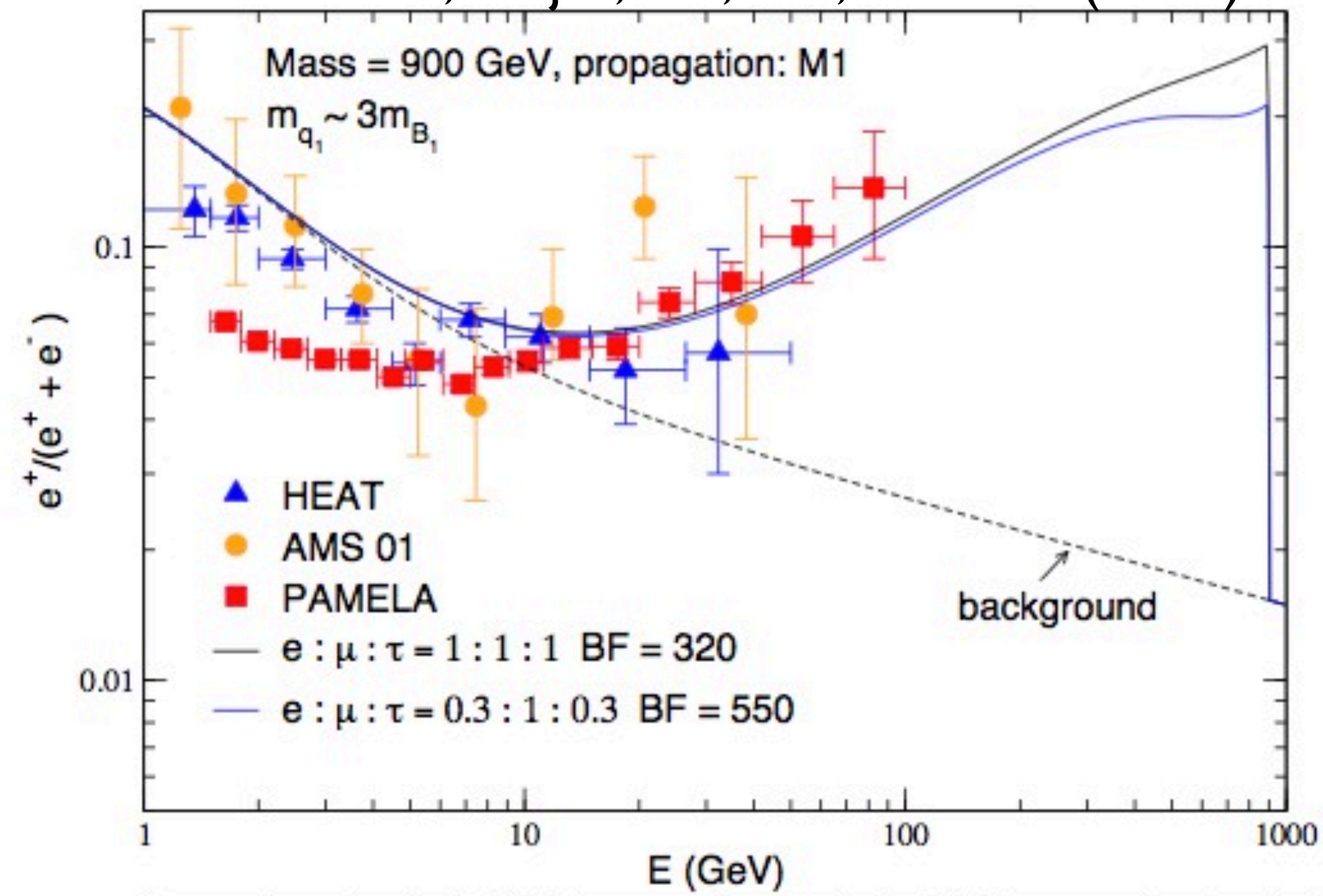


1/R<1.5 TeV

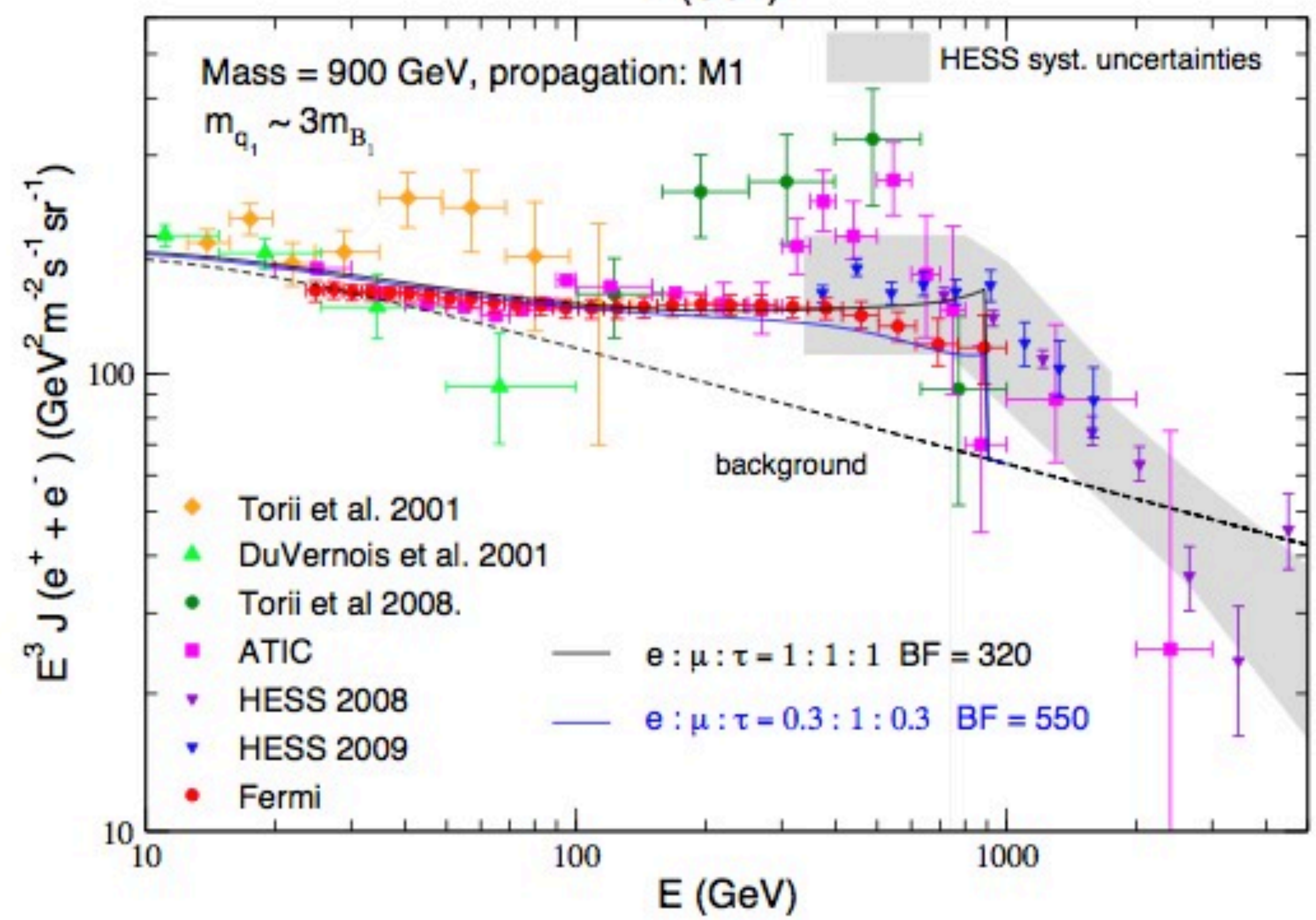
KK DM fits recent CR data reasonably.

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

Pamela

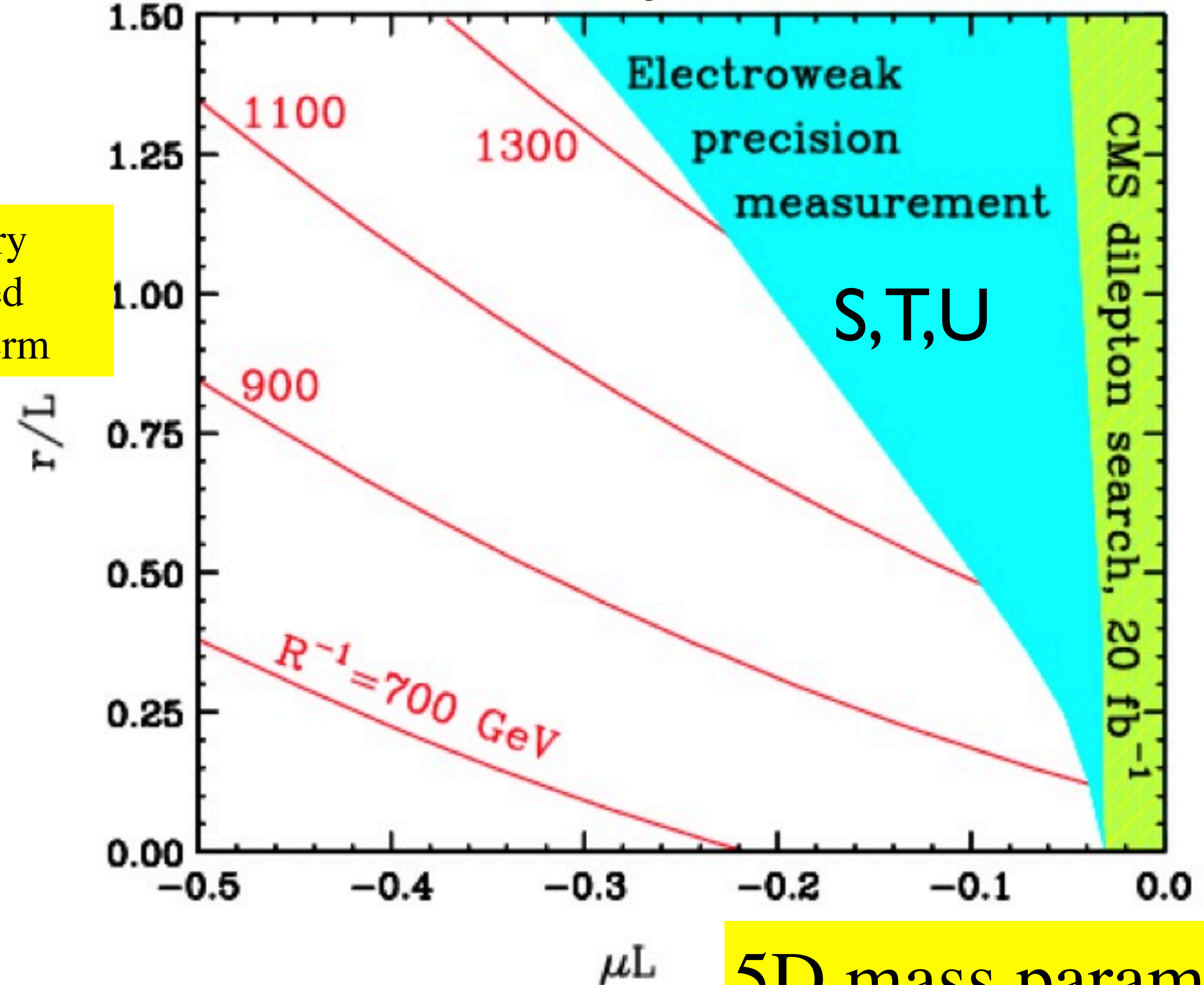


Fermi



Bound on 1/R for universal r,mu

Flacke, Kong, SCP JHEP 1305 (2013) 111



boundary localized kinetic term

5D mass parameter

ADD

- ArKani-Hamed, Dimopoulos, Dvali (1998)
- extremely large XD
- Only gravitons are in D>4 (others are confined on a "brane-world"
- Gravity becomes strong at a TeV scale
- KK graviton : jet+MET, photon+MET
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$$\ell_c = V_n^{1/n} \sim \begin{cases} 10^{12}\ \mathrm{m} & n=1, \\ 1\mathrm{mm} & n=2, \\ 10\ \mathrm{nm} & n=3, \\ 4\times 10^{4}\ \mathrm{fm} & n=4, \\ 10^{3}\ \mathrm{fm} & n=5, \\ 100\ \mathrm{fm} & n=6, \\ 20\ \mathrm{fm} & n=7. \end{cases}$$

Models / Theory

	UED (~2T RS)	RS	ADD
M_{KK}	~TeV	~TeV	only collectively seen
M_G	(too high to be seen)	~TeV	~TeV
LHC Phenomenology	MET(LKP) pairs of 1st KK peak of 2nd KK	G_{KK} resonance jet+MET $g_{KK} \rightarrow$ttbar.. BH(tops, Hs..)	jet+MET photon+MET BH(jets)

Models/Experiment

	split-UED (w/5D mass)	RS	ADD
LHC7 & 8	1/R>700 GeV (m~1 TeV)	M(graviton) excluded (1.0-1.45) TeV 1302.4794	collectively seen
Strong Gravity(BH)	(too high to be seen)	N/A	>4.3-6.2 TeV

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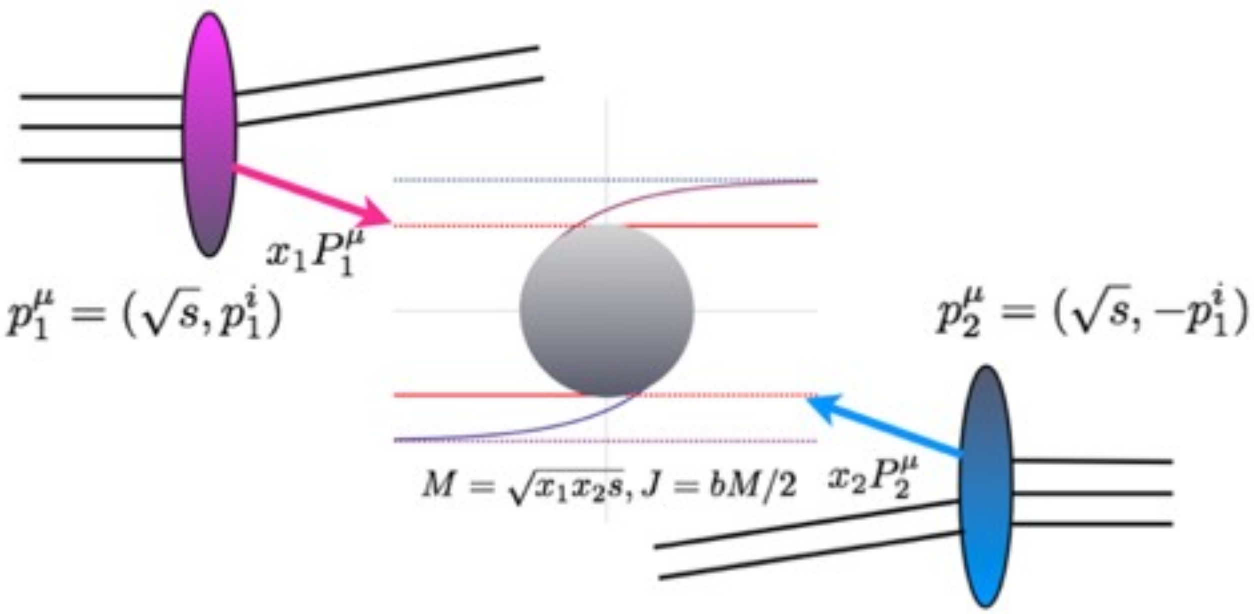
**should be careful in interpretation

BLACK HOLE



$$b_{\mathrm{Max}}(\sqrt{s}) = \frac{2}{\left(1+\left(\frac{D-2}{2}\right)^2\right)^{\frac{1}{D-3}}} r_s(\sqrt{s})$$

$$\sigma_{pp\to \mathrm{BH}+X} = \int_{M_D{}^2/s}^{1} du \int_u^1 \frac{dv}{v} \sum_{ij} f_i(v,\hat{s}) f_j\left(\frac{u}{v},\hat{s}\right) \hat{\sigma}_{ij\to \mathrm{BH}},$$

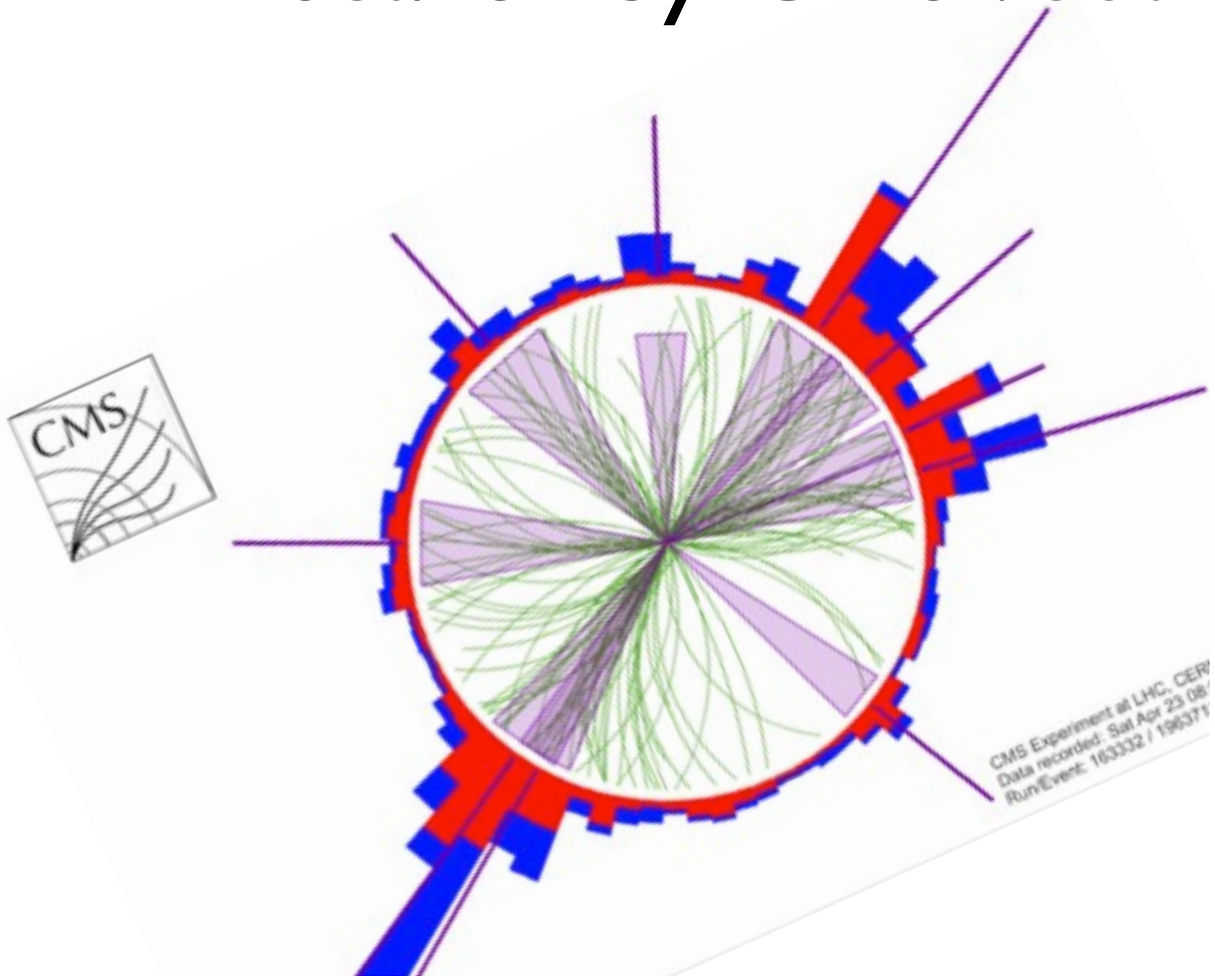
Greybody factor

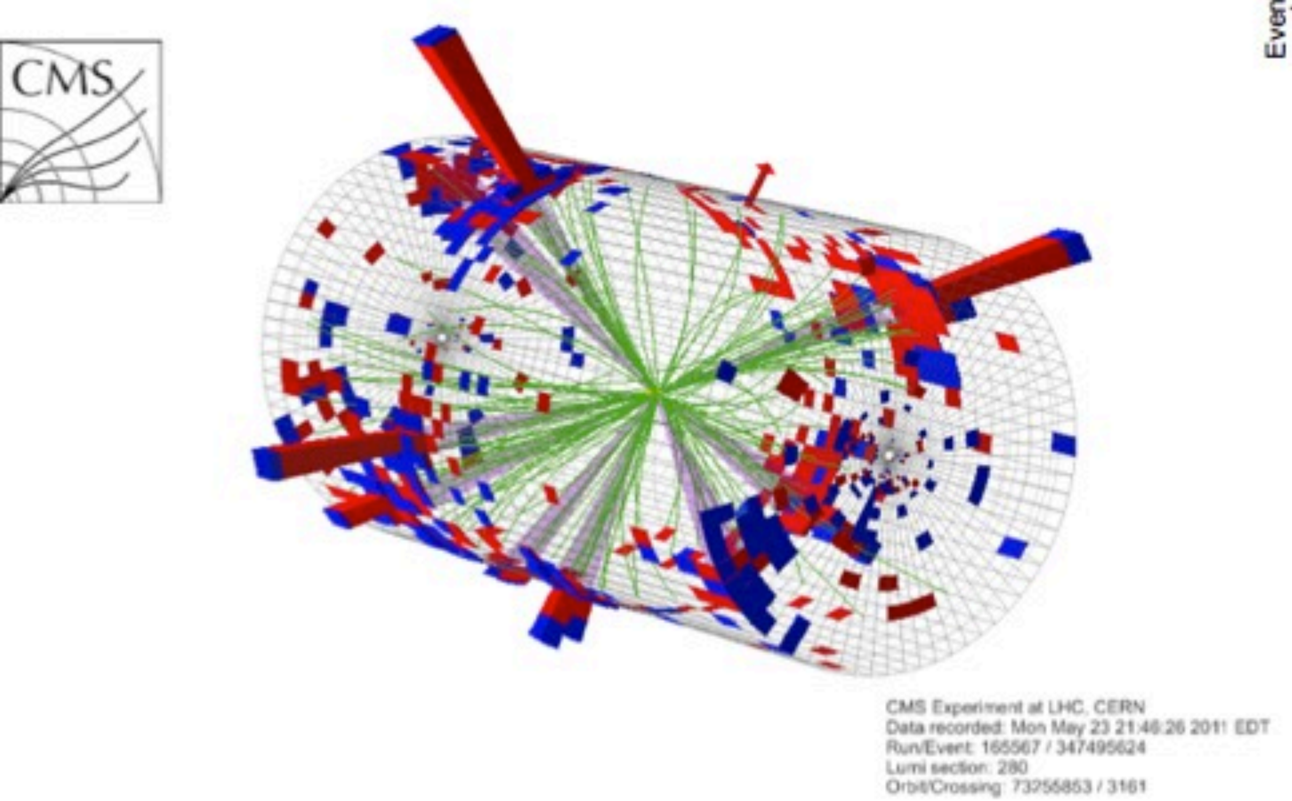
$$-\frac{dE_{s,l,m}}{dt} = \frac{g_s}{2\pi}\int d\omega \frac{{}_s\Gamma_{lm}\,\omega}{e^{\omega - m\Omega/T} \mp 1}$$

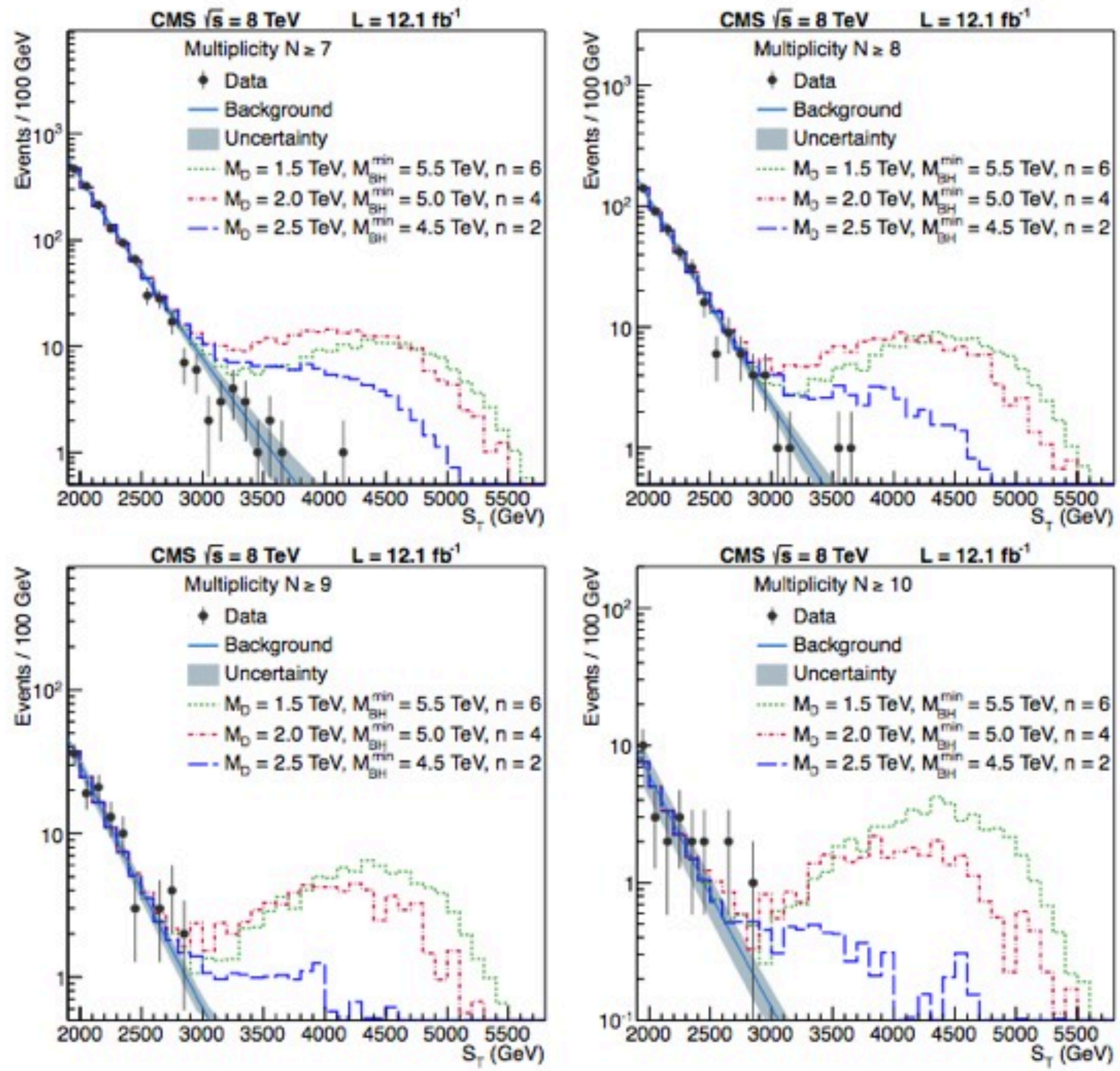
s,l,m=spin,angular q#s

- In ADD and RS, gravity becomes strong near TeV scale (no hierarchy)
- when two colliding particles are close enough they feel strong gravity and forms a black hole
- hoop conjecture $b < r_h(E) = (GE)^{1/D-3}$.
- Cross section= $\pi\, b_{max}^2 = \pi\, (GE)^{2/D-3}$
- Once produced, BH decays into SM particles via Hawking radiation. $T=1/r_h$ ..the hotter the smaller.. Thermal radiation to all kinds of SM particles

BH search by CMS : bounds 4.3-6.2TeV with M=1.5-2.5 TeV



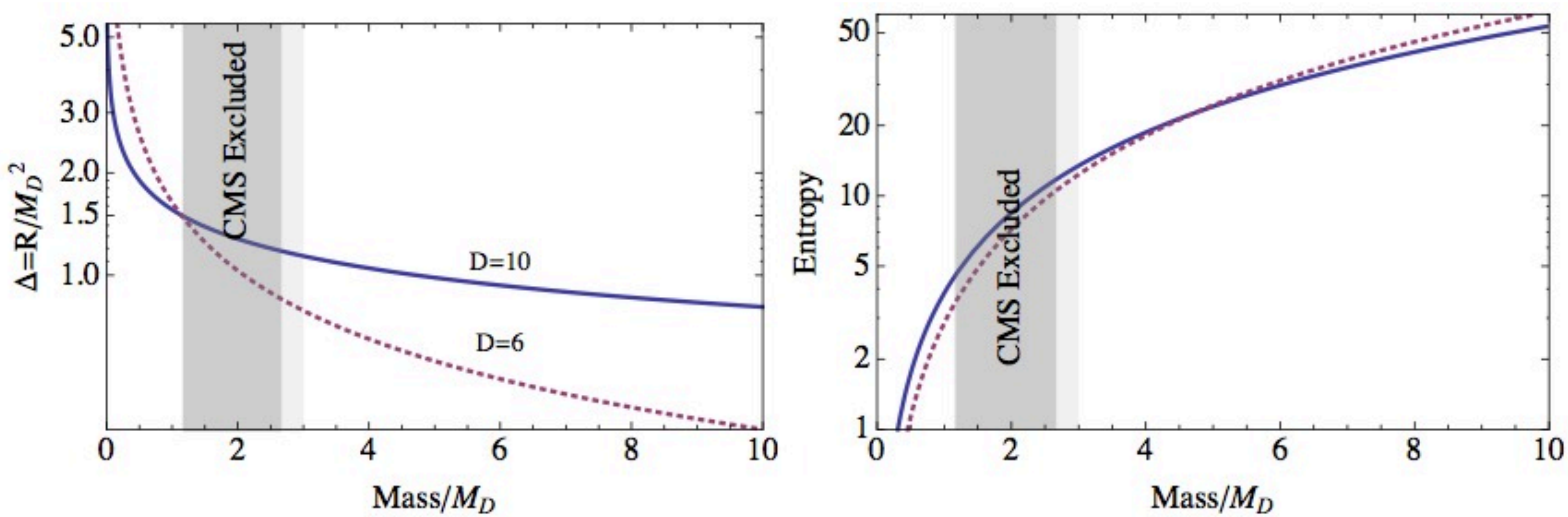




*large multiplicity + high Pt

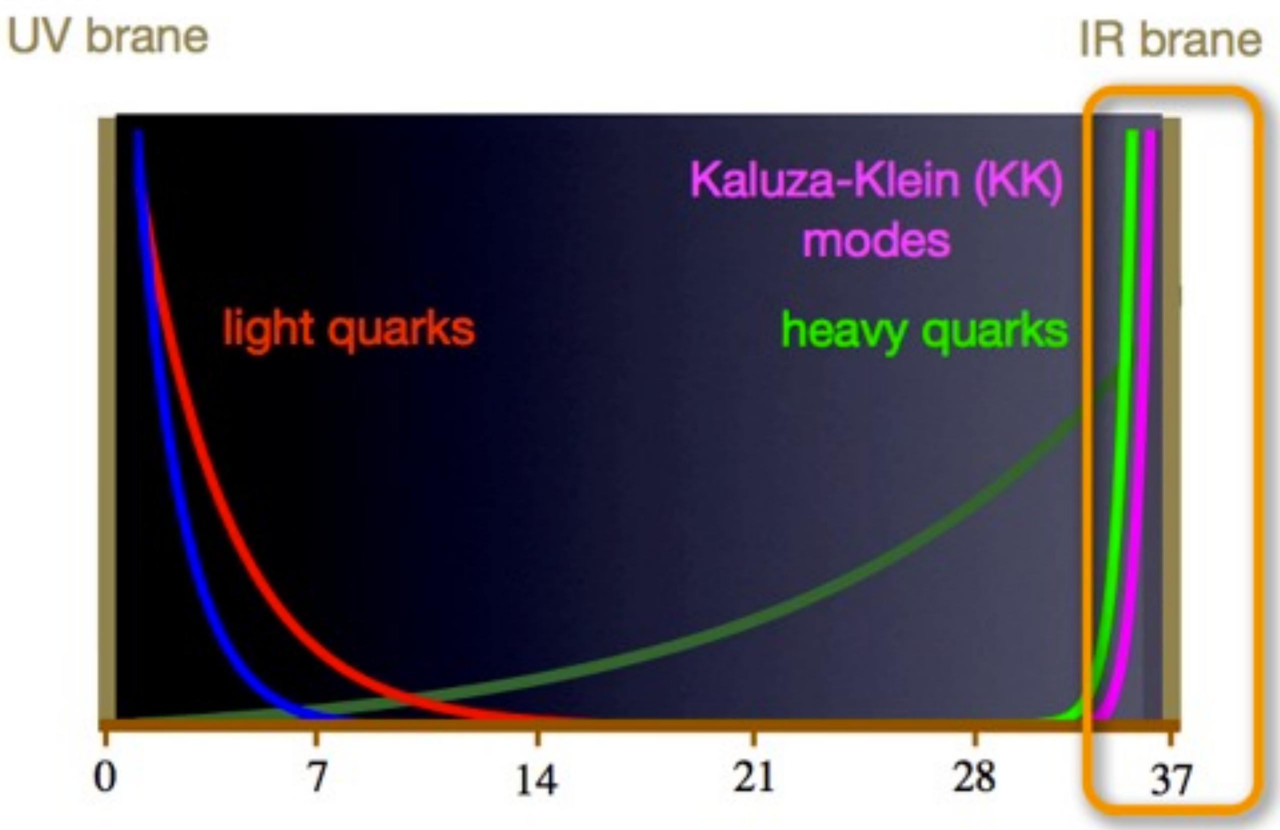
not really black hole..

SCP, Phys.Lett. B701 (2011) 587-590

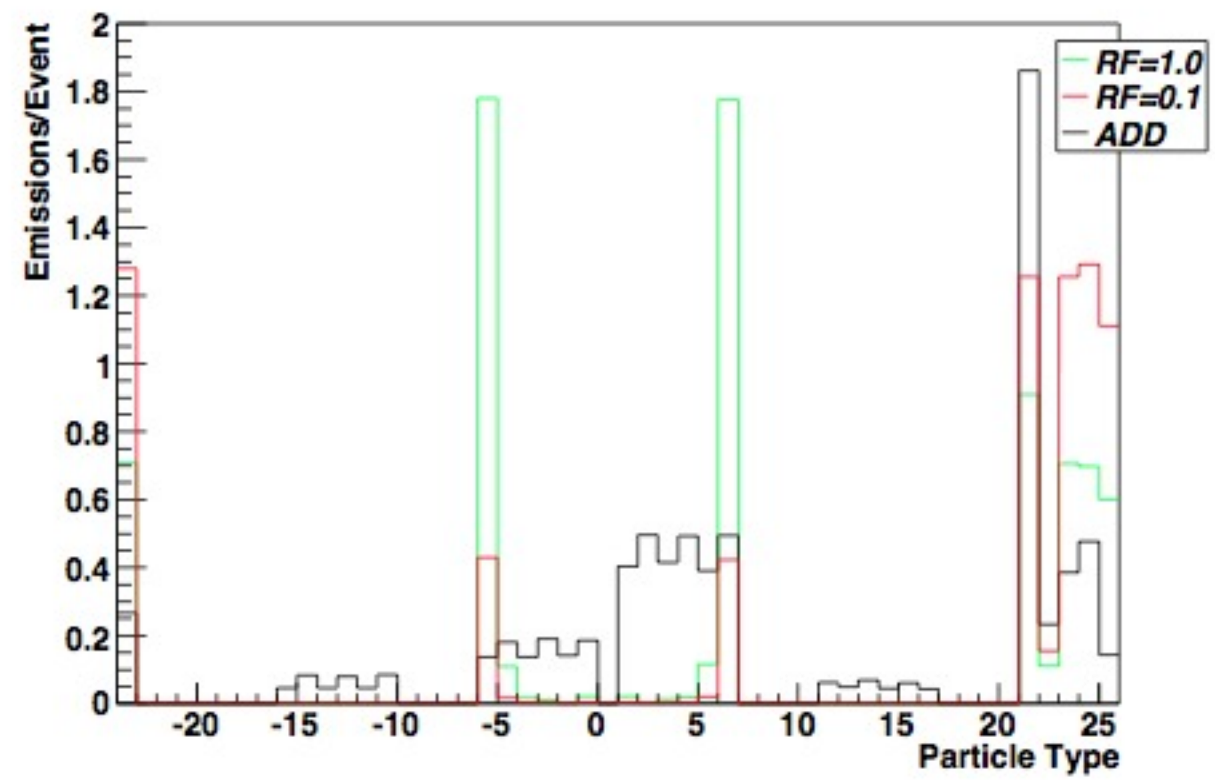


- A large QG effect expected..
- The CMS result still provides "model independent bound" which would be useful.
- 14 TeV run would be more reliable

RS BH



Frost, SCP (2013) in prep.

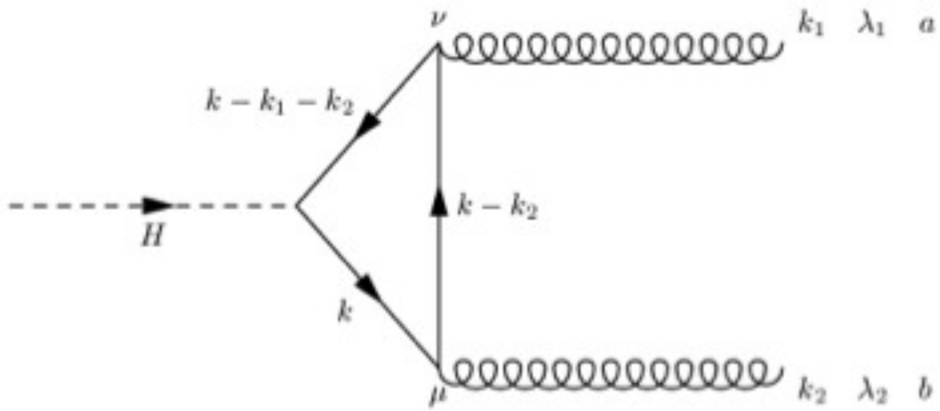


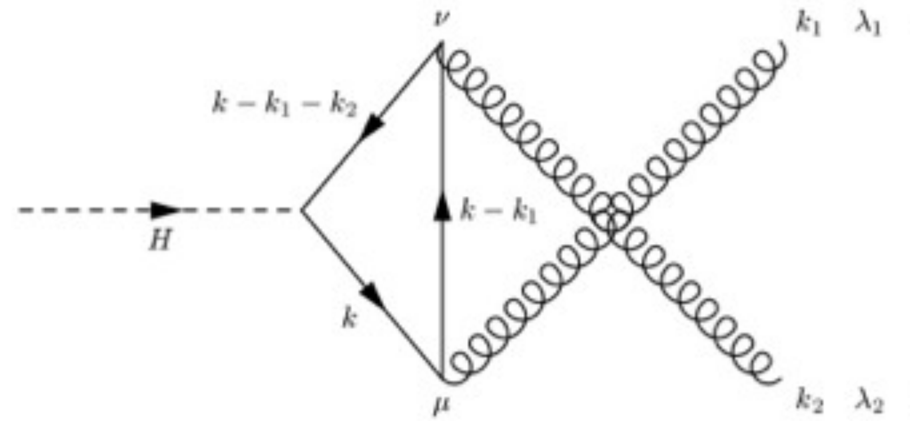
- Light quarks not contribute to BH formation :-(
- Gluon (the IR tip) dominate, 1/kL~1/30 suppressed ..
- Decays mostly to heavy quarks, gluons and Higgs
- Dedicated search is needed!

Higgs 125 GeV

- Here I focus on UED model (~2T RS)
- Higgs 125GeV is regarded as the zero mode of Higgs field in 5D..
- assume to have a flat profile along 5D (can be discarded)
- KK top quarks contribute to gluon fusion => enhance the cross section ~ $1+O(m_t/m_{KK})^2$
- KK tops and KK Ws contribute to diphoton decay => reduction
- (enhance)*(reduce) compete

top +KK-top in the loop





Pasario-Veltman

$$\mathcal{M} = (\#)\frac{\lambda_t \alpha_s}{8\pi}\left(F(\frac{m_h^2}{m_t^2}) + \sum_n 2\frac{m_t^2}{m_n^2}F(\frac{m_h^2}{m_n^2})\right)$$

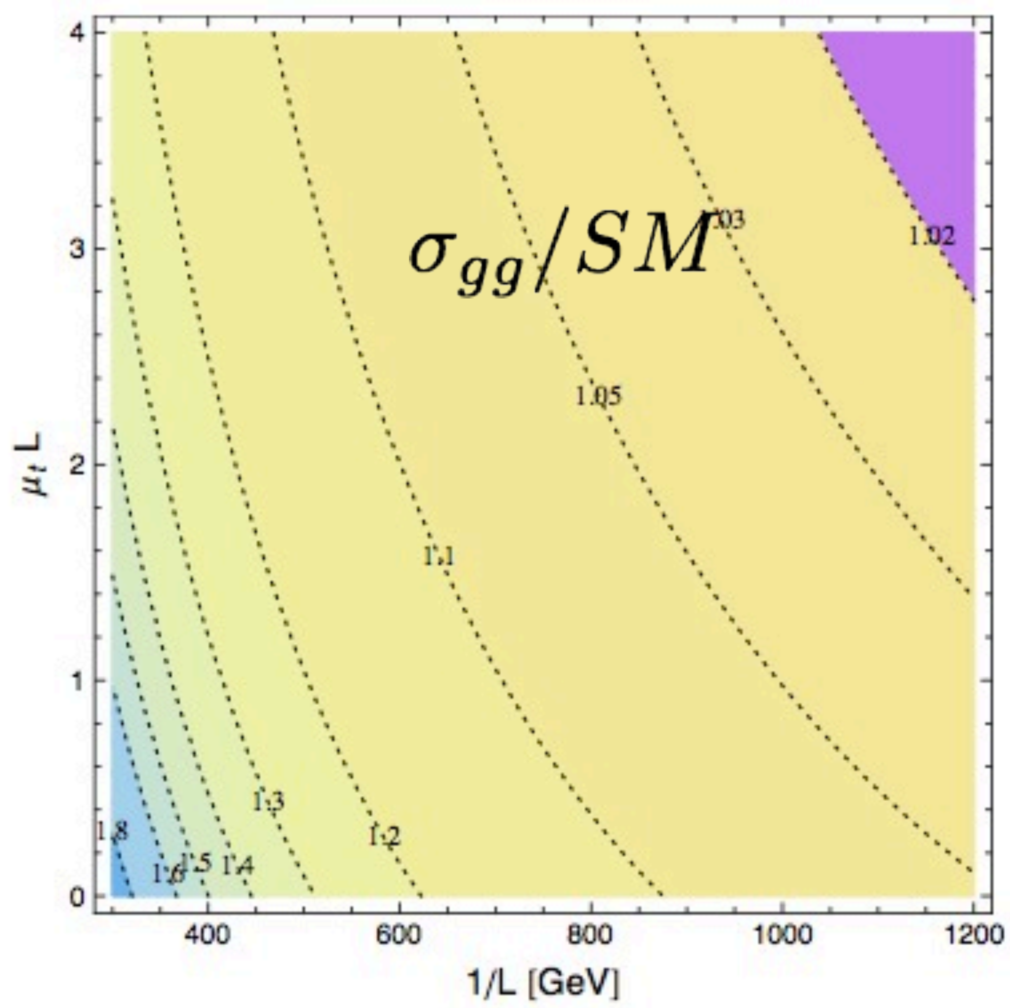
top

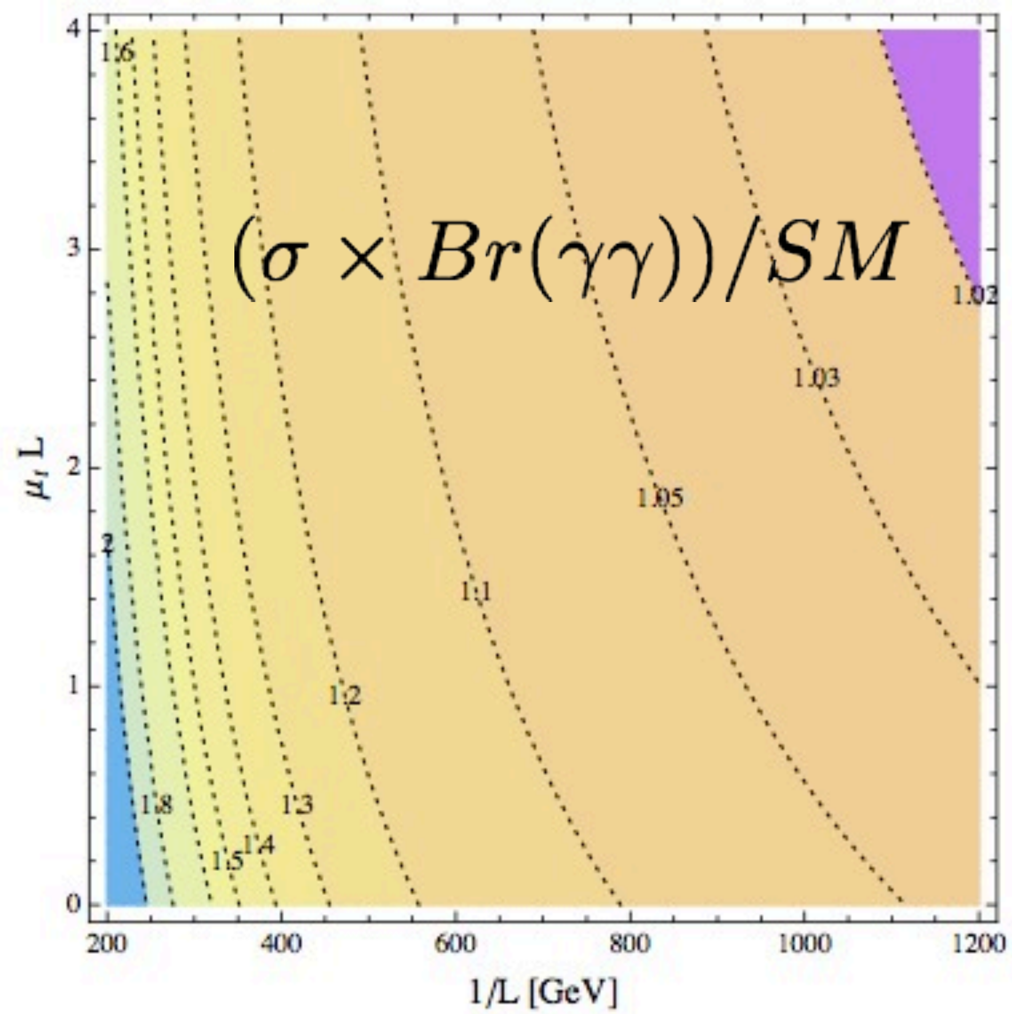
KK-top

$F \to 1 \text{ when } m_n \gg m_h$

HIGGS WITH KK TOP

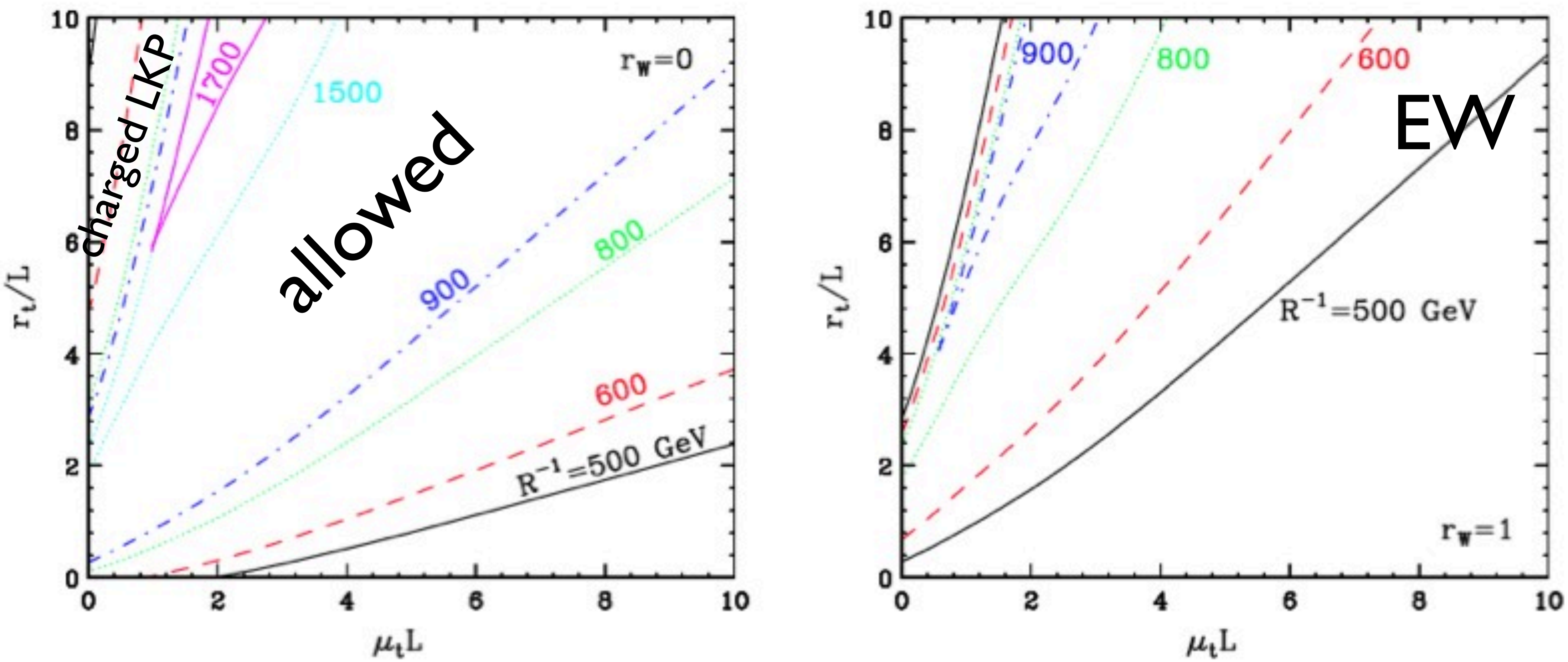
Flacke, Kong, SCP (2013)





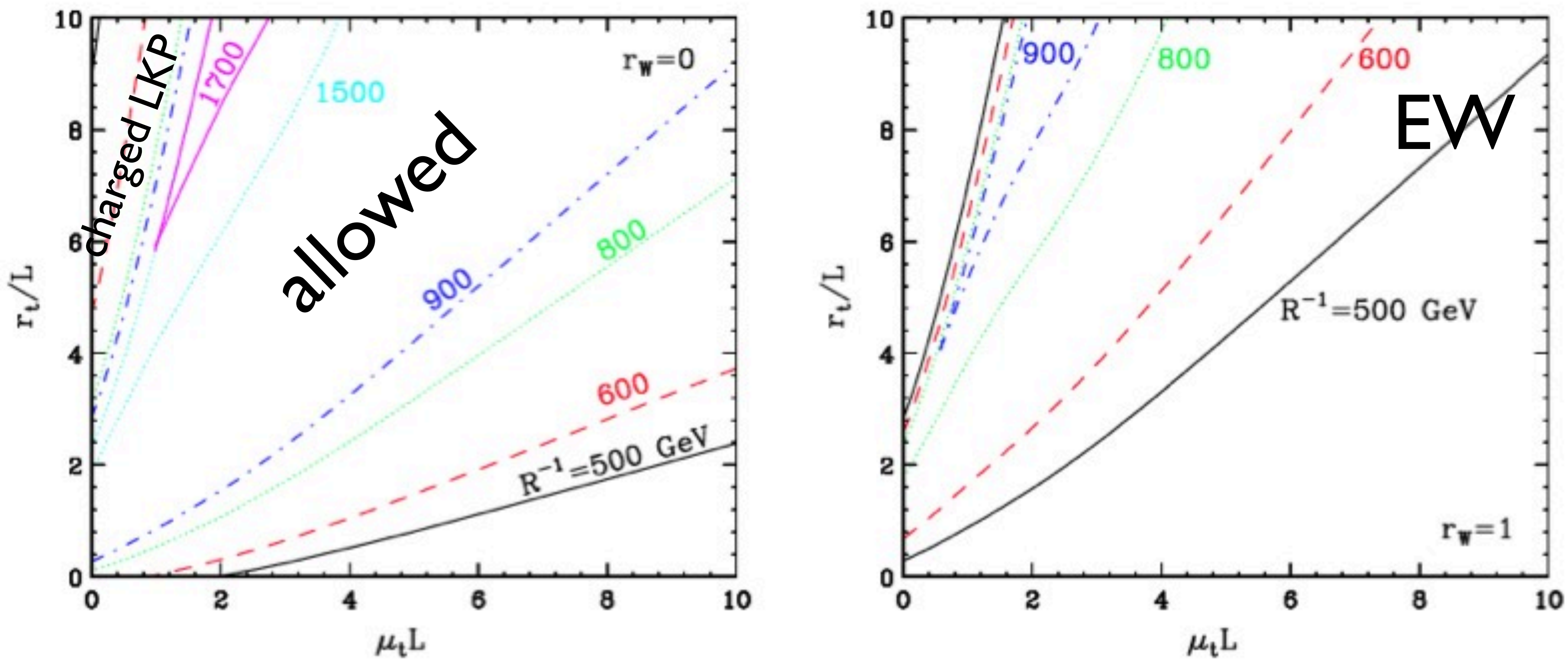
BULK MASS + BLKT

Flacke, Kong, SCP (2013)



Bulk mass + BLKT

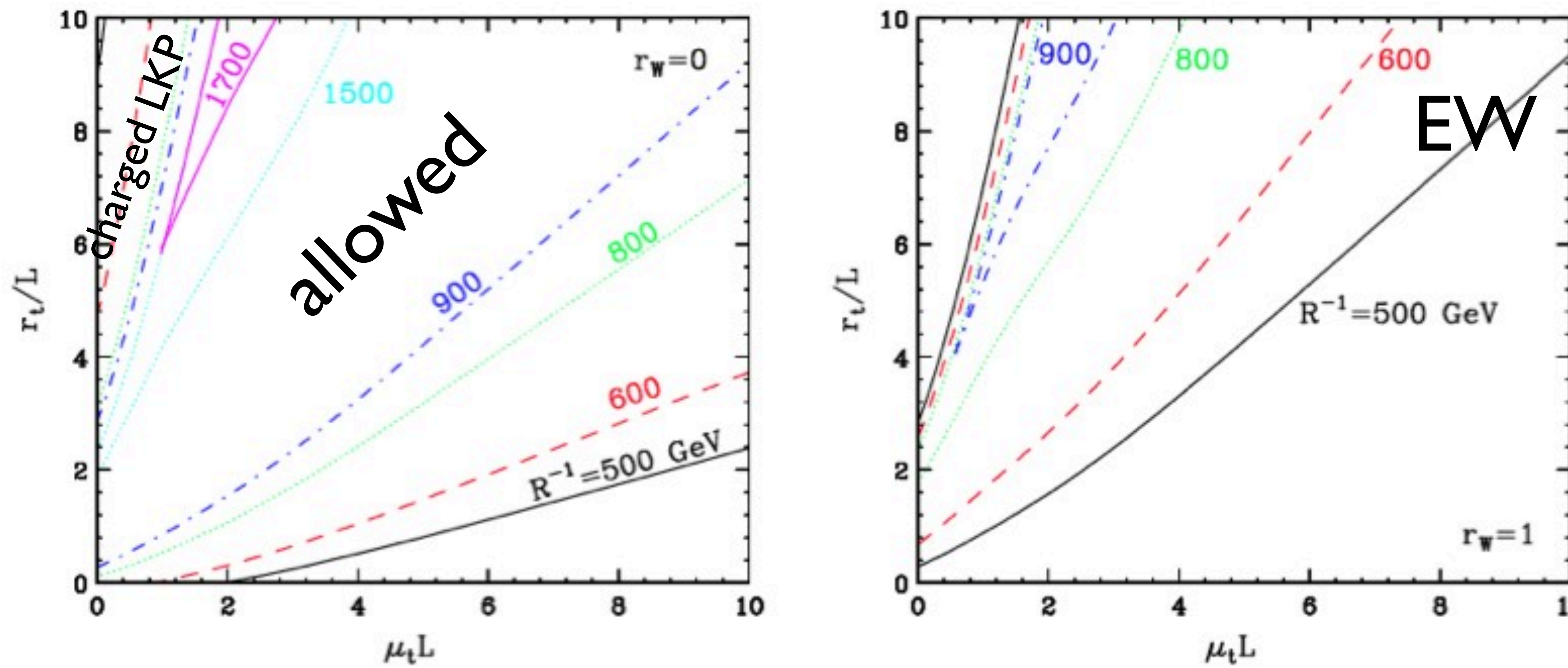
Flacke, Kong, SCP (2013)



- Region outside contours is disfavored

Bulk mass + BLKT

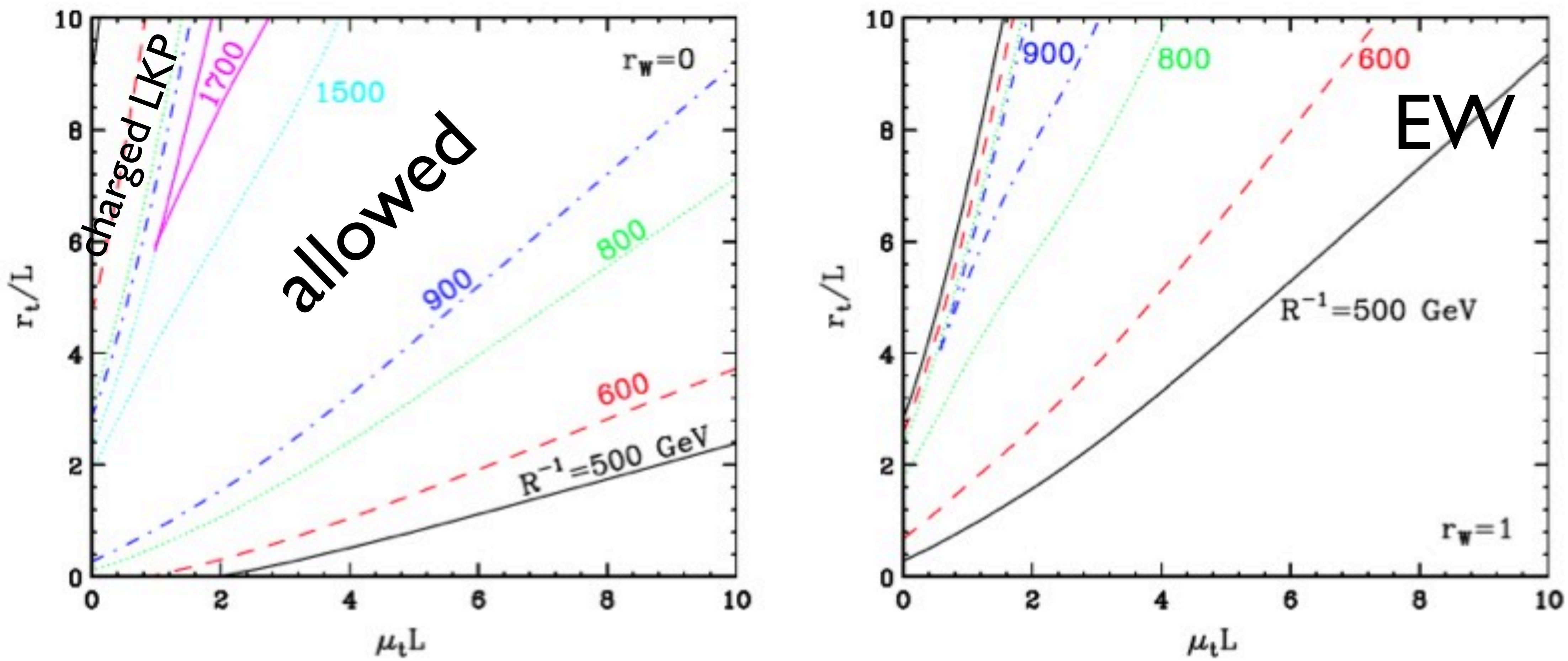
Flacke, Kong, SCP (2013)



- Region outside contours is disfavored
- The left-upper corner of each contour is excluded since KK photon is not LKP there

Bulk mass + BLKT

Flacke, Kong, SCP (2013)



- Region outside contours is disfavored
- The left-upper corner of each contour is excluded since KK photon is not LKP there
- Higgs data disfavors the right-bottom side (large mu, small r makes mKK heavy)

SUMMARY

- Large/highly warped XD can be tested at the LHC.
- KK-DM with KK-parity .. $1/R<1.5$ TeV in UED
- DM+LHC7&LHC8+EWPT+Higgs already started to probe a part of parameter space
- LHC 14 and future DM searches(Direct/Indirect) will give us more answers for XD