Dark matter in universal extra dimension models

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June 10, 2015, CosKASI Dark Matter Workshop 2015 @ KASI

Refs.:

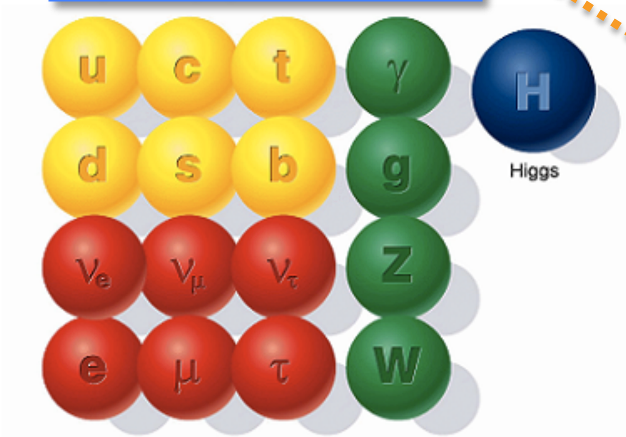
- M.Kakizaki, S.Matsumoto, Y.Sato and M.Senami,
  NPB 735, 84 (2006) [hep-ph/0508283]; PRD 71, 123522 (2005) [hep-ph/0502059].
- MK, S.Matsumoto and M.Senami,PRD 74, 023504 (2006) [hep-ph/0605280].
- G.Belanger, MK and A.Pukhov, JCAP 1102, 009 (2011) [arXiv:1012.2577 [hep-ph]].
- G.Belanger, A.Belyaev, M.Brown, MK and A.Pukhov,
  PRD87, no. 1, 016008 (2013) [arXiv:1207.0798 [hep-ph]].
- MK, in preparation
- (MK and K.Ishiwata, in preparation)

1. Motivations

- Discovery of a Higgs boson at the CERN LHC
  - The Standard Model (SM) is established as a low-energy effective theory below $O(100)$ GeV

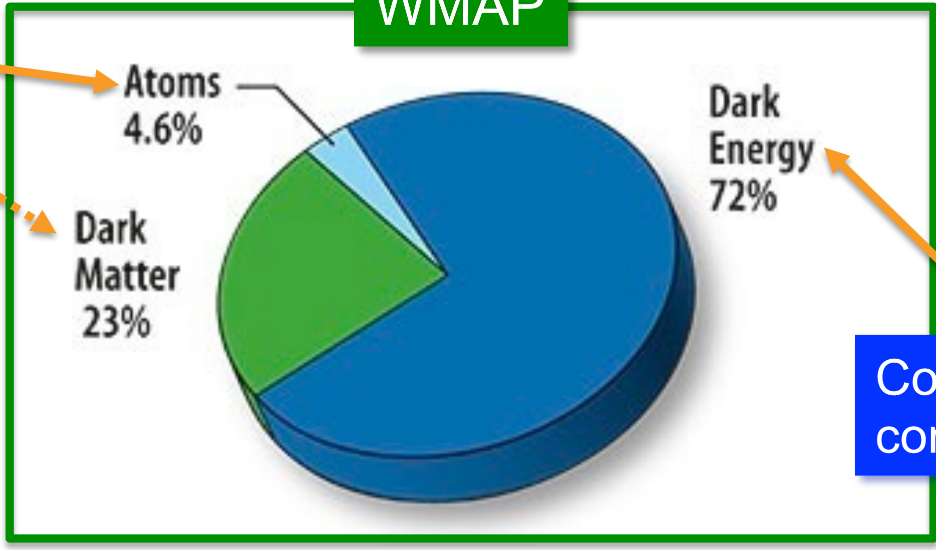
This is not the end of the story

Standard model (SM) particles



[www.physics.gla.ac.uk]

WMAP



[map.gsfc.nasa.gov]

Cosmological constant?

Existence of the dark matter ⟹ New physics beyond the SM

Dark matter candidates

- Interesting solution to the DM problem: Reductionist approach
  - DM candidates naturally accompany the SM particles
  - DM interactions are related to SM coupling constants

Weak-Scale Supersymmetry

- Vector superfield of the B-boson:

$$V(x^\mu, \theta, \bar{\theta}) = \theta\sigma^\mu\bar{\theta}\underbrace{B_\mu(x^\mu)}_{\text{SM B-boson}} + i\theta^2\bar{\theta}\bar{\chi}(x^\mu) - i\bar{\theta}^2\theta\underbrace{\chi(x^\mu)}_{\text{LSP DM}} + \cdots$$

- DM interactions are controlled by supersymmetry

Universal Extra Dimensions (UEDs) ← This talk

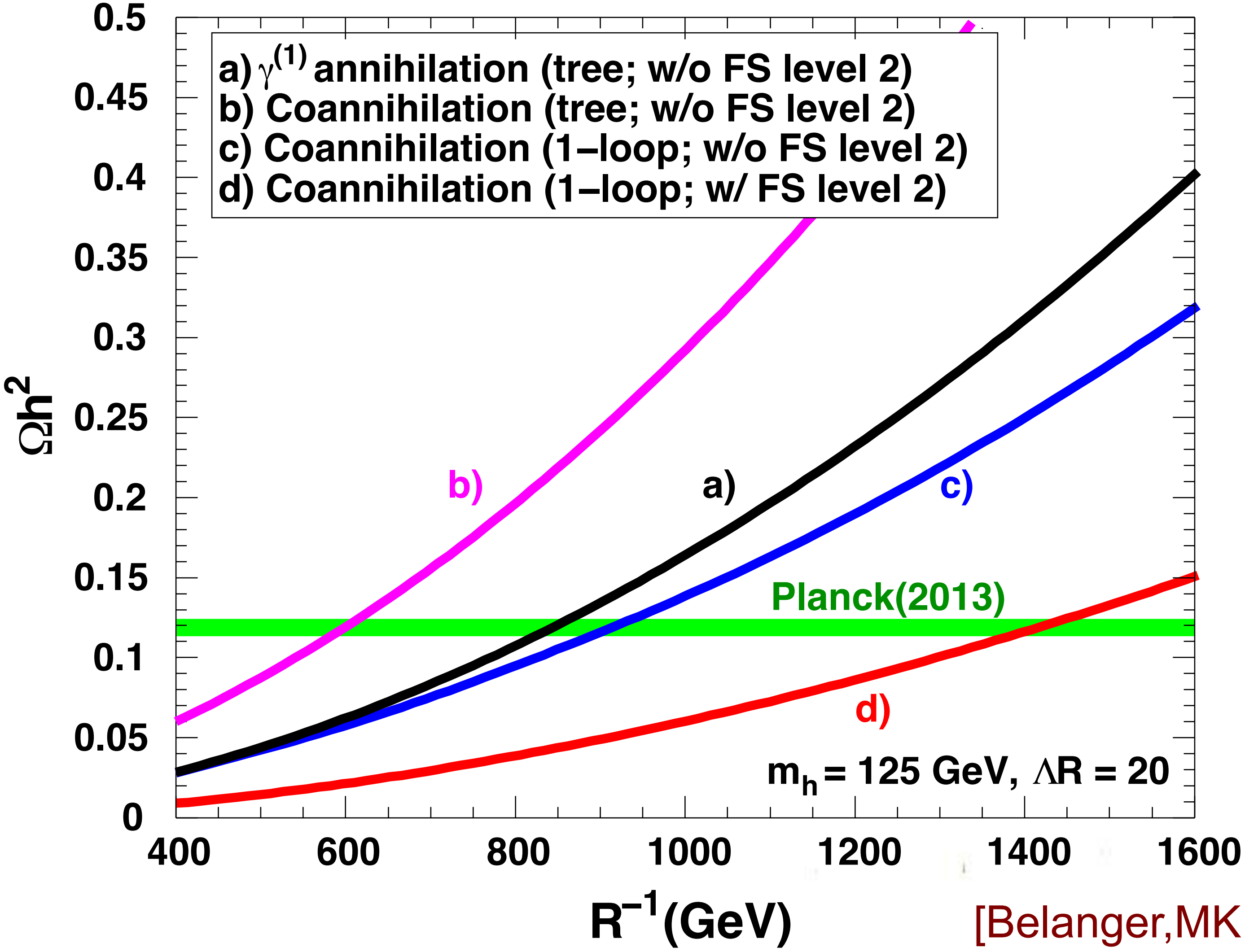
- 5D B-boson field:

$$B_\mu(x^\mu, x^5) = \frac{1}{\sqrt{2\pi R}}\underbrace{B_\mu^{(0)}(x^\mu)}_{\text{SM B-boson}} + \frac{1}{\sqrt{\pi R}}\underbrace{B_\mu^{(1)}(x^\mu)}_{\text{LKP DM}}\cos\left(\frac{x^5}{R}\right) + \cdots$$

- DM interactions are controlled by Lorentz invariance

This talk (1/2)

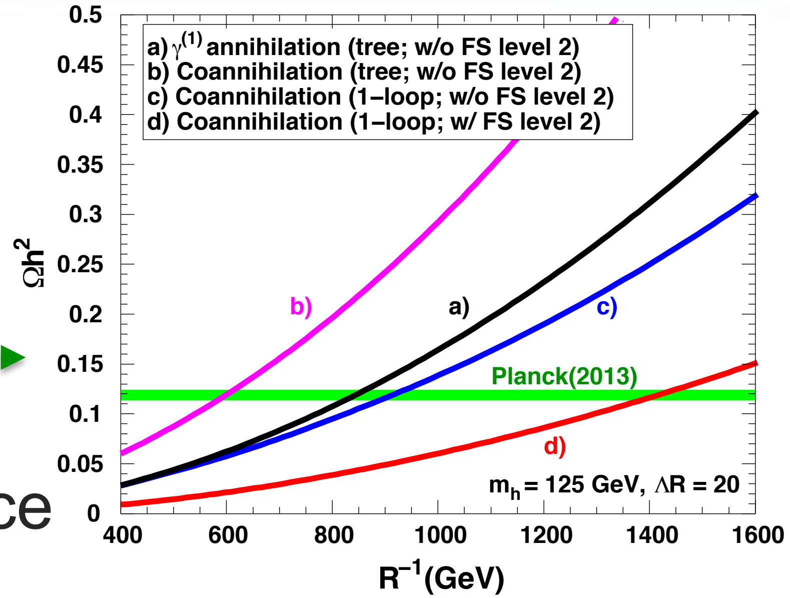
- Goal: Role of 2nd KK modes in the minimal UED (mUED):



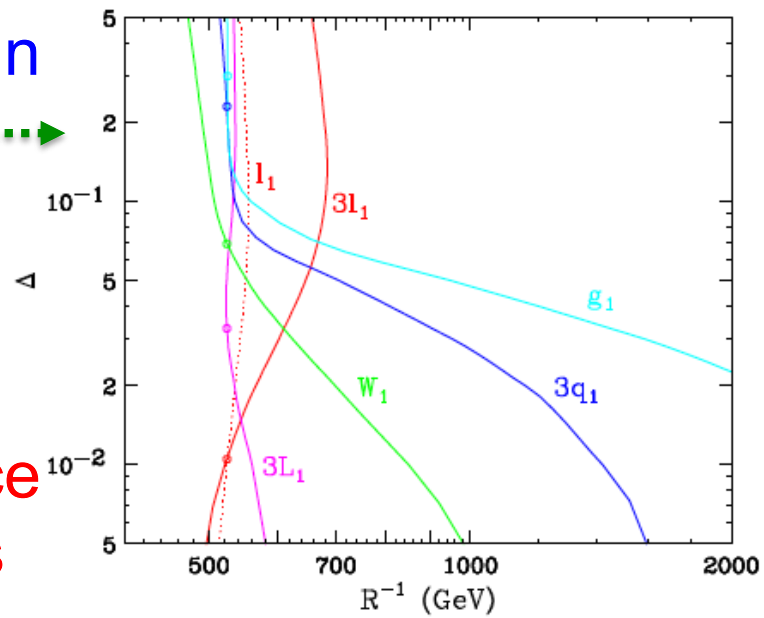
[Belanger,MK,Pukhov(2011); MK, in preparation]

This talk (2/2)

- Precise computation of the relic abundance is important because the scale of new physics is predicted
- In the minimal UED, 2nd Kaluza-Klein (KK) modes significantly affect the LKP abundance [Belanger,MK,Pukhov(2011)]



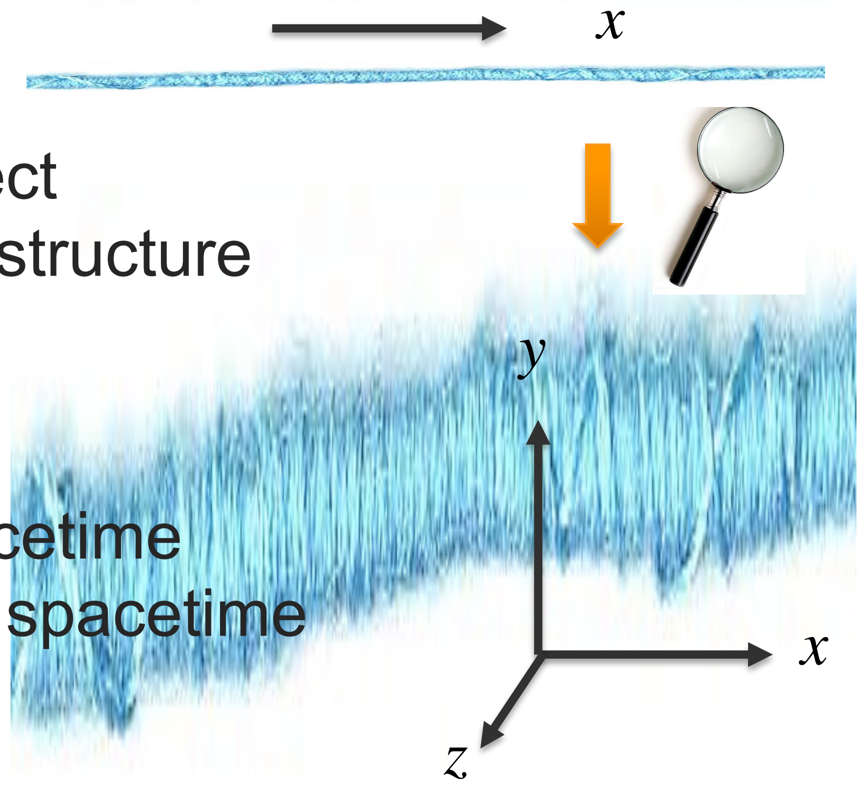
- Earlier work on the LKP abundance in phenomenological UEDs:
  - 2nd KK modes are neglected [Kong,Matchev(2006)]



- Goal:
  - Computation of the LKP abundance incl. 2nd KK modes in pheno-UEDs

Contents

Idea of extra dimensions



- Thread:
  - Macroscopic: 1-dimensional object
  - Microscopic: object with internal structure
- Our world :
  - Macroscopic: 4-dimensional spacetime
  - Microscopic: higher-dimensional spacetime
- Dispersion relation for a higher dimensional particle:

$$E^2 = \vec{p}^{\,2} + (p_5^2 + p_6^2 + \cdots + m^2)$$

➡ Momentum in the extra dim. = Mass in the 4-d viewpoint

Universal extra dimensions

- **Universal:** All SM particles propagate in flat compact spatial extra dimensions

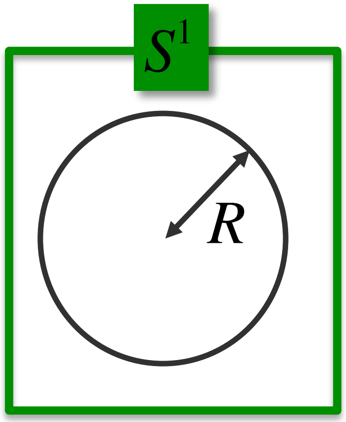
[Appelquist, Cheng, Dobrescu, PRD64, 035002 (2001)]

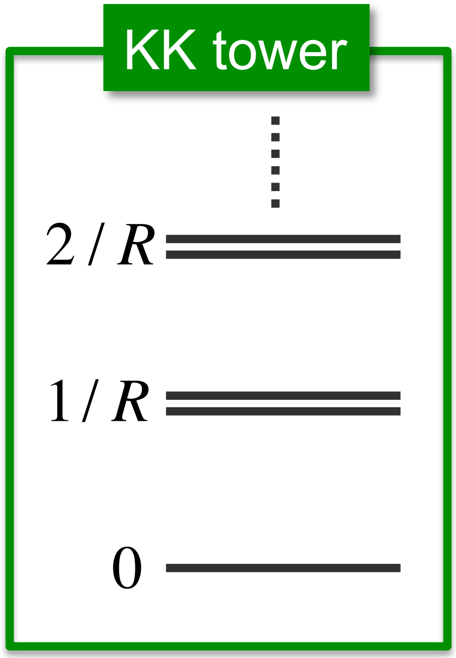
- S^1 compactification with radius R :

  Periodic boundary condition

  → $p_5 = n / R (n = 0, \pm 1, \pm 2, \cdots)$

  Kaluza-Klein (KK) tower in 4D



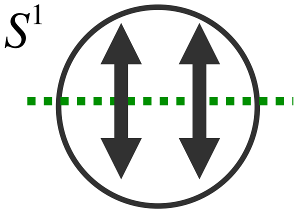


- Momentum conservation in the extra dimension

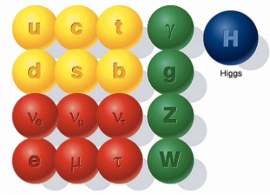
  → Conservation of KK number n at each vertex

Minimal Universal Extra Dimension (mUED)

- All the SM particles propagate in the orbifold: S^1/Z_2

S^1  → S^1/Z_2: $0 \quad y \quad \pi R$ → Chiral zero-mode fermions

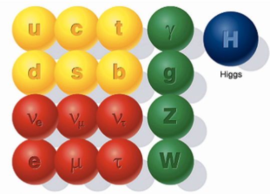
2nd KK particles



- Mass spectrum (KK tower):

$$p_5^2 = (2/R)^2$$
$$p_5^2 = 1/R^2$$
$$p_5^2 = 0$$

1st KK particles

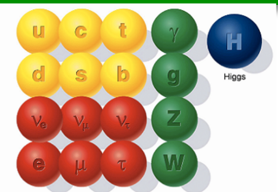


- KK-parity conservation: $P = (-1)^n$

  → Lightest KK particle (LKP) is stable

  (c.f. R-parity and LSP)

SM particles



- Only two undetermined parameters in the mUED:

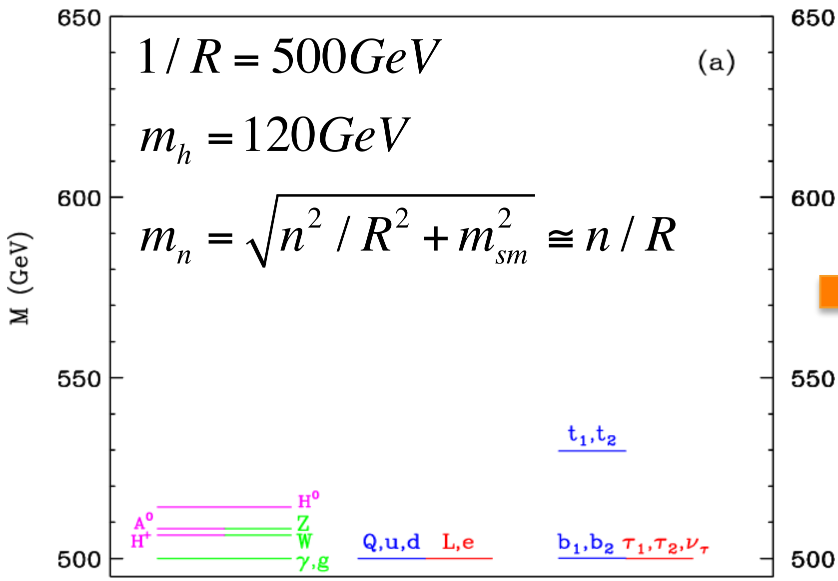
  R: size of the extra dimension $\quad \Lambda$: cutoff scale

Radiative corrections to KK masses

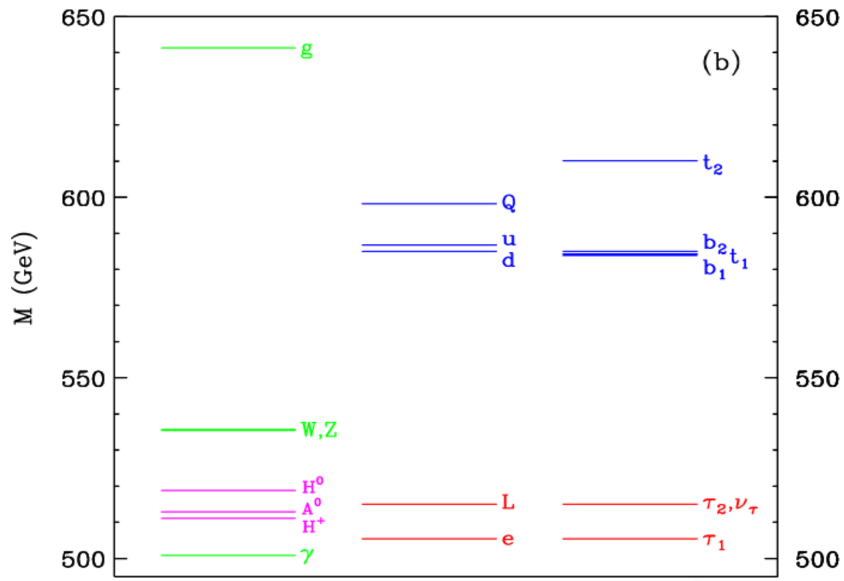
Compactification ⇨ ~~5-dimensional Lorentz invariance~~
Orbifolding ⇨ ~~Translational invariance in the 5th dimension~~
⇨ Radiative corrections generate KK mass splitting

[Cheng, Matchev, Schmaltz, PRD66, 036005 (2002)]

- 1^{st} KK masses at tree level



- 1^{st} KK masses at 1-loop level



Dark matter candidate in the mUED: 1^{st} KK photon

Contents

1. Motivation
2. Review on the minimal universal extra dimension (mUED)
3. Relic abundance of the 1st KK photon in mUED
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   in phenomenological UED
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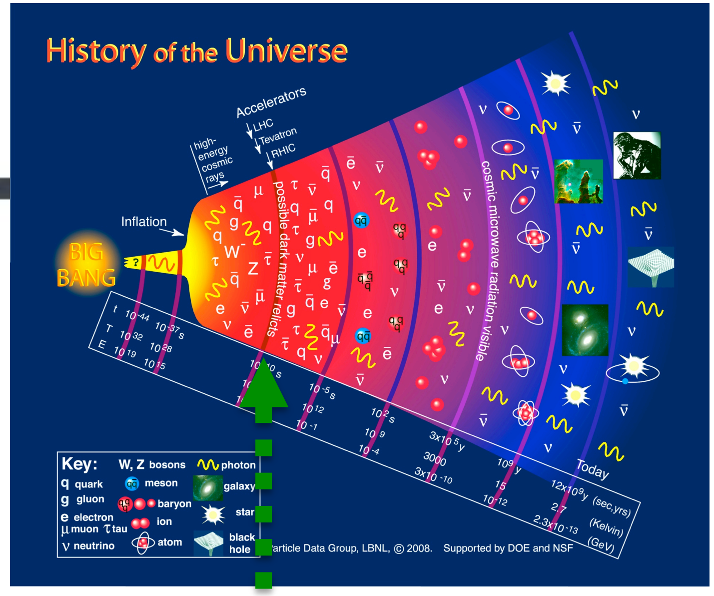
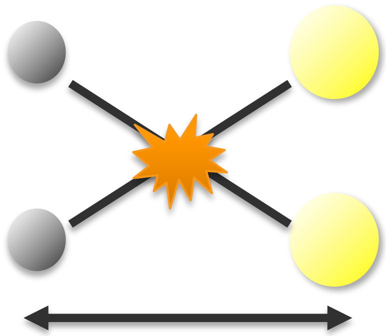
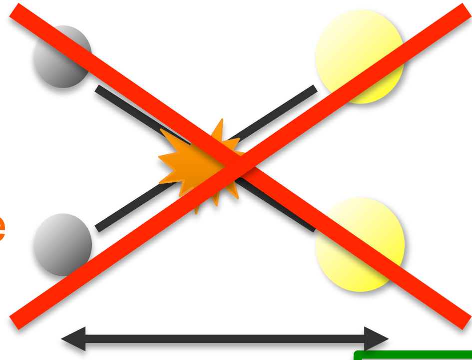
WIMP miracle



- Thermal production of WIMPs:



Temperature & # density decrease



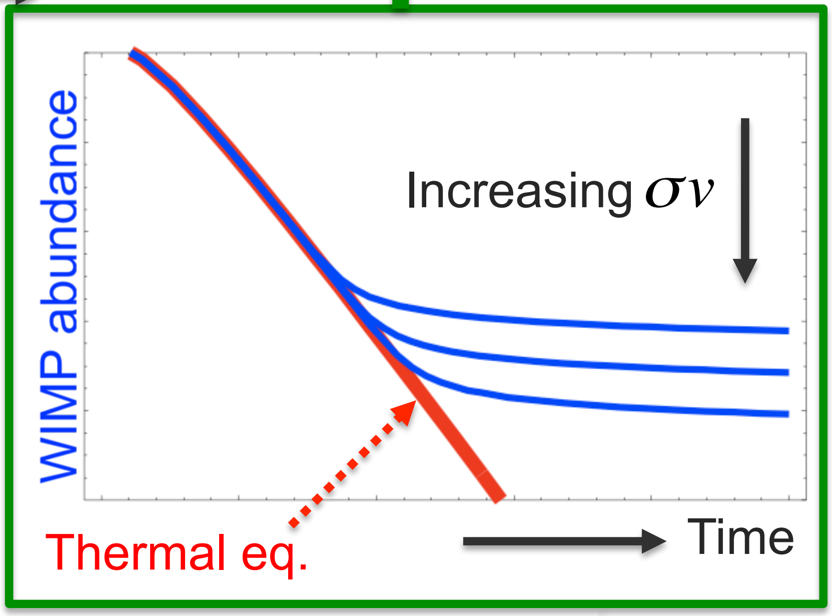
→ Prediction: $\Omega_\chi \approx 0.1 \times \left(\dfrac{1pb}{\langle \sigma v \rangle} \right)$

- Observed DM abundance:

$$\Omega_{DM} \cong 1/4$$

- For WIMP DM:

$$\sigma v \approx \frac{\pi\alpha}{m^2} \approx O(pb)$$

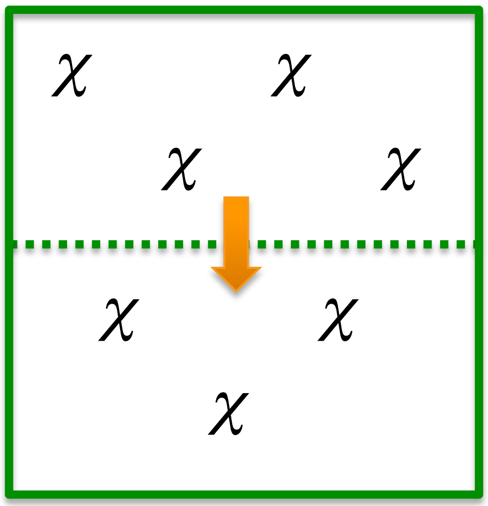


→ **There exist new physics at the TeV scale** [MSSM, UED, ...]

Including coannihilation

- Only self-annihilation:

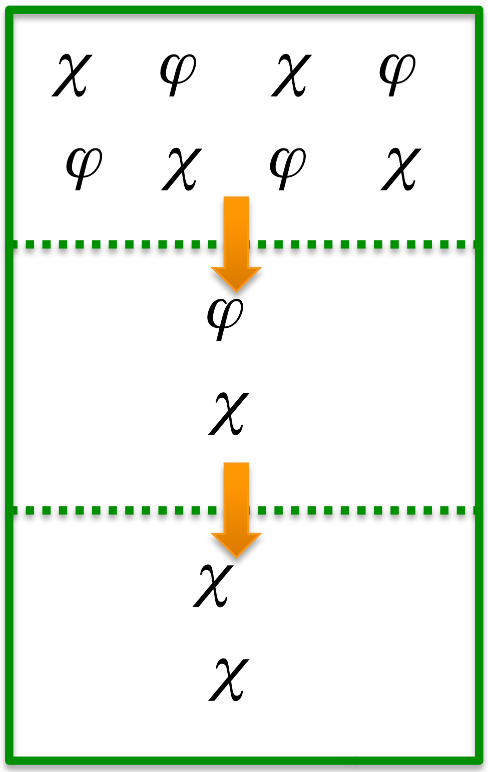
$$\chi\chi \to SM, SM$$



- Incl. coannihilation with next lightest particle φ :

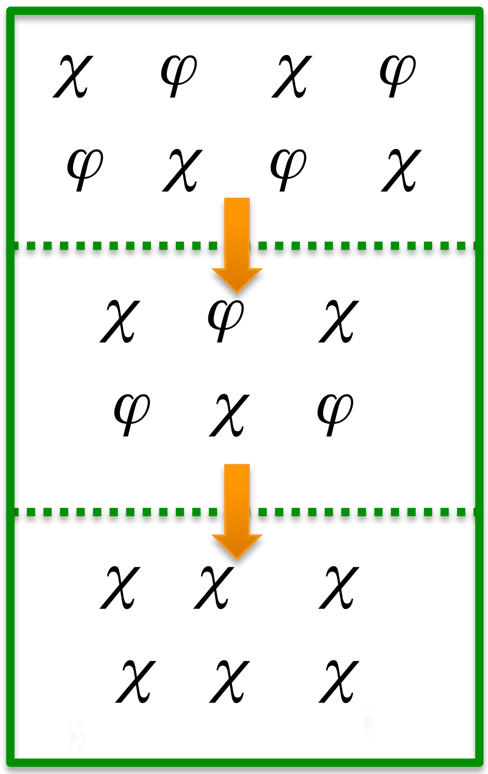
$$\chi\varphi, \varphi\varphi \to SM, SM$$

- If $\sigma_{co} >> \sigma_{self}$
  (e.g.:neutralino DM)



Time $\Omega_\chi h^2$

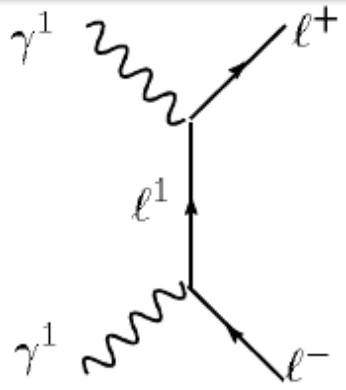
- If $\sigma_{co} \approx \sigma_{self}$
  (e.g.:1st photon DM)



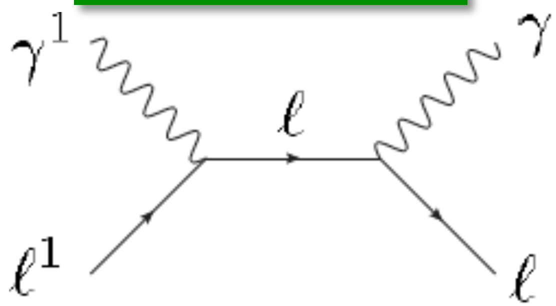
Time $\Omega_\chi h^2$

UED dark matter annihilation processes

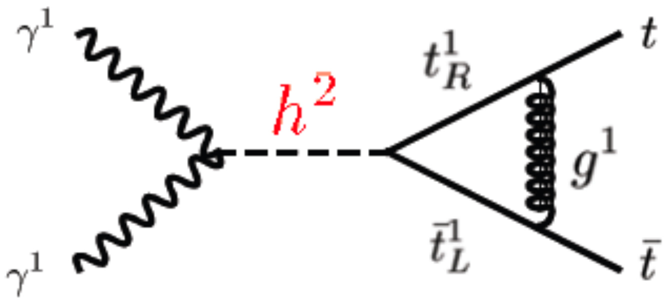
Self-annihilation



Coannihilation

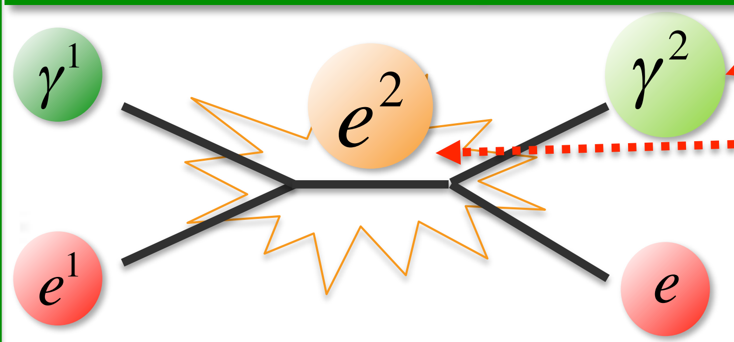


1-loop resonant process



[Servant,Tait,NPB650,391(2003);MK,Matsumoto,Sato,Senami,PRD71,123522(2005); NPB735,84(2006);Burnell,Kribs,PRD73(2006);Kong,Matchev,JHEP0601(2006); MK,Matsumoto,Senami,PRD74(2006)023504]

Final state level 2 production

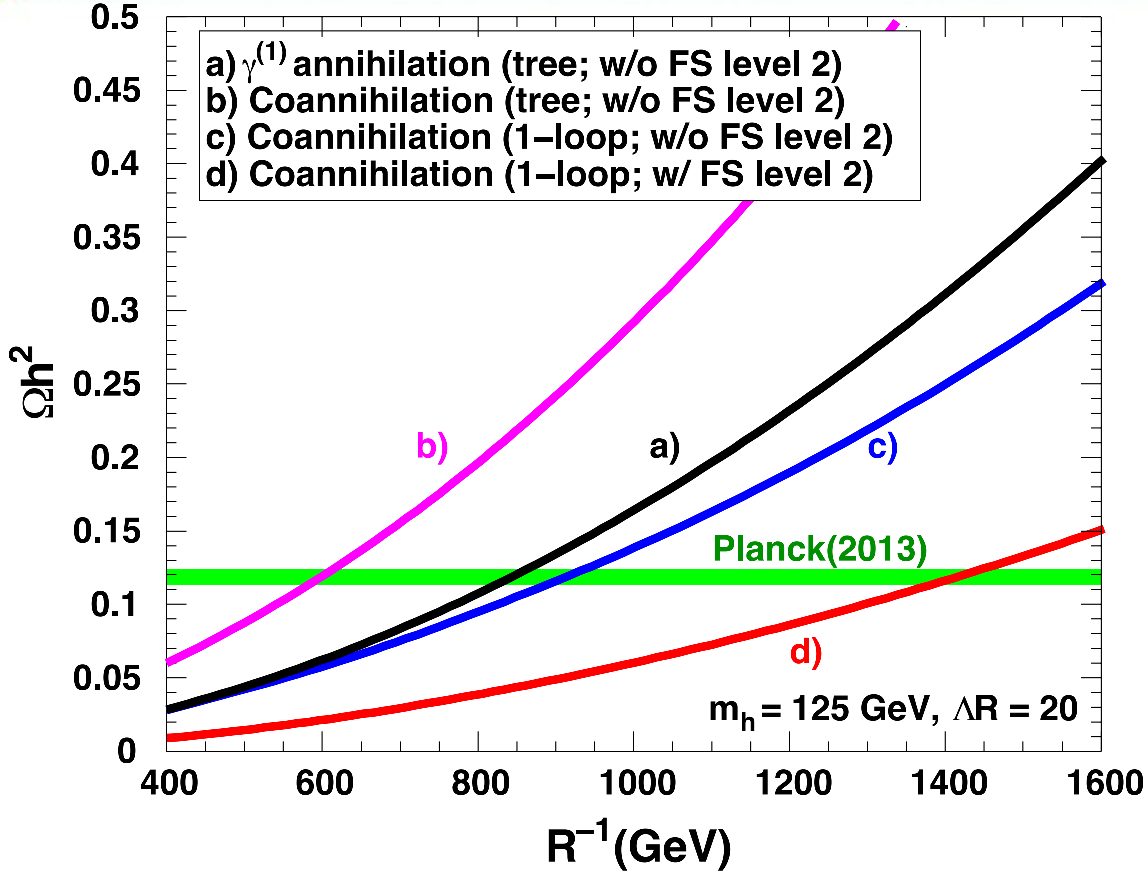


- $\gamma^2, h^2, h^{2\pm}, a^2$ decay mostly into SM particles
- $\sqrt{s} \approx m^{(1)} + m^{(1)} \approx m^{(2)}$

FS level 2 processes enhanced

[Belanger,MK,Pukhov,JCAP1102(2011)009]

Comparison of various effects in the mUED



	Self	Co	loop	FS Lv2
a)	X			
b)	X	X		
c)	X	X	X	
d)	X	X	X	X

Compactification scale (GeV)

($\cong \gamma^1$ mass)

[Belanger,MK,Pukhov(2011); MK, in preparation]

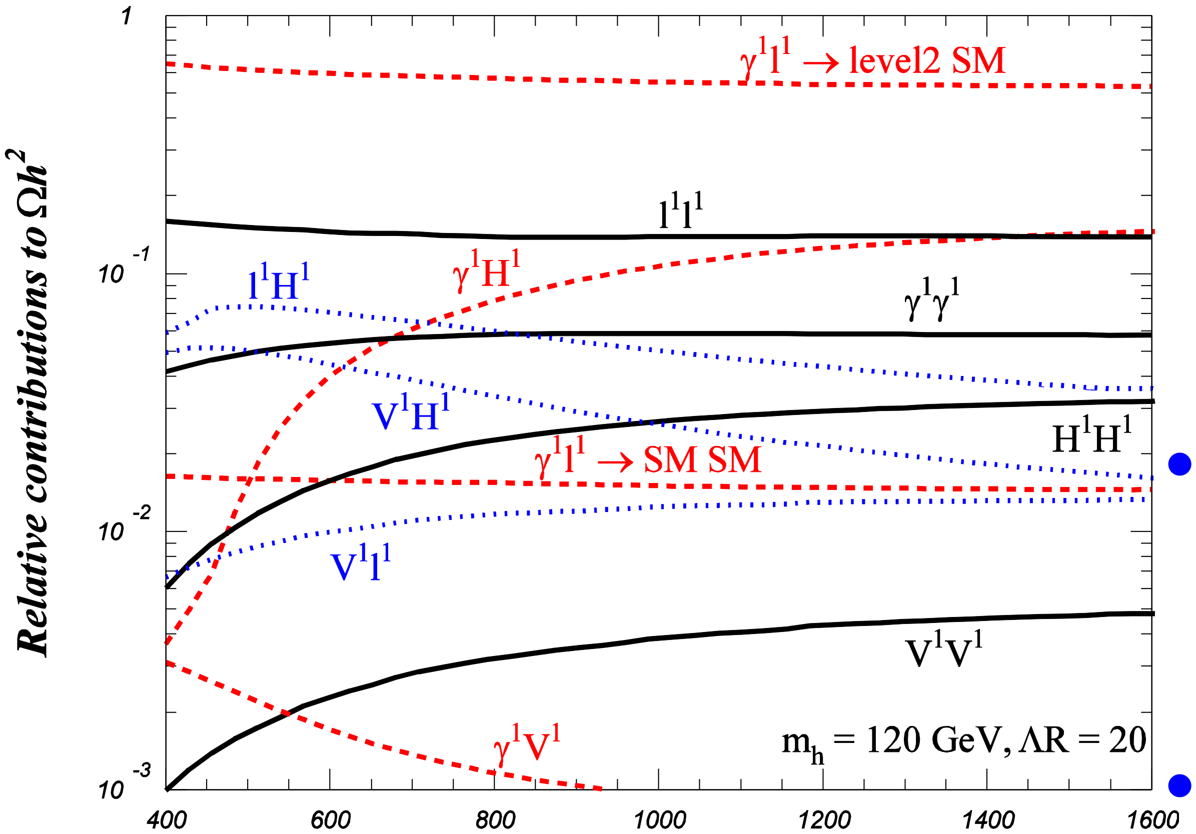
2nd KK resonance

→ Relic abundance reduced

→ DM mass pushed above TeV

Relative contributions

- At the freeze-out temperature:



Compactification scale (GeV) ($\cong \gamma^1$ mass)

$$\ell^1 = \ell^1_{L,R}, \nu^1_\ell;\ H^1 = h^1, h^{1\pm}, a^1;\ V^1 = W^1, Z^1$$

- Important processes:
  - $\gamma^1 \ell^1_{L,R} \to \ell^2_{L,R} \to \gamma^2 \ell$
  - $\gamma^1 \nu^1_\ell \to \nu^2_\ell \to \gamma^2 \nu_\ell$

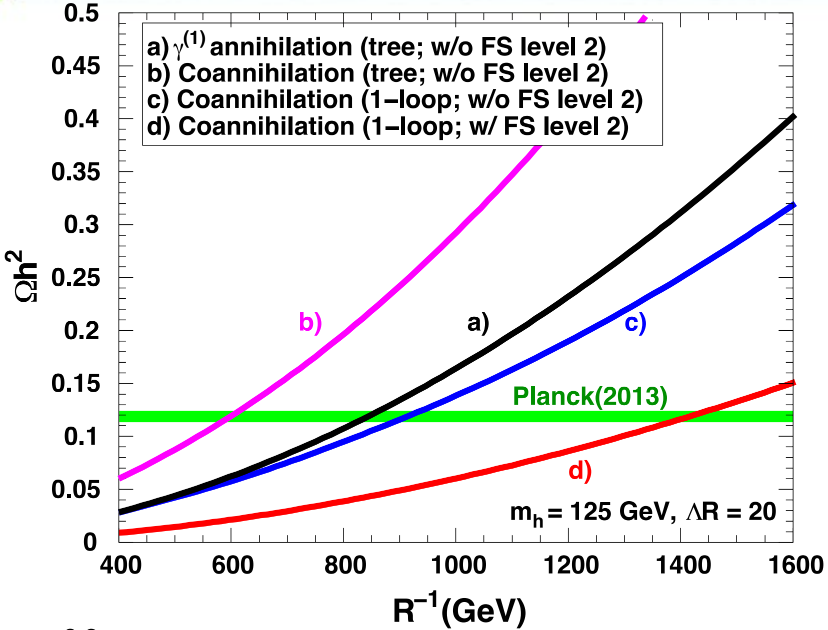
  More than 50%

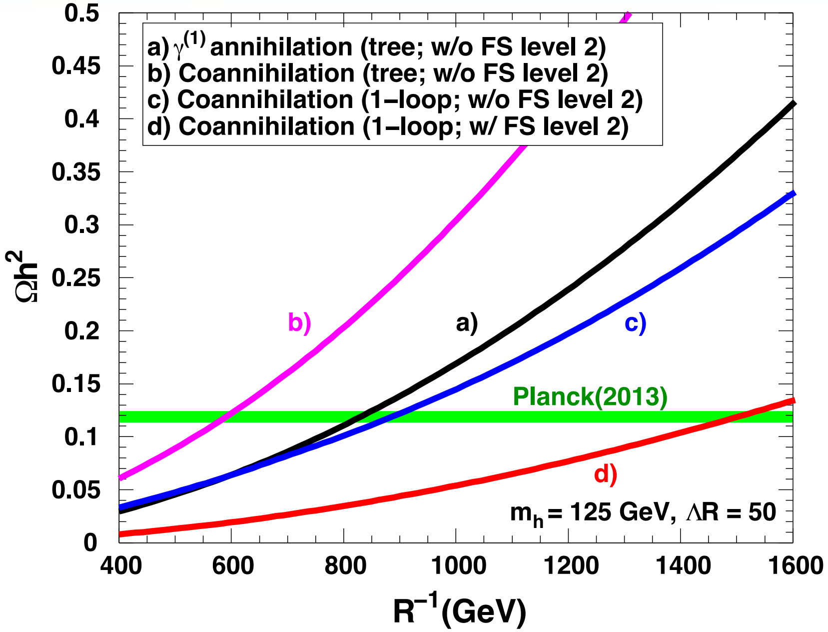
- Loop-induced resonant processes subdominant
- KK quark coannihilation negligible

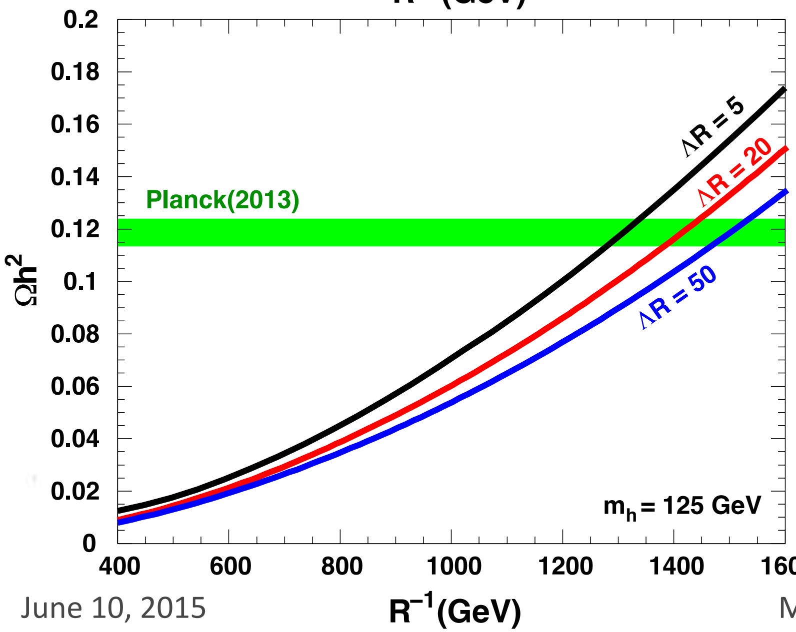
[Belanger,MK,Pukhov, JCAP1102(2011)009]

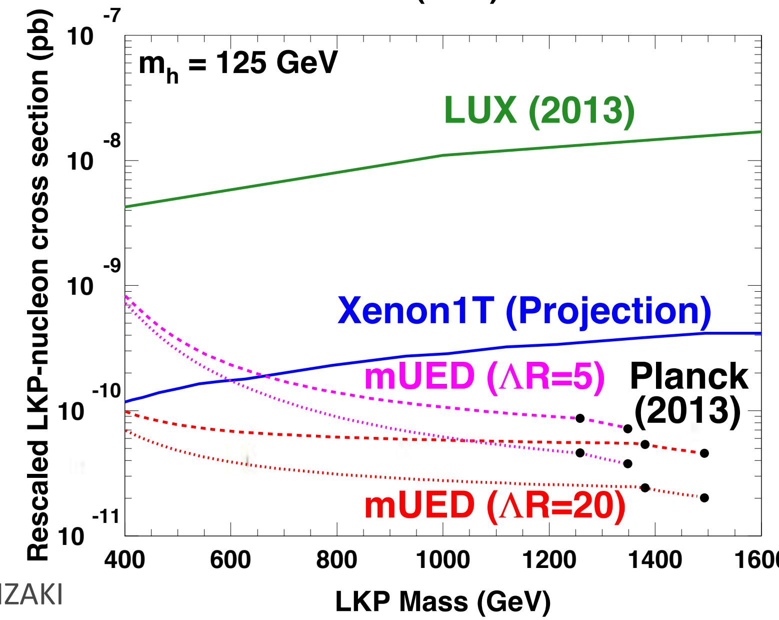
Updated Numerical Results in the mUED

[MK, in preparation]









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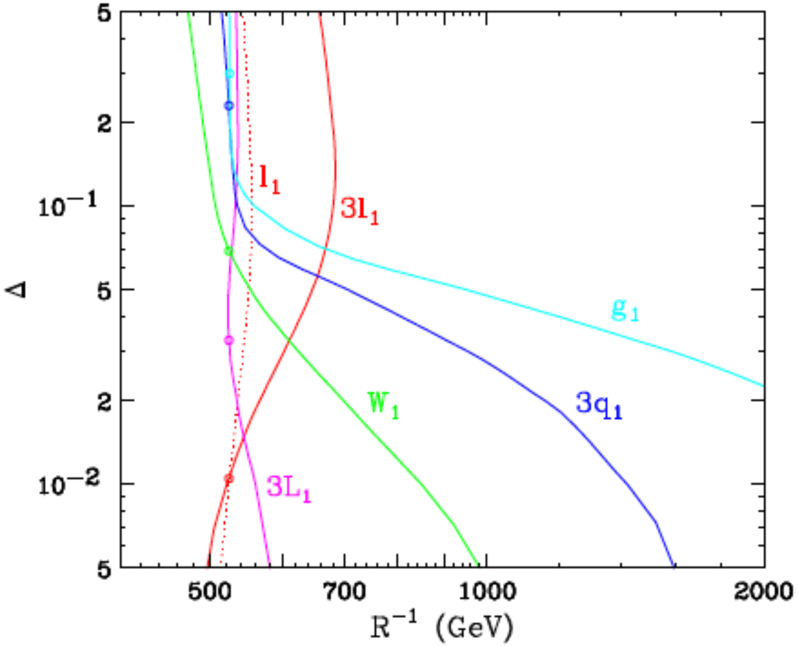
1st KK photon abundance in phenomenological UEDs

- 1st KK photon relic abundance vs mass splitting:

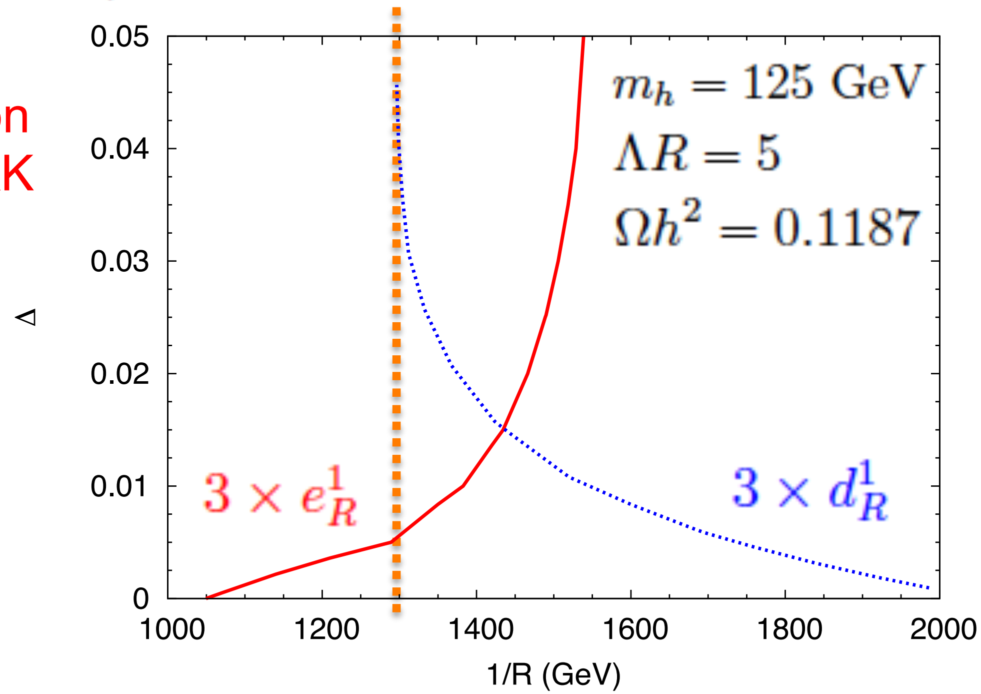
$$\Delta_{e_R} = \frac{m_{e_R^1} - m_{\gamma^1}}{m_{\gamma^1}} \qquad \Delta_{d_R} = \frac{m_{d_R^1} - m_{\gamma^1}}{m_{\gamma^1}}$$

mUED



[Kong,Matchev(2006)]

Inclusion of 2nd KK modes



The other parameters fixed to the mUED values

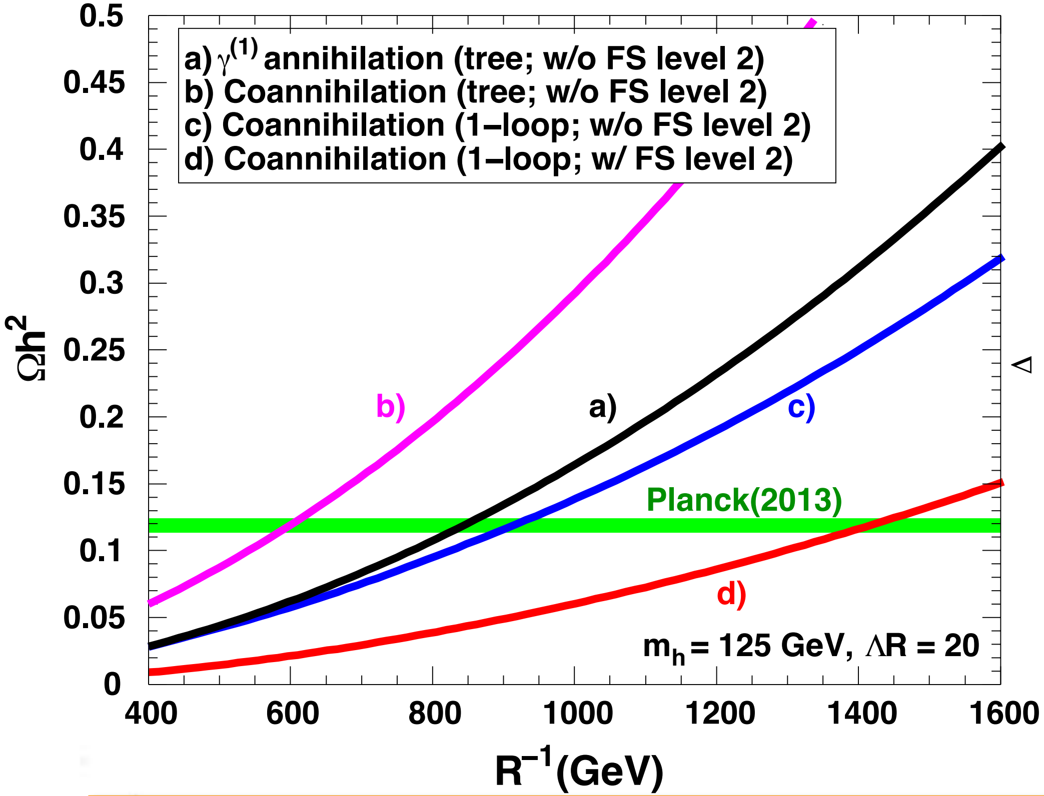
[MK, in preparation]

- The preferred 1st KK photon mass can be shifted upward or downward in pUED

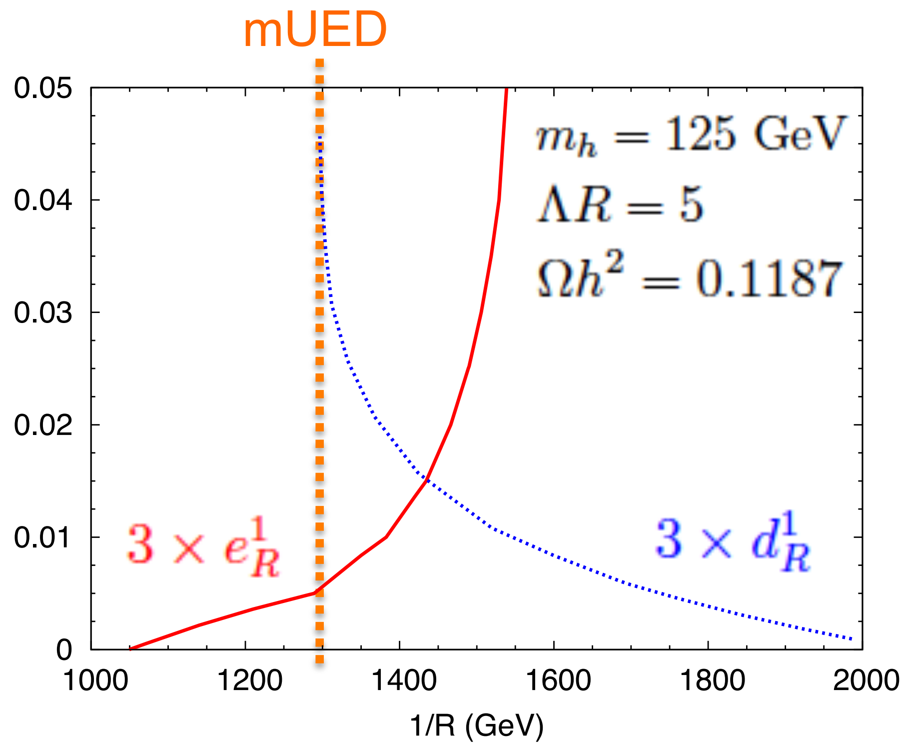
5. Summary

- Relic abundance of the 1st KK photon (mostly 1st KK hypercharge B-boson) in UED models

mUED



Phenomenological UEDs



Preferred 1st KK photon mass in the WIMP scenario: m>TeV

Discussion

1st KK photon DM scenario in 5D UED

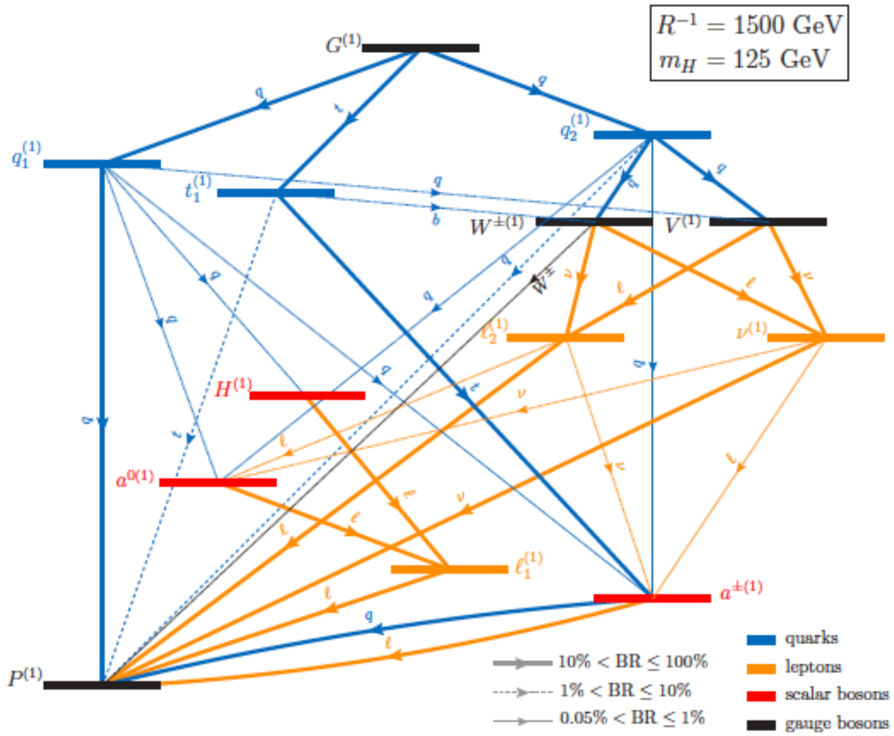
- DM abundance: OK
- EWPO: OK
- FCNC: OK
- LHC Run-I: OK
- Neutrino masses: can be incorporated [Matsumoto,Sato,Senami,Yamanaka (2007) for Dirac neutrinos]
- Baryon asymmetry: ???
- Inflation: ???
- Accelerated expansion: ???;
- Contribution to muon g-2: too small
- Hierarchy problem: ameliorated
- Little hierarchy problem: ???
- Vacuum stability/triviality: OK; ameliorated by extending the Higgs sector
- Radion stability: ???
- KK-parity: can be anomaly free
- Direct detection: challenging
- Indirect detections: challenging (Non-perturbative effects?)
- LHC Run-II: can cover the WIMP scenario
- Future linear colliders: can test deviations of the Higgs boson couplings

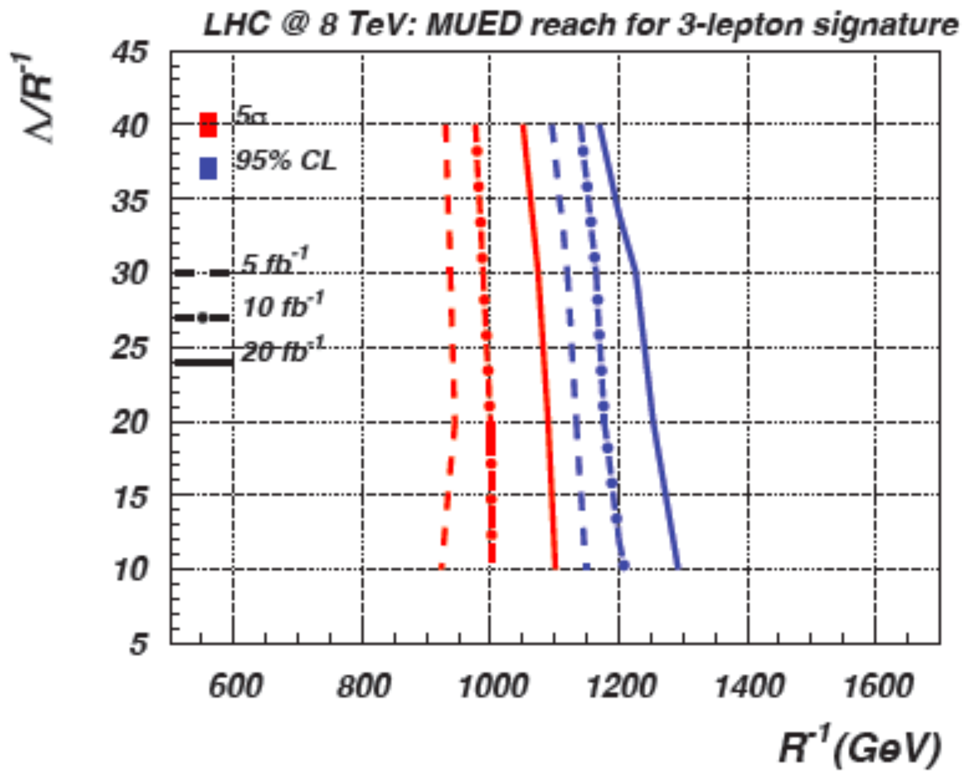
1st KK Z-boson DM scenario in 5D UED

- working with K.Ishiwata

Backup slides

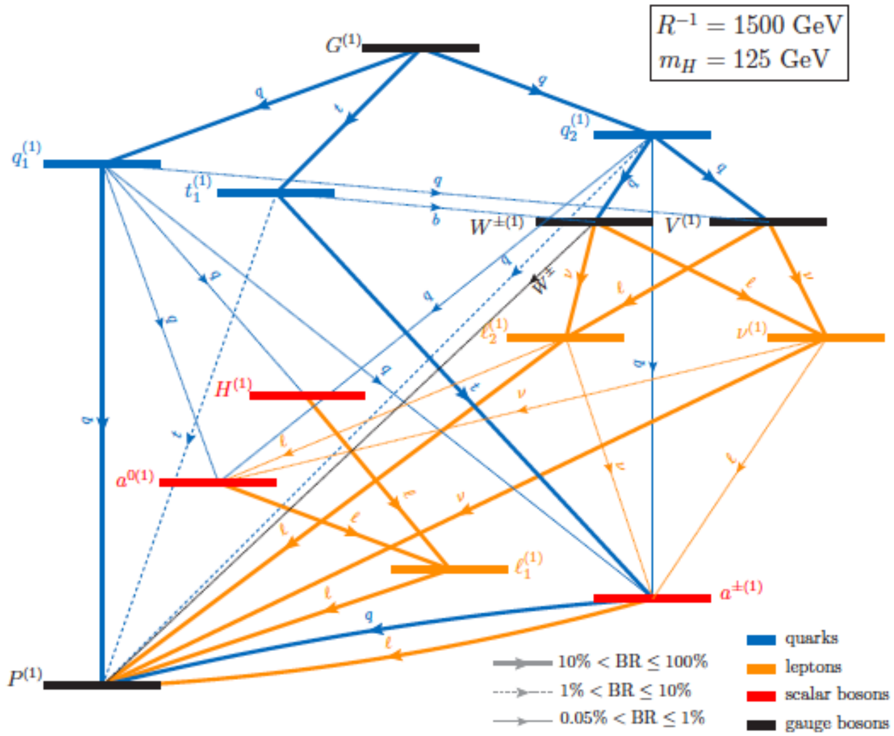
LHC8 constraints



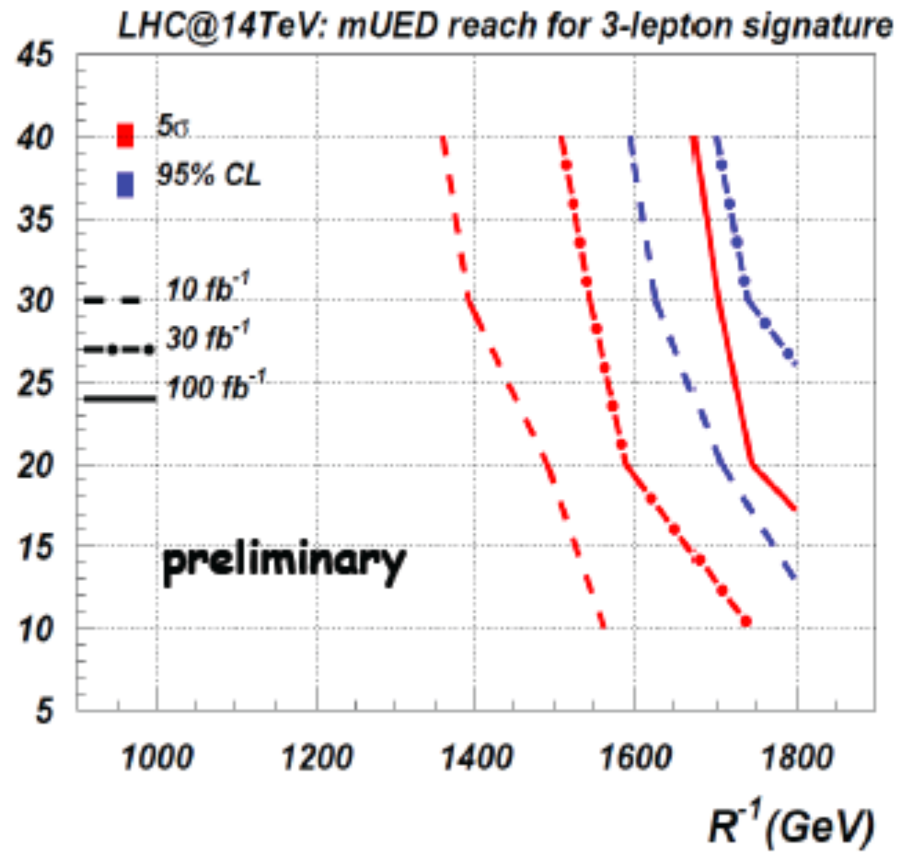


[Belyaev,Brown,Moreno,Papineau(2013)]

LHC14 constraints

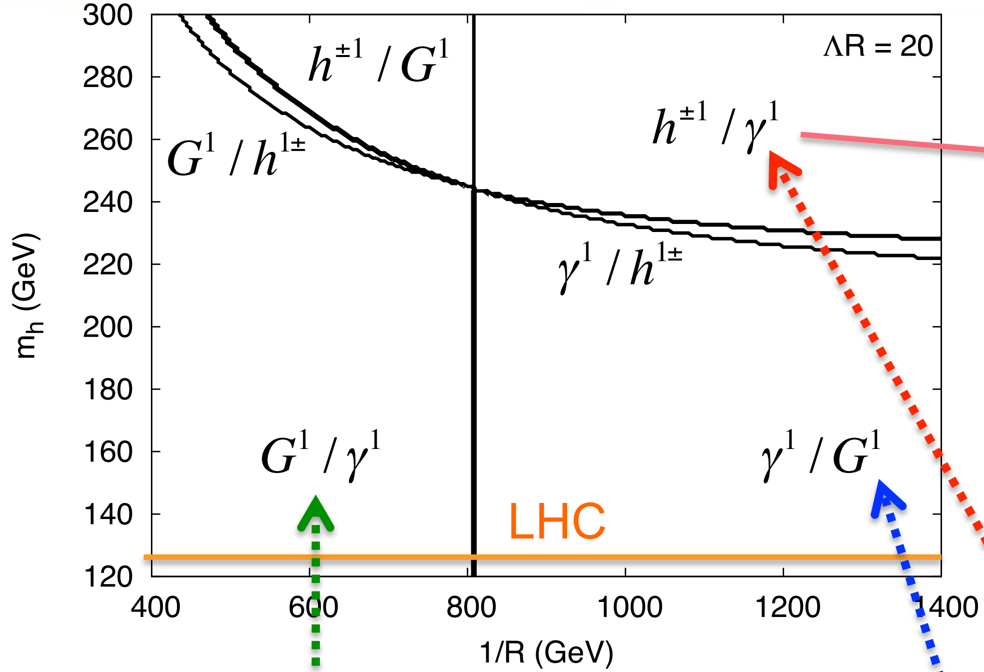


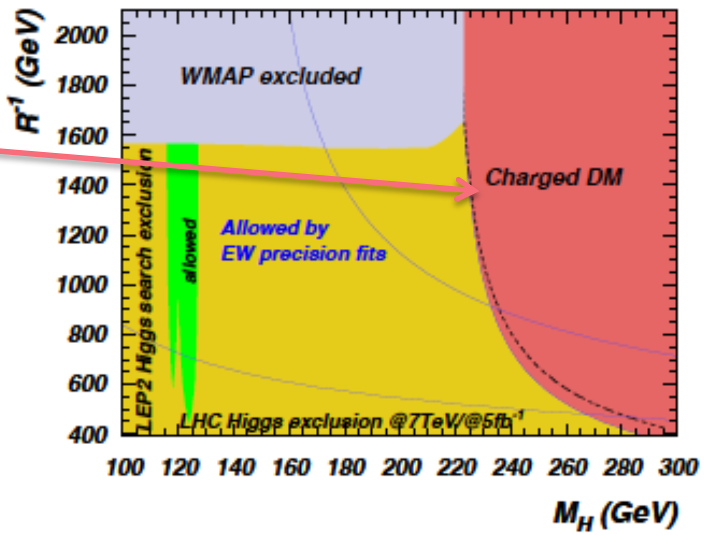
[Belyaev,Brown,Moreno,Papineau(2013)]



[Belyaev' talk at SUSY2013]

LKP/NLKP in the MUED





- SuperWIMP DM region (level-1 graviton LKP):

  $1/R < 800 GeV, m_h < 240 GeV$

  - Disfavored by CMB, diffuse photon spectrum

  [Feng,Rajaraman,Takayama,PRL91, 011302(2003);PRD68,085018(2003)]

- CHAMP region ($h^{1\pm}$ LKP):

  $m_h > 240 GeV$

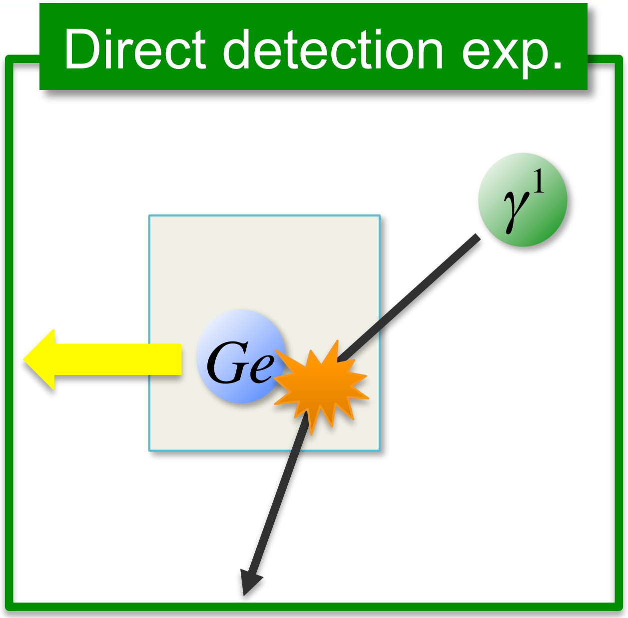
  - Excluded by LHC, sea water exp.

- WIMP DM region (γ^1 LKP):

  $1/R > 800 GeV, m_h < 220 GeV$

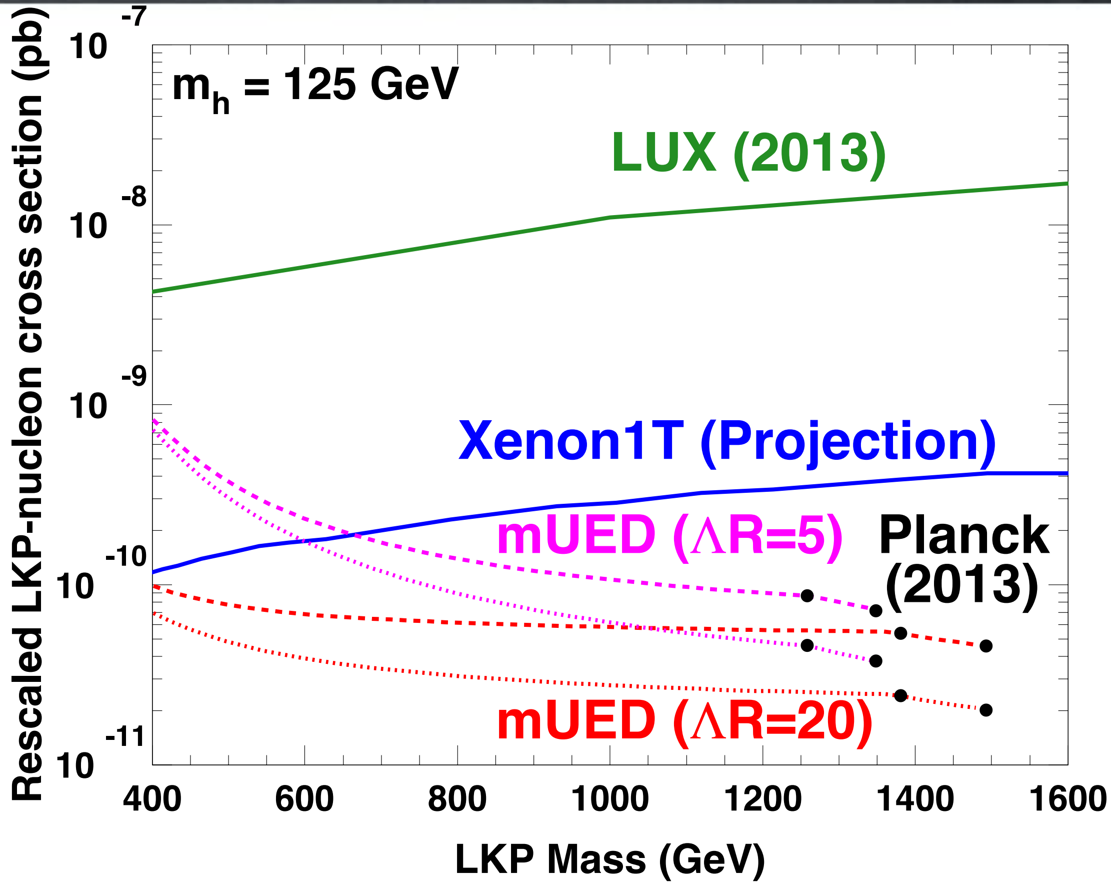
  - This talk

Direct detection of the 1st KK photon



- γ^1 −nucleon cross section in MUED :

$$\sigma_{Ge} = 10^{-11} - 10^{-10}\, pb$$



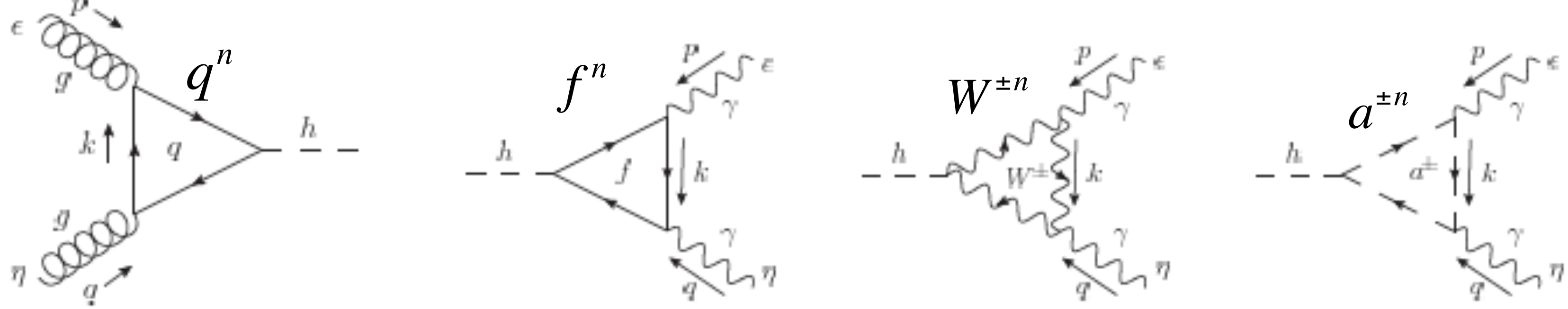
[From Belanger,MK,Pukhov,JCAP1102(2011)009; See also Servant,Tait,NPB650,391(2003)]

- A complete one-loop computation including KK quarks higher than 1 confirms these results

[Hisano,Ishiwata,Nagata,Yamanaka,PTP,126,435(2011)]

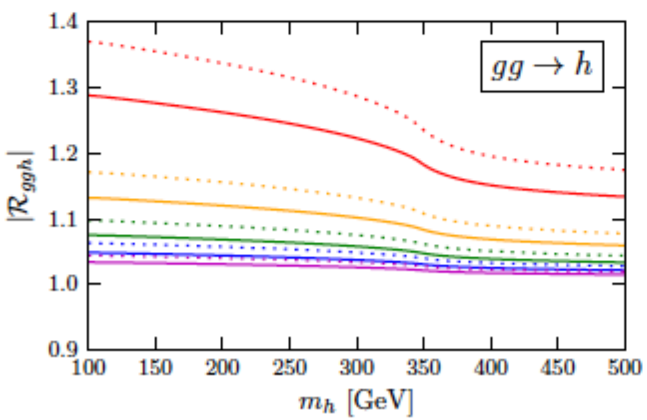
Higgs searches at the LHC

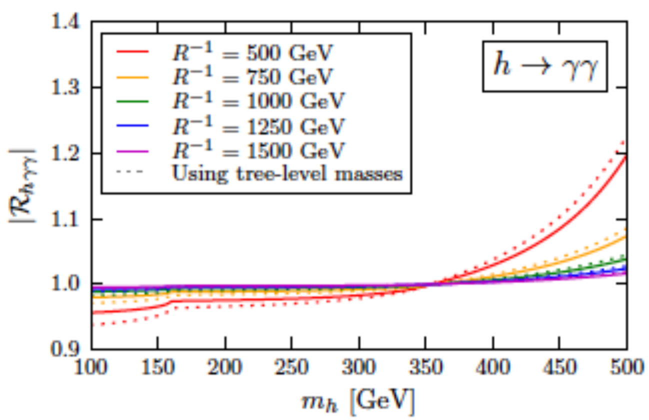
- Production and decay of the SM-like Higgs: $gg \to h \to \gamma\gamma$

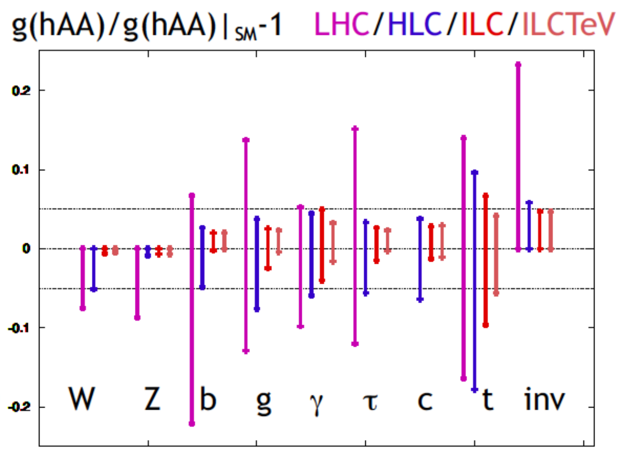


[Petriello,JHEP05,003(2002)]

- Deviations of the hgg and $h\gamma\gamma$ couplings from the SM values:





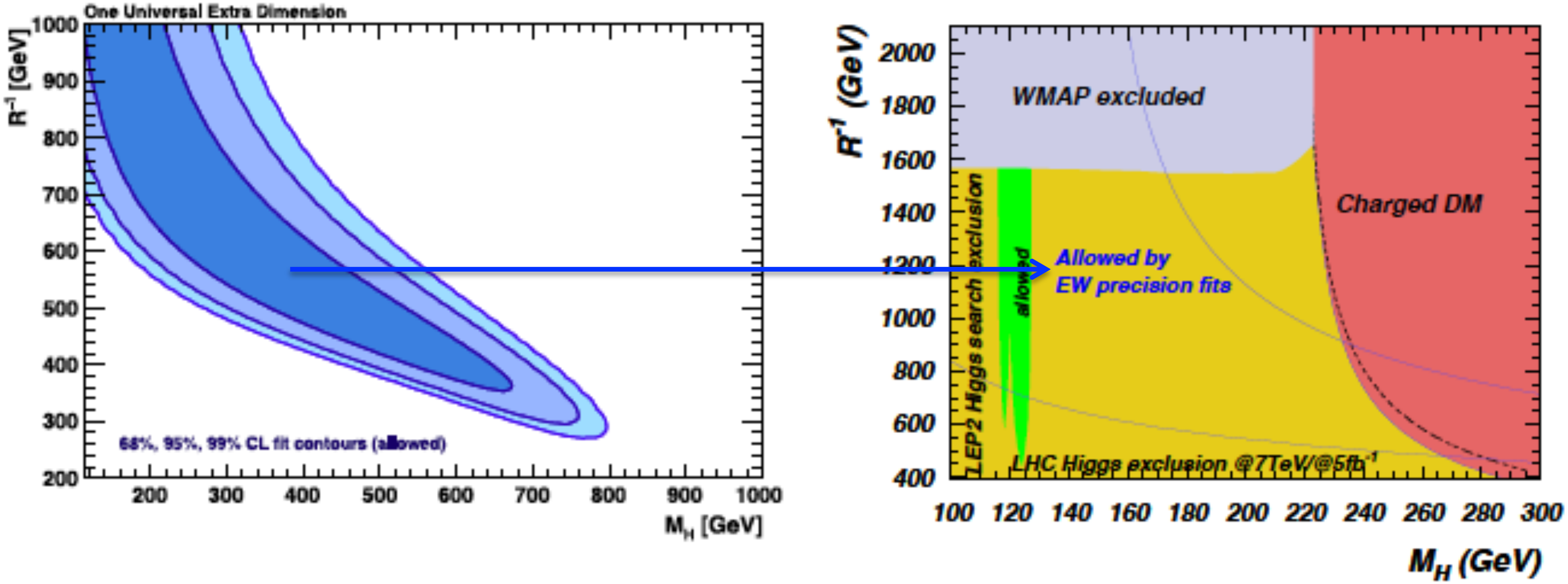


[From Belanger,Belyaev,Brown,MK,Pukhov,arXiv:1207.0798;
See also Nishiwaki,Oda,Okuda,Watanabe,PLB707,506(2012)]

[Peskin,1207.2516]

Electroweak precision measurements

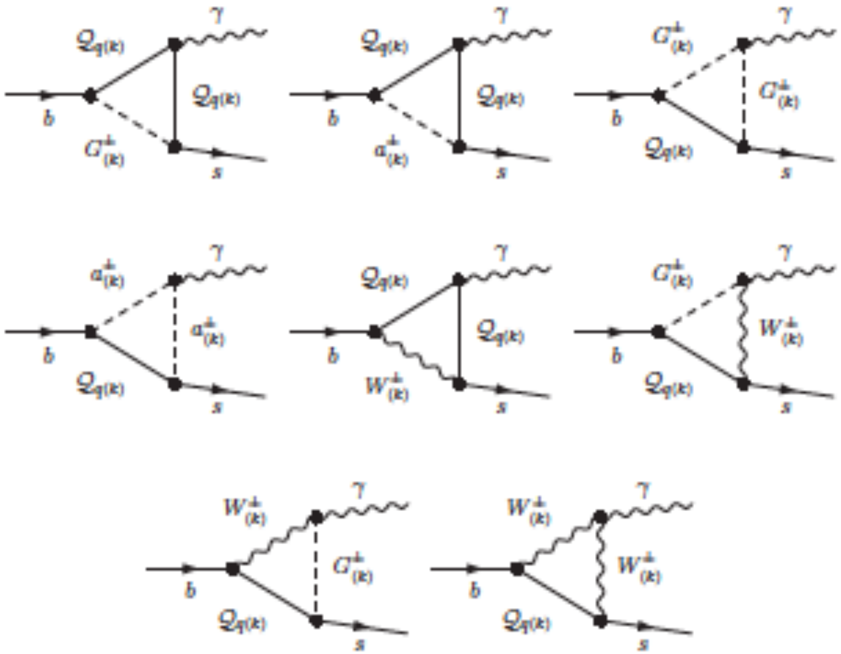
- KK parity ➡ Constraints on UEDs are weaker than those on other extra dimension models

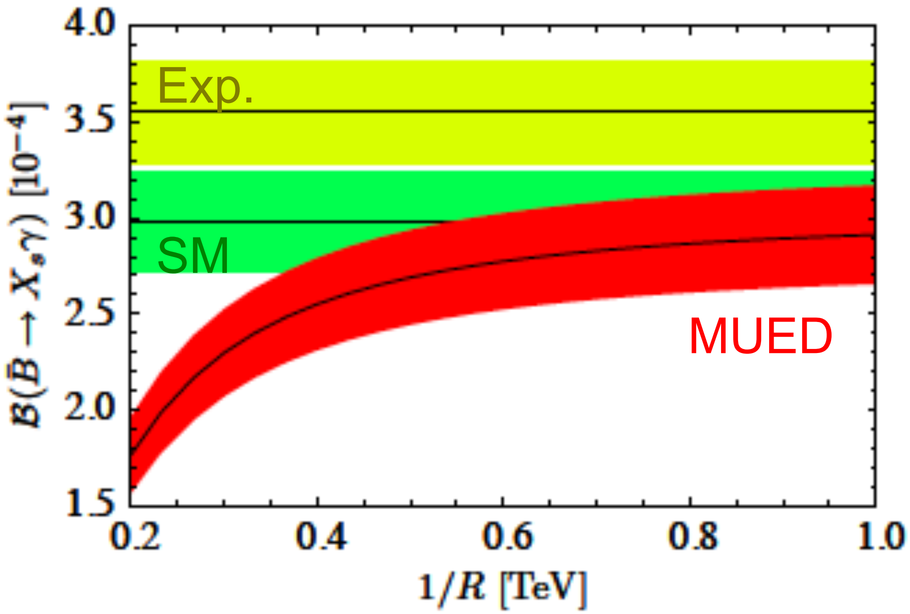


[From Baak,Goebel,Haller,Hoecker,Ludwig,Moenig,Schott,Stelzer, Eur.Phys.J.C72,2003(2012);See also Gogoladze,Macesanu,PRD74 (2006)]

Flavor changing neutral currents

- $B \to X_s \gamma$



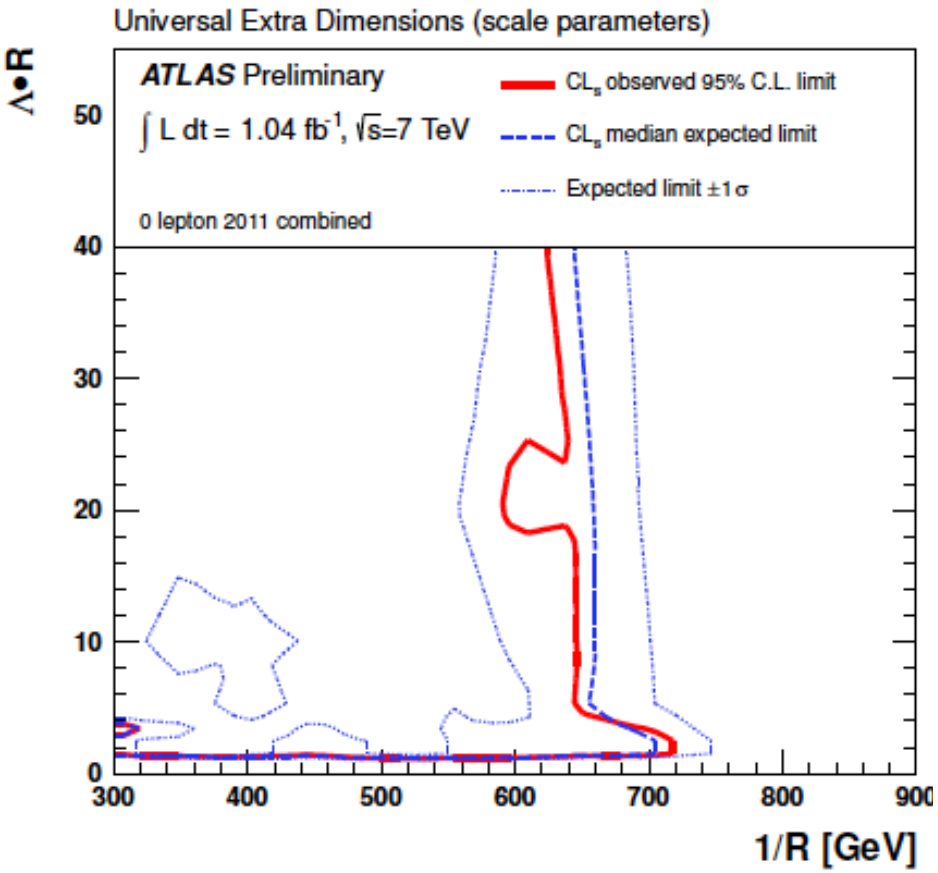


$$\Rightarrow \quad 1/R > 600 GeV (95\% CL)$$

[Haisch,Weiler,Phys.Rev.D76,034014(2007)]

LHC search for level-1 particles

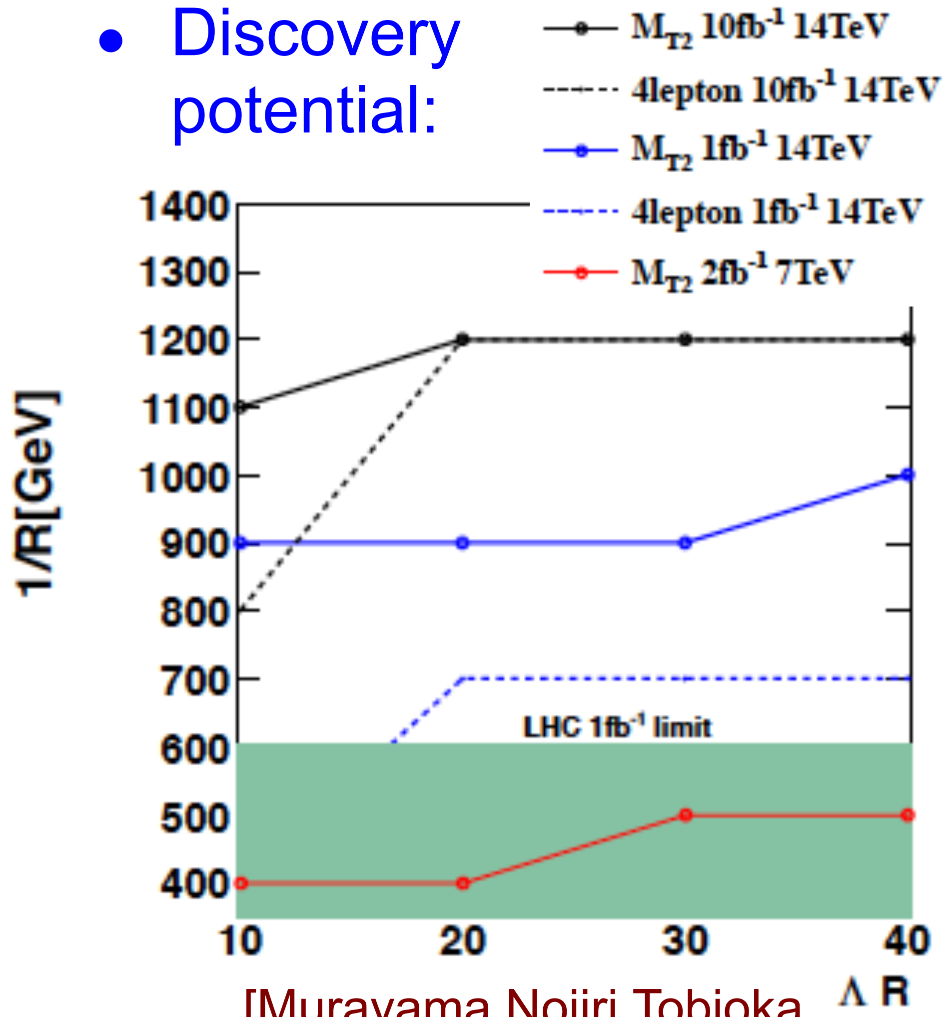
- Exclusion Limits:



[ATLAS-CONF-2011-155]

$\Rightarrow 1/R > 600GeV$

- Discovery potential:

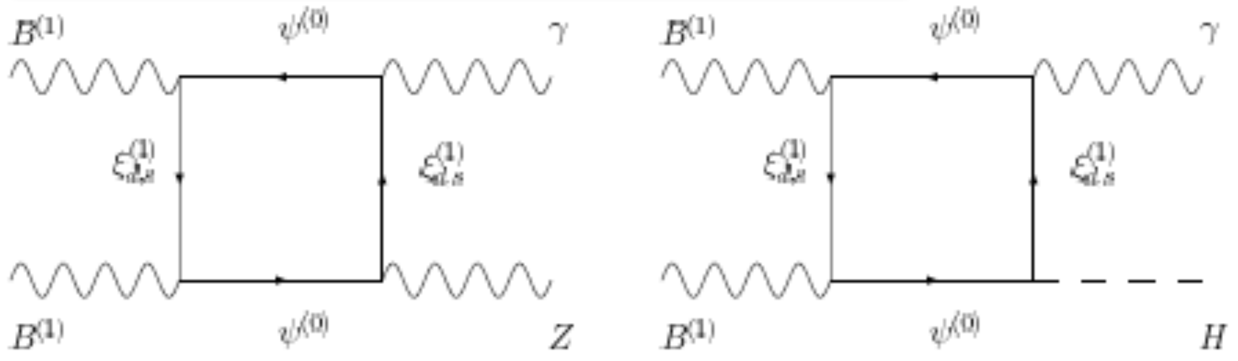


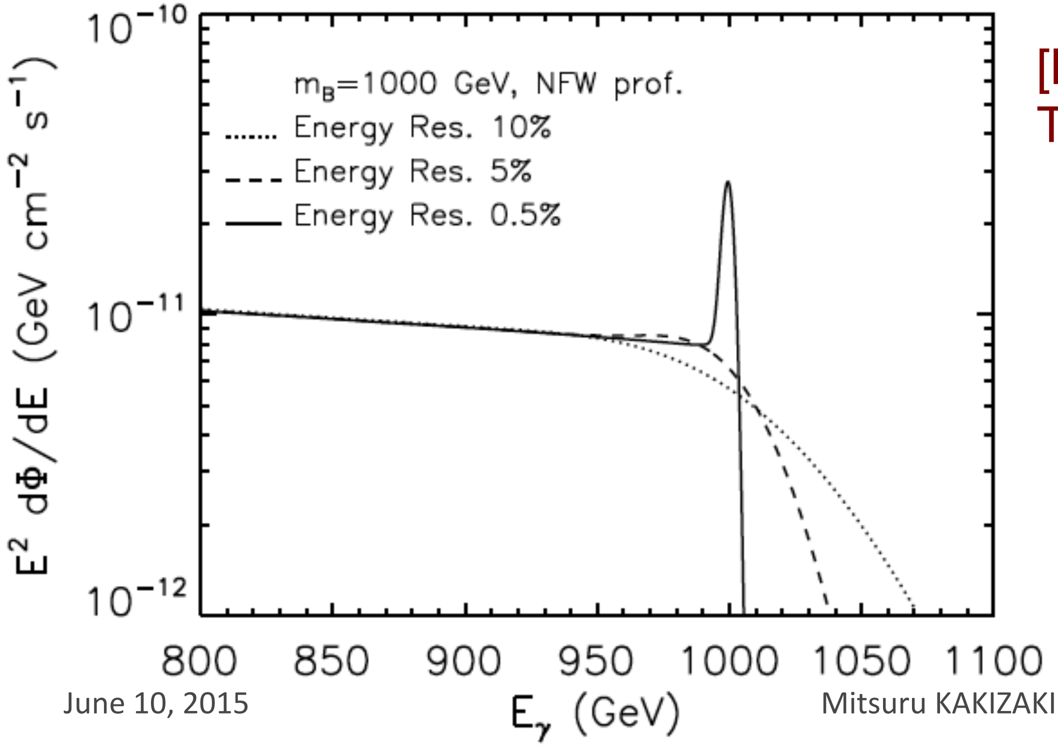
[Murayama,Nojiri,Tobioka, PRD84,094015 (2011)]

$\Rightarrow 1/R \sim 1.2TeV$

Indirect detection (Gamma rays)

Gamma-ray lines: $\gamma^1\gamma^1 \to \gamma\gamma, Z\gamma, h\gamma$





[Bertone,Jackson,Shaughnessy, Tait,Vallinotto,JCAP,1203,020(2012)]

Lines are very difficult to distinguish from the continuum

Vacuum stability

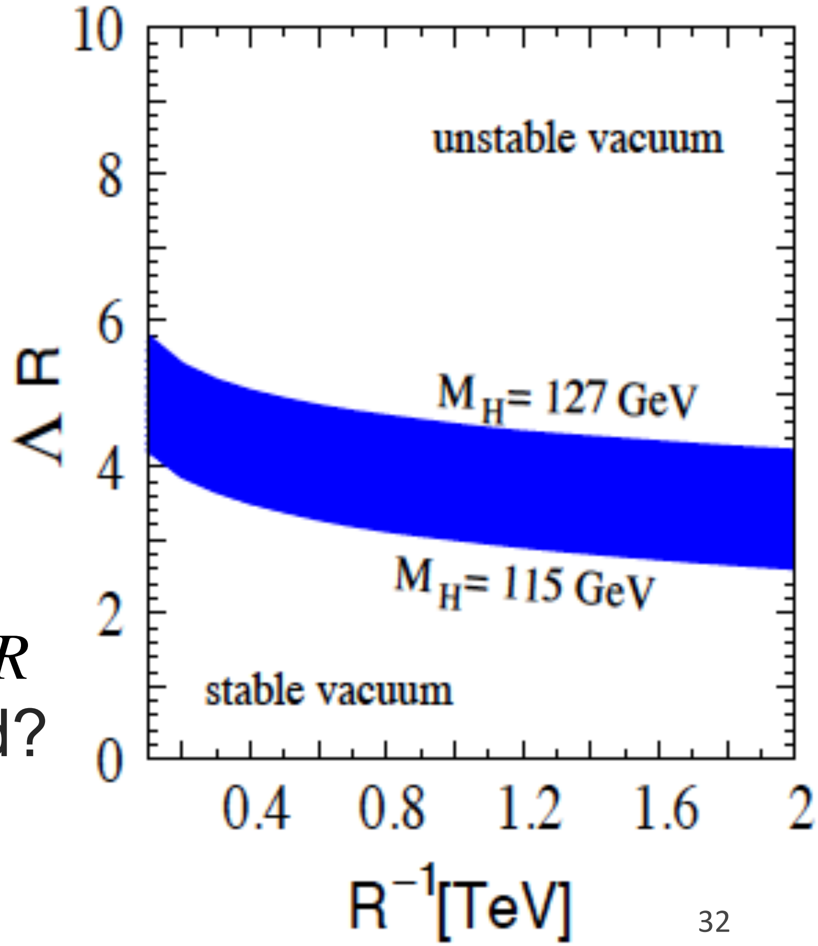
- Vacuum stability and triviality bounds:

$$148GeV < m_h < 186GeV \quad \text{for} \quad 1/R = 1TeV, \Lambda R = 30$$

[Bhattacharyya,Datta,Majee,Raychaudhuri,NPB760,117(2007)]

- Vacuum stability bounds
  for a light Higgs:

  [From Datta,Raychaudhuri,arXiv:1207.0476;
  See also Blennow,Melbeus,Ohlsson,Zhang,
  PLB712,419(2012)]

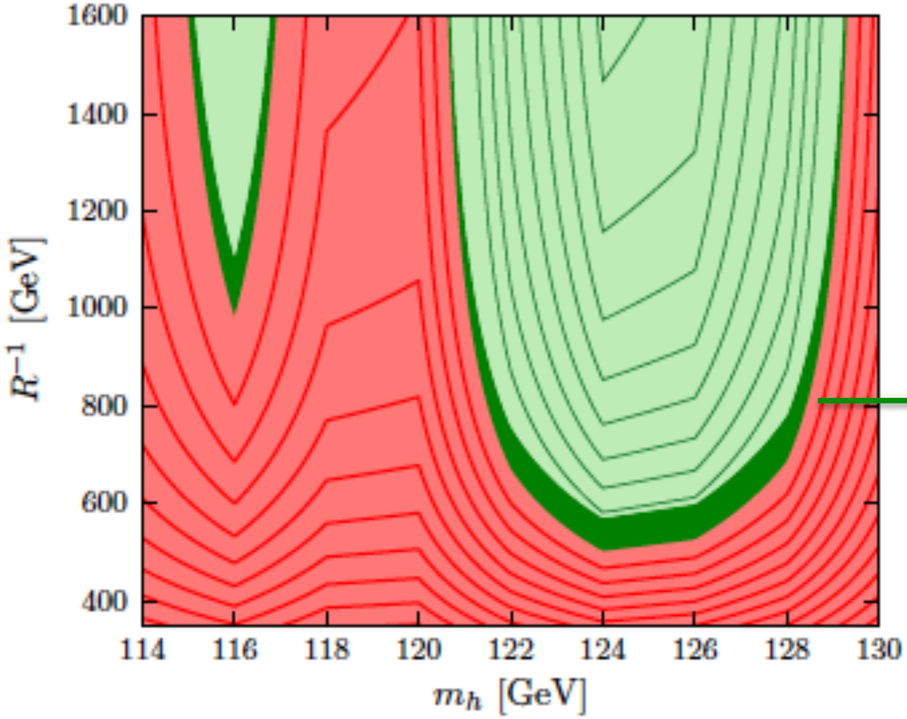


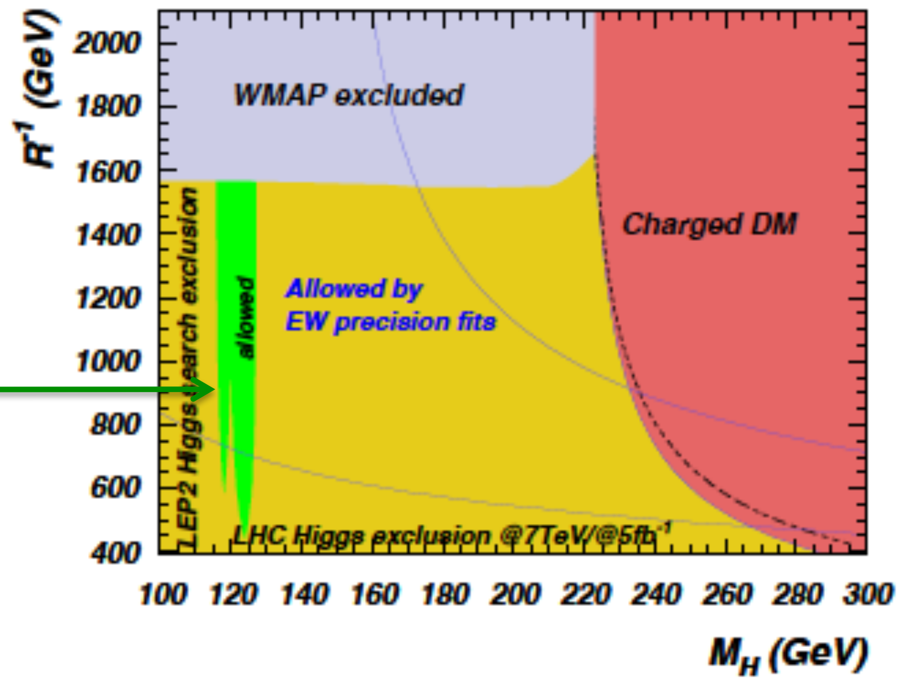
To what extent does the bound on ΛR get relaxed if metastability is allowed?

Limits on the MUED parameters space

- MUED-Higgs properties are similar to those of the SM-Higgs

LHC Higgs exclusion (7 TeV & 8 TeV) as of July 2012





$$\Rightarrow 1/R > 500 GeV (95\%CL)$$

[From Belanger,Belyaev,Brown,MK,Pukhov,arXiv:1207.0798;
See also Nishiwaki,Oda,Okuda,Watanabe,PLB707,506(2012)]

Public tools and UEDs

- New physics models are confronted by the LHC and future ILC data

  ➡ Precise computations of observables are needed to distinguish models

- Difficulties in universal extra dimensions (UEDs)
  - Many degenerate particles and interactions are involved

  ➡ Computing UED processes is tedious and error-prone

Public tools play a crucial role in obtaining reliable results

- Drawbacks in earlier UED implementations in public tools:
  - EW symmetry breaking effects are neglected in many places
  - The Higgs sector is incomplete

Strategy

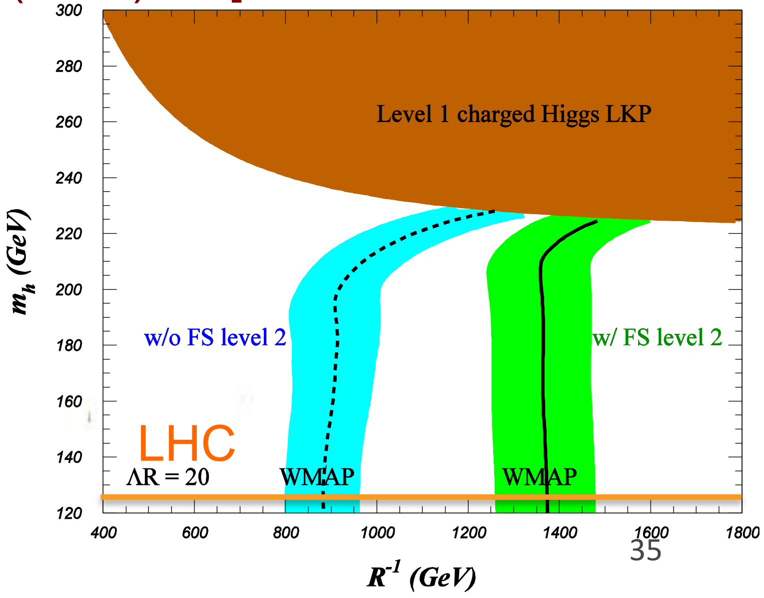
- Goal: Automated computations of UED processes with higher accuracy in anticipation of future exp. data
- First step: Automatic generation of 4D Feynman rules from 5D Lagrangian using LanHEP

  LanHEP “Package for the automatic generation of Feynman rules in field theory” [theory.sinp.msu.ru/~semenov/lanhep.html]

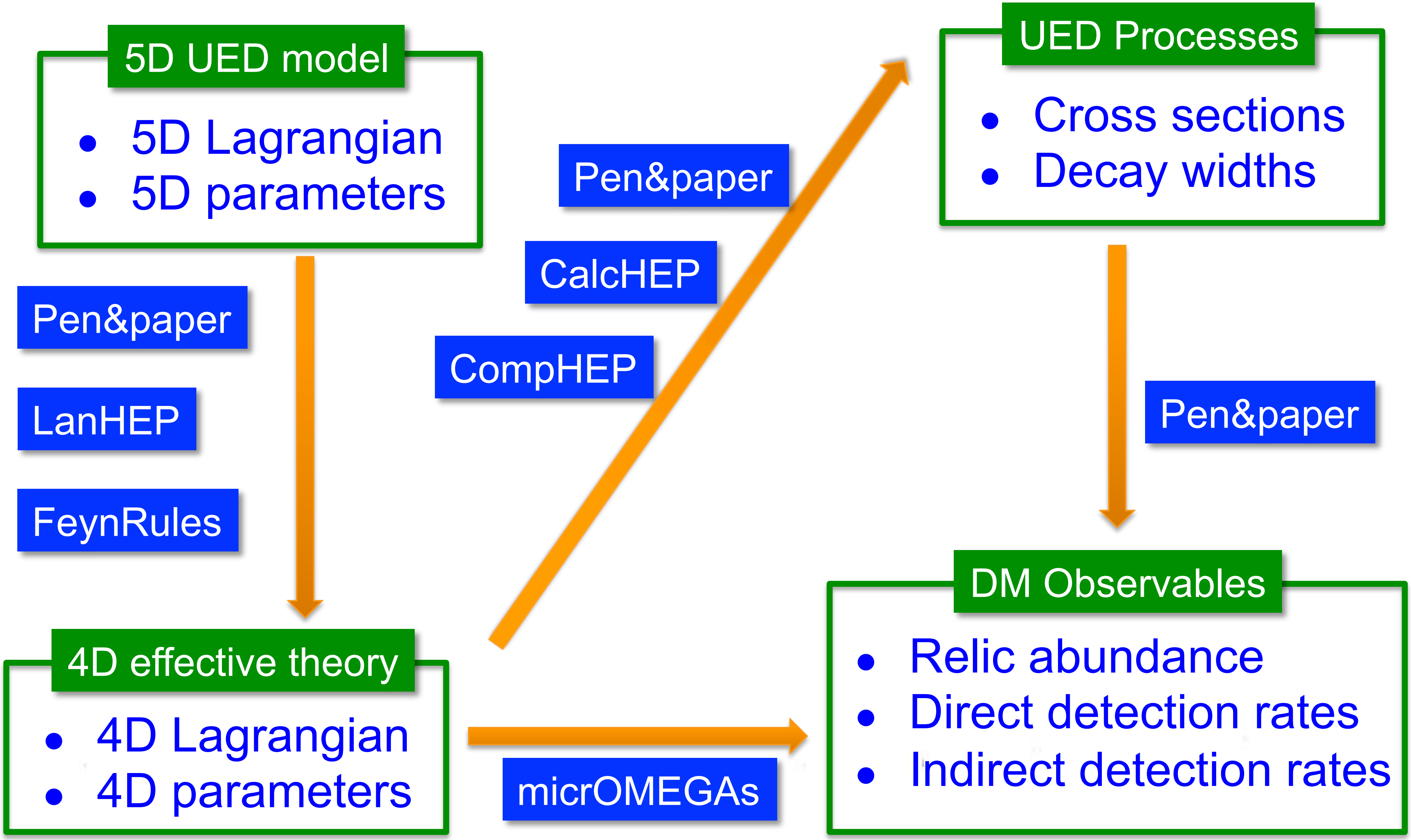
- Second step: [Belanger,MK,Pukhov,JCAP02(2011)009]

  Computing DM observables using micrOMEGAs

  micrOMEGAs “a code for the calculation of Dark Matter Properties” [lapth.in2p3.fr/micromegas/]



Flowchart


5D UED model
5D Lagrangian
5D parameters
Pen&paper
LanHEP
FeynRules
4D effective theory
4D Lagrangian
4D parameters
Pen&paper
CalcHEP
CompHEP
UED Processes
Cross sections
Decay widths
Pen&paper
micrOMEGAs
DM Observables
Relic abundance
Direct detection rates
Indirect detection rates

Present status of 5D UED implementations

- Public codes:

Datta, Kong, Matchev

[Datta,Kong,Matchev,NJP12(2010)075017; home.fnal.gov/~kckong/]

  - EW symmetry breaking effects are partially included
  - Only unitary gauge is available

Feynrules

"Mathematica package to generate Feynman rules for any Lagrangian"

[Christensen et al,arXiv:0906.2474; feynrules.phys.ucl.ac.be]

  - The Higgs sector is partially included
  - No 2nd KK mode is included
  - Only unitary gauge is available

- Our approach:
  - Updated LanHEP → Files w/ EWSB in Feynman gauge as well

    [Semenov,arXiv:1005.1909]

Vertices in LanHEP

- Define 5D fields:

Hyperchage B-boson

```
let BB5D = (CW*A - SW*Z)*cos(0)
         + ( (CW1*'~A1' - SW1*'~Z1')*cos(1,invR)
         + (CW2*A2 - SW2*Z2)*cos(2,invR) )*Sqrt2.
```

- Define 5D vertices:

EW interactions of left-handed fermions

```
lterm   anti(psi)*(gamma*(i*deriv-EE/SW*taupm*WW5D/2 - Y*(EE/CW)*BB5D))*psi
            where
                    psi=l1,  Y=-1/2;
                    psi=l2,  Y=-1/2;
                    psi=l3,  Y=-1/2;
                    psi=q1, Y= 1/6;
                    psi=q2, Y= 1/6;
                    psi=q3, Y= 1/6.
```

LanHEP

[Belanger,MK,Pukhov,Semenov, in preparation]

- 4D vertices:

```
E       |e      |A      |       |EE
       |G(m3)
```

```
E       |~e11  |~A1   |       |-EE/(4*CW*SW)
        |B01052*G(m3)*(1-G5)+2*CW1*SW*ca1e*G(m3)*(1+G5)
```

Goldstone boson/ghost in LanHEP

- Define 5D Goldstone/ghost fields:
  - KK modes of the 5th component of a gauge boson = Goldstone modes

Goldstone modes of gluons

```
let G5TH = ('~G1.f'*sin(1,invR) + 'G2.f'*sin(2,invR) )*Sqrt2/ZGs.
```

- Define 5D Goldstone/ghost interactions:

```
lterm (- i*SC*f_SU3*(deriv*GhG)*ghG*G5D
      + i*SC*f_SU3*(deriv*GhG)*G5D*ghG)/2.
```

LanHEP

[Belanger,MK,Pukhov,Semenov, in preparation]

- 4D Goldstone/ghost interactions:

```
G2.C   |~G1.c |~G1    |        |-SC*Sqrt2/2
        |m3.p1
```

```
G2.C   |~G1.c |~G1.f |        |-i*SC*Sqrt2*ZGs*invR
        |1
```

Automatic reconstruction of gluon vertices

- Auxiliary fields are needed to reconstruct 4-point (KK) gluon vertices in CalcHEP, CompHEP and MadGraph:

Auxiliary fields and their interactions in my notes

$$
\begin{aligned}
t^a_{\mu\nu} &= \frac{1}{\sqrt{2\pi R}} t^{(0)a}_{\mu\nu}(x^\mu) + \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} t^{(n)a}_{\mu\nu}(x^\mu) \cos\frac{ny}{R} \\
v^a_\mu &= \sum_{n=1}^{\infty} \frac{1}{\sqrt{\pi R}} v^{(n)a}_\mu(x^\mu) \sin\frac{ny}{R} \\
\mathcal{L}^{(5D)}_{\rm aux} &= \frac{1}{4} t^{a\mu\nu} t^a_{\mu\nu} + \frac{g_5}{2} f^{abc} t^{a\mu\nu} A^b_\mu A^c_\nu - \frac{1}{2} v^{a\mu} v^a_\mu - g_5 f^{abc} v^{a\mu} A^b_\mu A^c_5
\end{aligned}
$$

[Belanger,MK,Pukhov, Semenov, in preparation]

Auxiliary fields and their interactions in LanHEP

```
let GT5D = 'G.t'*cos(0) + ('~G1.t'*cos(1,invR) + 'G2.t'*cos(2,invR) )*Sqrt2.
lterm SC*f_SU3*GT5D*G5D*G5D/Sqrt2.
```

```
let '~v1' = AuxPrt(1, 8, 0),
    v2 = AuxPrt(1, 8, 0).
let GV5D = ('~v1'*sin(1,invR) + 'v2'*sin(2,invR) )*Sqrt2.
lterm - ZGs*Maux*SC*f_SU3*GV5D*G5D*G5TH.
```

KK mass shifts

- 5D Lorentz violating effects induce mass shifts from n/R :

Vector	$\mathcal{L}^{(5D)} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - \frac{1}{2}ZF^a_{\mu 5}F^{a\mu 5}$	$\Rightarrow m^2_{A(n)} = Z\frac{n^2}{R^2}$
Fermion	$\mathcal{L}^{(5D)}_\psi = \bar{\psi}i\gamma^\mu D_\mu - Z_\psi\bar{\psi}\gamma^5 D_5\psi$	$\Rightarrow m_{\psi(n)} = Z_\psi\frac{n}{R}$
Scaler	$\mathcal{L}^{(5D)}_\Phi = (D^\mu\Phi)^\dagger(D_\mu\Phi) - Z_\Phi(D_5\Phi)^\dagger(D_5\Phi) - \mu_5^2\Phi^\dagger\Phi$	$\Rightarrow m^2_{\Phi(n)} = Z_\Phi\frac{n^2}{R^2} + \mu^2$

- The Z-factors are properly introduced in the Goldstone/ghost sector to retain gauge invariance

- The MUED KK spectrum is obtained by adjusting the Z-factors

[Belanger,MK,Pukhov,JCAP02(2011)009]

KK Higgs masses

- Covariant derivatives for the 5D Higgs doublet:

$$D_\mu \Phi = \partial_\mu \Phi + i\frac{g_5}{2} W_\mu^a T^a \Phi + i\frac{g_5'}{2} B_\mu \Phi\,,$$

[Belanger,MK,Pukhov,JCAP02(2011)009]

$$D_5 \Phi = \partial_5 \Phi + i g_5 \frac{W_5^a}{\sqrt{Z_W}} T^a \Phi + i\frac{g_5'}{2} \frac{B_5}{\sqrt{Z_B}} \Phi$$

- Zero mode Higgs vev: $\langle \Phi^{(0)} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

→ Mixing between the KK Higgs bosons and KK gauge scalars: $W_5^{\pm(n)}$, $W_5^{3(n)}$ $B_5^{(n)}$

	Physical modes	Goldstone modes
CP even KK Higgs:	$m_{h^{(n)}}^2 = Z_\Phi \frac{n^2}{R^2} + m_h^2$	
Charged KK scalar:	$m_{a^{\pm(n)}}^2 = \frac{Z_\Phi}{Z_W} m_{W^{(n)}}^2 = Z_\Phi \left(\frac{n^2}{R^2} + \frac{m_W^2}{Z_W} \right)$,	$m_{G^{\pm(n)}}^2 = \xi m_{W^{(n)}}^2$
CP odd KK scalar:	$m_{a^{0(n)}}^2 = Z_\Phi \left(\frac{n^2}{R^2} + \frac{m_Z^2 c_W^2}{Z_W} + \frac{m_Z^2 s_W^2}{Z_B} \right)$	$m_{G_A^{(n)}}^2 = \xi m_{A^{(n)}}^2$, $m_{G_Z^{(n)}}^2 = \xi m_{Z^{(n)}}^2$

UED processes

- 4D Lagrangian generated by LanHEP

↓ CalcHEP

- Cross sections & decay widths

$$\overline{\sum}|\mathcal{M}(gg\to g^*g^*)|^2 = \frac{9g_s^4}{4}\left[3M_1^4\frac{s^2+t_3^2+u_4^2}{t_3^2u_4^2} - 3M_1^2\frac{s^2+t_3^2+u_4^2}{st_3u_4} + 1 + \frac{(s^2+t_3^2+u_4^2)^3}{4s^2t_3^2u_4^2} - \frac{t_3u_4}{s^2}\right],$$

$$\overline{\sum}|\mathcal{M}(q\bar{q}\to g^*g^*)|^2 = \frac{2g_s^4}{27}\left[M_1^2\left(-\frac{4s^3}{t_3^2u_4^2}+\frac{57s}{t_3u_4}-\frac{108}{s}\right)+\frac{20s^2}{t_3u_4}-93+\frac{108t_3u_4}{s^2}\right].$$

[From Smillie, Webber, JHEP 0510, 069 (2005)]

- Analytic 1st KK quark/gluon production cross sections are consistent w/ earlier works both in unitary and Feynman gauges