Cosmological Constraint on the Minimal Universal Extra Dimension Model

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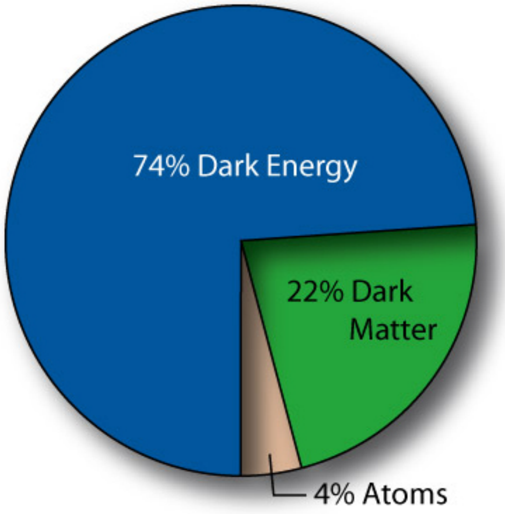
Refs:

- PRD 71 (2005) 123522 [hep-ph/0502059]
- NPB 735 (2006) 84 [hep-ph/0508283]
- PRD 74 (2006) 023504 [hep-ph/0605280]

1. Motivation



[http://map.gsfc.nasa.gov]

- Observations of
  - cosmic microwave background
  - structure of the universe
  - etc.

→ **Non-baryonic cold dark matter**

- Weakly interacting massive particles (WIMPs)

  → Correct relic abundance of CDM
  - Neutralino (LSP) in supersymmetric (SUSY) models
  - 1st KK mode of the B boson (LKP) in universal extra dimension (UED) models ← Today's topic
  - etc.

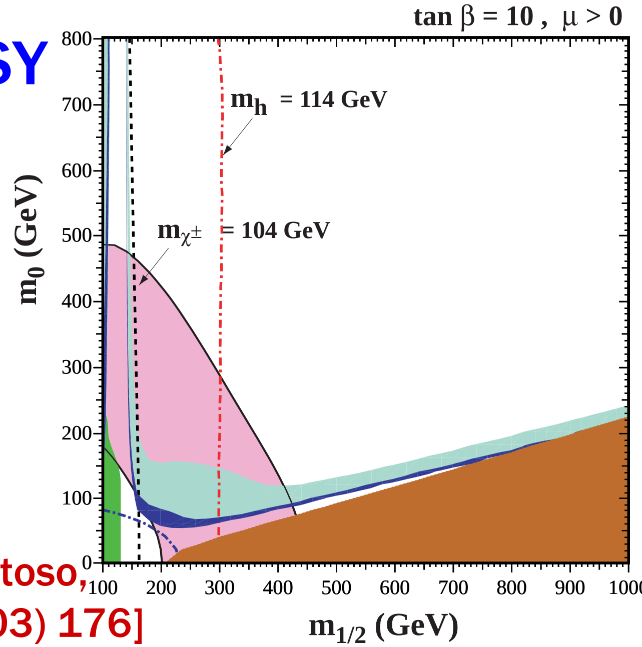
Outline

This work

- Reevaluation of the relic density of LKPs including both coannihilation and resonance effects

→ Cosmological constraint on the minimal UED model

c.f.: SUSY



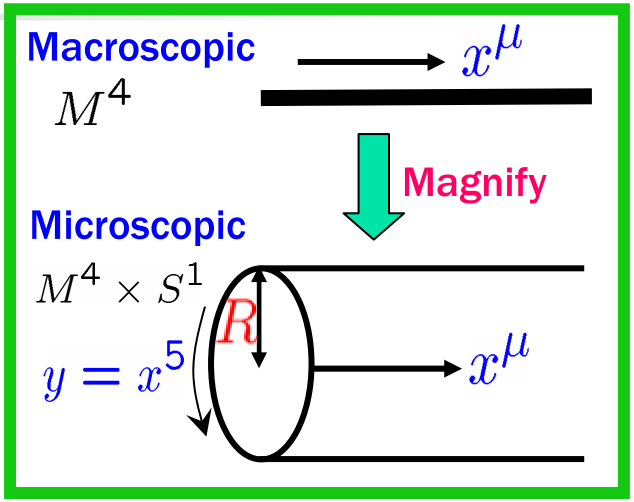
[From Ellis, Olive, Santoso, Spanos, PLB565 (2003) 176]

1. Motivation
2. Universal extra dimension (UED) models
3. Relic abundance of KK dark matter
4. Coannihilation processes
5. Resonance processes
6. Summary

2. Universal extra dimension (UED) models

Idea: All SM particles propagate in flat compact spatial extra dimensions

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



- **Dispersion relation:** $E^2 = \vec{p}^2 + (p_5^2 + M^2)$

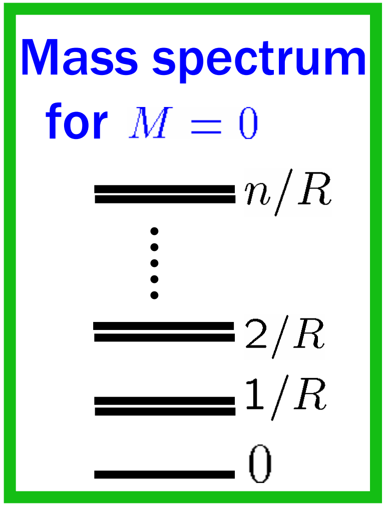
  ⇒ Momentum along the extra dimension = Mass in four-dimensional viewpoint

- S^1 compactification with radius R:

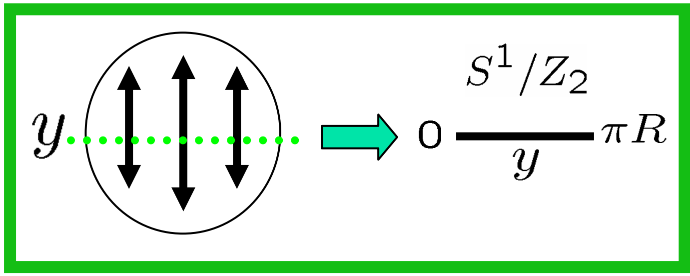
  $p_5 = n/R \quad (n = 0, 1, 2, \cdots)$ is quantized ⇒ KK tower

- Momentum conservation in the extra dimension

  ⇒ Conservation of KK number n at each vertex



Minimal UED (MUED) model

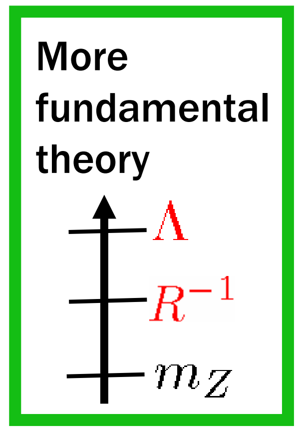


- In order to obtain chiral zero-mode fermions, the extra dimension is compactified on an S^1/Z_2 orbifold

- **Conservation of KK parity** [+ (–) for even (odd) n]

  ⇨ The lightest KK particle (LKP) is stable c.f. R-parity and LSP

  The LKP is a good candidate for dark matter



- **Only two new parameters appear in the MUED model:**

  R : Size of extra dimension Λ : Scale at which boundary terms vanish

  The Higgs mass m_h remains a free parameter

- **Constraints coming from electroweak measurements are weak**

  $R^{-1} > 500$ GeV for $m_h = 120$ GeV

  $R^{-1} > 250$ GeV for $m_h = 800$ GeV

  [Appelquist, Cheng, Dobrescu PRD64 (2001); Appelquist, Yee, PRD67 (2003); Gogoladze, Macesanu, hep-ph/0605207]

Mass spectra of KK states

- KK particles are degenerate in mass at tree level: $m^{(n)} = \sqrt{(n/R)^2 + m_{\rm SM}^2} \simeq n/R$

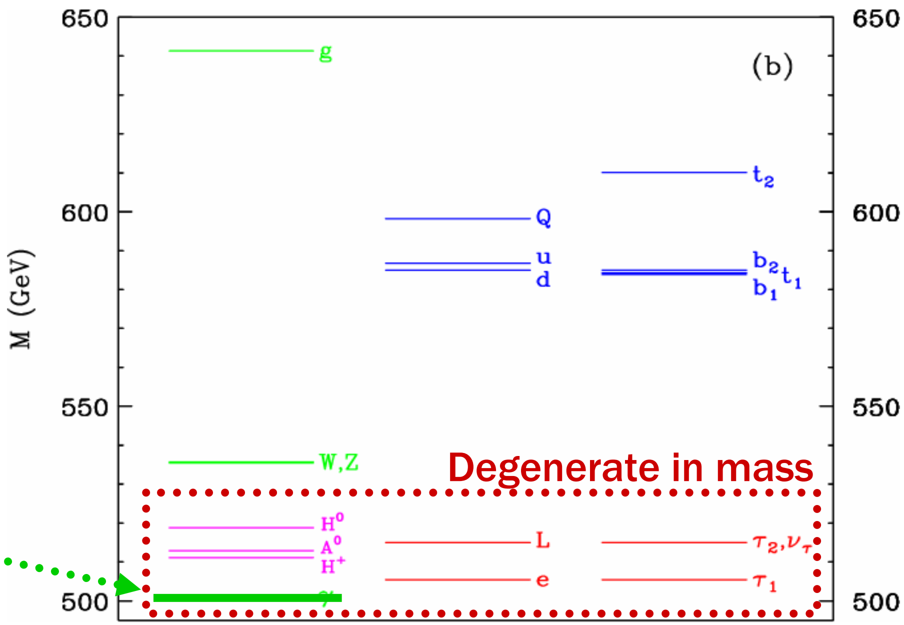
- Compactification → ~~5D Lor. inv.~~
  Orbifolding → ~~Trans. Inv. in 5th dim.~~

  → Radiative corrections relax the degeneracy →

  - Lightest KK Particle (LKP):
    $\gamma^{(1)}$ (mixture of $B^{(1)} - W^{3(1)}$)

- KK particles of leptons and Higgs bosons are highly degenerate with the LKP
  → ▪ Coannihilation plays an important role in calculating the relic density

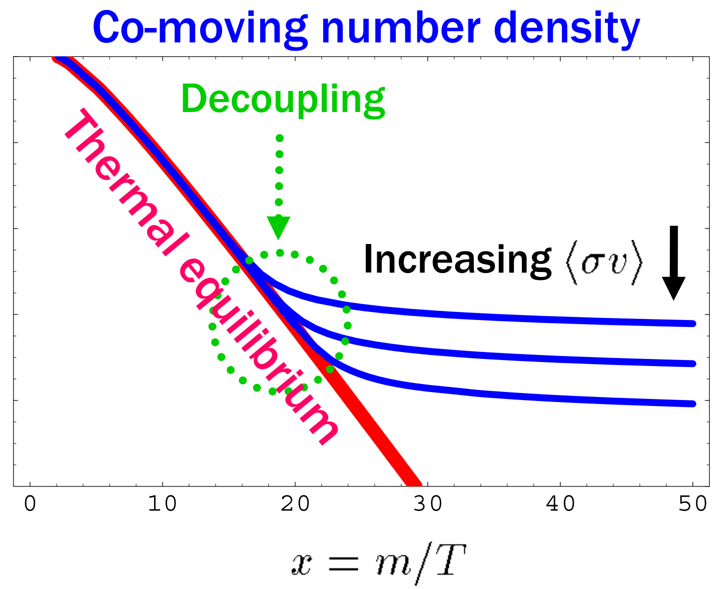
1-loop corrected mass spectrum at the first KK level



$R^{-1} = 500$ GeV, $\Lambda R = 20$, $m_h = 120$ GeV

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

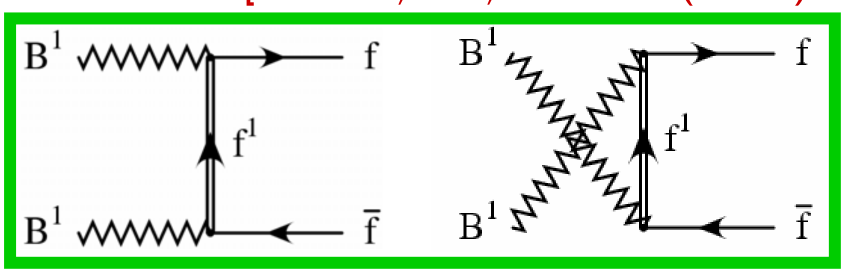
3. Relic abundance of KK dark matter

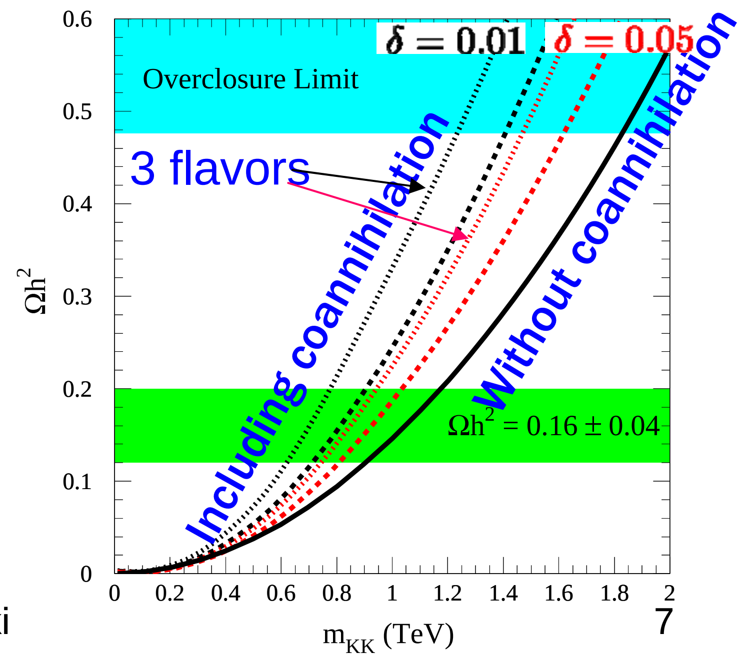


- Generic picture
  - Dark matter particles were in thermal equilibrium in the early universe
  - After the annihilation rate dropped below the expansion rate, the number density per comoving volume is almost fixed

- Relic abundance of the LKP $\gamma^{(1)}$

[Servant, Tait, NPB 650 (2003) 391]





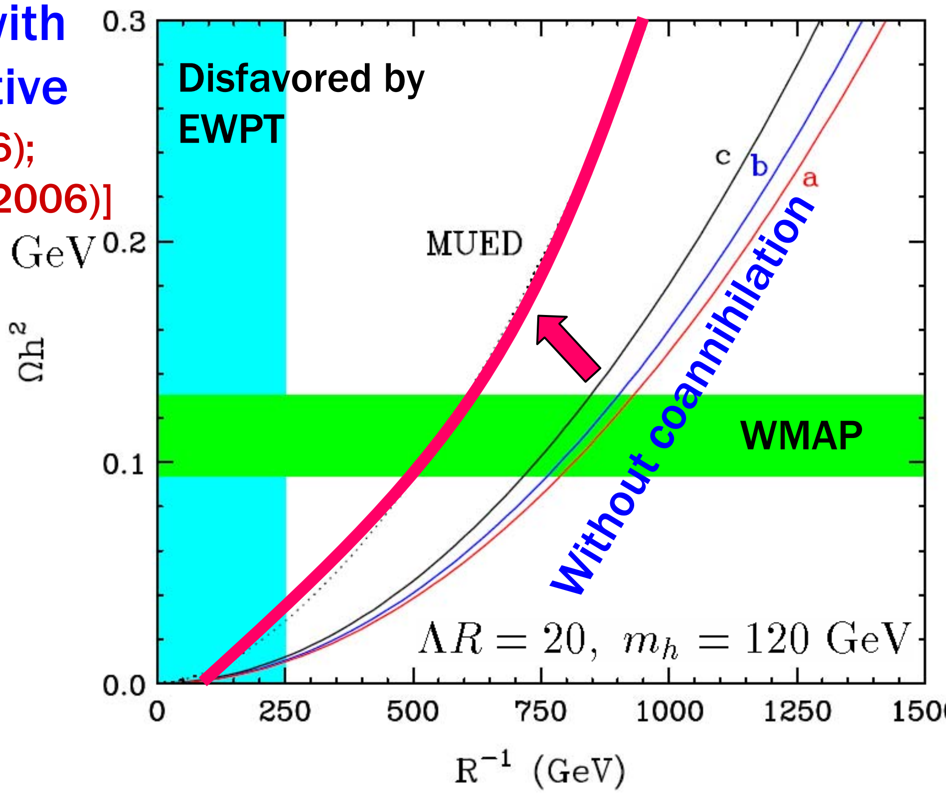
  - Coannihilation only with the NLKP $l_R^{(1)}$
  - No resonance process

4. Coannihilaition processes

- Previous calculation:
  - Inclusion of coannihilation modes with all 1st KK particles reduces the effective cross section [Burnell, Kribs, PRD73(2006); Kong, Matchev, JHEP0601(2006)]
  - The Higgs mass is fixed to $m_h = 120\ \mathrm{GeV}$
  - No resonance process is considered

- We emphasize:
  - The relic abundance depends on the SM Higgs mass
  - Resonance effects also shift the allowed mass scale

Relic abundance of the LKP



[From Kong, Matchev, JHEP0601(2006)]

Masses of the KK Higgs bosons

- 1^{st} KK Higgs boson masses:

$$m^2_{H^{(1)}} = 1/R^2 + m_h^2 + \delta m^2_{H^{(1)}}$$

$$m^2_{H^{\pm(1)}} = 1/R^2 + m_W^2 + \delta m^2_{H^{(1)}}$$

$$m^2_{A^{(1)}} = 1/R^2 + m_Z^2 + \delta m^2_{H^{(1)}}$$

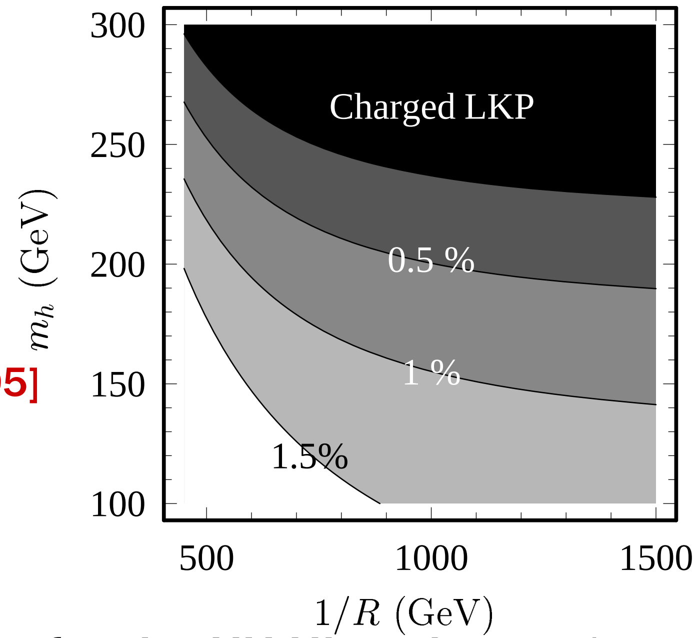
$$\delta m^2_{H^{(1)}} = \left(\frac{3}{2}g_2^2 + \frac{3}{4}g'^2 - \lambda_H\right)\frac{1}{16\pi^2 R^2}\ln(\Lambda^2 R^2)$$

⇒ $m^2_{H^{\pm(1)}} < m^2_{A^{(1)}} < m^2_{H^{(1)}}$

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

Contour plot of mass splitting

$(m_H^{\pm(1)} - m_\gamma^{(1)})/m_\gamma^{(1)}$



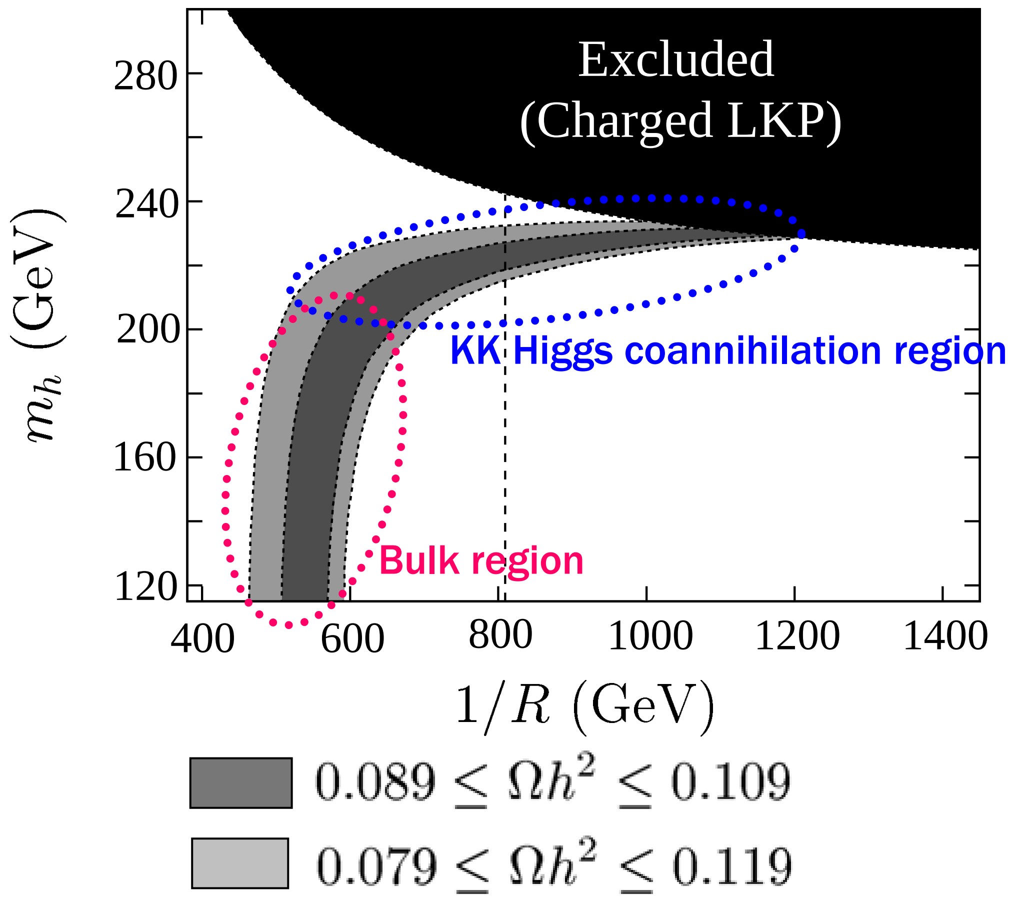
- Larger m_h

⇒ Larger $\lambda_H = m_h^2/v^2$; smaller δm_H^2

(Enhancement of the annihilation cross sections for the KK Higgs bosons)

- Too large m_h ⇒ The 1^{st} KK charged Higgs boson is the LKP

Allowed region without resonance processes



- We investigate dependence of the LKP relic abundance on the Higgs mass, including all coannihilation modes with 1st KK particles
- Bulk region (small m_h)

  The result is consistent with previous works
- KK Higgs coannihilation region (large m_h)

  $$\sigma(H^{\pm(1)}H^{\mp(1)} \to \mathrm{SM}) \gg \sigma(\gamma^{(1)}\gamma^{(1)} \to \mathrm{SM})$$

  ⇨ The relic abundance decreases through the Higgs coannihilation

  ⇨ Larger R^{-1} is allowed

5. Resonance processes

- KK particles are non-relativistic when they decouple

⇨ (Incident energy of two 1st KK particles)

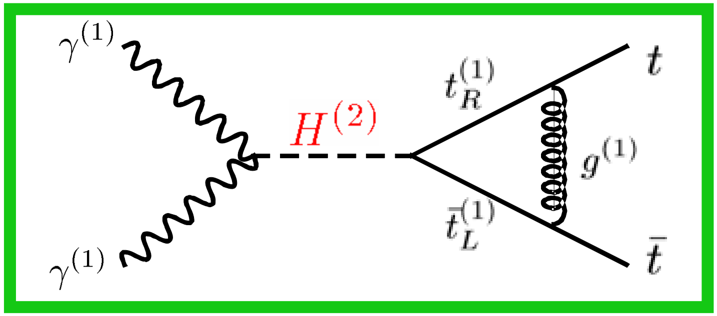
$\simeq$ (Masses of 2nd KK particles) $\sqrt{s} \simeq m^{(1)} + m^{(1)} \simeq m^{(2)}$

⇨ Annihilation cross sections are enhanced through s-channel 2nd KK particle exchange at loop level

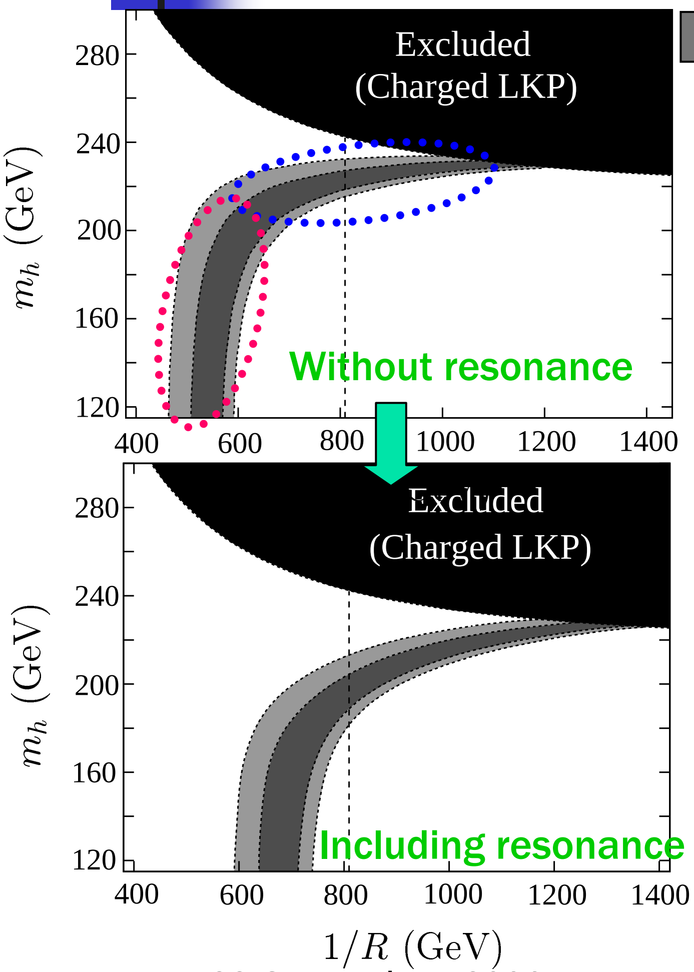
- Important processes:

$$\begin{aligned}
\gamma^{(1)}\gamma^{(1)} &\to H^{(2)} \to \text{SM particles} \\
e^{(1)}\bar{e}^{(1)}, \nu(1)\bar{\nu}^{(1)} &\to Z^{(2)} \to \text{SM particles} \\
e^{(1)}\bar{\nu}^{(1)} &\to W^{-(2)} \to \text{SM particles} \\
A^{(1)}A^{(1)}, H^{+(1)}H^{-(1)} &\to H^{(2)} \to \text{SM particles}
\end{aligned}$$

c.f.



Allowed region including coannihilation and resonance



$0.089 \leq \Omega h^2 \leq 0.109$; $0.079 \leq \Omega h^2 \leq 0.119$

- Cosmologically allowed region is shifted upward by $150 - 300\text{GeV}$
  - Bulk region: $W^{(2)}, Z^{(2)}$ -res. are effective
  - KK Higgs coannihilation region: $H^{(2)}$ -res. contributes as large as $W^{(2)}, Z^{(2)}$ -res.

- For $R^{-1} < 800$ GeV the LKP may be the KK graviton ⇒ 'KK graviton problem'
  - Some mechanism to make the KK graviton heavy is proposed [Dienes PLB633 (2006)]

6. Summary

- UED models contain a candidate particle for CDM:

  The 1st KK mode of the B boson (LKP)

- In UED models
  - $m_{\rm LKP} \simeq m^{(1)}$ ⇒ Coannihilation → should be included
  - $\sqrt{s} \simeq m^{(1)} + m^{(1)} \simeq m^{(2)}$ ⇒ Resonance → should be included

- We calculated the LKP relic abundance in the MUED model including the resonance processes in all coannhilation modes

- Cosmologically allowed region in the MUED model ⇒