Efficient coannihilation process through strong Higgs self-coupling in LKP dark matter annihilation

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Kaluza-Klein dark matter

- Non-baryonic cold dark matter is established.
- **Weakly Interacting Massive Particle (WIMP)** is excellent candidate
  - Relic abundance
  - Large scale structure
- WIMP candidate
  - Lightest supersymmetric particle
  - Lightest Kaluza-Klein particle (LKP) in universal extra dimension (UED) models
  - ...
Universal Extra Dimension model

Appelquist, Cheng, Dobrescu (2000)

Universal means all SM particles propagate in spatial extra dimensions

- KK tower appear
- KK number $n$ conservation

- Minimal Universal Extra Dimension model (MUED)
  - Five space-time dimension
  - The extra dimension is compactified on $S^1/Z_2$

KK number conservation $\rightarrow$ KK parity conservation

LKP is stable $\rightarrow$ candidate of dark matter

c.f. R-parity and LSP

- MUED model brings only two new parameters.
  
  $\frac{1}{R}$ (extra dimension size)
  
  $\Lambda$ (cut off scale)
Masses of KK particles

- KK particle has degenerate mass in tree level
  \[ \sqrt{m_n^2 + m_{SM}^2} \quad m_n = n/R \]
  (SM massless particles are exactly degenerate)

- Radiative corrections remove the degeneracy
  LKP : \( \gamma^{(1)} \)

- But, some KK particle are well degenerate with LKP

\[ l_{R}^{(1)}, l_{L}^{(1)}, \nu^{(1)}, H^{(1)}, A^{(1)}, H^{\pm(1)} \]

1/R=500 GeV, \( \Lambda R=20, m_h=120 \) GeV

Cheng, Matchev, Schmaltz (2002)

1 \sim 5\%
Coannihilation

- Some KK particles are degenerate with LKP in mass.

\[ \delta = O(1)\% : \text{MUED model} \]

- Relic abundance
  - Coannihilation should be considered.

- Coannihilation changes relic abundance of DM.

\[ \sigma_{\text{CO}} < \sigma(\gamma^{(1)}\gamma^{(1)} \to \text{SM}) \]
\[ l_R^{(1)}, l_L^{(1)}, \nu^{(1)} \]

\[ > \sigma(\gamma^{(1)}\gamma^{(1)} \to \text{SM}) \]
\[ H^{(1)}, A^{(1)}, H^\pm^{(1)} \]

C.f. SUSY models: coannihilation effects decrease the abundance
Relic abundance

- Relic abundance
  - Including coannihilation
- In their result, 
  \(1/R = 500 - 600 \text{ GeV}\) is reported for MUED
- \(m_h=120 \text{ GeV}\) was assumed.

But, the relic abundance is dependent on Higgs mass
KK Higgs mass

\[ m_{H^\pm(1)} < m_{A(1)} < m_{H(1)} \]

\[ m_{H(1)}^2 = \frac{1}{R^2} + m_h^2 + \delta m_{H(1)}^2 \]

\[ m_{H^\pm(1)}^2 = \frac{1}{R^2} + m_W^2 + \delta m_{H(1)}^2 \]

\[ m_{A(1)}^2 = \frac{1}{R^2} + m_Z^2 + \delta m_{H(1)}^2 \]

- larger \( m_h \)
  - larger \( \lambda_h \), smaller \( \delta m_{H}^2 \) (can be negative)
  - \[ \lambda_h \equiv \frac{m_h^2}{v^2} \]
  - \[ \delta m_{H(1)}^2 = \left[ \frac{3}{2} g^2 + \frac{3}{4} g'^2 - \lambda_h \right] \frac{\ln (\Lambda^2 R^2)}{16 \pi^2 R^2} \]

- For \( m_h \sim 200 \) GeV, mass difference between LKP and \( H^\pm(1) \) is very small

In summary

Larger \( m_h \) ➔ larger \( \lambda_h \) ➔ \( H^\pm(1) \) NLKP enhance annihilation of \( H^\pm(1) \)
Relic abundance of LKP

Allowed region: \(1/R = 500 - 1200 \text{ GeV}\)

for \(m_h = 120 - 230 \text{ GeV}\)
Conclusion

- Relic abundance of LKP
  - depend heavily on SM Higgs mass
  - Large $m_h$
  - large Higgs self coupling
    - $H^{\pm(1)}$ NLKP
    - large annihilation cross section of KK Higgs

Charged LKP region (Excluded)

0.094 < $\Omega h^2$ < 0.129
Electroweak Precision Measurement
Annihilation after decoupling

\[ \langle \sigma v \rangle \propto \sum \sigma_{ij} g_i g_j \]

- \( m_h = 230 \text{GeV} \)
- \( m_h = 120 \text{GeV} \)

- \( g \) : degree of freedom of KK particles

- \( m_h = 230 \text{GeV} \)
  - total
  - LKP
  - KK lepton
  - KK Higgs

- \( m_h = 120 \text{GeV} \)
  - total
  - LKP
  - KK lepton
  - KK Higgs

Difference: KK Higgs
KK Graviton

- $1/R < 800 \text{GeV}$
  - KK graviton may be LKP
    i.e. DM is SuperWIMP
  - CMB and diffuse gamma exclude KK graviton DM
    Feng, Rajaraman, Takayama, PRL91, PRD68

- $1/R > 800 \text{GeV}$
  - MUED is consistent with DM relic abundance
    only if $m_h > 220 \text{GeV}$.

- KK graviton become heavy
  - Higher space-time dimension $> \text{MUED}$
  - KK particle in MUED in five dimension space-time
  - KK graviton in higher dimensional space-time
Comparison

Our result is different from that of Kong and Matchev.

- Our result: $1/R = 500-1200$ GeV
- Kong and Matchev's result: $1/R = 500-700$ GeV

In UED model, we must solve the Boltzmann equation numerically.

Senami and Matsumoto, in preparation
Second KK s-channel

We find

- Since DM is non-relativistic, the incident energy of two LKPs is almost degenerate with the mass of second KK modes.
- In particular, s-channel LKP annihilation process mediated by $h^{(2)}$ competes with tree level diagrams because of the $h^{(2)}$ resonance.

One of the resonant diagrams:

We calculate these type of diagrams.

$h^{(2)}$ does not couple with SM particle at tree level.
Cross section

- For small mass difference $\delta$, incident energy matches the $h^{(2)}$ pole and averaged cross section is enhanced.
  \[ \delta \equiv \frac{m_{h^{(2)}} - 2m}{2m} \]
  where $m$ is LKP mass

- For smaller $\delta$, the averaged cross section is maximum at later time and has larger maximum value.

- Relic density is reduced compared to the tree result by this enhancement of the cross section.
Dark matter relic abundance

- **General picture**
  - At $T \sim m (x \sim 1)$, dark matter particle is in thermal equilibrium.
  - After annihilation rate dropped below the Hubble parameter, dark matter can not annihilate and the density per comoving volume is fixed.

- **Large cross section**
  - small relic abundance of dark matter
Tree level mass relation
Weak mixing angles

![Graph showing weak mixing angles in a log-log plot with different curves labeled as tree-level, any n, and one-loop with n=1, 2, 3, 4, 5. The graph is labeled by Cheng, Matchev, Schmaltz.](image)