Short overview of Universal Extra Dimensions (UEDs)

The relic density of Kaluza-Klein particles

Elastic scattering cross sections – predictions and limits

Limits on the degeneracy parameter $\Delta$, the Higgs mass $m_h$ and spin-dependent WIMP-nucleon couplings
- all Standard Model particles are promoted to one or more compactified flat extra dimensions

- infinite number of new particles (Kaluza-Klein tower)

- tree level masses:
  
  \[ m_n^2 = m^2 + \frac{n^2}{R^2} \]

  quantum number labelling the \( n^{\text{th}} \) KK mode

  mass of the associated SM particle

  compactification scale

- high degree of mass degeneracy
  
  radiative corrections are of crucial importance

- including radiative corrections yields KK parity \((-1)^n\) conservation
  
  stable level 1 particles

  possible dark matter candidates

- WIMP candidates:

  \[
  \begin{array}{c}
  \gamma_1 \quad Z_1 \quad H_1 \\
  \end{array}
  \]

  \[
  \begin{array}{c}
  \gamma_H \quad Z_H \\
  \end{array}
  \]

  \( 5D \)

  \( 6D \)
Relic density calculations

high degree of mass degeneracy
    → coannihilations with all n=1 KK particles were taken into account

lightest particle obeys the Boltzmann equation

\[
\frac{dn}{dt} = -3 H n - \langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)
\]

with

\[
\sigma_{\text{eff}}(x) = \sum_{ij}^{N} \sigma_{ij} \frac{g_i g_j}{g_{\text{eff}}} (1 + \Delta_i)^2 (1 + \Delta_j)^2 e^{-x(\Delta_i + \Delta_j)}
\]

\[
g_{\text{eff}}(x) = \sum_{i}^{N} g_i (1 + \Delta_i)^2 e^{-x \Delta_i}
\]

What about the masses?
assume vanishing boundary interactions at the cut-off scale (minimal UED)
    → radiative corrections to the masses can be computed (hep-ph/0204342)

LKP using MUED framework

\[
5D \quad \mathcal{Y}_1
\]

\[
6D \quad \mathcal{Y}_H
\]

But consider other possibilities as well...
Relic densities of Kaluza-Klein dark matter candidates in 5D UED

1) MUED framework
2) - assume certain mass splitting $\Delta$ between LKP and KK quarks
   - fix rest of the spectrum using MUED

- $Z_1$ and $W_1^\pm$ are degenerate
- gluon is heavier than $Z_1$ by 20%
- all other particles are heavier than $Z_1$ by 10%

- coannihilations are indeed important
- the sign of the effect cannot easily be predicted

Computations of the relic density for 6D including coannihilations do not exist yet.
Feynman diagrams for $\gamma_1$ - quark scattering (others are similar):

**Important parameters**

- SI WIMP-nucleon couplings $f_n, f_p$
- SD WIMP-nucleon couplings $a_n, a_p$
- Higgs mass $m_h$
- Degeneracy parameter $\Delta = \frac{m_{q_1} - m_{\gamma_1}}{m_{\gamma_1}}$
Spin-independent scattering

\[ \sigma_{\text{scalar}} = \frac{m_T^2}{4\pi(m_{\gamma_1} + m_T)^2} \left[ Zf_p + (A-Z)f_n \right]^2 \]

\[ f_{p,n} = \sum_{u,d,s} (\beta_q + \gamma_q) \frac{m_{p,n}}{m_q} f_{T_q} \]

\[ \beta_q = m_q \frac{e^2}{\cos^2 \theta_W} \left[ Y_{qL}^2 \frac{m_{\gamma_1}^2 + m_{\ell_1}^2}{(m_{\ell_1}^2 - m_{\gamma_1}^2)^2} + (L \rightarrow R) \right] \]

\[ \gamma_q = m_q \frac{e^2}{2 \cos^2 \theta_W} \frac{1}{m_h^2} \]

\[ m_h = 120 \text{GeV} \quad 0.01 < \Delta < 0.5 \]

- significant enhancement of cross sections for small \( \Delta \)
- CDMS and Xenon10 already exclude small mass splittings
- future ton-scale experiments should cover most of the interesting parameter space
Spin-dependent scattering

\[ \sigma_{\text{spin}} = \frac{32}{\pi} G_F^2 \mu^2 \frac{J_N + 1}{J_N} \left( a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2 \]

\[ a_{p,n} = \frac{e^2}{4 \sqrt{3} G_F \cos^2 \theta_W u,d,s} \sum \left[ \frac{Y_{qL}^2}{m_{qL}^2 - m_{\gamma_1}^2} + (L \rightarrow R) \right] \Delta_{q}^{p,n} \]

Proton and neutron SD cross sections are exactly equal in the case of \( Z_1 \).

Neutron SD cross sections are approximately equal for \( \gamma_1 \) and \( Z_1 \).
Spin-independent limits on $\Delta$ from 5D UED

- free parameters: LKP mass and $\Delta$
- Higgs mass is fixed at 120 GeV

The three probes are highly complementary.

Cosmology provides upper limit on LKP masses.
Colliders are sensitive to large $\Delta$.
Direct detection experiments are sensitive to small $\Delta$.

Include....
- direct detection limits
- relic density constrains
- collider studies (hep-ph/0205314)
LKP mass and $\Delta$ are primary parameters. $m_h$ plays only a secondary role.

Future direct detection experiments only probe a small part of the parameter space.

LHC will be able to test the whole parameter space shown here.
Spin-independent limits on $\Delta$ and $m_h$ from 6D UED

Limits on $\Delta$ for $m_h = 120\,GeV$

Limits on $m_h$ for $\Delta = 0.1$

$\gamma_H$

\[ \Delta g = \frac{\Delta m}{m_{\gamma H}} \]

\[ m_{\gamma H} \text{ (GeV)} \]

\[ m_h \text{ (GeV)} \]
Limits on $\Delta$ can also be computed considering spin-dependent interactions.

SD constrains are about an order of magnitude smaller than the SI limits.

The experiments' sensitivities to both interactions crucially depend on the used target material.
- free parameters $a_p$ and $a_n$

- limits from Xenon10: Introduce polar coordinates in $a_p - a_n$ plane.
  \[ \rightarrow \text{Scan over } \theta. \]

Combining limits from odd-neutron and odd-proton experiments substantially diminishes the allowed parameter space.
Conclusion

What has been done?
Comprehensive analysis of 5D and 6D Kaluza-Klein dark matter including constrains from...
- direct detection experiments
- collider studies
- cosmology

Results
- All three approaches are complementary and have the potential to cover a huge part of the relevant parameter space.
  - Direct detection experiments restrict small values of $\Delta$.
  - Colliders are sensitive to large $\Delta$s.
  - Cosmology rules out large LKP masses.
- Reasonable parameters to explore the KK phenomenology are $\Delta$ and $m_{\text{LKP}}$.
- Coannihilation processes are of crucial importance for relic density calculations.

What is missing?
- detailed LHC studies for small $\Delta$
- further relic density computations for e.g. the $\gamma H$ including coannihilations