Implementation of Universal Extra Dimensions in micrOMEGAs

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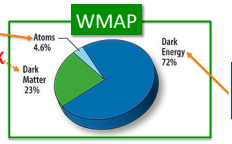
- G. Belanger, MK, A. Pukhov and A. Semenov, work in progress

1. Motivation

Standard model particles

[www.physics.gla.ac.uk]



[map.gsfc.nasa.gov]

Cosmological constant?

Existence of the dark matter ➡ New physics beyond the SM

- Weakly Interacting Massive Particles are good candidates
  - Neutralino in supersymmetic extensions of the SM
  - 1st Kaluza-Klein (KK) photon in universal extra dimensions (UEDs)
  - etc.

This talk

- UEDs have many degenerate particles
  - ➡ Computing UED processes is tedious and error-prone

Public tools play a crucial role in obtaining reliable results

Goal of this work

- Automated computations of DM observables in the 5D UED

LanHEP: 5D UED model
- 5D Lagrangian
- 5D parameters

➡ 4D effective theory
- 4D Lagrangian
- 4D parameters

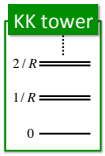
micrOMEGAs: DM Observables
- Relic density

2. 5D UED

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

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

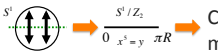
Periodic boundary condition ➡ $p_5 = n/R (n = 0, \pm1, \pm2, \cdots)$ ➡



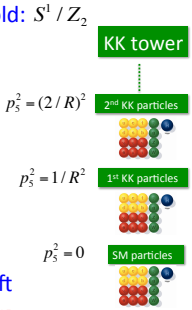
- Momentum conservation in the extra dimension
  - ➡ Conservation of KK number n at each vertex

Minimal universal extra dimension (MUED)

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



➡ Chiral zero-mode fermions



- KK-parity conservation: $P = (-1)^n$
  - ➡ Lightest KK particle (LKP) is stable (c.f. R-parity and LSP)
- Only two new parameters in the MUED:
  R : size of the extra dimension Λ: cutoff
- Radiative corrections generate KK mass shift
  The 1st KK mode of the photon is the LKP

3. Implementation of the 5D UED

3.1 Vertices

[Semenov,arXiv:1005.1909]

- Define 5D fields:

Hyperchage B-boson

```
let BBSD = (CW*A - SW*Z)*cos(0)
         + ( (CW1*'-A1' - SW1*'-Z1')*cos(1,invR)
         + (CWZ*A2 - SWZ*Z2)*cos(2,invR) )*Sqrt2.
```

- Define 5D vertices:

EW interactions of LH fermions

```
lterm   anti(psi)*(gammx*(i*deriv-EE/SW*toupm*WWSD/2 - Y*(EE/CW)*BBSD))*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

- 4D vertices:

```
E    le    lA    l    lEE
     lG(m3)
```

```
E    l-e11  l-A1   l    l-EE/(4*CW*SW)
     lB0105Z*G(m3)*(1-GS)+Z*CW1*SW*cole*G(m3)*(1+GS)
```

3.2 Goldstone boson/ghost

- Define 5D Goldstone/ghosts:
  (KK modes of gauge scalars = Goldstone modes)

Goldstone modes of gluons

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

- Define 5D Goldstone/ghost int.:

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

LanHEP

- 4D Goldstone/ghost int.:

```
G2.C  l-G1.c l-G1   l    l-SC*Sqrt2/2
      lm3.p1
```

```
G2.C  l-G1.c l-G1.f l    l-i*SC*Sqrt2*ZGs*invR
      i1
```

3.3 Automatic reconstruction of gluon vertices

- Auxiliary fields are needed to reconstruct 4-point gluon vertices

Auxiliary fields and their int.

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

let '-v1' = AuxPrt(1, 8, 0),
    v2 = AuxPrt(1, 8, 0).
let GVSO = ('-v1'*sin(1,invR) + 'v2'*sin(2,invR) )*Sqrt2.
lterm - ZGs*Mzuu*SC*f_SU3*GVSO*GSO*GSTH.
```

LanHEP ➡

```
G    l-G1   l-G1.t l    lSC*Sqrt2/2
     lm1.m3*m2.M3-m1.M3*m2.m3
```

4. Describing KK mass shifts

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

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

Vector $\mathcal{L}^{(5D)} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - \frac{1}{2}ZF^a_{\mu 5}F^{a\mu 5}$ $\quad m^2_{A^{(n)}} = Z\frac{n^2}{R^2}$

Fermion $\mathcal{L}^{(5D)}_{\psi} = \bar{\psi}i\gamma^\mu D_\mu - Z_\psi\bar{\psi}\gamma^5 D_5\psi$ ➡ $m_{\psi^{(n)}} = Z_\psi\frac{n}{R}$

Scaler $\mathcal{L}^{(5D)}_{\Phi} = (D^\mu\Phi)^\dagger(D_\mu\Phi) - Z_\Phi(D_5\Phi)^\dagger(D_5\Phi) - \mu_5^2\Phi^\dagger\Phi$ $\quad m^2_{\Phi^{(n)}} = Z_\Phi\frac{n^2}{R^2} + \mu^2$

- The Z-factors are properly introduced in the Goldstone/ghost sector to retain gauge invariance
- The MUED spectrum is obtained by adjusting the Z-factors

- Covariant derivatives for the 5D Higgs doublet:

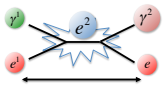
$$D_\mu\Phi = \partial_\mu\Phi + i\frac{g_5}{2}W^a_\mu T^a\Phi + i\frac{g'_5}{2}B_\mu\Phi,$$
$$D_5\Phi = \partial_5\Phi + ig_5\frac{W^a_5}{\sqrt{Z_W}}T^a\Phi + i\frac{g'_5}{2}\frac{B_5}{\sqrt{Z_B}}\Phi$$

- Zero mode Higgs vev
  - ➡ Mixing between the KK Higgs bosons and KK gauge scalars

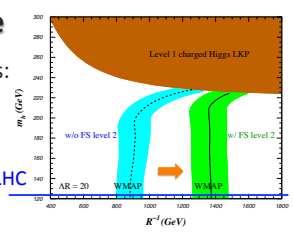
	Physical modes	Goldstone modes
CP even KK Higgs:	$m^2_{h^{(n)}} = Z_\Phi\frac{n^2}{R^2} + m_h^2$	
Charged KK scalar:	$m^2_{a^{\pm(n)}} = \frac{Z_\Phi}{Z_W}m^2_{W^{(n)}} = Z_\Phi\left(\frac{n^2}{R^2} + \frac{m_W^2}{Z_W}\right)$,	$m^2_{G^{\pm(n)}} = \xi m^2_{W^{(n)}}$
CP odd KK scalar:	$m^2_{a^{0(n)}}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

5. 1st KK photon abundance

- Process overlooked in earlier works:



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



6. Summary

- All 1st and 2nd KK particles of 5-dimensional universal extra dimension model implemented in micrOMEGAs
  - Wave function factors violating 5D Lorentz invariance ➡ KK mass shifts are described in a gauge invariant manner
  - Finite Higgs vacuum expectation value in the Higgs sector ➡ Correct KK Higgs masses and interactions obtained
- ➡ Precise computation of the relic abundance