Consistent Minimal Universal Extra Dimensions at the LHC

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Outline

LanHEP and CalcHEP

CalcHEP

Pukhov, Belyaev, Christensen

(`http://theory.sinp.msu.ru/~pukhov/calchep.html`)

- Automatically calculates decays widths, cross-sections and differential distributions
- Interfaces easily with event generators such as `PYTHIA`
- Produces output suitable for `micrOMEGAS` for dark matter calculations

LanHEP

Semenov, 2008 (arXiv:0805.0555, [hep-ph])

- Input is the model Lagrangian
- Produces Feynman rules in `CalcHEP` or `FeynArts` format
- Allows user to write in terms of 5D fields
- Support for Bessel functions (e.g. RS models) coming soon!

Status of other MUED implementations

Datta, Kong and Matchev, 2005 (arXiv:1002.4624 [hep-ph])

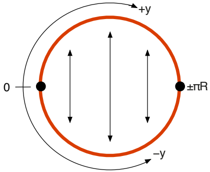
- Matchev's model is directly implemented in CalcHEP
- Only unitary gauge
- No EWSB for KK modes
- Bulk radiative corrections to masses may break gauge invariance
- Four-gluon vertices not implemented correctly

There is a parallel group in Annecy (Bélanger, Mitsuru, Pukhov and Semenov) working on their own LanHEP implementation. We are cross-checking our model with theirs

What is (Minimal) UED?

Appelquist, 2001 [arXiv:hep-ph/0012100]

- In MUED, there is one extra dimension compactified on an $S^1/\mathbb{Z}_2$ orbifold: a line segment of length πR



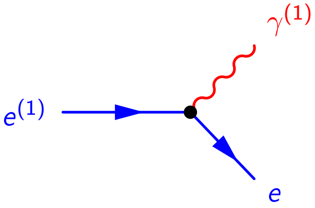
- Locally we have 5D Poincaré invariance and so there is a conserved momentum p_5, discretized to KK number n
- 5D Poincaré invariance is broken non-locally (i.e. in loops) but KK parity $= (-1)^n$ is conserved in MUED
- The lightest KK particle is a stable WIMP

Radiative corrections

Why do we bother?

At tree level, a particle's nth KK level mass is given by

$$m_n = \frac{n}{R} + m \text{ (fermions)}; \quad m_n = \sqrt{\left(\frac{n}{R}\right)^2 + m^2} \text{ (bosons)}$$



$$\boxed{\frac{1}{R} + m_e \overset{!}{>} m_e + \sqrt{\frac{1}{R^2}}}$$

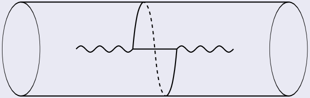
The $n = 1$ electron is stable $\Rightarrow$ Charged dark matter!

Radiative corrections

Bulk and orbifold corrections

Radiative corrections in 5D can be categorised as either bulk or brane corrections Cheng, Matchev, Konstantin and Schmaltz, 2002 [arxiv:hep-ph/0204342]

Bulk corrections



The two particles in a loop each pass through one of the boundary points

$$\delta m_n = A\frac{1}{R^2}$$

Orbifold corrections

Only one of the particles passes through a boundary point

$$\delta m_n = B\frac{n}{R}\ln\frac{\Lambda^2}{\mu^2}\ \text{(fermions)}$$

$$\delta m_n^2 = B\frac{n^2}{R^2}\ln\frac{\Lambda^2}{\mu^2}\ \text{(bosons)}$$

Radiative corrections

Orbifold corrections

- At one-loop, the self energy of a 5D electron leads to the running of terms localised on orbifold boundaries

$$\delta\bar{\mathcal{L}} \supset \left(\frac{\delta(y) + \delta(y - \pi R)}{2}\right) \frac{Rg^2}{64\pi} \ln \frac{\Lambda^2}{\mu^2} \times [\bar{\psi}_R \mathrm{i}\partial\!\!\!/ \psi_R + 5(\partial_5 \bar{\psi}_L)\psi_R + 5\bar{\psi}_R(\partial_5 \psi_L)].$$

- KK expanding leads to corrections to kinetic and mass terms:

$$\bar{\mathcal{L}}_4 \supset \bar{\psi}_L^{(n)} \mathrm{i}\partial\!\!\!/ \psi_L^{(n)} + Z_{nR} \bar{\psi}_R^{(n)} \mathrm{i}\partial\!\!\!/ \psi_R^{(n)} + Z_{n5} \frac{n}{R} \bar{\psi}^{(n)} \psi^{(n)}.$$

- The expansion also leads to a small mixing between KK modes which we neglect.

Implementing the mass corrections

Field strength renormalisation

- Can't add boundary terms in `LanHEP`. Instead, add gauge invariant but Lorentz-violating wavefunction renormalisation to the 5D Lagrangian, e.g.

$$\partial_M\phi\partial^M\phi = \partial_\mu\phi\partial^\mu\phi - \partial_5\phi\partial_5\phi \to \boxed{(\partial_\mu\phi)^2 - Z(\partial_5\phi)^2}$$

- Upon compactification, 5D kinetic terms lead to mass terms for each KK mode

$$m_n + \delta m_n = Z\frac{n}{R} \text{ (fermions)}; \quad m_n^2 + \delta m_n^2 = Z\left(\frac{n}{R}\right)^2 \text{ (bosons)}$$

Implementing the mass corrections
Problems with gauge invariance

- The brane corrections can be incorporated naturally in this fashion, e.g. for bosons:

$$\delta m_n^2 = B\frac{n^2}{R^2}\ln\frac{\Lambda^2}{\mu^2} \quad \Rightarrow \quad Z = 1 + B\ln\frac{\Lambda^2}{\mu^2}$$

- But if we include bulk corrections too, this would require Z to be KK-dependent, which is inconsistent:

$$Z = 1 + B\ln\frac{\Lambda^2}{\mu^2} + \frac{A}{n^2}$$

- Moreover, just including these corrections by hand – mode-by-mode at the 4D level – may break gauge invariance for non-Abelian groups

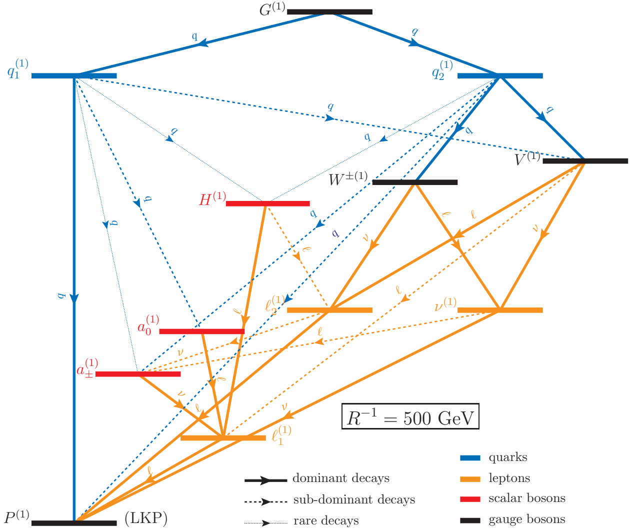
Electroweak symmetry breaking

- Particles get EW and KK contributions to their masses
- For $n > 0$, the mass mixing angles are different from in the Standard Model: they depend on Z and n
- Consider the mass matrix for $W^{3(n)}$ and $B^{(n)}$:

$$\begin{pmatrix} Z_B \left(\frac{n}{R}\right)^2 + \frac{1}{4} g_1^2 v^2 & -\frac{1}{4} g_1 g_2 v^2 \\ -\frac{1}{4} g_a g_2 v^2 & Z_W \left(\frac{n}{R}\right)^2 + \frac{1}{4} g_2^2 v^2 \end{pmatrix}$$

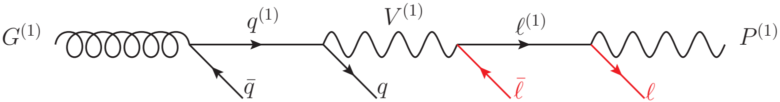
- So $W^{3(n)}$ and $B^{(n)}$ mixing does not give exactly $\gamma^{(n)}$ and $Z^{(n)}$. We call the mass eigenstates $P^{(n)}$ and $V^{(n)}$
- This mixing leads to vertices such as $P^{(n)} P^{(m)} H^{(l)}$, which do **not** appear in Matchev's implementation

First results from our implementation

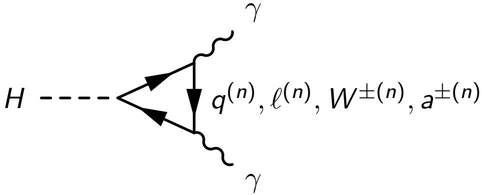


Plans for investigating phenomenology

- Multi-lepton final states are likely to be good signatures



- Higgs phenomenology is also very interesting: we are looking at $G, G \to H^{(0,n)}$ and $H^{(0,n)} \to \gamma, \gamma$ through loop diagrams with Annecy group



Conclusions

Summary

- MUED is implemented in unitary and Feynman gauges
- Four-gluon vertex splitting is implemented correctly
- Gauge invariance-violating bulk mass corrections left out
- EWSB is implemented consistently
- The problem of gauge invariance is an open question

Outlook

- Plan to systematically investigate phenomenology that will be of great interest at the LHC
- Will include KK-number violating vertices which are important for collider phenomenology as well as dark matter studies

Parameters and bounds

The extra dimension must be smaller than in ADD in order not to contradict existing experiments because all particles propagate in it[1]:

- $R < 10^{-19}$ m ($R^{-1} > 400$ GeV) – EW precision data
- $R > 10^{-20}$ m ($R^{-1} < 1400$ GeV) – leads to too much dark matter

The cutoff has to be $\Lambda \lesssim 20R^{-1}$ for the theory to remain perturbative

[1] Kakizaki, Matsumoto and Senami, 2006 [arXiv:hep-ph/0605280v1]

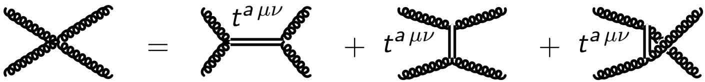
Gluon splitting

Consider the SM gluon kinetic term $-\frac{1}{4} G^a_{\mu\nu} G^{a\,\mu\nu}$. It contains

$$\mathcal{L} \; = -\frac{1}{4} g_3^2 f^{abc} f^{ade} G^b_\mu G^c_\nu G^{\mu\, d} G^{\mu\, e}$$

The trick is to replace this by

$$\mathcal{L} \; = -\frac{1}{2} t^a_{\mu\nu} t^{a\,\mu\nu} + \frac{i}{\sqrt{2}} g_3 \, f^{abc} \; t^{a\,\mu\nu} \; G^b_\mu G^c_\nu$$



In the case of MUED at one-loop with two KK modes, the 5D Lagrangian is

$$\mathcal{L}_5 \; = -\frac{1}{4} g_3^{(5)\,2} f^{abc} f^{ade} G^b_\mu G^c_\nu G^{\mu\, d} G^{\nu\, e} + \frac{Z_G}{2} g_3^{(5)\,2} f^{abc} f^{ade} G^b_\mu G^c_5 G^{\mu\, d} G^e_5$$

Need 5 tensors to split the 1st term and 4 vectors to split the 2nd.