Universal Extra Dimensions: Dark Matter and Collider Phenomenology

Matthew Brown, University of Southampton

Working with Drs. Alexander Belyaev,[1] Genevieve Bélanger,[2] Mitsuru Kakizaki[2,3] and Alexander Pukhov[4]

[1]NExT Institute, University of Southampton, UK
[2]LAPTH, Université de Savoie
[3]Institute for Theoretical Physics, Hamburg University
[4]Skobeltsyn Institute of Nuclear Physics, Moscow State University

New Paths to Particle Dark Matter, University of Oxford
30th March 2012

Outline

Where are we now?

Minimal Universal Extra Dimensions

Two motivations. . .

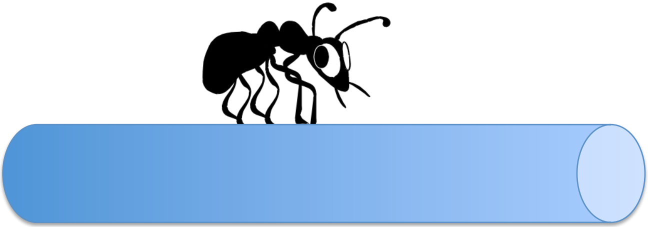
- Strings
- Extending symmetries
  - Internal symmetries → GUTs, technicolour...
  - Fermionic spacetime → SUSY
  - Bosonic spacetime → Extra dimensions

So where are they?

Minimal Universal Extra Dimensions Appelquist 2001, [arXiv:hep-ph/0012100]

Compactification!

- All fields propagate in the bulk
- Locally, space-time looks like 5D Minkowski space so all[1] Lagrangian terms are 5D Poincaré invariant
- Conserved p_5 discretised to n



[1]Well, *nearly* all...

Minimal Universal Extra Dimensions

Compactifying on a circle

$$\phi(x,y) = \frac{1}{\sqrt{2\pi R}}\phi_0(x) + \sqrt{\frac{\pi}{R}}\sum_{n=1}^{\infty}\left[\phi_n^+(x)\cos\frac{ny}{R} + \phi_n^-(x)\sin\frac{ny}{R}\right]$$

$$S = \int \mathrm{d}^4x \overbrace{\int_0^{2\pi R}\mathrm{d}y\, \underbrace{\frac{1}{2}\left[\partial_M\phi\partial^M\phi - m^2\phi(x,y)^2\right]}_{\mathcal{L}_5}}^{\mathcal{L}_4}$$

$$\mathcal{L}_4 = \frac{1}{2}\left[\partial_\mu\phi_0\partial^\mu\phi_0 - m^2\phi_0^2\right] + \sum_{n=1}^{\infty}\frac{1}{2}\left[\partial_\mu\phi_n^\pm\partial^\mu\phi_n^\pm - \overbrace{\left(m^2 + \frac{n^2}{R^2}\right)}^{m_n^2}\phi_n^{\pm\,2}\right]$$

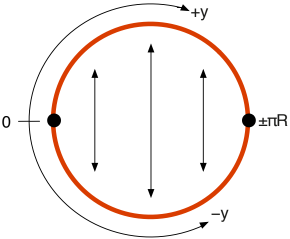
Minimal Universal Extra Dimensions

Compactifying on an orbifold

WARNING!! Notation here is opposite to standard conventions

- Choose action of $\mathbb{Z}_2$ reflection on Dirac fermions:

$$\psi_\pm(y) \mapsto \psi'_\pm(-y) = \pm\gamma^5\psi_\pm(y)$$



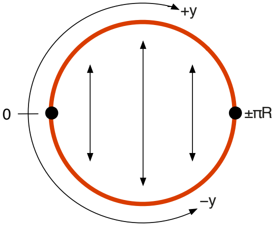
- If we identify $y \sim -y$ then we require $\psi'_\pm(y) = \psi_\pm(y)$, so

$$\psi_\pm(y) = \psi_0^{R,L} + \sum_n \left(\psi_n^{R,L}\cos_n + \psi_n^{L,R}\sin_n\right)$$

- KK number broken to KK parity, $(-1)^n$: LKP is stable

$\Rightarrow$ DM is candidate!

Minimal Universal Extra Dimensions



$S^1/\mathcal{Z}_2$ orbifold

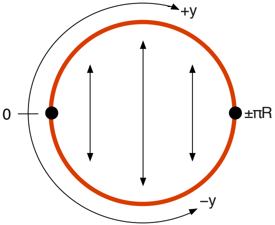
$$\boxed{SU(3) \times SU(2) \times U(1)}$$

SM Gauge group

$$\psi^{R,L}(x) \to \psi^{\pm}(x,y)$$
$$A_\mu(x) \to A_M(x,y)$$
$$\phi(x) \to \phi(x,y)$$

SM field content

Minimal Universal Extra Dimensions



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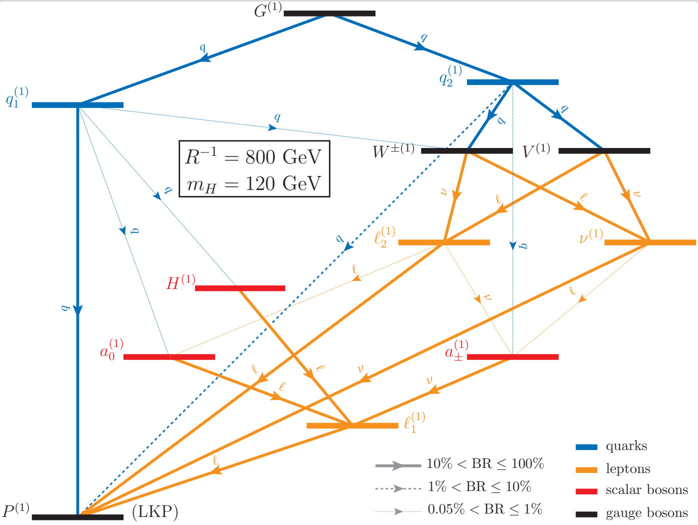
SM field content

(Oh, and brane localised terms are zero at the cutoff scale)

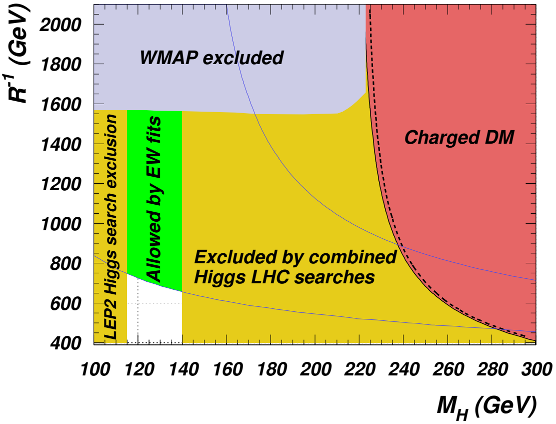
Spectroscopy



Where are we now?

Limits on parameter space

Two free parameters in the minimal theory: m_h and R^{-1}

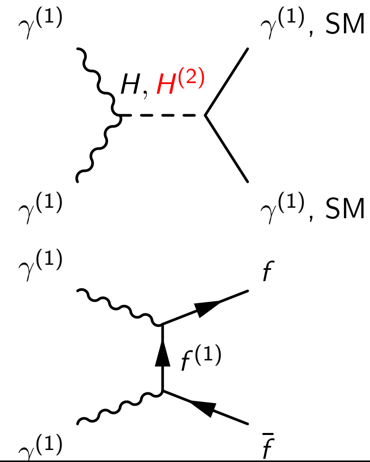


(Belyaev, Brown, Moreno and Papineau, preliminary)

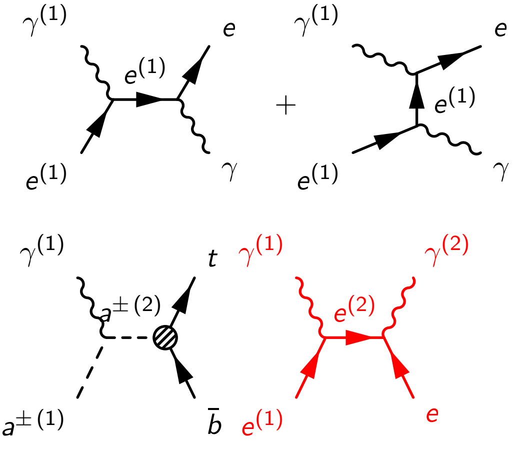
Annihilation processes

Processes important for calculating DM relic abundance...

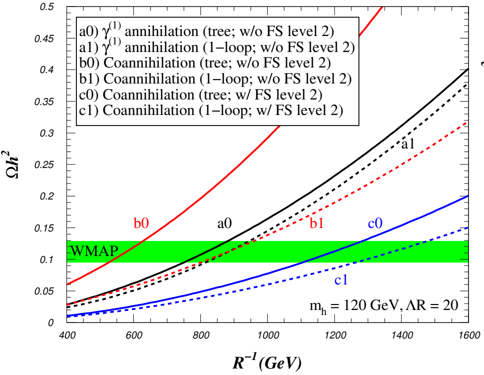
Self-annihilation

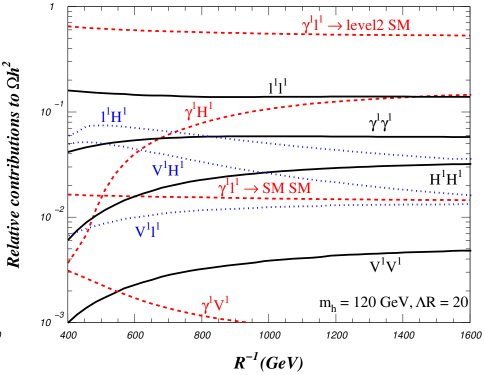


Co-annihilation



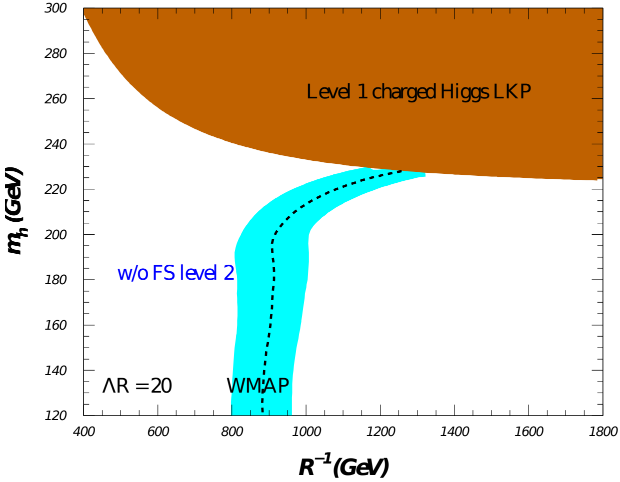
Dark matter limits: WMAP



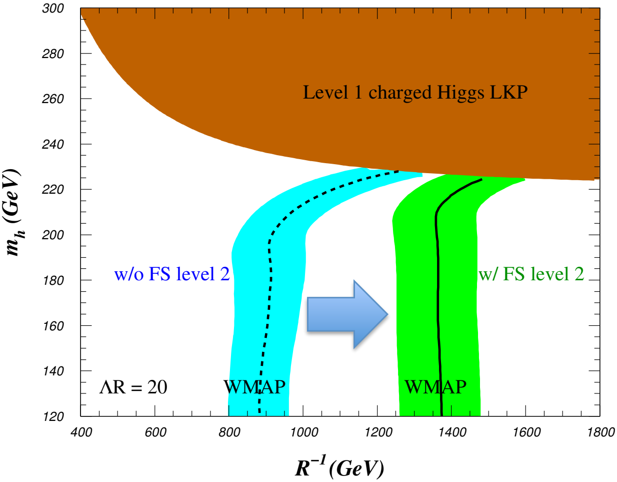


(Figs. 1 and 2, Bélanger *et al*, Dec 2010 [arXiv:1012.2577v1] [hep-ph])

Dark matter limits: WMAP

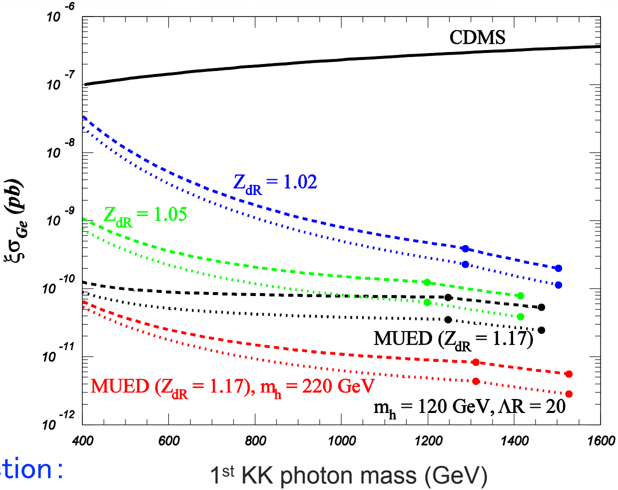


Dark matter limits: WMAP



(Fig. 3, left, Bélanger *et al*, Dec 2010 [arXiv:1012.2577v1] [hep-ph])

Dark matter limits: Direct detection



tion :

(Bélanger *et al*, in preparation)

Where are we now?

LanHEP and CalcHEP

- We created 1st fully consistent MUED software implementation:
  - Correct KK Higgs sector and EWSB
  - Correctly gauge invariant radiative corrections

LanHEP

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

- Input is the model Lagrangian
- Produces Feynman rules for `CalcHEP` or `FeynArts`
- Allows user to write in terms of 5D fields

CalcHEP

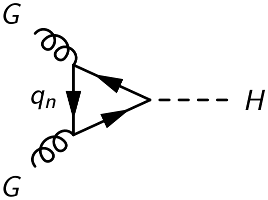
Pukhov, Belyaev, Christensen

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

Where are we now?

Higgs Production

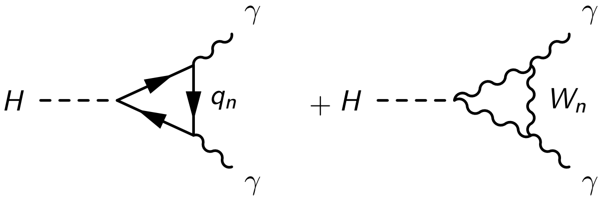
- Dominant production process at the LHC is G-G fusion



- Enhanced by KK quarks (particularly tops) running in the loop

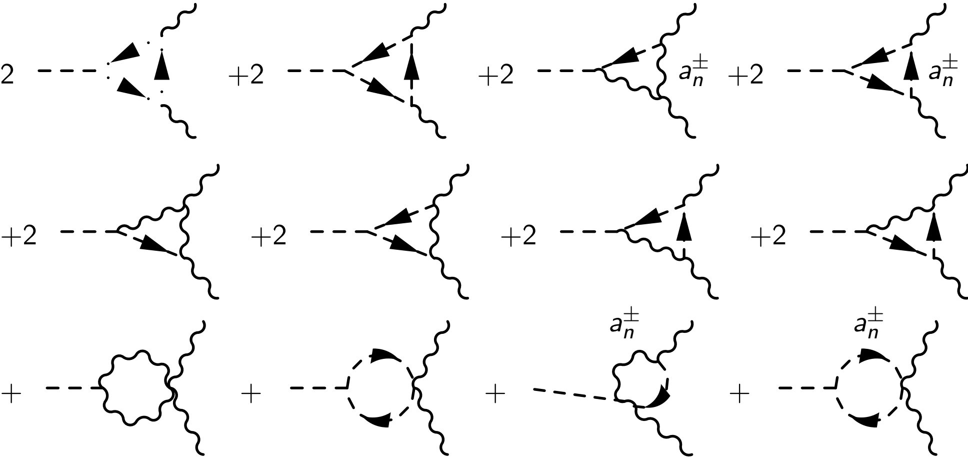
Higgs Decay

- Decay to photons is most promising channel for $m_H = 110$–130 GeV in SM



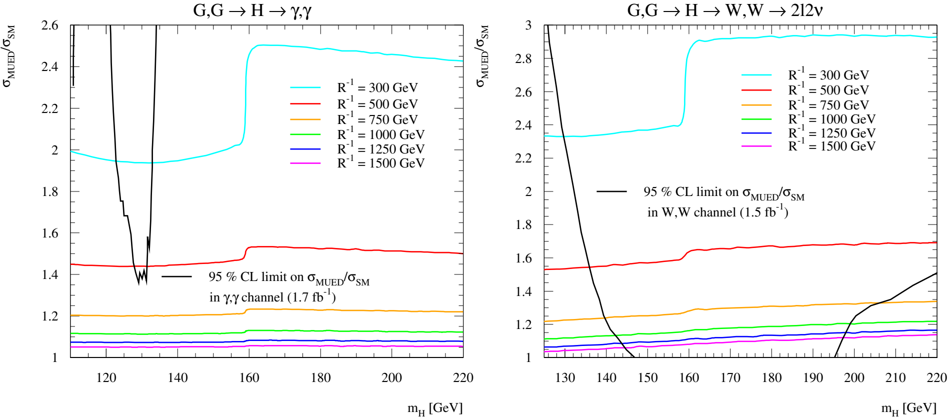
- In SM, W loop dominates and is partially cancelled by quark loop
- MUED enhances both loops, but enhances the quark loop more, *reducing* the overall decay width

Decay



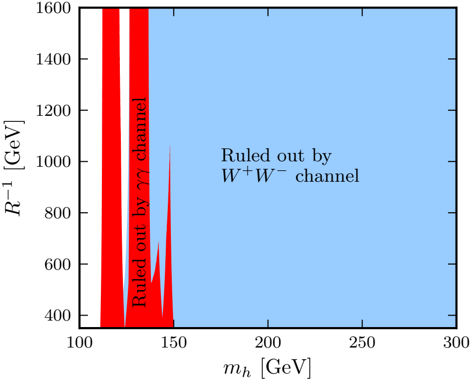
Enhancement

- Higgs production is enhanced in *all* channels relative to SM
- Size of enhancement is not the same in each channel



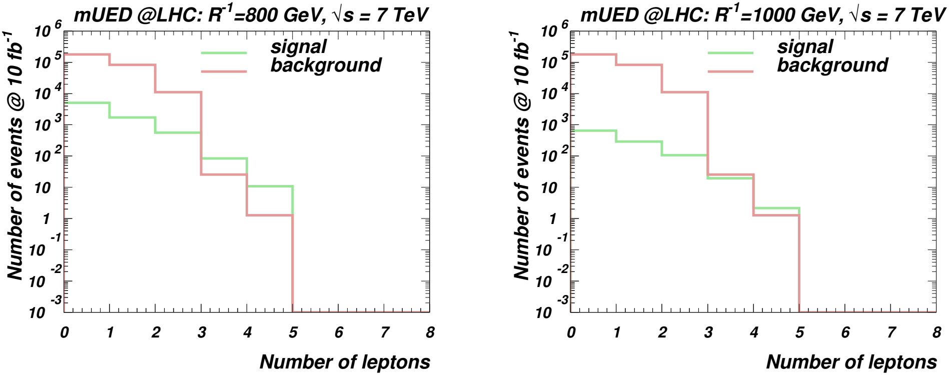
Higgs limits

Higgs searches rule out parameter space except for a ≈ 6 GeV slither around $m_h = 125$ GeV



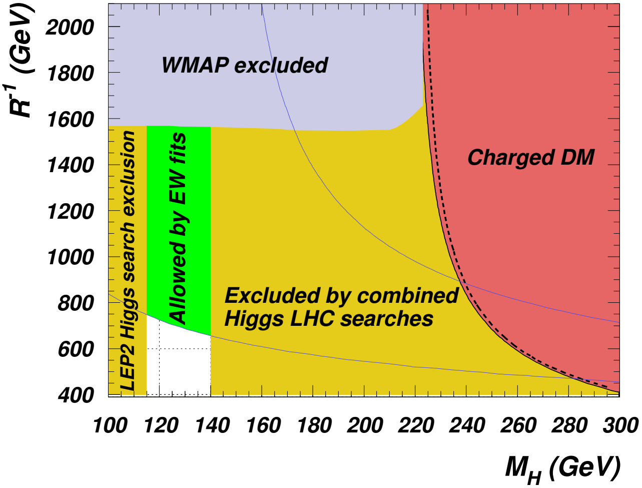
(Belyaev, Bélanger, Brown, Kakizaki and Pukov, [arXiv:1201.5582v1] [hep-ph])

Collider phenomenology

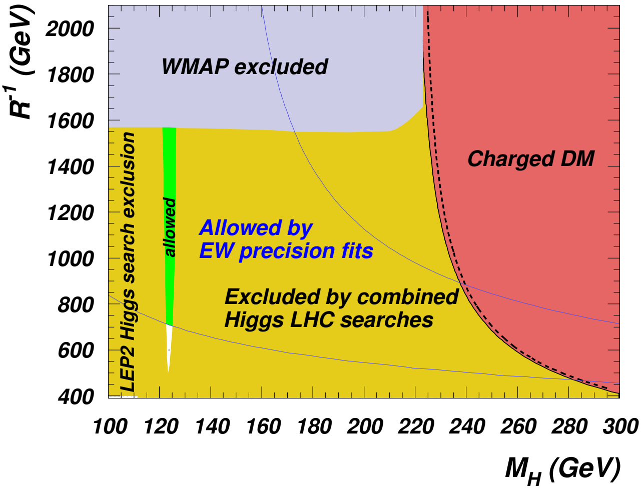


(Belyaev, Brown, Moreno and Papineau, in preparation)

Combined limits with cosmology (before)



Combined limits with cosmology (after)



(Belyaev, Brown, Moreno and Papineau, in preparation)

Where are we now?

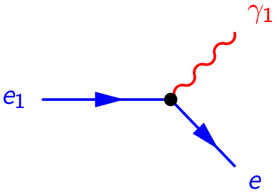
Conclusions

- Excellent, natural dark matter candidate in $\gamma^{(1)}$
- DM plays an important role in constraining MUED parameter space
- We have consistently implemented MUED in LanHEP/CalcHEP for the first time:
  - Correct Higgs sector
  - Radiative corrections implemented in gauge-invariant way
- We used the LHC Higgs searches to constrain the parameter space to 6 GeV region around 125 GeV

Radiative corrections
Why do we bother?

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

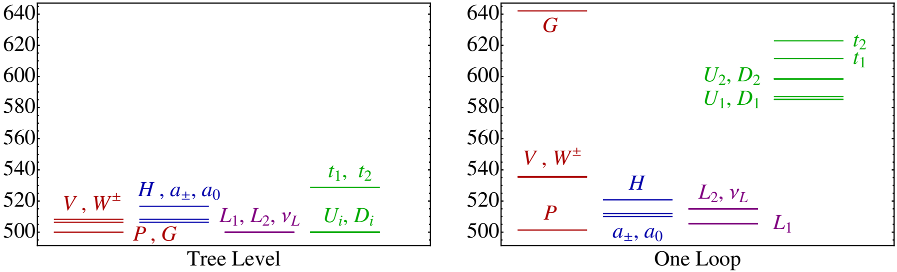
$$m_n = \frac{n}{R} + m \text{ (fermions)}; \quad m_n = \sqrt{\left(\frac{n}{R}\right)^2 + m^2} \text{ (bosons)}$$



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

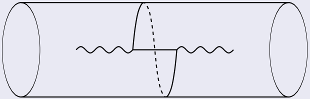
The $n = 1$ electron is stable $\Rightarrow$ Charged dark matter!

Radiative corrections
Why do we bother?



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

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

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

Parameters and bounds

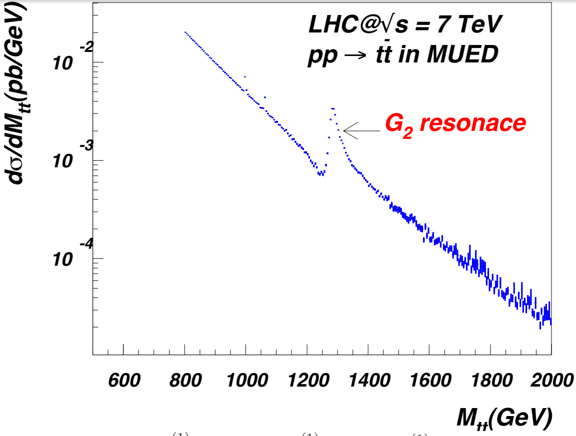
The extra dimension must be smaller than in ADD in order not to contradict existing experiments because all particles propagate in it[2]:

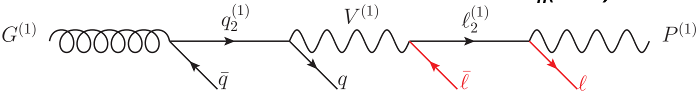
- $R < 10^{-19}$ m ($R^{-1} > 300$ GeV) – EW precision data
- $R > 10^{-20}$ m ($R^{-1} < 1600$ GeV) – leads to too much dark matter
- If we want LKP to be responsible for *all* dark matter, lower limit is also around 1600 GeV

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

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

Interesting phenomenology





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.

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 the SM