Electroweak constraints on non-minimal UED and split UED and implications for the LHC

Thomas Flacke

Universität Würzburg

TF, C. Pasold, arXiv:1111.7250

TF, arXiv:1112.xxxx

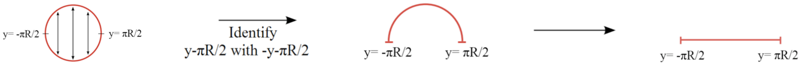
Outline

- UED review
- Modifying the UED mass spectrum
  - Motivation
  - non-minimal UED (nUED)
  - split UED (sUED)
- Electroweak precision constraints on sUED and nUED
- Conclusions and Outlook

UED: The basic setup

- UED models are models with flat, compact extra dimensions in which *all* fields propagate. 5D and 6D: [Appelquist, Cheng, Dobrescu,(2001)]

  see [Dobrescu, Ponton (2004/05), Cacciapaglia *et al.* , Oda *et al.* (2010)] for further 6D compactifications.
- The Standard Model (SM) particles are identified with the lowest-lying modes of the respective Kaluza-Klein (KK) towers.
- Here, we focus on one extra dimension: Compactification on S^1/Z_2



  allows for boundary conditions on the fermion and gauge fields such that
  - half of the fermion zero mode is projected out $\Rightarrow$ massless chiral fermions
  - $A_5^{(0)}$ is projected out $\Rightarrow$ no additional massless scalar
- The presence of orbifold fixed points breaks 5D translational invariance.

  $\Rightarrow$ KK-number conservation is violated, *but*
  a discrete Z_2 parity (KK-parity) remains.
  $\Rightarrow$ The lightest KK mode (LKP) is stable.

(M)UED pheno review

Phenomenological constraints on the compactification scale R^{-1}

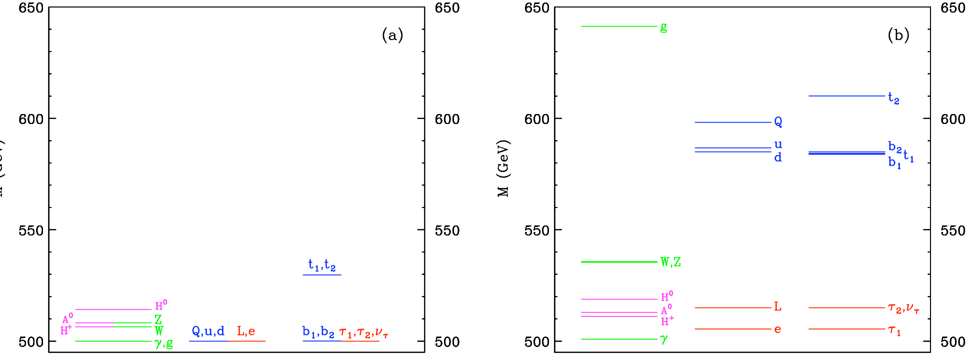
- Lower bounds:
  - FCNCs [Buras, Weiler *et al.* (2003); Weiler, Haisch (2007)]
    $R^{-1} \gtrsim 600(330)\,\mathrm{GeV}$ at 95% (99%) cl.
  - Electroweak Precision Constraints [Appelquist, Yee (2002); Gogoladze, Macesanu (2006); *Gfitter* (2011)]
    $R^{-1} \gtrsim 750(300)\,\mathrm{GeV}$ for $m_H = 115(800)\,\mathrm{GeV}$ at 95% cl.
  - no detection of KK-modes at LHC, yet [Murayama *etal.*; Bhattacherjee, Gosh (2011)
    $R^{-1} \gtrsim 500\,\mathrm{GeV}$ at 95% cl.
- Upper bound:
  - preventing over closure of the Universe by $B^{(1)}$ dark matter
    $R^{-1} \lesssim 1.5\mathrm{TeV}$ [Servant, Tait (2002); Matchev, Kong (2005); Burnell, Kribs (2005); Belanger *et al.* (2010)]

UED vs. SUSY at LHC:

- Determining the spin of particles [Barr *et al.* (2004), *c.f.* talk by K. Rolbiecki]
- Studying the influence of 2^{nd} KK mode particles [Datta, Kong, Matchev (2005), some follow-ups]
- Measuring total cross sections [Kane *et al.* (2005)], some follow-ups]
- Using differences of the UED and SUSY Higgs sector.

the MUED spectrum

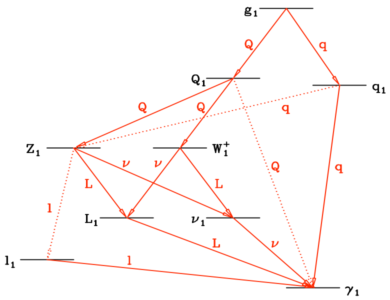
The UED mass spectrum at the 1st KK mode ($R^{-1} = 500\,\mathrm{GeV}$, $\Lambda R = 20$).



[Cheng, Matchev, Schmaltz, PRD **66** (2002) 036005, hep-ph/0204342]

Relevance of the detailed mass spectrum: LHC phenomenology

The KK mass spectrum determines decay channels, decay rates, branching ratios and final state jet/lepton energies at LHC.



[Cheng, Matchev, Schmaltz, PRD**66** (2002) 056006, hep-ph/0205314]

How much do we really know about the UED mass spectrum?

Taking the effective field theory approach to UED seriously,
we should include all operators which are allowed by all symmetries.
These are

1. Bulk mass terms for fermions (dimension 4 operators),
2. kinetic and mass terms at the orbifold fixed points
   (dimension 5; radiatively induced in MUED),
3. bulk or boundary localized interactions (dimension 6 or higher)

The former two operator classes modify the free field equations and thereby the spectrum and the KK wave functions.

split-UED: Bulk mass terms for fermions

[Park, Shu, *et al.* (2009); for earlier work, see Csaki (2003)]

In split UED (sUED), a fermion bulk mass term is introduced.
A plain bulk mass term for fermions of the form

$$S \supset \int d^5x \; - M\overline{\Psi}\Psi$$

is forbidden by KK parity, but
it can be allowed if realized by a KK-parity odd background field

$$S \supset \int d^5x - \lambda\Phi\overline{\Psi}\Psi,$$

where $\Phi(-y) = -\Phi(y)$
The simplest case: $M = \mu\theta(y)$
(similar to the bulk fermion mass term in Randall-Sundrum models)

Variation of the free action leads to the EOMs:

$$i\gamma^\mu \partial_\mu \Psi_R - \gamma^5 \partial_5 \Psi_L - m_5(y)\Psi_L = 0 \quad ,$$
$$i\gamma^\mu \partial_\mu \Psi_L - \gamma^5 \partial_5 \Psi_R - m_5(y)\Psi_R = 0 \quad ,$$

KK decomposition:

$$\Psi_R(x,y) = \sum_{n=0}^{\infty} \Psi_R^{(n)}(x)\, f_R^{(n)}(y)\,; \qquad \Psi_L(x,y) = \sum_{n=0}^{\infty} \Psi_L^{(n)}(x)\, f_L^{(n)}(y)\,,$$

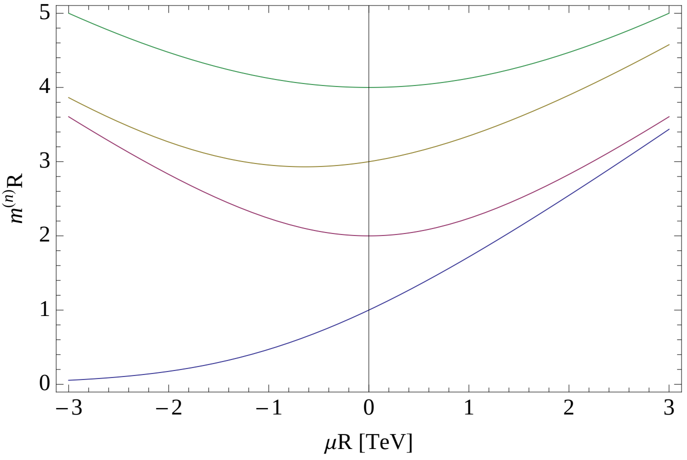
Solutions for a fermion with left-handed zero mode:

KK zero modes	even numbered KK-modes	odd numbered KK-modes
$f_L^{(0)}(y) = \sqrt{\frac{\mu}{e^{\mu\pi R}-1}}\, e^{\mu\|y\|}$	$f_L^{(n)}(y) = \mathcal{N}_L^{(n)}\left(\cos(k_n y) + \frac{\mu}{k_n}\sin(k_n\|y\|)\right)$	$f_L^{(n)}(y) = \mathcal{N}_L^{(n)} \sin(m_n y)$
$f_R^{(0)}(y) = 0$	$f_R^{(n)}(y) = \mathcal{N}_R^{(n)} \sin(m_n y)$	$f_L^{(n)}(y) = \mathcal{N}_R^{(n)}\left(\cos(k_n y) - \frac{\mu}{k_n}\sin(k_n\|y\|)\right)$
$k_0 = 0$	$k_n = n/R$	$\cot(\frac{\pi R}{2} k_n) = \mu$

and $m_n = \sqrt{k_n^2 + \mu^2}$.

(Solutions for right-handed zero mode: $L \leftrightarrow R$ and $\mu \rightarrow -\mu$)

sUED Fermion Mass Spectrum



Masses of the first four fermion KK modes in units of $1/R$ as a function of μR.

sUED overlap integrals

To obtain couplings between KK particles, we simply have to integrate over S^1/Z_2.

Compared to MUED, the fermion wave functions altered.

One obtains non-vanishing interactions of zero mode fermions with non-zero mode gauge bosons of strength

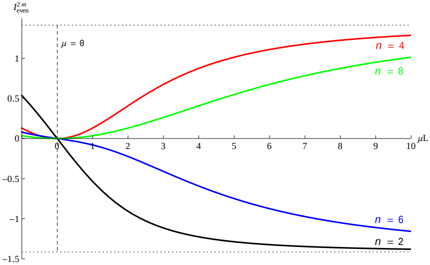
$$g_{eff}^{00n} = g_0 \mathcal{F}_{00n}$$

with the overlap integral given by

$$\mathcal{F}_{00n} \equiv \int_{-\pi R/2}^{\pi R/2} \frac{1}{\pi R} f_\psi^{(0)*} f_A^{(n)} f_\psi^{(0)}$$

$$= \frac{(\mu\pi R)^2(-1+(-1)^n e^{\mu\pi R}(\coth(\mu\pi R/2)-1)}{\sqrt{2(1+\delta_{0n}((\mu\pi R)^2+n^2\pi^2)}}$$

for n even and zero otherwise.



Boundary localized terms

Fermions: [Csaki,Hubisz,Meade(2001);Aguila, Perez-Victoria, Santiago(2003); TF, Gerstenlauer (in preparation)];
The fermion Lagrangian including BLKTs ("non-minimal UED") has the form:

$$\mathcal{S} = \int_{\mathbb{M}} \int_{S^1/\mathbb{Z}_2} \mathrm{d}^5 x \left[\frac{i}{2} \left(\overline{\Psi}\, \Gamma^M D_M \Psi - D_M \overline{\Psi}\, \Gamma^M \Psi \right) + \mathcal{L}_{BLKT} \right]$$

with

$$\mathcal{L}_{BLKT} = a_h \left[\delta\left(y - \frac{\pi R}{2} \right) + \delta\left(y + \frac{\pi R}{2} \right) \right] i \overline{\Psi}_h \not{D} \Psi_h \, ,$$

where $h = R, L$ represents the chirality and Γ^M is defined as $(\gamma^\mu, i\gamma^5)$.

For left-handed BLKTs, the KK decomposition leads to

KK zero modes	even numbered KK-modes	odd numbered KK-modes
$f_L^{(0)}(y) = \frac{1}{\sqrt{2a_L+\pi R}}$ $f_R^{(0)}(y) = 0$ $m_0 = 0$	$f_L^{(n)}(y) = -N\cos(m_n y)$ $f_R^{(n)}(y) = N\sin(m_n y)$ $\tan(\frac{\pi R}{2} m_n) = -a_L m_n$	$f_L^{(n)}(y) = N\sin(m_n y)$ $f_R^{(n)}(y) = N\cos(m_n y)$ $\cot(\frac{\pi R}{2} m_n) = a_L m_n.$

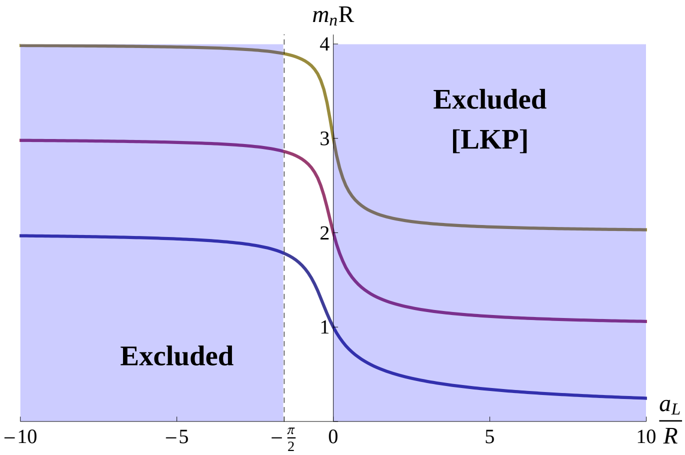
The fermion wave functions satisfy modified orthogonality relations

$$\delta_{mn} = \int_{-\frac{\pi R}{2}}^{\frac{\pi R}{2}} \mathrm{d}y \; f_L^{(n)}(y) f_L^{(m)}(y) \left(1 + a_L[\delta(y - \frac{\pi R}{2}) + \delta(y + \frac{\pi R}{2})]\right)$$

$$\delta_{mn} = \int_{-\frac{\pi R}{2}}^{\frac{\pi R}{2}} \mathrm{d}y \; f_R^{(n)}(y) f_R^{(m)}(y).$$

Results for right-handed BLKTs are given by $L \leftrightarrow R$.

nUED Fermion Mass Spectrum



Masses of the first three fermion KK modes in the presence of BLKTs. [D. Gerstenlauer, Diploma Thesis, Würzburg (2011)]

nUED: Electroweak sector and coupling constants

The BLKTs in the electroweak sector are:

$$\mathcal{L}_{BLKT,EW} = \left(-\frac{a_B}{4\hat{g}_1^2} B_{\mu\nu} B^{\mu\nu} - \frac{a_W}{4\hat{g}_2^2} W^a_{\mu\nu} W^{a,\mu\nu} - a_H (D_\mu H)^\dagger D^\mu H \right) \times \left[\delta\left(y - \frac{\pi R}{2} \right) + \delta\left(y + \frac{\pi R}{2} \right) \right]$$

For simplicity, we consider a common EW boundary parameter $a_B = a_W = a_H \equiv a_{ew}$.

For the generic case, *c.f.* [TF,Menon,Phalen(2009)].

KK decomposition yields the mass spectrum and wave functions of the Higgs and gauge bosons which resemble the fermionic wave functions.

Integrating over the extra dimension yields couplings of zero mode fermions to even KK mode gauge bosons:

$$g_{eff}^{00n} = g_0 \mathcal{F}_{00n} = g_0 \frac{(-1)^{n/2}\sqrt{2}(a_f - a_{ew})}{\pi R/2 + a_f} \sqrt{\frac{1 + a_{ew} 2/\pi R}{\sec^2(k_n R/2) + a_{ew} 2/\pi R}},$$

where a_f and a_{ew} are the fermion- and electroweak BLKT parameters, and k_n is determined from $k_n a_{ew} = -\tan[k_n R\pi/2]$.

Phenomenology: Electroweak precision constraints on sUED and nUED

If corrections to the SM only influence the gauge boson propagators, they can be parameterized by the Peskin-Takeuchi Parameters

$$\alpha S = 4e^2 \left(\Pi'_{33}(0) - \Pi'_{3Q}(0)\right) \quad ,$$

$$\alpha T = \frac{e^2}{\hat{s}_Z^2 \hat{c}_Z^2 M_Z^2} \left(\Pi_{11}(0) - \Pi_{33}(0)\right) \quad ,$$

$$\alpha U = 4e^2 \left(\Pi'_{11}(0) - \Pi'_{33}(0)\right)$$

where $\Pi(0)$ is the respective two-point function evaluated at a reference scale $p^2 = 0$,
and $\Pi'(0) = \left.\frac{d\Pi}{dp^2}\right|_{p^2=0}$.

Experimental values: [Gfitter(2011)]

$S_{BSM} = 0.04 \pm 0.10$
$T_{BSM} = 0.05 \pm 0.11$ reference point: $m_h = 120\,\mathrm{GeV}$, $m_t = 173\,\mathrm{GeV}$,
$U_{BSM} = 0.08 \pm 0.11$

with correlations of $+0.89$ $(S - T)$, -0.45 $(S - U)$, and -0.69 $(T - U)$.

In MUED, vertex corrections are small, and couplings of zero mode fermions to KK mode gauge bosons are only induced at loop level.
$\Rightarrow$ EW corrections in MUED can be parameterized via S, T and U.

Problem in nUED/sUED:
Fermion-to-KK-gauge-boson couplings are not small. This in particular leads to modifications to muon-decay $\Leftrightarrow$ determination of the Fermi-constant G_f

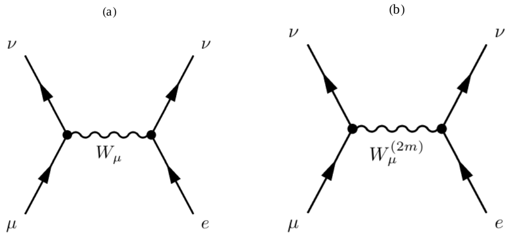


Figure: Muon decay. (a) The only diagram in the Standard Model. (b) additional diagrams for sUED/nUED where the KK modes of the W boson couple to the muon.

Solution: [Carena, Ponton, Tait, Wagner (2002)]

If the corrections are universal (which we for now assume), one can consider

$$G_{XY} \equiv \sum_{n=0}^{\infty} G_{XY}^{(n)}$$

as a generalized gauge boson propagator.

For LEP measurements (at $p^2 \sim m_Z^2$), the zero mode propagator is resonant, but for the G_f measurement (at $p^2 \sim m_\mu^2$), all propagators are off-resonance and contribute.

The measured value of G_f enters the S, T, U parameters, because the underlying SM parameters (g, g', v) are fixed from the observables (G_f, α, m_Z)

This effect can be compensated for by introducing the effective parameters

$$S_{eff} = S_{UED}$$

$$T_{eff} = T_{UED} + \Delta T_{UED} = T_{UED} - \frac{1}{\alpha}\frac{\delta G_f}{G_f^{obl}}$$

$$U_{eff} = U_{UED} = \Delta U_{UED} = U_{UED} + \frac{4\sin^2\theta_W}{\alpha}\frac{\delta G_f}{G_f^{obl}}$$

At tree level In nUED/sUED, the only contributions to the effective parameters arise from W KK excitations, so that

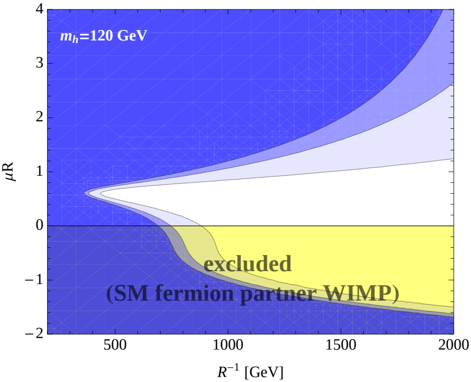
$$\frac{\delta G_f}{G_f^{obl}} = m_W^2 \sum_{n=1}^{\infty} \frac{(\mathcal{F}_{002n})^2}{m_W^2 + \left(\frac{2n}{R}\right)^2},$$

where again, $\mathcal{F}_{002n}$ are the overlap integrals which depend on μ (sUED) or respectively a_f, a_{ew} (nUED).
The leading one-loop contributions are

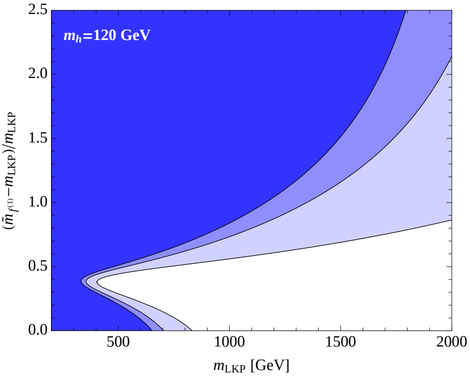
$$\begin{aligned} S_{UED} &\approx \frac{4\sin^2\theta_W}{\alpha}\left[\frac{3g^2}{4(4\pi)^2}\left(\frac{2}{9}\sum_n \frac{m_t^2}{m_{t^{(n)}}^2}\right) + \frac{g^2}{4(4\pi)^2}\left(\frac{1}{6}\sum_n \frac{m_h^2}{m_{h^{(n)}}^2}\right)\right], \\ T_{UED} &\approx \frac{1}{\alpha}\left[\frac{3g^2}{2(4\pi)^2}\frac{m_t^2}{m_W^2}\left(\frac{2}{3}\sum_n \frac{m_t^2}{m_{t^{(n)}}^2}\right) + \frac{g^2\sin^2\theta_W}{(4\pi)^2\cos^2\theta_W}\left(-\frac{5}{12}\sum_n \frac{m_h^2}{m_{h^{(n)}}^2}\right)\right], \\ U_{UED} &\approx -\frac{4g^2\sin^4\theta_W}{(4\pi)^2\alpha}\left[\frac{1}{6}\sum_n \frac{m_W^2}{m_{W^{(n)}}^2} - \frac{1}{15}\sum_n \frac{m_h^2 m_W^2}{m_{W^{(n)}}^4}\right]. \end{aligned}$$

Compare to experimental values (χ^2-test) $\Rightarrow$ Constraints on parameter space.

Constraints on the sUED parameter space and 1st KK-mode masses



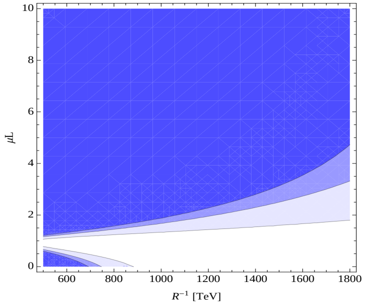
Left: 99%, 95%, and 68% exclusion contours in the μR vs. R^{-1} parameter space.



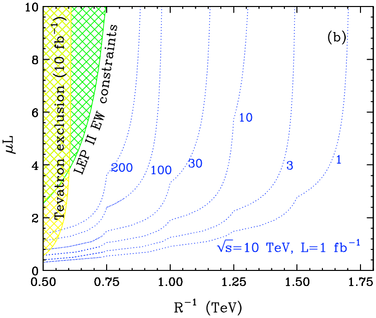
Right: Bounds on the rel. mass splitting at the first KK level vs. the mass of the LKP.

Comparison to LHC predictions

Comparison to potential LHC signals

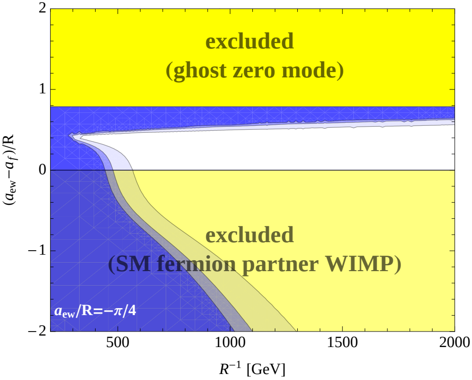


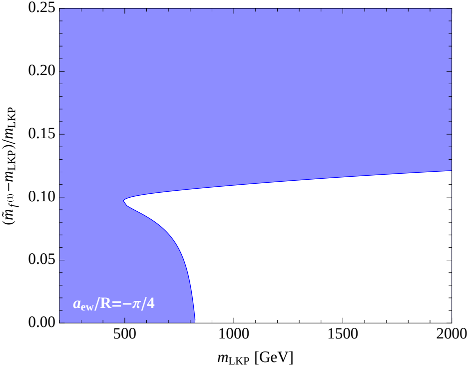
EW constraints on sUED



Predicted number of events in the di-lepton channel at LHC from [Kong, Park, Rizzo, JHEP 1004 (2010) 081]

Constraints on the nUED parameter space and 1^{st} KK-mode masses

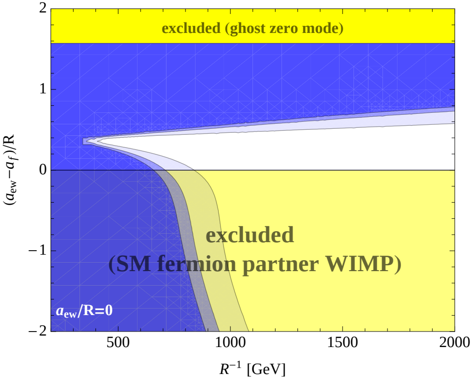


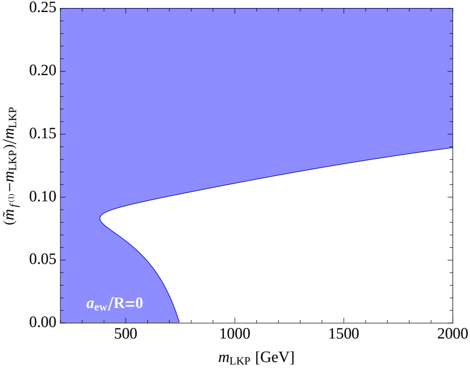


Left: 99%, 95%, and 68% exclusion contours in the $(a_{ew} - a_f)/R$ vs. R^{-1} parameter space for $a_{ew}/R = -\pi/4$

Right: 95% exclusion on the relative mass splitting at the first KK level vs. the mass of the LKP for $a_{ew}/R = -\pi/4$.

Constraints on the nUED parameter space and 1^{st} KK-mode masses

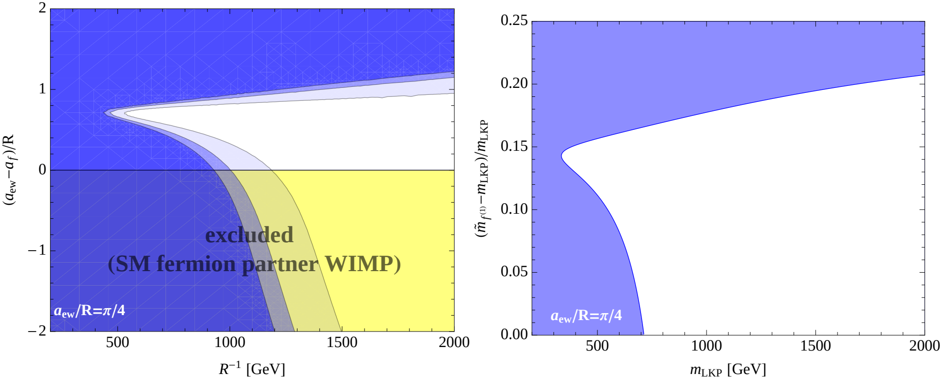




Left: 99%, 95%, and 68% exclusion contours in the $(a_{ew} - a_f)/R$ vs. R^{-1} parameter space for $a_{ew}/R = 0$

Right: 95% exclusion on the relative mass splitting at the first KK level vs. the mass of the LKP for $a_{ew}/R = 0$.

Constraints on the nUED parameter space and 1^{st} KK-mode masses



Left: 99%, 95%, and 68% exclusion contours in the $(a_{ew} - a_f)/R$ vs. R^{-1} parameter space for $a_{ew}/R = \pi/4$

Right: 95% exclusion on the relative mass splitting at the first KK level vs. the mass of the LKP for $a_{ew}/R = \pi/4$.

Conclusions and Outlook

Conclusions:

- Modifications of the KK fermion mass spectrum can occur due to boundary localized kinetic terms or fermion bulk mass terms.
- In both cases, the KK wave functions are altered which implies interactions of Standard Model fermions with all even KK modes of the gauge bosons.
- If present in the lepton sector, these interactions modify muon-decay
  $\Rightarrow$ the electroweak constraints turn out stronger than naively expected.
  $\Rightarrow$ upper bound on $m_{f^{(1)}} \cdot R$.

Outlook:

- We assumed universal bulk masses (sUED) or, respectively, BLKTs (nUED)
  $\rightarrow$ non-universal parameters require an electroweak fit
  beyond effective S, T, U parameters (work in progress).
- Modifications of fermion-to-KK gauge boson couplings also affect flavor constraints (in preparation). see also [D. Gerstenlauer, Diploma Thesis, Würzburg (2011)]