Electroweak constraints on non-minimal UED and split UED

Thomas Flacke

Universität Würzburg

TF, C. Pasold, arXiv:1110.xxxx

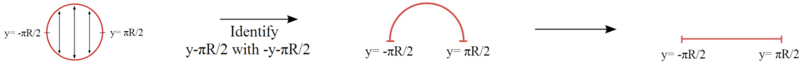
Outline

- 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.

the UED action

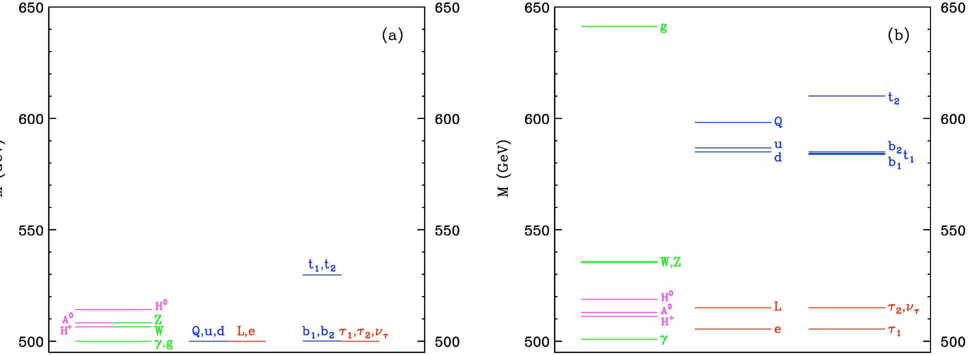
- UED action

$$S_{UED,bulk} = S_g + S_H + S_f,$$

with

$$\begin{aligned} S_g &= \int d^5x \left\{ -\frac{1}{4\hat{g}_3^2} G^A_{MN} G^{AMN} - \frac{1}{4\hat{g}_2^2} W^I_{MN} W^{IMN} - \frac{1}{4\hat{g}_Y^2} B_{MN} B^{MN} \right\}, \\ S_H &= \int d^5x \left\{ (D_M H)^\dagger (D^M H) + \hat{\mu}^2 H^\dagger H - \hat{\lambda}(H^\dagger H)^2 \right\}, \\ S_f &= \int d^5x \left\{ i\overline{\psi}\gamma^M D_M \psi + \left(\hat{\lambda}_E \overline{L} E H + \hat{\lambda}_U \overline{Q} U \tilde{H} + \hat{\lambda}_D \overline{Q} D H + \text{h.c.} \right) \right\}. \end{aligned}$$

the MUED spectrum



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

(M)UED pheno review

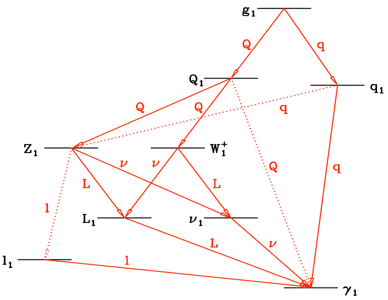
Phenomenological constraints on the compactification scale R^{-1}

- Lower bounds:
  - FCNCs [Buras, Weiler *et al.* (2003); Weiler, Haisch (2007)]
    $R^{-1} \gtrsim 650(330)\ \mathrm{GeV}$ at 95% (99%) cl.
  - Electroweak Precision Constraints [Appelquist, Yee (2002); Gogoladze, Macesanu (2006)]
    $R^{-1} \gtrsim 650(300)\ \mathrm{GeV}$ for $m_H = 115(800)\ \mathrm{GeV}$ at 95% cl.
  - no detection of KK-modes at LHC, yet [see plenary talk of Nojiri]
    $R^{-1} \gtrsim 500\,\mathrm{GeV}$ 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 [Barr *et al.* (2004); Datta, Kong, Matchev (2005); Kane *et al.* (2005) *and many more*]

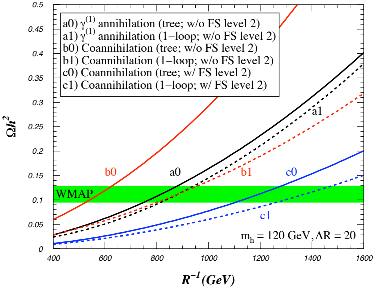
Relevance of the detailed mass spectrum I: LHC phenomenology

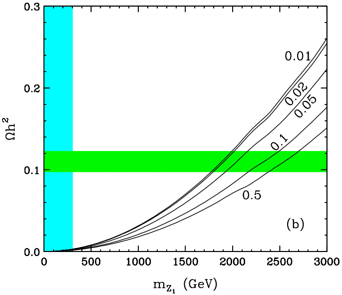
The KK mass spectrum determines decay channels, decay rates and final state jet/lepton energies at LHC.



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

Relevance of the detailed mass spectrum II: Dark Matter relic density





Left: Relic density for $\gamma^{(1)}$ dark matter in MUED including coannihilation effects of first and second KK modes [Belanger *et al.* (2010)]

Right: Relic density for $W^{3(1)}$ dark matter including coannihilation effects with first KK modes and different mass degeneracies [Arrenberg, Kong (2008)].

Realization of $W^{3(1)}$ dark matter, see [TF, Menon, Phalen (2008)]

UED as an effective field theory

- UED is a five dimensional model
  $\Rightarrow$ non-renormalizable.
- It should be considered as an effective field theory with a cutoff Λ.
- Naive dimensional analysis (NDA) result: $\Lambda \sim 50/R$.
  This cutoff is low!
- Bounds from unitarity imply $\Lambda \sim \mathcal{O}(10)$ [Chivukula, Dicus, He (2001)]
- Underlying assumption in MUED: all boundary localized terms vanish at the cutoff Λ and are only induced at lower energies via RG running.

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 modify the free field equations and thereby the spectrum and the KK wave functions.

Boundary localized terms for fermions

Concerning boundary localized kinetic terms (BLKTs), today we focus on fermions. [Csaki,Hubisz,Meade(2001);Aguila, Perez-Victoria, Santiago(2003)]

For gauge boson BLKTs, see [Carena, Tait, Wagner(2002); TF, Menon, Phalen(2009)]

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 $(\gamma^\mu, i\gamma^5)$.

We choose left-handed BLKTs (right-handed BLKTs are treated analogously).

Variation of the free action, leads to conditions

$$\delta\overline{\Psi}_L : \quad 0 = i\partial\!\!\!/\Psi_L + \partial_5\Psi_R - \frac{1}{2}\Psi_R\Big|_{-\frac{\pi R}{2}}^{\frac{\pi R}{2}} + a_L\left[\delta(y - \frac{\pi R}{2}) + \delta(y + \frac{\pi R}{2})\right] i\partial\!\!\!/\Psi_L \,,$$

$$\delta\overline{\Psi}_R : \quad 0 = i\partial\!\!\!/\Psi_R - \partial_5\Psi_L + \frac{1}{2}\Psi_L\Big|_{-\frac{\pi R}{2}}^{\frac{\pi R}{2}} \,.$$

We perform the KK decomposition with the ansatz

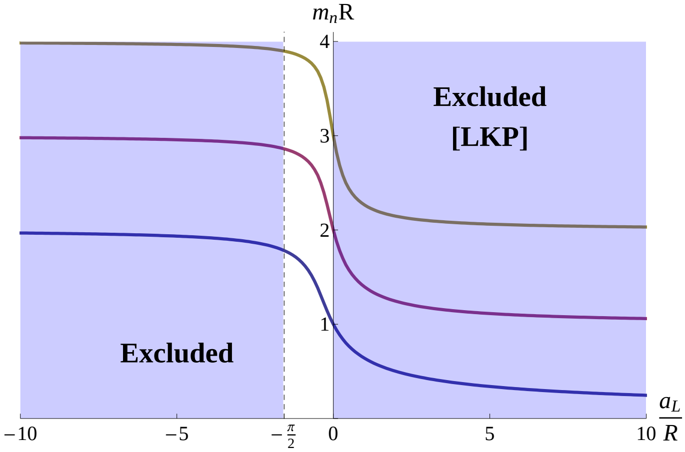
$$\Psi_R(x,y) = \sum_{n=0}^{\infty}\Psi_R^{(n)}(x)\, f_R^{(n)}(y)\,; \qquad \Psi_L(x,y) = \sum_{n=0}^{\infty}\Psi_L^{(n)}(x)\, f_L^{(n)}(y)\,,$$

to obtain

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 analogous results for right-handed BLKTs are obtained 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 - Remark concerning orthogonality conditions

With the inclusion of BLKTs, the 5D wave functions form an orthonormal basis with respect to the modified scalar product [analogous to Carena, Tait, Wagner(2002)]

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

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

for left-handed BLKTs, and anologous for right-handed BLKTs.

Note: Non-zero even gauge KK modes couple to fermion zero modes with

$$g_{eff}^{00n} = g_0 \mathcal{F}_{00n} \equiv g_0 \int dy \frac{1}{\pi R} f_\psi^{(0)*} f_A^{(n)} f_\psi^{(0)} \left(1 + a_h[\delta(y - \pi R/2) + \delta(y + \pi R/2)]\right)$$

$$= g_0 (-1)^{n/2} \frac{\sqrt{8} a_h}{2 a_h + \pi R}$$

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:

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

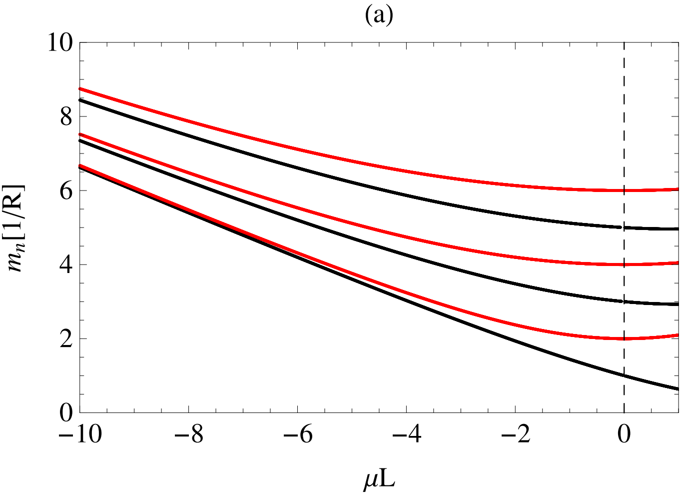
Solutions for a left-handed zero mode:

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

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



Fermion KK masses as a function of $\mu L \equiv \mu \pi R/2$.

sUED overlap integrals

To obtain the overlap integrals in sUED, we simply have to integrate over S^1/Z_2, but now, the zero mode wave functions are not flat
$\Rightarrow$ like in nUED, one obtains non-vanishing interactions of zero mode fermions with non-zero mode gauge bosons of strength

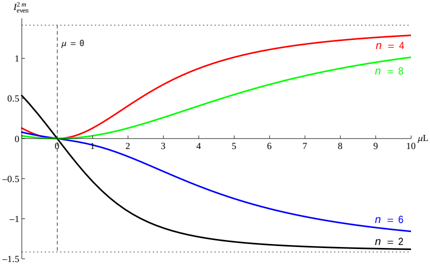
$$g_{eff}^{00n} = g_0 \mathcal{F}_{00n}$$

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.



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 $\Pi'(0) = \frac{d\Pi}{dp^2}\Big|_{p^2=0}$.

Experimental values: [PDG / Erler, Langacker]:

$$S_{BSM} = 0.01 \pm 0.10$$
$$T_{BSM} = 0.03 \pm 0.11$$
$$U_{BSM} = 0.06 \pm 0.10$$

for $m_H = 117$ GeV

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

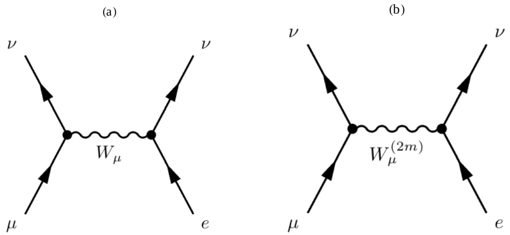


Figure: Muon decay. (a) The only diagram in the Standard Model. (b) additional diagrams for sUED/nUED where the KK modes of the W boson couple to the muon.

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

$$S_{eff} = S$$

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

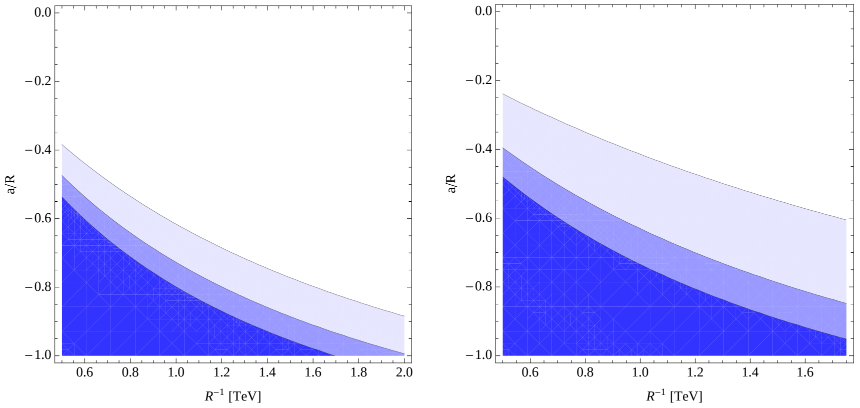
$$U_{eff} = U = \Delta U = U + \frac{4\hat{s}_Z^2}{\alpha}\frac{\delta G_f}{G_f^{obl}}$$

In nUED/sUED, the tree-level contributions to S, T, U vanish, so all we need to calculate is $\frac{\delta G_f}{G_f^{obl}}$. But this is just the relative correction to the W propagator from W KK excitations, so that

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

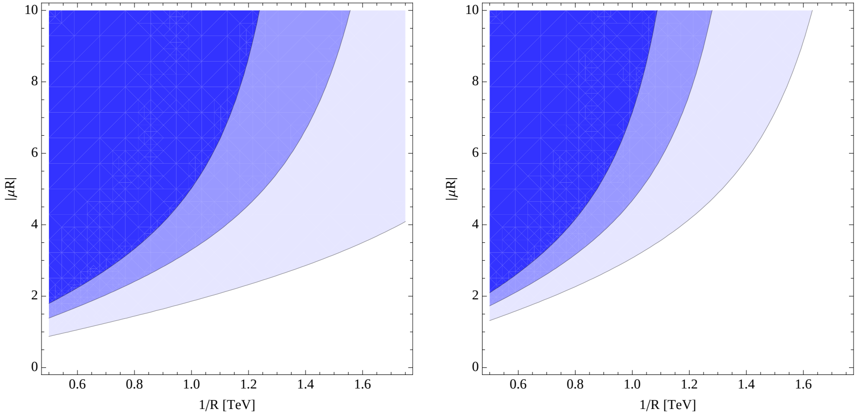
where again, $\mathcal{F}_{002n}$ are the overlap integrals which depend on μ (sUED) or respectively a (nUED).

Constraints on the nUED parameter space



1,2, and 3 σ c.l. constraints from T_{eff} (left) and U_{eff} (right) on the nUED parameter space ($m_H = 117\,\mathrm{GeV}$).

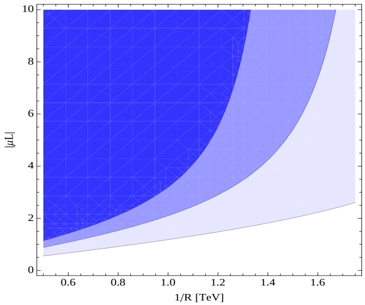
Constraints on the sUED parameter space



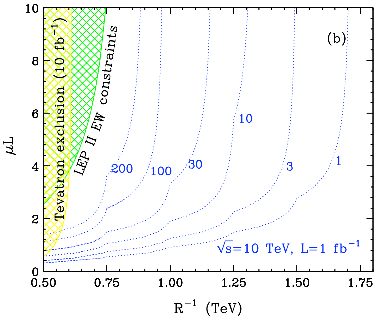
1,2, and 3 σ c.l. contraints from T_{eff} (left) and U_{eff} (right) on the sUED parameter space ($m_H = 117\,\mathrm{GeV}$).

Comparison to LHC predictions

Comparison to potential LHC signals



EW constraints on sUED (from T parameter at $m_H = 117$ GeV)



Predicted number of events in the Dilepton channel at LHC

from [Kong, Park, Rizzo, JHEP 1004 (2010) 081]

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:

- The current analysis is only performed at tree-level
  $\rightarrow$ inclusion of the one-loop contributions to S, T, U (in preparation).
- 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)]