Constraining universal extra dimensions with LHC and precision tests

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TF, C. Pasold, arXiv:1111.7250

TF, arXiv:1206.xxxx

TF, A. Menon, Z. Sullivan, arXiv:1206.xxxx

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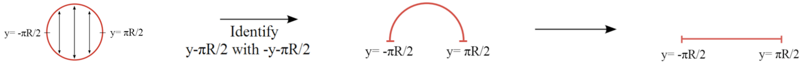
Outline

- UED
  - Review
  - Modifying the UED mass spectrum
- Constraints from $pp \rightarrow W' \rightarrow tb$ at the LHC
- Electroweak precision constraints
- 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)]
    $R^{-1} \gtrsim 600\,\mathrm{GeV}$ at 95% cl.
  - Electroweak Precision Constraints [Appelquist, Yee (2002); Gogoladze, Macesanu (2006); *Gfitter* (2011)]
    $R^{-1} \gtrsim 750\,\mathrm{GeV}$ for $m_H = 125\,\mathrm{GeV}$ at 95% cl.
  - no detection of KK-modes at LHC, yet [Murayama *et al.* (2011)]
    $R^{-1} \gtrsim 600\,\mathrm{GeV}$ at 95% cl.
- Upper bound:
  - preventing too much dark matter by $B^{(1)}$ dark matter
    $R^{-1} \lesssim 1.5\mathrm{TeV}$ [Belanger *et al.* (2010)]

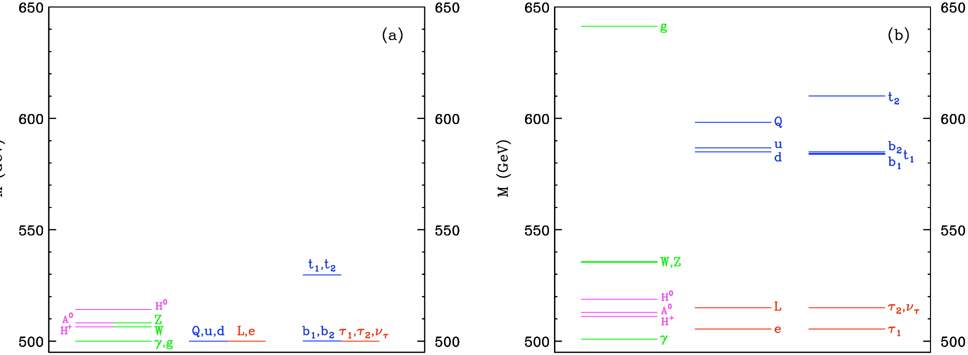
UED vs. SUSY at LHC:

- Determining the spin of particles [Barr *et al.* (2004) and many follow-ups]
- Studying the influence of 2nd KK mode particles

  [Datta, Kong, Matchev (2005), Kim, Oh, Park (2011), Chang, Lee, Song (2011)
- Measuring total cross sections [Kane *et al.* (2005)], some follow-ups]

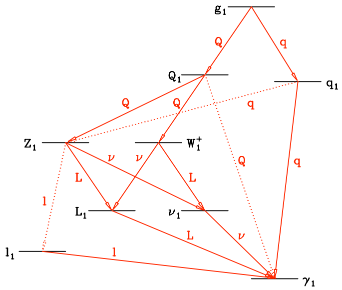
the MUED spectrum

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

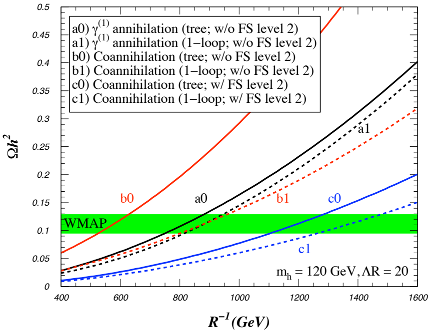


[Cheng, Matchev, Schmaltz, PRD **66** (2002) 036005, hep-ph/0204342]

Relevance of the detailed mass spectrum



[Cheng, Matchev, Schmaltz, PRD**66** (2002) 056006]



[Belanger, Kakizaki, Pukhov, JCAP 1102 (2011) 009]

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

The DM relic density is highly sensitive to mass splittings at the first and between the first and second KK level.

modifying the UED mass spectrum - why? and how?

- 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: $\Lambda \lesssim 50/R$.
  A light Higgs and vacuum stability even implies $\Lambda \lesssim 6/R$. [Ohlsson *et al.* (2011)]
  if higher dimensional operators and a Higgs brane mass are not included.
- Assumption in MUED: all higher dimensional operators vanish at Λ.
- Effective field theory $\Rightarrow$ include all operators allowed by symmetries.

1. Bulk mass terms for fermions ($dim = dim(\mathcal{L})$) $\Rightarrow$ split UED (sUED),
2. kinetic and mass terms at the orbifold fixed points,
   ($dim = dim(\mathcal{L}) + 1$; radiatively induced in MUED)
   $\Rightarrow$ nonminimal UED (nUED),
3. bulk or boundary localized interactions ($dim > dim(\mathcal{L}) + 1$)

The former two operator classes modify the free field equations and thereby alter the Kaluza-Klein decomposition
$\Rightarrow$ different mass spectrum and different KK wave functions.

Model I: sUED - Bulk mass terms for fermions

In sUED, a KK parity conserving fermion bulk mass term is introduced.

[Park, Shu (2009); Csaki *et al.* (2001)]

$$S \supset \int d^5x - \mu\theta(y)\overline{\Psi}\Psi.$$

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

Solutions for a fermion with right-handed zero mode:

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

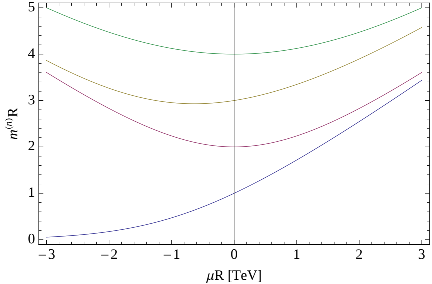
and $m_n = \sqrt{k_n^2 + \mu^2}$.
(Solutions for left-handed zero mode: $L \leftrightarrow R$ and $\mu \rightarrow -\mu$)

sUED couplings

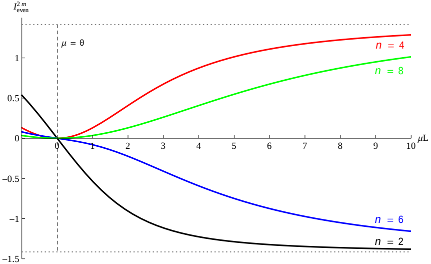
Couplings between KK particles and SM particles , follow from overlap integrals

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

with $\mathcal{F}_{002n} \equiv \int_{-\pi R/2}^{\pi R/2} \frac{1}{\pi R} f_\psi^{(0)*} f_A^{(n)} f_\psi^{(0)} = \frac{(\mu\pi R)^2(-1+(-1)^n e^{\mu\pi R}(\coth(\mu\pi R/2)-1)}{\sqrt{2(1+\delta_{0n}}((\mu\pi R)^2+n^2\pi^2)}$



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



relative couplings of the first four even KK modes

Model II: nonminimal UED - Boundary localized terms

[Csaki *et al.* (2001);Aguila *et al.* (2003); Carena *et al.* (2002); TF,Menon,Phalen(2009); TF, (in preparation)]

We include the boundary kinetic action

$$\mathcal{S}_{bd} = \int_{\mathbb{M}} \int_{S^1/\mathbb{Z}_2} d^5x \left(-\frac{a_B}{4\hat{g}_1^2} B_{\mu\nu} B^{\mu\nu} - \frac{a_W}{4\hat{g}_2^2} W^a_{\mu\nu} W^{a,\mu\nu} - \frac{a_G}{4\hat{g}_3^2} G^A_{\mu\nu} G^{A,\mu\nu} \right.$$
$$\left. + a_h \overline{\Psi}_h \not{D} \Psi_h + a_H (D_\mu H)^\dagger D^\mu H \right) \times \left[\delta\left(y - \frac{\pi R}{2}\right) + \delta\left(y + \frac{\pi R}{2}\right) \right],$$

where $h = R, L$ represents the chirality.

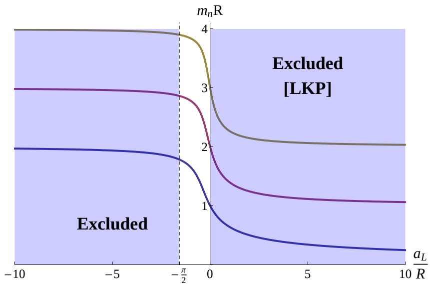
For simplicity, we consider a common electroweak boundary parameter

$a_B = a_W = a_H \equiv a_{ew}$. For the generic case, *c.f.* [TF,Menon,Phalen(2009)].

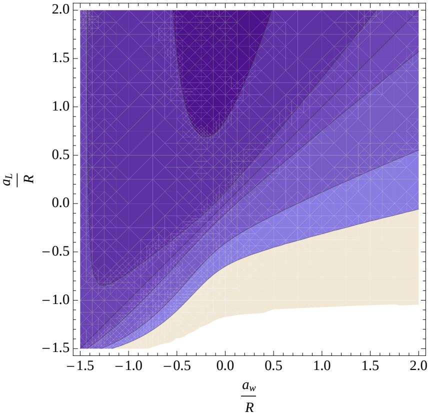
The boundary terms modify the boundary conditions on the 5D wave functions

$\Rightarrow$

- modified mass quantization conditions: *e.g.*
  - $\tan(\frac{\pi R}{2} k_n) = -a_L k_n$ for even numbered KK modes
  - $\cot(\frac{\pi R}{2} k_n) = a_L k_n$ for odd numbered KK modes
- modified orthogonality relations for KK wave functions, *e.g.*
  - $\delta_{mn} = \int \mathrm{d}y\ f_L^{(n)}(y) f_L^{(m)}(y) \left(1 + a_L[\delta(y - \frac{\pi R}{2}) + \delta(y + \frac{\pi R}{2})]\right)$
  - $\delta_{mn} = \int \mathrm{d}y\ f_R^{(n)}(y) f_R^{(m)}(y)$.



Masses of the first three fermion KK modes in nUED

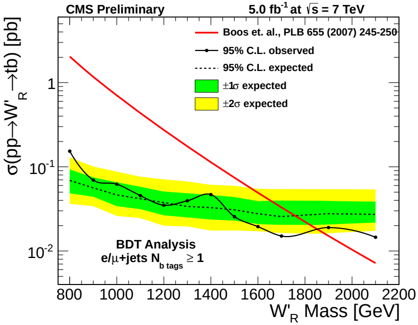


Relative coupling strength g^{002}/g_{SM}
Contours: $(-0.5, -0.1, 0, 0.1, 0.5, 1.0)$

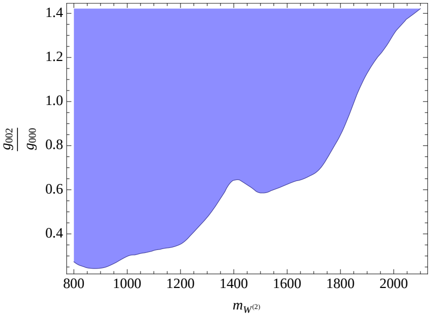
... again, the KK mass spectrum is altered,
but at the same time, KK number violating couplings are induced.

Constraints from $pp \rightarrow W^{(2)} \rightarrow tb$

The KK number violating couplings in nUED and sUED imply W', Z', g', ... - like signatures from the s-channel resonances of $W^{(2)}$, $Z^{(2)}$, $\gamma^{(2)}$, $G^{(2)}$ at LHC.
Here, we focus on $pp \rightarrow W' \rightarrow tb$ (other channels: work in progress).

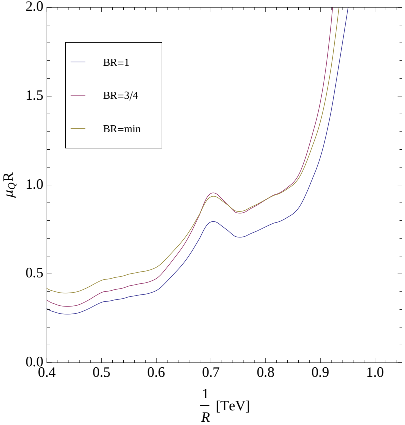


CMS bounds on $pp \rightarrow W' \rightarrow tb$
$5fb^{-1}@\sqrt{s} = 7\,\mathrm{TeV}$, [CMS PAS EXO-12-001]
for ATLAS bounds, *c.f.* [arXiv:1205.1016]
for earlier W' bounds *c.f.* Sullivan (2003)

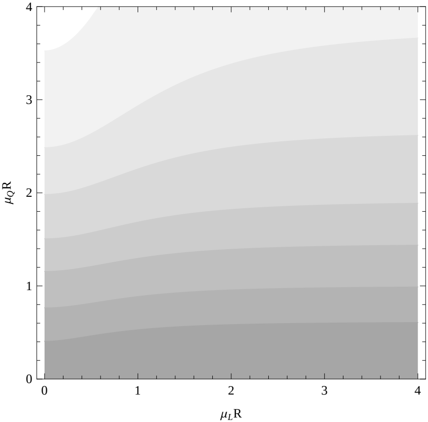


CMS bounds on $pp \rightarrow W' \rightarrow tb$, converted into a bound on g'/g

Resulting sUED bounds

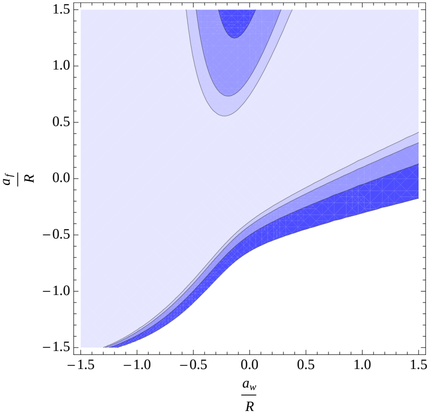


Upper bounds on $\mu_Q R$
for different branching ratios
$\sigma(W^{(2)} \rightarrow QQ)/\sigma(W^{(2)} \rightarrow all)$

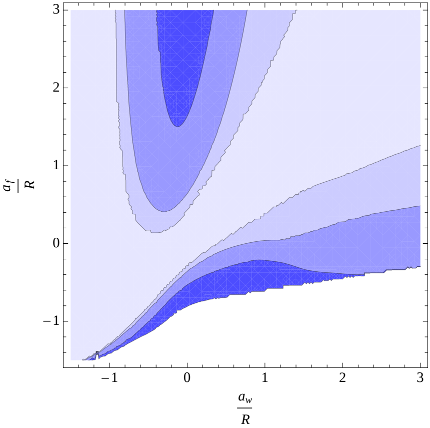


Contours of maximally allowed R^{-1}
in the $\mu_Q R$ vs. $\mu_L R$ plane
Contours:
$R^{-1} = (1., .975, .95, .925, .9, .8, .6,)\,\mathrm{TeV}$

Resulting nUED bounds



Bounds in the $\frac{a_f}{R}$ vs. $\frac{a_w}{R}$ plane
for $m_{W^{(2)}} = (0.8, 1.2, 1.5, 2.0)\,\mathrm{TeV}$
(for $BR_{QQ} = 3/4$)



Bounds in the $\frac{a_f}{R}$ vs. $\frac{a_w}{R}$ plane
for $m_{LKP} = (0.4, 0.6, 0.8, 1.0)\,\mathrm{TeV}$
(for $BR_{QQ} = 3/4$)

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: [*Gfitter*(2011)]

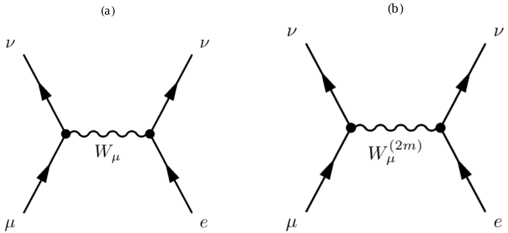
$$S_{BSM} = 0.04 \pm 0.10$$
$$T_{BSM} = 0.05 \pm 0.11$$
$$U_{BSM} = 0.08 \pm 0.11$$

reference point: $m_h = 120\,\mathrm{GeV}$, $m_t = 173\,\mathrm{GeV}$,

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

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



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

We for now restrict ourselves to universal fermion bulk masses / boundary terms. Then, the modifications to G_f can be compensated for by introducing

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

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

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

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

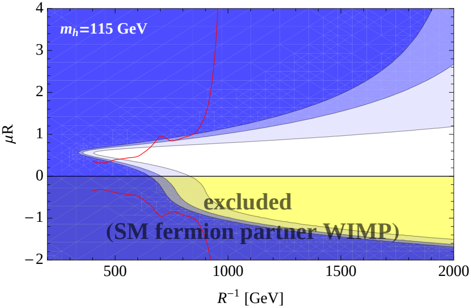
$$S_{UED} \approx \frac{4\sin^2\theta_W}{\alpha}\left[\frac{3g^2}{4(4\pi)^2}\left(\frac{2}{9}\sum_n \frac{m_t^2}{m_{t^{(n)}}^2}\right) + \frac{g^2}{4(4\pi)^2}\left(\frac{1}{6}\sum_n \frac{m_h^2}{m_{h^{(n)}}^2}\right)\right],$$

$$T_{UED} \approx \frac{1}{\alpha}\left[\frac{3g^2}{2(4\pi)^2}\frac{m_t^2}{m_W^2}\left(\frac{2}{3}\sum_n \frac{m_t^2}{m_{t^{(n)}}^2}\right) + \frac{g^2\sin^2\theta_W}{(4\pi)^2\cos^2\theta_W}\left(-\frac{5}{12}\sum_n \frac{m_h^2}{m_{h^{(n)}}^2}\right)\right],$$

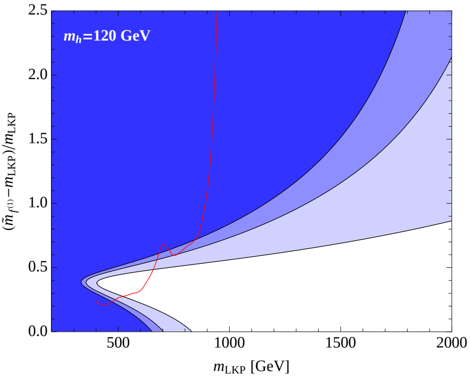
$$U_{UED} \approx -\frac{4g^2\sin^4\theta_W}{(4\pi)^2\alpha}\left[\frac{1}{6}\sum_n \frac{m_W^2}{m_{W^{(n)}}^2} - \frac{1}{15}\sum_n \frac{m_h^2 m_W^2}{m_{W^{(n)}}^4}\right].$$

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

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

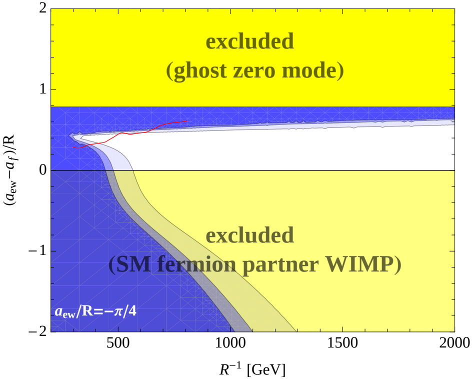


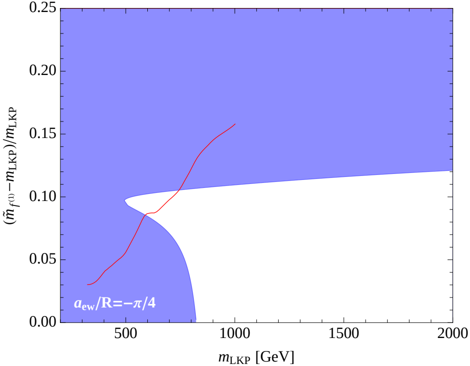
Left: 99%, 95%, and 68% exclusion contours in the μR vs. R^{-1} parameter space.
Red: Lower exclusion bound from $W^{(2)} \rightarrow tb$.



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

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

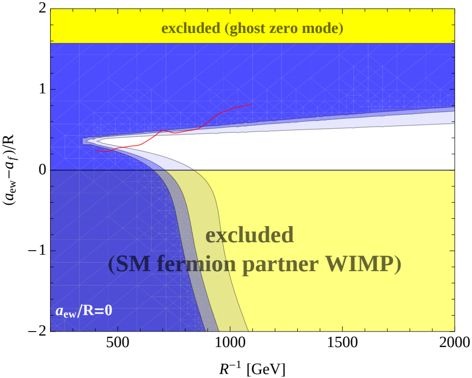


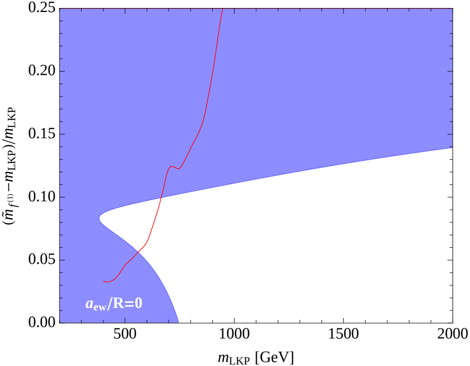


Left: 99%, 95%, and 68% exclusion contours in the $(a_{ew}-a_f)/R$ vs. R^{-1} parameter space for $a_{ew}/R=-\pi/4$

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

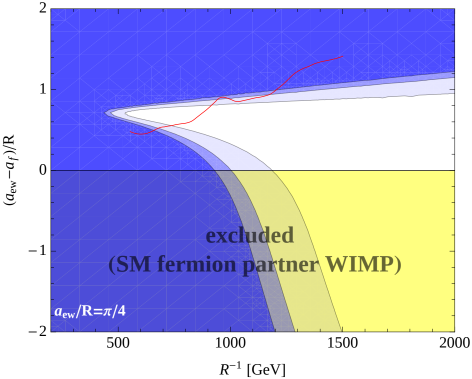


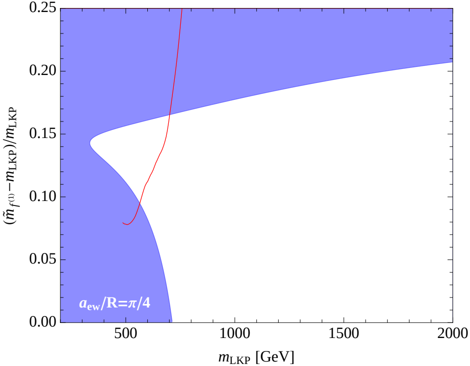


Left: 99%, 95%, and 68% exclusion contours in the $(a_{ew} - a_f)/R$ vs. R^{-1} parameter space for $a_{ew}/R = 0$

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 1st 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 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.
- EWPT: 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 mass splittings between the LKP and KK fermions.
- The LHC starts to improve the sUED / nUED parameter space constraints now in resonance searches for the 2^{nd} KK mode: $W', Z', \gamma', g', \ldots$.

Outlook

- The analysis for $W', Z', \gamma', g', ...$ searches is under way, which constrains several different combinations of lepton- and quark-mass/boundary terms.
- Our EW analysis so far was restricted to a uniform fermion mass / BLKT as we worked with the universal parameters $S_{eff}, T_{eff}, U_{eff}$.
  We work on a more general analysis, which also includes non-universal contributions.

Request

- When running UED analyses, remember that MUED is only one point in a vast parameter space.
- But when varying mass spectra, note that wave functions and thereby couplings are also influenced.