Phenomenological Implications of general UED

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TF, C. Pasold, PRD85 (2012) 126007

TF, A. Menon, Z. Sullivan, arXiv:1207.4472

TF, KC Kong, SC Park, arXiv:1211.xxxx

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Outline

- UED
  - Review
  - Generalized UED
- Constraints from $pp \to W' \to tb$ at the LHC
- Some pre-LHC constraints
- Outlook on further LHC constraints
- Conclusions

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; $x_5 \equiv y \in [-\pi R/2, \pi R/2] \equiv [-L, L]$
  - allows for chiral zero mode fermions
  - allows for gauge field zero modes without additional scalars
- 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}

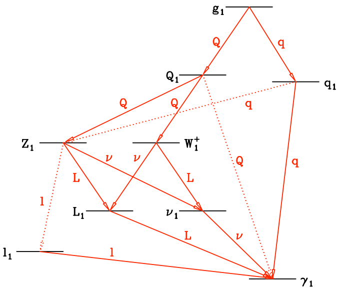
- Lower bounds:
  - FCNCs [Buras, Weiler *et al.* (2003); Weiler, Haisch (2007)]
    $R^{-1} \gtrsim 600\,\mathrm{GeV}$ at 95% cl.
  - Electroweak Precision Constraints [Appelquist, Yee (2002); Gogoladze, Macesanu (2006); *Gfitter* (2011)]
    $R^{-1} \gtrsim 750\,\mathrm{GeV}$ for $m_H = 125\,\mathrm{GeV}$ 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)]

"Standard" mass spectrum:

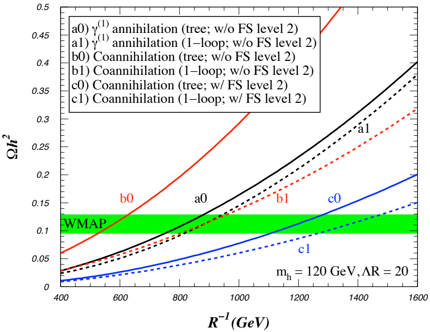
$$m^2_{\phi^{(n)}} = (\frac{n}{R})^2 + m^2_{\phi,SM} + \delta m^2_{\phi^{(n)}}$$

Note:
UED Phenomenology depends sensitively on the KK mode mass spectrum.

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.

Generalized UED

- 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.

mass modifying operators

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

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

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

In nUED one includes the boundary kinetic action

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

where $h = R, L$ represents the chirality.
For simplicity, in what follows we consider a common electroweak boundary parameter $r_B = r_W = r_H \equiv r_{ew}$. For the generic case, *c.f.* [TF,Menon,Phalen(2009)].

Kaluza-Klein decomposition

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

- Bulk mass terms modify the 5D EOM.
- BLKTs modify the boundary conditions of this Sturm-Liouville problem.

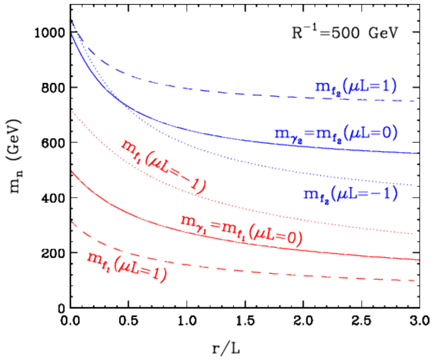
$\Rightarrow$ KK-masses and wave-functions are modified.

Solutions for a fermion with left-handed zero mode:

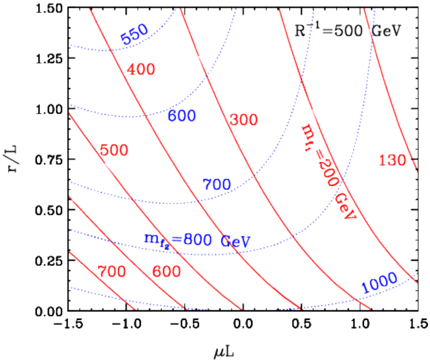
KK zero modes	even numbered KK-modes	odd numbered KK-modes
$f_L^{(0)}(y) = \mathcal{N}_L^{(0)} e^{\mu\|y\|}$	$f_L^{(n)}(y) = \mathcal{N}_L^{(n)} \left(\cos(k_n y) + \frac{\mu}{k_n}\sin(k_n\|y\|)\right)$	$f_L^{(n)}(y) = \mathcal{N}_L^{(n)} \sin(k_n y)$
$f_R^{(0)}(y) = 0$	$f_R^{(n)}(y) = \mathcal{N}_R^{(n)}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

and $m_n = \sqrt{k_n^2+\mu^2}$.
(Solutions for left-handed zero mode: $L \leftrightarrow R$ and $\mu \to -\mu$,
Solutions for gauge bosons / scalars: $\mu \to 0$)

Masses

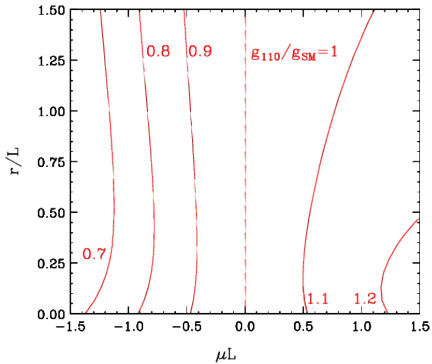


Masses of the first and second KK mode for different μ (m_n vs. r/L)

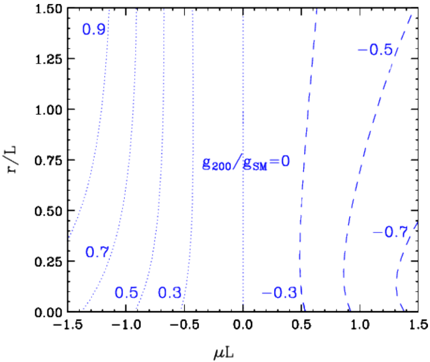


Masses of the first and second KK mode (r/L vs. μL for $R^{-1} = 500\,\mathrm{GeV}$)

Couplings



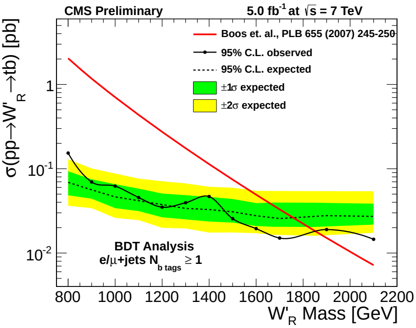
Coupling $g^{(1)} f^{(1)} f^{(0)}$
(normalized w.r.t. $g^{(0)} f^{(0)} f^{(0)}$ coupling)



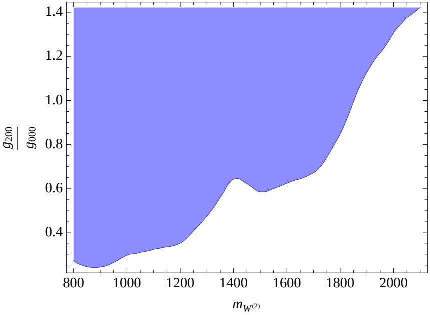
Coupling $g^{(2)} f^{(0)} f^{(0)}$
(normalized w.r.t. $g^{(0)} f^{(0)} f^{(0)}$ coupling)

Constraints from $pp \to W^{(2)} \to tb$ [TF, Menon, Sullivan (2012)]

The KK number violating couplings in nUED and sUED imply $W', Z', g', \ldots$ - like signatures from the s-channel resonances of $W^{(2)}, Z^{(2)}, \gamma^{(2)}, G^{(2)}$ at LHC.
We first focus on $pp \to W' \to tb$.

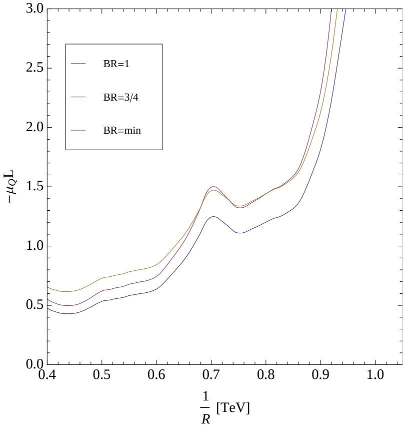


CMS bounds on $pp \to W' \to tb$
$5 fb^{-1} @ \sqrt{s} = 7\,\mathrm{TeV}$, [CMS PAS EXO-12-001]
for ATLAS bounds, *c.f.* [arXiv:1205.1016]
for earlier W' bounds *c.f.* Sullivan (2003)

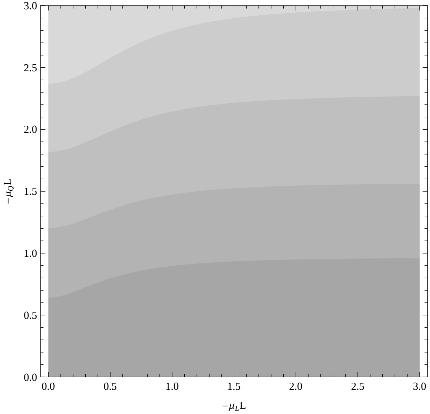


CMS bounds on $pp \to W' \to tb$, converted into a bound on g'/g

Resulting sUED bounds

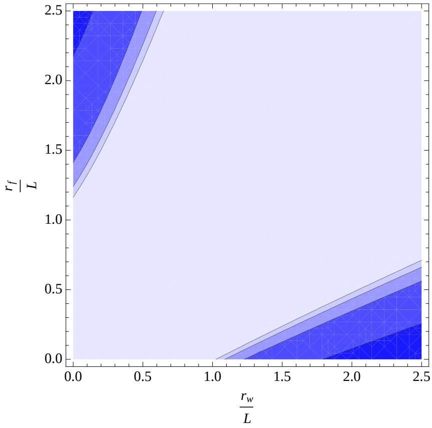


Upper bounds on $\mu_Q L$
for different branching ratios
$\sigma(W^{(2)} \to QQ)/\sigma(W^{(2)} \to all)$

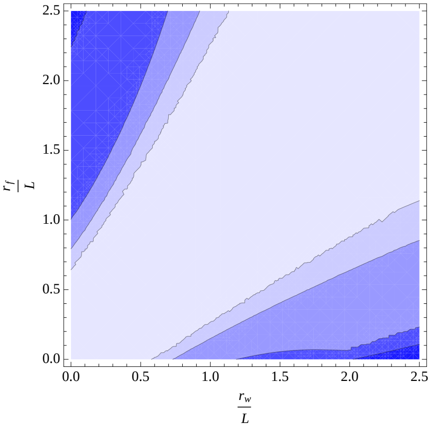


Contours of maximally allowed R^{-1}
in the $\mu_Q L$ vs. $\mu_L L$ plane
Contours:
$R^{-1} = (.925, .9, .8, .6)\,\mathrm{TeV}$

Resulting nUED bounds



Bounds in the $\frac{r_f}{L}$ vs. $\frac{r_w}{L}$ plane
for $m_{W^{(2)}} = (0.8, 1.0, 1.2, 1.5)\,\mathrm{TeV}$
(for $BR_{QQ} = 3/4$)



Bounds in the $\frac{r_f}{L}$ vs. $\frac{r_w}{L}$ plane
for $m_{LKP} = (0.4, 0.5, 0.6, .7)\,\mathrm{TeV}$
(for $BR_{QQ} = 3/4$)

Electroweak precision I: S, T, U parameters [TF, Pasold (2012); TF, Kong, Park (in prep.)]

In the presence of bulk masses and boundary terms, electroweak corrections are not oblique *but* if we assume a common boundary term r and a common boundary term μ, corrections are universal.
$\Rightarrow$ can be treated in terms of effective S, T, U parameters: [Carena, Ponton, Tait, Wagner (2002)]

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

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

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

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 ($T - U$).

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

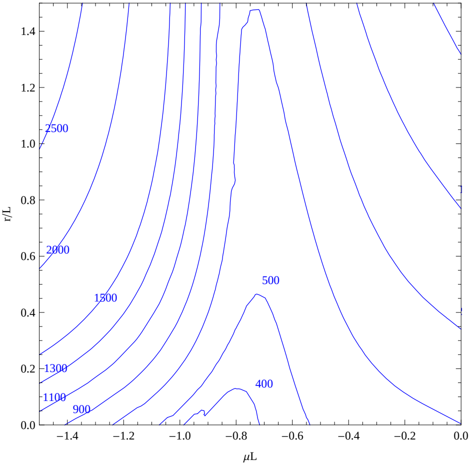
$$\frac{\delta G_f}{G_f^{obl}} = m_W^2 \sum_{n=1}^{\infty} \frac{(\mathcal{F}_{002n})^2}{m_W^2 + \left(\frac{2n}{R}\right)^2},$$

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

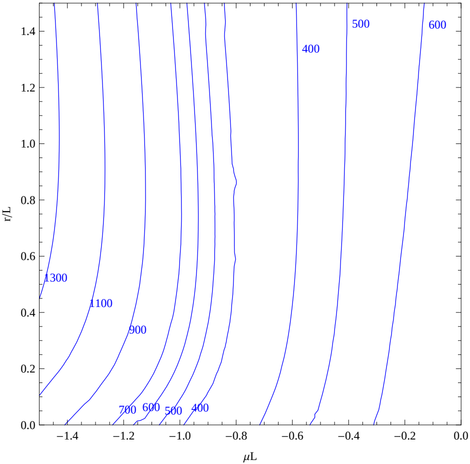
$$\begin{aligned}
S_{UED} &\approx \frac{4\sin^2\theta_W}{\alpha}\left[\frac{3g^2}{4(4\pi)^2}\left(\frac{2}{9}\sum_n \frac{m_t^2}{m_{t^{(n)}}^2}\right) + \frac{g^2}{4(4\pi)^2}\left(\frac{1}{6}\sum_n \frac{m_h^2}{m_{h^{(n)}}^2}\right)\right],\\
T_{UED} &\approx \frac{1}{\alpha}\left[\frac{3g^2}{2(4\pi)^2}\frac{m_t^2}{m_W^2}\left(\frac{2}{3}\sum_n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

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

Constraints on the UED parameter space



Contours of minimally allowed R^{-1} (at 2σ c.l.) in the r/L vs. μL plane



Contours of minimally allowed m_{LKP} (at 2σ c.l.) in the r/L vs. μL plane

EWPT II: (non-universal) four-fermi operator bounds

Parameterization of the four-fermi interactions:

$$\mathcal{L}_{eff} \supset \sum_{f_1,f_2} \sum_{A,B=L,R} \eta^s_{f_1 f_2,AB} \frac{4\pi}{(\Lambda^s_{f_1,f_2,AB})^2} \bar{f}_{1,A}\gamma^\mu f_{1,A}\bar{f}_{2,B}\gamma_\mu f_{2,B},$$

where $f_{1,2}$ are the contributing fermions and $\eta^s_{f_1 f_2,AB} = \pm 1$.
Four-fermi interaction bounds: [PDG 2011]

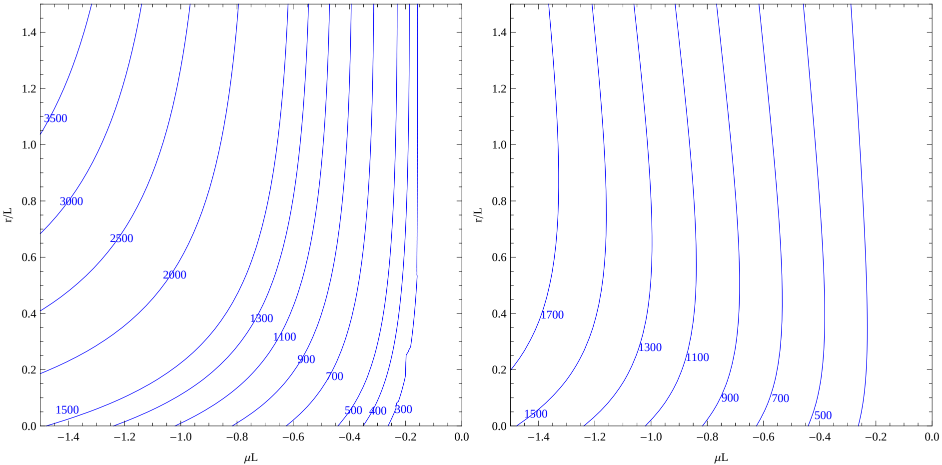
TeV	$eeee$	$ee\mu\mu$	$ee\tau\tau$	$\ell\ell\ell\ell$	$qqqq$	$eeuu$	$eedd$
Λ^+_{LL}	> 8.3	> 8.5	> 7.9	> 9.1	> 2.7	> 23.3	> 11.1
Λ^-_{LL}	> 10.3	> 9.5	> 7.2	> 10.3	2.4	> 12.5	> 26.4

Effective four-fermi operators in UED:

$$\mathcal{L}^{UED}_{eff} \supset 4\pi N_c \sum_{n=1}^{\infty} \left(\mathcal{F}^{2n}_{00}(r/L, \mu L)\right)^2 \times \left[\frac{3}{5}\frac{\alpha_1 Y_{e_A} Y_{q_B}}{Q^2 - M^2_{B_{2n}}} + \frac{\alpha_2 T^3_{e_A} T^3_{q_B}}{Q^2 - M^2_{W^3_{2n}}}\right]$$

$$\approx -12\pi \sum_{n=1}^{\infty} \left(\mathcal{F}^{2n}_{00}(r/L, \mu L)\right)^2 \times \left[\frac{3}{5}\frac{\alpha_1 Y_{e_A} Y_{q_B}}{M^2_{B_{2n}}} + \frac{\alpha_2 T^3_{e_A} T^3_{q_B}}{M^2_{W^3_{2n}}}\right],$$

Constraints on the UED parameter space



Contours of minimally allowed R^{-1} (at 2σ c.l.) in the r/L vs. μL plane

Contours of minimally allowed m_{LKP} (at 2σ c.l.) in the r/L vs. μL plane

Dark Matter relic abundance

- Obtaining (at most) as much DM as observed by WMAP yields an upper bound on m_{LKP}.
- In Minimal UED, the correct relic abundance is obtained for
  - $m_{LKP} \sim 1.5\,\mathrm{TeV}$ if 2nd KK mode *s*-channel resonances and co-annihilation are taken into account [Belanger *et al.* (2010)]
  - $m_{LKP} \sim 800\,\mathrm{GeV}$ in the absence of co-annihilation [Kong, Matchev (2005); Burnell, Kribs (2005)]
  - *s*-channel resonances and co-annihilation only occur if the KK mass spectrum is given by $m_n \approx n/R \rightarrow$ can be ignored for $\mu L, r/L \gtrsim .1$.

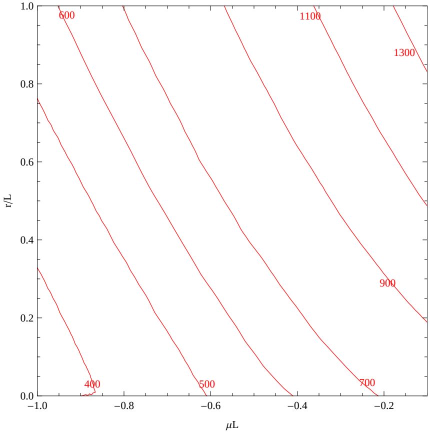
In this case, the relic density can be calculated in the standard way from the non-relativistic limit of the annihilation X-section $\sigma_{tree} v = a + bv^2 + \mathcal{O}(v^4)$ with

[Kong,Matchev (2005)]

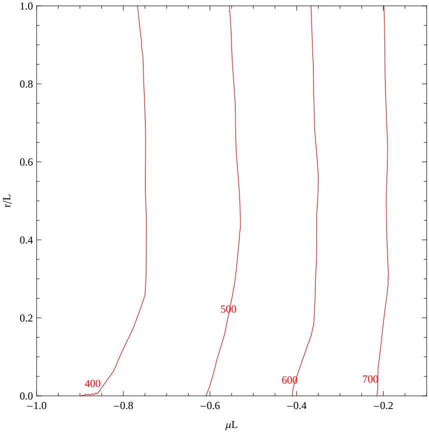
$$a = \sum_f \frac{32\pi\alpha_Y^2 N_c m_{\gamma_1}}{9} \left(\frac{Y_{f_L}^4}{(m_{\gamma_1}^2 + m_{f_{L1}}^2)^2} + \frac{Y_{f_R}^4}{(m_{\gamma_1}^2 + m_{f_{R1}}^2)^2} \right)$$

$$b = -\sum_f \frac{4\pi\alpha_Y^2 N_c m_{\gamma_1}}{27} \left(Y_{f_L}^4 \frac{11 m_{\gamma_1}^4 + 14 m_{\gamma_1}^2 m_{f_{L1}}^2 - 13 m_{f_{L1}}^4}{(m_{\gamma_1}^2 + m_{f_{L1}}^2)^4} + Y_{f_R}^4 \frac{11 m_{\gamma_1}^4 + 14 m_{\gamma_1}^2 m_{f_{R1}}^2 - 13 m_{f_{R1}}^4}{(m_{\gamma_1}^2 + m_{f_{R1}}^2)^4} \right)$$

Constraints on the UED parameter space

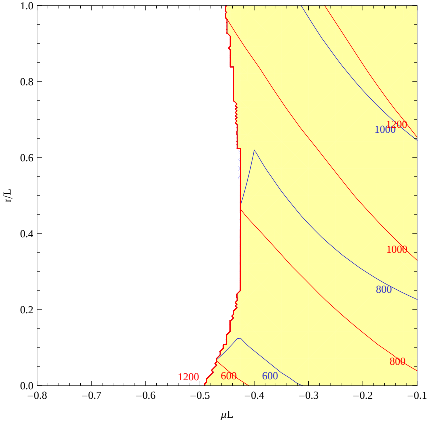


Contours of maximally allowed R^{-1} in the r/L vs. μL plane

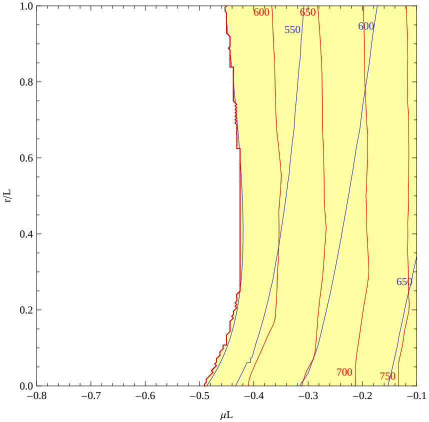


Contours of maximally allowed m_{LKP} in the r/L vs. μL plane

Combined constraints on the UED parameter space (pre-LHC)



Contours of maximally allowed R^{-1} in the r/L vs. μL plane



Contours of maximally allowed m_{LKP} in the r/L vs. μL plane

Outlook on further LHC constraints

Our W' analysis was particularly simple because

- for the signal, only one resonance ($W^{(2)}$) plays a role,
- the only relevant BSM coupling is the $Q^{(0)}Q^{(0)}W^{(2)}$ coupling.

$\Rightarrow$ This justifies to simply use model-independent bounds on $\frac{g_{200}}{g_{000}}(m_{W^{(2)}})$ provided by Atlas/CMS.

This does not hold for other channels.
Example: resonant $pp \to X \to ll$ ("Z' searches")

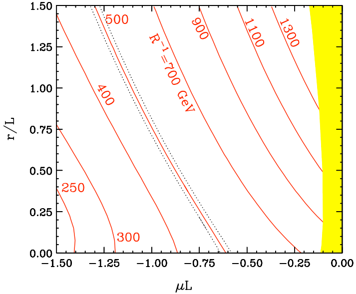
- Contributing resonances: $Z^{(2)}$, $\gamma^{(2)}$,
- relevant couplings: $q^{(0)}q^{(0)}Z^{(2)}/\gamma^{(2)}$ *and* $l^{(0)}l^{(0)}Z^{(2)}/\gamma^{(2)}$ where $q \in \{Q, U, D\}$ and $l \in \{L, E\}$,
- which are relevant for the process *and* branching ratios.

Resulting bound on the parameter space
$\Rightarrow$ need to make simplifying parameter choices and use event generators.

Example: resonance search in the di-lepton channel

- We assume universal boundary localized terms $r \equiv r_B = r_W = r_H = r_q = r_l$ and universal bulk mass terms $\mu \equiv \mu_q = \mu_l$.
- We use CalcHEP and CTEQ 5M PDF to evaluate cross sections.
- We compare results to current CMS bounds (CMS PAS EXO-12-015; 7 TeV run and 4.1 fb^{-1} at 8 TeV)

Preliminary



Red: contours of maximal R^{-1} allowed by WMAP

Yellow: Parameter region allowed by resonance search in the di-lepton channel

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.
- Combination of DM, electroweak, and $W', Z', \gamma', g', \ldots$ LHC constraints put substantial bounds on bulk masses while still allowing for large boundary kinetic terms.
- The presented results are only a first step.
  There is lots of work to do in terms of precision
  and more systematic studies of the general parameter space.