

EXTRA DIMENSION VERSUS *SUPERSYMMETRY* AT THE LHC

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1409 (2014) 076 and K. Ghosh, D. Karabacak and S. Nandi (to appear)]

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Overview

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minimal Universal Extra Dimension

In minimal UED \Rightarrow mUED, 5D space-time is $M^4 \times S_1/Z_2$

- There are **KK-excitations** of every SM particles

KK-parity conserved



- Can only be pair produced
- Gives Dark Matter

$$m_n = \frac{n}{R}$$



Radiative corrections
breaks mass
degeneracy.



Spectra depends on the
cut-off scale Λ and R^{-1}

- Λ can not be too large, otherwise gauge couplings blow off.
- Spectra of KK-particles is pretty degenerate at each level

With only level-1 KK excitations, similar to compressed SUSY

Extra Dimension vs SUSY at the LHC

However, most SUSY breaking scenarios do not give such a compressed spectra

- Pair production of SUSY particles and their decay gives high p_T jets plus missing transverse energy.
 - Classic signals of SUSY
 - Will distinguish SUSY from UED

However, LHC Higgs data do not agree with mUED at the 1σ level

Need to go beyond mUED \implies non-minimal UED \implies nmUED

Model: nmUED

$$S = S_{bulk} + S_{BLKT}$$

$$S_{bulk} = \int d^4x \int_{-L}^L dy \left[\sum_{\mathcal{A}}^{G,W,B} -\frac{1}{4} \mathcal{A}_{MN} \mathcal{A}^{MN} + \sum_{\Psi}^{Q,U,D,L,E} i \bar{\Psi} \overleftrightarrow{D}_M \Gamma^M \Psi - M_{\Psi} \bar{\Psi} \Psi \right]$$

$$S_{bdry} = \int d^4x \int_{-L}^L dy \left(\sum_{\mathcal{A}}^{G,W,B} -\frac{r_{\mathcal{A}}}{4} \mathcal{A}_{\mu\nu} \mathcal{A}^{\mu\nu} + \sum_{\Psi=Q,L} i r_{\Psi} \bar{\Psi}_L D_{\mu} \gamma^{\mu} \Psi_L \right. \\ \left. + \sum_{\Psi=U,D,E} i r_{\Psi} \bar{\Psi}_R D_{\mu} \gamma^{\mu} \Psi_R \right) \times [\delta(y-L) + \delta(y+L)].$$

Parameters:

- Coefficients of the BLKT terms
 - $r_A \implies r_g, r_W, r_B$
 - $r_{\psi} \implies r_U, r_D, r_E$
- Also involve $M_{\psi} = \mu \theta(y) \implies$ 5D fermion bulk mass.

Masses of the KK-gauge bosons and fermions are determined by solving transcendental equations

Constraints on the parameters

- $\frac{r_\Psi}{L} > \frac{\exp^{-2\mu L} - 1}{2\mu L}$ to avoid ghosts and/or tachyons in the fermion sector.
- $r_A/L > -1$ to avoid ghosts and/or tachyons in the gauge sector.
- The bounds on the parameters are also obtained from the low-energy observables. [T. Flacke, K. Kong and S. C. Park, JHEP **1305**, 111 (2013)]
 - KK-parity conserving interactions, \mathcal{L}_{002n}
 - $Z^{(2)}$ contribute to 4-fermi interactions
 - $r_A > 0.5L$ for $\mu L = -0.1$ and fixed R^{-1}
 - However, for $0 > \mu L > -0.03$ and $R^{-1} \approx 850$ GeV, g_{200} will be small and $M_{Z^{2n}}$ will be heavy enough to escape this bound
- EW precision test and the collider searches are insensitive to small values of μ , for example $\mu L = -0.02$

Phenomenology

We discuss the implications of nmUED in the context of the Higgs data and multijets plus E_T searches at the 8 TeV LHC

- Parameters of the model:
 - $r_\psi, \Psi = Q, U, D, L, E$
 - $r_A, A = G, W, B$
 - $\mu \implies$ Bulk fermion mass term
- Take universal boundary parameters for all quarks and leptons
 $\implies r_F$
- For gauge sector, we choose $r_g \neq r_W = r_B$
- Also choose $\mu L = -0.02$

Mass spectra for level-1 KK-excitations

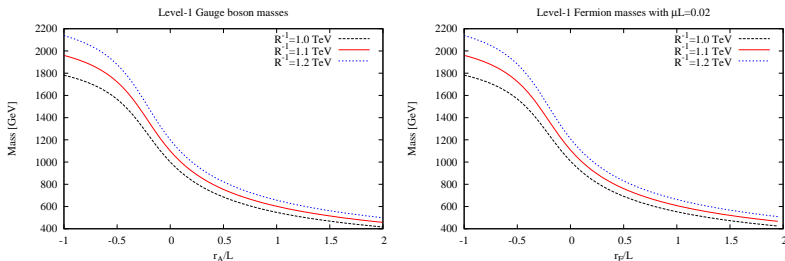


Figure : Level-1 gauge boson (left panel) and fermion (right panel) as a function of r/L for three different values of R^{-1} . For the level-1 fermion masses in the right panel, we consider $\mu = -0.02L$.

NOTE:

- Masses of KK-excitations are very sensitive to the BLKT parameters \implies Large splitting even at the tree level
- Both level-1 KK-fermions and gauge bosons masses increase if we decrease r/L .

Higgs Phenomenology

- $m_H = 125 \text{ GeV} \implies \lambda = 0.129$ in the SM
- $\lambda \rightarrow 0$ at $Q = 10^{11} \text{ GeV} \implies$ Vacuum instability
- For mUED, λ evolves much faster because of KK-excitations
 - $\lambda \rightarrow 0$ at $4\text{-}6 R^{-1}$
 - For subsequent analysis, we take $\Lambda = 5R^{-1}$
- Higgs production measured in different channels at the LHC

$$\mu_i = \frac{(\sigma \times \text{BR})_i}{(\sigma \times \text{BR})_i^{\text{SM}}}$$

- $H \rightarrow gg$: Only KK-tower of **top** contributes
- $H \rightarrow \gamma\gamma$: KK-towers of **top and W** both contribute

Combined best-fit values for μ_i

[G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, PRD **88**, 075008 (2013)]

$\gamma\gamma$ decay channel		VV decay channel	
$\hat{\mu}^{ggF}$	$\hat{\mu}^{VBF}$	$\hat{\mu}^{ggF}$	$\hat{\mu}^{VBF}$
0.98 ± 0.28	1.72 ± 0.59	0.91 ± 0.16	1.01 ± 0.49

Table : Combined best-fit Higgs signal strengths for different Higgs production and decay modes.

Results for mUED: has only 2 parameters $\Rightarrow \Lambda$ and R^{-1}

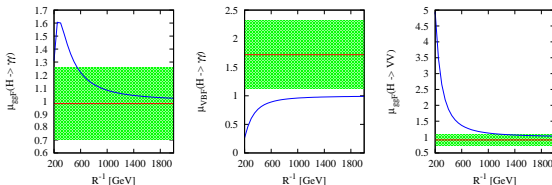


Figure : Higgs signal strengths relative to the SM expectations: $\mu_{ggF}^{H \rightarrow \gamma\gamma}$ (left panel), $\mu_{VBF}^{H \rightarrow \gamma\gamma}$ (middle panel) and $\mu_{ggF}^{H \rightarrow VV}$ (right panel), in the context of mUED scenario as a function of R^{-1} . The combined best-fit values (from Table 1) of the abovementioned Higgs signal strengths are also presented.

Can not fit data at 1σ level (see middle panel)

Results for nmUED

In addition to R^{-1} and Λ , we have several additional parameters coming from the BLK terms

- $r_\psi, \Psi = Q, U, D, L, E$
- $r_A, A = G, W, B$
- $\mu \implies$ Bulk fermion mass term
- We choose cut-off scale $\Lambda = 5R^{-1}$
- Universal r_F
- But, for gauge sector, we choose $r_g \neq r_W = r_B$
- Also choose $\mu L = -0.02$

We have scanned the parameter space (r_W, r_F) to fit the Higgs data in different channels for 2 values of R^{-1} (1.2 and 1.3 TeV)

Continued.

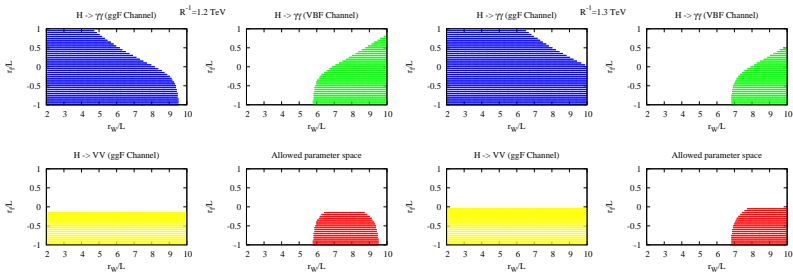


Figure : Scattered points in r_W/L - r_F/L plane which are consistent with the combined best-fit results of $\mu_{ggF}^{H \rightarrow \gamma\gamma}$, $\mu_{VBF}^{H \rightarrow \gamma\gamma}$, $\mu_{ggF}^{H \rightarrow VV}$ and all three together for $R^{-1} = 1.2$ TeV (left panel) and $R^{-1} = 1.3$ TeV (right panel).

All combined best-fit Higgs data is consistent with nmUED for large r_W and negative r_F

Collider Phenomenology at the LHC

- Multijets at high p_T plus large \cancel{E}_T signal
- Use the LHC data for SUSY search and if we can reproduce the exact limits for nmUED using the allowed parameter space
- We use 8 TeV LHC data with $L = 20.3 \text{ fb}^{-1}$
- SUSY limits: For $m_{\tilde{q}} = m_{\tilde{g}} < 1.7 \text{ TeV}$ is excluded from jets + \cancel{E}_T channel.
- Two questions:
 - Can we reproduce any SUSY signals from the level-1 KK particles using the allowed parameter space of nmUED ?
 - What limits we can put on $q^{(1)}$ and $g^{(1)}$ masses in nmUED ?

nmUED Benchmark point for multijets analysis

Benchmark Point (BP)					
R^{-1}	ΛR	μL	r_g/L	r_F/L	r_W/L
1.2 TeV	5	-0.02	-0.05	-0.42	7.4
Masses in GeV					
$m_{Q(1)}$	$m_{L(1)}$	$m_{G(1)}$	$m_{W(1)\pm}$	$m_{Z(1)}$	$m_{\gamma(1)}$
1800	1800	1265	275	275	260

- Produce $q^1 q^1$, $g^1 g^1$, $q^1 g^1$
- Decay these using the spectra for the benchmark point
- Apply the same cuts as ATLAS multijets SUSY searches

Results: ATLAS cuts

Cuts	A (2-jets)		B (3-jets)		C (4-jets)		D	E (6-jets)		
	L	M	M	T	M	T	(5-jets)	L	M	T
$\cancel{E}_T > [\text{GeV}]$	160									
$p_T^1 > [\text{GeV}]$	130									
$p_T^2 > [\text{GeV}]$	60									
$p_T^3 > [\text{GeV}]$	-		60		60		60		60	
$p_T^4 > [\text{GeV}]$	-		-		60		60		60	
$p_T^5 > [\text{GeV}]$	-		-		-		60		60	
$p_T^6 > [\text{GeV}]$	-		-		-		-		60	
$\Delta\phi(j_i, \vec{\cancel{E}}_T)_{min} >$	0.4 {i=1,2,3 if $p_T^3 > 40 \text{ GeV}$ }				0.4 {i=1,2,3}, 0.2 $p_T^{j_i} > 40 \text{ GeV}$					
$\cancel{E}_T / M_{eff}(N_j) >$	0.2	-	0.3	0.4	0.25	0.25	0.2	0.15	0.2	0.25
$m_{eff}(incl.) [\text{TeV}]$	1.0	1.6	1.8	2.2	1.2	2.2	1.6	1.0	1.2	1.5
$\sigma_{BSM} [\text{fb}]$	66.07	2.52	0.73	0.33	4.00	0.12	0.77	4.55	1.41	0.41

Table : Cuts used by the ATLAS collaboration to define the signal regions. $\Delta\phi(jet, \vec{\cancel{E}}_T)$ is the azimuthal separations between $\vec{\cancel{E}}_T$ and the reconstructed jets. $m_{eff}(N_j)$ is defined to be the scalar sum of the transverse momenta of the leading N jets together with \cancel{E}_T . However, for $m_{eff}^{incl.}$, the sum goes over all jets with $p_T > 40$ GeV. Last column corresponds to the 95% C.L. observed upper limits on the non-SM contributions σ_{BSM} .

Results: Cut-flow table.

Process	Supersymmetry $\tilde{g}\tilde{g}$ one-step	nmUED $g^{(1)}g^{(1)}$ one-step	
Point	$m_{\tilde{g}} = 1265$ GeV $m_{\tilde{\chi}_1^\pm} = 865$ GeV $m_{\tilde{\chi}_1^0} = 465$ GeV	$m_{g^{(1)}} = 1265$ GeV $m_{W^{(1)\pm}} = 865$ GeV $m_{\tilde{\gamma}^{(1)}} = 465$ GeV	
Cuts (E-tight)	Absolute efficiency in %		
	ATLAS Appendix-C of [?]	Our Simulation	Our Simulation
0-lepton	63.5	66.1	57.3
$E_T > 160$ GeV	55.6	57.6	54.7
$p_T^{j1} > 130$ GeV	55.6	57.5	54.7
$p_T^{j2} > 60$ GeV	55.6	57.5	54.6
$p_T^{j3} > 60$ GeV	55.4	57.3	51.8
$p_T^{j4} > 60$ GeV	53.4	55.2	41.3
$p_T^{j5} > 60$ GeV	46.3	47.1	27.4
$p_T^{j6} > 60$ GeV	31.7	31.1	15.0
$\Delta\phi(j_i, E_T), i = 1, 2, 3$	26.5	26.1	12.2
$\Delta\phi(j, E_T), p_T^j > 40$ GeV	21.3	21.6	9.7
$E_T/m_{\text{eff}}(N_j) > 0.25$	12.0	12.7	4.7
$m_{\text{eff}}(\text{incl.}) > 1.5$ TeV	7.9	8.3	4.5

- Our simulation agrees very well with the ATLAS simulations
- nmUED signals are pretty close to the SUSY for similar cuts

Results

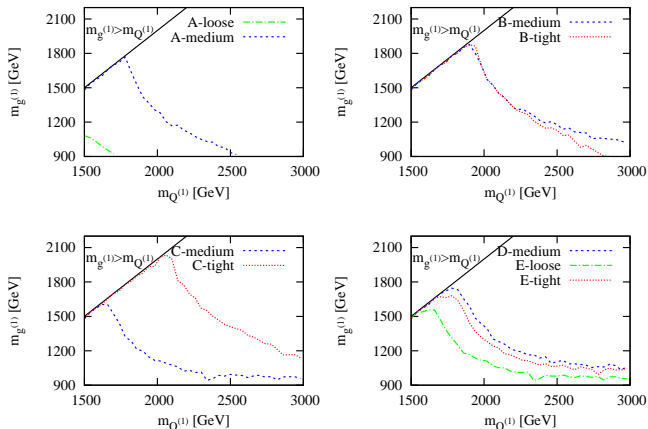


Figure : The exclusion limits on $m_{Q^{(1)}} - m_{g^{(1)}}$ plane from 8 TeV 20.3 inverse femtobarn integrated luminosity ATLAS data for different ATLAS defined signal regions. We have assumed fixed mass for the level-1 electroweak KK gauge bosons ($m_W^{(1)\pm} = m_{Z^{(1)}} = 275$ GeV and $m_{W\gamma^{(1)}} = 260$ GeV).

For $m_{q^1} = m_{g^1}$, the limit is 2.1 TeV.

Conclusion

- Though mUED signals are very different from the SUSY signals at the LHC, nmUED signals are not.
- With switable choice of BLK terms, we can reproduce any multijets + \cancel{E}_T signal given by SUSY in nmUED.
- If enhancement in $H \rightarrow \gamma\gamma$ persists in LHC Run 2, it is allowed in nmUED, but not in mUED.
- nmUED with the assumption $m_{q1} = m_{g1}$, 8 TeV LHC limit is ~ 2.1 TeV.
- Since nmUED can reproduce any SUSY signals, the production of level-2 KK excitations will be the key to distinguish between extra-dimension and supersymmetry if any signal is seen.