EXTRA DIMENSION VERSUS *SUPERSYMMETRY* AT THE LHC

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[Work done in collaboration with Kirtiman Ghosh and Durmus Karabacak **JHEP 1409 (2014) 076** and K. Ghosh, D. Karabacak and S. Nandi (to appear)]

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Overview

minimal Universal Extra Dimension

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

- There are KK-excitations of every SM particles

KK-parity conserved $\Longrightarrow$

- Can only be pair produced
- Gives Dark Matter

$m_n = \frac{n}{R}$ $\Longrightarrow$ Radiative corrections breaks mass degeneracy. $\Longrightarrow$ 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 $\Longrightarrow$ non-minimal UED $\Longrightarrow$ nmUED

Model: nmUED

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

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

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

Parameters:

- Coefficients of the BLKT terms
  - $r_A \Longrightarrow r_g,\ r_W,\ r_B$
  - $r_\psi \Longrightarrow r_U,\ r_D,\ r_E$
- Also involve $M_\psi = \mu\theta(y) \Longrightarrow$ 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 $\not{E}_T$ searches at the 8 TeV LHC

- Parameters of the model:
  - $r_\psi, \Psi = Q, U, D, L, E$
  - $r_A, A = G, W, B$
  - $\mu \Longrightarrow$ Bulk fermion mass term
- Take universal boundary parameters for all quarks and leptons $\Longrightarrow r_F$
- 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

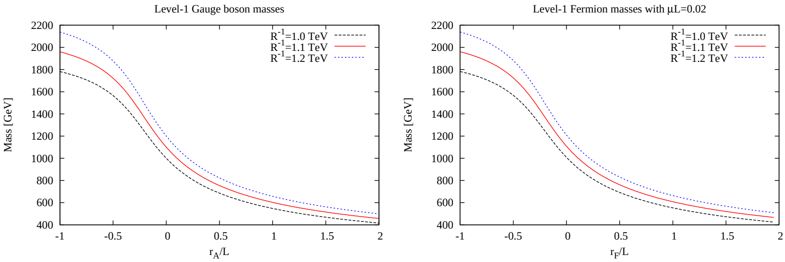

Figure : Level-1 gauge boson (left panel) and fermion (right panel) as a function of r/L for three different values of R^{-1}. For the level-1 fermion masses in the right panel, we consider $\mu = -0.02L$.

NOTE:

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

Higgs Phenomenology

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

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

- $H \to gg$: Only KK-tower of top contributes
- $H \to \gamma\gamma$: 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	
$\hat{\mu}^{ggF}$	$\hat{\mu}^{\mathrm{VBF}}$	$\hat{\mu}^{ggF}$	$\hat{\mu}^{\mathrm{VBF}}$
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 $\Longrightarrow$ Λ and R^{-1}

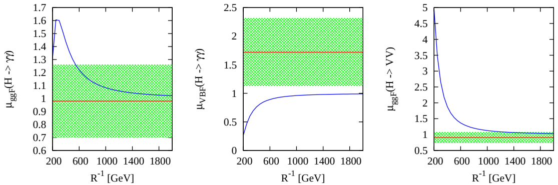

Figure : Higgs signal strengths relative to the SM expectations: $\mu_{ggF}^{H\to\gamma\gamma}$ (left panel), $\mu_{VBF}^{H\to\gamma\gamma}$ (middle panel) and $\mu_{ggF}^{H\to VV}$ (right panel), in the context of mUED scenario as a function of R^{-1}. The combined best-fit values (from Table 1) of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

- $r_\psi,\ \Psi\ =\ Q,\ U,\ D,\ L,\ E$
- $r_A,\ A\ =\ G,\ W,\ B$
- $\mu \Longrightarrow$ 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.

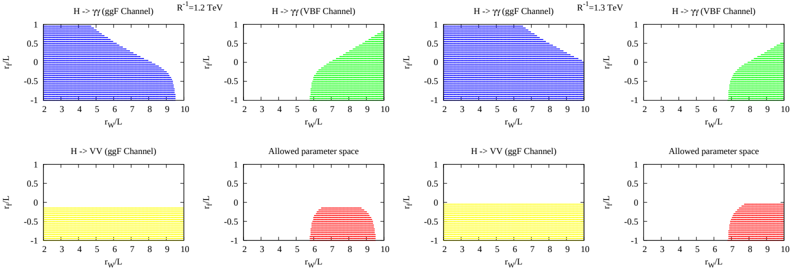

Figure : Scattered points in r_W/L-r_F/L plane which are consistent with the combined best-fit results of $\mu_{ggF}^{H\to\gamma\gamma}$, $\mu_{VBF}^{H\to\gamma\gamma}$, $\mu_{ggF}^{H\to VV}$ and all three together for $R^{-1} = 1.2$ TeV (left panel) and $R^{-1} = 1.3$ TeV (right panel).

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 $\not{E}_T$ 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 $L = 20.3\ \mathrm{fb}^{-1}$
- SUSY limits: For $m_{\tilde{q}} = m_{\tilde{g}} < 1.7$ TeV is excluded from jets + $\not{E}_T$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^1q^1, g^1g^1, q^1g^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) L	A (2-jets) M	B (3-jets) M	B (3-jets) T	C (4-jets) M	C (4-jets) T	D (5-jets)	E (6-jets) L	E (6-jets) M	E (6-jets) T
$\not{E}_T >$ [GeV]	160									
$p_T^{j1} >$ [GeV]	130									
$p_T^{j2} >$ [GeV]	60									
$p_T^{j3} >$ [GeV]	-		60		60		60	60		
$p_T^{j4} >$ [GeV]	-		-		60		60	60		
$p_T^{j5} >$ [GeV]	-		-		-		60	60		
$p_T^{j6} >$ [GeV]	-		-		-		-	60		
$\Delta\phi(j_i, \vec{\not{E}}_T)_{min} >$	0.4 {i=1,2,3 if $p_T^{j3} >$ 40 GeV}				0.4 {i=1,2,3}, 0.2 $p_T^{j_i} >$ 40 GeV					
$\not{E}_T/M_{eff}(N_j) >$	0.2	-	0.3	0.4	0.25	0.25	0.2	0.15	0.2	0.25
$m_{eff}(incl.)$ [TeV]	1.0	1.6	1.8	2.2	1.2	2.2	1.6	1.0	1.2	1.5
σ_{BSM} [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. $\Delta\phi(jet, \vec{\not{E}}_T)$ is the azimuthal separations between $\vec{\not{E}}_T$ 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 $\not{E}_T$. 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 $m_{\tilde{W}^{(1)\pm}} = 865$ 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
$\not{E}_T > 160$ 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
$\Delta\phi(j_i, \not{E}_T), i = 1,2,3$	26.5	26.1	12.2
$\Delta\phi(j, \not{E}_T), p_T^j > 40$ GeV	21.3	21.6	9.7
$\not{E}_T/m_{eff}(N_j) > 0.25$	12.0	12.7	4.7
$m_{eff}(incl.) > 1.5$ 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

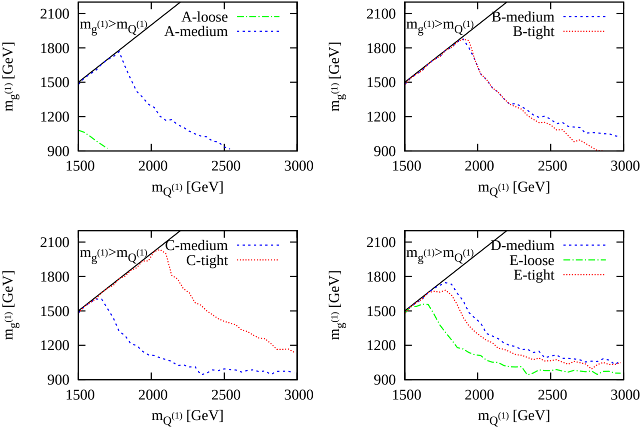

Figure : The exclusion limits on m_{Q^1}-m_{g^1} plane from 8 TeV 20.3 inverse femtobarn integrated luminosity ATLAS data for different ATLAS defined signal regions. We have assumed fixed mass for the level-1 electroweak KK gauge bosons ($m_W^{(1)\pm} = m_{Z^{(1)}} = 275$ GeV and $m_{W^{\gamma}}{}^{(1)} = 260$ 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 + $\not{E}_T$signal given by SUSY in nmUED.
- If enhancement in $H \to \gamma\gamma$ persists in LHC Run 2, it is allowed in nmUED, but not in mUED.
- nmUED with the assumption $m_{q^1} = m_{g^1}$, 8 TeV LHC limit is $\sim$ 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.