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Enriching the exploration of the mUED model with event shape variables at the CERN LHC

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ABSTRACT

We propose a new search strategy based on the event shape variables for new physics models where the separations among the masses of the particles in the spectrum are small. Collider signature of these models, characterized by low p_T leptons/jets and low missing p_T, are known to be difficult to look for. The conventional search strategies involving hard cuts may not work in such situations. As a case study, we have investigated the hitherto neglected jets + missing E_T signature – known to be a challenging one – arising from the pair productions and decay of $n = 1$ KK-excitations of gluons and quarks in the minimal Universal Extra Dimension (mUED) model. Judicious use of the event shape variables enables us to reduce the Standard Model backgrounds to a negligible level. We have shown that in mUED, R^{-1} up to 850 GeV can be explored or ruled out with 12 fb^{-1} of integrated luminosity at the 7 TeV run of the LHC. We also discuss the prospects of employing these variables for searching other beyond Standard Model physics with compressed or partially compressed spectra.

1. Introduction

One of the main goals of the ongoing LHC experiment at CERN is to find out any new dynamics that could be operative at the energy scale of teraelectron volts (TeV) among the elementary particles. Apart from the search of Higgs boson, both the ATLAS and the CMS experiments are engaged in looking for the signals of scenarios beyond the Standard Model. Among these, models defined in one or more space-like extra dimensions need special attention. These models can be divided broadly into two classes. In models proposed in [1] and [2], all the Standard Model (SM) fields are confined in a $(1+3)$-dimensional sub-space of a larger space–time manifold, while the gravitational interaction can perceive the full space–time manifold. After compactification of the extra space-like dimensions, the effective four-dimensional theory consists of towers of gravitons interacting with SM fields. However, we are interested in a class of models wherein some or all of the SM fields can access the extended space–time manifold [3,4]. Such extra-dimensional scenarios could lead to a new mechanism of supersymmetry breaking [5], relax the upper limit of the lightest supersymmetric neutral Higgs [6], address the issue of fermion mass hierarchy [7], provide a cosmologically viable dark matter candidate [8], interpret the Higgs as a quark composite leading to a successful EWSB without the necessity of a fundamental scalar or Yukawa interactions [9], and lower the unification scale down to a few TeV [10,11]. Our concern here is a particularly interesting framework, called the minimal Universal Extra Dimension (mUED) scenario, characterized by a single flat extra dimension, compactified on an S^1/Z_2 orbifold (with radius of compactification, R) [3]. This extra space-like dimension is accessed by all the SM particles. From a four-dimensional viewpoint, every field in the SM will then have an infinite tower of Kaluza–Klein (KK) modes, each mode being identified by an integer, n, called the KK-number. The zero modes ($n = 0$) are identified as the corresponding SM states. The orbifolding is essential to ensure that fermion zero modes have a chiral representation. But it has other consequences too. *First*, the physical region along the extra direction y is now smaller $[0, \pi R]$ than the periodicity $[0, 2\pi R]$, so the KK-number (n) is no longer conserved. What remains actually conserved is the even-ness and odd-ness of the KK states, ensured through the conservation of KK-parity, defined by $(-1)^n$. *Secondly*, Lorentz invariance is also lost due to compactification, and as a result the KK masses receive bulk and orbifold-induced radiative corrections [4,12]. The bulk corrections are finite and nonzero only for bosons. The orbifold corrections, which vary logarithmically with the cutoff (Λ), depend on group theoretic invariants, as well as Yukawa and quartic scalar couplings of the gauge and matter KK fields and hence are flavor-dependent. This induces a mass

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splitting among the different flavors of the same KK level, further to what has already been caused by the different zero-mode masses. The model thus can be described by *two dimensionful parameters*, namely the inverse of compactification radius, R^{-1} and the cutoff scale, Λ. We will not present the expressions for the radiatively corrected masses of the different KK-modes of the SM particles. However, these can be easily obtained from [13]. Independent of the values of the input parameters, the lightest among the $n = 1$ KK states turns out to be γ^1, the $n = 1$ KK-excitation of photon. Typically, if $R^{-1} = 500$ GeV, mass of γ^1 is slightly above 500 GeV, just above lie the KK leptons (L^1, ν^1) and weak bosons ($W^{\pm 1}$, Z^1) in the region of 500–550 GeV, further up are the KK quarks ($Q^1_{L,R}$) near 600 GeV, and at the peak the KK gluon, G^1, (the heaviest) hovers around 650 GeV.

Conservation of the KK-parity ensures the lightest KK particle (LKP) is stable (hence being a natural candidate for the dark matter [8]) and that the level-one KK-modes would be produced only in pairs. This also ensures that the KK-modes do not affect electroweak processes at the tree level. And while they do contribute to higher order electroweak processes, in a loop they appear only in pairs resulting in a substantial suppression of such contributions, thereby allowing for relatively smaller KK-spacings. In spite of the infinite multiplicity of the KK states, the KK-parity ensures that all electroweak observables are finite (up to one-loop) [14],[1] and a comparison of the observable predictions with experimental data yields bounds on the compactification radius R. Constraints on the UED scenario from the measurement of the anomalous magnetic moment of the muon [15], flavor changing neutral currents [16], $Z \to b\bar{b}$ decay [17], the ρ parameter [3,18], several other electroweak precision tests [19], yield $R^{-1} \gtrsim 300$ GeV.

The fact that such a small value for R^{-1} (equivalently, small KK-spacings) is still allowed, renders collider search prospects very interesting both in the context of hadronic [13,20–23] and leptonic [24,25] colliders.

At the very outset it was realized that the signatures of the mUED model at hadron colliders has an inherent problem [4]. The signature with the largest cross-section at hadron colliders is the jets + missing transverse momenta ($\not{E}_T$) which is similar to the traditional squark–gluino signal in supersymmetric (SUSY) models. There is, however, an important difference.

It has been already mentioned above that the spectrum of mUED is very much compressed. As a result, the transverse momenta/energy spectra of all the visible particles – the missing transverse momenta spectrum included – are soft. Consequently the conventional search strategies to dig out the signals of mUED from the SM backgrounds using strong cuts on visible/missing p_T are not very efficient. Such cuts on the other hand are the most potent tools in the arsenal of the SUSY hunter.

Subsequently the viability of jets + $\not{E}_T$ channel has never been explored in the framework of mUED, because of the general belief that the signal of mUED in this channel will be overwhelmed by the QCD background. All the earlier analyses in the context of mUED, in fact, are either based on search of $n = 2$ KK-excitations [21,25] of SM particles or on the $n = 1$ KK-excitations giving rise to multi-leptons in association with jets and $\not{E}_T$ [13,22,23]. The bulk of the collider events stemming from such model remains unexplored till date.

In this work we focus on this hitherto neglected channel. Moreover our analysis will be restricted to the search prospects at the ongoing experiments at 7 TeV. It would be important to mention here, that both the ATLAS and the CMS Collaborations have looked for the above jets + $\not{E}_T$ signature [26,27] using the accumulated data of 1.04 fb^{-1} from the current LHC run at 7 TeV. In principle, these analyses could be used to constrain the mUED parameters. However, the CMS/ATLAS analyses are aimed for SUSY models motivated by the minimal gravity mediated SUSY breaking (mSUGRA), where + the masses of the sparticles are well separated over most of the parameter space. As a result high p_T jets/leptons and a hard $\not{E}_T$ spectrum is expected in the signal. Thus the search strategies of the LHC Collaborations involve hard cuts on p_T and $\not{E}_T$ to suppress the huge SM backgrounds (including QCD). For example, only those events are retained which have $\not{E}_T$ greater than 100 GeV. Moreover, the leading jet is required to have p_T greater than 100 GeV.

We shall show the distributions of $\not{E}_T$ and the p_T of the leading jet for a representative mUED model in a later section. They will indicate unambiguously that the signatures of this model cannot survive the hard cuts usually employed by the LHC Collaborations. Thus it is quite possible that the signatures of the mUED model remain buried in current LHC data.

It should emphasized that this is a generic problem (not specific to mUED only) which confronts the search strategy for any model having a compressed mass spectrum. For example, in an unconstrained Minimal Supersymmetric Standard Model (MSSM) it is quite possible that the entire sparticle spectrum is quite compressed. Based on various theoretical motivations, models with partially compressed mass spectra have also been proposed [28,29]. It would be interesting to device an alternative search strategy for such scenarios.

In this Letter we will show that judicious use of the event shape variables (defined below) would be very efficient in reducing huge SM background from QCD, $t\bar{t}$ and W/Z + jets events confronting the jets + $\not{E}_T$ signal. Using this new strategy, we could also push up the sensitivity of the current LHC experiments to the parameters of the mUED model compared to an earlier analysis using the kinematic variable M_{T2} [30].

Before delving into the analysis let us briefly discuss the processes and the relevant decay cascades that contribute to the signal. We will confine to the production of $n = 1$ KK-level excitations only. These particles can only be produced in pairs by the virtue of KK-parity conservation. In LHC, the colliding partons being the gluons or quarks, pair production of $Q^1_{L,R} Q^1_{L,R}$, $G^1 G^1$, $G^1 Q^1_{L,R}$ would be highly enhanced and these processes contribute to our signal significantly. Once produced, G^1 will decay to a $Q^1_{L,R}$ along with a SM quark ($Q^0_{L,R}$) with equal probabilities. Q^1_R only can decay to Q^0_R and the LKP (γ^1). On the other hand, Q^1_L decays to $W^{\pm 1}$ or Z^1 (with Brs. $\frac{2}{3}$ and $\frac{1}{3}$ respectively) with a SM quark.

It may be recalled that Z^1 or $W^{\pm 1}$ does not decay hadronically. Z^1 decays either into $\nu\bar{\nu}\gamma^1$ (with Br. of 0.5) or into $l_L \bar{l}_L \gamma^1$ (with Br. of 0.16 for each lepton flavor). On the other hand, W^1 decays into $l\nu\gamma^1$ (with Brs. of 0.33 for each lepton flavor). It must be emphasized here, that decay patterns and branching fractions of $n = 1$ KK-mode fields are independent of the mUED model parameters.

Following the above discussions one can see that the $G^1 G^1$ production is the source of 4 jets, while $G^1 Q^1$ ($Q^1 Q^1$) production leads to 3 (2) jets at the parton level. In addition, τ (coming from W^1/Z^1) decay in hadronic channels will also contribute to our signal enhancing the number of jets at the parton level itself. Consequently, the pair production of $n = 1$ KK-gluons and quarks, would most of the time end up in producing jets + $\not{E}_T$ final state. Demanding leptons in the final state would necessarily mean that production of $Q^{(1)}_L$s are only being considered and we are throwing away the dominant part of the cross-section involving productions of $Q^{(1)}_R$s.

All the previous analyses of mUED signal at the LHC were done with multi-lepton final state, which necessarily has a smaller

[1] The observables start showing cutoff sensitivity of various degrees as one goes beyond one-loop or considers more than one extra dimension.

Table 1
Cross-sections, number of generated events and effect of cuts (C1–C5) for the signal and relevant background processes. Second column shows the cross-sections of respective processes in pb. Column, marked with N_{EV}, shows total the number of events generated for our analysis, subjected to the selection criteria defined in the text. Successive columns (marked with C1–C5) show the remaining number of events after the application of the corresponding cut, for signal and background processes. Here, P7, in the first row, corresponds to mUED parameters $R^{-1} =$ 700 GeV and $\Lambda R = 10$. In the table '$*$' indicates the background rate is negligible.

	σ (pb)	N_{EV}	C1	C2	C3	C4	C5
P7	1.9	0.1M	59778	53814	2169	153	130
QCD1	8.6×10^7	50M	49885275	336450	207	0	0
QCD2	1775.0	8M	7984488	2161548	88093	0	0
$t\bar{t}$	56.8	1M	621233	183320	29288	17	$*$
$W+1j$	13390	5M	4088569	217476	1241	0	0
$W+2j$	3073	3M	2448188	252165	5726	0	0
$Z+1j$	4235	4M	3674020	275566	1036	0	0
$Z+2j$	970	1M	918306	128750	2387	0	0

(effective) signal cross-section. Of course, there is one advantage using the leptonic final states. The SM background rate for the multi-lepton final state is also moderate and easy to tame with more conventional kinematic cuts used in new particle searches. However, as already mentioned all kinds of signals arising from the particular new physics model must be looked for. Throwing away a class of signatures which has the largest cross-section, makes the search incomplete.

In this work we have taken a strategy which removes this incompleteness and utilizes the large cross-section of jets + $\not{E}_T$ final state. The SM background in this channel (arising from QCD production of jets, $t\bar{t}$ production, W/Z + jets production) is undoubtedly challenging and orders of magnitude are larger than the signal. Kinematic cuts, like lower cuts on the p_T of particles in the final state or $\not{E}_T$, which are generally used for new particle searches, are not very effective in reducing the backgrounds. At this juncture the event shape variables, namely, α_T and R_T, play a crucial role in taming these huge backgrounds without affecting the signal too much.

In the next section we will in detail describe our analysis with emphasis on the event shape variables. However, before delving into the details, few features on the parameters of the mUED model need our attention. Existing collider and other low energy experimental data allow values of R^{-1} to be higher than 300 GeV. On the other hand, the analysis of relic density of LKP dark matter sets an upper limit of 700 GeV according to [31]. However, we will not be restricted by this upper limit in the following analysis and will try to see how much one can push up the search limit with the 7 TeV run of LHC.

2. Analysis and results

At the LHC, total production cross-sections of G^1G^1, G^1Q^1, Q^1Q^1 pairs are 0.03 pb, 0.66 pb and 1.21 pb respectively at the leading order (LO) for $R^{-1} = 700$ GeV with $\Lambda R = 40$. In the absence of any next-to-leading order (NLO) QCD corrections to the pair production cross-sections of strongly interacting $n = 1$ KK-excitations in mUED, we have used only the LO signal cross-sections in our analysis. It is also worth noting that the NLO corrections to the lowest order QCD di-jet cross-section is also not known. If the K-factor arising from the NLO corrections to the signal cross-section is approximately the same as that for the overall background, $S/\sqrt{B}$ will increase by $\sqrt{K}$. Since K is expected to be $\geqslant 1$, the NLO cross-section is likely to give a better significance. On the other hand using a typical value of $K = 1.5$ for the signal, we find that even if the over all K-factor of the background is 3, the significance computed from the LO cross-section will reduce by 0.9. Thus the estimates based on the LO cross-sections are likely to be fairly conservative.

Signal cross-sections are estimated with the Pythia-6.4.20 [32] using the LO CTEQ6L parton distribution functions (PDF) [33], setting both the scales of PDF and the α_s at $\sqrt{\hat{s}}$ where $\hat{s}$ is the partonic CM energy. The dominant SM backgrounds that can give rise to jets + $\not{E}_T$ energy signature are $t\bar{t}$ + jets, W/Z + jets, QCD production of jets. The sub-dominant contributions come from WW + jets, WZ + jets and ZZ + jets productions. $t\bar{t}$ production and QCD production of jets have been estimated using Pythia, while cross-sections for the W/Z productions have been calculated using ALPGEN [34] in conjunction with Pythia.[2] The cross-sections for QCD events have been computed by Pythia in two bins: (a) 25 GeV $< \sqrt{\hat{s}} <$ 400 GeV (denoted by QCD1 in Table 1) and (b) 400 GeV $< \sqrt{\hat{s}} <$ 1000 GeV (denoted by QCD2 in Table 1). The contributions from other bins being negligible will not be shown any further. In our simulation using Pythia we have taken into account the effects of initial and final state radiation as well as fragmentation and hadronization. A simple toy calorimeter simulation has been implemented with the following criteria:

- The calorimeter coverage is $|\eta| < 4.5$ with segmentation of $\Delta\eta \times \Delta\phi = 0.09 \times 0.09$ which resembles a generic LHC detector.
- A cone algorithm with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$ has been used for jet finding.
- Jets are ordered in E_T with $E_{T,\min}^{\text{jet}} = 20$ GeV.

Here, η and ϕ are the pseudo-rapidity and azimuthal angle of the respective visible objects. To take into account, the finite detector resolution we have smeared the jets E_T using a Gaussian smearing with standard deviation: $\delta E_T = 1.2\sqrt{E_T}$. However, we emphasize the need of a full detector simulation in this analysis.

The total background cross-section overwhelms the signal by several orders of magnitude. So one needs to choose some judicious set of cuts to enhance the signal to background ratio. Dominant, SM backgrounds do not have real source of missing energy (i.e. neutrinos). Apparent p_T imbalance arises from the finite detector resolution and mis-measurement of jet energies in the detector. Thus one may think that using a rather hard cut on $\not{E}_T$ could tame the SM backgrounds for the jets + $\not{E}_T$ signature. However, due to highly compressed mUED mass spectrum, jets (in general any visible SM particle) coming from the decay of KK-quarks and gluons in case of the signal are quite soft, producing a rather soft visible p_T spectrum, which in turn gives rise to a soft $\not{E}_T$ spectrum. To demonstrate this, we have plotted the p_T distributions of two leading jets and the $\not{E}_T$ in Fig. 1 for signal (with $R^{-1} = 700$ GeV and $\Lambda R = 10$) and dominant SM backgrounds. One can see from the figures that for both the signal and the SM pro-

[2] The cross-sections for $W/Z+n$-jets, $WW/ZZ/WZ+n$-jets ($n = 1, 2$) have been calculated using ALPGEN subjected to the initial selection cuts of $p_T > 20$ GeV, $|\eta| \leqslant 4.5$ and the jet–jet separation, $\Delta R(j, j) > 0.5$. These cross-sections then were fed into Pythia for parton showering and to include the ISR/FSR effects.

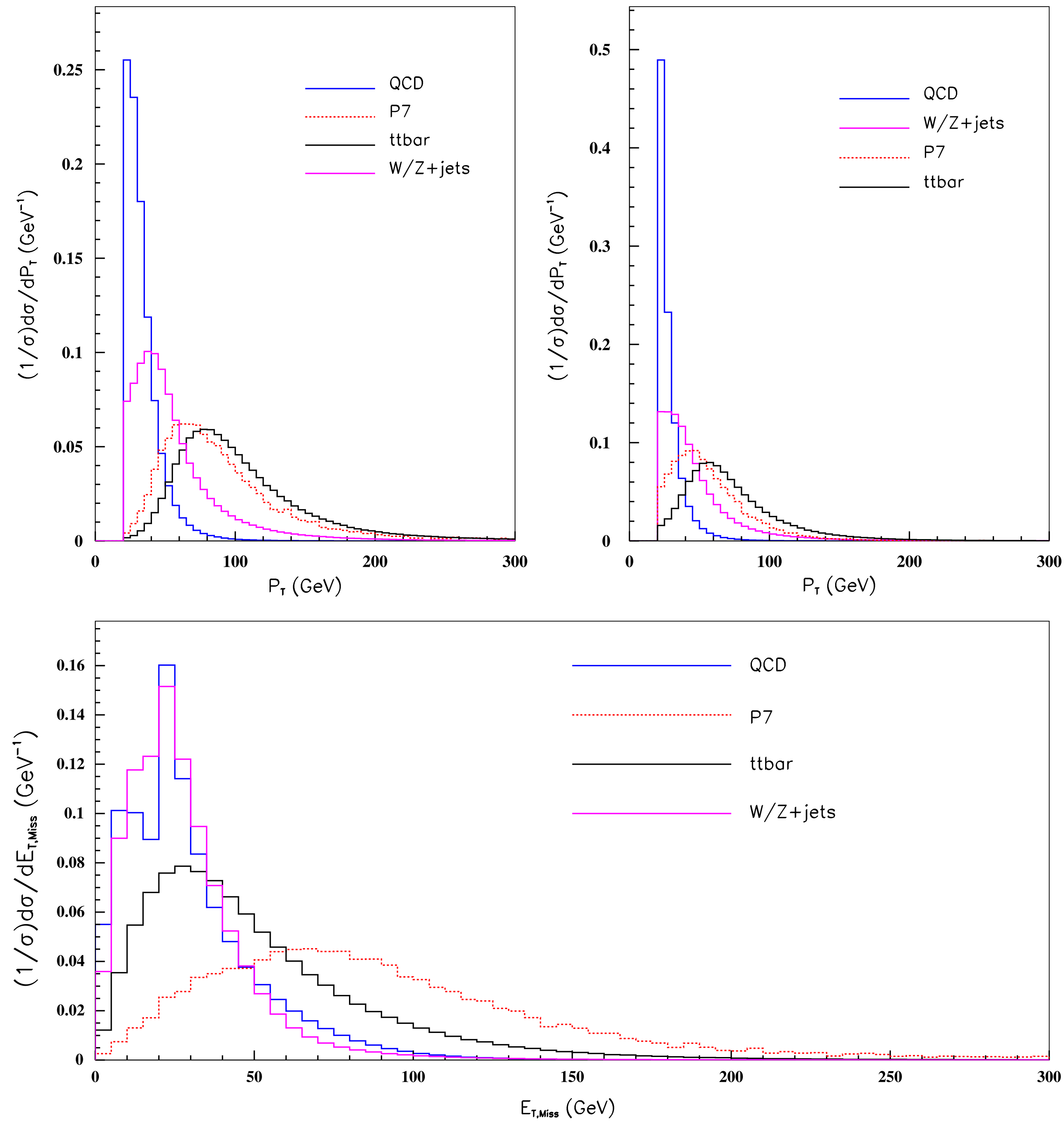

Fig. 1. Normalized p_T distributions of two highest p_T jets (upper panels) and normalized missing E_T distributions of signal and SM backgrounds (lower panel). In the figures, P7 denotes signal with $R^{-1} = 700$ GeV and $\Lambda R = 10$.

cesses, above distributions peak around rather low values of the respective kinematic variables. Consequently, one cannot require events with high p_T (typically $p_T^j > 100$) [26,27]. Rejection of hard leptons in the final state would further restrict our control in reducing the SM background.

In such a situation (events with low missing energy and no lepton), *event shape variables*, namely R_T [35] and α_T [36], are known to be very useful. The CMS Collaboration has used the variable α_T for controlling the background while looking for the signature of SUSY from the jets $+ \not{E}_T$ data at the 7 TeV run of LHC. It has also been shown recently in [35], that the SM backgrounds to SUSY signals can be brought down to a negligible size by using R_T at the LHC.

The *event shape* variable, R_T, is defined by:

$$R_T = \frac{\Sigma_1^{n_j^{\min}} p_T^{j_i}}{H_T}$$

where H_T is defined to be the scalar sum of p_T of all jets. Here, $n_j^{\min}$ denotes the required minimum number of jets satisfying the criteria: $p_T > 40$ GeV and $|\eta_j| \leqslant 3$.

In fact, R_T gives us a control over the number and hardness of the reconstructed jets simultaneously. In our case, signal events are mainly comprised of 2/3/4 partonic jets, which justifies our choice of ($n_j^{\min} =$) 3 leading jets in defining (the numerator of) R_T.

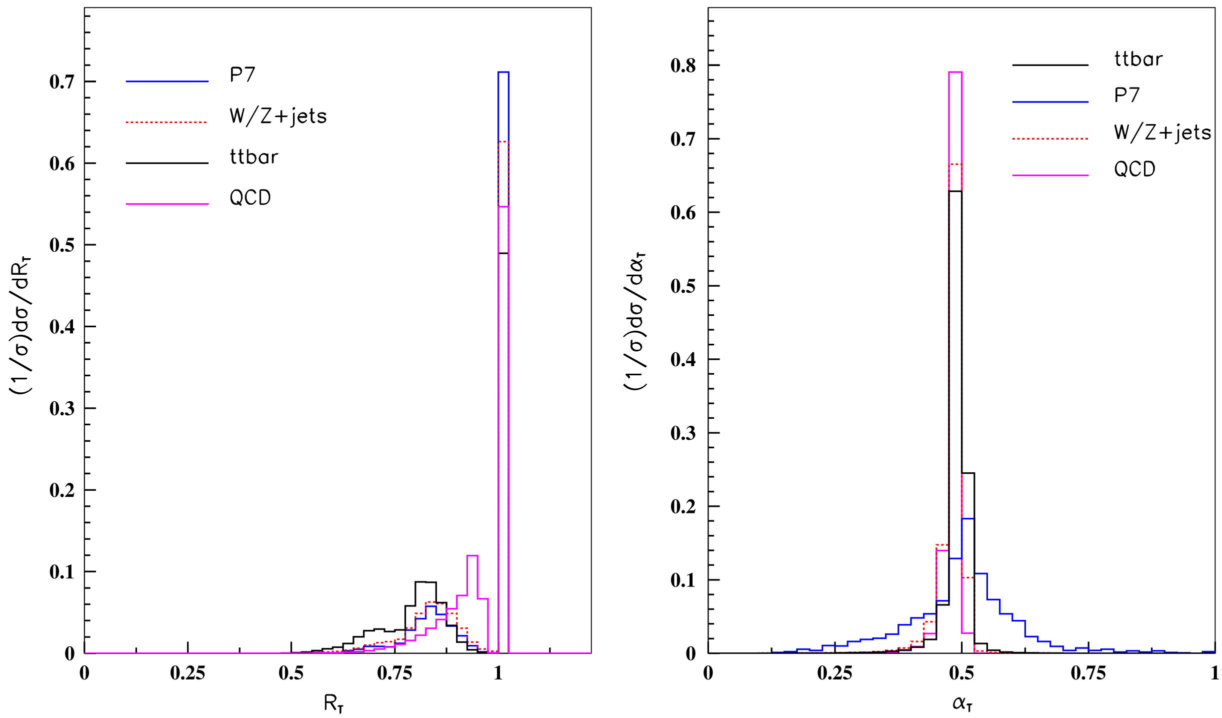

Fig. 2. Normalized R_T (left panel) and α_T (right panel) distributions of signal and SM backgrounds. In the figures, P7 denotes signal with $R^{-1} = 700$ GeV and $\Lambda R = 10$.

The variable α_T is defined as the ratio of the p_T of the second hardest jet to the invariant mass of the two highest p_T jets [36] and is well known to be very potent in reducing the QCD di-jet events in particular.

To demonstrate the usefulness of R_T and α_T, we will plot the distributions of these variables for signal and backgrounds in Fig. 2. It is evident from R_T and α_T distributions in Fig. 2, that a judicious choice of these variables can isolate the signal events from the backgrounds.

We have implemented following cuts in succession to enhance the signal to background ratio.

- **C1**: No isolated lepton (e, μ) with $p_T > 10$ GeV and $|\eta| < 2.5$ are required. Isolated leptons are identified with the criterion $\Delta R(l, j) > 0.5$, where $\Delta R(l, j)$ denotes the separation between a lepton (l) and a jet (j) in the η–ϕ plane.
- **C2**: Events with $\not{E}_T > 50$ GeV are selected.
- **C3**: Events with $R_T \leqslant 0.8$ only are selected.
- **C4**: Events with $H_T > 400$ GeV and $\alpha_T > 0.60$ (discussed earlier) are selected.
- **C5**: b-jet identification has been performed in our analysis according to the following procedure. A reconstructed jet with $|\eta| < 2.5$ corresponding to the coverage of tracking detectors matching with a B-hadron of decay length > 0.9 mm has been marked *tagged*. This criterion ensures that single b-jet tagging efficiency (i.e., the ratio of tagged b-jets and the number of taggable b-jets) $\epsilon_b \approx 0.5$ in $t\bar{t}$ events. Finally in our signal we have required *the signal to be free from tagged b-jet events*.

We note in passing that a trigger $H_T > 250$ GeV like the one employed by the CMS Collaboration in their α_T analysis [37] of jets + $\not{E}_T$ signal can be quite efficient for our signal. However, it should be stressed that for a model where the particle spectrum is not compressed α_T is one of the many variables which can distinguish the signal and the background. In fact both the CMS and the ATLAS Collaborations have analyzed LHC data without using the event shape variables and, in the context of mSUGRA for example, have obtained stronger constraints. In contrast for models with compressed spectra the options are rather limited and α_T and/or other event shape variables may be invaluable for establishing the signal.

Let us discuss the effects of the above cuts on the signal and background. More than 90% (70%) of QCD1 (QCD2) jets + $\not{E}_T$ events are removed by C2. Remaining events are taken care by application of C3 and C4. There is no real source of missing energy in QCD processes. The missing energy in these events arises mainly from the jet energy mis-measurements. As a result a cut of 50 GeV could kill a substantial part of this background. C3 and C4 play the pivotal role to reduce the $t\bar{t}$, W/Z + jets events to a negligible level. In addition the veto against tagged b-jets further reduce the $t\bar{t}$ events. We have summarized the effects of the cuts in Table 1.

We present the main results of our analysis in Table 2. The number of events after all cuts for 1 fb^{-1} luminosity, is presented in Table 2, for R^{-1} values starting from 400 GeV up to 850 GeV in steps of 50 GeV (we denote these parameter points by P1, P2, ..., P10) with two values of $\Lambda R = 10$ and 40.

As the SM background events have been reduced to negligible levels, 10 signal events could be a potentially good number for the discovery. It is evident from the table that, with an accumulated luminosity of 12 fb^{-1} (could be easily attainable by the end of 7 TeV run of the LHC), mUED model can easily be probed via the jets + $\not{E}_T$ channel up to R^{-1} of 850 GeV. However, even at 5 fb^{-1} integrated luminosity such signal can be probed up to $R^{-1} = 700$ GeV.

At this point it is worthwhile to compare our results with two other similar analyses [23,30], involving signals containing one or more leptons, on exploring mUED at the LHC running at 7 TeV. Analysis presented in [23] has used the conventional weapons of visible p_T and $\not{E}_T$ distributions to fight with the SM backgrounds. However, authors in Ref. [23] used the multi-lepton (2- and 3-leptons) final states in association with jets (using 2 fb^{-1} data at 7 TeV run of LHC), to look for the mUED signal. Assuming 5 events

Table 2
Cross-sections for different representative parameter points in mUED model. Here R^{-1} is in GeV. σ_{10} and σ_{40} denote the total cross-sections (in pb) from G^1G^1, G^1Q^1 and Q^1Q^1 production for $\Lambda R = 10$ and $\Lambda R = 40$ respectively. $(\sigma \times \epsilon)_{10,40}$ in 3rd and 4th rows denote jets + $\not{E}_T$ cross-sections (in fb) subjected to the cuts C1–C5, from mUED model (for different values of R^{-1}) for $\Lambda R = 10$ and $\Lambda R = 40$ respectively.

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
R^{-1}	400	450	500	550	600	650	700	750	800	850
σ_{10}	116.2	55.4	28.6	15.3	8.4	4.8	2.8	1.64	1.01	0.59
σ_{40}	83.5	40.3	20.3	10.7	5.8	3.2	1.9	1.08	0.64	0.38
$(\sigma \times \epsilon)_{10}$	17.4	12.6	10.30	4.60	3.95	3.02	2.52	1.32	1.01	0.72
$(\sigma \times \epsilon)_{40}$	23.4	17.3	14.82	8.35	5.28	3.71	2.68	2.16	1.03	0.69

to be the benchmark for discovery for a background free signal, the R^{-1} reach in this Letter, is in the ballpark of 700 GeV, with 2 fb^{-1} of data. According to Ref. [23], the best reach is obtained in the tri-lepton (+ jets) channel. This is somehow expected, as the SM background rate in this channel is practically vanishing. Mass reach obtained in Ref. [23] is also very similar to what has been obtained in our analysis. In another recent work [30], authors have used a somewhat new strategy to explore the mUED parameter space again at 7 TeV run of LHC. Here kinematic variable M_{T2} has been used to dig out the 1 *lepton + jets* signal arising from mUED, from the SM background. However, projected mass reach with 2 fb^{-1} luminosity ($R^{-1} = 550$ GeV with $\Lambda R = 10$ and $R^{-1} = 600$ GeV with $\Lambda R = 40$) in our analysis is certainly better than that ($R^{-1} = 400$ GeV with $\Lambda R = 10$ and $R^{-1} = 500$ GeV with $\Lambda R = 40$) presented in Ref. [30].

Here it would be prudent to compare our analysis with some recent studies on collider search on so-called simplified SUSY models at the LHC [38]. Unlike our case, the mass separation among the particles in the SUSY simplified models are usually large and the authors in Ref. [38] can employ slightly harder cuts on m_{eff}, $\not{E}_T$ and H_T. Our analysis based on the event shape variables, appropriate for more compressed spectra, is complementary to theirs. However it would be interesting to investigate whether the event shape-based analysis can be fruitfully exploited also in the search for the simplified models.

Before we conclude, let us make some brief remarks about the possible sources of uncertainties which may affect the results. The dominant theoretical uncertainty is that due to the next-to-leading order (NLO) effects which could be $\sim 100\%$. This can potentially much larger than the uncertainties due to the choice of parton density functions (pdf). The uncertainty due to the pdfs are typically a few percent. However, as we have already mentioned if the NLO corrections to the signal and the background are of the same order, it would finally result in a higher significance of the signal. The largest experimental uncertainties arise from the model-dependent jet energy scale and resolution uncertainties and this can amount to 8%. Finally there can be an uncertainty which can be as large as 6%, creeping in from the luminosity measurement. However, at the moment it may be difficult to fully appreciate the impact of these uncertainties on our results in view of the above large theoretical uncertainty arising from NLO effects.

3. Conclusion

To summarize, we have explored the possibility of discovering the mUED model at the LHC using the jets + $\not{E}_T$ channel, which among various signatures of mUED has the largest cross-section. It is well known that the mass splittings among different $n = 1$ KK-excitations of the SM particles are generically small as they are generated by loop driven effects. As a result, typical signatures of mUED would involve relatively low p_T leptons and/or jets accompanied by a soft $\not{E}_T$ spectrum (see Fig. 1). In contrast, in mSUGRA motivated SUSY models the corresponding signals consist of jets, leptons and $\not{E}_T$ which are considerably harder. Thus the traditional strong cuts on visible or $\not{E}_T$ which are often useful in isolating SUSY and other new physics signals from the SM backgrounds, may not be very efficient while searching for $n = 1$ KK-excitations in mUED.

For final states involving multiple leptons of moderately large p_T signals of mUED may still be viable both at the LHC at 7 TeV [23,30] and 14 TeV [13,22] runs. However, the jets + $\not{E}_T$ signal with the largest cross-sections did not receive the due attention because of the apprehension that in the absence of the conventional strong cuts, this signal will be swamped by a large QCD background.

We, however, feel that this signature having the largest cross-sections, should be looked for at the LHC for a complete understanding of the mUED model. To this end we have proposed a new search strategy. In view of our generator level simulations it appears that even in the absence of the standard cuts usually employed for establishing new physics signals, a healthy signal in the above channel can be established by a judicious use of the event shape variables α_T and R_T.

We have generated the jets + $\not{E}_T$ signal in mUED using Pythia. The SM backgrounds have been estimated using ALPGEN and Pythia. As expected attempts to remove the SM background by applying strong cuts on p_T of the jets and $\not{E}_T$, turned out to be futile (see Fig. 1). On the other hand demanding α_T to be greater than 0.56 has eventually removed all the QCD and W/Z + jets backgrounds. Additionally, demanding R_T to be less than 0.85 completely killed the $t\bar{t}$ and residual W/Z + jets events (see Table 1). Requiring 10 signal events after all cuts is then sufficient to claim a discovery for this background free signal. We find that in mUED, R^{-1} up to 850 GeV (700 GeV) can be probed at the ongoing LHC experiments with 7 TeV center of mass energy with an integrated luminosity of 12 fb^{-1} (5 fb^{-1}) (Table 2). Looking at the present performance of the LHC experiments, it may be expected that this amount of data will be available by the end of 7 TeV run.

Though, we have demonstrated the utility of the event shape variables in the context of mUED, these variables can as well be used for searching a large class of new physics scenarios with compressed mass spectra.

A case in point is the unconstrained Minimal Supersymmetric Standard Model (MSSM) with a mass difference of a few hundred GeV separating the heaviest strongly interacting superparticle and the lightest supersymmetric particle (LSP). It can be readily checked that the p_T distributions and the $\not{E}_T$ distribution in a typical SUSY signal in such a scenario will be relatively soft. Consequently the signal will be rather insensitive to the SUSY searches by the ATLAS and the CMS Collaborations even if the squark–gluino masses are relatively small, and cannot be constrained by the present LHC data. It will be interesting to develop an alternative search strategy based on the event shape variables for these models.

It may be recalled that it was pointed out long ago [4] that the signatures of mUED and R-parity conserving mSUGRA could be similar. However, in most versions of the MSSM like mSUGRA, the sparticle spectra are well spread out and standard hard cuts can separate the MSSM signal from the signatures of mUED. However, the compressed version of the MSSM will indeed give rise to signals very similar to the signals of mUED. It would then especially challenging to differentiate between this compressed SUSY with mUED in the jets + $\not{E}_T$ channel. Event shape variables may play a crucial role to this end.

Several authors have discussed [28,29] the possibility of partially compressed spectra in the framework of supersymmetry for various theoretical reasons. Characteristic signals at the LHC of such compressed spectra in mSUGRA type scenarios have also been discussed [28]. However, it should be noted that in neither of the models discussed above the mass spectrum is as compressed as in the mUED model. Consequently, exploration/exclusion of such models at the LHC can still be possible using large visible/missing energy cuts. However, it would be interesting to see whether the event shape variables can extend the mass reach at the LHC in these cases.

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