LHC bounds on MUED after Run 2
and the impact of parton shower uncertainties

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Abstract

We present the updated LHC limits on the minimal universal extra dimensions (MUED) model from the Run 2
searches. We scan the parameter space against a large number of searches implemented in the public code C
heck-MATE and show that large uncertainties in the limits exist when modelling using parton showers alone due to di-
ferences in the evolution starting scale, especially in the compressed spectra. This motivates us to incorporate matching,
thus deriving the most up-to-date limits on the MUED parameter space from 13 TeV searches.

1. Introduction

Over the years, the LHC collaborations have put em-
phasis on probing various incarnations of low energy
supersymmetry (SUSY) such as minimal supergravity
(mSUGRA) \cite{1}, gauge-mediated SUSY \cite{2}, anomaly-
mediated SUSY \cite{3, 4}, phenomenological Minimal Su-
persymmetric Standard Model (pMSSM) \cite{5}, and the
electroweak-MSSM \cite{6}, usually represented by simpli-
fied models. After extensively collecting data for al-
most a decade however, no convincing signal of super-
symmetric models have been seen. This naturally led
to a growing interest in various alternative beyond-the-
Standard-Model (BSM) scenarios. Among these are the
Universal Extra Dimensions (UED) \cite{7} which represent
a simple extension of the Standard Model (SM) that in-
clude a dark matter candidate and are also testable at
the LHC. Here we focus on the minimal version, Mini-
mal UED (MUED) \cite{8}. The phenomenology of MUED
model bears some similarities to SUSY in that each par-
ticle of the SM has a heavier Kaluza-Klein (KK) part-
ner with the same gauge quantum. However, in contrast
to SUSY, KK-particles have the same spin as their SM
counterparts. The lightest particle in the KK spectrum
is assumed stable and can be a dark matter candidate.

Consequently the usual collider signatures of the
MUED are similar to the SUSY missing energy signa-
tures with additional jets and leptons. The most impor-
tant differences are the degenerate spectrum of a typical
MUED model and several times higher cross-section,
for the same overall mass scale. The definitive differen-
tiation between these models requires a detailed anal-
ysis of angular and invariant mass distributions of the
final state products \cite{9, 10, 11, 12, 13, 14}. Thus, SUSY
searches should provide a high discovery and exclusion
potential for the MUED model. Since ATLAS and CMS
have performed many searches targeted at SUSY, these
can be recast to provide bounds on the MUED model as
was done in \cite{15, 16, 17, 18}. In addition, non-SUSY-
like searches can provide bounds as well, for example
the CMS search for a di-lepton resonance at 8 TeV with
20.6 fb\textsuperscript{-1} which can be used to set limits on the second
KK-photon \cite{19}.

A huge advantage of MUED is its predictivity and
simplicity since it only depends on two parameters, the
compactification radius of the extra dimension \(R\), and a
cutoff scale \(\Lambda\) at which it is replaced by a high-energy
theory. The inverse compactification radius \(R^{-1}\) sets
the mass scale of the first KK excitations while \(\Lambda R\) con-
trols the allowed KK modes present in the spectrum below
the cutoff. Existing bounds prior to this paper exclude
models with \(R^{-1}\) values of up to 1500 GeV \cite{16, 18}.

As already mentioned, MUED spectra tend to have
smaller mass splittings than supersymmetric spectra
which results in softer final state products and thus de-
creased missing transverse energy. As a result, exclu-
sion limits rely on initial state radiation (ISR) which
provides transverse boost to the hard scattering system,
especially for low values of \( \Lambda \cdot R \). As pointed out in Refs. [20, 21] this may result in significant QCD uncertainties when setting limits. In this Letter we explore how different settings in Monte-Carlo (MC) event generator Pythia 8 [22], affect constraints and their uncertainties when setting limits on the MUED parameter space. We note that this question was not considered in the earlier studies [16, 17]. Additionally, we take advantage of several ATLAS studies using full luminosity collected in Run 2. Although a thorough study of parton shower uncertainty should include a comparison of different MC event generators (e.g. Herwig [23] or Sherpa [24]) and a variation of all parton shower parameters [25], this is beyond the scope of this work. We rather focus on the change of the parton shower scale as discussed in [26, 27].

This paper is arranged as follows: Section 2 gives a brief overview of the MUED model. Section 3 then explains the need for matching and the procedure employed to achieve this. Section 4 provides the details of the numerical simulations and analysis as well as a discussion of our bounds in the \( R^{-1} - \Lambda \cdot R \) plane.

2. MUED Overview

We focus on the LHC phenomenology of the first KK level excitation. In that case, each chiral SM fermion \((Q_i, u_i, d_i, L_i, e_i)\) (where \( i \) is the SM generation index) has one Dirac-fermion partner \((Q^{(1)}_i, u^{(1)}_i, d^{(1)}_i, L^{(1)}_i, e^{(1)}_i)\), each SM gauge boson \(g_\mu, W_\mu, B_\mu\) has a massive boson partner \(g^{(1)}_\mu, W^{(1)}_\mu, B^{(1)}_\mu\), and the Higgs partner sector contains a scalar, a pseudo-scalar and a charged partner \((h^{(1)}, A_0, H^+_e)\). The couplings between new states are equal to the SM couplings of their partners. The masses of the KK modes are at the tree level given by

\[
m_n = \sqrt{(n/R)^2 + m_{SM}^2} \quad \text{for } n \geq 1, \tag{1}
\]

where \( n \) is the KK level. Since the KK modes at \( n = 1 \) are the lightest, they can be abundantly produced at the LHC and will be our main focus. Equation (1) suggests a very compressed mass spectrum. However, at the loop level, the near-mass-degeneracy is partially lifted with splittings growing with \( \Lambda \cdot R \), making the KK-glueon the heaviest state and the KK-partner of the \( U(1)_B \) gauge boson the lightest state at each KK level.

We restrict ourselves to the strong production of the colored KK-modes, i.e. KK-gluons and KK-quarks,

\[
pp \rightarrow g^{(1)}(g^{(1)}), \quad pp \rightarrow Q^{(1)}_i Q^{(1)}_j, \quad pp \rightarrow g^{(1)}Q^{(1)}_j, \tag{2}
\]

where \( Q^{(1)} = Q^{(1)}_d, q^{(1)}_d \) and \( Q^{(1)} = Q^{(1)}_u, q^{(1)}_u \) denotes the SU(2) doublet quark partners (or their anti-particles) and \( q^{(1)}_d, d^{(1)}_d \) is the SU(2) singlet quark partners (or their anti-particles). The production of other states is suppressed by the electroweak couplings [19].

The typical decay patterns of the KK-states, shown diagrammatically in Fig. 1 proceed as follows. The KK gluon is the heaviest particle and decays into KK-doublet and singlet quarks with about equal branching ratio. The KK-quark decay modes depend mainly on its SU(2) charge. The SU(2) singlet KK-quark directly decays to the KK-photon which is stable and the lightest KK particle (LKP). The SU(2) doublet KK-quarks mainly decay into the KK-gauge-bosons \( W^{(1)}_\pm \) and \( Z^{(1)} \). The KK-W and Z bosons are lighter than the KK-quarks and so decay mostly into leptonic KK-states which in turn decay further to the LKP and a lepton. Hence, events usually have a relatively large lepton multiplicity, multiple jets, and missing transverse momentum \( (E_T) \) in the final states, although all decay products can be relatively soft due to the compressed spectrum. Explicit mass spectra are shown in Table II for various benchmark points with \( \Lambda \cdot R = 5 \) at \( \sqrt{s} = 13 \text{ TeV} \).

3. ISR and the matching procedure

For models with compressed mass spectra, a large recoil is necessary to produce a signature with relatively low SM background. The recoil provides large missing transverse momentum (if there are heavy particles escaping detection) and gives additional transverse boost to leptons if present. The recoil is provided by the initial state radiation from incoming partons. At the MC level the ISR can be produced in the hard matrix elements or in parton shower. However, modeling ISR using a parton shower approach results in large uncertainties which are mainly due to a choice of starting scale for parton shower evolution. This is known to have a

\[\text{[19].}\]
large effect in squark and gluino production, where the uncertainty can be illustrated by varying between the “wimpy” and “power” shower settings, which respectively refers to the {	t SPACESHOWER:PTmaxMatch = 1} and \texttt{SPACESHOWER:PTmaxMatch = 2} in \textsc{Pythia} 8\cite{20, 28, 29}.

In \textsc{Pythia} 8 for the “default” shower setting (which is \texttt{SPACESHOWER:PTmaxMatch = 0}) \texttt{pT}_{max} is chosen to be the factorization scale for internal processes and the scale value for Les Houches input if the final state of the hard process (not counting subsequent resonance decays) contains at least one quark (excluding top), gluon or photon. If this is not the case, the emissions are allowed to go all the way up to the kinematical limit. This is because in the former set of processes the ISR emission of yet another quark, gluon or photon could lead to double-counting, while no such danger exists in the latter case. The “wimpy” setting, on the other hand, always uses the factorization scale for an internal process and the scale value for Les Houches input, i.e. the lower value. This avoids double-counting, but may leave out some emissions that ought to have been simulated. Finally, the “power” setting always allows emissions up to the kinematical limit which will simulate all possible event topologies, but may lead to double-counting \cite{22}.

Since \textsc{MUED} has a compressed spectrum especially in the low $\Lambda$-$R$ region of its parameter space as discussed in Section 2 and suggested by Eq. (1), we must rely on the ISR as well and therefore expect this variation when using different shower settings. This can be seen in Fig. 2 for example where production of KK gluon was done via the \textsc{Pythia} 8 setup found in the Appendix C of Ref. \cite{18} for the benchmark point $R^{-1} = 1700$ GeV and $\Lambda \cdot R = 5$ with 10,000 events at 13 TeV and analysed using \textsc{Rivet} \cite{30}.

Therefore, if our search strategy relies on the presence of ISR, we cannot solely use parton shower simulation for determination of limits. The simulation of additional emissions at the hard matrix element level matched to the parton shower is the method that reduces the uncertainty due to ISR modelling.

| $R^{-1}$ [GeV] | Total $\sigma$ [fb] | $g^{(1)}$ | $Q^{(1)}$ | $W^{(1)}$ | $L^{(1)}$ | $\gamma^{(1)}$ |
|---------------|---------------------|----------|----------|----------|----------|----------|
| 1700          | 76.858              | 1970.48  | 1878.22  | 1854.21  | 1755.49  | 1727.33  | 1698.55  |
| 1800          | 45.614              | 2086.39  | 1988.7   | 1963.28  | 1858.54  | 1828.94  | 1798.40  |
| 1900          | 27.209              | 2202.3   | 2099.19  | 2072.35  | 1961.60  | 1930.54  | 1898.26  |
| 2000          | 16.335              | 2318.22  | 2209.67  | 2181.14  | 2064.68  | 2032.15  | 1998.11  |

Table 1: The total production cross sections, $\sqrt{s} = 13$ TeV, and mass spectra for various $R^{-1}$ with $\Lambda \cdot R = 5$.

Figure 2: A comparison of the leading jet $p_T$ distribution between the “wimpy” and “power” settings for the production of KK gluons using \textsc{Pythia} 8 for the benchmark point $R^{-1} = 1700$ GeV and $\Lambda \cdot R = 5$ with 10,000 events at 13 TeV normalised using an integrated luminosity of 150 fb$^{-1}$.

4. Numerical Analysis

The samples, either with or without matching, of QCD production of KK-particles, as outlined in Section 2, are generated using \textsc{MadGraph} 5 with the UFO \cite{31} implementation of \textsc{MUED} \cite{32, 33, 34, 35} and the parton distribution function (PDF) set NN23LO1 \cite{36, 37}. For the matched samples we use MLM matching \cite{38} implemented in \textsc{Pythia} 8 and matrix element with up to one extra parton. The matching scale was varied in the range between $(m_1 + m_2)/2$ and $(m_1 + m_2)/3$, where $m_1$ and $m_2$ are the masses of the final state KK-particles and the resulting cross section was stable regardless of the parton shower setting. In the following we present the results for a matching scale equal to $(m_1 + m_2)/3$. With these settings, we scanned the parameter space $R^{-1}$-$\Lambda \cdot R$ producing 50,000 events at each grid point.

The events where then fed into \textsc{CheckMATE} \cite{39, 40, 41} for detector simulation and checked for exclusion against 30 ATLAS and 4 CMS searches, corresponding to version 2.0.30. Each analysis typically contains a large number of signal regions which target differ-
ent mass hierarchies and final state multiplicities. For a given search, the best signal region for each point in the parameter space is defined by CheckMATE as the one with the largest expected exclusion potential. This criterion is then repeated to select the best search which is defined as the search whose best signal region provides the strongest exclusion. This means that the best observed limit is not always used but it ensures that the result is less sensitive to downward fluctuations in the data that are bound to be present when scanning over many searches and many signal regions. Once the best search is found for a given point in the parameter space, the signal yield in our model is then compared to the observed limit at 95% confidence level (CL),

\[ r = \frac{S - 1.64 \cdot \Delta S}{S_{\text{obs}}} \]  

where \( S \) denotes the number of signal events, \( \Delta S \) is the 1-\( \sigma \) on \( S \) combining the statistical MC uncertainty and the 10% systematic cross section uncertainty, and \( S_{\text{obs}}^{95} \) is the observed 95% CL exclusion limit. The quantity \( S - 1.64 \cdot \Delta S \) corresponds to the 95% CL lower bound on our prediction for the number of signal events, which ensures that the limits we set are conservative. The \( r \) value is only calculated for the expected best signal region. CheckMATE does not, by default, combine signal regions or analyses in order to optimize exclusion since the correlations between different searches and signal regions are not known in most cases. We consider a model point as excluded if \( r > 1 \).

The searches which turn out to be the most sensitive to the MUED model are atlas_conf_2019_040 (2-6 jets and \( E_T \) at 139 fb\(^{-1}\)) [43], atlas_2101_01629 (1 lepton, jets and \( E_T \)) [44], and cms_sus_16_039 (2 same-sign leptons or at least 3 leptons plus \( E_T \) at 35.9 fb\(^{-1}\)) [45]. These analyses are also summarized in Table 2.

We start our numerical analysis by comparing an exclusion limit in the \( R^{-1} - \Lambda \cdot R \) plane obtained for different showering settings in both matched and unmatched samples as discussed in Section 3. As can be seen in Fig. 3 for most of the parameter space the limit derived from the matched samples is stronger regardless of the shower setting. A band between power and wimpy setting can be understood as an uncertainty in the exclusion limit due to showering. As expected from the discussion in Section 3 it becomes more pronounced towards lower values of \( \Lambda \cdot R \) which correspond to compressed mass spectra. Notably, apart from the weaker limit, the unmatched sample results in a much higher uncertainty on \( R^{-1} \) at \( \Lambda \cdot R = 5 \): 140 GeV compared with 40 GeV for a matched sample.

Figure 4 compares limits from the above mentioned searches, which have the highest sensitivity to the MUED signal. We see that the strongest limit comes from atlas_2101_01629 search for any value of \( \Lambda \cdot R \). Figure 5 shows the three best signal regions that provide the strongest exclusion for this particular search. For \( \Lambda \cdot R < 10 \), the most sensitive signal region (SR) is 2J squark discovery SR (CheckMATE label 2J_disc_squark) which requires at least two jets and a low-\( p_T \) lepton: \( p_T > 7(6) \) GeV for electron (muon) and \( p_T < 20 \) or 25 GeV, depending on a number of jets. The requirements placed on missing transverse momentum and effective mass, \( E_T^{\text{miss}} > 400 \) GeV, \( m_{\text{eff}} > 1200 \) GeV, enhance the sensitivity by selecting signal events with boosted final-state particles recoiling against energetic ISR jets. It is therefore well-suited for probing parameter space with low mass splitting, as it is the case for \( \Lambda \cdot R < 10 \). As we go up in \( \Lambda \cdot R \), the sensitivity then shifts to the 4J low-x SR (CheckMATE label 4J_4x_bveto_1600) which corresponds to a higher jet multiplicity (with no b-jets) of 4 to 5, and effective mass \( m_{\text{eff}} > 1600 \) GeV, which is again expected in the larger

Table 2: Relevant \( \sqrt{s} = 13 \) TeV analyses used in our study. The middle column denotes the target final state while the last column shows the total integrated luminosity.

| Analysis                  | Final State | \( L \) [fb\(^{-1}\)] |
|---------------------------|-------------|----------------------|
| atlas_2101_01629          | 1l + jets + \( E_T \) | 139                  |
| atlas_conf_2019_040       | jets + \( E_T \) | 139                  |
| cms_sus_16_039            | leptons + \( E_T \) | 35.9                 |


\footnote{This approximately amounts to a size of the next-to-leading order corrections to the cross section [43].}
mass splitting region of higher $\Lambda \cdot R$.

It is also illuminating to look at the next two most sensitive searches just to understand the shape of exclusion lines. For the search $\text{cms\_sus\_16\_039}$, the most sensitive signal regions are SR\_A14 (SR\_A09) where events with three electrons or muons that form at least one opposite-sign same-flavor pair and with $E_T^{\text{miss}} \geq 250$ GeV (200 GeV) are the strongest. Notably, the multi-lepton search using 35.9 fb$^{-1}$ of data reaches similar sensitivity to the multi-jet search $\text{atlas\_conf\_2019\_040}$ using 139 fb$^{-1}$.

As already suggested, the leptonic searches can be expected to have an improved sensitivity to MUED due to the relatively large expected number of leptons in the final state compared to e.g. SUSY. Indeed, our study finds the 1-lepton search, $\text{atlas\_2101\_01629}$, having the best sensitivity in the full data set but the CMS multilepton search, $\text{cms\_sus\_16\_039}$ using $L = 36$ fb$^{-1}$, was also very promising and it is likely that a similar study using the full data set will be at least as sensitive as the ATLAS search. We note that in Ref. [15] it was found that same-sign/3-lepton search [46] was the most constraining for moderate to large values of $\Lambda \cdot R$. In our study, however, the ATLAS same-sign leptons study, $\text{atlas\_1909\_08457}$, was lagging behind in sensitivity. Similarly, at low $\Lambda \cdot R$ Ref. [15] points to a search based on 2 soft leptons [47]. Again, it turns out that the full luminosity search for soft-leptons final states, $\text{atlas\_1911\_12606}$ [48], is not as strong as the 1-lepton search $\text{atlas\_2101\_01629}$.

Finally, in Fig. 6 we summarize our findings. It shows the exclusion line of the MUED model for the matching case with the default shower setting. We extend the range of $\Lambda \cdot R$ up to 100. The exclusion in $1/R$ shows little variation at large $\Lambda \cdot R$, stabilizing around 1860 GeV.

In the LHC-allowed region above $R^{-1} \sim 1700$ GeV the dark matter relic density is too high [49]. Thus, the LHC constraints together with the dark matter relic density bound essentially rule out MUED, at least for the standard cosmology.
5. Conclusion

We showed that in updating the limits for the MUED parameters, using parton showers alone yields large uncertainty at lower $\Lambda$ - $R$ corresponding to a low mass spectrum. This clearly demonstrates the case for employing an appropriate matching procedure. We then updated existing limits using the current LHC searches concluding that the strongest limit comes from the atlas_2101_01629, which targets the final states with one lepton, jets and missing transverse energy.

Note

We are aware of the work [50] and the discrepancies between our results and those presented therein. We are in touch with the authors in order to resolve these differences.

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