DISCOVERY POTENTIAL FOR UNIVERSAL EXTRA DIMENSIONS SIGNALS WITH FOUR LEPTONS IN THE FINAL STATE*

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The search for Universal Extra Dimensions for four values of the compactification radius in the $4e, 4\mu$ and $2e\,2\mu$ channels is presented. It is shown that the CMS detector is sensitive up to $R^{-1} = 900\,\mathrm{GeV}/c^2$ for an integrated luminosity of $30\,\mathrm{fb}^{-1}$.

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1. Introduction

The Universal Extra Dimensions model (UED) [1] is an extension of the sub-millimeter extra dimensions model (ADD) [2, 3] in which all Standard Model (SM) fields, fermions as well as bosons, propagate in the extra dimension (ED) bulk. In the minimal UED (mUED) scenario only one ED is needed to create an infinite tower of modes of Kaluza–Klein (KK) particles with the same spin and couplings as the corresponding SM particles. In the *first level* excitation mode KK particles appear with masses below TeV scale, accessible at LHC. All Standard Model particles have KK partners, which are indicated with the subscript related to the n-th mode of excitations, *e.g.* at the first level: $g_1, Z_1, u_{\mathrm{L}1}, e_{\mathrm{R}1}, \gamma_1$.

A new quantum number KK-parity is conserved, which has important phenomenological consequences: the first level KK states must be pair produced and the lightest KK particle (LKP) is a neutral and stable KK photon γ_1. In the mUED model masses of KK particles are defined by three parameters: R^{-1}— a size of the ED given as a compactification radius (approximately the value of the LKP mass), ΛR — a number of KK levels

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present in the effective theory, which is valid up to the cut-off scale Λ and $m_{\rm h}$ — a parameter of the Higgs sector, which has no influence on KK masses besides KK partners of Higgs particles.

Precision electroweak data measurements set a lower bound of $R^{-1} > 600\,{\rm GeV}/c^2$ [4] for a SM Higgs mass of $115\,{\rm GeV}/c^2$ and top quark mass of $173\,{\rm GeV}/c^2$. However, assuming a large Higgs mass (few hundreds of ${\rm GeV}/c^2$) this limit can be as low as $\sim 300\,{\rm GeV}/c^2$ [1,4].

The KK mass spectrum is highly degenerated, because masses are proportional to $m_n^2 = n^2/R^2 + m_{\rm SM}^2$ at tree level and radiative corrections does not introduce larger splitting. Typically there is about $100\,{\rm GeV}/c^2$ between the heaviest and lightest KK particle. Thus, the experimental signatures for KK production are soft leptons and/or jets radiated in the cascade decay process in addition to the relatively small missing energy carried away by the LKPs. However, the mUED events are rich in isolated leptons. This characteristic was exploited to discriminate the signal from the background.

2. Signal and background processes

Signal events were generated at four points (with different LKP mass) of the mUED parameter space: $m_{\rm h} = 120\,{\rm GeV}/c^2$, $\Lambda R = 20$ and $R^{-1} \in \{300, 500, 700, 900\}\,{\rm GeV}/c^2$ as a pair of strongly interacting particles. Three significant subprocesses were considered:

$$pp \to g_1 g_1\,, \quad pp \;\to\; Q_1/q_1\, Q_1/q_1\,, \quad pp \to g_1 Q_1/q_1\,,$$

where

$$(Q_1, q_1) \;=\; (U_1, d_1)\,. \tag{2.1}$$

Singlet and doublet KK quarks of the first generation were taken into account. The total cross section (Table I) strongly depends on the compactification radius. The decay to leptons takes place in the following way:

$$g_1 \to Q_1 Q\,, \quad Q_1 \to Z_1 Q\,, \quad Z_1 \to L_1 \ell^{\pm}\,, \quad L_1 \to LKP(\gamma_1)\ell^{\mp}\,. \tag{2.2}$$

Within a decay branch the pair of SM leptons ($\ell^{\pm}\ell^{\mp}$) has the same flavor and opposite sign. Three possible combinations of four leptons arise, namely $4e$, 4μ and $2e2\mu$, studied in three separated channels.

Signal events were simulated with CompHEP with model files taken from Ref. [5] at leading order (LO). In the cross section calculation the QCD scale was set to $2/R$, the radiative corrections were also evaluated at $2/R$ and the CTEQ5L parton distribution functions (PDF) were used. The dedicated program UEDDECAY-3.00 was used to decay the KK particles. Only decays that allow the production of four lepton final states were switched on.

TABLE I

Total cross sections and branching ratios for the mUED signal with four leptons in the final state. Leptons were accepted under the same preselection as for the $t\bar{t}$ samples (Table II).

Channel	mUED R^{-1} (GeV/c^2)	$\sigma_{\rm tot}$ (pb)	BR	$\sigma_{\rm tot}$BR (pb)	ε_1	$\sigma_{\rm tot}$BR ε_1 (fb)
$4e$			2.33E−4	5.10E−1	0.64	3.27E+2
4μ	300	2.19E+3	2.33E−4	5.10E−1	0.60	3.06E+2
$2e2\mu$			4.66E−4	1.02E+0	0.61	6.23E+2
$4e$			3.52E−4	5.80E−2	0.77	4.47E+1
4μ	500	1.65E+2	3.52E−4	5.80E−2	0.74	4.30E+1
$2e2\mu$			7.03E−4	1.16E−1	0.75	8.71E+1
$4e$			4.38E−4	1.14E−2	0.83	9.45E+0
4μ	700	2.60E+1	4.38E−4	1.14E−2	0.80	9.11E+0
$2e2\mu$			8.76E−4	2.28E−2	0.82	1.87E+1
$4e$			5.21E−4	3.05E−3	0.89	2.72E+0
4μ	900	5.86E+0	5.21E−4	3.05E−3	0.87	2.66E+0
$2e2\mu$			1.04E−3	6.10E−3	0.88	5.37E+0

The background to mUED signals results from SM processes with four leptons in the final state. The dominant sources were the continuum production of $(Z^*/\gamma^*)(Z^*/\gamma^*)$ and real ZZ, processes involving pair production of heavy quark flavors such as $t\bar{t}$ and $b\bar{b}b\bar{b}$, and the associated production of $Zb\bar{b}$, listed in Table II. The ZZ and $Zb\bar{b}$ background event samples were simulated with CompHEP and Pythia with forced leptonic decays of Z-boson and free decays of b-quark. Top and bottom samples were generated with Alpgen. The lepton decay branch was chosen for the W and the semileptonic decay for b-hadrons. If particles decay into taus, the taus were also forced to decay into electrons or muons. The NLO values of cross section have been applied to all background samples.

All samples contained only preselected events with at least four leptons in the final state. The study was performed for the LHC run at low luminosity assumed to be 2×10^{33}cm^{-2}s^{-1}.

TABLE II

The background samples. The σ_{NLO} refers to the production cross-sections of the heavy states ZZ, $t\bar{t}$, *etc.*, not including the branching fraction of the leptonic decays. The BR refers to forced leptonic decay channels. Samples were preselected (ε_1) to have a $4e$, 4μ or $2e2\mu$ final state with the geometrical and kinematical requirements for leptons as listed. The top and b-quark samples contained all four lepton final states.

Process	Preselection ε_1	σ_{NLO} (pb)	$\sigma_{\mathrm{NLO}}\mathrm{BR}\,\varepsilon_1$ (fb)
$t\bar{t}$		3.47E+2	3.21E+2
$t\bar{t}j$	$p_{\mathrm{T}}{}^{e} > 1.0\,\mathrm{GeV}/c$, $\lvert\eta^{e}\rvert < 2.5$	3.10E+2	3.31E+2
$t\bar{t}jj$	$p_{\mathrm{T}}{}^{\mu} > 1.0\,\mathrm{GeV}/c$, $\lvert\eta^{\mu}\rvert < 2.4$	1.83E+2	2.13E+2
$b\bar{b}b\bar{b}$		4.78E+2	3.31E+2
$ZZ\to 4e$		2.89E+1	2.00E+1
$Zb\bar{b}\to 4e$	$p_{\mathrm{T}}{}^{e} > 5.0\,\mathrm{GeV}/c$, $\lvert\eta^{e}\rvert < 2.7$	2.76E+2	1.20E+2
$ZZ\to 4\mu$		1.53E−1*	8.74E+1
$ZZ\to 2\mu 2\tau\to 4\mu$	$p_{\mathrm{T}}{}^{\mu} > 3.0\,\mathrm{GeV}/c$, $\lvert\eta^{\mu}\rvert < 2.5$	2.12E−1*	1.63E+0
$Zb\bar{b}\to 4\mu$		2.78E+2	2.90E+2
$ZZ\to 2e2\mu$		2.89E+1	3.70E+1
$Zb\bar{b}\to 2e2b\to 2e2\mu$	$p_{\mathrm{T}}{}^{e} > 5.0\,\mathrm{GeV}/c$, $\lvert\eta^{e}\rvert < 2.7$	2.76E+2	2.62E+2
$Zb\bar{b}\to 2\mu 2b\to 2e2\mu$	$p_{\mathrm{T}}{}^{\mu} > 3.0\,\mathrm{GeV}/c$, $\lvert\eta^{\mu}\rvert < 2.4$	2.79E+2	1.28E+2

* value includes leptonic decay branching fraction.

3. Event reconstruction

The default algorithms for the lepton reconstruction at the CMS detector have been used [6]. The global muon reconstruction algorithm used seeds of the all muon subsystems and tracker information. A reconstructed electron was a pair of an electromagnetic calorimeter (ECAL) supercluster associated with a charged track from the silicon tracker. Additional requirements were applied to distinguish electrons from jets based on the difference between an electromagnetic and a hadronic shower: $E_{\mathrm{HCAL}}/E_{\mathrm{HCAL}} < 0.1$ and the energy from the ECAL in comparison to track momentum: $0.9 < E/p < 1.5$. Due to the presence of tracker material embedded in a strong magnetic field a significant amount of the energy radiated by the electron may be lost in the supercluster reconstruction process. On the other hand, early electron radiation may lead to an important underestimation of the electron momentum measured in the tracker.

Reconstructed leptons were preselected in transverse momentum p_{T} and in pseudorapidity η as follows: electrons with $p_{\mathrm{T}} > 7.0\,\mathrm{GeV}/c$ and $|\eta| < 2.5$, muons with $p_{\mathrm{T}} > 5.0\,\mathrm{GeV}/c$ and $|\eta| < 2.4$. Electrons and muons used in the analysis were also required to fulfill the isolation criteria. The dedicated isolation algorithm (cone $R = 0.3$, Σp_{T}(no lepton tracks) $> 3\,\mathrm{GeV}/c$) strongly improved the rejection of background events with leptons produced inside jets and enhanced the purity of samples to 99.6–99.8%.

4. Event selection

The cuts applied to reduce the background are summarized in Table III. The single and double electron and muon set of the first level and high level triggers were first applied. The L1 and HLT trigger efficiencies for the signal with $R^{-1} = 300\,\mathrm{GeV}/c^2$ were at the level of 50%, 64% and 90% for the $4e$, $2e2\mu$ and 4μ channels, respectively. The same efficiencies increased to 94%, 95% and 99% for $R^{-1} = 900\,\mathrm{GeV}/c^2$, reflecting the increase with R^{-1} of the average p_{T} of leptons from the signal. The trigger efficiency for channels with electrons was lower than for channels with muons mainly due to the higher p_{T} thresholds of the electron triggers.

TABLE III

Summary table of applied cuts for the mUED $4l$ analysis.

Symbol	Meaning
ε_1	preselection at MC level: e, μ with $p_{\mathrm{T}} > p_{\mathrm{T}}{}^{\min}$ and $|\eta| < \eta^{\max}$
L1 HLT	Level 1 Trigger* High Level Trigger**
ε_2	preselection at reconstruction level: e with $p_{\mathrm{T}} > 7.0\,\mathrm{GeV}/c$ and $|\eta| < 2.5$ μ with $p_{\mathrm{T}} > 5.0\,\mathrm{GeV}/c$ and $|\eta| < 2.4$
2OSSF	at least two pairs of opposite sign same flavour leptons
4iso	isolation criteria on; at least 4 isolated leptons
Bveto	event was rejected if it had one or more tagged b-jet
lept p_{T}	lepton p_{T} of $1^{\mathrm{st}}, 2^{\mathrm{nd}}, 3^{\mathrm{rd}}, 4^{\mathrm{th}} < (70, 60, 40, 30)\,\mathrm{GeV}/c$
$\not{E}_{\mathrm{T}}$	$\not{E}_{\mathrm{T}} > 60\,\mathrm{GeV}/c$
Zveto	event was rejected if it had one or more OSSF lepton pair with $\mathrm{M_{inv}} < 5\ \mathrm{GeV}/c^2$ or $\mathrm{M_{inv}} > 80\ \mathrm{GeV}/c^2$

* single $p_{\mathrm{T}}{}^{e/\mu} > 23/14\,\mathrm{GeV}/c$, double $p_{\mathrm{T}}{}^{e/\mu} > 12/3\,\mathrm{GeV}/c$.

** single $p_{\mathrm{T}}{}^{e/\mu} > 26/19\,\mathrm{GeV}/c$, double $p_{\mathrm{T}}{}^{e/\mu} > 14.5/7\,\mathrm{GeV}/c$.

The presence of at least two pairs of opposite sign and same flavor leptons (2OSSF) with the kinematical preselection was required. At least four leptons (4iso) were required to be isolated. These were the main criteria for the identification of signal events. After it about 16% ($4e$), 28% ($2e2\mu$) and 55% (4μ) of signal events for the heaviest LKP mUED point $R^{-1} = 900\,\mathrm{GeV}/c^2$ remained.

The next cuts were intended to reject the background as much as possible while preserving high signal efficiency. Because a substantial fraction of the background leptons results from b-quark leptonic decays, events where one or more B-jets were identified (Bveto), were removed. Due to the complex decay cascade associated to the relatively narrow mass splitting of KK particles, the mUED leptons have on average lower transverse momentum than some of the background channels. For this reason upper bound cuts on the leptons p_{T} (lept p_{T}) were applied.

A missing transverse momentum cut ($\not{E}_{\mathrm{T}}$) proved to be important especially for high R^{-1} values. Finally, a selection on the invariant mass of the lepton pairs (Zveto) was used, which was aimed to reject remaining events containing Z-boson. The final selection efficiency worked in the most effective way on the point $R^{-1} = 900\,\mathrm{GeV}c^2$ where 8.7%($4e$), 19%($2e2\mu$) and 27%(4μ) of signal events remainted after the full set of cuts applied.

5. Systematic uncertainties

Systematic uncertainties were estimated for integrated luminosity of 10–30 fb^{-1}. At that stage of the detector operation the cross section of the backgrounds processes will be measured and should be know with accuracy better than 20%, which was conservatively assumed as a theoretical uncertainty. The estimation of experimental systematics included: missing transverse energy (METs) scale uncertainty due to jet scale uncertainty of 3–10% (p_{T} dependent) and the B-jet tagging uncertainty about 4% in the barrel and 5% in endcaps. After change of the $\not{E}_{\mathrm{T}}$ value for each event induced by the METs uncertainty, the selection efficiency of the $\not{E}_{\mathrm{T}}$ cut was varied by less than 7%. The efficiency of the Bveto cut was affected by B-jet tagging uncertainty and changed by less then 10%. In average, the total experimental uncertainty was approximately 6% for all channels. The final numbers of background events with theoretical and experimental uncertainties at 30 fb^{-1}, are given in Table IV.

The other sources of systematic errors were assumed to be negligible for the integrated luminosity of 30 fb^{-1}. Uncertainties due to incomplete understanding of the detector (*e.g.* mis-alignments and mis-calibrations) were not considered.

TABLE IV

Results on detectability of mUED signal with $R^{-1} \in \{300, 500, 700, 900\}\,\mathrm{GeV}/c^2$: the signal ($\sigma_{\mathrm{Signal}}$) and background ($\sigma_{\mathrm{B}}$) cross sections after all selection cuts, the number of expected events for the signal (N_{Signal}) and background (N_{B}) and their ratio (S/B). The signal significance (S_{12}) measured in standard deviations is shown for the integrated luminosity of $30\,\mathrm{fb}^{-1}$. The integrated luminosity ($\mathcal{L}$) needed to obtain a signal significance of five standard deviations is also presented. The results are obtained without (first value of S_{12}, $\mathcal{L}$) and with (second value of S_{12}, $\mathcal{L}$) theoretical and experimental systematic uncertainties.

mUED R^{-1}	σ_{Signal} (fb)	N_{Signal} @30 fb^{-1}	S/B @30 fb^{-1}	S_{12} @30 fb^{-1}	$\mathcal{L}$ (fb^{-1}) $S_{\mathrm{cP}} = 5\sigma$
4 electrons channel					
Background	$\sigma_{\mathrm{B}} = 3.67\mathrm{E}{-2}\,\mathrm{fb}$	$N_{\mathrm{B}} = 1.10 \pm 0.22^{\,\mathrm{TH}} \pm 0.06^{\,\mathrm{EXP}}$			
300	1.33E+0	40	36	11	3.7–4.0
500	1.19E+0	35.7	32	10–9.8	4.3–4.6
700	5.13E−1	15.9	14	6.2–5.9	13–14
900	2.23E−1	6.7	6.1	3.5–3.3	46–54
4 muons channel					
Background	$\sigma_{\mathrm{B}} = 1.35\mathrm{E}{-1}\,\mathrm{fb}$	$N_{\mathrm{B}} = 4.06 \pm 0.81^{\,\mathrm{TH}} \pm 0.25^{\,\mathrm{EXP}}$			
300	1.72E+1	517	126	42–41	< 1
500	7.79E+0	234	57	27–26	< 1
700	2.38E+0	71.4	17	13	2.7–3.0
900	7.28E−1	21.8	5.3	6.1–5.7	15–18
2 electrons 2 muons channel					
Background	$\sigma_{\mathrm{B}} = 1.60\mathrm{E}{-1}\,\mathrm{fb}$	$N_{\mathrm{B}} = 4.80 \pm 0.96^{\,\mathrm{TH}} \pm 0.28^{\,\mathrm{EXP}}$			
300	7.86E+0	236	49	27–26	< 1
500	6.53E+0	196	41	24–23	< 1
700	2.84E+0	85.1	18	15–14	2.2–2.5
900	1.04E+0	31.2	6.5	7.6–7.2	9.5–11

6. Results

The final number of expected events after all selection cuts for an integrated luminosity of $30\,\mathrm{fb}^{-1}$ of mUED signal and total background are presented in Table IV. The background were satisfactorily suppressed for tree four-lepton channels providing a large signal to background S/B ratio. The largest background contributions were given by the top and ZZ events.

A common significance estimator was used, S_{cP} [7]. The S_{cP} gives the probability from Poisson distribution with mean N_{B} to observe equal or greater than $N_{\mathrm{O}} = N_{\mathrm{S}} + N_{\mathrm{B}}$ events, converted to equivalent number of standard deviations of a Gaussian distribution. If N_{B} was too small the S_{cP} had been approximated by a significance $S_{12} = 2\sqrt{N_{\mathrm{S}} + N_{\mathrm{B}}} - \sqrt{N_{\mathrm{B}}}$. The significance S_{12} (5^{th} column in Table IV) was calculated without and with taking into account the experimental systematic uncertainties and the cross-section uncertainties of the background (valid for an integrated luminosity of 10–30 fb^{-1}).

In the last column of the Table IV and in Fig. 1 the integrated luminosity required for a 5σ standard deviation significance was also calculated without including and including systematics uncertainties. A discovery of mUED physics with $R^{-1} = 300$ and $500\,\mathrm{GeV}/c^2$ could be possible with a luminosity below $1\,\mathrm{fb}^{-1}$.

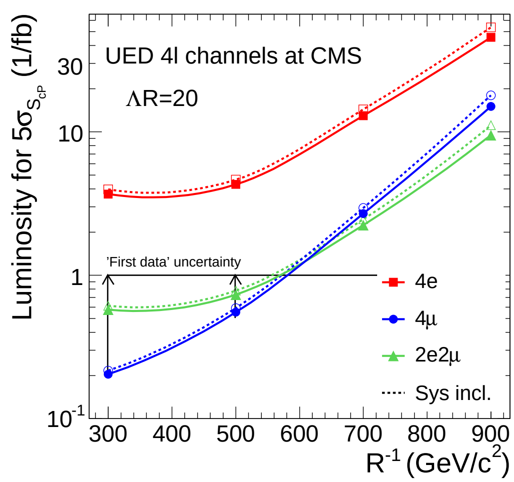

Fig. 1. The discovery potential of mUED signals in the four-lepton channels defined as the integrated luminosity needed to measure a signal with a significance (S_{cP}) of five standard deviations. The dashed (solid) lines show results including (not including) systematical uncertainties. During the first phase of the LHC data taking, the uncertainties due to the limited understanding of the detector performance will limit the sensitivity below $1\,\mathrm{fb}^{-1}$ (horizontal "First data uncertainty" line).

In general, the signal significance strongly decreases with increasing values of R^{-1} due to smaller signal cross sections. The highest significance was achieved for the channels with muons, because trigger and reconstruction efficiencies were larger than with electrons, especially for low p_{T} values. For $R^{-1} = 300\,\mathrm{GeV}/c^2$ the lepton spectrum was the softest (with respect to other mUED points) and, as a consequence, the 4μ channel was more effective. Above $R^{-1} = 600\,\mathrm{GeV}/c^2$ (Fig. 1), the $2e2\mu$ channel became the most sensitive as the cross section was twice as large as the 4μ channel, and it was not significantly affected by the trigger inefficiency for low p_T electrons. Systematical uncertainties had not changed significantly the results.

7. Conclusions

A study of the discovery potential for extra dimensions at CMS within the context of the mUED model at the CMS was presented. The processes in Eq. 2.1 were analyzed after full simulation and reconstruction for four points of the parameter space: $m_\mathrm{h} = 120\,\mathrm{GeV}/c^2$, $\Lambda R = 20$ and $R^{-1} \in \{300, 500, 700, 900\}\,\mathrm{GeV}/c^2$. The decay branches with four-leptons ($4e$ or 4μ or $2e2\mu$) in the final state were selected. The considered background sources were $ZZ(Z^*/\gamma^*)$, $Zb\bar{b}$, $t\bar{t}$, $t\bar{t} + n\,\mathrm{jets}$ and $b\bar{b}b\bar{b}$ channels. Selection cuts allowed the background to be strongly reduced. For the three leptonic channels and for the integrated luminosity of $30\,\mathrm{fb}^{-1}$, the signal significance S_cP was above the background by a few standard deviation and therefore the mUED signal could be detected at the CMS experiment during the first few years of data taking.

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