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Discovery potential for Universal Extra Dimensions signals with four leptons in the final state

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Abstract

The search for Universal Extra Dimensions for four values of the compactification radius in the $4e$, 4μ and $2e2\mu$ 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 nth mode of excitations, e.g. at the first level: $\mathrm{g_1, Z_1, u_{L1}, e_{R1}}, \gamma_1$.

A new quantum number KK-parity is conserved, which has important phenomenological consequences:
1. The first level KK states must be pair produced,
2. 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:

$\mathrm{R^{-1}}$	–	the size of the ED given as a compactification radius (approximately the value of the LKP mass),
$\Lambda\mathrm{R}$	–	number of KK levels present in the effective theory, which is valid up to the cut-off scale L,
$\mathrm{m_{Higgs}}$	–	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 $\mathrm{R^{-1}} > 600\ \mathrm{GeV/c^2}$ [4] for a SM Higgs mass of 115 $\mathrm{GeV/c^2}$ and top quark mass of 173 $\mathrm{GeV/c^2}$. However, assuming a large Higgs mass (few hundreds of $\mathrm{GeV/c^2}$) this limit can be as low as ∼300 $\mathrm{GeV/c^2}$ [1, 4].

The KK mass spectrum is highly degenerated, because masses are proportional to $\mathrm{m}_n^2 = n^2/\mathrm{R}^2 + \mathrm{m}_{\mathrm{SM}}^2$ at tree level and radiative corrections does not introduce larger splitting. Typically there is about 100 $\mathrm{GeV/c^2}$ 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 successfully.

2 Signal and background processes

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

$$\mathrm{pp{\rightarrow}g_1g_1,\ \ pp{\rightarrow}Q_1(q_1)Q_1(q_1),\ \ pp{\rightarrow}g_1Q_1(q_1),\ \ where\ \ (Q_1, q_1) = (U_1, d_1).} \tag{1}$$

Singlet and doublet KK quarks of the first generation were taken into account. The total cross section (Tab.1) strongly depends on the compactification radius. The decay to leptons takes place in the following way:

$$\begin{array}{llll} \mathrm{g_1} \rightarrow & \mathrm{Q_1 + Q} & & \\ & \hookrightarrow & \mathrm{Z_1 + Q} & \\ & & \hookrightarrow & \mathrm{L_1} + \ell^{\pm} \\ & & & \hookrightarrow\ \ell^{\mp} + \mathrm{LKP}(\gamma_1) \end{array} \tag{2}$$

Within a decay branch the pair of SM leptons ($\ell^{\pm}\ell^{\mp}$) has the same flavour 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 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 the decays that allow the production of four lepton final states were switched on.

The background to mUED signals results from SM processes with four leptons in the final state. The dominant sources were the continuum production of $(\mathrm{Z}^*/\gamma^*)(\mathrm{Z}^*/\gamma^*)$ and real ZZ, processes involving pair production of heavy quark flavours such as tt and bbbb, and the associated production of Zbb, listed in Tab.2. indicated

The ZZ and Zbb background event samples were simulated with CompHEP and Pythia with forced leptonic decays of boson Z 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 $2\text{x}10^{33}\text{cm}^{-2}\text{s}^{-1}$.

Channel	mUED R^{-1} (GeV/c^2)	σ_{tot}(pb)	BR	σ_{tot}BR (pb)	ε_1	$\sigma_{\text{tot}}\text{BR}\,\varepsilon_1$ (fb)
$4e$	300	2.19E+3	2.33E-4	5.10E-1	.64	3.27E+2
4μ			2.33E-4	5.10E-1	.60	3.06E+2
$2e2\mu$			4.66E-4	1.02E+0	.61	6.23E+2
$4e$	500	1.65E+2	3.52E-4	5.80E-2	.77	4.47E+1
4μ			3.52E-4	5.80E-2	.74	4.30E+1
$2e2\mu$			7.03E-4	1.16E-1	.75	8.71E+1
$4e$	700	2.60E+1	4.38E-4	1.14E-2	.83	9.45E+0
4μ			4.38E-4	1.14E-2	.80	9.11E+0
$2e2\mu$			8.76E-4	2.28E-2	.82	1.87E+1
$4e$	900	5.86E+0	5.21E-4	3.05E-3	.89	2.72E+0
4μ			5.21E-4	3.05E-3	.87	2.66E+0
$2e2\mu$			1.04E-3	6.10E-3	.88	5.37E+0

Table 1: Total cross sections and branching ratios for the mUED signal with 4 leptons in the final state. Leptons were accepted under the same preselection as for the tt samples (Tab.2).

Process	Preselection ε_1	σ_{NLO} (pb)	$\sigma_{\text{NLO}}\text{BR}\,\varepsilon_1$ (fb)
tt		3.47E+2	3.21E+2
ttj	$\text{p}_\text{T}{}^e > 1.0$ GeV/c, $\lvert\eta^e\rvert < 2.5$	3.10E+2	3.31E+2
ttjj	$\text{p}_\text{T}{}^\mu > 1.0$ GeV/c, $\lvert\eta^\mu\rvert < 2.4$	1.83E+2	2.13E+2
bbbb		4.78E+2	3.31E+2
ZZ→$4e$		2.89E+1	2.00E+1
Zbb→$4e$	$\text{p}_\text{T}{}^e > 5.0$ GeV/c, $\lvert\eta^e\rvert < 2.7$	2.76E+2	1.20E+2
ZZ→4μ		1.53E-1⋆	8.74E+1
ZZ→$2\mu2\tau$→4μ	$\text{p}_\text{T}{}^\mu > 3.0$ GeV/c, $\lvert\eta^\mu\rvert < 2.5$	2.12E-1⋆	1.63E+0
Zbb→4μ		2.78E+2	2.90E+2
ZZ→$2e2\mu$		2.89E+1	3.70E+1
Zbb→2e2b→$2e2\mu$	$\text{p}_\text{T}{}^e > 5.0$ GeV/c, $\lvert\eta^e\rvert < 2.7$	2.76E+2	2.62E+2
Zbb→2μ2b→$2e2\mu$	$\text{p}_\text{T}{}^\mu > 3.0$ GeV/c, $\lvert\eta^\mu\rvert < 2.4$	2.79E+2	1.28E+2

⋆ value includes leptonic decay branching fraction.

Table 2: The background samples. Sigma NLO refers to the production cross-sections of the heavy states ZZ, tt, etc, not including the branching fraction of the leptonic decays. BR refers to forced leptonic decay channels. Samples were preselected 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.

3 Event reconstruction

The default algorithms for the lepton reconstruction at the CMS detector have been used [5]. 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: $\text{E}_{\text{HCAL}}/\text{E}_{\text{HCAL}} < 0.1$ and the energy from the ECAL in comparison to track momentum: $0.9 < \mathrm{E/p} < 1.5$. 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 $\mathrm{p_T}$ and in pseudorapidity η as follows:

- electrons with $\mathrm{p_T}$>7.0 $\mathrm{GeV/c}$ and $|\eta| < 2.5$,
- muons with $\mathrm{p_T}$>5.0 $\mathrm{GeV/c}$ and $|\eta| < 2.4$.

The electrons and muons used in the analysis were also required to fulfill the isolation criteria. The dedicated isolation algorithm (cone R=0.3, $\Sigma\mathrm{p_T}$(no lepton tracks)>3 $\mathrm{GeV/c}$) strongly improves the rejection of background events with leptons produced inside jets and enhances the purity of samples to 99.6-99.8%.

4 Event selection

The cuts applied to reduce the background are summarized in Tab.3.

Symbol	Meaning
ε_1	Preselection at generation level: electrons, muons with $\mathrm{p_T}>\mathrm{p_T}^{min}$ and $|\eta| < \eta^{max}$
L1	Level1 Trigger (e.g. single $\mathrm{p_T}^{e/\mu}$ >23/14 $\mathrm{GeV/c}$, double $\mathrm{p_T}^{e/\mu}$ >12/3 $\mathrm{GeV/c}$)
HLT	High Level Trigger (e.g. single $\mathrm{p_T}^{e/\mu}$ >26/19 $\mathrm{GeV/c}$, double $\mathrm{p_T}^{e/\mu}$ >14.5/7 $\mathrm{GeV/c}$)
ε_2	Preselection at reconstruction level: electrons if $\mathrm{E_{HCAL}/E_{ECAL}} < 0.1,\ 0.9 < \mathrm{E/p} < 1.5$ with $\mathrm{p_T}$>7.0 $\mathrm{GeV/c}$ and $|\eta| < 2.5$, muons with $\mathrm{p_T}$>5.0 $\mathrm{GeV/c}$ and $|\eta| < 2.4$
2 OSSF	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 $\mathrm{p_T}$	lepton $\mathrm{p_T}$ of 1^{st},2^{nd},3^{rd},4^{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 $\mathrm{M_{inv}} > 80\ \mathrm{GeV/c^2}$

Table 3: Summary table of applied cuts for the mUED 4l analysis.

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 $\mathrm{R^{-1}}$=300 $\mathrm{GeV/c^2}$ were at the level of 50%, 64% and 90% for the 4e, 2e2μ and 4μ channels, respectively. The same efficiencies increased to 94%, 95% and 99% for $\mathrm{R^{-1}}$=900 $\mathrm{GeV/c^2}$, reflecting the increase of the average $\mathrm{p_T}$ of leptons from the signal with $\mathrm{R^{-1}}$. The trigger efficiency for channels with electrons was lower than for those that include muons mainly due to the higher $\mathrm{p_T}$ thresholds of the electron triggers.

The presence of at least two pairs of opposite sign and same flavor leptons, with the kinematical preselection listed before, was required. At least four leptons were required to be isolated. These were the main criteria for the identification of signal events. After it about 16%(4e), 28%(2e2μ) and 55%(4μ) of signal events for the heaviest LKP mUED point $\mathrm{R^{-1}}$=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, 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 $\mathrm{p_T}$ were applied.

A missing transverse momentum cut proved to be important especially for high $\mathrm{R^{-1}}$ values. Finally, a selection on the invariant mass of the lepton pairs 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 $\mathrm{R^{-1}}$=900 $\mathrm{GeV/c^2}$ where 8.7%(4e), 19%(2e2μ) 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 10-30fb^{-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 (MET) 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.

The sensitivity of the selection efficiency of the MET cut was estimated to be smaller then 10% and for the B-veto to smaller than 5%. In average the total experimental uncertainty was about 6% for all channels. The final numbers of background events with theoretical and experimental uncertainties at 30fb^{-1} are given in Tab.4.

In the initial LHC operation phase for integrated luminosity below 1fb^{-1} the systematic uncertainties due to incomplete understanding of the detector (e.g. mis-alignments and mis-calibrations) were expected be higher than the presented estimations.

6 Results

The final number of expected events after all selection cuts for an integrated luminosity of 30fb^{-1} for mUED signal and total background are presented in Tab.4. The backgrounds were satisfactorily suppressed for the three analyzed lepton channels with a large signal to background S/B ratio. The largest contributions were given by the top and ZZ events.

A common significance estimator was used, S_{cP} [6]. The S_{cP} gives the probability from Poisson distribution with mean N_B to observe equal or greater than $N_O = N_S + N_B$ 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 $S_{12} = 2\sqrt{N_S + N_B} - \sqrt{N_B}$. The first value of the S_{12} (Tab.4, 7th column) gives a reference estimation value corresponding to the expected numbers of signal and background events. The second significance was calculated taking into account the experimental systematic error (valid for an integrated luminosity of 10-30 fb^{-1}) and the background cross-section uncertainty.

In the last column of the Tab.4 and in Fig.1 the required integrated luminosity for a 5σ significance (reference value and value including systematics) is also shown. A discovery of mUED physics with $R^{-1} = 300$ and 500 $\mathrm{GeV/c^2}$ will be possible with a luminosity below 1 fb^{-1}. The detailed systematic uncertainties of the first phase of the LHC running have not been taken into account.

In general, the signal significance (or luminosity of 5σ discovery) decreases (increases) with R^{-1}, because the signal cross section is strongly dependent on R^{-1}. For a given mUED point (R^{-1}) the highest significance values (the smallest $\mathcal{L}(5\sigma_{S_{cP}})$) are obtained for channels with muons because the trigger and reconstruction efficiencies are significantly larger for muons than for electrons. The softer spectrum of leptons the worse low momentum electron reconstruction and the larger splitting between results for $4e$ and 4μ channels.

For $R^{-1} = 300\ \mathrm{GeV/c^2}$ the lepton spectrum is more soft then for other values of R^{-1} and in consequence the 4μ channel is the most effective, although the $2e2\mu$ channel has two times larger cross section. Above $R^{-1} = 600\ \mathrm{GeV/c^2}$ the $2e2\mu$ channel becomes more efficient then 4μ due to higher lepton spectrum which is less affected by the trigger and reconstruction inefficiency for electrons. Systematic errors do not change results significantly.

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.1 were analyzed after full simulation and reconstruction for four points of the parameter space: $m_h = 120\ \mathrm{GeV/c^2}$, $\Lambda R = 20$ and $R^{-1} \in \{300, 500, 700, 900\}\ \mathrm{GeV/c^2}$, Only light quarks u or d were taken into account and the decay branches for which there were four leptons ($4e$ or 4μ or $2e2\mu$) in the final state were chosen. The considered background sources were $ZZ(Z^*/\gamma^*)$, Zbb, tt, tt+$n$jet and bbbb channels. Selection cuts allowed the background to be strongly reduced. For the three leptonic channels and for the integrated luminosity of 30 fb^{-1}, the signal significance S_{cP} was well above few σ. The study showed that the CMS detector is sensitive to mUED signal.

R^{-1}	σ_{Signal} (fb)	σ_B (fb)	N_{Signal} @30/fb	$N_{Background}$ @30/fb	S/B @30/fb	S_{12} @30/fb	$\mathcal{L}$ (1/fb) S_{cP}=5σ
4 electrons channel							
300	1.33E+0	6.75E-3	40	$1.10 \pm 0.22^{TH} \pm 0.06^{EXP}$	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 (7.7 – 7.3)*	13 – 14
900	2.23E-1		6.7		6.1	3.5 – 3.3 (4.0 – 3.7)*	46 – 54
4 muons channel							
300	1.72E+1	1.35E-1	517	$4.06 \pm 0.81^{TH} \pm 0.25^{EXP}$	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 (7.1 – 6.5)*	15 – 18
2 electrons 2 muons channel							
300	7.86E+0	1.60E-1	236	$4.80 \pm 0.96^{TH} \pm 0.28^{EXP}$	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

* S_{cP} was calculated. In other cases S_{cP} was approximated by S_{12}.

Table 4: Results on detectability of mUED signal with R^{-1}= 300, 500, 700, 900 GeV/c^2. The table shows the signal and background cross sections after all selection cuts, the number of expected events for the signal and background and their ratio S/B. Intervals of the signal significance S_{12} (for the reference value of N_B and value including systematic uncertainties) were shown for an integrated luminosity of 30 fb^{-1}. Additionally, the required integrated luminosity range for a 5σ S_{cP}, significance level was also presented. All lower bounds of significance ranges were obtained with the theoretical and experimental systematic uncertainties.

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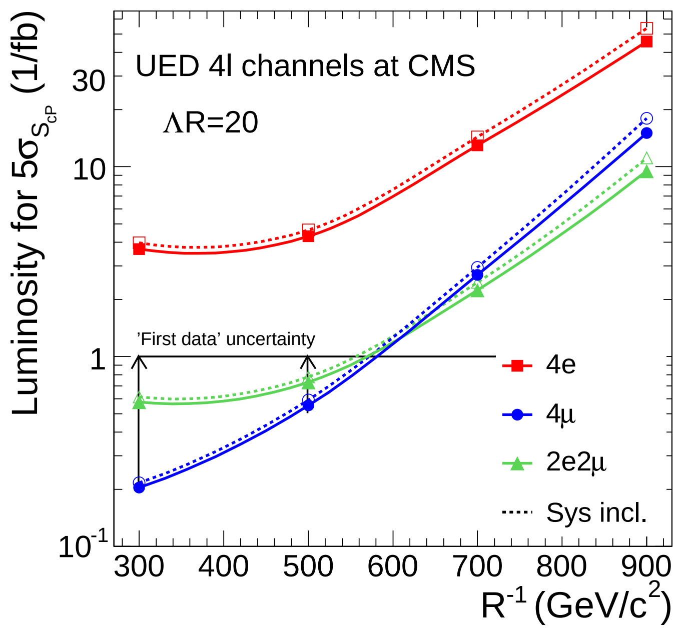

Figure 1: Discovery potential of UED signals (ΛR=20) in $4l$ channel defined as the required luminosity for 5σ $\mathrm{S_{cP}}$ signal significance. The doted lines show the influence of experimental uncertainties (valid for an integrated luminosity of 10-30 fb^{-1}) and the background cross-section uncertainty. The detailed systematic uncertainties of the first phase ($\mathcal{L} = 1\,\mathrm{fb}^{-1}$) of running LHC have not been taken into account.