CMS Physics Analysis Summary

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Search for Large Extra Dimensions in Dimuon Events in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration

Abstract

We report the results of a search for large spatial extra dimensions in events with two muons collected in proton proton collisions at $\sqrt{s} = 7$ TeV with the CMS (Compact Muon Solenoid) detector at the LHC (Large Hadron Collider). The dimuon invariant mass spectrum measured in 40 pb^{-1} of data is found to be well described by the standard model expectation. Limits of up to 2.15 TeV at 95% C.L. are set on the effective Planck scale, depending on the number of extra dimensions and the validity range of the theory.

The extension of space-time plays an important role in the search for a unified theory of physics. Extra dimensions have also been proposed as a possible solution to the hierarchy problem in the standard model (SM) of particle physics [1].

In the presented analysis we investigate a possible enhancement of dimuon events at high invariant masses due to virtual graviton processes in the ADD (Arkani-Hamed, Dimopoulos, Dvali) model [1, 2].

The ADD model postulates the existence of additional compactified extra dimensions. Gravity is assumed to propagate in the entire higher-dimensional space while particles of the standard model are confined to a $3 + 1$ dimensional subspace, a brane.

The resulting effective Planck energy scale M_D in the ADD model can be reduced to significantly lower values than the $3 + 1$ dimensional Planck mass M_{Pl}. This allows for possible phenomenological effects that can be tested with proton-proton collisions at the LHC. M_D is often set into relation with a string scale M_s which is typically presumed to be of order M_D. Here it will be assumed that the added spatial dimensions are compactified on a torus and of the same size L. M_D is in this case related to M_{Pl} via

$$M_D^{n+2} = \frac{M_{Pl}^2}{(8\pi)\, L^n} \quad , \tag{1}$$

where n is the number of additional dimensions.

The coupling of the Kaluza-Klein modes to the SM energy-momentum tensor results in an effective theory with virtual graviton exchange at leading order. A phenomenological consequence is a non-resonant enhancement of expected dilepton events at high invariant masses. Depending on the details of the assumed model, the virtual contributions might provide the dominant experimental signature of the ADD model at high energy colliders [3, 4].

Several ways of parameterizing the leading order differential cross sections are used in the literature, including the HLZ (Han, Lykken, Zhang) convention [3] and the GRW (Giudice, Rattazzi, Wells) convention [4]. In the GRW convention the leading order phenomenology after summing over the Kaluza-Klein states is controlled by a single parameter Λ_T, which is given by

$$\Lambda_T^4 = \frac{8\pi\,\Gamma\,(n/2)}{2\pi^{n/2} c_1} \cdot \frac{M_D^{n+2}}{\Lambda^{n-2}} \quad . \tag{2}$$

The parameter Λ corresponds to the ultraviolet cutoff, and c_1 is a parameter which is not directly predicted by the ADD model. Γ denotes the Gamma function.

Results on Λ_T can be related to the HLZ convention, which describes the phenomenology in terms of the parameters M_s and n. These parameters have the advantage of offering a more direct interpretation in terms of the topology of the $4 + n$ dimensional space. However, one needs to carefully interpret the formally straightforward relation between the two conventions as the calculations for the HLZ convention assume that the center of mass energy $\sqrt{\hat{s}}$ of the hard process is sufficiently smaller than M_s.

The model is expected to break down at energy scales at which the underlying theory of quantum gravity sets in. One can assume that the validity range is characterized by a value $\sqrt{\hat{s}_{\max}}$, roughly corresponding to the dimuon invariant mass. No clear prediction for this scale can be made within the ADD-model itself. One might expect that $\sqrt{\hat{s}_{\max}} \approx M_s \approx M_D$, although unitarity constraints suggest that also somewhat more optimistic values of $\hat{s}_{\mathrm{max}}$ are plausible [4]. At the LHC the effects of an assumed cutoff scale $\hat{s}_{\mathrm{max}}$ cannot be neglected. Hence, the results of the present analysis need to be presented as a function of $\hat{s}_{\mathrm{max}}$ or a related variable. For practical purposes the limits in this analysis are shown in terms of a maximal dimuon mass M_{max} .

The analysis uses CMS data collected in 2010 corresponding to an integrated luminosity of 39.7 pb^{-1} of proton-proton collisions.

A detailed description of CMS can be found elsewhere [5]. The central feature of the Compact Muon Solenoid (CMS) apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are measured with detection planes made of three technologies: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers.

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x-axis pointing to the centre of the LHC, the y-axis pointing up (perpendicular to the LHC plane), and the z-axis along the anticlockwise-beam direction. The polar angle, θ, is measured from the positive z-axis and the azimuthal angle, ϕ, is measured in the x-y plane.

The data sample has been collected using a single muon trigger with the lowest p_{T} threshold varying between 9 GeV/c and 15 GeV/c over the course of the data taking period. The thresholds are sufficiently low to be efficient with respect to the Z resonance. For the given selection criteria the trigger efficiency with respect to standard model Drell-Yan (DY) and signal events is 99% with an uncertainty below 1%.

The event selection criteria follow closely the recently published search for Z' bosons [6]. Candidate events are required to have a reliably reconstructed vertex with $|z| < 24\,\mathrm{cm}$ and $r = \sqrt{x^2 + y^2} < 2\,\mathrm{cm}$. Muons are required to be identified both in the central tracker and in the muon system, where the central track must include at least one pixel hit and more than 10 hits in the strip tracker. Hits from at least two muon stations need to be included in the track. Since we are interested in the high mass region of the central dimuon invariant mass spectrum muons with pseudorapidity $|\eta| < 2.1$ and transverse momentum $p_{\mathrm{T}}^{\mu} > 30$ GeV/c are considered.

Selected muons are required to be isolated with $\sum p_{\mathrm{T}} / p_{\mathrm{T}}^{\mu} < 0.1$, where the sum extends over all charged particle tracks within a cone in η-ϕ-space of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the muon direction of flight, excluding the muon itself.

To reject background from cosmic ray muons, an impact parameter with respect to the primary vertex of $d_{xy} < 0.2$ cm and an opening angle of $\alpha_{\mu\mu} < \pi - 0.02$ between the two muon momentum vectors is required.

All events with two muons passing the selection criteria are used for the following analysis.

The PYTHIA 8 [7, 8] event generator version 8.135 is used for the simulation of the expected signal. Interference terms between the standard model DY process and the virtual graviton are taken into account in the signal generation. The applied parton distribution function is CTEQ6L1 [9].

The DY process is expected to be the dominant background in the present analysis. We use the PYTHIA 6.422 event generator [10] for the simulation of the DY background, including several cross-checks and corrections as described below. Both the signal and the background simulated events are passed through a detailed detector simulation based on GEANT4, assuming a realistic CMS alignment scenario. The detector simulation is followed by the same reconstruction chain as applied on data.

The DY production with PYTHIA 6 evaluates the Feynman diagrams at leading order. The dimuon mass dependent higher order corrections have been studied to improve the DY prediction. Next-to-leading (NLO) electroweak and QCD effects [11] have been evaluated respectively using higher order calculations of HORACE [12] and MC@NLO [13, 14], focusing on the mass region of 500-800 GeV/c^2 which is most relevant for the background prediction in this analysis. The effect of electroweak NLO corrections is found to be negligible if compared with the QCD NLO contribution. Next-to-next-to-leading (NNLO) corrections have been studied with the higher order calculations of FEWZ [15]. The applied mass dependent k-factor on the cross section evaluates to 1.4 in the region around the Z resonance and to 1.45 at masses of 600 GeV/c^2.

Smaller background contributions which have been considered include the pair production of top pairs and QCD multijet production. The $t\bar{t}$ contribution is by one order of magnitude smaller than the DY background, deduced from simulation and the recent measurement of the $t\bar{t}$ cross section [16]. The applied isolation cut and the high invariant mass threshold reduce a possible contamination with QCD events. It has been shown that the QCD background in the dimuon high mass region is negligible [6].

Due to the high efficiency of the dimuon angular requirement, remaining background from cosmic muons is negligible [6].

Using Z candidate events, detailed studies of possible differences in the reconstruction efficiencies of simulated events and data have been performed [17]. No significant deviations have been found up to the statistical limit of about $p_{\mathrm{T}} \approx 200$ GeV/c. This suggests that to the first approximation one can rely on the reconstruction efficiencies as indicated by the simulated events. The uncertainty on the simulated acceptance and reconstruction efficiency in the DY high mass region is estimated to be 3%. The known physical effects for high dimuon masses (Bremsstrahlung) make downward fluctuations of the efficiencies the more likely option. Thus only possible downward fluctuations are taken into account for the statistical evaluation of the overall reconstruction uncertainty. A more conservative value of 4% is used for the respective uncertainty on reconstruction efficiency and acceptance of the signal contribution.

A slight ϕ-dependence of the Z mass has been observed in the 2010 collision data, likely related to the CMS detector alignment. The resulting uncertainty on the background prediction is less than 1%.

The steeply falling DY background is subject to potential changes if the muon momentum resolution deviates from the expected value. Varying the resolution between an ideal detector and a conservatively estimated alignment scenario, the difference in the expected number of background events as a function of the invariant mass cut ranges between 1% and 4% with an increasing tendency towards higher mass cuts. Possible deviations in the muon momentum resolution have a negligible effect on the expected signal contribution with non-resonant mass shape.

The parton distribution functions (PDFs) affect both the expected signal and the expected dominant DY background process. Both the PDF uncertainty of the DY process and the signal have been evaluated using the CTEQ6.6 error PDFs [18]. The resulting relative uncertainty on the integrated standard model DY distribution for masses above $400 - 700$ GeV/c^2 is approximately 5%. For the signal, the uncertainty has been evaluated for all simulated parameter points in

Λ_T, and increases as a function of the dimuon invariant mass, from about 5% at 500 GeV/c^2 to about 15% at $M_{\mu\mu} = 1000$ GeV/c^2.

The luminosity assumed for the statistical evaluation of the dimuon invariant mass spectrum is estimated by scaling the expected DY background in the invariant Z mass region between 60 GeV/c^2 and 120 GeV/c^2 to the measured data distribution. The DY background from the detector simulation is corrected with an NNLO k-factor. The systematic uncertainty on the normalization is estimated to 5.6%, dominated by 5.0% due to PDF uncertainties and higher order corrections, and 2.3% due to muon reconstruction and acceptance. The calculated normalization factor of the simulation to the data is 0.98. This number is well within the estimated uncertainty on the nominal integrated luminosity of 39.7 ± 1.6 pb^{-1}.

The systematic uncertainties are summarized in Table 1. They are given for the integrated dimuon invariant mass spectrum with $M_{\mu\mu} > 600$ GeV/c^2.

Table 1: Summary of the systematic uncertainties for the integrated dimuon invariant mass spectrum with $M_{\mu\mu} > 600$ GeV/c^2.

Systematic Uncertainty	Related Parameter	Signal Uncertainty	Background Uncertainty
Trigger and reconstruction efficiency bkg.	$\epsilon_{\mathrm{reco,b}}$	—	3%
Trigger and reconstruction efficiency signal	$\epsilon_{\mathrm{reco,s}}$	4%	—
Muon momentum resolution	$\epsilon_{\mathrm{res,b}}$	—	4%
Drell-Yan higher order corrections	σ_{b}	—	15%
Drell-Yan PDF uncertainties	σ_{b}	—	5%
Z normalisation	$\mathcal{L}$	6%	6%
Others		—	1%

In Fig. 1 the full dimuon invariant mass spectrum is shown, including the expected contribution from a simulated signal with $\Lambda_T = 1600$ GeV. Data and SM prediction are found to be fully compatible, and no significant excess of events is observed in the dimuon high invariant mass region.

We perform the statistical analysis as a counting experiment with respect to the integrated dimuon invariant mass spectrum above an optimized threshold $M_{\mu\mu,\mathrm{cut}}$. With the final cut value, the probability of observing a number N_{obs} of events is given by the Poisson likelihood

$$L\left(N_{\mathrm{obs}}\right) = \frac{a^{N_{\mathrm{obs}}}}{N_{\mathrm{obs}}!} \cdot e^{-a} \quad , \tag{3}$$

where a is the assumed Poisson mean. Both the background and a potential signal can contribute to the Poisson mean. Summarizing the information from above, it is reasonable to decribe a by

$$a = \mathcal{L} \cdot \left(\epsilon_{\mathrm{reco,s}} \cdot \sigma_s + \epsilon_{\mathrm{reco,b}} \cdot \epsilon_{\mathrm{res,b}} \cdot \sigma_{\mathrm{b}}\right) \quad , \tag{4}$$

where σ_s and σ_{b} are the respective cross sections of the signal and the background. $\mathcal{L}$ is the luminosity and the parameters ϵ_{reco} refer to the reconstruction efficiencies of signal and background. A separate nuisance parameter $\epsilon_{\mathrm{res,b}}$ is used to model the uncertainty on the muon momentum resolution.

Using a Bayesian approach, the limits on the parameter of interest σ_s can be calculated from the posterior distribution given by

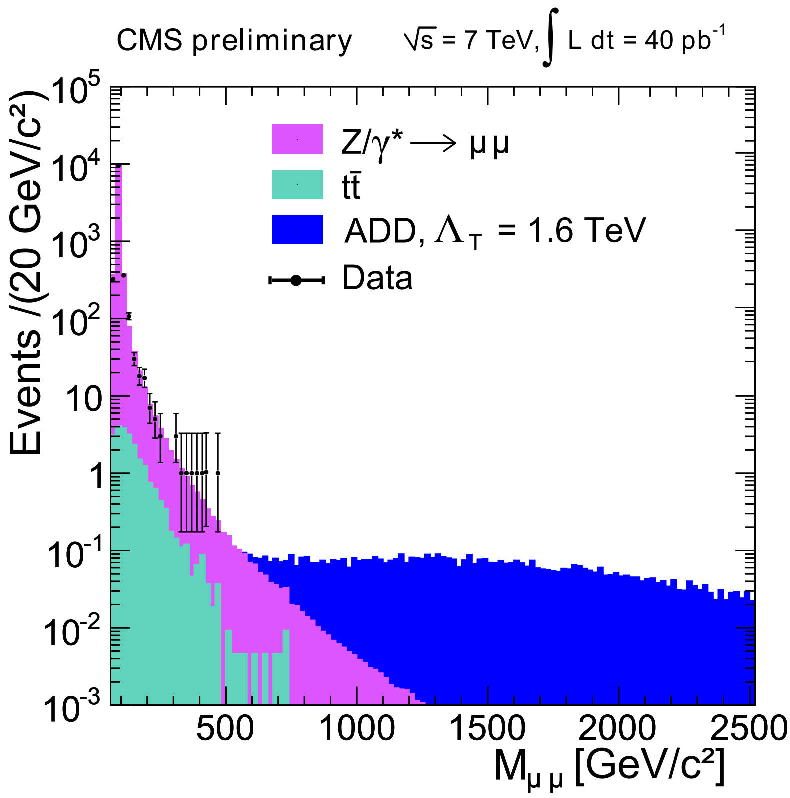

Figure 1: Dimuon invariant mass spectrum compared with the SM prediction and a simulated ADD signal with $\Lambda_T = 1.6$ TeV.

$$\Pi_{\text{post}}\left(\sigma|N_{\text{obs}}\right) = \int d\mathcal{L}\, d\epsilon_{\text{res,b}}\, d\epsilon_{\text{reco,b}}\, d\epsilon_{\text{reco,s}}\, d\sigma_{\text{b}}\, \frac{a^{N_{\text{obs}}}}{N_{\text{obs}}!} \cdot e^{-a} \cdot \pi\left(\mathcal{L}, \epsilon_{\text{res,b}}, \epsilon_{\text{reco,b}}, \epsilon_{\text{reco,s}}, \sigma_{\text{b}}\right) \cdot \pi_{poi}\left(\sigma_s\right) \quad , \tag{5}$$

where the terms $\pi\left(\cdot\right)$ refers to the combined prior function for the nuisance parameters. A flat prior $\pi_{poi}\left(\sigma_s\right)$ is applied as prior function of the parameter of interest.

The BATCalculator tool which is included in BAT (Bayesian Analysis Toolkit) [19] and connects the BAT package with RooStats [20] is used to calculate the limits with the help of Markov Chain Monte Carlo methods.

Limits on σ_s can be translated into limits on Λ_T in the GRW convention by combining the information on the expected signal efficiency from the simulated signal samples with additional LO cross section information calculated with PYTHIA 8.135.

The lower bound on $M_{\mu\mu}$ is optimized with respect to the expected Bayesian 95% upper limit on Λ_T at 40 pb^{-1}. The optimal cut value $M_{\mu\mu,\text{cut}}$ depends only slightly on the assumed validity range of the model, which we vary between M_s and $\sqrt{s} = 7$ TeV. Based on simulation studies we choose $M_{\mu\mu,\text{cut}} = 600$ GeV/c^2 for the final analysis.

No events are observed in the data above $M_{\mu\mu,\text{cut}} = 600$ GeV/c^2, in agreement with the background expectation of 0.48 events. The signal efficiencies for ADD models in the interval $\Lambda_T \in [0.8, 1.8]$ TeV and the considered validity ranges in $M_{\mu\mu}$ between 1 TeV/c^2 and 7 TeV/c^2 vary from 82% to 94%. The corresponding observed 95 % Bayesian upper limits on σ_s are found to be between 0.088 and 0.098 pb.

The limits on σ_s are translated into exclusion limits on the ADD model parameter Λ_T in the GRW convention. Fig. 2 shows the observed limits obtained under the hypothesis of different ranges of validity of the model, assuming no signal contribution beyond a given cut-off. The limits on Λ_T are shown for the leading order ADD scenario and for an assumed conservative NLO k-factor of 1.3 for the ADD signal contribution, based on QCD NLO corrections on dilepton processes in the ADD model [21, 22].

Additionally, the observed limit on σ_s can be interpreted in terms of the HLZ parameters n and M_s as shown in Fig. 2.

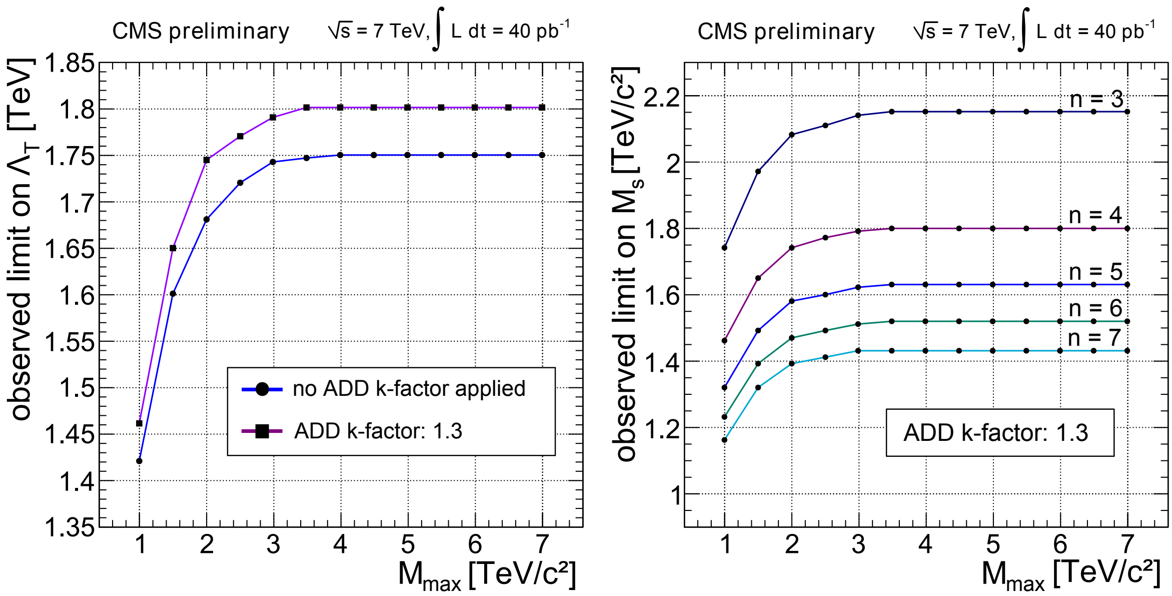

Figure 2: (Left) Observed 95% upper limit on Λ_T for different cut-offs $M_{\max}$ for the validity of the ADD model. (Right) Observed 95% upper limits on M_s for different numbers of extra dimensions n.

Table 2 summarizes the limits for the two cases of full model validity in $\sqrt{\hat{s}}$ and truncation at $M_{\mu\mu} = M_s$.

Table 2: Observed 95% upper limits in TeV with respect to GRW and HLZ conventions for full model validity in $\sqrt{\hat{s}}$ and truncation at $M_{\mu\mu} = M_s$. A k-factor of 1.3 is assumed for the ADD signal.

	Λ_T [TeV] (GRW)	M_s $\left[\mathrm{TeV}/c^2\right]$ (HLZ)					
		$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
Full	1.80	1.75	2.15	1.80	1.63	1.52	1.43
Truncated	1.68	1.67	2.09	1.68	1.49	1.34	1.24

In conclusion, we have presented a search for the effects of large extra dimensions in the dimuon invariant mass spectrum using the CMS detector at the LHC. Data and SM prediction have been found to be fully compatible, and no significant excess of events has been observed in the dimuon high invariant mass region. No events are observed above the optimized cut of $M_{\mu\mu} = 600$ GeV/c^2. The observed 95% C.L limits on ADD models for $n > 2$ are found to improve the current Tevatron limits [23], if the description of the ADD model with an effective field theory is valid up to sufficiently high energies, and provide the best limits based on dimuon events to date.

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