

Search for TeV-scale bosons in the dimuon channel at the LHC.

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Extended gauge models and the Randall-Sundrum model with extra-dimension predict the existence of TeV-mass resonances. The LHC potential for a five sigma level discovery was investigated as described in this document. Final states containing large invariant mass di-muons from Z' and the RS1 graviton were studied. The possibility of discriminating between different Z' model by measuring the muon forward-backward asymmetry was investigated. The determination of the spin of the resonance is also discussed.

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1 Introduction

The Standard Model (SM) has been tested by the experiments at LEP, SLC and Tevatron with a high accuracy. In particular, the yield of lepton pairs produced mainly via Drell-Yan processes, i.e. quark-antiquark annihilation by exchange of photons or Z bosons, is predicted by the SM with a per mille precision. So far, the experimental data have shown no significant deviation from the SM predictions for the Drell-Yan continuum up to TeV-energy-scale. The high-order calculations of lepton pair production cross section in the mass region of $0.1 \div 1 \text{ TeV}/c^2$ are indeed in good agreement with D0 and CDF data [1, 2].

At present, however, there are many theoretical attempts to extend the bounds of the SM in order to incorporate the unification of strong and electroweak interactions, the mass hierarchy and CP-violation problems, the arbitrariness of flavor mixing and the number of generations, etc. Supersymmetry is the most popular theoretical extension to the SM. However, as an alternative, also extended gauge models, based on symmetry groups wider than in the SM, have been considered. This way leads to the various left-right symmetric models, extended gauge theories including grand unification theories, and models of composite gauge bosons [3, 4]. In all these cases, new vector bosons, neutral Z' and charged W' , would appear at a mass scale of the order of one TeV/c^2 what can be observed at LHC.

One of the most attractive and exciting, although the most complicated, goal of modern theoretical physics is to provide a "unified" description of all forces known in nature and give an adequate explanation of the creation and the evolution of the Universe. The quite new paradigm of the gravity at TeV energies, as given in the large or infinite extra dimension (LED) and brane world scenarios, which propose a solution of gauge hierarchy problem, have recently discussed [5].

One of the possible LED scenarios is the Randall-Sundrum (RS) approach [6] based on the warp phenomenology of the AdS_5 nonfactorizable geometry with the curvature $k \sim M_{\text{Pl}} \sim 10^{19} \text{ GeV}/c^2$ and the metric

$$ds_2^2 = e^{-kr_c\phi} \eta_{\mu\nu} dx^\mu dx^\nu + r_c^2 d\phi^2.$$

Here, r_c , is the compactification radius of the extra dimension, $\eta_{\mu\nu}$ is the standard four-dimensional Minkowski metric, x^μ are ordinary four-dimension coordinates and ϕ is the extra dimension coordinate. The distinctive feature of the RS phenomenology with two branes (one with positive tension σ at $\phi = 0$ and the other with negative tension $-\sigma$ at distance r_c), so-called RS1 model [6], is the infinite tower of Kaluza-Klein graviton modes appearing at the scale $\Lambda_\pi = M_{\text{Pl}} e^{-kr_c\pi}$. It has a zero mode, $m_0 \sim e^{-kr_c}$, describing the usual four-dimensional gravity and massive modes with the mass splitting between them of order $\Delta m \sim k e^{-kr_c}$. The exponential factor $e^{-kr_c\pi}$ removes the hierarchy between the Planck and electroweak scales if $kr_c \approx 11 \div 12$. The first Kaluza-Klein graviton mode (called the RS1 graviton below), as well as Z' , is strongly coupled to ordinary particles.

In both the conceptions above, the width of the predicted resonances is not fixed, it can vary widely depending on the model parameters. It implies that these states can appear as individual resonances or can affect the high- p_T lepton pairs continuum leading to an excess of Drell-Yan production. Thus, the distinctive experimental signature for these processes is a pair of well-isolated high- p_T leptons with opposite charges coming from the same vertex.

These measurements can be performed at the both LHC experiments, ATLAS and CMS, which is expected to be able to trigger and identify hard muons with a transverse momentum up to several TeV. The ability of the LHC experiments to detect virtual RS1 graviton in the muon mode was investigated as described in Ref. [7]. In this paper, the analysis of the LHC discovery limit of Z' and both virtual and real RS1 gravitons are presented.

2 Extra gauge bosons

2.1 Signal and background simulations

The signal simulation is done for the parton subprocess $q\bar{q} \rightarrow Z'$ in the QCD leading order without high order corrections. To generate the Z' boson and its decay to a muon pair as well as the relevant background events, the PYTHIA 6.217 [8] package with the CTEQ5L parton distribution function was used. There are many possible non Standard Model scenarios which predict the existence of heavy neutral Z' and/or charged W' gauge bosons (reviews in [3]). The Z' models which were used for this analysis are the following:

1. The Left-Right model (LR) [9] based on the electroweak gauge group symmetry $\text{SU}(2)_L \times \text{SU}(2)_R \times \text{U}(1)_{B-L}$ (here, B and L are the baryon and lepton numbers) with default PYTHIA couplings which are the same for both left- and right-handed type of fermions and are set to the same values as in the

SM, $g_L = g_R = 0.64$. The number of extra fermion generations is equal to three.

2. Z'_χ -, Z'_{η^-} -, and Z'_ψ -models which naturally arise as a result of the sequential breaking of $SO(10)$ or E_6 group symmetry for Grand Unified Theories (GUT) [4]: $E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi \rightarrow SM \times U(1)_{\theta_6}$. The linear combination of the hypercharges of the two groups $U(1)_\chi \times U(1)_\psi$ gives the charge of the lightest Z' at the symmetry-breaking energies $Z' = Z'_\chi \cos(\theta_{E_6}) + Z'_\psi \sin(\theta_{E_6})$. The numerical values of the couplings for these models are taken from Ref. [10]
3. Also used for Monte Carlo studies is the "sequential" standard model (SSM) [11] in which the heavy bosons (Z' and W') are assumed to couple only to one fermion type (left) with the same parameters (couplings and the total width) as for ordinary Z^0 and W^\pm in the Standard Model.

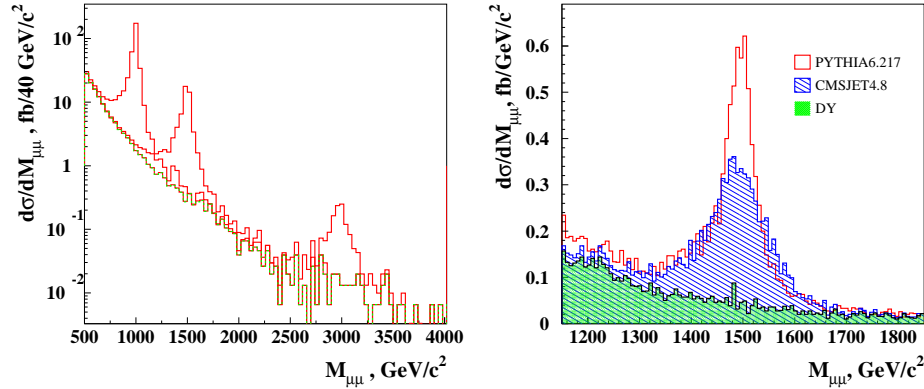


Fig. 1. Production cross section of muon pairs as a function of their invariant mass. Muons from Z'_χ decay over Drell-Yan continuum, as generated by PYTHIA 6.217 (left), and after reconstruction with CMSJET 4.8 (right). The generated distribution is presented as the open histogram, the detector response by line hatched one, and the Drell-Yan background after CMSJET by full hatched one.

The non-reducible background considered is the Drell-Yan processes $pp \rightarrow Z/\gamma \rightarrow \mu^+\mu^-$ which gives nearly 95 % of the the Standard Model muon continuum. The contribution from the other reaction (vector boson pair production (ZZ , WZ , WW), and $t\bar{t}$ production) is very small and is neglected in this study. In the SM the expected number of di-muon events is not very large and the Z' resonance peak exceeds the background by about a factor ten (Fig. 1, left plot).

2.2 Z' discovery limits

Event samples for seven mass values were generated with the above-mentioned model parameters. To take into account the detector response the parametrization

of the muon momentum (p) resolution, $4\%/\sqrt{p/\text{TeV}}$, was used. The di-muon is accepted when both decay muons pass through all chambers of the CMS muon detector system covering the pseudorapidity region of $|\eta| \leq 2.4$ with the efficiency presented in the Fig. 2 (left plot, upper line). No cuts are made on the isolation of muons in the tracker and calorimeter. For each mass point, muon pairs were selected inside the mass window defined as $\pm 3\Gamma_{obs}$ around the Z' mass. The Γ_{obs} is defined as the observed width of the resonance state after smearing due to detector effects. In addition, the cut $p_T \geq 20 \text{ GeV}/c$ was applied on each muon. The total efficiency of dimuon selection, ϵ , is given in Fig. 2 (left plot, lower line). As Fig. 1 (right plot) shows, the detector effects lead to significant smearing (line hatched histogram) of the initial resonance peak (open histogram), but it is still clearly visible over Drell-Yan background (full hatched).

The product of the Z' production cross section and the branching ratio is shown in Fig. 2 (right plot) for Z'_{SSM^-} , Z'_{χ^-} , Z'_{ψ^-} , Z'_{η^-} -models (the curve corresponding Z'_{LR^-} -model is not drawn). The efficiency of di-muon pair selection, ϵ , is also taken into account.

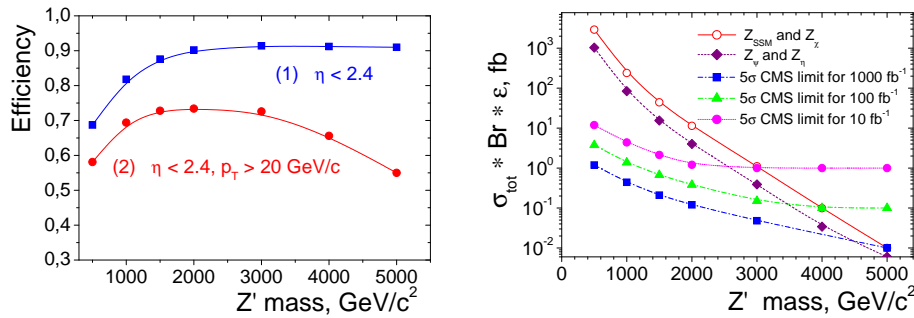


Fig. 2. Efficiency of the di-muon selection as a function the di-muon effective mass (left). The product of the cross section and the branching ratio for the Z' decay into muon pairs (right). The five σ LHC limits to observe these states are also presented for various integrated luminosities.

To estimate the Z' discovery limit the expected significance of the signal, S/\sqrt{B} , was computed, where S is the number of signal events passed through all kinematics cuts and B is the number of background events. In order to insure the statistical significance of the signal for low background the minimal number of signal events, S_{min} , equal to ten has been required, i.e. $S_{min} = \max(5\sqrt{B}, 10)$.

The discovery limits for a five σ signal are presented in Fig. 2 (right plot) for various integrated luminosity: 10 fb^{-1} , 100 fb^{-1} , 1000 fb^{-1} (three bottom-up curves). As shown in this picture, the Z' boson can be detected up to masses given in Table 1.

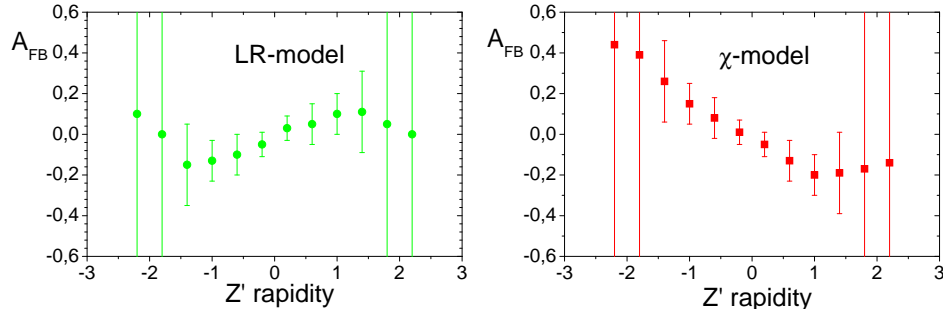
The detection of the Z' peak and the very precise measurement of its mass and width do not allow the theoretical model describing the Z' to be identified. To test the helicity structure of the boson and discriminate between the Z' models, the leptonic forward-backward asymmetry can be used (see, for an example, [12]).

The asymmetry is defined as the ratio $A_{FB} = \frac{(F-B)}{(F+B)}$, where F and B are the number of the events in the forward and backward direction, respectively. Forward (backward) is defined as the hemisphere with $\cos(\theta) > 0$ ($\cos(\theta) < 0$), where θ is the angle between the outgoing negative lepton and the quark q in the $q\bar{q}$ rest frame. Such definition assumes that the original quark direction is known, but this is not the case for the pp-experiment. In Ref. [13], however, it was shown that it is possible to approximate the quark direction with the boost direction of the di-muon system with respect to the beam axis.

Table 1. The Z' search reach for CMS in TeV/c^2 .

Models	10 fb^{-1}	100 fb^{-1}	1000 fb^{-1}
SSM, χ	3.01	3.96	5.0
ψ, η	2.54	3.46	4.48
LR	2.96	4.08	5.35

One of the features of the asymmetry, A_{FB} , is the distinctive rapidity-dependence for different Z' models. Such dependence is shown in Fig. 3 for the Z'_{LR} (left picture) and the Z'_{χ} (right picture) under assumption of a mass $M_{Z'} = 2.0 \text{ TeV}/c^2$, for 100 fb^{-1} integrated luminosity.

Fig. 3. Muon forward-back asymmetry as function of the Z' rapidity, $M_{Z'} = 2.0 \text{ TeV}/c^2$.

3 RS1 graviton

3.1 Signal and background simulations

The ability to test experimentally the RS1 scenario predictions depends on the model parameter $c = k/M_{Pl}$ which controls the coupling of the graviton to the ordinary particles and the width of the resonance $\Gamma \sim \rho m_0 c^2$, where the constant ρ is determined by the number of open decay channels. The theoretical limitations give the allowed range for the coupling constant $0.01 \leq c \leq 0.1$.

The graviton resonances can be produced *virtually* via quark-antiquark annihilation $q\bar{q} \rightarrow G_{KK}$ as well as gluon-gluon fusion $gg \rightarrow G_{KK}$. The first of these

processes is identical to the Standard Model s -channel exchange of an intermediate γ^* or Z vector boson, while the second one has no SM analogue. Other partonic sub-processes are also possible, $gg \rightarrow g G_{KK}$, $q\bar{q} \rightarrow g G_{KK}$, $gq \rightarrow q G_{KK}$, which form a *real* graviton via the t -channel exchange (graviton emission).

To simulate both real and virtual graviton production in the proton-proton collisions at 14 TeV center-of-mass energy, PYTHIA 6.217 was used in which the RS1 scenario was implemented with CTEQ5L parton distribution functions.

The graviton production cross section for all five possible diagrams is presented in Table 2. Here, two opposite possibilities for model parameter c were considered. For the first case, which is the most difficult case for experimental detection, the constant $c = 0.01$ was used (the number in the brackets), and the second, the most optimistic, scenario when c is equal to 0.1. The majority (at least 50 ÷ 60 % depending on the mass) of the gravitons is produced in processes of gluon-gluon fusion with real graviton emission, whereas the virtual graviton production adds up to 15 % only of the total cross-section.

Table 2. Cross sections of G_{KK} production in fb. The CTEQ5L parton distributions and K -factor=1 have been used.

Mass, TeV/ c^2	1.0	1.5	3.0
$q\bar{q} \rightarrow G_{KK}$	129 (1.34)	23 (0.24)	0.633 (0.006)
$gg \rightarrow G_{KK}$	567 (5.33)	62 (0.53)	0.94 (0.004)
$q\bar{q} \rightarrow g G_{KK}$	345 (3.29)	65 (0.64)	1.84 (0.017)
$qg \rightarrow q G_{KK}$	599 (5.78)	72 (0.64)	1.05 (0.007)
$gg \rightarrow g G_{KK}$	3350 (31.5)	368 (3.32)	4.98 (0.028)
Total	4990 (47.2)	590 (5.38)	9.45 (0.062)

The Standard Model background for this channel is the same as for the Z' case.

3.2 Detection of RS1-graviton resonance and discovery limits

The simulation of the detector response for the graviton decay into muon pair is similar to the Z' case (Sect. 2.2). To estimate the discovery limit for the RS1 graviton the same procedure as for the Z' case was applied. The cross section of G_{KK} production and the corresponding cross section limits to observe a five σ signal, for various integrated luminosity, are presented in Fig. 4. As shown in the figure, the LHC can test the RS1 scenario in the whole range of the model parameter ($c = 0.01$) up to a mass of 2.0 TeV/ c^2 even with a low luminosity of 10 fb $^{-1}$. In the more favourable case with $c = 0.1$ the accessible mass region is extended up to 3.7 TeV/ c^2 . With 100 fb $^{-1}$ the reach increases to 2.6 TeV/ c^2 for $c = 0.01$ and 4.8 TeV/ c^2 for $c = 0.1$.

The results of the combined analysis in the RS1 scenario [14] show that the value of the dimensionless coupling constant c and the corresponding value of the graviton

mass are strongly restricted due to the experimental Tevatron data and theoretical constraints to assure the model hierarchy ($\Lambda_\pi < 10$ TeV). The limitations lead, in particular, to the conclusion that the constant c can not be less than 0.027, for the graviton mass of one TeV/c^2 , and less than 0.1, for the mass of $3.7 \text{ TeV}/c^2$. The direct comparison of these results with the data of the Fig. 4 shows that the whole space of the RS1-model parameters is accessible to CMS at luminosity of 100 fb^{-1} , and the RS1 graviton can be discovered with the five σ significance. These conclusions, however, are not definitive, since the initial theoretical constraints are very arbitrary.

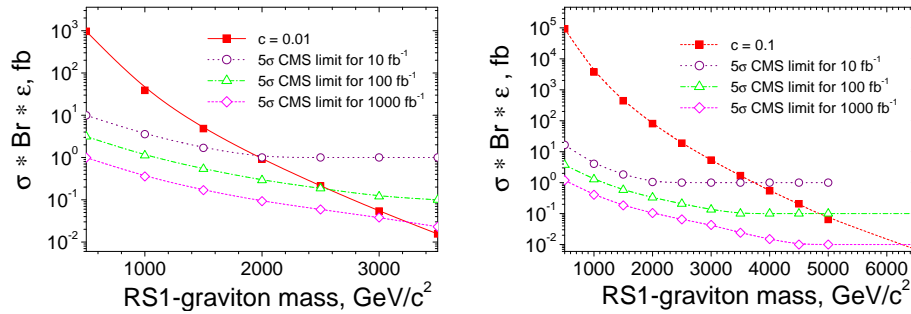


Fig. 4. Cross section of the G_{KK} production *vs* their mass for $c = 0.01$ (left) and $c = 0.1$ (right). The five σ limits to observe these states are also presented for various integrated luminosities.

Under the assumption that the new resonance state is observed at LHC, the nature of this object should be understood (in principle, it can come from the extended gauge sector as well as from any version of extra dimensions). The major difference between the Z' and the RS1 graviton should appear in the $\cos(\theta^*)$ distribution (where θ^* is the polar angle of the muons in the center-of-mass system of the di-muon pair) which is strongly spin dependent. Certainly, these distributions will be distorted by acceptance cuts, especially in the region of large angles, and the expected theoretical predictions will differ from experimental ones. Nevertheless Fig. 5 shows a distinct difference between the spin-1 (Z') and the spin-2 (RS1 graviton) curves obtained for muons after all cuts. To ease the comparison, these plots were obtained for resonance states with mass of $1.5 \text{ TeV}/c^2$, and normalized to 6000 events that correspond to an approximate integrated luminosity of 10 fb^{-1} for graviton production with $c = 0.1$ and 100 fb^{-1} for Z' boson.

4 Summary

This work presents the discovery potential of Z' gauge bosons as well as RS1 gravitons in the muon channel at the LHC experiments. The estimated discovery limit for Z' is about $3.5 \div 4.0 \text{ TeV}/c^2$, depending on the couplings, for 100 fb^{-1} integrated luminosity. At the same luminosity, zero KK-modes of the RS1 graviton

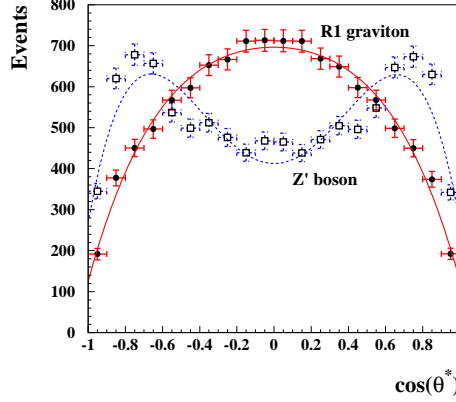


Fig. 5. Angular distributions $\cos(\theta^*)$ of the muons from the G_{KK} (solid marker) and the Z' (open box) decays.

state can be observed up to $2.6 \text{ TeV}/c^2$ and $4.8 \text{ TeV}/c^2$ for $c = 0.01$ and 0.1 , respectively. The angular distribution of the muons in the final state can be used to distinguish the spin-1 and the spin-2 hypotheses, at least in the mass region up to $1.5 \text{ TeV}/c^2$. The different Z' models can be distinguished (up to mass of two TeV/c^2) because of the different the leptonic forward-backward asymmetry.

Further detailed studies are required on the theoretical side in order to identify other possible physics observables. This would be helpful to better understand the LHC discovery conditions and limits.

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