Search for new heavy resonances at the LHC

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Abstract

In this article we carry out an analysis of LHC potential to search for new dimuon resonance states from extended gauge models and the Randall-Sundrum scenario of TeV-scale gravity.

1 Introduction

The Standard Model (SM) had been tested in many 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 deviations from 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 $0.1 \div 0.8$ TeV/c^2 are in good agreement with LEP and D0 data [1, 2]. At present, however, there are many theoretical attempts to extend the bounds of the SM in order to reach unification of strong and electroweak interactions or remove an arbitrariness in values of coupling constants in some other way and also to pull through known disadvantages of SM like the mass hierarchy problem, CP-violation problem etc. Supersymmetry is the most popular theoretical extension of the SM, however, some other alternatives also exist. Between them one can consider extended gauge models (what contain extended sector of gauge bosons in comparison with the SM). Consideration of symmetry groups wider than in the SM and appearance of extra gauge bosons is common feature of various left-right symmetric models, all variants of Grand Unification theories and models of composite gauge bosons [3, 4]. For all of these cases new vector bosons, neutral Z' and charged W', would appear at the mass scale of order of one TeV/c^2 what can be observed at the LHC. Another alternative way to go beyond the SM can be to consider so-called TeV-scale gravity models, as given by brane world scenarios with large or compact extra spatial dimensions (LED) [5, 6]. These models give in particular a set of new particle - massive Kaluza-Klein modes of graviton what can interact with the usual matter and contribute to the SM processes causing some new interesting physics at the TeV energy scale (for more details and a phenomenology review see, for example [8, 9]).

In our consideration we touch on only one of the possible LED scenarios, the Randall-Sundrum (RS1) approach [6]. The standard setup for this approach contains two three-branes embedded into the external curve five-dimensional space, one brane is with negative tension (our world with all usual SM fields) and another one is with positive tension (Planckian brane) what is needed to reproduce the SM mass hierarchy. The usual assumption is that all the SM fields and fields from the planckian sector are confined on corresponding branes and effectively four-dimensional. Graviton is only really multidimensional field what can travel freely through the whole space (the bulk space). Because of nonzero curvature of the bulk space (what is represented by a slice of the five-dimensional AdS space bounded by two branes) and the specific space-time geometry new very interesting physics can be realized at our brane. In particular, in any model with compact extra spatial dimensions each matter field will have an infinite tower of massive excitations called Kaluza-Klein modes (four-dimensional "projections" of multidimensional fields from our point of view). These modes can be visible at energy above the fundamental theory scale, say, from energies above one or a few TeV. Then our usual massless four-dimensional graviton can be treated as the zero mode from the KK-tower. But the distinctive feature of particular RS1 phenomenology is that excited massive graviton states are strongly coupled to ordinary particles (not suppressed below the planckian scale like for ordinary graviton in usual description of gravity) and can contribute significantly to the SM processes above the fundamental scale. Mass splitting between KK-modes of graviton is of order $\Delta m \sim k e^{-k r_c}$ [8], and values of masses start from the TeV scale. So, at least the first Kaluza-Klein mode (called RS1 graviton below) can in principle be observed at the LHC as individual heavy (quite narrow or not) resonance.

At this point it is interesting to note that there exist also some realizations of TeV-scale gravity models where fields other than graviton can have Kaluza-Klein modes, see for example a number of papers [7] [1]. In the papers interesting scenarios based on superstring theory were proposed in which all gauge bosons and higgses as far as their superpartners had KK-excitations. We will not touch on such scenarios in our further discussion but we would stress that study of phenomenological consequences of the existence of KK-modes of Z^0 or photon can be done exactly in the same spirit as it is presented in subsections 2.1 – 2.2 below for Z' including an asymmetry analysis.

For both of the conceptions considered, Z' and RS1 graviton, a width of predicted resonances is not fixed but 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 pair 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.

Such the measurements can be performed at the both of LHC experiments, ATLAS and CMS, which are 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 RS1 graviton in the dielectron mode was investigated as described in Ref. [10]. In this paper, we present the analysis of the LHC discovery limit on Z' and RS1 gravitons in dimuon mode in assumption of the CMS acceptance.

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 leading order of QCD without higher order corrections. To generate Z' boson and its decay to a muon pair as well as the relevant background events, the PYTHIA 6.217 package [11] with the CTEQ5L parton distribution function was used. There exist a number of possible non Standard Model scenarios which predict appearance of heavy neutral Z' and/or charged W' gauge bosons (for review see [3]). But only following Z' models were used in our analysis:

1. The Left-Right model (LR) [12] based on the electroweak gauge group symmetry $SU(2)_L{\times}SU(2)_R{\times}U(1)_{B-L}$ with an additional left-right symmetry (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. $Z'_\chi-$, $Z'_\eta-$, and Z'_ψ - models which naturally arise as a result of sequential breaking of SO(10) or E_6 symmetry group in 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 under the two groups $U(1)_\chi{\times}U(1)_\psi$ gives the charge of the lightest Z' at the symmetry-breaking energies Z' $= Z'_\chi cos(\Theta_{E_6}) + Z'_\psi sin(\Theta_{E_6})$. Numerical values of the couplings for these models are taken from Ref. [13].

3. For Monte Carlo studies the sequential standard model (SSM) [14] was also used in which heavy bosons (Z' and W') are assumed to couple only to one fermion type (left) with the same parameters (couplings and total widths) as for ordinary Z^0 and $W^\pm$ in the Standard Model.

The non-reducible background considered is the SM Drell-Yan process $pp{\rightarrow}Z/\gamma{\rightarrow}\mu^+\mu^-$ which gives nearly 95 % of the Standard Model muon continuum. Contributions from other reaction (vector boson pair production ZZ, WZ, WW, quark-antiquark production $t\bar{t}$ etc) are very small and neglected in this study. In the SM the expected number of dimuon events is not very large and the Z' resonance peak exceeds the background by above a factor ten (Fig. 1, the left plot). The mass dependence of Z' production cross secrion times on dimuon branching are given in Fig. 1 (the right plot). For comparison the cross section for standard Drell-Yan muon pair production as a function of their invarinat masses is also presented on the same figure.

[1]Authors are grateful to I.Antoniadis who has drawn our attention to this issue

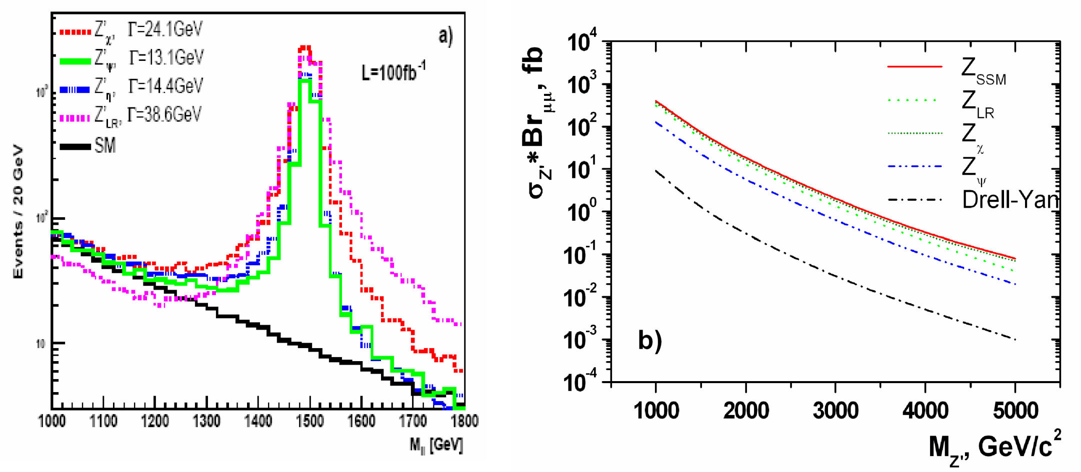

Figure 1: Invariant mass distribution of dimuon pairs for extended gauge models and SM (a) (from [15]). Cross section of dimuon produced from Z' decay in dependence on a mass scale (b). Also the SM prediction for DY is presented (the lower curve)

2.2 Z' discovery limits

Event samples for seven mass values were generated with above-mentioned model parameters. To take into account the detector response the parametrization of a muon momentum (p) resolution, $4\%/\sqrt{p/TeV}$ [16], was used. The dimuon is accepted when both decay muons are within detector system covering the pseudorapidity region of $|\eta| \leq 2.4$. In addition, the cut $p_T \geq 20$ GeV/c was applied on each muon. No cuts were made on isolation of muons in the tracker and the calorimeter. The total efficiency dimuon selection, ε, is about 83÷91 %.

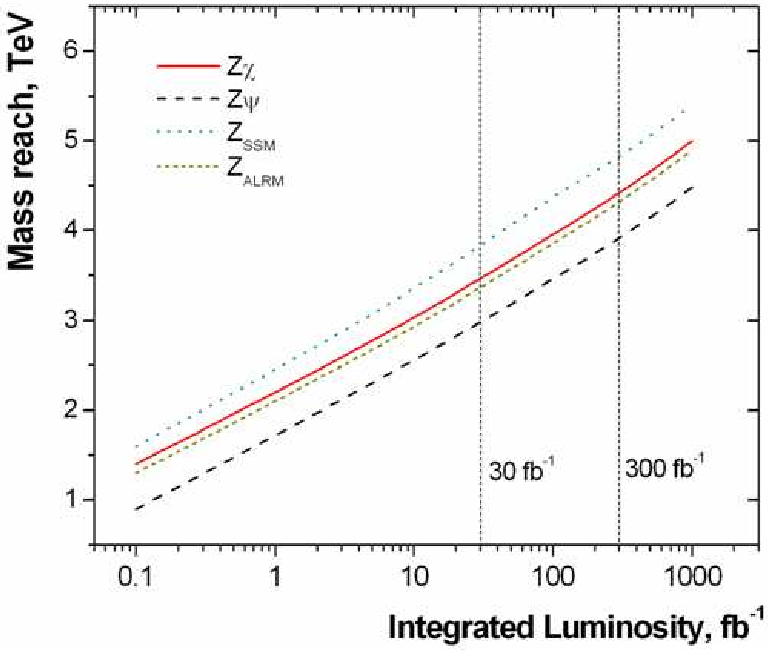

Figure 2: Upper limit for Z' mass with statistical significance of the signal of 5σ

To estimate the Z' discovery limit expected significance of the signal, S_{c12}=$\sqrt{S+B}$-$\sqrt{B}$, was computed, where S is the number of signal events passed through all kinematics cuts and B is the number of background events. The discovery limits for a five σ signal are presented in Fig. 2.

Detection of the Z' peak itself and precise measurement of its mass and width does not allow an underlying theoretical model describing the Z' to be identified. To test a helicity structure of the boson and discriminate between a number of Z' models, a leptonic forward-backward asymmetry can be used (see, for example, [17]). The asymmetry is defined as the ratio $A_{FB} = \frac{(F-B)}{(F+B)}$, where F and B are the numbers of events in the forward and backward directions, respectively. Forward (backward) is defined as the hemisphere with $cos(\Theta) > 0$ ($cos(\Theta) < 0$), where Θ is an angle between the outgoing negative lepton and the quark q in the $q\bar{q}$ rest frame. Such a definition assumes that the original quark direction is known, but this is not the case for the pp-experiment. In Ref. [18], however, it was shown that it is possible to identify the quark direction with the boost direction of the dimuon system with respect to the beam axis.

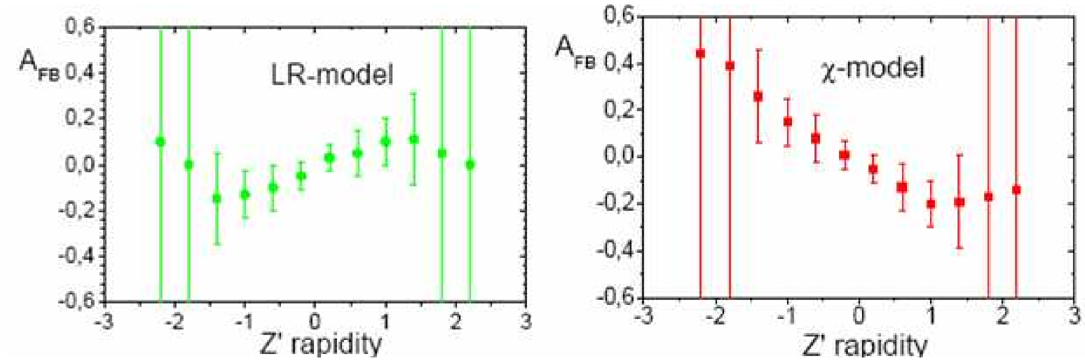

Figure 3: Forward-backward asymmetry for different Z' models.

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

Logic of such an analysis looks quite consequent but it is not complete in general as another one possibility is not accounted by it. As it was yet pointed out (see comments on the theme in Introduction above) one can image a situation when we will see a resonance at collider with a mass about TeV and quantum numbers of gauge boson what can be in principle not Z' from the extended gauge sector but Kaluza-Klein excitation Z_{KK} coming from models with extra spatial dimensions. The only way to distinguish these quite different cases when will be to look for other KK-excitations of other gauge bosons (photon, gluon) what must exist in the presence of extra dimensions [7].

3 RS1 graviton

3.1 Signal and background simulations

As it was mentioned above the RS1 model predicts massive KK-modes of graviton ($m_{KK} \approx$ a few TeV) which can been observed in experiments as heavy narrow resonance states (Fig. 4). It is necessary to note here that an effect from KK-gravitons can also been extracted from changing of Higgs boson rates because of mixing of them with radion (see Ref. [19])

The ability to test experimentally RS1 scenario predictions depends on the model parameter $c = k/M_{Pl}$ which controls coupling of graviton to the ordinary particles and a width of the resonance $\Gamma \sim \rho m_0 c^2$; where the constant ρ is determined by the number of open decay channels. Results of the combined analysis in the RS1 scenario [20] show that a value of the dimensionless coupling constant c and a corresponding value of graviton mass is restricted due to the experimental Tevatron data and theoretical constraints to assure the model hierarchy ($\Lambda_\pi < 10$ TeV). These 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 TeV/c^2. We operated in our consideration the range for coupling constant $0.01 \leq c \leq 0.1$. Graviton resonances can be produced via quark-antiquark annihilation $q\bar{q} \to G_{KK}$ as well as gluon-gluon fusion $gg \to G_{KK}$. The first of these processes is identical to the Standard Model s-channel exchange by an intermediate $\gamma^\star$ or Z vector boson, while the second one has no SM analogue. Other

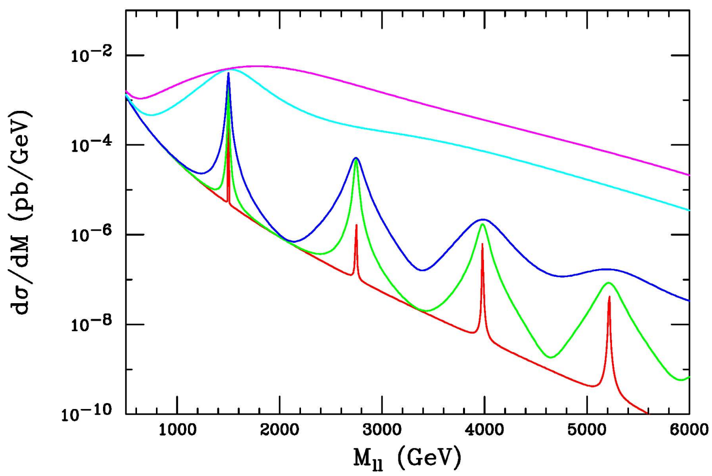

Figure 4: Invariant mass distributions for Drell-Yan process for the LHC. From top to bottom, the curves are for coupling values c = 1, 0.5, 0.1, 0.05, 0.01 (taken from [20])

partonic sub-processes are also possible, $gg \to gG_{KK}$, $q\bar{q} \to gG_{KK}$, $gq \to qG_{KK}$, which form real graviton production 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 1. Here, two extreme possibilities for model parameter c were considered. The first one was the most optimistic scenario when c is equal to 0.1. The second number in each row (in brackets) corresponds to the most difficult for experimental observation case when the coupling value $c = 0.01$. The majority (at least 50÷60 % depending on a mass) of gravitons was produced in the process of gluon-gluon fusion with real graviton emission, whereas virtual graviton production added only up to 15 % of the total cross-section. The Standard Model background for this channel was the same as for the Z' case.

Table 1: Leading-order cross section of $\mathrm{G_{KK}}$ production in fb. The CTEQ5L parton distributions have been used.

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

3.2 Detection of RS1-graviton resonance and discovery limits

Simulation of the detector response for graviton decay into muon pair is similar to the Z' case. To estimate the discovery limit for RS1 graviton excitations the same procedure as for the Z' case was applied. The cross section of G_{KK} production and corresponding cross section limits to observe a five σ signal for various integrated luminosity cases are presented in Fig. 5. As shown in the figure, the LHC can test the RS1 scenario in the whole range of the model parameter c up to the mass of 2.0 TeV/c^2 even at the 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} of integrated luminosity the reach increases up to 2.6 TeV/c^2 for c=0.01 and 4.8 TeV/c^2 for c=0.1.

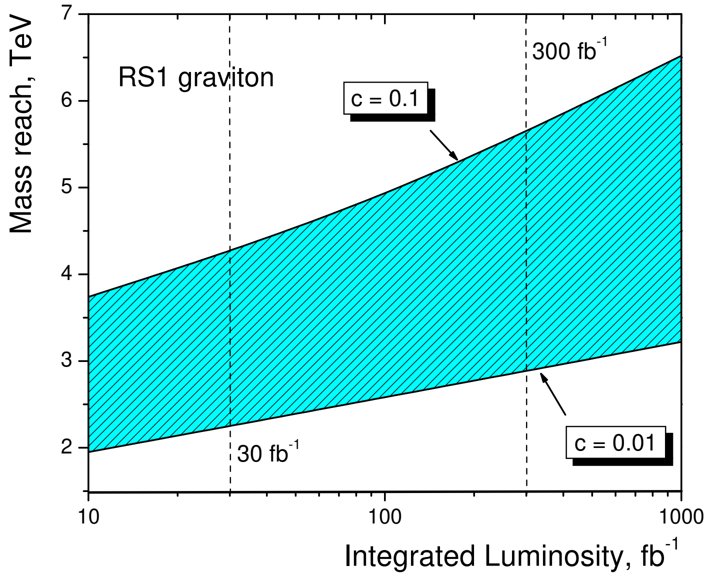

Figure 5: Five σ discovery limits for RS1 graviton decayed into dimuon pair.

The direct comparison of results on an allowed region for c with the data of the Fig. 5 shows that the whole space of the RS1-model parameters is accessible at the luminosity of 100 fb^{-1}, and RS1 graviton can be discovered with the five σ significance. These conclusions, however, are not definitive, since initial theoretical constraints are very arbitrary.

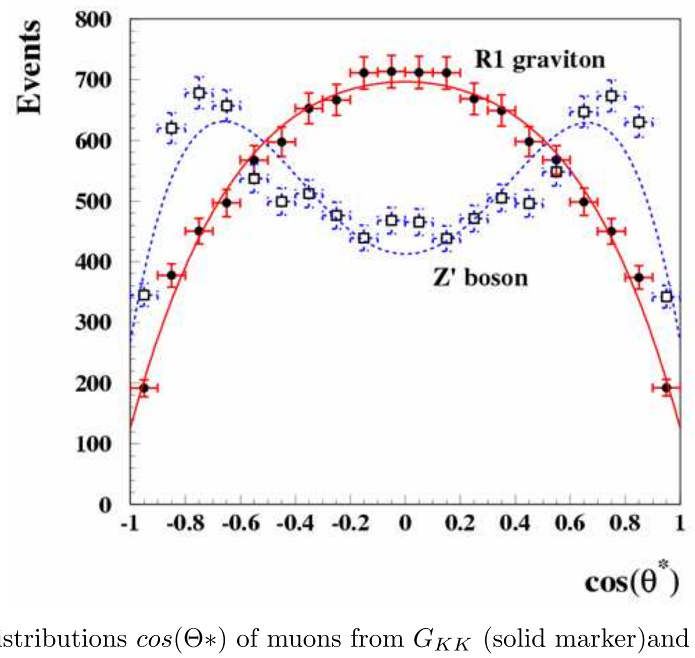

Figure 6: Angular distributions $cos(\Theta*)$ of muons from G_{KK} (solid marker)and Z' (open box) decays

Under the assumption that a new resonance state was observed at the LHC, nature of this object should be understood in further analysis (in principle, the resonance can come from the extended gauge sector as well as from some version of extra dimension models). The major difference between Z' and RS1 graviton should appear in the $\cos(\theta^{\star})$ distribution (where $\theta^{\star}$ is the polar angle of muons in the center-of-mass system of the dimuon pair) which is strongly spin dependent. Course, these distributions will be distorted by acceptance cuts, especially in the region of large angles, and expected theoretical predictions will differ from experimental ones. Nevertheless Fig. 6 shows the 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 the same masses of 1.5 TeV/c^2 and normalized to 6000 events that correspond to the approximate integrated luminosity of 10 fb^{-1} for graviton production with c=0.1 and 100 fb^{-1} for Z' boson.

4 Summary

In this work we present 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÷4.0 TeV/c^2 depending on the couplings for 100 fb^{-1} integrated luminosity. At the same luminosity the first KK-mode of RS1 graviton can be observed up to the mass values of 2.6 TeV/c^2 and 4.8 TeV/c^2 for $c = 0.01$ and 0.1, respectively. The angular distribution of muons in the final state can be used to distinguish the spin-1 and the spin-2 resonance states, at least in the mass region up to 2.3 TeV/c^2. The different Z' models can be distinguished (up to the mass value of 2.5 TeV/c^2) using 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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