SPIN-IDENTIFICATION OF RANDALL-SUNDRUM GRAVITON RESONANCES IN DILEPTON AND DIPHOTON PRODUCTION PROCESSES AT THE LARGE HADRON COLIIDER WITH ATLAS EXPERIMENT

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The possibility of the ATLAS experiment at the LHC to detect massive Randall-Sundrum gravitons and determine their spin is discussed. The search reach is estimated for the channel with the graviton, produced in proton-proton collision, decaying into a pair of electrons and photons. A method for determining the graviton's spin-2 nature by analyzing angular distributions of it's photons and electrons decay products via the integrated center-edge asymmetry is presented. Our finding is that for graviton masses up to 1.2 TeV (2.9 TeV) with $c = 0.01$ ($c = 0.1$) the spin-2 nature of the graviton will be determined with 95 % C.L. by means of electrons while diphoton channel gives 1.6 TeV (3.1 TeV) with $c = 0.01$ ($c = 0.1$) mass limits, respectively.

1. Introduction

Heavy resonances with mass around 1 TeV or higher are predicted by numerous New Physics (NP) scenarios, candidate solutions of conceptual problems of the standard model (SM). In particular, this is the case of models of gravity with extra spatial dimensions, grand-unified theories, electroweak models with extended spontaneously broken gauge symmetry, and supersymmetric theories with R-parity breaking. These new heavy objects, or "resonances", with mass $M >> M_{W,Z}$, may be either produced or exchanged in reactions among SM particles at high energy colliders such as the LHC and ILC.

For any model, given the expected statistics and experimental uncertainties, one can assess the corresponding discovery reach by determining the upper limit of the mass range M_R where the resonance signal can be detected above the SM cross section to a given confidence level.

On the other hand, once a peak in the cross section is observed, further analysis is needed to distinguish the underlying model against the other scenarios that potentially may cause a similar effect. In this regard, the expected identification reach is defined as the upper limit of the mass range where the model could be identified as the source of the peak or, equivalently, the other competitor models can be excluded for all values of their parameters. The determination of the spin of the resonance represents therefore an important selection among different classes of non-standard interactions.

The determination of the spin-2 of the lowest-lying Randall - Sundrum (RS) graviton resonance exchange against the spin-1 hypothesis in the Drell-Yan (DY) lepton-pair production processes in the context of experiments at LHC has recently been discussed, e.g., in Refs. [1 - 5], and some attention to the case of the spin-0 hypothesis has been given in Ref. [3]. An experimental search for spin-2, spin-1 and spin-0 new particles decaying to DY dilepton pairs has recently been performed at the Fermilab Tevatron $p\bar{p}$ collider [6].

We would like to complement those analyses and assess the extent to which the domain in the RS parameters allowed by the discovery reach on the resonance is reduced by the request of exclusion of the hypothesis of spin-0 exchanges with the same mass, and mimicking the same peak in the diphoton invariant mass distribution.

Here, we consider the discrimination reach on the lowest-lying spin-2 RS graviton resonance [7], that could be obtained from measurements of the photon-pair production processes at the LHC:

$$pp \to \gamma\gamma + X \ . \tag{1}$$

Diphoton final state are a signature of many interesting physics processes. For instance, one of the main discovery channels for the Higgs boson search at the LHC is the $\gamma\gamma$ final state. An excess of $\gamma\gamma$ production could be a signature of interactions beyond the SM. In addition, the diphoton final state is interesting in its own right. The detection of a resonance in the diphoton channel, in addition to DY channels with dielectrons, will present an evidence that this resonance is RS graviton, or any other particle with spin 0 or 2. It will exclude large number of models where large resonances with spin 1 does exist, like Z', for example, because Z' has spin 1 and cannot decay in two photons (what is in contrast to DY lepton pair production processes). Such observation might occur before having accumulated the large amount of data needed to analyze the angular distributions in the dilepton channels.

As is well known, the main tool to differentiate among the spin exchanges in the diphoton processes uses the different, and characteristic, dependencies on the angle $\theta_{\rm cm}$ between the incident quark or gluon and the final photon in the diphoton center-of-mass (c.m.) system. Our discussion is based on the center-edge asymmetry $A_{\rm CE}$ [8, 9].

2. Discovery and Identification Reach

Randall and Sundrum [7] have proposed a novel approach in dealing with the hierarchy problem. Such a model leads to very interesting and predictive phenomenology that can be explored in detail at colliders [10]. In the simplest scenario the SM fields are constrained to lie on the TeV brane while gravitons can propagate in the bulk in which case only two parameters are necessary to describe the model: $c = k / \bar{M}_{Pl}$, which is expected to be near though somewhat less than unity, and $m_1 (\equiv M_G)$, which is the mass of the first graviton Kaluza-Klein excitation. While the massless zero mode graviton couples in the usual manner as $\left(\bar{M}_{Pl}\right)^{-1}$, the tower states instead couple as Λ_π^{-1} and, hence Kaluza - Klein gravitons can be detected as massive resonances in collider experiments. Coupling of an excited graviton to matter is described by

$$L = -\frac{1}{\Lambda_\pi} T^{\mu\nu} \sum_{n=1}^{\infty} h_{\mu\nu}^{(n)}, \tag{2}$$

where $T^{\mu\nu}$ is the energy-momentum tensor of the matter field, $h_{\mu\nu}^{(n)}$ is the n^{th} excitation of the graviton.

As mentioned above, two parameters control the properties of the RS model, M_G and constant c, determining graviton couplings and widths:

$$\Gamma_n = \rho m_n x_n^2 (k / \overline{M}_{Pl})^2, \quad (3)$$

where ρ is a constant depending on the number of open channels. The constant c varies in the range $0.01 \le c \le 0.1$. Two theoretical constraints exist on these two parameters. The first one is a limit on the curvature originally formulated as $k < M$, where $M \sim \bar{M}_{Pl}$ is the fundamental five-dimensional Planck scale. The second constraint, $\Lambda_\pi < 10$ TeV, assures that no new hierarchy appears between M_{EW} and Λ_π. Current discovery limits at 95 % C.L. from the Fermilab Tevatron collider are for the graviton mass: 300 GeV for $c = 0.01$ and 900 GeV for $c = 0.1$ [11].

In hadronic collisions, photon pairs can be produced by quark-antiquark annihilation

$$q + \bar{q} \to \gamma + \gamma, \tag{4}$$

as well as by gluon-gluon fusion

$$g + g \to \gamma + \gamma. \tag{5}$$

Assisted by a toy Monte Carlo simulation of the approximate acceptance of the ATLAS experiment, we give rough estimates for the level at which LHC experiments may be expected to classify the spin of new resonances. More detailed calculations, including full detector simulation, reconstruction effects, and systematic uncertainties, are being pursued within the LHC collaborations and are beyond the scope of present paper. Simulations were done with PYTHIA 6.4 [12], set to produce gravitons in proton-proton collisions at 14 TeV c.m. energy and they take into account the angular distributions of the RS graviton decaying into two photons. By default this version of PYTHIA uses the CTEQ6L parton distribution functions. The influence of parton distribution functions choice will be taken into account as systematic uncertainties.

Detector response has been taken into account by passing generated signal and background events through the ATLFAST fast simulation program [13]. In ATLFAST the photons considered are the two isolated highest transverse momentum photons with $|\eta| \le 2.4$ and $p_T \ge 40$ GeV.

Graviton can be seen as a peak in the invariant mass distribution of photons $M_{\gamma\gamma}$. For each mass value, the peak region of the distribution is fitted with a gaussian. A mass window is defined as $\pm 3\sigma$ for the narrow peaks corresponding to the two coupling cases, $c = 0.01$ and $c = 0.1$. The σ of the fit reflects the detector energy resolution and the natural width of the resonance. The number of signal events N_S as well as the number of background events N_B (prompt photon background) are computed in the mass window. Also, in numerical computation we have assumed a uniform efficiency of reconstruction of both signal and background is of the order of 0.8.

The process (1) must be detected above the background from the SM processes $q\bar{q} \to \gamma\gamma + X$. The diphoton channel will be analyzed at the LHC in the ATLAS and CMS detectors, and both detectors have the ability to probe the narrow graviton resonance [4, 5]. The detection of a 5σ signal is calculated as the number of signal events equal to max ($5\sqrt{N_B}$, 10) in order to ensure that the signal is statistically significant. The discovery limit for a 5σ signal has been estimated taking into account only the prompt photon background. One finds that a mass of 2.25 TeV (4.50 TeV) can be reached with a luminosity of 100 fb^{-1} for $c = 0.01$ ($c = 0.1$).

The spin-2 nature of the graviton was tested by comparing angular distributions in $\cos\theta_{\text{cm}}$ (the angle between the beam direction and photon momentum in the diphoton centre-of-mass frame) of the observed photon pairs, with distributions expected from a spin-0 intermediate state which can be considered as alternative hypothesis yielding the

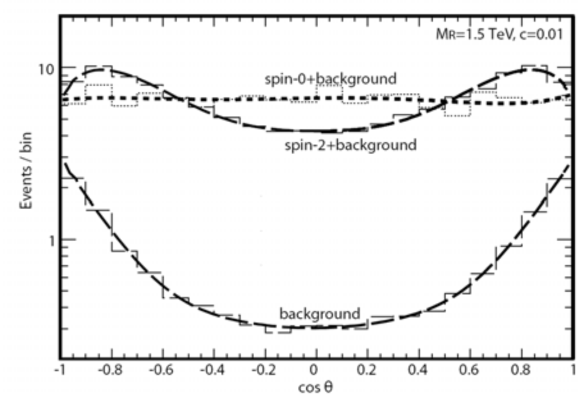

Fig. 1. Angular distribution of photons in the diphoton c.m. system for (i) spin-2 graviton resonant production, $\mathrm{d}\sigma(pp \to G \to \gamma\gamma)/\mathrm{dz}$, in the RS model with $c = 0.01$; (ii) spin-0 resonant production, $\mathrm{d}\sigma(pp \to S \to \gamma\gamma)/\mathrm{dz}$, and (iii) prompt photon background. We take $M_R = 1.5$ TeV ($R = G, S$). The S distribution is normalized so that the total number of events is the same for the graviton G and the scalar S.

same number of events. The expected distributions are shown in Fig. 1. The graviton is produced in either $q\bar{q}$ or gg interaction, and both processes contribute with a different angular distribution to the overall shape. Angular distributions in the c.m. frame of the final diphoton state give clear signatures of the spin of the produced heavy resonance. As shown in Figure 1 angular distributions are a powerful tool in distinguishing the spin-2 particle G from S, a spin-0 particle. In addition, for a 1500 GeV graviton, this angular distribution discriminates well the signal from the SM background, due the spin-2 of the graviton. This holds also for spin-0 case. One finds that decreasing the rapidity acceptance range from $|\eta| < 2.4$ to $|\eta| < 1.5$ will result in a significant loss of the discriminating power.

To quantify the distinction between spin-2 and spin-0 resonances it is conveniently to use an integrated asymmetry, center-edge asymmetry [3, 8, 9, 14] which can be written as follows:

$$\sigma_{\mathrm{CE}} \equiv \left[\int_{-0.5}^{0.5} - \left(\int_{-1}^{-0.5} + \int_{0.5}^{1}\right)\right] \frac{\mathrm{d}\sigma}{\mathrm{dz}} \mathrm{d}z,$$

$$\sigma \equiv \int_{-1}^{1} \frac{\mathrm{d}\sigma}{\mathrm{dz}} \mathrm{dz}. \qquad (6)$$

The center-edge asymmetry for a given diphoton invariant mass $M_{\gamma\gamma}$ can be defined as

$$A_{\mathrm{CE}}(M_{\gamma\gamma}) = \frac{\mathrm{d}\sigma_{\mathrm{CE}} / \mathrm{d}M_{\gamma\gamma}}{\mathrm{d}\sigma / \mathrm{d}M_{\gamma\gamma}}, \qquad (7)$$

where $M_{\gamma\gamma}$ being the invariant mass of the photon pair, a convolution over parton momenta is performed, and we obtain $\mathrm{d}\sigma_{\mathrm{CE}} / \mathrm{d}M_{\gamma\gamma}$ and $\mathrm{d}\sigma / \mathrm{d}M_{\gamma\gamma}$ from the inclusive differential cross sections $\mathrm{d}\sigma_{\mathrm{CE}} / \mathrm{d}M_{\gamma\gamma}\, dy\, dz$ and $\mathrm{d}\sigma / \mathrm{d}M_{\gamma\gamma}\, dy\, dz$, respectively, by integrating over z and over rapidity y between $-Y$ and Y, with $Y = \log(\sqrt{s} / M_{\gamma\gamma})$ [8].

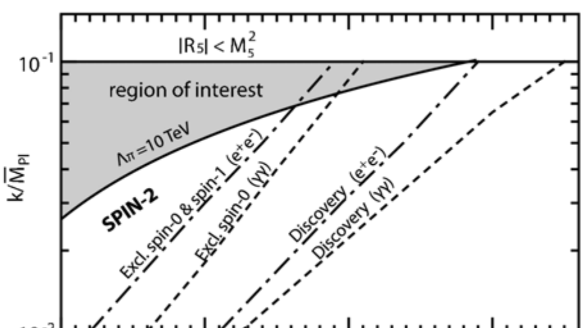

Fig. 2. Discovery limits and identification reaches on the spin-2 graviton parameters in the plane (M_G, c), using the photon and electron pair production cross sections and center–edge asymmetry in the the ATLAS experiment at the LHC with integrated luminosity of 100 fb^{-1}.

We assume now that a deviation from the SM is discovered in the cross section in the form a resonance. We will investigate in which regions of the RS parameter space such a deviation can be *identified* as being caused by spin-2 exchange. The results of both the G discovery and spin determination analysis are shown in Figure 2. As can be seen from the Fig. 2, LHC should probe the whole theoretically allowed region. The comparison of discovery and spin-2 determination regions for the RS graviton decaying into diphoton as well as into electron pair [3, 15, 16] channels as a function of the coupling parameter c and graviton mass for $L_{\mathrm{int}} = 100$ fb^{-1} in the plane of the coupling parameter c and graviton mass M_G is given in Fig. 2. The left part of each curve labeled *Discovery* is the region where the significance exceeds 5σ. The curves labeled *Exclusion* mark the regions of rejection of the spin-0 hypothesis with diphoton channel and rejection of both spin-1 and spin-0 hypotheses with dielectron channel at 95 % C.L. Both of them determine the regions laying above the corresponding curves and marked as *Spin-2* that corresond to the identification of spin-2 RS graviton. The theoretically favored region, $\Lambda_\pi < 10$ TeV (hatched), is also indicated.

For masses under 4.5 TeV, the diphoton channel gives a higher search reach than electrons. The reach for 95 % C.L. graviton spin determination is lower, but still a large part of the interesting region in parameter space should be probed. Specifically, for graviton masses up to 1.2 TeV (2.9 TeV) with $c = 0.01$ ($c = 0.1$) the spin-2 nature of the graviton will be determined with 95 % C.L. by means of electrons while diphoton channel gives 1.6 TeV (3.1 TeV) with $c = 0.01$ ($c = 0.1$) mass limits, respectively. The results presented in this paper are all based on fast detector simulation, and therefore should be treated as a first approximation. An analysis with full detector simulation and reconstruction is in progress.

3. Conclusions

In conclusion, we have considered the RS scenario parametrized by M_G and $k/\bar{M}_{Pl}$. Although somewhat higher sensitivity reaches on M_G than obtained here are given by other approaches, this method based on A_{CE} in diphoton channel is suitable for actually *pinning down* the spin-2 nature of the KK gravitons up to very high M_G for graviton masses up to 1.6 TeV ($c = 0.01$) in case of weak coupling between graviton excitations and a "hypothetical" spin-0 scalar bosons (see Fig. 2) and 3.1 TeV for larger coupling constant ($c = 0.1$).

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