SPIN IDENTIFICATION OF RANDALL-SUNDRUM GRAVITON IN PROTON-PROTON COLLISIONS AT LHC WITH 8 TEV AND 14 TEV

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ABSTRACT. New physics models, widely discussed in the literature, predict the existence of new heavy resonances with mass above 1 TeV that can possibly be observed at the Large Hadron Collider (LHC). These resonances, predicted by different nonstandard models can generate peaks with the same mass and same number of events under the peak. In this case, spin determination of a peak becomes crucial in order to identify the relevant new physics scenario. Here we discuss a possibility for spin identification of spin-2 Randall-Sundrum graviton excitations against spin-1 heavy neutral gauge bosons Z' and scalar heavy bosons in Drell-Yan dilepton and diphoton events at the LHC at $\sqrt{s} = 8$ TeV and 14 TeV by using a center-edge asymmetry.

Key words: Randall-Sundrum graviton, center-edge asymmetry, LHC.

1. Introduction

The existence of new heavy bosons predicted by many models beyond the standard model, with mass scales $M \gg M_{W,Z}$. They can be signalled by the observation of (narrow) peaks in the cross sections for reactions among standard model particles at the LHC. However, the observation of a peak/resonance at some large mass $M = M_R$ may not be sufficient to identify its underlying nonstandard model, in the multitude of potential sources of such a signal. Indeed, in 'confusion regions' of the parameters, different models can give the same M_R and same number of events under the peak. In that case, the test of the peak/resonance quantum numbers, the spin first, is needed to discriminate the models against each other in the confusion regions. Specifically, one defines for the individual nonstandard scenarios a *discovery reach* as the maximum value of M_R for peak observation over the standard model (SM) background, and an *identification reach* as the maximum value of M_R for which the model can be unambiguously discriminated from the other competing ones as the source of the peak. Particularly clean signals of heavy neutral resonances are expected in the inclusive reactions at the LHC:

$$p + p \to l^+l^- + X \quad (l = e, \mu), \quad p + p \to \gamma\gamma + X, \quad (1)$$

where they can show up as peaks in the dilepton and diphoton invariant mass M. While the total resonant cross section determines the number of events, hence the discovery reaches on the considered models, the angular analysis of the events allows to discriminate the spin-hypotheses from each other, due to the (very) different characteristic angular distributions. In the next sections we discuss the identification of the spin-2 against spin-1 and spin-0 hypotheses (and spin-0 only for diphoton case), modeled by the Randall-Sundrum model with one warped extra dimension [1], a set of Z' models [2], and the R-parity violating sneutrino exchange [3] (spin-0 scalar [4] for diphoton final states), respectively.

2. Cross sections and center-edge asymmetry

The total cross section for a heavy resonance discovery in the events (1) at an invariant dilepton (or diphoton) mass $M = M_R$ (with $R = G, Z', \tilde{\nu}$ denoting graviton, Z' and sneutrino, respectively) is:

$$\sigma(pp \to R) \cdot \mathrm{BR}(R \to l^+l^-) = \int_{-z_{\rm cut}}^{z_{\rm cut}} \mathrm{d}z \int_{M_R-\Delta M/2}^{M_R+\Delta M/2} \mathrm{d}M \int_{y_{\rm min}}^{y_{\rm max}} \mathrm{d}y \frac{\mathrm{d}\sigma}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}z}. \quad (2)$$

Resonance spin-diagnosis makes use of the comparison between the different differential angular distributions:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z} = \int_{M_R-\Delta M/2}^{M_R+\Delta M/2} \mathrm{d}M \int_{y_{\min}}^{y_{\max}} \frac{\mathrm{d}\sigma}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}z}\mathrm{d}y. \qquad (3)$$

In Eqs. (2) and (3), $z = \cos\theta_{\mathrm{cm}}$ and y are the lepton-quark (or photon-quark) angle in the dilepton (or diphoton) center-of-mass and the dilepton rapidity, respectively, and cuts on phase space due to detector acceptance are indicated. For integration over the full phase space, the limits would be $z_{\mathrm{cut}} = 1$ and $y_{\max} = -y_{\min} = \log(\sqrt{s}/M)$ with $\sqrt{s}$ the LHC collider center-of-mass energy. Furthermore, ΔM is an invariant mass bin around M_R, reflecting the detector energy resolution [5]. To evaluate the number N_S of resonant signal events time-integrated luminosities of 100 fb^{-1} for 14 TeV LHC (the ultimate expectations) and 20 fb^{-1} for 8 TeV LHC (expected to be archived before long shutdown) will be assumed, and reconstruction efficiencies of 90% for both electrons and muons and 80% for photons). Typical experimental cuts are: $p_\perp > 20$ GeV and pseudorapidity $|\eta| < 2.5$ for both leptons; $p_\perp > 40$ GeV and $|\eta| < 2.4$ for photons. Finally, with N_B the number of 'background' events in the ΔM bin, determined by the SM predictions, the criterion $N_S = 5\sqrt{N_B}$ or 10 events, whichever is larger, will be adopted as the minimum signal for the peak discovery. To evaluate Eqs. (2) and (3) the parton subprocesses cross sections will be convoluted with the CTEQ6.6 parton distributions of Ref. [6]. Next-to-leading QCD effects for dilepton case can be accounted for by K-factors, and for simplicity of the presentation we here adopt a flat value $K = 1.3$. For diphoton case the full NLO calculations were done [7]. In practice, due to the completely symmetric pp initial state, the event-by-event determination of the sign of z may at the LHC be not fully unambiguous. This difficulty may be avoided by using as the basic observable for angular analysis the z-evenly integrated center-edge angular asymmetry, defined as [8,9]:

$$A_{\mathrm{CE}} = \frac{\sigma_{\mathrm{CE}}}{\sigma};\ \sigma_{\mathrm{CE}} \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-z_{\mathrm{cut}}}^{-z^*} + \int_{z^*}^{z_{\mathrm{cut}}}\right)\right]\frac{\mathrm{d}\sigma}{\mathrm{d}z}\mathrm{d}z. \quad (4)$$

In Eq. (4), $0 < z^* < z_{\mathrm{cut}}$ defines the separation between the 'center' and the 'edge' angular regions and is *a priori* arbitrary, but the numerical analysis shows that it can be 'optimized' to $z^* \simeq 0.5$. The additional advantage of using A_{CE} is that, being a ratio of integrated cross sections, it should be much less sensitive to systematic uncertainties than 'absolute' distributions (examples are the K-factor uncertainties from different possible sets of parton distributions and from the choice of factorization vs renormalization mass scales).

3. New physics models

RS model with one compactified extra dimension. Originally, this model was proposed to solve the so-called gauge hierarchy problem, $M_{\mathrm{EW}} \ll M_{\mathrm{Pl}} \simeq 10^{16}$ TeV. The simplest set-up, called RS, consists of one warped extra spatial dimension, y, two three-dimensional branes placed at a compactification relative distance $y_c = \pi R_c$, and the specific 5-D metric [1]

$$ds^2 = \exp(-2k|y|)\eta_{\mu\nu}dx^\mu dx^\nu - dy^2. \qquad (5)$$

In (5), $\eta_{\mu\nu}$ is the usual Minkowski tensor and $k > 0$ is the 5-D curvature. SM fields are localized to the so-called TeV brane, and gravity can propagate in the full 5-D 'bulk', included the other, so-called Planck, brane. On this brane, the effective 4-D mass scale is related to the Newton constant by the relation $\overline{M}_{\mathrm{Pl}} = 1/\sqrt{8\pi G_{\mathrm{N}}} = 2.44\times 10^{15}$ TeV. Denoting by M_* the 5-D effective mass scale, analogously related to the cubic root of the 5-D Newton constant, the relation can be derived: $\overline{M}_{\mathrm{Pl}}^2 = (M_*^3/k)(1-\exp(-2k\pi R_c))$. Under the basic 'naturalness' assumption $\overline{M}_{\mathrm{Pl}} \sim M_* \sim k$, needed to avoid further fine tunings, for $kR_c \sim 11$ the geometry of Eq. (5) implies that the mass spectrum on the Planck brane, of the 10^{15} TeV order, can on the TeV brane where SM particles live and interact, be exponentially 'warped' down to the effective scale $\Lambda_\pi = \overline{M}_{\mathrm{Pl}}\exp(-k\pi R_c)$ of the one (or few) TeV order. Interestingly, this brings gravitational effects into the reach of LHC. Junction conditions on the graviton field at the branes y-positions imply the existence of a tower of spin-2 graviton excitations, $h_{\mu\nu}^{(n)}$, with a specifically spaced mass spectrum $M_n = x_n k\exp(-k\pi R_c)$ in the TeV range (x_n are the roots of $J_1(x_n) = 0$). Denoting by $T^{\mu\nu}$ the SM energy-momentum tensor, and by $h_{\mu\nu}^{(0)}$ the zero-mode, ordinary, graviton, the couplings of graviton excitations to the SM particles are only $(1/\Lambda_\pi)$ suppressed (not $1/\overline{M}_{\mathrm{Pl}}$):

$$L_{\mathrm{TeV}} = -\left[\frac{1}{\overline{M}_{\mathrm{Pl}}}h_{\mu\nu}^{(0)}(x) + \frac{1}{\Lambda_\pi}\sum_{n=1}^{\infty} h_{\mu\nu}^{(n)}(x)\right]T^{\mu\nu}(x). \qquad (6)$$

The RS model can be conveniently parameterized by the mass of the lowest graviton excitation $M_G \equiv M_1$, the only one presumably in the reach of LHC, and the 'universal', dimensionless, coupling constant $c = k/\overline{M}_{\mathrm{Pl}}$. The scale Λ_π and the (narrow) widths $\Gamma_n = \rho M_n x_n^2 c^2$ (with $\rho \simeq 0.1$), are then derived quantities. Theoretically 'natural' ranges expected for these parameters are $0.01 \le c \le 0.1$ and $\Lambda_\pi < 10$ TeV. Current 95% limits from ATLAS and CMS experiments are, at the 7 TeV, 5 fb^{-1} LHC [10,11]: $M_G > 910$ GeV ($c = 0.01$) up to $M_G > 2160$ GeV ($c = 0.1$).

Heavy neutral gauge bosons. The spin-1 hypothesis is in process (1) realised by $q\bar{q}$ annihilation into lepton pairs through Z' intermediate states [2]. Such bosons are generally predicted by electroweak models beyond the SM, based on extended gauge symmetries. Generally, Z' models depend on $M_{Z'}$ and on the left- and right-handed couplings to SM fermions. Further results will be given for a popular class of models for which the values of these couplings are fixed theoretically, thus only $M_{Z'}$ is a free parameter. These are the Z'_χ, Z'_ψ, Z'_η, $Z'_{\rm LR}$, $Z'_{\rm ALR}$ models, and the 'sequential' $Z'_{\rm SSM}$ model with Z' couplings identical to the Z ones. Current experimental lower limits (95% CL) on $M_{Z'}$ depend on models, and range from 2260 GeV for Z'_ψ up to 2590 TeV for $Z'_{\rm SSM}$ [12]. The leading *z*-even angular distributions for the LO partonic subprocess $\bar{q}q \to Z' \to l^+l^-$ has the same form as the SM and, therefore, the resulting $A_{\rm CE}$ is *the same for all* Z' models.

***R*-parity violating sneutrino exchange.** R-parity is defined as $R_p = (-1)^{(2S+3B+L)}$, and distinguishes particles from their superpartners. In scenarios where this symmetry can be violated, supersymmetric particles can be singly produced from ordinary matter. In the dilepton process (1) of interest here, a spin-0 sneutrino can be exchanged through the subprocess $\bar{d}d \to \tilde{\nu} \to l^+l^-$ and manifest itself as a peak at $M = M_{\tilde{\nu}}$ with a flat angular distribution [3]. Results on next-to-leading QCD orders available in the literature indicate the possibility of somewhat large K-factors, in particular due to supersymmetric QCD corrections. Besides $M_{\tilde{\nu}}$, the cross section is proportional to the R-parity violating product $X = (\lambda')^2 B_l$ where B_l is the sneutrino leptonic branching ratio and λ' the relevant sneutrino coupling to the $\bar{d}d$ quarks. Current limits on the relevant λ' s are of the order of 10^{-2}, and the experimental 95% CL lower limits on $M_{\tilde{\nu}}$ range from 397 GeV (for $X = 10^{-4}$) to 866 GeV (for $X = 10^{-2}$) [13]. We take for X, presently not really constrained for sneutrino masses of order 1 TeV or higher, the (rather generous) interval $10^{-5} < X < 10^{-1}$.

Model for scalar particle exchange. For the process with diphoton final states we consider the simple model of a scalar particle S, singlet under the SM gauge group and with mass $M \equiv M_S$ of the TeV order, proposed in Ref. [4]. The trilinear couplings of S with gluons, electroweak gauge bosons and fermions, are in this model:

$$L_{\rm Scalar} = c_3 \frac{g_s^2}{\Lambda} G^a_{\mu\nu} G^{a\mu\nu} S + c_2 \frac{g^2}{\Lambda} W^i_{\mu\nu} W^{i\mu\nu} S + c_1 \frac{g'^2}{\Lambda} B_{\mu\nu} B^{\mu\nu} S + \sum_f c_f \frac{m_f}{\Lambda} \bar{f}\, f\, S. \quad (7)$$

In Eq. (15), Λ is a high mass scale, of the TeV order of magnitude, and c's are dimensionless coefficients that are assumed to be of order unity, reminiscent of a strong novel interaction. Following Ref. [4], we assume $\Lambda = 3$ TeV and allow the coefficients c_i to take values equal to, or less than, unity. The leading order diphoton production process is in this model dominated by the s-channel exchange $gg \to S \to \gamma\gamma$. Numerically, it turns out from the cross section that there exist a 'confusion region' of the c's where scalar diphoton states can be produced with same mass M_S and number of events as the RS gravitons, and the width Γ_S comparable to (or smaller than) the mass window ΔM. The difference lies in the differential cross section, which in this case has the flat z-behavior.

4. Spin identification with center-edge asymmetry

The nonstandard models briefly described in the previous section can mimic each other as sources of an observed peak in M, for values of the parameters included in so-called 'confusion regions' (of course included in their respective experimental and/or theoretical discovery domains), where they can give same numbers of signal events N_S. The M_R - N_S plots in Fig. 1 show as an example 'confusion regions' between spin-2 graviton and spin-0 sneutrino, spin-1 Z' for dilepton process and spin-0 scalar for diphotons. The number of events needed for 5-σ discovery at the 8 TeV LHC with luminosity $L_{\rm int} = 20\,{\rm fb}^{-1}$ and current limits on RS resonance obtained from 7 TeV LHC data are also shown. In such confusion regions, one can try to discriminate models from one another by means of the angular distributions of the events, directly reflecting the different spins of the exchanged particles. We continue with the examples of confusion regions in Fig. 1 and start from the assumption that an observed peak at $M = M_R$ is the lightest spin-2 graviton (thus, $M_R = M_G$). We define a 'distance' among models accordingly:

$$\Delta A^{Z'}_{\rm CE} = A^G_{\rm CE} - A^{Z'}_{\rm CE}; \qquad \Delta A^{\tilde{\nu}}_{\rm CE} = A^G_{\rm CE} - A^{\tilde{\nu}}_{\rm CE}. \quad (8)$$

To assess the domain in the (M_G, c) plane where the competitor spin-1 and spin-0 models giving the same N_S under the peak can be *excluded* by the starting RS graviton hypothesis, a simple-minded χ^2-like criterion can be applied, which compares the deviations (8) with the uncertainty (statistical and systematic combined) $\delta A^G_{\rm CE}$ pertinent to the RS model. We impose the two conditions

$$\chi^2 \equiv \left(\Delta A^{Z',\tilde{\nu}}_{\rm CE} / \delta A^G_{\rm CE}\right)^2 > \chi^2_{\rm CL}. \quad (9)$$

Eq. (9) contains the definition of χ^2, and the $\chi^2_{\rm CL}$ specifies a desired confidence level (3.84 for 95% CL). This condition determines the minimum number of events, $N_S^{\rm min}$, needed to exclude the spin-1 and spin-0 hypotheses (hence to establish the graviton spin-2), and this in turn will determine the RS graviton *identification* domain in the (M_G, c) plane. Of course, an analogous procedure can

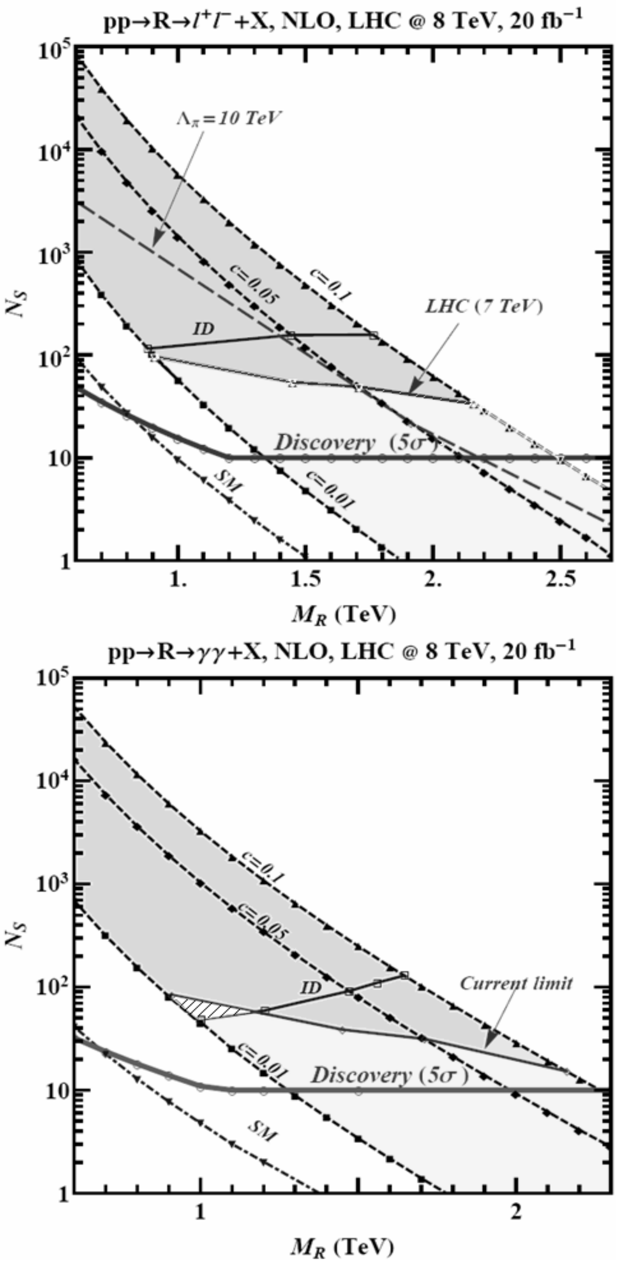

Figure 1. Number of resonance (signal) events N_S *vs* M_R ($R = G$) at the LHC with $\sqrt{s} = 8$ TeV and $L_{int} = 20$ fb $^{-1}$ for the process $pp \to G \to l^+l^- + X$ (top panel) and $pp \to G \to \gamma\gamma + X$ (bottom panel). The shaded area corresponds to the KK graviton signature space for $0.01 \le c \le 0.1$. Current experimental limits, 5σ discovery level and minimal number of events for RS graviton identification are also shown.

be applied to the identification of Z' and $\tilde{\nu}$ exchanges against the two competing ones as sources of a peak in process. In process for RS graviton identification exploiting the same procedure one needs to exclude spin-0 only, since spin-1 resonance is forbidden by Landau-Yang theorem. Figure 2 show the identification domain for the RS graviton excitation, foreseeable from both the diphoton and the dilepton events, at the 8 TeV LHC with luminosity 20 fb^{-1}. Specifically: the regions to the left of the 'Discovery' lines are discovery domains at 5σ; the identification domains at 95 % CL are to the left of the 'ID' lines; the line 'LHC (7 TeV)' represents the current experimental lower limits from the 7 TeV LHC, it delimits the 'allowed' region from below; the line 'oblique corrections' represents constraints (from below) from a fit to the oblique EW parameters.

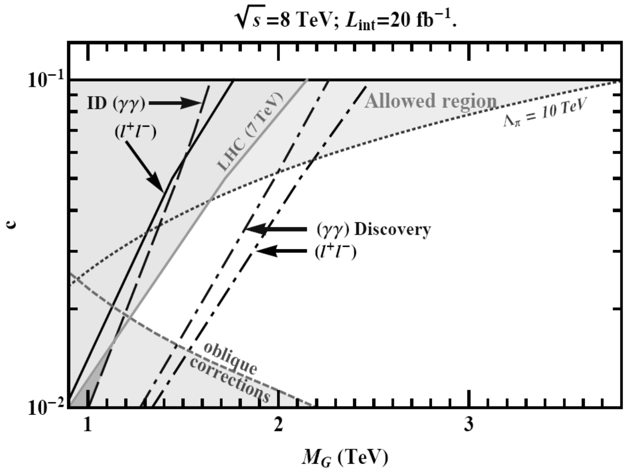

Figure 2. Discovery and identification on RS graviton at the 8 TeV LHC with luminosity 20 fb^{-1}.

Table 1: Discovery and identification reaches (in TeV) on RS graviton mass for 14 TeV LHC with L_{int} = 100 fb^{-1}.

c	Discovery	Identification
	$pp \to l^+l^- + X$	
0.01	2.5	1.6
0.1	4.6	3.2
	$pp \to \gamma\gamma + X$	
0.01	2.5	2.0
0.1	4.3	3.3

Fig.1 and Fig.2 show that accounting the current LHC (7 TeV) limits on RS graviton parameters and masses as well as those obtained from low energy data (oblique corrections) the discovery of heavy graviton excitations is still possible at LHC with $\sqrt{s} = 8$ TeV, while identification of their spin will be impossible.

Table 1 represents the discovery (5σ) and identification (95%CL) reaches on RS graviton at the 14 TeV LHC with luminosity 100 fb^{-1}. Table 1 shows that the χ^2-based angular analysis of dilepton and diphoton events described here can at the 14 TeV LHC provide identification limits on the RS graviton resonance ranging from M_G = 2.0 TeV (c = 0.01) up to M_G = 3.3 TeV (c = 0.1).

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