Spin identification of new heavy neutral resonances at the LHC

A. A. Pankov and A. V. Tsytrinov

The Abdus Salam ICTP Affiliated Centre, Technical University of Gomel, 246746 Gomel, Belarus

Abstract

New Physics models generally predict the existence of very heavy quantum states that can manifest themselves as peaks in the cross sections at the LHC. For values of the parameters in certain domains, different nonstandard models can generate peaks with the same mass and same number of events. In this case, the spin determination of a peak, requiring the angular analysis of the events, becomes crucial in order to identify the relevant nonstandard source. We discuss in Drell-Yan dilepton and diphoton events at LHC the identification reach of the following heavy bosons: spin-2 Randall-Sundrum graviton excitations; spin-1 heavy neutral gauge bosons Z'; and spin-0 SUSY R-parity violating sneutrinos.

1 Introduction

Searches for neutral resonances have historically brought major breakthroughs by either confirming important predictions or discovering unexpected particles [1]. The 1974 discovery of the J/ψ meson [2] as a $c\bar{c}$ bound state confirmed the GIM mechanism [3] for preventing flavor-changing neutral currents, and the discovery of the Z boson [4] confirmed the gauge unification of the electromagnetic and weak forces [5]. Meanwhile, the discovery of the upsilon [6] was completely unexpected, and increased the number of known fermion generations to three.

Turning to the future, there are reasons to expect the next important particle physics discovery will be a neutral resonance. In addition to the well-motivated Higgs boson [7] of the standard model (SM), there are many new resonances predicted by proposed extensions to the SM. These extended theories can address unexplained features of the SM, such as: the lack of gauge unification and the hierarchy between the electroweak and Planck scales (through supersymmetry [8] or the presence of extra dimensions [9]); and parity violation and light neutrino masses (through an additional $\mathrm{SU(2)_R}$ gauge symmetry [10], which has weak couplings to right-handed fermions).

The most sensitive direct searches for neutral resonances at high mass come from the Large Hadron Collider (LHC) [11] data. Future searches in pp collisions from LHC will increase the probed mass range. As larger datasets with higher energies are studied, enhancements to the search strategy can improve sensitivity and facilitate the analysis.

A neutral resonance decaying to fermion pairs can have intrinsic spin equal to 0, 1, or 2. Beyond the SM, there could be multiple Higgs bosons with varying properties [12]. In supersymmetric models, there are spin-0 partners to fermions that could be produced as resonances in pp collisions [13]. Any model with an additional U(1) gauge group will have a new spin-1 gauge boson, generically referred to as a Z' boson [14]. Models of extra dimensions at the electroweak scale predict spin-2 graviton resonances [15].

New heavy bosons 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 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:

$$p + p \to l^+ l^- + X \quad (l = e, \mu) \quad \text{and} \quad p + p \to \gamma\gamma + X, \tag{1}$$

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.

Due to the completely symmetric *pp* initial state, one uses as the basic observable for angular analysis the z-evenly integrated center-edge angular asymmetry ($z \equiv \cos\theta_{\text{c.m.}}$), defined as [16]:

$$A_{\text{CE}} = \frac{\sigma_{\text{CE}}}{\sigma} \quad \text{with} \quad \sigma_{\text{CE}} \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-z_{\text{cut}}}^{-z^*} + \int_{z^*}^{z_{\text{cut}}}\right)\right] \frac{\mathrm{d}\sigma}{\mathrm{d}z}\,\mathrm{d}z. \tag{2}$$

In Eq. (2), $0 < z^* < z_{\text{cut}}$ 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).

2 New physics models

RS model with one compactified extra dimension

Originally, this model was proposed to solve the so-called gauge hierarchy problem, $M_{\text{EW}} \ll M_{\text{Pl}} \simeq 10^{16}$ 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 [17]

$$ds^2 = \exp\left(-2k|y|\right)\, \eta_{\mu\nu} dx^\mu dx^\nu - dy^2. \tag{3}$$

In (3), $\eta_{\mu\nu}$ 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 $\overline{M}_{\text{Pl}} = 1/\sqrt{8\pi G_{\text{N}}} = 2.44 \times 10^{15}$ 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: $\overline{M}_{\text{Pl}}^2 = ({M_*}^3/k)(1 - \exp\left(-2k\pi R_c\right))$. Under the basic 'naturalness' assumption $\overline{M}_{\text{Pl}} \sim M_* \sim k$, needed to avoid further fine tunings, for $kR_c \sim 11$ the geometry of Eq. (3) 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 $\Lambda_\pi = \overline{M}_{\text{Pl}} \exp\left(-k\pi R_c\right)$ 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 $M_n = x_n k \exp\left(-k\pi R_c\right)$ 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 $1/\overline{M}_{\rm Pl}$):

$$\mathcal{L}_{\rm TeV} = -\left[\frac{1}{\overline{M}_{\rm Pl}} h^{(0)}_{\mu\nu}(x) + \frac{1}{\Lambda_\pi}\sum_{n=1}^{\infty} h^{(n)}_{\mu\nu}(x)\right] T^{\mu\nu}(x). \tag{4}$$

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 $c = k/\overline{M}_{\rm Pl}$. 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 $0.01 \leq c \leq 0.1$ and $\Lambda_\pi < 10$ TeV [18]. Current 95% limits from ATLAS and CMS experiments are, at the 7 TeV, 5 fb^{-1} LHC [19, 20]: $M_G > 910$ 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 [21]. 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 $Z'_{\rm SSM}$ [22].

The leading z-even angular distributions for the leading-order 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 [23]. 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 $X = 10^{-2}$) [24]. 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. [25]. The trilinear couplings of S with gluons, electroweak gauge bosons and fermions, are in this model:

$$\mathcal{L}_{\rm Scalar} = c_3 \frac{g_s^2}{\Lambda} G^a_{\mu\nu} G^{a\ \mu\nu} S + c_2 \frac{g^2}{\Lambda} W^i_{\mu\nu} W^{i\ \mu\nu} S + c_1 \frac{g'^2}{\Lambda} B_{\mu\nu} B^{\mu\nu} S + \sum_f c_f \frac{m_f}{\Lambda} \bar{f} f S. \tag{5}$$

In Eq. (5), 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. [25], we assume $\Lambda = 3$ TeV and allow the coefficients c_i to take values equal to, or less than, unity.

3 Spin identification

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. 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 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:

$$\Delta A_{\rm CE}^{Z'} = A_{\rm CE}^{G} - A_{\rm CE}^{Z'} \qquad \text{and} \qquad \Delta A_{\rm CE}^{\tilde{\nu}} = A_{\rm CE}^{G} - A_{\rm CE}^{\tilde{\nu}}. \tag{6}$$

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 (6) with the uncertainty (statistical and systematic combined) $\delta A_{\rm CE}^{G}$ pertinent to the RS model. We impose the condition

$$\chi^2 \equiv |\Delta A_{\rm CE}^{Z',\tilde{\nu}}/\delta A_{\rm CE}^{G}|^2 > \chi^2_{\rm CL}. \tag{7}$$

Eq. (7) 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 be applied to the identification of Z' and $\tilde{\nu}$ exchanges against the two competing ones as sources of a peak in process $p + p \to l^+l^- + X$. In $p + p \to \gamma\gamma + X$ 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.

To evaluate the number N_S of resonant signal events time-integrated luminosity of 100 fb^{-1} for 14 TeV LHC 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 (invariant mass bin around M_R), 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. The parton subprocesses cross sections will be convoluted with the CTEQ6.6 parton distributions of Ref. [26]. 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 [27]. Table 1 represents the discovery (5σ) and identification (95% CL) reaches on RS graviton at the 14 TeV LHC with luminosity 100 fb^{-1}.

In conclusion, Table 1 shows that the $A_{\rm CE}$-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 $M_G = 2$ TeV ($c = 0.01$) up to $M_G = 3.3$ TeV ($c = 0.1$). The diphoton and dilepton channels can be considered as being complementary for both discovery and identification. The combination of their angular analyses should provide reliable method for identification of the RS graviton model.

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

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

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