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Spin and model determination of Z′ - boson in lepton pair production at CERN LHC

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Abstract. Many new physics models predict production of heavy resonances in Drell-Yan channel and can be observed at the CERN LHC. If a new resonance is discovered as a peak in the dilepton invariant mass distribution at the LHC, the identification of its spin and couplings can be done by measuring production rates and angular distributions of the decay products. Here we discuss the spin-1 identification of Z'-boson for a set of representative models (SSM, E_6, LR, and ALR) against the spin-2 RS graviton resonance and a spin-0 sneutrino resonance with the same mass and producing the same number of events under the resonance peak. We use the center-edge asymmetry for spin identification, as well as the total dilepton production cross section for the distinguishing the considered Z'-boson models from one another.

1. Introduction

New heavy resonances 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 (GUT), and supersymmetric (SUSY) theories with R-parity breaking ($\not{R}_p$). These new heavy resonances, with mass $M \gg M_Z$, may be either produced or exchanged in reactions among SM particles at the high energy collider LHC. A particularly interesting process to be studied in this regard at the LHC is the Drell-Yan (DY) dilepton production ($l = e, \mu$)

$$p + p \to l^+ l^- + X, \tag{1}$$

where exchanges of the new particles can occur and manifest themselves as peaks in the (l^+l^-) invariant mass M. Once the heavy resonance is discovered at some $M = M_R$, further analysis is needed to identify the theoretical framework for NP to which it belongs. Correspondingly, for any NP model, one defines as *identification* reach the upper limit for the resonance mass range where it can be identified as the source of the resonance, against the other, potentially competitor scenarios, that can give a peak with the same mass and same number of events under the peak. This should be compared to the *discovery* reach, which specifies the (naturally more extended) mass range where the peak in the cross section pertaining to the model can just be observed experimentally. Clearly, the determination of the spin of the resonance with

center-edge asymmetry $A_{\rm CE}$ represents an important aspect of the selection among different classes of non-standard interactions giving rise to the observed peak. The potential advantages of $A_{\rm CE}$ to discriminate the spin-2 graviton resonance against the spin-1 and spin-0 hypotheses were discussed in Refs. [1, 2, 3, 4].

Here, we apply $A_{\rm CE}$ to the spin-1 identification of a peak observed in the dilepton mass distribution of process (1) at the LHC, against the spin-2 and spin-0 alternative hypotheses.

The existence of heavy neutral Z' vector bosons are a feature of many extensions of the SM. They arise in extended gauge theories including grand unified theories, superstring theories, and Left-Right symmetric models and in other models such as the BESS model and models of composite gauge bosons. For explicit NP realizations, for the spin-1 Z' models we refer to Refs. [5]; for the alternative spin-2 and spin-0 hypotheses we refer for the Randall-Sundrum [6] graviton excitation (RS) and for the SUSY $\not{R}_p$ sneutrino exchange to [7], respectively.

The search reach at a collider for new gauge bosons is somewhat model dependent due to the rather large variations in their couplings to the SM fermions which are present in extended gauge theories currently on the market. This implies that any overview of the subject is necessarily incomplete. Hence, we will be forced to limit ourselves to a few representative models. To be specific we consider the so-called $Z'_{\rm SSM}$, Z'_{E_6}, $Z'_{\rm LR}$, $Z'_{\rm ALR}$ models. In this note we study the discovery potential of the experiments that will be performed at the LHC. In addition to the discovery reach we also examine the diagnostic power of the LHC for heavy gauge boson physics.

2. Observables and considered NP models

The parton model cross section for inclusive production of a dilepton with invariant mass M can be written as

$$\frac{{\rm d}\sigma(R_{ll})}{{\rm d}M\,{\rm d}y\,{\rm d}z} = K\frac{2M}{s}\sum_{ij} f_i(\xi_1,M) f_j(\xi_2,M)\frac{{\rm d}\hat{\sigma}}{{\rm d}z}(i+j\to l^+ + l^-). \tag{2}$$

Here, s is the proton-proton center-of-mass energy squared; $z=\cos\theta_{\rm c.m.}$ with $\theta_{\rm c.m.}$ the lepton-quark angle in the dilepton center-of-mass frame; y is the dilepton rapidity; $f_{i,j}(\xi_{1,2},M)$ are parton distribution functions in the protons P_1 and P_2, respectively, with $\xi_{1,2}=(M/\sqrt{s})\exp(\pm y)$ the parton fractional momenta; finally, ${\rm d}\hat{\sigma}_{ij}$ are the partonic differential cross sections. In (2), the factor K accounts for next-to-leading order QCD contributions. For simplicity, and to make our procedure more transparent, we will use as an approximation a global flat value $K=1.3$.

Since we are interested in a (narrow) peak production and subsequent decay into the DY pair, $pp\to R\to l^+l^-$, we consider the lepton differential angular distribution, integrated over an interval of M around M_R:

$$\frac{{\rm d}\sigma(R_{ll})}{{\rm d}z} = \int_{M_R-\Delta M/2}^{M_R+\Delta M/2}{\rm d}M\int_{-Y}^{Y}\frac{{\rm d}\sigma}{{\rm d}M\,{\rm d}y\,{\rm d}z}\,{\rm d}y. \tag{3}$$

The number of events under the peak, that determines the statistics, is therefore given by:

$$\sigma(R_{ll})\equiv\sigma(pp\to R)\cdot{\rm BR}({\rm R}\to{\rm l^+l^-}) = \int_{-{\rm z_{cut}}}^{\rm z_{cut}}{\rm dz}\int_{\rm M_R-\Delta M/2}^{\rm M_R+\Delta M/2}{\rm dM}\int_{-\rm Y}^{\rm Y}{\rm dy}\frac{{\rm d}\sigma}{{\rm dM\,dy\,dz}}. \tag{4}$$

For the full final phase space, $z_{\rm cut}=1$ and $Y=\log(\sqrt{s}/M)$. Concerning the size of the bin ΔM, it should include a number (at least one) of peak widths to enhance the probability to pick up the resonance. In our analysis, we adopt the parametrization of ΔM vs. M exploited in Ref. [10] and, denoting by N_B and N_S the number of 'background' and 'signal' events in the bin, the criterion $N_S=5\sqrt{N_B}$ or 10 events, whichever is larger, as the minimum signal for the peak discovery.

2.1. Z' models

The list of Z' models that will be considered in our analysis is the following:

(i) The three possible $U(1)$ Z' scenarios originating from the exceptional group E_6 spontaneous breaking. They are defined in terms of a mixing angle β. The specific values $\beta = 0$, $\beta = \pi/2$ and $\beta = \arctan -\sqrt{5/3}$, correspond to different E_6 breaking patterns and define the popular scenarios Z'_χ, Z'_ψ and Z'_η, respectively.

(ii) The left-right models, originating from the breaking of an $SO(10)$ grand-unification symmetry, and where the corresponding $Z'_{\rm LR}$ couples to a combination of right-handed and $B-L$ neutral currents (B and L denote lepton and baryon currents), specified by a real parameter $\alpha_{\rm LR}$ bounded by $\sqrt{2/3} \lesssim \alpha_{\rm LR} \lesssim \sqrt{2}$. We fix $\alpha_{\rm LR} = \sqrt{2}$, which corresponds to a pure L-R symmetric model.

(iii) The $Z'_{\rm ALR}$ predicted by the 'alternative' left-right scenario.

(iv) The so-called sequential $Z'_{\rm SSM}$, where the couplings to fermions are the same as those of the SM Z.

Current Z' mass limits from the LHC are 4.5 TeV [8] (ATLAS) and 4 TeV [9] (CMS).

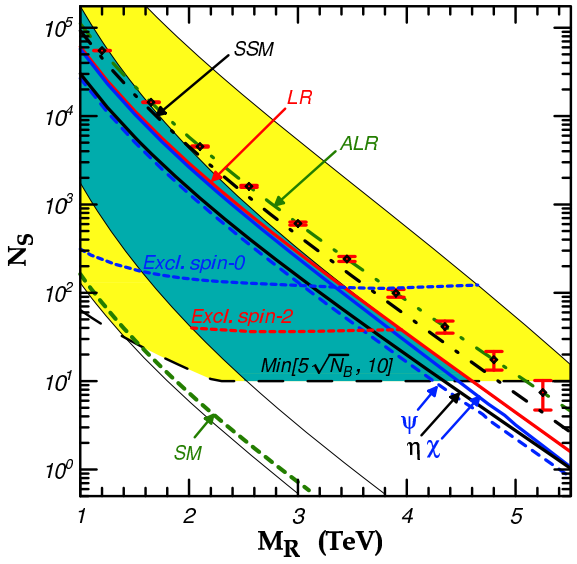

Figure 1. Expected number of resonance (signal) events N_S vs. M_R ($R = Z', G, \tilde{\nu}_\tau$) at the 14 TeV LHC with $\mathcal{L}_{\rm int} = 100\ fb^{-1}$ for the process $pp \to R \to l^+l^- + X$ ($l = e, \mu$) [10]. Event rates for various Z' models are shown. Green area corresponds to graviton signature space for $0.01 < c < 0.1$ while the yellow area is the sneutrino signature space for $10^{-5} < X < 10^{-1}$. Minimum number of signal events needed to detect the resonance (5-σ level) above the background and the minimum number of events to exclude the spin-2 and spin-0 hypotheses at 95% C.L. are shown. Error bars correspond to the statistical uncertainties for the ALR model.

2.2. RS graviton excitation

We consider the simplest scenario in the class of models based on one compactified warped extra dimension and two branes, proposed in the context of the SM gauge-hierarchy problem in [6]. The model predicts a tower of narrow Kaluza–Klein (KK), spin-2, graviton excitations $G^{(n)}$ ($n \geq 1$) with the peculiar mass spectrum $M^{(n)} = M^{(1)} x_n / x_1$ (x_i are the zeros of the Bessel function, $J_1(x_i) = 0$). Their masses and couplings to the SM particles are proportional to Λ_π and $1/\Lambda_\pi$, respectively, with Λ_π the gravity effective mass scale on the SM brane. For Λ_π of the TeV order, such RS graviton resonances can be exchanged in the process (1) and mimic Z' exchange. The independent parameters of the model can be chosen as the dimensionless

ratio $c = k/\overline{M}_{\rm Pl}$ (with k the 5-dimensional curvature and $\overline{M}_{\rm Pl} = 1/\sqrt{8\pi G_{\rm N}}$ the reduced Planck mass), and the mass M_G of the lowest KK resonance $G^{(1)}$. Accordingly, $\Lambda_\pi = M_G/cx_1$.

There are two partonic subprocesses, $q\bar{q} \to \gamma, Z, G \to l^+l^-$ and $gg \to G \to l^+l^-$, needed to describe hadronic production of lepton pair within KK models. The theoretically 'natural' ranges for the RS model parameters are $0.01 \leq c \leq 0.1$ and $\Lambda_\pi < 10\,$TeV. Current lower bounds at 95% C.L. from the LHC are: $M_G > 4.1$ TeV for $c = 0.1$ (ATLAS) [11].

2.3. Sneutrino exchange

Sneutrino ($\tilde{\nu}$) exchange can occur in SUSY with R-parity breaking, and represents a possible, spin-0, interpretation of a peak in the dilepton invariant mass distribution of the process (1). The cross section for the relevant partonic process, $q\bar{q} \to \tilde{\nu} \to l^+l^-$, is flat in z and expressed in terms of two Yukawa couplings, λ and λ', are the R-parity-violating sneutrino couplings to l^+l^- and $d\bar{d}$, respectively. Actually, in the narrow-width approximation, the partonic cross section turns out to depend on the product $X = (\lambda')^2 B_l$, with B_l the sneutrino leptonic branching ratio. Current limits on X are rather loose, and we may consider for this parameter the range $10^{-5} \leq X \leq 10^{-1}$. For $10^{-4} \leq X \leq 10^{-2}$, the range is $M_{\tilde{\nu}} \gtrsim 280 - 800$ GeV [12].

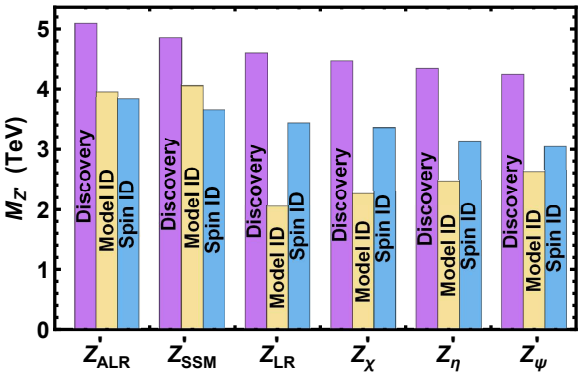

Figure 2. Discovery limits on $M_{Z'}$ (5-σ level) and Z' spin identification reaches (95% C.L.) for neutral gauge bosons of representative models, using the lepton-pair production cross section $\sigma \cdot B_l$ ($l = e, \mu$) and center-edge asymmetry A_{CE}, respectively, at the 14 TeV LHC with integrated luminosity of 100 fb^{-1}. Also, Z'-model distinction reaches (95% C.L.) are obtained from the analysis of the leptonic event rates.

3. Model signature spaces

In Fig. 1, we show the predicted number of resonance (signal) events N_S in the Drell-Yan process (1) at LHC, *vs.* M_R, where $R = Z', G, \tilde{\nu}$ denotes the three alternative possibilities outlined in the previous subsections. The assumed integrated luminosity is $\mathcal{L}_{\rm int} = 100 fb^{-1}$, the cuts in phase space relevant to the foreseen detector acceptance specified above have been imposed, and the channels $l = e, \mu$ have been combined. Also, the minimum signal for resonance discovery above the 'background' at 5σ is represented by the long-dashed line.

For any model, one can define a corresponding *signature space* as the region, in the (M_R, N_S) plot of Fig. 1, that can be 'populated' by the model by varying its parameters in the domains mentioned above. Clearly, in regions where the signature spaces overlap, the values of M_R are such that it is not possible to distinguish a model as the source of the peak against the others, because the number of signal events under the peak can be the same. Further analyses are needed in these cases to perform the identification of the peak source. For example, the 'blue' area in Fig. 1 corresponds to the graviton signature space for $0.01 \leq c \leq 0.1$, while the yellow area (which has substantial overlap with the blue one—indicated as green) is that for the sneutrino signature space corresponding to $10^{-5} \leq X \leq 10^{-1}$.

As regards the discovery and identification of Z' we are interested in, the signature spaces in Fig. 1 reduce to the lines labelled by the different models, because the event rates are fixed,

Table 1. Discovery and model identification (in TeV) for Z'-models at 14 TeV LHC in high luminosity modes.

Z' model	Discovery 300 fb^{-1}	Model ID 300 fb^{-1}	Discovery 3000 fb^{-1}	Model ID 3000 fb^{-1}
Z'_{ALR}	5.7	4.4	6.9	4.9
Z'_{SSM}	5.4	4.4	6.5	4.9
Z'_{LR}	5.1	2.2	6.3	2.4
Z'_{χ}	5.0	2.5	6.0	2.8
Z'_{η}	4.9	2.7	6.1	2.9
Z'_{ψ}	4.8	2.9	5.9	3.3

Table 2. Spin identification (in TeV) of Z'-models under considertion at 14 TeV LHC.

	100 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
Z' spin ID	3.0	3.8	5.0

once M'_Z is given, through the couplings in Table 1 of Ref. [10]. Fig. 1 shows that, with the assumed luminosity of 100 fb^{-1}, Z' gauge boson masses up to 4–5 TeV are in principle within the 5-σ reach of the LHC, consistent with earlier studies. We here assume that the Z' can only decay to pairs of SM fermions in order to obtain the leptonic branching ratio B_l. It is important to note that in many models, where Z' can also decay to exotic fermions and/or SUSY particles this overestimates B_l and, thus, the search reach.

On the other hand, Fig. 1 demonstrates that, as far as the production rate of DY pairs is concerned, there is a substantial overlap between the Z' and the $\tilde{\nu}$ signature spaces, which determines a domain in $(M_{\tilde{\nu}}, X)$ where spin-0 $\tilde{\nu}$ exchange and Z' exchanges are not distinguishable because they lead to the same event rate under the peak. The same is true for the spin-2, RS model. However, as shown by Fig. 1, in this case it is interesting to note that, if one literally takes the suggested range $c \leq 0.1$ as the 'naturally' preferred one, the ALR and SSM scenarios can be discriminated against the RS (spin-2) resonance *already* at the level of event rates in a wide range of mass values accessible to the LHC, with no need for further analyses. Conversely, only the E_6 and LR Z' models possess a 'confusion region' with the RS resonance G, concentrated near the upper border of the graviton signature domain.

In fact, the spin-0 exclusion is more restrictive than that for spin-2, as discussed above. Fig. 2 gives the 'translation' of the discovery reach on Z' models as well as identification reach on Z' spin presented in Fig. 1, in the form of the histograms. As one can see from Fig. 2, the spin-1 identification (or, actually, the spin-0 and spin-2 exclusion) can be obtained up to Z' mass of the order of 2.5–3.5 TeV, depending on the specific model. The model dependence of the spin identification reach is due to the difference in statistics, stemming from the different cross sections associated with these models.

4. Concluding remarks

Table 1 shows that Z' boson can be observed at 14 TeV LHC in high luminosity modes up to $M'_Z \approx 6.9$ TeV. The center-edge asymmetry, A_{CE}, will allow to determine the spin-1 (i.e., exclude spin-0 and spin-2) of heavy Z' gauge boson up to $M'_Z \approx 5.0$ TeV, at 95% C.L. (Table 2). With 3000 fb^{-1} of integrated luminosity, one can distinguish among different Z'-models under study up to $M'_Z \approx 2.4$ TeV (95% C.L.).

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