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SPIN DETERMINATION AND MODEL IDENTIFICATION OF Z′ BOSONS AT THE LHC

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Heavy resonances arising in the dilepton channel may be the first new physics to be observed at the proton-proton CERN LHC. If a new resonance is discovered at the LHC as a peak or bump in the dilepton invariant mass distribution, the characterization of its spin and couplings will proceed via measuring production rates and angular distributions of the decay products. The discovery potential and diagnostic abilities of the LHC for new heavy neutral Z' gauge bosons are studied. We discuss the discrimination of the spin-1 of Z' representative models ($Z'_{\rm SSM}$, Z'_ψ, Z'_η, Z'_χ, $Z'_{\rm LR}$, $Z'_{\rm ALR}$ within the class of Abelian Z') against the Randall-Sundrum graviton resonance (spin-2) and a spin-0 resonance (sneutrino). We find that the spin of a heavy Z' gauge boson within the class of Abelian can be established up to $M_{Z'} \simeq 6.5$ TeV while its discovery reach extends up to 8 TeV, for an integrated luminosity of 100 fb^{-1}. We also examine the distinguishability of the considered Z' models from one another, once the spin-1 has been established. We find that one might be able to distinguish among these Z' models at 95% C.L. up to $M_{Z'} \simeq 2$ TeV.

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 represents an important aspect of the selection among different classes of non-standard interactions giving rise to the observed peak. Tests of the spin-2 of the Randall-Sundrum [1] graviton excitation (RS) exchange in the process (1) at LHC, against the spin-1 hypothesis, have been recently performed, e.g., in Refs. [2] on the basis of the lepton differential polar angle distribution. The identification of the spin-1 Z's has been discussed in [3]. The above-mentioned differential angular analysis in the polar angle has been applied to the search for spin-2, spin-1 and spin-0 exchanges in the experimental studies of process (1) at the Fermilab Tevatron proton-antiproton collider [4].

In Ref. [5], the discrimination reach at the LHC on the spin-2 RS graviton resonance or, more precisely, the simultaneous rejection of *both* the spin-1 and spin-0 hypotheses for the peak, has been assessed by using as basic observable an angular-integrated center-edge asymmetry, $A_{\rm CE}$, instead of the 'absolute' lepton differential angular distribution. The potential advantages of the asymmetry $A_{\rm CE}$ to discriminate the spin-2 graviton resonance against the spin-1 hypothesis were discussed in Refs. [6, 7, 9].

Here, along the lines of Ref. [8] but in the reverse direction, we apply the same basic observable $A_{\rm CE}$, 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

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e-mail: [a]gulov@ff.dsu.dp.ua, [b]pankov@ictp.it, [c]skalozubv@daad-alumni.de, [d]tsytrin@gstu.by 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. [10, 11]; for the alternative spin-2 and spin-0 hypotheses we refer for the RS graviton resonance to [1] and for the SUSY $\not{R}_p$ sneutrino exchange to [12], 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 and also the generic class of the Abelian Z' models [13, 14, 15]. Particular attention has recently been devoted to the phenomenological properties and the search reaches on such scenarios, and in some sense we may consider these Z' models as representative of this NP sector. In this note we study the discovery potential of the experiments that will be performed over the next decade at the LHC. In addition to the discovery reach we also examine the diagnostic power of the LHC for heavy gauge boson physics.

It turns out that $A_{\rm CE}$ should provide a robust spin diagnostic for the spin-1 case also. Moreover, we examine the possibility, once the spin-1 for the discovered peak is established, of differentiating the various representative Z' models from one another. For this purpose, we must use the total dilepton production cross section or, equivalently, the rate of events of reaction (1) under the peak. Identification of Z' models have been discussed recently in, e.g. [3] with different sets of observables, namely, forward-backward asymmetry $A_{\rm FB}$ on and off the Z' resonance, Z' rapidity distribution, cross section times total width, $\sigma\times\Gamma_{Z'}$. It was found that, on the basis of $A_{\rm FB}$ only, pairs of Z' models become indistinguishable at a given level of significance, starting from relatively low values of $M_{Z'}$ of the order of 1–2 TeV, even at $\mathcal{L}_{\rm int}$ much higher than 100 fb^{-1}. These ambiguities can be reduced by the combined analysis of the observables mentioned above, and at $\mathcal{L}_{\rm int} = 100$ fb^{-1}, some models could be discriminated up to Z' mass of the order of 2–2.5 TeV. As we will note below, on the basis of a simple χ^2 criterion, the precise determination of the total cross section itself might provide a somewhat stronger discrimination potential, in the sense that all models could be pairwise distinguished from one another up to Z' masses of about 2 TeV.

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:

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

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. [8] 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.

To evaluate the statistics, we shall use in Eqs. (3) and (4) the CTEQ6.5 parton distributions [16], and impose cuts relevant to the LHC detectors, namely: pseudorapidity $|\eta|<2.5$ for both leptons assumed massless (this leads to a boost-dependent cut on z [7]); lepton transverse momentum $p_\perp > 20\,{\rm GeV}$. Moreover, the reconstruction efficiency is taken to be 90% for both electrons and muons.

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.

(v) The Abelian Z' boson. The Z'-boson can be introduced in a phenomenological way by specifying its effective low-energy couplings to the known SM particles [13, 14]. Considering the Z' effects at energies much below the Z' mass, it is enough to parametrize the tree-level Z' interactions of renormalizable types, only. The low energy Z' couplings to a fermion f are parameterized by two couplings, the axial-vector and vector fermion coupling. It was shown in Ref. [15], for any renormalizable theory beyond the SM these parameters content some relations which follow from the renorlalization group equations and the decoupling theorem. In case of the Z' boson this is reflected in correlations between a'_f and v'_f. These correlations are model-independent in a sense that they do not depend on an particular underlying model. The detailed discussion of these issues and the derivation of the RG relations are presented in Ref. [15].

Current Z' mass limits, from the Fermilab Tevatron collider, are in the range $800 - 1000$ GeV, depending on the model [17].

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 [1]. 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 $\Lambda_\pi < 10\,\mathrm{TeV}$. Current lower bounds at 95% C.L. from the Fermilab Tevatron collider are: $M_G > 300$ GeV for $c = 0.01$ and $M_G > 900$ GeV for $c = 0.1$ [17].

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 [17].

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

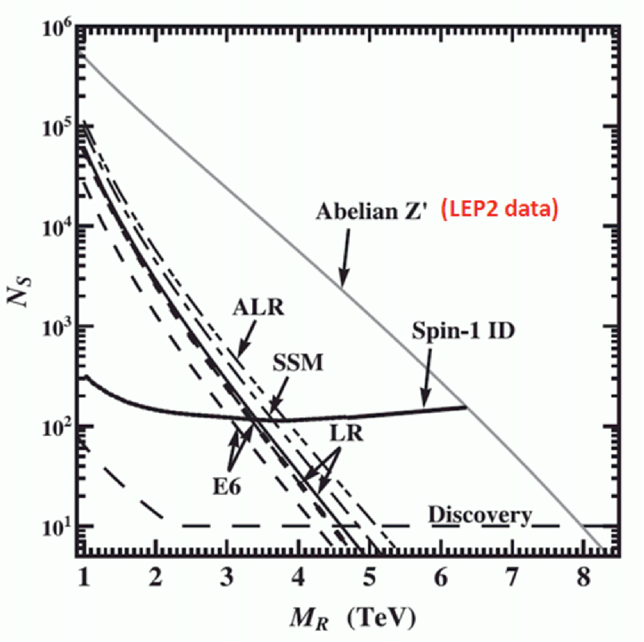

Figure 1. Expected number of resonance events at the LHC with $\mathcal{L}_{\rm int} = 100$ fb^{-1} for the process $pp \to R \to l^+l^- + X$, $(l = e, \mu)$. Event rates for various popular Z' models and the maximum possible resonant even rates for Abelian Z'-bosons are shown. The minimum number of signal events needed to detect the resonance (5σ-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 ("Spin-1 ID"). The area above the line "Abelian Z'" is excluded by the LEP2 data.

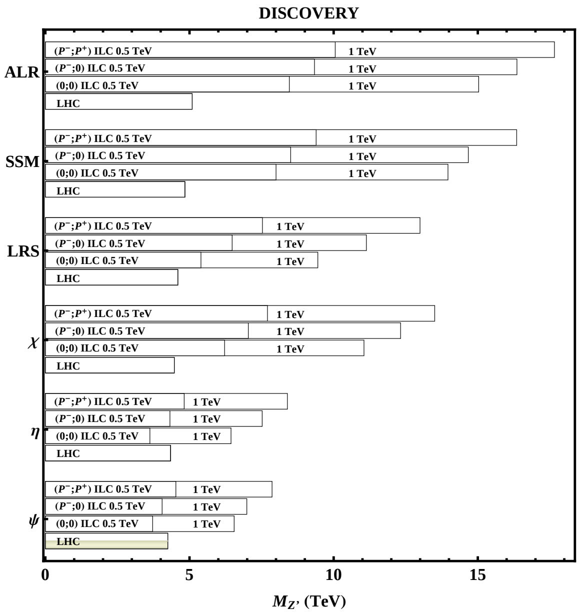

Figure 2. Discovery reaches on Z' models obtained from combined analysis of the unpolarized and polarized processes $e^+ + e^- \to f + \bar{f}$, $f = e, \mu, \tau, c, b$. (95% C.L.) at the ILC with $\sqrt{s} = 0.5$ TeV (1 TeV) and $\mathcal{L}_{\rm int} = 500$ fb^{-1} (1000 fb^{-1}), compared to the results expected from Drell-Yan processes at the LHC at the 5-σ level. Three options of polarization are considered at the ILC: unpolarized beams, $P^- = P^+ = 0$; polarized electron beam, $|P^-| = 0.8$; both beams polarized, $|P^-| = 0.8$ and $|P^+| = 0.6$.

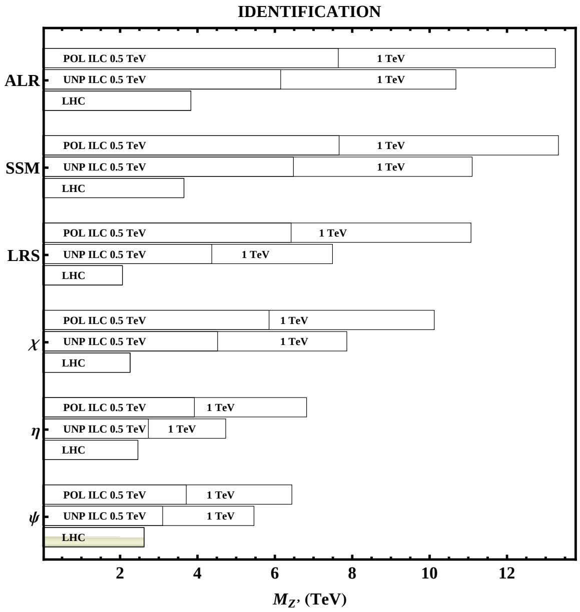

Figure 3. Comparison of the Z'-model distinction bounds on $M_{Z'}$ obtained from combined analysis of the unpolarized and polarized processes $e^+ + e^- \to f + \bar{f}$ at the ILC with $\sqrt{s} = 0.5$ TeV (1 TeV) and $\mathcal{L}_{\rm int} = 500$ fb^{-1} (1000 fb^{-1}), compared to the results expected from Drell-Yan processes at the LHC at 95% C.L. Two options of polarization are considered: unpolarized beams $P^- = P^+ = 0$ and both beams are polarized, $|P^-| = 0.8$ and $|P^+| = 0.6$.

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 with center-edge asymmetry. From Fig. 1 one finds that the spin of a heavy Z' gauge boson within the class of Abelian one can be established up to $M_{Z'} \simeq 6.5$ TeV while its discovery reach extends up to 8 TeV, at the LHC with the integrated luminosity of 100 fb^{-1}.

Fig. 2 and Fig. 3 show the comparison of discovery and identification reaches (or distinction bounds) on the Z'-models considered in Fig. 1, obtained from the process $pp \to l^+l^- + X$ at the LHC with c.m. energy 14 TeV and time-integrated luminosity 100 fb^{-1}. For comparison, the discovery and identification reaches obtained in Ref. [9] for the International Linear Collider (ILC) are also shown in Figs. 2 and 3. The figure speaks for itself, and in particular clearly exhibits the roles of the ILC parameters. One might be able to distinguish among the considered Z' models at 95% C.L. up to $M_{Z'} \simeq 3.1$ TeV (4.0 TeV) for unpolarized (polarized) beams at the ILC (0.5 TeV) and 5.3 TeV (7.0 TeV) at the ILC (1 TeV), respectively.

In the LHC discovery range, the cleaner ILC environment, together with the availability of beam polarization, allow for an identification of the particular Z' version realized. Actually, this ILC identification range extends considerably beyond the LHC discovery range. Specifically, the ILC with polarized beams at $\sqrt{s} = 0.5$ TeV and 1 TeV allows to identify all considered Z' bosons if $M_{Z'} \lesssim (6-7)\cdot\sqrt{s}$, substantially improving the LHC reach.

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