Disentangling between $Z'$ and $Z^*$ with first LHC data

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The resonance production of new chiral spin-1 excited bosons, $Z^*$, and their detection through the Drell–Yan process in the first physical runs at the CERN LHC are considered. The new neutral chiral bosons can be observed as a Breit–Wigner resonance peaks in the invariant dilepton mass distribution in the same way as the well-known hypothetical gauge bosons, $Z'$. However, unique new signatures of the chiral bosons exist. These signatures could be very important for the interpretation of the first LHC data. First, there is no Jacobian peak in the lepton transverse momentum distribution at the kinematical endpoint of the new resonance. Second, the lepton angular distribution in the Collins–Soper frame for the high on-peak invariant masses of the lepton pairs has a peculiar “swallowtail” shape.

I. INTRODUCTION

Although the LHC has been designed to solve the Higgs puzzle, it is obvious that the Higgs sector of the electroweak theory cannot be investigated at the first stage of the LHC running. While the discovery of the resonantly produced new neutral heavy bosons, having nonzero decay widths into charged leptons, could be followed immediately after detectors calibration at the hadron colliders. A presence of partons with a broad range of different momenta allows to flush the whole energetically accessible region, roughly, up to $\sqrt{s}/6$, where $\sqrt{s}$ is the center-of-mass collider energy. Even for this year LHC runs, which will be probably at a mere $\sqrt{s} = 10$ TeV, it allows to step above the Tevatron reach.

Two main circumstances designate the Drell–Yan process $q\bar{q} \rightarrow \ell^+\ell^-$ not only as a gold discovery channel, but also as a precise tool to unveil the resonance properties. First of all it

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provides a very low and theoretically well-understood background at high invariant leptonic masses. The second feature is related to the very clean signature of the process and almost totally reconstructible kinematics\(^1\), which allows to investigate the details of the production and the decay of the new bosons.

In this paper we will consider the case of the resonance production of new spin-1 heavy bosons and their detection in the Drell–Yan process using the first CERN LHC data.\(^2\) In the case that such bosons will be observed as resonance peaks above the \(Z\) boson tail in the invariant dilepton mass distribution, we suggest to investigate in addition three more experimentally accessible distributions already on the early stage of the LHC data-taking. These are the differential distributions as functions of a transverse momentum of the lepton, its pseudorapidity and the Collins–Soper angle.\(^1\) All these distributions are related to the spin properties of the new boson and should play crucial role in the analysis of their interactions.

II. NEUTRAL SPIN-1 BOSONS

New heavy neutral *gauge* bosons are predicted by many extensions of the Standard Model (SM). They are associated with additional \(U(1)’\) gauge symmetries and are generically called \(Z’\). The *gauge* interactions of these bosons with matter lead to a specific angular distribution of the outgoing lepton in the dilepton center-of-mass reference frame with respect to the incident parton

\[
\frac{d\sigma_{Z'}}{d\cos\theta^*} \propto 1 + \text{ASYM} \cdot \cos\theta^* + \cos^2\theta^*,
\]

which at present is interpreted as a canonical signature for the intermediate bosons with spin 1. The coefficient ASYM defines the backward-forward asymmetry, depending on \(P\)-parity of \(Z’\) couplings to fermions. Experimental uncertainties in the sign of \(\cos\theta^*\) in symmetric \(pp\) collisions and in the transverse momenta of the annihilating partons dilute the apparent value of ASYM and it can be neglected in the “first data” analysis.

In addition to the gauge bosons, another type of spin-1 bosons may exist, which have only a Pauli-like anomalous coupling to fermions instead of the gauge one. In contrast to

\(^1\) Up to small individual transverse momenta of the quarks.

\(^2\) The cases of spinless and spin-2 bosons can be also incorporated and will be considered elsewhere.
gauge couplings, where either only left-handed or right-handed fermions participate in the interactions, the anomalous couplings mix both left-handed and right-handed fermions and lead to different angular distribution than Eq. (1). Therefore, these bosons carry a nonzero chiral charge, like the Higgs particles.

A corresponding extension of the SM with the new type of spin-1 particles, chiral bosons, has been proposed in [2]. According to the symmetry of the SM the new chiral bosons have been introduced in doublets, just as the Higgs particles. In order to compensate the contributions of the new couplings of the chiral bosons into the chiral anomaly, the doubling of the doublets both for the chiral and Higgs particles is needed. Besides this, in order to prevent also the presence of flavor-changing neutral currents, up and down type fermions should couple to different doublets of the Higgs and chiral bosons.

Among all introduced new states of the chiral bosons there exist two heavy neutral CP-even and CP-odd bosons, which couple to down type fermions and, therefore, have nonzero decay widths into charged leptons. These bosons have nearly degenerate masses, predicted to be slightly above 1 TeV [3]. However, it is impossible to distinguish them in the case of the light final fermions at the hadron colliders without a spin correlation analysis. Therefore, in the following we will consider only one type of these bosons, namely the CP-even one.

It has been noted that for the resonance production of the chiral bosons the original lagrangian in [3] can be substituted by a more simple one for the excited bosons $Z^*$

$$\mathcal{L}_{\text{excited}} = \frac{g}{2\sqrt{2}M} \left( \bar{\ell} \sigma^{\mu\nu} \ell + \bar{d} \sigma^{\mu\nu} d \right) \left( \partial_\mu Z^*_\nu - \partial_\nu Z^*_\mu \right),$$

which has been investigated in [4]. Here $M$ is the boson mass and $g$ is the coupling constant of the $SU(2)_W$ weak gauge group. The bosons, coupled to the tensor quark currents, are some types of “excited” states as far as the only orbital angular momentum with $L = 1$ contributes to the total angular moment, while the total spin of the system is zero. This property manifests itself in their derivative couplings to fermions and a different chiral structure of the interactions in contrast to the gauge ones.

Let us assume for definiteness that the mass of the new $Z^*$ bosons is equal to 1 TeV, which is above the Tevatron reach, but they could be reliably discovered at the LHC even with very low integrated luminosity, less than 100 pb$^{-1}$. For comparison we will consider topologically analogous but minimal interactions of the gauge $Z'$ boson

$$\mathcal{L}_{\text{gauge}} = \frac{g}{2} \left( \bar{\ell} \gamma^\mu \ell + \bar{d} \gamma^\mu d \right) Z'_\mu,$$
with the same mass $M$. The coupling constants are chosen in such a way that all fermionic decay widths in the Born approximation of the both bosons are identical. It means that their total production cross sections at the hadron colliders are nearly equal up to next-to-leading order corrections. Their leptonic decay width

$$\Gamma_{\ell} = \frac{g^2}{48\pi}M \approx 2.8 \text{ GeV}. \quad (4)$$

is sufficiently narrow so that they can be identified as resonances at the hadron colliders in the Drell–Yan process.

III. NUMERICAL SIMULATIONS

Up to now, the excess in the Drell–Yan process with high-energy invariant mass of the lepton pairs remains the clearest indication of the heavy boson production at the hadron colliders. In the following for the numeric calculations of various distributions we will use the CalcHEP package \footnote{CalcHEP} with a CTEQ6M choice for the proton parton distribution set at $\sqrt{s} = 10$ TeV. For both final leptons we impose angular cuts relevant to the LHC detectors on the pseudorapidity range $|\eta| < 2.5$ and, in addition, the transverse momentum cuts $p_T > 20$ GeV. The resonance peaks of new boson production are shown in Fig. 1. It can

FIG. 1: The invariant dilepton mass distributions for the gauge $Z'$ boson (blue) and the chiral excited $Z^*$ boson (red) with the Drell–Yan SM background at the CERN LHC.
be concluded that their cross sections at the peak are above two order of magnitude higher than the corresponding Drell–Yan background.

The peaks in the invariant mass distributions originate from the Breit–Wigner propagator form, which is the same both for the gauge and the chiral bosons in the Born approximation. However, the common wisdom, that a peak in the invariant mass distribution of the two final particles must correspond to the Jacobian peaks in their transverse momentum distributions, is not valid for the chiral bosons due to the following fact. The main feature of the interactions (2) consists in different angular distribution of final fermions \[ \frac{d\sigma_{Z^*}}{d\cos\theta^*} \propto \cos^2\theta^* \] (5) in comparison with the distribution (1) for the gauge interactions. It leads to a step-wise lepton transverse momentum distribution, rather than to the Jacobian peak at the kinematical endpoint \( M/2 \) for the gauge bosons (Fig. 2). Therefore, already the lepton transverse momentum distribution demonstrates a difference between the gauge and the chiral bosons. In order to make more definite conclusions, let us investigate other distributions selecting only “on-peak” events with the invariant dilepton masses in the range \( 800 \text{ GeV} < M_{\ell\ell} < 1200 \text{ GeV} \).

FIG. 2: The differential cross sections for the gauge \( Z' \) boson (blue) and the chiral excited \( Z^* \) boson (red) with the Drell–Yan SM background as functions of the lepton transverse momentum at the CERN LHC.
The integrated luminosity around $50 \, \text{pb}^{-1}$ can be reached this year for two months LHC running at the initial luminosity of $10^{31} \, \text{cm}^{-2}\text{s}^{-1}$. Therefore, in the following calculations we will use this value to estimate the expected number of events. The histograms on-peaks events with theoretical curves are presented in Fig. 3. They correspond to $\sigma_{Z'} = 0.45 \, \text{pb}$

FIG. 3: The invariant dilepton mass distributions for the gauge $Z'$ boson (left) and the chiral excited $Z^*$ boson (right).

and $\sigma_{Z^*} = 0.41 \, \text{pb}$, and contain 22.5 and 20.6 events for the gauge and chiral bosons, respectively.\(^3\) The irreducible Drell–Yan SM background contributes only with $\sigma_{\text{bkgd}} = 5.75 \, \text{fb}$ or 0.29 events. Therefore, the predicted numbers of the signal events correspond to about 12 $\sigma$ significant level of the discovery.\(^4\)

In Fig. 4 we present the histograms and the theoretical curves as functions of the lepton transverse momentum. It can be seen that these distributions, in contrast to the previous ones, are completely different one from another. Besides different shapes they lead also to different ratios of the total number events in the histograms in Fig. 4 to the total number events under the corresponding peaks in Fig. 3

$$\frac{N_{Z'}^{T}}{N_{Z'}^{\text{tot}}} = 0.54 \pm 0.11, \quad \frac{N_{Z^*}^{T}}{N_{Z^*}^{\text{tot}}} = 0.26 \pm 0.10. \quad (6)$$

\(^3\) The slight difference in the numbers is due to different angular distributions and the applied cuts (see [7] for more details).

\(^4\) The significances have been calculated according the method presented in Appendix A of Ref. [8], which follows directly from the Poisson distribution.
FIG. 4: The differential distributions for the gauge $Z'$ boson (left) and the chiral excited $Z^*$ boson (right) as functions of the lepton transverse momentum.

Their difference is not statistically significant\(^5\) at this stage yet, but the last ratio shows a tendency the transverse momentum distribution for the exited bosons to be much softer than the analogous distribution for the gauge bosons.

Let us turn now to the leptonic pseudorapidity distributions, which are directly connected to the angular distributions (1) and (5) up to the longitudinal boosts. To calculate the corresponding distributions we need to fold the parton cross sections with the parton luminosities \((dN_{gq}(x, \bar{x})/dx d\bar{x})\), where the fractions of the quark and the antiquark momenta in the proton

\[
x = \frac{M_{\ell\ell}}{\sqrt{s}} \exp(y) ; \quad \bar{x} = \frac{M_{\ell\ell}}{\sqrt{s}} \exp(-y)
\]

can be expressed through the center-of-mass energy, $\sqrt{s}$, the invariant dilepton mass, $M_{\ell\ell}$, and the $\ell^-$ lepton pseudorapidity, $y$, in the laboratory reference frame. Hence, the parton luminosity is very sensitive to the latter. As far as the neutral heavy bosons are produced at the LHC in $pp$ collisions, the antiquarks come always from the sea and, in general, $\bar{x} < x$. This means that the center of the $d\bar{d}$ distribution will be shifted to positive $y$. The asymmetry is compensated by the opposite shift of the $\bar{d}d$ distribution, which finally leads to the symmetric form (see Fig. 5).\(^6\)

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\(^5\) The variances have been calculated according to the binomial distribution.

\(^6\) The contributions of $u$-type quarks are two orders of magnitude smaller than the corresponding resonance
FIG. 5: The differential distributions for the gauge $Z'$ boson (left) and the chiral excited $Z^*$ boson (right) as functions of the lepton pseudorapidity. The corresponding $d\bar{d}$ and $\bar{d}d$ contributions are shown as dashed and dotted curves, respectively.

According to Eq. (5), for the chiral bosons there exists a characteristic plane, perpendicular to the beam axis in the parton rest frame, where the emission of the final-state pairs is forbidden. The nonzero probability in the perpendicular direction in the laboratory frame is only due to the longitudinal boosts of the colliding partons. This property is responsible for the additional dips in the middle of the lepton pseudorapidity distributions for the chiral bosons in contrast to the gauge ones (see the right panel of Fig. 5). Therefore, the corresponding distribution looks flatter at $\eta_\ell = 0$ than the one for the gauge bosons. However, this property is typical only for low values of the center-of-mass energy, as $\sqrt{s} = 10$ TeV or less, i.e. when the corresponding parameter $\tau = M^2/s \geq 0.01$. At the nominal $\sqrt{s} = 14$ TeV the CERN LHC is sufficiently powerful to produce heavy bosons of the mass $M = 1$ TeV with high longitudinal boosts, which fill the dips, and the distributions for the gauge and chiral bosons look almost similar (see 4).

A crucial confirmation for the existence of the new interactions (2) should come from the analysis of the angular distribution of the final leptons with respect to the boost direction of the heavy boson in the rest frame of the latter (the Collins–Soper frame). In Fig. 6 we compare the differential cross sections for the gauge $Z'$ boson and the chiral excited $Z^*$ contributions of down type quarks in the on-peak region.
FIG. 6: The differential distributions of the gauge \( Z' \) boson (left) and the chiral excited \( Z^* \) boson (right) as functions of \( \cos \theta^*_{CS} \).

The gauge boson decaying to the lepton pairs with the invariant mass \( 800 \text{ GeV} < M_{\ell\ell} < 1200 \text{ GeV} \) as functions of \( \cos \theta^*_{CS} \).

Instead of a smoother angular distribution for the gauge interactions, a peculiar “swallowtail” shape of the chiral boson distribution occurs with a profound dip at \( \cos \theta^*_{CS} = 0 \). It is obvious that such form of the angular distribution will lead to the large and negative value of the centre-edge asymmetry \( A_{CE} \), defined as

\[
\sigma A_{CE} = \int_{-\frac{1}{2}}^{+\frac{1}{2}} \frac{d\sigma}{d \cos \theta^*_{CS}} \ d \cos \theta^*_{CS} - \left[ \int_{+\frac{1}{2}}^{+1} \frac{d\sigma}{d \cos \theta^*_{CS}} \ d \cos \theta^*_{CS} + \int_{-1}^{-\frac{1}{2}} \frac{d\sigma}{d \cos \theta^*_{CS}} \ d \cos \theta^*_{CS} \right].
\] (8)

Indeed, the corresponding values of the gauge and chiral bosons are

\[
A_{CE}^{Z'} = -(0.11 \pm 0.06), \quad A_{CE}^{Z^*} = -(0.69 \pm 0.10),
\] (9)

which differ at about 5\( \sigma \) level. Therefore, the discovery of the large negative \( A_{CE} \) value will indicate the existence of the heavy spin-1 boson with the new interactions already in the first data. Neither scalars nor other particles possess such a type of angular behavior.\(^7\)

\(^7\) The scalar and spin-2 particles lead to the nonnegative \( A_{CE} \) values and their signatures can be rejected even at a more significant level.
IV. CONCLUSIONS

In this paper we have considered the experimental signatures of the chiral excited bosons, \(Z^*\), and compared them to the gauge \(Z'\) bosons. It has been stressed that the chiral bosons have a new distinctive angular distribution, yet unknown by experimentalists. It leads to an absence of the Jacobian peak in the transverse momentum distribution and to a profound dip in the angular distribution at the rest frame of the heavy chiral bosons. These features could help to discriminate the chiral boson production from a resonance production of other particles using the first LHC data.

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