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Z' Boson at the LHC and at Future Hadron Colliders

S SAHOO
Department of Physics, National Institute of Technology
Durgapur-713209, West Bengal, India
E-mail: sukadevsahoo@yahoo.com

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Abstract : Z' bosons are a feature of many models of physics beyond the standard model (BSM) and their discovery could possibly be the first evidence for new physics. It is possible to detect these bosons in the leptonic Drell-Yan mode, hence it is expected that the LHC would be able to see evidence for a Z' boson. In this article, we discuss the discovery possibility of Z' boson at the LHC and at future Hadron Colliders briefly.

Keywords: Models beyond the standard model; Grand unified theories; Z' boson.

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1. Introduction

The Z' gauge boson is predicted by a wide variety of extensions of the standard model (SM) [1,2]. It is an electrically neutral colourless spin-1 gauge boson. Theoretically it is predicted that these bosons exist in grand unified theories (GUTs), left-right symmetric models, Little Higgs models, technicolour models, superstring theories and theories with large extra dimensions. But experimentally Z' boson is not discovered so far. Experimental searches of Z' boson from Drell-Yan cross sections at Tevatron have put lower limits on the mass range 0.6 – 1.0 TeV at 95 % C. L. depending on the specific models [2]. From the electroweak precision data analysis, the improved lower limits on the Z' mass are given in the range 1.1– 1.4 TeV at 95 % C. L. [3]. These limits on Z' boson mass favours higher energy ($\geq$ 1 TeV) collisions for direct observation of the signal. It is also possible that the Z' bosons can be much heavy or weak enough to escape beyond the discovery reach expected at the

LHC. In this case, only the indirect signatures of Z' exchanges may occur at the high energy colliders [4]. For an experimentalist a Z' is a resonance 'bump' more massive than the Z of the SM which can be observed in Drell-Yan production followed by its decay into lepton-antilepton pairs [5]. For a phenomenologist a Z' boson is a new massive electrically neutral, colourless boson (equal to its own antiparticle) which couples to SM matter. For a theorist it is useful to classify the Z' according to its spin, even though actually measuring its spin will require high statistics.

In the Z' sector, there has been a great deal of investigation [6–11] to understand the underlying physics beyond the SM. It has been shown that a leptophobic Z' boson can appear in E_6 gauge models due to mixing of gauge kinetic terms [12,13]. Flavor mixing can be induced at the tree level in the up-type and/or down-type quark sector after diagonalizing their mass matrices. Mixing between ordinary and exotic left-handed quarks induces *Z*-mediated flavor-changing neutral currents (FCNCs). The right-handed quarks d_R, s_R and b_R have different $U(1)'$ quantum numbers than exotic q_R and their mixing will induce Z'-mediated FCNCs [8,12] among the ordinary down quark types. Tree level FCNC interactions can also be induced by an additional Z' boson on the up-type quark sector [9]. Over the past years, processes induced by FCNC have been under sharp scrutiny, as these processes are forbidden at the tree level and thus arise only at the loop level within SM. Many new physics (NP) models have different patterns with SM and enhance the FCNC transition at the tree or loop level, which are likely to affect some physical observables sizably compared to SM. Recently Sahoo et al. [10,11] have studied the effect of Z'-mediated FCNCs on different B meson decays and B meson mixing. In this article, we want to discuss the discovery possibility of Z' boson at the LHC and at future Hadron Colliders briefly.

2. Z' Gauge Boson in different Models

2.1 E_6 Based Models

Extra U(1) gauge symmetries appear in the decomposition of the SO(10) or E_6 GUT groups. The group E_6 has rank 6. So the E_6 model predicts the existence of Z' boson. Additional Z' bosons, originating from E_6 grand unified theories can be expressed in terms of the decay chain [14]

$$E_6 \to SO(10)\times U(1)_\psi$$
$$\to SU(5)\times U(1)_\chi \times U(1)_\psi \to SM \times U(1)_{\theta_{E_6}} \quad , \qquad (1)$$

where $U(1)_{\theta_{E_6}}$ remains unbroken at low energies.

Now consider the models in which the linear combination [15],

$$U(1)' = \cos\beta\ U(1)_\chi + \sin\beta\, U(1)_\psi\,, \qquad (2)$$

survives down to the EW scale, using a convention in which the mixing angle in Equation (2) satisfies $-90^0 < \beta \le 90^0$.

(a) $Z_\chi : \beta = 0^0 \Rightarrow Z' = Z_\chi$. This Z_χ boson is also defined by $SO(10) \to SU(5)\times U(1)_\chi$. This boson is the unique solution to the conditions of (i) family universality, (ii) no extra matter other than the right-handed neutrino, (iii) absence of gauge and mixed gauge/gravitational anomalies, and (iv) orthogonality to the hypercharge generator.

(b) $Z_\psi : \beta = 90^0 \Rightarrow Z' = Z_\psi$. This Z_ψ boson is also defined by $E_6 \to SO(10)\times U(1)_\psi$. It possesses only axial-vector couplings to the ordinary fermions.

(c) $Z_\eta : \beta = -\arctan\sqrt{5/3} \approx -52.2^0 \Rightarrow Z' = \sqrt{3/8}\, Z_\chi - \sqrt{5/8}\, Z_\psi \equiv Z_\eta$. It occurs in Calabi-Yau compactification scheme [16] of the heterotic string [17] if E_6 breaks directly to a rank-5 subgroup via the Hosotani mechanism [18].

(d) $Z_I : \beta = \arctan\sqrt{3/5} \approx 37.8^0 \Rightarrow Z' = \sqrt{5/8}\, Z_\chi + \sqrt{3/8}\, Z_\psi \equiv -Z_I$. This boson is orthogonal to Z_η. This boson [19] has the defining property of vanishing couplings to up-type quarks. Its production is thus suppressed at hadron colliders, especially at the Tevatron since in high energy $p\bar{p}$ collisions Z' production through down quarks is suppressed by a factor of 25 relative to up quarks [20].

(e) Z_S : $\beta =$ arctan $\sqrt{5/27} \approx 23.3^0 \Rightarrow Z' =$ $\sqrt{27/32}\, Z_\chi + \sqrt{5/32}\, Z_\psi \equiv Z_S$, numerically close to the Z_I. A supersymmetric model with a secluded $U(1)'$ breaking sector and a large supersymmetry breaking A-term was introduced (i) to provide an approximately flat potential allowing the generation of a $Z-Z'$ mass hierarchy [21] and (ii) to produce a strong first order EW phase transition for EW baryogenesis [22].

(f) Z_N : $\beta =$ arctan $\sqrt{15} \approx 75.5^0 \Rightarrow Z' =$ $(Z_\chi + \sqrt{15}\, Z_\psi)/4 \equiv Z_N$. The Z_N boson appears in the ESSM [23] or the E_6SSM [24,25].

(g) Z_R : All models discussed so far neglected the kinetic mixing between the gauge kinetic term for the $U(1)'$ and $U(1)_Y$ gauge boson. In the E_6 context, one can write the Z' as the general combination:

$$Z' = \cos\alpha \cos\beta\, Z_\chi + \sin\alpha \cos\beta\, Z_Y + \sin\beta\, Z_\psi . \qquad (3)$$

$$\alpha = \text{arctan } \sqrt{3/2} \approx 50.8^0 \Rightarrow Z' = \sqrt{2/5}\, Z_\chi + \sqrt{3/5}\, Z_Y \equiv Z_R$$

(h) Z_{LR} : The group SO(10) has rank 5, so the SO(10) GUT does predict the existence of a Z'. Since SO(10) has a larger rank than that of G_{321}, there are several ways in which it can be broken down to $G_{321} =$ $SU(3)_C \times SU(2)_L \times U(1)_Y$. For example;

$$SO(10) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$$
$$\rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}, \qquad (4)$$

where *B* is baryon number and *L* is lepton number. The first chain gives the additional boson Z_χ, while second chain yields the left-right symmetric model [26]. The SM gauge group is extended to $SU(2)_L \times SU(2)_R \times U(1)$ resulting in a right-handed charged boson and an additional Z'.

$Z_{LR} = \sqrt{3/5}\left(\bar{\alpha}\, Z_R - Z_{B-L}/2\bar{\alpha}\right), Z' = \sqrt{3/5}\, Z_\chi - \sqrt{2/5}\, Z_Y$ $\equiv -\sqrt{3/8}\, Z_{B-L}$, $\alpha = -\arctan\sqrt{2/3} \approx -39.2^0$. The parameter $\bar{\alpha} = \sqrt{g_R^2/g_L^2 \cot^2\theta_W - 1}$, θ_W is the weak mixing angle. Manifest left-right symmetry requires $g_L = g_R$, while very strong coupling limit $\left(\bar{\alpha}, g_R/g_L \to \infty\right)$ implies $Z_{LR} \to Z_R$.

(i) Z_L : A leptophobic Z' has vanishing $U(1)'$ charges to charged leptons and left-handed neutrinos. The choice $(\alpha, \beta) = \left(\arctan\sqrt{8/27}, -\arctan\sqrt{9/7}\right)$ $\approx \left(28.6^0, -48.6^0\right) \Rightarrow Z' = \sqrt{27/80}\ Z_\chi + 1/\sqrt{10}\ Z_Y - 3/4\ Z_\psi \equiv Z_L$ [12].

2.2 Sequential Z'

The Z_{SSM} boson has the same couplings to fermions as the SM Z boson. Such a boson is not observed in the gauge theories unless it has different couplings to exotic fermions than the ordinary Z. However, it serves as a useful reference case when comparing constraints from various sources.

2.3 Superstring Z'

The Z_{string} boson appears in a specified model [27] based on the free fermionic string construction with real fermions. While this model itself is not realistic the predicted Z_{string} it contains is itself not ruled out. Its coupling strength is predicted and so are its fermionic couplings. Such a Z_{string} can be naturally at the electroweak scale [28,29].

3. Z' Boson at the LHC and at Future Hadron Colliders

Hadron colliders can produce a Z' boson via Drell-Yan production, which would then be observed in the invariant mass distribution of the pair produced final state particles. At the LHC, the researchers concentrate on the dilepton processes $pp \to Z' \to \ell^+\ell^- + X$, $\left(\ell = e, \mu\right)$: these two very clean channels to look for, and after simple generous cuts the irreducible background is dominated by the well-understood SM Drell-Yan (DY) processes [30]. Recently the ATLAS [31] has obtained exclusion limits at 95% C.L. for the mass of Z'

boson $M(Z'_{SSM}) > 2.86$ TeV, $M(Z'_{\eta}) > 2.44$ TeV , $M(Z'_{\chi}) > 2.54$ TeV and $M(Z'_{\psi}) > 2.38$ TeV from 8 TeV collisions with 20 fb^{-1} integrated luminosity. Similarly, the CMS [32] has obtained exclusion limits at 95% C.L. for the mass of Z' boson $M(Z'_{SSM}) > 2.96$ TeV and $M(Z'_{\psi}) > 2.60$ TeV from 8 TeV collisions with 20 fb^{-1} integrated luminosity.

The LHC is shut down from February, 2013 for upgradation for approximately two years to boost its energies from 7 TeV to 14 TeV. When the LHC reaches its design energies and luminosity it should be able to see evidence for Z' up to ~ 5 TeV for a large variety of BSM models and the high luminosity upgrade LHC (HL-LHC) will extend this reach up to ~ 6 TeV. The high energy LHC (HE-LHC) would substantially extend this reach to ~ 11 TeV while the 100 TeV very high energy LHC (VHE-LHC) could see evidence for Z' up to ~ 30 TeV [33].

The first 14 TeV run of the LHC will be started on January 1, 2015 (tentatively) with integrated luminosity of 100 fb^{-1} [34]. Run 2 of the 14 TeV LHC will be started on January 1, 2019. By the end of Run 2, 300 fb^{-1} would be collected by the snowmass detector. Run 3 of 14 TeV LHC will be began on January 1, 2022. The end of the LHC Run 3 with its 14 TeV centre of mass energy and 3000 fb^{-1} of collected data will come about in the year 2025. The lower limits on the mass of Z' boson at the LHC is given in the Table [34]:

Table. Lower mass limits at 95% CL for various Z' models

Integrated Luminosity (at $\sqrt{s}$ = 14 TeV)	Z'_{ψ} (TeV)	Z'_{LR} (TeV)	Z'_{SSM} (TeV)
300 fb^{-1}	5.01	5.62	6.44
3003 fb^{-1}	6.29	7.52	~ 8.50

CERN has planned to build a “very high energy large hadron collider” that would pass under the Lake Geneva. It would have acircumference of 80 – 100 km and a collision energy of 100 TeV (Compared with the present planned LHC with circumference: 27 km and collision energy 14 TeV) [35]. CERN accelerator physicist Michael Benedikt suggests that construction might begin in the 2020s, so that the machine could be completed soon after the LHC shuts down for good around 2035.

If a Z' were discovered at a hadron collider, its precision measurements can be used to constrain its mass and the couplings. These facts lead to enrichment in the phenomenology of Z' boson and physics beyond the SM will show up after the discovery of the Z' boson.

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