

Z' Discovery Reach at Future Hadron Colliders: A Snowmass White Paper

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Extra neutral gauge 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. In this Snowmass white paper we compare the discovery reach of the high energy hadron colliders considered by the Snowmass study for a broad range of BSM models. It is expected that the LHC should be able to see evidence for a Z' arising from a large variety of BSM models up to a mass of ~ 5 TeV when the LHC reaches its design energy and luminosity, and up to ~ 6 TeV with the high luminosity upgrade. Further into the future, the high energy LHC would substantially extend this reach to ~ 11 TeV, while the 100 TeV VHE-LHC could see evidence for Z' 's up to ~ 30 TeV.

I. INTRODUCTION

Extra gauge bosons, including Z' 's and W' 's, are a feature of many models of physics beyond the SM [1–5]. Examples of such models are Grand Unified theories based on groups such as $SO(10)$ or E_6 [5], Left-Right symmetric models [6], Little Higgs models [7–10], and Technicolour models [11–14] to name a few. In addition, resonances that arise as Kaluza-Klein excitations in theories of finite size extra dimensions [15] would also appear as new gauge bosons in high energy experiments. It is therefore quite possible that the discovery of a new gauge boson could be one of the first pieces of evidence for physics beyond the SM. Evidence for extra gauge bosons can take two forms: either from direct production, or indirectly via deviations from standard model predictions. The first approach is limited by the kinematic reach of direct production at hadron colliders or e^+e^- colliders. However, given that the current direct limits of Z' 's are ~ 3 TeV, it is clear that Z' 's will not be produced directly at any of the high energy lepton colliders envisaged for the foreseeable future.

Currently, the highest mass bounds on most extra neutral gauge bosons are obtained by searches at the Large Hadron Collider by the ATLAS and CMS experiments. Recent results based on dilepton resonance searches in $\mu^+\mu^-$ and e^+e^- final states use data from the 7 TeV proton collisions collected in 2011 and the more recent 8 TeV data collected in 2012. ATLAS [16] obtains exclusion limits at 95% C.L. of $M(Z'_{\text{SSM}}) > 2.86$ 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, while CMS [17] obtains 95% C.L. exclusion limits of $M(Z'_{\text{SSM}}) > 2.96$ TeV and $M(Z'_\psi) > 2.60$ TeV from 8 TeV collisions using $\sim 20 \text{ fb}^{-1}$ of luminosity. For these values, SSM refers to the sequential standard model which has the same fermion couplings as the Stan-

dard Model and is often used as a reference when comparing constraints from different measurements. The labels η , χ , and ψ refer to Z' 's arising from different symmetry breaking scenarios of the E_6 group [5].

II. Z' PRODUCTION AT HADRON COLLIDERS

Hadron colliders can produce a Z' boson via Drell-Yan production [2, 18–21], which would then be observed in the invariant mass distribution of the pair produced final state particles. For most models with a Z' , the cleanest final state is dileptons, both muons and electrons, due to low backgrounds and clean identification. A very small number of dilepton events clustered in one or two bins of the invariant mass distribution would be taken as an obvious signal for new physics. To quantify this, we consider two opposite sign leptons and impose kinematic cuts of $|\eta_l| < 2.5$ and $p_{T_l} > 20$ GeV to reflect detector acceptance. For the discovery limits, we assumed a criteria of 5 isolated dimuon pair events, with a signal-over-background ratio of at least 5, within $\pm 3\Gamma_{Z'}$ of the resonance peak.

In Fig. 1 we show the discovery limits for the various models for several hadron collider benchmark energies and luminosities. When the LHC reaches its design energy and luminosity it should be able to see evidence for Z' 's up to ~ 5 TeV for a large variety of BSM models [18, 21–24], and the high luminosity upgrade (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' 's up to ~ 30 TeV. For these future searches, the di-electron final state will be the most important as the electromagnetic calorimeters will still be able to measure the electron energy accurately, while the muon energy, measured from the curvature of the track, will not be easily measurable with the existing magnetic field for muons with transverse momenta much above 1 TeV [25].

For models with a leptophobic Z' and W' , the dominant decay mode for the gauge bosons are to diquarks and leads to a resonance in the dijet invariant mass dis-

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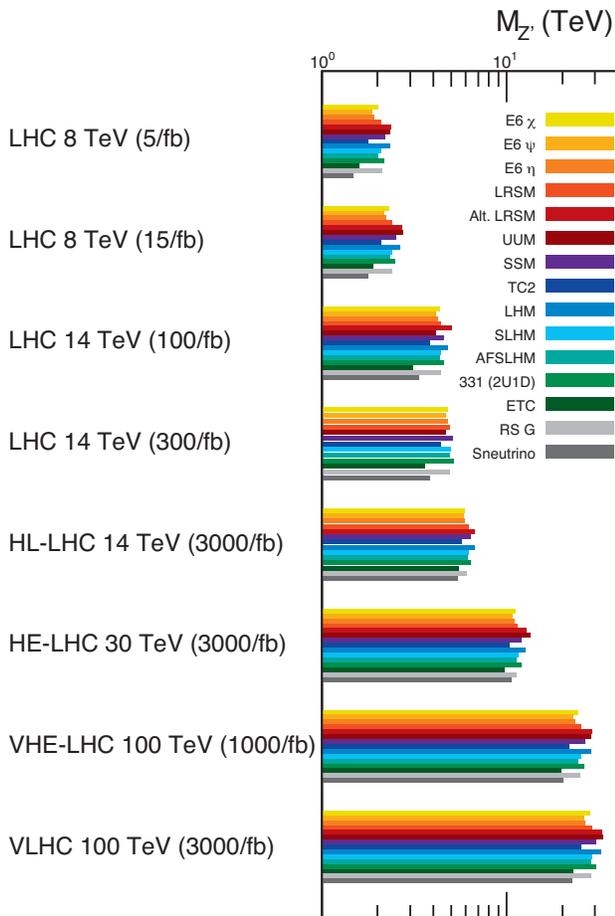


FIG. 1: Z' discovery reach at high energy hadron colliders.

tribution. Searches have been performed that require two well-separated jets with high transverse momentum. The CMS collaboration excludes the existence of a SSM Z' boson with mass between 1.20 and 1.68 TeV at 95% C.L. and a SSM W' with mass between 1.20 and 2.29 TeV using the $\sqrt{s} = 8$ TeV, $\mathcal{L}_{\text{int}} = 20.0 \text{ fb}^{-1}$ dataset [26]. The CMS collaboration have also developed a dedicated search for $b\bar{b}$ resonances and excluded the existence of a SSM Z' boson within the range of 1.20 to 1.68 TeV at 95% C.L. in the $b\bar{b}$ channel [27]. For models with larger branching fractions to b -quarks the limit improves considerably, excluding a larger mass range.

To search for evidence of models with generation dependent couplings, such as technicolor models, both CMS and ATLAS have performed searches for Z' resonances in the $t\bar{t}$ final state. The CMS searches in the dilepton plus jets final state[28] have excluded masses below 1.3 TeV (1.9 TeV) for a Z' width of $\Gamma_{Z'}/M_{Z'} = 0.012$ (0.10), while the search in the lepton plus jets final state[29] have excluded masses below 1.49 TeV (2.04 TeV). Similarly, ATLAS has excluded a Z' resonance decaying to $t\bar{t}$ in topcolor assisted technicolor models within the mass

range of $0.5 < M_{Z'} < 1.8$ TeV at 95% C.L. in the single lepton plus jets final state, using 14 fb^{-1} integrated luminosity [30]. It is more difficult to project limits in the $t\bar{t}$ and $b\bar{b}$ channels to higher energies because of the added complications in dealing with hadronic final states so this topic is left for a future study.

III. EFFECTS OF Z' 'S AT HIGH ENERGY e^+e^- COLLIDERS

The other way to search for evidence for extra neutral gauge bosons is to look for deviations from the standard model due to interference and virtual effects. In particular, high energy e^+e^- colliders will be sensitive to new gauge bosons with $M_{Z'} \gg \sqrt{s}$. We mention results for the sensitivity of high energy e^+e^- colliders to Z' 's for comparison purposes and refer the interested reader to the existing literature [22, 23, 31, 32] including another contribution to the 2013 Snowmass study [33].

In e^+e^- collisions below the on-shell production threshold, extra gauge bosons manifest themselves as deviations from SM predictions due to interference between the new physics and the SM γ/Z^0 contributions. $e^+e^- \rightarrow f\bar{f}$ reactions are characterized by relatively clean, simple final states where f could be leptons (e, μ, τ) or quarks (u, d, s, c, b, t), for both polarized and unpolarized e^\pm . The basic $e^+e^- \rightarrow f\bar{f}$ processes can be parametrized in terms of four helicity amplitudes which can be determined by measuring various observables: the leptonic cross section, $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, the ratio of the hadronic to the QED point cross section $R^{\text{had}} = \sigma^{\text{had}}/\sigma_0$, the leptonic forward-backward asymmetry, A_{FB}^ℓ , the leptonic longitudinal asymmetry, A_{LR}^ℓ , the hadronic longitudinal asymmetry, $A_{\text{LR}}^{\text{had}}$, the forward-backward asymmetry for specific quark or lepton flavours, A_{FB}^f , the τ polarization asymmetry, A_{pol}^τ , and the polarized forward-backward asymmetry for specific fermion flavours, $A_{\text{FB}}^f(\text{pol})$ [31]. The indices $f = \ell, q, \ell = (e, \mu, \tau), q = (c, b)$, and $\text{had} = \text{'sum over all hadrons'}$ indicate the final state fermions. Precision measurements of these observables for various final states ($\mu^+\mu^-, b\bar{b}, t\bar{t}$) can be sensitive to extra gauge boson masses that by far exceed the direct search limits that are expected at the LHC [18, 22, 31–33]. Further, precision measurements of cross sections to different final state fermions using polarized beams can be used to constrain the gauge boson couplings and help distinguish the underlying theory [32–38]. A deviation for one observable is always possible as a statistical fluctuation and different observables have different sensitivities to different models (or more accurately to different couplings). As a consequence, a more robust strategy is to combine many observables to obtain a χ^2 figure of merit.

The ILC sensitivity to Z' 's is based on high statistics precision cross section measurements so that the reach will depend on the integrated luminosity. For many models a 500 GeV e^+e^- collider with as little as 50 fb^{-1} in-

tegrated luminosity would see the effects of a Z' with masses as high as ~ 5 TeV [22]. Recent studies [32, 33] find that a 500 GeV ILC with 500 fb^{-1} and a 1 TeV ILC with 1 ab^{-1} can see evidence or rule out a Z' with masses that can exceed ~ 7 and ~ 12 TeV respectively, for many models. These results also consider various polarizations for the e^- and e^+ beams and show that beam polarization will increase the potential reach of the ILC. It should be noted that in the case of e^+e^- colliders the exclusion limits are very sensitive to the specific model in contrast to hadron colliders where the exclusion limits are far less model dependent.

IV. FINAL COMMENTS

We presented the discovery reach for extra gauge bosons that are possible for various high energy hadron colliders that have been considered for the Snowmass study. The LHC should be able to see evidence for Z' 's

up to ~ 5 TeV for a large variety of BSM models, the HL-LHC will extend this reach up to ~ 6 TeV, the 30 TeV HE-LHC to ~ 11 TeV and the 100 TeV VHE-LHC up to ~ 30 TeV. In comparison, a 500 GeV, 500 fb^{-1} e^+e^- collider would be sensitive to Z' 's ~ 6 TeV comparable to the HL-LHC and a 1 TeV, 1 ab^{-1} e^+e^- collider would be sensitive to Z' 's ~ 12 TeV comparable to the HE-LHC. We did not discuss the issue of Z' identification if a Z' were discovered. If a Z' were discovered at a hadron collider, precision measurements at a high energy e^+e^- collider would give valuable information on its couplings which could not be obtained at hadron colliders on the same time scale.

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