Comparison of Diagnostic $Z'$ Physics at Future $pp$ and $e^+e^-$ Colliders

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UPR-597-T
December 1993

Abstract

We present recent developments in the diagnostic study of heavy gauge bosons at future $pp$ (CERN LHC) and $e^+e^-$ (NLC) colliders with the emphasis on the model independent determination of gauge couplings of $Z'$ to quarks and leptons. The analysis reflects a complementary diagnostic power of the LHC and the NLC (c.m. energy 500 GeV, integrated luminosity 20 fb$^{-1}$). At the NLC for $M_{Z'} \sim 1$ TeV all the quark and lepton charges can be determined to around $10^{-20\%}$, provided heavy flavor tagging and longitudinal polarization of the electron beam is available. At the LHC primarily the magnitude of three (out of four) normalized couplings can be determined, however typical uncertainties are by a factor $\sim 2$ smaller than at the NLC.
Introduction

If heavy gauge bosons $Z'$'s turn out to have a mass up to around 5 TeV, future hadron colliders, e.g., the large hadron collider (LHC) at CERN, would be an ideal place to discover them. An immediate need after $Z'$ discovery would be to learn more about its properties. In particular, a determination of $Z'$ couplings to quarks and leptons is useful. By now a series of such probes was proposed, allowing for a model independent determination of quark and lepton charges provided $M_{Z'} < \sim 2$ TeV.

On the other hand, future $e^+e^-$ colliders with large enough c.m. energy, e.g., $\sqrt{s} = 2$ TeV, could provide a clean way to discover and study the properties of $Z'$'s. A more likely possibility, however, is the next linear collider (NLC) with $\sqrt{s} = 500$ GeV. There, due to the interference effects of the $Z'$ propagator with the photon and $Z$ propagator, the probes with the two–fermion final states yield a complementary information on the existence of a $Z'$. An extensive study [2, 3] showed that effects of $Z'$'s would be observable at the NLC for a large class of models with $M_{Z'}$ up to $1-3$ TeV. In particular, sensitivity of the NLC to discriminate between specific classes of extended electroweak models, e.g., different $E_6$ motivated models described by a parameter $\cos \beta$ (the mixing between the $Z$ and the $Z'$ defined below) or left-right symmetric models parameterized by the ratio $\kappa = g_R/g_L$ for the SU(2)$_{L,R}$ gauge coupling constants $g_{L,R}$, was explored. Most recently, a model independent determination of $Z'$ couplings to quarks and leptons and a comparison with the LHC colliders was performed in Ref. [4].

Probes at the LHC

In the main production channels, $pp \to Z' \to \ell^+\ell^-$ ($\ell = e, \mu$) one would be able to measure the mass $M_{Z'}$, the total width $\Gamma_{tot}$ and the total cross section $\sigma_{\ell\ell}$. The quantity $\sigma_{\ell\ell}\Gamma_{tot}$ would in turn yield information on an overall strength of the $Z'$ gauge coupling. On the other hand there is a need for probes which are sensitive to the relative strength of $Z'$ couplings. The nature of such probes can be classified according to the type of channel in which they can be measured.

- (i) The forward-backward asymmetry [5],
- (ii) the ratio of cross-sections in different rapidity bins [6],
constitute distributions, i.e., “refinements” in the main production channel. The forward-backward asymmetry was long recognized as useful to probe a particular combination of quark and lepton couplings. The rapidity ratio is a useful complementary probe separating the $Z'$ couplings to the $u$ and $d$ quarks due to the harder valence $u$-quark distribution in the proton relative to the $d$-quark.

- (iii) Rare decays $Z' \to W\ell\ell$ [13, 14],
- (iv) associated productions $pp \to Z'V$ with $V = (Z,W)$ [10] and $V = \gamma$ [13].

If the proton polarization were available the corresponding asymmetries would also to be useful [6]. In other two-fermion channels measurements of the $\tau$ polarization in the $pp \to Z' \to \tau^+\tau^-$ channel [9], is also a useful probe. Measurements of the cross section in $pp \to Z' \to jet jet$ channel is the only probe available for the left-handed quark coupling [10]. Recent studies [4, 12] indicate that the measurement of the cross-section in this channel might be possible with appropriate kinematic cuts, excellent dijet mass resolution, and detailed knowledge of the QCD backgrounds.

1 For a recent review of $Z'$ physics at future hadron colliders see Ref. [5].
2 For a related work on the bounds for leptonic gauge couplings see Ref. [4].
provide another set of useful probes in the the four-fermion final state channels. These probes have suppressed rates compared to the two-fermion channels. Rare decays turn out to have sizable statistics, however only the modes $Z' \rightarrow W \ell \nu$ \cite{14, 15, 16} with appropriate cuts are useful without large standard model and QCD backgrounds. These modes probe a left-handed leptonic coupling. On the other hand the associated productions turn out to be relatively clean signals \cite{10} with slightly smaller statistics than rare decays. They probe a particular combination of the gauge couplings to quarks and are thus complementary to rare decays.

### Probes at the NLC

There the cross sections and corresponding asymmetries in the two-fermion final state channels, $e^+e^- \rightarrow f\bar{f}$, will be measured. The analysis is based on the following probes:

$$
\sigma^\ell, \quad R^{\text{had}} = \frac{\sigma^{\text{had}}}{\sigma^\ell}, \quad A^\ell_{FB}.
\tag{1}
$$

In the case that longitudinal polarization of the electron beam is available there are additional probes:

$$
A^{\ell,\text{had}}_{LR}, \quad A^\ell_{LR, FB}
\tag{2}
$$

Here $\sigma$, $A_{FB}$, $A_{LR}$ and $A_{LR, FB}$ refer to the corresponding cross-sections, forward-backward asymmetries, left-right asymmetries and left–right–forward–backward asymmetries, respectively. The index $\ell$ refers to all three leptonic channels (considering only $s$-channel exchange for electrons) and had to all hadronic final states. The above quantities distinguish among different models\cite{4}, however, they do not yield information on all the $Z'$ couplings.

If one assumes\footnote{\cite{5} Z' \rightarrow Z\ell^+\ell^- does not significantly discriminate between models.}, an efficient heavy flavor \footnote{\cite{6} Note that at the LEP an efficient tagging of the charm and bottom flavors was achieved.} (c, b, t) tagging there are the following additional observables:

$$
R^f = \frac{\sigma^f}{\sigma^\ell}, \quad A^f_{FB} ; \quad f = c, b, t
\tag{3}
$$

and with available polarization:

$$
A^f_{LR}, \quad A^f_{LR, FB} ; \quad f = c, b, t
\tag{4}
$$

These additional probes in turn allow for complete determination of the $Z'$ gauge couplings to ordinary fermions\cite{7}.

### Determination of gauge couplings at the LHC

We assume the c.m. energy $\sqrt{s} = 16$ TeV\footnote{\cite{8} See Ref. \cite{9} for detailed discussions.} and integrated luminosity $L_{int} = 100 \text{ fb}^{-1}$. We consider only statistical uncertainties associated with the probes (i-iv), which yield sufficient qualitative information. Realistic fits, which include updated structure functions, kinematic cuts, and detector acceptances are expected to give larger uncertainties for the couplings.

We consider the following typical models: $Z_\chi$ in $SO_{10} \rightarrow SU_5 \times U_{1\chi}$, $Z_\psi$ in $E_6 \rightarrow SO_{10} \times U_{1\psi}$, $Z_\eta = \sqrt{3/8}Z_\chi - \sqrt{5/8}Z_\psi$ in superstring inspired models in which $E_6$ breaks directly to a rank 5 group, and $Z_{LR}$ in LR symmetric models. For conventions in the neutral current interactions see Ref. \cite{10}. In the following we assume family universality, neglect $Z - Z'$ mixing and assume $[Q', T_i] = 0$, which holds for $SU_2 \times U_1 \times U'_1$ and LR models. Here, $Q'$ is the $Z'$ charge and $T_i$ are the $SU_{2L}$ generators which incidentally is satisfied by the above models.

The relevant quantities \cite{12, 13} to distinguish between different models are the charges, $\tilde{g}^{\mu}_{L2} =$\footnote{For the new projected c.m. energy $\sqrt{s} = 14$ TeV, the cross section in the main production channel decreases by $\sim30\%$ and thus the statistical error bars on the probes increase by $14\%$.}
Table 1: Values of the couplings (5) for the typical models. The statistical error bars indicate how well the coupling could be measured at the LHC (c.m. energy $\sqrt{s} = 16$ TeV and integrated luminosity $L_{\text{int}} = 100$ fb$^{-1}$) for $M_{Z'} = 1$ TeV.

|    | $\chi^L$ | $\psi^L$ | $\eta^L$ | $LR^L$ |
|----|----------|----------|----------|--------|
| $\gamma^L$ | 0.9 ± 0.018 | 0.5 ± 0.03 | 0.2 ± 0.015 | 0.36 ± 0.007 |
| $\gamma^D$ | 0.1 | 0.5 | 0.8 | 0.04 |
| $\bar{U}$ | 1 ± 0.18 | 1 ± 0.27 | 1 ± 0.14 | 37 ± 8.3 |
| $\bar{D}$ | 9 ± 0.61 | 1 ± 0.41 | 0.25 ± 0.29 | 65 ± 14 |

Figure 1: 90% confidence level ($\Delta \chi^2 = 6.3$) contours for the $\chi$, $\psi$ and $\eta$ models are plotted for $\bar{U}$, versus $\bar{D}$, versus $\gamma^L$. The input data are for $M_{Z'} = 1$ TeV at the LHC ($\sqrt{s} = 16$ TeV and $L_{\text{int}} = 100$ fb$^{-1}$) and include statistical uncertainties only.

$$\hat{g}^d_{L2} = \hat{g}^u_{L2}, \quad \hat{g}^u_{R2}, \quad \hat{g}^d_{R2}, \quad \hat{g}^\gamma_{L2} = \hat{g}^\ell_{L2}, \quad \text{and} \quad \hat{g}^\ell_{R2}, \quad \text{and the gauge coupling strength} \quad \hat{g}_2.$$ The signs of the charges will be hard to determine at hadron colliders. Thus the following four “normalized” observables can be probed:

$$\gamma^\ell = \frac{(\hat{g}^\ell_{R2})^2}{\hat{g}_{L2}^2 + (\hat{g}^\ell_{R2})^2}, \quad \gamma^L = \frac{(\hat{g}^L_{R2})^2}{\hat{g}_{L2}^2 + (\hat{g}^L_{R2})^2}, \quad \bar{U} = \frac{(\hat{g}^u_{R2})^2}{\hat{g}_{L2}^2}, \quad \bar{D} = \frac{(\hat{g}^d_{R2})^2}{\hat{g}_{L2}^2}.$$ (5)

The values of these couplings for the typical models and the corresponding statistical uncertainties for the $\gamma^\ell_L$, $\bar{U}$, and $\bar{D}$ couplings are given in Table 1. In particular, $\gamma^\ell_L$ can be determined very well, primarily due to the small statistical errors for the rare decay modes. On the other hand the quark couplings have larger uncertainties. In Figure 1 90% confidence level ($\Delta \chi^2 = 6.3$) contours are given in a three-dimensional plot for $\bar{U}$ versus $\bar{D}$ versus $\gamma^\ell_L$ for the $\eta$, $\psi$ and $\chi$ models (the $LR$ model is in a different region of the parameter space). Note a clear separation between the models.

For $M_{Z'} \simeq 2$ TeV a reasonable discrimination between models and determination of the couplings may still be possible, primarily from the forward-backward asymmetry and the rapidity ratio. However, for $M_{Z'} \simeq 3$ TeV there is little ability to discriminate between models.

**Determination of gauge couplings at the NLC**

We assume the c.m. energy $\sqrt{s} = 500$ GeV and the integrated luminosity $L_{\text{int}} = 10$ fb$^{-1}$. For probes (1-4) we use the exact tree level expressions and assume 100% efficiency for the heavy flavor tagging (probes (3-4)) and 100% longitudinal polarization of the initial electron beam for probes (2) and (4). Only statistical uncertainties are taken into account. If a new $Z'$ is known to exist, a realistic fit should include full radiative corrections, true experimental cuts and detector acceptances, which are expected to increase the uncertainties.

Because the photon couplings are vector-like and the $\ell$ couplings to $Z$ have the property on the more familiar two-dimensional parameter subspaces correspond to $\Delta \chi^2 = 4.6$. 

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8 $\gamma^\eta_L$ could be determined by measuring the branching ratio $B(Z' \to q\bar{q})$. See the footnote on the previous page.

9 The 90% confidence level contours for projections
Table 2: The value of the couplings for typical models and statistical error-bars as determined from the probes (1-4) at the NLC (c.m. energy $\sqrt{s} = 500$ GeV and integrated luminosity $\mathcal{L}_{\text{int}} = 20 \text{ fb}^{-1}$). $M_{Z'} = 1$ TeV. 100% heavy flavor tagging efficiency and 100% longitudinal polarization of the electron beam is assumed for the first set of error bars, while the error bars in parentheses are for the probes without polarization.

| $P^\ell_V$ | $P_\ell^L$ | $P_\ell^R$ | $P_{R_R}^\eta$ | $P_{R_R}^\epsilon$ | $\chi$ | $\psi$ | $\eta$ | $LR$ |
|-----------|-----------|-----------|----------------|------------------|--------|--------|--------|-----|
| $2.0 \pm 0.08 (0.26)$ | $0.0 \pm 0.04 (1.5)$ | $-3.0 \pm 0.5 (1.1)$ | $-0.15 \pm 0.018 (0.072)$ | $-0.5 \pm 0.04 (0.10)$ | $0.5 \pm 0.10 (0.2)$ | $2.0 \pm 0.3 (1.1)$ | $-0.14 \pm 0.037 (0.07)$ | $-1.0 \pm 0.15 (0.19)$ | $-1.0 \pm 0.11 (1.2)$ | $-1.0 \pm 0.15 (0.24)$ | $-6.0 \pm 1.4 (3.3)$ | $3.0 \pm 0.24 (0.51)$ | $-1.0 \pm 0.21 (2.8)$ | $0.5 \pm 0.09 (0.48)$ | $8.0 \pm 1.9 (4.1)$ | $0.071 \pm 0.005 (0.018)$ | $0.121 \pm 0.017 (0.02)$ | $0.012 \pm 0.003 (0.009)$ | $0.255 \pm 0.016 (0.018)$ |

For the model $\varphi L$, the fine structure constant. Note that relative error bars are typically by a factor of $\sim 2$ bigger than the corresponding ones at the LHC. Without polarization the error bars increase by a factor $2-10$, and thus yield only marginal information about the couplings. The $\psi$ model has particularly poorly determined couplings without polarization. In Fig. 2, 90% confidence level ($\Delta \chi^2 = 6.3$) contours are given in a three dimensional plot of $P_{R_R}^\eta$ versus $P_{R_R}^\psi$ versus $P_V^\ell$ for the $\chi$, $\psi$ and $\eta$ models (the $LR$ model is in a different region of the parameter space).

In the case of smaller, say, 25%, heavy flavor tagging efficiency and in the case that the electron beam polarization is reduced to, say, 50%, the determination of the couplings is poorer, however still useful. For $M_{Z'} \sim 2$ TeV, the uncertainties for the couplings in the typical models are too large to discriminate between models.

**Conclusions**

The analysis demonstrates complementarity between the NLC and the LHC colliders, which in conjunction allow for determination of the $M_{Z'}$, an overall $Z'$ gauge coupling strength as well as a unique determination of *all* the quark...
and lepton charges with sufficiently small error bars, provided $M_{Z'} \lesssim 1$ TeV.

**Acknowledgment**

I would like to thank F. del Aguila and P. Langacker for enjoyable collaboration. The work was supported by the Department of Energy Grant # DE–AC02–76–ERO–3071, and the Texas National Research Commission Laboratory.
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