CLIC AS A Z' FACTORY

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ABSTRACT
CLIC could be a very interesting Z' factory, with a large event rate (one event every few seconds or minutes) enabling us to make detailed studies of the major Z' decay modes (Z' → H, W+W-) and search for rare modes such as Z' → Z + Higgs (H). These possibilities are illustrated with examples of superstring-inspired Z' bosons.

1. INTRODUCTION
Most of our detailed knowledge of the properties of vector bosons comes from e+e− machines. This includes the J/ψ — whose initial simultaneous discovery in hadron–hadron and e+e− collisions was followed by a wealth of information from e+e− storage rings; and the T resonances — whose discovery in hadron–hadron collisions was mainly followed up in e+e− collisions. We expect the same to be true of the Z0, with its initial discovery at the CERN pp Collider being followed by detailed studies at the SLC and LEP, operated as Z0 factories. If there is another neutral gauge boson Z', as advocated in many theories [1], the same sequence of events may occur again. Even if it is discovered first at a hadron–hadron collider such as the LHC or the SSC, it may be explored in detail at CLIC operated as a Z' factory.

In this contribution, we first remind the reader of the general formulae for cross-sections and event rates on the peaks of resonances in e+e− annihilation [2]. Then we illustrate these formulae with the results for three specific superstring-inspired Z' bosons. We discuss common and rare decay modes of the Z', including Z' → H, W+W−, and Z0 + H.

2. GENERAL FORMULAE
The total cross-section for e+e− → X via an intermediate vector boson such as the Z' is determined by unitarity to be [2]

\[
\frac{\sigma(e^+e^- \rightarrow Z' \rightarrow X)}{\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-)} = \frac{9}{\alpha^2} \frac{BR(Z' \rightarrow e^+e^-) BR(Z' \rightarrow X)}{BR(\gamma^* \rightarrow e^+e^-)}
\]

(1)

where branching ratios are denoted generally by BR. If we sum over all the possible final states X in Eq. (1), the total cross-section on the Z' peak is evaluated to be [2]

\[
\sigma(e^+e^- \rightarrow Z' \rightarrow \text{all}) = \frac{13}{m_{Z'}} \frac{BR(Z' \rightarrow e^+e^-)}{(\text{TeV})^2} \frac{m_{Z'}}{m_{Z'}}^4
\]

(2)

The Standard Model Z0 has BR(Z0 → e+e−) = 3%. If we adopt this number as an estimate of BR(Z' → e+e−) (which is not unreasonable as we will see in Section 3), then Eq. (2) gives one event per three seconds (one event per minute) for mZ' = 1 (4) TeV if L = 10^{33} cm^{-2} s^{-1}. A typical estimate of \Gamma(Z')/m_{Z'} is 0.03, the same as \Gamma(Z0)/m_{Z0} (see Section 3 again), which is rather narrower than the beam energy spread. Therefore the Breit–Wigner formulae (1) and (2) may not be applied, just as the beam energy spread reduces \sigma(e^+e^- → J/ψ → all) on the peak of the
resonance. The amount of this reduction depends sensitively on the machine parameters, but is typically $O$(few) [3]. However, it does indicate that pilot studies of a $Z'$ can be made even if the initial CLIC luminosity is considerably below the target of $10^{13}$ to $10^{14}$ cm$^{-2}$ s$^{-1}$ advocated elsewhere in these Proceedings [4]. Conversely, with the target luminosity one can hope to obtain event samples of $10^4$ to $10^6$ $Z'$ decays, enabling one to study common decays in detail and to search for rare decays.

3. SUPERSTRING-INSPIRED $Z'$ BOSONS

We now illustrate the possibilities of CLIC as a $Z'$ factory with three examples of superstring-inspired $Z'$ bosons, whose couplings are specified in Table 1. Model A is the minimal rank-5 gauge group obtainable from the 10-dimensional heterotic string by compactification on a Calabi-Yau manifold [5]. Models B and C are obtained from rank-6 gauge groups by assuming a large vacuum expectation value (v.e.v.) for some SU(3)$_c$ × SU(2)$_L$ × U(1)$_Y$-singlet scalar field [6]. Listed in the first column of Table 1 are all the particles in a 27 representation of $E_6$.

<table>
<thead>
<tr>
<th>Possible neutral currents in superstring models</th>
</tr>
</thead>
<tbody>
<tr>
<td>T$_{3L}$</td>
</tr>
<tr>
<td>(u,d)$_t$</td>
</tr>
<tr>
<td>u$_L$</td>
</tr>
<tr>
<td>d$_L$</td>
</tr>
<tr>
<td>(e,$\bar{\nu}$)$_L$</td>
</tr>
<tr>
<td>e$_L$</td>
</tr>
<tr>
<td>D$_L$</td>
</tr>
<tr>
<td>D$_R$</td>
</tr>
<tr>
<td>$\nu_L$</td>
</tr>
<tr>
<td>N$_L$</td>
</tr>
<tr>
<td>(H$^+$,H$^0$)$_t$</td>
</tr>
<tr>
<td>(H$^0$,H$^-$)$_t$</td>
</tr>
</tbody>
</table>

Model A: $Z'$ couples to $Y$.
Model B: $Z'$ couples to $(\sqrt{3/5}Y' - \sqrt{\lambda/3}Y^*)$.
Model C: $Z'$ couples to $(\sqrt{3/5}Y' + \sqrt{\lambda/3}Y^*)$.

into pairs of which the $Z'$ could decay. To estimate the total decay width and BR($Z' \to e^- e^-$) for each model, we adopt two alternative hypotheses which bracket the reasonable possibilities: either a) the $Z'$ decays into quarks $q$ and leptons $\ell$, but not into squarks $\tilde{q}$ or sleptons $\tilde{\ell}$ or any exotic particles from the 27 of $E_6$; or b) the $Z'$ decays into all particles and sparticles in the 27 representations of $E_6$. Other decay modes of the $Z'$ could be interesting, such as $Z' \to W^+ W^-$, $W^+ W^-$, or $Z^0 \to H$, but these are unlikely to have branching ratios of more than a few per cent.

Using the decay hypotheses (a) and (b) above, we find the predictions of Table 2 for the total decay width $\Gamma(Z' \to all)$, for BR($Z' \to e^- e^-$), for $\sigma(e^- e^- \to Z' \to all)$, and for the mean time between successive $Z'$ decay events assuming a luminosity of $10^{13}$ cm$^{-2}$ s$^{-1}$. All the results quoted are for $m_{Z'} = 1$ TeV; for other values of $m_{Z'}$, $\Gamma(Z' \to all) \propto m_{Z'}$, BR($Z' \to e^- e^-$) is constant, $\sigma(e^- e^- \to Z' \to all) \propto m_{Z'}^2$, and the mean time between events $\propto m_{Z'}^2$. As is shown elsewhere [2, 3], the event rate can be significantly reduced by the beam energy spread, but remains large enough to search for rare $Z'$ decays.
Table 2
Z' properties and event rates for m_{Z'} = 1 TeV

<table>
<thead>
<tr>
<th>Model</th>
<th>A</th>
<th></th>
<th>B</th>
<th></th>
<th>C</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay hypothesis</td>
<td>(a)</td>
<td>(b)</td>
<td>(a)</td>
<td>(b)</td>
<td>(a)</td>
<td>(b)</td>
</tr>
<tr>
<td>\Gamma(Z' \to all)/m_{Z'} (%)</td>
<td>0.65</td>
<td>3.8</td>
<td>1.2</td>
<td>3.8</td>
<td>0.65</td>
<td>3.8</td>
</tr>
<tr>
<td>BR(Z' \to e^+e^-) (%)</td>
<td>3.6</td>
<td>0.6</td>
<td>5.9</td>
<td>1.8</td>
<td>5.4</td>
<td>0.9</td>
</tr>
<tr>
<td>\sigma(e^+e^- \to Z' \to all)</td>
<td>0.46</td>
<td>0.077</td>
<td>0.76</td>
<td>0.23</td>
<td>0.69</td>
<td>0.12</td>
</tr>
<tr>
<td>Mean time between events^{a3} (s)</td>
<td>2.2</td>
<td>13</td>
<td>1.3</td>
<td>4.3</td>
<td>1.4</td>
<td>8.7</td>
</tr>
</tbody>
</table>

a) Calculated assuming \( L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \) and neglecting the effects [2, 3] of beam energy spread.

4. POSSIBLE RARE Z' DECAYS

\( Z' \to W^+W^- \): This may occur through Z' mixing with the Z^0 and the Z'W^+W^- vertex of the Standard Model [6]. The amount of this mixing is model-dependent but decreases for larger m_{Z'}. at fixed values of the other parameters. However, because of the momentum dependence in the three-boson vertex, BR(Z' \to e^+e^-) is essentially constant and typically O(1 to 3)% in many models. Precisely because of its model-dependence, this decay mode would be a good probe of different models.

\( Z' \to d\bar{d} + aD \): In some models, the conventional charge \(-1/3\) quarks d, s, and b can mix with the exotic charge \(-1/3\) fermions called generically D in Table 1, enabling this decay mode to be present. The branching ratio for this decay mode is sensitive to unknown ratios of generalized Higgs v.e.v.'s and Yukawa couplings [7]. Therefore a search for it would be very interesting. The D fermions are expected [8] to decay into final states with leptoquark quantum numbers, such as \( \ell q\bar{q}, \ell q, \ell \bar{q} \), or with antidiquark quantum numbers such as \( \bar{q}q\bar{q}, \bar{q}q \), which should be easy to pick out.

\( Z' \to Z^0 + H^0 \): This may have a large branching ratio in some models, and we refer the interested reader to Refs. [9] and [10] for more details.

\( Z' \to W^* + H^* \): This may also have an observable branching ratio, as emphasized in Ref. [10].

5. CONCLUSIONS

CLIC may be able to produce O(10^4 to 10^5) Z' decays when operated as a Z' factory. Such large event samples would enable one to search for rare Z' decay modes, which would reveal many interesting model-dependent parameters that could not be measured in a simple Z' discovery experiment.
REFERENCES

[1] See the contributions by
F. Del Aguila, M. Quirós and F. Zwirner, these Proceedings;
U. Baur, M. Lindner and K.H. Schwarzer, these Proceedings;
and references therein.

[2] See, for example,


