HOW TO STUDY WEAKLY COUPLED NEUTRAL VECTOR BOSONS

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A weakly coupled new neutral gauge boson, forming a narrow resonance, can be efficiently produced at $e^+e^-$ colliders through radiative return processes if the collider energy is larger than the gauge boson mass. This contribution analyzes the sensitivity of a future linear collider for weakly coupled gauge bosons and briefly discusses how, in case of discovery, its properties can be determined with high precision.

Many extensions of the Standard Model (SM) predict new neutral gauge bosons as part of extended or additional gauge groups. Such a $Z'$ boson can have a mass as low as the order of the $Z$ mass, in accordance with all experimental bounds, if its couplings to the SM fermions are very weak. Current limits placed by searches at LEP\(^2\) and the Tevatron\(^3\) could be improved by a future $e^+e^-$ high-energy linear collider with high luminosity\(^4\). In this contribution the reach of a 1 TeV linear collider for new $Z'$ bosons is analyzed, focusing on very weakly coupled $Z'$ bosons with masses below the center-of-mass energy.

It is assumed that mixing effects between the $Z$ and $Z'$ bosons are negligible, so that no constraints on the $Z'$ boson arise from $Z$-pole data. In this case, the most stringent bounds are obtained from direct $Z'$ production. For very small coupling strength, the $Z'$ will form a very narrow resonance, that will lead to a significant signal in the process $e^+e^- \rightarrow f\bar{f}$ only if the $Z'$ mass is close to the center-of-mass energy, $M_{Z'} \approx \sqrt{s}$. If instead $M_{Z'} < \sqrt{s}$, the most stringent constraints are obtained from the process involving the additional radiation of an initial-state photon\(^1,2,4\),

$$e^+e^- \rightarrow Z' + n\gamma \rightarrow f\bar{f} + n\gamma,$$

so that the $Z'$ boson can still be produced on-shell. In this analysis, the leading initial-state radiation effects due to large logarithms, $L = \log s/m_e^2$, have been included through the structure-function approach\(^5\) up to $O(\alpha^2 L^2)$. Besides initial-state radiation, beamstrahlung is taken into account, since it also leads to an effective reduction of the invariant $Z'$ mass. The dominant background

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processes are $e^+e^- \to \gamma/Z + n\gamma \to f\bar{f} + n\gamma$, and are included together with the signal process (1) into a Monte-Carlo simulation. The detector response has been modeled by performing a simple binned analysis in the $f\bar{f}$ invariant mass distribution, where the bin size is determined by the momentum and/or energy resolution for the particular particle species $f$. Due to the narrow width of the weakly coupled $Z'$ boson, the signal will appear as an excess in a single bin. For this study, the machine and detector resolution parameters have been taken from the Tesla design. The collider is likely to run at different center-of-mass energies for various physics studies. Here the following scenarios are taken into account: (i) $W$-boson threshold $\sqrt{s} = 170$ GeV, (ii) $t$-quark threshold $\sqrt{s} = 350$ GeV, (iii) base-line high-energy design $\sqrt{s} = 500$ GeV, and (iv) upgraded high-energy version $\sqrt{s} = 1000$ GeV.

Fig. 1 shows as an example the projected reach of a linear collider for the decay channel into light hadrons, $Z' \to q\bar{q}$, $q \neq t$. The plot shows that a $Z'$ boson with a signal rate about three orders of magnitude smaller than for a gauge boson with SM $Z$ couplings can be found throughout the range $50 \text{ GeV} < M_{Z'} < 1 \text{ TeV}$, except near the $Z$ resonance. In particular classes of models, these limits can be translated into limits on the $Z'$ couplings.

For $Z'$ masses $M_{Z'} > \sqrt{s}$, the sensitivity in the process $e^+e^- \to f\bar{f}$ falls off quickly, since the observable cross-section is modified only through off-shell propagator effects from the $Z'$ resonance tail. For sufficiently strong couplings, however, even $Z'$ bosons with masses about an order of magnitude larger than

![Figure 1: Projected sensitivity of a $e^+e^-$ collider for exclusion at 95% confidence level (hatched regions) and 5\(\sigma\) discovery (solid regions) of a $Z'$ gauge boson in the di-jet channel. The reach in terms of production cross-section times branching ratio, normalized to the value for a SM $Z$ boson, is shown as a function of the $Z'$ mass for various collider energies.](image-url)
Figure 2: Projected discovery reach of a future $e^+e^-$ collider with $\sqrt{s} = 1$ TeV and $\mathcal{L} = 1000\,\text{fb}^{-1}$ for a $Z_{B-L}$ boson, in comparison to the discovery reach of the LHC, the present limit from the Tevatron and the expected exclusion reach at the end of Tevatron Run II.

$\sqrt{s}$ can be discovered and their properties can be studied\(^7\). Fig. 2 compares the $5\sigma$ discovery limits for a $Z_{B-L}$ boson at a 1 TeV linear collider, inferred from total cross-section measurements, with the current and expected coverage of the Tevatron Run II\(^3,8\) and the LHC\(^9\). The linear collider provides very good sensitivity for $Z'$ bosons with masses below $\sqrt{s} = 1$ TeV and small couplings, and for large values of $M_{Z'}$, but relatively strong couplings. In the intermediate region $1\,\text{TeV} < M_{Z'} < 4\,\text{TeV}$, the coverage of the LHC is superior.

If a weakly coupled $Z'$ boson is discovered through the radiative-return method, the properties of the new particle can be studied precisely by tuning the collider energy to the $Z'$ resonance. As an example, a $Z_{B-L}$ boson with mass $M_{Z'} = 400\,\text{GeV}$ and lepton coupling $\tilde{g}_l = 0.006$ is considered, leading to a signal cross-section in the $\mu^+\mu^-$ channel that is about 1000 times smaller than for $Z$ couplings. The total width $\Gamma_{Z'} \simeq 0.6\,\text{MeV}$ is too small to be directly resolved from the resonance shape. However, from the analysis of decay ratios or asymmetries one can determine couplings ratios with high precision. In the given example, a measurement of the left-right and forward-backward asymmetries in the channel $e^+e^- \rightarrow Z' \rightarrow \mu^+\mu^-$ allows to determine the ratios of left- and right-handed $Z'ee$ and $Z'\mu\mu$ couplings with about 1% accuracy, using $20\,\text{fb}^{-1}$ at $\sqrt{s} = 400\,\text{GeV}^4$.

The boson mass can be determined very precisely from a scan around the resonance. Here the beam energy spread causes a strong correlation between the mass $M_{Z'}$ and the coupling $\tilde{g}_l$ of the $Z_{B-L}$ boson. A fit of these two
parameters to a three-point scan at $\sqrt{s} = 399, 400, 401$ GeV, spending $10 \text{ fb}^{-1}$ on each point, give the result $M_{Z'} = 400.0^{+0.007+0.040}_{-0.013-0.040}$. Here the first error is statistical, while the second error is from systematic effects, dominated by the uncertainty in the absolute beam energy.

It is also possible to search for invisible $Z'$ boson decays, which primarily decay into neutrinos or other weakly interacting particles, using the process $e^+e^- \to \gamma + \text{missing energy}$, where a hard photon is required for tagging. Since here the photon is not allowed to be in the kinematical region collinear to the beam pipe, the expected sensitivity will be roughly a factor $L = \log s/m_e^2$ lower than the limits shown in Fig. 1.

The measurement of the invisible $Z'$ decay modes allows in principle to determine absolute branching ratios and couplings. However, the precision of this method is limited due to the requirement of a non-collinear hard tagging photon, so that no collinear enhancement factor $L$ is present and the collider energy cannot be tuned directly to the $Z'$ resonance. For very weakly coupled $Z'$ bosons, as in the example presented above, it is therefore not possible to obtain a significant signal for the invisible decays. Nevertheless, for moderate coupling strength, for instance $\tilde{g}_l = 0.1$, a determination of absolute branching ratios at the per-cent level is achievable.

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