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Z'-Boson: LEP results as a guide for the LHC

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Model-independent relations between low energy couplings of Z' boson to leptons and quarks are used to introduce the observables which uniquely pick out Z' boson signals in leptonic processes. The data of LEP experiments are analyzed giving Z' hints in leptonic processes at 1-2 sigma confidence level. The corresponding Z' couplings to leptons and quarks are estimated at 95% confidence level. These estimates may serve as a guide for experiments at the Tevatron and/or LHC.

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1. Searching for Z' boson at low energies

Z' boson is a heavy neutral vector particle predicted by many theories beyond the standard model (SM). It is searched in experiments at modern colliders both in model-dependent and model-independent approaches (see review [?]). Model-independent searches are usually based on the low energy effective Lagrangian, which parameterizes the couplings of Z and Z' mass eigenstates to the SM fermions f,

$$\mathscr{L}_{Z\bar{f}f} = \tfrac{1}{2} i Z_\mu \bar{f}\gamma^\mu \left[(v_f^{\mathrm{SM}} + \gamma^5 a_f^{\mathrm{SM}})\cos\theta_0 + (v_f + \gamma^5 a_f)\sin\theta_0\right] f, \quad (1.1)$$
$$\mathscr{L}_{Z'\bar{f}f} = \tfrac{1}{2} i Z'_\mu \bar{f}\gamma^\mu \left[(v_f + \gamma^5 a_f)\cos\theta_0 - (v_f^{\mathrm{SM}} + \gamma^5 a_f^{\mathrm{SM}})\sin\theta_0\right] f,$$

where v_f^{SM}, a_f^{SM} are the SM couplings of Z boson, and θ_0 is the Z-Z' mixing angle determined by the Z' coupling to the SM scalars, $\tilde{y}_\phi$,

$$\theta_0 = \frac{\sin 2\theta_W}{2\sqrt{4\pi\alpha_{\mathrm{em}}}} \frac{m_Z^2}{m_{Z'}^2}\tilde{y}_\phi + O\left(\frac{m_Z^4}{m_{Z'}^4}\right), \quad (1.2)$$

where θ_W is the SM Weinberg angle, and α_{em} is the electromagnetic fine structure constant. Although θ_0 is a small quantity of order $m_{Z'}^{-2}$, it contributes to Z-boson exchange amplitudes and cannot be neglected at the LEP energies.

Because of a lot of unknown Z' parameters in (**??**), it is difficult to detect distinct Z' signals in experiments. Fortunately, model-independent relations between the Z' couplings and the Z-Z' mixing angle exist if one suppose some general natural conditions concerning an unknown underlying theory beyond the SM [?]. In particular, they hold in all the popular models containing one Abelian Z' at low energies (LR, ψ, SSM). Let f, $f^\star$ be the partners of a SM fermion doublet, and T_{3f} be the third component of the weak isospin. Then,

$$\frac{1}{2}(v_f - v_{f^\star}) = a_f = T_{3f}\tilde{y}_\phi. \quad (1.3)$$

As it is seen, the absolute value of a_f is flavor-independent, and $\theta_0 \sim a_f$. So, the number of independent Z' couplings is reduced. One vector constant v_f for each SM fermion doublet and one universal axial-vector constant a have to be measured in experiment. Due to a reduced number of unknown parameters, the special observables can be introduced to measure v_f and a_f.

2. Fits of the Z' couplings by LEP II data

The axial-vector coupling $a_e = a$ can be fitted from the LEP process $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$. Z' can manifest itself as a deviation of the differential cross-section from the SM value,

$$\frac{d\sigma'}{dz} = \frac{d\sigma}{dz} - \frac{d\sigma^{\mathrm{SM}}}{dz} = \text{superposition of } \frac{a^2}{m_{Z'}^2}, \frac{v_e v_{\mu,\tau}}{m_{Z'}^2}, \frac{v_e a}{m_{Z'}^2}, \frac{v_{\mu,\tau} a}{m_{Z'}^2},$$

where z is the cosine of the scattering angle. To measure a, we introduce the generalized forward-backward cross-section (see details and references in a review paper [?])

$$\sigma^* = \int_{z^*}^{1} \frac{d\sigma'}{dz} dz - \int_{-1}^{z^*} \frac{d\sigma'}{dz} dz.$$

At $\sqrt{s} = 200$ GeV the boundary angle $z^* = 0.38$ leads to a sign definite one-parameter observable $\sigma^* \sim -a^2/m_{Z'}^2$. Due to the s-channel kinematics it is possible to recalculate the observable from the more precise combined data on total cross-sections and forward-backward asymmetries. The most precise $\mu\mu$ data demonstrate 1σ hint,

$$\frac{a^2 m_Z^2}{4\pi m_{Z'}^2}: \qquad 3.66^{+4.89}_{-4.86} \times 10^{-5}\ (\mu\mu,\ 68\%\ \text{C.L.}), \qquad 1.33^{+3.89}_{-3.87} \times 10^{-5}\ (\mu\mu \text{ and } \tau\tau,\ 68\%\ \text{C.L.}).$$

Vector coupling v_e can be fitted from $e^+e^- \to e^+e^-$. The deviation of the differential cross-section from the SM value due to Z' is

$$\frac{d\sigma'}{dz} = \frac{d\sigma}{dz} - \frac{d\sigma^{\text{SM}}}{dz} \simeq f_1 \frac{v_e^2}{m_{Z'}^2} + f_2 \frac{a^2}{m_{Z'}^2} + f_3 \frac{v_e a}{m_{Z'}^2}.$$

The cross-section is divergent at $z \to 1$. Normalizing $d\sigma'/dz$ by the factor $f_1 > 0$ we obtain finite observable with equalized experimental uncertainties for different z. After the normalization the factor at a^2 is a sign-varying function which is small over the backward scattering angles for $\sqrt{s} \sim 200$ GeV. The factor at $v_e a$ is negligibly small. Thus, to measure v_e^2 the normalized cross-section has to be integrated over the backward angles:

$$\sigma_V \simeq \int_{-0.6}^{0.2} \frac{m_Z^2}{4\pi f_1} \frac{d\sigma'}{dz} dz \sim \frac{v_e^2}{m_{Z'}^2} \qquad \text{at } \sqrt{s} = 200\text{GeV},$$

where the integration interval is chosen to maximize both the relative contribution of v_e^2 (95%) and the interval length (statistics). The 1σ and 2σ hints are observed from the DEPHI and OPAL data,

$$\frac{v_e^2 m_Z^2}{4\pi m_{Z'}^2}: \qquad 1.60 \pm 1.46 \times 10^{-4}\ (\text{DELPHI, 68\% C.L.}), \qquad 2.42 \pm 1.27 \times 10^{-4}\ (\text{OPAL, 68\% C.L.}).$$

The combined LEP II value is $2.24 \pm 0.92 \times 10^{-4}$.

3. Conclusion

Searching for possible Z' signals from virtual states, one has to introduce effective observables. The observables used to treat the LEP data can be adopted for future ILC experiment. For Z' searches in the LHC experiment, it is also useful to find one-parametric observables.

There are relations between Z' couplings to the SM particles. They can be taken into account for simulations of the processes in the LHC.

The experimental constraints and maximum-likelihood estimates of some Z' couplings are obtained from the LEP data. They can serve as a guide in searching for Z' boson in the LHC experiments.

References

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