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~~e<sup>+</sup>e<sup>-</sup> COLLIDERS: THE WINDOW TO Z's BEYOND THE TOTAL ENERGY\*~~

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ABSTRACT:  $e^+e^-$  colliders offer a window to  $Z'$  resonances with masses beyond the total cm energy. We determine the area in the  $[m_{Z'}, \Gamma_{Z'}(\mu^+\mu^-)]$  plane that can be excluded in a model-independent way when the predictions of the standard model for the cross section and the forward-backward asymmetry are experimentally reproduced, for example, within an accuracy of 10%. Special attention is paid to the  $Z'$  in the minimal superstring inspired model that could reveal itself up to a mass of 4 TeV in a 2 TeV collider.

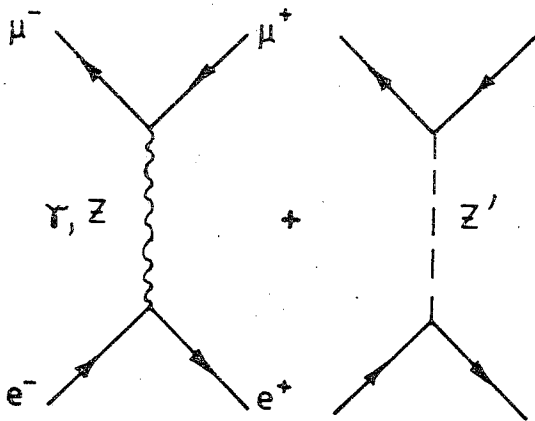
Electron-positron colliders are the ideal place to study neutral vector bosons. If the mass values are within the energy range of the machine, the resonances can be produced in large numbers so that the colliders can be operated as vector-boson factories. Particles with masses beyond the maximum energy, however, can only virtually be produced at a rate that drops fast with a probability of  $\sim 1/\sqrt{(m_R - \sqrt{s})^2 + \Gamma_R^2/4}$ . In this note we describe how large a window can be explored for new vector bosons  $Z'$  with masses beyond the maximum

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collider energy by measuring the total cross section and the forward-backward asymmetry for  $e^+e^- \rightarrow \mu^+\mu^-$ . As an example we will assume that these quantities can experimentally be determined to an accuracy of 10%, a goal that should be easy to achieve. The analysis will first be carried out in a model-independent way. For  $m_{Z'} - \sqrt{s} \gg \Gamma_{Z'}$  [the total width of the resonance] the cross section depends only on the left- and right-handed couplings of the leptons to  $Z'$  that can be bounded by the partial width  $\Gamma(Z' \rightarrow \mu^+\mu^-)$ . The  $Z$  couplings are assumed to be

accurately determined at low energies, incorporating possible mixing effects of the bare vector bosons. Through this procedure areas can be found in the  $[m_{Z'}, \Gamma_{Z'}(\mu^+\mu^-)]$  plane in which new vector bosons  $Z'$  can experimentally be excluded. Constraints on the vector-boson couplings that follow from specific models like the superstring inspired  $E_6$  GUT /1/, can be employed to refine the analysis for special cases /2/.



The cross section and the forward-backward asymmetry for  $e^+e^- \rightarrow \mu^+\mu^-$  can be expressed in terms of generalized charges as /3/

$$\sigma = \frac{4\pi\alpha^2}{3s} \frac{1}{4} \left[ |Q_{LL}|^2 + |Q_{RR}|^2 + |Q_{LR}|^2 + |Q_{RL}|^2 \right] \quad (1)$$

$$A_{FB} = \frac{3}{4} \frac{|Q_{LL}|^2 + |Q_{RR}|^2 - |Q_{LR}|^2 - |Q_{RL}|^2}{|Q_{LL}|^2 + |Q_{RR}|^2 + |Q_{LR}|^2 + |Q_{RL}|^2}$$

where

$$Q_{ij} = 1 + Z_i Z_j \frac{s}{s - m_Z^2 + im_Z \Gamma_Z} + Z'_i Z'_j \frac{s}{s - m_{Z'}^2 + im_{Z'} \Gamma_{Z'}} \quad [i, j = L, R] \quad (2)$$

The couplings of left- and right-handed leptons to  $Z$  and  $Z'$  are defined as  $e_0 Z_i$  and  $e_0 Z'_i$ , respectively,  $e_0^2 = 4\pi\alpha$ . [Without mixing effects,  $Z_{L,R} = (I_3^{L,R} + \sin^2\theta_W)/(\sin\theta_W \cos\theta_W)$  in the Glashow-Salam-Weinberg theory]. Fixing the partial width

$$(Z' \rightarrow \mu^+\mu^-) = \frac{\alpha}{6} (Z_L'^2 + Z_R'^2) m_{Z'} \quad (3)$$

the relative strength between left- and right-handed couplings can be parametrized by an angle  $\phi$  [ $0 \leq \phi \leq 2\pi$ ]:

$$\begin{aligned} Z_L' &= \sqrt{Z_L'^2 + Z_R'^2} \cos\phi \\ Z_R' &= \sqrt{Z_L'^2 + Z_R'^2} \sin\phi \end{aligned} \quad (4)$$

The cross section  $\sigma$  and the forward-backward asymmetry  $A_{FB}$  depend only on  $\Gamma(Z' \rightarrow \mu^+\mu^-)$  and the angle  $\phi$  for a given mass value  $m_{Z'} \gg \sqrt{s}$  once the  $Z$  couplings are fixed at low energies. Given  $\sigma$  or  $A_{FB}$ , two solutions for  $\Gamma(Z' \rightarrow \mu^+\mu^-)$  can be found at each mass value  $m_{Z'}$ . They expand into two bands when the angle  $\phi$  is varied freely between its boundaries.

Let us assume that the standard model predictions for the cross section and the forward-backward asymmetry were reproduced in a measurement at collider energies  $\sqrt{s} = 500$  GeV or 2 TeV within an experimental accuracy of  $\pm 10\%$ . This would exclude the shaded areas shown in Fig. 1 as possible parameter sets  $m_{Z'}$  and  $\Gamma_{Z'}(\mu^+\mu^-)$  for a new resonance  $Z'$ . The form of the figure is physically plausible: a large width  $\Gamma_{Z'}(\mu^+\mu^-)$  would give a large production cross section while the resonance cannot frequently enough be formed if the coupling to leptons is small. Depending in detail on the strength of this coupling, the mass window in general extends to a factor 1.5 to 2 of the maximum collider energy. If the experimental error were reduced, the energy range could be expanded dramatically - as well-known from  $Z$  decay studies.

A particularly important example is provided by the superstring inspired  $E_6$   $Z'$  resonance. In the minimal model /1/ the bare couplings

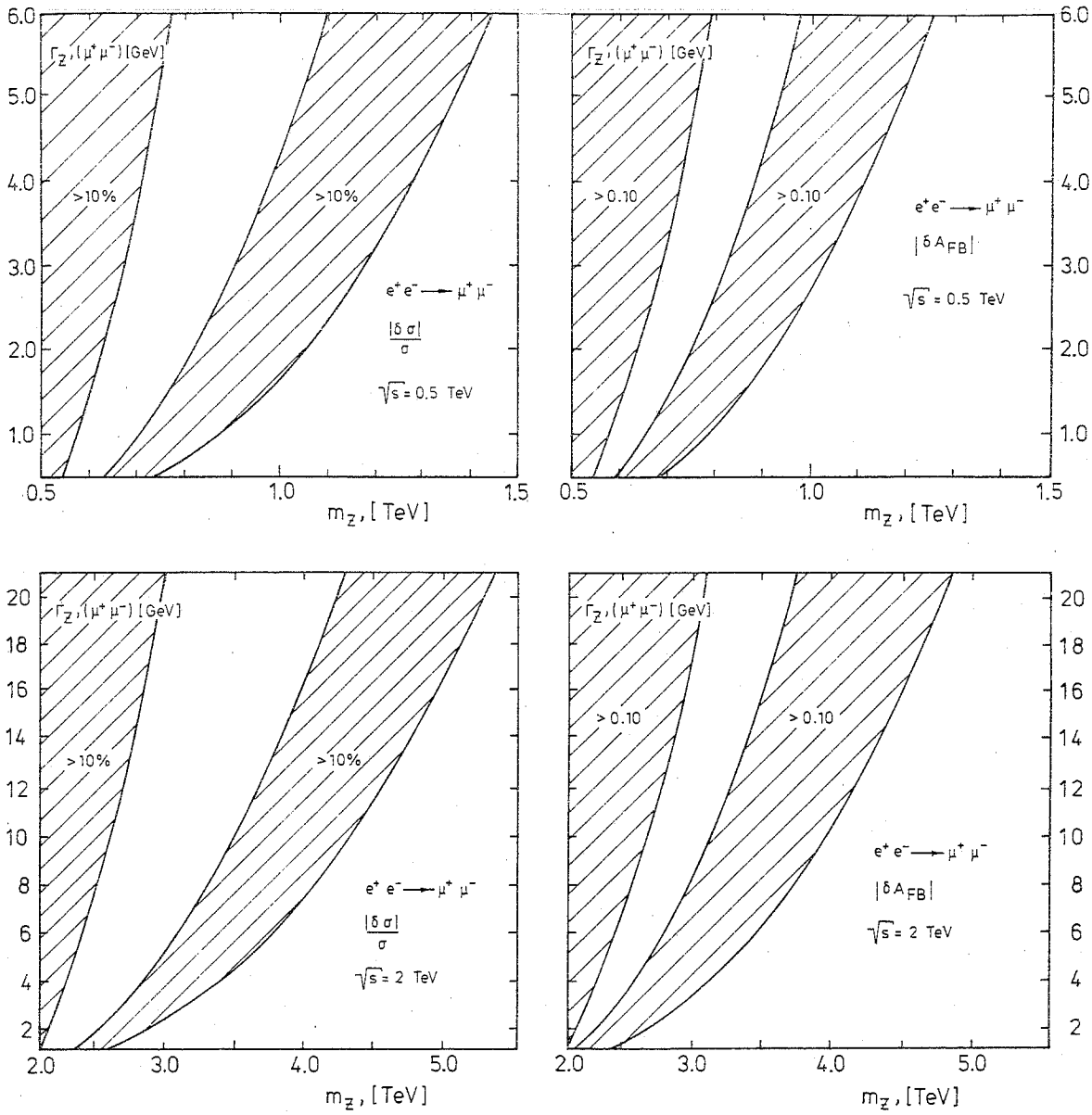


Fig. 1. Areas that can be excluded in the  $[m_{Z'}, \Gamma_{Z'}(\mu^+\mu^-)]$  plane of a resonance  $Z'$  by measurements of the cross section  $\sigma$  and the forward-backward asymmetry  $A_{FB}$  in  $e^+e^- \rightarrow \mu^+\mu^-$  to an accuracy of 10% relative to standard model values [shaded].

of the leptons to  $Z'$  are given by  $Z'_L = 1/6\cos\theta_W$  and  $Z'_R = 1/3\cos\theta_W$ . They are slightly mixed with the bare  $Z_{L,R}$  couplings through the gauge boson mixing that rotates the bare states into the physical states  $Z, Z'$ . Given the masses

$$m_{Z,Z'}^2 = \frac{m_{Z_0}^2}{2} \left[ (1+b) \mp \sqrt{(1-b)^2 + 4a^2} \right] \quad (5)$$

the mixing angle is fixed by

$$\tan 2\theta = \frac{2a}{1-b} \quad (6)$$

$m_{Z_0}$  is the Z mass in the original Glashow-Salam-Weinberg theory and defined as  $m_{Z_0} = m_W / \cos\theta_W$ ; a and b are related to vacuum expectation values of various Higgs fields. The deviation of the cross section and of the forward-backward asymmetry from the standard model can provide a lower bound on the mass of  $Z'$  /2/. Based on the present values of  $m_W = 82.4$  GeV,  $\sin^2\theta_W = 0.22$  and  $m_Z = 93.3$  GeV, we plot this deviation in Fig. 2 for  $\sigma$  and  $A_{FB}$  at  $\sqrt{s} = 2$  TeV. Assuming an experimental accuracy of 5 to 10%, the existence of a  $Z'$  could manifest itself up to a mass value of 3 to 4 TeV as far as the cross section is concerned, while this range extends to 2.5 - 3 TeV for the forward-backward asymmetry.

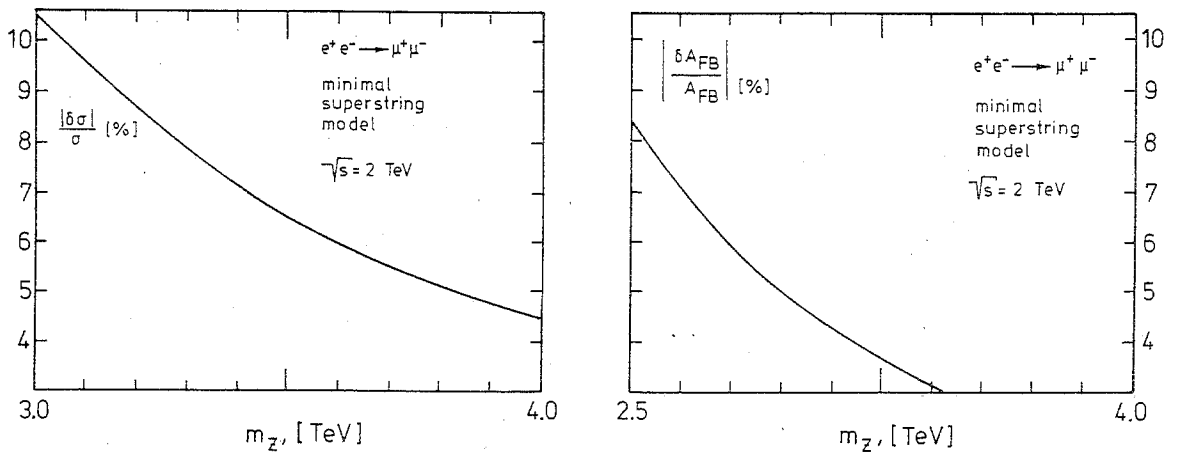


Fig. 2. Deviation of the  $e^+e^- \rightarrow \mu^+\mu^-$  cross section and forward-backward asymmetry from the standard model values in the minimal superstring inspired model /1/ as a function of the  $Z'$  mass.

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