Possibility of measuring the mass of the *W* boson in colliding e^+e^- beams

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The spectrum of muons produced in the reactions $e^+ + e^+ \rightarrow W^+ + W^-$, $W^- \rightarrow \mu^- + \tilde{\nu}_\mu$ and $e^+ + e^- \rightarrow Z + \gamma$, $Z \rightarrow \mu^+ + \mu^-$ is calculated. The contributions of these reactions can be separated over the entire energy range up to the threshold for the production of two *W* bosons.

A recent experiment on the CERN $p\bar{p}$ collider revealed the first indications of the existence of a *W* boson[1] with a mass of about 80 GeV, in agreement with the Glashow-Weinberg-Salam theory. At the luminosity which has been achieved in $p\bar{p}$ collisions on the SPS, however, all that can be established is that a *W* boson is produced, and limits on its mass can be estimated roughly.[2] Accordingly, a detailed study of the properties of the *W* boson, in particular, accurate measurements of its mass, its width, and the structure of the three boson vertices will become possible only on the new e^+e^- accelerators (the LEP,[3] the VLÉPP,[4] and the SLC[5]) and also in γe and $\gamma\gamma$ collisions.[6]

In the present letter we wish to point out that measurements of the inclusive spectra of muons in the reaction $e^+e^- \rightarrow \mu^- + X$ above the threshold for the production of a pair of *W* bosons will make it possible not only to reliably establish the very fact that the *W* boson is produced but also to measure its mass. The energy spectrum of muons from the reaction $e^+ + e^- \rightarrow W^+ + W^-(W^- \rightarrow \mu^- + \tilde{\nu}_\mu)$ has a maximum at $x = (1+\beta)/2$, where β is the velocity of the *W* boson in the c.m. frame of the beams, $x = 2\omega/\sqrt{s}$, and ω is the energy of the muon. In the Glashow-Weinberg-Salam theory the angular and energy distributions of muons in the reaction $e^+ + e^- \rightarrow W^+ + W^-(W^- \rightarrow \mu^- + \tilde{\nu}_\mu)$ are quite complex, but near the threshold $s \rightarrow 4M_W^2$ the following simple expression applies:

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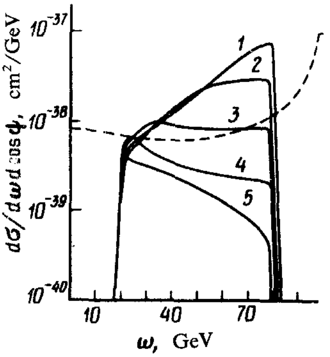

FIG. 1. Energy spectrum of the muons from the processes $e^+ + e^- \to W^+ + W^-$, $W^- \to \mu^- + \tilde{\nu}_\mu$, at $\sqrt{s} = 200$ GeV. 1 — 5—$\psi = 30°, 60°, 90°, 120°$, and 150°, respectively; dashed line—the reaction $e^+ + e^- \to \mu^+ + \mu^- + \gamma$ at $\psi = 30°$ and $\sqrt{s} = 200$ GeV ($x_W = 0.22$, $M_W = 81$ GeV, $M_Z = 91$ GeV, $\Gamma_W = 2.5$ GeV).

$$\frac{d\sigma}{d\cos\psi} = \frac{3\beta}{32\sqrt{2}} \frac{\alpha G}{x_W} B(W^- \to \mu^- \tilde{\nu}_\mu)(3 + 2\cos\psi - \cos^2\psi), \tag{1}$$

where ψ is the angle between the momenta of the initial e^- and the μ^- which is produced, $B(W^- \to \mu^- \tilde{\nu}_\mu) = \Gamma(W^- \to \mu^- \tilde{\nu}_\mu)/\Gamma_W = 0.08$, Γ_W is the width of the W boson, and $x_W = \sin^2\theta_W$. It can be seen from (1) that the muons are emitted primarily along the electron momentum, because of an exchange of neutrinos. The differential cross section for the reaction $e^+ + e^- \to \mu^- + X$ falls off with increasing angle (Fig. 1) at arbitrary s. Regardless of the angle ψ, the muon energy spectra decay sharply at $x \approx (1 + \beta)/2, \beta^2 = 1 - 4\tau, \tau = M_W^2/s$. At $\beta \ll 1$, the decay occurs in an interval $\Delta\omega \approx \Gamma_W M_W)^{1/2}/2$, while at $\beta \sim 1$ it occurs in an interval $\Delta\omega \approx M_W \Gamma_W/(2\beta\sqrt{s})$. By measuring the energy ω_0, at which the spectrum decays sharply (this energy can be measured with $\Delta\omega \approx 0.6$ GeV at $\sqrt{s} = 200$ GeV), we can find the mass of the W boson, using

$$M_W = \left[2\omega_0(\sqrt{s} - 2\omega_0)\right]^{1/2}.$$

The error in the mass measurement is $\Delta M_W = \Delta\omega(4\omega_0 - \sqrt{s})/M_W$, i.e., at $\sqrt{s} = 200$ GeV we have $\Delta M_W/M_W = 0.01$.

In this formulation of the experiment, the background processes are $e^+ + e^- \to \gamma + Z(Z \to \mu^+ + \mu^-)$, $e^+ + e^- \to \mu^+ + \mu^- + \gamma$, and $e^+ + e^- \to e^+ + e^- + \mu^+ + \mu^-$. The energy spectrum of muons from the reaction $e^+ + e^- \to Z + \gamma(Z \to \mu^+ + \mu^-)$ has, regardless of the angle ψ, two characteristic peaks at $x = 2\tau_Z/(1 + \tau_Z \mp (1 - \tau_Z)\cos\psi)$, $\tau_Z = M_Z^2$, which are due to the large cross section for the production of γ rays along or opposite the momentum of the initial electrons. As can be seen from Fig. 2, however, a study of the muon spectrum in the reaction $e^+ + e^- \to \mu^- + X$ would make it possible to distinguish the contributions of the reactions $e^+ + e^- \to W^+ + W^-$ and $e^+ + e^- \to Z + \gamma$ over the entire energy range up to the threshold for the reaction $e^+ + e^- \to W^+ + W^-$. The contribution of the reaction $e^+ + e^- \to \mu^+ + \mu^- + \gamma$ to the muon spectrum at $x \sim (1 + \beta)/2$ is small at $\psi \geqslant 30°$

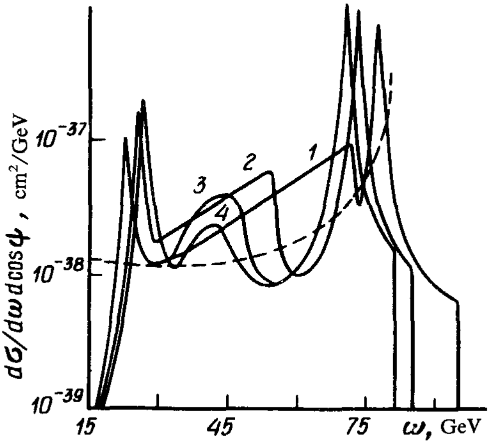

FIG. 2. Total energy spectrum of muons from the reactions $e^+ + e^- \to Z + \gamma$, $Z \to \mu^+ + \mu^-$ and $e^+ + e^- \to W^+ + W^-$, $W^- \to \mu^- + \tilde{\nu}_\mu$ at $\psi = 30°$. 1–4—$\sqrt{s} = 190$, 170, 164, and 162 GeV, respectively; dashed line—the reaction $e^+ + e^- \to \mu^+ + \mu^- + \gamma$ at $\sqrt{s} = 162$ GeV ($x_W = 0.22$, $M_W = 81$ GeV, $M_Z = 91$ GeV, $\Gamma_W = \Gamma_Z = 2.5$ GeV).

(Figs. 1 and 2).[7,8] The background from the reaction $e^+ + e^- \to e^+ + e^- + \mu^+ + \mu^-$ is also small ($\approx 2 \times 10^{-39}$ cm²/GeV) at these values of x.

In principle, another way to determine the mass of the W boson might be to measure the quantity[9] $R(s) = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$. It should be kept in mind, however, that at $\sqrt{s} > M_Z$ the primary source of hadrons is the reaction $e^+e^- \to Z + \gamma \to \text{hadrons} + \gamma$ (the γ rays are emitted primarily at very small angles from the direction of the beams and cannot be detected), whose cross section at $\sqrt{s} = 200$ GeV is 5.8 times that for the reaction $e^+e^- \to W^+ + W^- \to \text{hadrons}$.

The relative contribution of $e^+e^- \to W^+W^-$ to R is therefore small: $\Delta R/R \approx 0.11$. Consequently, in order to determine the mass of the W boson it is necessary to measure R highly accurately.

The reaction $e^+e^- \to W^+W^-$ can also be detected on the basis of four quark jets.[10] However, as follows from (1), the jets are directed primarily near the direction of the e^+e^- beams and may overlap.

In summary, study of muon spectra appears to us to be the most convenient method for measuring the mass of the W boson.

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