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Abstract

Three models for monojet events with large missing transverse momentum observed at the CERN $p\bar{p}$ collider are studied: i) Z decay into a neutral lepton pair where one of the pair decays within the detecter while the other escapes, ii) Z decay into two distinct neutral scalars where the lighter one is long lived, and iii) Z decay into two distinct higgsinos where the lighter one is long lived. The first model necessarily gives observable decay in flight signals. Consequences of the latter two models are investigated in both $p\bar{p}$ collisions at CERN and e^+e^- annihilation at PETRA/PEP energies.

One of the attractive possibilities to explain the large missing transverse momentum ($\not{p}_T$) and monojet events observed[1] at the CERN $p\bar{p}$ collider is to postulate a single production of a very heavy particle X whose subsequent decay leads to a jet and missing momentum. If the missing momentum comes from the $Z \to \nu\bar{\nu}$ decays, then the X mass is estimated to be in the 160 - 170 GeV range whereas it may be in the 100 - 120 GeV range if $\not{p}_T$ comes from a light stable particle[2]. The former scenario tends to require very large coupling to produce X with a sufficient rate[3] while the latter requires introduction of a new weakly interacting light particle, e.g. a photino[2].

Allowing for a large uncertainty in the $\not{p}_T$ measurement, the X particle in the latter scenario can be the Z boson (93GeV). The Z decay into a fourth generation neutrino pair[4] has been examined by Krauss, and Gronau and Rosner ; more recently Glashow and Manohar proposed[5] the Z decay into two distinct Higgs bosons as a possible mechanism.

In this paper we study the consequences of the Z-boson parent models for the large $\not{p}_T$ events. First, we present a simple argument that Z decay into a particle-antiparticle pair cannot account for the data. Secondly, the Glashow-Manohar model is examined in detail and its supersymmetric version, the Z decay into two higgsinos, is also studied as an example of a model with fermion decay mode of the Z boson. Observability of the signals of these models in e^+e^- annihilationm at PETRA/PEP energies is discussed at the end.

If the observed large $\not{p}_T$ plus monojet events come from a particle-antiparticle decay mode of the Z boson, then the particle lifetime should be such that the one decays in the detecter while the other doesn't[4]. The probability that one of the pair decays before flying a length l_0 and the other decays after l_1 reads

$$P(\langle l \rangle) = 2\, exp\left(-\frac{l_1}{\langle l \rangle}\right)\left[1 - exp\left(-\frac{l_0}{\langle l \rangle}\right)\right] \qquad (1)$$

where $\langle l \rangle$ denotes the mean-free-path of the particle. It is then easy to show that the probability is bounded by

$$P(\langle l \rangle) \leq 2\,\frac{l_0}{l_1}\left(1 + \frac{l_0}{l_1}\right)^{-(1+l_1/l_0)} \qquad (2)$$

where the maximum value is taken when $\langle l \rangle = l_0 / \ln(1+l_0/l_1)$. Since no visible decay in flight signal has been reported[1], the detected particle cannot fly significantly while the other should at least fly more than 1 m before decay. With $l_0 = 1$ cm and $l_1 = 1$ m as a very conservative guess, we find that the probability cannot be larger than 0.7% which excludes the scenario.

Glashow and Manohar proposed a model [5] with Z boson decay into a scalar (h_1) and a pseudoscalar (h_2), where h_1 has a long lifetime and remains undetected while h_2 decays into ordinary hadrons to form a monojet. This scenario has been achieved within the two Higgs doublet extention[6] of the standard model, where the two scalar doublets φ and ψ have vacuum expectation values (v.e.v.) u and v, respectively, with $v/u \ll 1$. Flavor changing neutral currents are avoided[7] by imposing the discrete symmetry $\psi \to -\psi$ in both the scalar potential and Yukawa couplings; only φ couples to fermions. Among the three neutral physical bosons h_1 and h_2 are the almost purely real and imaginaly part of ψ, respectively, and thus have small couplings to fermions suppressed by v/u. The scalar h_1 is light since its mass (m_1) is proportional to the small v.e.v. of v, while the pseudoscalar mass (m_2) is small due to a broken continuous symmetry (ψ number conservation) in the massless limit.

The production cross section for the process $f\bar{f} \to h_1 h_2$ reads

$$\frac{d\sigma}{d\cos\theta} = \xi \frac{\pi \alpha^2 (a_f^2 + b_f^2)\, s}{64 N x_W^2 (1-x_W)^2 [(s-m_Z^2)^2 + m_Z^2 \Gamma_Z^2]} \lambda^{3/2}\left(1, \frac{m_1^2}{s}, \frac{m_2^2}{s}\right) \sin^2\theta \qquad (3)$$

where N = 1 (3) for color singlet (triplet) f, $x_W = \sin^2\vartheta_W$, $a_f = I_{3f} - 2 x_W Q_f$, $b_f = I_{3f}$, I_{3f} and Q_f are the weak isospin and electric charge of f, and $\lambda(a,b,c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ca$. The factor ξ measures the mixing in the neutral boson sector[6], which in the present case reads $\xi = 1 - O(v^2/u^2)$. When $\xi = 1$ and $m_1 = m_2 = 0$, the total production rate is half the neutrino-pair production rate. If $m_2 > m_1$, then the pseudoscalar h_2 decays either into a fermion pair with the rate

$$\Gamma(h_2 \to f\bar{f}) = \eta \frac{N G_F m_f^2}{4\sqrt{2}\,\pi} m_2 \left(1 - \frac{4 m_f^2}{m_2^2}\right)^{3/2} \qquad (4)$$

where the mixing factor $\eta = O(v^2/u^2)$, or into a fermion pair and h_1 via virtual Z exchange

$$d\Gamma(h_2 \to h_1 f\bar{f}) = \frac{1}{2m_2} \Sigma \; d\Phi_3 \qquad (5a)$$

with

$$\Sigma = \frac{\xi N e^4 (a_f^2 + b_f^2)}{2 x_W^2 (1-x_W)^2 (m_Z^2 - q^2)^2} \left\{ 4 (f h_1)(\bar{f} h_2) - q^2 m_1^2 + \frac{2 b_f^2 m_f^2}{a_f^2 + b_f^2} \left[m_1^2 + m_2^2 - \frac{q^2}{2} - \frac{(m_1^2 - m_2^2)^2}{2 m_Z^2} \left(2 - \frac{q^2}{m_Z^2}\right) \right] \right\} \qquad (5b)$$

where we use the particle labels as their four momenta, $q = f + \bar{f} = h_2 - h_1$, and the three body phase space reads

$$d\Phi_3 = (2\pi)^{-5} \delta^4(P - p_1 - p_2 - p_3) \prod_{i=1}^{3} \frac{d^3 p_i}{2E_i} \qquad (5c)$$

In the m_f/m_2, m_1/m_2, and $m_2/m_Z \to 0$ limit, the integrated decay rate is

$$\Gamma(h_2 \to h_1 f\bar{f}) = \xi \frac{N G_F^2 (a_f^2 + b_f^2)}{384 \pi^3} m_2^5 \qquad (6)$$

The scalar h_1 is sufficiently long lived to escape detection as far as $m_1 < 2m_\mu$ and $\eta < 10^{-2}$. Its suppressed coupling to fermions makes it difficult to observe h_1 at lower energy hadronic collisions, e.g. in the beam dump experiments. The branching fraction for the direct decay modes $h_2 \to f\bar{f}$,

$$r = \sum_f \Gamma(h_2 \to f\bar{f}) \Big/ \left[\sum_f \Gamma(h_2 \to f\bar{f}) + \sum_f (h_2 \to h_1 f\bar{f}) \right] \qquad (7)$$

depends on the masses m_1 and m_2, and the suppression factor η. We find $r > 90\%$ for $m_2 < 10$ GeV and $\eta = 10^{-3}$.

Shown in Fig.1 as solid lines are the predictions of the Glashow-Manohar model for the $\not{p}_T$ distribution in $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV. We used the Duke-Owens[8] parton distributions with $\Lambda = 0.2$ GeV, $m_Z = 93$ GeV, $\Gamma_Z = 3$ GeV, $\xi = 1$ and the QCD motivated factor K = 1.4. The r=1 case shows a clear Jacobian peak at $\not{p}_T \sim m_Z/2$ while the r=0 case ($h_2 \to h_1 f\bar{f}$ decay only) shows a much softer distribution because of the cancellation between two missing h_1 momenta. The Jacobian peak is sharper than those observed in W and Z leptonic decays due to the $\sin^2\vartheta$ angular distribution (Eq.(3)) characteristic of scalar-pair production from a vector boson.

The integrated cross section for $\not{p}_T > 35$ GeV is

$$\sigma(\not{p}_T > 35\text{GeV}) = 33 \text{ pb} \qquad \text{for } r = 1 \qquad (8a)$$

$$\sigma(\not{p}_T > 35\mathrm{GeV}) = 8\ \mathrm{pb} \qquad \text{for } r = 0 \tag{8b}$$

The latter cross section should be further multiplied by the branching fraction to hadronic decay modes which is roughly 60% for three neutrinos in the region $4 < m_2 < 10$ GeV. The spectra are found to be virtually independent of m_2 below 20 GeV. In order to have a significant contribution to the monojet cross section of about 50 pb[1], the branching fraction r cannot be much less than unity. The observed smallness of the charged multiplicity of the monojets[1] then implies that m_2 be at least below bottom-pair threshold. The main decay modes of h_2 would be into $c\bar{c}$ and $\tau\bar{\tau}$ or $s\bar{s}$ depending on m_2.

The Z boson decay into two distinct fermions necessarily violates flavor diagonality of the neutral current in the standard model. Interesting fermion decay modes of the Z boson, however, can appear[9] in the supersymmetric extention of the standard model: $Z \to \chi_1 \chi_2$ where χ_1 and χ_2 are mass eigenstates of the neutral gaugino-higgsino sector. Here we assume χ_1 to be lighter than χ_2 ($m_1 < m_2$) and to have a long lifetime so that it escapes detection at the collider experiments. The production cross section for $f\bar{f} \to \chi_1\chi_2$ near the Z boson pole is

$$\frac{d\sigma}{d\cos\theta} = \zeta \, \frac{\pi\alpha^2(a_f^2+b_f^2)\, k\, [\, E_1E_2 - \eta_1\eta_2 m_1 m_2 + k^2\cos^2\theta \,]}{4N\, x_W^2(1-x_W)^2\sqrt{s}\, [(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2]} \tag{9}$$

where $k = \lambda^{1/2}(s, m_1^2, m_2^2)/2\sqrt{s}$ is the momentum of χ_1 and χ_2 in the colliding $f\bar{f}$ c.m. frame, $E_i = (k^2+m_i^2)^{1/2}$, $\eta_i = \pm 1$ the sign of the Majorana condition $\chi_i = \eta_i C\bar{\chi}_i$, and the mixing factor ζ corresponds to $(\delta_1\delta_2 - \gamma_1\gamma_2)^2$ in the notation of Ellis et al[9]. At $\zeta = 1$ with $m_1 = m_2 = 0$, the total production rate is twice that of a neutrino-pair. A large cross section is expected for $\zeta \sim 1$, in which case χ_2 decays into $\chi_1 f\bar{f}$ mainly via virtual Z exchange; the spin averaged decay distribution reads in this case

$$d\Gamma(\chi_2 \to \chi_1 f\bar{f}) = \frac{1}{2m_2}\,\frac{1}{2}\,\tilde{\Sigma}\; d\Phi_3 \tag{10a}$$

with

$$\tilde{\Sigma} = \frac{\zeta\, 2Ne^4}{x_W^2(1-x_W)^2(m_Z^2-q^2)^2}\Big\{ (a_f^2+b_f^2)[(f\chi_1)(\bar{f}\chi_2) + (f\chi_2)(\bar{f}\chi_1) + \eta_1\eta_2 m_1 m_2 (f\bar{f})]$$
$$+ (a_f^2 - b_f^2)\, m_f^2\, [(\chi_1\chi_2) + 2\eta_1\eta_2 m_1 m_2] \Big\} \tag{10b}$$

where we used the particle labels for their four momenta as before. We remark here that the produced χ_2 has a net polarization due to parity violation. Hence the spin-averaged decay distribution (10) can be used only when one does not distinguish between f and $\bar{f}$ in the final state. The asymmetry is expected to be small in e^+e^- annihilation because the Z coupling to electrons is almost parity conserving. In the limit of m_f/m_2, m_1/m_2 and $m_2/m_Z \to 0$, the integrated decay rate is

$$\Gamma(\chi_2 \to \chi_1 f\bar{f}) = \zeta\, \frac{N G_F^2 (a_f^2+b_f^2)}{192\pi^3}\, m_2^5 \tag{11}$$

The $\not{p}_T$ distribution expected in this model is shown as a dashed line in Fig.1 for $\zeta = 1$. We set $m_1 = m_f = 0$ in this calculation. The distribution is rather insensitive to m_2 below 20 GeV and the mean invariant mass of the jet system is roughly 50% of m_2. The area under the dashed curve is four times larger than the area under the solid curves. The integrated cross section for $\not{p}_T > 35$ GeV reads

$$\sigma(\not{p}_T > 35\mathrm{GeV}) = 24\ \mathrm{pb}. \tag{12}$$

One should further multiply this value by the hadronic branching fraction which is around 50-70% in the range $2 < m_2 < 20$ GeV. Hence the significant contribution from this source can be expected only when ζ is very near to 1. This then implies, as emphasized by Ellis et al[9], that our long lived particle χ_1 cannot be the lightest mass eigenstate of the neutral gaugino-higgsino secter in the minimal supergravity induced supersymmetry breaking model. It is not clear whether one can make a realistic model with the large $Z \to \chi_1\chi_2$ decay branching fraction and the sufficiently long χ_1 lifetime.

The most important consequence of the models where the large $\not{p}_T$ events come from anomalous Z decays is that they predict anomalous $\not{p}_T$ events in e^+e^- annihilation at PETRA/PEP energies via virtual Z exchange. In Fig.2, we show the total cross section versus e^+e^- c.m. energy $\sqrt{s}$ for the processes $e^+e^- \to h_1h_2$ (solid lines) and $e^+e^- \to \chi_1\chi_2$ (dashed lines) with the maximum couplings $\xi = 1$ and $\zeta = 1$, respectively. Since m_1 should be small in the h_1h_2 model to make h_1 lifetime long and also in the $\chi_1\chi_2$ model to give hard $\not{p}_T$ spectrum, we set $m_1 = 0$ and show two curves for $m_2 = 2$ GeV (upper lines) and 20 GeV (lower lines). With the present integrated luminosity of about 100 pb^{-1} per each group at $\sqrt{s} = 27 - 47$ GeV (PETRA) and about 200 pb^{-1} at $\sqrt{s}$ = 30 GeV (PEP), we should expect a sufficiently large number of events to test the models.

Difference between the scalar-pair model (h_1h_2) and the fermion-pair model ($\chi_1\chi_2$) is made apparent in e^+e^- annihilation experiments by their angular distributions, $\sin^2\vartheta$ (Eq.(3)) and $1 + \cos^2\vartheta$ (Eq.(9)), respectively. In Fig.3, we show the angular distribution of monojets in e^+e^-annihilation at $\sqrt{s}$ = 45 GeV for the two models with typical experimental cuts: $\not{p}_T > 0.15\sqrt{s}$ and $E_{jet} > 0.25\sqrt{s}$. The heavier mass (m_2) is set to 5 GeV and the lighter mass (m_1) is set to zero. The $\chi_1\chi_2$ model shows two peaks at higher $|\cos\vartheta|$ while the h_1h_2 model gives a peak at $\cos\vartheta = 0$ as expected. Since in e^+e^- annihilation experiments the $\not{p}_T$ cut can be made much smaller than that imposed in the $p\bar{p}$ collider experiments, we can measure the h_1h_2 model signal even in the r=0 ($h_2 \to h_1 f\bar{f}$ only) case with comparable rate to the r=1 ($h_2 \to f\bar{f}$ only) case; the distinction between the two cases should be apparent from the E_{jet} distribution. The methods presented here can thus be used to detect neutral Higgs bosons when one of them is long lived.

After essentially completing this work, we received a preprint by J. Rosner[10] where related work is done.

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FIGURE CAPTIONS

FIG. 1 Missing transverse momentum distsribution from $Z \to h_1 h_2$ (solid lines) and $Z \to \chi_1 \chi_2$ (dashed line) with maximal couplings in $p\bar{p}$ collision at $\sqrt{s}$ = 540 GeV for m_1 = 0 and m_2 = 5 GeV. The r = 1 curve shows the case when all the energy of h_2 is detected via its $h_2 \to f\bar{f}$ decay modes. The r = 0 curve shows the other extremum when $BR(h_2 \to h_1\, f\bar{f}) = 1$ and part of the h_2 energy is carried away by h_1. We set m_f = 0 and a QCD motivated factor K = 1.4 has been included.

FIG. 2 Total cross section for $e^+e^- \to h_1 h_2$ (solid lines) and $e^+e^- \to \chi_1 \chi_2$ (dashed lines) with maximal couplings plotted against $\sqrt{s}$. Upper and lower lines correspond, respectively, to the case m_2 = 2 GeV and 20 GeV with m_1 = 0.

FIG. 3 Angular distributions of monojets produced in e^+e^- annihilation at $\sqrt{s}$ = 45 GeV for the $h_1 h_2$ model (solid lines) and the $\chi_1 \chi_2$ model (dashed line) with the cuts $\not{p}_T > 0.15\,\sqrt{s}$ and $E_{jet} > 0.25\,\sqrt{s}$. The parameters of the models are the same as those used in Fig.1.

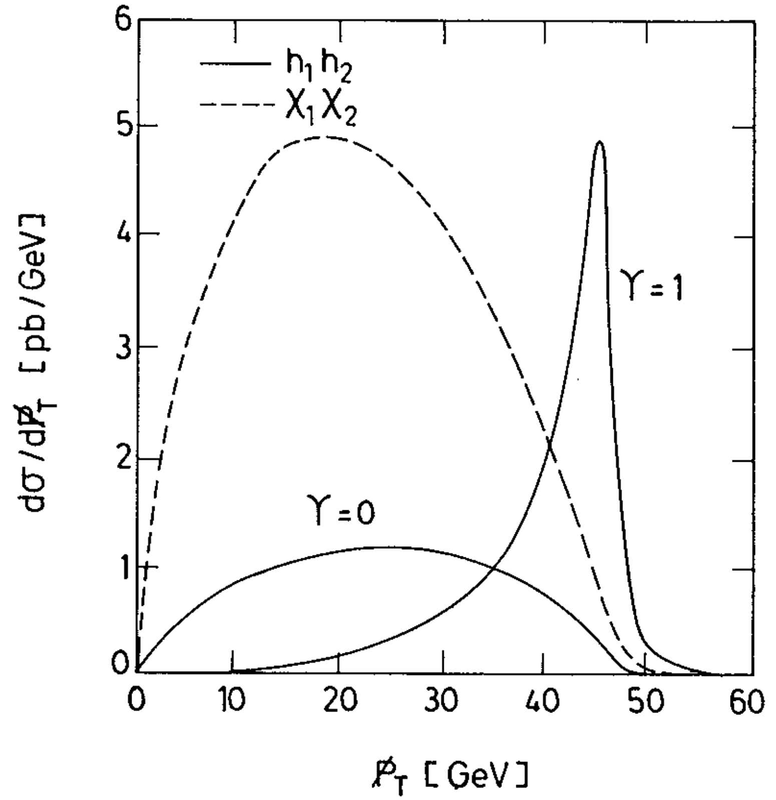

Fig. 1

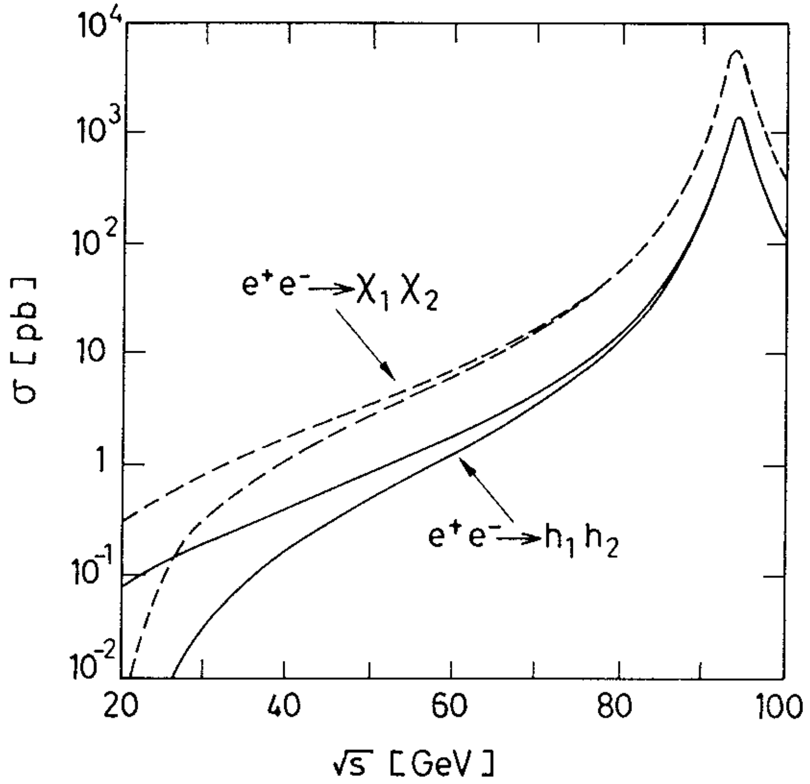
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
σ [pb]
$e^+e^- \rightarrow \chi_1\chi_2$
$e^+e^- \rightarrow h_1 h_2$
20
40
60
80
100
$\sqrt{s}$ [GeV]

Fig. 2

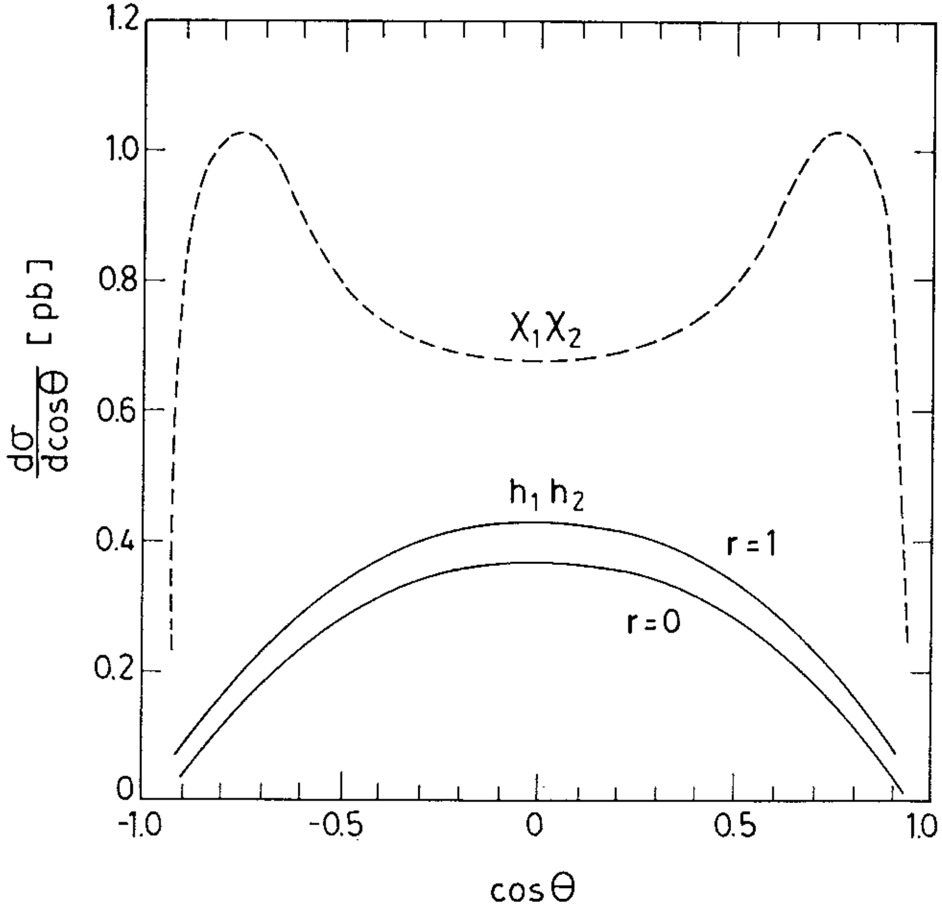
1.2
1.0
0.8
0.6
0.4
0.2
0
$\frac{d\sigma}{d\cos\Theta}$ [pb]
$\chi_1\chi_2$
$h_1 h_2$
r = 1
r = 0
-1.0
-0.5
0
0.5
1.0
$\cos\Theta$

Fig. 3