AN ALTERNATIVE INTERPRETATION OF THE CELLO DIMUON–DIJET EVENT

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Higgs boson pair production $e^+e^- \to h_1h_2$ with $m(h_1) \simeq 4$ GeV and $m(h_2) \simeq 32$ GeV followed by the decays $h_2 \to h_1\mu\bar{\mu}$ via virtual Z boson exchange and $h_1 \to$ hadrons can account for the characteristics of the dimuon plus dijet event observed by the CELLO collaboration at PETRA. The cross section is very small and while no further similar event is expected at PETRA/PEP energies, rich phenomena are expected at higher energies to be explored by TRISTAN, SLC, and LEP. Consequences of $Z \to h_1h_2$ decays in $p\bar{p}$ collisions are also studied.

The dimuon plus dijet event [1] observed by the CELLO collaboration in e^+e^- annihilation at $\sqrt{s}$ = 43.5 GeV at PETRA has the peculiar structure that all the four momenta have similar magnitude and are well isolated from each other in angular space. The large invariant masses of both the dimuon system ($\simeq$ 20 GeV) and the dijet system ($\simeq$ 17 GeV) are rather difficult to understand in terms of the standard electroweak processes.

The planar event structure suggested a threshold production of a pair of heavy particles of mass about 20 GeV which subsequently decay into a muon and a jet. Two proposals were made along this line; production of a heavy neutrino pair [1,2] and that of a leptoquark boson pair [3]. A detailed study [4] showed, however, that it is very unlikely for both jets to have rather small invariant masses ($\simeq$ 4 GeV) in the former scenario. On the other hand the leptoquark boson, being colored, should be pair produced at hadron colliders [3,5]. A conservative estimate for the pair-production cross section of a 20 GeV color-triplet scalar boson via the QCD fusion processes (gluon–gluon fusion and quark–antiquark fusion) with the set-I parton distributions of Duke and Owens [6] gives about 2 nb at $\sqrt{s}$ = 540 GeV and about 3 nb at $\sqrt{s}$ = 630 GeV in $p\bar{p}$ collisions. With the total integrated luminosity of 400 nb^{-1} gathered at the CERN $p\bar{p}$ collider, a thousand leptoquark pairs should have been produced. Failure to observe a significant deviation from the standard model expectation in the dimuon events at the CERN collider [7] should hence be regarded as evidence against the leptoquark interpretation of the CELLO event.

In view of the difficulties in the above two scenarios, we examine the possibility that three of the four energetic particles come from a heavy particle decay. There are only two combinations for the decay products; either a muon and dijets or a jet and dimuon. The former combination can be realized by associated production of an excited muon (μ^*) and a muon [1] followed by a $\mu^* \to \mu q\bar{q}$ decay via virtual Z boson exchange [8]. However, in order that the virtual Z decay modes dominate over the two-body $\mu^* \to \mu\gamma$ decay, the electromagnetic transition coupling should be strongly suppressed relative to the neutral-current one: In an obvious notation [9], we find

$$g^2_{\gamma\mu^*\mu}/g^2_{Z\mu^*\mu} \lesssim 10^{-6}\,.$$

Otherwise a clean $\mu\bar{\mu}\gamma$ event has a better chance to be observed. This strong suppression of the electromagnetic transition coupling between the charged particles is difficult to understand.

We are hence left with the possibility that a jet and a heavy particle are produced and the latter decays into a jet and a muon-pair. We reject an excited quark or any charged particle as a candidate for the heavy par-

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ticle by the same reasoning as before, i.e. to explain the dominance of the three-body decay. This scenario of producing a heavy and a light neutral particle is realized most simply in the two Higgs doublet extension [10] of the standard model, where the Z boson can couple to a neutral scalar (h_1) and a pseudoscalar (h_2) with a typical electroweak coupling while the photon has no coupling to them at the tree level. The same neutral-current coupling accounts for both the production $e^+e^- \to h_1 h_2$ and the decay $h_2 \to h_1 \mu\bar{\mu}$ processes. The lighter scalar, h_1, should then decay into hadrons via a heavy-quark pair or a heavy-lepton pair.

By taking a compromise value for the observed jet invariant masses, 2.4 GeV and 4.7 GeV, we take the mass m_1 of the lighter scalar (h_1) to be 4 GeV. Due to the symmetric nature of the event, the mass of the heavier particle (h_2), m_2, or the mass of the muon-pair and a jet system is almost uniquely determined to be about 32 GeV. Analytic expressions for the $h_1 h_2$ production and the h_2 decay distributions can be found in ref. [11].

Shown in figs. 1a and 1b are, respectively, the dimuon and dijet invariant mass distributions obtained by the Monte Carlo method. The CELLO event points are shown by arrows at the top of each figure. We show in fig. 2 the invariant mass distribution of μ-jet systems summed over all four combinations. The CELLO event values are also shown as four arrows. It is amusing to observe that all the distributions are peaked around the CELLO data points. In other words, if the scalar pair production ($e^+e^- \to h_1 h_2$) followed by the decay $h_2 \to h_1 \mu\bar{\mu}$ via virtual Z boson exchange occurs at all, then a typical event structure would look like the CELLO event.

We show in fig. 2 the two-dimensional distribution of muon-jet invariant masses summed over the two combinations of mutually exclusive pairs of μ-jet systems. The higher mass combination of the data point (22 GeV, 19 GeV) is shown by arrows. Although very near to the phase-space boundary, it stays in the most highly populated region. Hence the observed rough coplanarity can be understood in this picture as a consequence of a particular but likely kinematical configuration where both μ-jet pairs have large invariant masses.

The total cross section for the process $e^+e^- \to h_1 h_2$ is plotted against the CM energy $\sqrt{s}$ as a solid line in fig. 3. The mixing factor (denoted by ξ in ref. [11]) has been chosen to be unity as explained in the following. Due to the P-wave threshold suppression, the cross section is small at the highest PETRA energies ($\sqrt{s} \simeq 45$ GeV). With an integrated luminosity of 25 pb^{-1}, we can expect only one or two events per experiment. Since the branching fraction of the decay $h_2 \to h_1 \mu\bar{\mu}$ is at best 3%, it is unlikely that a similar event be observed again at PETRA.

In order that the $h_2 \to h_1 \mu\bar{\mu}$ decay occurs with non-negligible probability, the branching fraction for the decays via virtual Z-boson

$$r = \frac{\sum_f \Gamma(h_2 \to h_1 f\bar{f})}{\sum_f \Gamma(h_2 \to h_1 f\bar{f}) + \sum_f \Gamma(h_2 \to f\bar{f})}$$

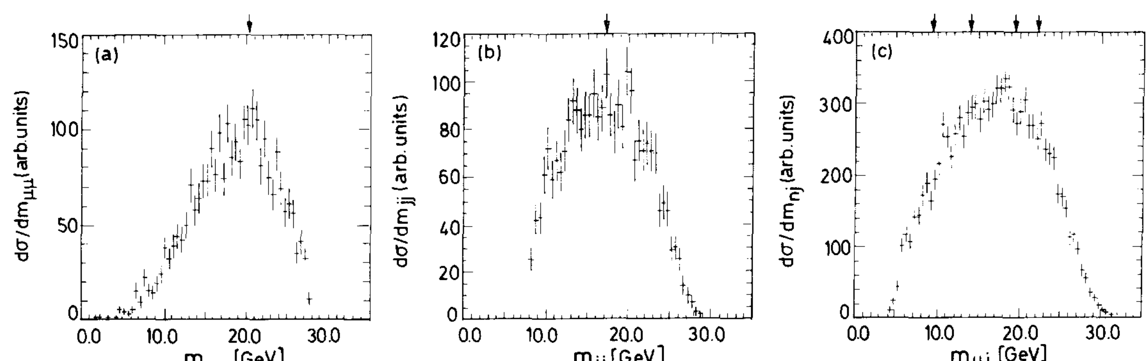

Fig. 1. Dimuon (a), dijet (b) and muon-jet (c) invariant mass distributions from the process $e^+e^- \to h_1 h_2$; $h_2 \to h_1 \mu\bar{\mu}$ with m_1 = 4 GeV and m_2 = 32 GeV at $\sqrt{s}$ = 43.5 GeV obtained by the Monte Carlo method. The CELLO event points are shown by the arrows at the top of each figure. All four combinations of the μ-jet systems are summed over in (c).

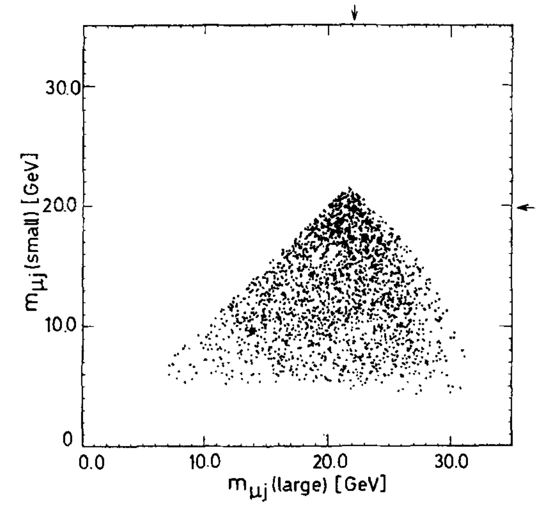

Fig. 2. The two-dimensional distribution of muon-jet invariant masses from the same process as in fig. 1. Two combinations of choosing mutually exclusive pairs of μ-jet systems are summed over. The higher mass combination of the CELLO event point is shown by arrows.

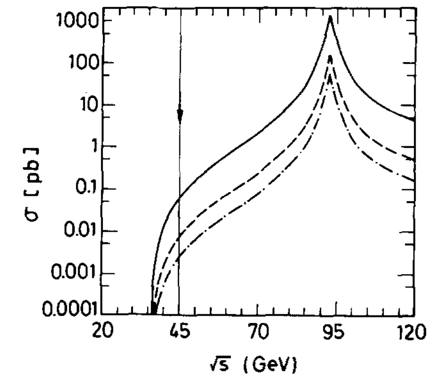

Fig. 3. The total h_1h_2 production cross section (solid line), the dijet plus missing p_T event rate with $\not{p}_T > 0.15\sqrt{s}$ for three neutrino flavors and $r = \Sigma\, BR(h_2 \to h_1 f\bar{f}) = 1$ (dashed line), and the dimuon–dijet event rate with $r = 1$ (dash-dotted line) plotted against e^+e^- CM energy, $\sqrt{s}$. The typical highest PETRA energy of $\sqrt{s} = 45$ GeV is shown by an arrow. The parameters chosen are $m_Z = 93$ GeV, $\Gamma_Z = 3$ GeV, and $\sin^2\theta = 0.22$.

should be substantial. If we require the probability to observe one $h_2 \to h_1\mu\bar{\mu}$ event in all the PETRA experiments to be greater than 10%, then r should be greater than one half. This then requires that the Yukawa coupling of h_2 to fermions should be suppressed by a factor of 1/20 compared to the standard (minimal) Higgs couplings. This is achieved in the two-doublet model [10] with natural flavor conservation [12] by requesting the extra scalar doublet to have no Yukawa coupling and a small vacuum expectation value (VEV) $v < (1/20)V$, $V \simeq 250$ GeV being the standard VEV. Then the lightness of h_1 is understood as being proportional to v, the Yukawa couplings of h_1 and h_2 are suppressed by v/V, and the aforementioned mixing factor ξ multiplying the $e^+e^- \to h_1h_2$ amplitude is $1 - O(v^2/V^2)$.

As is clearly seen from fig. 3, the production cross section for the h_1h_2 pair grows rapidly with energy reaching its maximum on top of Z-boson resonance where the rate becomes four orders of magnitude larger than that at the highest PETRA energies. At TRISTAN energies ($\sqrt{s} = 60$–70 GeV), the rate is still modest and the study of other decay modes will be important to test the model. The main decay modes should be either $h_2 \to b\bar{b}$ or $h_2 \to h_1 q\bar{q}$ where the final state would look like ordinary three- or four-jet events but always containing a very narrow ($\simeq 4$ GeV) jet with a fixed energy, $(s - m^2)/2\sqrt{s}$, and with $\sin^2\theta$ angular distribution. Aside from the dijet plus dilepton events, the most exciting signal would be the dijet plus missing transverse momentum ($\not{p}_T$) events from the $h_2 \to h_1\nu\bar{\nu}$ decay. The rate of such events should be at least 6 times larger than the $h_2 \to h_1\mu\bar{\mu}$ rate. Shown by the dashed line in fig. 3 is the event rate with $\not{p}_T > 0.15\sqrt{s}$ assuming three neutrinos and $r = 1$. The dotted line shows the dimuon–dijet rate with $r = 1$.

At $p\bar{p}$ colliders, the h_1h_2 pair should be produced via Z boson decays. The branching fraction is comparable to that of e^+e^- decay. Aside from the dimuon–dijet events, the best signal would again be the missing p_T from $h_2 \to h_1\nu\bar{\nu}$. We show in fig. 4 the p_T distributions of dijet and $\not{p}_T$ at $\sqrt{s} = 630$ GeV with $r = 1$. An especially sharp jacobian peak of very narrow ($\lesssim 4$ GeV) jets is due to the $\sin^2\theta$ angular distribution in the colliding parton CM frame. Although coincidence of a narrow jet of $p_T \simeq 40$ GeV and a large $\not{p}_T$ will help in identifying the signal, more integrated luminosity is needed for quantitative studies.

Most likely the CELLO dimuon–dijet event [1] will turn out to be just a large fluctuation of standard model physics as did [13] most anomalies reported recently from the CERN collider. It is, however, worth

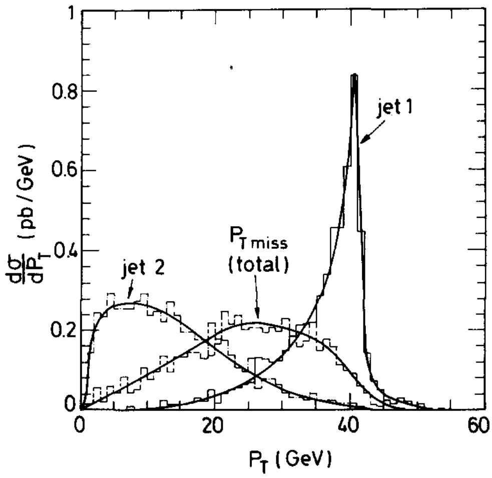

Fig. 4. The transverse momentum distributions of an energetic jet, missing p_T, and a softer jet in the process $p\bar{p} \to Z$; $Z \to h_1 h_2$; $h_2 \to h_1 \nu\bar{\nu}$ with three neutrino species and $r = 1$ at $\sqrt{s} = 630$ GeV obtained by the Monte Carlo method. Set-I parton distributions parametrized by Duke and Owens [6] were used and no QCD enhancement factor (K-factor) was introduced. Numerical constants are the same as those used in fig. 3.

mentioning that it may still be a signal of new physics, which can be tested in the near future.

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