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by

K. Hagiwara

*Deutsches Elektronen-Synchrotron DESY, Hamburg*

S. Komamiya

*Physikalisches Institut, Universität Heidelberg*

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An alternative interpretation of the CELLO dimuon-dijet event

K. Hagiwara<sup>1</sup> and S. Komamiya<sup>2</sup>

<sup>1</sup>DESY, Hamburg, Fed.Rep. Germany

<sup>2</sup>Physikalisches Institut der Universität, Heidelberg, Fed.Rep. Germany

Abstract

Higgs boson pair production  $e^+e^- \rightarrow h_1 h_2$  with  $m(h_1) \approx 4$  GeV and  $m(h_2) \approx 32$  GeV followed by the decays  $h_2 \rightarrow h_1 \mu \bar{\mu}$  via virtual Z boson exchange and  $h_1 \rightarrow$  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  $Z \rightarrow h_1 h_2$  decays in  $p\bar{p}$  collisions are also studied.

The dimuon plus dijet event<sup>1</sup> 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 others in angular space. The large invariant masses of both the dimuon system ( $\approx 20$  GeV) and the dijet system ( $\approx 17$  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<sup>1,2</sup> and that of a lepto-quark boson pair<sup>3</sup>. A detailed study<sup>4</sup> showed, however, that it is very unlikely for both jets to have rather small invariant masses ( $\approx 4$  GeV) in the former scenario. On the other hand the leptoquark boson, being colored, should be pair produced at hadron colliders<sup>3,5</sup>. 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<sup>6</sup> 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  $400 \text{ nb}^{-1}$  gathered at the CERN  $p\bar{p}$  collider, a thousand leptoquark pair should have been produced. Failure to observe a significant deviation from the standard model expectation in the dimuon events at the CERN collider<sup>7</sup> should hence be regarded as an 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 associate production of an excited muon ( $\mu^*$ ) and a muon<sup>1</sup> followed by a  $\mu^* \rightarrow \mu q \bar{q}$  decay via virtual Z boson exchange<sup>8</sup>. However, in order that the virtual Z decay modes dominate over the two-body  $\mu^* \rightarrow \mu \gamma$  decay, the electromagnetic transition coupling should be strongly suppressed relative to the neutral-current one: In an obvious notation<sup>9</sup>, we find

$$g_{\gamma \mu^* \mu}^2 / g_{Z \mu^* \mu}^2 \lesssim 10^{-6}$$

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 is 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 particle 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<sup>10</sup> 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  $e^+e^- \rightarrow h_1 h_2$  and the decay  $h_2 \rightarrow h_1 \mu\bar{\mu}$  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<sup>1</sup>, 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 heavier particle ( $h_2$ ) mass  $m_2$  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  $\mu$ -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 ( $e^+e^- \rightarrow h_1 h_2$ ) followed by the decay  $h_2 \rightarrow h_1 \mu\bar{\mu}$  via virtual Z boson exchange occurs at all, then a typical event structure would look like the CELLO event. We further confirmed in the two dimensional distribution of mutually exclusive pairs of  $\mu$ -jet system masses, that the higher mass combination of the data point (22 GeV, 19 GeV),

though very near to the phasespace boundary, stays in the most highly populated region. Hence the observed rough coplanarity can be understood as just a consequence of a particular but likely kinematical configuration of the event.

The total cross section for the process  $e^+e^- \rightarrow h_1 h_2$  is plotted against the c.m. energy  $\sqrt{s}$  as a solid line in Fig.3. The mixing factor (denoted by  $\xi$  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 ( $\sqrt{s} \approx 45$  GeV). With an integrated luminosity of  $25 \text{ pb}^{-1}$ , we can expect only one or two events per experiment. Since the branching fraction of the decay  $h_2 \rightarrow h_1 \mu\bar{\mu}$  is at best 3%, it is unlikely that a similar event be observed again at PETRA.

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

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

should be substantial. If we require the probability to observe one  $h_2 \rightarrow h_1 \mu\bar{\mu}$  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<sup>10</sup> with natural flavor conservation<sup>12</sup> by requesting the extra scalar doublet to have no Yukawa coupling and a small vacuum expectation value (v.e.v.)  $v < (1/20)V$ ,  $V \approx 250$  GeV being the standard v.e.v. 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  $\xi$  multiplying the  $e^+e^- \rightarrow h_1 h_2$  amplitude is  $1 - O(v^2/V^2)$ .

As is clearly seen from Fig.3, the production cross section for the  $h_1 h_2$  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  $h_2 \rightarrow b\bar{b}$  or  $h_2 \rightarrow h_1 q\bar{q}$  where the

final state would look like ordinary three or four jet events but always containing a very narrow ( $\approx 4$  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 ( $p_T$ ) events from the  $h_2 \rightarrow h_1 \nu \bar{\nu}$  decay. The rate of such events should be at least 6 times larger than the  $h_2 \rightarrow h_1 \mu \bar{\mu}$  rate. Shown by the dashed line in Fig.3 is the event rate with  $p_T > 0.15 \sqrt{s}$  assuming three neutrinos and  $r = 1$ . The dotted line shows the dimuon-dijet rate with  $r = 1$ .

At  $p\bar{p}$  colliders, the  $h_1 h_2$  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  $h_2 \rightarrow h_1 \nu \bar{\nu}$ . We show in Fig.4 the  $p_T$  distributions of dijet and  $p_T$  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 c.m. frame. Although coincidence of a narrow jet of  $p_T \approx 40$  GeV and a large  $p_T$  will help in identifying the signal, more integrated luminosity is needed for quantitative studies.

Most likely the CELLO dimuon-dijet event<sup>1</sup> will turn out to be just a large fluctuation of standard model physics as did<sup>13</sup> most anomalies reported recently from the CERN collider. It is, however, worth mentioning that it may still be a signal of new physics, which can be tested in the near future.

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Figure Captions

- Fig. 1 Dimuon (a) and dijet (b) invariant mass distributions from the process  $e^+e^- \rightarrow h_1 h_2$ ;  $h_2 \rightarrow h_1 \mu \bar{\mu}$  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.
- Fig. 2 The invariant mass distribution for the  $\mu$ -jet system summed over all four combinations from the same process as in Fig.1. The CELLO event gives four points shown by the arrows.
- Fig. 3 The total  $h_1 h_2$  production cross section (solid line), the dijet plus missing  $p_T$  event rate with  $p_T > 0.15 \sqrt{s}$  for three neutrino flavors and  $r = \sum BR(h_2 \rightarrow h_1 f \bar{f}) = 1$  (dashed line), and the dimuon-dijet event rate with  $r = 1$  (dash-dotted line) plotted against  $e^+e^-$  c.m. 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  $\sin^2 \theta = 0.22$ .
- Fig. 4 The transverse momentum distributions of an energetic jet, missing  $p_T$ , and a softer jet in the process  $p\bar{p} \rightarrow Z$ ;  $Z \rightarrow h_1 h_2$ ;  $h_2 \rightarrow h_1 \mu \bar{\mu}$  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<sup>6</sup> were used and no QCD enhancement factor (K-factor) was introduced. Numerical constants are the same as those used in Fig.3.

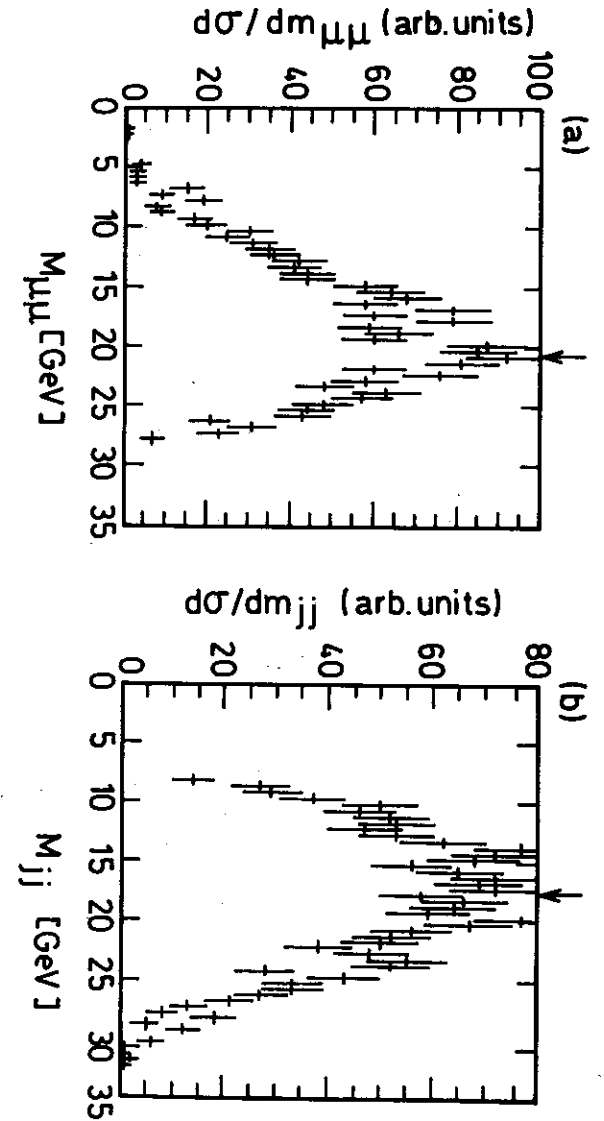
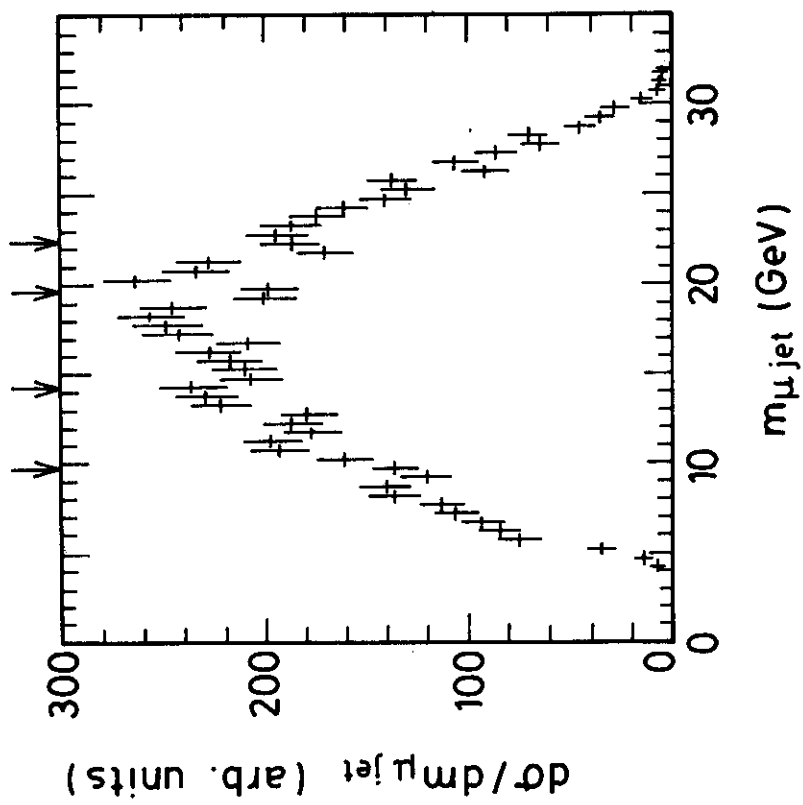


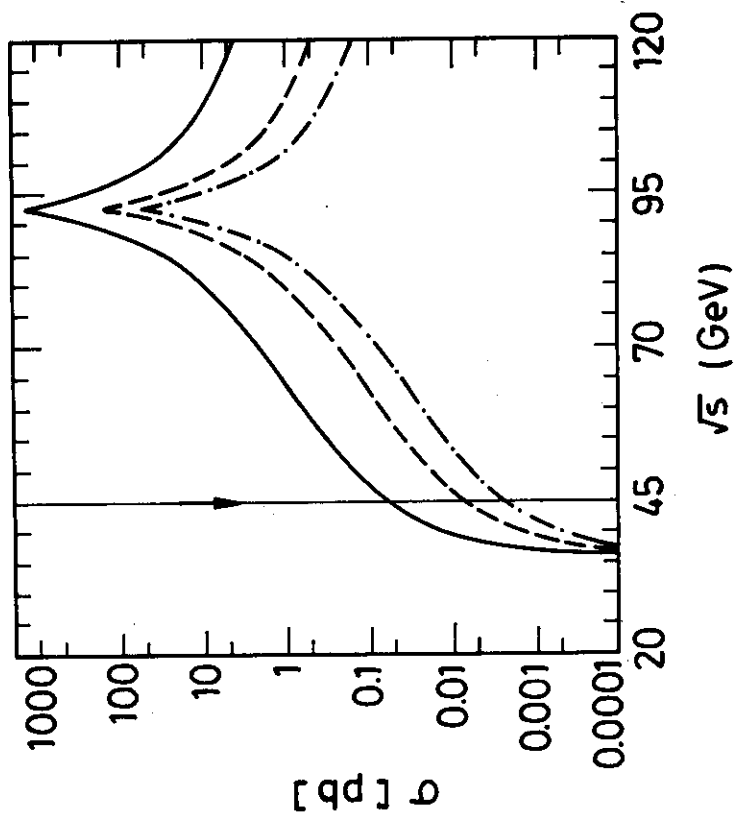
Fig. 1

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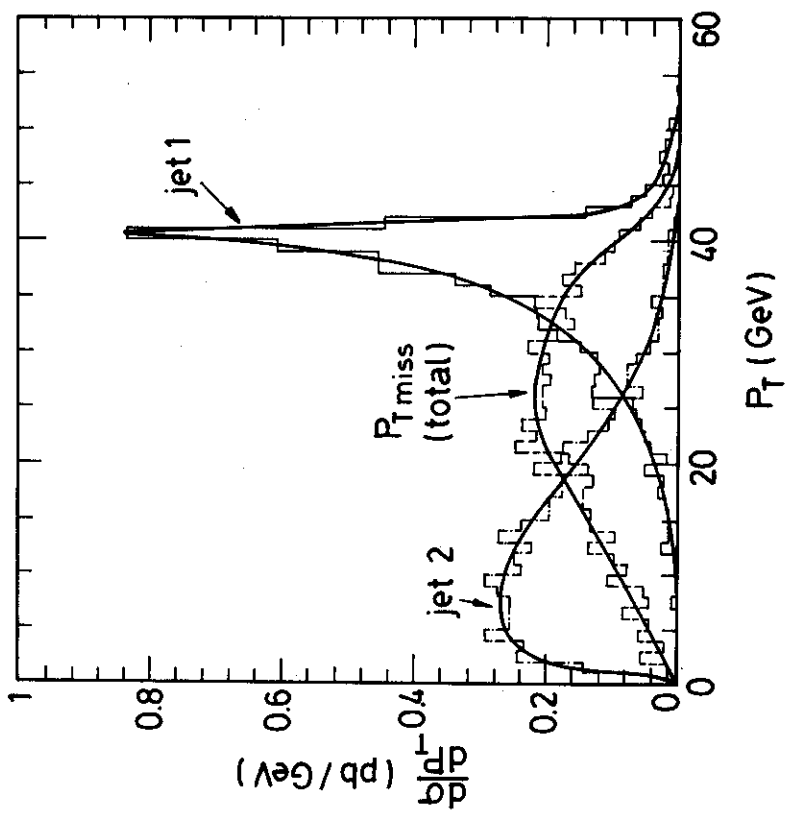
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Fig. 2



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Fig. 3



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Fig. 4