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INTERPRETATION OF UNUSUAL EVENTS FROM CERN AND DESY

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ABSTRACT

Several classes of interesting and unusual events from the Sp $\bar{p}$ S and from PETRA are studied with two purposes in mind. Firstly, varieties of background within the standard $SU(3) \times SU(2) \times U(1)$ model are described, together with estimates of the number of expected events. Secondly, a review of the recent explanations of the events involving new physics is given. Critical assessments of these proposals focus on the assumptions made, expected rates for the unusual events, and the ability to account for events of several categories.

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I. INTRODUCTION

The 1983 run of the CERN SppS collider of 113 nb^{-1} at $\sqrt{s} = 540 \text{ GeV}$ gave physicists their first post-ISR view of hadron collider results. As well as identifying W, Z and top-like decays, the UA1 and UA2 detectors observed at least 30 unexpected events with clean, unusual signatures. Unusual events may also be appearing at the highest PETRA energies. This paper is an outgrowth of the SSC Workshop on Electroweak Symmetry Breaking held at LBL in June 1984. A working group studied six classes of unusual events from the SppS collider and two from PETRA. The salient features of these events are summarized in Table 1. A shortened form of this paper will be published in the Snowmass SSC Workshop Proceedings. However, we hope that rapid circulation of the present paper will aid critical assessment of the new physics proposals as further runs of higher luminosity are performed. To be as useful as possible, we have generally emphasized those features of proposals which do not work, or are highly unlikely.

The CERN collider events of type (I)-(VI) are published or mentioned in Conference Proceedings¹⁾⁻⁶⁾ and have been reviewed⁷⁾. We have not included all reported interesting new signatures, such as the 3σ bump in the multijet invariant mass distribution at $147 \pm 5 \text{ GeV}$ containing 50 ± 16 events seen by UA2⁵⁾. We also discuss two classes of event from CELLO⁸⁾ and MARK J⁹⁾ collaborations.

In Section II, we discuss the events themselves, and standard model backgrounds to some of them. Section III considers proposals introduced primarily to explain the $\ell^+ \ell^- \gamma$ events, while in Section IV we consider those primarily aimed at explaining events with large missing transverse momentum ($\not{p}_T$). Section V considers origins of both same and opposite sign dimuons, and conclusions are drawn in Section VI. This section contains a summary table of the proposed explanations for each class of events.

We have tried to include all proposals which have appeared in written form. Given the rapid development of the subject, we are sure to have missed interesting papers, and thus apologize to authors whose work we have ignored and to others whose ideas we have misrepresented.

II. THE EVENTS, AND THE STANDARD MODEL

In this section, we consider the eight classes of event shown in Table 1, and consider possible origins within the standard model.

The properties of the "radiative Z decays"^{4),5)} are shown in Table 2. The background to these $\ell^+\ell^-\gamma$ events, which are kinematically consistent with radiative Z decays, comes from QED bremsstrahlung. The most notable feature of the three observed events is that they cluster very strongly in the Dalitz plot, as shown in Fig. 1. This clustering along the region of maximum E_1 is because the γ does not have a large angular separation from the lepton of energy E_2 . However, this angular separation is still considerably larger than would be expected for bremsstrahlung.

The UA2 group⁵⁾ computed the probability to find an $e^+e^-\gamma$ event from Z decay with both photon energy and $e\gamma$ opening angle larger than they observed, compared with that for a $Z \rightarrow e^+e^-$ decay: $P(e^+e^-\gamma/e^+e^-) = 1/200$. This would lead to an expectation of $8/200 = 1/25$ events in the UA2 detector, since eight $Z \rightarrow e^+e^-$ decays were seen. However, the UA2 group later pointed out that this is an underestimate¹⁰⁾. A configuration is said to be less likely than the observed one if its differential cross-section is smaller than that calculated at the point corresponding to the observed $Z \rightarrow e^+e^-\gamma$ event. A more relevant quantity is the probability of observing an $e^+e^-\gamma$ event with any configuration which is less likely than the event observed, and which leads to a signature of three separate electromagnetic energy depositions. The UA2 collaboration then find a probability of 1% for their observed $e^+e^-\gamma$ event for each e^+e^- event, or 8% to observe at least one such event in a sample of eight. A similar analysis on the combined UA1 and UA2 sample of twelve $Z \rightarrow e^+e^-$ or $e^+e^-\gamma$ events suggests that the probability of observing two or more $e^+e^-\gamma$ events in this sample is of the order of 5%.

The absence of isolated hard photons in W decay⁴⁾ implies $p(e\nu\gamma/e\nu) < 1/50$ for isolated γ . The UA2 collaboration have one event consistent with $W \rightarrow e\nu\gamma$ ¹⁰⁾, where separate showers for e and γ cannot be resolved. The presence of the hard nearly collinear photon can be inferred because the momentum of the charged track in the forward calorimeter does not match the EM shower energy. Nine of the 37 UA2 W events pass through the forward calorimeter, and the probability for the source of this event to be QED external bremsstrahlung is computed to be¹⁰⁾ $9/200 \sim 1/20$.

Other QED calculations have been done¹¹⁾ which concentrate on the energy and angular resolutions of the detector. These give radiative event probabilities of order 1/10 per observed $Z \rightarrow e^+e^-$ and 1/20 per observed $W \rightarrow \nu e$, for an energy resolution of 3 GeV and an angular resolution of 10^{-3} radians. However, the observed events are much less likely than the minimum resolvable bremsstrahlung.

The CELLO dimuon event⁸⁾ shown in Fig. 2 also has a possible QED explanation. The event cannot be interpreted as the semileptonic decay of t and $\bar{t}$ quarks because there is insufficient rise in R and no toponium resonance. The data cannot rule out a fourth down-type quark, but even in this unlikely event, its semileptonic decay would be expected to yield much larger missing energy and momentum than is observed. The CELLO collaboration claim a background of $O(10^{-3})$ expected events⁸⁾ from the standard model radiative processes shown in Fig. 3. This could be increased by as much as an order of magnitude if the background is obtained by integrating over all phase space in which the squared matrix element is smaller than near the observed event. Since the background processes shown in Fig. 3 have a very low energy threshold, and since many PEP and PETRA detectors would be sensitive to such events, it is tempting to multiply the low probability of the event by the integrated luminosity gathered by many detectors at both machines over a wide range of energy. This would greatly diminish the peculiarity of this event. In addition, one should perhaps sum over the probabilities for all unusual standard model processes which have a probability of $O(10^{-2})$ or less. This illustrates the difficulty in assigning a "new physics confidence level" to a single event. However, the event is very interesting and if more such events are seen by CELLO and other groups, the situation will become very exciting. MARK J have also seen events with μ pairs and jets, but the background analysis has not yet been completed¹²⁾. In addition, MARK J have seen a number of single muon plus jet events in a run at the highest PETRA energy ($\sqrt{s} \gtrsim 46$ GeV). The events are consistent with heavy flavour decays (e.g., coplanar hadrons, some missing energy), but a toponium search for $\sqrt{s} \lesssim 46$ GeV was negative. CELLO, JADE and TASSO have not seen any events of this form and the rate in the four detectors may not be too far above standard model backgrounds.

The events of UA1 with jet(s) or an electromagnetic shower opposite missing transverse momentum are shown in Fig. 4. The background from QCD jets (with one jet missed) falls quickly with missing energy and is very small for $E_M > 35$ GeV. One monojet event (F) is consistent with expectations for $W \rightarrow \nu \tau$ with $\tau \rightarrow \nu j$ ¹⁾, and since the transverse mass for $j + \cancel{p}_T$ is 73 GeV, we ignore this event. The remaining five events, A-E, are inconsistent with this interpretation. However,

the errors on the transverse mass are quite large, and it has recently been claimed that the number of monojet events expected from $W \rightarrow \nu\tau$ is larger than previously expected¹³⁾. The two- and three- π decay modes of τ give 0.5 events with $p_T > 40$ GeV, and it has been estimated that the four- π decay mode may be even more important¹³⁾. However, the decay of τ into electromagnetic energy (i.e., only π^0 's), is estimated to yield only 0.02 of a monoshower event with $p_T > 40$ GeV¹³⁾, and is therefore unimportant. We are also inclined to ignore the monoshower event G, because it has an azimuth angle $\phi \sim 0$ corresponding to an insensitive region of the central detector: the event may be $W \rightarrow e\nu$. The UA2 events $e j p_T$ are shown in Fig. 5. Event D has a possible explanation of a heavy quark pair production followed by a semileptonic decay of one of the quarks. This is not the case for A, B and C, as the missing p_T lies opposite the electron direction. In fact, these three events are consistent with $W+j(s)$ followed by $W \rightarrow \nu e$.

It is possible that UA2 may also uncover some monojet events; however, UA1 do not see any $e j p_T$ -type events. (Event A in Fig. 4 contains a muon in the jet, however.) Both classes of events have an $O(\alpha_s)$ background consisting of hard gluon bremsstrahlung with $Z(\rightarrow \nu\bar{\nu})$ for monojets) or $W(\rightarrow \nu e)$ for $e j p_T$ production. The tail of the transverse momentum distribution of the W in Drell-Yan production¹⁴⁾ is shown in Fig. 6. Appropriate cuts appear to halve the size of this tail¹⁵⁾. It is quite a hard distribution. For example, UA1 would expect 1.5 of their reduced sample of 43 $W \rightarrow e\nu$ events to have $q_T > 25$ GeV. In fact, they have two events with $22 < q_T < 24$ GeV¹⁶⁾. Similarly, UA2 would expect ~ 1 event with $q_T > 25$ GeV (they have three: A,B,C) and $\sim 1/10$ event with $q_T > 50$ GeV (event B). This suggests that event A could well be QCD background. However, events B and C have a jet topology which is less likely than this q_T analysis suggests. Event B has a jet with $p_T = 67$ GeV, while event C has jets of $p_T = 38$ and 21 GeV separated in azimuth by 128° .

The tail of the q_T distribution for Z production does not differ greatly from that for W production. A similar naive estimate gives a QCD monojet background of ~ 1 expected event for $q_T > 25$ GeV (six observed) and $\sim 1/10$ (two observed) expected event for $q_T > 50$ GeV. These estimates are borne out by more complete calculations (P. Aurenche and R. Kinnunen, private communication). For the monoshower event, the background would be a hard photon bremsstrahlung together with a $Z \rightarrow \nu\bar{\nu}$. This is down by a further α/α_s , giving $1/100$ expected events with $q_T > 50$ GeV.

We conclude that there are five $j p_T$, three $e j p_T$ and one γp_T events which cannot be easily dismissed, with a background of Zg , Wg and $Z\gamma$ which is at least an order of magnitude below the observed rate.

In type VI events, more hadronic activity is seen by UA1 accompanying Z production than W production^{2),6)}. UA1 consider a sample of 68 $W \rightarrow \nu_\ell \ell$ and nine $Z \rightarrow \ell^+ \ell^-$ events, which have no selection bias toward or against hadronic activity. The Z events have a higher scalar transverse energy sum, a higher occurrence of jets, and a higher charged track multiplicity per unit rapidity at the $2-3\sigma$ level. The jets occurring with W production are found by UA1 to agree with QCD expectations, so it is the high activity Z events which are anomalous. The UA2 Collaboration do not find anomalous jet activity in Z events.

This interpretation must be made cautiously, however, since a new phenomenon producing jetty Z and W events at equal rates would appear more prominently in the Z channel, where the conventional event rate is lower.

The UA1 collaboration see events with μ pairs of invariant mass between 6 and 22 GeV together with jet(s). Seven of the events have opposite sign muons, while three have like sign. The jets typically contain a high abundance of strange particles. Like-sign dimuons could come from $t\bar{t}$ or $b\bar{b}$ production, provided one muon is prompt and the other secondary. Both muons could be prompt if the origin is $W \rightarrow t\bar{b}$, although the invariant mass of one $\mu^+ \mu^- j(s)$ event is far too large to be from W decay. The two other like-sign dimuon events contain Λ : $\mu^+ \mu^+ j(s) \supset \Lambda$, $\mu^- \mu^- j(s) \supset \bar{\Lambda}$. It is very tempting to assign these to $B_s^0 - \bar{B}_s^0$ mixing¹⁷⁾. At first sight, the Λ have the wrong strangeness for the sign of the muons. B_s^0 has $b \rightarrow \bar{\nu}_\mu c$ and $c \rightarrow s$ so that $\mu^- \mu^- \Lambda$ might be expected. However, this overlooks the presence of spectator $\bar{s}$ quarks, which could yield $\bar{\Lambda}$. It has been estimated¹⁷⁾ that a $b\bar{b}$ production cross-section of $O(\mu b)$ would yield ~ 7 opposite-sign and ~ 2 like-sign dimuons passing the UA1 selection criteria. However, it should be mentioned⁷⁾ that neither $b\bar{b}$ or $c\bar{c}$ production mechanisms fit the kinematics of several of the events.

At the highest PETRA energy, the MARK J collaboration have seen several rather planar events with a muon isolated from jets⁹⁾. Although a very slight rise in R, and a possible resonance at 44 GeV have been seen¹⁸⁾, a toponium state below 46.52 GeV has been ruled out¹⁸⁾. A fourth, heavy, down-type quark has not been ruled out, however.

III. NEW PHYSICS EXPLANATIONS OF $\ell^+\ell^-\gamma$ EVENTS

The $\ell^+\ell^-\gamma$ events seen at CERN, which many (although not all) interpret as radiative Z decays, are very different from the other CERN events which contain large $\not{p}_T$ and jets. Few authors have explained both sets of events from the same idea, and hence we consider explanations primarily aimed at the $\ell^+\ell^-\gamma$ events in this section, and those mainly concerned with jets and $\not{p}_T$ in the next.

The $\ell^+\ell^-\gamma$ events have three features which make them extraordinarily hard to understand. The rate for these events is large: about 25% of the $Z \rightarrow \ell^+\ell^-$ rate. New physics which is able to accommodate such a rate often predicts values for $(g-2)_\ell$ above the experimental limits¹⁹⁾⁻²¹⁾. Secondly, if these events are interpreted as radiative Z decays, the absence of similar radiative W decays at the 2% level must be explained⁴⁾. The single radiative W decay seen at UA2 does not have the photon shower resolved from the lepton shower, and hence has a much higher probability of being bremsstrahlung.

Finally, it is very hard to understand by any mechanism other than bremsstrahlung why the three observed events should cluster so strongly against one edge of the Dalitz plot, as shown in Fig. 1. We emphasize this point quite strongly, as the clustering is very marked. The lepton energies E_1 and E_2 are given by

$$E_{1,2} = \frac{M}{2} \left(1 - \frac{m_{\gamma\ell,2}^2}{M^2} \right)$$

where $m_{\gamma\ell}^2$ is the squared invariant mass of the lepton photon pair. It is often remarked that one such pair mass (or, equivalently, their angular separation) is rather small in these events. The Dalitz plot displays the events in a kinematically unbiased manner, so that the correct small parameter is $m_{\gamma\ell}^2/M^2$, which is $\sim 10^{-3}$ for all events. Many of the proposed explanations ignore this clustering and assume that it is due to a statistical fluctuation. This seems less likely to us than the possibility that these events are QED bremsstrahlung. Those ideas which attempt to explain the clustering [e.g., Ref. 22)] must rely on the momentum dependence of the matrix element. This is never sufficient to give the observed clustering.

Several authors^{23),24)} have explored the possibility that these events are due to Z decay via an excited lepton ℓ^* ($Z \rightarrow \ell\ell^*$, $\ell^* \rightarrow \ell\gamma$) which may be expected

in schemes of composite quarks and leptons. The excited lepton is produced and decays via a transition magnetic moment operator of the generic form

$$\frac{1}{\Lambda} \bar{l}^* \sigma^{\mu\nu} l F_{\mu\nu} \quad (3.1)$$

where $F_{\mu\nu}$ can be the SU(2) or hypercharge field strength. To obtain sufficient rate, the scale of compositeness Λ must not be larger than about 100 GeV. Although this is not necessarily ruled out, it is uncomfortably low as there are limits on the compositeness scale in the multi-TeV range from other operators^{25),26)}. To be consistent with $g-2$ ¹⁹⁾⁻²¹⁾, no one-loop diagram should exist where the helicity flip comes from the internal heavy excited lepton, thus ensuring $(g-2)$ contributions of order $(m_l/m_{l^*})^2$, rather than (m_l/m_{l^*}) . This can be arranged by having both helicity components of l^* transform either as SU(2) doublets or as singlets.

The process $W \rightarrow \gamma l^*$, $l^* \rightarrow l \gamma$ can be suppressed (forbidden) by making m_{l^*} near (above) M_W .

While the rates can be made plausible, the excited lepton scenario has severe difficulties with the Dalitz plot. Both the high and low $(l\gamma)$ invariant masses differ by $\sim 3\sigma$ for the $e^+e^- \gamma$ events. l^* is assumed to correspond to the high value, as the low value is less than 10 GeV. A 10 GeV l^* would have been seen at PEP and PETRA. It is then extremely improbable that the γ should be correlated with the prompt lepton to give such low values for the invariant mass. The operator (3.1) leads to an essentially flat distribution in this invariant mass²¹⁾.

An alternative explanation of these $l^+l^-\gamma$ events via Z decays is also motivated by compositeness, or perhaps technicolour²⁷⁾⁻³¹⁾. It is quite probable that scalars and pseudoscalars are considerably lighter than the compositeness or technicolour scale, so that the Z could decay into them:

$$Z \rightarrow X \gamma \quad \xrightarrow{\quad} l^+ l^- \quad (3.2)$$

The observed l^+l^- invariant masses, shown in Table 2, are within 2σ of each and the lowest (42.7 GeV) is 2σ away from the limit on the X boson mass (>47 GeV) from Bhabha scattering^{27),18)}.

The nature of X and its couplings varies from one scheme to another. The X's may be the pseudo Goldstone bosons of chiral symmetry breaking induced by a

new strong interaction²⁹⁾. They could be expected to include an isotriplet and an isosinglet. Alternatively, if the $SU(2) \times U(1)$ gauge bosons are viewed as 1^- bound states, they may have scalar weak isotriplet and isosinglet partners²⁸⁾.

Whatever the underlying motivation, the minimal requirements are met by having X as an $SU(2)$ singlet which is produced in Z decay via the operator $(1/\Lambda) \tilde{W}W X$, where W is the $SU(2)$ field strength tensor, and the compositeness scale Λ can be taken to be $\sim 0(\text{TeV})$, more comfortable than before. This operator gives a width for $X \rightarrow \gamma\gamma$ of $O(10 \text{ MeV})$ ³²⁾, and to ensure a sufficient branching ratio ($\sim 5\%$) to e^+e^- , X must couple to fermions: $h_i \bar{f}_i f_i X$. If this coupling violated chiral symmetry, one would expect $h_e \ll h_\mu$, etc., and it seems best to assume that X is complex, so that h_i preserve chiral symmetry and may be taken to be i independent.

A sufficient rate for $Z \rightarrow e^+e^- \gamma$ seems quite plausible in this scheme. Furthermore, there is no analogous radiative W decay if X is an $SU(2)$ singlet. There are several other interesting features of this scheme. The UA1 monoshower event is explained if h_i is independent of i , since then $X \rightarrow \nu\bar{\nu}$. The $\tilde{W}W X$ operator also gives $X \rightarrow \gamma\gamma$, so that trishower events are anticipated with total invariant mass M_Z , and one pair invariant mass of $M_X \sim 50 \text{ GeV}$.

The operator $X \bar{f} f$ is rather a bad one from the viewpoint of the Dalitz plot. The X decays isotropically, and no correlation with the photon direction is expected. This is the major failing of this scheme in explaining the observed events.

It is quite possible that the scalars expected in composite and technicolour schemes are heavier than the Z . In this case, they could still provide an explanation for the $\ell^+ \ell^- \gamma$ events, providing their mass is less than $\sim 100 \text{ GeV}$ ²²⁾. In this scheme, the scalar (or pseudoscalar) boson R is taken to have large couplings to fermions only if these couplings are chirally invariant. Dimension 5 operators, such as $R \bar{f} \not{D} f$, can be rotated away, so that the first such operators of importance are dimension 7, for example, $\partial^\mu \partial^\nu R \bar{f}_\mu \not{D}_\nu f$ and $F^{\mu\nu} \partial_\mu R \bar{f}_\nu f$. These operators give matrix elements for $R \rightarrow \ell^+ \ell^- \gamma$ which vanish in the soft photon limit and peak along the edges of the Dalitz plot. The peaking is not sharp enough to predict the observed distribution, but it is a step in the right direction. If the scale in front of these operators is low enough, the dimension 9, 11, ... operators would also contribute. Some of these enhance the peaking

near the edge of the Dalitz plot, and some of them tend to flatten it. Thus a certain conspiracy is needed at higher order. When f is a neutrino, operators involving $F_{\mu\nu}$ lead to monoshower events.

Dimension 7 operators would also be responsible for the production of R , together with a hard gluon: $q\bar{q} \rightarrow Rg$. To obtain $\sigma \sim 0.1$ nb, the scale Λ should be ~ 100 GeV. If this production mechanism dominated, the resulting events would be $\ell^+\ell^-\gamma j$. One way around this problem is to assume that the production of R occurs dominantly through the two-gluon piece of the dimension 7 operator $q\bar{q} \rightarrow Rgg$, since this matrix element does not vanish for soft gluons. The production can be improved by using a RGG operator where G is the gluon field strength. However, the dominant decay of R is to jets, and an order of magnitude in the $\ell^+\ell^-\gamma$ signal is lost.

An interesting point about both X and R boson mechanisms is that $q\bar{q}\gamma$ events are expected which have invariant masses $O(M_Z)$. In fact, UA1 has 85 events of the $j\bar{j}\gamma$ type which have a broad distribution in invariant mass peaked near M_Z^2 .

The Z would appear to have anomalous decay modes if it was degenerate and mixed with some other state. One such model³³⁾ envisages the Z mixing with an excited 1^{--} onium state of a quark with exotic colour. This is assumed to decay to the lowest 1^{--} state of mass ~ 50 GeV via the emission of one hard photon to a 0^{++} χ state, followed by a soft photon. The lowest 1^{--} state will occasionally decay to $\ell^+\ell^-$, giving the observed signature. A sufficient rate requires essentially complete mixing of the states, with a 2% branching ratio for the $\ell^+\ell^-\gamma$ decay chain.

Several features of the signatures for this scheme coincide with the signatures for $Z \rightarrow X\gamma$, $X \rightarrow \ell^+\ell^-$. Clearly, both have a strong peak in $m(\ell^+\ell^-)$ around 50 GeV; furthermore, both can generate $\gamma\nu_T$ and $Xq\bar{q}$ events when the X or lowest 1^{--} state decays into neutrinos or quarks. The correlation in angle between the γ and the ℓ of low $m(\ell\gamma)$ is not explained. Also, both schemes are motivated by, but do not necessitate, composite scenarios. Moreover, each has one major assumption. For the X boson, a large $(1/\Lambda) W\tilde{W}X$ is required for a sufficient rate. The exotic onium scheme assumes that the strong binding associated with quarks of higher colour representations will produce an extraordinary spectrum of states, and that the 1^{--} onium is accidentally degenerate with the Z , with roughly the same width.

The explanations discussed so far do not require the Z to be anything other than the usual fundamental gauge field. An alternative explanation supposes the Z itself to be a composite^{19),30),34)-36)}, in which case operators of the form $(G/\Lambda^2) F^{\mu\nu} Z_\mu \square Z_\nu$ could occur. The branching ratio for radiative decays is then³⁴⁾

$$\frac{\Gamma(Z \rightarrow \ell^+ \ell^- \gamma)}{\Gamma(Z \rightarrow \ell^+ \ell^-)} \sim 10^{-4} G^2 \frac{M_Z^4}{\Lambda^4} \quad (3.3)$$

This is sufficient only if $G \gg 1$ and $\Lambda \lesssim M_Z$.

It is very hard to believe that such strong interactions amongst particles of the standard model can be tolerated at scales as low as M_Z ³⁷⁾: why do we not observe a momentum dependence of the vector boson masses? Why is ρ so close to unity? Why are there not also large radiative W decays? At the very least, one might expect to observe $Z \rightarrow q\bar{q}\gamma$ ³⁸⁾ or $Z \rightarrow q\bar{q}g$ (i.e., jjj)³⁵⁾.

Perhaps the worst feature of this scheme is that it prefers large invariant masses for both $(\gamma\ell)$ pairs, rather than one large and one small. This has been emphasized³⁹⁾ by comparing the Dalitz plot distributions of the data Fig. 7a, with that of bremsstrahlung (7b), the X boson (7c), excited leptons (7d) and a composite Z (7e). Bremsstrahlung does the best, and a composite Z the worst. Since none of the new physics explanations do very well, we find them all unlikely.

A model with an effective $Z\gamma\gamma$ vertex⁴⁰⁾, instead of a $ZZ\gamma$ vertex, is motivated by the idea that it could be induced by a bound state of a monopole and a charged fermion with a mass of a few hundred GeV. However, such a model has the same problem in the Dalitz plot of Fig. 7e.

All new physics explanations of the $\ell^+ \ell^- \gamma$ events discussed so far have had compositeness as a motivation. However, a final explanation requires no extensions of the standard model. The Higgs mass is taken to be large and the resulting strong forces between longitudinal W bosons are assumed to yield bound states of vector bosons in the 100 GeV mass region³⁷⁾. Although no calculations support such a low value for the mass of this bound state, the resulting eight-fermion

effective operators could explain same-sign, multi-muon events in neutrino scattering as well as the $\ell^+\ell^-\gamma$ events. Further effective interactions of the bound state could lead to the monoshower event, and would allow the bound state to be produced with a γ at e^+e^- machines⁴¹⁾.

Unfortunately, we believe the production rate of such a bound state is far too small for it to be relevant for the unusual events. A rough estimate of the production rate can be obtained by comparing with the production rate of a 100 GeV Higgs via W fusion. This has a quark subprocess cross-section of less than 10^{-4} nb ⁴²⁾. Quark luminosity factors reduce the $p\bar{p}$ cross-section still more. Even allowing for effects for strong WW interactions, it is very unlikely that 50 such bound states would have been produced by a 100 nb^{-1} exposure. This must be considered an unlikely explanation of the $\ell^+\ell^-\gamma$ events.

IV. NEW PHYSICS EXPLANATIONS OF EVENTS WITH $\cancel{p}_T$.

In this section, we consider the diverse ideas which have been introduced primarily to explain those CERN events with large values of $\cancel{p}_T$; types I, II and IV in Table 1. The explanations vary from minor modifications of the standard model to models incorporating completely new symmetries and interactions.

It is important to try to see aspects of these various events which might point to a common origin. In this regard, it is interesting to note that the monojet, monoshower and $jj\cancel{p}_T$ events seen by UA1 are all consistent with a total invariant mass of 160 GeV, assuming the missing energy to be $Z \rightarrow \nu\bar{\nu}$. This is illustrated in Fig. 8⁶⁾. Furthermore, of the five jetty Z events, four have $m(Z+j(s))$ consistent with 160 GeV⁶⁾. Also, the UA2 collaboration see a bump in jj nearby at 150 GeV. The UA1 monojet events have low invariant mass and low numbers of reconstructed charged tracks with $p_T > 0.5 \text{ GeV}/c$ (1,3,1,4,2 for A-E)¹⁾. This is to be compared with an average charged multiplicity of 12 for a 60 GeV jet reported by UA2. If an explanation of these low multiplicities is found, then it would be a very plausible extrapolation to consider the monoshower to be a monojet with charge multiplicity zero.

The following six subsections consider ideas involving major extensions of the standard model. We emphasize here that some events can be explained on an individual basis as a fluctuation of a standard process. For example, the UA2 event C of type II could be due to pair production of quarks which are just

heavier than the W . They each decay to Wq , with one W decaying hadronically and the other to νe ⁴³⁾. This is four times more probable than the QCD gluon bremsstrahlung background.

(1) A copiously produced 150 GeV Higgs

Could these unexpected events with $\cancel{p}_T$ be due to the standard Higgs particle? In the standard model the answer is negative, as the Higgs production rate is too low. It is conceivable that structure in the hundreds of GeV range induces a large coupling of the Higgs doublet H to the QCD field strength G : $(1/\Lambda^2)H^\dagger H G^2$. With $\Lambda \sim O(100 \text{ GeV})$, the production rate of a 150 GeV Higgs is enhanced by a factor of 10^6 , so that 10^3 would have been produced at CERN. It has been proposed that the subsequent decay of these Higgs is responsible for $ej(s)\cancel{p}_T$, $jj\cancel{p}_T$ and $\gamma\cancel{p}_T$ events⁴⁴⁾.

The standard model Higgs has a partial width to gluons $\Gamma(H \rightarrow gg) \sim 2 \cdot 10^{-4} \text{ GeV}$, for a Higgs mass of 150 GeV, and assuming the top quark to have a mass $\gtrsim 35 \text{ GeV}$. Thus the new physics which enhances the coupling of the Higgs to gluons gives the Higgs a width of $\sim 200 \text{ GeV}$. In fact, the Higgs will be produced much more copiously than naively expected: it is so broad that the production rate on the low energy side of the resonance will be considerably enhanced, due to the increased gluon luminosity at lower centre-of-mass energies. Of course, the majority of decays are into gluons giving a broad addition to the two-jet signal.

The decay to $t\bar{t}$ is quite rare for a top mass of $\sim 45 \text{ GeV}$; but we might expect there to be large $H^\dagger H W_{\mu\nu}^{\mu\nu}$ and $H^\dagger H B_{\mu\nu}^{\mu\nu}$ operators, where $W_{\mu\nu}^{\mu\nu}$ and $B_{\mu\nu}^{\mu\nu}$ are the $SU(2) \times U(1)$ field strengths. Hence occasionally $H \rightarrow \gamma Z$, giving a monoshower when $Z \rightarrow \nu\bar{\nu}$. The UA2 events of $ej(s)\cancel{p}_T$ are compatible with $H \rightarrow W^+W^-$, followed by one leptonic and one hadronic W decay. One serious difficulty for this scheme is obtaining a monojet signal. $H \rightarrow ZZ$ with one $Z \rightarrow \nu\bar{\nu}$ and the other $Z \rightarrow q\bar{q}$ should produce $jj\cancel{p}_T$ with $m(jj) \sim M_Z$. The jet activity associated with Z production could be due to $H \rightarrow Z_1 Z_2$, $Z_1 \rightarrow \ell^+ \ell^-$ and $Z_2 \rightarrow q\bar{q}$. In the WW and ZZ modes, one boson is off-shell.

This scheme illustrates an interesting point: several of the unusual events at CERN could be due to a state decaying to a pair of $SU(2) \times U(1)$ gauge bosons.

If this idea is correct, $\gamma\gamma$, $e\mu\not{p}_T$ and $\ell^+\ell^-\ell'^+\ell'^-$ events should be seen during the next run.

It has recently been pointed out^{45),46)} that for any colour singlet scalar produced by gluon fusion, the unitarity bound on the production cross-section $\hat{\sigma} < (\pi/16m_\phi^2)$ makes it unlikely that any such scalar heavier than 100 GeV is responsible for the $\not{p}_T$ events. For instance, from Fig. 9, an 80 GeV scalar with a 10 GeV width has $\sigma(p\bar{p} \rightarrow \phi) \sim 10$ nb, so that about 10 non-gluonic decays could be expected with 100 nb^{-1} . The number of events falls rapidly with m_ϕ .

(2) A new gauge interaction

The monojet events could be due to a completely new confining gauge interaction. Many versions of this game can be played according to the strength of the new gauge coupling and the masses of fermions carrying this new quantum number. We consider the case of "odour"⁴⁷⁾, a proposed interaction with $\Lambda_0 \sim \Lambda_{\text{QCD}}$ and with the lightest odour quark O having a mass ~ 75 GeV.

A spectrum of odouronium $O\bar{O}$ bound states between 150 and 300 GeV is expected. It is necessary in this scheme that the cross-section for producing such states be ~ 1 nb. A perturbative estimate gives about a factor of 100 less for colour-triplet odour quarks. These states decay by soft gluon (g) and odour gluon (G) emission so that statistically one quarter end up in the lowest O^- state, and three quarters in the lowest 1^- state. Table 3 gives our expectations for the number of events with specific decay modes which would have occurred at UA1. These rough estimates use $\alpha_s \sim \alpha_0 \sim 10\alpha \sim 10\alpha_H$, where α_H describes the Higgs coupling to the odour quark. Without knowing the $SU(2) \times U(1)$ quantum numbers of O , we have assumed decay rates to the Z to occur at $(\alpha_2/\alpha) \sim (1/\sin^2\theta)$ compared to photons.

The bump in the jj cross-section reported by UA2⁵⁾ at 150 GeV could be explained - providing an even larger bump occurs in the jjj cross-section at the same mass. The monojet events are assumed to be the decay of the 1^- to ZH with $Z \rightarrow \nu\bar{\nu}$. It is possible that some of the $j\not{p}_T$ and $jj\not{p}_T$ events in Fig. 4 which lie close to the 4σ cut are also ZH or ZGG decays of the 1^- odoronium state. If the odoronia states were ~ 130 GeV, as originally proposed, we consider it unlikely that they would give quite such spectacular events, although boosting their mass

to 150 GeV decreases their production rate. Similarly, the interpretation of the γp_T event as $0^- \rightarrow Z\gamma$ with $Z \rightarrow \nu\bar{\nu}$ favours the higher mass for the odoronium ground state.

An original motivation for odour was that $l^- \rightarrow Zgg$ could explain the excess of jet activity in the UA1 Z events compared to their W events. We mention that the Z and W production rates are consistent with expectations, but it is not ruled out that 50% of the observed Z's and W's have an unconventional source.

The Higgs must be light in this scenario. If it were lighter than twice the b quark mass, the monojets would be $H \rightarrow \tau\bar{\tau}$ or $c\bar{c}$. The $H \rightarrow \tau\bar{\tau}$ decay would explain the low invariant mass and charged multiplicity of the monojets, but it becomes less likely that they will have such large values for E_T , since τ decays involve substantial missing energy. The $H \rightarrow c\bar{c}$ decay would not yield monojets of low charged multiplicity.

The new odour interaction gives many interesting new signatures. It is possible, but surprising, that the monojets have such large E_T and small invariant masses and multiplicities. The copious production of a 150 GeV object is a little troublesome, but there are many bumps at 150 GeV to search for: jjp_T , γj or γjj .

It has been pointed out to us⁴⁸⁾ that at least five e^+e^- and five $\mu^+\mu^-$ events would be expected from the l^- decay. The absence of any such events may provide a challenge to model builders developing the idea of a fifth force.

(3) Coloured octet mesons

In the introduction to this chapter, we stressed that many of the events listed in Table 1 are consistent with the production of a 160 GeV state. In the previous two sections, we have seen that attempts to produce such a state via gg fusion have led to insufficient rates, especially for the Higgs case. It has been suggested that these problems can be overcome by producing a mesonic state, predominantly via $q\bar{q}$ fusion, which is a colour octet⁴⁹⁾. The first advantage with this idea is that the $u\bar{u}$ differential luminosity at $\sqrt{s} = 540$ GeV and $M = 160$ GeV is six times larger than that of gg. The second advantage is that decay channels involving a weak boson (such as gW , gZ , $g\gamma$) have a rate which is only down by one power of α/α_s compared to the leading decay channel. In the case of the Higgs, the decays of interest were down by $(\alpha/\alpha_s)^2$ compared with the dominant

decay mode. Finally, a colour octet meson is preferred to a colour singlet, because for a given partial width to $\bar{q}q$, the production cross-section is a factor of 8 larger for the octet case.

The origin and structure of this postulated meson, M_8 , are not important to the present discussion. We will follow Ref. 49) and assume it to be a $J^P = 0^-$, $SU(3)$ octet, $SU(2)_L$ triplet state, seen as a pole singularity in short-range $\bar{q}q$ scattering amplitudes. It would be expected to have a width dominated by $\bar{q}q$: $\Gamma(M_8 \rightarrow \bar{q}q) \sim \alpha_s^2 M \sim 2 \text{ GeV}$, so that it decays inside the confinement scale. Knowing its $\bar{q}q$ width, and mass $M = 160 \text{ GeV}$, one can estimate⁴⁹⁾ that the M_8 production at the CERN collider was approximately one third of the W production rate. This is not a firm number, and in Table 4 we have assumed equal W and M_8 production rates. Drell-Yan production rates for the W and Z are shown for comparison. From the last three lines, one finds very encouraging results: four monojets, two or three $e j \cancel{p}_T$ events, and a 15% rate for jetty Z production. There are two apparent difficulties, however: there is an order of magnitude too many events in the jj bump, and there are 100 dramatic γj events. These latter events (they also occur in heavy neutral lepton and excited quark schemes, which are discussed below) have not been observed by UA1, as can be seen from Fig. 3 of Ref. 1). It has recently been proposed that coloured octet mesons expected in some composite models yield monojet signatures⁷⁸⁾.

(4) Neutral heavy leptons

The previous three explanations have assumed the $\cancel{p}_T$ to be $Z \rightarrow \nu\bar{\nu}$, where ν is a conventional neutrino. It has been suggested that the $\cancel{p}_T$ could be carried away by a fourth sequential neutrino^{50),51)} of mass $\sim 2 \text{ GeV}$, or by a mirror neutrino⁵⁰⁾⁻⁵²⁾. Sequential neutrinos, pair-produced by $Z \rightarrow \nu_4 \bar{\nu}_4$, could travel a mean distance of $O(1 \text{ metre})$ before decaying to $\gamma \nu_\tau$. It is possible that one of the pair would decay within the detector and one outside, yielding the monoshower event. Since the mean distance travelled is proportional to $m_{\nu_4}^{-6}$, the mass must be chosen very carefully for this to be reasonable. If more monoshower events are seen at CERN, this explanation predicts $\gamma \gamma \cancel{p}_T$ events with $m(\gamma \gamma \cancel{p}_T) < M_Z$.

A fourth sequential neutrino can also decay by tree-level W exchange to $\tau \nu_\chi \bar{\ell}$ or to $\tau q \bar{q}$. Here we assume for illustration that ν_4 mixes mainly with ν_τ . This decay will dominate the one-loop $\gamma \nu$ mode unless it is phase space suppressed, in which case the decay of one ν_4 from Z decay within the detectors could yield a monojet signature. However, this is an unlikely explanation, even for the three monojets with kinematics consistent with Z decay. Since ν_H is expected to travel

some distance before decay, the monojets would not be expected to have charged tracks all the way to the inside of the central detector.

Although a fourth sequential neutrino could lead to an $\ell^+\ell^-\gamma$ signature⁵⁰⁾: $Z \rightarrow \nu_4 \bar{\nu}_4$, $\bar{\nu}_4 \rightarrow \bar{\nu}\gamma$, $\nu_4 \rightarrow \nu_\ell \ell^+\ell^-$, this would have a low mass $\ell^+\ell^-$ pair recoiling against a γ , with probable $\cancel{p}_T$.

It is not necessary to assume a detectable ν_4 lifetime if the decay $\nu_4 \rightarrow \nu\bar{\nu}$ can occur. One way to ensure this is to assume $\nu_4 = \nu_M$, a mirror neutrino. The mixing of ordinary and mirror neutrinos would allow neutral current decays $\nu_M \rightarrow \nu\bar{\nu}$, as well as $\nu_M \rightarrow \nu + \text{hadrons}$, $\ell\bar{\ell}\nu$ and $\ell + \text{hadrons}$. Thus $Z \rightarrow \bar{\nu}_M \nu_M$, with $\bar{\nu}_M$ decaying invisibly, and $\nu_M \rightarrow \nu j(s)$, $\ell j(s)$, or $\ell'\bar{\ell}\nu_\ell$ gives rise to monojets. The event rate is plausible⁵²⁾ and the narrow jets favour a mass of a few GeV for ν_M .

In future runs, the sequential⁵⁰⁾ and mirror⁵²⁾ neutrino schemes can be differentiated. The long-lived sequential neutrino has a sizeable radiative decay so that we should see γj , $\gamma\ell$ events. Also the charged tracks in these and further monojet events should originate well away from the beam pipe. This contrasts with the shorter-lived ν_M , which gives $j\cancel{p}_T$ and jj events having charged tracks passing through the entire central detectors. The jets from both schemes have a high leptonic component.

There are still many of the unusual events left unclarified by these simple heavy lepton schemes. Many of them can be explained, event by event, by introducing more structure. The spectacular monojet (event A) could be explained by $Z' \rightarrow \nu_R \bar{\nu}_R$ with subsequent ν_R decays⁵²⁾. Here Z' is the neutral gauge boson of $O(10)$ which is not in $SU(5)$. Some of the dimuon events seen by UA1²⁾ could be due to other decays of ν_R ⁵²⁾. In particular, like-sign dimuons can result if ν_R has a Majorana mass. For further decays of ν_R to yield any of the UA2 $ej(s)\cancel{p}_T$ events would require ν_R to be quite heavy.

(5) Excited quarks⁵³⁾

Motivated in part by the excited lepton model for $\ell^+\ell^-\gamma$ events, the authors of Ref. 53) suggested that the production and decay of a heavy excited quark, q^* , could produce anomalous events at the CERN collider. Many variations are possible, but to be definite we follow Ref. 53) and assign q^* to a colour 3, flavour

doublet with charges $2/3$ and $-1/3$. We take $M(q^*) \approx 150$ GeV. There is little advantage in other assignments. The q^* is assumed to be produced by $q\bar{q}$ fusion via the operator

$$\frac{g_s}{2\Lambda} \bar{q}^* \sigma^{\mu\nu} q_\nu \frac{\lambda^a}{2} q G_\mu^a + h.c. \quad (4.1)$$

with g_s the colour coupling and $G^{\mu a}$ the gluon vector potential. A natural choice for Λ is a compositeness scale, which might also be $M(q^*)$. q^* decay occurs via gauge boson emission: $q^* \rightarrow qg, q\gamma, qZ$ and qW . The decay is assumed to occur via operators analogous to (4.1), suitably modified to preserve $SU(2) \times U(1)$:

$$\frac{g}{2\Lambda'} \bar{q}^* \sigma^{\mu\nu} q_\nu \frac{Y}{2} q_L \bar{W}_\mu + \frac{g'}{2\Lambda'} Y \bar{q}^* \sigma^{\mu\nu} q_\nu q_L B_\mu + h.c. \quad (4.2)$$

where $Y = 1/6$. For $\Lambda = \Lambda' = M(q^*)$, the anticipated number of events for 137 nb^{-1} are shown in Table 5⁵³⁾.

Although there are signatures for event categories I and II as well as the jj bump at 150 GeV, there are several rate problems. To obtain sufficient $j\cancel{p}_T$ events, we must increase the production rate by a factor of ~ 100 . This would correspond to $\Lambda \sim 15$ GeV, which is disturbingly low, as other high dimension operators with the same scale (e.g., $\bar{\lambda}\lambda\bar{q}q$) are excluded by present data²⁵⁾. Such a Λ makes the jj bump at 150 GeV unacceptably large - the only possibility is to increase the coefficient of (4.2) relative to (4.1). For example, if Λ is taken to be ~ 50 GeV, and $\Lambda' \sim 15$ GeV, then one obtains the following number of events: 80(jj), 20($j\gamma$), 4($j\cancel{p}_T$) and 4($j\cancel{p}_T$). The number of $j\gamma$ events is still unacceptably large; however, it would be reduced to five events if the q^* was of charge $-1/3$ rather than $2/3$.

In conclusion, it appears possible, but somewhat contrived, to obtain $j\cancel{p}_T$, $j\cancel{e}\cancel{p}_T$ and a jj bump at 150 GeV from excited quarks. The next run at the CERN collider should then not only confirm the jj bump, but also find a spectacular $j\gamma$ bump at the same mass.

(6) Supersymmetry^{54),55)}

A missing transverse energy signature has been recognized as a signal for the production of supersymmetric partners of the known particles, both at e^+e^- colliders⁵⁶⁾ and at $p\bar{p}$ colliders^{57),58)}. The most favoured supersymmetric phenomenologies have an unbroken R parity ensuring the stability of the lightest superpartner, taken to be the photino $\tilde{\gamma}$. This neutral particle, which interacts with strengths similar to that of the neutrino, is expected to carry off missing transverse energy. However, the observed events with large p_T do not fit neatly into previous expectations. For example, the monojets have small invariant masses, unlike the predicted "Zen" events⁵⁷⁾. "Zen" events result from $W \rightarrow \tilde{\omega}\tilde{\gamma}$, $\tilde{\omega} \rightarrow q\bar{q}\tilde{\gamma}$ (the $\tilde{\omega}$ and $\tilde{\gamma}$ are the lightest charged and neutral eigenstates of the gaugino-Higgsino mass matrix). The two jets from q and $\bar{q}$ (which may coalesce into a single broad jet) recoil against p_T . Those $j\cancel{p}_T$ and $jj\cancel{p}_T$ events, which UAI report close to their 4σ p_T cut, could be Zen events if $m_T(j(s)\cancel{p}_T) < M_W$. Further analysis with more statistics is necessary to place a limit (value) on the $\tilde{\omega}$ mass, and to distinguish these events from the decay of W to a fourth sequential lepton pair.

Nevertheless, supersymmetric models have a great deal of structure, and we know of five possible sources of monojets arising in a variety of supersymmetric models. These correspond to production of $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}^+$, $\tilde{q}$, $\tilde{q}\tilde{g}$ and even $\tilde{\gamma}\tilde{\gamma}$. We comment on each of these in turn.

It has been realized for some time that the CERN collider would pair-produce light gluinos copiously⁵⁹⁾. Indeed, isolated $\cancel{p}_T$ signatures have been proposed for gluino searches up to a mass of 50 GeV⁶⁰⁾. However, it has only recently been realized that gluino^{60),61)} and squark⁶²⁾ pair production yields monojet events under the UAI event selection criterion. At first this is surprising, since $\tilde{g} \rightarrow q\bar{q}\tilde{\gamma}$ and $\tilde{q} \rightarrow q\tilde{\gamma}$ would naively lead to $4j\cancel{p}_T$ and $jj\cancel{p}_T$ events. The crucial point is that the number of expected jets can decrease because

- (a) events with large p_T tend to have fewer apparent jets, because some jets do not pass the $p_T > 10$ GeV cut, or
- (b) two jets are coalesced into one if close in azimuth (ϕ) and rapidity (y):
 $(\Delta\phi)^2 + (\Delta y)^2 < 1$.

To illustrate point (a), consider (light) squark-antisquark decay in the pair's rest frame. When the two photinos have comparable energies there is no $\cancel{p}_T$

signature. When one photino is much more energetic, there is a p_T signal and one quark jet is very soft, yielding a jp_T signature. It is important that monojets result from (a) rather than (b), as the latter leads to a jet of large invariant mass. For production of both squark and gluino pairs, it is crucial to ask: what fraction of the predicted monojets have more than a single primary quark in them? If the sparticles are produced at rest, selection of large p_T will favour more than one primary quark in the monojet. However, this need not be the case for sparticles produced with large speeds. Recent work shows that the majority of monojets from $\tilde{g}\tilde{g}$ pair production have more than one primary parton⁷⁷⁾, and the same is true for the highest p_T monojets from $\tilde{q}\tilde{q}^+$ production⁷⁸⁾.

The p_T spectrum arising from $\tilde{q}\tilde{q}^+$ production is harder than from $\tilde{g}\tilde{g}$ production⁶²⁾, so that $\tilde{q}\tilde{q}^+$ is preferred. However, most models do not give squarks much lighter than the gluino^{63),64)} so it is likely that both mechanisms contribute.

The predicted jp_T and jjp_T rates for various squark masses, assuming the UA1 selection criteria, are shown in Fig. 10. Squark masses much below 35 GeV are ruled out by the observed monojet rate, and similar limits apply to the gluino mass. The predicted p_T distribution of monojets and dijets from the source, for various squark masses, is compared with the data in Fig. 11. The fit is quite good for five degenerate squark flavours of mass 40 GeV. However, certainly monojet A, and probably monojet B, together with the $3jp_T$ event, are left unexplained. They could be large p_T fluctuations of this process, or maybe they are due to some other physics. Similarly, the monoshower can only be explained from this source if the charged multiplicity of the jet fluctuates to zero.

Although a gluino between 15 and 25 GeV appears to be ruled out by jjp_T data [see Ref. 64) for a discussion], it is possible that a gluino between 3 and 15 GeV could lead to single squark production via $\tilde{g}q \rightarrow \tilde{q}$. The resulting jp_T signature from $\tilde{q} \rightarrow q\tilde{\gamma}$ was predicted some time ago⁶⁵⁾.

This mechanism could account for the observed number of monojets, even if $m_{\tilde{q}} \sim 150$ GeV⁶⁶⁾. This is most interesting, because the dominant $\tilde{q}$ decay is to $q\tilde{g}$, giving the squark a width of $O(10)$ GeV and providing $O(80)$ jj events at 150 GeV, as seen by UA2. Furthermore, the decay $\tilde{q} \rightarrow \tilde{u}q$ followed by $\tilde{u} \rightarrow W\tilde{\gamma}$ (as expected for the heavier of the two Dirac charginos) and $W \rightarrow e\nu$ yields ejp_T and a possible explanation of the spectacular UA2 event B shown in Fig. 5. If both squarks and gluinos are near to the mass limits mentioned earlier, it has been pointed out that excitation of the supersymmetric sea of the proton could lead to monojets via such processes as $\tilde{g}q \rightarrow \tilde{\gamma}g$ ⁶⁷⁾. Using sea distributions valid for

the infinite Q^2 limit gives large event rates, but it would be interesting to know the dependence on $m_{\tilde{g}}$ and $m_{\tilde{q}}$. If the gluino structure functions resemble those for heavy quarks (such as t) in the proton⁶⁸⁾, they come nowhere near being able to account for the observed rates.

It should be noted that there are alternative supersymmetric scenarios for monojets^{69),77)}. If the gluino mass were in the 3-15 GeV window, squarks could be produced singly, even if their mass were as large as 100 GeV: $gq \rightarrow \tilde{g}q$. The gluino is often soft and missed, and the $\sim 1\%$ branching ratio for $\tilde{q} \rightarrow q\tilde{g}$ would yield the monojet signature. For events with large p_T , the monojets have smaller invariant masses than with $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}^+ \rightarrow \text{monojets}$ ⁷⁷⁾. The Jacobian peak of the p_T spectrum is sufficiently smeared to accommodate the data.

A more speculative scenario for monojets is the pair production of 5-8 GeV $\tilde{\gamma}$'s. In one model in which R parity is broken, these photinos will decay to $\tau\tau\nu_\tau$ ⁷⁰⁾. The resulting jets will be thin, have low charged multiplicities and some will have charged leptons. The majority of events will appear as two-jet events, but occasionally one $\tilde{\gamma}$ will throw the ν_τ forward and the $\tau^+\tau^-$ pair will produce a jet with $p_T < 10$ GeV. Although an unlikely scenario, this yields low monojet multiplicities which will give a monoshower on fluctuating to zero charged multiplicity.

It has been pointed out that $ej(s)p_T$ event signatures could result from constituent processes: $q\bar{q} \rightarrow \tilde{\omega}\tilde{g}$ and $qg \rightarrow \tilde{\omega}q$ ⁷¹⁾. Rates for these processes are generically down by at least an order of magnitude compared to $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}$ and $\tilde{g}q$ production⁵⁵⁾. Optimal values for $\tilde{g}$, $\tilde{q}$ and $\tilde{\omega}$ masses could enhance the signal⁷²⁾. The $\tilde{\omega}$ would have to be quite light so that a $W \rightarrow \tilde{\omega}\tilde{\gamma}$ "Zen" signature should show up soon.

V. EXPLANATIONS OF DILEPTON EVENTS

Ten dimuon events (three same sign) with jet activity have been reported by UA1. At PETRA, the CELLO collaboration sees a spherical $\mu^+\mu^-jj$ event at $\sqrt{s} = 43.5$ GeV. One scheme for explaining the CELLO event^{73),74)} involves heavy neutrinos of mass $O(20 \text{ GeV})$ pair-produced from the decay of a Z' gauge boson of mass ~ 60 GeV: $e^+e^- \rightarrow Z' \rightarrow \nu_R \bar{\nu}_R$. Each neutrino then decays to a muon and a jet by mixing in the lepton sector.

The ten UA1 dimuon events are very diverse. Although they are characterized by high occurrences of strange particles, they vary greatly in their jet activity and in their invariant masses. Some could be due to new physics such as $Z' \rightarrow \nu_R \bar{\nu}_R$, but many are probably due to processes of the standard model which have a poor quantitative understanding. For example, it is possible that there is a large gluon fragmentation $g \rightarrow c\bar{c}, b\bar{b}$ occurring in energetic gluon jets, thereby enhancing the dilepton signal⁷⁵⁾. This gives essentially the same number of same-sign as opposite-sign dimuons. However, such a fragmentation is a phenomenological input, and is non-perturbative.

The possibility that the like-sign dimuons are due to $B^0\bar{B}^0$ mixing¹⁷⁾ was discussed in Section II. More statistics will confirm interesting standard model physics ($B\bar{B}$ oscillations, t quark), or demand a new physics explanation.

It has been suggested that the CELLO event is due to production of a pair of (scalar) leptoquarks⁷⁶⁾, each of mass ~ 20 GeV. Normally one would expect the production cross-section for a pair of scalar particles to behave as β^3 near threshold, and hence not to be appreciable at $\sqrt{s} = 43.45$ GeV. It is argued in Ref. 76) that because these leptoquarks are contained in (fermionic) hadrons, the cross-section can rise much more steeply near threshold.

The leptoquarks proposed in Ref. 76) carry colour, and can be produced in pairs in hadronic interactions. They should be visible in the dimuon event sample of UA1. It is possible that this sample may be used to place bounds on the existence of leptoquarks or, more optimistically, to discover them.

VI. CONCLUSIONS

A summary of our findings is presented in Tables 6 and 7. A glance at Table 6 is quite rewarding. Theorists have found the kinematics of the $\lambda^+\lambda^-\gamma$ events essentially impossible to explain. There must be some level of statistical fluctuation, and perhaps bremsstrahlung then appears to be the most probable source.

The events with large p_T are easier to invent explanations for; but few explanations have success with several event categories, and few explain the event topologies and rates in a natural way.

There are many ways of searching for, and distinguishing between, the new physics ideas reviewed here. One very prominent signature which should be searched for is γj . This is predicted by colour octet meson, excited quark and certain neutral lepton scenarios. In view of the low multiplicity in the monojets, it would be very interesting to know if there is any peak in the invariant mass spectrum of jj events where both jets have low multiplicity. Improved statistics are also essential and are eagerly awaited. No doubt some classes of event will not persist, while others will show further characteristics. Many of the ideas presented here may then fall by the wayside, but the remainder will be ripe for more detailed analysis.

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EVENT	#	GROUP	REF.	FEATURES	COMMENTS
I	6 0 1	UA1	1,2	Jets of low charged multiplicity and low invariant mass against large missing P_T .	If P_T cut is relaxed to 4σ limit: $j\bar{p}_T$ $j\bar{j}\bar{p}_T$ $>2j\bar{p}_T$
II	4	UA2	3	A hard e isolated from j(s).	In addition UA1 reduced sample of 43 events contains 2 with $q_T(W) > 22$ GeV.
III	2 1	UA1, UA2 UA1	4,5	EM shower isolated from lepton pair $m(\ell^+\ell^-\gamma) \sim M_Z$.	UA1 sees no radiative W decays. UA2 has one W $\rightarrow e\nu\gamma$ with e, γ nearly collinear.
IV	2	UA1	1,2	$E_\gamma = 53, 54$ GeV.	One event may be W $\rightarrow e\nu$ with missed charged track.
V	7 3	UA1	2	$6 \text{ GeV} < m(\mu\mu) < 22 \text{ GeV}$. Most events have j. Large abundance of K, Λ .	
VI	5	UA1	2,6	Hadronic activity associated with Z. Four events consistent with $m(Zj(s)) \sim 160$ GeV.	More j, larger E_T , larger n_{ch} than seen in W production, and expected from QCD.
VII	1	CELLO	8	$\sqrt{s} = 43.45$ GeV. Little missing energy. All pair invariant masses large.	MARK J has similar events under analysis.
VIII	6	MARK J	9	$\sqrt{s} = 46.5$ GeV. $E_{vis} \sim 30$ GeV. High sphericity.	Hadron distribution too coplanar for $t\bar{t}$ interpretation ($2-3\sigma$ level).

j(s) : hadron jet(s) (occasionally includes charged lepton).

$\bar{p}_T$: a substantial imbalance in the observed momentum transverse to beam.

γ : large EM shower with no charged track pointing to it.

Table 1 : Salient features of eight categories of unusual events

	$e^+e^- \gamma$		$\mu^+\mu^- \gamma$
	UA1	UA2	UA1
$m(\ell^+\ell^-\gamma)$	98.7 ± 5	90.6 ± 1.9	$88.4^{+46.1}_{-15.2}$
$m(\ell^+\ell^-)$	42.7 ± 2.4	50.4 ± 1.7	$70.9^{+37.2}_{-12.4}$
$m(\ell\gamma)_{\text{low}}$	4.6 ± 1.0	9.1 ± 0.3	5.0 ± 0.4
$m(\ell\gamma)_{\text{high}}$	88.5 ± 2.5	74.7 ± 1.8	$52.5^{+27.5}_{-9.3}$
$\theta_{\ell\gamma}$	14.4 ± 4.0^0	25.0 ± 1.0^0	7.9^0
E_γ	38.8 ± 1.5	24.4 ± 1.0	28.3 ± 3.0

Table 2 : Radiative Z^0 decays [from Ref. 7)]

1^- DECAY TO	EXPECTED EVENTS	POSSIBLE SIGNATURE
ggg	45	jjj bump at $m = 150$ GeV
GGG	45	odour glueballs: invisible
G^2g^3	$\frac{1}{2}$	} $j(s)\cancel{p}_T$
G^3g^2	$\frac{1}{2}$	
$ZH, Z \rightarrow \nu\bar{\nu}$	5	$j\cancel{p}_T$
$ZGG, Z \rightarrow \ell^+\ell^-$	1	$\ell^+\ell^-\cancel{p}_T$
$Zgg, Z \rightarrow \ell^+\ell^-$	1	$\ell^+\ell^-j(s)$
$ZGG, Z \rightarrow q\bar{q}$	10	$jj\cancel{p}_T$
$\gamma H, H \rightarrow b\bar{b}$	5 (unless $m_H < 2m_b$)	γj
γgg	5	γjj
$e^+e^-, \mu^+\mu^-$	> 5 each	high inv. mass $\ell^+\ell^-$
0^- DECAY TO	EXPECTED EVENTS	POSSIBLE SIGNATURE
gg	15	jj bump at $m = 150$ GeV
GG	15	odour glueballs: invisible
g^2G^2	1/7	$jj\cancel{p}_T$
$Z\gamma, Z \rightarrow \ell^+\ell^-$	1/20	$\ell^+\ell^-\gamma$ with $m(\ell^+\ell^-\gamma) = 150$ GeV
$HGG, H \rightarrow b\bar{b}$	1	$j\cancel{p}_T$
$Z\gamma, Z \rightarrow \nu\bar{\nu}$	1/3	$\gamma\cancel{p}_T$

Table 3

Decay modes and expected number of events for odoronium bound states in 1983 CERN collider run. Here g denotes a gluon and G an odour gluon. $\ell^+\ell^-$ includes e^+e^- and $\mu^+\mu^-$ contributions.

SIGNAL CHANNELS		W,Z CHANNELS FOR COMPARISON	
DECAY MODE	# EVENTS	DECAY MODE	# EVENTS
$M_8 \rightarrow \bar{q}q$	500	$W \rightarrow q\bar{q}$ $Z \rightarrow q\bar{q}$	500 100
$M_8 \rightarrow gW$	37	-	-
$M_8 \rightarrow gZ$	23	-	-
$M_8 \rightarrow g\gamma$	100	-	-
$M_8 \rightarrow gZ \rightarrow \nu\bar{\nu}$	4	-	-
$M_8 \rightarrow gW \rightarrow \nu e$	2.2	$W \rightarrow \nu e$	36
$M_8 \rightarrow gZ \rightarrow e^+e^-$	0.7	$Z \rightarrow e^+e^-$	4

Table 4 [based on the Table of Ref. 49)]

Signal and background rates for colour octet meson production in 1983 run of CERN collider.

		$\Lambda=\Lambda'=150 \text{ GeV}$	$\Lambda=50, \Lambda'=15 \text{ GeV}$
MODE	SIGNATURE	# EVENTS	# EVENTS
$q^* \rightarrow qg$	jj bump at 150 GeV	10	80
$q^* \rightarrow \gamma q$	j γ bump at 150 GeV	0.2	20
$q^* \rightarrow qW_{\rightarrow e\nu}$	j $\cancel{p}_T^e$	0.04	4
$q^* \rightarrow qZ_{\rightarrow \nu\nu}$	j $\cancel{p}_T$	0.04	4

Table 5

Expected numbers of events at CERN collider (137 nb^{-1}) for various excited quark decays [see Ref. 53)].

NEW PHYSICS EXPLANATION	REF.	III		IV
		$\ell^+\ell^-\gamma$		$\gamma\cancel{P}_T$
$Z \rightarrow \ell\ell^*$ $\hookrightarrow \ell\gamma$	23,24	☼	■	-
$Z \rightarrow X\gamma$ $\hookrightarrow \ell^+\ell^-$	27-31	☼	■	✓
$R \rightarrow \ell^+\ell^-\gamma$	22	☼ ✓		✓
$Z \leftrightarrow Q\bar{Q}$	33	☼	■	✓
COMPOSITE W AND Z	19,30 34-36	☼	■	✓
WW BOUND STATES	37	☼	■	✓

Table 6
Proposed explanations for $\ell^+\ell^-\gamma$ events.

- Comments: (1) all schemes fail to account for the Dalitz plot distribution; however, $R \rightarrow \ell^+\ell^-\gamma$ does the best in this regard.
(2) none of these schemes has an obvious mechanism for explaining any of the other events in Table 1.

Symbols :

- ☼ primary motivation
- ✓ qualitative explanation
- fails to give quantitative explanation
- ★ Quantitative explanation
- No obvious explanation

NEW PHYSICS EXPLANATION	REF.	I	II	III	IV	V, VII	VI	COMMENTS
		$j\bar{p}_T$	$e j(s) \bar{p}_T$	$\lambda^+ \lambda^- \gamma$	$\gamma \bar{p}_T$	CERN, CELLO $\mu\mu j(s)$	$Z j(s)$	
150 GeV HIGGS	44	$\star$ $\square$ $\star$	$\star$ $\star$ $\star$	-	$\star$ $\star$ $\star$	-	$\star$	No clear $j\bar{p}_T$ signal Rate assumed, and conflicts with unitarity
ODOUR	47	$\star$ $\star$ $\star$	-	-	$\star$ $\star$ $\star$	-	$\star$ $\star$ $\star$	Can explain UA2 jj bump at 150 GeV Predicts too many e^+e^- , $\mu^+\mu^-$ events at 150 GeV
COLOURED OCTET MESONS	49	$\star$ $\star$ $\star$	$\star$ $\star$ $\star$	-	$\star$ $\star$ $\star$	-	$\star$	Can explain UA2 jj bump at 150 GeV Rate good. Predicts $j\bar{p}_T$ events at 150 GeV
ν_4	50	$\bullet$ $\star$ $\square$	-	$\bullet$	$\star$ $\star$ $\star$	-	-	$\bullet$ - these signatures exist, but would not look like observed events
OTHER NEUTRAL HEAVY LEPTONS	50 51 52	$\star$ $\star$ $\star$ $\star$	-	-	$\star$ $\star$ $\star$	$\bullet$ $\star$	-	$\star$ - could be j with $n_{ch} = 0$ $\bullet$ - monojet A and $\mu\mu$ require Z' boson
EXCITED QUARKS	53	$\star$ $\star$ $\star$	$\star$ $\star$ $\star$	-	-	-	-	Predicts jj bump at $M(q^*)$
SUPERSYMMETRY	60-62 65-67	$\star$ $\star$ $\star$	$\star$ $\star$ $\star$	-	$\star$ $\star$ $\star$	-	-	$\star$ - could be j with $n_{ch} = 0$ $\bullet$ - monojet A unlikely

Table 7

Symbols : as for Table 6

FIGURE CAPTIONS

- Fig. 1 : The Dalitz plot for the three $\ell^+\ell^-\gamma$ events. E_2 is the energy of the lepton which has the smaller angular separation from the photon. M is the mean invariant mass of the events.
- Fig. 2 : The dimuon CELLO event at $\sqrt{s} = 43.5$ GeV. Pair invariant masses are tabulated in GeV. Energies are shown in GeV.
- Fig. 3 : A typical $O(\alpha^4)$ contributions to $\mu^+\mu^-jj$, together with the expected number of events plotted in bins of pair invariant masses [from Ref. 8)]. Observed event is marked by a cross.
- Fig. 4 : Scatter plot of missing p_T^2 versus E_T , showing all events whose missing p_T 's are greater than 4σ ($\sigma = 0.7 \sqrt{E_T}$), including mono-jet events, "photon" events and multijet events [from Ref. 1)].
- Fig. 5 : View in the plane transverse to the beam axes of the UA2 $e + \text{jet} + \text{missing } p_T$ events [from Ref. 3)].
- Fig. 6 : Transverse momentum distribution for W production. UA2 events A, B and C are shown.
- Fig. 7 : Dalitz plots for $\ell^+\ell^-\gamma$ events. $X_L = (m_L^2(\ell\gamma)/M^2(\ell^+\ell^-\gamma))$; $X_H = (m_H^2(\ell\gamma)/M^2(\ell^+\ell^-\gamma))$ [from Ref. 39)].
- Fig. 8 : Allowed invariant mass ranges for events A-H of the UA1 collaboration¹⁾, assuming p_T is $Z + \nu\bar{\nu}$ [from Ref. 6)].
- Fig. 9 : Unitarity bound for the process $gg + \phi \rightarrow gg$ in $p\bar{p}$ collisions for two gluon distribution functions (a) and (b). The dashed line denotes the QCD jj cross-section [from Ref. 45)].
- Fig. 10 : The total and topological cross-section for $\tilde{q}\tilde{q}^*$ production followed by $\tilde{q} \rightarrow q\gamma$ decay giving one- or two-jet final states with $p_T^{\text{miss}} > 4\sigma$, and fulfilling the UA1 trigger conditions [from Ref. 62)].

Fig. 11 : a) Comparison of the observed p_T^{miss} distribution for the monojet events taken from Fig. 2b of Ref. 1), with expectations from $\tilde{q}\bar{q}$ production. Note the events below 1000 GeV^2 are compatible with the estimated background⁴⁾.

b) The same comparison as in a), but for events of the multijet type.

Both taken from Ref. 62).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11a

Fig. 11b