INTERPRETATION OF UNUSUAL EVENTS FROM CERN AND DESY

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Abstract

Several classes of interesting and unusual events from the S$\bar{p}$pS and from PETRA are studied with two purposes in mind. Firstly, varieties of background within the standard SU(3)×SU(2)×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.

I. Introduction

The CERN SPS $\bar{p}p$ collider data taken up to 1983 have yielded more than 30 unexpected events in addition to those (W,Z,t candidates) anticipated. In e^+e^- interactions at the highest PETRA energies, unusual signatures also may be appearing. In this report we summarize consideration of these events by a working group of the LBL SSC Workshop on Electroweak Symmetry Breaking. For long-term planning, this exercise illustrates the surprises that arise when a set of detectors planned for one kind of physics encounters yet another. In the near term, we hope to aid critical assessment of the new physics interpretations of these events as further data are accumulated. To that end, we are preparing an expanded version of the present article [1].

Six classes of unusual events from the CERN SPS collider and two from PETRA were considered. We discuss the events themselves, and standard physics backgrounds to them, in Section II. Section III deals with proposals for explaining a class of radiative Z decays, while Section IV treats suggestions primarily motivated by events with large missing transverse momentum. Section V considers origins of dimuon events (in $\bar{p}p$ collisions) and both 2μ and certain 1μ events in e^+e^- annihilations. Conclusions are drawn in Section VI.

II. Events and Background

We summarize the events to be discussed [2-8] in Table I. These have been reviewed in Ref. [10,11]. We have not included all reported interesting new signatures, such as the 3σ bump in the multijet invariant mass distribution around 150 GeV seen by UA2 [12].

A. Apparent $Z\to\ell^+\ell^-\gamma$ decays

Each of the UA1 samples of 4 $Z\to e^+e^-$ and 5 $Z\to\mu^+\mu^-$ decays contains an event with a hard photon, such that $M(\ell^+\ell^-\gamma)\approx M_Z$. The UA2 sample of 8 $Z\to e^+e^-$ decays also contains one such event (see Table 1).

An important conventional source of these events is QED internal Bremsstrahlung. No other explanation is capable of reproducing the strong observed clustering in the Dalitz plot [Fig. 1]. This clustering expresses the small angle between the photon and one of the leptons; one lepton-photon invariant mass $m_{\ell\gamma}$ in Table II is low. The lepton energies in the Z^0 rest frame are:

$$E_i = \frac{M_Z}{2}\left(1 - \frac{m^2_{\ell_i\gamma}}{M_Z^2}\right) \quad (2.1)$$

External Bremsstrahlung (in which the lepton encounters material after being produced and then radiates) is unlikely since then $m_{\ell\gamma}$ would be extremely low.

The difficulty with an internal Bremsstrahlung explanation of the $\ell\bar{\ell}\gamma$ events is the high observed event rate. The UA2 collaboration has calculated the probability of observing an $e^+e^-\gamma$ event which is less likely than the event observed (and which leads to a signature of three separate electromagnetic energy depositions): $P(e^+e^-\gamma)$=1.0% per e^+e^- event. This would correspond to a probability of 8% for one such $e^+e^-\gamma$ event in the eight e^+e^- events observed. A parallel calculation based on a simulation program gives 13% for this last figure, or 25% if one adds together all configurations including ones in which one electron and the photon are not resolved.

TABLE 1
SALIENT FEATURES OF 8 CATEGORIES OF UNUSUAL EVENTS

EVENT	#	GROUP	REF	FEATURES	COMMENTS
$j\not{p}_T$ $jj\not{p}_T$ $>2j\not{p}_T$	6 0 1	UA1	2,3	Jets of low charged multiplicity and low invariant mass against large missing p_T	If p_T cut is relaxed to 4σ limit: $j\not{p}$ 17, $jj\not{p}_T$ 5, $>2j\not{p}_T$ 3
$ej(s)\not{p}_T$	4	UA2	4	A hard e isoloated from j(s)	In addition UA1 reduced W sample of 43 events contains 2 with $q_T(W)\gtrsim$22GeV
$e^+e^-\gamma$ $\mu^+\mu^-\gamma$	2 1	UA1 UA2 UA1	5,6	EM shower isolated from lepton pair $m(\ell^+\ell^-\gamma)$ ~M_Z	UA1 sees no radiative W decays. UA2 has one $W\to e\nu\gamma$ with e,γ nearly collinear.
$\gamma\not{p}_T$	2	UA1	2,3	Eγ=53,54 GeV	One event may be $W\to e\gamma$ with missed charged track.
$\mu^+\mu^-j(s)$ $\mu^\pm\mu^\pm j(s)$	7 3	UA1	3	6 GeV <m(μμ)< 22 GeV Most events have j. Large abundance of K,Λ.	
Zj(s) $\hookrightarrow \ell^+\ell^-$	5	UA1	3,7	Hadronic activity associated with Z. 4 events consistent with m(Zj(s))∿160 GeV	More j, larger E_T, large n_{ch} than seen in W production, and expected from QCD.
$\mu^+\mu^-jj$	1	CELLO	8	$\sqrt{s}$=4.5 GeV; Little missing energy; All pair invariant masses large.	Mark J has similar events under analysis.
μj(s)	6	MARK J	9	$\sqrt{s}$=46.5 GeV; E_{vis} ~30 GeV; High sphericity.	Hadron distribution too coplanar for $t\bar{t}$ interpretation (2-3σ level).

j(s): hadron jet(s) (occasionally includes charged lepton).
$\not{p}_T$: a substantial imbalance in the observed momentum transverse to beam.
γ : large EM shower with no charged track pointing to it.

The absence of isolated hard photons in W decay [5] implies $P(e\nu\gamma/e\nu) \lesssim 1/50$ (for isolated γ). The UA2 collaboration observes one event consistent with $W \to e\nu\gamma$ in which separate showers for e and γ cannot be resolved. The probability for this event to be external Bremsstrahlung has been calculated to be 4.5% [6].

B. Events with jet(s) or isolated photon and missing p_T

The UA1 collaboration [2] has drawn attention to six events with a jet (A-F in Fig. 2), two with a photon (G,H), and one with 3 or more jets (Δ), opposite large missing p_T. The finite coverage of the UA2 detector prevents a similar statement from UA2, but one candidate for a photon opposite missing p_T has been reported [12]. The UA1 events A-H are summarized in Table III.

The background from QCD jets (with one jet missed) falls quickly with missing energy and is very small for $\Delta E_M \sim 35$ GeV. One monojet event (F) is consistent for expectations for $W \to \nu\tau$ with $\tau \to \nu j$, and will be ignored henceforth. The remaining 5 monojet events A-E have

TABLE II
RADIATIVE Z^0 DECAYS

	$e^+e^-\gamma$		$\mu^+\mu^-\gamma$
	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	$70.9^{+37.2}_{-12.4}$
$m(\ell\gamma)_{low}$	4.6±1.0	9.1±0.3	5.0 ± 0.4
$m(\ell\gamma)_{high}$	88.5±2.5	74.7±1.8	$52.5^{+27.5}_{-9.3}$
$\theta_{\ell\gamma}$	14.4±4.0°	25 ± 1°	7.9°
E_γ	38.8±1.5	24.4±1.0	28.3 ± 3

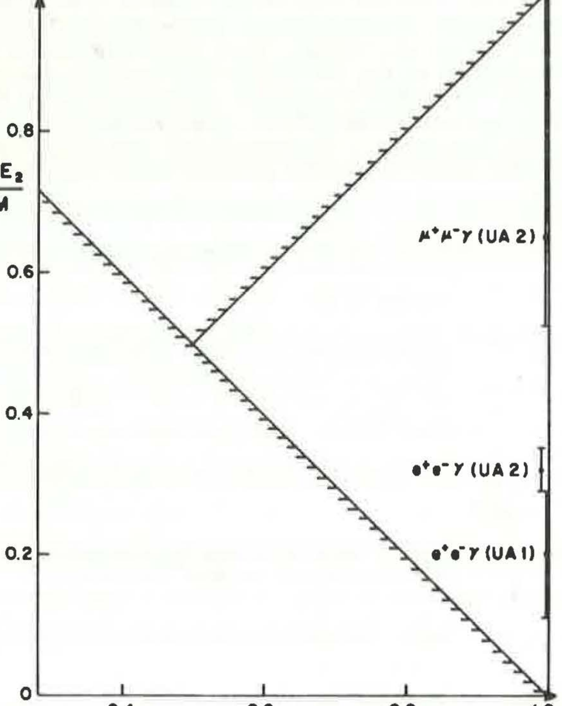


Fig. 1. Dalitz plot for $\ell\bar{\ell}\gamma$ events. E_2 is the energy of the lepton with smaller angular separation from the photon. M is the mean invariant mass of the events.

TABLE III

Properties of events with jet or isolated phonton and missing p_T. "Charged tracks" denote those with p_T 0.5>GeV/c.

	Event (Ref. 5)	j or γ E_T (GeV)	ΔE_M (GeV)	M_T(j or γ, ΔE_M) (GeV/c²)	COMMENTS
j	A	25(71[a])	24±4.8 (66±8[a])	130±16	a) Value if hard muon included in jet.
	B	48	59±7	106±12	Three charged tracks m_{eff}=0.79±0.12 GeV/c²
	C	52	46±8	97±17	E_T^{em}=44.4 GeV. One visible charged track.
	D	43	42±6	85±12	Four charged tracks. (two in K^0), m_{eff}= 3.14±0.38 GeV/c².
	E	46	41±7	87±14	Unreconstructed tracks.
	F	39	34±7	73±14	Possible $W \to \tau\nu$
γ	G	44	40±6	84±6	Possible $W \to e\nu$, e track missed.
	H	54	40±4	93±5	

been claimed inconsistent with this interpretation, though it is possible that the τ background was underestimated in Ref. [2]. If the $\tau \to (\geq 4\pi)\nu_\tau$ modes are sufficiently important, a background to events B-E of nearly 2 events of $W \to \tau\nu$ was estimated in Ref. [13]. Without a contribution from $\tau \to (\geq 4\pi)\nu_\tau$, however, the estimate drops to 0.6 event. The background to the events G, H is estimated to be negligible.

The single-shower event G has an azimuth angle $\phi \sim 0$ corresponding to an insensitive area of the central detector: the event may be $W \to e\nu$. The shower in event H, by contrast, occurs in a region where a charged track would be hard to miss.

The monojet events and those involving W + jet(s) (to be discussed below) have an $O(\alpha_s)$ background consisting of hard gluon Bremsstrahlung with $Z(\to \nu\bar{\nu}$ for monojets) or $W(\to \bar{\nu}e$ for $ej\not{p}_T)$. The transverse momentum distribution of W's in Drell-Yan production has been evaluated [13]; it is quite hard. A similar naive estimate gives a QCD monojet background of ~ 1 expected event for $q_T > 25$ GeV (6 observed) and $\sim 1/10$ expected event for $q_T > 50$ GeV (2 observed). These estimates are borne out by more complete calculations [14]. For the monoshower event, the background would be a hard photon Bremsstrahlung together with $Z \to \nu\bar{\nu}$. This is down by a further α/α_s, giving 0.01 expected event with $q_T > 50$ GeV.

We conclude that events A-E and H of Table III cannot be easily dismissed. With the exception of the open

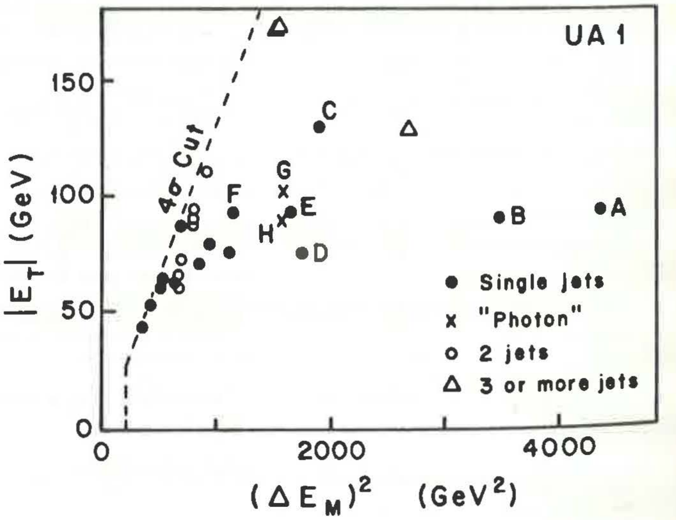


Fig. 2. Events with jet(s) or isolated photon and missing p_T. The dashed line corresponds to $p_T > 4\sigma$, $\sigma = 0.7\sqrt{|E_T|}$. Here $|E_T|$ is the scalar sum of the transverse energy in the detector. From Ref. [5].

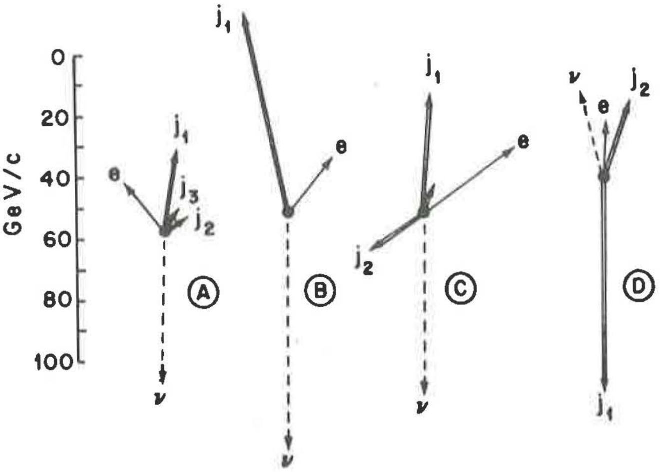
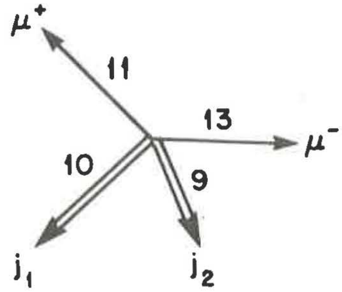


Fig. 3. UA2 events with e + jet(s) + missing p_T, viewed transversely [4].



	μ^+	μ^-	j_1
j_2	19	9	17
j_1	14	22	
μ^-	20		

Fig. 4. The dimuon CELLO event [8] at $\sqrt{s}$ = 43.45 GeV. Pair invariant masses and energies are shown in GeV.

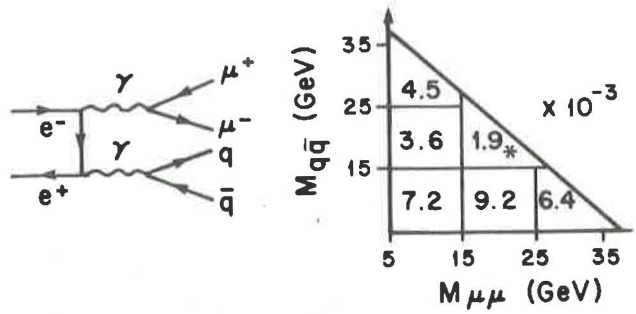


Fig. 5. The $O(\alpha^4)$ contributions to $\mu^+\mu^-jj$ together with the expected number of events plotted in bins of pair invariant masses (from [8]). Observed event is marked by a star.

question of some $W\to\tau\nu$ contamination in events B-E, the backgrounds to these events are all at least an order of magnitude below the observed rate.

C. Apparent W + hard jet(s) events

The UA2 group observes four events with e+jet(s)+ (missing transverse momentum), shown in Fig. 3 [4]. One of them [D] could be a heavy quark pair, followed by semileptonic decay of one of the quarks. This is not so for events A-C, for which the missing p_T lies opposite the electron direction. In fact these events are consistent with W+jet(s) followed by $W\to\nu e$.

On the basis of calculated W transverse momentum spectra [13], UA2 would expect ~1 event with q_T>25 GeV (they have 3: A-C) and ~0.1 event with q_T>50 GeV (event B). This suggests that event A could be QCD background, as noted in Ref. [4]. The UA1 collaboration would expect 1.5 of their sample of 43 "clean" $W\to e\nu$ events to have q_T>25 GeV. In fact, they have two events with 22<q_T<24 GeV [15], but none higher.

D. "Noisy" Z events

The UA1 collaboration has observed that Z production is accompanied by substantial jet activity. Of their sample of 4 $Z\to e^+e^-$ and 5 $Z\to\mu^+\mu^-$ decays, the fractions with (0,1,2,3) jets are (33%,11%,22%,33%). By contrast, their 68 $W\to e\nu$ candidates are accompanied by (0,1,2,3) jets (69%,24%,4.4%,2.9%) of the time [3,7]. The jets occurring with W production are found to agree with QCD expectations, so it is the high activity Z events which appear anomalous. (A signal of equal magnitude in W production could not be ruled out with present statistics, however.)

The calculations made for high-q_T production of Z referred to earlier are relevant here as well. Since one expects $B(Z\to\ell^+\ell^-)/B(Z\to\text{all } \nu\bar{\nu})\gtrsim 1/6$, the backgrounds are expected to be 1/6 of those to monojets.

E. Low-mass dimuons, sometimes with jets

The ability to identify muons has permitted the UA1 group to study a sample of 10 $\mu\mu$+jet(s) events, 7 with $\mu^+\mu^-$ and 3 with $\mu^\pm\mu^\pm$, having $m_{\mu\mu}$ between 6 and 22 GeV/c^2. [Other $\mu\mu$ events are consistent with Z production.] These low-mass $\mu\mu$ events are characterized by high occurrences of strange particles, and vary greatly in their jet activity and invariant masses. Many could be due to processes of the standard model only partially understood, such as gluon fragmentation to $c\bar{c}$, $b\bar{b}$, ... [16]. Heavy (b) quark pair production followed by semileptonic decays of both quarks may also play a role [17]. In this connection two of the three same-sign $\mu\mu$ events may be due to B_s^0-$\bar{B}_s^0$ mixing [17]. However [10], neither $b\bar{b}$ nor $c\bar{c}$ production mechanisms fit the kinematics of several of the events.

One $\mu^-\mu^-$ event could be due to $W^-\to\bar{t}b$, $\bar{t}\to\mu^-+\ldots$, $b\to\mu^-+\ldots$. (Some jets in this event must then not have come from the W). Similarly, it is not excluded that one or more $\mu^+\mu^-$ events come from $W\to t\bar{b}$ or hadronic $t\bar{t}$ production [18]. The recent announcement of events compatible with $W\to t\bar{b}$, $t\to b\ell\nu$ [19] should allow more precise calculation of rates in dilepton channels. The UA1 detector will resume running in September, 1984 with enhanced muon detection capability, and the t signal will certainly be searched for in the dilepton channel [20].

F. CELLO $\mu\mu$ + 2 Jet event

Fig. 4 shows a sketch of an interesting event seen in e^+e^- interactions at $\sqrt{s}$ = 43.45 GeV [8]. The event cannot be interpreted as the semileptonic decay of t and $\bar{t}$ quarks because there is insufficient rise in R and no $t\bar{t}$ onium resonance. The data cannot rule out a fourth Q=-1/3 quark, but its semileptonic decay would be expected to yield much larger missing energy and momentum than seen.

This event does have a possible QED explanation. A dominant graph and its expected contribution are shown in Fig. 5. The CELLO collaboration claim a background of ~10^{-3} expected events [8] from such standard radiative processes. 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 its value near the observed event. In addition, it is tempting to ask what the probability is that the many PEP and PETRA detectors might have observed such an event so near the kinematic boundary. Since the process in Fig. 5 has a low threshold, and since these detectors have accumulated a great deal of integrated luminosity, the event then might appear not nearly as peculiar. Mark J has also seen events with μ pairs and jets, but the background analysis has not yet been completed [21].

G. Mark-J μ + (planar topology) events

The Mark-J group studied events of the form $e^+e^-\to\mu$+ (hadrons). When a cut on events with thrust<0.8 was applied, one expected a background of 1.1 events at the highest energy ($\sqrt{s}\gtrsim$46.5 GeV) by extrapolating from lower-energy data. Instead, 7 events were seen [22]. The hadronic activity in these events is predominantly confined to a plane which, however, does not contain the muon.

The study of these events is continuing, plagued by the difficulties of running PETRA at such high energies.

III. NEW PHYSICS IN $\ell\bar{\ell}\gamma$ EVENTS?

A. Excited leptons

The decay $Z\to\bar{\ell}\ell^*$, $\ell^*\to\ell\gamma$ is expected in some schemes of composite quarks and leptons. Several authors [23, 24] have ascribed the observed $\ell\bar{\ell}\gamma$ events to this process. The excited lepton is produced and decays via a transition magnetic moment operator of the form

$$\frac{1}{\Lambda}\,\bar{\ell}^*\sigma^{\mu\nu}\ell F_{\mu\nu} \qquad (3.1)$$

A small scale $\Lambda\lesssim 100$ GeV is needed to obtain sufficient rate. This is uncomfortably low in view of limits on other operators [25,26]. To be consistent with g-2 [27-29], further chiral constraints on couplings are necessary. The process $W\to\nu\ell^*$, $\ell^*\to\ell\gamma$ can be suppressed (forbidden) by making m_{ℓ^*} near (above) M_W.

The excited lepton scenario has severe difficulties with the Dalitz plot. Both the high and low $(\ell\gamma)$ 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-mass ℓ^* would have been seen at PEP or PETRA. It is then very improbable that the γ should be correlated with the prompt lepton to give such low invariant mass values. The operator (3.1) leads to an essentially flat distribution in this mass [24].

B. Scalar boson in Z decay

An alternative explanation of $\ell^+\ell^-\gamma$ events via Z decays involves the chain [30-34]

$$Z \to X\gamma,\quad X \to \ell^+\ell^- \qquad (3.2)$$

where X is a scalar or pseudoscalar boson. The observed $\ell^+\ell^-$ invariant masses are barely compatible with one another and with limits ($M_X\geq 47$ GeV) from Bhabha scattering [34,35]. A band at fixed $\ell^+\ell^-$ mass is expected in the Dalitz plot. A persistent feature of such schemes is the prediction of a large $X\to\gamma\gamma$ width, leading to the decay $Z\to 3\gamma$.

C. Scalar state $\to \ell\bar{\ell}\gamma$

It is possible that scalars expected in composite or technicolor schemes are heavier than the Z. In this case they could still yield the observed $\ell\bar{\ell}\gamma$ events provided their mass is less than $\sim$100 GeV [36]. In this scheme the scalar (or pseudoscalar) boson R is taken to have large couplings to fermions only if these couplings are chirally invariant. A class of dimension 7,9,... operators then arises which leads to matrix elements for $R\to\ell^+\ell^-\gamma$ 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. Operators in which ℓ is replaced by ν also occur, leading to mono-shower events.

The scale factor needed to obtain suitable production rates is, as usual, uncomfortably [26] low: $\Lambda\sim 100$ GeV.

In both X and R boson mechanisms, $q\bar{q}\gamma$ events are expected with $M(q\bar{q}\gamma)=M_Z$. Present data cannot exclude such events [3].

D. Z mixing with exotic quarkonium

The Z would appear to have anomalous decay modes if it was degenerate and mixed with some other state. One such model [37] envisages the Z mixing with an excited 1^{--} onium state of a quark with exotic color. This is assumed to decay to the lowest 1^{--} state of mass $\sim$50 GeV via emission of a hard photon to a 0^{++} state, followed by a soft (unobserved) 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.

This scheme has much in common with the X boson idea mentioned above. Moreover, it requires the binding of quarks with higher color representations to produce an extraordinary spectrum of states, with the lowest P state nearly degenerate with 1S and the Z nearly degenerate with 2S.

E. Composite W,Z

If the W and Z are composite [27,33,38-40], operators of the form $(G/\Lambda^2)\,F^{\mu\nu}\,Z_\mu\,\Box\,Z_\nu$ could occur. The branching ratio for radiative decays is then [38]

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

This is sufficient only if $G\gg 1$ for $\Lambda\lesssim M_Z$. One would then expect to see $Z\to q\bar{q}\gamma$ [41] or $Z\to q\bar{q}g$ (i.e., jjj) [39]. If Λ is so low [41], however, one would expect a momentum dependence of vector boson masses, deviation of ρ from unity, and W radiative decays at a large rate.

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 emphasized in Ref. 42 by comparing the Dalitz plot distributions of the data with that of Bremsstrahlung, the X boson, excited leptons, and a composite Z. Bremsstrahlung does the best, and a composite Z the worst.

A model with an effective $Z\gamma\gamma$ vertex [43] also has been proposed. It has the same difficulties with the Dalitz plot distribution.

F. WW bound states

It has been proposed [41] that for very heavy Higgs mass the resulting forces between longitudinal W bosons are strong enough to bind them into a state of mass $\sim$90 GeV. This state would then decay to a virtual $Z(\to e^+e^-)+\gamma$, in the manner of the R boson discussed earlier. The resulting eight-fermion operators coming from strong W-W interactions are conjectured to be responsible for same-sign multimuon events in neutrino scattering. One would also expect the 90 GeV state to decay to virtual $Z(\to\nu\bar{\nu})+\gamma$, giving the monoshower event(s), and to be produced in e^+e^- interactions via virtual Z exchange in association with a photon [44].

We believe the production rate for such a bound state is far too small to be relevant for the unusual events. For comparison, a 100 GeV Higgs boson is produced via W fusion with a quark subprocess cross section of less than 10^{-4} nb [45]. Quark luminosity factors reduce the $\bar{p}p$ cross section still more.

IV. NEW PHYSICS IN EVENTS WITH MISSING p_T?

A. Remarks on the 160 GeV mass region

Many of the unusual events we discuss seem to point to a common origin in the mass range of 160 GeV. (See in particular Ref. 7.) These include monojets (if interpreted as $j+Z$, $Z\to\nu\bar{\nu}$); monoshowers (if $\gamma+Z$, $Z\to\nu\bar{\nu}$), "noisy" Z events, and W + jet(s) events. This mass range will be more efficiently studied by raising the SPS energy ($\sqrt{s}$ = 630 GeV in the forthcoming run), and in particular at the Tevatron ($\sqrt{s}$ > 1.6 TeV). Meanwhile a cautionary note is that the selection of events containing W or Z (or their analysis as such), combined with cuts on a steeply falling p_T(jet) spectrum, can conspire to produce a peak.

B. Higgs bosons

It has been proposed that many unusual SPS events (ej(s)$\not{p}_T$, j$\not{p}_T$, $\gamma\not{p}_T$) come from decay of a 160 GeV Higgs particle [46]. The cross section must be enhanced by $\sim 10^6$ with respect to naive estimates in order to obtain a sufficient event rate ($\sim 10^3$ produced at CERN). This enhancement makes the Higgs boson so broad ($\Gamma \gtrsim 200$ GeV) that a peak is unlikely, and production violates unitarity [47,48].

C. New gauge interaction

As an example, we consider the case of "odor" [49], a proposed interaction with $\Lambda_O \sim \Lambda_{QCD}$ and with the lightest odor quark having a mass of $\sim$75 GeV. A spectrum of $O\bar{O}$ ("odoronium") bound states between 150 and 300 GeV is then expected. $O\bar{O}$ production leads almost exclusively to odoronium. It is necessary in this scheme for the $O\bar{O}$ cross section to be $\sim$1 nb. (A perturbative estimate falls short by about a factor of 100, for color triplet O quarks.) The observed events are then ascribed to specific products of $O\bar{O}$ annihilation, e.g.

$$O\bar{O}(1^-) \rightarrow Z\,H \quad (Z \rightarrow \nu\bar{\nu}) \quad : \quad j\not{p}_T \qquad (4.1)$$

$$O\bar{O}(0^-) \quad Z\,\gamma \quad (Z \rightarrow \nu\bar{\nu}) \quad : \quad \gamma\not{p}_T \qquad (4.2)$$

However, many other decay modes are expected, and it is not clear they all occur with consistent branching ratios. [See Table IV] Notable is the prediction [50] that approximately 10e^+e^- and $\mu^+\mu^-$ events would be expected from the 1^- decay. The jet-jet bump seen by UA2 [12] around 150 GeV should also appear in the 3j spectrum. It is not clear whether odor gluon (G) emission is visible; odor gluons should form odor glueballs (GG or GGG) which are invisible except via energy and momentum balance.

D. Color octet mesons

In the previous two sections we saw that attempts to produce a 160 GeV state have generally led to insufficient rates, especially for a Higgs boson. It has been suggested that these problems can be overcome by producing a mesonic state, predominantly via $q\bar{q}$ fusion, which is a color octet [51]. This idea takes advantage of the large $q\bar{q}$ differential luminosity (6 times larger for $u\bar{u}$ than for gg at $\sqrt{s}$ = 540 GeV and M=160 GeV), and allows for decay channels involving a weak boson (such as gW, gZ, gγ) at a rate down by only one power of α/α_s compared to the leading decay channel. Furthermore, for a given partial width to $q\bar{q}$, the production cross section for a color octet meson M_8 is 8 times larger than for a color singlet.

In Table V we show the number of events expected at the CERN collider if $\sigma(M_8)=\sigma(W)$. Drell-Yan production rates for the W and Z are shown for comparison. From the last three lines one finds 4 monojets, 2-3 $ej\not{p}_T$ events, and a 15% rate for jetty Z production. However, there are also an order of magnitude too many events in the jj bump, and 100 dramatic γj events. These latter should be searched for.

TABLE IV

1^- DECAY TO	EXPECTED EVENTS	POSSIBLE SIGNATURE
ggg	45	jjj bump at m=150 GeV
GGG	45	odor glueballs: invisible
G^2g^3	1/2	j(s) $\not{p}_T$
G^3g^2	1/2	j(s) $\not{p}_T$
ZH, $Z\rightarrow\nu\bar{\nu}$	5	j $\not{p}_T$
ZGG, $Z\rightarrow\ell^+\ell^-$	1	$\ell^+\ell^-$ $\not{p}_T$
Zgg, $Z\rightarrow\ell^+\ell^-$	1	$\ell^+\ell^-$ j(s)
ZGG, $Z\rightarrow q\bar{q}$	10	jj$\not{p}_T$
γH, $H\rightarrow b\bar{b}$	5(unless $m_H<2m_b$)	γj
γgg	5	γ j
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 MeV
GG	15	odor glueballs: invisible
g^2G^2	1/7	jj $\not{p}_T$
Zγ, $Z\rightarrow\ell^+\ell^-$	1/20	$\ell^+\ell^-\gamma$ with $m(\ell^+\ell^-\gamma)$=150 GeV
HGG $H\rightarrow b\bar{b}$	1	j $\not{p}_T$
Zγ, $Z\rightarrow\nu\bar{\nu}$	1/3	γ$\not{p}_T$

$\ell^+\ell^-$ includes e^+e^- and $\mu^+\mu^-$ contributions.

TABLE V. Decays of color octet mesons (based on Table of [51])

DECAY MODE	# EVENTS	DECAY MODE	# EVENTS
$M_8\rightarrow q\bar{q}$	500	$W\rightarrow\bar{q}q$	500
$M_8\rightarrow gW$	37	$Z\rightarrow q\bar{q}$	100
$M_8\rightarrow gZ$	23		
$M_8\rightarrow g\gamma$	100		
$M_8\rightarrow gZ$, $Z\rightarrow\nu\bar{\nu}$	4		
$M_8\rightarrow gW$, $W\rightarrow\nu e$	2.2	$W\rightarrow\nu e$	36
$M_8\rightarrow gZ$, $Z\rightarrow e^+e^-$	.7	$Z\rightarrow e^+e^-$	4

TABLE VI. Decay modes of an excited quark [from Ref. 56]

MODE	SIGNATURE	Λ=Λ'=150 GeV # EVENTS	Λ=50,Λ'=15 GeV # EVENTS
$q^*\rightarrow qg$	jj bump at 150 GeV	10	80
$q^*\rightarrow\gamma q$	jγ bump at 150 GeV	.2	20
$q^*\rightarrow qW$, $W\rightarrow e\bar{\nu}$	j$\not{p}_T$e	.04	4
$q^*\rightarrow qZ$, $Z\rightarrow\nu\bar{\nu}$	j$\not{p}_T$	.04	4

E. Neutral leptons

The previous three explanations have assumed $\not{p}_T$ to be $Z\rightarrow\nu\bar{\nu}$, where ν is a conventional neutrino. It is also possible that $\not{p}_T$ could be carried off by a heavy neutral lepton ν_H of a few GeV mass, such as a fourth sequential neutrino ν_4 [52,53] or a mirror neutrino ν_M [52-54], produced in the decay $Z\rightarrow\nu_H\bar{\nu}_H$.

A sequential neutrino ν_4 typically has neutral-current decays suppressed via the GIM mechanism. To give missing p_T, it must decay outside the detector. Its mass must be chosen very carefully for this to be reasonable. It could give monoshower events by occasionally decaying to $\gamma+\nu_i$ (i=e,μ,τ). In that case one would also expect $\gamma\gamma\not{p}_T$ events, with $M(\gamma\gamma\not{p}_T)\leq M_Z$. In many cases the neutrino ν_4 must decay inside the detector, giving rise to monojets with charged tracks originating some distance away from the interaction point.

For a mirror neutrino ν_M, the GIM mechanism is frustrated, and one expects [54,55] $B(\nu_M\rightarrow\nu\nu\bar{\nu})$=0.1, $B(\nu_M\rightarrow\nu$+hadrons)=0.2, $B(\nu_M\rightarrow\ell\bar{\ell}'\nu)$=0.2, $B(\nu_M\rightarrow\ell$+hadrons)=0.5, where ℓ is a charged lepton. The missing p_T signature is then expected to come from $\nu_M\rightarrow\nu\nu\bar{\nu}$. The monojets come from such decays as $\nu_M\rightarrow\ell$+hadrons. The low charge multiplicity in the observed monojets and their low effective mass (when all tracks are reconstructed) argues for $M(\nu_M)\lesssim$ (few GeV). The mono-shower events correspond in this scheme to a less likely decay such as $\nu_M\rightarrow\nu$+(all neutral hadrons).

In future runs the sequential [52] and mirror [54] schemes may be differentiated. The sequential neutrino is expected to have a sizeable radiative decay, so that γj, γℓ events should be seen. The charged tracks should in general originate a detectable distance from the beam pipe, reflecting the finite lifetime needed to account for events with missing transverse momentum. The scheme based on neutrinos with a $\nu\nu\bar{\nu}$ decay mode can account for monojets without finite lifetime effects, but predicts jj as well as $j\not{p}_T$ events in which j has a high lepton content. Both schemes have difficulty in accounting for the most spectacular $j\not{p}_T$ event ("A" of UA1) unless another Z is postulated [54].

F. Excited quarks

A model [56] which could account for anomalous events at the CERN collider postulates an excited quark q* belonging to a color 3, flavor doublet, with charges 2/3 and -1/3, and $M(q^*)\sim$150 GeV. The q-q*-gluon coupling is assumed to be of the anomalous moment type with scale Λ, and q-q*-(W or B) couplings are also assumed to exist (B is the boson of electroweak $U(1)_Y$) with scale Λ'. A natural choice for these scale factors would be a compositeness scale, which might also be M(q*). q* is produced by quark-gluon fusion and decays via $q^*\rightarrow qg, q\gamma, qZ, qW$. The expected number of events for $\int \mathcal{L}dt=137nb^{-1}$ are shown in Table VI [56].

Although there are signatures for $j\not p_T$, $j\not p_T e$, and jj events expected, there are rate problems if $\Lambda=\Lambda'=150$ GeV. It would seem necessary to lower $\Lambda=\Lambda'$ to 15 GeV to obtain a sufficient rate for $j\not p_T$ and $j\not p_T e$, but then the jj rate would be too high. Moreover, other high dimension operators with the same scale (e.g., $\ell\bar{\ell}q\bar{q}$) are excluded by present data [26]. The result of taking $\Lambda\neq\Lambda'$ is also shown in Table VI. The number of $j\gamma$ events is still large (shown for $Q(q^*)=2/3$). It would be reduced to 5 events if $Q(q^*)=-1/3$. Again (as for color octet mesons) the γj signature appears worth looking for.

G. Supersymmetry [57,58]

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^- colliders [59] and at $\bar{p}p$ colliders [60,61].

The most favored 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 $\not p_T$ do not involve the predicted broad jets [60] opposite this momentum which would result from $W\to\tilde{w}\tilde{\gamma}$, $\tilde{w}\to q\bar{q}\gamma$. Instead, the jets appear narrow. Any supersymmetric scenario must cope with this feature. We are aware of five variants, involving production of $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}^\dagger$, $\tilde{q}\tilde{g}$, $\tilde{w}\tilde{g}$ and even $\tilde{\gamma}\tilde{\gamma}$, upon which we now comment.

1,2. Gluino, squark pairs. The CERN collider can produce light gluino pairs copiously [62], and isolated $\not p_T$ signatures have been recognized as useful for gluino searches [63]. Gluino [64,65] and squark [66] pair production in fact yields monojet events under the UA1 event selection criteria, as a result of loss of soft jets or coalescence of two jets. The $\not p_T$ spectrum resulting from $\tilde{q}\tilde{q}^\dagger$ production ($\tilde{q}\to q\tilde{\gamma}$, $\tilde{q}^\dagger\to q^\dagger\tilde{\gamma}$) is harder than that from $\tilde{g}\tilde{g}$ production ($\tilde{g}\to q\bar{q}\tilde{\gamma}$) [65], and the jets are narrower, so $\tilde{q}\tilde{q}^\dagger$ is preferred. However, since most models do not give squarks much lighter than the gluino [66,67], it is likely that both mechanisms contribute.

The predicted $j\not p_T$ and $jj\not p_T$ rates for various squark masses, assuming the UA1 selection criteria, are shown in Fig. 6. Squark masses much below 35 GeV are ruled out by the observed monojet rate, and similar limits apply to the gluino mass. The spectacular monojet event "A" of UA1, and possibly the event "B", are left unexplained for a squark or gluino mass of 40 GeV, which otherwise fits the observed p_T distributions.

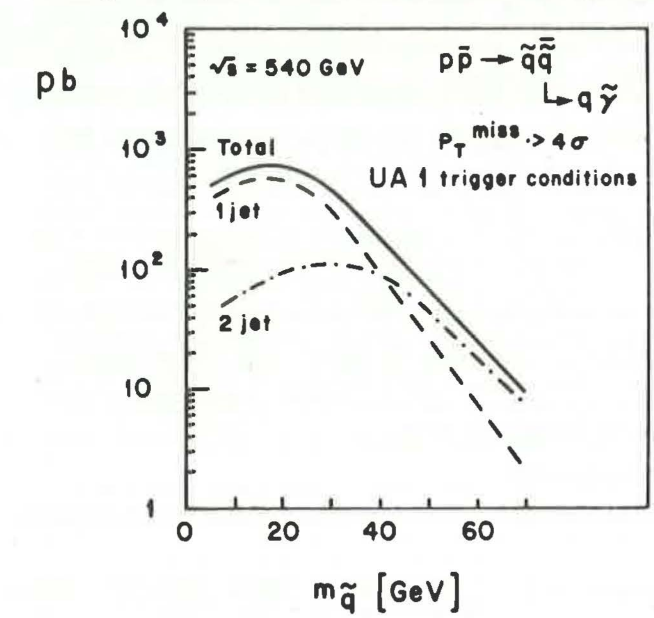


Fig. 6. The total and topological cross-section for $\tilde{q}\bar{\tilde{q}}$ production followed by $\tilde{q}\to q\tilde{\gamma}$ decay giving one- or two-jet final states with $p_T^{miss}>4$, and fulfilling the UA1 trigger conditions.

3. Singly produced squarks. The mechanism $\tilde{g}q\to\tilde{q}$ could lead to single squark production. One would require a gluino of about 25 GeV (a lighter $\tilde{g}$ seems ruled out by $jj\not p_T$ data [67]). The signature would be $\tilde{q}\to q\tilde{\gamma}$ [68]. This mechanism could account for the observed number of monojets, even if $m_{\tilde{q}}\sim150$ GeV [69]. The decay $\tilde{q}\to q\tilde{g}$ can provide a jj bump at 150 GeV, as seen by UA2 [12], and $\tilde{q}\to\tilde{w}q$, $\tilde{w}\to W\tilde{\gamma}$, $W\to e\nu$ yields $ej\not p_T$ and a possible explanation of the UA2 event "B" of Fig. 3. A related mechanism, $\tilde{g}q\to\tilde{\gamma}q$, has also been proposed as a source of monojets [70]. However, all these mechanisms require far more $\tilde{g}$ in the proton than one might expect for heavy quarks (such as t [71]).

4. Heavy squark, light gluino [72]. If the gluino were only slightly more massive than the photino it could escape the detector before decaying to $q\bar{q}\tilde{\gamma}$, thus frustrating the 25 GeV lower bound on its mass. In this case squarks could be produced singly even if their mass were as large as 100 GeV: $gq\to\tilde{g}\tilde{q}$. Presumably the monojet signature would come from $\tilde{q}\to q\tilde{g}$, where the energetic gluino is missed.

5. Photino pairs. One model with broken R-parity envisions production of a pair of 5-8 GeV $\tilde{\gamma}$'s, followed by $\tilde{\gamma}\to\tau\bar{\tau}\nu_\tau$ [73]. The monojets occur when one photino produces a fast ν_τ and a $\tau^+\tau^-$ pair with $p_T<10$ GeV, while the other throws the $\tau^+\tau^-$ forward. The monoshower event is viewed as a fluctuation to zero observed charged multiplicity of the $\tau\bar{\tau}$ decay products.

6. $\tilde{w}\tilde{g}$ production. The processes $q\bar{q}\to\tilde{w}\tilde{g}$ and $qg\to\tilde{w}\tilde{q}$ [74] can give $ej(s)\not p_T$ signatures. Rates for these processes are generically down by at least an order of magnitude compared to $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{q}^\dagger$, and $\tilde{g}\tilde{q}$ production [58]. Optimal values for $\tilde{g}$, $\tilde{q}$, and $\tilde{w}$ masses could enhance the signal [75].

H. Heavy quark

We note that one UA2 event of $e2j\not p_T$ ("C" of Fig. 4) is barely compatible with heavy quark pair production, $p\bar{p}\to Q\bar{Q}+\ldots$, $Q\to W+q$, $W\to e\nu$; $\bar{Q}\to W+\bar{q}$, $W\to q\bar{q}$ [76]. Here q has to be light ($m_q\lesssim$few GeV), which may not be favored if Q is the lightest member of a fourth generation [77].

V. MECHANISMS FOR $\mu\mu$ + jet(s) AND μ + (PLANAR EVENTS)

A. Leptoquarks

It has been suggested [78] that the CELLO event [8] is due to the reaction $e^+e^-\to L\bar{L}$, where L is a leptoquark which decays to μ + jet. This possibility can explain the apparent back-to-back nature of each μ + jet in the event. However, it entails large cross section for leptoquark pair production at the CERN collider. The observed 2μ + jet(s) signal mentioned in §II.E can be used either to bound leptoquark pair production, or to provide confirmation of the hypothesis.

B. Neutral heavy leptons

One possibility suggested for the CELLO event is the production of a pair of neutral leptons $\nu_H\bar{\nu}_H$, either via a virtual Z^0 [8,79] or via a new, weakly coupled "Z_x" in the 50-70 GeV range [79]. In the latter case, ν_H could be a right-handed neutrino "N" of the type described in Refs. [54,55]. The decays $Z^0\to\nu_H\bar{\nu}_H$ or $Z_x\to N\bar{N}$ should then be observable at the CERN collider. A Z_x (50-70 GeV) should also have an observable e^+e^- decay mode, and should affect electroweak asymmetries at PETRA. Both signatures will be visible in forthcoming improvements of present data.

A neutral heavy lepton, produced in pairs, also could be responsible for the Mark-J events discussed in §II.G. One neutral lepton would decay to μ+(hadrons) and the other to (say) $\ell\ell'\nu$ or ν+(hadrons).

C. Heavy quarks

The Mark-J events have some properties in common with semileptonic decays of heavy quarks. Possibly related features are that (i) the largest fluctuation in R occurs at $\sqrt{s}$=44 GeV, and cannot exclude the 1S bound state of a Q=-1/3 quark and its antiquark; (ii) R is sufficiently poorly measured above 45 GeV that one cannot exclude the threshold for a Q=-1/3 quark. Further study of the $\sqrt{s}$=44 GeV region is in progress, and will probably be able to settle the question of whether a new quark is responsible for the events in the near future.

VI. CONCLUSIONS

A summary of our findings is presented in Table VII and VIII. A glance at Table VII is quite rewarding. Theorists have found the kinematics of the $\ell^+\ell^-\gamma$ events essentially impossible to explain except as a statistical fluctuation of bremsstrahlung, which thus remains the most likely source.

It is easier to invent explanations for events with large $\not{p}_T$, but few ideas apply to several event categories at once, and few explain the event topologies and rates in a natural way.

Many explanations are based on new physics in the 160 GeV mass range, with characteristic γj and jj peaks expected at this mass. All would benefit from improved statistics, which are eagerly awaited.

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TABLE VII

NEW PHYSICS EXPLANATION	REF	III $\ell^+\ell^-\gamma$	IV $\gamma\not{p}_T$
$Z\to\ell\ell^*$, $\ell^*\to\ell\gamma$	23,24	☼ ◪	-
$Z\to X\gamma$, $X\to\ell^+\ell^-$	30-34	☼ ◪	✓
$R\to\ell^+\ell^-\gamma$	36	☼✓	✓
$Z^*\to Q\bar{Q}$	37	☼ ◪	✓
COMPOSITE W AND Z	29,33 38-40	☼ ◪	✓
WW BOUND STATES	41	☼ ◪	✓

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

Symbols:
- ☼ primary motivation
- ✓ qualitative explanation
- ◪ fails to give quantitative explanation
- ✶ Quantitative explanation
- \- No obvious explanation

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TABLE VIII

NEW PHYSICS EXPLANATION	REF.	I $j\not{p}_T$	II $ej(s)\not{p}_T$	III $\ell^+\ell^-\gamma$	IV $\gamma\not{p}_T$	V $\mu\mu j(s)$	VI $Zj(s)$	VII CELLO $\mu^+\mu^-jj$	VIII MARK I $\mu j(s)$	COMMENTS
150 GeV Higgs	46	☼ ◪	☼✓	-	☼✓	-	✓	-	-	No clear $j\not{p}_T$ signal. Rate assumed, and conflicts with unitarity.
ODOR	49	☼✓	-	-	✓	-	☼✓	-	-	Can explain UA2 jj bump at 150 GeV. Predicts too many e^+e^-, $\mu^+\mu^-$ events at 150 GeV.
COLORED OCTET MESONS	51	☼✓	✓	-	✓	-	✓	-	-	Can explain UA2 jj bump at 150 GeV. Rate good. Predicts $j\gamma$ events at 150 GeV.
ν_4	52	• ◪	-	•	☼✓	-	-	-	-	•These signatures exist, but would not look like observed events.
OTHER NEUTRAL HEAVY LEPTONS	53 54	☼✓ •	-	-	✓*	•	-	✓	-	*could be j with n_{ch}=0 •Monojet A and $\mu\mu$ require Z' boson
EXCITED QUARKS	56	☼✓	✓	-	-	-	-	-	-	Predicts jj bump at M(q*).
SUPER-SYMMETRY	68-70	✶ •	✓	-	✓*	-	-	-	-	*could be j with n_{ch}=0. •Monojet A unlikely.

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