CDFR/ANAL/EXOTIC/3571
Version 1.0
March 3 , 1996
Updated: March 21, 1996

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Minimal Zoosy: Four Events

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Abstract

In order to move toward quantitative comparisons with Monte Carlo, we try to characterize the kinematics of three events found in the inclusive $\ell\gamma\not{E}_t$ and $\gamma\gamma$ searches in terms of decay chains in a SUSY-like model, with a photino that decays to γHiggsino, inspired by the $ee\gamma\gamma\not{E}_t$ event. These three events, the $ee\gamma\gamma\not{E}_t$ event, the $\mu\mu\gamma\gamma\not{E}_t$ event, and the $e\gamma\not{E}_t j_{fat}$ event, are at (approximately) the predicted cross-sections and in reasonable decay modes in the model of Kane et al, but have (at least for two of them) small estimated cross-sections in the Standard Model. Using the 'zoo' events as 'signposts', we have begun to develop qualitative rules for parsing the zoo events in a cascade-decay framework; this process may be necessary to allow fixing enough of the free parameters so that tests of Monte Carlo predicted mass spectra in some channels versus the data can be made. We conclude that (in general) the 'zoo' events involving multiple leptons and photons are robust and can be taken seriously. Not all of them can be easily accomodated in the present understanding: we give the $ee\mu$ trilepton event in the top dilepton sample as a particularly difficult example.

1 Introduction

We present here an examination of four otherwise-bizarre multi-lepton and/or photon events as examples of selectron, smuon, and possibly stau production and decay. The individual particles are well-measured[1]. The three events from the inclusive $\ell\not{E}_t\gamma$ and $\gamma\gamma$ searches[1]

[1] A 25 GeV electron muon, or photon is measured to $\pm3\%$.

are made at approximately the cross-section predicted in a MSSM model[2]. The fourth event, chosen as a contrarian example, is the top trilepton event; the best we can do so far in parsing it still leaves it as rather unexpected in the model of Kane et al. There is (presumably) much more to be learned from the data about what is going on[1].

These four events are just some of a large number of well-measured but difficult-to-explain events in our data[3] that can be examined with a fresh eye. Much as in the case of the $ee\gamma\gamma\not{E}_t$ event, theoretical prejudice should be guided by the data (in this case we had been emphatically assured by many theorists that photons were not a good signature for supersymmetry). Once the bigger picture is clearer, detailed Monte Carlo comparisons of existing observed discrepancies in spectra with supersymmetric model predictions will be more meaningful. We see three phases to this work:

1. A qualititative close reading of the zoo events to establish the fundamental properties of whatever new phenomena are going on, including decay chains (such as $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$ postulated from the $ee\gamma\gamma\not{E}_t$ event) and mass relationships.

2. An identification of the 'golden' channels in which to look for statistically significant effects beyond the standard model predictions in spectra (i.e. not at the single-event level).

3. A quantitative comparison of observed discrepancies with beyond-the-SM Monte Carlos with input parameters determined from the first phase.

We understand that new phenomena are not to everybody's taste. We ask indulgence from the 'purists'; the initial methods that may be necessary to winkle out new physics and develop a fresh eye[4] may also be new and less comfortable than the usual.

2 Cascade Decay Chains and the Many Alternatives

We are just getting our feet wet (so to speak) in the murky business of parsing these zoo events in terms of SUSY[5] decay chains. We are certain that many if not most of the details of the decay chains offered here are probably wrong. But the process is instructive, and being really close to the data is a wise thing. This process is not yet systematic, but can be made so. The examples below represent our heuristic start on what may be a real process. Some specific hunches[6] we have are:

- The higher momentum objects statistically are favored to come out in the first generation of the cascade[2].

- The $\not{E}_t$, often coming at the end of the cascade, and often balanced between the two hemispheres (see below about high p_T production of pairs) can be quite low.

[2]Monte Carlo work is underway by Steve Mrenna at Argonne to make this quantitative.

- There are often several possible decay chains for a given signature: it will take putting together a coherent picture to sort these out.
- Chargino and neutralino pair production often offer possible decay chains.
- Some events have the topology of two highly-boosted relatively-light systems recoiling against each other, possibly signaling a new production mechanism. This mechanism seems to exist in the neutral current and not in the charged current.
- The 'cousin' method[7] is very powerful; postulated decay chains have specific predictive powers. The *absence* of predicted signatures is also information in a given model.

For an example of alternative possible decay chains, the $ee\gamma\gamma\not{E}_t$ event [1] could be produced through $\tilde{e}\tilde{e}$ pair production,

$$\tilde{e}\tilde{e} \to (e\tilde{\chi}_2^0)(e\tilde{\chi}_2^0) \to [e(\gamma\tilde{\chi}_1^0)][e(\gamma\tilde{\chi}_1^0)] \tag{1}$$

or through χ pair production, with the initial state being $\tilde{\chi}_i^+\tilde{\chi}_i^-$, where $\tilde{\chi}_i^+$ is either $\tilde{\chi}_1^+$ or $\tilde{\chi}_2^+$[8]. The charged χ's, which in the scheme of Kane et al [2] are each a mix of a gaugino and Higgsino, decay into sleptons: $\tilde{\chi}_i^+ \to \tilde{\ell}\nu$, and the slepton decays as before to $\ell\tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \to \gamma\tilde{\chi}_1^0$. An alternative production and decay chain involving $\tilde{\chi}_2^+\tilde{\chi}_2^-$ production[3] is thus:

$$\tilde{\chi}_2^+\tilde{\chi}_2^- \to (\tilde{\ell}_i\nu)(\tilde{\ell}_j\nu) \to (\ell_i\tilde{\chi}_2^0\nu)(\ell_j\tilde{\chi}_2^0\nu) \to (\ell_i\gamma\tilde{\chi}_1^0\nu)(\ell_j\gamma\tilde{\chi}_1^0\nu) \tag{2}$$

where ℓ_i can be e, μ, or τ. The null result of the search[1] for the $\tilde{e}\tilde{\nu}$ cousins of this event is consistent with this hypothesis, provided that $m_{\tilde{\chi}_1^0} < m_W$. Note also that the cross-section for χ pair production is an order of magnitude larger than for slepton pair production, although branching ratios are expected to be on order of 10%. One distinguishing feature is that χ pair channel will make dilepton events of different lepton generations (*e.g.* $e\tau$), as opposed to direct slepton pair production.

We have conjectured[1], based on very high energy events with Z's, γ's, and leptons (including four of the top dilepton events) that there are two production mechanisms for channels that couple to the neutral current: the normal Drell-Yan mechanism, and a new high mass neutral current amplitude (that we call Z'). The latter mechanism would produce light particles like the χ's in a distinctive high-$\mathrm{p_T}$ back-to-back configuration, with total visible energies in the 400-500 GeV range. Events with lower visible energies are (presumably) made by the normal mechanism. Some of the events below have very high total energies.

[3]From the questions to presentations at the Exotics Meetings it seems as if it cannot be repeated too many times that these are alternative possiblities that need to be quantitatively compared. We are *not* saying that $\tilde{\chi}_2^+$ production is favored over slepton production.

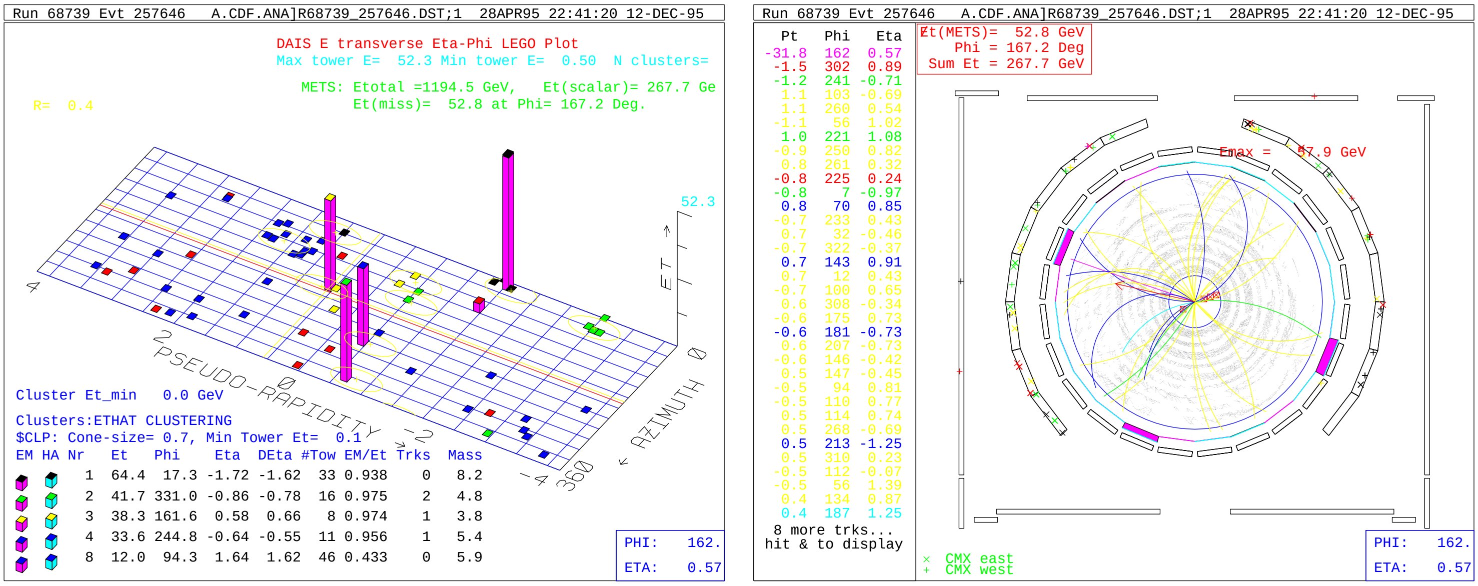

Figure 1: The lego and CTC plots for Run 68739/Event 257646.

3 The $ee\gamma\gamma\not\!\!E_t$ Event: R68739/E257646

The Lego and CTC plots for this event are shown in Figure 1. The kinematics of the event are consistent with Equation 1, which we propose as a possible alternative production process to slepton pair production for at least some of these events. The kinematics of the event are described in Table 1, and the pair-wise masses are compared to those of the $\mu\mu\gamma\gamma\not\!\!E_t$ event in Table 3.

Our best guess for the mechanism for this event is[1] $\tilde{e}\tilde{e}$ pair production,

$$\tilde{e}\tilde{e} \rightarrow (e\tilde{\chi}_2^0)(e\tilde{\chi}_2^0) \rightarrow [e(\gamma\tilde{\chi}_1^0)][e(\gamma\tilde{\chi}_1^0)]. \quad (3)$$

	P_x	P_y	P_z	E	E_T
e^+	58.75	18.44	-167.24	178.21	61.58
e^-	-33.41	11.13	21.00	41.00	35.21
γ_1	-12.98	-29.68	-22.69	39.55	32.39
γ_2	31.53	-17.48	-34.77	50.09	36.05
$\not\!\!E_t$	-51.40	12.12	—	—	52.81

Table 1: Kinematics of R68739/E257646. Energies are corrected.

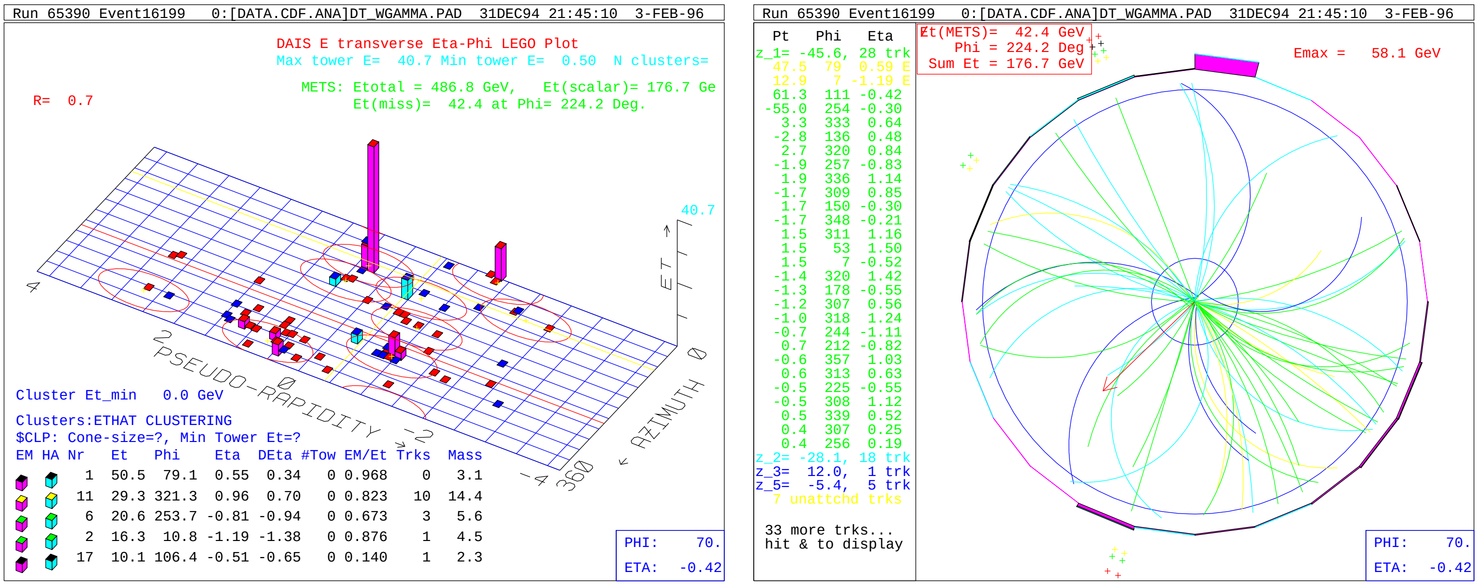

Figure 2: The lego and CTC plots for Run 65390/Event16199.

4 The $\mu\mu\gamma\gamma \not\!\!E_t$ Event: R65390/E16199

The $\mu\mu\gamma\gamma \not\!\!E_t$ event[1] is very similar to the $ee\gamma\gamma \not\!\!E_t$ event except that it has three central jets in addition to the two leptons, two photons, and $\not\!\!E_t$. The jets have E_T = 29.3, 20.6, and 10.1 GeV, respectively. The pair masses of the jets are m_{12} = 56 GeV, m_{13} = 43 GeV, and m_{23} = 28 GeV. The mass of the three jet system is 76 GeV. The Lego and CTC plots for this event are shown in Figure 2. The momenta of the various objects in the event (where we have taken $P_Z = 0$ for the $\not\!\!E_t$) are given in Table 2. We note again[1] that one muon fails the 6 GeV cut on Em+Had energy, although by less than a GeV (this is another cut that is too tight for searches.)

The jets are possibly worrying in an explanation of the event as Drell-Yan smuon pair production. They can be initial state radiation, but they are central, and the jet invariant masses are suggestive of W or Z bosons. We consequently ask if there is a mechanism that produces slepton pair production with jets.

If the smuon is heavy enough, the jets can be produced by slepton production as follows:

$$\tilde{\mu}\tilde{\mu} \to (\mu\tilde{\chi}_2^0)(\mu\tilde{\chi}_3^0) \to (\mu\gamma\tilde{\chi}_1^0)(\mu Z\tilde{\chi}_2^0) \to (\mu\gamma\tilde{\chi}_1^0)(\mu q\bar{q}\gamma\tilde{\chi}_1^0) \tag{4}$$

An alternative mechanism would be the production of a two charginos/neutralinos where one decays to $\tilde{\mu}\nu$ and the other decays to a mode containing a $\tilde{\mu}$ and a W or Z (depending on the charge of the parent) which then decays to the jets.

The invariant masses of this event are given in Table 3, as well as those for the $ee\gamma\gamma \not\!\!E_t$ event. Note that the pair masses of one of the combinations of the leptons and photons is essentially identical with one of the combinations of the $ee\gamma\gamma \not\!\!E_t$ event. One of the pairings

	P_x	P_y	P_z	E	E_T
μ^+	-20.19	53.00	-24.97	61.97	56.72
μ^-	-15.52	-52.46	-16.66	57.19	54.71
γ_1	9.38	48.82	29.70	57.91	49.71
γ_2	11.99	1.51	-20.87	24.12	12.09
$\not{E}_t$	2.09	-26.99	—	—	27.02
Jet_1	-8.73	-28.12	-29.77	42.01	29.54
Jet_2	16.41	-6.82	14.91	23.54	18.04
Jet_3	-4.21	13.60	-6.54	15.74	14.30

Table 2: Kinematics of R65390/E16199. Energies are corrected.

gives mass of 63 GeV and 52 GeV, to be compared with [1] masses of 63 GeV and 56 GeV.

We can calculate the masses of various objects in combination to get lower limits on sparticle masses, given some assumptions about the decay chain. Associating the jets with each $\mu\gamma$ pair in turn, we get M($\mu_1\gamma_1 jjj$)= 182.8 GeV and M($\mu_2\gamma_2 jjj$)= 132.5 GeV. These would be lower limits on the parent particle mass (subject to resolutions) given the assumed decay chains. The total invariant mass of the event is M($\mu\mu\gamma\gamma\not{E}_t + jjj$)=320 GeV, which can be compared to the invariant mass in the $ee\gamma\gamma\not{E}_t$ event, M($ee\gamma\gamma\not{E}_t$) = 300 GeV[4].

Run 65390/Event 16199				Run 68739/Event 257646			
	γ_1	γ_2	μ_1		γ_1	γ_2	e_1
μ_2	114.0	51.7	105.8	e_2	63.2	89.8	158.6
μ_1	63.0	48.4		e_1	95.5	56.2	
γ_2	60.2			γ_2	46.5		

Table 3: Invariant masses of the $\mu\mu\gamma\gamma + \not{E}_t$ and $ee\gamma\gamma + \not{E}_t$ events in GeV.

[4]The total mass is the $\hat{s}$ for the event, and speaks to the production mechanism as well as to the decay.

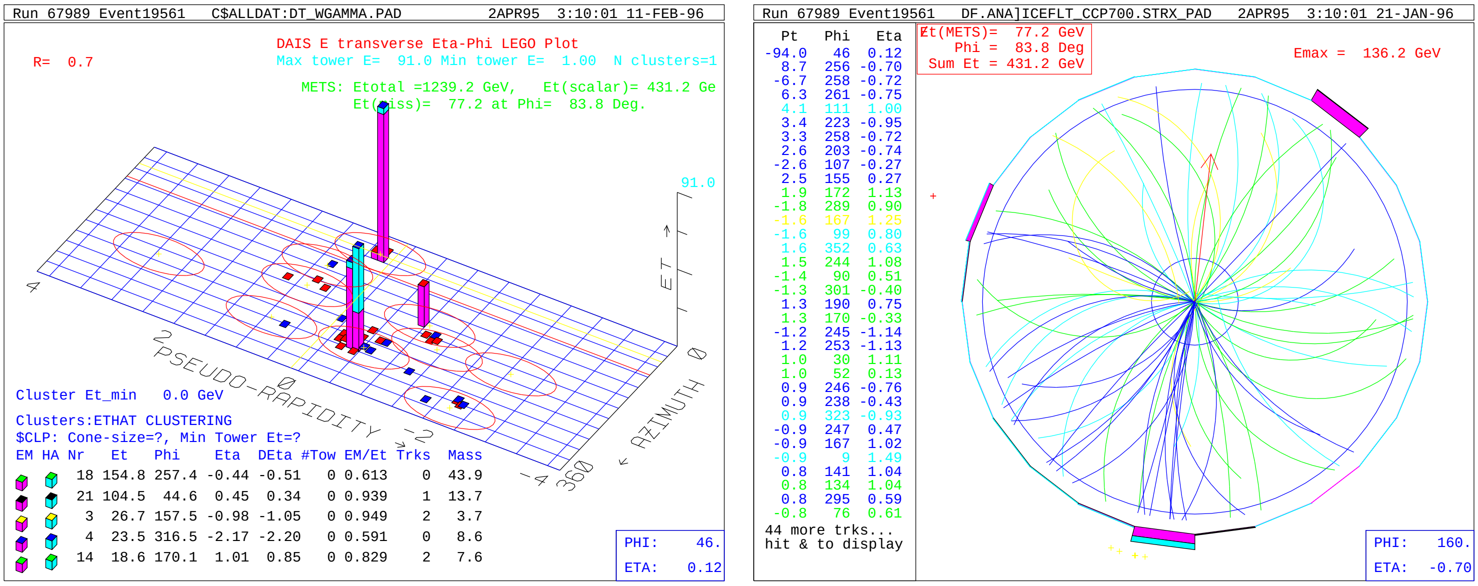

Figure 3: The lego and CTC plots for Run 67989/Event19561.

5 The $e\gamma \not\!\!E_t j_{fat}$ Event:R67989/E19561

The event is shown in Figure 4. The kinematical quantities for the particles in this event are listed in Table 4. Guessing at a possible explanation, we parse the event as having a very stiff jet (172 GeV) in one hemisphere, with a stiff electron (102 GeV), large $\not\!\!E_t$ (77 GeV), and a non-trivial photon (26 GeV) in the other hemisphere. A possible decay chain is:

$$\tilde{\chi}_2^+\tilde{\chi}_2^- \rightarrow (\tilde{e}\nu_e)(W^-\tilde{\chi}_1^0) \rightarrow (e\tilde{\chi}_2^0\nu_e)(q\bar{q}'\tilde{\chi}_1^0) \rightarrow (e\gamma\tilde{\chi}_1^0\nu_e)(q\bar{q}'\tilde{\chi}_1^0) \tag{5}$$

	P_x	P_y	P_z	E	E_T
e^+	70.39	74.12	12.38	102.97	102.22
γ_1	-24.09	10.03	-29.41	39.32	26.09
$\not\!\!E_t$	8.38	76.7	—	—	77.2
Jet_1	-31.96	-167.78	-70.43	186.07	172.02
Jet_2	20.41	-20.02	-121.06	124.59	28.64
Jet_3	-16.53	-5.24	-30.02	34.90	17.46

Table 4: Kinematics of R67989/E19561. Energies are corrected. The mass of jet 1 is 59 GeV (cone of 1.0). Note that Jet 2 is at η of 2.1.

The mass of the $e\gamma$ system, which in the assumed decay scheme is a lower limit on the mass of the $\tilde{\chi}_2^+$, is 104 GeV. The invariant mass of the 'fat' jet is, for cones of 0.4, 0.7, and 1.0, respectively, 22 GeV, 54 GeV, and 59 GeV, compatible with being a virtual W decaying into coalesced jets. The invariant mass ($\hat{s}$) of the system is M($e\gamma jjj \not\!\!E_t$)=511 GeV (taking $p_z = 0$ for the $\not\!\!E_t$.)

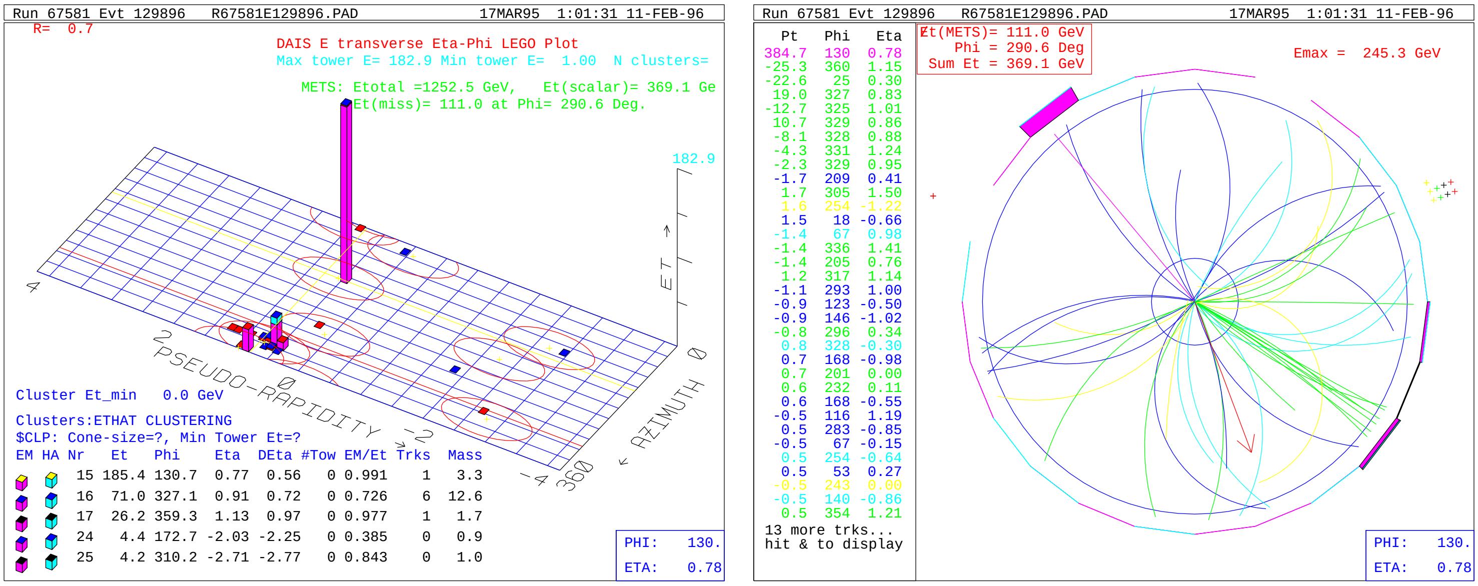

Figure 4: The lego and CTC plots for Run 67581/Event129896.

6 The Trilepton Event: R67581/E129896

This event differs from the previous three in that it did not come from the $\ell\gamma\not\!\!E_t$ search[1], but instead from the top dilepton search. We consider it here as an example of a 'zoo' event that does not parse particularly well in our current non-SM framework. The event R67581/E129896[9] is normally characterized as an $e\mu$ + 2 jet event. One of the jets is a non-fiducial electron, with an $x_{local} = -20.86$ cm (the cut is at 20 cm[10]). The electron passes all of the other TOPFND tight electron cuts. We have been preaching for some time that the fiducial cut for central electrons is too tight for searches as the other cuts are redundant- if the electron passes all the strip chamber cuts it is probably ok. We had consequently in CDF3387 (*i.e. a priori*) relaxed the fiducial cut[9]. The event is thus *not* a dilepton+2 jet event, but is a trilepton event+jet ($e^+e^-\mu^-\not\!\!E_t$+jet). The event is shown in Figure 4. The kinematic quantities of the event are given in Table 5. There is an immensely energetic e^+ ($\mathrm{E_T} = 192$), large $\not\!\!E_t$ (= 116 GeV), and two substantial isolated leptons, a 26 GeV ($\mathrm{E_T}$) e^- and a 28 GeV μ^-. In addition there is a jet with jet mass = 42 GeV and $\mathrm{E_T}$ = 96 GeV (corrected). So the event includes three isolated pretty leptons, large missing Et, and a high $\mathrm{E_T}$ massive jet.

The mass of the ee pair is 132 GeV, with a $\mathrm{p_T}$ of 176 GeV. The mass of the $\mu\not\!\!E_t jet$ system (taking $p_z = 0$ for the $\not\!\!E_t$) is 171 GeV, with a $\mathrm{p_T}$ of 196 GeV. While this could possibly be top with one b quark somehow giving a massive jet and the other giving an isolated 26 GeV lepton, this would be very atypical. Normal diboson production (WZ) is not favored as the mass of the ee pair is 132 GeV.

Parsing the event with a SUSY eye, we note that the most energetic objects in the

	P_x	P_y	P_z	E	E_T
e^+	-123.40	147.50	165.82	253.93	181.75
e^-	26.45	-0.02	37.68	46.04	23.43
μ^-	24.78	11.36	7.34	28.23	27.26
$\not\!\!E_t$	15.76	-114.56	—	—	115.64
j_1	79.59	-51.53	98.79	137.97	95.54

Table 5: Kinematics of 67581/129896. Energies are corrected.

two opposing hemispheres are an e^+ and $\not\!\!E_t$, respectively. Additionally, there is nothing else visible in the electron hemisphere; in the $\not\!\!E_t$ hemisphere there is a massive energetic jet and two same-sign (negative) 25 GeV leptons. We consequently want a decay chain that produces an electron on one side early in the decay cascade, and $\not\!\!E_t$ (either neutrinos or LSP's, or both) on the other. In addition, on the $\not\!\!E_t$ side we want something that can give a leptonic cascade, with both leptons being the same sign. The decay of a $\tilde{\tau}$ is a possibility[5]: we note that a τ decay gives a cascade of same-sign leptons, $\tau \to \mu\nu\nu \to e\nu\nu\nu\nu$. The same arguments apply to the supersymmetrized decay chains. So, invoking $\tilde{\tau}$ decay as our current best shot, one possible sequence is:

$$\tilde{\chi}_2^+\tilde{\chi}_2^- \to (W^+\tilde{\chi}_1^0)(\tilde{\tau}^-\nu_{tau}) \tag{6}$$

In the electron hemisphere we have:

$$\tilde{\chi}_2^+ \to W^+\tilde{\chi}_1^0 \to (e^+\nu_e)\tilde{\chi}_1^0 \tag{7}$$

and in the other hemisphere:

$$\tilde{\chi}_2^- \to \tilde{\tau}^-\nu_{tau} \to (\tilde{\nu}_\tau W^{*-})\nu_{tau} \tag{8}$$

followed by the decays of the $\tilde{\nu}_\tau$ and the W^{*-}:

$$\tilde{\nu}_\tau \to \tau^-\tilde{\chi}_1^+, \quad W^{*-} \to \mu^-\nu, \tag{9}$$

followed by the decays of the τ^- and the $\tilde{\chi}_1^+$:

$$\tau^- \to e^-\nu\nu, \quad \tilde{\chi}_1^+ \to W^{*+}\tilde{\chi}_1^0 \to q\bar{q}'\tilde{\chi}_1^0, \tag{10}$$

and the two jets from the $\tilde{\chi}_1^+$ decay are coalesced into a 'fat' jet.

We note that the predicted cross-section for $\tilde{\chi}_2^+\tilde{\chi}_2^-$ production varies between 600 fb and 100 fb for possible $\tilde{\chi}_2^+$ masses in the range of 100 to 140 GeV[11]. Branching ratios for $\tilde{\chi}_2^+$ into $e\tilde{\nu}_e$ are expected to be up to 20%[11]. In contrast, the tri-lepton signature of three stiff isolated leptons, with two the same sign close to each other, is very difficult to make in any garden-variety decay mode in the Standard Model.

The invariant mass of the e^-, the μ^-, and the jet, in the assumed decay scheme and subject to resolution, is a lower limit for the $\tilde{\chi}_2^+$ mass. We find $M(e^-\mu^-j) = 72$ GeV. The invariant mass of the whole event ($\hat{s}$) is 491 GeV.

[5]Note that a $\tilde{\nu}_\tau$ decay also might be a possible alternative.

7 Conclusions

Picking the three 'zoo' events involving leptons and photons that come from the inclusive $\ell\gamma\not{E}_t$ and $\gamma\gamma$ searches, we find that they have characteristic SUSY signatures involving production modes with (predicted) reasonable cross-sections, and decay modes with (also predicted) reasonable branching ratios. The process is not purely *ad hoc*; these events were found in an *a priori* fashion based on a hypothesis formed on the $ee\gamma\gamma\not{E}_t$ event used as a 'sign-post'. The 'zoo' events involving multiple well-measured leptons are very robust, and have to be taken extremely seriously. There may be other, more plausible, explanations of these events; we must compare the most plausible scenarios and decide on a global picture of these events[12]. With suitable Monte Carlos and specific models we can begin on making this process quantitative. Lastly, we have examined the top trilepton event as a sobering example of how little we know about what really is going on, and present a $\tilde{\tau}$ decay chain as an exercise in the parsing of events.

References

[1] Previous notes that may or may not be helpful are: R. Culbertson, H. Frisch, and D. Toback, *Search for Cousins of the* $ee\gamma\gamma \not{E}_t$ *Event In the Diphoton Channel*, CDF/ANAL/EXOTICS/3456; J. Berryhill, R. Culbertson, H. Frisch, and D. Toback, *A Search for SUSY Cousins of the* $ee\gamma\gamma \not{E}_t$ *Event in the* $l\gamma \not{E}_t$ *Channel*, CDF/ANAL/EXOTICS/3555. J. Berryhill, R. Culbertson, H. Frisch, and D. Toback; *Speculations on High-mass Neutral Current Events*, CDF/ANAL/EXOTICS/3556.

[2] Preprint hep-ph/9602239, *Supersymmetric analysis and predictions based on the CDF* $ee\gamma\gamma$ *+ missing* E_T *event*, S. Ambrosanio, G. L. Kane, G. D. Kribs, S. Martin (U. Michigan), and S. Mrenna (Argonne).

[3] Both the $ee\gamma\gamma \not{E}_t$ and $\mu\mu\gamma\gamma \not{E}_t$ events have expectations below 10^{-5} in the Standard Model— see CDF3555.

[4] Any explanation of a physical effect must satisfy Occam's Razor: briefly put- "is there a simpler explanation?" We point out only that it is a double-edged razor.

[5] H. Nilles, Phys. Rep. 110,1 (1984) ; H. Haber and G. Kane, Phys. Rep. 117, 75 (1985). In particular see S Mrenna, G. Kane, G. Kribs, and J. Wells, *Possible Signals of Constrained MSSM at a High Luminosity Fermilab Tevatron Collider*,May 1995, hep-ph/9505245. See also J. Ellis, J. Lopez, and D. Nanopoulos, *Supersymmetry and* R_b *in the light of LEP 1.5*, Dec. 1995, hep-ph/951288. Note that the use of the word 'model' as generally applied to supersymmetry is a misnomer- a model is the realization of more general principles in order to make specific testable predictions. We are trying to move towards a model.

[6] We know from long experience that this is the kind of word that raises hackles among the 'purists'. We respectfully and humbly again ask them to stop reading and go do something useful. There is lots to be done getting ready for Run II.

[7] By 'cousins' we mean events related by branching ratios. For example, if the $ee\gamma\gamma \not{E}_t$ event were from WW production with the photons radiated by the W's, one would expect cousins with two photons, and either 4 jets (both W's decay hadronically) or 2 jets + leptons+$\not{E}_t$ (one W decays hadronically).

[8] It is conjectured that there are two charged χ's and four neutral. The charged χ's are conjectured[2] both mixtures of the Wino and Charged Higgsino (the names are just simply awful); the neutral ones mixtures of the two neutral Higgsino's, the photino, and the Zino (or Bino). The $\tilde{\chi}_2^0$ is taken to be mostly photino, the $\tilde{\chi}_1^0$ mostly Higgsino, and the heavier neutral χ's mixtures of Zino and Higgsino.

[9] *Separating Top and Z's in Dilepton Events inside the Z mass Window*, H. Frisch, CDF/ANAL/TOP/3387

[10] The fiducial cut at $x_{local} = 20\ cm$ was instituted to be overly conservative in the first R analysis as a small ($< 10\%$) loss was an easy price to pay for security against systematics in acceptance for a precision ratio measurement. It has persisted as CDF folk-lore (the F in CDF), but is inappropriate for searches. The misclassification of this event is an example of why we need to fix the mislabelling of electrons that fail the cuts (but are still more probably electrons than jets).

[11] G. Kane and S. Mrenna, private communication.

[12] If anyone can come up with a plausible explanation for these four events in the Standard Model they can have Larry's 500 bucks.