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The 930 GeV $\mathbf{Z^0} \to e^+e^-$ + 2 Jets Event: Does It Have $\mathbf{Z^0} \to q\bar{q}$ + 2 Jets Cousins?

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1 Introduction

There is one striking event in the Z +2 jet electron sample. The invariant mass of the two jets is 732.4 GeV. The electrons are back to back, as are the two jets: the two electrons from the Z have an azimuthal separation of 176 degrees; the two jets have an azimuthal separation of 179.4 degrees. The event balances very well in Et: the missing Et is only 30.5 Gev. The invariant mass of the 4 clusters reconstructed as jets (i.e. the electrons as jets) is 934 GeV.

The event is shown in Figures 1a-d. The electrons are of good quality with the exception that one has a value of E/p of 2.3. The jets also seem reasonable, with em fractions of 0.13 and 0.38 respectively, and a number of stiff tracks for the jet that is central enough to traverse part of the CTC.

The event is interesting because it appears separated from the observed tail of the 2-jet mass distribution in Z + 2 jet events, shown in Figure 2a for electrons and 2b for muons.

If this event represents a real phenomenon, rather than arcane background or rare double fluctuation in calorimeter response, it should appear in other channels. In particular, events in which the Z has decayed hadronically rather than leptonically should appear. The branching ratio to hadrons is 22 times larger than to e pairs. We have thus looked for 'cousins' of this one event in events with 4 or more jets, where two of the jets would be from a hadronic Z decay.

One has to make assumptions about the phenomenon one is looking for. We have assumed the one event we do have is typical of the topology, particularly in that the jets are back-to-back, and the Z has low $\mathrm{p_T}$. As a straw model for what kind of physics could produce such an event, we have had in mind the production of a heavy excited state that has $\mathrm{p_T}$ small compared to its mass, plausible given that the mass is 934 GeV, a substantial fraction of $\sqrt{s}$. If the excited state is one quantum mass above the ground state, as in the Δ or the D^*, the Z will be emitted at very low $\mathrm{p_T}$ itself, and the ground state, being heavy, remains at low $\mathrm{p_T}$. The ground state then decays into a pair of jets. A technirho, for example, could in principle behave this way.

$$\rho_T^* \to \pi_T + Z \qquad (1)$$

Decays with the quantum being a photon or a W could also then exist, but the expectations would depend on the model. But if the event we see is 'real' and typical, then there should be events of similar topology (i.e. jets back-to-back, the Z at low p_T), with the Z decaying hadronically, at a rate approximately 15-20 times that of the $Z^0 \to e^+e^-$ decay.

2 $Z^0 \to e^+e^-$ and $Z^0 \to \mu^+\mu^-$ event samples

The electron Z sample is derived from 21.4 pb-1 of Express inclusive electrons. A central leg is demanded with the cuts given in Table 1. A second leg is then required with looser cuts. For both electrons one and only one 3-D track is required to be in the ELES bank.

First Electron			Second Electron		
E_T	$>$	20.0 GeV	E_T	$>$	20.0 GeV
Iso	$<$	0.1	Iso	$<$	0.1
Had/Em	$<$	$0.055 + 0.045 \times E/100$	Had/Em	$<$	0.1
χ^2_{Strip}	$<$	10.0			
$Lshr$	$<$	0.2			
E/p	$<$	2.0			
$\lvert\Delta Z\rvert$	$<$	3.0 cm			
$\lvert\Delta R\phi\rvert$	$<$	1.5 cm			
$\lvert Z_{vert}\rvert$	$<$	60.0 cm			
$N_{3Dtracks}$	$=$	1	$N_{3Dtracks}$	$=$	1

Table 1: Summary of the central electron selection requirements. The second electron has only the cuts listed. In addition, both electrons are required to have one and only one 3-D track.

The muon Z sample is derived from 21.4 pb-1 of Express muon data. The sample has been tracked with 6.1 express production. The cuts on the muons to make the sample are listed in Table 2.

The invariant mass distribution for the pair of jets having the highest mass in Z+jets events for all events with ≥ 2 jets of 20 GeV jets or higher is shown in Figure 2a for the electron sample and 2b for muons in the muon sample.

3 Expectations for the $Z^0 \to jj$ channel

We see one Z plus high mass dijet event in the $Z^0 \to e^+e^-$ channel and none in the $Z^0 \to \mu^+\mu^-$ channel. The four-jet sample we are using comes from 20.43 pb-1 of Stream 1 data, versus the 21.4 pb-1 of Express line data used for the Z sample.

First Muon			Second Muon		
p_T	$>$	20.0 GeV	E_T	$>$	20.0 GeV
E_{had}	$<$	6.0 GeV	E_{had}	$<$	6.0 GeV
E_{em}	$<$	2.0 GeV	E_{em}	$<$	2.0 GeV
$\|\Delta X\|_{CMU}$	$<$	2.0 cm	$\|\Delta X\|_{CMU}$	$<$	2.0 cm
$\|\Delta X\|_{CMP}$	$<$	5.0 cm	$\|\Delta X\|_{CMP}$	$<$	5.0 cm
$\|\Delta X\|_{CMX}$	$<$	8.0 cm	$\|\Delta X\|_{CMX}$	$<$	8.0 cm
Impact Par	$<$	0.2	Impact Par	$<$	0.2
$\|Z_{trk} - Z_{vtx}\|$	$<$	7.5 cm			

Table 2: Summary of the muon selection requirements.

To estimate how many $Z^0 \to jj$ events we should have seen, we have used a very crude model. We assume that the events are triggered on and selected on the large jets, so that the sample is largely unbiased with respect to whether the Z decayed into leptons or jets. We then need the ratio of acceptances for the Z to be detected in the jj mode versus the ee or $\mu\mu$ modes.

We have used Isajet and QFL to calculate a crude relative acceptance for centrally-produced $Z^0 \to jj$ and $Z^0 \to e^+e^-$ events. While the x and pt distributions of the Z's are (most-likely) different from those from a heavy decay into Z with a low Q value, the ratio of acceptances is probably not too far off for Z's in the central region. We require $|\eta|$ to be less than 1.0 for each daughter from the Z to keep it central, and Pt_Z to be less than 30 GeV. The $Z^0 \to e^+e^-$ decays are required to have two electrons in the fiducial region that satisfy the electron cuts listed in Table I. We find an acceptance A_{ee} of $54.1 \pm 1.18\%$.

For the $Z^0 \to jj$ sample, we require the two highest Et jets that are within $|\eta| < 1.0$ and have $E_T > 20$ GeV/c to fall within an invariant mass window of 65-115 GeV. In addition the two-jet system is required to have a reconstructed $E_T < 30$ GeV. The invariant mass spectrum of the two highest Et jets that are within $|\eta| < 1.0$ and have $E_T > 20$ GeV/c is shown in Figure 3b; Figure 3a shows the same spectrum with the η cut removed. We find an acceptance of $A_{jj} = 74.6 \pm 1.06\%$. The ratio of the two acceptances is A_{jj}/A_{ee}=1.38. The result is thus that we have a larger acceptance for $Z^0 \to jj$ than we do for $Z^0 \to e^+e^-$ for centrally produced low-p_T Z decays, due to the electron fiducial cuts and identification efficiencies. This conclusion should be fairly robust for different Z production mechanisms as long as they are central and low pt.

We have similarly calculate the $Z^0 \to \mu^+\mu^-$ acceptance and obtain $50.2 \pm 1.21\%$. (The event will trigger on the big jets). No events are observed in this channel.

Finally, we use [1] the branching ratios for the Z of $BR(Z^0 \to jj) = 69.8 \pm 0.3\%$ and $BR(Z^0 \to e^+e^- = 3.345 \pm 0.08\%$ to calculate the ratio of branching ratios: $BR(Z^0 \to jj)/BR(Z^0 \to e^+e^-) \;=\; 20.9 \pm 0.2$.

Putting it all together, we expect:

$$N(\mathrm{Z}^0 \to jj) = N(\mathrm{Z}^0 \to e^+e^-) \cdot \frac{A_{jj}}{A_{ee} + A_{mumu}} \cdot \frac{L_{jj}}{L_{ee}} \cdot \frac{BR(\mathrm{Z}^0 \to jj)}{BR(\mathrm{Z}^0 \to e^+e^-)} \tag{2}$$

$$= 1 \text{ event} \cdot (.746/1.043) \cdot (1.0) \cdot (20.9) \;=\; 15 \text{ events} \tag{3}$$

Any uncertainty is small compared to the uncertainty of the one $\mathrm{Z}^0 \to e^+e^-$ event cross-section.

4 Data set selection

The data come from the ETQ1 stream, defined at Level 3 as $\sum E_T > 175$ GeV. The selection for this analysis requires:

1. $\sum E_T < 2$ TeV , $\sum E_{out-of-time} < 10$ GeV.
2. At least two jets with $E_T > 20$ GeV. The cone size used is R=0.7, and the E_T is corrected with the routine JTC90S.
3. The largest dijet mass of all jet combinations > 400 GeV.
4. the vertex position along the beam line to be within $\pm$ 60 cm of the nominal center of the interaction region.
5. $\frac{\sum E_T}{\sum E} > 0.15$ to remove remaining noise and main ring induced events.

The numbers of events passing these cuts in turn are given in Table 3.

Table 3: Number of events passing the sample selection cuts

Cut			Number of events
Good runs			176470
$\sum E$	$<$	2 TeV	171814
$\sum E_{out-of-time}$	$<$	10 GeV	150588
2 jets with E_T	$>$	20 GeV	137170
M_{jj}^{high}	$>$	400 GeV/c ^{2}	22287
N. primary vert.	$>$	0	22274
$\lvert z_{vtx} \rvert$	$<$	60 cm	21299
$\frac{\sum E_T}{\sum E}$	$>$	0.15	21267

Figures 4a-f shows the distributions in these variables we cut on. Figures 4a, b and c are the total $\mathrm{E_T}$, $E_{out-of-time}$, and the number of primary vertices per event, respectively, after cuts 1,2, and 3. Figure 4d is the Z_{vertex} distribution after requiring in addition there be at least one vertex. Figure 4e is the distribution of sum $\mathrm{E_T}$ divided by sum E after requiring the highest-class (best) vertex be within 60 cm of zero in z. Figure 4f is the distribution of invariant masses for the 2 jet pair that makes the highest invariant mass in the event after all the cuts. The solid curve is before any cuts; the dashed curve is after all the above cuts.

Because we are focused here on the signature of the one event we DO have, we further select on event topology. The jets are ordered by $\mathrm{E_T}$, with jet 1 being the highest Et jet. We are searching for events where jets 1 and 2 have the large mass ($\approx 750GeV$), and an additional pair of jets forms a Z mass. The additional topology cuts after the above sample-selection cuts are:

1. Jets 1 and 2 must be close to back-to-back : $\phi_{12} > 150°$.

2. At least two jets (but not jets 1 and 2) with $|\eta|_j < 1.0$ and $\mathrm{E_T} > 20$ GeV. (The system of these two jets should form a Z in the signature we are looking for.)

3. Of these jets, there should be at least one pair with invariant mass between 65 and 115 GeV.and $\mathrm{p_T} < 30$ GeV. If there is more than one pair satisfying these two cuts, the pair with the mass closest to the Z mass is chosen (about 1% of the events have more then one combination of jet pairs in the Z mass window)

5 Single jet distributions

The distributions in $\mathrm{E_T}$ for the four highest $\mathrm{E_T}$ jets are given in Figures 5a-d. The line histogram is for events passing the sample selection cuts, and the filled histogram is after the topology cuts above. Figure 6 shows the corresponding distributions in the electromagnetic fraction (EM/Total). Figure 7 shows the distributions in η (these are always interesting, but rarely understood: take a look!).

6 Jet pair mass and $\mathrm{p_T}$ distributions

In Figure 8 we show the mass and Pt of both the massive dijet (Jets 1 and 2), and for the dijet that makes up the 'Z'. Figure 8a shows the pt spectrum of the dijet; Figure 8c shows the invariant mass. The upper histogram again is for the cuts that define the sample, and the filled histogram is for the topology cuts. Note that there is no pt cut on this pair, but there is the back-to-back angle cut. Figure 8b shows the pt spectrum of the 'Z'; the filled histogram shows the pt cut on this pair. Figure 8d shows the mass of the 'Z' pair. Note that our procedure makes a peak at the Z mass in the histogram without the topology cuts: selecting the best pair at a different mass (e.g. 120 GeV rather than 90) will produce a peak there. However when one looks at the 'Z' mass distribution in the filled histogram (after the topology cuts) there is no excess in the Z region, where we would expect an excess of 15 events at a mean of 90 GeV with a sigma of 12 GeV or so (see Fig. 3).

In Figure 9a we show the scatter plot of the the mass of the best Z combination versus the mass of the dijet system after the topology cuts; in Fig. 9b we select the mass of the best Z combination to lie in the window 65 to 115 GeV, and plot the dijet mass of jets 1 and 2. There is again no excess where we would expect an excess of 15 events at a mean of 750 GeV with a sigma of approximately 75 GeV. In Figure 9c we do the complementary exercise: we require the dijet mass to lie between 600 and 900 GeV, and look at the best Z dijet combination. Again we see no peak. Finally, in Fig 9d we plot the mass of the 4 jets system for events with both dijets in the respective mass windows.

To visualize what 15 $Z^0 \rightarrow jj$ events would look in our M(j3,j4) distribution, we superimpose to Fig.9c a Gaussian distribution of mean = 90 GeV and width = 12.5, normalized to 15 events. Although the distribution could accommodate these events, is also consistent with a smooth background drawn through the mass regions below and above the Z.

7 Conclusions

We do not have obvious evidence of 'cousins' of the one dijet+$Z^0 \rightarrow e^+e^-$ event in the hadronic decay mode channel of the Z, dijet+$Z^0 \rightarrow jj$. Only more statistics can give a conclusive answer.

References

[1] Particle Data Group, June 1992

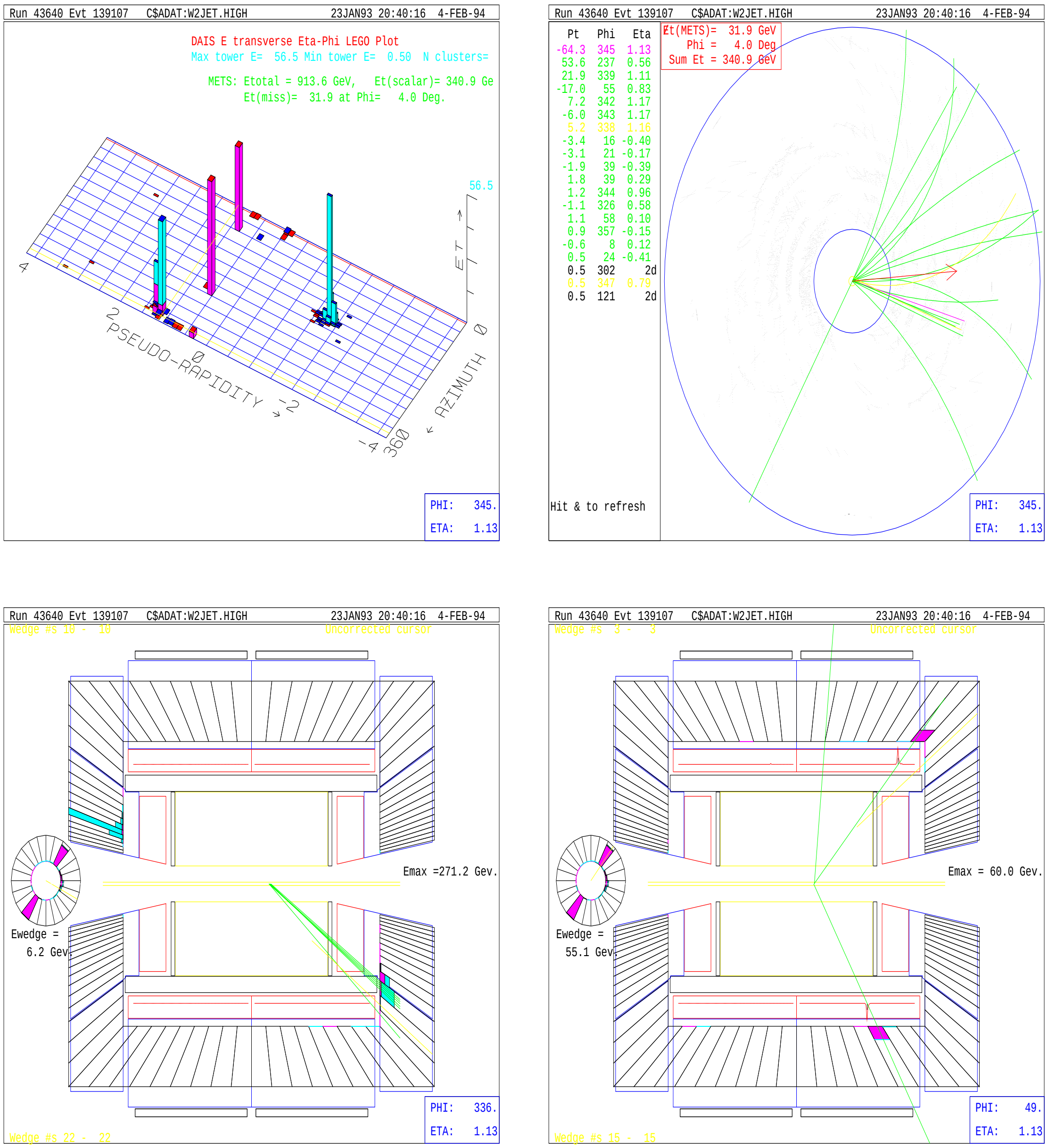

Figure 1: (a) The Lego display for the Event 139107-Run 43640. (b) The CTC display. (c) The side view in the plane of the two electrons (d) The side view in the plane of the two jets.

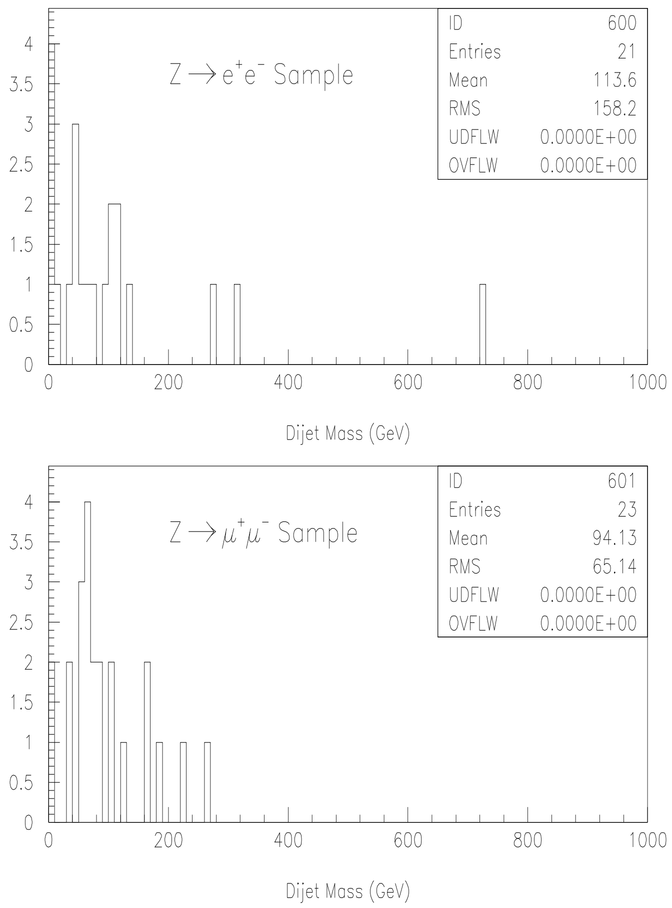

Figure 2: (a)The dijet invariant mass distribution of the 2 jets in Z+2 jet events from the Zee sample. (b)The dijet invariant mass distribution of the 2 jets in Z+2 jet events from the $Z^0 \to \mu^+\mu^-$ sample.

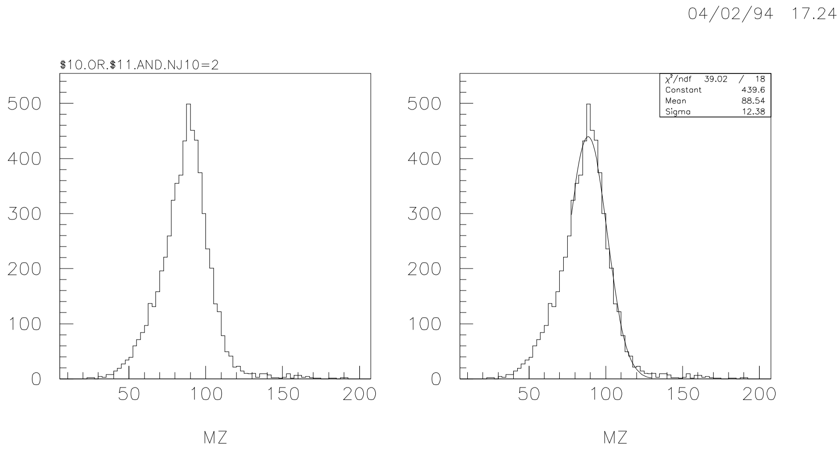

Figure 3: a) The $Z^0 \rightarrow jj$ invariant mass distribution from Isajet for Z's with $\eta_{jet} < 1.0$. b) The $Z^0 \rightarrow jj$ invariant mass distribution from Isajet for Z's with η_{jet} unrestricted.

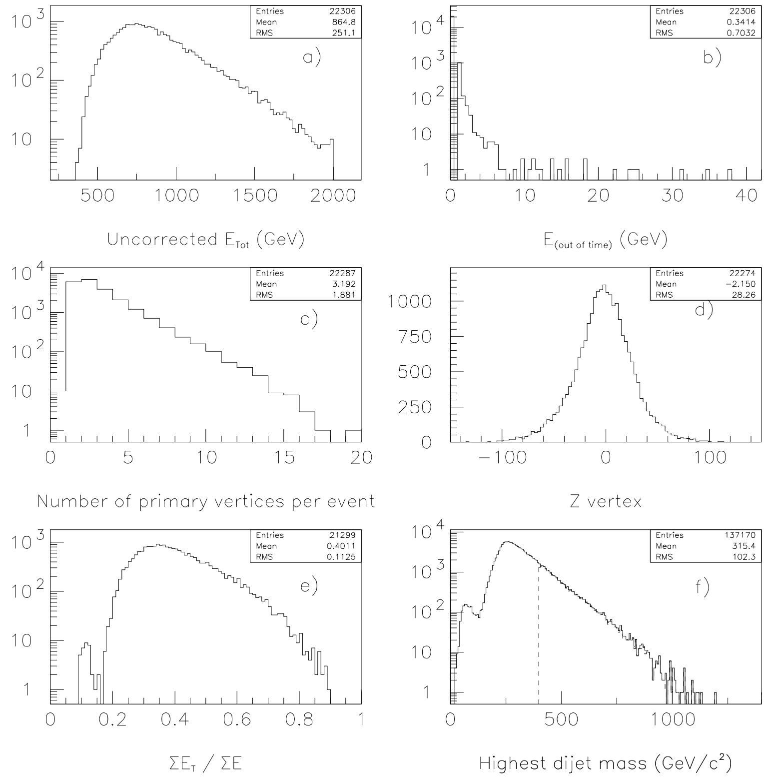

Figure 4: Distributions from the data samples of variables that have been cut on in the data selection. Figures 4a, b and c are after only the cuts on total energy < 2000 and $E_{out-of-time}$ cuts; a) is the uncorrected total energy, b) is the $E_{out-of-time}$, and c) is the number of primary vertices per event. Figure d) is the Z_{vertex} distribution after requiring in addition there be at least one vertex. Figure e) is the distribution of sum $\mathrm{E_T}$ after requiring there be at least one vertex and in addition any vertex be within 60 cm of zero. Figure f is the distribution of invariant masses for the 2 jet pair that makes the highest invariant mass in the event.

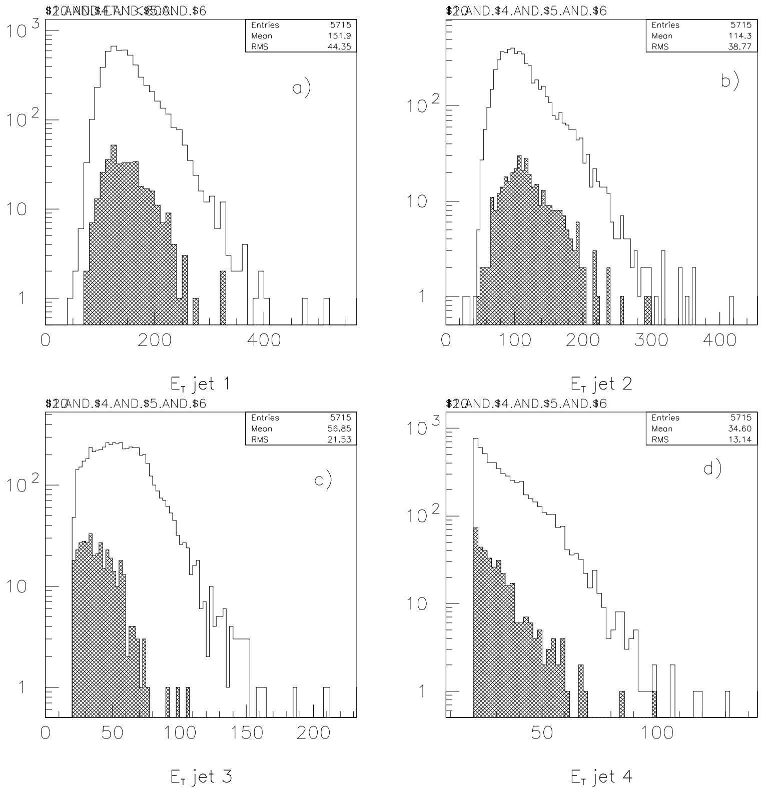

Figure 5: The Et distribution of jets 1,2,3, and 4 for all events with 4 jets with $\mathrm{E_T} > 20$ GeV (open) and then with the cuts $\mathrm{p_T^Z} < 30$ GeV, $|\eta|_j < 1.0$ for jets 3 and 4, and $\phi_{12} > 150°$ (filled).

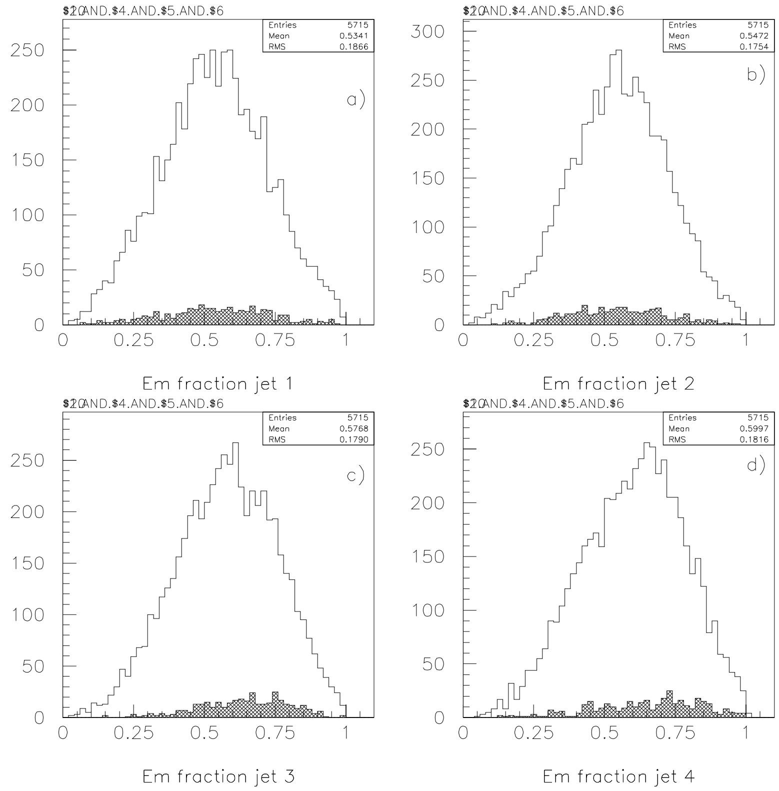

Figure 6: The Em fraction distribution of jets 1,2,3, and 4 for all events with 4 jets with $E_T > 20$ GeV (open) and then with the cuts $p_T^Z < 30$ GeV, $|\eta|_j < 1.0$ for jets 3 and 4, and $\phi_{12} > 150°$ (filled).

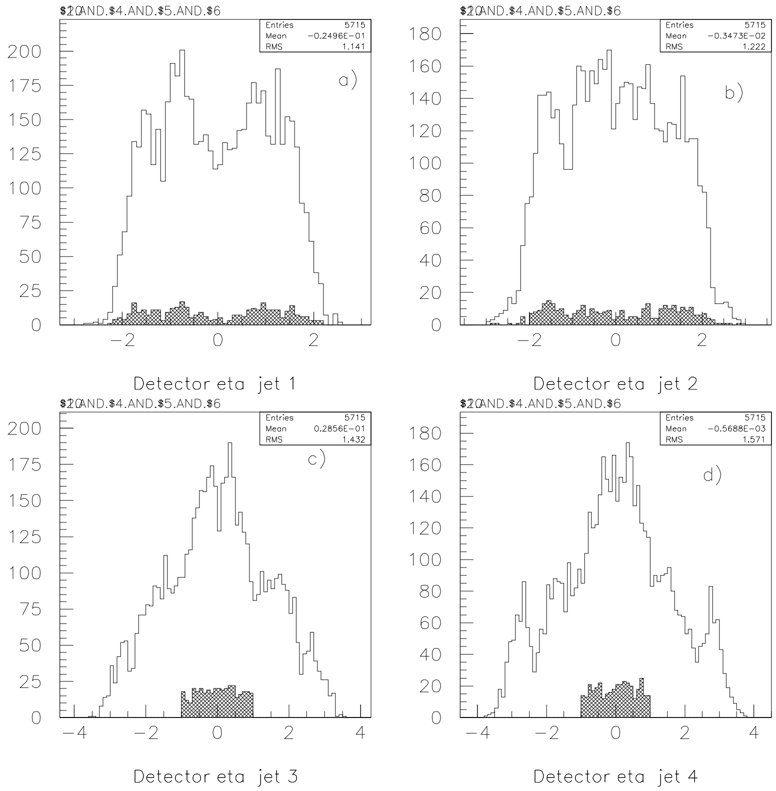

Figure 7: The eta distribution of jets 1,2,3, and 4 for all events with 4 jets with $\mathrm{E_T} > 20$ GeV (open) and then with the cuts $\mathrm{p_T^Z} < 30$ GeV, $|\eta|_j < 1.0$ for jets 3 and 4, and $\phi_{12} > 150^{\circ}$ (filled).

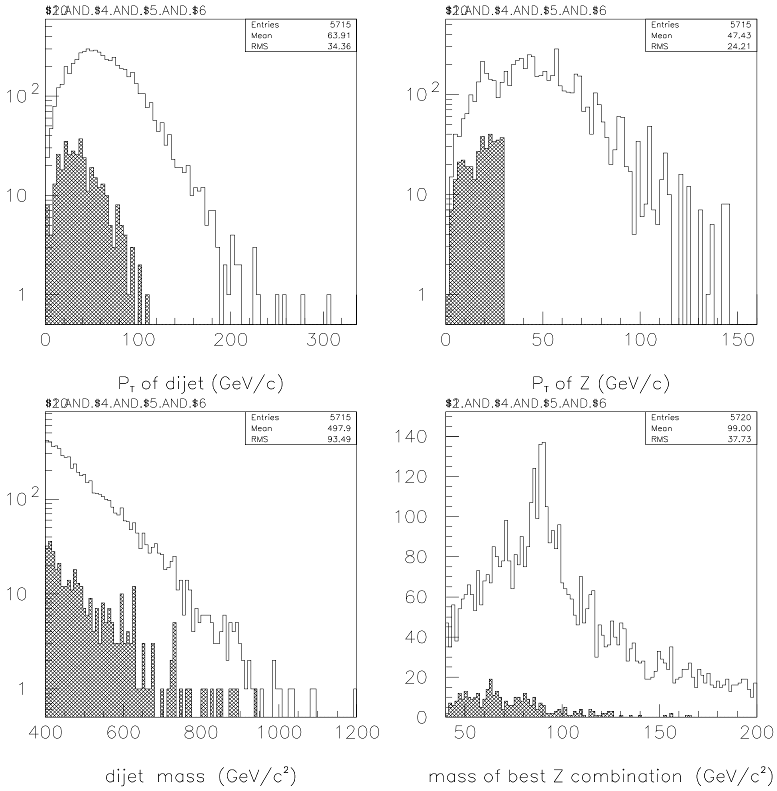

Figure 8: The Pt distribution and invariant mass of jets 1,2 (Fig.8a and 8c) and of jets 3,4 (Fig.8b and 8d).

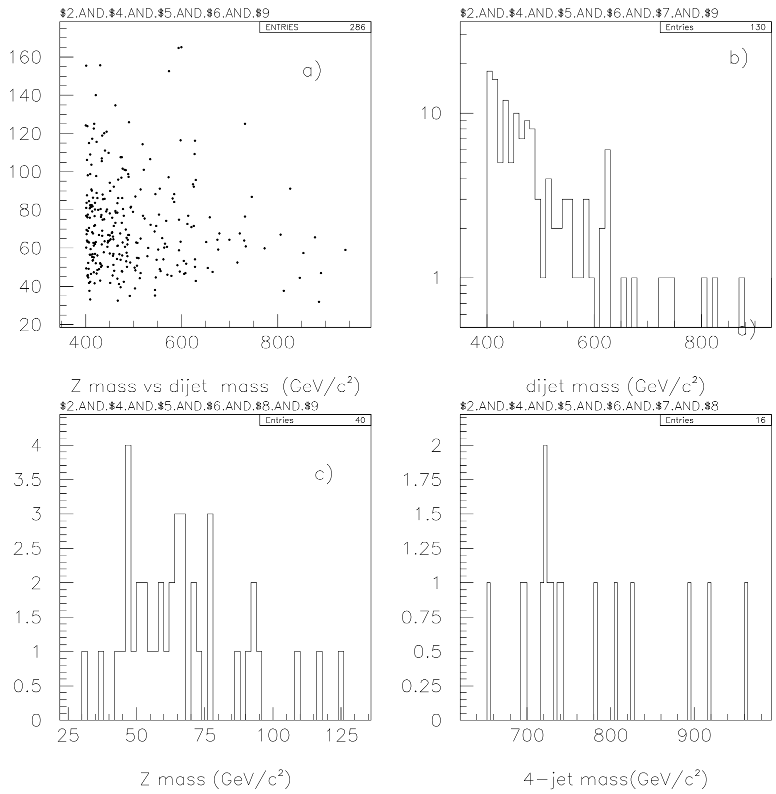

Figure 9: a) The 2-D plot of the dijet mass (jets 1 and 2) versus the 'Z' dijet mass; b) the dijet mass (jets 1 and 2) when the 'Z' dijet mass is required to be $65 < M_Z < 115$ GeV; c) the Z dijet mass when the dijet mass (jets 1 and 2) is required to be $600 < M_Z < 900$ GeV; d) the invariant mass of the four jets system for events with the dijets masses in the corresponding windows.

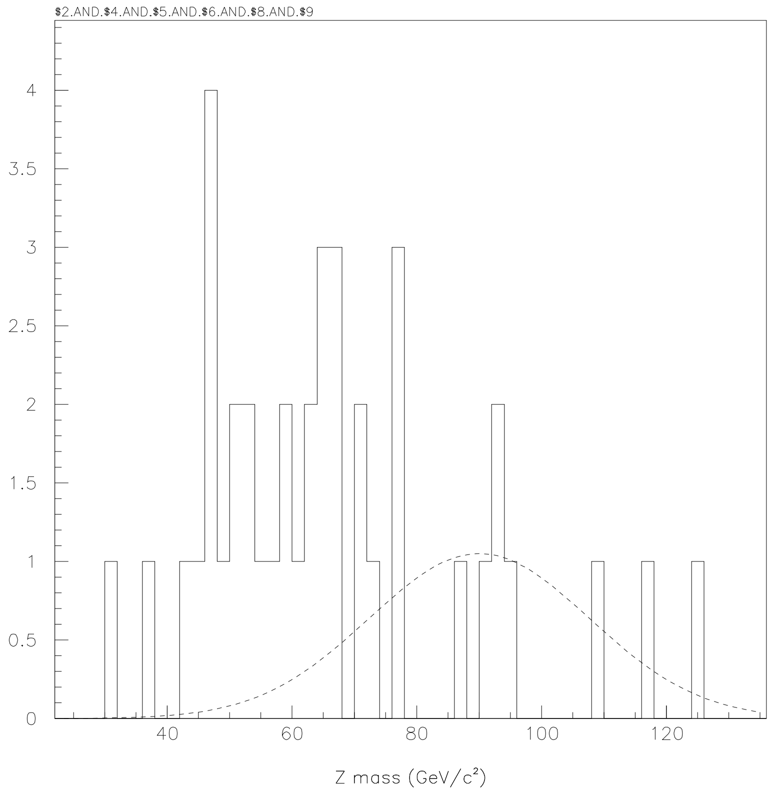

Figure 10: The Z dijet mass (dijet mass $600 < M_Z < 900$ GeV). The dash line represents 15 $Z^0 \to jj$