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Search For the Top FCNC Radiative Decays $t \to c\gamma$ and $t \to u\gamma$

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1 Introduction

One signature of new physics is a change in the rates of Flavor Changing Neutral Currents (FCNC's). For example, the presence of the charmed quark was inferred from the depression in the rate $K_L^0 \to \mu^+\mu^-$. On the other hand, certain models with charged Higgs bosons can increase the rate of the FCNC decay $b \to s\gamma$. Standard Model predictions for the branching fractions of the decays $t \to c\gamma$ and $t \to u\gamma$ are around 10^{-10}. [1] Any observation of these decays in a CDF-sized data set would be very surprising and would be incontrovertible evidence for physics beyond the Standard Model. This note describes limits that can be set on the branching fractions $BF(t \to q\gamma)$ [1], using approximately 110 pb^{-1}: 19.3 pb^{-1} from Run 1A and 91.6 pb^{-1} from Run 1B.

The basic strategy of this search is to take advantage of the fact that top quarks are produced in pairs. We search for events where one top decays to $q + \gamma$, and the second decays via the Standard Model decay $t \to Wb$. There are two signatures of events with $t \to q\gamma$ decays, depending on the decay mode of the W from the second t in the event. If it decays leptonically, the event will have a high p_T lepton, missing E_T, two jets, and a photon. If the W instead decays hadronically, the event will have a photon and four jets. (Of course, since jets can radiate other jets, merge, or be lost, the number of jets can vary.) These photons are highly energetic: typical photon E_T's are of order $m(t)/2$. The photon spectrum is shown in Figure 1.

This analysis centers on finding the photon from the FCNC decay, and partial reconstruction of the other top in the event: finding the $W \to l\nu$, or the b-jet in the

[1] Here we use $t \to q\gamma$ to indicate either the decay $t \to c\gamma$ or the decay $t \to u\gamma$, since we can't easily distinguish u and c jets.

case where the W decayed hadronically, as well as substantial jet activity. That is, we require:

- A high E_T photon (from $t \to q\gamma$)

- A W (high p_T lepton and missing E_T) OR a SECVTX b tag (both the W and the b are from the $t \to Wb$ decay)

- Substantial jet activity in the event (from daughters of both the top quarks)

The cuts are chosen so that we expect 0-1 background events in each sample: these are set by looking at jetless $W + \gamma$ events and γ+multijet events without requiring a b-tag.

2 Photon Selection

Our strategy here is to use photon requirements very similar to those used by the $W + \gamma$ group, for consistency and ease of calculation of acceptances and efficiencies. The requirements are:

- The CEM clusters must have $E_T > 20$ GeV and satisfy FIDELE fiducial cuts.

- The ratio of excess E_T in a cone of 0.4 to the E_T of the CEM cluster, $\Sigma E_T/E_T$ has to be less than 0.15. (ET4/ET)

- The 3-tower LSHR must be less than 0.2.

- No 3-D tracks point to the cluster. (N3D)

- HAD/EM $< 0.055 + 0.00045 \times E$, where E is the total (not transverse) CEM energy. (The "ABW cut")

- The average χ^2 for the CES wires and strips must be less than 20.

These differ slightly from the cuts chosen by the diboson group in CDF-3099 [2]. The differences include a slightly tighter LSHR cut (0.2 rather than 0.5), and the CES shape cuts. Both are reasonably loose, and the efficiency change is discussed in the limits section. Also, the ΔR cut between the W lepton and photon direction is relaxed. This is intended to reduce bremsstrahlung events, but this is a very small source of photons at these energies.

Originally, we had hoped to keep the photon cuts identical in the leptonic and hadronic channels. However, the large QCD background in the hadronic channel relative to the small W+photon+jets background in the leptonic case makes this goal unrealistic. We have settled on a photon requirement of 30 GeV for the leptonic W case and 50 GeV for the hadronic W case.

3 Limits from the Leptonic Channel

As previously outlined, we select events that are $W + \gamma$ candidates: have a 20 GeV muon or electron that passes the $W + \gamma$ cuts (the "R" cuts), 20 GeV of missing E_T, and a 30 GeV photon passing the above cuts. Additionally, because these events are from a $t\bar{t}$ pair, there should be a lot of jet activity in these events, so we require at least two jets above 15 GeV. This is a very minimal requirement, considering all the jet activity from the top daughters. Events are required to pass either the standard top triggers or the photon triggers: CEM23 for Run 1B, CEM16 with an offline 23 GeV cut for Run 1A.

To calculate the branching fraction, we compare the $q\gamma$ mode to the Wb mode. Here we use the lepton plus jets decay mode to normalize to, since there are more events in that channel than the dilepton channel. Also, we only use SECVTX tags, since the smaller background results in a more precise measurement.

The number of events reconstructed in the various modes can be calculated from the acceptances and branching fractions. Note that a fraction of events with one top decaying to $q + \gamma$ will appear as lepton plus 3 more more jets events: the photon is identified as a jet. In fact, there are no such events like this observed, but it is nonetheless part of our acceptance.

We define the following three efficiencies - including branching fractions:

	Decay	Reconstructed As
E_1	$t \rightarrow Wb\ \bar{t} \rightarrow Wb$	lepton+jets
E_2	$t \rightarrow Wb\ \bar{t} \rightarrow q\gamma$	lepton+jets
E_3	$t \rightarrow Wb\ \bar{t} \rightarrow q\gamma$	lepton+photon + jets

The number of events observed in the photon+lepton channel would then be:

$$N_{l-\gamma} = N_{t\bar{t}} \left[2E_3 BF(t \rightarrow Wb) BF(t \rightarrow q\gamma) \right]$$

and the number observed in the lepton + jets channel would be:

$$N_{l-jets} = N_{t\bar{t}} \left[E_1 BF(t \rightarrow Wb)^2 + 2E_2 BF(t \rightarrow Wb) BF(t \rightarrow q\gamma) \right]$$

We can solve for the branching fraction $BF(t \to q\gamma)$, under the conservative assumption that $BF(t \to Wb) = 1 - BF(t \to q\gamma)$, and using R to notate the ratio of observed lepton+photon events to lepton+jets events:

$$BF(t \to q\gamma) = \frac{RE_1}{2E_3 + (E_1 - 2E_2)R}$$

3.1 Calculating Efficiencies

First, it should be noted that only the *relative* efficiencies of the various modes enter into the determination of the branching fraction; we don't need to know the absolute efficiencies. We calculate the acceptances and efficiencies with ISAJET, using two samples: STDTOP, where the only allowed decays are $t \to W + b$ and TGAMMA, where one top decays to $W + b$ and the other to $q + \gamma$. The events are then simulated with QFL. The ISAJET+QFL combination should be reliable in calculating the ratios. To be conservative, we assume that the ratios are no more accurate than to 5% - that is, the uncertainty on these ratios is given by the larger of the statistical uncertainty on the Monte Carlo, or 5%. (We have generated a sufficiently large Monte Carlo sample that this is always 5%.)

The other element in calculating efficiencies is the SECVTX efficiency. We use $45 \pm 7\%$ as the efficiency given that the jet is in the SVX, a 42% probability that both b's are in the SVX, and a 26% probability that only one is. This results in an efficiency for tagging at least one b given two in the event of $41 \pm 5\%$, and a probability for tagging the only b in the event of $25 \pm 4\%$.

To get E_1, we look at the STDTOP sample, where 50,000 events were generated, and 3953 pass the lepton plus jets cuts. Of these, $41 \pm 5\%$ would be tagged. Although we are only interested in the relative size of the various efficiencies, if we go through the machinery to calculate the absolute cross section, we get approximately 8 pb, in good agreement with the more detailed analyses on this topic.

To get E_2, we look at the TGAMMA sample, where we have generated 100,000 events, of which 3481 pass the lepton plus jets cuts. Because there is only one b in these events, only $25 \pm 4\%$ are tagged. The ratio E_2/E_1 is $0.268 \pm 0.013 \pm 0.018$, where the second uncertainty is the portion due to the b-tagging efficiency.

Finally, to get E_3, we again look at the TGAMMA sample, but in this case we require the event to pass the lepton plus photon cuts. 9145 events (again, of 100,000) pass. We have to include the $82.0 \pm 2.6\%$ photon efficiency [3], but we must be careful not to double count:

• The $98.0 \pm 0.3\%$ HAD/EM efficiency, already included in the Monte Carlo definition of a photon.

• The photon conversion probability of $3.5 \pm 1.0\%$, which has already been included in QFL.

Additionally, we have slightly tighter LSHR and CES cuts, the effect of which is to lower our efficiency by $0.8 \pm 0.8\%$. (This comes from looking at even more extreme cuts, which have a reduction of signal of 1.6%.) Putting them all together, we have to correct this efficiency by $86.0 \pm 2.7\%$. That yields a ratio E_3/E_1 of $2.43 \pm 0.14 \mp 0.30$. The majority of the systematic uncertainty is from the b tagging efficiency, which we keep signed to simplify handling the correlations.

We can put these values into our expression for branching fraction, and doing this we get:

$$BF(t \to q\gamma) = \frac{R}{(4.85 \pm 0.29 \mp 0.59) + (0.46 \pm 0.03 \pm 0.04)R}$$

3.2 Measuring R

There is one event, Run 69519, Event 430034, which passes all cuts: it contains a 72 GeV CMP-only muon, 24 GeV of muon-corrected missing E_T, 3 jets, and an 88 GeV photon candidate. Oddly, it passed neither the photon nor muon triggers, makes it it into the top sample only because it passes the missing E_T trigger. The uncorrected missing E_T is pointing within 20° of the muon, and has almost the same magnitude. Correcting the missing E_T for both the muon and the jets (which is neither the prescription for the standard top analysis nor this one) reduces the missing E_T to 15 GeV. The event primary vertex is outside the SVX fiducial region.

This event is kinematically consistent with the decays $t \to W^+b$, $W^+ \to \mu^+\nu$ and $\bar{t} \to W^-\gamma\bar{b}$, $W^- \to jj$: under this hypothesis, the $\bar{b}$ jet has only about 3 GeV of p_T in the lab frame, and is lost. We expect about 0.2 events of this sort in a data sample of this size, although most such events have lower E_T's than we observe here: an 80 GeV photon is highly unusual.

The CTC and LEGO plots of this event are shown in Figures 2 and 3.

The number of lepton plus 3 more more jets events with an SECVTX tag (in 99.6 pb^{-1}) is 32, with 8 events double tagged. The background is estimated to be 9.2 ± 2.8 *tags*. To go back to the number of events, we consider the two extremes: background events have the same number of b's as signal events, and thus the same ratio of double to single tags, and background events have only a single b. These two extremes yield backgrounds of 7.9 ± 2.2 and 9.9 ± 2.8 events; we use 8.9 ± 3.8 events, which brackets both possibilities. That gives us a signal of $23.1 \pm 5.7 \pm 2.8$ events, for 99.6 pb^{-1}, or $25.5 \pm 6.2 \pm 3.1$ for 110 pb^{-1}.

An observation of 1 event in the $t \to q\gamma$ channel gives a 95% confidence limit of 4.74 events, without considering uncertainties. When the uncertainties are included the limit becomes 5.73 events, and $R < 22.5\%$. This limit is calculated under the conservative assumption that all observed events are signal events.

3.3 Backgrounds

The dominant backgrounds will be real and fake $W + \gamma$ events, plus two jets. There are approximately 0.1 $W + \gamma$ candidates with $E_T > 30$ GeV per inverse picobarn. The number of $W + \gamma$ events (real and background) should scale with number of additional jets in a similar fashion to the inclusive W sample, where 1.5% of the W events have two or more jets. In 110 pb^{-1}, we therefore expect about 1/6 of an event.

3.4 Limits on $BF(t \to q\gamma)$

We now have all the necessary ingredients to set a limit on the FCNC branching fraction $BF(t \to q\gamma)$. Putting the above limit of R into the previously derived relation:

$$BF(t \to q\gamma) = \frac{R}{(4.85 \pm 0.29 \mp 0.59) + (0.46 \pm 0.03 \pm 0.04)R}$$

Or, for the 95% upper limits,

$$BF(t \to q\gamma) < 2.9\%$$

for 0 observed events, and

$$BF(t \to q\gamma) < 4.8\%$$

for 1 observed event. New systematic uncertainties are introduced in going from the measured ratio of events to the branching fractions. If one treats these as an increase on the limit of the number of events, the 95% limit is fewer than 6.04 events for 1 observed event.

4 Limits from the Hadronic Channel

One obvious area in which we can extend this limit is by including the hadronic decays of the W. Unfortunately, the photon plus multijet background is much larger than the lepton plus multijet background, so we need some way of reducing it. Fortunately, these are not ordinary multijets: they are from top decays. In particular, one of these jets contains the daughters of a b quark, and can be identified via SECVTX. (The larger backgrounds than in the $t \to Wb$ analysis make including SLT tagging difficult to justify.)

As before, to calculate the branching fraction we compare the $q\gamma$ mode to the Wb mode. To do this, we need to define another efficiency, again, including branching fractions. E_4 is the efficiency for reconstructing a $t \to Wb\,\bar{t} \to q\gamma$ event in the photon + multijet sample.

The number of events observed in the photon + multijet channel would then be:

$$N_{l-\gamma} = N_{t\bar{t}}\left[2E_4 BF(t \to Wb)BF(t \to q\gamma)\right]$$

and the number observed in the lepton + jets channel would (still) be:

$$N_{l-jets} = N_{t\bar{t}}\left[E_1 BF(t \to Wb)^2 + 2E_2 BF(t \to Wb)BF(t \to q\gamma)\right]$$

we can solve for the branching fraction $BF(t \to q\gamma)$, under the conservative assumption that $BF(t \to Wb) = 1 - BF(t \to q\gamma)$, and using R to notate the ratio of observed photon+multijet events to lepton+jets events:

$$BF(t \to q\gamma) = \frac{RE_1}{2E_4 + (E_1 - 2E_2)R}$$

4.1 Event Selection

In this sample, events are required to have a 50 GeV photon, a SECVTX b tag, and four or more jets. Additionally, there must be at least one photon-jet combination with a mass between 140 and 210 GeV. (The $t \to q\gamma$ decay) Only loose identification cuts are required on the other t-quark: the transverse energies of the other jets ($E_T > 15$ GeV) in the event are summed, and this value is required to be above 150 GeV. Figure 4 shows that this requirement is relatively efficient for signal events, but rejects a great deal of background.

No events pass these cuts. If one relaxes the 50 GeV cut to 30 GeV and loosens the photon requirements, 3 events survive. Two of these have "photons" which are likely to be π^0's. None of these events would pass a ΣE_T cut of 200 GeV, although if these were real $t \rightarrow q\gamma$ events we would expect around two to pass. From this, we conclude that these cuts are not too tight.

4.2 Calculating Efficiencies

Once again, to get E_4, we use ISAJET. The appropriate sample here is ALLHAD, where (like TGAMMA) one top decays to $W + b$ and the other to $q + \gamma$. Unlike TGAMMA, however, we do not require a lepton in the event. As before, the events are simulated with QFL, and again as before, we limit the accuracy of this procedure to 5%. 10,000 events are generated, and 2314 survive the cuts, of which 25% are b-tagged. The ratio E_4/E_1 is therefore $1.54 \pm 0.09 \mp 0.10$, including the photon requirements.

Note that E_4 is about 2/3 of E_3. 40% of our total acceptance is in the photon plus multijet mode, and 60% in the lepton plus photon mode. Clearly, b tagging gives CDF a large advantage over other experiments that do not have it - almost a factor of 2.

We can put these values into our expression for branching fraction, and doing this we get:

$$BF(t \rightarrow q\gamma) = \frac{R}{(3.07 \pm 0.18 \mp 0.20) + (0.46 \pm 0.03 \pm 0.04)R}$$

4.3 Limits on $BF(t \rightarrow q\gamma)$

We again have all the necessary ingredients to set a limit on the FCNC branching fraction $BF(t \rightarrow q\gamma)$ in the all hadronic mode. R is determined as before for 0 observed events.

$$BF(t \rightarrow q\gamma) = \frac{R}{(3.07 \pm 0.18 \mp 0.20) + (0.46 \pm 0.03 \pm 0.04)R}$$

Or (at 95% confidence, where 0 observed events works out to fewer than 3.57 events),

$$BF(t \rightarrow q\gamma) < 4.5\%$$

5 Combining the Limits

Since the two samples are independent, the simplest way to combine the limits is to calculate the combined efficiency and acceptance that an event of interest will appear in *either* the lepton plus photon or photon plus multijet analysis.

The number of events observed in either channel is:

$$N_{t\to c\gamma} = N_{t\bar{t}}\left[2(E_3+E_4)BF(t\to Wb)BF(t\to q\gamma)\right]$$

and the number observed in the lepton + jets channel would be, once again:

$$N_{l-jets} = N_{t\bar{t}}\left[E_1 BF(t\to Wb)^2 + 2E_2 BF(t\to Wb)BF(t\to q\gamma)\right]$$

so the branching fraction limit becomes:

$$BF(t\to q\gamma) = \frac{RE_1}{2(E_3+E_4)+(E_1-2E_2)R}$$

or, putting the numbers in:

$$BF(t\to q\gamma) = \frac{R}{(7.92\pm 0.34\mp 0.79)+(0.46\pm 0.03\pm 0.04)R}$$

Which yields a 95% confidence limit of

$$BF(t\to q\gamma) < 2.9\%$$

for one observed event. When one includes the uncertainties, the limit on the number of $t\to q\gamma$ events, is that there are fewer than 5.95.

Note that $BF(t\to q\gamma) = BF(t\to c\gamma) + BF(t\to u\gamma)$. Although we make no attempt to separate the two processes, at least one of them must have a branching fraction less than 1.5%.

6 Uncertainties

The dominant uncertainty in this analysis is the normalization: how many $t\bar{t}$ events do we see in the lepton + 3 more more jets (at least one jet b-tagged) in 110 pb^{-1}?

That uncertainty is 27%, which works out to 14-18 % in the branching fraction limit. Granted, it's scaled from 100 pb^{-1}, so in principle we can improve this to 26% or 25% soon. It is, however, unlikely that we can make great strides in this direction in the near future: we're fighting $1/\sqrt{N}$.

The next largest is the b-tagging efficiency uncertainty, which contributes a 10% uncertainty in the efficiency and the acceptance. While in principle this might be reduced to 8% or 7%, since it's added in quadrature with such a large number, the improvement in the final result would be small. This uncertainty contributes about 3% to the branching fraction limit.

The next largest are the acceptance uncertainty (5%) and photon identification uncertainty (3%). These are almost negligible once added in quadrature to the other uncertainties.

To summarize, it seems unlikely that reducing the systematic uncertainties further will make any difference in the final result: we're dominated by the number of events in the Standard Model decay channel, and the only way that number will increase is by taking more data. Adding in the SLT data, with it's larger background, doesn't improve this, introduces a new uncertainty (SLT efficiency) and increases the impact of the SVX tagging efficiency uncertainty. It does not improve the final result. In fact, adding more data helps with the search channel ($1/N$) even more than in the normalization channel ($1/\sqrt{N}$).

7 Conclusions

We have searched for the FCNC decay $t \to u(c) + \gamma$. One event passing all cuts is seen in the lepton + photon + jets channel and no evenys passing all cuts is seen in the photon plus multijets channel with 110 pb^{-1} of data, allowing us to set the following limits:

$$BF(t \to c\gamma) + BF(t \to u\gamma) < 2.9\%$$

One of the two branching fractions (we can't tell which one) has to be under 1.5%.

References

[1] S. Parke, *Summary of Top Quark Physics*, FERMILAB -Conf-94/322-T. Presented at DPF'94, University of New Mexico, Alburquerque, NM, August 2-6,

1994

[2] CDF Note 3099: "Preliminary measurement of $W\gamma$ and $Z\gamma$ Production in Run 1A and Run 1B"

[3] CDF Note 2133: "Measurement of $W+\gamma$ and $Z+\gamma$ Cross Sections in the Electron and Muon Channels in $\sqrt{s} = 1.8$ TeV $\overline{p}p$ Collisions". There are similar numbers for Run 1. See, for example, D. Benjamin, "Search for Anomalous Couplings and Diboson Production", Talk at the 10th Topical Workshop on Proton Antiproton Collider Physics, May 11, 1995.

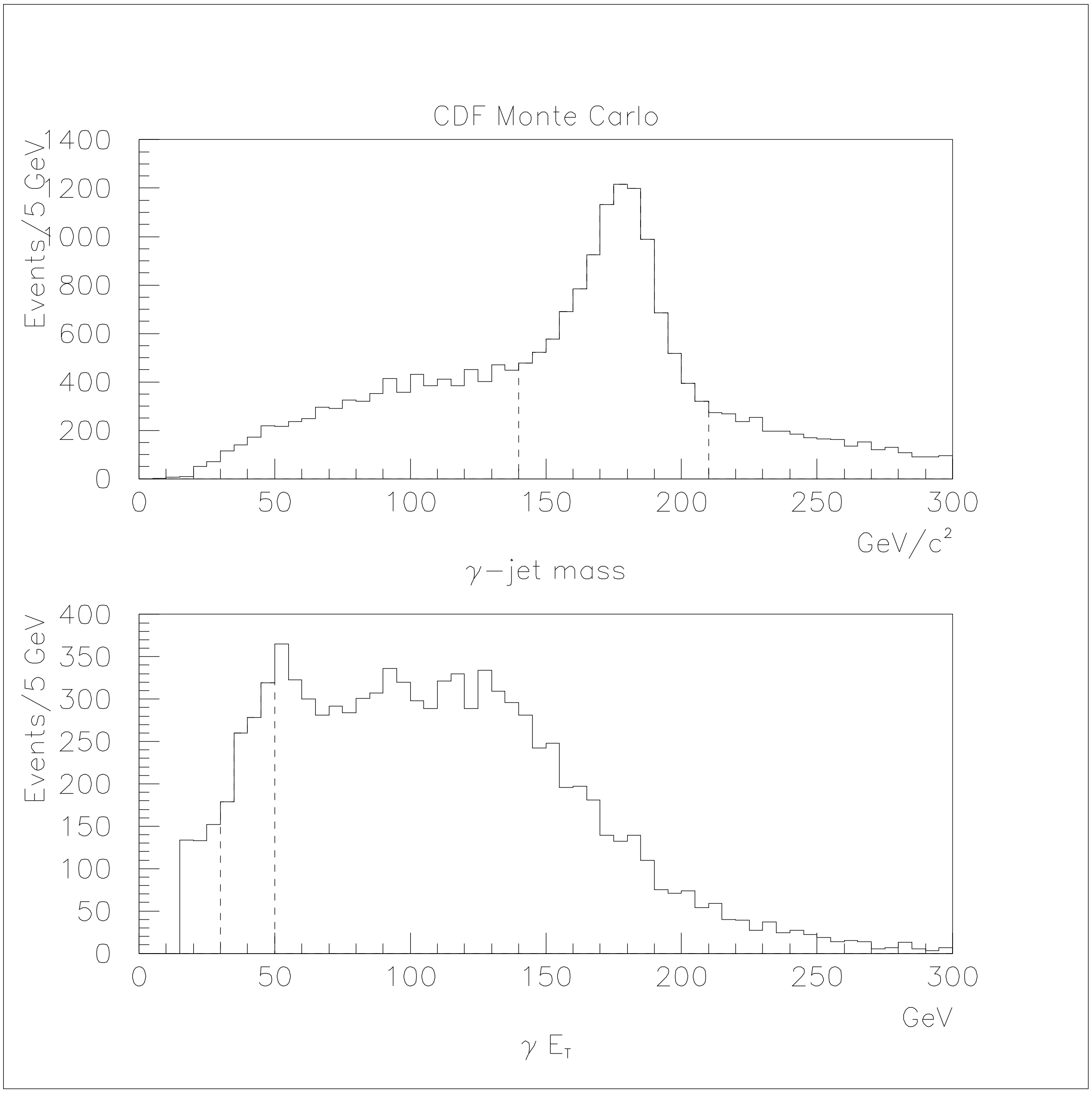

Figure 1: Top: Photon-jet mass for Monte Carlo $t \rightarrow q\gamma$ events. The dashed lines indicate the mass windows of 140-210 GeV used in the search in the $b + \gamma$+jets mode. Bottom: Photon transverse energy for Monte Carlo $t \rightarrow q\gamma$ events. Dashed lines are at 30 GeV (cut in the $W + \gamma$+jets mode) and 50 GeV (cut in the $b + \gamma$+jets mode.)

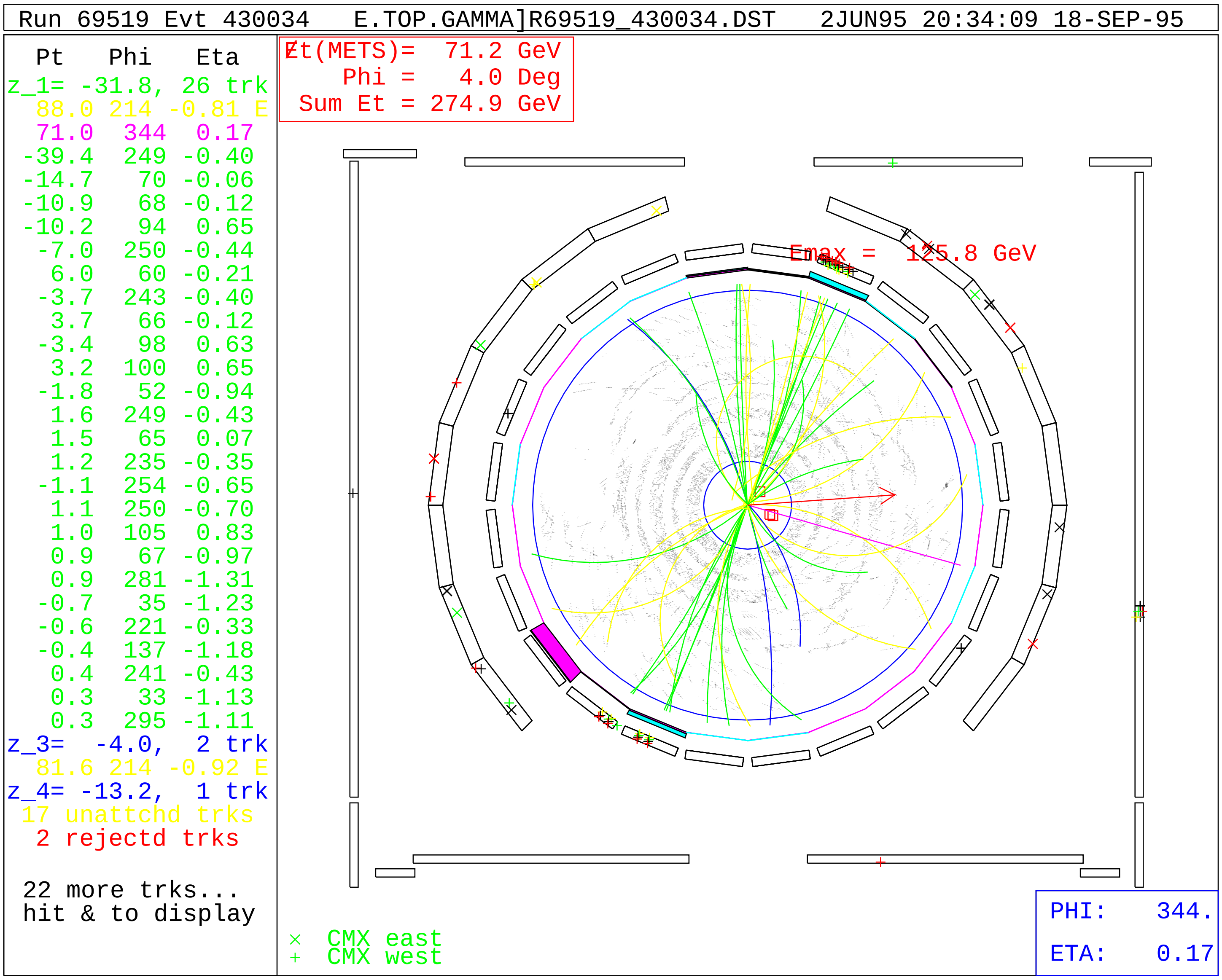

Figure 2: CTC Display for the unusual $W+\gamma$ event. The CMP muon is between wedges 22 and 23.

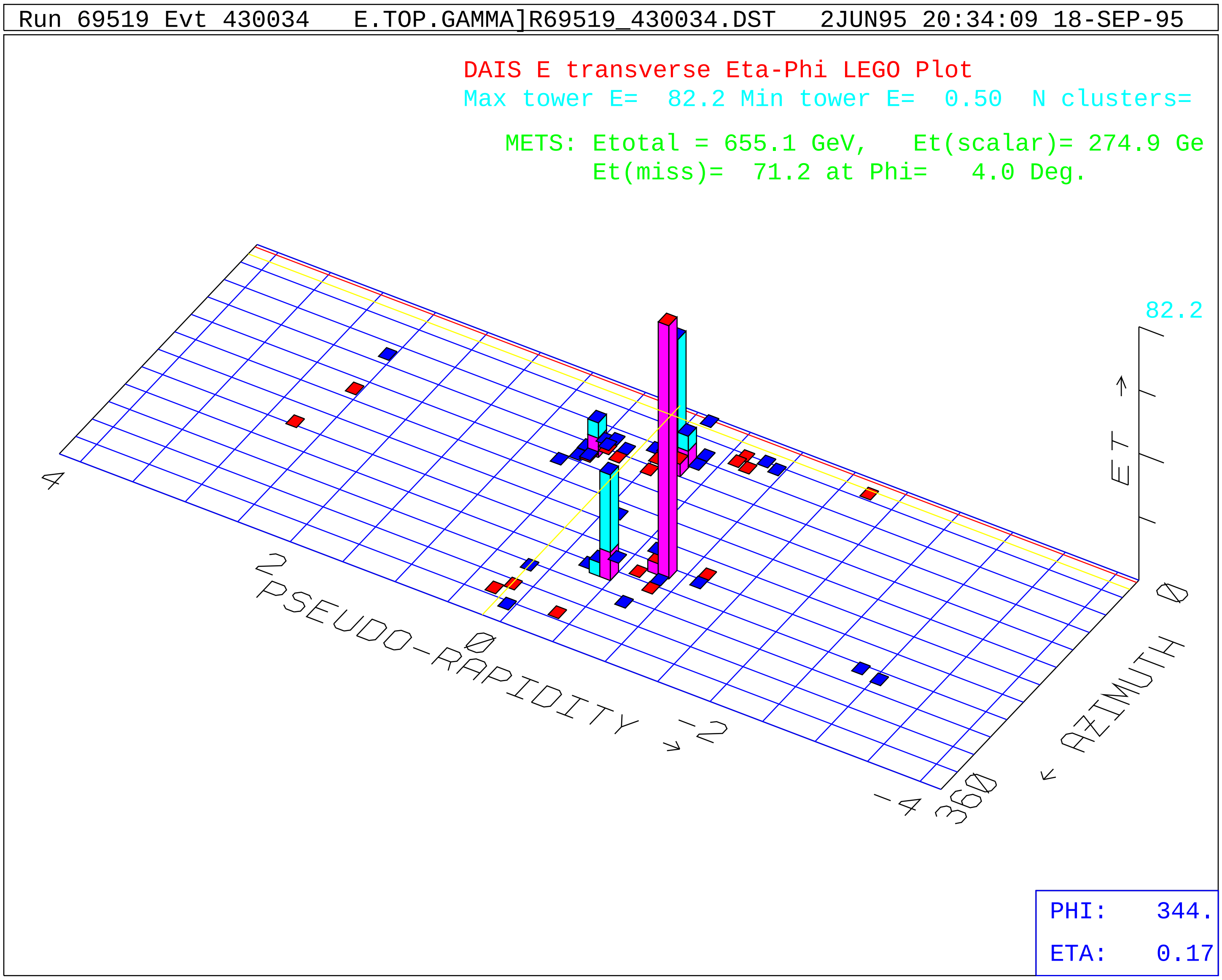

Figure 3: Lego Display for the unusual $W + \gamma$ event. It looks better with ϕ reversed, but DF is being stubborn about displaying in that view.

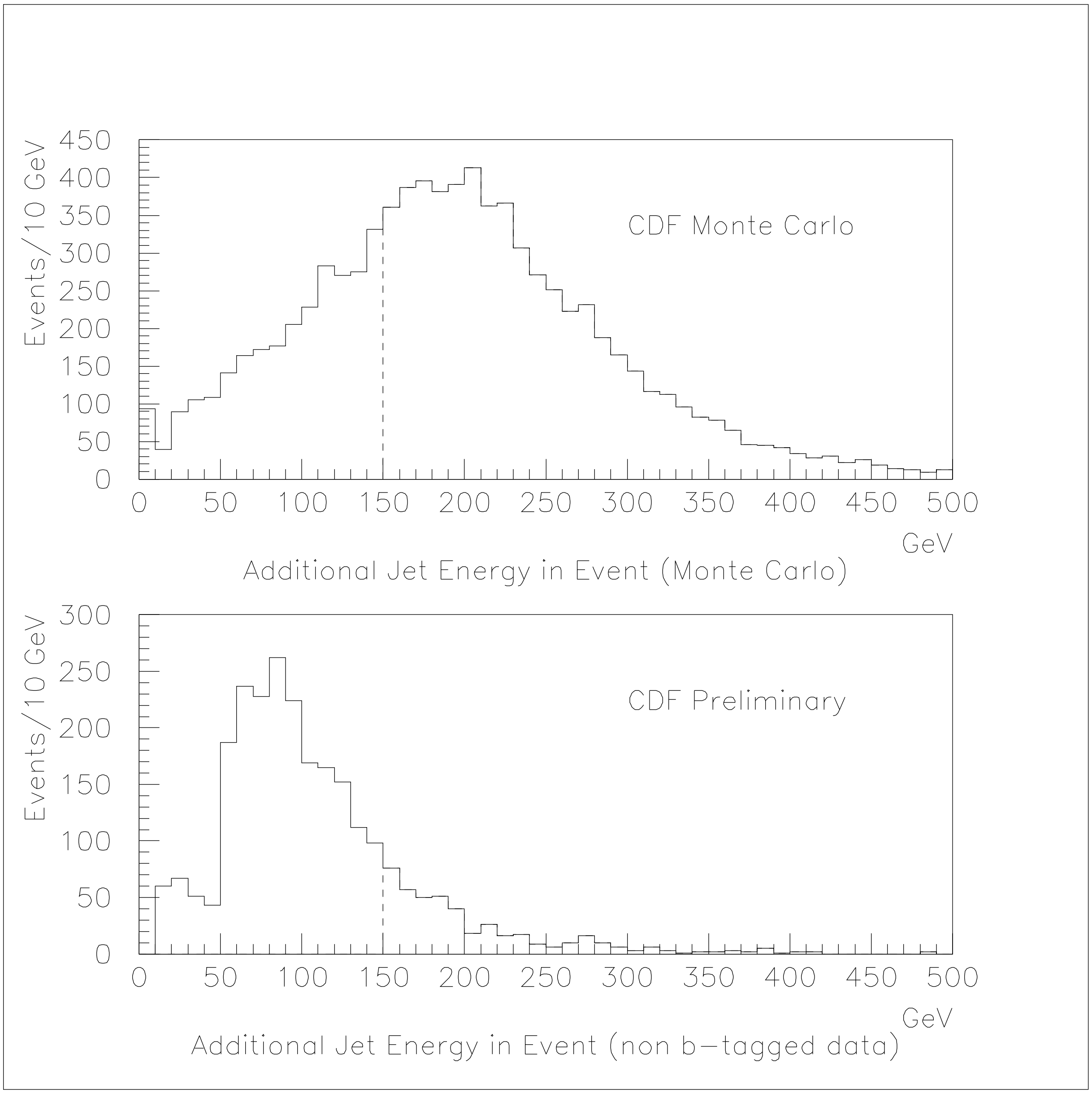

Figure 4: Top: The scalar transverse energy sum of jets above 15 GeV in Monte Carlo $t \to q\gamma$ events, after the jet participating in the top γ-jet combination has been removed. Bottom: The same distribution in pre b-tagged data. The "edge" at 50 GeV is an artifact of the 50 GeV photon cut.