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SOLENOIDAL DETECTOR NOTES

Forward Jets and Missing E_T

R. D. Field

Institute for Fundamental Theory, Department of Physics

University of Florida, Gainesville, FL 32611

Abstract

In 40 TeV proton-proton collisions a high transverse momentum jet which at $\theta_{cm}(\text{jet}) = 90°$ would have its particles located within a "cone" with a half angle of roughly 28°, when boosted to the forward direction, $\eta(\text{jet}) < 4$ ($\theta_{cm} < 2°$), becomes a "disk" with an angular width of $\Delta\theta_{cm} < 1°$. This report examines how much these forward jets contribute to the missing transverse energy if they are not measured (due to lack of rapidity coverage) or if they are inaccurately measured (due to, for example, a large calorimeter cell size and hence bad spatial resolution). Missing a forward jet (or assigning it the wrong transverse momentum) results in "fake" missing transverse energy (*i.e.*, missing transverse energy that is not due to neutrinos, photinos, *etc.*). "Fake" missing E_T is a background to the *true* missing E_T that can be used as a signal for new physics.

UNIVERSITY OF FLORIDA
Gainesville, Florida 32611

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In 40 TeV proton-proton collisions a high transverse momentum jet which at $\theta_{cm}(\text{jet}) = 90°$ would have its particles located within a "cone" with a half angle of roughly 28°, when boosted to the forward direction, $\eta(\text{jet}) < 4$ ($\theta_{cm} < 2°$), becomes a "disk" with an angular width of $\Delta\theta_{cm} < 1°$. This report examines how much these forward jets contribute to the missing transverse energy if they are not measured (due to lack of rapidity coverage) or if they are inaccurately measured (due to, for example, a large calorimeter cell size and hence bad spatial resolution). Missing a forward jet (or assigning it the wrong transverse momentum) results in "fake" missing transverse energy (*i.e.,* missing transverse energy that is not due to neutrinos, photinos, *etc.*). "Fake" missing E_T is a background to the *true* missing E_T that can be used as a signal for new physics.

I. Introduction

In hadron-hadron collisions at high energy jets in the forward region (*i.e.*, $\eta(\text{jet}) > 3$) arise from two-to-two subprocess in which the parton-parton center of mass is "boosted" along the incident proton direction (*i.e.*, along the $\hat{z}$-axis). Because of the Lorentz contraction "jets" no longer appear, on the average, as cones. The shape in the azimuthal angle ϕ remains roughly invariant, while the shape in θ_{cm} is compressed. The width of a jet in rapidity remains invariant. Shapes in pseudorapidity remain roughly invariant except for slow particles where mass effects become important. This means that jets in the forward region look, in the laboratory, more like sections of a "disk". In 40 TeV proton-proton collisions a 90° jet with a "radius" $R = 0.5$ when "boosted" in the forward region to $\eta(\text{jet}) = 4$ ($\theta_{cm} = 2°$) appears in the laboratory as "disk" with an azimuthal width of $\Delta\phi = 28°$ and an angular width of $\Delta\theta_{cm} = 1°$ [1].

There are several reasons why accurate measurements of these forward jets might be important. For example, "tagging" forward jets enhances certain subprocesses such as WW or ZZ fusion relative to the background. Also, accurate determination of the forward jets is necessary in order to veto on missing transverse energy opposite to the jet. This is an important ingredient in enhancing the heavy gluino signal [2]. In this report I will not discuss why forward jets should be measured, but instead concentrate on what happens if they are *not* measured . Missing a forward jet (or assigning it the wrong transverse momentum) results in "fake" missing transverse energy (*i.e.*, missing transverse energy that is not due to neutrinos, photinos, *etc.*). "Fake" missing E_T is a background to the *true* missing E_T that can be used as a signal for new physics. Jets can produce "fake" missing transverse energy due to the following:

- **Rapidity Coverage:** A jet can "leak" outside the rapidity coverage of the experiment and not be observed.
- **Cell Size:** The jet momentum can be determined inaccurately due the cell size of the calorimeter. A calorimeter with large cell size and thus bad position resolution cannot accurately determine the momentum and transverse energy of the jet.

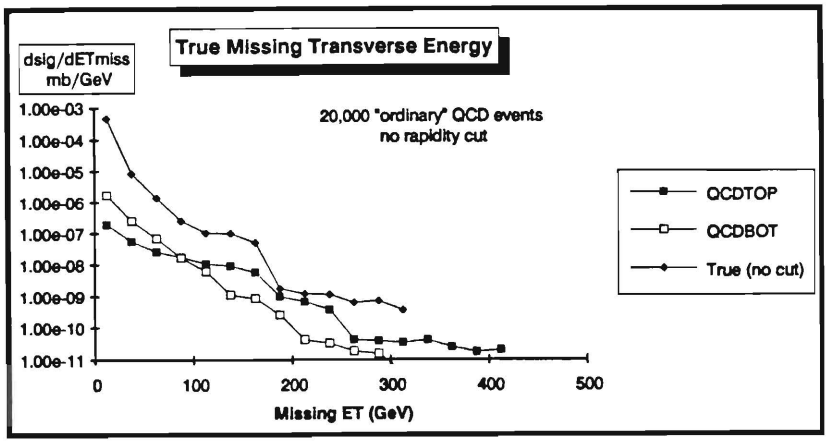

Figure 1 Shows the *true* missing transverse energy from a perfect calorimeter with complete rapidity coverage, $\not{E}_T$(true no cut), for "ordinary" QCD "two-jet" events in proton-proton collisions at 40 TeV. Also shows the contribution to $\not{E}_T$(true no cut) from $b\bar{b}$ and $t\bar{t}$ production.

- **Energy Resolution:** The jet energy and hence transverse energy can be determined inaccurately due the energy resolution of the calorimeter.

The *true* missing transverse energy in an event is caused by neutrinos or other (as yet undiscovered) very weakly interacting particles that are not be detected. "Fake" missing transverse energy results from a lack or rapidity coverage or an imperfect calorimeter. A perfect "4π" calorimeter would yield only the *true* missing transverse energy. I will examine in detail the "fake" missing transverse energy generated by lack of rapidity coverage and by bad spatial resolution (due to a large calorimeter cell size). The energy resolution does not play a major factor in generating "fake" missing E_T and, thus, I will only discuss it briefly.

II. Event Generation

ISAJET is used to generate ordinary "two-jet" QCD events in 40 TeV proton-proton

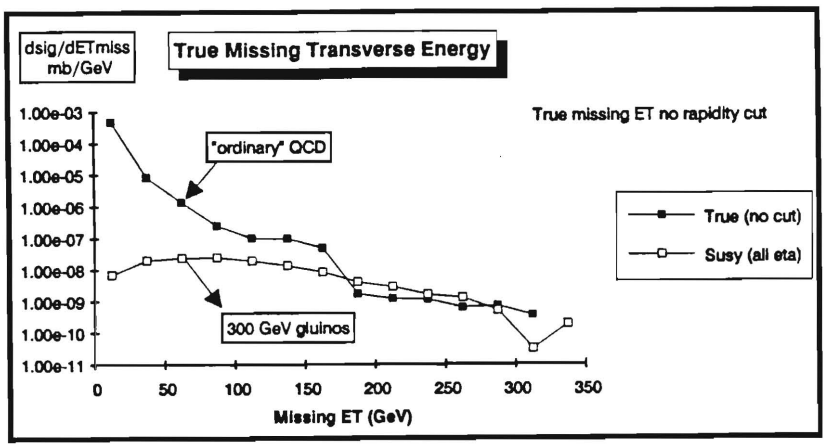

Figure 2 Shows the *true* missing transverse energy from a perfect calorimeter with complete rapidity coverage, $\not{E}_T$(true no cut), for "ordinary" QCD "two-jet" events (same as Fig. 1) together with the $\not{E}_T$(true no cut) resulting from the production of 300 GeV gluinos in proton-proton collisions at 40 TeV.

collisions with the hard-scattering transverse momentum, $\hat{k}_T$, in the range $100 \leq \hat{k}_T \leq 500$ GeV and with no restriction on the pseudorapidity of the jets.

III. Missing Transverse Energy

In order to examine the various sources of missing transverse energy it is instructive to define the following quantities:

- **$\not{E}_T$(true no cut):**

  This is the *true* missing E_T in the event. Every particle is included except neutrinos (*i.e.*, perfect calorimeter, total η-ϕ coverage). This is the exact transverse momentum of neutrinos in the event.

- **$\not{E}_T$(true cut):**

  This is the *true* missing E_T computed for a perfect calorimeter covering a finite rapidity region (or cut). The difference between $\not{E}$(true cut) and $\not{E}$(true no cut)

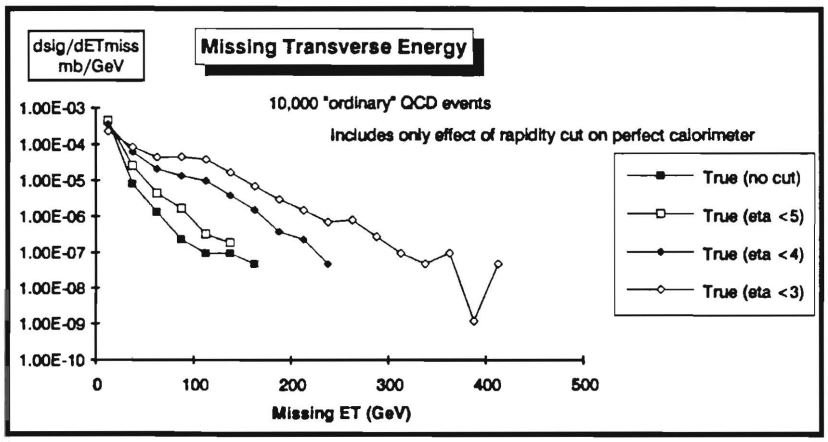

Figure 3 Illustrates the effect of rapidity coverage on the missing transverse energy by comparing $\not{E}$(true no cut) with $\not{E}$(true cut) for several rapidity ranges in "ordinary" QCD "two-jet" events in proton-proton collisions at 40 TeV.

is due entirely to the lack of complete rapidity coverage.

- **$\not{E}_T$(grid):**

  This is the missing E_T computed in a given rapidity region (or cut) using transverse energy cells of a given size (*i.e.*, $\Delta\eta\Delta\phi$). The difference between $\not{E}$(grid) and $\not{E}$(true cut) is due entirely to the calorimeter resolution(*i.e.*, cell size and energy resolution). The difference between $\not{E}$(grid) and $\not{E}$(true no cut) is due to both the resolution (*i.e.*, cell size) ***and*** to the lack of complete rapidity coverage.

- **$\not{E}_T$(true cut) - $\not{E}_T$(true no cut):**

  This quantity measures the "fake" missing E_T resulting from incomplete rapidity coverage.

- **$\not{E}_T$(grid) - $\not{E}_T$(true cut):**

  This quantity measures the "fake" missing E_T resulting from the calorimeter resolution (*i.e.*, grid cell size and energy resolution).

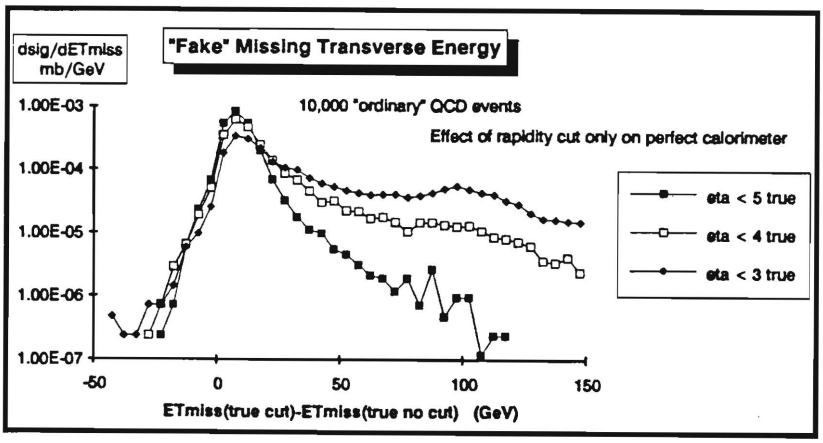

Figure 4 Shows the "fake" missing transverse energy, $\not{E}_T$(true cut) - $\not{E}_T$(true no cut), produced from the lack of rapidity coverage in "ordinary" QCD "two-jet" events in proton-proton collisions at 40 TeV.

- **$\not{E}_T$(grid) - $\not{E}_T$(true no cut):**

  This quantity measures the "fake" missing E_T resulting from both the calorimeter resolution *and* the lack of complete rapidity coverage.

Fig. 1 shows the *true* missing transverse energy from a perfect calorimeter with complete rapidity coverage (*i.e.*, $\not{E}$(true no cut)) resulting from 20,000 "ordinary" QCD "two-jet" events in proton- proton collisions at 40 TeV. The *true* missing E_T is precisely the net transverse momentum of the neutrinos in the event. The production of $b\bar{b}$ and $t\bar{t}$ pairs contributes significantly to $\not{E}$(true no cut). Missing transverse energy is one signal of "new" physics. For example, Fig. 2 compares the *true* missing transverse energy resulting from the production of 300 GeV gluinos with $\not{E}$(true no cut) from Fig.1. The decay chain of the gluions eventually produce photinos which act like neutrinos and are not detected, thus producing large amounts of $\not{E}$(true no cut). Missing transverse energy can be used to get a handle on the "new" physics as long as the missing E_T signal from the "new" physics is comparable or greater than the "fake" missing transverse energy from the ordinary QCD

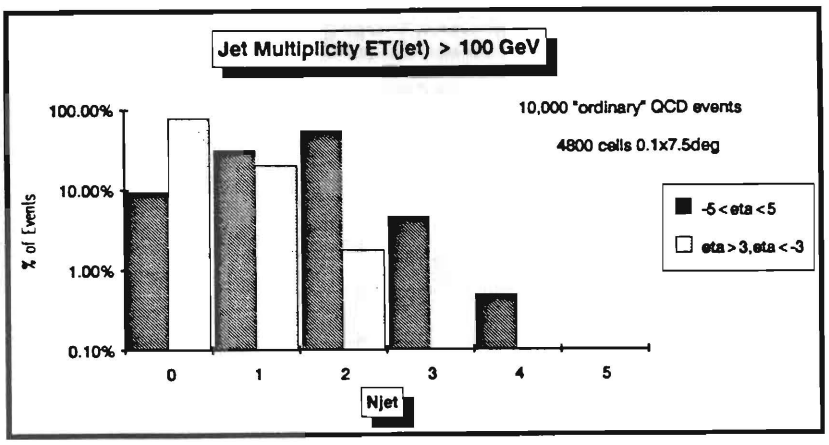

Figure 5 Shows the number of jets with $E_T(jet) > 100\,\mathrm{GeV}$ (ΔR=1.0)produced in "ordinary" QCD "two-jet" events in proton-proton collisions at 40 TeV in the pseudorapidity range $-5 < \eta < 5$ and in the pseudorapidity range $3 < |\eta| < 5$.

background.

The more $\not{E}_T$(true cut) and $\not{E}_T$(grid) deviate from $\not{E}$(true no cut) the larger the background becomes and the missing E_T becomes a less effective handle. Fig. 3 illustrates the effect of rapidity coverage on the missing transverse energy from "ordinary" QCD "two-jet" events by comparing $\not{E}_T$(true no cut) with $\not{E}_T$(true cut) for several rapidity cuts. Fig. 4 shows the "fake" missing transverse energy, $\not{E}_T$(true cut) - $\not{E}_T$(true no cut), produced from the lack of rapidity coverage in "ordinary" QCD "two-jet" events. The source of the "fake" missing E_T is obvious. If one has incomplete rapidity coverage than occasionally one misses a forward going jet which then is interpreted as missing transverse energy. Figs. 5 and 6 show the number of jets with $E_T(jet) > 100\,\mathrm{GeV}$ in the pseudorapidity range $-5 < \eta < 5$ and in the pseudorapidity range $3 < |\eta| < 5$. Roughly 20% of the time there is one jet with $E_T > 100\,\mathrm{GeV}$ in the region $3 < |\eta| < 5$ and missing these jets results in a large "fake" missing E_T signal.

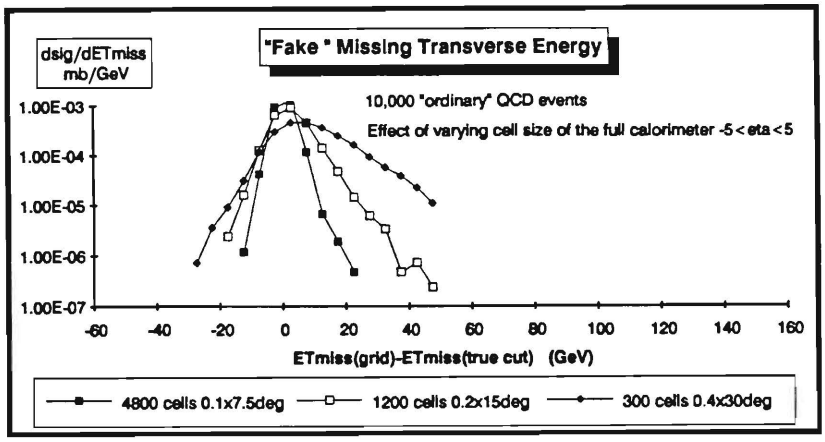

Figure 6 Shows effect of varying the cell size of the full calorimeter covering the rapidity range $-5 < \eta < 5$ on the "fake" missing transverse energy, $\not{E}_T$(grid) - $\not{E}_T$(true cut), in "ordinary" QCD "two-jet" events in proton-proton collisions at 40 TeV.

Fig. 7 shows effect of varying the cell size of the full calorimeter covering the rapidity range $|\eta| < 5$ on the "fake" missing transverse energy, $\not{E}_T$(grid) - $\not{E}_T$(true cut), in "ordinary" QCD "two-jet" events. The calorimeter is varied from 4,800 cells with size $\Delta\eta\Delta\phi = 0.1 \times 7.5°$ to 300 cells with size $\Delta\eta\Delta\phi = 0.4 \times 30°$. Here the energy resolution is taken as perfect with the "fake" missing transverse energy being produced solely by a lake of spatial resolution (*i.e.*, the cell size). Fig. 8 shows the combined effect of rapidity coverage *and* cell size on the "fake" missing transverse energy for the calorimeter choices in Fig. 7.

Figs. 9 and 10 examines the effect of varying the cell size of the forward ($3 < \eta < 5$) and backward ($-5 < \eta < -3$) calorimeter. Here the central calorimeter ($-3 < \eta < 3$) is fixed with 2,280 cells with size $\Delta\eta\Delta\phi = 0.1 \times 7.5°$ and the forward (and backward) calorimeter is varied from one cell to 960 cells. Fig. 9 shows $\not{E}_T$(grid) - $\not{E}_T$(true cut) and thus reflects *only* the effect of forward calorimeter cell size on the "fake" missing transverse energy. Fig. 10, on the other hand, shows $\not{E}_T$(grid) - $\not{E}_T$(true no cut) and thus illustrates

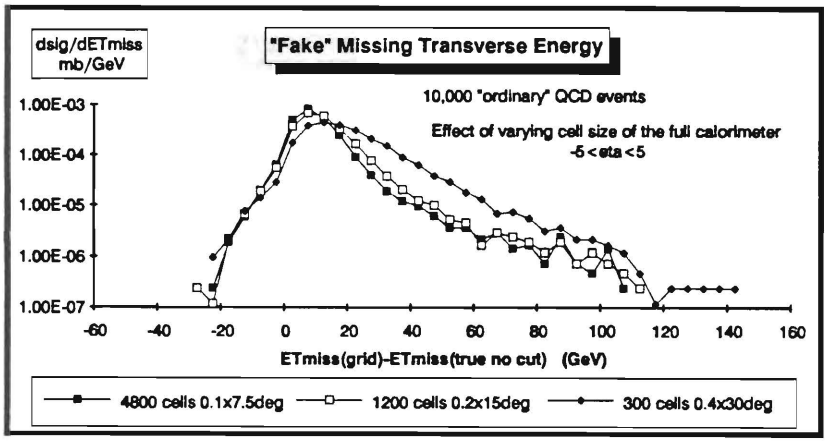

Figure 7 Shows the combined effects of rapidity coverage *and* cell size on the "fake" missing transverse energy, $\not{E}_T$(grid) - $\not{E}_T$(true cut), in "ordinary" QCD "two-jet" events in proton-proton collisions at 40 TeV for the calorimeters ($|\eta| < 5$) in Fig.6 .

the combined effect of rapidity coverage *and* forward calorimeter cell size.

Rapidity coverage is clearly the dominate factor. Whereas decreasing the calorimeter cell size results in a steady improvement in Fig. 9 (*i.e.*, less "fake" missing E_T), in Fig. 10 one soon reaches a limiting curve that is determined by the overall rapidity coverage. For example, Fig. 10 shows that one cell in the forward calorimeter is useless, however by the time one increases to 32 cells ($\Delta\eta\Delta\phi = 0.5 \times 45°$) one has almost reached the limit dictated by the overall rapidity coverage, $|\eta| < 5$. Decreasing the cell size further does not significantly reduce the "fake" missing transverse energy.

IV. Summary and Conclusions

Rapidity coverage is key factor in reducing the "fake" missing transverse energy produced by ordinary QCD events. If one has incomplete rapidity coverage than occasionally one misses a forward (or backward) going jet which then is interpreted as missing trans-

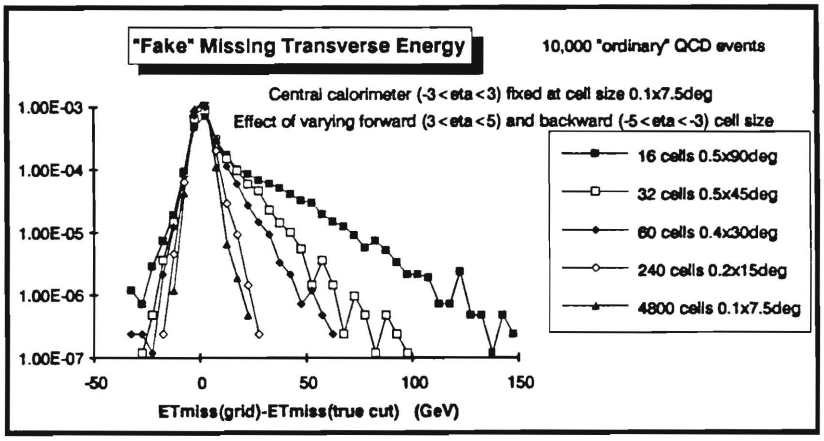

Figure 8 Shows the effect of varying the cell size, $\Delta\eta\Delta\phi$, of the forward (and backward) calorimeter covering the rapidity range $3 < \eta < 5$ ($-5 < \eta < -3$) on the "fake" missing transverse energy, $\not{E}_T$(grid) - $\not{E}_T$(true cut), in "ordinary" QCD "two-jet" events in proton-proton collisions at 40 TeV. The central calorimeter ($|\eta| < 3$) has the cell size $\Delta\eta\Delta\phi = 0.1 \times 7.5°$.

verse energy. If jets had their particles located, on the average, within "cones" of fixed angular size (for example, $\Delta\theta = 28°$), then one would not loose much of the overall jet transverse energy in a small beam hole of 2° or 3°! However, in high energy proton-proton collisions the width of a jet in rapidity remains invariant. In 40 TeV proton-proton collisions this jet, when boosted to the forward direction, becomes a "disk" with an angular width of $\Delta\theta_{cm} < 1°$. Such a compressed jet can easily "squeeze" outside the rapidity coverage (carrying its transverse energy with it).

In reducing "fake" missing transverse energy, the calorimeter cell size is not nearly as important as the rapidity coverage. A crude calorimeter does fine. However, if the cell size in the forward region is too large one effectively looses rapidity coverage. A cell size of $\Delta\eta = 0.1$ in the forward region is fine for the missing E_T. In fact, $\Delta\eta = 0.2$ would be acceptable. Energy resolution is even less important than the cell size. From the "fake" missing E_T point of view a crude forward calorimeter covering a large rapidity region is

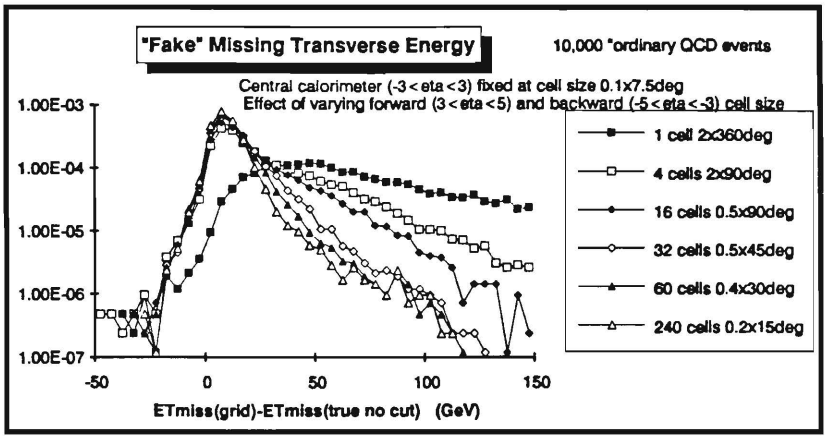

Figure 9 Shows the effect of varying the cell size, $\Delta\eta\Delta\phi$, of the forward (and backward) calorimeter covering the rapidity range $3 < \eta < 5$ $(-5 < \eta < -3)$ on the "fake" missing transverse energy, $\not{E}_T$(grid) - $\not{E}_T$(true no cut), for "ordinary" QCD "two-jet" events in proton-proton collisions at 40 TeV. The central calorimeter ($|\eta| < 3$) has the cell size $\Delta\eta\Delta\phi = 0.1 \times 7.5^\circ$.

better than a good calorimeter covering a small rapidity range. There are, of course, other reasons for wanting a forward calorimeter with good spatial and energy resolution.

It is important not to miss too many of the forward jets in high energy proton-proton collisions. In a subsequent report, I will investigate the usefulness of observing and measuring these forward jets.

References

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2. *Determining the Mass of the Gluino at the SSC*, R. M. Barnett, J. F. Gunion, and H. E. Haber, Research Directions for the Decade, Snowmass 1990, p. 201.

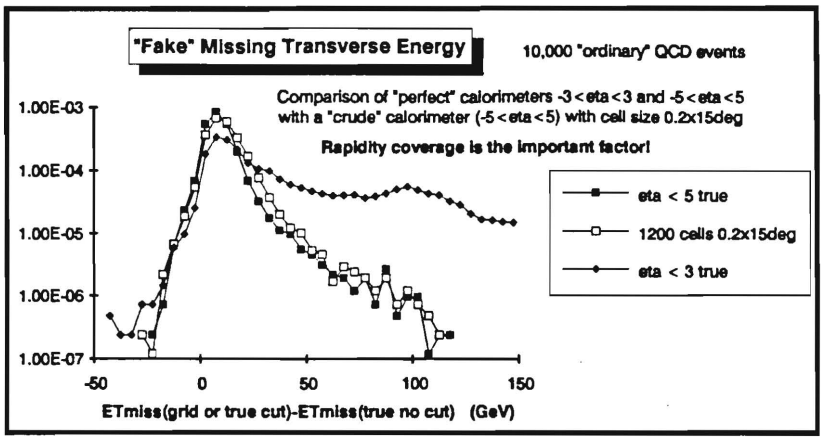

Figure 10 Comparison of the "fake" missing transverse energy, $\not{E}$(true cut) - $\not{E}$(true no cut) from perfect calorimeters covering $|\eta| < 5$ and $|\eta| < 3$ with the fake missing transverse energy, $\not{E}_T$(grid) - $\not{E}_T$(true no cut), from a coarse calorimeter ($|\eta| < 5$) with cell size $\Delta\eta\Delta\phi = 0.2 \times 15^\circ$, for "ordinary" QCD "two-jet" events in proton-proton collisions at 40 TeV.