IDENTIFICATION OF THE FOURTH GENERATION QUARK AT THE SSC

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1. Summary

The identification of the 4-th generation quark, Y quark, at the SSC is studied about the Y quark decaying into a t quark and a real W. The results show that the present procedure is able to find the Y quark with mass of 500 GeV/c^2 in reasonable separation from W^+W^- events.

2. Introduction

The feasibility of identifying the 4-th generation quark , Y quark, is studied with a simulation at the SSC, pp collider at $\sqrt{s}$ = 40 TeV. The question how many quark/lepton generations are is one of the outstanding puzzles in the present understanding of particle physics. It has been studied how to find the 4-th generation quark at a hadron collider .[1] The SSC with its huge cms energies available provides a good place to search for new heavy particles.

In the present analysis, the mass of Y quark was assumed to be 500 GeV/c^2 so that the Y quark decays predominantly into a t quark and a real W. The algorithm to identify $Y\bar{Y}$ event requires the decay mode of Y ($\bar{Y}$) $\rightarrow$ t ($\bar{t}$) + $W^-(W^+)$ $\rightarrow$ t ($\bar{t}$) + $e^-(e^+)$ + $\bar{\nu}_e(\nu_e)$, and $\bar{Y}$ (Y) $\rightarrow \bar{t}$ (t) + $W^+(W^-) \rightarrow \bar{t}$ (t) + q + $\bar{q}'$. These events are identified as W^- + W^+ + t + $\bar{t}$ with one of W decaying leptonically, another W decaying hadronically and both t quarks identified as 2 or more jets.

3. General Description of the Simulation Procedures

Events were generated with the ISAJET, the version 5.20 in the CDF offline package Version 4.0. The parton distribution functions used in the program are those of Eichten et al.[2] The mass of the top quark was assumed to be 40 GeV/c^2. The QCD (quark or gluon) jets generated in parton-parton collisions or via W decays are evolved into an ensemble of final partons using the leading-log QCD procedure of Fox and Wolfram,[3] with a cutoff mass of 7 GeV/c^2. These final partons are then fragmented into hadrons by the Field-Feynman ansatz.[4] The cut Reggeon field theory of Abramovski et al.[5] is used to generate the beam jets.

A simplified model of the calorimeters was assumed in the simulation. The calorimeters had an angular coverage of $|\eta| <$ 6.0, with (η, ϕ) segmentations of $\Delta\eta$ = 0.03 and $\Delta\phi$ = 0.03. The energy resolutions of the calorimeters were 15%/$\sqrt{E(GeV)}$ for electrons and photons, and 60%/$\sqrt{E(GeV)}$ for hadrons. Jets were reconstructed from energy depositions in the calorimeter cells by the clustering algorithm[6], in which the magnitude of the jet transverse energy was taken into account in defining the cluster cone size. The clusters were required to have a transverse energy larger than 5 GeV. Two adjacent clusters were merged into a jet if their separation in the (η , ϕ) space was smaller than the cluster sizes.

4. Event generation

The 4-th generation Y quarks will be pair-produced copiously in pp collisions at $\sqrt{s}$ = 40 TeV, if its mass is below 1 TeV.[2] The feasibility of detecting $Y\bar{Y}$ pairs was investigated through the decay channel in which one of the pair quarks decayed semileptonically and the other decayed hadronically:

$$p + p \rightarrow Y + \bar{Y} + \text{anything} \quad (1)$$
$$\hookrightarrow \bar{t} + W^+ \hookrightarrow e^+ + \nu_e$$
$$\hookrightarrow t + W^- \hookrightarrow q + \bar{q}'$$

The mass of Y was assumed to be 500 GeV/c^2. 100,000 events were generated in the Pt range 10 to 200 GeV/c. In order to identify these events as the $Y\bar{Y}$ events, we imposed the following criteria. Both Y quarks decay into W and t quark. One of W should decay leptonically into (a) a high Pt electron with Pt > 25 GeV/c and (b) a high Pt neutrino (missing Pt) with Pt > 25 GeV/c. The following additional cuts were also applied to reject the events which have more than one neutrino: (c) There should be no muons with Pt > 10 GeV/c, and there should be one and only one electron with Pt > 10 GeV/c. The other W should decay hadronically into (d) 2 jets with Pt > 20 GeV/c. Both t quarks decay into (e) 2 or more jets with Pt > 20 GeV/c. The total number of jets required in the above criteria is 6 or more. Figure 1a and 1b show the distribution of the number of jets for all events and the distribution of the number of jets after the high Pt electron cut (Pt > 25 GeV/c), respectively. Figure 1c shows the distribution of the number of electrons with Pt > 25 GeV/c. From Figs.1a and 1b we find that, irrespective of the high Pt electron cut, more than 75 % of the events satisfy the criteria that the number of jets be 6 or more.

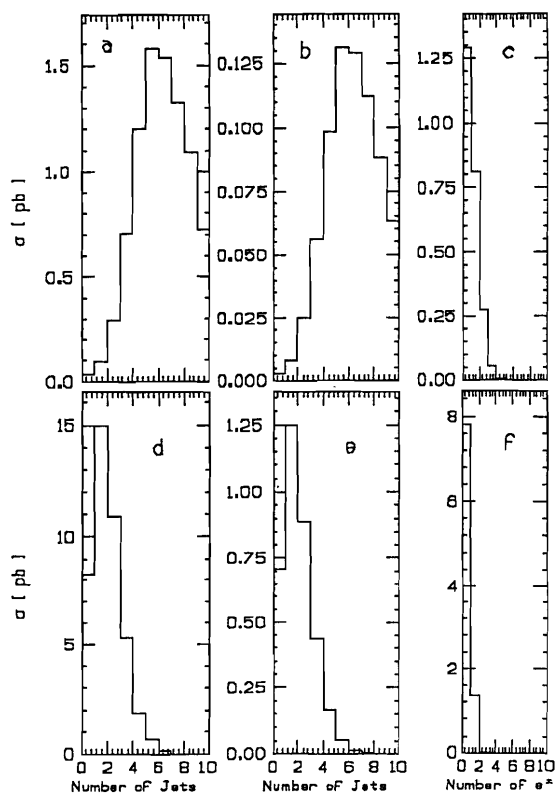

Fig.1. The distributions of (a) the number of jets, (b) the number of jets after the high Pt electron cut (Pt^e > 25 GeV/c), and (c)the number of electrons with Pt above 25 GeV/c for those $Y\bar{Y}$ events.
(d) - (f) The similar distributions for W^+W^- events.

For the W which decayed leptonically, the transverse mass was formed from a high Pt electron and the missing Pt as shown in Fig.2a. (f) Events with the transverse mass between 50 GeV/c^2 and 100 GeV/c^2 were retained. For the W which decayed hadronically, the two jet mass was formed as shown in Fig.3a. It shows two clear peaks around the W mass and the t quark mass. A criteria was imposed here that at least one 2-jet mass be in the mass range between 65 GeV/c^2 and 105 GeV/c^2. For the top quarks, the multi-jets mass was formed from two jets and 3 jets as shown in Figs.3a and 4a. Here we also imposed a criteria that at least two multi-jet mass be in the range between 30 GeV/c^2 and 50 GeV/c^2. Thus (g) one W was required as two jet and two top quarks were required as 2 or 3 jets.

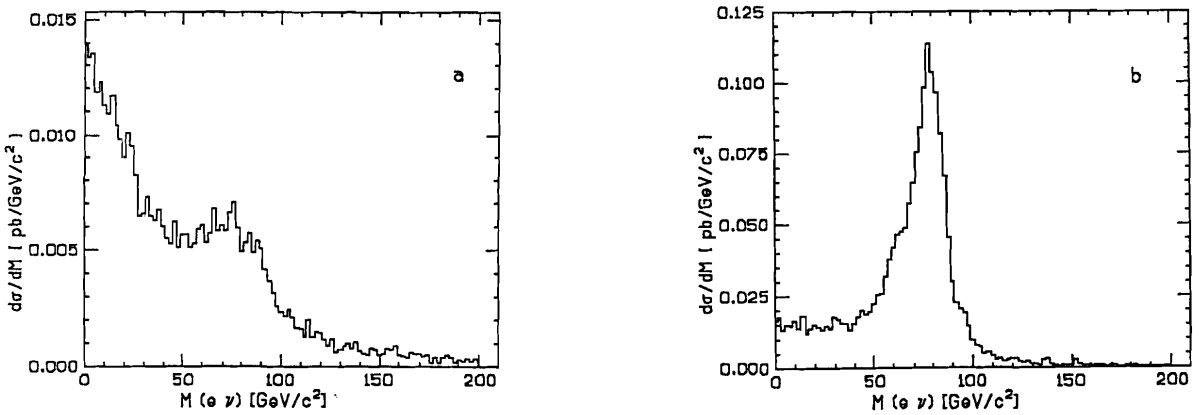

Fig.2. The distributions of transverse mass formed from a high Pt electron and the missing Pt for (a) $Y\bar{Y}$ events and (b) W^+W^- events.

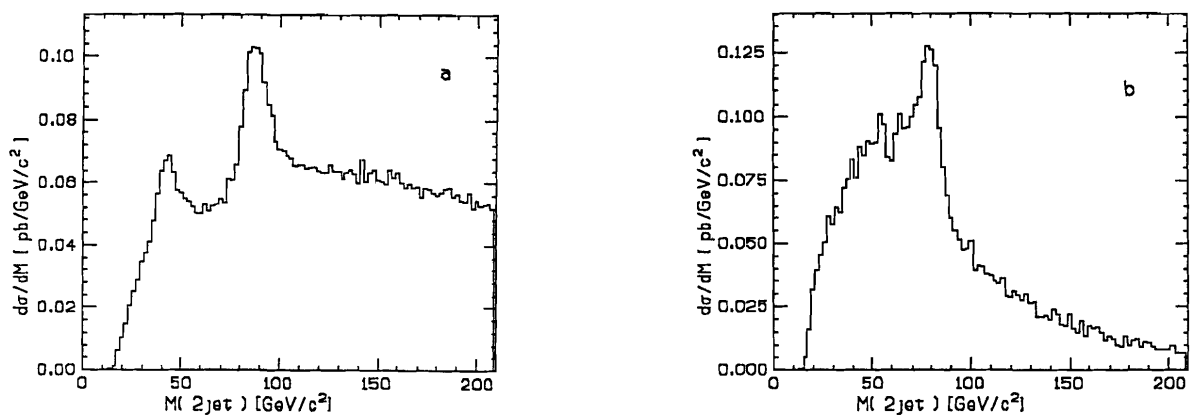

Fig.3. The distributions of 2 jet mass formed from all combinations of 2 jets for (a) $Y\bar{Y}$ events and (b) W^+W^- events.

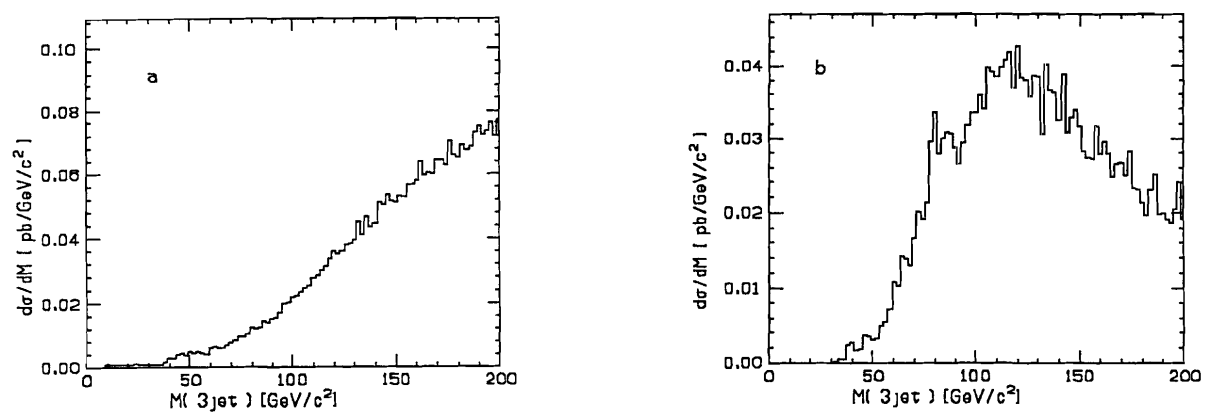

Fig.4. The distributions of 3 jet mass formed from all combinations of 3 jets for (a) $Y\bar{Y}$ events and (b) W^+W^- events.

For the Y quarks which decayed hadronically via real W, we formed the multijet mass, M(multijet), from a t quark(2 or 3 jets) and a W (2 jets). The mass formed from a t quark (2jets) and a W (2jets) is shown for all combinations in Fig.5a. It shows a clean peak around the Y mass of 500 GeV/c^2 with signal-to-noise ratio of 1. The mass formed from a t quark (3jets) and a W (2jets) is shown for all combinations in Fig.6a. It also shows a clean peak around the Y mass of 500 GeV/c^2. The number of Y quarks found in Fig.5a is 10 times larger than that in Fig.6a. This means that most of top quarks are identified as 2 jets rather than as 3 jets under the present condition. Hereafter we identify a top quark as 2 jets.

For the Y quarks which decayed semileptonically via real W, we formed the mass, M(ev +jets), from a t quark consisting of 2 jets and a W consisting of a high Pt electron and the missing Pt. Here we formed the Y masses from W(ev) and t(2jets) and from W(2jets) and t(2 jets) without any double counting of jets. The combination of jets was chosen so that both Y masses are the nearest to each other. Thus obtained distribution of the (e v + jets) mass formed from W(e v) and t(2jets) is shown in Fig.7a. The distribution of the reconstructed Y mass from W(2jets) and t(2jets) is also shown in Fig.8a. From Figs.7a and 8a we find that the distribution of the mass formed from W(2jets) and t(2 jets) has a tail in the low mass region, and that, aside from the tail, it shows a narrower peak than the mass formed from W(e v) and t(2jets). If we impose the criteria that (h) the multijet Y mass be in the range between 450 and 550 GeV/c^2, we get 357 $Y\bar{Y}$ events (0.36 %) out of the 100,000 generated events. The corresponding integrated luminosity was 0.99 x 10^{40} cm^{-2}.

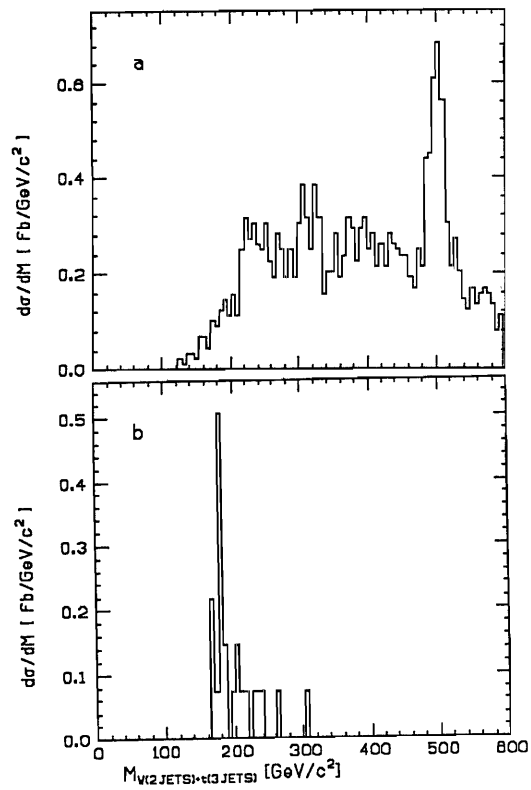

Fig.6 The distributions of Y mass formed from all combinations of W(2 jets) and t(3 jets) for (a) $Y\bar{Y}$ events and (b) W^+W^- events.

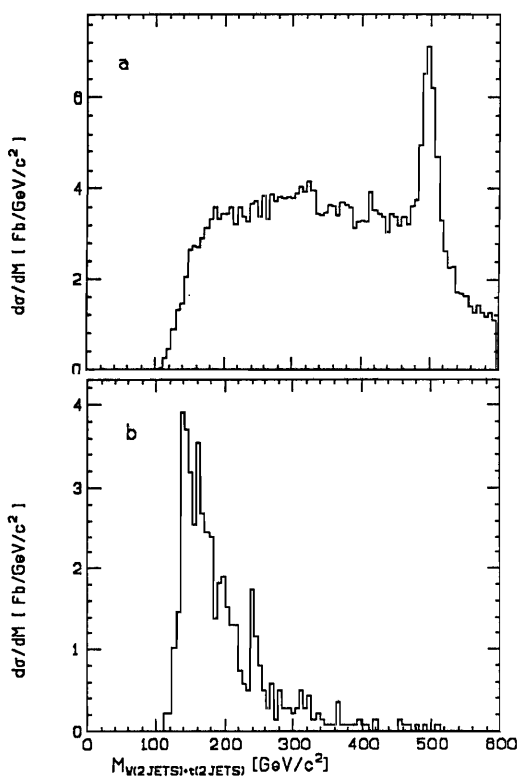

Fig.5. The distributions of Y mass formed from all combinations of W(2 jets) and t(2 jets) for (a) $Y\bar{Y}$ events and (b) W^+W^- events.

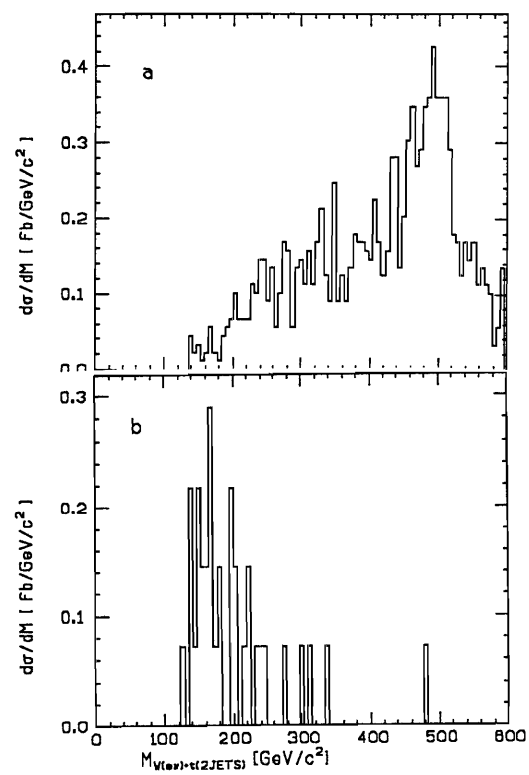

Fig.7. The distributions of Y mass formed from W(e v) and t(2 jets) under the criteria that both Y masses formed from W(e v) and t(2 jets) and from W(2 jets) and t(2 jets) are the nearest to each other for (a) $Y\bar{Y}$ events and (b) W^+W^- events.

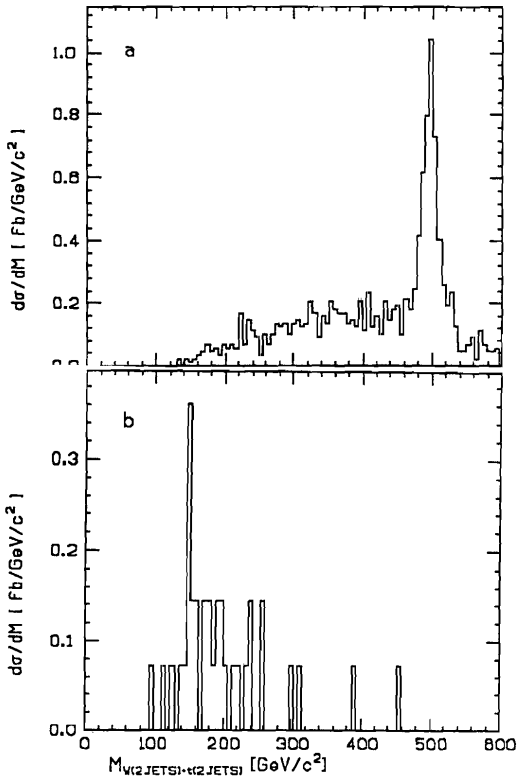

Fig.8. The distributions of Y mass formed from W(2 jets) and t(2 jets) under the criteria that both Y masses formed from W(e ν) and t(2 jets) and from W(2 jets) and t(2 jets) are the nearest to each other for (a) $Y\bar{Y}$ events and (b) W^+W^- events.

5. W^+W^- events as backgrounds

The main sources of background to the $Y\bar{Y}$ jet events identified by the procedures described above will be

$$p + p \rightarrow W^+ + W^- + \text{jets} \qquad (2)$$
$$\quad W^- \hookrightarrow e^- + \bar{\nu}_e$$
$$\quad W^+ \hookrightarrow q + \bar{q}'$$

A sample of 100,000 W^+W^- events were generated in the Pt range 10 to 200 GeV/c with $|\eta_W| < 2.5$. The corresponding integrated luminosity was 0.23×10^{40} cm^{-2}. In Figs.1d and 1e we show the distributions of the number of jets and the number of jets after the high Pt electron cut (Pt > 25 GeV/c), and Fig.1f shows the distribution of the number of electrons with Pt > 25 GeV/c. Fig.1e shows the number of jets is 6 or more in 2 % of the events. From the W^+W^- events which passed the same cuts as applied to $Y\bar{Y}$ events, the (e ν + 2jets) mass and the multijet mass were formed in the same way as before. Their distributions are shown in Figs. 6b, 7b and 8b. The number of W^+W^- events which passed the mass cut is 1 as shown in Fig.8b. In Table 1 we listed the numbers of signal and background events at each stage of the cuts, normalized to the integrated luminosity of 1×10^{40} cm^{-2}. The production cross section of $Y\bar{Y}$ events is found to be about half of that calculated by Eichten et al.[2] Though it may be underestimated, the signal of $Y\bar{Y}$ events was found to be 100 times larger than the background from W^+W^- events.

Table 1. The number of $Y\bar{Y}$ and W^+W^- events for an integrated luminosity of 1×10^{40} cm^{-2} in the Pt range of 10 to 200 GeV/c with $|\eta_W| < 2.5$.

CUT	$Y\bar{Y}$	W^+W^-
No Cut	101,000	434,782
(a), (b) and (c)	8,207 (8.2%)	36,361 (8.4%)
(d) and (e)	6,306 (6.3%)	665 (0.15%)
(f)	2,326 (2.3%)	400 (0.092%)
(g)	789 (0.8%)	152 (0.035%)
(h)	381 (0.4%)	4 (0.001%)

References

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