SEARCH FOR NEW HEAVY TECHNIPARTICLES

C. Baltay
Columbia University, New York, NY 10027

H. Gordon
Brookhaven National Laboratory, Upton, NY 11973

Introduction

Testing the standard model, as has been extensively discussed at this summer study, is clearly one of the most important goals of particle physics research in the next few years. However, it is also clear that even if all the tests prove to be satisfied, the standard model in itself cannot be a complete theory because it does not explain the masses of the various particles. A new class of particles, the Higgs particles, are needed for this purpose. There has been intense theoretical activity recently concerning these particles, i.e. the origin of the masses in the observed particle spectrum; technicolor and supersymmetry are among the most favored current ideas. Both of these models predict the existence of new classes of particles with a characteristic mass scale of around a TeV ($\pm$?). However, some of the expected particles are much lighter than a TeV, just as the π-meson is much lighter than the typical one GeV mass scale of the presently seen hadrons. Some of the predictions are summarized in Table I. Some of these lighter particles, in the 100 to 300 GeV mass range, are beyond the masses that can be produced by e^+e^- colliders in the foreseeable future. Thus hadron-hadron colliders with total center of mass energies of the order of one to several TeV will play an important role in the search for these new particles.

In this article, we consider in some detail an experiment to search for a typical member of this new zoology, the Technieta (η_T), which is expected to be in the 100 to 300 GeV mass range. For the sake of concreteness we use the predictions of the technicolor models; however, it might be better to think of these considerations as an example of the kind of searches that should be carried out with the next generation of hadron-hadron colliders, without putting too much importance on the details of the theoretical models that happen to be in fashion at this time. The general notion of a $\sim$ TeV mass scale and the rough value of the coupling strengths of the new mass scale to the present quarks, leptons, and gluons seem more reliable than details of the particular models.

Production Cross Sections and Rates

The dominant production mechanism for the Technieta seems to be the collision of two gluons from inside the colliding protons

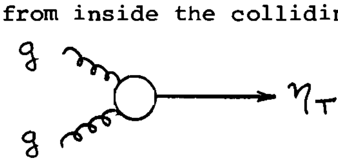

Table I

Some Theoretically Predicted New Heavy Particles

1. Higgs

H^0	Standard Model Higgs		
$\phi^{\pm}$, ϕ^0	More complicated Higgs		

2. Supersymmetry

$\tilde{G}$			
$\tilde{\gamma}$, $\tilde{g}$, $\tilde{Z}$, $\tilde{W}$			
$\tilde{\ell}$ like $\tilde{\tau}$, $\tilde{\mu}$, $\tilde{e}$, $\tilde{\nu}$, etc.			
$\tilde{q}$ like $\tilde{u}$, $\tilde{d}$, $\tilde{t}$, etc.			

3. Technicolor

$(Q\bar{Q})_1 + (L\bar{L})_1$	Technipions	$p^{\pm}$, p^0, p_0'	5-40 GeV
$(LL)_1$	Technidileptons		$\sim$ 70 GeV
$(LQ)_3$, $(L\bar{Q})_3$	Technileptoquarks		$\sim$ 150 GeV
$(Q\bar{Q})_8$	Technieta		$\sim$ 200 GeV
$(QQ)_{6,3}$	Technidiquarks		$\sim$ 150 GeV
$(Q\bar{Q}_x)$	Technihadrons	ρ_T, ω_T	$\sim$ 1 TeV

4. Composite Leptons and Quarks

ℓ^*			
q^*			

The cross section for this process has been estimated by Kane and Rebbi; by Girardi, Mery, and Sorba; and by J. Leveille; and by F. Paige at this summer study. Their results are in good agreement. The cross sections as a function of η_T mass are shown in Fig. 1 for hadron-hadron colliders with total center of mass energies $\sqrt{s}$ = 0.8 and 2.0 TeV. Note that the cross sections for these gluon-gluon induced processes are expected to be the same for pp and $\bar{p}$p collisions.

To calculate production rates, we use 10^7 seconds for the total datataking time and use luminosities of $\mathcal{L} = 10^{33}$ cm^{-2}sec^{-1} for the $\sqrt{s}$ = 0.8 TeV collider and $\mathcal{L} = 10^{30}$ cm^{-2}sec^{-1} for the $\sqrt{s}$ = 2 TeV collider. The results are shown in Fig. 2. We are encouraged by the very high rates of 10^3 to 10^6 total technietas produced in these examples.

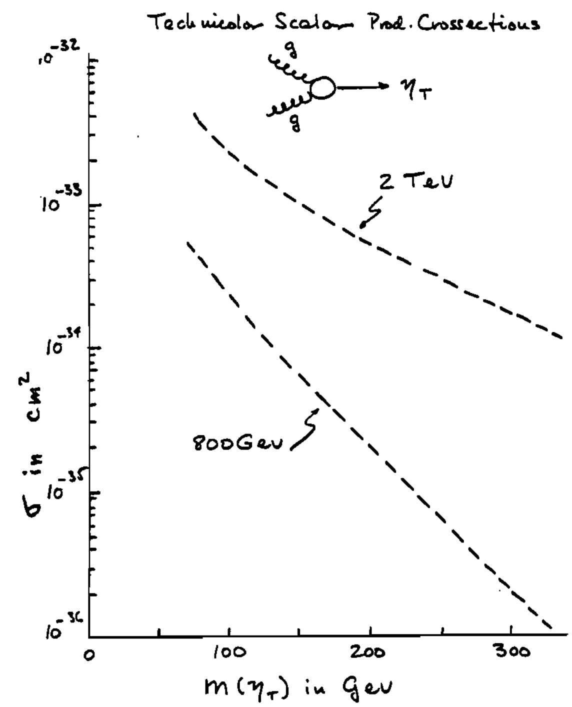

Fig. 1

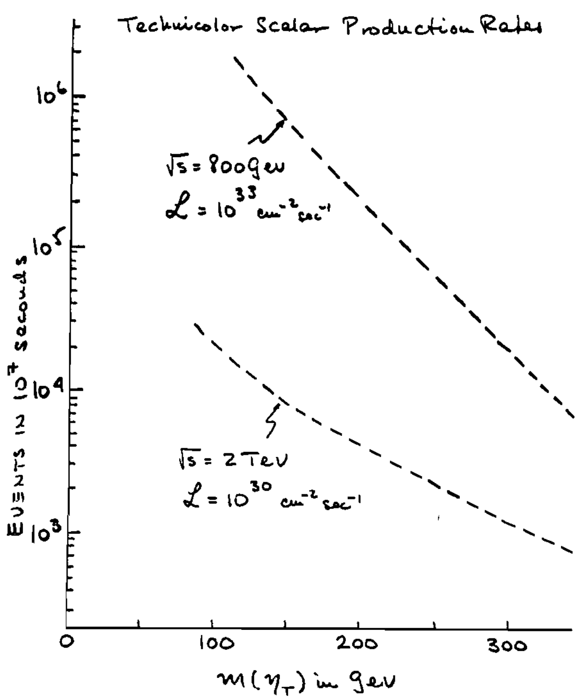

Fig. 2

Signature for the Detection of the Technieta

The techniparticles, similar to the Higgs particles, are expected to couple preferentially to the largest mass decay products. In the case of the η_T, the dominant decay is thus expected to be into a pair of top quarks:

$$\eta_T \rightarrow t + \bar{t} \ .$$

The t and the $\bar{t}$ quarks are expected to hadronize and come out as two hadron jets with 25 to 50 hadrons each. To detect and momentum analyze each of these hadrons and thus reconstruct the η_T mass seems like quite a difficult task. It seems easier to use a finely segmented hadron calorimeter to detect and measure the energy and momenta of the jets as a whole and try to reconstruct the jet-jet effective mass, i.e. do jet-jet mass spectroscopy.

A suitable detector for this search would be a large solid angle all purpose detector including a high resolution ($\pm$ 20 μ) vertex detector, a drift chamber tracking system in a moderate magnetic field, an electromagnetic and a finely segmented hadron calorimeter covering close to 4π solid angle, and a muon detector outside. The crucial component is the hadronic calorimeter which has 15 cm x 15 cm towers 150 cm from the interaction point (i.e. about 5^o x 5^o cells). A high energy jet is likely to subtend a cone of 20^o half angle so that a single jet covers dozens of calorimeter cells. Algorithms have been developed by Babcock and Cutkosky that can assign the particles (i.e. calorimeter cells) to a particular jet and find the jet axis with some reliability. We measure the energy E_i in each cell, and the angle θ_i between the center of the i^{th} cell and the jet axis. We can then calculate the total energy and the momentum of the jet as:

$$E_{jet} = \Sigma\, E_i$$

$$\vec{P}_{jet} = \Sigma\, E_i \cos\theta_i \qquad \text{along the jet axis.}$$

Here we have made an approximation of neglecting the mass of the individual hadron hitting the i^{th} calorimeter cell. The mass of the particle decaying into two jets then is:

$$M(\eta_T) = \sqrt{(E_1+E_2)^2-(\vec{P}_1+\vec{P}_2)^2}$$

where E_1, E_2, and $\vec{P}_1$, $\vec{P}_2$ are the total energies and momenta of the two jets. For very heavy parent particles, the two jets will typically be at large angles with each other (i.e. back to back). In this case, the resolution in $M(\eta_T)$ will be dominated by the resolution of the jet energy. We can expect to have a very good hadronic calorimeter with $\Delta E/E \sim 30\%/\sqrt{E}$. For $M(\eta_T) \sim 200$ GeV, $E_{jet} \sim 100$ GeV, and $\Delta E/E \sim 3\%$. This would lead to a mass resolution of around 2%. However, we will not do this well due to systematic effects connected with how we define a jet (i.e., how large a cone) and what energy is outside the cone and therefore lost. Some Monte Carlo studies of this problem carried out by Stumer, Gordon, and Benary indicate that a mass resolution of $\pm$ 5% is not unreasonable for light quark jets (see Fig. 3a). For heavy quark jets (i.e., $t\bar{t}$), the resolution function has a broadening on the low mass side (Fig. 3b) due to the fact that there will be semileptonic decays in the heavy quark decay chain with missing neutrinos. To get around this deterioration in the mass resolution, we have to somehow suppress jets with energetic semileptonic decays, for example by selecting only those jets that do not have an energetic $e^{\pm}$ or $\mu^{\pm}$ in them. In this way, we can hope to attain a mass resolution of

$$\frac{\Delta m}{m} = \pm 5\% \quad .$$

Thus to summarize, the signature for the $\eta_T \to t + \bar{t}$ decay will be a pair of close to back-to-back jets with transverse momenta of 50 to 150 GeV/c each.

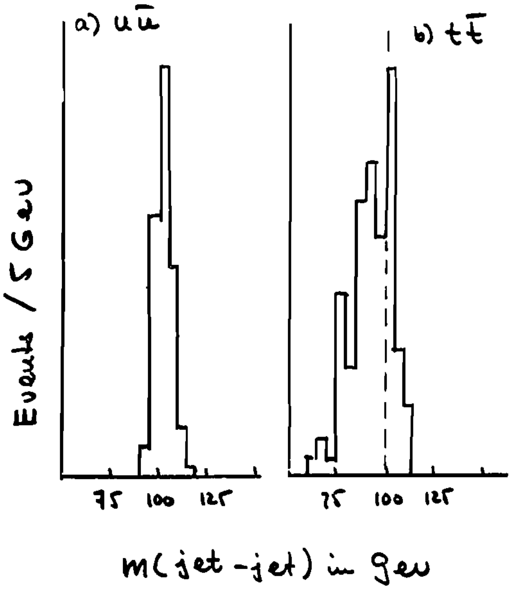

Fig. 3

Background Rejection

The background to the above signature is expected to be the high P_t large angle pairs of QCD jets. These QCD jets will have a very forward-backward angular distribution, while the jets from η_T decay will be more isotropic (see Fig. 4). We therefore expect the best signal to noise around 90°, and impose a selection in rapidity of the jets of $y = 0 \pm 1$. The number of background QCD jet pairs near 90° has been calculated by the program ISAJET and is shown on Fig. 5, as a function of the effective mass of the two jets. We see that the light quark (u,d, s) and gluon jets dominate and are about 1000 times the level of the $t\bar{t}$ jets. The ($c\bar{c}$ + $b\bar{b}$) jets are about three times higher than the $t\bar{t}$ jets. The expected η_T signals are shown as the bumps at 200 and 300 GeV.

We can think of two techniques to reduce these large backgrounds:

1. The shape or the effective mass of the individual jets. We expect a t quark jet to be broader and to have some substructure (i.e. have higher internal mass) than the lighter (b,c,u, etc.) jets. This, of course, depends on the mass of the t. For a 20 GeV t quark, with appropriate cuts we estimate a reduction of the lighter quark backgrounds by a factor of at least three with larger reductions if the t quark is heavier.

2. The charm content of the jet. Assuming that the dominant t decays will be into b quarks, which will dominantly decay into c quarks, the t quark jet should have several charmed particles in each. The light quark or gluon jets on the other hand will have charmed particles in them only rarely due to $c\bar{c}$ pair production. At Fermilab energies, $c\bar{c}$ pair production is $\sim 10^{-3}$ of the total cross section. However, this fraction is likely to be higher in high P_t jets. There is no data on this; for the purposes of this paper, we take the charm content of the light quark jets to be as high as 5%. Then if we require charm to be present in both jets in the pair, we can expect a reduction of the light quark and gluon jet background by a factor of 400 or so.

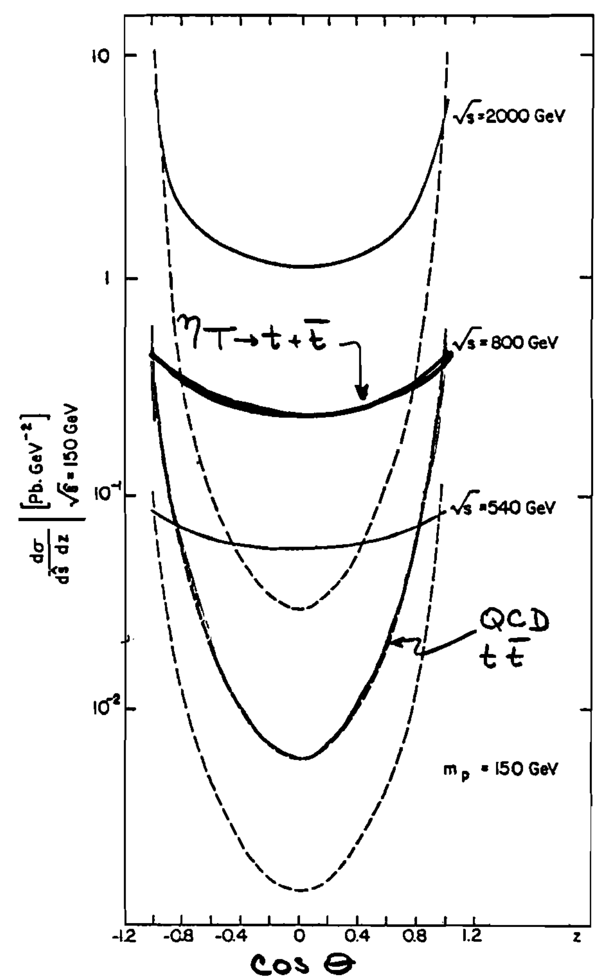

Fig. 4

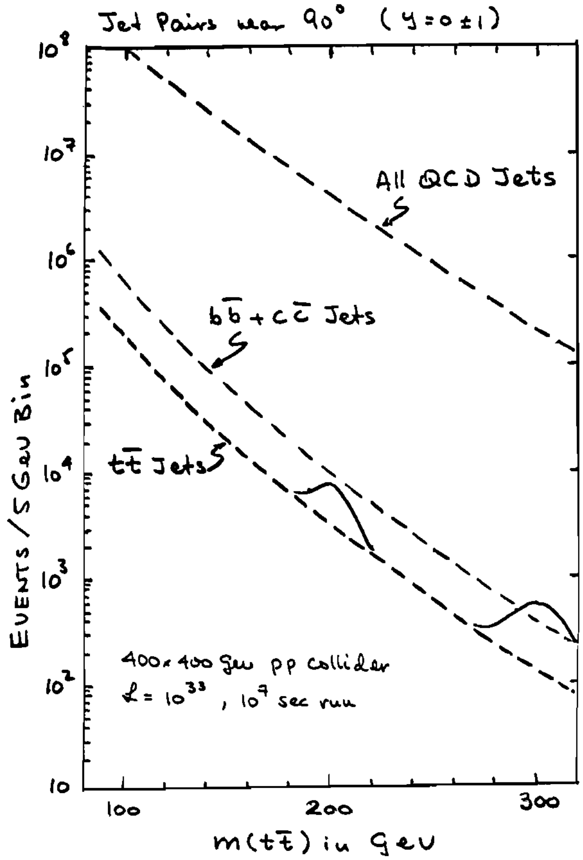

Fig. 5

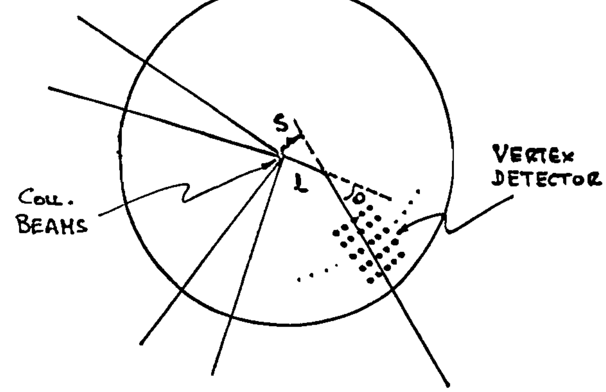

Fig. 6

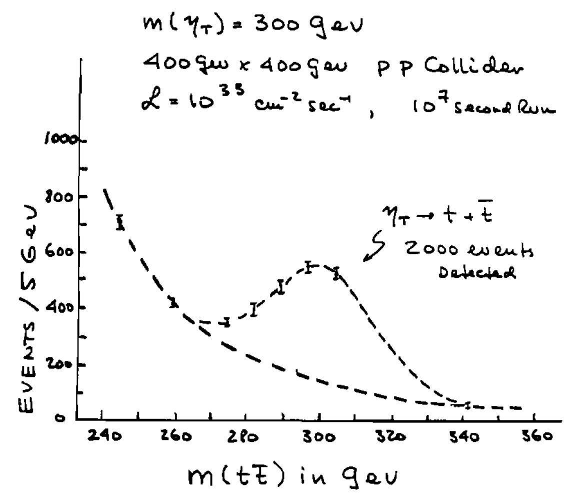

Fig. 7

We would use the high resolution vertex detector to detect the presence of a charmed particle in the jet by seeing several particles that do not come from the main interaction vertex. Figure 6 schematically illustrates how this would work. The decay length $\ell = \beta\gamma\tau c$, and the decay angle is typically $\theta \sim 1/\gamma$. Thus the impact parameter $s = \ell\theta = \tau c$. For the D^+ this is $\sim 240\ \mu$ and for the D^o about $120\ \mu$. For a vertex detector with a $20\ \mu$ resolution, and insisting on an impact parameter larger than 4σ, we should detect $e^{-80/240} \sim 72\%$ of the D^+'s and $e^{-80/120} \sim 51\%$ of the D^o's, or $\sim 61\%$ of the D's on the average. Since a t quark jet is expected to have several D's in it, the probability of missing both D's is $(1-0.61)^2$ or $\sim 16\%$. Thus the efficiency of tagging both jets in a pair of $t\bar{t}$ jets is $(1-0.16)^2 \sim 0.7$. In summary then, we can expect a high resolution vertex detector to reduce the light quark jet pair background by a factor of 400 or so, and to tag $t\bar{t}$ jet pairs with a 70% efficiency.

The combination of the charm tagging by the vertex detector and the shape of the jets is expected to reduce the u,d,s or gluon jets by a factor of 1/3 x 1/400, to below the $t\bar{t}$ background. The $b\bar{b}$ and $c\bar{c}$ jets are reduced by a factor of $\sim 1/3$ to be at the level of the $t\bar{t}$ background. The $\eta_T \to t\bar{t}$ signal should then be visible as a bump over the $t\bar{t}$ background in the effective mass distribution, as shown in Fig. 7.

Detection Efficiency for the η_T

A rough estimate of the acceptances and detection efficiencies for the η_T signal are as follows:

Branching ratio $\eta_T \to t+t$	0.85(?)
Solid angle acceptance ($y=0\pm1$)	0.6
Require no energetic $e^\pm$ or $\mu^\pm$ in either jet	0.4
Charm trigger	
D lifetimes detected	0.7
Geometry of vertex detector	0.7
Net Efficiency	0.1

The solid angle acceptance has been calculated by the ISAJET program. The loss due to the requirement that neither jet has an energetic semileptonic decay has been estimated using a 10% branching ratio for each semileptonic decay mode of the t or the b, i.e. $t \to \mu\nu_\mu + \ldots/t \to \text{all} \sim 10\%$ etc.

The 70% efficiency of D detection has been discussed in the previous section. We put in a further 0.7 for the geometric acceptance of the vertex detector. We thus expect to see about 10% of the η_T's produced.

Conclusions

At the $\sqrt{s} = 0.8$ TeV collider, we expect a total of 2×10^4 η_T produced for a $M(\eta_T) =$ 300 GeV (see Fig. 2). With a detection efficiency of 10%, we should see 2000 $\eta_T \to t\bar{t}$ decays in the final sample. As shown in Fig. 7, such a signal would be quite significant over the expected $t\bar{t}$ background. In fact, things could be quite a lot worse than our estimates here indicate and a signal should still be visible.

Table II summarizes the numbers of η_T events detected above backgrounds for $M(\eta_T)$ of 100 to 400 GeV at the two collider energies considered. We see from this table that these searches might be sensitive to masses up to 400 GeV.

It should also be clear that this whole discussion has been at best at the summer study level, i.e. there are lots of uncertainties like for example the $c\bar{c}$ content of high P_t light quark jets. Good mass resolution, of the order of $\pm$ 5%, seems critical. Another challenge will be to develop a high resolution vertex detector that can operate in the high luminosities envisioned here. One should therefore interpret this analysis more in the spirit of what kind of things we will have to be able to do to search for these very heavy new particles.

Table II

Expected Rates for $\eta_T \to t+\bar{t}$ Jets for Two

Typical Hadron-Hadron Colliders

for 10^7 sec Runs

$M(\eta_T)$ GeV	800 GeV, $\mathcal{L} = 10^{33}$			2 TeV, $\mathcal{L} = 10^{30}$		
	$\sigma(cm^2)$	Total Events	Events Detected	$\sigma(cm^2)$	Total Events	Events Detected
100	2×10^{-34}	2×10^6	2×10^5	2×10^{-33}	2×10^4	2×10^3
200	2×10^{-35}	2×10^5	2×10^4	5×10^{-34}	5×10^3	500
300	2×10^{-36}	2×10^4	2×10^3	1.5×10^{-34}	1.5×10^3	150
400	2×10^{-37}	2×10^3	200	6×10^{-35}	6×10^2	60