Fermi National Accelerator Laboratory

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# Search for Heavy Stable Particles at the Fermilab Collider *

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**Abstract**

A search was made for heavy stable charged particles produced in 1.8 TeV proton-antiproton collisions. No such particles were found in 26.2 $nb^{-1}$ of data. Cross section limits are presented and mass limits of the order of 100 GeV are set for particles containing excited quarks in higher color representations.

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Numerous theories[1,2], which go beyond the standard model, predict the existence of new, massive particles. These theories include supersymmetry, mirror fermions, technicolor, and compositeness. Since the lightest member of a new family of particles is usually prohibited from decaying into known particles, it is expected to be stable. Although the mass scale of many of these new particles is expected to be of the order of one TeV, some may have masses considerably less than that and may therefore be produced at present day colliders[3]. Existing experimental lower limits on the mass of stable charged particles are about 30 GeV set at lower energy accelerators[4].

Here we describe a search for heavy stable charged particles in proton-antiproton collisions at a center-of-mass energy of 1.8 TeV using the Collider Detector at Fermilab (CDF)[5]. By a stable particle we mean one sufficiently long-lived to enable it to traverse the minimum distance of 3.5 m required to exit the detector before decaying. This search took advantage of three distinguishing characteristics of heavy stable particles: low velocity, high transverse momentum, and muon-like penetration through matter. The muon-like penetration arises from the kinematically limited energy that can be transferred in collisions with the much lighter nucleons.

The detector combines electromagnetic and hadronic calorimeters in a projective tower geometry with charged particle tracking. The key systems used in this study were the beam-beam counters[5], the central tracking chamber[6], the central hadron calorimeters[7], the central muon chambers[8] and the trigger system[9].

The beam-beam counters consist of planes of scintillation counters located 5.8 m upstream and downstream of the interaction point.

The central tracking chamber (CTC) operates in a 1.5 Tesla solenoidal magnetic field and provides momentum measurement of charged particles with a resolution of $\sigma_{p_T}/p_T^2 \simeq 0.002$ (GeV/c)$^{-1}$. From a study of minimum bias events, the CTC reconstruction efficiency for tracks with transverse momentum ($p_T$) > 0.4 GeV/c was determined to be nearly 100%[10].

The central calorimeters consist of separate electromagnetic and hadronic detectors and cover the approximate pseudorapidity range $|\eta| \leq 1.0$, where $\eta = -\ln(\tan(\theta/2))$ and $\theta$ is the polar angle. The coverage in azimuth ($\phi$) is complete. Each calorimeter tower subtends 0.1 units of pseudorapidity and 15 degrees of azimuth. For each hadron calorimeter tower the light from 32 layers of scintillator is collected by wavelength shifter strips and is brought by light guides to two 12-stage THORN-EMI 9954 phototubes[11] located on opposite sides in azimuth. Signals from the last dynode stage of the two phototubes are first amplified and summed together. Then the resulting pulse is discriminated and converted to a voltage proportional to the time elapsed between the discriminator firing and a common stop signal using a custom designed time-to-digital-converter (TDC) circuit[12]. The 16 bit TDC has a full scale range of 3.2$\mu$s. However, during data taking the TDC's were only active from 150 ns before the beam crossing to 550 ns after. The RMS intrinsic resolution of the TDC was measured to be better than 200 ps. The TDC's were at least 97% efficient for energy depositions in excess of 0.7 GeV in the hadron calorimeter.

Corrections were applied for time slewing due to pulse height differences and for variations in particle path lengths. Event to event variations in the interaction time were determined by the beam-beam counters. The resolution of these counters is better than 200 ps. A sample of 10,000 "jet" events was used to determine the TDC offsets. The mean value for each tower was found from a Gaussian fit to the data. An offset for each individual TDC was defined to make this mean time for $\beta = 1$ particles equal to zero. The resulting time distribution for all towers summed is shown in Figure 1A. The resolution ($\sigma$) is 1.5 ns. The excess of early times is an instrumental effect due to particles near the azimuthal detector boundaries.

Since the TDC's fire on the first particle to strike a particular calorimeter tower, it is possible for a slow particle to be missed because a faster particle in the same tower had already fired the TDC. The magnitude of this effect was checked using minimum bias data taken with only a beam-beam counter requirement in the trigger, which revealed that on average only 1 of the 384 TDC channels fired in a given event. The particles accompanying a massive object are expected to be relatively soft[13] and therefore would be unlikely to strike the same tower. This is in agreement with

ISAJET[14] Monte Carlo predictions.

The central muon detector consists of 4 layers of drift chambers located behind the central calorimeters which provide at least 5.0 absorption lengths of material. The muon detector covers the pseudorapidity range $|\eta| \leq 0.65$.

The trigger required both sets of beam-beam counters to fire together with a pattern of hits in the muon chambers indicative of a high transverse momentum particle. About one half of the data was taken with a $p_T$ cut of 5 GeV/c and one half with a $p_T$ cut of 10 GeV/c. The overall trigger efficiency depends on particle scattering as well as the performance of the trigger hardware. The calculated inefficiency due to multiple Coulomb scattering ranged from 7% for unit-charged particles with masses of 50 GeV to 0.2% for masses of 200 GeV. Inefficiency due to elastic scattering from nucleons was estimated to be negligible. Tracks were reconstructed using the online hardware track finder and a $\phi$ match was required between the extrapolated location of the track and hits in the muon chambers. The hardware trigger efficiency was estimated to be $68 \pm 18\%$. The overall trigger efficiency is listed in Table 1.

To reduce the background arising from muons, it was required that a candidate particle have $p_T > 20$ GeV/c and be late by more than 4.5 ns ($3\sigma$) compared to a $\beta = 1$ particle. This corresponds to an upper $\beta$ limit to our sensitivity of 0.7. The lower limit is determined by the energy loss of the particles and ranges from $\beta = 0.2$ to $\beta = 0.4$. An energy deposition of at least 1.5 GeV was required in the hadron calorimeter in order to obtain a sufficient pulse height to provide reliable timing information. Minimum ionizing tracks typically deposit about 1.8 GeV. The effects of these cuts applied in the order listed on the single particle detection efficiency are summarized in Table 1. The detection efficiency was determined using the ISAJET Monte Carlo program. Pairs of stable charged particles of various masses were generated predominantly via gluon-gluon fusion. The resulting events were run through a detector simulation program and then processed using the same analysis chain as the real data.

The data sample used in this analysis corresponds to an integrated luminosity of 26.2 $nb^{-1}$ and was taken during the 1987 run at a center-of mass-energy of 1.8 TeV. The TDC timing information for the sample of events with a $p_T > 20$ GeV/c track is shown in Figure 1B. Cosmic rays were easily identified since they appeared as two tracks 180° apart in $\phi$ with a time difference of about 20 ns; 10 such events have been removed from this sample. No late times were observed in the remaining sample.

Based on no observed events, the integrated luminosity of 26.2 $nb^{-1}$, the Monte Carlo determined acceptance, and the trigger efficiency, a 95% confidence level upper limit on the cross section for producing heavy charged stable particles was determined. The systematic uncertainty in the luminosity was estimated to be 15%. The acceptance was defined as the probability of at least one of the pair of heavy particles passing all the cuts used on the data sample. It was assigned a systematic error of 20% associated mainly with uncertainties in the modeling of the TDC response. The uncertainty in trigger efficiency ranged from about 45% for 50 GeV particles to 25% for higher mass particles. The additional uncertainty at low masses was due to the possible effect of elastic scattering from nucleons in addition to Coulomb scattering.

The systematic errors were then added in quadrature and the resulting error in the cross section limit ranged from 55% at M = 50 GeV to 35% at M = 200 GeV. Figure 2 gives the 95% confidence level cross section limits for the pair-production of unit-charged stable particle of equal mass. The one standard deviation systematic uncertainties are indicated. Results are not presented for masses less than 50 GeV because of our low detection efficiency there. In principle, our results apply to masses above 200 GeV. However, such limits would not be very meaningful due to the small theoretical cross sections in that mass region.

For each specific model for the production of massive stable particles, one can in principle derive a lower limit on the mass. One such class of models involves composite quarks belonging to various color multiplets. If the compositeness scale is large, resulting in tightly bound quarks, the particles are pair-produced by conventional QCD processes with gluon fusion dominating. The expected cross-sections for color triplets as a function of mass are given by Altarelli et al.[15]. The corresponding cross-sections for color sextets, octets, and decuplets are obtained by scaling the triplet cross-sections by the appropriate color factors[2].

Unlike the production cross-sections, the charges of the physical heavy particles are in general not known. Such particles carry fractional, unit, or multiple charge or they may be neutral. Our efficiency depends on the assumed charge. We considered two cases: (i) both particles produced carry unit charge and (ii) the two particles are assumed equally likely to be unit charged or neutral. The resulting 95% confidence level lower mass limits for case i (ii) are 98(84) GeV for color sextets, 99(86) GeV for octets, and 137(121) GeV for decuplets. Systematic errors were taken into account by reducing the predicted number of events by one standard deviation in its overall systematic uncertainty. Triplet cross-sections are too small to allow us to set a limit with this data sample. Masses below 50 GeV cannot be ruled out in this sample due to our low detection efficiency in that region.

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| | 50 GeV | 100 GeV | 150 GeV | 200 GeV |
|---|---|---|---|---|
| $p_T$ cut | $.76 \pm .03$ | $.91 \pm .02$ | $.96 \pm .02$ | $.98 \pm .02$ |
| Geometry Cut | $.24 \pm .03$ | $.26 \pm .03$ | $.27 \pm .03$ | $.30 \pm .03$ |
| $E_{hadron}$ cut | $.68 \pm .07$ | $.71 \pm .07$ | $.75 \pm .07$ | $.73 \pm .07$ |
| $\beta$ cut | $.75^{+.08}_{-.22}$ | $.88^{+.09}_{-.16}$ | $.90^{+.09}_{-.15}$ | $.86^{+.09}_{-.14}$ |
| Trigger | $.63 \pm .28$ | $.67 \pm .20$ | $.68 \pm .18$ | $.68 \pm .18$ |
| Total | $.06 \pm .03$ | $.10 \pm .04$ | $.12 \pm .04$ | $.13 \pm .04$ |

Table 1: Analysis selection efficiencies, overall trigger efficiency, and their product for single unit-charged stable particles of different masses. The uncertainties listed include systematic effects and Monte Carlo statistical errors.

## Figure Captions

Fig. 1. TDC times for (a) the sample of jet events used for calibration and (b) high $p_T$ penetrating particles. The cut used to define late hits is indicated. Times are measured with respect to $\beta = 1$ particles.

Fig. 2. 95% confidence level upper cross section limits for the pair-production of stable unit-charged particles as a function of their mass. The one standard deviation systematic uncertainties are indicated by the dashed lines.

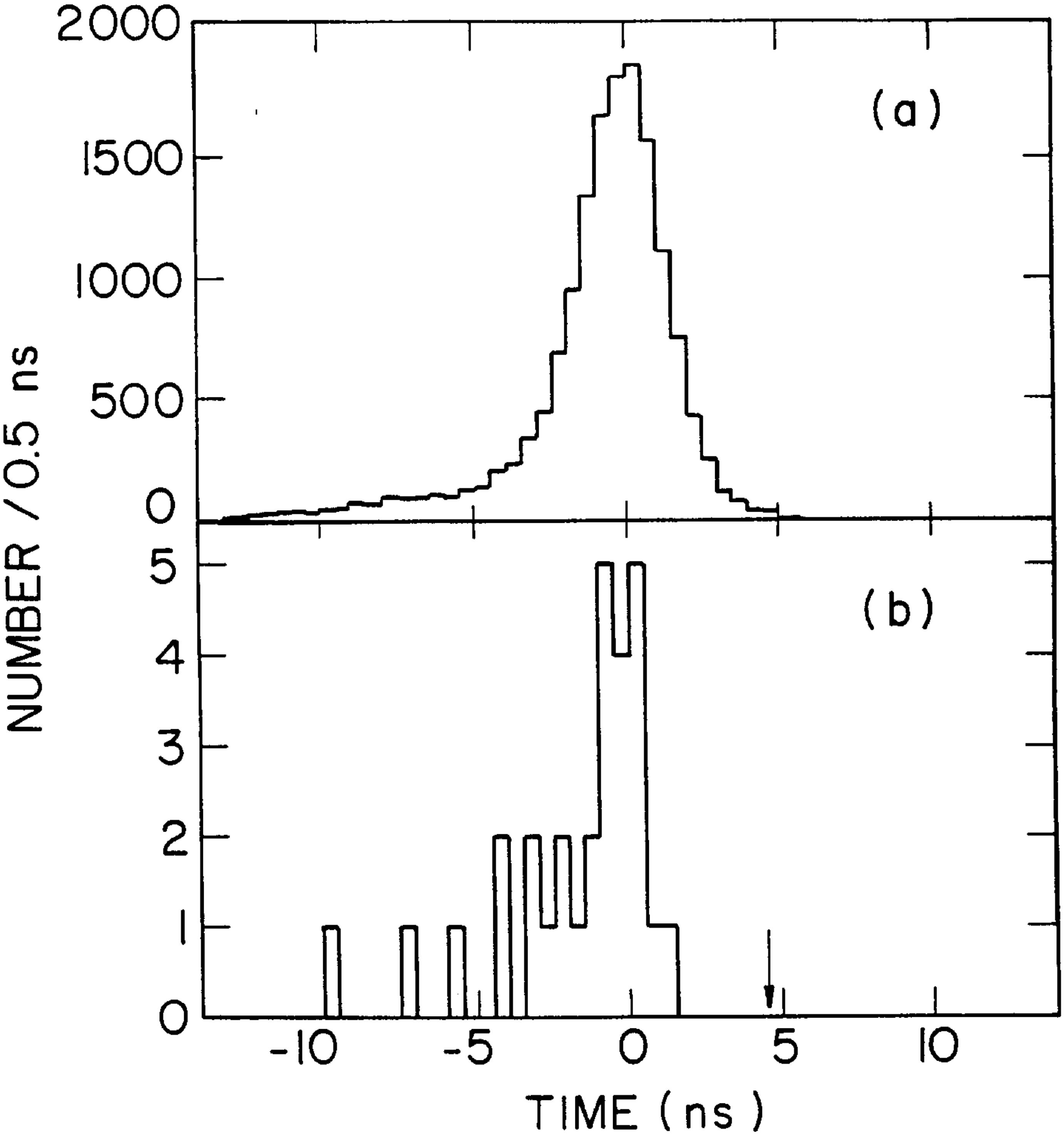


Figure 1

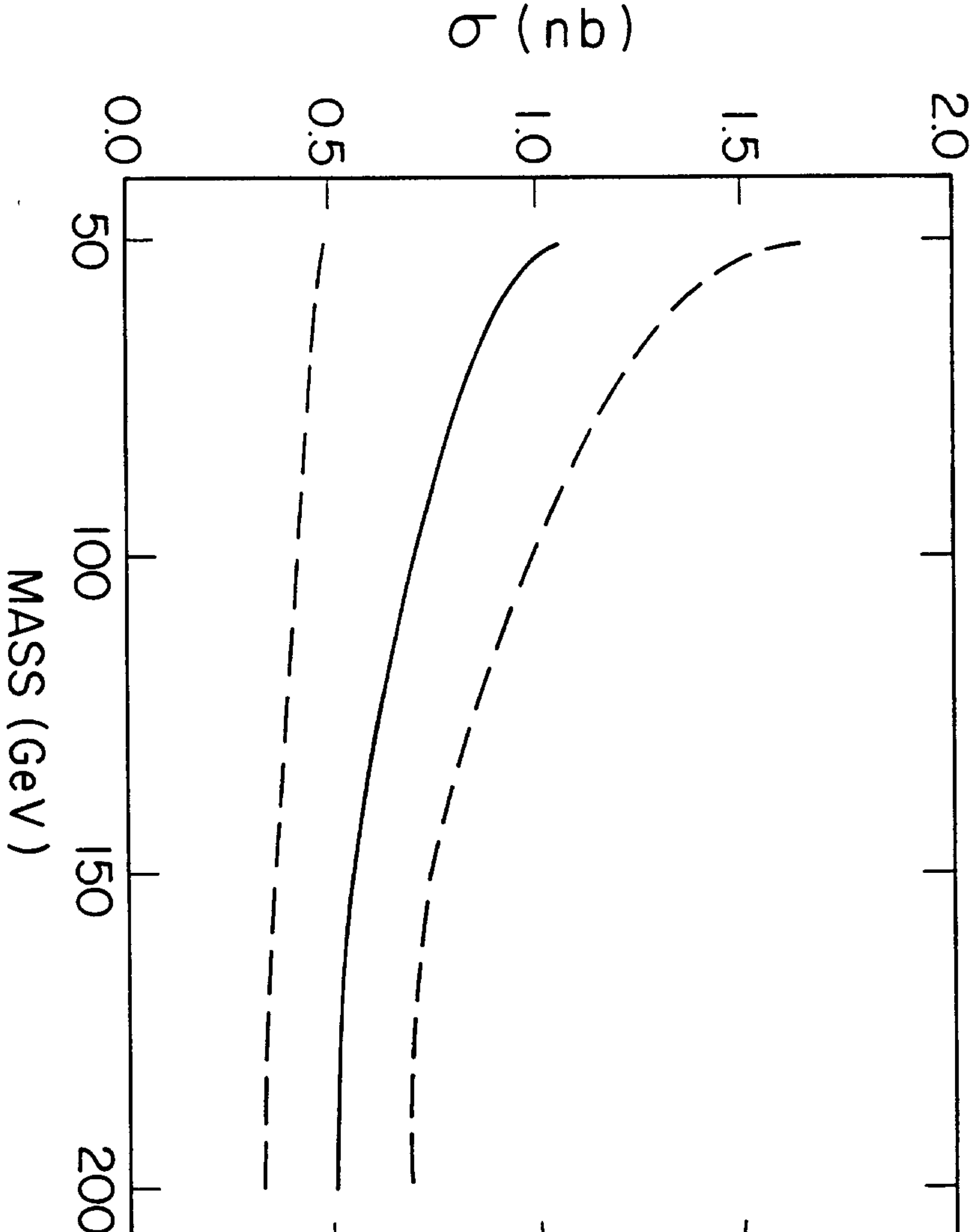


Figure 2