SEARCH FOR THE SUPERSYMMETRIC PARTNER OF THE TOP QUARK IN DILEPTON EVENTS PRODUCED IN PROTON-ANTIPROTON COLLISIONS AT $\sqrt{s}$= 1.8 TeV

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Dedicated to Šárka, my mother Rózsika and father Gyula.

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ABSTRACT

Pompoš, Arnold, Ph.D., Purdue University, December, 2002. Search for the Supersymmetric Partner of the Top Quark in Dilepton Events Produced in Proton-Antiproton Collisions at $\sqrt{s}$= 1.8 TeV. Major Professors: Virgil Barnes, Daniela Bortoletto.

Supersymmetric partners of top quarks, stops, will be pair produced at the Fermi National Accelerator Laboratory in proton-antiproton collisions at a center-of-mass energy $\sqrt{s}$= 1.8 TeV if kinematically accessible. Within the framework of the Minimal Supersymmetric extension of the Standard Model, the stop quarks are assumed to decay into a lepton, a bottom quark and a supersymmetric neutrino, sneutrino. Thus the experimental signature of stop presence in the data would be two opposite electric charge leptons, hadronic jets and substantial energy imbalance in the detector due to the escaping, undetected sneutrinos. We searched a total of $\int \mathcal{L}\mathrm{dt} = 107.2\ \mathrm{pb}^{-1}$ of data collected by the Collider Detector at Fermilab experiment. No evidence of a stop signal has been found which allows us to calculate a 95% confidence level upper limit on the number of stop-originated events in the data of this size. We have translated this into a 95% confidence level exclusion region in the stop versus sneutrino mass plane.

1. Introduction

Each era of human history had great thinkers who believed that "law and order" exist in our Nature. They were convinced that Nature, its structure and laws can be described and understood all the way down to the most fundamental levels. Due to the tremendous technical improvements of available experimental techniques, the view of the underlying structure and governing law of the world is constantly evolving. First, it was the theory of four elements, fire, water, soil and air. It continued through Dalton's atomic theory to the deterministic description of solid bodies, light, thermodynamic ensembles, electromagnetic and gravitational field. At the frontier today, we believe the right description of Nature is the probabilistic theory of the tiniest elements of our world, the smallest entities we are made of, the elementary particles. The understanding and description of this microworld reveals its very fundamental connection to the megaworld of stars, galaxies and ultimately the universe itself.

So far the most successful theory of elementary particles and their interactions is the Standard Model (SM) [1, 2, 3]. It is based on fundamental symmetries existing in the quantum world. It gives a very good description of all phenomena existing at energy levels we can probe with current experiments. Nevertheless, physicists realize that it cannot be the ultimate theory of everything, because it does not answer some fundamental questions. It fails to incorporate gravity, it breaks down at very high energy scales and does not predict the values of its parameters. Therefore, there must be a theory beyond the Standard Model.

One good candidate for such a theory is the Minimal Supersymmetric extension of the Standard Model (MSSM) [4, 5, 6]. It introduces the idea of the existence of a new symmetry of Nature, supersymmetry (SUSY), which unifies the spin-half fermions

Table 1.1
Running periods of the Fermilab Tevatron and corresponding luminosities collected by the CDF experiment.

	Run 1A	**Run 1B**
Data Taking Period	08/1992 - 05/1993	01/1994 - 06/1995
Integrated Luminosity	18.6 pb^{-1}	88.6 pb^{-1}

with integer-spin bosons. SUSY doubles our world of elementary particles, because it assigns to each SM particle a supersymmetric partner whose spin differs by one half.

In this thesis we present the results of our experimental search for the supersymmetric partner of the top quark, the stop quark. We searched the proton-antiproton collision data (see Tab. 1.1) produced at a center-of-mass energy of 1.8 trillion electron volts, collected by the Collider Detector at Fermilab (CDF) at the Fermi National Accelerator Laboratory, near Chicago, USA.

The thesis has the following structure. In chapter 2 we give a brief introduction to the Standard Model. Chapters 3 and 4 summarize the theory of supersymmetry, describe the Minimal Supersymmetric Standard Model and show its particle content focusing on particles related to our search. In chapter 5 we describe the experimental apparatus, Fermilab's proton-antiproton collider, the Tevatron, and the detector of the $p\bar{p}$ collision products, the CDF detector. In chapter 6 we introduce our strategy of the search for the superpartner of the top quark. Chapters 7 and 8 define particles in terms of detector measurable quantities. Chapter 9 introduces the data set in which we searched for the stop quark. Various background sources mimicking the stop signal are described in chapter 10. In chapter 11 we introduce the Monte Carlo event generator which allows us to study in great detail the expected stop and background events. The first comparison of observed data with expected signal and background is done in chapter 12. In chapter 13, selection cuts on various event variables are developed in order to enhance the signal and reduce the background. The uncertainties of our measurement are discussed in chapter 14. Finally, results of the search and the conclusion are presented in chapters 15 and 16. Appendices A-E describe some of the mathematical tools used to build the MSSM. Appendix F lists the lepton identification cuts applied to select the Run 1A and Run 1B SUSY dilepton samples. Appendix G shows the trigger spectrum of the analyzed data, and Appendix H summarizes the number of generated and expected stop events for various points in the MSSM parameter space.

15. Results and Setting Mass Limits

We have done a "blind" search for the stop quark. This means the collected data were explored only with loose preliminary cuts, where the expected signal is still swamped by background, until we developed the sets of selection cuts (done on MC generated events and "fake lepton" events simulated from non-search-sample CDF data) that would distinguish in a statistically significant way the stop signal from expected backgrounds. After applying the selection cuts to the search data sample, no evidence was found for the existence of a light stop quark that would decay into a light sneutrino, lepton and a bottom quark. The zero observed events are consistent with the expected small background. This allowed us (see below) to set a 95% confidence level (C.L.) upper limit on the number of signal events which could have been in a search sample of this size.

Since the number of experimentally observed events n_0 is a result of drawing from a Poisson distributed variable whose mean is μ, the probability of observing n_0 events is given by

$$P(n_0;\mu) = \frac{\mu^{n_0} e^{-\mu}}{n_0!} \ .$$

We wish to find a real number N, such that there is a probability ϵ to observe n_0 or fewer events, (*i.e.* a probability $1-\epsilon$ to observe more than n_0 events)

$$\epsilon = \sum_{n=0}^{n_0} P(n;N) = \sum_{n=0}^{n_0} \frac{N^n e^{-N}}{n!} \ .$$

If the predicted number of events for a given $m_{\tilde{t}}$, $m_{\tilde{\nu}}$ exceeds N, there is even less than ϵ probability of seeing as few events as are observed, and we are able to rule out such region of $m_{\tilde{t}}$, $m_{\tilde{\nu}}$ parameter space with even greater than $1-\epsilon$ confidence level. In our case $n_0 = 0$ events[1]. We have $0.05 = P(0;N) = \frac{N^0 e^{-N}}{0!}$, therefore $N =$

[1] Since we do not observe any events, we also do not observe any background μ_b among them and our formulae will be somewhat simpler than the ones which include possible background subtraction.

$-\ln 0.05 = 2.99$. This result tells us that with a 95% probability, at most three stop signal events statistically, might have been observed in the data. Therefore, any mass combination of stop and sneutrino predicting more than three events after all selection cuts were placed is excluded with 95% probability. This would be true, if we were able to predict the possible stop signal events without any uncertainty. In Sec. 14.3, we found a combined theoretical and experimental uncertainty of $\delta_{signal} = 37.8\%$. To incorporate them into the upper limit N, we must determine the mean of a Poisson distribution which is "smeared" by a Gaussian distribution of width δ_{signal}, such that the probability of observing zero events is 95%. While for the no-uncertainty case we were able to find an analytic solution, we use a Monte Carlo procedure to fold in the uncertainties.

The CDF experiment has adopted the following method of determining the upper limit N for non-zero δ_{signal}. We assume a Gaussian distribution $G(N, \delta_{signal}) = \frac{1}{\sqrt{2\pi\delta^2_{signal}}} e^{-\frac{(x-N)^2}{2\delta^2_{signal}}}$ with mean N and width δ_{signal}. We assume a Poisson probability distribution $P(n_0, N) = \frac{N^{n_0} e^{-N}}{n_0!}$ for the measured number of events n_0 with a mean N. This N is to be determined. We start from an arbitrary initial value of N denoted N_{init}. We randomly generate a real ν according to $G(N_{init}, \delta_{signal})$. We repeat this 10,000 times. We count how many times (denoted c) we obtain a non-negative ν such that after using it as the mean of a Poisson distribution we generate an integer number that is greater than n_0. The ratio $\frac{c}{10000}$ is called ϵ_{init}. Then we check if this ϵ_{init} coincides with the desired ϵ (of course within desired precision). If not, the initial guess N_{init} is adjusted to N_1 and with the above procedure ϵ_1 (instead of ϵ_{init}) is determined. We repeat the search for N_i until the desired confidence level $1 - \epsilon_i = 1 - \epsilon$ is reached. We use `poilim.f`, a CDF program[72] for executing the above procedure.

In our case, when we observed $\boxed{n_0 = 0}$ events with the uncertainty of the expected signal being $\boxed{\delta_{signal} = 37.8\%}$ the 95% C.L. upper limit of stop events in the data is determined to be $\boxed{N = 4.01}$ events. This allows us to exclude at 95% C.L. any stop and sneutrino mass combination (listed in Tab. H.1), that predicts[2] at least 4.01 signal events in the CDF Run 1 data.

The CDF excluded region is graphically shown on Fig. 15.1 as a shaded contour. We also show the results of Fermilab's DØ experiment[73] and CERN's LEP experiments[33, 34, 35] (for the minimum stop mixing angle $\theta = 0°$ *i.e.* the maximal reach). The band at $m_{\tilde{\nu}} = 44.7$ GeV is the current most general, model independent upper limit on the sneutrino mass[13]. Our exclusion contour starts at $m_{\tilde{t}} = 80$ GeV/c^2 because those are the lowest stop mass Monte Carlo points we have generated to have a good overlap with LEP's excluded region. Close to the kinematic limit, $m_{\tilde{t}} \geq m_{\tilde{\nu}} + m_b$, our sensitivity is limited by the ability to detect the low energetic leptons and jets, eventually losing the stop signature, i.e the required two leptons and jet. In the high stop mass region, our reach is determined by the rapidly falling stop production cross section. In contrast to the DØ strategy, with our selection cuts, we select a kinematic region with the smallest possible background and large enough signal[3]. This way, we minimize the impact of the rather large systematic uncertainties on our result.

The maximum sneutrino mass we exclude is $m_{\tilde{\nu}} = 88.4$ GeV/c^2 for $m_{\tilde{t}} = 126 - 127$ GeV/c^2 . The highest stop mass we reach is $m_{\tilde{t}} = 135$ GeV/c^2 for $m_{\tilde{\nu}} = 72 - 79$ GeV/c^2 .

[2]with either the high or low $\Delta(m_{\tilde{t}}, m_{\tilde{\nu}})$ mass gap set of cuts

[3]If we loosen some of the cuts designed to distinguish stop signal from top background, we would gain back some signal events compensating the falling cross section, but with the available integrated luminosity we would not be able to distinguish them anymore from the $t\bar{t}$ background.

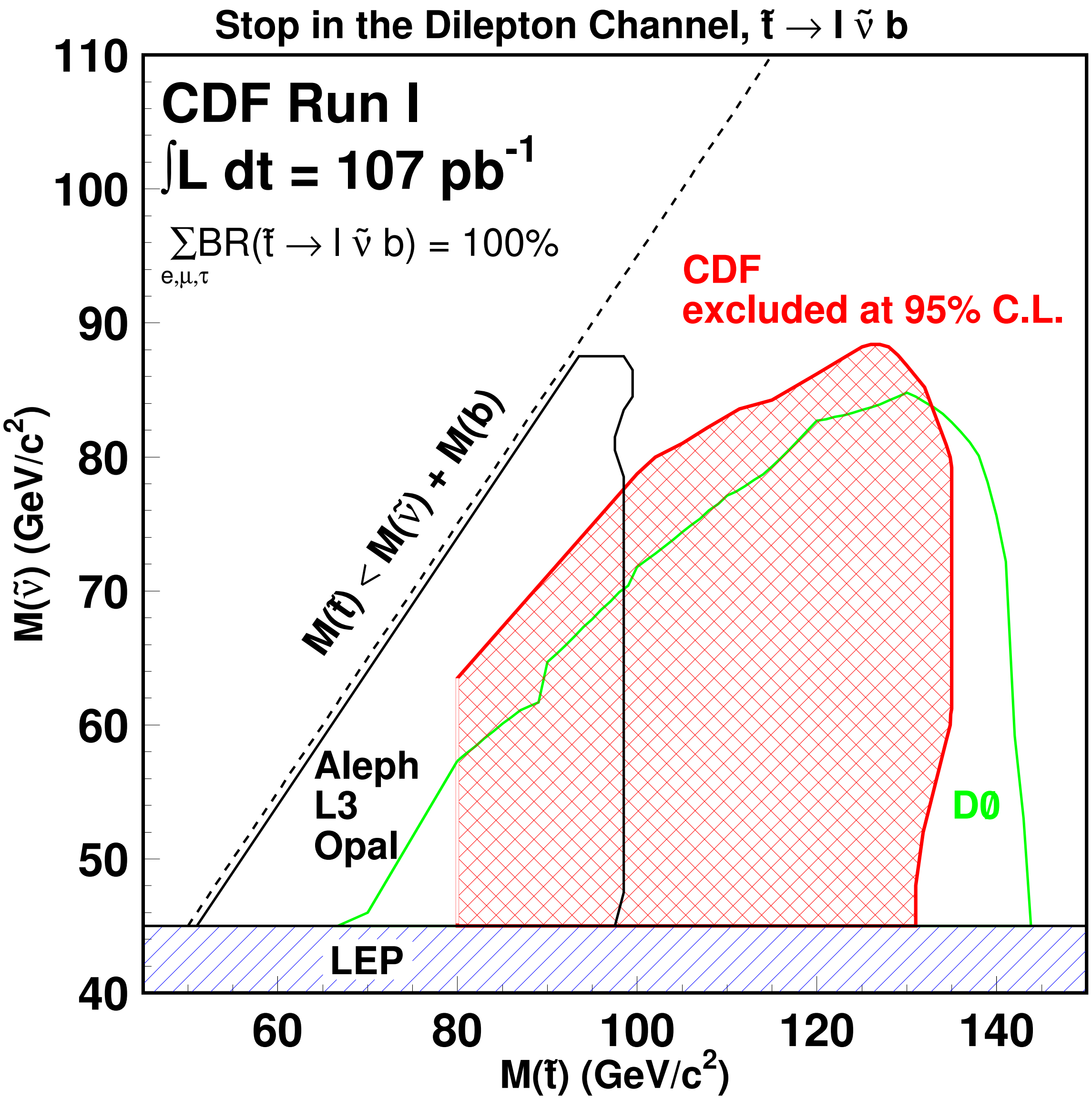

Figure 15.1. CDF 95% C.L. excluded region in the $m_{\tilde{t}}$, $m_{\tilde{\nu}}$ parameter plane. For the 3-body stop decay, $\tilde{t} \rightarrow\ l\tilde{\nu}b$, a 33.3% branching ratio to each of the three lepton flavors is used.

16. Conclusion

In the work documented in this thesis we searched for the presence of the supersymmetric partner of the top quark in $\int \mathcal{L}\mathrm{dt} = 107.2\ pb^{-1}$ of the Run 1 dilepton data sample collected by the CDF experiment at Fermilab. Stop anti-stop pairs would be strongly pair produced at the Tevatron if kinematically allowed. We considered the three body decay of the stop quark $\tilde{t} \rightarrow bl\tilde{\nu}$ to dominate, taking 100% of the branching ratio with $l \in \{e, \mu, \tau\}$. The signature the stop-antistop pairs would leave in the detector would denote the presence of energetic, opposite electric charge leptons, bottom quark jets and substantial missing transverse energy. The main background mimicking this signature comes from events with $t\bar{t}$, $b\bar{b}$, $c\bar{c}$ production and decays, Drell-Yan events, diboson production and decays and events with misidentified or non-prompt leptons. The background and stop signal events were generated with the ISAJET generator and they underwent a full CDF detector simulation. We placed selection cuts on various kinematic variables in order to enhance the statistical significance of stop events in the data while at the same time reducing the background. We found that the relative uncertainty in determining the amount of stop events in the data was 37.8%. We observed zero events in agreement with the predicted background. This allowed us to set an upper limit of 4.01 events on the amount of stop signal in the data and we determined our excluded region in the stop versus sneutrino mass plane. The highest stop mass we were able to reach was $m_{\tilde{t}} = 135$ GeV/c^2 and the highest excluded sneutrino mass was $m_{\tilde{\nu}} = 88.4$ GeV/c^2 . We observed no sign of supersymmetry manifesting itself in our data, and we look forward to the results of Run 2 at Fermilab and, later, the results from the Large Hadron Collider of CERN, both of which will extend the reach of the analysis presented here.