July 27, 2004

Research Overview for the Oral Candidacy Exam

Kristian Hahn
University of Pennsylvania

1 Introduction

This document is an outline of the work I have done and will perform to fulfill the University's thesis requirements. I describe a search for R-Parity violating sneutrino decay in Sections 2 and 3. The methodology developed for that analysis is additionally applicable to ZZ and ZW decays and the sneutrino search will eventually expand to include these processes. A brief plan for this analysis is provided in Section 4. Both analyses are works done in collaboration with Prof. Nigel Lockyer and Dr. Peter Wittich. Finally, Section 5 lists some of the contributions I have made to the PULSAR project, the Run-II upgrade to CDF's Level 2 Trigger. This work has been performed within the larger context of Penn's involvement in the project.[1]

2 Theory Overview

2.1 Supersymmetery and R-Parity

Supersymmetery (SUSY) is an extension to the Standard Model (SM) that offers compelling solutions to problems that arise in that theory. A primary motivation for SUSY its ability to resolve the 'hierarchy problem' of the SM Higgs potential. The Higgs mass term in the SM receives quadratically divergent corrections from every energy scale however these divergences can be made to cancel with the introduction of supersymmetery. For the cancellation to occur, each Standard Model (SM) particle is paired with a corresponding 'superpartner' of equal charge and alternate spin-statistic. Physics in a SUSY model is determined by a Lagrangian formulated in terms of 'supermultiplets' of SM fields and their SUSY partners. In the Minimal Supersymmetric extension to the Standard Model (MSSM), the Lagrangian is defined to respect a discrete symmetry referred to as 'R-parity'. This symmetry is introduced as a means of preserving baryon (B) and lepton (L) number conservation, features of the SM that arise naturally from the requirement of renormalization. In SUSY models, however, renormalization alone no longer serves to maintain B and L conservation and either may be violated by including appropriate R-parity violating (RPV) terms in the Lagrangian.

Standard Model particles are even under R-parity while SUSY particles are odd, as may be seen from the representation of the symmetry shown in Eq. (1)[1]. An equivalent representation, known as 'matter parity', is shown in Eq. (2). Since supermultiplets are comprised of both SM and SUSY particles, each having different values of R-parity, it is difficult to use Eq. (1) to identify RPV terms in the Lagrangian. Because matter parity violating terms are necessarily R-parity violating, the formulation in Eq. (2) allows the RPV terms in a SUSY Lagrangian to be identified more easily[2].

[1]Penn's PULSAR group includes: P.T. Keener, Prof. J. Kroll, C. Neu, D. Whiteson, P. Wittich, R. Van Berg

[2]The L_i multiplet has L=1 while $\bar{e}_i$ carries L=−1. Q_i carries B=1/3 and $\bar{u}_i, \bar{d}_i$ are B=−1/3.

$$P_R = (-1)^{3(B-L)+2s} \tag{1}$$
$$P_M = (-1)^{3(B-L)} \tag{2}$$

The MSSM Lagrangian conserves R-parity by including only terms of matter parity of +1. In contrast, a more general SUSY Lagrangian also contains RPV terms and violates B and L conservation. Equation Eq. (3) lists a few matter parity +1 terms from the MSSM Lagrangian that respectively describe couplings between right-handed u and d type (s)quarks and the left-handed (s)quark multiplet and couplings between conjugate right-handed (s)leptons and the left-handed (s)lepton multiplet. Equation Eq. (4) shows RPV terms that describe sneutrino production from $p\bar{p}$ and its leptonic decay[2]. Indicies on the λ and $\lambda^{'}$ couplings refer to lepton or quark generation. Including *both* L and B violating terms in the SUSY Lagrangian results in a model in which the proton rapidly decays. In order to describe physics consistent with phenomenology the Lagrangian must include only L (or only B) violating terms. The sneutrino interactions in which we are interested contain L violating terms only.

$$\bar{u}\mathbf{y_u}QH_u, \quad \bar{d}\mathbf{y_d}QH_d, \quad \bar{e}\mathbf{y_e}LH_d \tag{3}$$
$$\lambda^{'ijk}L_iQ_j\bar{d}_k, \quad \lambda^{ijk}L_iL_j\bar{e}_k \tag{4}$$

Supersymmetery predicts that SM particles and their SUSY partners have equal mass. Because equal mass superpartners are not observed experimentally, supersymmetery must be broken. The Run-I CDF $\tilde{\nu} \to e\mu$ search, discussed in Section 3, limits sneutrino mass to $\geq \sim$350 GeV for certain values of λ and $\lambda^{'}$. A more recent Run-II dimuon analysis sets limits of 400, 660 and 840 GeV, corresponding to a range of $\lambda^{'}$ values[3].

2.2 RPV Sneutrino Decay

The sneutrino is the superpartner of the neutrino and is a heavy, neutral, scalar particle. Figure 1 shows the process for which we will search in Run-II; sneutrino production from $p\bar{p}$ and its decay into different flavor leptons. Both vertices shown in the diagram are R-parity violating and each is separately described by an RPV terms Eq. (4). The relevant couplings for sneutrino production are $\lambda^{'}_{311}$ and $\lambda^{'}_{211}$ which describe $\tilde{\nu}_\tau$ and $\tilde{\nu}_\mu$ sneutrino production from d and $\bar{d}$. Lepton flavor violating sneutrino decays are governed by the λ_{132} λ_{231}, λ_{233} and λ_{122} couplings, which $e\mu$, $e\tau$ and $\mu\tau$ final-states. Limits for these couplings are provided by low energy experiments sensitive to deviations from SM predictions[4].

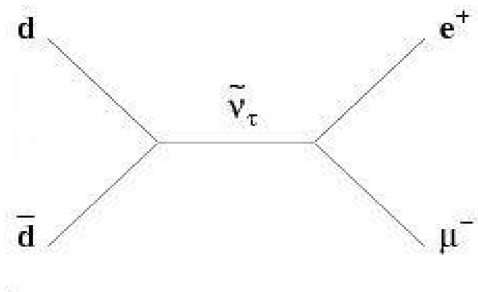

Figure 1: A diagram for the R-parity violating production and decay of the sneutrino.

3 The Sneutrino Analysis

I detail the current state of our sneutrino search in the following section. The search for $\tilde{\nu} \rightarrow e\mu$ was first performed by CDF in Run-I[5]. Work to continue the analysis in Run-II has so far consisted of the calculation of signal and background acceptances. Section 3.2 describes the work needed to complete the analysis. Tasks listed in both sections will be repeated using cdfsoft 5.3.x once that software is deemed stable.

3.1 Current Status

As in the Run-I analysis, we use Pythia to model $\tilde{\nu} \rightarrow e\mu$ with sneutrino mass ranging from 50 to 800 GeV. Because Pythia does not include the sneutrino by default, we substitute the Higgs particle and force its decay to $e\mu$. Event selection consists of requiring an identified electron and muon that pass the standard Top/EWK lepton cuts. Table 1 compares our signal acceptance to that found in the Run-I analysis. While the results are generally consistent, we are examining how changes in the Monte Carlo seed effect the differences observed.

Sneutrino Mass (GeV)	**50**	**100**	**200**	**300**	**400**	**500**	**600**	**700**	**800**
Run I (%)	2.20	15.2	22.5	28.3	31.6	35.2	37.5	39.2	40.5
Run II (%)	8.30	18.7	22.2	26.3	28.7	29.1	27.9	32.0	31.5

Table 1: Monte Carlo Signal Acceptances in the Run I, Run II Analyses.

Because of its considerable mass, the sneutrino's decay products emerge with large transverse momentum. The signature of two high p_T leptons of different flavor allows us to suppress most SM backgrounds. We present acceptances for the major backgrounds to $\tilde{\nu} \rightarrow e\mu$ in Table 2. Values that are yet to be determined in the Run-II analysis are listed as '–'. Pythia-generated samples of 150-300K events were used in the acceptance calculation for $Z \rightarrow \tau\tau$, top and WW.

Background Channel	$Z \to \tau\tau$	**WW**	**tt**	**WZ**	$Z \to \mu\mu$	**ZZ**
Run I (%)	0.21	2.83	0.45	4.00	0.001	7.23
Run II (%)	0.39	3.12	0.41	–	–	–

Table 2: Monte Carlo SM Background Acceptances in the Run I, Run II Analyses.

Values of signal and background acceptance allow us to calculate a sensitivity curve for the $\tilde{\nu} \to e\mu$ cross-section. Following the method used in the Run-I analysis, we interpolate signal acceptance between mass points with a step size equal to three times the RMS of the signal invariant mass. This technique provides good statistical coverage and removes dependence on statistical errors in the width and mean of the invariant mass distribution. The number of observed and expected background events in each mass bin, together with the interpolated signal acceptance, is input to a low statistics Poisson formula that provides the number of expected signal events at 95% C.L.[6]. Results from this procedure are shown in Figure 2. The Run-I result, shown with the theoretical Run-I limit superimposed, is scaled by the $Z \to ee$ cross-section.

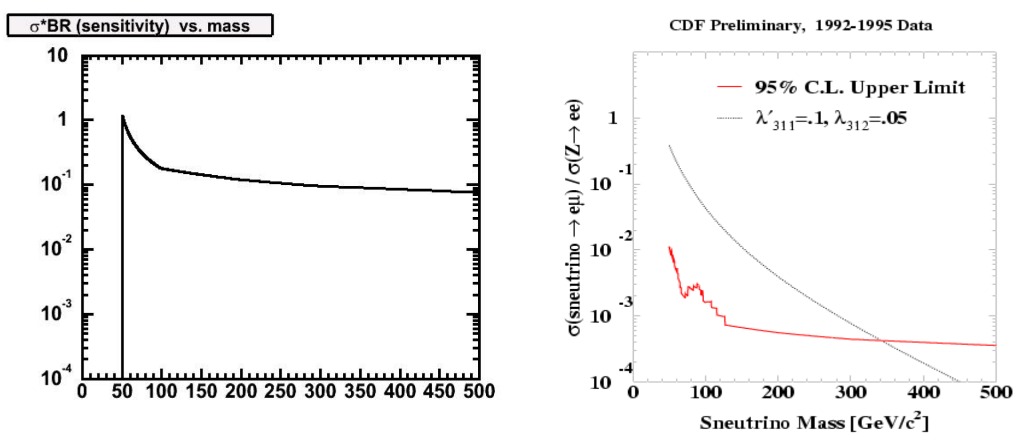

Figure 2: $\sigma \times BR$ Limits. Left: the sensitivity curve for Run-II. Right: the limit set in Run-I and corresponding theory curve.

3.2 Future Work

The next step in the analysis will be to estimate the background contribution from the remaining SM processes in Table 2 and from fake leptons. The expected number of fake leptons will be obtained by calculating a fake rate in the QCD sample and applying that rate to lepton+jet data. We will also compare electron and muon cut efficiencies in data and Monte Carlo using events selected from $Z \to ee$ and $Z \to \mu\mu$ samples that include at least one tight and one loose lepton. Efficiencies will be determined by applying the tight lepton requirements to the loose lepton of selected events. We must account for systematic uncertainties.

We will eventually include $\tilde{\nu} \to e\tau \to \nu_\tau \bar{\nu}_\mu e\mu$ and $\tilde{\nu} \to \mu\tau \to \nu_\tau \bar{\nu}_e e\mu$ channels. The reconstruction of leptonically decaying taus will require that we introduce cuts on missing energy ($\not{E}_T$). Because tau decay products are colinear, the Run-I analysis requires that the angle between $\not{E}_T$ and a lepton to be smaller the 60 degrees for the lepton to be classified as having come from a tau decay. For events passing this criterion, tau momentum is reconstructed using the formulae below.

$$p_x^\tau = p_x^l + \not{E}_x \tag{5}$$

$$p_y^\tau = p_y^l + \not{E}_y \tag{6}$$

$$p_z^\tau = p_z^l \times (1 + \not{E}_T / p_T^l) \tag{7}$$

We will perform the sneutrino search as a ‘blind analysis’ in RunII. To establish the accuracy of our Monte Carlo predictions, we will apply our event selection criteria to control regions in the full data sample and compare the observed level of background with our expectation. By applying the selection to signal-like regions of background we will be able to cross-check our overall procedure.

In completing the tasks described above we will effectively reproduce the Run-I sneutrino decay analysis in Run-II. We additionally plan to investigate modifications to the orignal analysis that may improve our statistical reach. For instance, loosening the event selection criteria from the requirement of two identified leptons to the less restrictive lepton+track approach used by the top dilepton group may help us to increase signal acceptance. In doing so, however, we may loose some of the rejective power of the flavor-different signature with respect to our SM background. We may also seek to gain further acceptance by incorporating single-prong taus (in the lepton+track approach) and Phoenix electrons.

4 ZZ, ZW

Our search for an $e\mu$ decay signature is also sensitive to ZZ and ZW diboson production. An application of the methods developed in the sneutrino analysis to these processes would compliment CDF’s current ZZ-ZW analysis[7]. ZZ and ZW production, not yet observed at the Tevatron, arise from different mechanisms in the SM. Figure 3 shows the leading-order contributions. The ZW diagram involves a coupling of three gauge-bosons, whereas ZZ is produced via two separate Z-quark vertices. Observed deviations in the SM cross-section for these processes would indicate new physics.

We will search for the ZW and ZZ decays in which both bosons decay leptonically. We anticipate a limited amount of signal, given that the theoretical production cross sections are small (1.39pb for ZZ and 3.65pb for ZW) and given the low relative

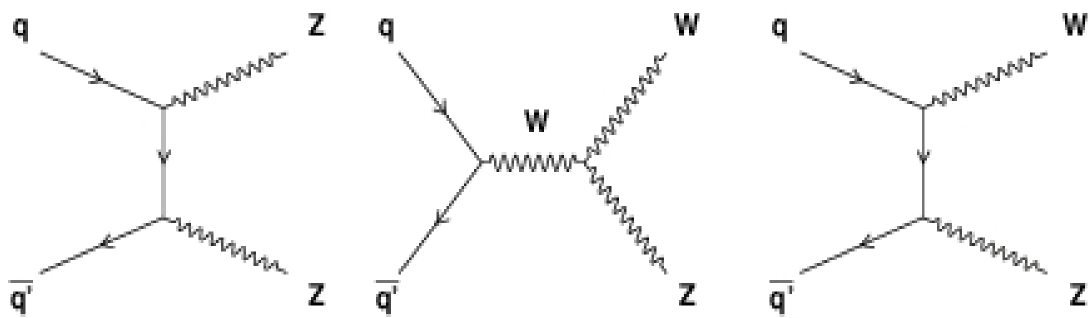

Figure 3: diagram for ZZ and ZW production from $p\bar{p}$

branching ratios of Z into leptons. A search using $e\mu$ alone would prevent the individual reconstruction of the Z or W. Instead, we will combine the $e\mu$ and lepton+track approaches used in the sneutrino analysis and reconstruct Z's and W's using $e\mu + 2$ tracks.

5 Level 2 Trigger

In addition to my thesis work, I have also been active in the PULSAR (Pulser And Recorder) upgrade to the Level-2 (L2) Trigger. The PULSAR design removes the MagicBus and the various interface boards used to route detector information from the Level-1 readout to the L2 processor. In their place, a number of modular PULSAR VME boards will collect event data and deliver it to the Level-2 processor over optical links. The design also replaces the custom-built L2 processor board (equipped with an obsolete DEC alpha chip) with commodity dual-processor PC's running Linux. My involvement in the project is centered on this latter aspect of the system.

The L2 trigger is expected to receive events for processing at a maximum rate of 40kHz[8]. For the trigger to operate efficiently, the L2 system must reach a trigger decision approximately 20μs after an L1 accept. To meet this requirement, we attempt to minimize the time for data transfer to and from the PC as well as the time the PC spends running the trigger algorithms. After porting the trigger code from the alpha to the PC, I performed a number of performance studies, on various architectures, using PC's to process real event data.

I have also helped to develop the mechanism by which the L2 processors interact with CDF's overall data acquisition system. This has involved the writing of multi-threaded code to isolate the critical data I/O and algorithm functionality on one CPU. Separate threads, run on the other CPU, handle the transmission and reception of control and monitoring information over ethernet.

References

[1] Martin, Stephen P., hep-ph/9709356.

[2] D. Choudhury, S. Majhi and V. Ravindran (2002), hep-ph/0207247.

[3] Unel et al., *Searches in High Mass Dimuon Channel in*

*[4] V. Barger, G.F. Gidice and T. Han, Phys. Rev. D**40**, 2987 (1989).*

[5] CDF Collaboration, D. Acosta et al., Phys. Rev. Lett. ***91****, 171602 (2003). CDF Run II* 2/2004. CDFNote 6879.

[6] R. M. Barnett et al., Phys. Rev. D **54**, 1 (1996).

[7] S. Cabrera, et al. *Search for ZZ and ZWproduction in* $p\bar{p}$ *collisions at* $\sqrt{s} = 1.96\,TeV$ 7/2004. CDFNote 7094.

[8] CDF PULSAR Group. *RunIIb Upgrade for CDF L2Decision Crate,* 9/2002. CDFnote 6259.