

Search for Neutral Higgs Bosons of the
Minimal Supersymmetric Extension of the
Standard Model with SLD

by

Ji Ma

A dissertation submitted in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

University of Washington

1994

Approved by



(Chairperson of Supervisory Committee)

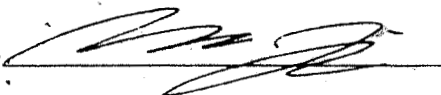
Program Authorized

to Offer Degree Department of Physics

Date December 9, 1994

In presenting this dissertation in partial fulfillment of the requirements for the Doctoral degree at the University of Washington, I agree that the Library shall make its copies freely available for inspection. I further agree that extensive copying of this dissertation is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for copying or reproduction of this dissertation may be referred to University Microfilms, 1490 Eisenhower Place, P.O. Box 975, Ann Arbor, MI 48106, to whom the author has granted "the right to reproduce and sell (a) copies of the manuscript in microform and/or (b) printed copies of the manuscript made from microform."

Signature



Date

December 8, 1994

University of Washington

Abstract

Search for Neutral Higgs Bosons of the
Minimal Supersymmetric Extension of the
Standard Model with SLD

by Ji Ma

Chairperson of Supervisory Committee: *Professor Paul Mockett*
Department of Physics

We searched for the light neutral scalar Higgs boson h^0 and the pseudoscalar Higgs boson A^0 of the Minimal Supersymmetric Extension of the Standard Model (MSSM) for the case $\tan\beta < 1$. The experiment was done with the SLD detector at the Stanford Linear Accelerator Center (SLAC). This analysis is based on the data set collected during the 1993 physics run which contained about 50,000 hadronic Z^0 events. (About 38,000 events have Central Drift Chamber (CDC) information recorded). After the event selection cuts for hadronic Z^0 decays with CDC information, we select 27,560 events. The Monte Carlo (MC) simulated event distributions agree very well with the data. Good agreement is achieved between MC and the data on the number of events passing each of the event selection cuts.

The invariant mass spectrum is generated from those events that pass the Higgs filter. A bin-by-bin comparison of the spectrum shows the data is consistent with the MC with no Higgs contribution. No evidence for the existence of the neutral Higgs bosons h^0 and A^0 is found. The results from this Higgs search show that MSSM tree level neutral Higgs with masses $m_{h^0} \leq 42.7 \text{ GeV}/c^2$ and $m_{A^0} \leq 42.7 \text{ GeV}/c^2$ for $\tan\beta < 1$ have been excluded at 95% confidence level.

TABLE OF CONTENTS

List of Figures	iv
List of Tables	viii
Glossary	ix
Chapter 1: Introduction	1
1.1 Motivation	1
1.1.1 Theoretical Basis	1
1.1.2 Experimental Motivation	2
1.2 Thesis Outline	2
Chapter 2: Theory	4
2.1 Standard Model	5
2.2 General Two-Higgs Doublet Model	6
2.3 Minimal Supersymmetric Extension of the Standard Model	8
2.3.1 Higgs Production	10
2.3.2 Higgs Decay	10
2.4 Comments on $\tan \beta$ Value	12
2.5 Branching Fraction Calculations	12
2.6 One-loop Radiative Corrections and Their Impacts	13
2.7 Current MSSM Higgs Search Limits	16
Chapter 3: Experimental Apparatus	19
3.1 The Stanford Linear Collider	19
3.1.1 Beam Energy Measurement	22
3.2 The Stanford Large Detector	23
3.2.1 The Vertex Detector	25

3.2.2	The Luminosity Monitor	27
3.2.3	The Drift Chamber System	29
3.2.4	The Magnet and Flux-return	31
3.2.5	The Cherenkov Ring Imaging Detector	31
3.2.6	The Calorimeter System	31
Chapter 4: Data Analysis		37
4.1	Data Selection	37
4.1.1	Online Event Trigger	37
4.2	The SLD Monte Carlo	38
4.2.1	Event Generators	38
4.2.2	Detector Simulation	39
4.2.3	Event Reconstruction	40
4.3	Hadronic Z^0 Event Filter	41
4.4	Higgs filter	42
4.4.1	The Visible Energy Cut	42
4.4.2	The Jet Reconstruction and Four Jet Cut	45
4.4.3	Global Energy-Momentum Constrained Fit	46
4.4.4	Reconstruction of the Higgs Masses	48
4.4.5	The Jet Angle Cuts	53
4.4.6	Vertex Related Cuts	53
4.5	Software Implementation	62
Chapter 5: Results		66
5.1	Confidence Level	66
5.2	MC and Data comparison	67
5.3	Performance of the Hadronic Z^0 Filter	67
5.4	Performance of the Higgs Event Filter	71
5.5	Results	73
5.5.1	Excluded Region	74
5.5.2	Binning Issue in Data and MC comparison	76
5.5.3	Comparison with LEP Results	79

5.6 Conclusions	79
Bibliography	84
Appendix A: The Partial Widths of MSSM Higgs Decay to Quark Pairs	87
Appendix B: The Angle Factors in MSSM	89

LIST OF FIGURES

2.1	MSSM tree level Higgs couplings to gauge bosons and quarks	11
2.2	Radiative correction to the tree level prediction. (a) no correction (b) $m_t = 100 \text{ GeV}/c^2, m_{\bar{t}} = 140 \text{ TeV}/c^2$ (c) $m_t = 100 \text{ GeV}/c^2, m_{\bar{t}} =$ $500 \text{ TeV}/c^2$ (d) $m_t = 190 \text{ GeV}/c^2, m_{\bar{t}} = 1 \text{ TeV}/c^2$	15
2.3	OPAL 95% CL exclusions in the MSSM parameter space for various values of $\tan \beta$ (indicated in the figure). The diagonal line is the Z^0 decay kinematic limit.	17
2.4	Current CERN MSSM neutral Higgs search results ($\tan \beta > 1$). The dark region is excluded, the hatched region allowed, and the light region not allowed by the theory.	18
3.1	Layout of the SLAC Linear Collider.	20
3.2	Schematic of the SLC energy spectrometer. One for each arc just before the beam dump.	22
3.3	A quadrant view of SLD. The lower left corner corresponds to the SLD interaction point. Notice the projective tower geometry of the calorimeter system.	24
3.4	The SLD vertex detector	27
3.5	A reconstructed event with VTX. Picture shows VTX has four loosely spaced CCD ladders. The scale on the side shows the size of the VTX	28
3.6	Arrangement of the superlayers and cells in the CDC	30
3.7	Barrel LAC module and cryostat assembly	33
4.1	Charged track energy of $Z^0 \rightarrow \text{hadrons}$	43
4.2	Charged track energy of $Z^0 \rightarrow h^0 A^0$	43
4.3	Charged particle momentum versus its jet angle	44
4.4	Neutral particle momentum versus its jet angle	44

4.5	The determinant of the balance coefficient matrix versus balance coefficient for four already balanced momentum vectors. It shows for small value of the determinant, coefficients are uncertain.	47
4.6	Higgs invariant mass plot (lower mass versus higher mass) for the correct jet pairing	48
4.7	Higgs invariant mass plot (mass sum versus mass difference) for the wrong jet pairing	49
4.8	Higgs invariant mass plot (mass sum versus mass difference) for the correct jet pairing).	50
4.9	Higgs mass sum peak projected into MS axis. This is for $m_{h^0} = 30 \text{ GeV}/c^2, m_{A^0} = 40 \text{ GeV}/c^2$. The fit gives 69.66 ± 1.83	51
4.10	Higgs mass sum peak projected into MS axis. This is for $m_{h^0} = 30 \text{ GeV}/c^2, m_{A^0} = 40 \text{ GeV}/c^2$. The fit gives 9.51 ± 4.54	51
4.11	L3 reconstructed neutral Higgs masses	52
4.12	Higgs mass peak projected into MD axis. It shows half a Gaussian peak because the degeneracy of our Higgs masses.	52
4.13	Smallest versus next smallest angle between jets for $Z^0 \rightarrow \text{hadrons}$	54
4.14	Smallest versus next smallest angle between jets for $Z^0 \rightarrow h^0 A^0$. Notice that for QCD background, θ_1, θ_2 are small while for Higgs events the distribution is rather uniform. The rejection was around the top right corner.	54
4.15	The vertex view of a hadronic Z event	55
4.16	The vertex view of a $Z^0 \rightarrow h^0 A^0$ event	56
4.17	Total number of linked "good" vertex tracks for $Z^0 \rightarrow \text{hadrons}$	57
4.18	Total number of linked "good" vertex tracks for $Z^0 \rightarrow h^0 A^0$. Notice that the 4-jet background has fewer "good" vertex tracks than the Higgs events have. The selection cut is $N_{\text{utrck}} > 2$	57
4.19	Normalized impact parameter for $Z^0 \rightarrow \text{hadrons}$	58
4.20	Normalized impact parameter for $Z^0 \rightarrow h^0 A^0$. Notice that the high B_{norm} tail in Higgs event.	58
4.21	Momentum versus normalized impact parameter for $Z^0 \rightarrow \text{hadrons}$	59

4.22	Momentum versus normalized impact parameter for $Z^0 \rightarrow h^0 A^0$. The Higgs events spread more outward from origin than QCD background. A selection cut around the origin was used to suppress the background.	59
4.23	Impact moment for $Z^0 \rightarrow hadrons$.	60
4.24	Impact moment for $Z^0 \rightarrow h^0 A^0$. The difference here is more prominent than previous two plots. The optimal cut is $\mathcal{M} > 44$.	60
4.25	Software Flow Chart for Higgs Filter; It is totally isolated from the SLD off-line system by pair of the interface routines.	64
5.1	The number of charged tracks	68
5.2	The number of linked charged tracks. Note that 90% of the CDC tracks are linked.	68
5.3	Total charged track energy ($E_{visible}$).	69
5.4	The event thrust distribution.	69
5.5	Transverse momentum of the charged tracks.	70
5.6	Normalized impact parameters of linked vertex tracks.	70
5.7	MC backgrounds in the MS, MD phase space	75
5.8	Contour of excluded region in M_{h^0} and M_{A^0} space. The dash line corresponds to the Z^0 decay kinematic limit.	77
5.9	Comparison between MC and data. The difference of significance has mean of 0.170 ± 1.0 .	78
5.10	DELPHI 95% excluded region (1992). (A) h^0 decays to SM H^0 (B) h^0, A^0 decays to $\tau^+\tau^-$ (C) h^0, A^0 giving 4 jets	80
5.11	SLD 95% excluded region (1994). h^0, A^0 decays to 4 c-quark jets. The dash line is the mass kinematic limit.	80
5.12	Invariant mass plot (mass sum versus mass difference) for MC.	81
5.13	Invariant mass plot (mass sum versus mass difference) for Data.	81
5.14	Higgs invariant mass plot (mass sum versus mass difference) for wrong pairing.	82
5.15	Higgs invariant mass plot (mass sum versus mass difference) for correct pairing.	82

5.16 MC Higgs invariant mass plot of the correct jet pairing for mass sum
(top), low mass versus high mass (bottom). 83

LIST OF TABLES

2.1	MSSM Higgs couplings to different fermions	9
2.2	MSSM Higgs production mode: “bremsstrahlung” and “pair production” and their limits	10
2.3	Quark and lepton masses used in branching ratio calculation	13
3.1	LAC Longitudinal Segmentation	34
3.2	LAC module and tower counts	35
5.1	Explanation of the veto bits	71
5.2	Summary of event veto at various stage of the Higgs filter	72
5.3	Summary of Data, MC and Higgs sample passing the hadron selection and the Higgs filter (properly normalized)	74
5.4	Higgs finding efficiency for various different Higgs mass pairs	76
5.5	Bin by bin invariant mass comparison between Monte and Data. Numbers are $N_\sigma = (N_{data} - N_{mc})/\sigma$. Notice that most of them are less than 1.	78

GLOSSARY

SLAC: Stanford Linear Accelerator Center at Stanford University.

SLC: the SLAC Linear Collider.

SLD: Stanford Large Detector.

MSSM: Minimal Supersymmetric Extension of the Standard Model.

IDA: SLD Interactive Data Analysis program.

VEV: Vacuum Expectation Value.

CERN: European Organization for Nuclear Research.

LEP: The Large Electron-Positron storage ring at CERN.

DELPHI, ALEPH, L3, OPAL: 4 detectors on LEP storage ring.

ACKNOWLEDGMENTS

I would like to thank the entire SLD/SLC collaboration. This thesis would not be possible without their joint efforts. Although I don't know many people from the SLC, their hard work in continually improving the luminosity is very much appreciated. I would also like to thank Tom Junk and Niel Homer for their help on Monte Carlo study and in-depth discussions of the data analysis.

I am particularly grateful to my thesis advisor, Professor Paul Mockett, for his great patience, guidance and deep physics insight, and for reading through this thesis many times and providing many thoughtful comments.

I am indebted to the entire UW High Energy Physics group. They have given me much valuable help when I encounter either administrative problems or academic ones.

Finally I want to thank my wife, Xiao-zhen, for her support, encouragement. She always makes me feel happy and relaxed.