SEARCHING FOR HIGGS BOSONS AND NEW PHYSICS AT HADRON COLLIDERS

Final Report for an EPSCoR State-DOE Laboratory Partnership Award

- DOE award grant Number: DE-FG02-03ER46040
- Recipient: University of Oklahoma (OU)
- Project: Searching for Higgs Bosons and New Physics at Hadron Colliders
- Principal Investigator: Chung Kao (University of Oklahoma)
- National Laboratory Collaborator: Sally Dawson (Brookhaven National Lab)
- Date of award period covered: June 1, 2003 - May 31, 2006,
  No cost extension: June 1, 2006 - May 31, 2007.
- Approved budget amount: $579,723 = $450,000 (DOE EPSCoR) +129,723 (OU).

1 Overview

During the past four years, the DOE EPSCoR supported partnership in particle physics research between the University of Oklahoma (OU) and the Brookhaven National Laboratory (BNL) has made significant progress in both theoretical and experimental High Energy Physics. This research program involves faculty members at OU and BNL, as well as undergraduate students, graduate students and postdoctoral fellows at OU.

2 Goals and Objectives

The goal of our research program is to investigate, both theoretically and experimentally, the fundamental physics associated with electroweak symmetry breaking, supersymmetry, unification, CP violation, and extra dimensions at the Fermilab Tevatron Collider and the CERN Large Hadron Collider. To carry out these studies, we have calculated production rates for Higgs bosons and new particles associated with various extensions to the Standard Model (SM) as well as relevant SM backgrounds.

The objectives of our research activities are predicting the production cross section and decay branching fractions of Higgs bosons and new particles at hadron colliders, developing techniques and computer software to discover these particles and to measure their properties, and searching for new phenomena and new interactions at the Fermilab Tevatron and the CERN Large Hadron Collider. The results of our project could lead to the discovery of Higgs bosons, new particles, and signatures for new physics, or we will be able to set meaningful limits on important parameters in particle physics.

3 Theoretical Research Activities

At present, our theory group consists of two faculty members (C. Kao and K. Milton), a postdoctoral fellow and five graduate students. Since June 2003, fifteen research papers have been published or submitted to physics journals [1]-[11] and proceedings of conferences [12]-[15] for publication, and several papers are in progress. In addition, twenty-two seminars and colloquia have been presented at international conferences, universities, and national laboratories.

3.1 Discovering Higgs Bosons at the Large Hadron Collider

We investigated the prospects for the discovery of a neutral Higgs boson produced with one bottom quark (b or $\bar{b}$) via $bg \to b\phi^0, \phi^0 = h^0, H^0,$ or A^0 followed by Higgs decays into muon pairs [2], tau lepton pairs [9] or bottom quark pairs [11] at the CERN Large Hadron Collider (LHC) within the framework of the minimal supersymmetric standard model (MSSM).

In Figure 1, we present the 5σ discovery contours for the MSSM Higgs bosons where the discovery region is the part of the parameter space above the contour. We have chosen a common mass for supersymmetric (SUSY) particles, $M_{\rm SUSY} = m_{\tilde{g}} = m_{\tilde{q}} = m_{\tilde{\ell}} = \mu = 1$ TeV. If $M_{\rm SUSY}$ is smaller, the discovery region of $A^0, H^0 \to \mu^+\mu^-$ will be slightly reduced for $m_A \gtrsim 250$ GeV, because the Higgs bosons can decay into SUSY particles and the branching fraction of $\phi^0 \to \mu^+\mu^-$ is suppressed.

The muon pair decay mode is a promising channel for the discovery of the neutral Higgs bosons in the minimal supersymmetric standard model at the LHC. The A^0 and the H^0 should be observable in a large region of parameter space with $\tan\beta \gtrsim 10$. The associated final state of $b\phi^0 \to b\mu^+\mu^-$ could discover the A^0 and the H^0 at the LHC with an integrated luminosity of 30 fb^{-1} if $m_A \lesssim 600$ GeV. At a higher luminosity of 300 fb^{-1}, the discovery region in m_A is expanded up to $m_A \lesssim 800$ GeV for $\tan\beta \sim 50$. This discovery channel with one energetic bottom quark greatly extends the discovery potential of the LHC beyond the inclusive channel $pp \to \phi^0 \to \mu^+\mu^- + X$. For large $\tan\beta$, the muon pair discovery mode might be the only channel at the LHC that allows precise reconstruction of the A^0 and the H^0 masses. The discovery of the associated final states of $b\phi^0 \to b\mu^+\mu^-$ and $b\bar{b}\phi^0 \to b\bar{b}\mu^+\mu^-$ will provide important information about the Yukawa couplings of $b\bar{b}\phi^0$ and an opportunity to measure $\tan\beta$. The discovery of $\phi^0 \to \tau\bar{\tau}$ [9], $\phi^0 \to \mu^+\mu^-$ and $\phi^0 \to b\bar{b}$ will allow us to understand the Higgs Yukawa couplings with the leptons and the bottom quarks.

3.2 Detecting a Higgs Pseudoscalar with a Z Boson

In a two Higgs doublet model (2HDM), there are three neutral Higgs bosons: two CP-even scalars H^0 (heavier) and h^0 (lighter) as well as a CP-odd pseudoscalar (A^0). We investigated the prospects of detecting a Higgs pseudoscalar (A^0) in association with a Z gauge boson produced from bottom quark fusion ($b\bar{b} \to ZA^0$) at the CERN Large Hadron Collider. A general two Higgs doublet model and the minimal supersymmetric standard model are adopted to study the discovery potential of $pp \to ZA^0 \to \ell\bar{\ell}b\bar{b} + X, \ell = e$ or μ, via $b\bar{b} \to ZA^0$ with physics backgrounds and realistic cuts. Promising results are found

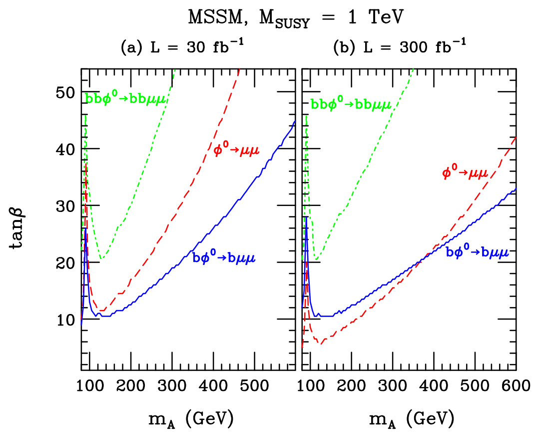

Figure 1: The 5σ contours at the LHC in the m_A versus $\tan\beta$ plane.

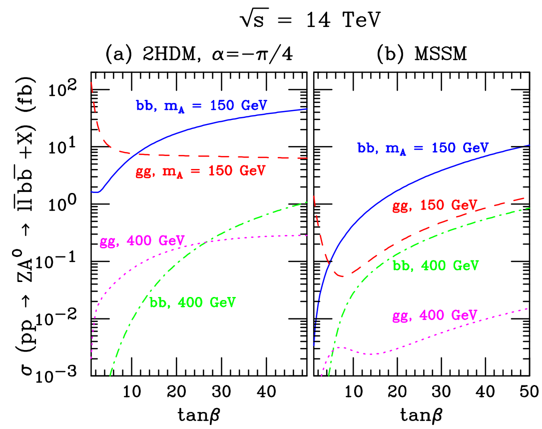

Figure 2: The cross section at the LHC for $pp \to ZA^0 + X \to \ell\bar{\ell}b\bar{b} + X$.

for $m_A \lesssim 400$ GeV in a general two Higgs doublet model when the heavier Higgs scalar (H^0) can decay into a Z boson and a Higgs pseudoscalar ($H^0 \to ZA^0$).

Figure 2 shows the cross section of $pp \to ZA^0 \to \ell\bar{\ell}b\bar{b} + X$ via $b\bar{b} \to ZA^0$ and $gg \to ZA^0$ as a function of $\tan\beta$ in a general two Higgs doublet model and the minimal supersymmetric standard model. While gluon fusion [1] is the major source for producing a Higgs pseudoscalar associated with a Z boson at the LHC for $\tan\beta \lesssim 10$, bottom quark fusion [4] can make dominant contributions for $\tan\beta \gtrsim 10$. We have chosen $m_H = m_A + 100$ GeV, $m_h = 120$ GeV, and $\alpha_H = -\pi/4$ for the 2HDM. It is clear that the cross section in a 2HDM can be significantly larger than that in the the MSSM when the H^0 can decay into ZA^0 with $m_H > m_A + M_Z$ since m_H and α_H are free parameters in a 2HDM. In the MSSM with $\tan\beta \gtrsim 10$, m_A and m_H are almost degenerate when $m_A \gtrsim 125$ GeV. Therefore, the decay $H^0 \to ZA^0$ is kinematically inaccessible in the MSSM.

We have found promising results for $pp \to ZA^0 \to \ell\bar{\ell}b\bar{b} + X$ via $b\bar{b} \to ZA^0$ in two Higgs doublet models at the LHC with $L = 300$ fb^{-1} for $m_A \lesssim 400$ GeV, $\tan\beta \gtrsim 5$, $|\alpha_H| \lesssim 1$, and $m_H = m_A + 100$ GeV. In the MSSM with $m_A \gtrsim 125$ GeV, $m_A \sim m_H$, and the production cross section of $pp \to ZA^0 + X$ is usually small.

In a general two Higgs doublet model, the cross section of $b\bar{b} \to ZA^0$ and $gg \to ZA^0$ can be greatly enhanced when the heavier Higgs scalar (H^0) can decay into the Higgs pseudoscalar and a Z boson. This discovery channel might provide a good opportunity to discover two Higgs bosons simultaneously if the heavier Higgs scalar (H^0) can decay into a Z boson and a Higgs pseudoscalar (A^0).

3.3 Supersymmetric Models with an Extra U(1) Symmetry

We have been studying the phenomenology of a supersymmetric $U(1)'$ model with Higgs singlets to break the extra gauge symmetry spontaneously at the TeV scale. This model is a natural extension of the MSSM to solve the μ problem and the cosmological domain wall problem as well as to provide a sufficiently strong first order phase transition for electroweak baryogenesis over most of the parameter space. Additional $U(1)$ gauge symmetries are predicted in many types of new theories including superstrings, grand unification, dynamical symmetry breaking, extra dimensions, and little Higgs models [16].

Recent mapping of the Cosmic Microwave Background (CMB) anisotropy has provided precision information on the densities of matter and dark energy in the Universe. The major part of the matter is non-relativistic and non-baryonic (cold and dark). When the Sloan Digital Sky Survey (SDSS) data on large scale structure are analyzed in combination with the Wilkinson Microwave Anisotropy Probe (WMAP) data, a cold dark matter (CDM) relic density

$$\Omega_{\rm CDM} h^2 = 0.12 \pm 0.01 \ \ ({\rm SDSS} + {\rm WMAP}) \tag{1}$$

is found [17, 18].

A neutral, stable, massive particle that interacts weakly is a natural candidate for CDM. In supersymmetric models with R-parity conservation, the lightest neutralino is the favored lightest supersymmetric particle (LSP) and CDM candidate. We investigated the properties of the lightest neutralino and evaluate its relic density in an extended model of the MSSM with an extra $U(1)$ gauge symmetry and four extra Higgs singlets (S, S_1, S_2, and S_3) [3].

This model allows a lightest neutralino mass up to about 300 GeV with the gaugino unification assumption $M_{1'} = M_1 = [(5/3)g_1^2/g_2^2]M_2$, but only up to $m_{\chi^0} \lesssim 100$ GeV in the limit with $M_{1'} \gg M_1 = [(5/3)g_1^2/g_2^2]M_2$. We quantitatively studied this model in the limit where M_1', $\langle S_i \rangle$ are much larger than the electroweak scale. In this limit the $Z\chi^0\chi^0$ coupling is enhanced compared to the MSSM due to the singlino component. This explains the relic density over a considerable fraction of the parameter space.

The anomalous magnetic moment of the muon $a_\mu = (g-2)_\mu/2$ is one of the most precisely measured physical quantities. Its current value from the Brookhaven National Laboratory E821 experiment is [19]

$$a_\mu({\rm exp}) = (11\ 659\ 208 \pm 6) \times 10^{-10},$$

which is a 2.4σ deviation from the Standard Model prediction. We study the muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$ in a supersymmetric $U(1)'$ model. We found that there are regions of the parameter space that can explain the experimental deviation of a_μ from the Standard Model calculation and yield an acceptable cold dark matter relic density without conflict with collider experimental constraints.

At present, we are investigating the discovery potential of the Tevatron Run II for detecting the supersymmetric trilepton signal in this model. The production of a chargino associated with a neutralino might lead to the promising signature of trileptons with large missing energy at the Fermilab Tevatron

3.4 $B_S \to \mu^+\mu^-$ versus direct Higgs searches at Colliders

We investigated the prospects for the discovery of neutral Higgs bosons with a pair of muons by direct searches at the CERN Large Hadron Collider (LHC) as well as by indirect searches in the rare decay $B_s \to \mu^+\mu^-$ at the Fermilab Tevatron and the LHC. Promising results are found for the minimal supersymmetric standard model, the minimal supergravity (mSUGRA) model, and supergravity models with non-universal

Higgs masses (NUHM SUGRA). For $\tan\beta \simeq 50$, we find that (i) the contours for a branching fraction of $B(B_s \to \mu^+\mu^-) = 1 \times 10^{-8}$ in the parameter space are very close to the 5σ contours for $pp \to b\phi^0 \to b\mu^+\mu^- + X, \phi^0 = h^0, H^0, A^0$ at the LHC with an integrated luminosity (L) of 30 fb^{-1}, (ii) the regions covered by $B(B_s \to \mu^+\mu^-) \geq 5 \times 10^{-9}$ and the discovery region for $b\phi^0 \to b\mu^+\mu^-$ with 300 fb^{-1} are complementary in the mSUGRA parameter space, (iii) in NUHM SUGRA models, a discovery of $B(B_s \to \mu^+\mu^-) \simeq 5 \times 10^{-9}$ at the LHC will cover regions of the parameter space beyond the direct search for $b\phi^0 \to b\mu^+\mu^-$ with $L = 300$ fb^{-1}.

In Figure 3, we present the contours for the branching fraction in the MSSM $B(B_s \to \mu^+\mu^-) = 1.5 \times 10^{-7}$ (current experimental limit), 3×10^{-8} , 1×10^{-8}, and 5×10^{-9} as well as the discovery contours of $b\phi^0 \to b\mu^+\mu^-$ for integrated luminosities of 30 fb^{-1} and 300 fb^{-1} at the LHC in the $(m_A, \tan\beta)$ plane for two values of common masses: (a) $M_{\rm SUSY} = m_{\tilde{g}} = m_{\tilde{f}} = 350$ GeV, and (b) $M_{\rm SUSY} = m_{\tilde{g}} = m_{\tilde{f}} = 1000$ GeV.

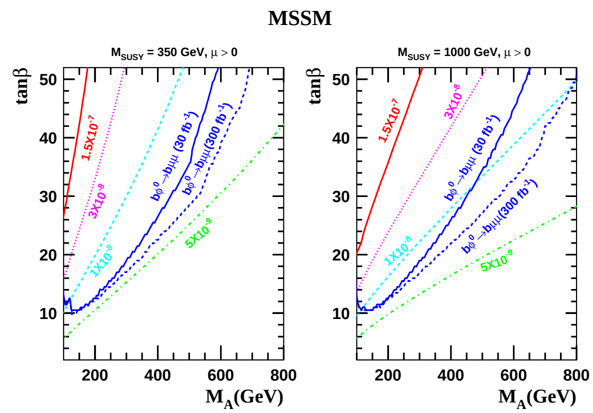

Figure 3: Discovery contours for $pp \to b\phi^0 \to b\mu\bar{\mu} + X$ at the LHC and contours of the branching of $B_s \to \mu^+\mu^-$ in the minimal supersymmetric standard model for (a) $m_{\tilde{g}} = m_{\tilde{f}} = 350$ GeV $= -A_f$ and (b) $m_{\tilde{g}} = m_{\tilde{f}} = 1000$ GeV $= -A_f$. The discovery region is the part of the parameter space above the contour.

We note that for $M_{\rm SUSY} = 350$ GeV, the LHC will be able to discover $pp \to b\phi^0 \to b\mu^+\mu^- + X$ with an integrated luminosity (L) of 30 fb^{-1} in a significantly large region of the parameter plane beyond $B(B_s \to \mu^+\mu^-) = 3 \times 10^{-8}$. If the gluino and scalar fermions have a common mass of approximately 1 TeV then the contour for a branching fraction of $B(B_s \to \mu^+\mu^-) = 1 \times 10^{-8}$ in the parameter plane is very close to the 5σ contour for $pp \to b\phi^0 \to b\mu^+\mu^- + X$ at the LHC with $L = 30$ fb^{-1}.

Furthermore, with a higher luminosity of 300 fb^{-1}, the LHC will be able to discover $pp \to b\phi^0 \to b\mu^+\mu^- + X$ for $M_{\rm SUSY} = 1000$ GeV in a very large region of the $(m_A, \tan\beta)$ plane. The discover contour for high luminosity with a large $M_{\rm SUSY}$ is very close to the contour for $B(B_s \to \mu^+\mu^-) = 5 \times 10^{-9}$ that is not far away from the SM expectation.

3.5 QCD Corrections to Higgs Pair Production

We presented a complete next-to-leading order (NLO) calculation for the total cross section of inclusive Higgs pair production via bottom-quark fusion ($b\bar{b} \to hh$) at the CERN Large Hadron Collider (LHC) in the Standard Model. The NLO QCD corrections lead to less dependence on the renormalization scale (μ_R) and the factorization scale (μ_F) than the leading-order (LO) cross section, and they slightly increase the LO cross section. The rate for inclusive Higgs pair production is small in the Standard Model, but can be large in models with enhanced couplings of the b quark to the Higgs bosons.

In addition, we evaluated complete next-to-leading order corrections to the inclusive Higgs pair production via bottom-quark fusion at the CERN Large Hadron Collider in the minimal supersymmetric standard model (MSSM) and the minimal supergravity model (mSUGRA). We emphasize the contributions of squark and gluino loops (SQCD) and the decoupling properties of our results for heavy squark and gluino masses. The enhanced couplings of the b quark to the Higgs bosons in supersymmetric models with large $\tan\beta$ yield large NLO SQCD corrections in some regions of parameter space.

4 Experimental Research Activities

The experimental high energy physics group at the University of Oklahoma consists of four faculty members (B. Abbott, P. Gutierrez, P. Skubic, and M. Strauss). We are members of the DØ and the ATLAS collaborations.

4.1 Introduction

Over the past four years, the OU higher energy experimental group has concentrated on the analysis of heavy flavor data including c, b, and t quarks. In the area of c-physics, we participated in the extraction of the $X(3872)$ signal and the investigation of its properties [20], in particular looking for electromagnetic decays to determine if this is a $c\bar{c}$ state or some more exotic particle. In the area of b physics, we are contributing to the study of B_s-meson mixing and setting limits or measuring the mixing frequency Δm_s. Our studies of the top-quark are connected to the search for single top production; we are also repeating a previous analysis with Run I data–the search for top-quark decays to charged Higgs [23] using Run II data. The following gives a brief outline of the work we have done over the past year on the single top and charged Higgs searches.

4.2 Heavy Flavor Physics

This past year has been a very successful year in heavy flavor physics for the University of Oklahoma experimental high energy group. B. Abbott and I. Hall have finalized their study of $X(3872)$ by studying the branching ratio of the $X(3872) \to J/\psi\gamma$. The Belle collaboration has ruled out almost all states except J^{pc}=1^{++}. If the $X(3872)$ is a $c\bar{c}$ state and J^{pc}=1^{++}, then it should decay to $J/\psi\ \gamma$ with a large branching ratio; much larger than $J/\psi\pi^+\pi^-$. The presence of absence of this decay can help shed light on the nature of the $X(3872)$. Our results show no indication of a signal in the decay $X(3872) \to J/\psi\gamma$ and so a limit can be placed on this branching ratio. A 90% CL limit on $X(3872) \to J/\psi\gamma$ relative to $X(3872) \to J/\psi\pi^+\pi^-$ of 1.5 was obtained. This result, along with isospin arguments, indicate that the $X(3872)$ cannot be a $c\bar{c}$ state with J^{pc}=1^{++}. I. Hall has written his dissertation on this topic and has graduated.

Additionally B. Abbott was involved in the discovery of a new B baryon. Within the quark model, numerous B baryons are predicted to exist, however, previous to this discovery only one B baryon had been directly observed, the Λ_b. The Ξ_b^- is an interesting

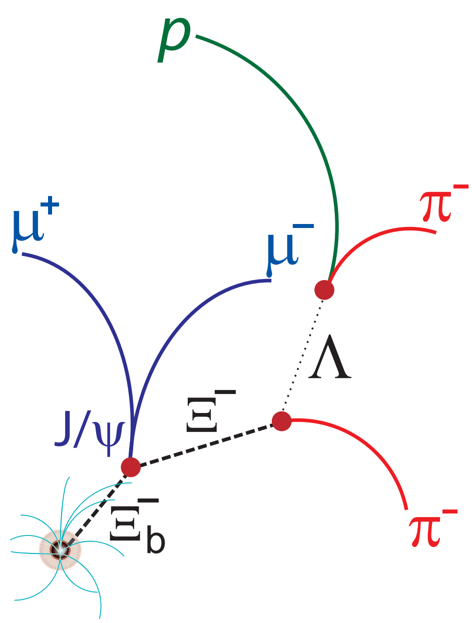

Figure 4: Schematic of the $\Xi_b^- \rightarrow J/\psi\Xi^- \rightarrow J/\psi\Lambda\pi^- \rightarrow (\mu^+\mu^-)(p\pi^-)\pi^-$ decay. The Ξ_b^- has an expected decay length of a few mm; the Λ and Ξ^- baryons have decay lengths of a few cm.

baryon in that it contains quarks from all three generations (dsb). The Ξ_b^- follows a fairly complex decay chain. The Ξ_b^- first decays into $J/\psi\Xi^-$. The Ξ^- then decays into $\Lambda\pi$ and then the Λ decays into proton π, see Fig. 4.

The DØ detector is very efficient at triggering and reconstructing J/ψ decays, but the efficiency for reconstructing long lived particles such as the Ξ^- was poor. In order to increase the efficiency of reconstructing the Ξ^-, 30 million events containing J/ψ candidates were re-reconstructed using a special tracking algorithm. After the re-reconstruction of the data, the Ξ^- yield increased by a factor of 5, allowing for a search of the Ξ_b^-.

We observed 15.2 $\pm$ 4.4(stat) +1.9-0.4(syst.) Ξ_b^- candidates at a mass of 5.774 $\pm$ 0.011(stat.) $\pm$ 0.015(syst.), see Fig. 5. The signal significance is greater than 5 σ, allowing for the observation of the Ξ_b^-. In addition we measured the relative rate of $\Xi_b^- \rightarrow J/\psi\Xi^-$ to $\Lambda_b \rightarrow J/\psi\Lambda$ to be 0.28 $\pm$ 0.09(stat) + 0.09 - 0.08(syst.). This result has been published in PRL. Subsequent to our observation, the CDF collaboration confirmed the DØ result on the observation of the Ξ_b^-.

Over the past years, the experimental program at OU has made a number of significant contributions to the B physics program at DØ. From 2001-2003 B. Abbott was one of the physics conveners of the B group. From 2003-2005 B. Abbott was a convener of the B mixing and lifetime subgroup. During this time, OU contributed to a number of different areas within B physics. In particular, Xiaojian Zhang, a graduate student of P. Gutierrez, studied flavor tagging using opposite side jet tagging as a thesis topic. B. Abbott and I. Hall confirmed the existence of the X(3872) particle and studied a number of its production and decay characteristics. This led to the second paper from

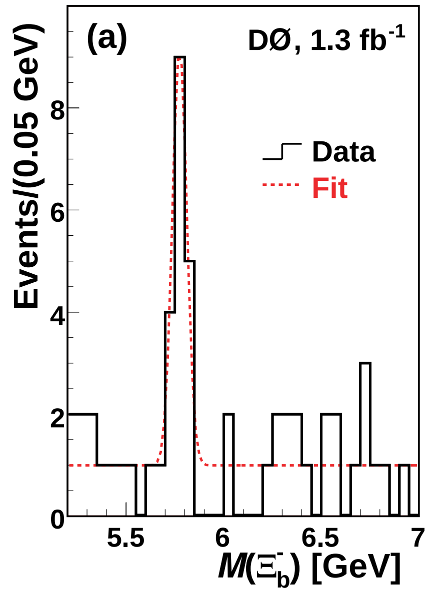

Figure 5: The M(Ξ_b^-) distribution for all Ξ_b^- candidates. The dotted curve is an unbinned likelihood fit to the model of a constant background with a Gaussian signal.

DØ Run II.

OU has been very active in the measurement of the B_s mixing frequency Δm_s. The principle B_s decay channel used in the mixing analysis is $B_s \to D_s \mu X$, with $D_s \to \phi\pi$. B. Abbott and a student from Delhi University (Md. Naimuddin) analyzed a second D_s decay channel, $D_s \to K^* K$, in order to increase the B_s statistics and improve the Δm_s limit.

The first major achievement was the completion of the analysis in the $D_s \to K^* K$ channel using ~ 1.2 fb^{-1} of data. This analysis yields a lower limit on the B_s mixing frequency of $\Delta m_s > 9.3$ ps^{-1} at the 95% C.L with an expected limit of 11.7 ps^{-1}. This analysis resulted in a dissertation for Md. Naimuddin.

The second major achievement was the publication of the paper "Direct Limits on the B_s Oscillation Frequency". This is the first direct two-sided bound measured by a single experiment. This paper shows that $17 < \Delta m_s < 21$ ps^{-1} at the 90% CL, see Fig. 6. One of the primary reasons to study B_s oscillations is that it is a good place to search for physics beyond the Standard Model. If the value of Δm_s is greater than that predicted by the Standard Model, it may indicate some new physics. The Standard Model predicts that Δm_s is less than ~ 30 ps^{-1} so our result shows no new physics beyond the Standard Model is necessary. Subsequent to our paper, the CDF experiment has made an observation of B_s mixing with the mixing parameter within the range found by the DØ experiment.

M. Strauss, B. Abbott and M. Rominsky continue their study of the decay mode $B \to J/\psi K^{*+}\pi^-$. This decay channel contains a long lived particle, the K_s. Using the J/ψ data re-processed for the Ξ_b^- search, the B yield has significantly increased, allowing for a better measurement of this decay. This should lead to the world's best measurement for the branching ratio $B_d \to J/\psi K^{*+}\pi^-$ and provide the first branching

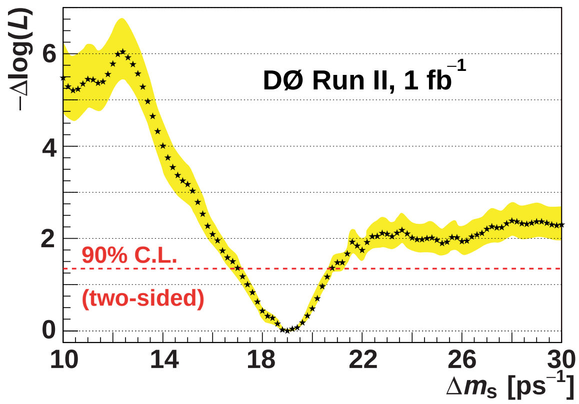

Figure 6: Value of -Δ log(L) as a function of Δm_s

ratio limit on $B_s \rightarrow J/\psi K^{*+}\pi^-$. In addition, this study should also give the best measurements for the branching ratios $B_d \rightarrow J/\psi K^o \rho$ and $B_d \rightarrow J/\psi K^o \pi^+\pi^-$.

In summary the major achievements of the OU experimental group in the past several years in heavy flavor physics are:

- P. Gutierrez, X. Zhang: Dissertation on opposite side jet flavor tagging.
- B. Abbott, I. Hall: PRL on properties of X(3872) [20].
- B. Abbott, P. Gutierrez: PRL on direct limits for B_s mixing [21].
- B. Abbott, I. Hall: Dissertation on $X(3872) \rightarrow J/\psi\gamma$.
- B. Abbott, Md. Naimuddin: Dissertation on $B_s \rightarrow D_s \mu\nu$ with $D_s \rightarrow K^* K$.
- B. Abbott: PRL on Observation of the Ξ_b^- baryon [22].
- B. Abbott, M. Strauss, M. Rominsky: Branching ratios of $B \rightarrow K^{*+}\pi^-$.

4.3 Single Top-Quark Production

We presented a first evidence for the production of single top quarks at the Fermilab Tevatron $p\bar{p}$ collider [25]. The top quark was first discovered in 1995 at the Tevatron itself, but in pair production mode ($t\bar{t}$ events) involving strong interactions. But the standard model (SM) also predicts the production of single top quarks through the electroweak exchange of a W boson. There are two dominant modes of single top production at the Tevatron energies: the s-channel and t-channel processes as shown in Fig. 7, with a total predicted cross section of 2.86 ± 0.33 pb. The study of single top quark production provides the possibility of investigating top quark related properties that cannot be measured in top quark pair production. The most relevant of these are the direct measurements of the CKM matrix element $|V_{tb}|$ and top quark polarization. It would also enable to probe possible new physics in the top quark sector.

We analysed 0.9 fb^{-1} of DØ data in the lepton+jets channel, and applied three different multi-variate techniques: Decision trees (DT), Matrix elements (ME), and

Figure 7: Representative Feynman diagrams for electroweak top quark production at the Tevatron Collider via the s-channel and t-channel modes.

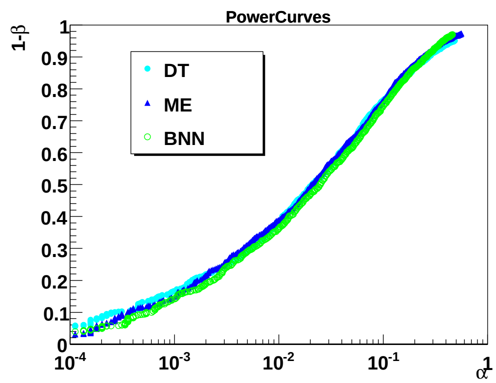

Figure 8: The p-value computed from the SM signal+background ensemble versus that from the background-only ensemble for reference cross sections from $0 - 10$ pb.

Bayesian neural networks (BNN), to separate single top signal from the overwhelming backgrounds. The correlation between the three analyses is shown in the matrix below:

$$\rho = \begin{pmatrix} DT & ME & BNN & \\ 1 & 0.64 & 0.66 & DT \\ 0.64 & 1 & 0.59 & ME \\ 0.66 & 0.59 & 1 & BNN \end{pmatrix},$$

Their performance is found to be similar as seen in the power curves in Fig. 8. A power curve is a plot of the p-value, $1 - \beta$, for the signal+background hypothesis (H_1) versus the p-value, α, for the background-only or null hypothesis (H_0); it shows the probability to accept the signal+background hypothesis, if true, versus the significance level α based on ensembles of pseudo-datasets.

The measured single top cross sections from each analysis as well as their combination is summarized in Fig. 9.

The significance of the measurements is determined using background-only ensembles and are shown in Table 1. The expected significance is defined with respect to the SM cross section of 2.86 pb, while the observed significance is relative to the measured cross section for each analysis.

As more data is collected at the Tevatron, the sensitivity of single top cross section measurement is expected to increase. An estimate of the improvement can be seen in Fig. 10 based on projections from our across-the-ring (CDF) collaboration. Also shown in the plot are the current measurements from DØ.

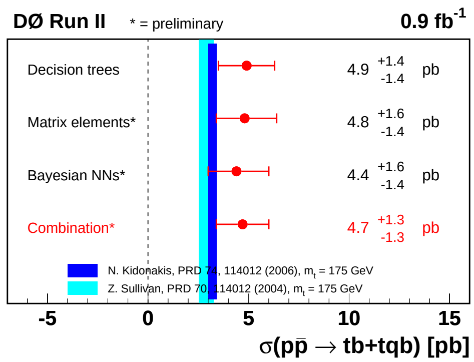

Figure 9: The single top cross section measurements from the individual analyses and combination.

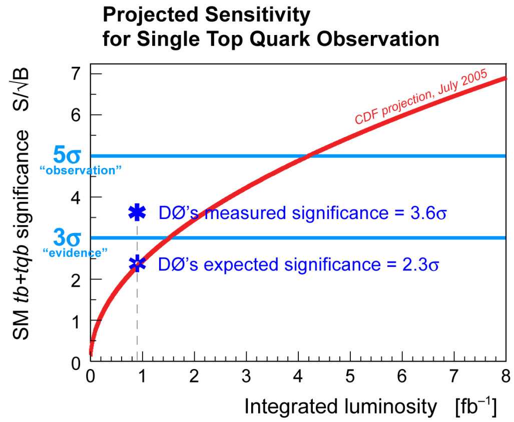

Figure 10: Projected sensitivity for single top quark observation.

Table 1: The expected and observed significances for individual and combined analyses

Analysis	Expected significance [std. dev.]	Observed significance [std. dev.]
Decision trees (DT)	2.1	3.4
Matrix elements (ME)	1.9	3.2
Bayesian neural networks (BNN)	2.2	3.1
Combined	2.3	3.6

4.4 Charged Higgs Boson

The outstanding problem in high energy physics (HEP) at the moment is to understand the electroweak symmetry breaking sector. For experimentalist, this means finding the Higgs-boson and studying its properties. DØ at the moment has collected almost 3 fb^{-1} of data and is therefore closing in on the predicted standard model Higgs cross section. The currently analysed 1 fb^{-1} of data, has expected limits 6 (4) times higher than the expected cross section for a 115 (160) GeV mass Higgs. But as more data is collected, the analysis techniques are also improving, therefore the limits are improving much faster than what one would expect from statistics alone. In addition, many extensions to the standard model predict large cross sections for Higgs production, which are also being pursued by DØ.

Given that at the present time there is no experimental data that limits the form of the Higgs sector to that required in the standard model, we carry out a search for evidence that it has a more complex structure. The simplest extension to the standard model Higgs sector is the addition of a second complex isoscalar doublet. After electroweak symmetry breaking, there are a total of 5 scalar particles, two that are charged, and three that are neutral. We carry out a search for evidence of a charged Higgs. In particular, we have selected a model where the fermion couplings are such that the weak isospin $t_3 = +1/2$ fermions couple to one isoscalar doublet and the weak isospin

$t_3 = -1/2$ fermions couple to the other. These are the same couplings required by the minimal super-symmetric models. The search is carried out in terms of $\tan\beta$, the ratio of the vacuum expectation values of each of the Higgs doublets and the mass of the charged Higgs. For large values of $\tan\beta$, the charged Higgs decays predominately to $\tau\nu_\tau$.

In this model with $H^\pm$ masses less than the top-quark mass, the $H^\pm$ can have a large coupling to the top-quark. Therefore, this search is carried out in events with top-quark production $\bar{p}p \to t\bar{t}$ with subsequent decay of the top-quark to a charged Higgs $t \to H^+ + b$. Given the relatively large top-quark cross section, if the branching ratio to charged Higgs is significant, one would expect to find evidence for $H^\pm$ in the accumulated data set. The search is carried out using the unique signature for these events of the presence of a τ lepton, two b-quark jets, significant missing transverse energy (from neutrinos), and, depending on the W boson decay mode, either an additional lepton or two jets. The main sources of background are $t\bar{t}$ production and events with misidentified τ leptons.

The primary OU people who have been involved in this analysis are S. Jain, A. Pompoš, S. Hossain, and P. Gutierrez. This analysis is being bootstrapped off the measurement of the top-quark cross section using the $t \to \tau + \text{jets}$ analysis, which is nearing completion. Much of the remaining work is in understanding the QCD multijet background faking τ-leptons with missing E_T.

We have also concentrated some effort in understanding the physics signature for this process, learning how to distinguish $t \to Wb$ events from $t \to H^\pm b$ events in particular understanding the difference in the τ-lepton kinematics.

Even though much work has been done by the DØ experiment in finding the best τ-lepton identification variables to maximize the tau finding efficiencies, these variables, however, were fine tuned for selection of $Z \to \tau\tau$ events used for $p\bar{p} \to Z \to \tau^+\tau^-$ cross section and branching ratio measurements. In the charged Higgs analysis, one of the major background sources is $t\bar{t}$ pair production and their subsequent decays. In these decays, the τ-lepton emerges from the W-boson decay, a spin 1 particle. Since the $H^\pm$-boson has spin 0, it has been pointed out that this can be used to distinguish τ-leptons from $H^\pm$'s and $W^\pm$'s. Therefore, we are revisiting and fine tuning the τ-lepton identification variables, adjusting them for the needs of the charged Higgs analysis. This is being done using $W \to \tau\nu_\tau$ Monte Carlo events with full detector simulation, and in the near future $H^\pm \to \tau^\pm\nu_\tau$ Monte Carlo events, also with full detector simulation. In addition, we are also following closely work of other of our DØ collaborators on $W \to \tau + \nu_\tau$ and $t \to W + b \to \tau + \nu_\tau + b$.

We expect the $H^\pm$ signal Monte Carlo event generation to be finished in the near future, which uses the current DØ reconstruction code. This will result in a significant $H^\pm$ Monte Carlo data set, which we are going to use to study signal from background discriminating variables and set limits if no signal is found. As stated earlier, special attention will be given to the fact that in the charged Higgs case, the τ-lepton is the decay product of a spin 0 particle, but for the $t \to W^+b$ background, the τ-lepton comes from spin 1 W-boson decays.

A significant amount of work has also gone into identifying a suitable DØ data set that will be used for the $H^\pm$ search. The data set is specified by the triggers used to record it. Trigger efficiencies have been studied and calculated in order to optimize the search. In addition, we are helping with the commissioning of the recently implemented τ-trigger, which should help improve the efficiency for charged Higgs detection.

4.5 Summary for the DØ Experiments

At the present time, the experimental group is contributing to the study of charm, bottom and top quark physics. This includes a postdoc funded under this grant, 2 additional postdocs funded under our base DOE grant, four faculty, and two graduate students, in addition to one graduate student who recently received his Ph.D. We are aiming to study and uncover phenomena that was outside the reach of the Tevatron Run I data sample and other current and past experiments.

4.6 Software Development for the ATLAS and the DØ

The Grid Computing effort at OCHEP has made very good progress over the past several years, both in ATLAS computing and grid middleware development/testing. It started in 2001 with the deployment of a 2 node test cluster on which we installed an early version of the Globus grid middleware, and has since evolved into on of the most successful grid computing groups in US ATLAS.

We deployed a 40 node, 80 CPU cluster as part of the US ATLAS SouthWest Tier 2 Center at OU in early Spring of 2006, which has been operating continuously since its deployment and consistently out-performed most other US ATLAS Tier 2 clusters in terms of job throughput, with 100uptime and close to 1004 TB storage space is very well utilized and will to be upgraded soon. We just acquired 184 more compute cores and 15 more TB and will incorporate them into the cluster as soon as it is moved from one machine room on campus to another next month.

Besides MC production, this cluster will soon be used for data analysis as well.

We also added more compute nodes to our OUHEP desktop cluster, which now has 35 nodes, 45 CPUs. The cluster is part of the Open Science Grid (OSG) integration testbed, which develops, tests, and deploys new versions of the OSG grid middleware. We also brought up a small 8 node test cluster on which we have done several rounds of testing of new versions already, and the next version is being tested right now.

Besides being used for grid computing research, the OUHEP cluster is also being used for ATLAS and D0 MC production and data analysis jobs submitted via the OSG grid interface, as well as local theory calculations. It also houses a SAMGrid-OSG "SAM station", which serves D0 data and MC to all OSG sites nationwide.

In addition, the grid middleware stack is also installed on several OU OSCER clusters, which are also being used for ATLAS and D0 MC production and data analysis whenever there are unused resources available. The OU wide Condor pool, which also has the grid middleware stack installed, is being used for D0 production, which is now possible on a Condor pool with no shared file system. ATLAS production still requires a shared file system, which we are in the process of deploying on the OU Condor pool.

5 Personnel Supported by the EPSCoR Award

We have used this EPSCoR grant along with the OU matching funds to support 2 Postdoctoral Fellows in Particle Theory (Peter Williams and Yili Wang), 1 Postdoctoral Fellow in High Energy Experiment (Supriya Jain), 2 Graduate Research Assistants (Ines Cavero-Pelaez and Shankar Sachithanandam), and 2 Undergraduate Research Assistant (Blake Burdett and Arnold Braker). In order to promote undergraduate research and women in science, we have supported two undergraduate students, a female graduate student and two female postdoctoral fellows.

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