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U.C. DAVIS PARTICLE PHYSICS RESEARCH

TECHNICAL PROGRESS REPORT - FINAL

March 1, 1989 - August 31, 1992.

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Abstract

During the period of this contract, the participants carried out theoretical and experimental researches in high energy particle physics.

The experimental group has been working at Fermilab studying the collisions of high energy hadrons on fixed targets; at the KEK laboratory in Japan participating in the AMY collaboration at the high energy electron-positron collider, Tristan; at the DESY laboratory in Germany participating in the H1 collaboration at the newly commissioned electron-proton collider, Hera; and in collaboration with LBL on pixel detector design for the SSC, while waiting for high luminosity running to start at PEP.

The theoretical group has been engaged in phenomenological studies of high energy interactions, particularly those associated with the higgs field and various aspects of symmetry breaking, heavy flavor decays and CP noninvariance, super symmetry, Yang-Mills theory and electroweak symmetry breaking. Lattice gauge calculations on finite temperature phase transitions have also been under study, as well as work on string theory.

EXPERIMENT

Progress Report (R. Breedon, M. Forbush, L. Godfrey, W. Ko, R. Lander, K. Maeshima, S. Mani, V. Paolone, D. Pellett, F. Rouse, J. Smith, P. Yager)

The Fermilab work focussed on data reduction of the E653 experiment on charm and beauty production by 800 GeV protons and 600 GeV pions on beryllium. At the same time, preparations for, and operation of, E687, photoproduction of charm mesons in a beryllium target, were carried out. This experiment ran quite well, with a very high data collection rate. Eight papers were published in the period. Two on the spectrometers for E653 and E687, four describing properties of charm meson production and decay from E653, and one from E687. (See list of publications.) Other analyses were continuing.

Another effort at Fermilab, E706, on detection of direct photons from hadronic interactions was aimed at studying the gluon structure function of the nucleon and charged pions. One of our new faculty members had been a participant earlier, and we developed a small effort here. Three papers from E706 were published during this period.

Some work was also done on a fast feedback system for the Stanford Linear Collider, resulting in one publication.

The work for the H1 experiment at the Hera electron-proton collider in Germany continued on the analog readout electronics for the "tailcatcher" calorimeter. For the system, some 4,000 channels of analog readout electronics were fabricated at UC Davis, with 128 channels on a single large PC board multiplexed to one output on each of 40 such boards, including spares. Each of the 128 channels on a board contains a line receiver, shaper, and sample-and-hold card. Each board contains a 128-1 multiplexer and output driver card to drive the 75 meter cable to the ADC circuits. For electronic calibration of the system, we designed and built a set of 64-fold fanouts identical in output to better than 1%. A commercial Digital Signal Processor (DSP) is used to perform pedestal subtraction, readout of channels above some specified threshold along with their neighbors, and quadratic conversion of the ADC counts to collected charge. Software to program these somewhat complicated procedures was also developed and installed. The

system was designed, fabricated, tested, and installed at Hera quite successfully. In fact, it was the first of the H1 subdetectors to be operational during the commissioning of H1 with cosmic rays. The system is still functioning in H1. First collisions in the accelerator were obtained on October 19, 1991, but serious data collection did not start until 1992, with no journal publications appearing during the period of this contract. The hardware work is to be combined with other detectors in an overall paper on the H1 detector.

At KEK in Japan, the AMY detector running got into full swing during this period. Nineteen papers were published in refereed journals on physics results, including searches for new physics at this higher energy, tests of QCD theory, and the structure function of the photon. Hardware construction included fabrication of large printed circuit boards for the endcap electromagnetic shower counter and participation in construction of a new inner straw chamber, VTX. A new computer system was installed at UCD to handle AMY analysis "at home". The three MicroVax 3200's and the AMY software "ported" to them was used to analyze the jet charge F/B asymmetry and higgs search in the tau mode. A trans-Pacific link allowed convenient transfer of data from KEK. A paper on the AMY barrel electromagnetic shower counter also appeared during this contract period.

While analysis of data from earlier PEP running continued (see TPC/Two-Gamma in publication list) with six publications in refereed journals, we participated in the preparations for high-luminosity running of the TPC/Two Gamma detector in the PEP accelerator at SLAC. We had responsibilities particularly with respect to Monte Carlo software. Also, we participated in studies of pixel detectors for the SSC with David Nygren's group at LBL. A facility to test silicon pixel detectors was set up at UCD, including a probe station and an HP 4145B transistor parameter analyzer. Irradiation of a PIN diode at the 63 MeV proton cyclotron at UCD demonstrated a damage effect that confirmed earlier suggestions of how the damage ratio should change at this lower energy.

Publications from Experimental Work
March 1, 1989 - August 31, 1992

85. Measurements of the e^+e^- Total Hadronic Cross Section and a Determination of M_Z and $\Lambda_{\overline{MS}}$. AMY Collaboration. Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, K. Sparks, M.C.S. Williams, and others. Phys. Lett. B218:499.

86. Experimental Evidence for the Non-Abelian Nature of QCD from a Study of Multi-Jet Events in e^+e^- Annihilations. AMY Collaboration. Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, K. Sparks, M.C.S. Williams, and others. Phys. Rev. Lett. 62:1713.

87. Search for the Substructure of Leptons in High Energy QED Processes at TRISTAN. AMY Collaboration. Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, K. Sparks, M.C.S. Williams, and others. Phys. Lett. B223:476.

88. Search for Unstable Heavy Neutral Leptons in e^+e^- Annihilations at $\sqrt{s}$ from 50 to 60.8 GeV. AMY Collaboration. R.E. Breedon, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, K. Sparks, M.C. S. Williams, and others. Phys. Rev. Lett. 63:1342.

89. Search for Non-Minimal Higgs Production in e^+e^- Annihilations at $\sqrt{s} \simeq 56$ GeV. AMY Collaboration. R.E. Breedon, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, K. Sparks, D. Stuart, M.C.S. Williams, and others. Phys. Lett. B228:548.

90. Comparison of Quark and Gluon Jets Produced in High-Energy e^+e^- Annihilations. AMY Collaboration. R.E. Breedon, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, D. Stuart, M.C.S. Williams, and others. Phys. Rev. Lett. 63:1772.

91. Search for a Fourth-Generation Charge -1/3 Quark. AMY Collaboration. R.E. Breedon, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, D. Stuart, M.C.S. Williams and others. Phys. Rev. Lett.63:1910.

92. Exclusive Production of $p\bar{p}$ $\pi^+\pi^-$ in Photon-Photon Collisions. TPC/Two-Gamma Collaboration. D.E. Pellett, J.R. Smith, C. Zeitlin, and others. Phys. Rev. D40:2772.

93. Measurement of $e^+e^- \to b\bar{b}$ Forward-Backward Charge Asymmetry between $\sqrt{s} = 52$ and 57 GeV. AMY Collaboration. Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, K. Sparks, D. Stuart, M.C.S. Williams, and others. Phys. Rev. Lett. 63:2341.

94. Evidence of Soft and Collinear Gluon Emission in e^+e^- Hadronic Events. TPC/Two-Gamma Collaboration. D.E. Pellett, J.R. Smith, C. Zeitlin, and others. Z.Phys. C 44:357.

95. Investigation of the Electromagnetic Structure of η and η' Mesons by Two-Photon Interactions. TPC/Two-Gamma Collaboration. D.E. Pellett, J.R. Smith, and others. Phys. Rev. Lett. 64:172.

96. A Search for SUSY Particles in e^+e^- Annihilations at $\sqrt{s}$ = 50-60.8 GeV. AMY Collaboration. R.E. Breedon, G.N. Kim, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, D. Stuart, M.C.S. Williams, and others. Phys. Lett. B234:534.

97. Forward-Backward Charge Asymmetry in $e^+e^- \rightarrow$Hadron Jets. AMY Collaboration. D. Stuart, R.E. Breedon, G.N. Kim, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, and others. Phys. Rev. Lett. 64:983.

98. Hybrid Emulsion Spectrometer for the Detection of Hadronically Produced Heavy Flavor States. Fermilab E653 Experiment. R.L. Lander, A. Mokhtarani, V.S. Paolone, J.O. Wilcox, P.M. Yager, and others. Nuclear Instruments and Methods in Physics Research A289:146.

99. A Search for Leptoquark and Colored Lepton Pair Production in e^+e^-Annihilations at TRISTAN. AMY Collaboration. G.N. Kim, R.E. Breedon, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, D. Stuart, and others. Phys. Lett. B240:243.

100. A Measurement of the Total Hadronic Cross Section in Tagged $\gamma\gamma$ Reactions. TPC/Two-Gamma Collaboration. D.E. Pellett, J.R. Smith, and others. Phys. Rev. D41:2667.

101. Multihadron-event Properties in e^+e^- Annihilation at $\sqrt{s}$ = 52-57 GeV. AMY Collaboration. R.E. Breedon, G.N. Kim, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, D. Stuart, and others. Phys. Rev. D41:2675.

102. Observation of Anomalous Production of Muon Pairs in e^+e^- Annihilation into Four-Lepton Final States. AMY Collaboration. R.E. Breedon, G.N. Kim, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, D. Stuart, and others. Phys. Lett. B244:573

103. Charged-particle Multiplicities in e^+e^- Annihilations at $\sqrt{s}$ = 50-60.8 GeV AMY Collaboration. R.E. Breedon, G.N. Kim, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, D. Stuart, and others. Phys. Rev. D42:737.

104. Mass Limits of Charged Higgs Boson at Large tan (β) from e^+e^- Annihilations at $\sqrt{s}$ = 50-60.8 GeV. AMY Collaboration. J.R. Smith, R.E. Breedon, G.N. Kim, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J. Rowe, D. Stuart, and others. Phys. Rev. D42:949.

105. Measurements of R for e^+e^- Annihilation at the KEK collider TRISTAN. AMY Collaboration. R.E. Breedon, G.N. Kim, Winston Ko. R.L. Lander, K. Maeshima, R.L. Malchow, J.R. Smith, D. Stuart, and others. Phys. Rev. D42:1339.

106. A Measurement of the Photon Structure Function F_2. AMY Collaboration. R.E. Breedon, G.N. Kim, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J. Rowe, J.R. Smith, D. Stuart, and others. Phys. Lett. B252:491.

107. Inclusive $D^{*\pm}$ Production in Photon-Photon Collisions. TPC/Two-Gamma Collaboration. D.E. Pellett, and others. Phys. Lett. B252:499.

108. Test of Spin Dependence in Charm-Quark Fragmentation to D^*. TPC/Two-Gamma Collaboration. D.E. Pellett, J.R. Smith, and others. Phys. Rev D43:29.

109. Search for Charged Heavy Leptons with Arbitrary Neutrino Masses in e^+e^- Annihilations at $\sqrt{s} = 50 - 60.8GeV$. AMY Collaboration. J.R. Smith, R.E. Breedon, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J. Rowe, D. Stuart, and others. Int. Journal of Modern Physics A6:2583.

110. Measurement of the Relative Branching Fraction $\Gamma(D^0 \to K\mu\nu)/\Gamma(D^0 \to \mu X)$. Fermilab E653 Collaboration. V.S. Paolone, J.O. Wilcox, P.M. Yager, and others. Phys. Rev 66:1819.

111. Charm Meson Production in 800 GeV/c Proton-Emulsion Interactions. Fermilab E653 Collaboration. V.S. Paolone, J.O. Wilcox, P.M. Yager, and others. Phys. Lett. B263:573.

112. Charm Pair Correlations in 800 GeV/c Proton-Emulsion Interactions. Fermilab E653 Collaboration. V.S. Paolone, J.O. Wilcox, P.M. Yager, and others. Phys. Lett . B263:579.

113. A Study of Massive Electron Pairs and Associated Particles Produced at the CERN ISR. CMOR Collaboration. A.L.S. Angelis, R.E. Breedon and others. Nucl. Physics B348:1-22.

114. Measurement of the Form Factor Ratios in the Decay $D^+ \to \bar{K}^*(892)^0\mu^+\nu$ Fermilab E653 Collaboration. K. Kodama, V.S. Paolone, J.O. Wilcox, P.M. Yager, and others. Phys. Lett. B274:246.

115. Evidence for Hard Scattering of Hadronic Constituents of Photons in Photon-Photon Collisions at TRISTAN. AMY Collaboration. R.E. Breedon, Winston Ko, R.L. Lander, K. Maeshima, R.L. Malchow, J. Rowe, J.R. Smith, D. Stuart, and others. Phys. Lett. B277:215.

116. Design and Operation of Large Straw-Tube Drift Chamber Planes. C. Bromberg, S. Mani, and others. Nucl. Inst. and Methods in Phys. Res. A307:292.

117. A Database Driven Fast Feedback System for the Stanford Linear Collider. F. Rouse, S. Castillo, S. Allison, T. Gromme, L. Hendrickson, T. Himel, K. Krauter, R. Sass and H. Shoaee. Nucl. Instr. and Methods in Phys. Res. A316:343.

119. Charm Meson Production in 600 GeV/c π^- Emulsion Interactions. Fermilab E653 Collaboration. K. Kodama, V.S. Paolone, J.O. Wilcox, P.M. Yager, and others. Phys. Lett. B284:461.

120. Direct Photon Production at High p_T in π^- Be and pBe Collisions at 500 GeV/c. Fermilab E706 Collaboration. G. Alverson, S. Mani, and others. Phys. Rev. Lett. 68:2584.

121. Production of π^0 Mesons at High p_T in π^- Be and pBe Collisions at 500 GeV/c. Fermilab E796 Collaboration. G. Alverson, S. Mani, and others. Phys. Rev. D45:R3899.

122. The AMY Barrel Electromagnetic Shower Counter at TRISTAN A. Abashian, W. Ko, R.L. Lander, K. Sparks, M.C.S. Williams, and others. Nucl. Instr. and Methods A317:75.

123. Description and Performance of the Fermilab E687 Spectrometer. Fermilab E687 Collaboration. P.L. Frabetti, V. Paolone, P.M. Yager, and others. Nucl. Instrum. and Methods A320:519.

124. Measurement of the Branching Ratio for $D^+ \to \bar{K}^*(892)^0 \mu^+ \nu$. Fermilab E653 Collaboration. K. Kodama, V.S. Paolone, J.O. Wilcox, P.M. Yager, and others. Phys. Lett. B286:187.

THEORY

Progress Report (J. Gunion)

1. J.F. Gunion, H.E. Haber, G. Kane and S. Dawson, "The Higgs Hunters Guide", Addison and Wesley (1990) Frontiers in Physics Series.

The physics of Higgs bosons, whether that of the Standard Model or those of extended models, and their detection has become an extremely involved and extensive subject over the last few years. As a result, a group of us decided to write a Physics Report on the subject containing a systematic study and survey of all the accumulated knowledge, including a full detailing of existing experimental constraints on and future probes of the Higgs boson sectors of all attractive models considered in the literature to date. The material eventually reached such a length that we decided to turn it into a book. We hope that this book will become a standard reference for this type of physics. It includes a complete listing of all relevant Feynman rules, branching ratios, and so forth. Along the way we encountered several areas where we felt old results could be improved or required correction, and have included much of this material in the book. We have done nearly everything with far greater thoroughness and perspective than any previous such survey. In addition, it contains much original material not available anywhere in the literature.

2. S. Dawson, J.F. Gunion, and H.E. Haber, "Are Light Higgs Bosons Allowed?" *Phys. Rev.* **D41** (1990) 2844.

The purpose of this paper was to survey the limitations on Higgs bosons deriving from relatively low-energy, pre-LEP, experiments. There had been several papers along this line prior to ours, all of which we felt to be inadequate or misleading in a variety of ways. Our survey included a detailed reassessment of predictions (using low-energy theorems and the like) for Kaon and B-meson rare decays to Higgs bosons, as well as the decays of the Higgs boson itself. A number of experiments were reanalyzed, either by us, or at our request by spokesmen for the experiments themselves, resulting in considerable clarification, and often substantial improvement on the bounds that could be placed on the Higgs boson. Our final conclusion was that the Standard Model Higgs boson could be ruled out for masses up to about $2m_\tau$, a result now confirmed by ALEPH and other experiments at LEP. For non-standard model Higgs bosons, the results of our analysis of low-energy experiments and the restrictions from the LEP experiments are in many ways complementary. In particular, the low-energy experiments are largely sensitive to Higgs bosons with fermionic couplings, while the LEP experiments are essentially only sensitive to Higgs bosons with couplings to vector bosons. Our analysis shows that Higgs bosons with SM-like fermionic couplings and mass up to and of order $2m_\tau$ are pretty much ruled out, barring certain "fine-tuned" cancellations between different amplitudes contributing to the rare K and B decays.

3. J.F. Gunion, "Probing Higgs Bosons/Electroweak Symmetry Breaking in Purely Leptonic Channels at Hadron Colliders", UCD-89-24, to appear in Proceedings of "Higgs Particles: Physics Issues and Experimental Searches in High Energy Collisions", 8th Erice Workshop, Erice, Italy, July 15-26, 1989.

It has long been recognized that the cleanest channels in which to search for the Standard Model Higgs boson at a hadron collider are those where the Higgs boson decays entirely to leptons. Such channels are free of hadronic backgrounds deriving from quark jets and the like. The extent to which such channels can be employed for the Standard Model Higgs boson has been the subject of numerous Snowmass studies, and other published work. In contrast, prior to this workshop study which I performed, almost no attention had been paid to the question of sensitivity to non-standard Higgs bosons in purely leptonic channels. Considerations, such as production rates and decay branching ratios, for neutral Higgs bosons are often very different from those appropriate to the Standard Model scenario. And, of course, charged Higgs bosons (singly or doubly charged were examined) are entirely without a Standard Model analogue. In this workshop article I present the results of extensive calculations of event rates and relevant backgrounds for a variety of non-standard Higgs sector scenarios. The results are surprisingly encouraging for the SSC (though quite discouraging for the LHC): substantial

sensitivity to non-standard Higgs bosons, even those with reduced vector boson-vector boson couplings, exists. Charged Higgs bosons in triplet and higher representation models yield often dramatic signals in the purely leptonic final state channels.

4. J.F. Gunion, "The SSC: Status and Physics Update", UCD-89-27, to appear in Proceedings of the 1989 European Physical Society Meeting, Madrid, Spain, September 1989.

This article was divided into two distinct parts. In the first, I reviewed the status of the SSC program and funding, and high-lighted the short time scale (as of the time of the article) for 'letter-of-intent' type proposals and the like. My primary goal was to make the European experimental community fully cognizant of the fact that the SSC had become a reality, and that if they were to participate in its program they should get moving. The second part of the article was devoted to a review of recent progress in developing techniques for isolating the physics signals likely to be of importance at the SSC. The subjects considered included: the like-sign dimuon signatures for supersymmetry developed by myself, Barnett and Haber;[1] the use of hadronic multiplicity to isolate the signal for a heavy $\sim 1\ TeV$ Standard Model Higgs boson as developed by me and a number of collaborators;[2] the status of the intermediate mass Higgs boson search modes (pointing out, in particular, the inadequacies and necessary improvements in several of the studies performed at Snowmass 1988 claiming large backgrounds — these I claimed could be eliminated by various cuts I outlined); and, finally, the techniques developed by Hinchliffe[3] for isolating a signal for a heavy lepton. In general, I hope I succeeded in high-lighting the enormous physics potential for the SSC that has emerged as a result of detailed studies of signals for new physics. The talk itself was very well received at the meeting, and made many of the European physicists acutely aware of some of the short comings of the LHC — most of the techniques and signals mentioned above would not be viable there.

5. J.F. Gunion and B. Grzadkowski, "Limits on the Top Quark and on the Charged Higgs Boson of a Two-Doublet Model from $\overline{K^0} - K^0$ mixing, $B_d - \overline{B_d}$ mixing, and $b \to u$ Decays", UCD-89-30, to appear in Physics Letters.

Two very interesting types of new physics are intimately connected — namely the physics of the top quark and the physics of a charged Higgs boson. For instance, a top quark can decay into a charged Higgs boson for $m_t \gtrsim m_{H^+} + m_b$, while the charged Higgs decay modes are dominated by $t\bar{b}$ if $m_{H^+} \gtrsim m_t + m_b$. Less obvious, but equally important, are the interconnections between a charged Higgs and the top quark in the area of rare K and B decays, and $\overline{K} - K$ and $\overline{B} - B$ mixing. For instance, in the latter, Feynman graphs involving the H^+ are at least as important as the standard box diagrams involving the W^+. In this paper, we combine the existing results for such mixing with limits from $b \to u$ decays on the crucial V_{bu} entry of the Cabibbo-Kobayashi-Maskawa matrix to place limits, both on the top quark and on the two crucial parameters of a two-doublet Higgs sector — the mass of the H^+ and the ratio of vacuum expectation values for the two Higgs doublets, normally called $\tan\beta$. Among other things we demonstrated that there is an m_t-dependent boundary in $m_{H^+} - \tan\beta$ parameter space that separates the domain of allowed from that of disallowed solutions. Roughly, the larger $\cot\beta$ is (*i.e.* the larger the H^+ coupling to the $t\bar{b}$) the heavier the Higgs boson must be. These bounds are quite significant and will play an important role in suggesting the most reasonable ranges of parameter space in which to search for a charged Higgs boson. In the paper, we also demonstrate that the weak-mixing and $b \to u$ results combine (in the absence of a charged Higgs boson) to exclude a range of m_t that depends upon the so-called bag parameters B_K and B_B describing the hadronic expectation value of the relevant quark-level matrix elements. Thus, discovery of the top quark at a particular mass, in combination with a fairly reliable lattice computation of B_K and B_B (something to be expected in the not too distant future) could easily imply that a charged Higgs boson (or other new physics that influences mixing) is required, and would place a strong constraint on its mass and the value of $\tan\beta$. A number of other issues of a similar nature are also considered in this paper.

6. S. Dawson, J.F. Gunion, H.E. Haber, A. Seiden, and G. Kane, "The Search for Higgs Bosons of Any Mass", *Comm. Nucl. Part. Phys.* **14** (1990) 259.

In this paper, we summarize and review the techniques required to discover the Standard Model Higgs boson at the SSC throughout the entire mass range from $\sim m_Z$ (the highest value that will be probed by LEP-II) up to $\sim 1\ TeV$. Our primary emphasis was upon the fact that at the SSC there are no mass regions where discovery is not possible, so long as appropriate detectors are constructed, whereas at the LHC there are regions of Higgs mass (in the intermediate mass region and in the TeV region) that simply cannot be probed for any conceivably realistic detector design. The level of presentation was that appropriate to a large audience of general physicists and experimentalists who have not been active in SSC studies. In part, our goal was to make it clear that the SSC design really will allow our first true probe of Electroweak Symmetry breaking, regardless of the mass at which the important signals appear.

7. J.F. Gunion, R. Vega, and J. Wudka, "Higgs Triplets in the Standard Model", UCD-89-13, to appear in *Phys. Rev.* **D**.

Relatively little attention has been devoted to the subtleties associated with probing a Higgs sector that contains Higgs representations higher than doublets. In part this is because Higgs sectors with triplets and higher representations must be rather carefully constructed in order to avoid conflicting with the observed value of $\rho \equiv m_W/(m_Z c_W) \simeq 1$. Nonetheless, models can be easily constructed containing triplet Higgs representations (usually in combination with doublet representations in order to give fermions mass) which exhibit a custodial $SU(2)$ symmetry at tree-level that preserves $\rho = 1$ even when the neutral members of the triplet representations acquire a non-zero vacuum expectation value. An example of such a model is that discussed by Georgi and collaborators.[4] In this paper, we explore the rather intricate and subtle structure of the signatures for the Higgs bosons of this model. In particular, we demonstrate that decays of one Higgs boson into several others will often dominate over the more standard decays of a Higgs boson into vector boson pairs. Indeed, unless the triplet Higgs fields are given an overwhelming share of the vacuum expectation value required to give the W and Z their observed mass, the former decays are likely to be dominant. This leads to many unexpected signals, unusually long lifetimes, *etc.* for the Higgs bosons of the model. Production cross sections are also significantly dependent upon the amount of vacuum expectation value given to the triplet fields. All these issues are explored at some depth in the paper, and appropriate strategies for the detection of the Higgs bosons of such a triplet model outlined. Also presented are all the Feynman rules and couplings required for these and future calculations within this type of model, including the critical Higgs self-couplings.

8. N. Deshpande, J.F. Gunion, B. Kayser, and F. Olness, "Left-Right Symmetric Electroweak Models with Higgs Triplets", NSF-ITP-90-69, submitted to *Phys. Rev.* **D**.

In an extensive series of papers, I, Boris Kayser, and Fred Olness, along with assorted collaborators have explored the physics of left-right symmetric gauge models and the potential of the SSC for probing such physics.[5] Aside from the production cross sections and phenomenology as a function of Higgs boson mass scale pursued in these early studies, the most crucial issue is the mass scale itself. In this paper, we use the full structure of the most general Higgs potential for such a model, along with a full analytic minimization of this potential, in order to completely implement all the constraints on the model. We demonstrate that 'see-saw' relations among the vacuum expectation values for the different neutral Higgs fields emerge. In combination with the mass see-saw relation responsible for determining the masses of the charged leptons and neutrinos, the VEV see-saw relations yield extraordinarily powerful constraints upon the parameters of the model. In particular, we conclude that the natural mass scale for all new gauge bosons and Higgs bosons is of order $10^3\ TeV$ (or higher), *i.e.* not accessible at the SSC, unless certain terms in the Higgs potential are either absent (perhaps by virtue of symmetries from a higher GUT scheme — we demonstrate that obvious phase and other symmetries are not adequate) or else fine-tuned at a level of 10^{-6} (at least) relative to their natural

order of magnitude. Even if a GUT symmetry does indeed eliminate these terms in the Higgs potential, we enumerate many other severe difficulties (which are only apparent after complete minimization of the Higgs potential) that must be circumvented. Such circumvention is certainly possible, but the resultant phenomenology is rather more strongly constrained than one might have supposed. The most easily discoverable Higgs bosons, and their signatures, are enumerated.

1. J.F. Gunion, H.E. Haber, G. Kane and S. Dawson, "The Higgs Hunters Guide", Addison and Wesley (1990), Frontiers in Physics Series.
2. S. Dawson, J.F. Gunion, and H.E. Haber, "Are Light Higgs Bosons Allowed?" *Phys. Rev.* **D41** (1990) 2844.
3. J.F. Gunion, "Probing Higgs Bosons/Electroweak Symmetry Breaking in Purely Leptonic Channels at Hadron Colliders", UCD-89-24, to appear in Proceedings of "Higgs Particles: Physics Issues and Experimental Searches in High Energy Collisions", 8th Erice Workshop, Erice, Italy, July 15-26, 1989.
4. J.F. Gunion, "The SSC: Status and Physics Update", UCD-89-27, to appear in Proceedings of the 1989 European Physical Society Meeting, Madrid, Spain, September 1989.
5. J.F. Gunion and B. Grzadkowski, "Limits on the Top Quark and on the Charged Higgs Boson of a Two-Doublet Model from $\overline{K^0} - K^0$ mixing, $B_d - \overline{B_d}$ mixing, and $b \to u$ Decays", UCD-89-30, to appear in *Phys. Lett.* **B.**
6. S. Dawson, J.F. Gunion, H.E. Haber, A. Seiden, and G. Kane, "The Search for Higgs Bosons of Any Mass", *Comm. Nucl. Part. Phys.* **14** (1990) 259.
7. J.F. Gunion, R. Vega, and J. Wudka, "Higgs Triplets in the Standard Model", UCD-89-13, to appear in *Phys. Rev.* **D.**
8. N. Deshpande, J.F. Gunion, B. Kayser, and F. Olness, "Left-Right Symmetric Electroweak Models with Higgs Triplets", NSF-ITP-90-69, submitted to *Phys. Rev.* **D.**

J.F. Gunion: Invited Talks and Seminars

1. "Triggering on Crucial Physics-Signatures at the SSC", SSC Trigger Workshop on Trigger Algorithms, LBL, June, 1989.
2. Two Talks: "Higgs Boson Cross Sections and Event Rates — A Comparative Study of LHC/SSC/Eloisatro: Colliders", and "Exotic Higgs Sectors: Theory and Experiment", INFN Eloisatron Project, 8th Workshop: Higgs Particles - Physics Issues, Ettore Majorana Centre for Scientific Culture, Erice, Italy, July, 1989.
3. Two Talks: "SSC Physics and Status" and "Higgs Bosons: Standard Model and Beyond", 1989 European Physical Society Meeting, Madrid, Spain, September, 1989.
4. "Non-Minimal Higgs Bosons", Univ. Autonoma, Barcelon, Spain, September, 1989.
5. "Higgs Hunting", DESY Theory Workshop, October, 1989.
6. "Probing New Physics at the SSC", Colloquium at University of Southern California, October, 1989.
7. "The Top Quark and the Charged Higgs Boson: Limits from Weak Decays and Impact on Future Searches", NSF-ITP Meeting on "Thinking about the Top Quark", U.C. Santa Barbara, February, 1990.

8. "New Results for the old Left-Right Symmetric Model", Institute for Theoretical Physics, U.C. Santa Barbara, April, 1990.

J.F. Gunion: Additional Activities *etc.*..,

1. Elected to APS Fellowship, December 1989.
2. Member of SSC Adhoc Committee on Energy/Luminosity Reassessment, SSC Laboratory, Nov. 30 - Dec. 1, 1989.
3. Participant in "Physics Below the Planck Scale", Institute for Theoretical Physics, UCSB, February-May, 1990.
4. Extensive organization of lobbying for the SSC within California. As I did last year, I again orchestrated the contacting of most of the California House and Senate members by individuals from their own districts, February-April, 1990.
5. Session chair, "New Topics in Electroweak Physics", SSC Laboratory, May 30 - June 1, 1990.
6. Organizer, "Intermediate Mass Higgs Bosons", Snowmass, 1990.

J.F. Gunion: Meetings and Workshops

1. SSC Trigger Workshop, Lawrence Berkeley Laboratory, June, 1989.
2. 8th INFN Eloisatron Project Workshop on "Higgs Particles, ...", July, 1989.
3. 1989 Symposium on Lepton-Photon Interactions, Stanford Linear Accelerator Center, Stanford, CA, August, 1989.
4. 1989 European Physical Society Meeting, Madrid, Spain, September, 1989.
5. DESY Theory Workshop, DESY, Hamburg, West Germany, October, 1989.
6. NSF-ITP Workshop on "Thinking About the Top Quark", Institute for Theoretical Physics, UCSB. February, 1990.
7. NSF-ITP Workshop on "Heavy Quark Physics", Institute for Theoretical Physics, UCSB, May, 1990.

Progress Report (J. Gunion)

1. J.F. Gunion, H.E. Haber, G. Kane and S. Dawson, "The Higgs Hunters Guide", Addison and Wesley (1990) Frontiers in Physics Series, second edition.

The physics of Higgs bosons, whether that of the Standard Model or those of extended models, and their detection has become an extremely involved and extensive subject over the last few years. As a result, a group of us decided to write a Physics Report on the subject containing a systematic study and survey of all the accumulated knowledge, including a full detailing of existing experimental constraints on and future probes of the Higgs boson sectors of all attractive models considered in the literature to date. The material eventually reached such a length that we decided to turn it into a book. The first edition of the book has become something of a standard reference for this type of physics. It includes a complete listing of all relevant Feynman rules, branching ratios, and so forth. Also included are treatments of several areas where we felt old results could be improved or required correction. In addition, it contains much original material not available anywhere in the literature. The second edition, now in press, will update the first edition by including recent limits on Higgs bosons from LEP and top quark mass limits from CDF and elsewhere. A host of minor improvements and a few corrections have been incorporated.

2. J.F. Gunion and D. Wyler, "Inducing a Large Neutron Electric Dipole Moment via a Quark Chromoelectric Dipole Moment", *Phys. Lett.* **B248** (1990) 170.

Recently, the possibility of developing a large neutron EDM in theories with CP violation in the Higgs sector has been emphasized by Weinberg and others. Despite the large amount of attention this issue has received in the recent literature, we found a new contribution to the quark chromo-electric dipole moment that, in turn, yields a contribution to the neutron EDM which is larger than any of those previously considered in the literature. As part of this work, we also discuss in detail the (previously unappreciated) extent to which predictions for the neutron EDM are sensitive to the model employed to incorporate, at the hadron level, the relatively definitive quark/gluon level CP-violation predictions. The physics underlying the different models is explored.

3. J.F. Gunion and R. Vega, "The Electron Electric Dipole Moment for a CP-violating Neutral Higgs Sector", *Phys. Lett.* **B251** (1990) 157.

Referring to the description of the previous project, CP-violating Higgs sectors also give rise to an EDM for the electron. An important top-loop contribution to the electron EDM was explored by Barr and Zee, along with an additional W-loop diagram that I pointed out to them. Nonetheless, there are many more diagrams, even within the Standard Model ('standard' aside from the Higgs sector) that had not been considered. We computed the contributions of the remaining diagrams, in particular those from an especially subtle and easily-overlooked class. Our results show that the contributions to the electron EDM from this latter sub-class are opposite in sign to, although somewhat smaller than, the W-loop diagrams computed by Barr and Zee. Since the top-loop contribution is also opposite in sign to the W-loop contribution, substantial cancellation occurs. As a result, it turns out that current experimental limits on the electron EDM are only just on the verge of providing significant constraints on the amount of explicit or spontaneous CP violation that can be associated with the Higgs potential.

4. J.F. Gunion, H.E. Haber, and J. Wudka, "Sum Rules for Higgs Bosons", *Phys. Rev.* **D43** (1990) 904.

The construction of consistent quantum field theories containing massive vector bosons presented a major challenge to theorists in the 1960's. In general, such models are non-renormalizable. Moreover, the tree-level amplitudes for scattering processes exhibit bad high energy behavior, *i.e.* they increase with the center-of-mass energy, in violation of unitarity. It was later shown that spontaneously broken gauge theories (with the possible addition of massive $U(1)$ vector bosons) are the only renormalizable and consistent quantum field theories involving massive vector boson states. Soon after, it was established that such theories are also the unique class of theories involving vector bosons in which the

tree-level amplitudes for all scattering processes do not grow with the center of mass energy.[6,7] Such a result is possible, because relations among parameters of the theory imposed by the gauge invariance are precisely what is needed to cancel out bad high energy behavior among tree-level Feynman diagrams. In other words, the required cancellation of bad high energy behavior leads to a series of sum rule relations among various coupling constants of the theory. These sum rules were examined more explicitly in refs. 8 and 9, where bounds on Higgs boson masses were extracted. Nonetheless, the actual physical content of these sum rules remained somewhat obscure and difficult to extract from the existing literature. In this paper, we give a very explicit and easy to use formulation of the unitarity sum rules. In addition, we found a few discrepancies in some of the sum rules as previously published. We believe that we have have developed a presentation of the sum rules that is fully transparent to the experimental community. Our results will, we hope, soon become important since experimental accessibility to Higgs bosons is now becoming significant. Aside from the general formulation of the sum rules, we demonstrate their utility in a number of selected scenarios. When we discover one or more Higgs bosons, the most important immediate goal will be to measure their couplings and determine the extent to which they satisfy the unitarity sum rules. By doing so, we can determine whether the Higgs bosons and gauge bosons observed up to that moment could be a complete set, and if not the sum rules will provide a guide as to what Higgs bosons with what couplings remain to be discovered.

5. J.F. Gunion, R. Vega, and J. Wudka, "Naturalness Problems for $\rho = 1$ and Other Large One-Loop Effects for a Standard Model Higgs Sector Containing Triplet Fields", *Phys. Rev.* **D43** (1991) 2322.

Relatively little attention has been devoted to the subtleties associated with probing a Higgs sector that contains Higgs representations higher than doublets. In part this is because Higgs sectors with triplets and higher representations must be rather carefully constructed in order to avoid conflicting with the observed value of $\rho \equiv m_W/(m_Z c_W) \simeq 1$. Nonetheless, models can be easily constructed containing triplet Higgs representations (usually in combination with doublet representations in order to give fermions mass) which exhibit a custodial $SU(2)$ symmetry at tree-level that preserves $\rho = 1$ even when the neutral members of the triplet representations acquire a non-zero vacuum expectation value. An example of such a model is that discussed by Georgi and collaborators.[10] In a previous paper, we explored the rather intricate and subtle structure of the signatures for the Higgs bosons of this model. We found many unexpected signals, unusually long lifetimes, *etc.* for the Higgs bosons of the model. Production cross sections are also significantly dependent upon the amount of vacuum expectation value given to the triplet fields. All these issues were explored at some depth in the paper, and appropriate strategies for the detection of the Higgs bosons of such a triplet model outlined. Also presented were all the Feynman rules and couplings required for these and future calculations within this type of model, including the critical Higgs self-couplings.

The second paper is a continuation of our earlier work on Higgs triplet models. In particular, we have succeeded in demonstrating that even though $\rho = 1$ can be made natural at tree-level as a result of imposing a custodial symmetry on the tree-level Higgs potential, the gauge interactions necessarily violate this custodial symmetry and lead to infinite contributions to ρ. In order to carry out the usual renormalization program for these infinite contributions, counterterms must be introduced into the Higgs potential that violate the custodial symmetry. Since only the infinite part of these counterterms is determined by the renormalization program, arbitrary finite violations of $\rho = 1$ remain possible. While such violations can be related to other phenomenological observables, our conclusion is that in triplet models the value of ρ must be counted among the observables required to fully specify the theory (in particular, the Higgs potential), and therefore ρ is no longer predictable in such a model. We fully specify those observables related to the renormalization of ρ that must be measured in order to test the internal consistency of this type of theory.

6. D.A. Dicus, J.F. Gunion, and R. Vega, "Isolating the Scattering of Longitudinal W^+'s at the SSC Using Like-Sign Dileptons", *Phys. Lett.* **B258** (1991) 475.

If the interaction of vector bosons (V) becomes strong at high energy (as, for instance, in the Standard Model when the Higgs boson mass is taken to be large), then studying the interesting physics will require measuring VV scattering processes ($qq \to qqVV$) at subprocess energies at and above 1 TeV. A characteristic feature of such processes should be an enhanced probability for finding longitudinally polarized vector bosons in the final state. However, backgrounds to VV dectection in final state decay modes containing quark jets from a V decay are very large. Ideally one would like to study VV final states in purely leptonic final state modes. Many channels for this can be envisioned — $W^+W^- \to l^+l^-\nu\bar{\nu}$, $ZZ \to l^+l^-l^+l^-$, and $W^+W^+ \to l^+l^+\nu\nu$ (and charge conjugate). However, irreducible $q\bar{q}$ continuum electroweak backgrounds contribute to the first two final states, and are quite large. The W^+W^- channel also has a large background from $t\bar{t} \to W^+W^-b\bar{b}$ processes.

The l^+l^+ channel has the advantage of having intrinsically much smaller backgrounds. The only irreducible background comes from $qq \to qqW^+W^+$ production processes that yield transversely polarized W^+'s. The difficulty with this channel (as well as the W^+W^- channel) would seem to be determining when there is an enhancement in the number of longitudinaly polarized W bosons in the final state. (One cannot detect the neutrino, so there is no chance of determining the W^+ polarization directly.) In this study, we develop a number of cuts on the leptons, and an anti-tagging cut on the associated spectator jets that allow us to suppress the number of events in which the W^+ bosons are produced with transverse polarization to a level below the number of events in which both W^+'s are produced with longitudinal polarization. In addition, we discuss how to combine these with a single jet tag cut in order to get rid of a remaining $t\bar{t}$ background coming from $t+\bar{t} \to l^+\nu b + jj\bar{c}l^+\nu$ in which the second l^+ came from decay of the $\bar{b}$ emerging from the $\bar{t}$. The end result is that more than half of the interesting signal events (predicted for SM Higgs mass of 1 TeV) are retained, while the transverse polarization and $t\bar{t}$ backgrounds are reduced to less than 50% of the longitudinally polarized W^+W^+ signal. At canonical luminosity of 10 fb^{-1} only a handful of signal events (about 8) remain, but for enhanced luminosity, detection of the longidutinally polarized W^+W^+ signal should be possible. Further study of our techniques and alternative cuts is underway as reviewed later.

7. B. Grzadkowski, J.F. Gunion, and P. Krawczyk, "Neutral Current Flavor Changing Decays for the Z-boson and the Top Quark in Two-Higgs-Doublet Models", preprint UCD-90-34, to appear in *Phys. Lett.* **B**.

Two very interesting types of new physics are intimately connected — namely the physics of the top quark and the physics of a charged Higgs boson. For instance, a top quark can decay into a charged Higgs boson for $m_t \gtrsim m_{H^+} + m_b$, while the charged Higgs decay modes are dominated by $t\bar{b}$ if $m_{H^+} \gtrsim m_t + m_b$. Less obvious, but equally important, are the interconnections between a charged Higgs and the top quark in the area of rare K and B decays, and $\overline{K} - K$ and $\overline{B} - B$ mixing. For instance, in the latter, Feynman graphs involving the H^+ are at least as important as the standard box diagrams involving the W^+. In an earlier paper,[11] we combined the existing results for such mixing with limits from $b \to u$ decays on the crucial V_{bu} entry of the Cabibbo-Kobayashi-Maskawa matrix to place limits, both on the top quark and on the two crucial parameters of a two-doublet Higgs sector — the mass of the H^+ and the ratio of vacuum expectation values for the two Higgs doublets, normally called $\tan\beta$. Among other things we demonstrated that there is an m_t-dependent boundary in $m_{H^+} - \tan\beta$ parameter space that separates the domain of allowed from that of disallowed solutions. Roughly, the larger $\cot\beta$ is (*i.e.* the larger the H^+ coupling to the $t\bar{b}$) the heavier the Higgs boson must be. These bounds are quite significant and will play an important role in suggesting the most reasonable ranges of parameter space in which to search for a charged Higgs boson. In the paper, we also demonstrate that the weak-mixing and $b \to u$ results combine (in the absence of a charged Higgs boson) to exclude a range of m_t that depends upon the so-called bag parameters B_K and B_B describing the hadronic expectation value of the relevant quark-level matrix elements. Thus, discovery of the top quark at a particular mass, in combination with a fairly reliable lattice computation of B_K and B_B

(something to be expected in the not too distant future) could easily imply that a charged Higgs boson (or other new physics that influences mixing) is required, and would place a strong constraint on its mass and the value of $\tan\beta$.

Charged Higgs bosons also can have a strong influence on flavor changing neutral current decays, such as $t \to cZ$. Such decays are predicted to have very small branching ratio in the SM without a charged Higgs. A charged Higgs boson will yield loop contributions in addition to those that involve the W boson. In this paper, we investigated the magnitude expected for such FCNC decays *given the constraints of the previous paragraph from B and K phenomenology.* Although the charged Higgs can substantially enhance the rate of FCNC decays, one finds that the constraints from B and K phenomenology are such that the FCNC decays are still predicted to be too small for detection.

8. J.F. Gunion, "Associated Top-Antitop-Higgs Production as a Large Source of WH Events: Implications for Higgs Detection in the Lepton-Neutrino-Photon-Photon Final State", *Phys. Lett.* **B261** (1991) 510.

Hadron collider studies of past years have all suggested that detection of a SM Higgs boson in the intermediate mass range ($80 \leq m_{h_{SM}} \leq 2m_Z$) is something of a challenge. In earlier work, I and collaborators showed that $h_{SM} \to ZZ^* \to l^+l^-l^+l^-$ decays provide a very clean signature for $130 \lesssim m_{h_{SM}} \lesssim 2m_Z$. Masses below about 130 GeV can in principle be probed by inclusive Higgs boson production followed by $h_{SM} \to \gamma\gamma$ decay. However, the large $\gamma\gamma$ and γj continuum backgrounds imply that very fine mass resolution in the $\gamma\gamma$ final state is required and that a very high level of *jet*-γ discrimination must be achieved. It is often suggested that a special purpose detector will be required. (For instance, the SDC detector will not have the necessary resolution and discrimination factor.)

Recently, a number of studies have pointed out that backgrounds in the $W + h_{SM} \to l\nu\gamma\gamma$ final state are much smaller, and that if there are enough signal events, detection of the Higgs boson should be possible even if the $\gamma\gamma$ resolution and j-γ discrimination are not extremely good. The first production mechanism for such a final state that comes to mind is $q\bar{q} \to W^* \to Wh_{SM}$. This was studied by a number of groups.[12] However, the SSC rate predicted is very small for canonical $L = 10$ fb^{-1} luminosity — roughly 4 to 5 events. Very recently, I and another group[13] realized that the cross section for associated $t\bar{t}h_{SM}$ production, followed by one top quark decaying to and W (which in turn decays to $l\nu$) and $h_{SM} \to \gamma\gamma$ leads to exactly the same background free $l\gamma\gamma$ final state. For canonical $L = 10$ fb^{-1} luminosity, this process yields about 15 to 25 events after cuts throughout the mass range $80 \lesssim m_{h_{SM}} \lesssim 140$ GeV. This development now allows us to say with confidence that the Superconducting Super Collider can detect the SM Higgs boson throughout the possibly crucial intermediate mass region using the combination of the $Wh_{SM} \to l\nu\gamma\gamma$ and $ZZ^* \to 4l$ final states.

9. H. Baer, M. Drees, R. Godbole, J.F. Gunion and X. Tata, "Phenomenology of Light Top Squarks at the Fermilab Tevatron", preprint FSU-HEP-910308, to appear in *Phys. Rev.* **D**.

It is, of course, widely known that the Fermilab CDF experiment can rule out squarks (if all are degenerate) and gluinos with masses below about 150 GeV, and a top quark with mass below about 89 GeV, *provided* that all decay canonically. In this paper, we considered the scenario, often encountered in a renormalization group treatment of supersymmetry, in which the stop squark ends up with mass substantially smaller than that of the other squarks, and even substantially smaller than the top quark itself. We demonstrate that this scenario leads to dramatically different phenomenology for top, squark, and gluino detection at Fermilab energies. In fact, it is not impossible that the top quark could be lighter than 89 GeV and have remained undetected. A light stop squark is itself more difficult to detect since its cross section is only 1/6 that normally employed in setting limits for six degenerate squarks, and, in addition, it has rather unusual decay modes. It is even possible that a light gluino (*e.g.* with mass of order 100 GeV) could be hidden by unexpected decays of the gluino to the stop squark. However, the Tevatron luminosity upgrade should go a long way towards eliminating (or confirming) this type of scenario.

10. J.F. Gunion, "Non-minimal Higgs Sectors: Probes at 'Low-Energy' e^+e^- Colliders and in Top-Quark Decays", to appear in *Proceedings of the Workshop on Physics at Future Colliders*, La Thuile 1990.

In this talk, I reviewed the (then) available limits on Higgs bosons, in particular those appearing in models with non-standard Higgs sectors. Techniques for exploring such Higgs sectors at the Tristan and LEP e^+e^- colliders and at the Tevatron and CERN hadron colliders were detailed.

11. R.M. Barnett *etal.*, including J.F. Gunion, "Report of the Subgroup on the Top Quark", preprint ANL-HEP-EP-90-98 (1990), to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

This research report details the results of a number of subgroups in which I and others explored the physics of the top quark at existing and future accelerators. In particular, we developed techniques for accurate determination of the top quark mass in a variety of final state modes, and for detecting a charged Higgs boson should it appear in the decays of the top quark. The utility of polarization measurements was explored.

12. J.F. Gunion, G.L. Kane, *etal.*, "Overview of Progress in Higgs Boson Physics for the Superconducting Super Collider", preprint UCD-91-0010, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*. Snowmass, CO, June 25 – July 13, 1990.

In this report, the results obtained by a number of subgroups exploring Higgs boson physics were amalgamated. Substantial progress was made at Snowmass in finding ways of probing Higgs boson scenarios that had previously seemed difficult to explore experimentally at hadron colliders such as the SSC. For instance, the $l\nu\gamma\gamma$ final state mode of associated $W + Higgs$ production was given a first appraisal for the Standard Model. Various scenarios and appropriate detection techniques for the charged Higgs boson of a two-doublet model were explored, with particular attention to top quark induced backgrounds. The feasibility of detecting the presence of strong longitudinal gauge boson scattering using purely leptonic final states was demonstrated.

13. J.F. Gunion and L. Roszkowski, " Ruling Out the Minimal Supersymmetric Model at LEP-200", preprint UCD-90-26, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

In this paper, we demonstrate that LEP-200 will be able to either confirm or rule out the Higgs sector predicted by the minimal supersymmetric model *if* the top quark mass is sufficiently small ($\lesssim 110\,\mathrm{GeV}$) that radiative corrections to tree-level predictions are small. In particular, we focused on using b-tagging to isolate the signals from one or more of the neutral Higgs bosons of the model. We demonstrated that, with sufficiently efficient and pure b-tagging, separation of the Higgs signal from ZZ continuum and other backgrounds should be feasible even in the most difficult case where the only kinematically accessible Higgs boson has mass near m_Z and only relatively modest integrated luminosity is available.

14. J.F. Gunion and H.E. Haber. "Expected Limits on Supersymmetric Parameters at LEP-200", preprint UCD-90-27, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

In this report, we explore the region of minimal-supersymmetric-model parameter space over which detection of either neutralino-neutralino or chargino-chargino pair-production will be possible at LEP-200. In particular, we demonstrate that chargino-chargino production will yield an observable rate essentially wherever such pair production is kinematically allowed. The portion of the supersymmetric $\mu - M$ parameter space that will thereby be explored is given.

15. R.M. Barnett, J.F. Gunion, and H.E. Haber, "Determining the Mass of the Gluino at the SSC", preprint UCD-90-28, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

This paper develops a highly effective procedure for determining the mass of the gluino using the like-sign detection channel for gluino pair production. The particular mass variable and cuts employed are shown to provide a sensitive measure of the gluino mass at a hadron collider such as the SSC. Before including systematics due to model uncertainties, the error on the gluino mass determined in the suggested way can be as small as 5 GeV.

16. J.F. Gunion and G. Kane, "Motivation for an SSC Detector with Ultrahigh Resolution Photon Detection", preprint UCD-90-29, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

In this report, we review the many physics motivations for a detector capable of $\lesssim 1$ GeV resolution in $\gamma\gamma$ invariant mass. In particular, we focus on the sensitivity to new physics (such as new W bosons or heavy fermion families) of the two-photon decays of Higgs bosons (both Standard Model and beyond). We argue that the potential for uncovering new high-mass physics, not to mention simply discovering one or more Higgs bosons, via the $\gamma\gamma$ spectrum is so great that a detector with ultra-fine resolution in this channel should be a priority.

17. J.F. Gunion, "Electric Dipole Moments for a CP-violating Neutral Higgs Sector", preprint UCD-90-30, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

This survey reviews recent developments regarding contributions to electric dipole moments arising from a Higgs sector which exhibits spontaneous or explicit CP violation. In particular, the work by Vega and myself on the electron's EDM and by D. Wyler and myself on the neutron's EDM was discussed and compared to other contributions and calculations. Sensitivity of the neutron EDM to techniques for turning quark/gluon level predictions into a prediction at the composite neutron level were outlined, as was the physics behind the various techniques.

18. J.F. Gunion and H.E. Haber, "Higgs Boson Production in Photon-Photon Collisions at as High Energy e^+e^- Linear Collider", preprint SCIPP-90-22, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

In this work, we demonstrate that production of neutral Higgs bosons (whether that of the Standard Model or those appearing in the Minimal Supersymmetric Model) via $\gamma\gamma$ collisions of back-scattered laser beams generally yields a very observable signal. For instance, we show that the Standard Model Higgs boson can be detected in either the $b\bar{b}$ or ZZ decay modes (the mode depends on Higgs mass) for Higgs boson masses up to nearly the full e^+e^- machine energy of $\sqrt{s} = 500$ GeV considered. This represents a significant improvement over the more conventional direct e^+e^- collision production of neutral Higgs bosons, which will only allow discovery of a SM Higgs boson up to masses of order $\frac{1}{2}\sqrt{s}$. Further, back-scattered photon-photon production allows detection of the SUSY Higgs bosons over much of the $\lesssim \sqrt{s}$ mass region, whereas conventional e^+e^- production at most will probe masses $\lesssim \frac{1}{2}\sqrt{s}$ and could have quite limited sensitivity to one or more of the SUSY neutral Higgs bosons.

19. R.M. Barnett, J.F. Gunion and B. Hubbard, "Determining the Mass of the Top Quark with the SDC Detector", preprint SDC-90-00146, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

This report details techniques that were developed by us at Snowmass for directly (*i.e.* via mass peak reconstruction) determining the top quark mass using $t\bar{t}$ pair production events at a hadron collider such as the SSC. The procedure we develop is at least as good as that based on the $e-\mu$ final state channel.

20. R.M. Barnett, J.F. Gunion, H.E. Haber, I. Hinchliffe, B. Hubbard, and H. Trost, "Searching for Top Decays to Charged Higgs Bosons with the SDC Detector", preprint UCD-90-32, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

This report presents the techniques that we developed for detecting a charged Higgs boson of a two-doublet Higgs sector when its mass is such that it is produced in the decays of the top quark. We show that two distinct procedures are adequate to ensure discovery of the H^+ over the entire physically interesting region of $\tan\beta$ space ($\tan\beta$ is the ratio of vacuum expectation values of the neutral doublet members). For small $\tan\beta$ we show how to detect the H^+ via direct mass peak reconstruction in its hadronic decay modes (the dominant ones for small $\tan\beta$). When $\tan\beta$ is large, H^+ decays of the top quark result in an easily detectable violation of $e-\mu-\tau$ universality. We find that the two detection techniques substantially overlap in $\tan\beta$ parameter space.

21. G.H. Trilling *etal.*, including J.F. Gunion, [Solenoid Detector Collaboration], "Letter of Intent by the Solenoidal Detector Collaboration to Construct and Operate a Detector at the Superconducting Super Collider", publication SSCL-SR-1153A.

This is the principal document produced by the SDC collaboration as part of the detector approval process. My particular role in producing this document was in the area of physics processes. In particular, the PAC wished to have detailed results for a number of Higgs boson processes. An example is the detection of a charged Higgs boson in top quark decays (the project outlined just above). In fact, many of the Higgs detection techniques explored in the LOI had their origin in earlier work by myself and collaborators. My advice to and consultation with the experimentalists involved in SDC over the last five or so years played. I believe, a significant role in deciding upon the physics considerations used to determine the design of the detector.

22. J.F. Gunion, "An Overview of, and Selected Signatures for, Higgs Physics at Colliders", preprint UCD-91-9, to appear in *Proceedings of the 'Workshop in High Energy Physics Phenomenology — II'*, Calcutta (January, 1991).

In this report, I give a wide-ranging review of Higgs physics, with particular attention to the most recently developed techniques for detecting Higgs bosons and/or strong W scattering. Based upon the number of requests for this report that I have received, I would say that the community has found this summary of the current situation to be quite valuable.

23. E. Ma *etal.*, including J.F. Gunion, "Report From Working Group III: Quest for New Physics", to appear in *Proceedings of the 'Workshop in High Energy Physics Phenomenology — II'*, Calcutta (January, 1991).

In this report, we present results obtained at the WHEPP-II workshop by the New Physics working group. One of our focuses was the area of CP violation in the Higgs boson sector, my principal area of interest at the workshop. We made significant progress in understanding the types of CP violation that might arise, and what their physical manifestation at accelerators would be. Work in this area is still continuing.

1. J.F. Gunion, H.E. Haber, G. Kane and S. Dawson, "The Higgs Hunters Guide", Addison and Wesley (1990), Frontiers in Physics Series, second edition.

2. J.F. Gunion and D. Wyler, "Inducing a Large Neutron Electric Dipole Moment via a Quark Chromoelectric Dipole Moment", *Phys. Lett.* **B248** (1990) 170.

3. J.F. Gunion and R. Vega, "The Electron Electric Dipole Moment for a CP-violating Neutral Higgs Sector", *Phys. Lett.* **B251** (1990) 157.

4. J.F. Gunion, H.E. Haber. and J. Wudka, "Sum Rules for Higgs Bosons", *Phys. Rev.* **D43** (1990) 904.

5. J.F. Gunion, R. Vega, and J. Wudka, "Naturalness Problems for $\rho = 1$ and Other Large One-Loop Effects for a Standard Model Higgs Sector Containing Triplet Fields", *Phys. Rev.* **D43** (1991) 2322.

6. D.A. Dicus, J.F. Gunion, and R. Vega, "Isolating the Scattering of Longitudinal W^+'s at the SSC Using Like-Sign Dileptons", *Phys. Lett.* **B258** (1991) 475.

7. B. Grzadkowski, J.F. Gunion, and P. Krawczyk, "Neutral Current Flavor Changing Decays for the Z-boson and the Top Quark in Two-Higgs-Doublet Models", preprint UCD-90-34, to appear in *Phys. Lett.* **B.**

8. J.F. Gunion, "Associated Top-Antitop-Higgs Production as a Large Source of WH Events: Implications for Higgs Detection in the Lepton-Neutrino-Photon-Photon Final State", *Phys. Lett.* **B261** (1991) 510.

9. H. Baer, M. Drees, R. Godbole, J.F. Gunion and X. Tata, "Phenomenology of Light Top Squarks at the Fermilab Tevatron", preprint FSU-HEP-910308, to appear in *Phys. Rev.* **D.**

10. J.F. Gunion, "Non-minimal Higgs Sectors: Probes at 'Low-Energy' e^+e^- Colliders and in Top-Quark Decays", to appear in *Proceedings of the Workshop on Physics at Future Colliders*, La Thuile 1990.

11. R.M. Barnett *etal.*, including J.F. Gunion, "Report of the Subgroup on the Top Quark", preprint ANL-HEP-EP-90-98 (1990), to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

12. J.F. Gunion, G.L. Kane. *etal.*, "Overview of Progress in Higgs Boson Physics for the Superconducting Super Collider", preprint UCD-91-0010, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

13. J.F. Gunion and L. Roszkowski, " Ruling Out the Minimal Supersymmetric Model at LEP-200", preprint UCD-90-26. to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass. CO. June 25 – July 13, 1990.

14. J.F. Gunion and H.E. Haber, "Expected Limits on Supersymmetric Parameters at LEP-200", preprint UCD-90-27, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass. CO, June 25 – July 13. 1990.

15. R.M. Barnett. J.F. Gunion, and H.E. Haber. "Determining the Mass of the Gluino at the SSC", preprint UCD-90-28, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13. 1990.

16. J.F. Gunion and G. Kane. " Motivation for an SSC Detector with Ultrahigh Resolution Photon Detection", preprint UCD-90-29. to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

17. J.F. Gunion, "Electric Dipole Moments for a CP-violating Neutral Higgs Sector", preprint UCD-90-30, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

18. J.F. Gunion and H.E. Haber, "Higgs Boson Production in Photon-Photon Collisions at a High Energy e^+e^- Linear Collider", preprint SCIPP-90-22, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

19. R.M. Barnett, J.F. Gunion and B. Hubbard, "Determining the Mass of the Top Quark with the SDC Detector", preprint SDC-90-00146, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

20. R.M. Barnett, J.F. Gunion, H.E. Haber, I. Hinchliffe, B. Hubbard, and H. Trost, "Searching for Top Decays to Charged Higgs Bosons with the SDC Detector", preprint UCD-90-32, to appear in *Proceedings of the 1990 Summer Study on High Energy Physics*, Snowmass, CO, June 25 – July 13, 1990.

21. G.H. Trilling *etal.*, including J.F. Gunion, [Solenoid Detector Collaboration], "Letter of Intent by the Solenoidal Detector Collaboration to Construct and Operate a Detector at the Superconducting Super Collider", publication SSCL-SR-1153A.

22. J.F. Gunion, "An Overview of, and Selected Signatures for, Higgs Physics at Colliders", preprint UCD-91-9, to appear in *Proceedings of the 'Workshop in High Energy Physics Phenomenology — II'*, Calcutta (January, 1991).

23. E. Ma *etal.*, including J.F. Gunion, "Report From Working Group III: Quest for New Physics", to appear in *Proceedings of the 'Workshop in High Energy Physics Phenomenology — II'*, Calcutta (January, 1991).

J.F. Gunion: Invited Talks and Seminars

1. "Intermediate Mass Higgs Bosons: An Overview", Snowmass Workshop, June 27, 1990.
2. "Detecting $t \to H^+$ Decays via a Violation of Lepton Universality", Snowmass Workshop, June 29, 1990.
3. "The Neutron Electric Dipole Moment", Snowmass Workshop, July 10, 1990.
4. "Large Contributions to the Neutron Electric Dipole Moment", Aspen Center for Physics, July 17, 1990.
5. "Electric Dipole Moments for a CP-violating Neutral Higgs Sector", SLAC, Sept. 5, 1991.
6. "Electric Dipole Moments for a CP-violating Neutral Higgs Sector", Institute for Theoretical Physics, Sept. 21, 1990.
7. "Electric Dipole Moments for a CP-violating Neutral Higgs Sector", Beyond the Standard Model – II, Oct. 31 - Nov. 3, 1990.
8. "Electric Dipole Moments for a CP-violating Neutral Higgs Sector", WHEPP-II Workshop, Jan. 1-14, 1991.
9. "Overview of Higgs Physics", WHEPP-II Workshop, Jan. 1-14, 1991.
10. "Strongly Interacting Gauge Boson Theories — Heavy Higgs", WHEPP-II Workshop, Jan. 1-14, 1991.
11. "Electric Dipole Moments for a Neutral Higgs Sector", LBL, Jan. 28, 1991.
12. "Selected Signatures for Higgs Bosons: Standard Model and Beyond", SSC Physics Symposium, Feb. 25-27, 1991.

J.F. Gunion: Meetings and Workshops

1. Workshop on Tests and Extensions of the Standard Model, Aspen Institute, July 2 – July 27, 1990.
2. 1990 Summer Study on High Energy Physics, Snowmass, CO, June 25 – July 13, 1990.
3. Beyond the Standard Model — II, Oklahoma U., Oct. 30 – Nov. 3, 1990.
4. Workshop in High Energy Physics Phenomenology — II, Calcutta, Jan. 1 – Jan 14, 1991.
5. SSC Physics Symposium, Madison, Wisconsin, Feb. 25 – Feb. 28, 1991.
6. SDC Detector Performance Workshop, SSC Laboratory, May 31 – June 1, 1991.

J.F. Gunion: Additional Activities *etc.*

1. Organizer, 'Intermediate Mass Higgs Bosons', Snowmass, 1990.
2. Organized 'Higgs Working Group', Workshop for High Energy Physics Phenomenology, Calcutta, India, Jan. 1 – Jan 14, 1991.
3. Member of Working Group on the Next Linear Collider, Stanford Linear Accelerator, Sept. 1990 — present.
4. Extensive organization of lobbying for the SSC within California. As I did last year, I again orchestrated the contacting of most of the California House and Senate members by individuals from their own districts, February-April, 1991. This year's effort does not seem to have been as successful as last year.

Progress Report (J. Gunion)

1. J.F. Gunion, H.E. Haber, G. Kane and S. Dawson, "The Higgs Hunters Guide", Addison and Wesley (1991) Frontiers in Physics Series, second edition.

The physics of Higgs bosons, whether that of the Standard Model or those of extended models, and their detection has become an extremely involved and extensive subject over the last few years. As a result, a group of us decided to write a book on the subject containing a systematic study and survey of all the accumulated knowledge, including a full detailing of existing experimental constraints on and future probes of the Higgs boson sectors of all attractive models considered in the literature to date. The first edition of the book became something of a standard reference for this type of physics. It included a complete listing of all relevant Feynman rules, branching ratios, and so forth. Also included were treatments of several areas where we felt old results could be improved or required correction. In addition, it contained much original material not available anywhere in the literature. The second edition, was published this last year. It updates the first edition by including recent limits on Higgs bosons from LEP and top quark mass limits from CDF and elsewhere. A host of minor improvements and a few corrections have been incorporated.

2. R.M. Godbole *etal.*, including J.F. Gunion. "New Particle Searches and Structure Functions: Group Report", to appear in *Proceedings of the 'Workshop in High Energy Physics Phenomenology — II'*, Calcutta (January, 1991).

In this group report, we summarize a number of new results obtained during the course of the workshop regarding extended models and the new particles contained in such models. We focused on predictions that could be tested at hadron supercolliders, although there were a few ideas relevant to physics at HERA.

3. D.A. Dicus, J.F. Gunion, L.H. Orr, and R. Vega, "Isolating Purely-Leptonic Signals for Strong W Scattering Using Anti-Tagging, Jet-Tagging and Lepton Isolation", preprint UCD-91-10 (1991).

In this paper, we complete (following up the work of Dicus, Gunion and Vega in *Phys. Lett.* **B258** (1991) 475) our delineation of the procedures required to isolate a purely leptonic final state signal for strong VV scattering ($V = W, Z$) at a hadron supercollider. We demonstrate that by anti-tagging against central jets, tagging forward jets, and placing certain back-to-back cuts on the final leptons, one can reduce all backgrounds, especially those from $t\bar{t}$ production, to a level below the strong VV signal. In addition, we quantify the requirements for lepton isolation such that it could be used to eliminate the $t\bar{t}$ background to the the like-sign dilepton signal in the W^+W^+ channel. The techniques of this paper have been taken up by the many experimental collaborations in their detailed proposals for the SSC and LHC. In particular, the SDC Technical Design report pursued our ideas and arrived at optimistic conclusions regarding the ability of the detector to isolate such signals for strong VV scattering.

4. J.F. Gunion and M. Mangano, "Comments on Higgs Detection in the $WH \to l\nu\gamma\gamma$ Final State", report SDC-91-00057 (1991).

In this report, we study in detail the effects of altering the rapidity coverages of the electromagnetic and muon chambers of the SDC detector upon the ability to detect an Intermediate Mass Higgs boson in the $WH \to l\nu\gamma\gamma$ Final State. Both the $W^* \to WH$ and $t\bar{t}H \to WHX$ production modes were simulated. This study was used as one of the bases for deciding the most optimal way of minimizing costs for these components of the detector, while maintaining physics capability.

5. J.F. Gunion and L.H. Orr. "Detecting the Higgs Bosons of the Minimal Supersymmetric Model", preprint UCD-91-15 (1991), to be published in *Phys. Rev.* **D**.

This is one of a trio of papers in which a systematic study is made of the ability to discover the Higgs bosons of the Minimal Supersymmetric Model (MSSM) at the SSC or LHC. *using the same*

(or very similar) relatively clean modes as would be employed for discovery of the Standard Model (SM) Higgs boson (h_{SM}). Recall that if $m_{h_{SM}} \lesssim m_Z$ then the h_{SM} can be found at LEP-II in the process $Z^* \to Zh_{SM}$. For $m_Z \lesssim m_{h_{SM}} \lesssim 140\,\text{GeV}$, the h_{SM} can be detected at the SSC or LHC using associated $W + h_{SM}$ production followed by $h_{SM} \to \gamma\gamma$ decay, while triggering on an isolated l from the decay of the W. For $130\,\text{GeV} \lesssim m_{h_{SM}} \lesssim 2m_Z$, detection of the h_{SM} at the SSC/LHC is possible using gg fusion production of the h_{SM} followed by $h_{SM} \to ZZ^* \to l^+l^-l^+l^-$ ($4l$ for short) decays. And for $2m_Z \lesssim m_{h_{SM}} \lesssim 800\,\text{GeV}$, detection in the double on-shell decay $h_{SM} \to ZZ \to 4l$ is straightforward.

In this paper, we explore the use of the $W + Higgs \to l\nu\gamma\gamma$ final state mode. (The inclusive $Higgs \to \gamma\gamma$ mode was also studied, but is more difficult than the $l\gamma\gamma$ mode because of large backgrounds.) At tree level, in the MSSM the Higgs sector is fixed by specifying just two parameters, $\tan\beta = v_2/v_1$ (the ratio of vacuum expectation values) and m_{A^0} (the mass of the pseudoscalar CP-odd Higgs boson). After including one-loop radiative corrections, one must specify in addition the top quark and stop squark masses. In our work, we include all radiative corrections and delineate as a function of the top quark mass the regions of $\tan\beta$–m_{A^0} parameter space for which each of the neutral Higgs bosons of the MSSM (the h^0, H^0 and A^0) can be found in this mode. This required generating Monte Carlo event rates for both $W^* \to W + Higgs$ and $t\bar{t} + Higgs$ after cuts, compiling all backgrounds after cuts (including the $t\bar{t}\gamma\gamma$ continuum background), computing all decay widths (after radiative corrections) so as to obtain the $\gamma\gamma$ branching ratios, and so on. Our results demonstrate that this is one of the two most important modes for MSSM Higgs detection at the SSC and LHC, and is especially useful when m_t is large and MSSM Higgs detection at LEP-200 is rather unlikely.

In this paper, we also compile and present an overall survey of the results for other channels to be discussed below, and come close to establishing a no-lose theorem. According to this theorem, at low $m_t \sim 100\,\text{GeV}$ and/or low values of the stop quark mass, LEP-II provides the best opportunity for MSSM Higgs discovery, allowing discovery of one or more of the h^0, H^0, A^0, H^+ for essentially all of m_{A^0}–$\tan\beta$ parameter space. If the stop quark mass is large ($\sim 1\,\text{TeV}$), then at moderate $m_t \sim 150\,\text{GeV}$, LEP-II covers only a portion of parameter space, but the SSC can cover essentially all of the remainder (there is a small uncertain hole that may be filled by other modes currently being explored). At large $m_t \sim 200\,\text{GeV}$, discovery of a MSSM Higgs at LEP-II is possible only in a small region of parameter space, but at the SSC discovery of one or more MSSM Higgs boson is possible throughout all of parameter space using one or more of the same detection modes that would be used for detection of the Standard Model Higgs boson. Thus, the no-lose theorem states that *one or more of the Higgs bosons of the MSSM will be discovered either at LEP-II or at the SSC, regardless of m_t!* The machines play an important complementary role. Development of the techniques required to be certain of this theorem was an arduous task and one of the major accomplishments in the Higgs field this last year.

6. J.F. Gunion, "Exploring Higgs Bosons/Electroweak Symmetry Breaking Physics at 200 TeV", preprint UCD-91-22 (1991), to appear in *Proceedings of 'QCD at 200 TeV'*, Ettore Majorana Centre for Scientific Culture, INFN Eloisatron Project, Erice, Plenum Publications.

In this workshop report, I explore the ability of a 200 TeV hadron collider to follow up discoveries in the Higgs sector made by the SSC/LHC colliders. I also explore the relative virtues of such a 200 TeV hadron collider as compared to a TeV-scale e^+e^- collider for performing such studies. The many detailed conclusions cannot be fully given here. But overall, a 200 TeV hadron collider would expand considerably our ability to fully explore the detailed features of the Higgs boson/Electroweak Symmetry Breaking sector. Its greatest advantage over any e^+e^- collider other than one with super high energy ($> 4\,\text{TeV}$) would emerge if there is no light Higgs boson (or equivalent), implying that there would be strong interactions in VV scattering at energy scales at and above a TeV. However. even if one or more light Higgs bosons do exist, a 200 TeV collider can perform many tasks that the

SSC cannot and Higgs studies performed at it could end up nicely complementing the information available from a 0.5 to 2 TeV e^+e^- collider.

7. J.F. Gunion, R. Bork. H.E. Haber, and A. Seiden, "Searching for CP-Even Higgs Bosons of the Minimal Supersymmetric Model at Hadron Supercolliders", preprint UCD-91-29 (1991), to appear in *Phys. Rev.* **D**.

This is the second of a trio of papers (UCD-91-15, UCD-91-29, and UCD-91-32) in which a full exploration of detecting the Higgs bosons of the minimal supersymmetric model (MSSM) at the SSC is performed, including corrections to the masses and interactions of the Higgs bosons due to one-loop radiative corrections. In this paper, we focus on the CP-even Higgs bosons (h^0 and H^0). We first compute the decay widths for all channels, and all the production cross sections for these two Higgs bosons (including $gg \to Higgs$ fusion and $gg \to Q\overline{Q} + Higgs$, $Q = b$ or t). We next focus on determining the range of m_{A^0}–$\tan\beta$ parameter space (see the discussion for UCD-91-15 given earlier) for which discovery in the $h^0, H^0 \to l^+l^-l^+l^-$ decay modes would be possible at the SSC. We demonstrate that this $4l$ gold-plated mode is viable over a remarkably large segment of parameter space for $m_t \gtrsim 150\,\text{GeV}$. This mode contributes to our ability to demonstrate the no-lose theorem for Higgs discovery at LEP-II and the SSC, discussed earlier under the summary for UCD-91-15.

8. J.F. Gunion, H.E. Haber, and C. Kao, "Searching for the CP-Odd Higgs Boson of the Minimal Supersymmetric Model at Hadron Supercolliders", preprint UCD-91-32 (1991), to appear in *Phys. Rev.* **D**.

This is the final paper of the above-mentioned trio. It focuses on the CP-odd Higgs boson (A^0) of the minimal supersymmetric model. We compute its decay widths and branching fractions to all relevant channels, as well as its production cross sections via the various gg induced processes. We then evaluate carefully the possibility of searching for it in the gold-plated $4l$ mode. In the case of the A^0 the $4l$ decays come from one-loop-induced $A^0 \to ZZ$ couplings (such couplings are forbidden at tree-level). The $4l$ signals are, of course, very much smaller than found for the CP-even Higgs bosons which have tree-level $A^0 \to ZZ$ couplings. Nonetheless, for $\tan\beta \lesssim 1.5$, we find that for m_{A^0} in the vicinity of $2m_t$ one could discover the A^0 at the SSC in the $4l$ channel. In this paper, we also survey the possible utility of a large variety of other detection modes. A number of very promising options are pointed out, but their detailed investigation is part of ongoing work.

9. A. Brignole, J. Ellis, J.F. Gunion, M. Guzzo, F. Olness, G. Ridolfi, L. Roszkowski, and F. Zwirner, "Higgs Bosons in the Minimal Supersymmetric Extension of the Standard Model", preprint (1991), to appear in *Proceedings of the Workshop on "e^+e^- Linear Colliders at 500 GeV: the Physics Potential"*, Saariselka, Finland.

In this workshop paper, we perform a complete survey of the potential of a 500 GeV e^+e^- linear collider to detect and study the Higgs bosons of the Minimal Supersymmetric Model (MSSM). The hallmark of this effort was the inclusion of the one-loop radiative corrections to the masses and couplings of the MSSM Higgs bosons as a function of the top and stop masses. Radiative corrections alter rather drastically the discovery potential for the MSSM Higgs bosons at the lower energy 200 GeV energy of LEP-II. But, as demonstrated in this paper, a 500 GeV machine is guaranteed to find at least the lightest CP even state (the h^0) and will find *all* of the MSSM Higgs bosons if $m_{A^0} \lesssim 220\,\text{GeV}$, regardless of the values of $\tan\beta$ and m_t (so long as $m_t \lesssim 200\,\text{GeV}$ as required from LEP data).

10. J.F. Gunion, 'Notes and Questions Regarding Effects of Calorimeter Segmentation/Descoping on Important Physics', private communication to SDC Collaboration.

In this internal note, I point out the impact of various calorimeter descoping options upon the ability of the SDC detector to discovery a variety of different types of physics, especially Higgs boson/electroweak symmetry physics. I also raised a number of questions that had not been directly addressed in the LOI regarding the then current calorimeter design and various alternatives that were

under consideration. I enclose below an introductory paragraph which summarizes the main points of the letter.

There are three basic points which I first summarize and then discuss in a bit more detail in the following paragraphs. First, while it may be true that some signal for most any type of new physics will probably be observable without fine segmentation using basically leptonic type final states, event rates for these channels that do not necessarily (but in some cases do) demand fine segmentation are often quite low. Integrated L of at least 10 fb^{-1} is often required. In contrast, if final states containing a mixture of leptons and jets can be employed (which requires good segmentation) it is quite possible that viable signatures for new physics could be achieved with less L. Second, I have numerous questions as to the extent to which signal events would be removed from the low rate purely leptonic signals as a result of reduced segmentation. Third, even if the full L is available and a 'purely' leptonic signature for some form of new physics is established, further exploration or confirmation of the details of the new physics will almost certainly require probing it in a variety of final state channels, especially channels containing both leptons and jets. Thus, if only small saving can be achieved by reduced segmentation, such a compromise of future physics capability for the SDC detector would seem to me to be very unwise.

11. J.F. Gunion, "New Techniques for Higgs Boson Detection", *Proceedings of the 1991 Vancouver Meeting of the Division of Particles and Fields of the APS*, Vancouver, Canada, August 18-22,1991, ed. D. Axen *etal.*, World Scientific, Singapore (1992), p. 378.

In this talk writeup, I summarize the progress made in developing techniques for Higgs detection (both for the Standard Model Higgs boson and for the Higgs bosons of the Minimal Supersymmetric Model) that had occurred in the preceding one to two years. Much of this progress was a direct result of the work of myself and collaborators as summarized above, and in last year's proposal. This rather succinct talk and writeup brought this material to the attention of the broader particle physics community for the first time, and occasioned much discussion at the DPF meeting.

12. J.F. Gunion, "Experimental Probes of Higgs Bosons and Electroweak Symmetry Breaking", preprint UCD-92-4 (1992), to appear in *Proceedings of the "International Workshop on Electroweak Symmetry Breaking"*, Hiroshima, Japan (1991), ed. J. Kodaira, World Scientific.

This talk and writeup reviewed the current status of our ability to detect both the Standard Model Higgs boson and the Higgs bosons of the Minimal Supersymmetric Model. Like the previous talk, it emphasized the progress that had been recently made in this area. In addition, it included a review of the ability of the SSC to detect a signal for strong WW scattering using purely leptonic final states. As summarized in earlier items, we have developed techniques that will make this possible if the SSC reaches full luminosity. Aside from educating some of my more formally inclined colleagues on this subject matter, I believe this talk had a dramatic impact upon the Japanese physicists. They had been unaware of just how much progress we had made in demonstrating that the SSC was an excellent machine for studying electroweak physics. and certainly far superior to the LHC in the event that strong WW scattering is present. Many of them came to me after the talk wishing to be certain that they had understood correctly what I was saying, and these conversations have continued via bitnet and personal interactions during my CERN visit this past year. If the SSC succeeds in obtaining Japanese support, I think I will have played a not insignificant role in motivating this support.

13. J.F. Gunion and B. Grzadkowski, "Detecting CP Violation in $t \to W^+b$ Decays", preprint UCD-92-7 (1992), to appear in *Phys. Lett.* **B**.

One of the most interesting issues, in considering extensions of the Higgs sector beyond the minimal one-doublet field of the Minimal Standard Model, is whether or not such an extended Higgs sector is intrinsically CP-violating. An enormous amount of theoretical work has been performed in this area, but even a semi-realistic way of detecting such CP violation has been elusive. Neutron and electron electric dipole moments are sensitive to CP violation in the Higgs sector, but the predicted EDM's are at most just large enough to be seen in the next round of experiments (see work summarized in previous

proposal for 1991). Even if a non-zero EDM is found, it could derive from sources other than the Higgs sector. In this paper, we examine whether or not CP violation in the Higgs sector could lead to non-zero values for certain asymmetries that can be defined in $t \to W^+b$ decays; and to differences for these asymmetries in comparing t to $\bar{t}$ decays. We define a particularly useful (from an experimental point of view) asymmetry and compute the magnitude expected for maximal CP violation in the neutral Higgs sector of a two-doublet model. For the standard 10 fb^{-1} SSC integrated luminosity, the predicted asymmetry (of order 0.1% since it derives from one-loop diagrams) unfortunately turns out to be a bit too small to be measurable. With 100 fb^{-1} it could be measured. Nonetheless, the asymmetry and experimental techniques discussed can certainly isolate CP violation at the 1% level, and should be of great interest once the large sample of top events that will be produced at the SSC has been collected.

14. R.M. Barnett, R. Cruz, J.F. Gunion, and B. Hubbard, "Charged Higgs Bosons at the SSC", preprint UCD-92-14 (1992), submitted to *Phys. Rev.* **D**.

This paper represents a fairly definitive study of the detection of a charged Higgs boson in $t \to H^+b$ decays at the SSC using the SDC detector. It includes full simulation and Monte Carlo treatments of all processes, using the resolutions etc. of the SDC detector as given in the SDC Technical Design Report. We demonstrate that detection of the charged Higgs boson of the theoretically preferred Model-II type of two doublet Higgs sector will be possible for virtually all choices of parameters. If the ratio of vacuum expectation values ($\tan\beta$) is small, then detection of $H^+ \to c\bar{s}$ decays will be possible by direct reconstruction of a mass peak in the two-jet channel. Techniques for extracting this two-jet signal from the $t \to W^+b$ background are developed and proven to be viable. For larger $\tan\beta$, detection of the H^+ employs the $H^+ \to \tau\nu$ decay channel. The presence of the H^+ in t decays always leads to a large violation of lepton universality. Techniques for tagging $\tau \to \pi\nu$ decays and establishing lepton universality violation are developed. We even define two 'mass' variables that could allow us to determine the H^+ mass despite the presence of the two ν's in the $H^+ \to \tau\nu \to \pi\nu\nu$ decay sequence.

Charged Higgs detection will only become difficult if m_{H^+} is very near to m_t. For small $\tan\beta$ we our results imply that $BR(t \to H^+b) \gtrsim 0.05$ is required; for larger $\tan\beta$ values the requirement is even less restrictive — $BR(t \to H^+b) \gtrsim 0.003$ provides a fully viable signal in the $\tau\nu$ channel. These branching ratios limits are employed in the earlier outlined survey paper for the MSSM Higgs bosons (UCD-91-15) in determining the region of the $\tan\beta$–m_{A^0} parameter space in which detection of the H^+ of the MSSM will be possible at the SSC.

15. R. Cruz, B. Grzadkowski, and J.F. Gunion. "$t \to W^+b \to \tau^+\nu_\tau b$ Decays as a Probe of CP Violation in the Charged Higgs Sector", preprint UCD-92-15 (1992), submitted to *Phys. Lett.* **B**.

Beginning with an early paper by Weinberg, it has long been known that CP violation in the charged Higgs sector is only possible for Higgs sectors containing at least three doublets of Higgs fields. However, given current constraints on the mass of the lightest H^+ from LEP ($m_{H^+} \gtrsim 43\,\text{GeV}$), detection of such CP violation is extremely difficult. In this paper, we explore the possibility of detecting CP violation in the charged Higgs sector by looking for a difference between the decay rates for $t \to W^+b \to \tau^+\nu_\tau b$ and $\bar{t} \to W^-\bar{b} \to \tau^-\bar{\nu}_\tau\bar{b}$. CP-violating virtual H^+ exchange interferes with the real W^+ decay, giving rise to such an asymmetry. We perform a realistic study of the feasibility of detecting this asymmetry using the tagging and other detailed techniques developed in the previous paper (UCD-92-14). We conclude that detection of the maximal possible asymmetry is on the verge of being feasible. Probably with 30 fb^{-1} of integrated luminosity at the SSC, it could be done. Should the H^+ be light enough to appear on-shell in $t \to H^+b$ decays, we expect the maximal predicted asymmetry to be measurable even for the canonical $L = 10$ fb^{-1} — a full study is under way. Many interesting and very general subtleties are revealed in our work. In any case, a measurement of the asymmetry could reveal other types of CP violation that are present in such decays, and should certainly be pursued when a large enough sample of top events becomes available.

16. G.H. Trilling *etal.*, including J.F. Gunion, [Solenoid Detector Collaboration], "Technical Design Report for the Solenoidal Detector Collaboration", publication SDC-92-201 (1992).

The TDR for the SDC collaboration hardly needs any general discussion of its importance. However, I wish to point out important contributions made by my group to this report. First, on a general level, I would say that something like one-half to two-thirds of the signals for new physics explored in the TDR had their origination in work performed by me and my collaborators. (In some cases, of course, other groups developed similar ideas independently.) Here, I would like to focus on certain very specific contributions made to the TDR document itself. First is the study with Mangano, later picked up and further elaborated upon by Einsweiler, regarding the impact of electromagnetic calorimeter and muon detector coverages on the $l\gamma\gamma$ signal for an intermediate mass Higgs boson. Second, I continually pushed Einsweiler and others to explore at a detailed simulation level the jet tagging and lepton isolation techniques for extracting a signal from strong WW scattering. Much progress was made in this area, substantially confirming our earlier results obtained using parton level Monte Carlo's. I believe I was the first to emphasize to the collaboration that the SDC was perhaps unique (relative to GEM) in having a strong enough magnetic field and good enough tracking to determine the lepton charge with sufficient precision to avoid contamination of the like-sign signal by the much larger unlike-sign background. This was studied for the TDR by the collaboration and successfully demonstrated. My note, itemized above, regarding calorimeter segmentation led to investigation by my experimental colleagues of a number of the questions I raised — the results form an important component of the TDR physics simulation section. I and collaborators originated the like-sign dilepton technique for detecting heavy gluinos, one of the now canonical gluino signals explored by all detector collaborations; heavy use was made of ideas developed in earlier work performed by myself and Barnett. The $t \to H^+ b$ detection section of the TDR is basically an extract from one of the papers itemized above (UCD-92-14), the $\tau\nu$ section of which was basically the work of my student R. Cruz. Thus, I feel that both directly and indirectly, my group's work played an important, perhaps even pivotal role, in making the TDR such a definitive verification of the physics capabilities of the SDC detector.

J.F. Gunion: Publications/Preprints

1. J.F. Gunion, H.E. Haber, G. Kane and S. Dawson, "The Higgs Hunters Guide", Addison and Wesley (1991), Frontiers in Physics Series, second edition.
2. R.M. Godbole *etal.*, including J.F. Gunion, "New Particle Searches and Structure Functions: Group Report", to appear in *Proceedings of the 'Workshop in High Energy Physics Phenomenology — II'*, Calcutta (January, 1991).
3. D.A. Dicus, J.F. Gunion, L.H. Orr, and R. Vega, "Isolating Purely-Leptonic Signals for Strong W Scattering Using Anti-Tagging, Jet-Tagging and Lepton Isolation", preprint UCD-91-10 (1991), to appear in *Nucl. Phys.* **B**.
4. J.F. Gunion and M. Mangano, "Comments on Higgs Detection in the $WH \to l\nu\gamma\gamma$ Final State", report SDC-91-00057 (1991).
5. J.F. Gunion and L.H. Orr, "Detecting the Higgs Bosons of the Minimal Supersymmetric Model", preprint UCD-91-15 (1991), to be published in *Phys. Rev.* **D**.
6. J.F. Gunion, "Exploring Higgs Bosons/Electroweak Symmetry Breaking Physics at 200 TeV", preprint UCD-91-22 (1991), to appear in *Proceedings of 'QCD at 200 TeV'*, Ettore Majorana Centre for Scientific Culture, INFN Eloisatron Project, Erice, Plenum Publications.
7. J.F. Gunion, R. Bork, H.E. Haber, and A. Seiden, "Searching for CP-Even Higgs Bosons of the Minimal Supersymmetric Model at Hadron Supercolliders", preprint UCD-91-29 (1991), to appear in *Phys. Rev.* **D**.
8. J.F. Gunion, H.E. Haber, and C. Kao, "Searching for the CP-Odd Higgs Boson of the Minimal Supersymmetric Model at Hadron Supercolliders", preprint UCD-91-32 (1991), to appear in *Phys. Rev.* **D**.
9. J.F. Gunion, 'Notes and Questions Regarding Effects of Calorimeter Segmentation Options on Important Physics', private communication to SDC Collaboration.
10. A. Brignole, J. Ellis, J.F. Gunion, M. Guzzo, F. Olness, G. Ridolfi, L. Roszkowski, and F. Zwirner, "Higgs Bosons in the Minimal Supersymmetric Extension of the Standard Model", preprint (1991), to appear in *Proceedings of the Workshop on "e^+e^- Linear Colliders at 500 GeV: the Physics Potential"*, Saariselka, Finland.
11. J.F. Gunion, "New Techniques for Higgs Boson Detection", *Proceedings of the 1991 Vancouver Meeting of the Division of Particles and Fields of the APS*, Vancouver, Canada, August 18-22.1991, ed. D. Axen *etal.*, World Scientific, Singapore (1992), p. 378.
12. J.F. Gunion, "Experimental Probes of Higgs Bosons and Electroweak Symmetry Breaking", preprint UCD-92-4 (1992), to appear in *Proceedings of the "International Workshop on Electroweak Symmetry Breaking"*, Hiroshima, Japan (1991), ed. J. Kodaira, World Scientific.
13. J.F. Gunion and B. Grzadkowski, "Detecting CP Violation in $t \to W^+b$ Decays", preprint UCD-92-7 (1992), to appear in *Phys. Lett.* **B**.

14. R.M. Barnett, R. Cruz. J.F. Gunion. and B. Hubbard. "Charged Higgs Bosons at the SSC". preprint UCD-92-14 (1992), submitted to *Phys. Rev.* D.

15. R. Cruz, B. Grzadkowski. and J.F. Gunion. "$t \to W^+b \to \tau^+\nu_\tau b$ Decays as a Probe of CP Violation in the Charged Higgs Sector", preprint UCD-92-15 (1992), submitted to *Phys. Lett.* B.

16. G.H. Trilling *etal.*, including J.F. Gunion, [Solenoid Detector Collaboration], "Technical Design Report for the Solenoidal Detector Collaboration", publication SDC-92-201 (1992).

J.F. Gunion: Invited Talks and Seminars

1. "Studies of Higgs Properties at Supercolliders", Erice INFN Eloisatron Workshop on 'QCD at 200 TeV', June 11-17, 1991, Erice, Sicily.
2. "Summary and Conclusions", U.C. Davis Higgs/Electroweak Symmetry Breaking Workshop, July 1-12, 1991, U.C. Davis.
3. "Higgs Bosons/Electroweak Physics Beyond the Standard Model", Division of Particles and Fields Meeting, Vancouver B.C., August 18-22, 1991.
4. "Back-scattered Laser Beams for Higgs Detection", Workshop on Physics and Experiments with Linear Colliders, September 9-14, 1991, Saariselka, Finland.
5. "Experimental Probes of Higgs Bosons and Electroweak Symmetry Breaking", International Workshop on Electroweak Symmetry Breaking, November 12-15, 1991, Hiroshima, Japan.
6. "Probing New Physics at the Superconducting Supercollider", U.C. Riverside Colloquium, December 5, 1991, U.C. Riverside.
7. "Searching for the Higgs", 1992 Aspen Winter Physics Conference on Elementary Particle Physics, January 12-18, 1992, Aspen, Colorado.
8. "Higgs Bosons in the Minimal Supersymmetric Model", ORSAY Laboratory, February 21, 1992, Orsay, France.
9. "Searching for Higgs Bosons", ORSAY Laboratory, February 21, 1992, Orsay, France.
10. "Searching for Higgs Bosons", Zurich ETH Institute, February 26, 1992, Zurich Switzerland.
11. "Searching for Higgs Bosons", CERN, March 13, 1992, Geneva, Switzerland.
12. "Searching for Higgs Bosons", University of Barcelona, March 23, 1992, Barcelona, Spain.
13. "Searching for the Higgs Boson(s): Standard Model and Beyond", SSC Physics Symposium, April 13-15, 1992, University of Wisconsin, Madison, Wisconsin.

J.F. Gunion: Meetings and Workshops .

1. 17th INFN Eloisatron Project Workshop "QCD at 200 TeV", Ettore Majorana Centre for Scientific Culture, Erice, Sicily.
2. U.C. Davis Workshop on Higgs Bosons/Electroweak Symmetry Breaking, July 1-12, U.C. Davis. Davis, California.
3. Aspen Summer Institute on Tests and Extensions of the Standard Model, July 9-17, 1992, Aspen. Colorado.
4. Division of Particle and Fields 1991 Meeting, August 18-22. 1991, University of British Columbia. Vancouver, B.C.

5. 1992 Aspen Winter Physics Conference on Elementary Particle Physics, January 12-18, Aspen, Colorado.
6. 1992 Moriond Meeting on Electroweak Physics, March 15-21, 1992, Les Arcs, France.
7. SSC Physics Symposium, April 13-15, 1992, University of Wisconsin, Madison, Wisconsin.

J.F. Gunion: Additional Activities *etc.*

1. Organizer of U.C. Davis Workshop on Higgs Bosons/Electroweak Symmetry Breaking, July 1-12, 1991, U.C. Davis, Davis, California.
2. One of many authors of a Letter to the HEPAP Witherell panel regarding physics potential for a next generation e^+e^- Collider.
3. Member of Working Group on the Next Linear Collider, Stanford Linear Accelerator, Sept. 1990 — present.
4. Visiting Scientist, CERN, Geneva, Switzerland, February 1 - March 28, 1992.

Progress Report (J. Kiskis, R. Narayanan, and P. Vranas)

Introduction

The general goal of this research is to further the understanding of non-Abelian gauge fields in nonperturbative regions. We are particularly interested in the interplay of gauge symmetry and vacuum structure.

Some research has also been carried out in the areas of massive field theories in two dimensions and quantum statistical models in one and two dimensions.

Non-Abelian gauge theories are the foundation of the Standard Model. In particular, it is generally accepted that the $SU(3)$ gauge theory of quarks and gluons describes the strong interactions. For those physical processes that are controlled by short-distance interactions and that are relatively insensitive to large-distance effects, the results of perturbative calculations and experiments can be compared quantitatively. For most reactions, this is not the case, because large-distance, nonperturbative effects are important. Confinement is only the most dramatic example; hadronization and strong interaction corrections to weak decays are important, practical issues.

The perturbative calculations that are valid at short distance where the effective coupling is weak require a gauge fixing that obscures to some considerable extent the fundamental role of gauge symmetry. Lattice gauge theory is an approximation that is complementary to continuum perturbation theory in that it maintains manifest gauge invariance while sacrificing Poincaré symmetry. The spacetime symmetry is restored as the correlation length for lattice fields diverges (as measured in lattice units) and the lattice spacing approaches zero (as measured in physical units). This occurs at a second order phase transition. The long-distance, nonperturbative effects are more accessible in the lattice approximation.

Within the framework of lattice gauge theory, one can employ either approximate, analytical methods or a direct attack by numerical simulation. Our work exploits both approaches.

The zero-temperature pure gauge theory has no adjustable parameters. This is part of the reason that it is so difficult to approximate. A study of the theory at finite temperature introduces a parameter T that can be varied in a controlled way so as to probe different aspects of the theory. In particular, confinement, which is apparently present at low temperature, is absent at sufficiently high temperature. A study of the theory as the temperature is changed can yield useful information about the features that distinguish these two phases and thus contribute to an understanding of the vacuum state.

The first completed work is concerned with the screening of static quarks in representations higher than the fundamental. This gives information on the behavior of the gauge field both above and below T_c that is more detailed than that obtained by restricting oneself to the fundamental representation. This work relies heavily on numerical experiments.

The second completed project models the finite-temperature flux tube as a self-interacting random walk. This simple model seems to incorporate some of the nontrivial features of the critical behavior of the gauge theory as $T \rightarrow T_c$ from below.

Three active projects are concerned with $SU(2)$ gauge fields near the finite-temperature phase transition. The first is an analytical approximation developed to give a physical understanding of the value

of the adjoint Wilson line at $T = T_c$ that was computed numerically in the first completed project. The second is a numerical study of the critical properties of a flux model that can be used *above* T_c. The third will check for universality of amplitude ratios associated with the $SU(2)$, finite-temperature phase transition.

The next two sets of projects study models that share many problems and properties with the field theories that are directly related to high energy physics.

One project was completed in the area of exactly solvable massive field theories in two dimensions. A closely related work is now in progress. The goal is to understand conformal field theories away from criticality.

Two projects were completed in the area of quantum statistical mechanics. They deal with the anti-ferromagnetic Heisenberg model in one and two dimensions. The aim is to understand the ground state properties of this model and possibly shed some light into the area of high temperature superconductivity.

1. J. Kiskis. R. Narayanan and P. Vranas. "Random Walks. Critical Behavior. and Finite-Temperature, $SU(2)$, Lattice Gauge Theory", submitted to *Phys. Rev.* **D.**

We develop a flux tube model to improve upon the physical understanding of the $SU(2)$, finite-temperature phase transiton and its associated universality class. In this model, a color flux tube is formed between a static quark and an anti-quark. The flux tube is thought of as a thin string with a certain zero-temperature string tension which is a parameter of the model. The string connecting the two static sources can be of any length and is expected to fluctuate at any finite temperature. Different configurations of the string are weighted with a Boltzmann factor which is proportional to the length of the string.

Previous work in this area neglected the interactions of the string with itself and reduced the problem to that of an unconditional random walk. The result is a second order phase transition with gaussian exponents. This is not quantitatively correct because the lattice $SU(2)$ gauge theory has the nongaussian exponents of the Ising universality class. On the other hand, the flux tube formed between the static sources does have repulsive self interactions.

Model studies of random walks with interactions suggest that the exponent ν describing the vanishing of the string tension at the critical temperature is a product of two exponents ν_p and ν_θ. ν_p is altered by the non-Markov behavior coming from interactions of the walk with itself at intersections. ν_θ is altered by interactions of the walk with a background of loops. In the approximation where all space-like plaquettes are neglected, a random walk representation is developed for the $SU(2)$ lattice gauge theory and it is shown that the walk has both types of interactions.

2. R. Narayanan and R.R.P. Singh "Thermodynamic Properties of Spin-Chains as a Sum Over Contributions from Different Finite Chains", submitted to *Phys. Rev.* **B.**

Finite size studies of quantum spin Hamiltonians have proven very valuable in extracting the thermodynamic properties of the system. At $T = 0$, they have been used to determine the ground state energy, the excitation spectra and various correlation functions of the spin chains, while at finite temperatures they have led to estimates for the internal energy, the specific heat and other thermodynamic quantities. Much of the extrapolation has relied on the assumption that an extensive quantity P_l, for a chain of length l, takes the form $P_l = lp + q$, where p is the bulk density in the thermodynamic limit and q is the contribution from the boundary. A plot of P_l versus l was used to estimate p. In this extrapolation scheme the effects of correlations are ignored. Hence the extrapolation becomes unreliable when the correlation length is comparable to the size of the largest system considered.

In this project we consider a different scheme to obtain the thermodynamic quantities of interest by studying finite chains. It is based on a technique developed orginally for lattice gauge theories. The idea behind this scheme is to express the various thermodynamic quantities for the infinite chain as a sum over contributions associated with increasing length scales. The contribution to a given length scale l, is obtained from the thermodynamic properties for chains with free boundary conditions up to length l ($l + 1$ spins) and it accounts for correlations of that length in the infinite system. This method enables a systematic study of the convergence of various thermodynamic quantities and also in extracting the correlation length.

3. R.R.P. Singh and R. Narayanan, "Dimer versus Twist Order in the J_1-J_2 Model", submitted to *Phys. Rev. Lett.* .

Motivated by the discovery of antiferromagnetism in the insulating phase of high T_c materials and the suggestion that magnetic fluctuations may be central to a microscopic understanding of the high T_c phenomena, there have been several theoretical studies of ground state properties of frustrated square lattice Heisenberg models. Perhaps the simplest of these models is the J_1-J_2 model, with nearest neighbor antiferromagnetic exchange J_1 and the second neighbor exchange J_2. In the classical limit ($S \to \infty$), this model has a 2 sublattice Néel ground state for $J_2/J_1 < 1/2$ and a 4 sublattice Néel

ground state for $J_2/J_1 > 1/2$. At $J_2/J_1 = 1/2$ various states ordered at wave vectors (π, q), or (q, π), become degenerate. Expansion in powers of $1/S$ reveals that the magnetically ordered phases are pushed away from $J_2/J_1 = 1/2$ leaving an intermediate phase with no long range magnetic order. The nature of the ground state in this intermediate phase has been of considerable interest.

Earlier studies of the $1/S$ expansion suggested that the ground state in the intermediate phase was a resonating valence bond state with no long range order. On the other hand stuides based on a large N expansion suggested that the magnetically disordered phase obtained by quantum fluctuations may have long range dimer order, where the nearest neighbor spin correlations alternate in a column pattern. Other suggestions have included twist order as well as chiral order.

In this project we study the 4×4 periodic system at finite temperatures by a complete diagonalization. We study the specific heat, the static structure factors, as well as the squares of dimer and twist order parameters. We find that in the intermediate region around $J_2/J_1 = 1/2$ the specific heat of the system has a peak around a temperature of $0.27J_1$. Near this temperature the square of the bond order parameter, ψ, increases sharply as the temperature is lowered. Between a temperature of $0.5J_1$ and $0.1J_1$ it increases by roughly a factor of 2.5. The zero temperature value of ψ is roughly 0.4 times that of a fully dimerized state. This is a clear evidence for enhancement of dimer order. In contrast, the square of the twist order parameter, ϕ, does not show any significant enhancement with respect to the infinite temperature value. The only structure is a maximum increase of about twenty percent between $T = \infty$ and $T \approx 0.27J_1$, which is followed by a decrease as the temperature is further lowered. Hence, there is no indication of twist order at $T = 0$.

4. R. Narayanan and C.A. Tracy, "Holonomic Quantum Field Theory of Bosons on a Poincaré Disk and the Zero Curvature Limit", to appear in *Nucl. Phys.* **B**.

Conformal field theory tells us a great deal about correlation functions of critical, or equivalently massless, 2D quantum field theories. On the other hand, progress in correlation functions for *massive* 2D quantum field theories has been restricted to a smaller class of models. The most general methods presently available are those coming from the theory developed by Sato, Miwa, and Jimbo (SMJ) called *Holonomic Quantum Fields*. The most important special case of their theory is the massive Ising field theory on $\mathbf{R}^2$. One direction to pursue to enlarge the class of solvable, massive 2D quantum field theories, is to construct holonomic quantum field theories on two-dimensional manifolds other that $\mathbf{R}^2$. Since the hyperbolic plane is the universal covering space for Riemann surfaces of genus greater than one, it is natural to first extend the SMJ analysis to massive Klein-Gordon and Dirac operators on the hyperbolic plane. It is the purpose of this project to establish a detailed connection between the Euclidean results of SMJ and the hyperbolic results for the Klein-Gordon equation. The corresponding results for the Dirac case is currently under study.

The hyperbolic plane can also be modeled by the Poincaré disk of radius R, $\mathbf{D}_R$. In this model the curvature of the manifold is $-(2/R)^2$. This then is a convenient model to analyze the limit of zero curvature, or equivalently, $R \to \infty$. We show that the results associated with monodromy preserving deformation of the Klein-Gordon equation found in the work of SMJ can be obtained as the limiting case of the corresponding results on $\mathbf{D}_R$. It is interesting to note that the analysis on $\mathbf{D}_R$ is in some sense nicer than the Euclidean case, i.e. irregular singularities in $\mathbf{R}^2$ get replaced with regular singularities in $\mathbf{D}_R$, and the irregular singularities arise as a confluence of regular singularities as $R \to \infty$. This point was also observed by Atiyah while working on the problem of monopoles. The closed one form ω associated with the deformation equations is discussed. The importance of ω is that locally it is $d \log \tau$ where the τ function is precisely the n point function for certain interacting bosons defined on $\mathbf{D}_R$. The results are carefully analyzed and it is shown in detail that the theory developed by Sato, Miwa and Jimbo on the Euclidean plane is a limiting case of the corresponding theory on the Poincaré disk. The limiting procedure actually turns out to be quite subtle.

5. J. Kiskis. "Behavior of Higher Representation Wilson Lines in Finite-Temperature, $SU(2)$, Lattice Gauge Theory", *Phys. Rev.* **D41** (1990) 3204.

This project was a Monte Carlo numerical simulation of finite-temperature, $SU(2)$, pure gauge theory. The response of the gauge field to static color sources in representations $J = \frac{1}{2}$, 1, and $\frac{3}{2}$ was studied.

First P. Damgaard and then K. Redlich and H. Satz reported the intriguing numerical result that the expectation value of a source (Wilson line) in representation J is proportional to the expectation value of the fundamental line ($J = \frac{1}{2}$) raised to the power $2J$:

$$\langle L_J \rangle \propto \left\langle L_{\frac{1}{2}} \right\rangle^{2J} . \tag{1}$$

Although Damgaard showed that a mean field approximation can give this result, it is very difficult to understand how it can hold in the critical region where mean field theory is certainly not valid.

The relation (1) says that the gauge theory in the deconfined phase responds to a J source as if it were $2J$ sources with $J = \frac{1}{2}$. This would be a surprising result since it is believed that the confined phase system responds very differently to $J = \frac{1}{2}$ sources which are confined ($\left\langle L_{\frac{1}{2}} \right\rangle = 0$) and adjoint sources which can be screened by the field ($\langle L_1 \rangle \neq 0$).

My work adds to previous results in two ways. First, there are some theoretical predictions. One approach is based on a flux tube model of the deconfined phase. It leads to $\langle L_1 \rangle \rightarrow$constant and $\langle L_{3/2} \rangle \propto \langle L_{1/2} \rangle$ as $T \rightarrow T_c^+$. The other approach exploits the connection through universality with $(\phi^4)_3$ field theory and gives these predictions with additional corrections.

Then some Monte Carlo results are presented. The data are consistent with my theoretical predictions while the mean field result is excluded close to T_c. These data differ from previous results in that they were taken at smaller values of $(T - T_c)/T_c$.

In summary, this work indicates that even above T_c one can understand the $T \rightarrow T_c^+$ gauge field in simple terms. The dynamical field screens higher representation static color sources so that integer representations are completely screened while half-integer representations are screened to behave like $J = 1/2$ fundamental sources.

The numerical work was done on a VAXstation II at UCD and on the CRAY-2's at NMFECC. All are supported by DOE.

J.E. Kiskis, R. Narayanan, and P. Vranas:
Publications/Preprints

1. J. Kiskis, R. Narayanan and P. Vranas, "Random Walks, Critical Behavior, and Finite Temperature, SU(2) Lattice Gauge Theory", submitted to *Phys. Rev.* **D.**
2. R. Narayanan and R.R.P. Singh, "A Finite Lattice Expansion for Quantum Spin-Chains", submitted to *Phys. Rev.* **B.**
3. R.R.P. Singh and R. Narayanan, "Dimer versus Twist Order in the J_1-J_2 model", submitted to *Phys. Rev. Lett.*
4. R. Narayanan and C. Tracy, "Holonomic Quantum Field Theory of Bosons in the Poincaré Disk and the Zero Curvature Limit", to appear in *Nucl. Phys.* **B.**
5. J. Kiskis, "Behavior of Higher Representation Wilson lines in Finite-Temperature, SU(2), Lattice Gauge Theory", *Phys. Rev.* **D41**, 3204, (1990).

J.E. Kiskis, R. Narayanan, and P. Vranas:
Invited Talks and Seminars

1. J. Kiskis, "Behavior of Higher Representation Wilson Lines in Finite Temperature, SU(2), Lattice Gauge Theory", DPF90, Houston, January 1990.
2. R. Narayanan, "Flux Tube Model for the $SU(2)$ Deconfining Phase Transition", DPF90, Houston, January 1990.
3. P. Vranas, "A Technique for Analytical Calculation of Observables in Lattice Gauge Theories", LATTICE '89 Capri, Italy, September 1989.

Progress Report (J. Kiskis and S. Staniford-Chen)

The first completed work is closely related to the flux tube model for the finite-temperature phase transition. We have been able to correlate certain physical properties of an interacting random walk with the critical exponent for the vanishing string tension at the deconfining phase transition.

The second completed project explores the connection between the finite- temperature quantum gauge field and a classical statistical system at criticality. Universality relates the important properties of the two systems. The comparison of supposedly universal functions is a tough test for these ideas.

Two active projects are concerned with $SU(2)$ gauge fields near the finite-temperature phase transition. The first is an analytical approximation developed to give a physical understanding of the value of the adjoint Wilson line at $T = T_c$ that was computed numerically in earlier work. The second is a numerical and analytical study of the critical properties of a flux model that can be used above T_c

The third proposed work will explore a different direction. The low momentum structure of hadrons is experimentally important but not accessible in ordinary perturbative calculations. In particular, it is not currently possible to calculate the form of the structure functions. Numerical simulations applied to lattice gauge theory can address the issue, but it is quite demanding of computational resources. A particularly interesting topic of impending experimental importance is the power of the small x behavior of the gluon structure function. In a new project, we are engaged in feasibility studies for Monte Carlo calculations that bear on this issue.

The project above and many others are limited by the practical matter of finite computer resources. Algorithms that can use the existing resources more effectively are welcome. One big problem is the critical slowing down caused by growing correlation lengths. The multigrid approach promises to give substantial relief in that area. Our fourth proposed project will study and develop this new technique.

The following two projects are essentially complete but not yet written-up.

1. J. Kiskis, R. Narayanan, and P. Vranas, "Random Walks and Critical Exponents in Quantum Field Theory".

In the flux tube model of the SU(2), finite-temperature phase transition, a tube of color electric flux is formed between a static quark and an anti-quark. The deconfining phase transition occurs when the entropy of the fluctuations of the tube overcomes the energy cost of adding to the length of the tube. Early work on this model neglected the interactions of the tube with itself and with background loops of flux. This simple picture of a free random walk of flux correctly predicts that the transition is second order but incorrectly gives gaussian critical exponents. In previous work, we stressed that an improved physical picture which includes both interactions of the tube with itself and with the background loops is needed in order to understand the correct, nontrivial exponents. We showed that the exponent ν associated with the divergence of the correlation length is the ratio of an exponent related to the energy cost per step and the Hausdorff dimension of the walk.

In this work, we have investigated the problem in more detail in the context of quantum field theories that are related to the gauge theory by universality. On one hand, field theories can be given a random walk representation that provides an interesting physical picture that is complementary to textbook treatments. On the other hand, the calculations of critical exponents in field theory are not very illuminating. We have been able to establish a connection between these two approaches that associates with the exponents some physical intuition. If the random walk had only short-range, repulsive self interactions, the exponent ν would be the inverse of the Hausdorff dimension of a self avoiding walk - about 0.59. For a free walk, the value is 0.5, but the "correct" answer is 0.63. Including the effects of the background loops lowers the strength of the self interaction and increases the dimension of the walk. However, as the field goes critical the background loops have singular behavior, and the energy per step of the walk is not analytic in the bare mass. We have been able to identify this additional nonanalyticity with the crossover exponent that is discussed for other reasons in the context of the critical behavior of statistical systems. The exponent ν is then the ratio of the crossover exponent and the dimension of the self-interacting walk. The result is a physical understanding of the exponent ν and of the crossover exponent.

Now, upon returning to the gauge theory, we can give the numerical values for the Hausdorff dimension of the color flux tube when considered on different length scales. This is a nice improvement in our physical understanding of the deconfinement phase transition.

2. J. Kiskis and S. Staniford-Chen. "Universal Functions of Finite-Size Effects in the SU(2), Finite-Temperature Phase Transition".

The pure glue, $SU(2)$, finite-temperature, deconfining phase transition is second order. In the renormalization group picture, second order transitions are divided into universality classes. The $SU(2)$ transition is in the universality class of the three dimensional Ising model. Transitions in the same class have many common properties. The critical exponents that describe the singular behavior of observables are the same and have been extensively studied. Among high energy physicists, it is not as well known that there are also universal amplitudes and functions. In this project, we have studied the universality of functions associated with finite-size scaling.

Methods developed in the context of critical phenomena are applied to the gauge theory phase transition. Using published[14] Monte Carlo data, we can extract numerical results for some of these universal functions. As a stringent test of universality, they can be compared with Ising model numerical results and with quartic scalar field theory ϵ expansions. There is qualitative and rough quantitative agreement. However, there are some definite quantitative discrepancies. The systematic trends in these suggest that some of the data are not close enough to the critical point.

To the extent that the comparisons are satisfactory, they confirm and deepen our understanding of the gauge theory and its relationship to statistical systems. However, the quantitative missmatches serve to remind use that even our most ambitious numerical simulations suffer from inadequacies.

J.E. Kiskis: Publications/Preprints

1. J. Kiskis, 'Behavior of Higher Representation Silson Lines in Finite-Temperature, $SU(2)$, Lattice Gauge Theory", *Proceedings of the 1990 Meeting of the Division of Particles and Fields of the American Physical Society,* Rice University, Editors B. Bonner and H. Miettinen, World Scientific, Singapore (1990).

2. J. Kiskis, R. Narayanan, and P. Vranas, "Random Walk, Critical Behavior, and Finite-Temperature $SU(2)$ Lattice Gauge Theory", *Proceedings of the 1990 Meeting of the Division of Particles and Fields of the American Physical Society*, Rice University, Editors B. Bonner and H. Miettinen, World Scientific, Singapore (1990).

Progress Report (J. Kiskis and S. Staniford-Chen)

The first completed work is closely related to the flux tube model for the finite-temperature phase transition. We have been able to correlate certain physical properties of an interacting random walk with the critical exponent for the vanishing string tension at the deconfining phase transition. In addition, the Hausdorff dimension of the flux tube is computed.

The second and third completed projects explore the connection between the finite-temperature quantum gauge field and a classical statistical system at criticality. Universality relates the important properties of the two systems. The comparison of supposedly universal functions is a tough test for these ideas.

Two active projects are concerned with $SU(2)$ gauge fields near the finite-temperature phase transition. The first is an analytical approximation developed to give a physical understanding of the value of the adjoint Wilson line at $T = T_c$ that was computed numerically in earlier work. The second is a numerical and analytical study of the critical properties of a flux model that can be used *above* T_c. The third proposed work expands the application of universal scaling functions to other field theories.

The fourth proposed work will explore a different direction. The low momentum structure of hadrons is experimentally important but not accessible in ordinary perturbative calculations. In particular, it is not currently possible to calculate the form of the parton distribution functions. A particularly interesting topic of impending experimental importance is the power of the small x behavior of the gluon distribution function. We are exploring the applicability of nonperturbative methods to this problem.

1. J. Kiskis, R. Narayanan, and P. Vranas, "Random Walks and the Correlation Length Critical Exponent in Scalar Quantum Field Theory", submitted to *Phys. Rev.* **D.**

This project was nearly complete when last year's proposal was written. Since then, we have made some technical improvements, and prepared the paper for publication.

Last year's proposal gave a detailed discussion, so we can be brief here. There are two main results. One is a physical understanding of the correlation length exponent in the interacting random walk formalism. As a result, the correlation length exponent is expressed as the ratio of a crossover exponent and the dimension of the self-interacting walk. The other is the numerical values for the Hausdorff dimension of the color flux tube when considered on different length scales. This is a nice improvement in our physical understanding of the deconfinement phase transition.

2. J. Kiskis, "Universal Amplitude Ratios and Functions for the $SU(2)$, Finite-Temperature Phase Transition", *Phys. Rev.* **D** (in press).

This project was also nearly complete when last year's proposal was written. Since then, we have presented the results in a talk at the DPF meeting in Vancouver and written the paper, which has been accepted for publication in *Phys. Rev.* **D.**

We can again be brief. This paper has introduced a broad class of universal functions and amplitudes for use in understanding the $SU(2)$, finite-temperature, deconfining phase transition and its relation to statistical systems, where these quantities have already been studied in some detail.

3. S. Staniford-Chen, "Finite-size Scaling Surfaces in $SU(2)$ Lattice Gauge Theory and ϕ^4 Field Theory", preprint UCD-92-17.

It has been believed for a while that the effective theory of the Wilson lines in $SU(2)$ lattice gauge theory is in the same universality class as the Ising Model. The exponents have been checked with modest accuracy to be the same. We had earlier made attempts to check that other universal quantities such as amplitude ratios were the same. We had only moderate success.

In trying to understand the source of the systematic errors in our earlier procedures, we came up with an entirely new procedure for comparing different models. We were able to apply it to a comparison of $SU(2)$ with three-dimensional ϕ^4 field theory, which should be in the same universality class. The results were very satisfactory, and we believe provide significant new evidence that the $SU(2)$ model is in the Ising class. The method could also be used to make comparisons between models in other circumstances, and we believe it could be useful to other workers, both in particle physics and in condensed matter physics.

The essential result that we established was as follows: Take a physical system (let us say a piece of iron) near it's critical point, and then measure some property of it (let us say the magnetization). Now, provided the system is finite, the measurement will not give the same answer every time it is performed because of thermal fluctuations. So, instead, the values of the magnetization found in repeated experiments will be drawn from some probability distribution. The shape of this distribution will be a function of the temperature of the system, and also of the physical size of the sample. In the thermodynamic limit, the distribution will become a delta-function at the value of the observable for the infinite system, but finite systems will have the delta-function softened, to greater or lesser degrees, into a smooth function. What we showed is that the histograms for different lengths and temperatures can all be related to each other by a scaling form. To put the same thing a different way, they can all be simply rescaled into a single smooth surface. These results apply in principle to actual experimental data, but our use for them was in the context of Monte Carlo simulations of statistical systems.

Our claim was established theoretically from renormalization group arguments and confirmed by an investigation of simulation data in both models discussed. The surfaces for the two models were then compared and found to be the same within errors. This provides good evidence for the view that the models are in the same universality class.

4. J. Kiskis and P. Vranas, "$SU(2)$ Adjoint Wilson Line at T_c".

This is a continuing project. The progress that we have made in the past year is included in the description under point 1 of our "Proposed Research and Active Projects"

J.E. Kiskis and S. Staniford-Chen: Publications/Preprints

1. J. Kiskis and S. Staniford-Chen, "Universal Amplitude Ratios and Functions for the $SU(2)$, Finite-Temperature Phase Transition", *The Vancouver Meeting, Particles and Fields '91*, Editors D. Axen, D. Bryman, and M. Comyn, World Scientific, Singapore (1992).
2. J. Kiskis, "Universal Amplitude Ratios and Functions for the $SU(2)$, Finite-Temperature Phase Transition", *Phys. Rev.* **D** (in press).
3. J. Kiskis, R. Narayanan, and P. Vranas, "Random Walks and the Correlation Length Critical Exponent in Scalar Quantum Field Theory", submitted to *Phys. Rev.* **D**.
4. S. Staniford-Chen, "Finite-size Scaling Surfaces in $SU(2)$ Lattice Gauge Theory and ϕ^4 Field Theory", preprint UCD-92-17.

J.E. Kiskis: Invited Talks and Seminars

1. J. Kiskis, "Universal Amplitude Ratios and Functions for the $SU(2)$, Finite-Temperature Phase Transition", at the Vancouver Meeting, Particles and Fields, August, 1991

J.E. Kiskis: Meetings and Workshops

1. The Vancouver Meeting, Particles and Fields '91, August 18-22, 1991

Progress Report (L. Orr)

1. Lynne H. Orr and W.J. Stirling, "The Longitudinal Structure Function at Small x: the Effect of Next-to-Leading Order QCD Corrections and Heavy Flavor Thresholds", *Phys. Rev. Lett.* **66** (1991) 1673.

The behavior of the distribution of gluons inside the proton at small momentum fraction x is of great interest to high energy physics for several reasons. Many processes at high energy hadron colliders such as the SSC are dominated by small x gluons, and so it is necessary to know the gluon distribution in order to make accurate predictions for such experiments. There are now indications from QCD that the gluon distribution may be more singular at small momentum fraction x than is usually assumed. Measurements of the longitudinal structure function F_L at the *ep* collider HERA will probe the gluon distribution function at smaller values of x than has been possible in experiments up to now. These measurements should be able to distinguish between the standard and more singular behavior of the gluon distribution; however, this could be spoiled if higher order QCD corrections are too large. We studied the effects of next-to-leading order QCD corrections and heavy quark thresholds on predictions for F_L at HERA with both standard and singular gluon distributions at low x. We found that the corrections are small (and in particular are smaller than the expected measurement uncertainties), so that the relationship between F_L and the gluon distribution is preserved, and the standard and singular gluon distributions are still expected to be distinguishable at HERA. Thus we can remain confident that measurements at HERA will shed some light on QCD and the gluon distribution at small x. Our results have been published in *Physical Review Letters*. I continue to be interested in the subject of the gluon distribution, and I expect to become involved again as HERA experiments progress, through contact with experimentalists here at UC Davis who are members of the H1 collaboration.

2. Lynne H. Orr, "Decay versus Hadronization of Top Quarks Produced in Hadron Colliders", University of Chicago preprint EFI-90-78, *Phys. Rev.* **D** to be published.

Current limits place the top quark mass in the range where top's weak lifetime is comparable to typical time scales for hadronization. Thus a top quark, once produced, may decay before it has time to form a meson. In modeling top physics, whether for the top search at the Fermilab Tevatron or for experiments at the SSC where top provides enormous backgrounds to other physics of interest, one would like to know whether it is necessary to take hadronization into account. I addressed this question for top quarks produced in hadron colliders in an extension of previous work done in collaboration with J.L. Rosner. I compared the time scales for decay and hadronization for hadronically produced top quarks to determine for what top masses and momenta non-perturbative QCD effects are likely to appear before the top quark decays. I found that while top mesons are not necessarily expected to form, some hadronization effects can appear at the Tevatron up to masses of about 150 GeV; beyond that it is safe to neglect hadronization. My results for the SSC show that, because of the higher beam energies, hadronization effects can extend to higher masses; however, this may be modified substantially by higher order corrections. My results will be published in *Phys. Rev.* **D**. I am presently studying the perturbative side of the top fragmentation/decay interplay; see below.

L. Orr: Publications/Preprints

1. Lynne H. Orr and W.J. Stirling, "The Longitudinal Structure Function at Small x: the Effect of Next-to-Leading Order QCD Corrections and Heavy Flavor Thresholds", *Phys. Rev. Lett.* **66** (1991) 1673.
2. Lynne H. Orr. "Decay Versus Hadronization of Top Quarks Produced in Hadron Colliders", University of Chicago preprint EFI-90-78. *Phys. Rev.* **D** to be published.

Progress Report (L. Orr)

1. D.A. Dicus, J.F. Gunion. L.H. Orr, and R. Vega, "Isolating Purely-Leptonic Signals for Strong W Scattering Using Anti-Tagging, Jet-Tagging and Lepton Isolation", preprint UCD-91-10 (1991), to appear in *Nucl. Phys.* **B.**

Chances for success of the physics program at the SSC are greatly increased if it can be demonstrated that the possible scenarios for electroweak symmetry breaking give rise to detectable signals in SSC experiments. One class of scenarios involves strong couplings in the electroweak symmetry breaking (EWSB) sector of the theory, which could result from a very massive Higgs boson or from some as-yet-unknown EWSB sector dynamics. These strong couplings would appear as an enhancement in the scattering of the longitudinal components of vector bosons, and thus longitudinal W scattering would be a useful probe of a strongly interacting EWSB sector. For this to be possible one must be able to distinguish the process of interest from the large backgrounds due to scattering of transverse W's as well as other SM processes such as top production. Extending previous work of Dicus, Gunion, and Vega, we have studied the scattering of like-sign W's and the like-sign lepton pairs resulting from their decays. We have shown that it is possible, through a combination of kinematic cuts, to reduce backgrounds to manageable levels while retaining a detectable signal at the SSC. Our emphasis is on the SSC, but we also performed calculations for the proposed European proton colliders LHC and Eloisatron.

2. J.F. Gunion and L.H. Orr, "Detecting the Higgs Bosons of the Minimal Supersymmetric Model", preprint UCD-91-15 (1991), to be published in *Phys. Rev.* **D.**

For various theoretical reasons, the Standard Model of elementary particle physics is not completely satisfying, especially in the Electroweak Symmetry Breaking sector. An attractive alternative is the Minimal Supersymmetric Model (MSSM). (It has become even more attractive in light of recent results from the CERN e^+e^- collider LEP that show coupling constant unification to be possible in the context of the MSSM.) There are four physical Higgs bosons in the MSSM, and the theory predicts at tree level that at least one of them can be detected at the e^+e^- collider LEP II. However, recent calculations of radiative corrections show that, for some values of the MSSM parameters, even the lightest MSSM Higgs (h^0) can be too heavy for LEP II and must be sought at high energy hadron colliders such as the SSC. In that case, the h^0 (and possibly the other Higgses) will be in the "Intermediate Mass Region," where detection can be difficult. In our study we showed that by exploiting mechanisms that are known to be successful for the Standard Model Higgs (especially production in association with $t\bar{t}$ pairs and decays to two photons), the MSSM Higgs bosons would have observable signals at either the SSC or at the electron-positron collider LEP-II for nearly all values of the MSSM parameters. Thus the detectability of the MSSM Higgses is very nearly restored.

3. V. A. Khoze, W. J. Stirling, and L. H. Orr, "Soft Gluon Radiation in $e^+e^- \to t\bar{t}$," University of California, Davis preprint UCD-92-05 (1992), to be published in *Nucl. Phys.* **B**; and L. H. Orr, V. A. Khoze, and W. J. Stirling, "Gluon Radiation in Top Quark Production and Decay," presented at the XXVIIth Rencontres de Moriond, Les Arcs, France, March 22-28, 1992, University of California, Davis preprint UCD-92-10 (1992), proceedings to be published by World Scientific.

The large mass of the top quark leads to a large weak decay width and a lifetime comparable to strong interaction time scales. This, in turn, leads to the possibility of interplay between the strong and weak interactions of the top quark. I have studied the nonperturbative side of this question (decay vs. fragmentation) in previous work; here we studied the perturbative side. Typically (e.g. in Monte Carlo simulations), one treats heavy quark production and decay independently, and radiation of a gluon can be handled as a correction either to production or to decay. In the top case, however, the two processes may interfere and so should not be treated independently. We showed that such interference can occur and we studied its effects on the distribution of soft gluons in $e^+e^- \to t\bar{t}$. In particular, we

showed that the radiation pattern can be sensitive to the top quark width. This suggests a possible way to measure the top width; because it is so large, the usual methods are much more difficult than for the lighter quarks.

L. Orr: Publications/Preprints

1. D.A. Dicus, J.F. Gunion, L.H. Orr, and R. Vega, "Isolating Purely-Leptonic Signals for Strong W Scattering Using Anti-Tagging, Jet-Tagging and Lepton Isolation", preprint UCD-91-10 (1991).
2. L. H. Orr, "Strong W Scattering as a Probe of a Strongly Interacting Electroweak Symmetry Breaking Sector", *Proceedings of the Vancouver Meeting of the Division of Particles and Fields of the APS.* Vancouver, Canada, Aug. 18-22, 1991, ed. D. Axen *et al.*, World Scientific, Singapore (1992), p. 791.
3. J.F. Gunion and L.H. Orr, "Detecting the Higgs Bosons of the Minimal Supersymmetric Model", preprint UCD-91-15 (1991), to be published in *Phys. Rev.* **D**.
4. V. A. Khoze, W. J. Stirling, and L. H. Orr, "Soft Gluon Radiation in $e^+e^- \to t\bar{t}$," University of California, Davis preprint UCD-92-05 (1992), to be published in *Nucl. Phys.* **B**.
5. L. H. Orr, V. A. Khoze, and W. J. Stirling, "Gluon Radiation in Top Quark Production and Decay," presented at the XXVIIth Rencontres de Moriond, Les Arcs, France, March 22-28, 1992, University of California, Davis preprint UCD-92-10 (1992), proceedings to be published by World Scientific.

L. Orr: Invited Talks and Seminars

1. "Isolating Purely-Leptonic Signals for Strong W Scattering Using Anti-Tagging, Jet-Tagging, and Lepton Isolation," presented at the Workshop on Higgs Physics at Supercolliders, Davis, CA, July 1991.
2. "Strong W Scattering as a Probe of a Strongly Interacting Electroweak Symmetry Breaking Sector," presented at the 1991 Meeting of the Division of Particles and Fields of the American Physical Society, Vancouver, Canada, Aug. 1991.
3. "Two Topics in Higgs Searches at the SSC," presented at the SSC Fellows Meeting, SSC Lab, Dallas, TX, Nov. 1991.
4. "Gluon Radiation in Top Quark Production and Decay," presented at the XXVIIth Rencontres de Moriond, Les Arcs, France, March 1992.
5. "Closing in on the SUSY Higgses: $\gamma\gamma$ Signals," presented at the SSC Physics Symposium, Madison, WI, April 1992.
6. "Minimal SUSY Higgs Bosons at Future Hadron Colliders," presented at Physics Beyond the Standard Model III, Ottawa, Canada, June 1992.
7. Seminars at University of Durham, University of California at Los Angeles, University of Chicago, and Argonne National Laboratory.

L. Orr: Meetings and Workshops

1. Higgs/Electroweak Symmetry Breaking Physics Workshop, University of California at Davis, Davis, CA, July 1991.
2. Meeting of the Division of Particles and Fields of the American Physical Society, August 18-22, 1991, Vancouver, Canada.
3. SSC Fellows Meeting, SSC Laboratory, Dallas, TX, Nov. 1991.
4. Visiting Researcher, University of Durham, Durham, England, January 1992.
5. XXVIIth Rencontres de Moriond, Les Arcs, France, March, 1992.
6. SSC Physics Symposium. University of Wisconsin, Madison, WI, April 1992.
7. Physics Beyond the Standard Model III, Carleton University, Ottawa, Canada. June 1992. Convener, session on SSC/LHC Physics.

Progress Report (R. Kauffman)

1. S. Dawson and R.P. Kauffman, "Production Rates for Higgs Bosons Plus Multiple Jets at the Superconducting Super Collider", *Phys. Rev. Lett.* **68** (1992) 2273; and R.P. Kauffman, "Higher-Order Corrections to Higgs-Boson p_T", *Phys. Rev.* **D45** (1992) 1512.

The production of Higgs bosons in hadron collisions is dominated by the gluon fusion mechanism for Higgs masses below about 500 GeV. Since over much of this range the Higgs signal is weak (especially for $M_H < 2M_Z$) it is important to perform accurate calculations of the production distributions of the Higgs boson, in rapidity, transverse momentum, etc. The perturbative calculation of the transverse momentum distribution of Higgs bosons produced in gluon fusion is disrupted at small p_T ($p_T \ll M_H$) by the appearance of large logarithms. Each successive order in perturbation theory, instead of being suppressed by an additional power of α_s, is suppressed by $\alpha_s log^2(M_H^2/p_T^2)$ so that if p_T is small enough higher order terms become important. The Collins-Soper formalism allows the resummation of the higher order terms at small p_T. My recent work has been to incorporate the virtual corrections (calculated by Djouadi *et al* and Dawson) into this framework. By comparing the resummed form of the p_T distribution to the perturbative form I derived the so-called "coefficient functions" producing a resummed p_T distribution normalized to next-to-leading order in α_s

R. Kauffman: Publications/Preprints

1. S. Dawson and R.P. Kauffman, "Production Rates for Higgs Bosons Plus Multiple Jets at the Superconducting Super Collider", *Phys. Rev. Lett.* **68** (1992) 2273.
2. R.P. Kauffman, "Higher-Order Corrections to Higgs-Boson p_T", *Phys. Rev.* **D45** (1992) 1512.

R. Kauffman: Meetings and Workshops

1. SSC Physics Symposium, University of Wisconsin, Madison, WI, April 1992.

Progress Report (José Wudka)

1. "Higgs triplets in the standard model" (with J.F. Gunion and R. Vega) *Phys. Rev.* **D42** (1990).

The possibility of spontaneous symmetry breaking being produced by "exotic" Higgs representations was investigated in detail for the case of a model originally proposed by Georgi and Machacek (*Nucl. Phys.* **B262** (1985) 463). This model is constructed in such a way that the tree level value of the ρ parameter ($= m_W/(m_Z c_W)$) is equal to one: moreover the structure of the scalar sector is such that some of the scalars do not couple to fermions. These properties, together with the possible phenomenological relevance of this model, are studied in detail in our paper. We consider as well the possibility of detection of the new scalars present in this model and the expected discrepancies with respect to the standard model. The question of the naturalness (in the technical sense) of the model is also discussed.

2. "Adiabatic evolution of quantum mechanical systems" (with J. Vidal), U.C. Davis preprint UCD-89-22, submitted to *Nucl. Phys.* **B**.

In recent years, with the important remarks of Berry (*Proc. Roy. Soc., London* **A392** (1984) 45), the relevance of the adiabatic phases in a variety of fields of physics has been clarified. In this paper we present a discussion of the exact time evolution operator within the adiabatic approximation. Next we study the corrections to this approximation. While these cannot be evaluated in general, for the case of a quantum system interacting with rapidly varying external (classical) fields of arbitrary amplitude, we are able to calculate, to a very good approximation, all these corrections. Moreover, whereas in the case were the amplitude of the external fields is small the effects are irrelevant, in the case were the external fields are strong the effects are important and in fact will induce transitions which would otherwise be strongly suppressed.

3. "Screening of heavy Higgs radiative corrections", contributed paper to the International Europhysics Conference on High Energy Physics, Madrid (Spain), Sept 6–13 (1989).

In this paper I report the results of a collaboration, with M. Einhorn, where we studied the radiative effects of a heavy Higgs on low energy measurements. Our aim was to generalize Veltman's screening theorem for the standard model. We were able to state precisely such a theorem and to identify it as a renormalization effect; we provided also a proof to all orders in perturbation theory. As a spinoff of the calculation, we devised gauge–fixing conditions which have proved useful in other areas, such as detailed studies of the equivalence theorem.

4. "A comment on the Born–Oppenheimer approximation", *Phys. Rev.* **D41** (1990) 712.

In this brief note I have studied the applications of Berry's ideas to the concrete problem of the Born–Oppenheimer approximation. This approximation is not directly related to the definition of the adiabatic approximation used in connection with the topological phases. In fact, to relate the two approximations, a higher order correction must be calculated in the adiabatic approximation; as another product of the calculation I was able to quantify the accuracy of the Born–Oppenheimer approximation.

J. Wudka: Publications/Preprints

1. "Higgs triplets in the standard model" (with J.F. Gunion and R. Vega) *Phys. Rev.* **D42** (1990)
2. "Adiabatic evolution of quantum mechanical systems" (with J. Vidal), Univ. of Calif. at Davis preprint UCD–89–22, submitted to *Nucl. Phys.* **B**.
3. "Screening of heavy Higgs radiative corrections", contributed paper to the International Europhysics Conference on High Energy Physics, Madrid (Spain), Sept 6–13 (1989).
4. "A comment on the Born–Oppenheimer approximation", *Phys. Rev.* **D41** (1990) 712.

J. Wudka: Invited Talks and Seminars

1. "Solar neutrinos and the Sun's magnetic field ", Univ. of California, Riverside, Jan. 1990.
2. "On the adiabatic approximation", Universitat de València, València, Spain, Sept. 1989.
3. "Screening of heavy Higgs radiative effects", Univ. Autónoma de Barcelona, Barcelona, Spain, Sept. 1989.
4. "Introduction to Berry's phase", Instituto de Física, Universidad Nacional Autónoma de México, México, D.F., June 1989.

Progress Report (Ling-Lie Chau) (Earlier papers are included for reference.)

Two-body charm meson decays were analyzed in the general framework of the quark-diagram scheme. See Fig. 1. Several conclusions were drawn.

$D \to VP$ Decays: By analyzing the data of charm meson to vector pseudoscalar $D \to VP$ decays, using the quark diagram scheme we reach the following conclusions. For details, see Chau's publications.

1. To satisfactorily describe $D \to \bar{K}^* \pi$ decays, the consideration of final-state interactions is inevitable. Without such effects the prediction of $D \to \bar{K}^* \pi$ rates will be off by at least two standard deviations.

2. The data also implies the importance of W-annihilation in $D_s^+ \to VP$.

3. Perturbative QCD calculations always give $|\mathcal{A}'| > |\mathcal{B}'|$ due to the color suppression in the internal W-emission diagram $\mathcal{B}'$. The experimental fact that $|\mathcal{A}'| < |\mathcal{B}'|$ clearly indicates the importance of nonperturbative effects (e.g., soft-gluon exchange). The decay rates of some color-mismatched channels, e.g., $D^0 \to \omega \bar{K}^0$, $\phi \bar{K}^0$, $\pi^0 \bar{K}^0$, $D_s \to \bar{K}^{*0} K^+$ are not suppressed relative to that of color-matched modes. From the quark-diagram scheme we can predict that

$$Br(D^0 \to \phi \pi^0) = \frac{1}{2}(0.05) \frac{\Gamma(D^0)}{\Gamma(D^+)} Br(D^+ \to \phi \pi^+).$$

$D \to PP$ Decays: After analyzing the data of charm-meson decay into two pseudoscalars $D \to PP$, we reach the following conclusions:

1. The penguin diagram contribution is expected to be very small in charm decay because of the good approximation $V_{us} V_{cs}^* \simeq -V_{ud} V_{cd}^*$. Indeed, the new measurement of $D_s \to \bar{K}^0 K^+$ together with $D^+ \to \pi^+ \bar{K}^0$ and $D^+ \to \bar{K}^0 K^+$ implies that the penguin contribution in charm decay is negligible.

2. The *W-exchange and/or the W-annihilation diagrams play an essential role in* $D \to PP$ *decays.*

3. There are possible hairpin-diagram contributions to $D^0 \to \bar{K}^0\eta_0$ and $D_s \to \pi\eta_0$. If they are small we can make the following possible predictions

$$Br(D_s \to \pi\eta') \sim 1\% \qquad Br(D^0 \to \bar{K}^0\eta') \sim 1\%;$$

or

$$Br(D_s^+ \to \pi^+\eta') \sim 0.2\%, \quad Br(D^0 \to \bar{K}^0\eta') \sim 7\%$$

Any deviation from the above prediction might signal the importance of hairpin diagrams. A large branching ratio of about 19% for $D_s^+ \to \pi^+\eta'$ measured recently by Mark II indicates that hairpin diagrams may play an essential role in $D \to PP$ decays.

Non-resonant 3-body decays of charmed mesons are first studied in the approach of effective $SU(4) \times SU(4)$ chiral Lagrangians. It is pointed out that the predictions of the branching ratios in chiral perturbation theory are in general too small when compared with experiment. However, the experimental results are comprehensible in the general framework of the quark-diagram scheme. The existence of a sizable W-annihilation amplitude, which is evidenced by the observation $D_3^+ \to (\pi^+\pi^+\pi^-)_{NR}$, is the key towards an understanding of the 3-body non-resonant decays of D^+ and D_3^+. The measurement of $D^0 \to \bar{K}^0K^+K^-$ and $D^0 \to \bar{K}^0\pi^+\pi^-$ indicates that color suppression is not effective in the 3-body decay. Based on the quark-diagram analysis, predictions for some other non-resonant modes are given.

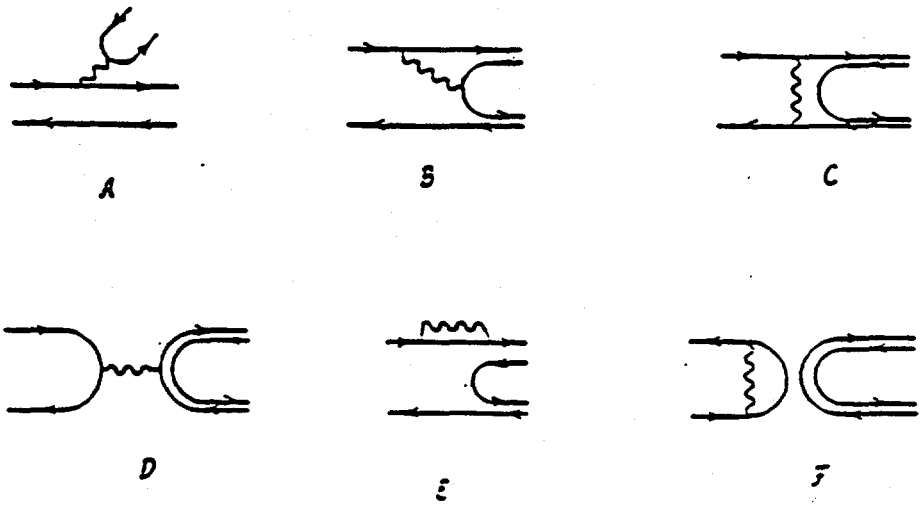

Figure 1. The six quark diagrams for a meson → two mesons.

Recently, experimental limits on some rare exclusive decays of B mesons have been given by Avery et al. (CLEO collaboration). We have studied their implications, as well as future calculations and measurements. For such discussions, we have used the model-independent quark-diagram scheme. Results are given in Table IV.

Supergravity

$D = 4$: It has been shown that light-like integrability conditions for $n \geq 5, 6, 7, 8$ lead to conformal supergravity equations of motion.[85-7]

$D = 4$: Linear systems have been constructed from all ($n = 1, ..., 8$) the light-like integrability conditions.[88-23] These linear systems help to solve the light-like constraints and thus equation of motion for $n = 5, 6, 7, 8$; and helps to solve the light-like constraints for $n = 1, 2, 3, 4$ for off-shell formulation.

$D = 10, n = 1$: It has been shown that light-like integrability constraints lead to equations (Poincare) of motion only if an additional algebraic constraint is imposed.[87-8] Thus the light-like integrability constraints can allow an off-shell formulation of the theory.

$D = 10, n = 1$: Linear systems and conservation laws can be constructed for the light-like integrability conditions,[89-3] and thus useful for the off-shell formulation of the $D = 10, n = 1$ supergravity theory. In the construction of the linear systems and conservation laws, it is essential to use the bi-spinor representation for the light-like vectors.

Supersymmetric Yang-Mills Theories

In addition to the similar developments[84-4] as mentioned in section for $D = 4$, supergravity theories, our recent new addition is the construction of linear systems, and an infinite number of nonlocal conservation laws using the bi-spinor representation[87-6] for any light-like vector in $D = 6$ and 10. These will be certainly useful for constructing new solutions in $D = 6$ and 10, and then in $D = 4$ by dimensional reduction.

Progress Made For The $D = 4$, Self-Dual Yang-Mills Equation

Permutability property has been shown to be true for the Chau-Prasad-Sinha Bäcklund transformations (BT).[85-6,86-3]

TABLE IV

	Reaction	Amplitude				$(Br)_{theory}$	*exp. limits from* ARGUS	CLEO
$B_d^0 \to$	$K^{*+}\rho^-$	$V_{us}V_{ub}^*$	$(\mathcal{A}+\mathcal{E}_{u-c})$	$+V_{ts}V_{tb}^*$	$(\mathcal{E}_{t-c})$	1.8×10^{-5}		
$\to$	$K^{*0}\bar{K}^{*0}$	$V_{ud}V_{ub}^*$	$(\mathcal{E}_{u-c}+\mathcal{F}_{u-c})$	$+V_{td}V_{tb}^*$	$(\mathcal{E}_{t-c}+\mathcal{F}_{t-c})$	9.6×10^{-7}		
$\to$	$K^{*0}\rho^0$	$V_{us}V_{ub}^*\frac{1}{\sqrt{2}}$	$(\mathcal{B}-\mathcal{E}_{u-c})$	$+V_{ts}V_{tb}^*\frac{1}{\sqrt{2}}$	$(-\mathcal{E}_{t-c})$	4.7×10^{-6}	4.6×10^{-4}	6.7×10^{-4}
$\to$	$K^{*0}\phi$	$V_{us}V_{ub}^*$	$(\mathcal{E}_{u-c})$	$+V_{ts}V_{tb}^*$	$(\mathcal{E}_{t-c})$	9.0×10^{-6}	3.2×10^{-4}	4.4×10^{-4}
$\to$	$K^{*0}\omega$	$V_{us}V_{ub}^*\frac{1}{\sqrt{2}}$	$(\mathcal{B}+\mathcal{E}_{u-c})$	$+V_{ts}V_{tb}^*\frac{1}{\sqrt{2}}$	$(\mathcal{E}_{t-c})$	8.1×10^{-6}		
$\to$	$\rho^+\rho^-$	$V_{ud}V_{ub}^*$	$(\mathcal{A}+\mathcal{C}+\mathcal{E}_{u-c}+\mathcal{F}_{u-c})$	$+V_{td}V_{tb}^*$	$(\mathcal{E}_{t-c}+\mathcal{F}_{t-c})$	3.4×10^{-5}	2.2×10^{-3}	
$\to$	$\rho^0\rho^0$	$V_{ud}V_{ub}^*\frac{1}{2}$	$(-\mathcal{B}+\mathcal{C}+\mathcal{E}_{u-c}+\mathcal{F}_{u-c})$	$+V_{td}V_{tb}^*\frac{1}{2}$	$(\mathcal{E}_{t-c}+\mathcal{F}_{t-c})$	1.6×10^{-6}	2.8×10^{-4}	3.4×10^{-4}
$\to$	$\rho^0\omega$	$V_{ud}V_{ub}^*\frac{1}{2}$	$(-\mathcal{B}+\mathcal{B}'-\mathcal{E}_{u-c}-\mathcal{E}'_{u-c})$	$+V_{td}V_{tb}^*\frac{1}{2}$	$(-\mathcal{E}_{t-c}-\mathcal{E}'_{t-c})$	3.9×10^{-7}		
$\to$	$\omega\omega$	$V_{ud}V_{ub}^*\frac{1}{2}$	$(\mathcal{B}+\mathcal{C}+\mathcal{E}_{u-c}+\mathcal{F}_{u-c})$	$+V_{td}V_{tb}^*\frac{1}{2}$	$(\mathcal{E}_{t-c}+\mathcal{F}_{t-c})$	2.8×10^{-6}		
$\to$	$\phi\phi$	$V_{ud}V_{ub}^*$	$(\mathcal{F}_{u-c})$	$+V_{td}V_{tb}^*$	$(\mathcal{F}_{t-c})$	— —		
$B_u^+ \to$	$K^{*+}\rho^0$	$V_{us}V_{ub}^*\frac{1}{\sqrt{2}}$	$(\mathcal{A}+\mathcal{B}+\mathcal{D}+\mathcal{E}_{u-c})$	$+V_{ts}V_{tb}^*\frac{1}{\sqrt{2}}$	$(\mathcal{E}_{t-c})$	7.6×10^{-6}		
$\to$	$K^{*0}\rho^+$	$V_{us}V_{ub}^*$	$(\mathcal{D}+\mathcal{E}_{u-c})$	$+V_{ts}V_{tb}^*$	$(\mathcal{E}_{t-c})$	8.0×10^{-6}	9.0×10^{-4}	
$\to$	$K^{*+}\phi$	$V_{us}V_{ub}^*$	$(\mathcal{D}+\mathcal{E}_{u-c})$	$+V_{ts}V_{tb}^*$	$(\mathcal{E}_{t-c})$	8.2×10^{-6}		
$\to$	$K^{*+}\omega$	$V_{us}V_{ub}^*\frac{1}{\sqrt{2}}$	$(\mathcal{A}+\mathcal{B}+\mathcal{D}+\mathcal{E}_{u-c})$	$+V_{ts}V_{tb}^*\frac{1}{\sqrt{2}}$	$(\mathcal{E}_{t-c})$	1.5×10^{-5}	1.3×10^{-4}	
$\to$	$K^{*+}\bar{K}^{*0}$	$V_{ud}V_{ub}^*$	$(\mathcal{D}+\mathcal{E}_{u-c})$	$+V_{td}V_{tb}^*$	$(\mathcal{E}_{t-c})$	1.0×10^{-6}		
$\to$	$\rho^+\rho^0$	$V_{ud}V_{ub}^*\frac{1}{\sqrt{2}}$	$(\mathcal{A}+\mathcal{B})$			1.4×10^{-5}	1.0×10^{-3}	
$\to$	$\rho^+\omega$	$V_{ud}V_{ub}^*\frac{1}{\sqrt{2}}$	$(\mathcal{A}+\mathcal{B}+2\mathcal{D}+\mathcal{E}_{u-c}+\mathcal{E}'_{u-c})$	$+V_{td}V_{tb}^*\frac{1}{\sqrt{2}}$	$(\mathcal{E}_{t-c}+\mathcal{E}'_{t-c})$	2.5×10^{-5}		

The sequence, Parametric BT → Riccati → linear systems, has been constructed for the self-dual Yang-Mills equations.[86-4]

A generalized Bäcklund transformation, which is capable of generating instanton solutions has been constructed for the (supersymmetric) self-dual Yang-Mills equations.[89-2]

The $D = 2$ Theories

The Ernst equations which are reduced non-linear systems of static and axially symmetric Einstein, or Yang-Mills equations: linear systems, infinite-nonlocal conservation laws, finite Riemann-Hilbert transforms, and infinitesimal RH transform ⇒ Kac-Moody algebra; Bäcklund transformations, etc. have been thoroughly discussed.[85-4]

All the integrability properties have been constructed for the super-chiral equations with Wess-Zumino term.[86-2]

A general gauge covariant formulation, as well as all the integrability properties have been constructed for general symmetric-space chiral fields.[84-2]

Using the special Riemann-problem technique of Zakharov et al., an explicit N-step Bäcklund transformation for a certain class of 2-d nonlinear evolution equations was derived and thus provided an alternative explicit expression of their N-soliton solutions.[90-5]

General Integrability Discussions

A unifying derivation of BT has been given from the point of view of finite Riemann-Hilbert transformation.

A general discussion of Kac-Moody algebra has been made from the point of view of infinitesimal Riemann-Hilbert transformation.[89-1]

Approach to Quantization

To approach quantum field theory from this geometrical-integrability point of view, the following work has been done:

We have studied the light-cone Hamiltonian formalism of the nonabelian chiral model with Wess-Zumino term in arbitrary coupling constant. The monodromy matrices and their bracket structure are derived explicitly and discussed.[90-4]

From an action for the self-dual Yang-Mills (SDYM) system, we have constructed a higher dimensional version of the Kac-Moody-Virasoro algebra which appears as the symmetry of this system. We have also constructed a SDYM hierarchy with using these algebras.[90-7]

We have studied a conformally invariant theory which consists of scalar fields on a Riemann surface Σ coupling to a Chern-Simons gauge filed on a three dimensional manifold B with boundary Σ. The presence of gauge fields introduces interesting phase factors given by the line integral of gauge potential in the correlation functions. After quantization to the gauge field, these phase factors are related to the Gauss linking number and the self-linking number for the $U(1)$ case, and the link polynomials for the nonabelian case.[90-6]

In addition, we have

Found ways to measure the hairpin diagrams in charmed meson decays (paper 91-3)

The possible presence of hairpin diagrams is analyzed in the model-independent quark-diagram scheme for two-body decays of charmed mesons. Current experimental data do not require the presence of hairpin diagrams in $D \to VP$ (V: vector meson, P:pseudoscalar meson), in accordance with the OZI rule. However, there is a possible indication that they are important in the decay of $D \to PP$. The measurement of $D_s^+ \to \pi^+\eta'$ is crucial to test the mechanism of hairpin diagrams.

Studied the charmless nonleptonic decays of B mesons using the quark-diagram-scheme and model calculations (paper 91-1)

Branching ratios of nonleptonic exclusive two-body decays of charged B mesons without final-state charm particles are studied in detail. The technique used for evaluating the nonleptonic decay amplitudes is elucidated. Charmless decay channels, such as $B_u^+ \to K^+\eta'$, $\pi^+\eta'$, $\rho^+\pi^0$, $\rho^+\eta$, $\rho^+\eta'$, $B_d^0 \to K^+\pi^-$, $\eta\eta'$, $\eta'\eta'$, $K^{*+}\pi^-$, $\rho^+\pi^-$, $K^{*+}\rho^-$, $\rho^+\rho^-$, should be accessible experimentally in the near future. The implications of the quark-diagram scheme are also discussed.

Generated N-soliton solutions in two-dimensions (Paper 91-2)

Using the special Riemann-problem technique of Zakharov *et al.* [Sov. Phys. JETP 47, 1017 (1978)], an explicit N-step Bäcklund transformation is derived for a class of 1 + 1-dimensional nonlinear evolution equations, thus providing an alternative explicit expression of their N-soliton solutions which no longer involves computations of the intermediate solutions, nor leaves any expansion of $N \times N$ determinants (and of their differentiation) to be done.

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August 29–September 9, 1983, Editions Frontieres, eds.
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Ling-Lie Chau

83–12. Emergence of Central Extension of Kac-Moody Algebra in Quantum Integrable Models
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Italy, (1983); Lecture Notes in Phyhsics #201,
Springer-Verlag, eds., G. Denardo, G. Ghirardi, and T. Weber.
G. Bhattacharya and Ling-Lie Chau (talk delivered by Chau).

83–13. Supersymmetric Yang-Mills Fields as an Integrable System and the Connection with Other Systems
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84–1. Supersymmetric Kac-Moody Algebra in Graded Chiral Models
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84–8. Concluding Remarks and Outlook

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84–9. Quark Mixing Phenomenology: The b Lifetime, ϵ'/ϵ, m_t, and CP Violation in Heavy Quark Decays

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Ling-Lie Chau

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84–15. Regular Riemnan-Hilbert Transforms, Backlund Transformations and Hidden Symmetry Algebra for Some Linearization Systems
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85–9. CP Violation in Decay rates of Neutral B Mesons

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85–10. Anticipating the Four Generation of Quarks from Rephasing Invariance of the Mixing Matrix

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(not published)

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85–13. Physics of Charm and Beauty, and Beyond

Proc. (copies of transparancies) of the Heavy Quark Workshop.

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Ling-Lie Chau

85–14. Certain Integrability Properties of Gauge Theories in Physics and Their Similarities to Nonlinear Systems

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Phys. Lett. B177, 368 (1986)

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86–5. Linear Systems and Conservation Laws of Gravitational Fields in Four Plus Extended Super Space, UCD–86–31

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With emphasis on physics for future machines

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Proceedings of the International Symposium on Production and Decays of Heavy Hadrons, Heidelberg, May 23–30, 1986

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Ling-Lie Chau

86–10. Geometrical Integrability and Equations of Motion in Physics: A Unifying Description

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86–11. Standard Model—Quark Mixing and All That

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Phys. Lett. B197, 244 (1987)

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Ling-Lie Chau

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Proceedings of the American Physical Society Meeting in Salt Lake City. Jan. 13–18, 1987
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87–12. B Mesons, A Beautiful Source for New Physics
Proceedings of the $B\bar{B}$ Factory Workshop at UCLA
Jan. 25–26, 1987
Ling-Lie Chau

87–13. In Search for the Beyond
Proceedings of the Int.'l Sym. for the 4^{th} Family of Quarks and Leptons. Santa Monica. Feb. 25–28, 1987
Ling-Lie Chau

87–14. Physics of Quark Mixing and CP Noninvariance: The Uses of

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Proceedings of the XXIInd Moriond Conference, Les Arcs,

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Ling-Lie Chau

87–16. Scientist and Society

Commencement Speech at the Commencement of

College of Letters and Science, UC Davis, June 20, 1988

Ling-Lie Chau

87–17. Geometrical Integrability of Supersymmetric Theories

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High Energy Physics, Uppsala, Sweden, June 25–July 1, 1987

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Physics and Field Theory

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87–20. Geometrical Integrability, and Equations in Physics: A Unifying View

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Equations in Physics: A Unifying View"

at Nankai University, Tianjing, China

Aug. 16–Aug. 23, 1987
Ling-Lie Chau

87–21. Heavy Quark Decays, Mixing. CP Noninvariance
Talks at the Workshop on "Heavy Quark Decays, Mixing,
CP Noninvariance", Nankai University, Tianjing, China
Aug. 24–Sept. 1, 1987
Ling-Lie Chau

88–1. A Unifying Description of Equations of Motion in Physics from Geometrical Integrability
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Ling-Lie Chau

88–2. Linear Systems and Conservation Laws of Gravitational Fields in Four Plus Extended SuperSpace
Physics Letters B202, 238-242
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88–3. $K \rightarrow 2\gamma$ and Other Interesting CP Noninvariance Phenomena
Proceedings of the Aspen Winter Conference on Particle Physics,
CP-Violation, Aspen, Jan. 10–16, 1988
Ling-Lie Chau

88–4 CP Noninvariance and Weak Decays After NA31
Invited talk in the Proceedings of the XXIInd Moriond Conference,
Les Arcs, March 6–13
Ling-Lie Chau

88–5 Status and Frontiers in Heavy Quark Decays, Mixing and CP Noninvariance
Invited talk in the Proceedings of the Third Asia Pacific Physics
Conference. Hong Kong. June 20-24
Ling-Lie Chau

88–6 Nonlinear Systems in Physics and Their Geometrical Integrability Properties
Invited talk in Proceedings of the Third Asia Pacific Physics

Conference. Hong Kong, June 20-24
Ling-Lie Chau

88–7 Geometrical Integrability Properties of Classical Field Theories
Invited talk in the Proceedings of the IXth Congress of International Association of Mathematical Physics, Swansea, July 17th–27th
Ling-Lie Chau

89–1 Kac-Moody Algebra from Infinitesimal Riemann-Hilbert Transform
Journal of Mathematical Physics 30 (1989) 166
Ling-Lie Chau and Mo-Lin Ge

89–2 A Generalized Bäcklund Transformation for the (Super Symmetric) Self-Dual Yang-Mills Fields
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Ling-Lie Chau. J.C. Shaw, and H.C. Yen

89–3 Linear Systems and Conservation Laws in d=10, N=1 Supergravity
Physics Letters B, 216 (1989) 330.
Ling-Lie Chau and B. Milewski

89–4 Geometrical Constraints for D=10, N=1 Supergravity
Modern Physics A, 4 (1989) 3819
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89–5 Quark-Diagram Scheme for the studies on the Two-Body Decays of Charm Mesons: Addendum on the Hairpin Diagrams
Physical Review. 39 (1989) 2788
Ling-Lie Chau and H.-Y. Cheng

89–6 Comments on QCD Sum-Rule Calculations of Exclusive Two-Body Decays of Charmed Mesons
Modern Physics Letter A, 4 (1989) 877
Ling-Lie Chau and H.-Y. Cheng

89–7 Analysis of the Recent Data of Exclusive Two-Body Charm Decays
Physics Letters. 222 (1989) 285

Ling-Lie Chau and H.-Y. Cheng

89–8 Charm, Beauty and Beyond

Invited talk at and to appear in the Proceedings of The International Symposium on the 4^{th} Family of Quarks and Leptons, Feb. 23-25. Los Angeles

Ling-Lie Chau

89–9 Physics of Doubly Cabbibo Suppressed Charm Decays

Invited talk, the Proceedings of International Tau-Charm Workshop, May 23-27, Stanford

Ling-Lie Chau

89–10 CP Noninvariance in Charm Decays

Invited talk, the Proceedings of International Tau-Charm Workshop, May 23-27, Stanford.

Ling-Lie Chau

89–11 Physics From Nonleptonic Charm Decays

Invited talk at and to appear in the Proceedings of the Workshop on Weak Interactions and CP Violation

Institute of High Energy Physics, Beijing, China, Aug. 22-26, 1989

Ling-Lie Chau

89–12 Decay Amplitude CP Noninvariance: A Charm Possibility

Invited talk at and to appear in the Proceedings of the Workshop on Weak Interactions and CP Violation

Institute of High Energy Physics, Beijing, China, Aug. 22-26, 1989

Ling-Lie Chau

89–13 Geometrical Integrability Properties of Gravitational and Other Classical Field Theories in Physics

Invited talk at and to appear in the Proceedings of the Third Hungarian Relativity Workshop. Budapest. Sept. 4-9. 1989

Ling-Lie Chau

89–14 In Search of CP Noninvariance in Heavy Quark Systems
In a book "CP Violation", publisher World Scientific, ed. by C. Jarlskog
Ling-Lie Chau

90–1 On the Non-Resonant Three-Body Decays of Charmed Meson
To appear in Phys. Rev.
Ling-Lie Chau, and H.Y. Cheng

90–2 Predictions for the Quark-Mixing Doubly Suppressed Decays of Charmed Mesons
to appear in Phys. Rev.
Ling-Lie Chau, and Hai-Yang Cheng

90–3 Ways to Measure the Hairpin Diagrams in Charmed Meson Decays
Submitted to Phys. Rev.
Ling-Lie Chau, H.Y. Cheng, and Tao Huang

90–4 Quantization of Chiral Model with Wess-Zumino term in the light-cone coordinate
Submitted to Phys. Rev.
Ling-Lie Chau and Itaru Yamanaka

90–5 An Alternative Explicit Construction of N-Soliton Solutions in Two Dimensions
Submitted to Jour. Math. Phys.
Ling-Lie Chau, J.C. Shaw and H.C. Yen

90–6 Chern-Simons Gauged Conformal Field Theories
Submitted to Phys. Rev.
Ling-Lie Chau and Yue Yu

90–7 A Virasoro Algebra in Self-Dual Yang-Mills System
Submitted to Phys. Rev.
Ling-Lie Chau and Itaru Yamanaka

90–8 Charmless Nonleptonic Rare Decays of B Mesons
Submitted to Phys. Rev.
Ling-Lie Chau, H.-Y. Cheng, W.K. Sze, H. Yao and B. Tseng.

90–9 Field Theory from Integrable-System Point of View
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90–10 The Integrable-System Connection.
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90–11 Rare Nonleptonic Decays of Charm and Beauty Mesons
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91–1 Charmless Nonleptonic Rare Decays of B Mesons
(163) Physical Review D43, 2176
Ling-Lie Chau, H.-Y. Cheng, W.K. Sze, H. Yao, and B. Tseng

91–2 An Alternative Explicit Construction of N-Soliton Solutions in Two Dimensions
(164) Journal of Mathematical Physics 32, 1737
Ling-Lie Chau, J.C. Shaw, and H.C. Yen

91–3 Ways to Measure the Hairpin Diagrams in Charmed Meson Decays
(165) Zeitschrift für Physik C, 53, (1992), 413
Ling-Lie Chau, H.Y. Cheng, and T. Huang

91–4 Overview of B and K Decays
(166) Invited talk and to appear in Proceedings of Conference on
"Rare and Exclusive B and K Decays and Novel Flavor Factories",
Santa Monica, California;
Ling-Lie Chau

91–5 Nonleptonic B,D,K Meson Decays and CP Noninvariance
(167) Invited talk and appeared in the Proceedings of
the Workshop on Physics and Detectors for KEK
Asymmetric B Factory, Tsukuba, Japan, April 15-18, 1991;
Ling-Lie Chau

91–6 Quantization of the Self-Dual Yang-Mills System and the WZNW Model:
(168) Quadratic and Exchange Algebras, and Modified Yang-Baxter Relations Systems
Invited talk and appeared in the Proceedings of the XX^{th} Int'l Conf. on
Differential Geometric Methods in Theoretical Physics, June 3-7, 1991,
New York;
Ling-Lie Chau and Itaru Yamanaka

Progress Report (A. Schwarz) (Earlier papers are included for reference.)

a) Constrained systems and BRST-approach

The most powerful method of quantization of constrained systems is based on the use of BRST-operator. In particular, BRST-operator plays an important role in very general Batalin-Fradkin-Vilkovisky (BFV) approach to quantization. It is shown in [7] that the appearance of BRST-operator in the analysis of quantum systems with constraints can be understood very easily within the framework of Lie algebra cohomology. (It is important to note that in this approach BRST-operator arises directly in quantum case and is not connected with quantization of classical system.)

The treatment in [7] is restricted to the case when there is only a finite number of constraints. The case of infinite number of constraints can be analyzed by means of the notion of semi-infinite cohomology groups of Lie algebra (paper in preparation). It is well-known that in general the standard construction of BRST-operator Q gives an operator that does not satisfy $Q^2 = 0$ due to some kind of anomaly. (In other words, the standard construction of semi-infinite cohomology can be applied only under certain conditions. I am planning to analyze the anomalous case in collaboration with A. Voronov). This is important for physical applications (for example, for strings in non-critical dimensions). The analysis can be based on the recent paper by Voronov. Voronov gave a general definition of semi-infinite cohomology groups; it is plausible that this definition can be applied to the anomalous case and gives correct quantum theory.

The analysis given in [7] must be generalized also to the case of reducible constraints. (First consideration of classical system with reducible constraints was given in [56]. Later corresponding BRST-operator was constructed in BFV-approach. I am planning to analyze a quantum system with reducible constraints.)

There are also some important questions concerning BFV-approach to quantization of constrained systems. In this approach the gauge condition can be interpreted as a choice of Lagrangian submanifold in a certain supermanifold with an odd symplectic structure. It is well-known that the physical quantities do not change by the continuous variation gauge condition. I hope to prove that two gauge conditions lead to the same answer if corresponding Lagragian manifolds are connected by Lagrangian cobordism. (One can construct examples

showing that in general the answer depends on the choice of gauge condition).

b) Topological quantum field theories (TQFT)

This branch of QFT attracts great attention especially after Witten's paper [24] in which it is shown that topological invariants arising from Chern-Simons Lagrangian are related with Jones polynomials in Knot theory. (The construction of topological invariants by means of Chern-Simons Lagrangian was proposed earlier in [17], in the same paper I conjectured that these invariants are connected with Jones polynomials. The method permitting to obtain topological invariants from QFT and the first example of TQFT were given long ago in my papers [18] and [19].) Witten has shown that TQFT can be useful not only for mathematics but also for physics [24], [23]. (See also papers by Moore and Seiberg, etc.) I am planning to return to TQFT, in particular, I intend to analyze TQFT connected with the moduli space of superconformal manifolds. Witten's results [23] give a hint that this theory can be useful in the analysis of two-dimensional supergravity coupled with superconformal matter.

c)Transmutation of statistics

In [9], I studied the statistics of skyrmions (particles corresponding to topologically non-trivial fields in non-linear σ-model.) I intend to continue the analysis of this question. I would like to analyze also more general questions connected with transmutation of statistics. These questions are interesting from the general viewpoint, but they are especially important in connection with discovery of anyon superconductivity. To establish the connection with real properties of novel superconductors it is necessary to study more carefully how fractional statistics arises in the quantum theories with elementary particles obeying bose and fermi statistics.

String theory

I intend to continue my work in the string theory (see [8], [10]-[17]). My last results in this field were motivated by the wish to go beyond the framework of perturbation theory [10]. I constructed the extension of super-Mumford form (holomorphic square root from the string measure on the moduli space) to the universal moduli space and expressed it in the terms of superanalog of Sato's τ-function. The universal moduli space contains moduli spaces for all general genuses and therefore in some sense corresponds to all orders of perturbation theory. Recently, very interesting results were obtained for non-critical bosonic strings

(strings in dimension < 1=matter with central charge < 1 coupled with two-dimensional gravity.) These results are much stronger because they give non-perturbative expression of the partition function and correlation functions in terms of τ-functions. I will think about the generalization of these results to the case of non-critical superstrings; one can hope the superanalog of the τ-function construction in [8] will be useful for such a generalization.

The construction of extension of super-Mumford form to the universal moduli space led to discovery of hidden $N = 2$ superconformal symmetry of this form [8]. I am planning the further study of the role of $N = 2$ superconformal symmetry in the standard ($N = 1$) superstring.

Mathematical results obtained in [10] can be used also to anlayze $N = 2$ superstring. It was shown in [25] that $N = 2$ superstring has many very interesting features. The results of [10] permit to calculate the string measure on the moduli space of $N = 2$ superconformal manifolds (paper in preparation).

I studied also the string field theory. In collaboration with A. Sen, I proved that Witten's open string field theory can be generalized to the string in arbitrary conformal background with central charge $c = 26$ [4]. In connection with open string filed theory I considered appropriate 2-dimensional conformal field theories in axiomatic approach and the relation between conformal background, appropriate for open and closed strings. It is possible that I continue this consideration.

In connection with string theory I am planing to study some mathematical questions concerning the so called model spaces. The paper [2] devoted to Virasoro model space can be considered as the first step in this direction.

I wrote a series of papers devoted to the investigation of some mathematical problems arising in the theory of non-critical strings. In particular, I described the space of solutions to the equation [P,Q]=const. where P and Q are ordinary differential operators. (This equation arises in the study of non-critical strings by means of matrix models and therefore it is known as string equation.) . I also proved that the generalization of string equation to the supersymmetric case is connected with the superanalogs of KP-hierarchy and studied (in collaboration with M. Bowick and K. Anagnostopoulos) the modification of string equation arising in the theory of unitary matrix models.

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