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Physics at Run II:
The Supersymmetry/Higgs Workshop

Editors: Marcela Carena and Joseph Lykken

PREFACE

The *Physics at Run II* workshop series was conceived by members of the Fermilab Theory Department, as a means to maximize the physics potential of the upcoming high luminosity collider runs at the Fermilab Tevatron. To date five Run II workshops have been organized, covering the following topics:

- Supersymmetry/Higgs,
- Top physics,
- New strong dynamics,
- QCD and weak boson physics,
- B physics.

The Supersymmetry/Higgs Workshop was the first to be organized, with initial preparations beginning in January of 1998. The basic framework of the workshop was adapted from the successful *Physics at LEP2* workshop, held at CERN in 1995, for which one of us was co-convener of the Higgs Working Group. The final structure was worked out in consultation with the spokespersons of the CDF and DØ collaborations, and with members of the Fermilab Theory Department. Four working groups were formed to cover the main physics areas, each with at least two theory conveners and two experimental conveners. The working group charges were chosen to achieve complete coverage of all conceivable manifestations of supersymmetry (SUSY) and Higgs physics at the Tevatron collider:

- Supergravity mediated SUSY models,
- Gauge mediated and other low energy SUSY models,
- Beyond the Minimal Supersymmetric Standard Model,
- Higgs.

A fifth working group on event generation was formed to support the simulation efforts of the other groups. For the final report, results related to R-parity violating SUSY were spun off from Beyond the MSSM and are presented separately. Individual working group meetings began in March 1998 and continued at frequent intervals throughout the year. In addition, three general meetings were held at Fermilab, May 14-16, September 2-4, and November 19-21. The process of refining and comparing analyses continued well into 2000.

The ambitious goals of the Supersymmetry/Higgs Workshop were detailed on our website in February 1998:

- Organize and improve our understanding of all possible variants of weak scale supersymmetry which may manifest themselves in collider experiments at Tevatron Run II. This includes identifying the most useful parametrizations of the minimal and near-minimal scenarios.
- Improve our ability to perform realistic simulations of all the interesting SUSY variants, as well as the relevant standard model backgrounds. This includes improved calculations of SUSY production mechanisms at the Tevatron, and upgrades of the existing event generators.
- Identify and organize the multichannel experimental signatures of each SUSY variant, explore novel signatures, devise improved strategies for combining information from multiple channels, and stimulate creative ideas for extending the reach of the Run II experiments.
- Improve our ability to translate the observation/nonobservation of SUSY signals in multiple channels into meaningful constraints on, and tests of, the theoretical assumptions underlying weak scale SUSY scenarios.
- Explore the theoretical upper bounds on the mass of the lightest Higgs in weak scale supersymmetry, given a variety of theoretical assumptions. Improve our understanding of multichannel Higgs searches at the Tevatron, and refine the reach estimates for integrated luminosities in the range 2 to 30 fb^{-1}.

Remarkably, all of these goals were achieved.

The success of the workshop is testimony to the strong efforts of the participants, and in particular to the dedication and skill of the working group conveners. Our conveners endured any number of personal, professional, and financial hardships, and always found a way to get the job done. The entire high energy physics community owes them a debt of gratitude.

Many individuals played special roles of importance which should acknowledge. Fermilab director John Peoples gave esssential moral and financial support to the workshop, which included an expansion of the Theory Dept. visitor program, allowing several of our theory conveners to remain onsite for long periods during the workshop. The DØ spokespersons, Hugh Montgomery and Harry Weerts, as well as the CDF spokespersons, Franco Bedeschi and Al Goshaw, provided absolutely crucial support and cooperation. The early planning of the workshop benefited greatly from the wisdom and advice of Bill Carithers, Estia Eichten, Keith Ellis, Henry Frisch, Chris Hill, and Chris Quigg. Lois Deringer handled with her customary skill the huge increase in visitors and meetings, while Cynthia Sazama and Patti Poole coped with three general meetings whose novel format was unlike anything ever attempted at this laboratory.

At the annual Fermilab Users Meeting in July 1999, incoming Fermilab director Mike Witherell, as well as Peter Rosen of the DOE, endorsed the central importance of Higgs and supersymmetry searches at the Tevatron. This report provides the roadmap for an ambitious and exciting collider program leading, we hope, to fundamental discoveries.

Marcela Carena and Joseph Lykken, Fermilab, Dec 2000.

Part I
Executive Summary

1 INTRODUCTION

With the discovery of the top quark and the tau neutrino at Fermilab, the Standard Model (SM) of particle physics appears close to final experimental verification. Ten years of precision measurements of electroweak observables at LEP, the SLC, the Tevatron, and elsewhere, have not produced any definitive departures from Standard Model predictions. In some cases, theoretical predictions have been checked with an accuracy of one part in a thousand or better. Belying its prosaic name, the Standard Model stands as one of the great intellectual and scientific triumphs of human civilization.

This triumph is only the beginning of a continuing journey of discovery. Many considerations, both experimental and theoretical, teach us that the Standard Model is not the ultimate theory of the fundamental particles and their interactions. To begin with, there is still no *direct* experimental evidence for the underlying dynamics responsible for electroweak symmetry breaking. The Standard Model posits a weakly self-interacting complex doublet of scalar fields, with a tachyonic mass term introduced to arrange that the neutral component of the scalar doublet acquires a vacuum expectation value, $v = 246$ GeV, which sets the scale of electroweak symmetry breaking. Consequently, three massless Goldstone bosons are generated, which become the longitudinal components of the $W^{\pm}$ and Z bosons, while the fourth scalar degree of freedom that remains in the physical spectrum is the CP-even neutral Higgs boson of the Standard Model. The mass of the Higgs particle is not predicted, although self-consistency of the weakly-coupled description bounds the mass to be less than about a TeV.

The *ad hoc* features of electroweak symmetry breaking conjectured by the Standard Model themselves suggest that a more fundamental picture is needed. Furthermore, the self-interacting scalar field is only one model of electroweak symmetry breaking; alternative approaches are possible. For example, one can introduce new fermions and new gauge forces such that the Goldstone bosons are a consequence of the strong binding of the new fermion fields. Present experimental data are not sufficient to identify with certainty the nature of the dynamics responsible for electroweak symmetry breaking, nor to ascertain the connection between this dynamics and the generation of quark and lepton masses. The quest to understand electroweak symmetry breaking requires continued experimentation at colliders which can probe the TeV energy regime: the upgraded Tevatron, the LHC, and proposed lepton colliders under development.

Even if the Standard Model picture is correct, such that both electroweak symmetry breaking and fermion mass generation proceed via a single self-interacting fundamental scalar field, the existence of a fundamental scalar particle itself strongly implies new physics in the TeV energy regime. The quantum loop corrections to the mass of the Higgs boson are quadratically divergent; as a result, the quantum-corrected Higgs mass is naturally of the order of the highest mass scale to which the Higgs is directly or indirectly coupled. This is known as the Higgs naturalness or Higgs fine-tuning problem. The validity of the Standard Model, extrapolated to any new high energy threshold, will depend on a mysterious fine-tuning of the quantum corrections to the Higgs sector. The most palatable resolution of this problem is that the Standard Model is an *effective field theory*, supplanted by new physics and a new effective description in the TeV energy regime.

Of course, if the new effective theory also contains fundamental scalars, the fine-tuning problem will reappear at higher energies. Supersymmetry offers a very attractive cure for the fine-tuning problem by generating another loop contribution, so that the sum of the loop contributions is free of quadratic divergence. Supersymmetry is a symmetry which connects bosons and fermions, and its multiplets contain bose and fermi helicity states in equal numbers. Thus supersymmetry (SUSY) stabilizes the Higgs boson mass against potentially dangerous quantum contributions from ultraviolet physics. Spontaneous SUSY breaking in general splits the particle and superpartner masses, consistent with the non-observation of Bose-Fermi degeneracy in the physical spectrum at low energies. In many supersymmetric extensions of the Standard Model with spontaneously broken supersymmetry, quantum effects involving the superpartners of the top quark lead naturally, through the large top quark Yukawa coupling, to the observed electroweak symmetry breaking. In this way the electroweak scale is *determined* by the superpartner masses. The search for superpartners with electroweak scale masses constitutes a major effort at present and future high energy colliders.

The Higgs naturalness problem is exacerbated by strong evidence for the existence of new physics at very high energy thresholds. It is almost certain that, at some high scale, quantum gravitational effects become significant and the Standard Model must be replaced by a more fundamental theory that incorporates gravity. This scale is usually assumed to be the Planck energy scale, $M_{\rm PL} \simeq 10^{19}$ GeV, obtained from the measured value of Newton's gravitational constant. Other indications of the existence of new high energy thresholds come from the behavior of the Standard Model couplings. The Standard Model is not an asymptotically free theory since some of the couplings (*e.g.*, the U(1) gauge coupling, the Higgs–top-quark Yukawa coupling, and the Higgs self-coupling) eventually blow up at some high energy scale. Even more intriguing is the observation that the Standard Model gauge couplings, extrapolated to high energies with renormalization group running implied by minimal supersymmetry, unify to good precision at an energy scale of order 10^{16} GeV. Another hint comes from the recent experimental evidence for neutrino masses, which cannot be strictly explained in the Standard Model. Yet, one can easily write down a dimension-5 operator that is suppressed by v/Λ, which is responsible for neutrino masses. If $m_\nu = 10^{-2}$ eV, then one obtains as a rough estimate $\Lambda \sim 10^{15}$ GeV. The apparent existence of new high energy thresholds, as much as 16 orders of magnitude above the electroweak scale, is known as the hierarchy problem of the Standard Model. The theoretical and experimental challenge is to show either that the hierarchies are not really there, or, if they are there, to identify the dynamical mechanisms that create them and stabilize them against quantum fluctuations.

Supersymmetry stabilizes hierarchically separated energy scales by the same Bose-Fermi cancellations that ameliorate the Higgs naturalness problem. Further, since in SUSY models the electroweak scale is determined by the superpartner masses, the Standard Model hierarchy problem is solved by identifying the dynamical mechanism by which supersymmetry is spontaneously broken. More precisely, SUSY models are differentiated by the nature of the "SUSY breaking sector" (the physics responsible for spontaneous SUSY breaking) and the "messenger sector" (the physics responsible for communicating this SUSY breaking to the Standard Model supermultiplets). In any viable SUSY model, the net result of the dynamics in these two sectors is to generate a particular spectrum of soft SUSY breaking parameters (as well as the supersymmetric Higgsino mass parameter μ) which are of order the electroweak scale.

The manner and scale at which supersymmetry is spontaneously broken has crucial implications for the phenomenology of collider searches for the superpartners. Superpartner particles are generally unstable to decays to lighter superpartners and Standard Model particles. The decay chains, branching fractions, and lifetimes depend sensitively on the soft SUSY breaking parameters. Different assumptions about the SUSY breaking and messenger mechanisms lead to different characteristic patterns of soft breaking terms, and thus to different experimental signatures and challenges.

Three other general features of SUSY models are important in classifying the resultant experimental signatures. One is particle content. The field content of the minimal supersymmetric extension of the Standard Model (MSSM), consists of the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge bosons, three generations of quarks and leptons, two complex Higgs doublets, and all their superpartners. Two complex Higgs doublets is the minimal Higgs sector that is free of gauge anomalies in the superpartner Higgsino sector, while allowing Yukawa couplings to both up quarks and to down quarks and leptons.

The second important feature turns on whether SUSY introduces new sources of CP violation. It is often assumed in MSSM analyses that all of the soft SUSY breaking parameters are real; if we allow a sufficient number of these parameters to instead have nontrivial phases, the phenomenology can change dramatically. Indeed there are strong constraints on these phases from the experimental bounds on the electric dipole moments of the electron and the neutron.

The third important feature regards the conservation of baryon and lepton number (B,L) in SUSY models. In the Standard Model B and L are automatically conserved, whereas in the MSSM one can write down a variety of supersymmetric and gauge invariant renormalizable couplings which violate B and/or L. These couplings are usually forbidden in SUSY models by invoking a discrete symmetry called R-parity. If R-parity is conserved then the lightest superpartner particle (LSP) is stable. Thus, in SUSY models which conserve R-parity, all superpartner decay chains terminate in the production of a stable LSP, whereas in most R-parity violating models superpartners decay entirely to Standard Model particles.

The considerations just described guided the creation of the working groups of this workshop, and the division of this report into five separate physics chapters. Below we give a brief introduction to the topics covered in each chapter. The physics results presented in each chapter are highlighted in the Executive Summary.

- **Supergravity mediated SUSY breaking models:**

  Supergravity (SUGRA) unification provides a framework for the spontaneous breaking of supersymmetry in a "hidden sector", which communicates with Standard Model particles (the "visible sector") only via supergravity couplings. These couplings vanish in the limit that $M_{\rm PL} \to \infty$, thus in supergravity models the soft SUSY breaking parameters of the MSSM also vanish in this same limit. Although it is possible to remain agnostic about the exact mechanism of SUSY breaking in the hidden sector, one particularly attractive possibility is condensation of the hidden sector gauginos, the supersymmetric partners of the hidden sector gauge bosons. For a gaugino condensate $\langle \lambda\gamma^0\lambda \rangle$, the resulting soft SUSY breaking in the visible sector is of order $\langle \lambda\gamma^0\lambda \rangle / M_{\rm PL}^2$, where the extra factor of $1/M_{\rm PL}$ is due to the fact that the gaugino condensate itself only breaks SUSY because of the presence of supergravity couplings. We see that to obtain visible sector SUSY breaking of order 1 TeV, we need a gaugino condensate scale on the order of 10^{12-13} GeV. This scale in turn can arise naturally as a result of the logarithmic running of the hidden sector gauge couplings.

Supergravity models are classified according to their particle content, gauge and other symmetries, and matter couplings specified by three functionals of the matter supermultiplets; these functionals are known as the superpotential, the Kähler potential, and the gauge kinetic function. Most of the SUGRA analyses in this report assume a particular theoretical paradigm known as minimal supergravity (mSUGRA). This framework assumes grand unification of the Standard Model supermultiplets at the energy scale $M_G \sim 10^{16}$ GeV indicated by extrapolation of the SM gauge couplings. It is assumed that SUSY breaks in a hidden sector, which has no superpotential couplings to the visible grand unified (GUT) sector. In addition, the gauge kinetic terms are assumed to have a minimal form and the Kähler potential is assumed to have no flavor dependent couplings with the hidden sector. The latter assumption is theoretically *ad hoc* but desirable phenomenologically to avoid unacceptably large flavor-changing neutral currents (FCNC).

Under these assumptions, the effective theory below the GUT scale M_G contains four soft breaking parameters: a universal scalar mass m_0, a universal gaugino mass $m_{1/2}$, and universal scalar couplings A_0 and B_0 proportional to the original cubic and quadratic superpotential couplings in the visible sector. In addition, there is one more parameter in the theory, the Higgs mixing parameter μ_0, the coefficient of a supersymmetric mass term that couples the two Higgs supermultiplets of the MSSM. Although μ_0 is not a soft SUSY breaking parameter, its origin (and magnitude) can be linked to soft SUSY breaking. The mSUGRA model at the GUT scale is then characterized by the five parameters, $m_0, m_{1/2}, A_0, B_0, \mu_0$. An essential feature of mSUGRA is that the soft breaking sector is protected against mass growths proportional to $M_G^2/M_{\rm PL}$, $M_G^3/M_{\rm PL}^2$,..., which all cancel in the low energy theory.

One of the remarkable aspects of mSUGRA is that it leads to radiative breaking of electroweak symmetry as a consequence of renormalization group effects. As one evolves the soft SUSY breaking parameters from the GUT scale towards the electroweak scale the determinant of the Higgs mass matrix in the Higgs potential turns negative, generating spontaneous breaking of electroweak symmetry. Minimization of the potential including loop corrections allows one to compute the two Higgs VEV's v_1 and v_2 in terms of the parameters of the theory. Alternately, one can use the minimization equations to eliminate μ^2, where μ is the value of μ_0 at the electroweak scale, in terms of the Z boson mass, and eliminate the parameter B_0 in terms of $\tan\beta \equiv v_2/v_1$. With these considerations mSUGRA can be characterized by four parameters and the sign of μ:

$$m_0, m_{1/2}, A_0, \tan\beta,\ \text{sign}(\mu) \tag{I.1.1}$$

One can identify a number of important phenomenological features which hold over large portions (but not all) of the mSUGRA parameter space. The LSP is usually $\tilde\chi_1^0$, the lightest of the four neutralino mass eigenstates, and usually this eigenstate is predominantly Bino. The neutralinos, charginos and gluino obey the approximate mass relations:

$$\begin{aligned} 2m^0_{\tilde\chi_1} \cong m^\pm_{\tilde\chi_1} \cong m^0_{\tilde\chi_2} \simeq \frac{1}{3} m_{\tilde g}\ , \\ m^0_{\tilde\chi_3} \cong m^0_{\tilde\chi_4} \cong m^\pm_{\tilde\chi_2} \gg m^0_{\tilde\chi_1}\ . \end{aligned} \tag{I.1.2}$$

Mass relations for the squarks and sleptons depend upon the relative size of m_0 versus $m_{1/2}$:

$$m_0 \gg m_{1/2} \Rightarrow m_{\tilde q_{1,2}} \cong m_{\tilde\ell} > M_{\tilde g}\ , \tag{I.1.3}$$

$$m_0 \ll m_{1/2} \Rightarrow M_{\tilde g} > m_{\tilde q_{1,2}} > m_{\tilde b} > m_{\tilde t} > m_{\tilde\ell}\ . \tag{I.1.4}$$

- **Low scale and gauge-mediated SUSY breaking models:**

Regardless of the ultimate source of supersymmetry breaking, a messenger sector must couple the SUSY breaking sector to the MSSM visible sector superpartners. The messenger sector is then said to "transmit" SUSY breaking to the visible sector. The MSSM visible sector superpartner masses, $\widetilde{m}$, are related to the intrinsic SUSY breaking scale $\sqrt{F}$, and the messenger sector mass scale, M_m, by

$$\widetilde{m} \propto \frac{F}{M_m}. \tag{I.1.5}$$

In the case of supergravity mediation considered above, the messenger interactions are of gravitational strength, $M_m \sim M_{\rm PL}$. In principle, however, the messenger scale can be anywhere between just above the electroweak scale up to the Planck scale. A messenger scale significantly below the Planck scale, $M_m \ll M_{\rm PL}$, is generally referred to as low-scale SUSY breaking. Note that with low-scale SUSY breaking, the gravitino mass is well below the MSSM superpartner masses: $m_{\widetilde{G}} \ll \widetilde{m}$ for $M_m \ll M_{\rm PL}$. So with low-scale SUSY breaking the gravitino is naturally the LSP, and the NLSP superpartner of an MSSM particle is unstable to decay to the Goldstino.

If the messenger scale is in fact well below the Planck scale, it is likely that the usual $SU(3)_C \times SU(2)_L \times U(1)_Y$ Standard Model gauge interactions play some role in the messenger sector. This is because the structure of supersymmetric gauge theories dictates that gauginos couple at the renormalizable level only through gauge interactions. If the MSSM scalars, including the Higgs bosons which determine the electroweak scale, received mass predominantly from non-gauge (and therefore non-renormalizable and hence suppressed) interactions, the gauginos would be unacceptably light. It is therefore natural within low-scale SUSY breaking, to consider theories of gauge-mediated SUSY breaking (GMSB). In general, GMSB arises if some massive fields which couple to the SUSY breaking sector, and therefore have a non-supersymmetric mass spectrum, also transform under the Standard Model gauge groups. These heavy fields are referred to as messengers, with the messenger masses determining the messenger scale M_m.

In GMSB theories the MSSM squarks, sleptons, and gauginos obtain mass radiatively from gauge interactions with the massive messengers. Since the messenger interactions are the usual gauge interactions, the superpartners generally acquire a mass in proportion to the associated gauge coupling squared or equivalently fine structure constant

$$\widetilde{m} \sim \frac{\alpha_a}{4\pi}\frac{F}{M_m} \tag{I.1.6}$$

where $\alpha_1, \alpha_2, \alpha_3$ are the fine structure constants for the SM gauge interactions. The precise definition of the minimal model of gauge-mediation (MGM) is given in Appendix A of Part III. The dependence of the fine structure constants generally leads to a hierarchy between the masses of the strongly interacting squarks and gluino, $\widetilde{Q}$ and $\widetilde{g}$, which couple to $SU(3)_C$, the Wino and left handed sleptons, $\widetilde{W}$ and $\widetilde{\ell}_L$, which couple to $SU(2)_L$, and the Bino and right handed sleptons, $\widetilde{B}$ and $\widetilde{\ell}_R$, which couple to $U(1)_Y$. The minimal expectation for the mass ordering of the superpartners with GMSB is then $m_{\widetilde{Q}}, m_{\widetilde{g}} \gg m_{\widetilde{W}}, m_{\widetilde{\ell}_L} > m_{\widetilde{B}}, m_{\widetilde{\ell}_R}$. Based on this mass ordering, either the Bino or right handed slepton, $\widetilde{B}$ and $\widetilde{\ell}_R$, are natural candidates within GMSB for the NLSP, which is crucial in determining the phenomenology. However, it is worth noting that this mass ordering is only representative of the minimal expectations for GMSB. The structure and representations of the messengers as well as their couplings to the SUSY breaking sector need not be universal. Almost any mass ordering can in fact be obtained from sufficiently general models of GMSB. So it is important when considering phenomenological signatures not to focus too closely on any one particular class of underlying model.

Perhaps the most appealing theoretical feature of GMSB is the natural lack of SUSY contributions to lepton flavor or quark flavor violating processes such as $\mu \to e\gamma$ decay, $K \leftrightarrow \bar{K}$ oscillations, or $b \to s\gamma$ decay. This arises because the leading contributions to visible sector soft SUSY breaking involving the squark and slepton superpartners depend only on gauge couplings. All soft SUSY-breaking parameters are then automatically flavor independent or aligned with the quark or lepton Yukawa couplings.

- **R-parity violating SUSY models:**

  R-parity is the discrete and multiplicative symmetry defined by

$$R_p = (-1)^{3B+L+2S}, \tag{I.1.7}$$

where B is baryon number, L is lepton number and S denotes the spin. All of the particles of the SM have even R-parity, while all of the superpartner particles have odd R-parity. Thus R-parity conservation implies that superpartner particles can only be created in pairs starting from SM initial states.

The most general renormalizable superpotential constructed from the fields of the MSSM contains both R-parity conserving and R-parity violating interactions. All of the R-parity violating interactions also violate conservation of baryon number, of lepton number, or both. These observations are connected to the fact that B and L conservation are accidental global symmetries of the Standard Model, but not of the MSSM. This leads to obvious problems with proton decay and with $\mu \to e\gamma$ or $\mu - e$ conversion in nuclei; suppressing these processes puts very severe constraints on certain products of R-parity violating couplings. In addition, generic values for the R-parity violating couplings will induce other flavor-violating effects in various Standard Model processes. There are therefore important constraints on the magnitude of various R-parity violating couplings coming from many sources, including charged current universality, atomic parity violation, $D^0 - \bar{D}^0$ mixing, neutrinoless double beta decay, and leptonic tau or pion decays.

The two main differences between the standard MSSM phenomenology and the phenomenology of explicit $\not{R}_p$ are

1. Single production of supersymmetric particles is possible. For example at a hadron collider we can have resonant slepton (charged and neutral) production via the operators $L_i Q_j \bar{D}_k$ and resonant squark production via the operators $\bar{U}_i \bar{D}_j \bar{D}_k$. This lowers the kinematic threshold for the discovery of supersymmetry.
2. The lightest supersymmetric particle (LSP) is not stable, and can possibly decay in the detector. If the LSP is the lightest neutralino it can decay, for example, via the operator $L_i Q_j \bar{D}_k$. However, since the LSP is not stable, the cosmological argument requiring it to be electrically and colour neutral no longer applies. To date there have been no systematic studies of non-neutralino LSPs in the context of $\not{R}_p$. If the LSP is charged and has an appreciable lifetime (or is stable), it can be detected in a search for charged massive particles (CHAMPs).

- **Beyond the Minimal Supersymmetric Standard Model:**

Most studies of discovery reach for supersymmetry and most of the current limits on the masses of supersymmetric particles have been obtained assuming R-parity conservation, the minimal matter content of the MSSM, and universal boundary conditions at M_G for the soft breaking parameters. While these minimal assumptions have the virtue of simplicity and can be reasonably motivated in certain theoretical contexts, other possibilities should certainly be considered. This leads of course to practical difficulties, since models with nonmiminal matter content and/or nonmimimal boundary conditions can have many more adjustable parameters. Even for a model with MSSM matter content and R-parity conservation, the most general form of soft breaking lagrangian allows for a total of 124 parameters (not counting certain additional parameters expected to be suppressed by $1/M_G$ factors). This is to be compared to the 19 parameters of the Standard Model. Expanding the Higgs sector or adding new matter generations introduces even more complexity.

Almost all of the most general parameter space is excluded by various phenomenological constraints (suppression of FCNC, proton stability, small EDM's, etc.). A sensible approach is to examine a selection of sub-spaces which differ drastically from the phenomenology of mSUGRA while maintaining consistency with all existing data. Some of these cases are nonminimal SUGRA, and others are beyond the MSSM framework entirely, possessing an extended Higgs sector, extra fermions, extra gauge bosons, or large extra dimensions.

Not surprisingly, our ability to probe some of the more exotic supersymmetry scenarios depends crucially on how well we can identify and resolve a variety of exotic experimental signatures. In some cases, this may involve dedicated searches or even hardware enhancements of the existing detectors. Thus it is important to have a clear understanding of the theoretical motivation for these scenarios, and to gear up in advance for the experimental challenges that they entail. Well-motivated examples include the possibilities of light gravitinos, gluino LSP, wino LSP, and Kaluza-Klein gravitons.

- **Higgs:**

In the Standard Model the Higgs mass is given by $m_{H_{SM}} = \lambda v^2$, where λ is the Higgs self-coupling and is an unknown parameter at present. Hence, the Standard Model Higgs mass is not predicted by the model. Current data gives no direct evidence of a Higgs boson implying a 95 % C.L. lower bound on the SM Higgs mass, $m_{H_{SM}} \gtrsim 115$ GeV (LEP). In addition a global fit to the precision electroweak data within the Standard Model yields $m_{H_{SM}} \lesssim 200$ GeV at the 95 % C.L. from the logarithmic sensitivity to the Higgs mass via virtual loop contributions.

The couplings of the Higgs boson to vector bosons and fermion pairs give the most important features of Higgs phenomenology at colliders. Within the SM these couplings are proportional to the gauge boson and fermion masses respectively.

$$g_{H_{SM}f\bar{f}} \propto -i\frac{gm_f}{2m_W}, \qquad g_{H_{SM}VV} \propto ig_V m_V \tag{I.1.8}$$

with $V = Z, W$ and $g_W = g_Z \cos\theta_W = g$. Hence, production process and decay rates can be computed as a function of the Higgs mass and the fermion and gauge boson masses. Based on these computations one can easily describe the most relevant processes for Higgs production and decay at colliders.

Another important component in determining the Higgs boson discovery potential is the background associated with a given signature. For example, at the Tevatron the main production channel for $m_{H_{SM}} <$ 135 GeV is via loop-induced gluon fusion to a Higgs with subsequent decay of the Higgs into a pair of bottom quarks. This channel, however, is swamped by QCD background. The next available channel is the associated production of a Higgs boson with a weak gauge boson, WH and ZH, with $H \to b\bar{b}$ and $V \to$ leptons, which turn to be the best search channel in this mass range.

For 135 GeV $< m_{H_{SM}} <$200 GeV, instead, the SM Higgs boson decays dominantly to $WW^{(*)}$ pairs and the dilepton channels coming from Higgs production via gluon fusion and the associated vector boson-Higgs production are the most promising channels.

In the supersymmetric case, the simplest realistic model of low energy supersymmetry contains a Higgs sector with two Higgs doublets. The physical Higgs spectrum consists of a charged Higgs boson $H^{\pm}$, a CP-odd scalar A and 2 CP-even scalars h and H. The supersymmetric structure of the theory imposes constraints on the Higgs sector of the model: The Higgs self interactions can be expressed in terms of the electroweak gauge couplings and at tree-level the Higgs sector is given as a function of two parameters, $\tan\beta = v_2/v_1$ (ratio of the two Higgs vacuum expectation values) and the CP-odd Higgs mass m_A.

After considering the quantum corrections, due to the interactions of the Higgs boson with the SM particles and their supersymmetric partners, the Higgs sector acquires a strong dependence on the supersymmetry breaking parameters via the third generation squark mass parameters and mixing angles. The Higgs masses and couplings, production and decay rates, are hence governed not only by the gauge boson and fermion masses (in particular the top quark mass) but also by $\tan\beta$, m_A and the SUSY breaking mass parameters of the stop and sbottom sector, m_Q, m_U, m_D, A_t and A_b, as well as the supersymmetric Higgs mass parameter μ. Within a specific supersymmetry breaking framework, the low energy values of the supersymmetry breaking parameters are determined, via their renormalization group evolution, by their high energy values. Although specific supersymmetry breaking scenarios are based on simplifying assumptions which are ad hoc, the resulting models do provide examples of how the soft supersymmetry breaking parameters may be correlated. The results of such correlations constrain the Higgs sector of a generic MSSM in various ways. For example, within the generic MSSM the lightest CP-even Higgs mass is bounded to be below 135 GeV, assuming that the SUSY particles are not much above the TeV Scale. Within the MSSM, restricted scenarios of SUSY breaking yield more stringent bounds on the lightest Higgs mass which are just above the experimentally tested region by LEP. On the other hand, in a general SUSY model, with non-minimal Higgs content, the lightest Higgs boson mass could be as large as about 200 GeV. The discovery of a Higgs boson of the MSSM will place important constraints on the underlying supersymmetric parameters.

In Run II of the Tevatron collider, with the new Main Injector and antiproton Recycler, the machine will deliver more than an order of magnitude more instantaneous luminosity, and ultimately two orders of magnitude more integrated luminosity to the CDF and DØ experiments than in Run I. More specifically, the initial goal of Run II (called Run IIa) is to deliver >2 fb^{-1} by the end of 2004 and about 15 fb^{-1} by the end of 2008.

The machine center of mass energy is increased from 1.8 TeV to almost 2.0 TeV. Both CDF and DØ will have greatly improved detectors, with all new charged particle tracking and vertexing, improved calorimetry and triggering, and new offline analysis software. This prospect greatly enhances the discovery potential for new particles. The aim of this report is to present a realistic study, as realistic as our present understanding of the collider and detector capabilities allows us, of the upgraded Tevatron potential to search for a SM Higgs boson as well as for physics signatures beyond the Standard Model: superpartner particles and the extended supersymmetric Higgs sector.

The results of the feasibility studies done during the SUSY/Higgs Run II workshop are very encouraging since they show a real window of opportunity for unraveling the essence of the physics beyond the Standard Model at the upgraded Tevatron.

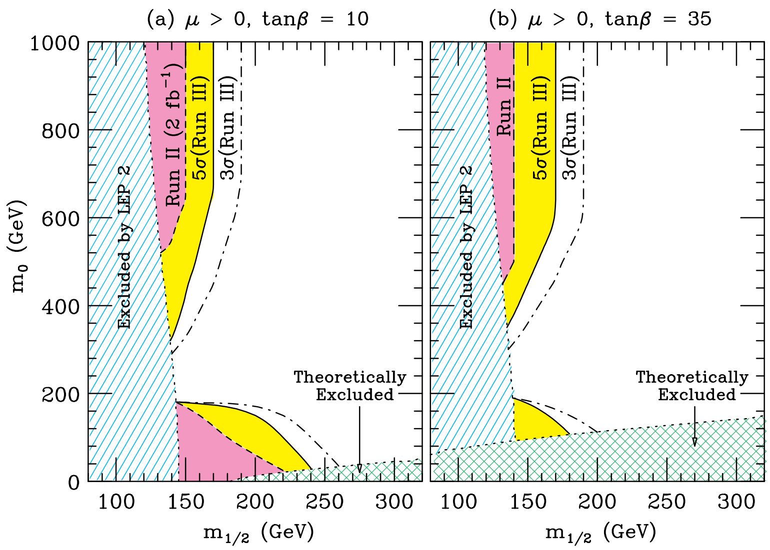

FIGURE I.1: The contours of 99% C.L. observation for 2 fb^{-1} and 5σ discovery as well as 3σ observation with 30 fb^{-1}, for $p\bar{p} \to$ SUSY particles $\to 3\ell + X$ with soft cuts, in the $(m_{1/2}, m_0)$ plane, for $\mu > 0$, with (a) $\tan\beta = 10$ and (b) $\tan\beta = 35$. Also shown is the region excluded by LEP2.

2 MSUGRA

Within the mSUGRA framework (or any model where gaugino masses are unified at some high scale), gluinos are much heavier than charginos and neutralinos. Furthermore, renormalization effects tend to make squarks even heavier. Thus for large enough gluino masses, electroweak production of charginos and neutralinos becomes the most important sparticle production mechanism at a high luminosity hadron collider. Indeed $\tilde{\chi}_1^\pm \chi_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production are the SUSY processes with the largest cross sections at the Tevatron. QCD radiative corrections increase the cross sections by 10–35%. $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production followed by their leptonic decays results in the clean trilepton signature for SUSY. This signal, together with the $jets + \not{E}_T$ (possibly with leptons) signal, had been exhaustively examined even before the Workshop, and have been generally viewed as the main channels for SUSY search at the Tevatron. Just before the start of the Workshop, it was pointed out that for large values of $\tan\beta$, charginos and neutralinos preferentially decay to third generation fermions (mostly taus), and possibly also sfermions. Thus cross sections for multilepton signals, including the much touted trilepton signal, could be much reduced relative to their expectation for low $\tan\beta$, and the reach of the Tevatron correspondingly diminished. Furthermore it was pointed out that alternative signatures involving b-jet and τ-lepton tagging might be necessary to extend the reach when $\tan\beta$ is large.

A mSUGRA with large $\tan\beta$

A major effort of the Workshop was to identify new signatures that would allow sparticle detection even for large values of $\tan\beta$. The Wisconsin Group first pointed out that by softening the cuts on the leptons, it may be

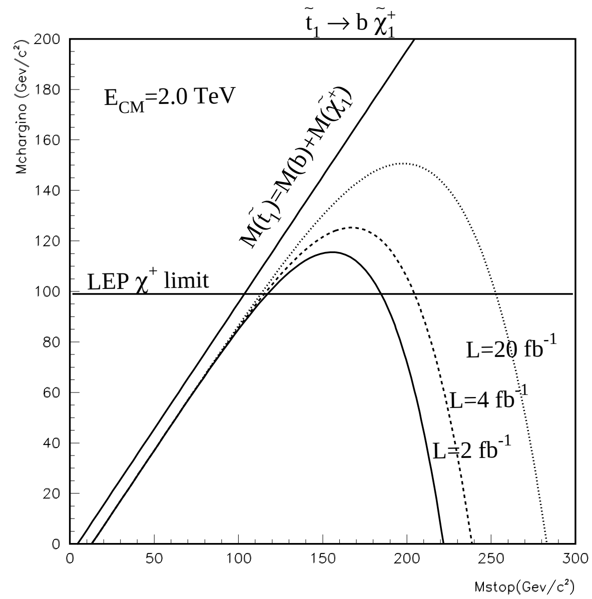

FIGURE I.2: Sensitivity to searches for stop pair production in $\tilde{t}_1 \to \tilde{\chi}_1^+ b$ channel.

possible to detect the trilepton signal from $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production even if these decayed to taus which subsequently decay to e or μ. Backgrounds to the soft lepton signals were carefully reassessed. It was found that W^*Z^* and $W^*\gamma^*$ production (where γ^* is virtual and the W and Z may be real or virtual) gave rise to trilepton events with a cross section of $\mathcal{O}(10)$ fb even within the Standard Model. While this level is negligible for Run I, new strategies had to be identified in order to maximize the reach for integrated luminosities envisioned for Run II, where signals at the fb level are potentially observable.

For low values of $\tan\beta$, experiments at Run IIa may probe $m_{1/2}$ values [1] beyond 250 GeV at the 5σ level if other parameters are in a favourable region, while at Run IIb this reach may exceed 275 GeV (corresponding to a gluino of almost 700 GeV in mSUGRA). The discovery potential is sensitive to $\tan\beta$, but even for $\tan\beta = 35$ experiments at Run II will probe beyond the reach of LEP 2, whereas with an integrated luminosity of 30 fb^{-1} SUSY discovery for $m_{1/2}$ values up to 180 GeV may be possible. The discovery contours are summarized in Fig. I.1 for two large values of $\tan\beta$.

Another interesting strategy for sparticle detection at large $\tan\beta$ explored at the Workshop entails direct detection of taus via their hadronic decays. This is especially interesting, as observation of an excess of τ leptons in SUSY events over corresponding e and μ signals, would suggest Yukawa interaction effects, and may thus serve to indicate that $\tan\beta$ is large. A particularly challenging scenario with $2m_{\tilde{\chi}_1^0} \sim (4/3)m_{\tilde{\tau}_1} \sim m_{\tilde{\chi}_1^{\pm}}$ (with other sparticles heavy), so that $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ almost exclusively decay via $\tilde{\chi}_1^{\pm} \to \tilde{\tau}_1\nu$ and $\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau$, respectively, was examined using TAUOLA and PYTHIA interfaced with the SHW detector simulation. The signatures consist of events with 'tau jets' and/or soft leptons from secondary decays of τs. It was confirmed that the usual trilepton signal is unobservable (at the 3σ level) even at Run IIb unless charginos are lighter than ~110 GeV, so that SUSY has to be searched for via channels with identified τs. The misidentification of QCD jets as taus is then an important (detector-dependent) background. Nonetheless, it was shown that SUSY signals in $\ell\ell\tau_h$ and $\ell^{\pm}\ell^{\pm}\tau_h$ channels (here, $\ell = e$ or μ, and τ_h denotes a tau tagged via its hadronic decay) would be observable at the 3σ level for integrated luminosities of a few to ~30 fb^{-1}, for a chargino mass up to 140 GeV. The same-sign dilepton plus tau channel has the better signal to background ratio, but suffers from low rates. The observability of the 'tau jets' is helped by the fact that $\tilde{\tau}_1$ is dominantly $\tilde{\tau}_R$ (in many models, as well as in this analysis) since the polarization of the daughter taus then results in the hadronic decay products being preferentially emitted along the tau direction, and so leads to harder 'jets' which are, of course, easier to detect: τ_h signals in (fortunately, unconventional) models where $\tilde{\tau}_1 \sim \tilde{\tau}_L$ would be more difficult to identify.

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1) The soft SUSY breaking $SU(2)$ gaugino mass is $\sim 0.8m_{1/2}$ and, as long as $|\mu|$ is not small, $m_{\tilde{\chi}_1^{\pm}} \sim (0.7-0.8)m_{1/2}$.

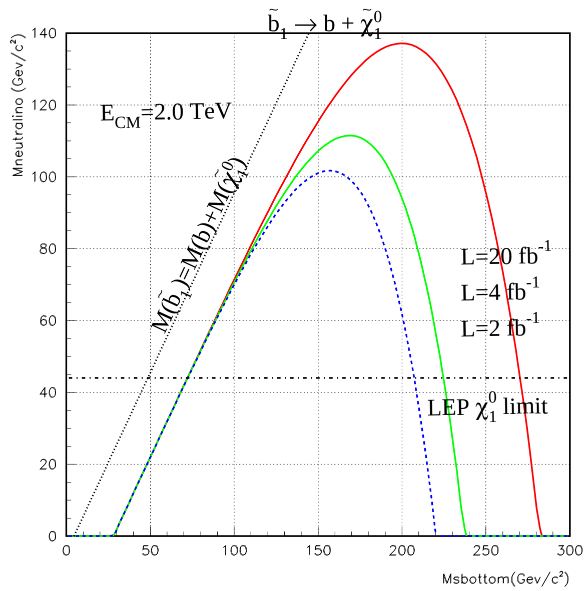

FIGURE I.3: CDF discovery potential of bottom squarks in the channel $\tilde{b}_1 \to b\tilde{\chi}_1^0$.

B Light stops and sbottoms

Large Yukawa couplings of the top quark, and if $\tan\beta$ is large, also of the bottom quark, make the corresponding squark lighter than other squarks. The reach of the Tevatron for stops and sbottoms is sensitive to how these decay. At Run IIa (Run IIb), experiments should be sensitive to stops as heavy as 180–200 GeV (250 GeV) if $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ or $\tilde{t}_1 \to b\ell\tilde{\nu}$, and is $\sim$ 40 GeV smaller if $\tilde{t}_1 \to c\tilde{\chi}_1^0$. This is exemplified in Fig. I.2. Experiments at Run IIa (Run IIb) should be sensitive to b-squarks heavier than 200 GeV (240 GeV) if they decay via $\tilde{b}_1 \to b\tilde{\chi}_1^0$. The degradation of the reach is expected to be smaller than 30–40 GeV even if $\tilde{b}_1$ decays via modes which make the signal more difficult to detect.

C Remarks on mSUGRA searches

While most of the focus of our Group was on Tevatron signals within the mSUGRA framework, we recognize that our conclusions about the Tevatron reach are sensitive to untested underlying assumptions about the symmetries of physics at higher energies. It could, however, be that these assumptions turn out to be incorrect, and the lightest neutralino decays into photons (as in some gauge-mediated SUSY breaking models, or into leptons (as in some R-parity violating models, which then provide additional handles to beat down Standard Model backgrounds, and hence, enhancing the reach of the Tevatron. On the down side, it is also possible that the lightest neutralino decays hadronically, and for one reason or another, leptons from cascade decays of sparticles are either soft or even entirely absent. In this case SUSY may well remain hidden at the Tevatron even if sparticles are light.

Even within the restricted framework of mSUGRA, there are many different sparticle discovery channels accessible at the Tevatron in Run II. New channels have been explored which extend the reach in the mSUGRA parameter space to new regions. Our simulations show that in many channels the Run II discovery potential goes significantly beyond what was probed by experiments at LEP and Tevatron Run I. Whereas large integrated luminosities will be important to maximize the discovery reach in several channels, a very genuine chance of mSUGRA sparticle discovery will already be available from the first few inverse femtobarns of Run II data.

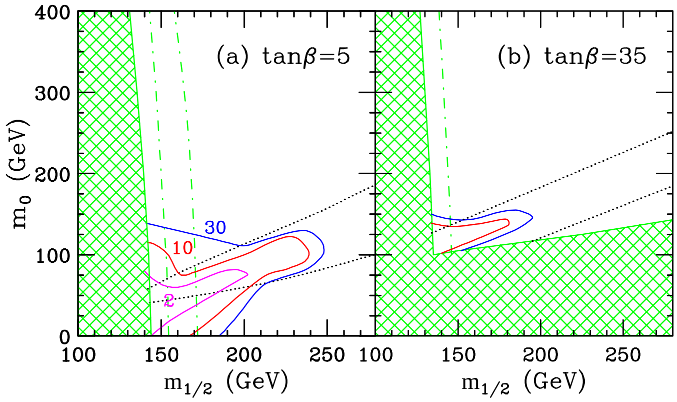

FIGURE I.4: Tevatron reach in the dilepton plus tau jet channel in the $M_0 - M_{1/2}$ plane, for fixed values of $A_0 = 0$, $\mu > 0$ and (a) $\tan\beta = 5$, or (b) $\tan\beta = 35$. Results are shown for 2, 10 and 30 fb^{-1} total integrated luminosity.

3 LOW-SCALE AND GAUGE-MEDIATED SUSY BREAKING

Low scale gauge mediated supersymmetry breaking provides a particularly attractive theoretical solution to the problem of flavor-violation in the supersymmetric Standard Model. The existence of a nearly massless Goldstino to which the NLSP can decay, provides an attractive and rich set of experimental possibilities for Run II, with a variety of potentially spectacular signals. The various classes of signals depend on the identity of the NLSP and its decay length.

The experimental signatures which have been identified in this report as being useful for the Tevatron Run II and future upgrades are summarized below.

A Bino-Like NLSP

- For prompt decays of a Bino-like $\widetilde{\chi}_1^0$ NLSP, there will be a very substantial reach in the $\gamma\gamma\ X\ \not{E}_T$ channel, where X can be anything, but likely includes jets.
- Cascade decays to the Bino-like $\widetilde{\chi}_1^0$ NLSP can include a neutral Higgs boson, h, with fairly high probability. The SUSY signature of two hard photons and $\not{E}_T$ could then be used as a unique method of obtaining a sample of Higgs bosons.
- For macroscopic decay lengths of a Bino-like $\widetilde{\chi}_1^0$ NLSP, the resulting displaced photons can be resolved and provide a useful signal. The properties of the DØ preradiator allow for a particularly sensitive probe of decay lengths down to the few centimeter level.

B Higgsino-Like NLSP

- Prompt decays of a Higgsino-like $\widetilde{\chi}_1^0$ NLSP can yield γ, h, and Z bosons, giving rise to signatures with photons, b-jets, jets, and reconstructed leptonic Z bosons in combinations that depend strongly on the underlying SUSY parameters. This allows for a particularly rich set of possibilities for event selections. Many of the signatures are interesting on general grounds, since they can arise in other, unrelated, new physics scenarios.

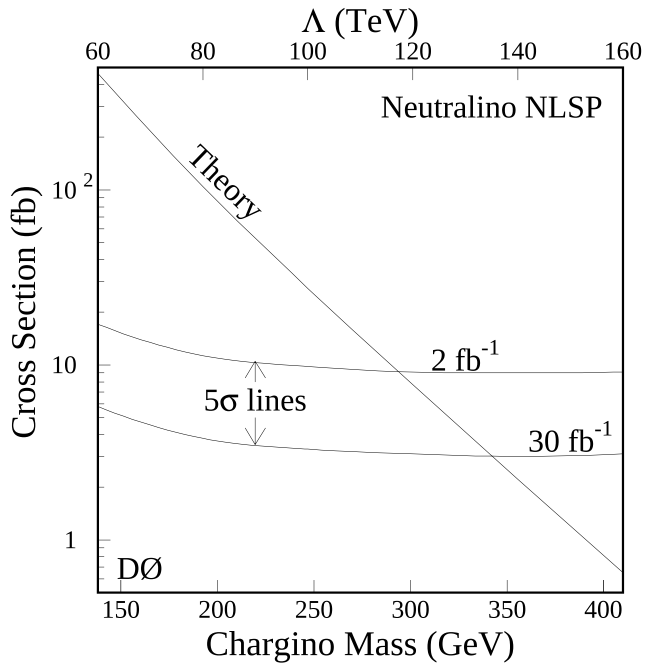

FIGURE I.5: The 5σ discovery cross section curves as functions of the chargino mass along with the SUSY cross sections for the Bino-like Neutralino Model Line in the DØ studies. The two curves correspond to integrated luminosities of 2 and 30 fb^{-1}.

TABLE I.1.: Projected limits and discovery potential for $\gamma\gamma X \not{E}_T$ events along the Bino-like Neutralino NLSP Model Line with 2 fb^{-1} in the CDF study.

Λ (TeV)	92	110	128	157
$m_{\tilde{\chi}_1^\pm}$ (GeV)	225	275	325	403
$m_{\tilde{\chi}_1^0}$ (GeV)	121	146	171	212
$\sigma\times$BR (fb)	46	14.0	4.0	0.60
Total $A \cdot \epsilon$ (%)	41	44	45	46
Signal events	38	12	3.6	0.55
95% C.L. limit (fb)	4.9	4.5	4.4	4.3
5σ discovery (fb)	21.0	19.0	19.0	19.0

- The presence of Higgs bosons from $\tilde{\chi}_1^0$ decays can lead to a interesting source of tagged Higgs events.

- For decays of a Higgsino-like $\tilde{\chi}_1^0$ NLSP with macroscopic decay length, but contained within the detector, displaced photons, displaced Z bosons, or displaced Higgs bosons arise. The displaced hadronic final states, including b-jets from displaced Higgs decay, yield tracks with large negative impact parameters (LNIPs) with reconstructed displaced jets pointing towards, rather than away from, the beam axis.

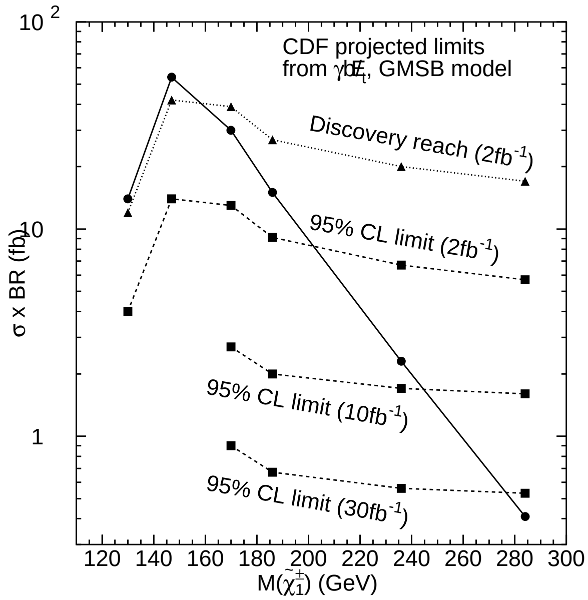

FIGURE I.6: CDF projected Run II limits on the total SUSY cross section times branching ratio in the $\gamma b X \not\!\!E_T$ channel along the Higgsino-like Neutralino Model Line I as a function of chargino mass. The solid line is the theoretical expectation from the Higgsino-like Neutralino NLSP Model Line I.

C Stau NLSP

- Prompt decays of a $\widetilde{\tau}_1$ NLSP give rise to events with same-charge taus (either manifested as hadronic one-prong or three-prong decays, or as leptonic decays). Depending on the underlying SUSY parameters a variety of different multi-lepton and multi-tau event selections are possible. In some cases, it is best to require an additional one or two hard jets, since these occur in SUSY cascade decays but not in relevant backgrounds. All these signatures depend crucially on tau identification efficiency, which will need to be evaluated once the detectors are operating.

- Stau decays that take place within the instrumented region of a detector yield events with a decay kink. Such a non-relativistic stau leaves a highly ionizing track (HIT) with a kink to a hadronic tau jet or an e or μ from a leptonic tau decay.

- Quasi-stable staus which traverse the entire detector before decaying will appear either as HITs or an excess of fake "muons", i.e. minimum ionizing tracks (MITs). Both CDF and DØ have found a significant reach in this search. In addition, the CDF time-of-flight (TOF) detector has been found to be quite useful in this search since the staus are non-relativistic. Stau pairs will often have the same charge, allowing another useful handle on the events.

- The charge changing three-body cascade decays of selectrons and smuons, for example, $\widetilde{e}_R^+ \to e^+ \tau^+ \widetilde{\tau}_1^-$, can also have a macroscopic decay length if the selectron (or smuon) is nearly degenerate with the stau. The electron and tau released in the decay are typically very soft (and could easily be missed) with the final state stau traveling in the forward direction. This gives rise to charge-changing HITs (CC-HITs), since the non-relativistic selectron (or smuon) can convert to a stau of the opposite charge within the tracking region.

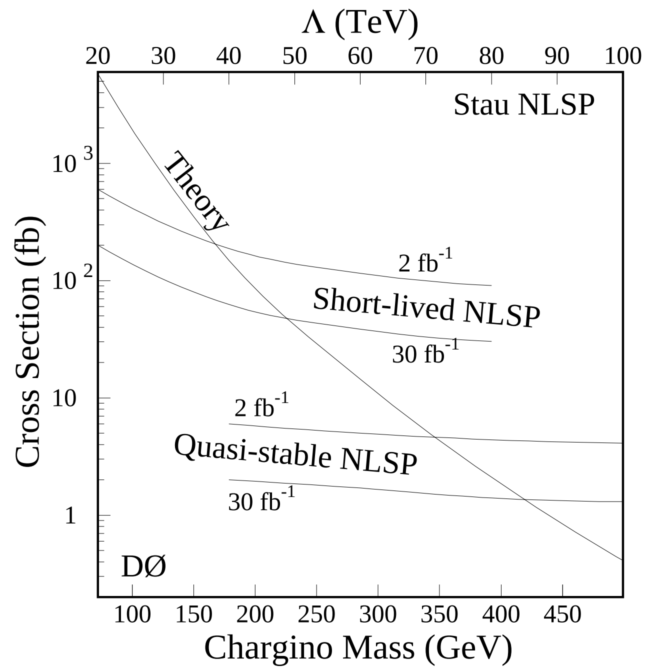

FIGURE I.7: The DØ 5σ discovery cross section curves as functions of mass of the lighter chargino and the supersymmetry breaking scale Λ for the Stau NLSP Model Line, along with the theoretical cross sections. The 5σ curves are shown for both short-lived NLSPs (combining $\ell^{\pm}\ell^{\pm}jj\not{E}_T$ and $\ell\ell\ell j\not{E}_T$ selections) and quasi-stable NLSP's ($\ell\ell + dE/dx$ selection) and for integrated luminosities of 2, 30 fb^{-1}.

D Slepton Co-NLSP

- If the three lightest sleptons $\tilde{\tau}_1$, $\tilde{e}_R$, and $\tilde{\mu}_R$ are degenerate in mass to within 1.8 GeV, then all three play the role of the NLSP. If the decays of the slepton co-NLSPs are prompt, a variety of signatures involving taus and leptons result. The event topologies are very similar to those in the Stau NLSP case, but the flavor and multiplicity profiles can be quite different. In particular, there is a greater tendency for lepton democracy in the events.
- As in the case of a Stau NLSP, macroscopic or long decay lengths for slepton co-NLSPs can give rise to HIT→ lepton kinks, HITs through the detector, an excess of fake “muons”, and an anomalous time-of-flight.

E Squark NLSP

- Prompt decay of a stop-like squark NLSP to a top-like final state gives a signature with a top quark event topology. Large $\not{E}_T$, lepton-b-jet invariant mass, and W boson polarization can be used to partially separate these from top quark backgrounds. Prompt decay to a charm final state can be searched for in a standard SUGRA analysis for stop pair production.
- Decay of a squark NLSP over a macroscopic distance, but contained within the tracking region, gives rise to displaced jets with large E_T and $\not{E}_T$. The angular distribution of the displaced jets is roughly uniform, and may be searched for in events with large negative impact parameters (LNIPs) with the reconstructed displaced jets pointing towards, rather than away from, the beams axis.
- Quasi-stable squarks (anti-squarks) will hadronize to form mesinos and sbaryons (anti-mesinos and anti-sbaryons). The slowly-moving anti-mesino and sbaryon bound states can exchange isospin and charge with background material in the course of traversing a detector. Non-relativistic bound states of these

types therefore yield intermittent charge-exchange associated with highly ionizing tracks (CE-HITs) which alternate between highly ionizing charged and neutral segments in the calorimeter. Mis-identification of CE-HITs can contribute to $\not\!\!E_T$. Quasi-stable mesinos or anti-sbaryons do not as readily charge exchange. Squark and gluino bound states can also yield fairly soft hadronic activity along a highly ionizing track (H-HIT). This is due to inelastic hadronic interactions of the bound state with the calorimeter materials. Even though non-relativistic hadronized NLSP squarks can carry significant momentum, they deposit little energy in the calorimeters. Both CE-HITs and H-HITs are likely to appear as HITs in the inner tracking region.

- NLSP squarks hadronized in mesino bound states can undergo mesino-antimesino oscillations. For stop-like squarks this yields events with a same sign top-top topology. Mesino oscillations might also be observed directly as oscillations in the signed decay length distributions.

F Gluino NLSP

- Prompt decay of a gluino NLSP will lead to events with two very hard gluon jets and very large $\not\!\!E_T$.
- For decays of a gluino NLSP with macroscopic decay length, but contained within the detector, large E_T displaced gluon jets with large $\not\!\!E_T$ result.
- Quasi-stable gluino NLSPs hadronize as R-hadrons and can charge exchange with matter, resulting in CE-HITs. Charged non-relativistic R-hadrons should appear as HITs in the inner tracking region and have anomalous time-of-flight.

It is an exciting challenge to implement these signatures in searches for low-scale supersymmetry using real Run II data.

4 R-PARITY VIOLATING MODELS

The most general R-parity violating renormalizable superpotential constructed out of MSSM superfields is

$$W_{\not R_p} = \frac{1}{2}\lambda_{ijk}\epsilon_{ab}L_i^a L_j^b E_k^c + \lambda'_{ijk}\epsilon_{ab}L_i^a Q_j^b D_k^c + \lambda''_{ijk}\epsilon_{xyz}U_i^{cx}D_j^{cy}D_k^{cz} + \kappa_i\epsilon_{ab}L_i^a H_2^b. \tag{I.4.9}$$

Here $i,j,k = 1,2,3$ are generation indices, $a,b = 1,2$ are $SU(2)$ isospin indices, and $x,y,z = 1,2,3$ are $SU(3)$ colour indices. $\lambda, \lambda', \lambda''$ are dimensionless Yukawa couplings. κ_i are mass terms mixing the leptonic and Higgs doublets. We have employed the standard notation for the chiral superfields of the MSSM.

A Single sparticle production

Single slepton production via $q\bar{q}^{(\prime)}$ annihilation at the Tevatron can occur through the λ' couplings. If this slepton decays to opposite sign leptons (through the λ couplings) then an event excess, clustered in mass, will be observed in the Drell-Yan channel similar to that expected for a new neutral or charged gauge boson, Z' or W'. Fig. I.8 shows the 95% C.L. Tevatron exclusion reach as a function of $X = (\lambda')^2 B_\ell$, where B_ℓ is the leptonic branching fraction of the sleptons. The figure indicates a very impressive improvement over the reach from Run I, both to very large masses and to small values of the R-parity violating couplings. In addition, both $\tilde{\ell}$ and $\tilde{\nu}$ resonances may decay hadronically via the same vertices that produced them, leading to potentially observable peaks in the dijet invariant mass distribution. This signal is also observable at the Tevatron over a wide range of parameters.

S-channel charged slepton production can be followed by an R-parity conserving decay to a charged lepton and the lightest neutralino. Subsequent decay of the neutralino via the R-parity violating λ' coupling yields a final signature containing like-sign dileptons. An analysis of the physics background for like-sign dilepton production at Run II shows that with an integrated luminosity of $2\,\mathrm{fb}^{-1}$, a cut on the transverse momentum of the leptons of 20 GeV and an isolation cut of 5 GeV the background is 0.14 ± 0.13 events. This means that

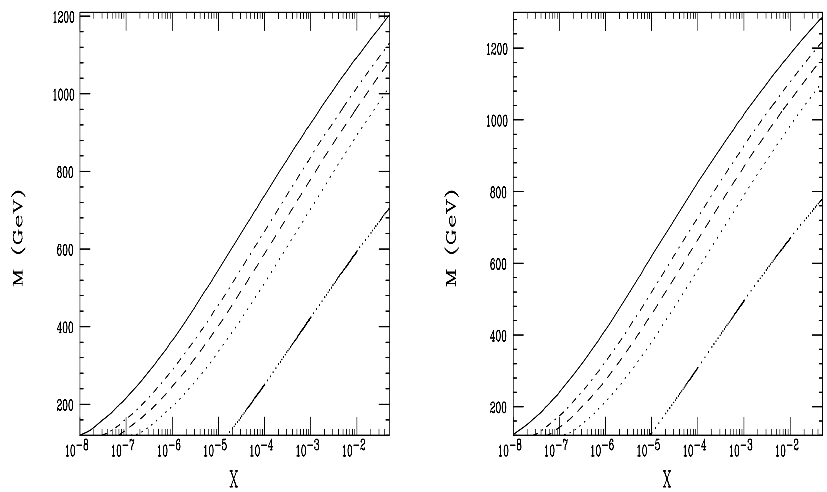

FIGURE I.8: Exclusion regions (lying below the curves) in the mass-coupling plane for $R\!\!\!/_p$ resonances in the neutral (left) and charged (right) Drell-Yan channels at the Run II Tevatron. From top to bottom the curves correspond to integrated luminosities of 30, 10, 5 and 2 fb^{-1}. The estimated reach for Run I is given by the lowest curve. The parameter X is defined in the text.

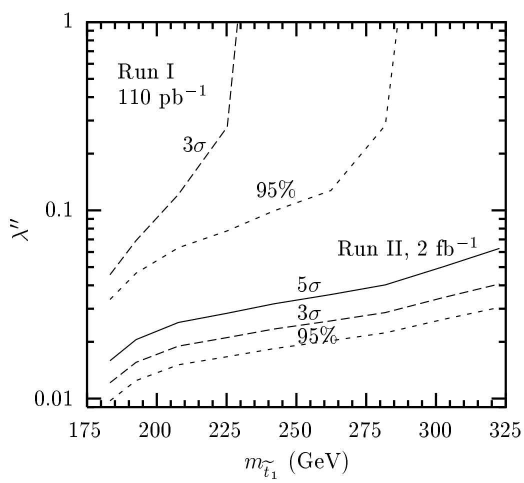

FIGURE I.9: Lower limits on discovery ($S/\sqrt{B} = 5$), evidence ($S/\sqrt{B} = 3$), and 95% confidence-level exclusion ($S/\sqrt{B} = 1.96$) for λ'' versus top-squark mass in Run I of the Tevatron ($\sqrt{s} = 1.8$ TeV, 110 pb^{-1}), and in Run II ($\sqrt{S} = 2$ TeV, 2 fb^{-1}).

4 signal events would correspond to a 5σ discovery, although in a full experimental analysis the non-physics backgrounds must also be considered.

S-channel production of a relatively light stop can occur via the R-parity violating λ'' coupling. One can probe this R-parity violating production process by considering the subsequent R-parity conserving decay $\tilde{t}_1 \to b\tilde{\chi}_1^+$, with $\tilde{\chi}_1^+ \to l^+ + \nu + \tilde{\chi}_1^0$. In Fig. I.9, we show the reach in λ'' for $180 < m_{\tilde{t}_1} < 325$ GeV. With an integrated luminosity of 2 fb^{-1} at $\sqrt{S} = 2$ TeV, discovery at the level of 5σ is possible provided that $\lambda'' >$ 0.02–0.05. Otherwise, a 95% confidence level exclusion can be set for $\lambda'' >$ 0.01–0.03. This is an improvement for Run IIa of about an order of magnitude over the reach from Run I.

B Sparticle pair production

Small R-parity violating couplings lead to scenarios where sparticle production is dominantly via R-parity conserving processes (which produce sparticles pairwise), while sparticle cascades always terminate with R-parity violating decays. These decay chains may be conventional SUSY cascades followed by R-parity violating decays of the LSP's, or they may involve direct R-parity violating decays of heavier sparticles into SM particles.

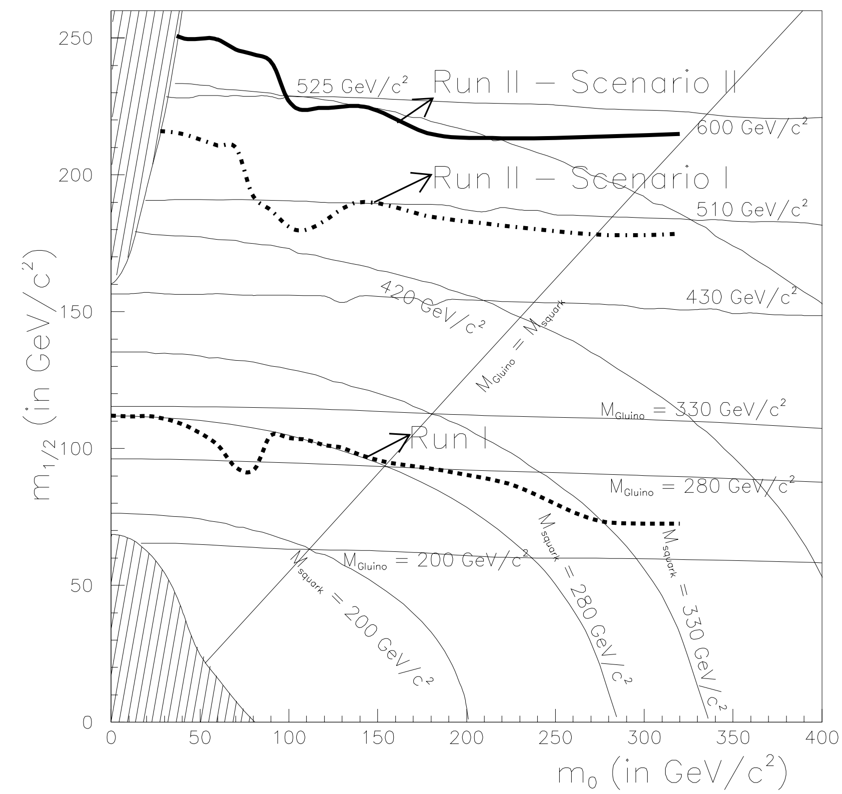

FIGURE I.10: Estimated exclusion contour for Run 2 in the $(m_0, m_{1/2})$ plane for $tan\beta = 2$, $A_0 = 0$, $\mu < 0$, from the $ee + 4$ jets channel, assuming no SUSY signal is observed. Scenario I corresponds to a background of $36 \pm 4 \pm 6$ events (direct scaling from Run 1); scenario II uses the background of $15 \pm 1.5 \pm 1.5$ events (scaling, but with improvements in the detector taken into account). The scenarios are defined in Part IV.

CDF and DØ studies of sparticle pair production were performed, concentrating mainly on λ' induced R-parity violating decays. The simulated signatures were dielectron and dimuon production accompanied by jets but no significant $\not{E}_T$. As can be seen in Fig. I.10, The Run IIa exclusion mass reach is very impressive, and is approximately double what could be achieved for Run I.

The case in which the only significant R-parity violating coupling is λ'' poses interesting challenges, since the classic SUSY missing energy signatures are replaced by multijet decays of the LSP. However a Workshop study showed even in this case, the very large number of jets expected for a typical SUSY event will allow us to isolate the SUSY signal so long as gluino (and/or squark) masses are sufficiently low that SUSY event rates are substantial. Further, there is the possibility of being able to measure the strength of the λ'' coupling, either from the decay length of the LSP, or by comparing the R-parity conserving and R-parity violating branching fractions of chargino decays.

Theoretical models with spontaneously broken R-parity can lead to a case where the only significant R-parity violating coupling is κ_3, the bilinear coupling of the 3rd generation lepton doublet to the up-type Higgs doublet. In this case the top-quark and the top-squark get additional decay modes, e.g. $t \to \tilde{\tau}_1^+ b$ or $\tilde{t}_1 \to \tau^+ + b$. The resulting nonstandard top decay signatures should be observable in Run IIa for branching ratio values as low as $10^{-3} - 10^{-2}$, depending on the mode. The R-parity violating 2-body stop decay channel is distinctive, and makes it phenomenologically acceptable to have a stop LSP. However Run I limits on third generation leptoquarks already exclude much of the parameter space for this scenario which would have been accessible in Run II.

5 BEYOND THE MSSM

A Gluino LSP

In mSUGRA, the LSP is essentially always a light bino-like neutralino, $\widetilde{\chi}_1^0 \sim \widetilde{B}$. However, there is substantial motivation for the possibility that the LSP is a massive gluino. This occurs if $M_3 \ll M_{1,2}$, as is possible in several well-motivated SUSY-breaking scenarios. As soon as a $\widetilde{g}$-LSP is produced in a detector, it picks up a gluon or quark-antiquark combination to form an 'R-hadron'; $R^0 = \widetilde{g}g$ is likely to be the lightest state, but color-singlet $\widetilde{g}q'\overline{q}$ states could have very similar mass, and if the difference in mass between such states and the R^0 were $< m_\pi$ they would be pseudo-stable in the detector. The behavior of a $\widetilde{g}$-LSP in a typical detector depends very much upon whether the dominant R-hadron fragment is charged (probability P) or neutral (probability $1-P$). Simple quark counting models suggest that $P < 1/2$. Accelerator data places quite significant constraints on a gluino LSP. Currently, for any reasonable value of the probability P for $\widetilde{g} \to$ charged R-hadron fragmentation ($P \leq 1/2$), $3 \lesssim m_{\widetilde{g}} \lesssim 130-150$ GeV is excluded at 95% CL by a combination of OPAL, LEP1 and CDF Run I jets+$\not{p}_T$ analyses. For the theoretically much less likely $P \geq 3/4$ range, there is a window $23 \lesssim m_{\widetilde{g}} \lesssim 50$ GeV that (depending upon the hadronic path length of the $\widetilde{g}$-LSP in the detector and the average energy deposited in each hadronic collision) might not be excluded by the jets+$\not{p}_T$ analyses and would also not be excluded by the OPAL and CDF searches for heavily ionizing tracks. However, it is apparent that more optimized CDF procedures are capable of easily excluding this window. The increase in the lower bound on $m_{\widetilde{g}}$ that will result from Run II Tevatron jets+$\not{p}_T$ data will be limited by the level of systematic uncertainty in the absolute normalization of the background level.

The scenario in which the gluino is the NLSP, with subsequent decay into the gravitino, was also considered. In this case, CDF Run I analysis excludes $m_{\widetilde{g}} \leq 240$ GeV (down to very low values), while Run II data can be expected to exclude at the very least $m_{\widetilde{g}} \leq 280$ GeV (assuming $S/B > 0.2$ is required — better if smaller S/B can be excluded).

B Wino LSP

Another possible arrangement of the gaugino masses that arises in string and brane models is $M_2 < M_1 < M_3$. In this case, the LSP $\widetilde{\chi}_1^0$ is wino-like and is highly degenerate with the lightest chargino. (This assumes $|\mu|$ is large, as usually implied by radiative electroweak symmetry breaking.) A wino-like LSP is also a feature of anomaly-mediated SUSY models. The resulting phenomenology differs greatly from mSUGRA phenomenology. If $\Delta m_{\tilde{\chi}} \equiv m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0} < m_\pi$, the chargino has an average decay length of a meter or more, and leaves a highly-ionizing track in the detector. If $m_\pi < \Delta m_{\tilde{\chi}} \lesssim 300$ MeV striking background-free signals for $\widetilde{\chi}_1^+\widetilde{\chi}_1^- + \widetilde{\chi}_1^\pm\widetilde{\chi}_1^0$ production will be present. For $\Delta m_{\tilde{\chi}}$ above 300 MeV, one begins to fight large hadronic backgrounds, and the chargino is not sufficiently long-lived to leave a visible track. In this case, for 300 MeV $\lesssim \Delta m_{\tilde{\chi}} \lesssim 10$ GeV, the most useful signal is $\gamma + \not{E}_T$, but detection of such charginos is a real challenge.

C Superlight gravitinos

If $m_{\widetilde{G}}$ is very small, the couplings of the $\widetilde{G}$ are sufficiently large that processes in which the $\widetilde{G}$ is directly produced have observable rates. Since the $\widetilde{G}$ is undetectable, the most basic signature is jets plus missing energy. If these processes are detected, they provide a measurement of the scale of supersymmetry breaking $\sqrt{F}$. The production of events with a high-E_T jet plus large $\not{E}_T$ at 2 TeV was studied with the help of Monte Carlo simulations for the production of superlight gravitinos and of Standard Model backgrounds. A

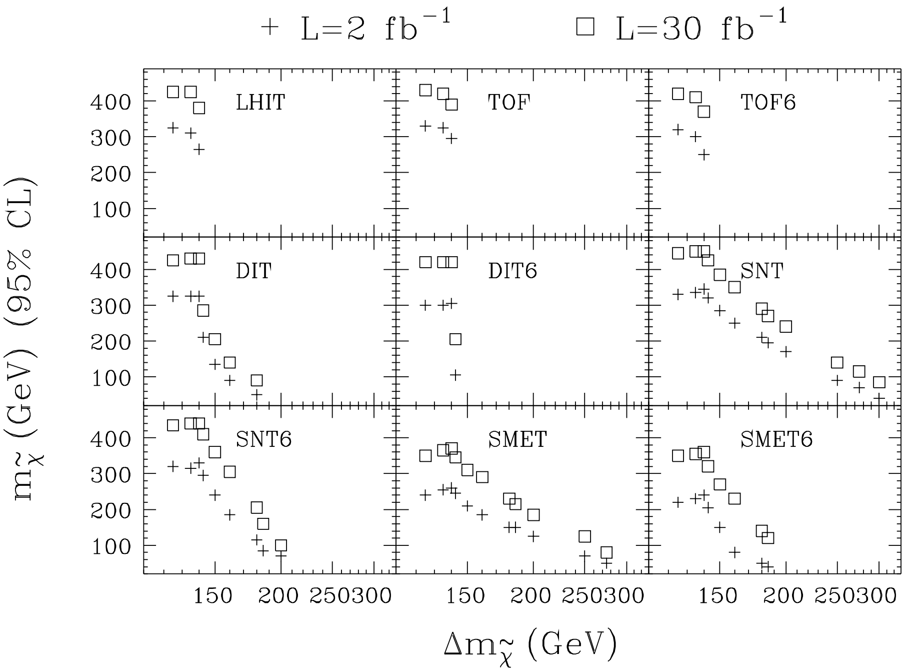

FIGURE I.11: 95% CL lower limits on $m_{\tilde{\chi}_1^\pm}$ as a function of $\Delta m_{\tilde{\chi}}$ for "background–free" signatures at Run II with $L = 2$ fb^{-1} and $L = 30$ fb^{-1}.

set of simple selection criteria was defined which are quite efficient on the signal but strongly suppresses the backgrounds. Comparing the estimated background to the expected signal as a function of $\sqrt{F}$, produced a 95% C.L. lower limit on the supersymmetry-breaking scale $\sqrt{F} \geq 290$ GeV for Run II with 2 fb^{-1}. This limit corresponds to a lower limit on the gravitino mass of 2.0×10^{-5} eV and is expected to improve once the systematic uncertainty on the background estimate is reduced.

D Very heavy superpartners

Most SUGRA models avoid unacceptably large FCNC by assuming either flavor universal scalar masses or flavor alignment at the high energy scale. An interesting alternative is the possibility that the scalar masses for all the sfermions of the first two generations are extremely heavy (> 10 TeV) and thus have greatly suppressed FCNC effects. Of course, to maintain naturalness for the Higgs sector the 3rd generation squarks should be below $\sim$ 1 TeV. This scenario is sometimes referred to as Superheavy Supersymmetry or More Minimal Supersymmetry.

A feature of this scenario is the expectation of many bottom quarks and τ leptons in the final state of SUSY production. For example, $p\bar{p} \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm$ will not be allowed to cascade decay through $\tilde{e}_L$ but may have hundred percent branching fractions to τ final states. Therefore the clean trilepton signals are generally suppressed in these models, and efforts to look for specific 3τ final states are relatively more important. Furthermore, light $\tilde{t}$ and $\tilde{b}$ production either directly or from gluino (chargino, stop) decays is of added interest and may lead to high multiplicity b-jet final states. Whereas detection of selectrons and smuons would exclude this scenario, detection of many staus and no $\tilde{e}$ or $\tilde{\mu}$ would be a good hint for it.

E NMSSM

The NMSSM (Next-to-minimal SSM) is defined by the addition of a gauge singlet superfield S to the MSSM. The superpotential W is scale invariant, i.e. there is no μ-term. The vev of S generates an effective μ-term with $\mu = \lambda\langle S\rangle$. The S quantum degrees of freedom result in 1 CP-even and 1 CP-odd Higgs bosons beyond the 2 CP-even and 1 CP-odd Higgs bosons of the MSSM. The spin-1/2 component of $\widehat{S}$ provides an additional neutralino, $\widetilde{S}$, that can mix with the usual four neutralinos of the MSSM. It is very natural for the LSP of this model to be the $\widetilde{S}$. All supersymmetric particles then cascade decay down to the $\widetilde{S}$.

The phenomenology of sparticle production in the NMSSM can differ considerably from the MSSM, depending on the mass of the additional state $\tilde{S}$ in the neutralino sector: If the $\tilde{S}$ is not the LSP, it will hardly be produced, and all sparticle decays proceed as in the MSSM with a LSP in the final state. If, on the other hand, the $\tilde{S}$ is the LSP, the sparticle decays will proceed differently: First, the sparticles will decay into the NLSP, because the couplings to the $\tilde{S}$ are too small. Only then the NLSP will realize that it is not the true LSP, and decay into the $\tilde{S}$ plus an additional cascade. These features of the NMSSM lead to unconventional signatures compared to the decay patterns of the MSSM:

- Additional cascades attached to the original vertex: one or two additional l^+l^-, $\tau^+\tau^-$ or $b\bar{b}$ pairs or photons, with the corresponding branching ratios depending on the parameters of the model.
- One or two additional l^+l^- or $\tau^+\tau^-$ pairs or photons with macroscopically displaced vertices, with distances varying from millimeters to several meters. These displaced vertices do not point towards the interaction point, since an additional invisible particle is produced.

F New physics beyond SUSY

In contemplating experimental approaches to weak scale supersymmetry, it is important to consider the possibility that supersymmetry is accompanied by other new physics. This other new physics will generally manifest itself as additional exotic particles, besides the superpartners and Higgs states predicted by supersymmetry. There are a number of well-motivated examples which have potential implications for Tevatron searches:

- An interesting question is whether superstring theory provides any guidance as regards boundary conditions and matter content for low energy supersymmetry. The detailed predictions of one sample superstring model are outlined as an example of what can generally be expected from weakly-coupled heterotic string theory. The model considered has a plethora of additional matter, including exotics, extra Higgs bosons, and extra gauge bosons.
- From the string point of view, new gauge bosons are perhaps one of the most natural extensions of the MSSM. The conventional approach in searching for new gauge bosons at hadron colliders is via the Drell-Yan channel where a resonant, on-shell particle is produced which subsequently decays to lepton pairs and is easily observable over any continuum background. The search reach is relatively straightforward to establish *under the assumption* that the new particle can only decay to SM fermion pairs. Using the canonical Z' from E_6 as an example and remembering that in this case the fermionic couplings depend on a parameter θ, we show in Fig. I.12 both the current exclusion reach from Run I as well as the search reach anticipated from Run II. As the Z' couplings vary the search reach also varies over a respectable range of $\simeq 150$ GeV.
- Is there room for a 4th family in supersymmetry? If the Yukawa couplings associated with the 4th family are to remain perturbative in evolving from $\sim m_Z$ up to some high scale, one finds that the leptons and quarks of the 4th family must be quite light. Experimental constraints are becoming very restrictive. A review of the current situation leads to the conclusion that the possibility of a 4th generation will be either confirmed or ruled out during Run II at the Tevatron.
- The possibility that left-right symmetry is restored at a high energy scale is motivated by unification ideas. In LR-symmetric models, proper symmetry breaking requires introduction of triplet Higgs representations that contain a doubly-charged Higgs field. In the supersymmetric context, these doubly-charged scalars have a doubly-charged higgsino partner. Careful investigation reveals that these are likely to be one of the lightest states in the superparticle spectrum. They will appear in cascade decays and can also be directly produced. Certain types of SUSYLR models produce large numbers of two and three τ-jet final states which are potentially observable at Run II of the Tevatron. This τ-jet signal is due in large part to pair production of the doubly charged Higgsino. The distribution in angle between the two highest E_T τ-jets is different from other models which do not have this doubly charged Higgsino.

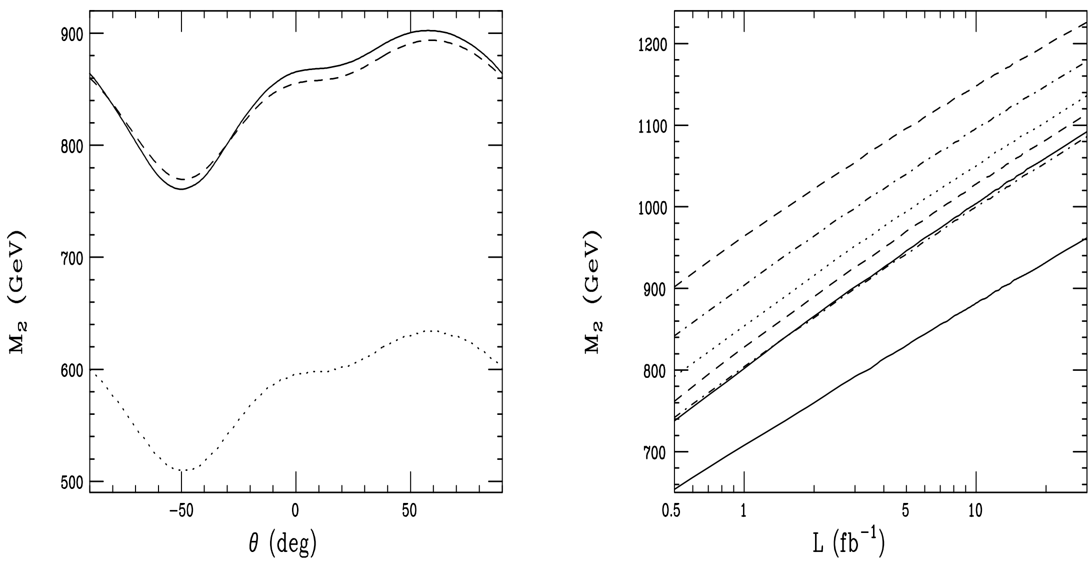

FIGURE I.12: (Left) Approximate 95%CL exclusion limit (dots) from Run I and the anticipated Run II (2 fb^{-1}) discovery reach (solid and dash) for a Z' arising from E_6 as a function of the parameter θ assuming decays to only SM fermions. The two curves represent the results obtained by employing CTEQ4M and MRST98 PDF's. (Right) Scaling behavior of Z' search reaches with integrated luminosity with Run II conditions for seven different extended models. Note the spread of $\simeq$ 300 GeV at any given luminosity.

- Recently, the possibility that there are large compactified extra dimensions has received much attention. One manifestation of theories with low scale quantum gravity is the existence of a Kaluza Klein (KK) tower of massive gravitons which interact with the SM fields. The indirect effects of these massive gravitons being exchanged affects Drell-Yan production. In particular, the contribution of gluon-gluon initiated processes to lepton pair production can produce novel features which are potentially observable at the Tevatron.

G Detector innovations

The CDF and DØ detectors have been upgraded dramatically for Run II. It is important to understand the extent to which they will be able to probe some of the more exotic models of new physics, e.g. fourth generation leptons and quarks, weak R_p violation, and gauge mediated SUSY breaking models. Particularly interesting are signals associated with long-lived charged particles, photons, vertices etc. which pose new challenges for the detectors.

Long-lived charged massive particles (CHAMPS) have a variety of characteristics which enable their identification, particularly in the analysis stage when the event's complete data set is available. Depending on the lifetime, a combination of time-of-flight, ionization (dE/dx) in several different detectors, and the muon-like penetration of a high momentum, isolated track all can be employed, with the additional presence of a kink where there is a decay within the detector volume. Even though discovery at the analysis stage seems possible, triggering proves to be crucial if heavy stable particles produced at the Tevatron are to be detected.

A strongly interacting CHAMP would have a large cross section (like that for top), which allows large masses to be probed with little background. CDF performed such a search in Run I using as a reference model a fourth generation quark with fragmentation to an integer charged meson within a jet.

In Run II, the CHAMP search will be enhanced by the larger integrated luminosity, higher cross section ($\sim$ 40%), and improved detector acceptance ($\sim$ 80%) due to the new tracking chambers. Moreover, a time of flight system has been added to the CDF detector. This will greatly help searches for weakly interacting CHAMPs, and will improve the acceptance for the analysis described here by $\sim 50\%$.

The importance of photon pointing was appreciated already in some Run I analyses. The central and forward preshower detectors of the DØ Upgrade provide a precision measurement of the photon cluster position. With the additional position measurement coming from the preshower detectors, pointing resolutions of $\sigma_z = 2.2$ cm, $\sigma_r = 1.4$ cm for central and $\sigma_z = 2.8$ cm, $\sigma_r = 1.2$ cm for forward photons can be obtained in Run II.

6 HIGGS

The search for the Higgs boson and the dynamics responsible for electroweak symmetry breaking is the central goal of high energy physics today. The Tevatron experiments, if given sufficient integrated luminosity, are poised to make major advances in meeting this goal.

The present feasibility studies for Higgs searches at the Tevatron during the upcoming data taking improve upon the earlier Run II studies in a number of significant ways. In this report, an improved background analysis and a more realistic detector simulation has been employed. In addition, results from all the leading channels were combined, and new channels relevant for the search for Higgs bosons of higher mass were examined. Estimating the discovery and exclusion reach for Higgs bosons requires accurate knowledge of the acceptance and expected backgrounds in the various channels. During the workshop, SHW—a simple Monte Carlo simulation— was developed to represent an "average" of the CDF and DØ experiments, taking into account the improvements to the detectors. SHW simulates the detector response to all the individual particles in the event, including tracking and calorimeter efficiency, resolution, and geometry, but does not simulate the effects of multiple interactions, the magnetic field, lateral shower development, secondary interactions, or details of the microvertex detectors. Comparisons of the simulation with the Run I full simulation and data show agreement at the 15-20% level in acceptance. Without the real Run II data, it is also difficult to get an accurate estimate of the b quark jet tagging efficiency and mistag rate, the $b\bar{b}$ jet-jet mass resolution, and certain backgrounds that must be estimated from actual data. The philosophy in this study is to make an optimistic yet realistic estimate of the Higgs boson discovery and exclusion reach, assuming improvements to these performance parameters for the detectors and analyses. These estimates are based on Run I experience, albeit with less capable detectors, and detailed simulations of b-tagging at the planned Run II detectors. The completion of the background analyses will also require direct handling of the actual Run II data.

In the mass region of interest to the Tevatron (100 GeV$\lesssim m_{h_{\rm SM}} \lesssim$ 200 GeV), the channels explored for SM Higgs boson production are

1. **For $m_{h_{\rm SM}} \lesssim 135$ GeV:** associated production of Higgs with vector bosons, $q\bar{q}' \to W/Zh_{\rm SM}$, with the dominant Higgs decay $h_{\rm SM} \to b\bar{b}$ and leptonic decay of the vector gauge bosons. These processes lead to four main final states: $\ell\nu b\bar{b}$, $\nu\bar{\nu}b\bar{b}$, $\ell^+\ell^-b\bar{b}$, and $q\bar{q}b\bar{b}$, with the first three being the significant ones. The signal efficiencies and backgrounds have all been estimated with both the CDF Run I detector simulation and with the simple SHW simulation. In addition, the selection was optimized using neural network techniques, resulting in a demonstrable gain in the significance of the Higgs signal for the $\ell\nu b\bar{b}$ and $\nu\bar{\nu}b\bar{b}$ channels.

2. **For $m_{h_{\rm SM}} \gtrsim 135$ GeV:** Gluon fusion via quark loops, $gg \to h_{\rm SM} \to WW^{(*)}$ (where W^* is a virtual W), and associated production of Higgs with vector bosons, $q\bar{q}' \to W/Zh_{\rm SM}$, with subsequent decay of the Higgs in $WW^{(*)}$. These processes lead to two main final states: $\ell^\pm\ell^\pm jj$ and $\ell^+\ell^-\nu\bar{\nu}$. For the high-mass channels, the $\ell^+\ell^-\nu\bar{\nu}$ channel has the most sensitivity, whereas the $\ell^\pm\ell^\pm jj$ channel has nearly as good sensitivity over a broader mass range.

A SM Higgs reach

Fig. I.13 shows the integrated luminosity required to either exclude the SM Higgs boson at 95% CL or discover it at the 3σ or 5σ level of significance, as a function of Higgs mass, for the SHW analyses with the neural net selection. The final combined result of the integrated luminosity required to exclude or discover the SM Higgs boson for a given Higgs mass is obtained by combining the sensitivity of all the channels described above, and assuming that the data from the CDF and DØ experiments can be combined. This result is achieved by forming a joint likelihood from the product of the Poisson probabilities of single-channel counting

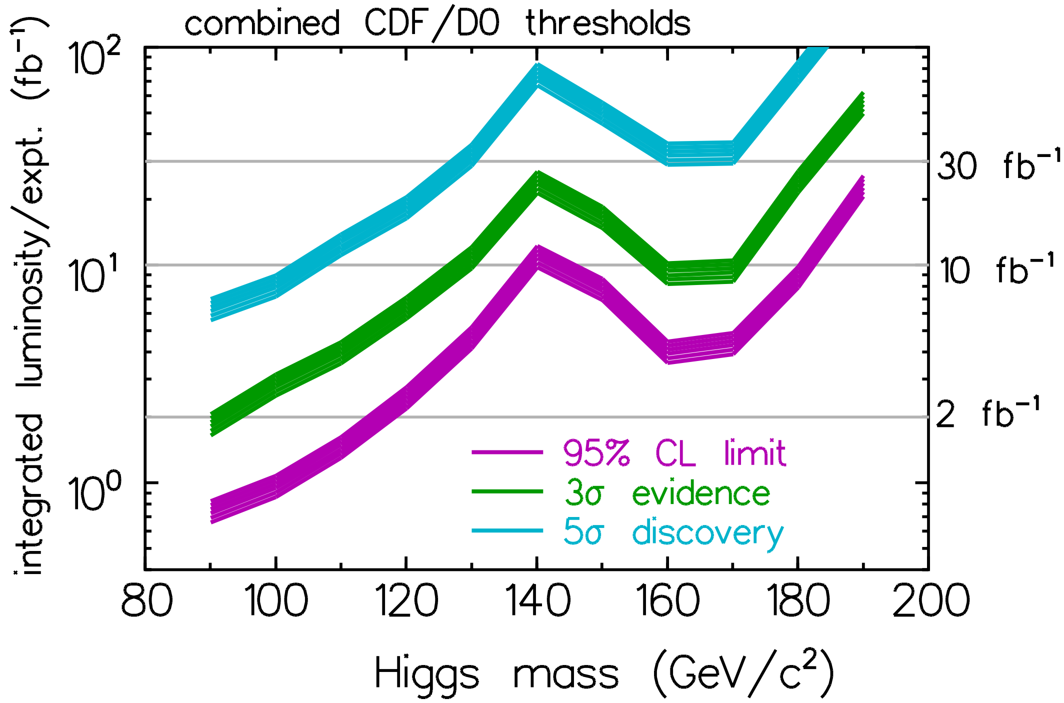

FIGURE I.13: The integrated luminosity required per experiment, to either exclude a SM Higgs boson at 95% CL or discover it at the 3σ or 5σ level, as a function of the Higgs mass. These results are based on the combined statistical power of both experiments. The curves shown are obtained by combining the $\ell\nu b\bar{b}$, $\nu\bar{\nu}b\bar{b}$ and $\ell^+\ell^-b\bar{b}$ channels using the neural network selection in the low-mass Higgs region (90 GeV $\lesssim m_{h_{\rm SM}} \lesssim$ 130 GeV), and the $\ell^\pm\ell^\pm jj$ and $\ell^+\ell^-\nu\bar{\nu}$ channels in the high-mass Higgs region (130 GeV $\lesssim m_{h_{\rm SM}} \lesssim$ 200 GeV). The lower edge of the bands is the calculated threshold; the bands extend upward from these nominal thresholds by 30% as an indication of the uncertainties in b-tagging efficiency, background rate, mass resolution, and other effects.

of signal and background in each channel. A nominal systematic error on the expected background was taken into account by Bayesian integration. For the b-tagging efficiencies, a "loose" b-tag efficiency of 75% at large jet E_T, and a "tight" b-tag efficiency of 60% at large jet E_T have been assumed. These are estimated to be realistic numbers, based on simulation studies. For the mass resolution, the final results assumed a 10% resolution on the "core" of the distribution; inefficiencies due to the low side tail remain after this rescaling of the simulation output. This is aggressive, but simulations suggest that a 10% $b\bar{b}$ mass resolution may be achievable. For backgrounds we have used Monte Carlo estimates everywhere except in the $\nu\bar{\nu}b\bar{b}$ channel, where there is a significant contribution from QCD $b\bar{b}$ dijet production. This background comes from the extreme tail of a very large cross section, and is thus very difficult to model. To be conservative, the unknown QCD $b\bar{b}$ dijet background to the $\nu\bar{\nu}b\bar{b}$ channel has been taken to be equal in size to the sum of all other contributing background processes. The bands in figure (I.13) extend from the calculated threshold on the low side upward in required integrated luminosity by 30% to the high side, as an indication of the range of uncertainty in the various factors discussed above.

The final result shows that for an integrated luminosity of 10 fb^{-1}, if the SM Higgs boson does not exist in the energy range explorable at the Tevatron, then one can attain a 95% CL exclusion for masses up to about 180 GeV. Moreover, if the SM Higgs happens to be sufficiently light ($m_{h_{\rm SM}} \lesssim$ 125 GeV), then a tantalizing 3σ effect will be visible with the same integrated luminosity. With about 25 fb^{-1} of data, 3σ evidence for the Higgs boson can be obtained for the entire Higgs mass range up to 180 GeV. However, the discovery reach is considerably more limited for a 5σ Higgs boson signal. Even with 30 fb^{-1} of integrated luminosity, only Higgs bosons with masses up to about 130 GeV can be detected with 5σ significance.

Suppose that the Higgs boson mass is about 115 GeV, which lies just above the 95% CL exclusion limit achieved by LEP and at a value that will be compatible with the Higgs-like events reported by the ALEPH and L3 collaborations. At the Tevatron, with 5 fb^{-1} of integrated luminosity per experiment, there would be sufficient data to see a 3σ excess above background, providing evidence for a Higgs boson. With 15 fb^{-1} of integrated luminosity per experiment, a 5σ discovery of the Higgs boson would be possible.

B MSSM Higgs reach

The SM Higgs feasibility studies discussed above can be expressed in a more model independent fashion, by defining the discovery and exclusion reach on the ratio of the beyond the standard model production process with respect to the analogous one in the SM, as a function of the Higgs mass. In particular for the MSSM it is possible to translate the SM studies of associated vector boson–Higgs boson production followed by Higgs decay to $b\bar{b}$, into studying the discovery and exclusion reach for CP-even Higgs bosons in analogous channels. For a given point in supersymmetric parameter space (which depends on $\tan\beta$, m_A, and other supersymmetric mass parameters, such as the third generation squark masses, the gaugino masses, the trilinear couplings A_t, A_b and higgsino mass parameter μ, which govern the size of the radiative corrections), one can compute the corresponding couplings and Higgs masses to evaluate the associated vector boson–Higgs boson production and subsequent Higgs decay to $b\bar{b}$. Using the model independent experimental sensitivities in the associated vector boson–Higgs boson production channel, one can then either exclude or discover a CP-even Higgs boson of a given mass for a fixed integrated luminosity. In this way, one can map out the MSSM Higgs parameter space in the m_A—$\tan\beta$ plane (under various assumptions for the values of the other supersymmetric parameters that govern the impact of the loop-effects) and determine which parameter regimes are accessible to the Tevatron Higgs search at a given luminosity.

We have studied three examples: (i) the top-squark (stop) mixing is set to zero, which minimizes the maximal value of the radiatively-corrected light CP-even Higgs mass (the so-called "minimal-mixing" or "no-mixing" scenario); (ii) the stop mixing parameters are chosen to maximize the value of the lightest CP-even Higgs mass (the "maximal-mixing" scenario); and (iii) the stop mixing parameters and the gluino mass are chosen in order to suppress the $b\bar{b}$ coupling of the Higgs state that is primarily produced in association with the gauge bosons (the "suppressed $V\phi \to Vb\bar{b}$ production" scenario). Case (iii) exemplifies a possible worst case scenario for the MSSM Higgs search at the upgraded Tevatron. In the case of minimal mixing, a Higgs boson produced in association with the gauge bosons may be excluded at the 95% CL with as little as 5 fb^{-1} of data per experiment, and can be discovered at the 5σ level over nearly the entire region of the m_A—$\tan\beta$ plane with less than 20 fb^{-1} per experiment. However, in the other two cases mentioned above, our results show that an integrated luminosity of order 20—30 fb^{-1} is required to obtain a 5σ discovery over a significant portion of the parameter space. Yet, even in these cases, 10 fb^{-1} is sufficient to exclude the Higgs sector of the MSSM at the 95% CL, for most values of m_A and $\tan\beta$ (independent of the values of the stop mixing parameters, assuming that the average top squark mass is not much larger than 1 TeV). However, in the suppressed $V\phi \to Vb\bar{b}$ production scenario, there is a non-negligible region of the MSSM parameter space in which even a 95% CL Higgs exclusion limit is not achievable at 30 fb^{-1}. Note that if the Higgs signature due to $t\bar{t}h_{\rm SM}$ (with $h_{\rm SM} \to b\bar{b}$) proves to be a viable discovery mode, then the analogous MSSM Higgs signatures could improve the Tevatron coverage of the MSSM Higgs parameter space described above.

In the large $\tan\beta$ regime of the MSSM, some of the neutral Higgs boson couplings to down-type fermions (such as $b\bar{b}$) are enhanced, and lead to production cross sections for Higgs bosons that are significantly larger than those of the Standard Model Higgs boson. As a result, in general two of the neutral Higgs bosons of the MSSM can also be discovered in an additional channel: $b\bar{b}\phi$ production, followed by $\phi \to b\bar{b}$ (where ϕ is either the CP-odd Higgs boson or the neutral CP-even Higgs boson with enhanced coupling to $b\bar{b}$, at large $\tan\beta$). The corresponding channel cannot be observed in the case of the SM Higgs boson, since the $h_{\rm SM}b\bar{b}$ coupling is suppressed by a factor of m_b/m_W and has no additional enhancement. The production of a neutral MSSM Higgs boson in association with a $b\bar{b}$ pair followed by Higgs decay to $b\bar{b}$ leads to a distinctive final state with four high-E_T b jets. These events can be observed by positively tagging at least three of these b-jets, which dramatically reduces the QCD multijet background. The cross section for this process is proportional to $\tan^2\beta$, and is thus greatly enhanced at large $\tan\beta$. The studies presented in this Workshop show that an interesting region of the MSSM parameter space at high $\tan\beta$ is accessible in Run 2. In particular, some limits already emerge with 2 fb^{-1} of data in the region of high $\tan\beta$ and low m_A. The region of sensitivity extends to slightly lower values of $\tan\beta$ and larger values of m_A as the luminosity is increased further. However, one finds that there are large supersymmetric and QCD corrections that must be taken into account, which will require detailed theoretical analysis in the coming years. Nevertheless, the enhanced $b\bar{b}\phi$ production process increases the overall sensitivity of the Tevatron MSSM Higgs search, and provides some complementary coverage in the m_A—$\tan\beta$ plane with respect to the associated vector boson–Higgs boson production discussed above.

Figure I.14 illustrates the results discussed above for the various channels involving the neutral Higgs sector of the MSSM in the maximal mixing scenario. For comparison, we show the LEP final coverage of the $m_A - \tan\beta$ plane obtained from the search mode $e^+e^- \to Z\phi$, with subsequent decay of $\phi = h$, H into $b\bar{b}$ or $\tau\bar{\tau}$.

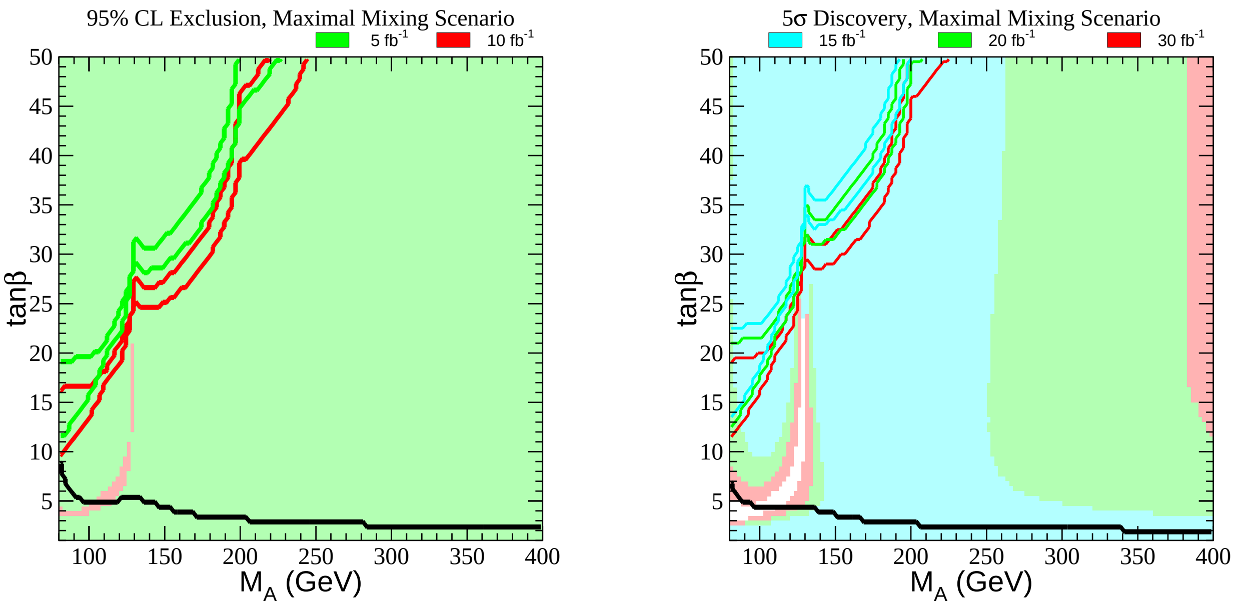

FIGURE I.14: (a) 95% CL exclusion region and (b) 5σ discovery region on the m_A–$\tan\beta$ plane, for the maximal mixing benchmark scenario and two different search channels: $q\bar{q} \to V\phi$ $[\phi = h,\, H]$, $\phi \to b\bar{b}$ (shaded regions) and $gg,\, q\bar{q} \to b\bar{b}\phi$ $[\phi = h,\, H,\, A]$, $\phi \to b\bar{b}$ (region in the upper left-hand corner bounded by the solid lines). Different integrated luminosities are explicitly shown by the color coding. The two sets of lines (for a given color) correspond to the CDF and DØ simulations, respectively. The region below the solid black line near the bottom of the plot is excluded by the absence of observed $e^+e^- \to Z\phi$ events at LEP2.

C Remarks on the Higgs search

Further challenges must be met in bringing the detectors on line and fully operational, and in developing the techniques and understanding, particularly in $b\bar{b}$ jet-jet mass reconstruction and b jet tagging, necessary to extract the faint signal of the Higgs boson from the larger Standard Model background. In some cases, we were perhaps optimistic with regard to the expected capabilities of the detector. However, this Report clearly points to some important goals that the experimental detectors and analysis methods must achieve if the Higgs search at the Tevatron is to be successful. In some cases, the magnitude of the Standard Model backgrounds are not known at the required level of accuracy. Additional theoretical work along with background studies once higher luminosity data become available will be crucial for improving the Higgs search strategies and maximizing the chances for uncovering the Higgs signal. We believe that the results obtained in this Report provide a useful attempt to devise a realistic search strategy for Higgs bosons, and provide a benchmark for future improvements.

LHC physics results are not expected before 2008. The search for the Higgs boson is one of the primary missions of the ATLAS and CMS detector collaborations. With much larger annual luminosities and energies, they will discover the Higgs boson (in most theoretical scenarios) if it has not yet been observed. The Tevatron will have a unique opportunity to search for a Higgs particle during Run II. The potential physics payoff is great, and provides a strong motivation to pursue this challenge in the years to come.