# The Case for Run II: Submission to the Particle Physics Project Prioritization Panel The CDF and DØ Experiments

**September 21, 2005**

This document addresses the physics potential of the Tevatron through the end of the decade by describing a "core" set of physics. Until the turn-on of the LHC, the Tevatron will remain the world's highest energy accelerator and can address some of the biggest questions in particle physics. It is the only place we can directly search for supersymmetry, the Higgs boson, and signatures of additional dimensions of space-time. It is the most likely place to directly observe something new and totally unexpected. It is also an excellent place for probing new physics with precision measurements.

As shown in Fig.1, the Tevatron luminosity projections by the end of FY2009 are in the range 4-8 $fb^{-1}$ of collisions to each experiment. The Tevatron has met or exceeded yearly luminosity goals since the inception of the current operation and upgrade plan in 2003. As an example, as shown in Fig. 2 the 2005 performance goals have already been met. Moreover, with the recycler now in daily operation and electron cooling regularly used to cool antiprotons in the recycler, there is every reason to believe that 8 $fb^{-1}$ will be delivered by the end of FY2009.

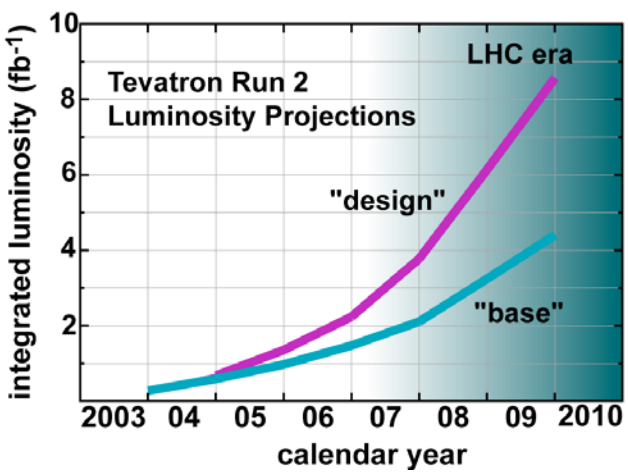


Figure 1: Luminosity projections as a function of calendar year. Design goal assumes the recycler and electron cooling are working to specifications. The "base" goal takes no credit for any but does include incremental improvements to the complex.

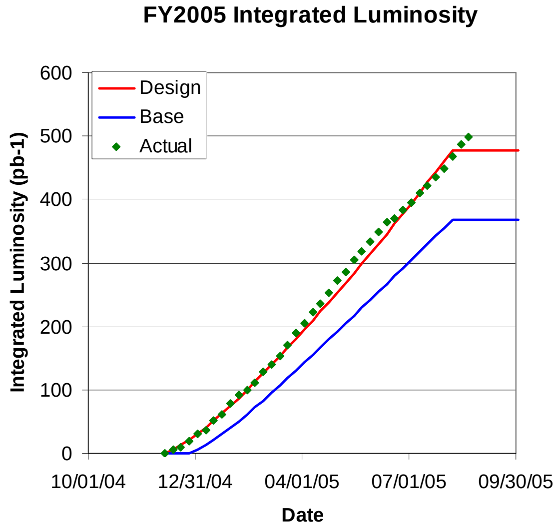


Figure 2. Luminosity delivered to each experiment as a function of month for FY05. Green symbols indicate delivered luminosity. Red (top) curve is design goal for the year, blue (bottom) curve is base goal for the year.

The CDF and D0 detectors have operated and continue to operate very well. Both experiments regularly take data with 85-90% efficiency. Detector subsystems meet or exceed specifications detailed in Technical Design Reports written almost a decade ago. CDF and D0 have individually collected ~1 $fb^{-1}$ of Run II data. Each experiment has analyzed a subset of this data (typically 300 to 500 $pb^{-1}$ and as much as 600 $pb^{-1}$) and presented a wide range of physics results at the summer 2005 conferences. Together the two collaborations expect to submit about 80 papers this year. These publications will confront the standard model through precise measurements of the strong interaction, the quark mixing matrix, and the electroweak force. Appropriately, as energy frontier experiments, the analyses also cover a wide range of new physics including searches for the Higgs, SUSY Higgs, SUSY particles, LED, and Z' bosons. The current precision and high mass search results form the basis for the discussions and projections in this document.

In this paper we have chosen to discuss ten "core" physics analyses that best represent the physics potential of the Tevatron program. These ten analyses are a mix of precision measurements and searches. Of course, the selected search topics are somewhat arbitrary since physics beyond the standard model is unknown. However, this minimal set demonstrates the full capability of the experiments. The following three chapters briefly review current results and present Run II projections.

# II. Electroweak Precision Measurements and Standard Model Higgs

Investigation of the mechanism that triggers electroweak symmetry breaking is one of the most intriguing questions still open in the standard model. In the standard model, the *W* and *Z* bosons and all the fundamental fermions gain mass from a field, called the Higgs field, which permeates the universe. It should be possible to excite this field and observe its quanta – the long sought Higgs boson. This is the last piece of the standard model, and is also the key to understanding any beyond-the-standard-model physics like supersymmetry. Finding it, or excluding it, is a very high priority in the field of high-energy physics.

Standard model quantum loops exhibit a small but important dependence on the Higgs mass, $m_H$. As a result, the value of $m_H$ can be predicted by comparing a variety of precision electroweak measurements with one another. The global fit to precision electroweak data prior to the Tevatron Run II gave $m_H = 126^{+73}_{-48}$ GeV and $m_H < 280$ GeV at 95% confidence level. These results were consistent with bounds from direct searches for the Higgs boson at LEP II via $e^+e^- \rightarrow ZH$, $m_H > 114.4$ GeV. Improvements to the electroweak precision measurements have already come from the Tevatron Run II *W* boson and top quark mass measurements; even more improvements are expected by the end of this decade.

### Measurement of the W Boson Mass

Currently the *W* boson mass is measured as $m_W = 80{,}425 \pm 34$ MeV (the LEP II data uncertainty is 42 MeV and the Tevatron's Run I data uncertainty is 59 MeV.) Fig. 3 shows the Tevatron measurements, the stars and squares are the Run I measurements from CDF and D0, respectively. The projections as a function of luminosity (shown as the solid and dashed curves) assume that statistical and systematic uncertainties due to the determination of energy and momentum calibration and the recoiling energy against the W boson scale with luminosity. The systematic uncertainties associated with W production and decay (parton distribution functions, $p_T$ of W, and higher order QCD and QED effects) are fixed between 20 MeV (dashed curve) and the current uncertainty of 30 MeV (solid curve). As shown in the figure, a Run II dataset of order 1 $fb^{-1}$ will significantly improve the world knowledge of $m_W$. Given 2 $fb^{-1}$ we will be able to drive the measurement uncertainty down to the 25 MeV level for each of the CDF and D0 experiments, with 4-8 $fb^{-1}$ the ultimate capability will be 20 MeV per experiment.

### Measurement of the Top Quark Mass

The Tevatron has been, and will continue to be until LHC turns on, the only place that can produce top quarks. With the Run I top-pair production data, the top quark mass was measured at $178.0 \pm 4.3$ GeV. In Run II, both the CDF and D0 collaborations have measured the top quark mass with about 320 $pb^{-1}$ of data in both the dilepton and lepton + jets channels:

Lepton+ Jets: $m_{top}$ (CDF+D0) = 172.7 ± 1.7 (stat.) ± 2.4 (syst.) GeV
Dilepton: $m_{top}$ (CDF) = 168.2 ± 4.5 (stat.) ± 3.7 (syst.) GeV.

These results are better than the estimates made in the Run II Technical Design Report. When the Run I and II results are combined, the top mass is

Run I and II combined: $m_{top}$ = 172.7 ± 2.9 GeV,

which is about 45% better than the Run I average.

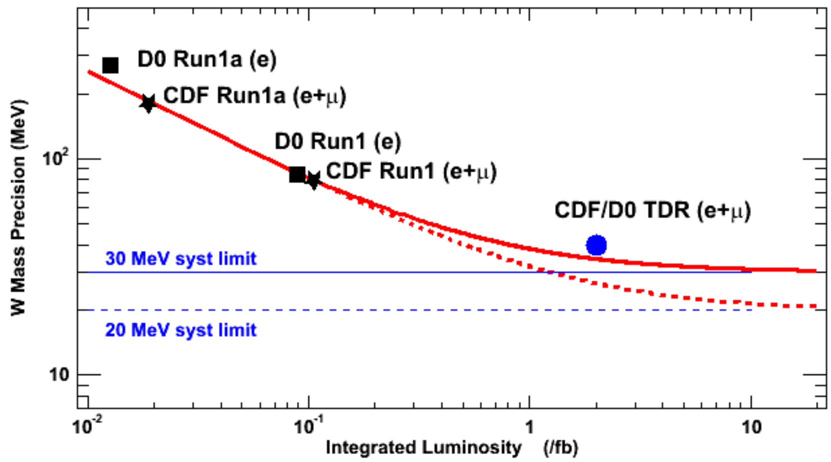


Figure 3. Uncertainties on the W boson mass measurement as a function of the integrated luminosity by a single experiment at the Tevatron. See text for details.

The Run II measurements in the lepton + jets channel use the PDG mass of the hadronically decaying W boson to constrain the jet energy scale. This new technique permits a more precise measurement of $m_{top}$ and the top-mass uncertainty due to the jet-energy scale is expected to scale with luminosity. As shown in Fig. 4, with 2 $fb^{-1}$ we expect a mass uncertainty of 1.8 GeV, which could be reduced to 1.2 GeV with 4-8 $fb^{-1}$. Here the limitation comes from understanding the initial and final state gluon radiation in Monte Carlo generators, the parton distribution functions, the hadronisation of b-quarks and the b-quark decay, and the higher order QCD effects. Fig. 5 shows the expected uncertainties on the Higgs mass prediction from the expected Run II measurements which approach 25% with 8 $fb^{-1}$.

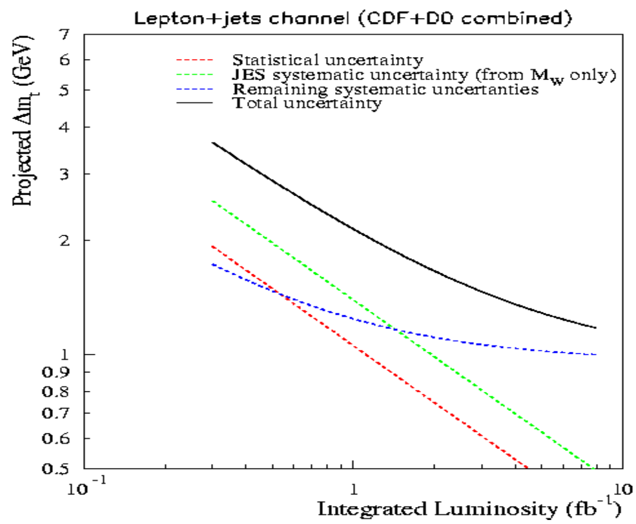


Figure 4. Uncertainties on the top quark mass measurement in the lepton + jets channel as a function of the integrated luminosity by a single experiment. Projections are based on the Run II measurements.

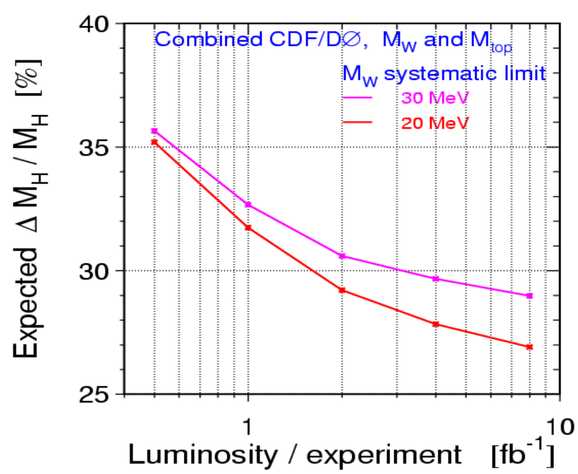


Figure 5. Expected uncertainties on the Higgs mass prediction from the Run II measurements of the top quark mass and the W boson mass.

Even if the Higgs boson were to be discovered, the *W* boson and top quark mass measurements would remain important. Through quantum loops new particles and forces can affect electroweak observables and thus cause a discrepancy between the indirect prediction and the direct measurement of $m_H$, thus providing indirect evidence for physics beyond the standard model.

**Direct Higgs Searches**

Understanding the sensitivity of the Tevatron experiments to either observe or rule out a low-mass standard model Higgs boson is another important Tevatron goal. As shown in Fig. 6, working groups with members of both the CDF and D0 collaborations have twice convened to estimate the expected sensitivity. The narrow curves are the estimations from 2003 Higgs Sensitivity Working Group study where systematic uncertainties are excluded, and the thicker curves are the results from 1999 SUSY/Higgs Working Group study. The 2003 study group benefited from more realistic Monte Carlo simulation and first Run II data. Each report includes calculations of the estimated luminosity required to exclude at 95% CL, assuming a Higgs boson is not present, as well as the luminosity requirements for a 3σ evidence and a 5σ discovery.

Now that both CDF and D0 have set upper bounds on the Higgs production cross-section times the relevant branching ratios with 200-400 $pb^{-1}$ of Run II data per experiment, the Higgs sensitivity has been reevaluated. The channels included in the reevaluation are WH → lνbb, ZH → $l^+l^-$bb, gg → H → $W^+W^-$, and WH → WWW. With the current Run II analyses, which did not utilize all the capabilities of the CDF and D0 experiments, the sensitivity is about an order of magnitude below that previously reported. Expected sources of increased sensitivity, include increased lepton acceptance (80-150%), increased b-tagging acceptance (~10%) and efficiency (~50%), improved jet-energy resolution (~70%), and enhanced techniques for the separation between background and signal events (~75%). Some of this work has already been done and will be imminently incorporated into the analyses. These anticipated improvements to the analysis should increase the sensitivity by a factor of 10, and confirms the results from the two previous sensitivity studies. With 2.5 $fb^{-1}$ masses below 115 GeV can be excluded at 95% confidence level. With 5 $fb^{-1}$ either masses less than 130 GeV can be excluded or a 3σ evidence for masses up to 115 GeV can be observed. Ensemble studies show that there is a 10% chance that a Higgs boson at 115 GeV can be discovered with a significance of > 5σ with 8 $fb^{-1}$.

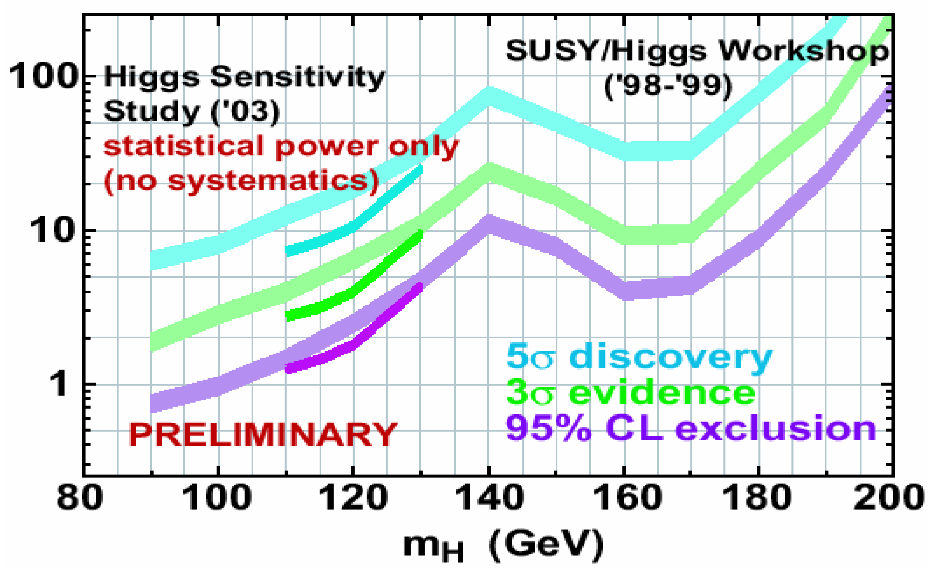


Figure 6. Integrated Tevatron luminosities per experiment for 95% confidence level exclusion, 3σ evidence, and 5σ discovery for $m_H$ = 90 – 200 GeV/$c^2$.

## Single Top Observation

Within the standard model, top-antitop quark pair production is the dominant way in which top quarks are produced. However, top quarks are also expected to be produced singly by the electroweak interaction involving a *Wtb* vertex. At the Tevatron, the two relevant production modes are the *t*- and *s*-channel exchange of a virtual *W* boson. The measurement of the single top cross section is particularly interesting because the production cross section is proportional to $|V_{tb}|^2$. Here $V_{tb}$ is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element which relates top and bottom quarks. Assuming three quark generations, the unitarity of the CKM matrix implies $|V_{tb}| \approx 1$. A measurement of the single top cross section allows for a direct determination of $|V_{tb}|$. Moreover, single top quark processes result in the same final state as the standard model Higgs boson process WH → lνbb and therefore impact future searches for the Higgs boson at the Tevatron described in the previous section.

With about 300 $pb^{-1}$ of Run II data, the CDF and D0 collaborations set the upper limits of 5.0 pb and 6.4 pb at 95% confidence level for the *t*-channel and *s*-channel single top production cross section, respectively. These can be compared with the standard model predictions of (1.98 ± 0.25) pb and (0.88 ± 0.11) pb when $|V_{tb}| = 1$ is assumed. With this assumption, a 3σ evidence requires 1.5 $fb^{-1}$ and 4 $fb^{-1}$ per experiment for the *t*- and *s*-channel, respectively. A 5σ discovery of the *t*-channel requires 4 $fb^{-1}$ per experiment (see Fig. 7). This also imply a $|V_{tb}|$ measurement with 9% accuracy.

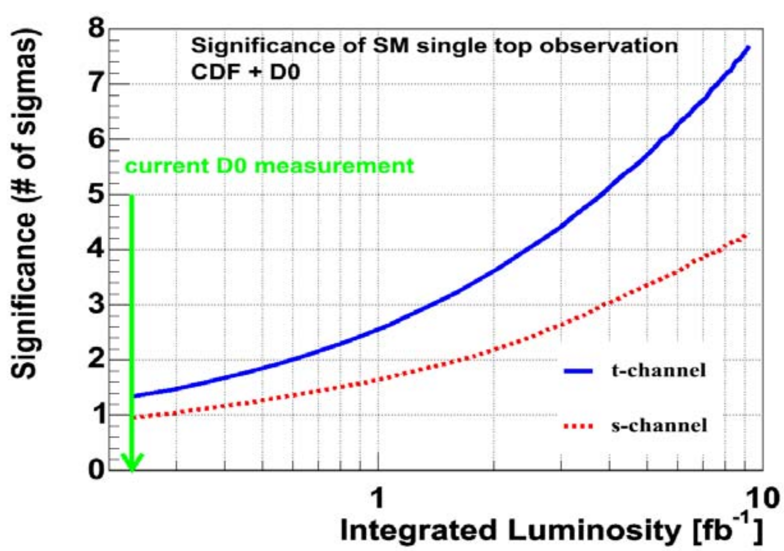


Figure 7. Significance of observation for the standard model single top production in the *t*- and *s*-channel as a function of the integrated luminosity per experiment.

# II. SUSY Searches and New Physics

## Supersymmetry

There is a wide spectrum of theories beyond the standard model, that predict signatures of new particles. Perhaps the foremost is Supersymmetry which introduces a symmetry between fermions and bosons, such that each Standard Model particle acquires a supersymmetric partner. The main attraction of supersymmertry is that it solves several problems of the standard model simultaneously: resolution of the hierarchy problem, unification of gauge forces, and identification of a natural candidate for cold dark matter in the universe. The latter is only achieved in models where the so-called R-parity is conserved, implying that supersymmetric particles can only be produced in pairs. For that reason we will focus on this class of models.

Within the Minimal Supersymmetric Model (MSSM) there are two Higgs doublets, and the ratio of their vacuum expectation values is given by a free parameter $\tan\beta$. These two doublets lead to five physical Higgs bosons: h, H, A and $H^{\pm}$. At large $\tan\beta$ the pseudo-scalar A is degenerate in mass with either the scalar h or H, the production cross sections are enhanced with $\tan^2\beta$. The cross sections are large enough to allow a discovery at the Tevatron if $\tan\beta$ is sufficiently large.

In this scenario the Higgs bosons can decay to two b-quarks (b-decay mode) with a branching ratio of about 90% and into two tau leptons (tau-decay mode) with a branching ratio of about 10%. The b-decay mode can be experimentally accessed only when the Higgs boson is produced in association with another b-quark. The tau decay mode can also be accessed in inclusive Higgs production. DØ have analyzed 260 $pb^{-1}$ of luminosity in the b-decay mode and CDF has analyzed 320 $pb^{-1}$ in the tau decay mode. In both analyses the data are consistent with Standard Model expectations. Limits on the mass of these Higgs bosons have been placed in dependence on the parameter $\tan\beta$. Limits for both decay modes are shown in Figure 8. Also shown are the expected limits for the tau channel at luminosities of 1 $fb^{-1}$, 4 $fb^{-1}$ and 8 $fb^{-1}$. The sensitivity of the b-decay and tau decay modes is comparable but the channels have different sensitivities to radiative corrections, and the optimal discovery reach is achieved by doing both analyses simultaneously.

The $3\sigma$ and $5\sigma$ discovery reaches have also been evaluated. For 2 $fb^{-1}$ the reach is $\tan\beta$=50 at $m_A$=150 GeV/$c^2$ and $\tan\beta$=90 at $m_A$=250 GeV/$c^2$ at $3\sigma$. For 8 $fb^{-1}$ the reach is improved to $\tan\beta$=35 at $m_A$=150 GeV/$c^2$ and $\tan\beta$=60 at $m_A$=250 GeV/$c^2$ at $3\sigma$. The $5\sigma$ reach is reduced by about 15 units in $\tan\beta$.

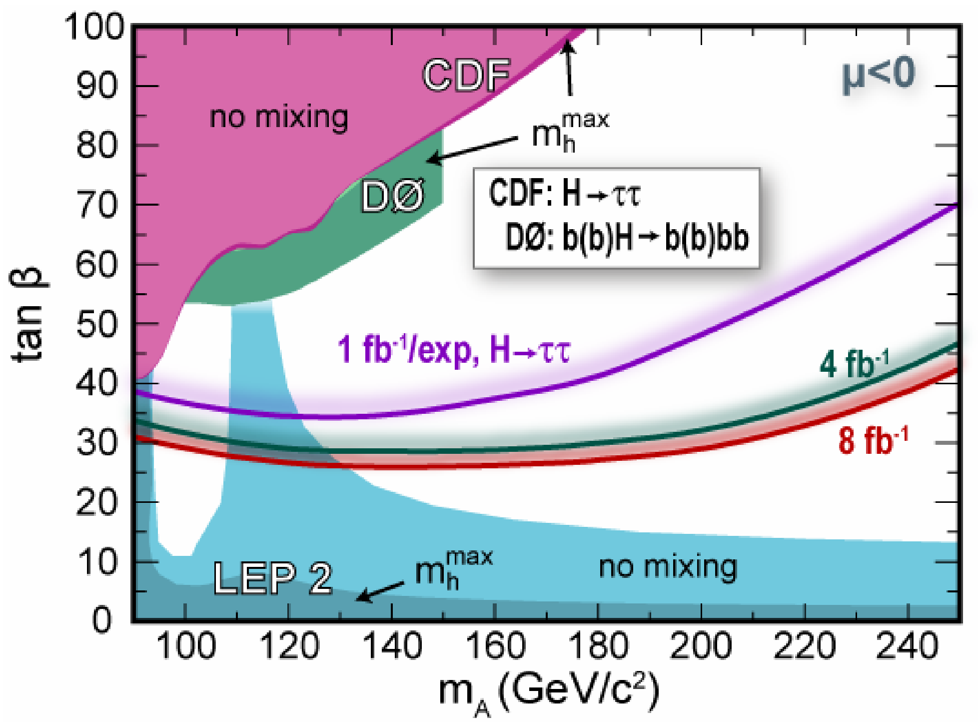


Figure 8: tanβ versus mass of the pseudo-scalar Higgs boson, A, in MSSM. Shown are the LEP exclusion region (blue), the CDF di-tau analysis exclusion region (pink), the extension of the exclusion region by D0 bbb analysis (green), and the future expected exclusion region for the di-tau channel at the Tevatron with 1, 4 and 8 $fb^{-1}$ of luminosity.

The "golden" search channel for charginos and neutralinos is the trilepton signature. The cascade decays of the charginos and neutralinos result in three leptons and a large imbalance in transverse momentum, missing $E_T$. This signature is sensitive to such production regardless of SUSY parameter assumptions. However, the sensitivity depends on the masses of sleptons and on tanβ.

Figure 9 shows the cross section for chargino-neutralino production times the branching ratio into three leptons as a function of chargino mass. Shown are the expected upper limits on the cross section times branching ratio for integrated luminosities of 1, 2, 4 and 8 $fb^{-1}$. These are based on the current Run II trilepton analysis from D0. The discontinuity at a mass of about 200 $GeV/c^2$ is due to the fact that at this point the chargino can decay into an on-shell Z boson and thus the analysis strategy changes.

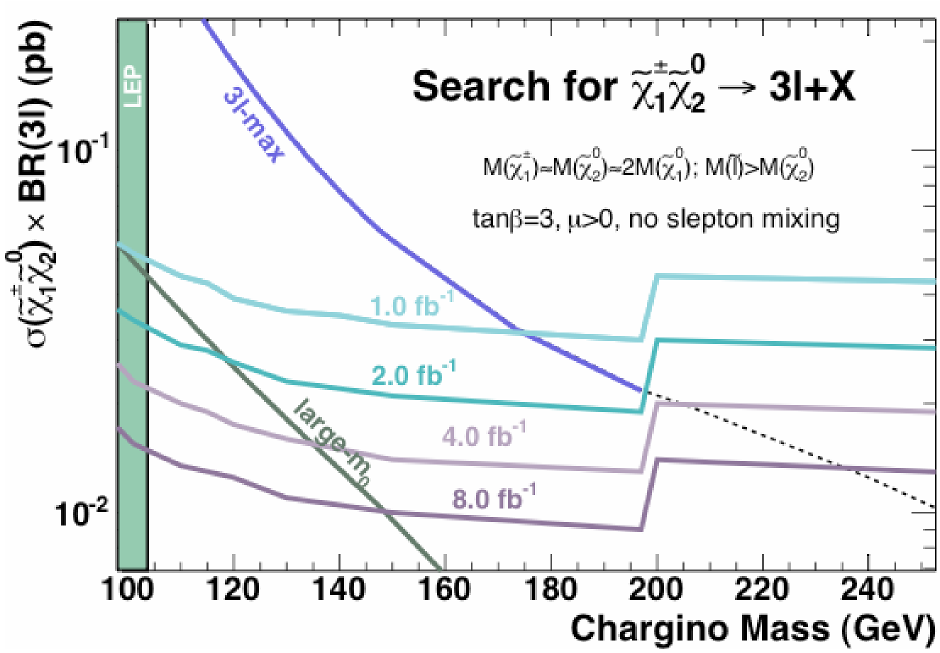


Figure 9: Cross section for chargino-neutralino production. Shown are the upper limits expected from the Tevatron for 1, 2, 4 and 8 fb$^{-1}$. Also shown are two different theoretical cross sections, labeled "3l-max" and "large $m_0$".

Also shown are the theoretical predictions for two different theoretical SUSY scenarios. The "3l-max" scenario is chosen such that the branching ratio into leptons is maximized. In this case the sleptons are only slightly heavier than the chargino. The "large m0" scenario represents the region where sfermions are very heavy. Thus the branching ratio into leptons is minimized. Both cross sections are for tanβ=3 and were calculated with the mSUGRA SUSY breaking scenario. The Tevatron sensitivity extends up to chargino masses of 150-240 GeV/c$^2$ depending on the theoretical assumptions. With the current Run II analysis the "3l-max" scenario is probed up to masses of 117 GeV/c$^2$ and the data are not yet sensitive to the "large $m_0$" scenario.

Squarks and gluinos are pair produced at the Tevatron via the strong interaction and are produced with large cross sections. The phenomenology of third generation squarks is rather different to that of the first two generations and is thus treated separately. For the generic search for squarks and gluinos the most sensitive signature is high $E_T$ jets and large missing $E_T$ since the squarks and gluinos typically decay into quarks and the lightest neutralino. The exact selection cuts depend on the mass hierarchy between the squarks and gluinos.

Figure 10 shows the excluded values for squark and gluino masses. Shown are the current most stringent limits from D0 of 233-333 GeV/c$^2$ on the gluino mass, depending on the squark mass. Also shown are future improvements expected with a luminosity of 2, 4 and 8 fb$^{-1}$. The exclusion region will be extended by about 100 GeV compared to the current results.

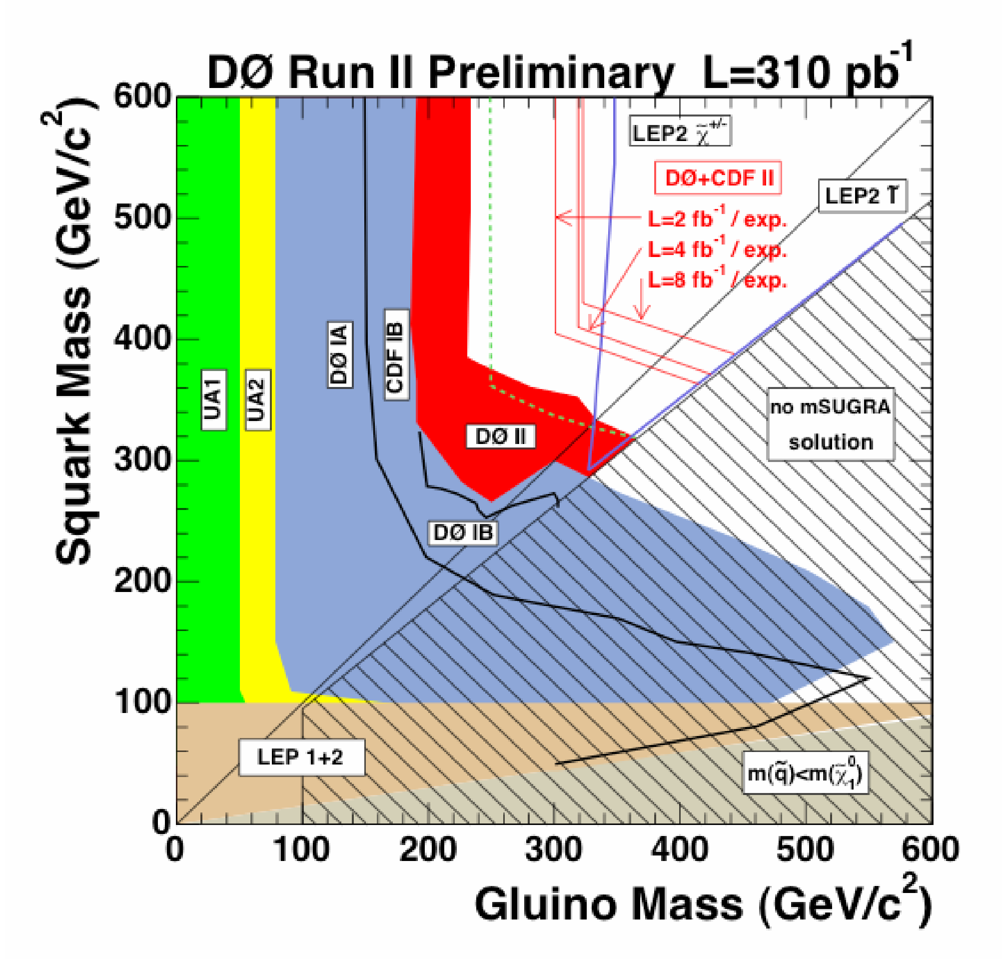


Figure 10: Squark mass versus gluino mass. The colored regions are excluded at 95% CL by previous experiments. The most stringent limits come from the Tvatron experiments and extend up to 350 GeV/$c^2$ in gluino and squark mass. Future improvements are also shown for 2, 4 and 8 $fb^{-1}$ of luminosity.

The super-partner of the top quark is particularly interesting since it is likely to be the lightest squark as a result of the large Yukawa coupling to the heavy top quark. The decay depends on the mass relations of charginos, sneutrinos, and the stop itself. If charginos and sneutrinos are heavy the only allowed decay mode is the decay to a charm quark and a neutralino. The future potential of this search is shown in Fig. 11, stop masses of up to 185 GeV/$c^2$ and neutralino masses up to 105 GeV/$c^2$ can be probed with 8 $fb^{-1}$ of data.

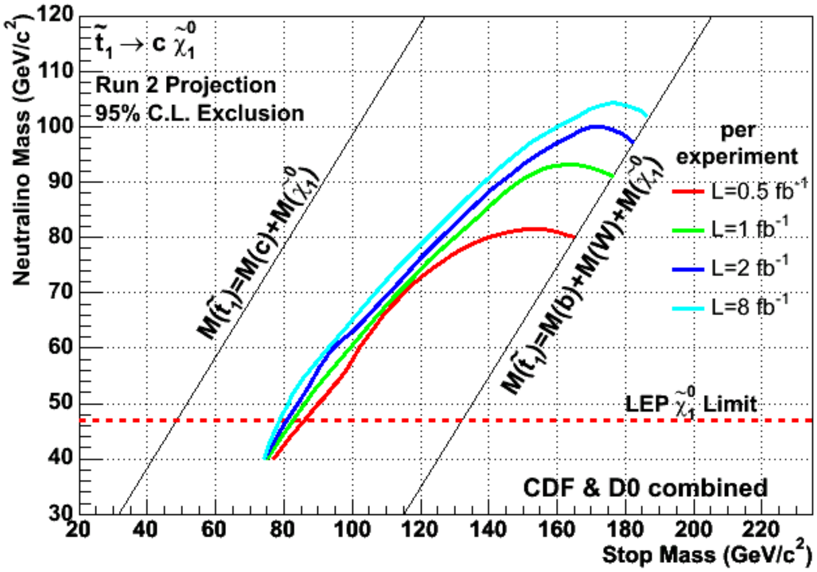


Figure 11: Neutralino mass versus stop quark mass. Diagonal lines indicate regions where the decay into charm and neutralino is suppressed. Horizontal dashed red line shows lower limit on the mass of the neutralino from LEP. The projected 95% CL limit is shown by coloured lines for integrated luminosities of 0.5, 1, 2 and 8 fb$^{-1}$.

## New Gauge Bosons and Extra Dimensions

Beyond Supersymmetry there are a number of other theoretical models for new physics with extremely interesting signatures at colliders. One particularly nice experimental signature is the production of dilepton or diphoton events at large mass, e.g. via a resonant production of a new particle such as new heavy gauge bosons and gravitons in extra dimension models. In these searches standard model background is very small, and a signal can be extracted unambiguously.

Table 1 shows the 5σ discovery and 95% C.L. exclusion reaches for a variety of models of Z' production and large extra dimensions as a function of integrated luminosity. The discovery reach improves typically by about 100 GeV/c$^2$ between 1 and 4 fb$^{-1}$. Another 50 GeV/c$^2$ improvement is achieved when doubling the dataset to 8 fb$^{-1}$. The exclusion reach improves similarly for specific Z' boson models, masses between 900 GeV/c$^2$ and 1 TeV/c$^2$ will be probed. However, the mass of the Z' could also be substantially lower if the couplings are smaller. Thus it is risky to make generalized statements about Z' discovery potential. For large extra dimensions in the ADD model the current limit is 1.43 TeV/c$^2$ in the GRW convention using dielectron and diphoton events and will improve by nearly 1 TeV/c$^2$ with an integrated luminosity of 8 fb$^{-1}$.

Table 1: The 5σ discovery and 95% C.L. exclusion reach for four Z' models, inspired by E6 theories for integrated luminosities of 1, 4 and 8 fb-1, combining CDF and D0 results. Also shown is the exclusion reach for large extra dimensions in the ADD model in the GRW convention. The row labeled "now" shows the current world's best limits from the Tevatron. All numbers are given in GeV/c$^2$.

| | $Z'_\eta$ 5σ | $Z'_\chi$ 5σ | $Z'_I$ 5σ | $Z'_\psi$ 5σ | $Z'_\eta$ 95%CL | $Z'_\chi$ 95%CL | $Z'_I$ 95%CL | $Z'_\psi$ 95%CL | LED 95%CL |
|---|---|---|---|---|---|---|---|---|---|
| Now | N/A | N/A | N/A | N/A | 715 | 720 | 625 | 690 | 1430 |
| 1 fb$^{-1}$ | 840 | 825 | 725 | 810 | 870 | 860 | 770 | 860 | 1800 |
| 4 fb$^{-1}$ | 950 | 915 | 820 | 920 | 980 | 950 | 840 | 960 | 2150 |
| 8 fb$^{-1}$ | N/A | N/A | 870 | N/A | N/A | 980 | 880 | 1020 | 2350 |

**Other Searches for New Physics**

There is a large number of additional searches for new physics ongoing in CDF and D0 at Run II. The breadth of these searches ensure sensitivity to unexpected manifestations of new physics. Examples are:

- R-parity violating Supersymmetry (which may explain neutrino oscillations) many different modes where different couplings and masses are probed.
- Models with gauge mediation that lead typically to photons in the final state and inspired by an extraordinary event observed by CDF in Run I.
- Charged massive particles that are long-lived such that they do not decay within the detectors. These are e.g. predicted in Anomaly Mediated SUSY models or in Split-SUSY models.
- New generation of quarks and excited states of the existing quarks and leptons.
- Leptoquarks that are hypothesized to be a parent particle to leptons and quarks.
- Resonance structures in dijet and ditop production.
- Monojet and monophoton signatures that probe extra dimensions and SUSY models.
- New W' bosons that appear in extended gauge theories or the Little Higgs model.
- Charged and doubly charged Higgs bosons.

In each of these searches the Tevatron provides the world's most stringent direct constraints. There are even more signatures under investigation, and as required to maximize sensitivity, many are model independent.

# IV. The *b*-quark Sector as a Probe for CP Violation and New Physics

The b-quark and heavy-flavor sectors offer an important laboratory to study QCD, the quark model of hadron formation, the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix, subtle violations of CP symmetry relating particles and antiparticles, and to search for new physics. New physics may be revealed by accurately measuring the parameters involved in the mixing matrix and in CP violation or by the unexpectedly large rates of rare *B* decays. The Tevatron collider *B*-physics program is well positioned to explore these possibilities by exploiting the large production cross sections of all b-hadron species, including those not produced at the electron-positron *B* factories, such as the $B_s$ and $B_c$ mesons and *b*-baryons.

The *B*-physics program at the Tevatron is strong and active. The excellent mass resolution of the CDF detector and the outstanding muon acceptance of the DZero detector offer powerful, complementary opportunities to capture and study rich, copious *b*-hadron samples. The CDF detector has particular strengths in extracting hadronic *B* decays, while the DZero detector is well suited to isolate large samples of semileptonic *B* decays. To date, CDF and DZero have published or submitted more than 20 papers on a diverse set of heavy-flavor physics topics including lifetimes, masses, and decay branching ratios of *B* and *D* mesons, as well as of the heavier *b*-hadrons $\Lambda_b$ and $B_s$; the lifetime difference between the different $B_s$ eigenstates; properties of the *X*(3872), which may be a new form of matter; limits on the rare FCNC decay $D^0$ and $B_s \rightarrow \mu^+\mu^-$ branching ratios; tests for CP violation in the *B* and *D* systems; and production cross sections of *b*-quarks, charm mesons, and heavy quarkonia states.

The Tevatron Run II *b*-physics capabilities are not only diverse, but also orthorgonal to the electron-positron *B*-factories. The *B*-factories have explored many aspects of the CKM matrix, and in the future will do so to unprecedented precision. However, only the Tevatron can currently produce the $B_s$ final state and have direct access to the associated elements of the CKM matrix to provide essential constraints on the CKM unitarity triangle. Observation of $B_s$ oscillations is therefore a key goal of the Run II physics program. The $B_s$ system also offers particularly rich opportunities to search for new physics. Three of the most promising opportunities involve measurements of the $B_s$ oscillation frequency, the lifetime difference between the $B_s$ mass or CP eigenstates, and rare FCNC $B_s$ decays.

### $B_s$ Mixing, Lifetime Differences, and Rare Decays

The measurement of $\Delta m_s$, the mass difference between heavy and light mass eigenstates of the $B_s$, and proportional to the oscillation frequency between $B_s$ and anti-particle of $B_s$, is one of the primary goals of the Tevatron program. Currently, the world limit at 95% C.L. is 14.4 ps$^{-1}$. Competitive results from CDF, $\Delta m_s > 7.9$ ps$^{-1}$ (with a sensitivity of 8.4 ps$^{-1}$) and DZero, $\Delta m_s > 7.3$ ps$^{-1}$ (with a sensitivity of 9.5 ps$^{-1}$), both at 95% C.L., were presented this year at the EPS International Conference 2005. At this time the uncertainty on $V_{td}$ is ~20%, but by measuring $\Delta m_s$, the uncertainty can be reduced to ~5%. Measuring $\Delta m_s$ in combination with the other precise experimental and theoretical results will greatly constrain CP violation and may uncover new physics effects. Even if $B_s$ oscillations are not observed, current constraints imply that if a limit of $\Delta m_s$ greater than 30 $ps^{-1}$ is set at a 95% C.L., then new physics beyond the Standard Model is indicated at the $3\sigma$ level.

Future projections for Tevatron reach, based on these first results and anticipated improvements, are illustrated in Fig. 12, and show that with sufficient luminosity, the Tevatron can shed light on most of the SM-allowed range of $\Delta m_s$. Certainly with luminosities in the range of 6 $fb^{-1}$, expected in 2008, the situation will become extremely interesting. Further, a proposal by DZero to double the bandwidth dedicated to *b*-physics and the improved resolution of the new silicon tracker inner layer will together permit the Tevatron to explore the entire SM region. If oscillations are not observed with this quantity of data, then limits will indeed be at the level indicating potentially new physics beyond the standard model.

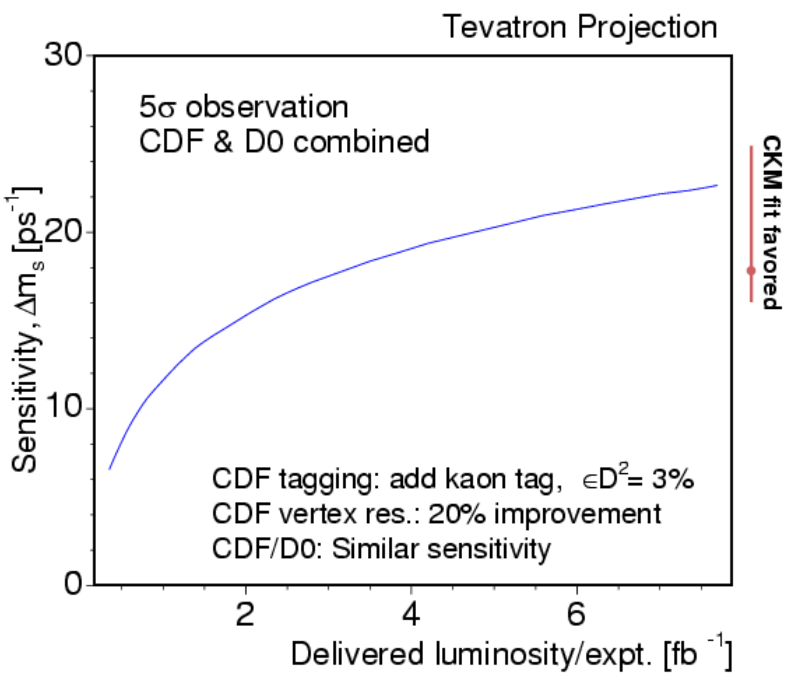


Figure 12: Expected reach for $\Delta m_s$ as a function of luminosity. The projections assume 20% improvement in the vertex resolution and an additional flavor tagging using same-side Kaons

The $B_s$ system is also particularly interesting at this time since initial measurements of the fractional width (i.e., lifetime) difference between the eigenstates of the $B_s$, $\Delta\Gamma_s/\Gamma_s$, are unexpectedly large, possibly indicating that non-Standard Model physics may manifest itself in the $B_s$ system. The current theoretical prediction of this parameter is $\Delta\Gamma_s/\Gamma_s = 0.12 \pm 0.05$. At present, from decays to $J/\psi\phi$, CDF and DZero measure values of 0.65 $^{+0.25}_{-0.33}$ (stat) ± 0.01 (syst) and 0.24 $^{+0.28}_{-0.38}$ (stat) ± 0.04 (syst), respectively. Although not yet significant, the large values are tantalizing and would also improve prospects for measuring CP violation. On the other hand, if it turned out that the measured value is significantly smaller than the SM prediction, it would indicate an anomalously large value of the CP-violating phase in the $B_s$ system and also new physics. Figure 13 shows the expectations for $\sigma(\Delta\Gamma_s/\Gamma_s)$ based on a projection of the current DZero measurement. The projected uncertainty is statistical only since it dominates the current measurement, the systematic uncertainty is expected to remain relatively small. With luminosities exceeding 4 fb$^{-1}$, expected in 2007 or 2008, precision will be adequate to test the SM.

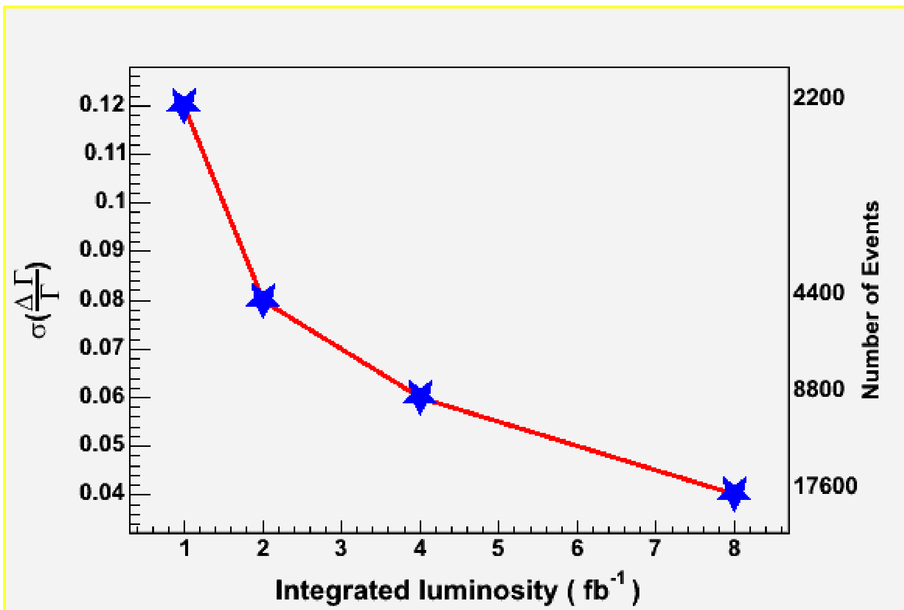


Figure 13: Expected uncertainty on as a function of integrated luminosity.

Decays of the $B_s$ meson to a pair of muons, $B_s \to \mu^+\mu^-$ or to a muon pair and a ϕ meson, $B_s \to \mu^+\mu^- \phi$, offer additional and extremely interesting windows onto new physics. In the SM, the decay $B_s \to \mu^+\mu^-$ is forbidden at the tree level and proceeds at a very low rate through higher-order diagrams. The latest SM prediction for the branching ratio is approximately $3\times10^{-9}$. However the branching fraction can be significantly enhanced in a number of extensions of the SM. For instance, in the MSSM, enhancements of about three orders of magnitude might be expected. Observation of the decay would then put an upper bound on masses in the MSSM (or general Two-Higgs Doublet Model) Higgs sector. CDF and DZero have recently reported an upper limit on the branching fraction of $1.2\times10^{-7}$ at a 95% C.L. As shown in the left panel of Fig. 14, the limit (single experiment) will be below around $2\times10^{-8}$ with an accumulation of 8 fb$^{-1}$ or more. Figure 15 shows the discovery limits for the rare decay.

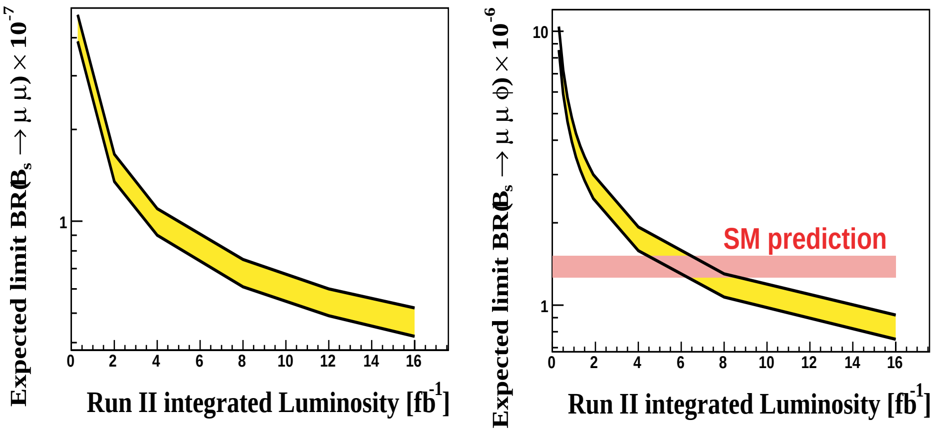


Figure 14: BR limits for $B_s$ decays as a function of luminosity.

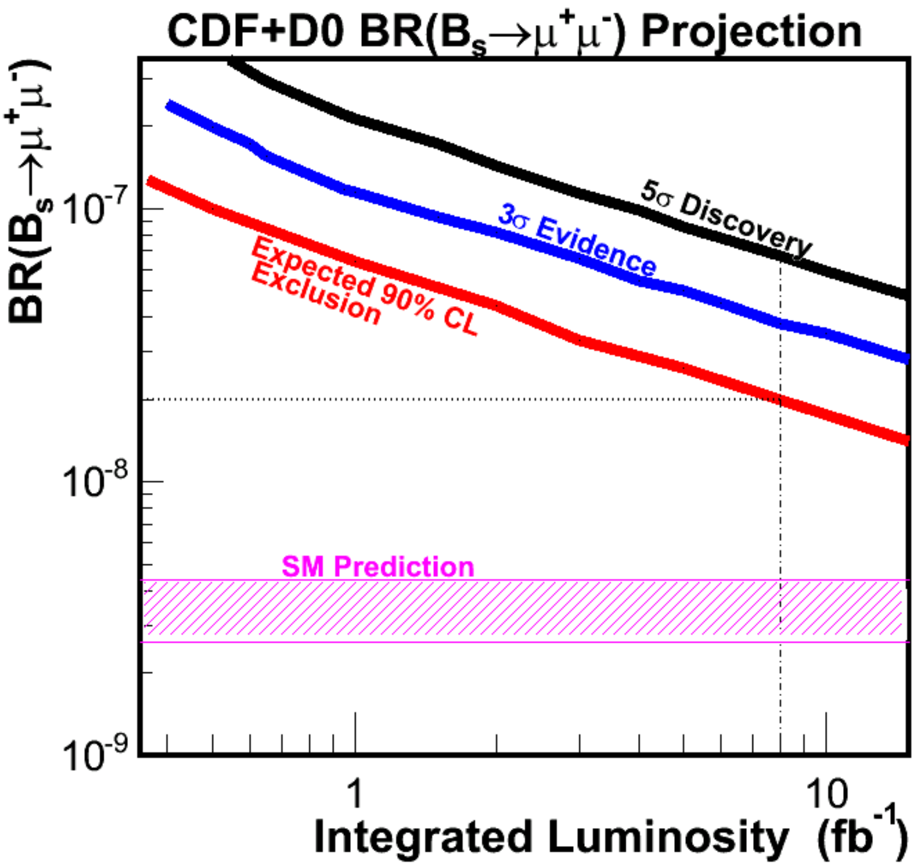


Figure 15: 95% CL limits, 3σ evidence and 5σ discovery as a function of luminosity.

As shown in the right panel of Figure 14, after an accumulation of 6 fb$^{-1}$, the decay $B_s \rightarrow \mu^+\mu^- \phi$ offers an extremely interesting and accessible test of the SM. Due to the final state meson, a number of decay amplitudes are not helicity suppressed (relative to the di-muon decay alone) and the SM expectations are near $1\times10^{-6}$. The projection is based on the current DZero 95% C.L. limit of $4.1\times10^{-6}$. By the year 2008 this measurement should present a challenge to the SM.

As might be expected, since the branching ratio $B_s \rightarrow \mu^+\mu^-$ and $B_s$ mixing are both sensitive to physics beyond the SM, a combination of the two can seriously constrain SUSY models. Fig. 16 shows allowed values of the branching ratio and mixing parameter in a minimal flavor violation model (Buras et al.) at $\tan\beta$=50 and $M_A$ = 200 GeV. The two bands represent two different (numerically) possible solutions, which depend on the sign of the different contributions for the MSSM correction to $\Delta M_s$. As can be seen the current measurements already eliminate much of the SUSY phase space and, with 8 $fb^{-1}$, the entire plane may be eliminated.

Figure 16: Current $B_s \rightarrow \mu^+\mu^-$ branching ratio limits and mixing limit imposed on SUSY parameter space. For 8 $fb^{-1}$, $\Delta m_s/\Delta m_s^{SM}$ would be beyond unity, but not shown due to the range of uncertainty on $\Delta m_s^{SM}$ .