Submission to the Particle Physics Project Prioritization Panel from the CDF and DØ Experiments

March 19, 2003

Executive Summary

The Tevatron is the world's highest energy accelerator. Until the LHC starts to produce physics, it is a unique energy-frontier facility that can address some of the biggest questions in particle physics:

- What is the structure and what are the symmetries of space-time?
- Why is the weak force weak?
- What is cosmic dark matter?

The Tevatron is the world's only source of top quarks. It is the only place we can directly search for supersymmetry, for the Higgs boson, and for signatures of additional dimensions of space-time. It is the most likely place to directly observe something totally unexpected. And it is the only opportunity to make any of these discoveries in the United States, if that is a political priority. **The central aim of the CDF and DØ upgrades is to maintain these physics capabilities throughout the duration of Run II, and to ensure that we can exploit the full physics potential of the accelerator and the detectors in which we have already invested so much.**

The Run IIb Detector Upgrade Projects have undergone extensive reviews:

- Director's Technical Review (December 2001)
- Director's Cost and Schedule Review (April 2002)
- A series of Fermilab PAC reviews, culminating in the recommendation for Stage I approval (June 2002)
- Director's Technical, Cost, Schedule, and Management Review (August 2002)
- DOE Baseline Readiness ("Lehman") Review (September 2002)
- DOE External Independent Review by the Jupiter Corporation (November 2002).

The design and physics performance of the trackers are described in detail in the Technical Design Reports and are well matched to the Run IIb physics goals. The Director's Technical Review Committee concluded in August 2002 that the "Designs are clearly mature and all major aspects of the upgrades are supported by in-depth studies." The External Independent Review Committee stated in November that the projects were "well managed", with cost estimates that are "reasonable and realistic". The CDF and DØ Run IIb Detector Projects have received DOE CD-3(a) approval, allowing the expenditure of FY03 equipment funds. These funds are being used in part to procure long-lead time production parts, including the silicon sensors. By the end of FY03, we expect to have obligated over one third of the total project cost of the upgrades.

The upgrade projects are technically sound, are on track, have the full support of the experimental collaborations, and address our highest priority physics goals. We believe they form an essential part of the US high energy physics program and should be pursued enthusiastically.

Physics Goals of the Run II Upgrades

The Run II physics program was developed and laid out at a series of workshops held at Fermilab between January 1998 and January 2000[1]. Our physics goals are pursued through direct searches for particles and forces not yet known, including both those that are predicted or expected (like the Higgs boson and supersymmetry) and those that would come as a surprise. At the same time we confront the Standard Model through precise measurements of the strong interaction, through measurements of the quark mixing matrix, and through precise measurements of the electroweak force and the properties of the W, the Z and the top quark. The experiments already have first results in all of these areas.

The Top Quark and Electroweak Physics

The top is the heaviest of the quarks and alone among them, couples strongly to the Higgs. We need to test its properties and decays with sufficient precision that the standard model can be confirmed or refuted. Here we can look forward to significant improvements in the short term because the Run I dataset was so statistically limited. The top quark was discovered by CDF and DØ in 1995 on the basis of a few tens of events — Run II will deliver top quarks in the thousands. Per inverse femtobarn, we will collect roughly 500 b-tagged top-pair events in the lepton + jets final state. The top mass is a critical parameter for precision electroweak fits. With 2 fb^{-1} we expect a mass uncertainty of 2.7 GeV per experiment[2], which could be reduced to 1.3 GeV with 15 fb^{-1}. It is worth asking why one would need such precise knowledge of this mass. Of course the smaller the uncertainty on m_t, the better the indirect constraints on the Higgs mass (Fig. 1); but once a light Higgs has been found, precise comparisons of m_H, m_t and m_W will allow us to understand if it is a SUSY Higgs (h) or not, and will permit limits to be placed on the stop sector in the MSSM if it is[3]. Both DØ and CDF have now "rediscovered" top for the spring 2003 conferences in the dilepton and lepton plus jets channels; the cross section at the new center of mass energy has been measured. CDF has a first Run II top mass measurement. New techniques are also being developed, helping to ensure that we can get the most physics out of the Run II dataset. For example, DØ has a new, preliminary determination of the top mass from Run I data that uses more information per event, obtains a better discrimination between signal and background than the published 1998 analysis, and improves the statistical error equivalently to a factor 2.4 increase in the number of events.

As well as improving the cross section and mass measurements, we will look for top-antitop spin correlations which can tell us if the top is really the spin-½ object it should be, and observe single top production (which allows a model-independent measurement of the CKM matrix element $|V_{tb}|$). Run II will also test beyond-the-standard-model theories that predict unusual top properties, states decaying into top, and anomalously enhanced single top production.

New particles and forces can be seen indirectly through their effects on electroweak observables[4]. The tightest constraints will come from improved determination of the masses of the W and the top quark. Currently, the W mass is known to be $m_W = 80\,451 \pm 33$ MeV; the measurement is dominated by LEP data. Our Run I results fixed the W mass at the 60 MeV level, but it will take

[1] http://fnth37.fnal.gov/run2.html
[2] M. Grunewald et al., hep-ph/0111217
[3] M. Beneke et al., hep-ph/0003033
[4] U. Baur et al., Fermilab-Pub-00/297

a Run II dataset of order 1 fb^{-1} before we can 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 per experiment, with an ultimate capability of 15 MeV per experiment[5] given 15 fb^{-1}]. Both experiments now have preliminary results from their Run II samples of W and Z candidates and have measured the cross sections at the Tevatron's new centre of mass energy of 1.96 TeV. CDF has also measured the forward-backward asymmetry in e^+e^- production in Run II and is preparing a paper on this subject.

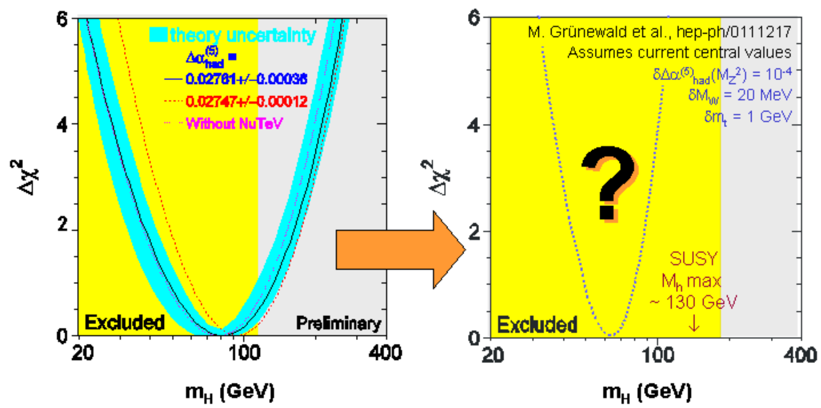

Fig 1. Current and possible future limits on the standard model Higgs, from direct searches (yellow exclusion region) and indirect measurements (parabola).

New Phenomena

As the world's highest energy collider, the Tevatron is the most likely place to directly discover a new particle or force. We know the standard model is incomplete; theoretically the most popular extension is to embed it within supersymmetry (which is a basic prediction of superstring models). Here each known particle has a so-far unobserved and more-massive partner, to which it is related through a change of spin. If it exists, the lightest supersymmetric particle would be stable. Vast numbers of them would pervade the universe, explaining the astronomers' observations of dark matter. The Tevatron is the only place to directly search for supersymmetry. In Run II, the opportunities for discovery[6] include squarks and gluinos, in final states with missing energy (E_T^{miss}) and jets (and lepton(s)); charginos and neutralinos through multilepton final states; gauge mediated SUSY in E_T^{miss} + photon(s) channels[7]; stop and sbottom; and R-parity violating models[8]. The Run II SUSY sensitivity extends up to squark and gluino masses of order 400-500 GeV and charginos 150-180 GeV. **It is important to note that luminosity is critical in maximizing the reach of these searches, as illustrated by Fig. 2:**

[5] M. Grunewald et al., hep-ph/0111217
[6] V. Barger, C.E.M Wagner et al., hep-ph/0003154
[7] R. Culbertson et al., hep-ph/0008070
[8] B. Allanach et al., hep-ph/9906224

There is a very significant gain in parameter space covered if the luminosity is increased from 2 to 10 fb^{-1} per experiment.

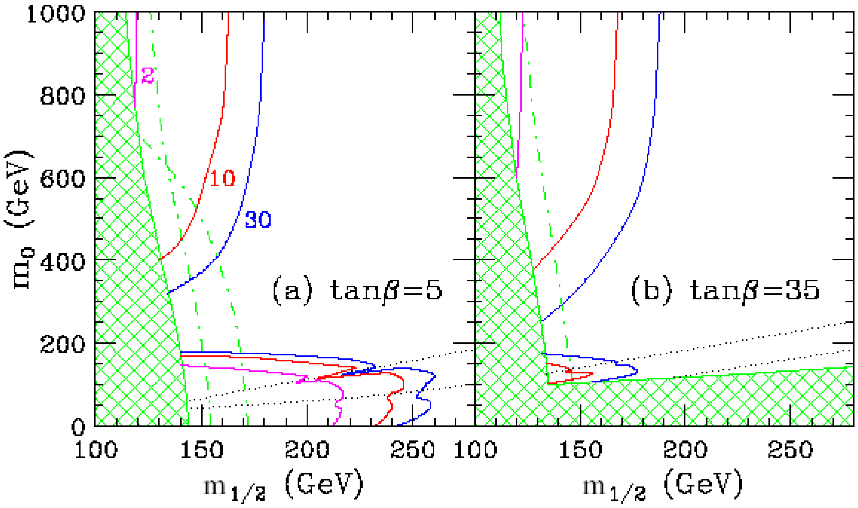

Figure 2. Tevatron reach in the trilepton channel in the m0-m1/2 plane, for fixed values of $A_0 = 0$, $\mu > 0$ and (a) tan β = 5, or (b) tan β = 35. Results are shown for 2, 10 and 30 fb^{-1} total integrated luminosity. The shaded regions are excluded (either by LEP or theoretically). For more details see V. Barger, C.E.M Wagner et al., hep-ph/0003154.

Searches for other new phenomena include leptoquarks, dijet resonances, new heavy W′ and Z′ bosons, massive stable particles, and monopoles.

The Tevatron allows us to experimentally test the new and exciting idea that gravity may propagate in more than four dimensions of spacetime. If there are extra dimensions that are open to gravity, but not to the other particles and forces of the standard model, then we could not perceive them in our everyday lives. But particle physics experiments at the TeV scale could see signatures such as a quark or gluon jet recoiling against a graviton, or indirect indications like an increase in high energy lepton-pair production. These studies use the Tevatron to literally measure the shape and structure of space-time.

While it is good to be guided by theory, one should also remain open to the unexpected. Therefore both experiments have developed quasi-model-independent (signature-based) searches, which look for significant deviations from the Standard Model. In the Run I dateset, no significant evidence for new physics was found. Perhaps revealing different psychologies, DØ has quantified its agreement with the Standard Model at the 89% confidence level, while CDF has preferred to highlight some potential anomalies as worth pursuing early in Run II.

The experiments have already embarked on a number of searches using Run II data. Work has started on understanding the E_T^{miss} distribution in multijet events as a prelude to squark and gluino searches; trilepton candidates are also being accumulated. At DØ, a gauge-mediated SUSY search has set a limit on the cross section for $\bar{p}p \rightarrow E_T^{miss} + \gamma\gamma$. Both experiments have searched for virtual effects of extra dimensions in e^+e^-, $\mu^+\mu^-$ and $\gamma\gamma$ final states, and limits on the scale of new dimensions at the TeV level can already be set (including first limits in the Randall-Sundrum framework, from CDF). Searches for leptoquarks decaying to electron+jet has been carried out. Several of these cross sections and mass limits are already better than published Run I results, showing that all the pieces are in place for the Run II physics program.

Electroweak Symmetry Breaking

In the standard model, the weak force is weak because the W and Z bosons gain mass from a field (called the Higgs field) that permeates the universe. This same field gives masses to all the fundamental fermions. It should be possible to excite this field and observe its quanta — the long sought Higgs boson. It is the last piece of the standard model, and also the key to understanding any beyond-the-standard-model physics like supersymmetry. Finding it, or excluding it, is a very high priority for the international high energy physics community.

The Higgs search at the Tevatron[9] covers the mass range between 115 GeV and roughly 180 GeV. Below about 140 GeV, the predominant decay mode is to b-quarks, and inclusive Higgs production is swamped by the QCD background. We therefore rely on associated production of the Higgs with a vector boson, whose leptonic decays allow us to reject many of the backgrounds. The most significant signals are obtained in the channels $WH \rightarrow l\nu\ \bar{b}b$, $ZH \rightarrow l^+l^-\ \bar{b}b$, and $ZH \rightarrow \nu\nu\ \bar{b}b$. At higher masses, the Higgs decays predominantly to W^+W^- and the signal can be pulled out of the continuum background using angular cuts. The very familiar Higgs reach plot is the result of combining all these search channels. It is worth noting several points about this analysis. The cross sections are low, so maximizing the luminosity plays a key role. Combining the results from two experiments effectively does this and greatly extends the reach. As shown in fig. 3, the range of Higgs masses that the Tevatron can cover corresponds exactly to those where the Higgs is most likely to lie, based on direct and indirect searches to date[10]. The figure also underlines the importance of the low-mass (115-125 GeV) search region. There are important results to be obtained at all integrated luminosities between 2 fb^{-1} (at which a 115 GeV Higgs could be excluded) and 15fb^{-1}. There is no luminosity which, if not reached, makes the program moot; nor is there any threshold beyond which further increases would be of marginal utility.

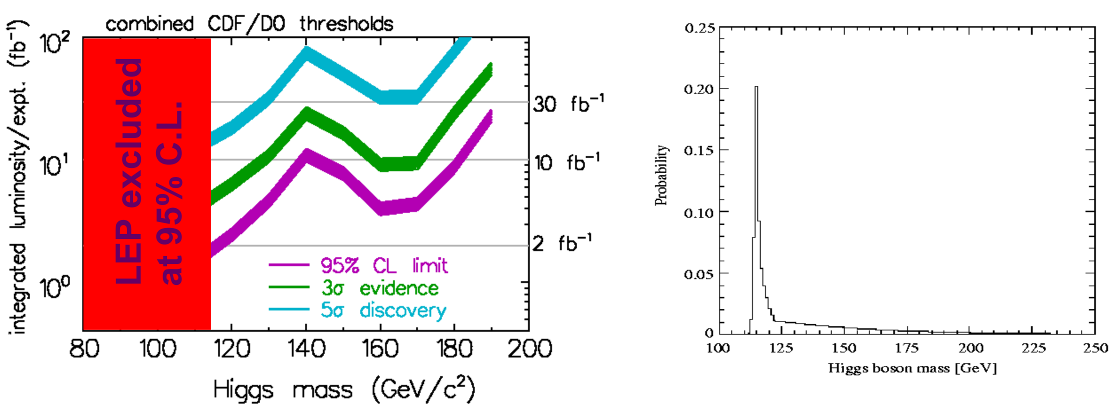

Figure 3. Run II Higgs reach as a function of luminosity (left) compared with Erler's estimation of the probability for the Higgs to have a given mass (right).

Since the Higgs reach estimates were all made before Run II began, the detector collaborations have embarked on a joint project to update and improve the estimates with the goal of having a document available by summer 2003. The improved estimates will be based on better detector simulations and will incorporate the knowledge we have gained of operations in the real Run II

[9] M. Carena et al., hep-ph/0010338

[10] J. Erler, Phys.Rev. D63 (2001) 071301

environment. It is important to stress, however, that we have no indications of any big problems with the earlier estimates.

Right now, we are developing the foundations needed for Higgs physics in Run II: good jet resolution, high b-tagging and trigger efficiencies, and a good understanding of all the backgrounds. One interesting subject that can be attacked with relatively modest luminosities in 2003 is the search for one or more of the extended suite of Higgs bosons that are predicted in supersymmetric models. Associated production of a SUSY Higgs together with a $b\bar{b}$ pair is enhanced at high $\tan\beta$, and tighter limits than those from LEP can already be set with a few hundred inverse picobarns. These limits will get tighter as the luminosity increases. With 5-10 fb^{-1} of recorded data, it will be possible to combine these searches with SM Higgs searches and exclude the whole of the SUSY Higgs (m_A, $\tan\beta$) plane[11] for maximal stop mixing if no Higgs signal is seen. Since a light Higgs is such a general prediction of SUSY, this would be very interesting

QCD

No one doubts that Quantum Chromodynamics (QCD) describes the strong interaction between quarks and gluons. Its effects are all around us: it is the origin of the masses of hadrons, and thus of the mass of stars and planets. This doesn't mean it is an easy theory to work with. As well as using hadron colliders to test QCD itself, we find that it is so central to the calculation of both signal and background processes that we need to make sure we can have confidence in our ability to make predictions in this framework. We need to resolve some outstanding puzzles and ensure we understand how to calculate the backgrounds to new physics[12].

Both CDF and DØ have now measured jet energy distributions from Run II. CDF is making use of their new forward calorimetry to cover the whole range of pseudorapidity. Jet calibrations are not yet final, but already we see events with transverse energies beyond 400 GeV. With 2 fb^{-1} transverse energy measurements as high as 600 GeV will be made, and with 15fb^{-1} to 700 GeV (Fig 4). The further we can reach, the better we can pin down the high-E_T behavior of the cross section, and thus the better we can determine the gluon content of the proton, which remains very poorly constrained at high momentum and thus a source of uncertainty on background estimates (also shown in Fig. 4). Increased reach in E_T also increases our reach for new physics. The high energy end of the spectrum is the place where new physics such as compositeness, or technicolor resonances, would show up as deviations from the QCD expectation. Any such deviation could be confirmed as new physics by studying the dijet angular distributions as a function of mass.

[11] M. Carena et al., hep-ph/0010338
[12] U. Baur et al., Fermilab-Pub-00/297

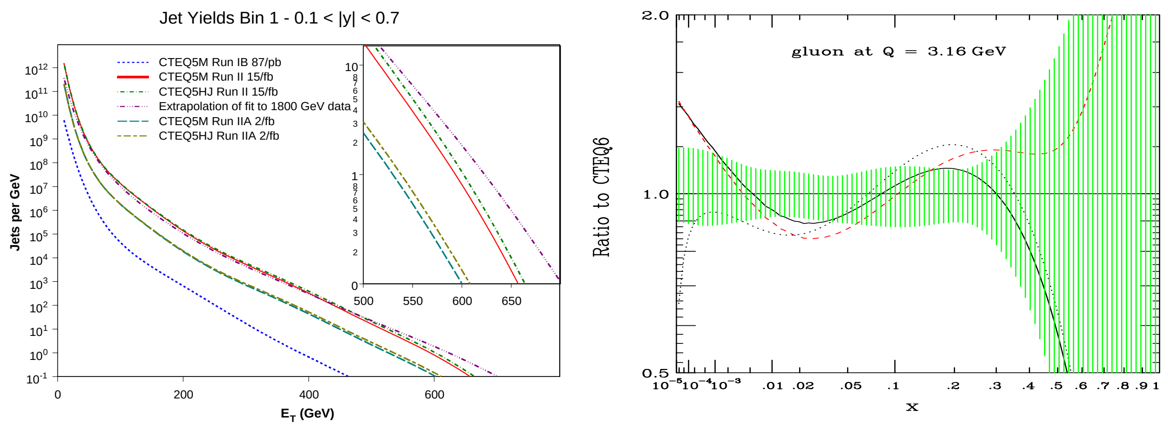

Figure 4. (Left) Tevatron reach in central jet transverse energy. The lower curve corresponds to Run I, the centre curves to $2fb^{-1}$, and the upper curves to $15\ fb^{-1}$. The different colors indicate different PDF choices. (Right) The green shading shows the current uncertainty on the gluon pdf as a function of x. The curves show how various recent PDF sets compare with CTEQ6.

B-Physics

The mixing between the three generations of quarks results in subtle violations of the so-called CP symmetry relating particles and antiparticles. Understanding this symmetry will help explain why the universe is filled with matter, not antimatter. In the decays of B-mesons, these symmetry violations can be large, and so B-hadrons have become an important laboratory to explore the "unitarity triangle," which relates the elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. In Run II we want to measure the elements of the CKM matrix in ways that are complementary to the electron-positron B-factories and which lay the foundation for the dedicated program to follow at BTeV.

The Tevatron Collider B-physics program is well suited to exploit the large production cross section of all b-quark species, such as the B_s, B_c, and the b-baryons such as the Λ_b. CDF has now demonstrated that it is possible to trigger on secondary vertices from the long-lived bottom and charmed mesons. DØ will institute a similar trigger this summer. The CDF B-physics program in Run IIa is focused on exploiting the event sample taken with this trigger, typically requiring two tracks with $p_T > 2$ GeV/c which have impact parameters greater than 100 microns. The beam conditions in the Tevatron have been sufficiently stable that such triggers are now well established and can be expected to be used to tag high p_T b-quark jets in the search for SUSY channels containg b-quark jets, as well as the SUSY and SM Higgs in Run IIb.

The present B Physics program at CDF is exploiting the uniqueness of the SVT two track triggers. Signals have been established in Λ_b decays, from which the lifetime and branching ratios will be measured by summer 2003. Lifetimes are being studied in very large samples of semileptonic decays, such as $B \rightarrow D^*l\nu$. The search for $Bs \rightarrow \mu\mu$ is underway and exclusive signals in the J/ψ modes have been established. Figure 5 shows a $B \rightarrow J/\psi\ K^+$ signal with a 100 micron cut on the path length. Figure 5 also shows the 2-body modes $B \rightarrow\ h^+h^-$ recorded by the SVT two track trigger. An analysis is under way to separate the individual components of the signal peak. The figure also shows the decay mode $B \rightarrow D^+\pi$, again triggered using the SVT. This mode is being used to study the yield of $B_s \rightarrow D_s\pi$, the main exclusive mode for B_s mixing.

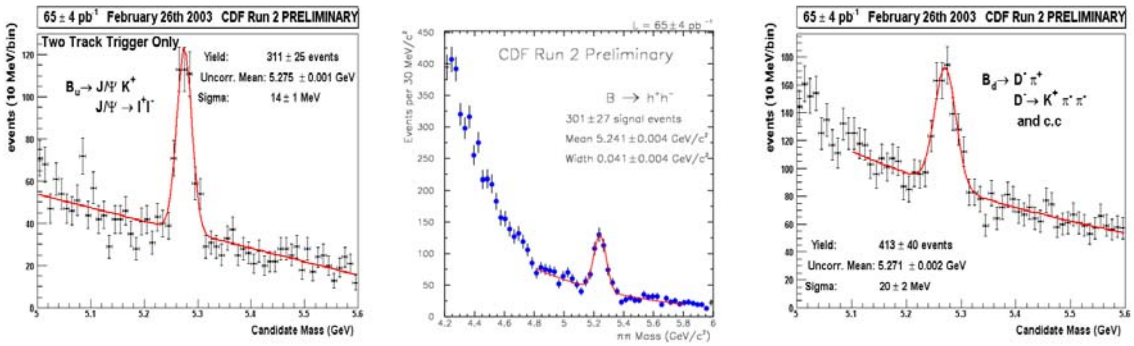

Figure 5. CDF B-meson signals from Run II: (left) $B \rightarrow J/\psi\ K^+$ signal, (center) $B \rightarrow h^+h^-$ signal recorded with the SVT trigger, and (right) $B \rightarrow D^+\pi$, again triggered using the SVT.

We also look forward to a charm physics program that will pursue rare decays and eventually study mixing and CP violation. CDF already has the world's best limit on the branching ratio for the rare decay $B(D \rightarrow \mu\mu) < 3.1\times10^{-6}$ (95% CL), a factor of two below the existing best limit. To set the scale of charm yields, a $D\rightarrow K\pi$ signal is shown in fig. 6; extrapolated to 2 fb^{-1}, we estimate that about 10 million decays will be recorded.

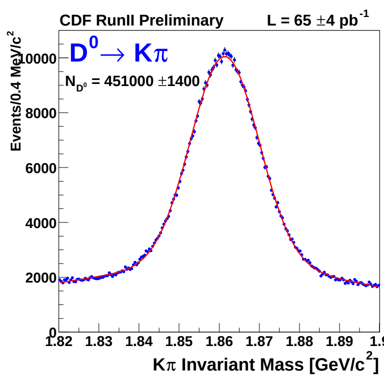

Figure 6. CDF charm signal from Run II in the $D\rightarrow K\pi$ mode.

The CDF experiment DAQ and trigger system has been designed for B physics in Run IIa, but given the present measured rates and extrapolation to Run IIb luminosity, there is no plan to devote a substantial amount of bandwidth for B physics in Run IIb: the available bandwidth is needed for high p_T triggers. DØ also emphasizes the high p_T program in Run IIb and will accomodate the higher luminosity with improved L1 trigger capabilities. After careful tuning of triggers, a small targeted program of B Physics may still be possible in Run IIb. Two possible physics topics that will be accessible to CDF and DØ and may be of interest will be the $B_s \rightarrow \mu\mu$ mode, which provides a powerful indirect test for new physics, such as SUSY, and the measurement of the unitarity triangle angle gamma from the two body decay modes.

Summary of Physics Goals

The Run II program exploits the highest accelerator energy, excellent detectors, enthusiastic collaborations and data samples that will double every year. We are guaranteed interesting new physics results at each step in luminosity, as shown in Fig. 7. Each step answers important questions. Each leads on to the next. In this way, we will lay the foundations for a successful LHC physics program — and hopefully a linear collider to follow.

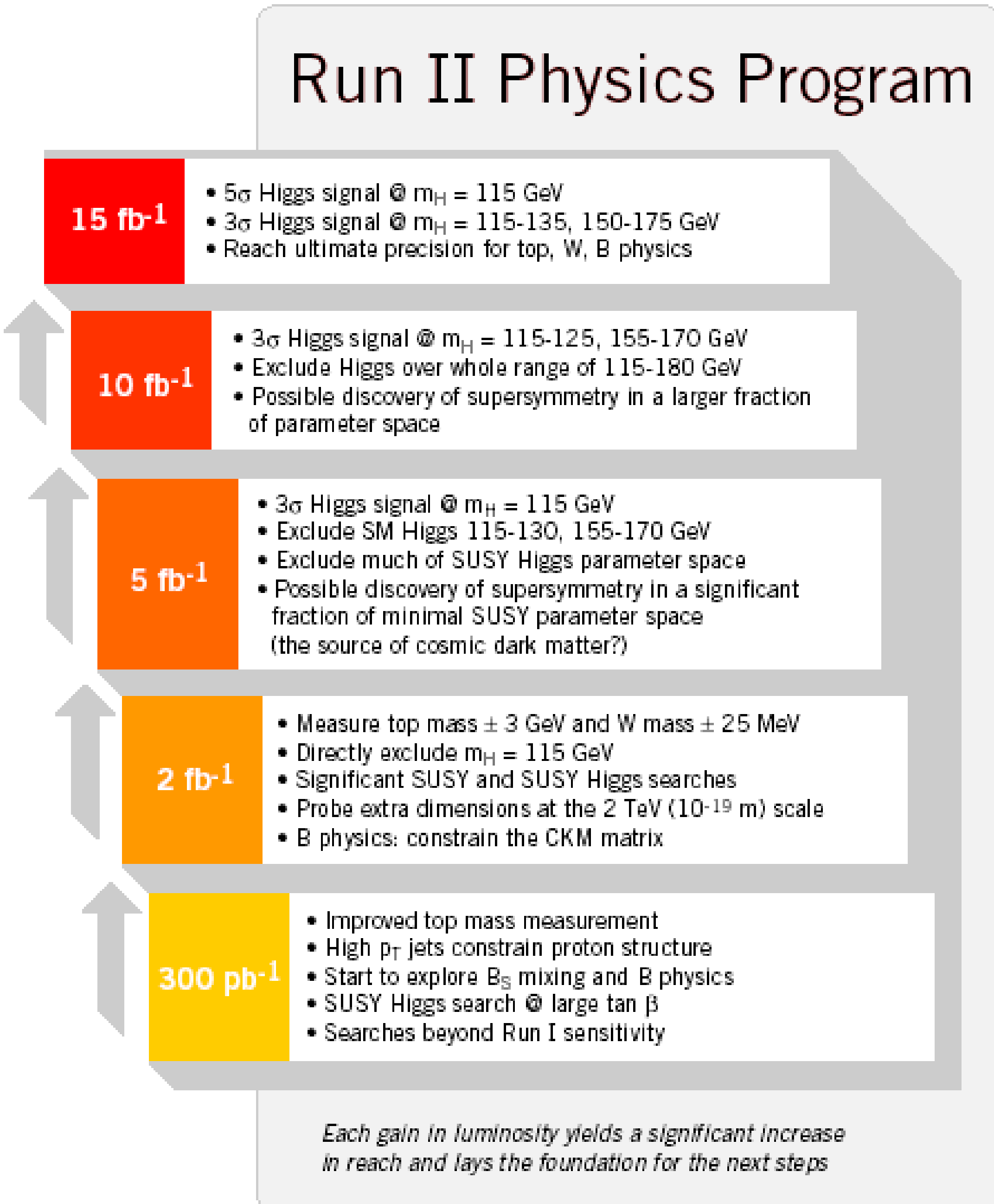

Fig. 7 Physics highlights of Run II as a function of luminosity.

The Two Detectors

While the CDF and DØ detectors both employ a silicon vertex detector, surrounded by a solenoidal magnetic tracker, a calorimeter and muon chambers, they use different technologies and place their emphases differently. The CDF detector emphasizes charged particle tracking with a very large tracking volume and the possibility to separate π and K-mesons by time of flight. The DØ detector emphasizes calorimetry and high-acceptance, stand-alone muon detection with three muon detector layers. Together with a higher level 1 trigger bandwidth, CDF's tracking emphasis makes it a stronger detector for beauty and charm physics, while DØ's calorimetry gives better jet and missing E_T resolution for searches. However, for the physics that is of interest in the later stages of Run II (top, vector bosons, high-p_T jets, high mass SUSY and Higgs searches) the two detectors have a very similar reach. Their acceptances are very similar, the electromagnetic energy resolution is the same, and the lepton, jet and b-tagging capabilities are comparable. We do not believe either detector is significantly better suited than the other to any of these high-p_T physics topics and the different technologies complement each other well.

The HEPAP subpanel appointed in March 1997 suggested that resources could be spared by upgrading only one of the two high-p_T detectors for what was then being called Run III. This recommendation was made assuming the Tevatron could deliver $10^{33}cm^{-2}s^{-1}$ and the upgraded detector could accumulate more than 20 fb^{-1} before the LHC started doing physics. The detector upgrades required to operate in those conditions would have been much more extensive than what we are currently building. Subsequently it became clear that the very high luminosities imagined in this scenario were simply not achievable. The Run II Physics workshops in 1998-2000 emphasized that the best way to maximize the physics reach is to operate two detectors and combine their results, and that has always been the policy of the present Fermilab Director. In fact the two collaborations are already combining their results.

As an energy frontier machine, the physics reach of the Tevatron will always be limited by statistics. This is not just true for Higgs searches, but also for supersymmetry (the multilepton signatures for example have very low cross sections and small SM backgrounds), and even for many of our top quark measurements. Operating two detectors is the most straightforward way to effectively double the luminosity of the accelerator. In fact the gain is greater than that, because the two detectors use complementary techniques and cross-check each other’s results. CDF and DØ complement each other very well: CDF’s strengths in tracking are matched by DØ’s strengths in calorimetry and stand-alone muon identification. The ability to obtain results based on different approaches and with different systematic uncertainties is a valuable one; so is the stimulating effect of competition. Operating two detectors also mitigates the risk of any unforseeable technical failure.

We understand that upgrading both detectors rather than one does imply investing resources. The return on this investment is a guaranteed factor of two increase in luminosity. Compared to any other way of achieving such a gain, the technical risk is extremely low and the payoff is certain. It is the most cost-effective way to double the useful luminosity.

The Context for these Upgrades

Background and current status

The CDF and DØ detectors completed Run I data taking in February 1996. Each experiment collected approximately 120 pb^{-1} of data at a center of mass energy of 1.8 TeV. The detectors were extracted from the collision halls, and extensively upgraded to improve performance and to accommodate the higher instantaneous and integrated luminosities to be provided by the Tevatron in Run II. In parallel with the detector upgrades, the Tevatron complex was upgraded to incorporate major new accelerator components, including the new 150 GeV Main Injector and the Antiproton Recycler. After a five-year upgrade project, the detectors were moved back into the Tevatron collision halls in March of 2001 and started operation with proton-antiproton collisions at the increased center of mass energy of 1.96 TeV.

The commissioning of these big detectors is a complex process. For each experiment, data from nearly one million sensors arrive at a rate of 2.5 million collisions per second. Proper electronics synchronization, detector calibration and the development of triggers for the selection of events to be analyzed require appreciable commissioning time. The first year of operation was primarily used to establish stable detector, trigger and data acquisition operation, with first physics quality data being recorded in the summer of 2002. Each experiment has now recorded between 70 and 90pb^{-1} of Run II physics data and by the summer of 2003, this will have increased to around 200 pb^{-1} (almost twice the Run I dataset). The centerpiece will be a greatly increased top quark sample, thanks to the higher beam energy and the much improved b-tagging capabilities of the detectors. A first look at B_s mixing will be possible, together with lifetimes and branching ratio measurements from the B, B_s, B_c, Λ_b and the huge charm samples. Jet distributions at the highest energies will constrain proton structure, and searches will follow up on Run I anomalies and extend the Run I reach for many extensions to the standard model.

The Run IIb Detector Upgrade Projects have undergone extensive reviews of technical, cost, schedule, and management issues during the past year as part of the process to obtain DOE approval. Links to the reports of these reviews are given below.

1. December 2001 Technical Review (chaired by J. Pilcher)
2. April 2002 Cost and Schedule Review[13] (chaired by E. Temple)
3. June 2002 PAC Review[14] (Stage 1 approval given to the CDF and DØ Run IIb Detector Projects)
4. August 2002 Technical, Cost, Schedule, and Management Review[15] (chaired by E.Temple)
5. September 2002 DOE Baseline Readiness Review[16] (chaired by D. Lehman)
6. November 2002 DOE External Independent Review[17] (Jupiter Corp.)

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[13] http://d0server1.fnal.gov/projects/Spokes/documents_2002/Dir_Review_RunIIb_report_April_2002.pdf
[14] http://www.fnal.gov/directorate/program_planning/phys_adv_com/June02PACPublic.pdf
[15] http://d0server1.fnal.gov/projects/run2b/Meetings/Temple/August02/Report/Combined_RunIIb_Review_Report.pdf
[16] http://www-cdf.fnal.gov/upgrades/run2b/Lehmann_Sep02/ExecutiveSummary.pdf
[17] http://d0server1.fnal.gov/projects/run2b/meetings/DOEReviews/EIR_Nov02/Reports/FINAL%20Fermi%20Lab%20EIR%20REPORT%2012-2-02.pdf

Following the December 2001 Technical Review, the CDF and DØ collaborations continued to develop detailed designs of new silicon trackers to replace the current devices to meet the needs of the experiments in Run IIb. The design and physics performance of the trackers are described in considerable detail by the Run IIb Technical Design Reports,[18,19] and are well matched to the Run IIb physics goals. For example, a Geant-based simulation study[19] of the DØ tracker with full pattern recognition finds a 67% increase in the double b-tagging rate for a fixed mistag rate. The Technical Review Committee returned in August 2002 to evaluate the Project's technical readiness for a DOE baseline review and concluded that the "Designs are clearly mature and all major aspects of the upgrades are supported by in-depth studies."[15]

At the present time, the CDF and DØ Run IIb Detector Projects have received DOE CD-3(a) approval, allowing the expenditure of FY03 equipment funds. These funds are being used in part to procure long-leadtime production parts, including the silicon sensors. By the end of FY03, we expect to have obligated over one third of the total project cost of the upgrades. Extensive prototype studies have been successfully performed for all major components, including the sensors, hybrids, SVX4 readout chips, and cable assemblies. Full system tests have demonstrated that the components work together as designed. The Projects are rapidly moving from the design and prototyping stages to the pre-production and production stages. CDF completed a Production Readiness Review of the outer layer sensors in early February, and DØ will conduct a similar review in early March. Placement of the silicon sensor orders is expected to follow shortly after these reviews.

International Setting and Running Time

We look forward to the operation of the ATLAS and CMS detectors at the LHC towards the end of this decade. The physics program that we are interested in during Run II will be carried forward and greatly extended at the LHC. Bringing the ATLAS and CMS detectors to the stage of taking physics quality data will be no less challenging than the Run II CDF and DØ detectors, and researchers at the LHC will also require sufficient time to understand systematic effects and backgrounds at the higher energy regime. (For example, low mass Higgs searches at LHC will require understanding of forward jet tags, b-tagging, and photon identification and separation from jets). It is then reasonable to allow some overlap after commissioning between the LHC and Tevatron physics programs. As discussed in the laboratory response, this type of transition is natural (it occurred between UA2 and CDF in the late 1980's). We believe the laboratory's long range plan embodies a sensible and prudent scenario. It will allow us to exploit the respective strengths of both the Tevatron and the LHC and to make the best use of the large investment made in both of these frontier high energy physics programs, provide the strongest basis for the US high energy physics program, and maximize the prospect of major discoveries.

The CDF and DØ detector upgrades are required in order to accumulate large datasets (more than 4-5 fb^{-1}) at high instantaneous luminosities. We acknowledge that there are serious concerns about accelerator performance and that the future plans indicate it will take longer to reach these high luminosities than had been hoped. Such is the price of realism. In both the base and the stretch scenarios, the accelerator will deliver significantly more luminosity than the current detectors can handle. Failure to upgrade the detectors would mean we could never exploit the full physics potential of the Tevatron: by 2005 we could be in the position of operating the world's highest energy accelerator at sufficient luminosity for major discoveries but with dead inner

[18] http://www-cdf.fnal.gov/upgrades/run2b/Documents/tdr_sep02.pdf
[19] http://d0server1.fnal.gov/projects/run2b/meetings/DOEReviews/EIR_Nov02/D0_Run2b_TDR.pdf

tracking systems unable to discover anything. There would be no time to address this mistake. Clearly the accelerator upgrade requires careful planning and technological improvements; our planning has to assume the success of these endeavours.

Manpower

For the DOE Cost and Schedule (Lehman) Review in 2002, we obtained MOU's, carried out interviews and polled the CDF and DØ collaborations on their plans, in order to verify that we have sufficient manpower available to build the upgrades. The institutional commitments were matched to the resource loaded schedules for the upgrades and were found to be adequate. The Particle Physics Division assigned a committee (chaired by Ron Ray) to independently assess the manpower needs and availability at SiDet to cover both the Run IIb upgrades and CMS, and found it to be adequate. Both the technical and physicist manpower are therefore on a firm footing. We should emphasize that this includes the extremely strong involvement of all our international collaborators. Our Canadian, French, German, Italian, Japanese, Netherlands, Swedish and UK groups are negotiating with their funding agencies to extend their involvement in CDF and DØ through the full remainder of Run II.

Conditions Requiring Silicon Replacement

The performance of the CDF and DØ silicon trackers is a key measure of the physics capabilities of the detectors. Some of the most interesting physics we hope to perform in Run II relies heavily on clean and efficient identification of b-quark jets. This capability is essential for the search for the Higgs boson, for studies of top quark properties, for many supersymmetry signatures such as gluino decays to sbottom and direct sbottom and stop searches, and for SUSY Higgs production in association with a $b\bar{b}$ pair. In addition, the large b-quark production cross section at the Tevatron provides CDF and DØ the opportunity to study B hadrons in ways that complement the capabilities of the B-factories.

The replacement of the silicon tracker is driven by the limited radiation tolerance of the present trackers. These trackers were designed to meet the original Run 2 goal of an integrated luminosity of 2 fb^{-1} and a lifetime of 2-3 years. Assessments[20,21] of the radiation tolerance of the current trackers indicate that they will meet these goals, but will require replacement once a dose of order 4-5 fb^{-1} has been accumulated. The lifetime assessments are based on the locations and types of detectors used, our knowledge and phenomenology of radiation damage as a function of dose, and our measurements of the actual dose received in the Tevatron. We expect that the lifetime of the detectors will be limited by micro-discharge breakdown of the junction in the detectors supplied by Micron Semiconductor. This begins to occur at bias voltages of ~150 V and all channels will fail at bias values of 200 V. This means that the DØ detector will start to lose a significant number of channels on the innermost silicon layer (crucial for b-tagging) at 3.6fb^{-1} and it would be totally dead by 4.9 fb^{-1}. The lifetime of the CDF silicon is estimated to be 5 fb^{-1} and the port cards (part of the readout mounted in the detector) will fail after 5.7 fb^{-1}.

We have not specifically studied the effect of radiation damage on our tracking or b-tagging capabilities, but we have studied[22] the effect of random loss of silicon ladders. Figure 8 shows how the b-tagging efficiency per jet degrades rapidly as silicon efficiency is lost. Anything more than about 10% dead ladders has a very serious impact.

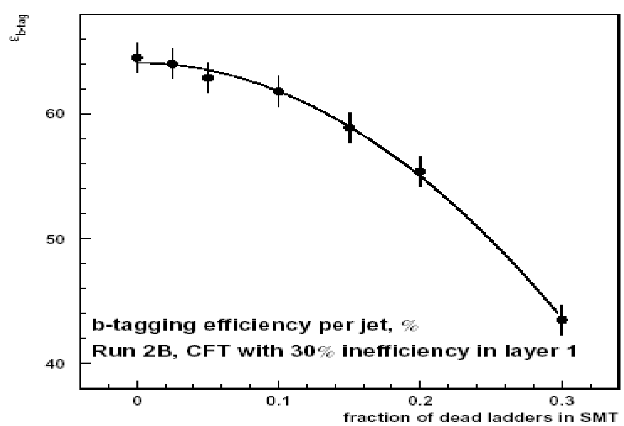

Figure 8. b-tagging efficiency per jet as a function of the fraction of dead silicon ladders, for the DØ Run IIb upgrade.

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[20] http://www-cdf.fnal.gov/upgrades/run2b/P5_Mar03/damage.ps
[21] http://d0server1.fnal.gov/projects/run2b/meetings/p5/march03/m_d0smtlifetime.pdf
[22] http://d0server1.fnal.gov/projects/run2b/meetings/PAC/april02/PACsilicon.pdf

Both the "base" and "stretch" projections of the delivered Tevatron luminosity exceed the radiation dose limit at approximately the time we expect to complete the Run IIb silicon trackers. This fact alone makes a convincing argument for replacing the CDF and DØ silicon trackers. Furthermore, the above estimates of the tracker lifetime require a large extrapolation from the present baseline. Making such a large extrapolation magnifies uncertainties in the magnitude of the radiation damage, the potential for damage from sudden beam losses, the rate at which sensors die from non-radiation causes, and the luminosity that will be delivered. The compelling physics motivation for Run II argues strongly for taking the prudent approach of completing the CDF and DØ silicon tracker upgrades that are underway.

As well as the increased integrated luminosity, the detector upgrades are needed in order to handle increased instantaneous luminosity. The upgrade projects contain the trigger and data acquistion system enhancements that allow us to deal with luminosities of $2\text{–}4\times10^{32}\text{cm}^{-2}\text{s}^{-1}$ and ten or more interactions per bunch crossing. These conditions have been fully simulated and the collaborations are confident that the upgraded detectors can operate well under these conditions.

Partial Replacement of Silicon Detectors

The feasibility of only replacing the innermost silicon detector layers (the "partial replacement" option) was extensively studied by both the CDF and DØ collaborations during the early phases of the project. Both collaborations came to the conclusion that the partial replacement option was not viable[23]. Among the concerns were:

- The present silicon trackers are extremely delicate devices that were not designed to be partially or fully dis-assembled. There is a high risk that the components to be preserved would be damaged during the dis-assembly/re-assembly process.
- The Run IIa trackers utilize double-sided sensors with limited cooling. To achieve radiation hardness, separate axial and stereo single sided sensors with improved cooling are planned for the Run IIb tracker upgrade. There is no obvious way to make such a replacement within the current geometrical constraints.
- The replacement of radiation damaged sensors cannot begin until the trackers are uncabled and moved to SiDet. There would then be a lengthy period required for dis-assembly and re-assembly before the detectors could be reinstalled and cabled. This process could not be completed during the relatively short shutdown envisioned for installation of the Run IIb detector upgrades. CDF estimated that partial replacement would add between 6 months and a year to the needed duration of the shutdown.
- The port cards, which are deeply embedded into the current CDF tracker are expected to fail after ~5.7 fb^{-1}, affecting both inner and outer layers of the SVX tracker.
- The possibility of inserting a rad-hard "Layer 0" inside the existing DØ silicon tracker was examined and rejected due to inadequate radial clearance.

The feasibility of the partial replacement option was also examined during the December 2001 Director's Technical Review of the CDF and DØ Run IIb upgrades. This review was conducted by an independent Technical Review Committee chaired by Jim Pilcher. In their report[24] they conclude: *"The groups have already examined the possibility of replacing only the inner layers and the disks of the present detector with radiation hard modules. Replacing the inner layers is very hard if not impossible mechanically. Another option would be to reuse the current staves on a new mechanical structure that would host the old staves at large radius and new ones at small radius. This would certainly imply a much longer downtime for the experiments."*

In summary, the possibility of replacing only the innermost sensors has been studied by the collaborations and the independent Technical Review Committee and found not to be feasible. The design of the silicon tracker upgrades has advanced to the point where a complete and detailed design has been developed and extensively prototype, and the procurement process for long-leadtime items, including sensors, has begun. Redirecting the project towards partial replacement at this time is not compatible with the Run II schedule and would result in a serious loss of effort.

[23] http://www-cdf.fnal.gov/upgrades/run2b/p5_mar03/cdf5425.ps
[24] http://www-cdf.fnal.gov/upgrades/run2b/TRC_Dec01/TRC_Report_3.4.htm