Future B physics prospects at hadron colliders

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Several new experiments with a B physics programme are planned to come into operation at hadron colliders in 2006 or later, after the current e^+e^- B factories have run for several years. These experiments will take advantage of the very large $b\bar{b}$ production cross-section in high-energy hadron collisions to push further the study of CP violation and of rare decays in the B sector, by improving on results obtained at B factories and performing new measurements with B_s^0 decays. After a motivation for pursuing a B physics programme at hadron colliders, these future detectors will be described with emphasis on the most important features for the detection of b-hadron decays, and several examples of the expected physics output will be given.

1. INTRODUCTION

A very large fraction of the available experimental measurements with b hadrons has been obtained at e^+e^- colliders running at the $\Upsilon(4S)$ and Z resonances. However, beauty was discovered in hadronic collisions, and the role of hadron colliders in the field of B physics is certainly far from being negligible: the CERN $p\bar{p}$ collider provided experimental evidence for the strong $B-\bar{B}$ mixing, and Fermilab's Tevatron contributed very significantly to the discovery and first studies of the B_s^0 and B_c^+ mesons. Although the B factories at the $\Upsilon(4S)$ have launched studies of CP violation in B decays with their recent first significant measurement of a non-zero CP asymmetry [1], we anticipate that future hadron collider experiments will play a very important role in our understanding of how much the CKM quark-mixing matrix of the Standard Model (SM) can accommodate the observed CP violation.

The running experiments active in B physics are BABAR and Belle, operating since a couple of years at the asymmetric B factories PEPII at SLAC and KEKB at KEK, as well as CDF and D0, which recently restarted data-taking at the Tevatron. Within the next 4–5 years, the Tevatron is expected to deliver 2 fb^{-1} of data (run IIa), while the B factories are planning to deliver each up to 500 fb^{-1}, representing a statistics equivalent to several 10^8 B mesons. With these data, the measurement of $\sin(2\beta)$ from the $B^0 \to J/\psi K_S$ CP asymmetry, where β is one of the angles of the CKM unitarity triangle, will reach an accuracy of ~ 0.03, still dominated by statistics. However, the other angles will not be measured very precisely. On the other hand, significant improvement of the knowledge on the lengths of the sides of the triangle will continue to depend on theoretical progress to relate them to the measurements of semi-leptonic B decays and B mixing, although the B_s^0 mixing frequency is expected to be measured at the Tevatron [2,7]. If, in 2006, $|V_{ub}|$ is known to 5–10% and $|V_{td}|/|V_{ts}|$ to few–5%, then the indirect determination of the angle β (from the sides of the triangle) can reach the same level of precision as the direct measurement. A comparison will then already allow a rather stringent test of the CKM picture. However, compatible data within the SM will not be sufficient at this point to exclude the presence of new physics in B mixing, as we would like to argue below. So in any case, further experimental investigation of the CKM triangle will be needed beyond 2006.

Most extensions to the SM predict the existence of new particles, which could appear in loop diagrams. Hence, new physics will likely affect B mixing and possibly Penguin decays, whereas tree decays can rather safely be assumed to remain unchanged. In this case, the side of the unitarity triangle opposite to β and proportional to $|V_{ub}|$ can still be extracted from the measurements of b $\rightarrow$ u tree transitions. However, the measured strength of B mixing may no longer be used directly to determine the side proportional to $|V_{\rm td}|$ (assuming $\Delta m_{\rm d} \propto |V_{\rm td}|^2$), and the measured $\rm B^0 \rightarrow J/\psi K_S$ asymmetry may no longer be identified with $\sin(2\beta)$. If the SM contribution to B mixing were known independently, then these two measurements could be used instead to extract the new physics amplitude contributing to B mixing. Hence, a precise determination of the CKM triangle independent of possible new physics in B mixing is needed. Combining the $|V_{\rm ub}|$ measurement with a clean determination of the angle γ is an obvious way to achieve this.

We mention here two ways of measuring the SM value of γ, even in presence of new physics in box diagrams. The proper-time dependence of the $\rm B^0 \rightarrow D^{*-}\pi^+$ and $\rm B^0 \rightarrow D^{*+}\pi^-$ CP asymmetries is driven by the CP-violating phase $\gamma + 2\beta$, where γ arises from the weak phase difference of the two tree diagrams involved, and 2β is the phase of $\rm B^0$ mixing. The latter, known from $\rm B^0 \rightarrow J/\psi K_S$, can be subtracted from the measured value of $\gamma + 2\beta$ extracted from the $\rm B^0 \rightarrow D^{*\mp}\pi^{\pm}$ analysis. However, this requires much more statistics than will be available in 2006, because one of the tree diagrams involved is doubly Cabibbo-suppressed with respect to the other one. This limitation is absent from the strange counterparts of these decays, $\rm B^0_s \rightarrow D^-_s K^+$ and $\rm B^0_s \rightarrow D^+_s K^-$. In this case, the CP-violating phase $\gamma - 2\delta\gamma$ can be measured; combining it with the measured value of (or a limit on) the $\rm B^0_s$ mixing phase $2\delta\gamma$ obtained from the $\rm B^0_s \rightarrow J/\psi\phi$ asymmetry will yield another clean determination of γ. However, very good particle identification is needed for this measurement, because of the very large Cabibbo-allowed $\rm B^0_s \rightarrow D^-_s \pi^+$ background. In addition it can only be performed at a high energy hadron collider and the statistics accumulated at the Tevatron by 2006 will not be sufficient.

The two examples above demonstrate that high statistics experiments at hadron colliders (even starting after the current B factory programme) will be able to provide valuable results to improve our knowledge on the CKM triangle and measure the effects of possible new physics, for example in $\rm B^0$ and $\rm B^0_s$ mixing.

2. STATUS AND MAIN FEATURES OF THE NEXT B PHYSICS EXPERIMENTS AT HADRON COLLIDERS

The $\rm b\bar{b}$ production cross-section is indeed very large at high-energy hadron colliders (Table 1): we expect $\sim 100\ \mu$b at Fermilab's Tevatron and $\sim 500\ \mu$b at CERN's LHC. At a luminosity of $10^{32}\ \rm cm^{-2}s^{-1}$, this represents already more than 10^{12} bottom quarks produced in one year, which will hadronize in all types of b hadrons (including 10% of $\rm B_s$ and 10% of b baryons). However, less than 1% of all inelastic events contain b quarks, so triggering is a critical issue. The bunch crossing rate at these machines will be quite high, with a very challenging 25 ns (132 ns) bunch spacing at the LHC (Tevatron), but not high enough to avoid multiple proton-(anti)proton interactions per bunch crossing (pileup) for luminosities of $10^{32}\ \rm cm^{-2}s^{-1}$ or larger. The many tracks produced along with the b hadrons can be used to determine the b production vertex rather easily. Flavour tagging is expected to be more difficult than at B factories, because of these extra tracks and because the time evolution of the two b hadrons is uncorrelated (mixing of the other b

Table 1
Approximate cross-sections (as predicted with PYTHIA 6) and main characteristics of the Tevatron and LHC machines. For LHC, the luminosity and pileup (defined as the number of inelastic interactions per bunch crossing) are given separately for IP8 (LHCb) and IP1,5 (ATLAS,CMS).

	Tevatron	LHC	
	(run II)	IP8	IP1,5
colliding beams	$\rm p\bar{p}$	pp	
$\sqrt{s}$	2 TeV	14 TeV	
$\sigma_{\rm b\bar{b}}$	0.1 mb	0.5 mb	
$\sigma_{\rm c\bar{c}}$	1 mb	3.5 mb	
$\sigma_{\rm inelastic}$	60 mb	80 mb	
$\sigma_{\rm total}$	75 mb	100 mb	
bunch frequency	7.6 MHz	40 MHz	
bunch spacing	132 ns	25 ns	
luminous region size, σ_z	30 cm	5.3 cm	
luminosity ($10^{33}\ \rm cm^{-2}s^{-1}$)	0.2	0.2	1–10
average pileup	1.6	0.53	2–20

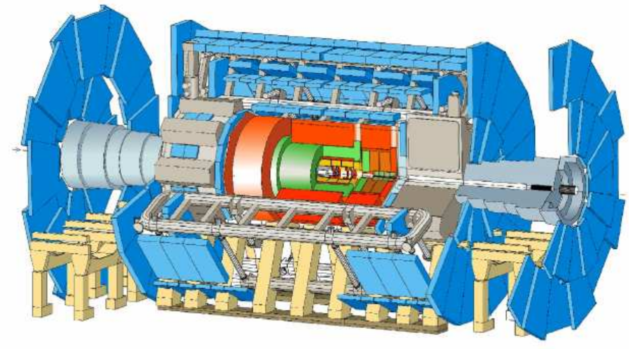

Figure 1. ATLAS detector at the LHC.

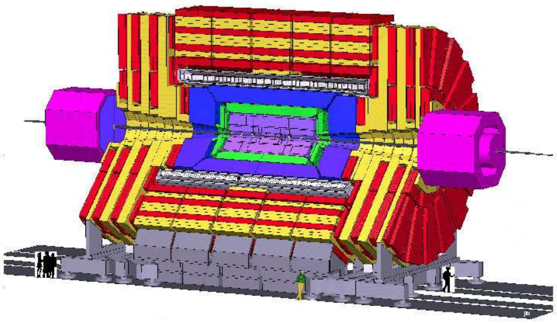

Figure 2. CMS detector at the LHC.

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Two experiments, CDF and D0, are presently taking data at the Tevatron; their expected B physics reach is described elsewhere [2,7]. We will discuss here four new experiments, currently under construction or in their R&D phase, which will aim for B physics at hadron colliders.

2.1. ATLAS and CMS [3]

Like CDF and D0, ATLAS (Fig. 1) and CMS (Fig. 2) are central detectors; they cover a pseudo-rapidity range of $|\eta| < 2.5$ and are designed primarily for high p_T physics (e.g. direct search for Higgs and supersymmetry). Proposed and approved at the LHC, their construction is well underway. Most of their B physics programme will be pursued during the initial period of operation, scheduled to start in 2006, when the LHC is expected to deliver luminosities of the order of 10^{33} cm^{-2}s^{-1}. Once the LHC will reach its design luminosity of 10^{34} cm^{-2}s^{-1}, after 2–3 years of operation, the large pileup (~ 20 inelastic interactions per bunch crossing on average) will preclude B physics, except, possibly, for very few specific topics involving a simple signature (like the search for rare $B^0_{(s)} \to \mu^+\mu^-$ decays). ATLAS and CMS will rely on their high-p_T lepton triggers for B physics. For single muons, a p_T threshold of 6–7 GeV/c is foreseen. CMS is also planning (and ATLAS studying the possibility) to trigger on single electrons above 12 GeV/c, or on pairs of leptons with a lower threshold. Such triggers are well suited to study B decay modes involving a J/ψ or $\psi(2S)$ meson, but perform rather poorly on fully hadronic decay modes for which a lepton from the other b-hadron decay is required (but useful for flavour tagging). Furthermore, these experiments will only have a very limited ability to distinguish kaons from pions. Hence, they are expected to be competitive with the dedicated experiments (described below) only for ψ channels where particle identification is not crucial.

2.2. LHCb [4]

Since its approval in 1998, LHCb (Fig. 3) is LHC's dedicated B physics experiment. Its complete technical design will be finished at the end of 2002, and some construction has already started. LHCb will be ready to take data from the start of LHC operation, and directly at its full physics potential since it is designed to run at an average luminosity of 2×10^{32} cm^{-2}s^{-1}. This luminosity is chosen to avoid too much pileup and radiation damage. It will be kept constant (even when ATLAS and CMS will run at high luminosity) by an appropriate defocusing of the beams at the LHCb interaction point. Although the LHCb detector is a spectrometer covering the forward region $1.9 < \eta < 4.9$, its acceptance for $b\bar{b}$ is comparable to that of the central detectors, because the b and $\bar{b}$ quarks are preferentially produced close to the beam axis and with correlated polar angles. The b hadrons are also predicted to have a harder momentum spectrum in the forward region, where the separation between the production and decay vertexes is therefore easier. The forward geometry also offers the possibilities, exploited in the LHCb design, to install vertex

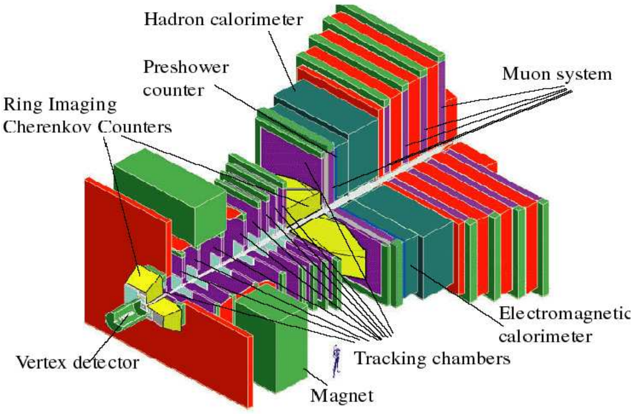

Figure 3. LHCb detector at the LHC.

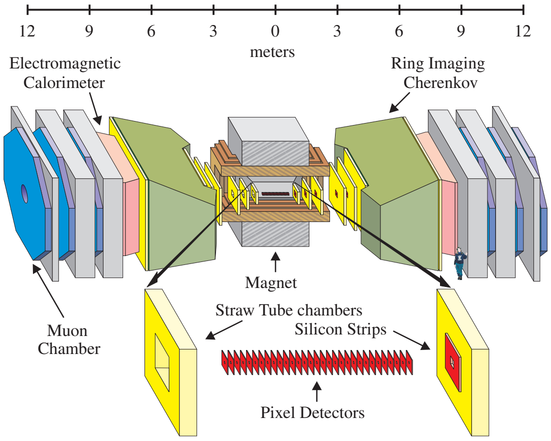

Figure 4. BTeV detector at the Tevatron.

detectors very close to the beams, to afford Ring Imaging Cherenkov (RICH) detectors for particle identification, and to use lower p_T thresholds in the calorimeter and muon triggers. LHCb will efficiently trigger on fully hadronic final states, in addition to modes involving leptons, exploiting both single particle p_T and detached vertexes in a multi-level scheme.

2.3. BTeV [5]

In 2000, another dedicated B physics experiment in the forward region, BTeV (Fig. 4), was proposed at the Tevatron, with a starting date close to that of LHCb. Luminosities of 2×10^{32} cm^{-2}s^{-1} are expected in the second part of Tevatron run II, where the $b\bar{b}$ production cross section is ~ 5 times smaller than at LHC. Hence, in order to be able to compete with (and possibly outperform) LHCb, the BTeV detector is based on a more aggressive (technologically) and expensive design. It consists of two arms, hence reaching twice the LHCb geometrical acceptance, and includes a high resolution calorimeter with $PbWO_4$ crystals to boost the performance for final states involving photons. Furthermore, BTeV aims at a more efficient trigger for inclusive b decays, based on vertexing only and accepting also events with pileup, as well as an ambitious data acquisition system dealing with larger event rates. The BTeV project, currently in its R&D phase, received Stage I approval at Fermilab, but is still waiting for a funding decision.

3. IMPORTANT DETECTOR CHARACTERISTICS OF LHCb AND BTeV

3.1. Vertex Detection

High-resolution vertexing detectors, to be used in the trigger decision, are needed to efficiently separate b-decay tracks from primary tracks. While the LHCb interaction region is almost field free, the BTeV dipole magnet, which serves for both arms of the spectrometer, is centered on the interaction region. The LHCb(BTeV) vertex detector consists of 25(31) stations of two silicon planes each, perpendicular to the beam axis, distributed over a little more than 1 m around the interaction region, and placed inside a vacuum tank in order to minimize the material (essentially just an RF shield) traversed by a track before the first measurement. The active silicon starts as close as 8 mm from the beams implying that radiation-hard technology be used and that the stations be split into two halves that can be separated during beam setup.

LHCb has opted for n-on-n sensors with r- and ϕ-measuring strips, and a varying strip pitch such as to keep the occupancy below 1% everywhere. A double metal-layer allows the readout electronics to sit outside of the acceptance. BTeV foresees 50×400 μm^2 pixels bump-bonded to readout chips. Pixels are intrinsically radiation hard and provide “3D hits”; however, many more channels are needed (30M, compared to 200k in LHCb), and more material is seen by the particles.

The proper time resolution for B_s^0 mesons fully reconstructed in the $B_s^0 \to D_s^- \pi^+$ mode, dominated by the vertexing resolution, is estimated to be 43 fs, which would allow an observation of B_s^0 oscillations ($\geq 5\sigma$) for values of Δm_s up to 48 ps^{-1} with one year of data at LHCb or BTeV.

3.2. Trigger

The data are pipelined in the front-end electronics while a low-level trigger decision is taken. After the data is read out, higher level decisions are taken by software algorithms running on commercial processors. Both LHCb and BTeV rely heavily on their vertex detector to trigger on b-decay vertexes at the low-level stage. In LHCb, a pre-trigger, called L0, will first reduce the nominal 40 MHz input rate (effectively only 12.4 MHz of inelastic interactions) to 1 MHz: this is done by rejecting events where multiple primary vertexes can be identified (pileup veto), and by requiring a single hadron, electron, photon or muon with a minimum E_T or p_T. Then the vertex detector data is used to identify detached vertexes to bring the rate down to 40 kHz (L1 trigger). High-level triggers will finally select of the order of 200 events/sec. In contrast, BTeV plans to reduce its 7.6 MHz input rate by two orders of magnitude at the very first level (L1) using the pixel detector data. Some bandwidth will also be given to a dimuon trigger. The final rate to tape will be around 3 kHz. These schemes result in very good efficiencies for specific b-hadron decays, including decays which don't involve leptons (Table 2).

Table 2
Efficiencies of the LHCb and BTeV low-level triggers for simulated signal events (in single pp interactions, in the case of LHCb) passing the offline selection. The second LHCb column includes the improvement obtained since 1998 by using the L0 information at L1, i.e. requiring the L0 p_T candidate not to come from the interaction vertex.

Channel	LHCb[4]	LHCb(now)	BTeV[5]
	L0*L1	L0*L1	L1
$B^0 \to J/\psi K_S$	0.88*0.50	0.88*0.90=0.79	0.50
$B^0 \to \pi^+\pi^-$	0.76*0.48	0.76*0.72=0.55	0.63
$B_s^0 \to D_s^- K^+$	0.54*0.56	0.54*0.70=0.38	0.74

3.3. Particle Identification

In LHCb, a first RICH detector, located before the dipole magnet, will contain two radiators: C_4F_{10} gas and aerogel. The latter will ensure a good K/π separation down to $\sim$ 2 GeV/c, needed for efficient flavour tagging with charged kaons. A second RICH device in front of the calorimeters, with CF_4 gas, will extend the K/π separation up to $\sim$ 100 GeV/c, fairly close to the high end of the momentum spectrum of tracks from two-body decays like $B^0 \to \pi^+\pi^-$. BTeV will have a single RICH detector, with aerogel and gas, to cover the momentum range 3–70 GeV/c.

For many important b-decay modes (including $B^0 \to \pi^+\pi^-$, $B_s^0 \to D_s^- K^+$, ...), such particle identification capability is essential, given the achievable mass resolutions, for rejecting efficiently physics backgrounds with the same decay topology as the signal (Fig. 5). Particle identification is also crucial for flavour tagging. Similar effective tagging efficiencies (ϵD^2) are expected in both experiments. LHCb quotes $\epsilon D^2 = 6.4\%$ using just the kaon and lepton tags from $b \to c \to s$ and $b \to \ell$ ($\ell = e, \mu$) decays of the other b-hadron, while BTeV assumes $\epsilon D^2 \sim 10\%$ once other methods are exploited in addition.

4. SUMMARY OF THE EXPECTED PHYSICS PERFORMANCE [6,7]

Future experiments at hadron colliders will be able to improve significantly on the CP asymmetry measurements performed by 2006. Us-

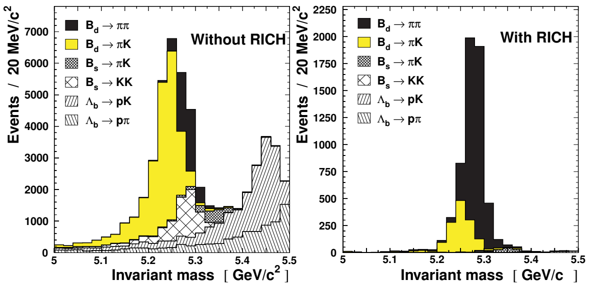

Figure 5. Reconstructed $\pi^+\pi^-$ mass before and after cuts based on RICH information, for $B^0 \to \pi^+\pi^-$ signal (black histograms) and background from various two-body b decays simulated in the LHCb detector.

ing $B^0 \to J/\psi K_S$ decays collected in one year, ATLAS, CMS, LHCb and BTeV will each reach a statistical precision in the range 0.015–0.025 for $\sin(2\beta)$. Large samples of cleanly identified $B^0 \to \pi^+\pi^-$ and $B^0 \to \pi^+\pi^-\pi^0$ decays (10k–20k and 3k–10k untagged events/year respectively, with $S/B > 1$) will be available from LHCb and BTeV, allowing important progress in the understanding of the Penguin contribution and in the extraction of the angle α. Furthermore, new measurements requiring high statistics or B_s^0 mesons will become possible, opening the possibility to establish CP violation in new channels.

The CP asymmetry in $B_s^0 \to J/\psi\phi$, a sensitive probe for new physics, can be investigated by all four experiments using very pure ($> 80\%$) samples of the order of 500k untagged events per year; a combined sensitivity of the order of 10^{-2} is expected on $\delta\gamma$, reaching (close to) the SM prediction. Contrary to the $J/\psi\phi$ final state, the $J/\psi\eta^{(\prime)}$ final state is a pure CP-odd state, and no angular analysis is needed to extract $\delta\gamma$: with its good photon detection performance, BTeV claims to reach an uncertainty of 0.033 on $2\delta\gamma$ with one year of data in this mode.

LHCb and BTeV will also be able to extract the angle γ independently of new physics in B mixing, using the two methods outlined in the introduction. Very large samples of $B^0 \to D^{*\mp}\pi^\pm$ decays can be obtained in LHCb using both exclusive and inclusive reconstruction of the neutral D from the D^* decay (180k and 1150k untagged events per year respectively, with $S/B > 4$). This will allow the extraction of both the weak phase $2\beta+\gamma$ and the strong phase difference between the two tree diagrams involved. The expected precision on γ after one year depends on the values of these phases, and will be 6.5° in the best case.

LHCb and BTeV are the only experiments that will be able to observe CP violation in the B_s^0 system using $D_s^\mp K^\pm$ final states, due to their good trigger efficiency (Table 2), particle identification, mass resolution (11 MeV/c^2 in LHCb and 17 MeV/c^2 in BTeV) and proper time resolution (43 fs). Using the branching ratio assumptions of Ref. [4], LHCb(BTeV) expects an annual yield of 6.4k(9.7k) untagged events with $S/B = 12(7)$. The sensitivity on γ, which depends on a few yet unknown physics parameters (measurable by then or at the same time as γ), will be of the order of 10° in each experiment after one year.

In conclusion, B physics will get a big boost from the future LHC and Tevatron data. Very large b-hadron samples will be produced, including B_s^0 mesons. Dedicated experiments are designed with the best trigger efficiency, resolution and particle identification capability. They will be able to use a large variety of b-decay modes suitable for comprehensive CP violation studies, beyond what is achievable at the present B factories. Clean determination of the CKM parameters will be made, regardless of new particles in virtual loops. A comparison with measurements on b decays involving such loops may then not only provide evidence for sources of CP violation beyond the SM, but will also allow the extraction of possible new physics contributions.

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REFERENCES

1. Y. Sakai and A. Mazzoni, these proceedings.
2. V. Papadimitriou, these proceedings.
3. W.W. Armstrong *et al.*, ATLAS Technical Proposal, CERN/LHCC 94-43, 1994; ATLAS Detector and Physics Performance Technical Design Report, CERN/LHCC 99-14 and 99-15, 1999; G.L. Bayatian *et al.*, CMS Technical Proposal, CERN/LHCC 94-38, 1994.
4. S. Amato *et al.*, LHCb Technical Proposal, CERN/LHCC/98-4, 1998.
5. A. Kulyavtsev *et al.*, BTeV Proposal, 2000, `http://www-btev.fnal.gov/btev.html`.
6. P. Ball *et al.*, "B decays at the LHC", hep-ph/0003238, proc. of the workshop on "Standard Model Physics (and more) at the LHC", CERN-2000-004, pp. 305–417, 2000.
7. K. Anikeev *et al.*, "B physics at the Tevatron: Run II and beyond", FERMILAB-Pub-01/197, hep-ph/0201071, 2001.