THE CDF AND DØ B PHYSICS UPGRADES

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The CDF and DØ detector upgrades are reviewed with an emphasis on their B physics capabilities. Projections for the observability of CP-violation and for the resolution of rapid B_s oscillations are made, based on upgrade simulations and on CDF performance from the last run. It is shown that measurements of $sin(2\beta)$ and $sin(2\alpha)$ can be achieved with uncertainties less than 0.15. For fully reconstructed (non-leptonic) B_s decays, both detectors have vertexing and momentum determination able to resolve $x_s \approx 20$.

1 Introduction

The next run of the Tevatron (Fermilab) in collider mode is scheduled to begin in late 1999 with major improvements to the accelerator and its two detectors, CDF and DØ. The main target in the accelerator upgrade is an order of magnitude increase in luminosity. The design goals of the new Tevatron are to reach 2×10^{32} cm^{-2}s^{-1} in instantaneous luminosity, and to deliver 2 $fb^{-1}$of $p\overline{p}$ collisions in about two years of running. A $\sqrt{s}$ increase from 1.8 to 2.0 TeV is also planned, and although of small significance to the B physics program, it represents a 40% increase in $t\bar{t}$ yields.

The centerpiece of the luminosity upgrade is the replacement of the Main Ring, the last pre-acceleration stage, which shares the same tunnel with the Tevatron, by the Main Injector, currently under construction and housed in a new tunnel adjacent to that of the Tevatron. The Main Injector, a 150 GeV proton synchrotron, will improve the $\overline{p}$ production rates and provide larger current transfer into the Tevatron. Coupled with upgrades in $\overline{p}$ cooling and stacking, the net result will be an overall increase both in bunch population and in number of bunches available for collisions.

To keep the average number $< N >$ of interactions per bunch crossing down to practical levels, the increased luminosity must be divided among more bunches than the 6 on 6 of Run-I (1992 – 1995), with consequent reduction in crossing intervals. Two bunch structures are envisaged for Run-II; initially

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36 on 36 with a crossing time interval of 396 ns, and later, when the higher luminosities are reached, 108 on 108 with 132 ns spacing.

It is this new luminosity and bunch spacing regime that requires the most significant changes in the detectors, which should be planned such that operation is reliable under multiple interactions ($< N > \sim 5$) per crossing, with readout and triggering compatible with 132 ns crossing interval. The detector upgrades are summarized in Sec. 2.

With a $b\bar{b}$ pair production cross section of $\sim$ 100 μb, the Tevatron rates are a huge 10 KHz of $b\bar{b}$ at $\mathcal{L} = 1 \times 10^{32}$ cm^{-2}s^{-1}. To illustrate how much of this cross section is actually visible to the collider detectors, the CDF Run-I measurement of the B^+ meson total production for $p_T \geq 6$ GeV/c and $|y| < 1$ is 2.5 μb. Generally lower thresholds and higher rapidity reach will significantly increase B hadron observability in Run-II.

While B mesons at the Tevatron are visible with cross sections that are three and four orders of magnitude larger than those of e^+e^- machines at the $Z^\circ$and $\Upsilon(4S)$ resonances respectively, sample purity in a hadron collider environment poses a formidable problem. With $(\sigma^{b\bar{b}}/\sigma^{p\bar{p}}) \simeq 10^{-3}$, good triggering becomes a vital ingredient. This issue will be addressed in Sec. 3.

The high statistics B samples of Run-II are expected to enable B_s mixing observations and the study of low branching ratio B physics, with access to CP-violation and CKM constraints, Standard Model tests with rare decays, B_c observation and more, as discussed in Sec. 4. The last section is a concluding summary.

2 Detector Upgrades

The Run-II Tevatron regime requires extensive changes in the detectors of Run-I. Of course, improved performance is sought wherever possible, but the main driving force in both CDF [1] and DØ [2] upgrades is the reduced bunch crossing interval from 3.5 μs in Run-I to 132 ns at the later stages of Run-II. Both detectors need fully revised electronics. A few of the necessary features in the upgrades are; faster signal integration, time stamps wherever detector response is slower than crossing intervals (*e.g.* scintillators covering muon chambers), a pipelined readout to cover trigger latencies, buffers between trigger levels to derandomize the triggers.

The expected increase in detector occupancy from a higher average number of interactions per crossing must be met with increased granularity, and scaled up electronics accordingly. Higher levels of radiation require extensive shielding, notably so for the more forward muon chambers. Also, very strict requirements of radiation hardness are needed for the vertex detectors whose inner layers are only 2.5 cm away from the beam line.

Beyond detector upgrades, the offline computing and data storage systems must be able to handle a ~ 50 fold increase in event collection with respect to Run-I.

The next two subsections present a separate overview of the CDF and DØ upgrades. Descriptive summaries of some of their main modifications from the previous run are presented, from the outer towards the inner layers. Although a B physics biased view is taken at this conference, it should be stressed that both CDF and DØ are general purpose detectors with very broad physics programs.

2.1 CDF

Already fully equipped for a very broad (and successful) B physics program in Run-I, CDF has produced a number of $p\overline{p}$ collider pioneering studies in B hadron production, lifetimes, branching ratios, including a measurement of the x_d mixing parameter and clear signals for Λ_b and $B \rightarrow J/\psi K_s$. This represents comfortable proof of the feasibility of precision B studies at hadron colliders.

Aside from preparing for the increased luminosity and crossing rates, the general trend of the CDF upgrade is to extend its pseudorapidity (η) reach. The central ($|\eta| < 0.6$) and extended ($|\eta| < 1.0$) muon system geometries from Run-I basically remain, but with increased azimuthal coverage and granularity. The very forward muon spectrometer of Run-I is removed due to incompatibility with Run-II conditions, but the steel from the forward magnets is brought in closer to the interaction region, as added shielding to a completely new forward barrel of muon chambers that extend the muon pseudorapidity coverage out to $|\eta| = 2$. The muon system is doubled by scintillator counters for triggering and time stamps, since muon chamber drift times span over five or more crossings at 132 ns bunch spacing.

Central calorimetry remains, with extensively revised electronics, and the end plug gas calorimeters are replaced by scintillator tiles for speed and added granularity. The new tiles follow the (η, ϕ) segmentation pattern of the central calorimeters, and are likewise equipped with shower maximum shape sensors for added electron identification.

Inside the 1.4 T superconducting solenoid the tracking volume components (Fig. 1) are completely new for Run-II, and come in three subsystems; (i) the Central Outer Tracker (COT), a drift chamber that preserves the Run-I CTC performance in the new luminosity regime, with eight superlayers of twelve sense wires each, smaller drift cells, improved stereo pattern recognition and dE/dx capability. (ii) the Intermediate Silicon Layers (ISL), two extra layers of

CDF Tracking Volume

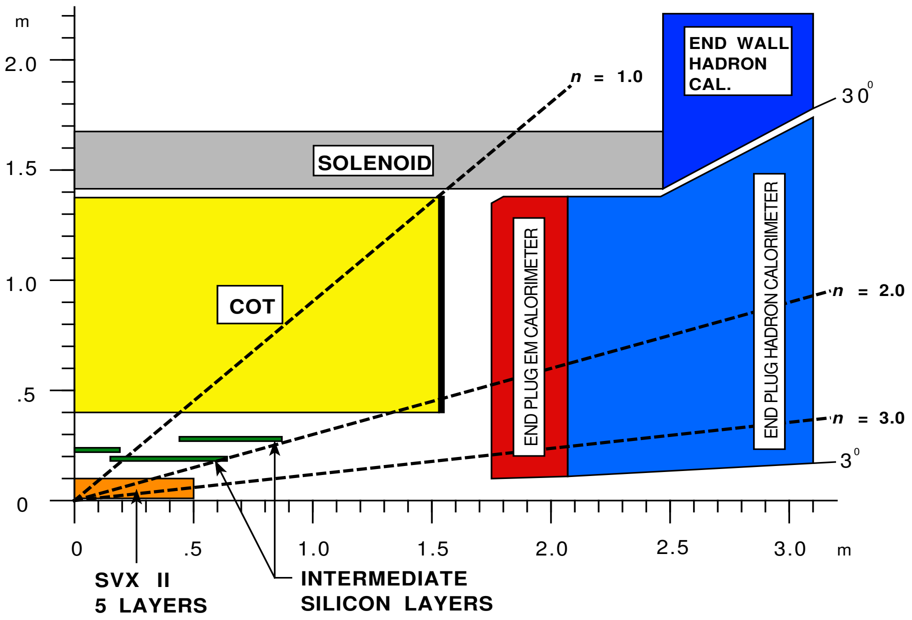

Figure 1: CDF tracking volume.

double sided silicon trackers to cover for the COT progressive loss of acceptance beyond $|\eta| = 1$ and extend tracking capability out to $|\eta| = 2$. (iii) Five layers of double sided Silicon Vertex Detectors (SVXII) with 3D readout and (r, ϕ) readout available for level-2 triggering. Being 96 cm long ($|\eta| < 2$) the SVXII doubles the fiducial vertexing volume available for Run-I, and covers 1.5σ of the luminous region ($z = 0 \pm 30\ cm$).

2.2 DØ

With extended muon coverage and excellent muon identification, DØ in Run-I has studied both central and forward inclusive muon, J/ψ and b-quark production, and has lowered the UA1 limits for $b \to s\mu^+\mu^-$ FCNC transitions. The upgraded DØ now receives for the first time a magnetic tracking volume and microvertexing capability. These features will significantly extend DØ's B physics program of Run-I, since the exclusive reconstruction of hadronic final states now becomes available.

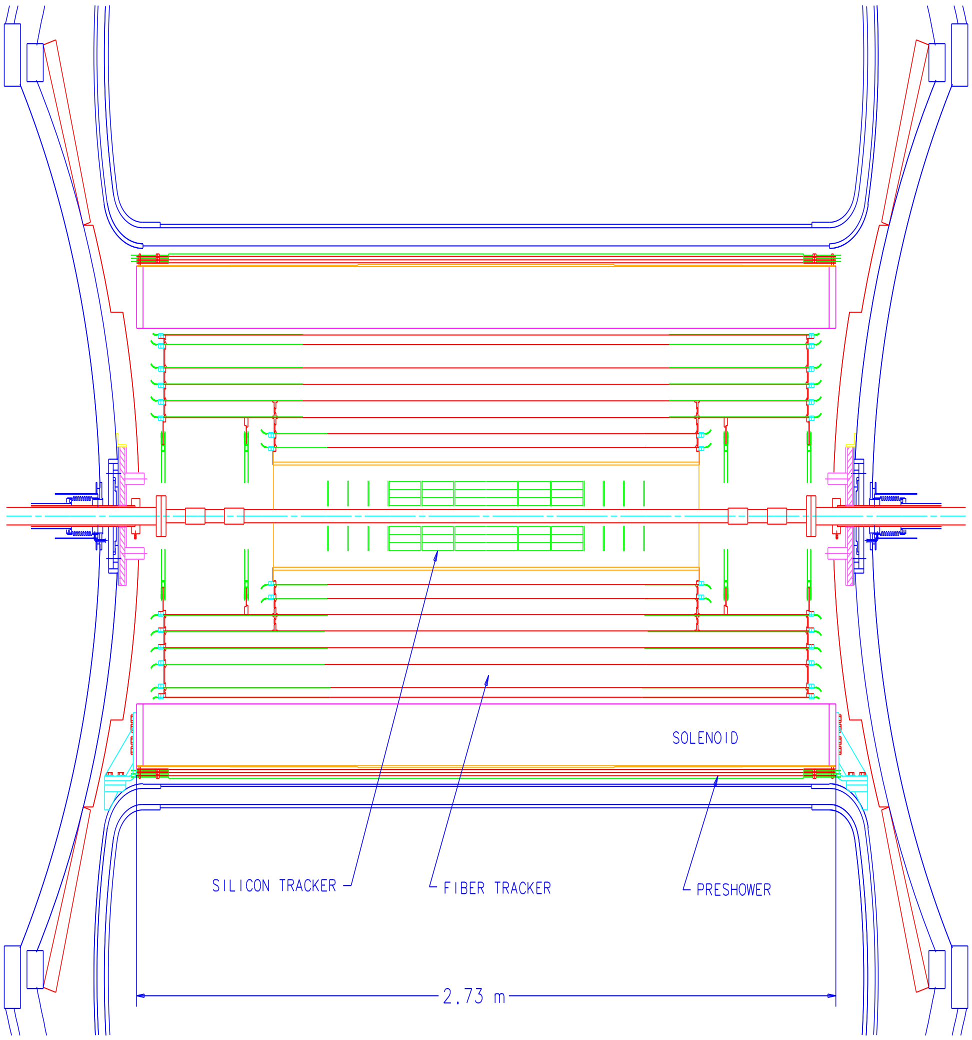

Figure 2: DØ tracking volume.

The DØ general characteristics of hermeticity and large rapidity range are retained from Run-I. There are significant changes in the muon system. The central ($|\eta| < 1$) three layers of proportional drift tubes (PDT) remain, and receive full inner and outer coverage from two layers of scintillator counters for triggering, time stamps and cosmic ray rejection (out of time with beam crossing). The forward PDT's are replaced by new mini drift tubes (MDT), with increased granularity ($1 \times 1\ cm^2$ in cross section), and extending out to $|\eta| = 2$. MDT drift times at $\sim 80\ ns$ are compatible with individual crossings. For trigger enhancement and added redundancy, three layers of pixel scintillator counters fully double the three layers of MDT's.

Of particular B physics relevance is the lowered muon p_T threshold from 4 GeV/c in Run-I to 1.5 GeV/c in Run-II. The muon system retains its stand-alone muon momentum determination with a resolution of about 20% at 10 GeV/c. The small angle muon system (SAMUS, $2.3 < |\eta| < 3.2$) of Run-I is removed due to incompatibility with Run-II conditions.

The ($ULAr$) calorimeter remains unchanged, except for a revised readout electronics. Inside the calorimeter DØ looses all its resemblance to the Run-I version. For added electron identification and triggering, preshower detectors (scintillating strips and lead absorbers) are mounted against the inner walls of the central and forward calorimeters.

The next layer inward is a 2 T superconducting solenoid which in turn houses two new subsystems (Fig. 2) inside its magnetic volume; (i) the Central Fiber Tracker (CFT), with eight superlayers of scintillating fibers, each arranged as two layers (axial and stereo) of staggered fiber doublets for hermetic coverage. Full acceptance for the eight superlayers from detector center extends to $|\eta| = 1.6$. (ii) The Silicon Vertex Detector (SVX), with 3D readout, consists of a hibrid combination of 6 barrels and 14 z-disks that extends out to $|z| = 1.2\ m$, $|\eta| = 3$. Barrels and disks are double sided, except for the two outermost disks on each end which are single sided and larger in diameter for extended tracking reach. Staggered sensors in the SVX barrels overlap such as to yield an average of 5.5 layers on track.

3 Triggering and Data Flow

Selective and efficient triggering is of vital importance in a hadron collider experiment. The clearest signatures for a B event are generally associated with leptons. Either single leptons, normally accompanied by jets, indicating a semileptonic decay, or dileptons of resonant ($J/\psi, \Upsilon$) or non-resonant (sequential or double semileptonic decay) origin. Over 20% of the J/ψ resonances at the Tevatron are of b-production origin. A prominent source of B decay analysis for CDF in Run-I (including the $B \rightarrow J/\psi K_s$ signal of Fig. 3) was a dimuon trigger with muon p_T thresholds at 2 GeV/c.

With respect to Run-I, the Run-II data acquisition needs are a $\sim$10 fold increase in background rejection at a $\sim$25 times faster pace. An average raw collision rate of 5 MHz must be reduced by triggering to a few tens of Hz, the expected write-to-tape capacity of the experiments.

Both CDF and DØ have had their trigger architecture and control systems completely redesigned into a deadtimeless tiered structure, organized in three levels of increasing information and resolution, featuring a pipelined readout and buffers between each of the three trigger levels.

The extra rejection is achieved with; (i) the introduction of additional trigger objects (*e.g.* electron pre-shower, SVX impact parameter) (ii) objects available at lower levels than in Run-I (*e.g.* track triggers at level-1) (iii) the possibility of inter relations between trigger objects by download to fast preprocessors at level-2 (*e.g.* invariant masses, opening angles, object isolation) and (iv) generally improved resolutions.

Of special B interest is CDF's plan to introduce a track-only trigger at level-1, that is a purely hadronic trigger, backed up by an impact parameter (SVXII) trigger at level-2. As detailed in Sec. 4., this trigger will enable the study of purely hadronic final states as is the case of CP-violation with $sin(2\alpha)$ in $B \rightarrow \pi\pi$ decays.

A broad description of the data flow through CDF and DØ starts with 5 MHz of raw collisions as input to trigger level-1. Level-1 is a synchronous 42 clock cycle deep pipeline with a latency of about 5 μs, with tracking capability in (r, ϕ). With a rejection power over 10^3, 10-40 KHz of data are output into event buffers for level-2 pickup.

Level-2 is an asynchronous two stage pipeline. Stage-1 consists of subdetector dedicated preprocessors for trigger object treatment. Stage-2 consists of global detector preprocessors for cross referencing the various subdetectors, and working out inter relations between trigger objects. An output in the range 300-1000 Hz is fed into the level-3 buffers.

Finally, Level-3 is a conventional multiprocessor farm, where each node receives one event at a time and performs full reconstruction for trigger object analysis. A 20-50 Hz output is written into a massive storage system.

4 B Physics Prospects for Run-II

Sections 2 and 3 have described two very ambitious detector upgrades featuring increased overall acceptances and resolutions, significantly enhanced triggering, and 3-dimensional vertexing. Such observation potential, coupled with the "B factory" character of the Tevatron (all B species produced) and 2 $fb^{-1}$of data by the year 2001, opens up a vast reach for B physics in the near future.

Primary interest will certainly focus in the study of CP-violation in the neutral B_d meson system, as well as in related CKM constraints such as V_{td}/V_{ts} from B_s mixing. The remaining subsections are dedicated to these issues.

Many other B topics of interest, while not considered here, are also within reach of the Run-II detectors. Among these is the observation of rare B decay modes. Notably, in the $b \rightarrow s\ l^+l^-$ case, Run-II conditions are such that the Standard Model observability limits will be comfortably surpassed. Such FCNC transitions are especially sensitive to higher order high mass loops and thus provide an extra window for new physics discovery beyond direct searches.

4.1 CP Asymmetry in $B_d \rightarrow J/\psi K_s$

This is the most promising mode for CP-violation searches in the B system due to the larger branching ratio than other candidate decays and a distinctive trigger signature from the J/ψ. Another advantage is the cleanliness of the Standard Model prediction for $sin(2\beta)$ (in the CKM unitarity triangle) which is free from hadronic uncertainties.

From the J/ψ event sample in Run-I CDF has reconstructed the $B \rightarrow J/\psi K_s$ signal of Fig. 3. J/ψ's were collected from a dimuon trigger with 2 GeV/c p_T threshold per muon. For the 2 fb^{-1} of Run-II, with lowered muon thresholds to 1.5 GeV/c and doubled pseudorapidity reach, plus contributions from the e^+e^- channel, one may expect a signal sample ranging from 10K to 15K decays. Tighter but more efficient offline selection, mainly due to the significantly extended SVXII coverage, may improve the signal to noise ratio (S/N) to 2.0.

Beyond signal event collection and purity, the experimental challenge resides in the flavor tagging for the B meson at production time, from which the CP violating imbalance in B *vs* $\overline{B}$ decays may be detected. Such tagging ability is quantified by ϵD^2, an "effective tagging efficiency", where ϵ represents the efficiency for how often a flavor tag is applicable in the signal sample, and D is the dilution originated from wrong tags.

Four different tagging methods have been studied by CDF with Run-I data. Table 1 displays the resulting values for ϵD^2 together with projections for Run-II. These are extracted from the Run-I performance modified by the upgrade enhancements listed as comments in the third column. They are; (i) extended rapidity coverage, improved particle identification. (ii) 3D vertexing and extended SVXII coverage. (iii) although not in the current version of the upgrade, CDF is studying the possible addition of a time of flight (TOF)

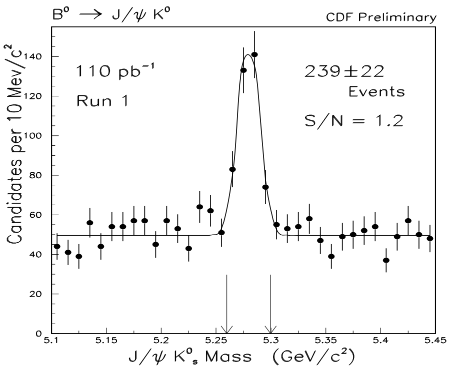

Figure 3: CDF Run-I signal for $B_d \rightarrow J/\psi K_s$.

Table 1: CDF values for ϵD^2 as measured in Run-I and expected in Run-II. Comments found in the text summarize where the improvements originate from.

Tag Method	Run-I (measured)	Run-II (expected)	Comment (see text)
muon	0.6 ± 0.1	1.0	(i)
electron	0.3 ± 0.1	0.7	(i)
jet charge	1.0 ± 0.3	3.0	(ii)
same side π	1.5 ± 0.4	2.0	(ii)
kaon	—	3.0	(iii)

system (with $\sim 2\sigma$ $\pi - K$ resolution) that would enable kaon tagging.

Combining all tag methods (there are applicability overlaps at $\sim 20\%$) the overall effective tagging efficiency ϵD^2 may be expected in the range 3% to 8%, where the lower end represents only a minor improvement over the Run-I results, and the upper end includes the (TOF) kaon tag.

From the above projections, CDF expects to reach an uncertainty δ on the measurement of $sin(2\beta)$ that ranges from $\delta = 0.14$ if the conservative projections are used, to $\delta = 0.08$ in the more optimistic scenario.

Preliminary simulation studies from DØ indicate that in the all muon channel ($J/\psi \rightarrow \mu\mu$, plus muon tag) an uncertainty $\delta = 0.15$ can be achieved. This value can be significantly reduced when the decay channel to electrons and the other flavor tagging methods are introduced.

4.2 CP Asymmetry in $B_d \to \pi^+\pi^-$

Although similar in method to $sin(2\beta)$, the measurement of $sin(2\alpha)$ is more difficult on all accounts. On the theory side the prediction is "polluted" by penguin diagrams that are difficult to estimate. Experimentally, the main challenges come from event collection (triggering without leptons) and background rejection.

This measurement is the main motivation behind CDF's plans for a hadron trigger. Two oppositely charged tracks at level-1 with p_T thresholds at 2 and 3 GeV/c, and azimuthal separation in the range (30° , 150°), are expected to trigger at 16 KHz. Such large rates are brought down to 10 Hz after level-2 with an SVXII impact parameter cut below 100 μm. This strategy should be $\sim$50% efficient for $B \to \pi\pi$ with an expected acceptance of 5K to 6K decays per fb^{-1}.

Backgrounds from $B \to K\pi$ and $B \to KK$ decays (including B_s) will all cluster around the signal mass peak if pion masses are assigned to kaon tracks. For this reason, besides excellent mass resolution, dE/dx is also needed for further background rejection.

Under conservative assumptions for the tagging efficiency and background contamination, CDF expects to reach an overall uncertainty for $sin(2\alpha)$ of $\delta = 0.14$. This could be pushed down to $\delta = 0.10$ as ϵD^2 nears 8%.

4.3 B_s mixing and x_s reach

Mixing in the neutral B system is expressed in terms of $x = \Delta m\, \tau$, representing the number of flavor oscillations in a lifetime. Δm is the difference in mass eigenstates (or oscillation frequency) and τ is the average lifetime of these states. Copious production of B_s at hadron colliders enables clean access to V_{td}/V_{ts} through the ratio x_d/x_s of the B_d and B_s mixing parameters, where theoretical uncertainties are greatly reduced.

While LEP measurements of x_d are accurate to a few percent, the much larger x_s remains undetected with lower experimental limits reaching 15. Such rapid oscillations require excellent resolution in proper decay time, that is, in B_s decay length and momentum reconstruction. Again, efficient flavor tagging at production time to separate the mixed from the unmixed decays is also crucial.

Semileptonic decay modes are easier to trigger, but the loss of the neutrino severely degrades the B_s momentum determination. CDF simulations show that, although comfortable in statistics, the observation reach with semileptonic decays becomes limited to $x_s < 15$ by proper decay time resolution.

Full reconstruction of a purely hadronic signal ($B_s \rightarrow D_s + n\pi$, all charged) provides the desired decay time accuracy, but the challenge is shifted to event collection (triggering). A strategy available to CDF is to use the purely hadronic trigger described in Sec. 4.2. Under the same assumptions as with $B \rightarrow \pi\pi$, some 1600 fully reconstructed and flavor tagged B_s decays are expected in the 2 $fb^{-1}$of Run-II. Under the ideal conditions of perfect tagging and no backgrounds, this signal yields a $\delta x_s / x_s$ precision reach of about 20% at $x_s = 20$.

An alternative strategy consists of triggering on the lepton that is going to be used as flavor tagger. A single lepton trigger with a low $p_T$threshold will produce unmanageably high rates. To optimize B acceptance one must keep the lepton threshold as low as possible, and further requirements must be added to the trigger.

A DØ single muon trigger ($\eta < 2, p_T > 1.5$ GeV/c) will produce level-1 rates of about 50 KHz. This can be brought down to a manageable 1 KHz by also requiring a jet trigger with a seed threshold at 5 GeV/c($\sim$ 60% efficient for a 20 GeV jet). Such configuration is expected to accept 2000 fully reconstructible B_s (plus 2000 $\overline{B_s}$) decays with an opposite side muon tag.

Allowing for offline selection losses, DØ has used a sample of 1000 fully reconstructed $B_s^0 \rightarrow D_s^- + n\pi, D_s^- \rightarrow K^+K^-\pi^-$ simulated decays for x_s resolution studies. Results are shown in Fig. 4. Figures (a) and (c) have respective x_s inputs of 12 and 20, and probe DØ resolution under ideal conditions of perfect tagging and no backgrounds. Figures (b) and (d) for each input x_s illustrate the degradation that is introduced by a 25% mistag rate coupled with added backgrounds at 1/1 to signal events. It can be seen that while detector vertexing and momentum resolutions are comfortable with $x_s = 20$, a rather conservative scenario for mistags and backgrounds is diluting the signal into marginal observability. This indicates the lower limits in tagging performance and sample purity such that $x_s = 20$ sensitivity can be reached. Such limits are well within the projected DØ performance.

5 Summary

A review of the CDF and DØ upgrades for Run-II, with comparisons to their Run-I versions, reveals two very ambitious projects with significantly enhanced B physics reach, notably due to their revised triggering powers.

CDF has already demonstrated in Run-I that precision B physics (spectroscopy, decays, lifetimes, mixing etc.) can be done successfully and competitively at the Tevatron. The upgraded DØ now receives a magnetic tracking volume, and acquires capability for vertexing and exclusive reconstruction of B decays.

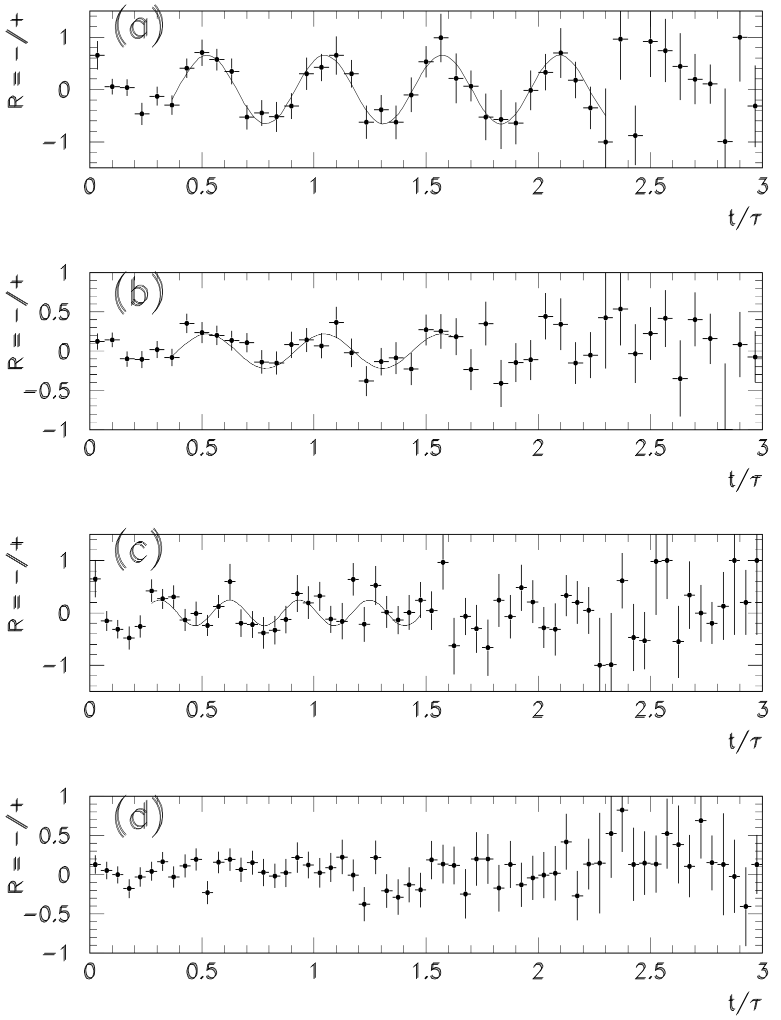

Figure 4: DØ simulations for x_s observability. Figures (a) and (c) show detector resolution for x_s inputs of 12 and 20. Figures (b) and (d) illustrate, for each input, signal dilution due to mistags and backgrounds (see text).

Detector simulations aided by extrapolations based on CDF's Run-I performance predict that many CKM topics of interest will come within reach of both CDF and DØ, such as measurement of $sin(2\beta)$ to better than $\pm$ 0.14. For fully reconstructed (non-leptonic) B_s decays, both detectors will have vertexing and momentum determination able to resolve $x_s \approx 20$.

DØ B strengths are in the lepton sector, with central and forward preshower triggers at Level-1, and excellent (stand alone) muon identification. CDF has plans for a hadron (track-only) level-1 trigger, backed by an SVXII impact parameter trigger at Level-2. With B dedicated extra trigger bandwidth, and a deep tracking volume, CDF expects to further extend its B program to include purely hadronic signatures, with *e.g.* access to $sin(2\alpha)$ with an uncertainty better than 0.15.

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