Status of D0 for B Physics

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1 Introduction

In light of the voluminous data being collected at the B factories, it is worthwhile examining why it is interesting to study B physics at the Tevatron at Fermilab (Batavia, Illinois). Both D0 and CDF enjoy a large rate of production with $\sigma(p\overline{p} \to b\overline{b}) \approx 150\ \mu$b at a collision energy of 2 TeV compared to $\sigma(e^+e^- \to b\overline{b}) \approx 7$ nb at the Z^0 peak, and $\sigma(e^+e^- \to B\overline{B}) \approx 1$ nb at the $\Upsilon(4S)$ peak. Also, in contrast to the B factories running at the $\Upsilon(4S)$ peak where only B_d^0 and $B^\pm$ are produced, all b hadron species including B_s, B_c, and Λ_b are produced. Measurements of B_s mixing are important in the understanding of the CKM triangle, and a great deal can be learned from the properties and behavior of hadrons containing heavier quarks besides the b.

2 Run 2 B Physics

Run 1 for D0 ended in 1996 and work began on the Main Injector and upgrading the detector as described in the next section. Run 2 is defined by the running of the Tevatron with the Main Injector at an increased collision energy of 2 TeV (from 1.8 TeV) and increased luminosity. Run 2a is planned to have an integrated luminosity of 2 fb^{-1} and Run 2b of 15–20 fb^{-1}.

Some of the more important topics of the planned D0 Run 2 B physics program are summarized in Table 1. Question marks following the decays $B \to \pi^+\pi^-$ and $B_s \to K^+K^-$ imply that although effort will be made to isolate these samples, it is unclear whether D0's triggering capability will allow this collection with reasonable bandwidth.

3 Upgraded D0 Detector

The described program of B physics could only be undertaken if the Run 1 D0 detector were upgraded. The Run 2 detector upgrade retained the excellent Run 1 liquid

QCD tests	cross sections, correlations,
charmonium polarization	
CP violation and CKM angles	$\sin 2\beta$ through $B \to J/\psi K_S$;
	α, γ through $B \to \pi^+\pi^-$?, $B_s \to K^+K^-$?
Non-SM CP Violation	$B_s \to J/\psi\phi$
B_s mixing	$B_s \to D_s n\pi$, $B_s \to D_s \ell\mu$
Spectroscopy and Lifetimes	B_d^0, B^+, B_s^0, B_c, Λ_b, double heavy baryons
Rare decays	$B \to \ell^+\ell^- X_s$, $B \to \ell^+\ell^-$

Table 1: Summary of important topics in planned B physics program.

argon/uranium calorimeter, while increasing the speed of its readout. The muon toroids were retained, and the muon system was upgraded for better muon identification and triggering, particularly suited for tagging b's decaying semileptonically. Most importantly for B physics, a new tracker operating in a solenoidal magnetic field was added. Further details of the detector can be found elsewhere [1].

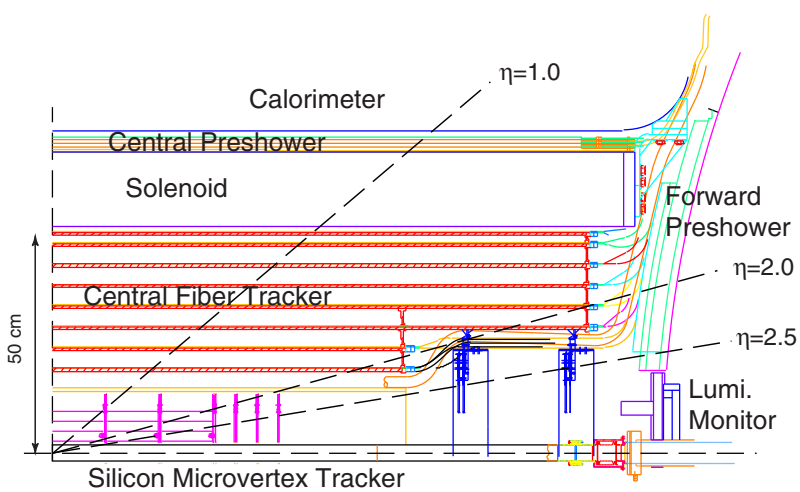

Figure 1: D0 Upgrade detector tracking system.

Figure 1 illustrates the new tracker. Working outwards in radius, the silicon microvertex detector (SMT) consists of six barrels (four layers) of single and double-sided silicon strip sensors interspersed with double-sided disks providing 800k channels with a single hit space resolution of 10 μm, leading to good impact parameter resolution. The central fiber tracker (CFT) provides the necessary momentum resolution, and is made up of eight concentric barrels of scintillating optical fiber doublets (half at stereo angles of $\pm 3^\circ$) mounted on carbon fiber tubes. Single hit r-ϕ resolutions are

80–100 μm. Clear optical fibers carry the light to 77k channels of visible light photon detectors and also provide a fast pick-off for a track trigger. Following a 2 T superconducting solenoid, a central (and forward at larger η's) preshower detector of triangular scintillator strips with embedded wavelength-shifting fibers improves non-isolated electron identification to aid in semileptonic b tagging.

Although the rate for b production is high, the hadronic environment still results in a challenging signal to background, with a total hadronic background of $\sigma_{\rm had}^{\rm tot} \approx 75$ mb to be compared to $\sigma_{bb} \approx 0.1$ mb. To address this, we have a pipelined Level-3 trigger that will have the capability to trigger on tracks with significant impact parameter at Level 2 and on tracks in given momenta ranges at Level 1. In addition, there will often be one or more overlapping minimum bias events on the event of interest, with an expected average of 2.0 at Run 2a's projected peak luminosity.

The projected performance of the D0 upgrade detector is a momentum resolution of $\delta p_T/p_T^2 = 0.002$ combining the SMT and CFT measurements and tracking out to $|\eta| < 3$ using the forward silicon disks. The fitted primary vertex should have a resolution of 15–30 μm in r-ϕ and secondary vertices found with resolutions of 40 μm (r-ϕ) and 80 μm (r-z). The upgrade detector has excellent lepton coverage for both triggers and identification: muons in the range $p_T > 2.0$ GeV, $|\eta| < 2.0$ and electrons over $p_T > 2.0$ GeV, $|\eta| < 2.5$. The impact parameter resolution is expected to asymptotically approach 15 μm for high-momentum tracks. Comparisons of detector performance to these expected benchmarks will be shown in the next section.

4 Current Data and Performance

The D0 upgrade detector physically rolled in to place Jan. 2001 and the first Run 2 collisions occurred in April 2001. Until Nov. 2001, activities were dominated by commissioning the silicon detector, establishing timing, and commissioning the DAQ and online systems. Given the importance of tracking in B physics, critical path items were late Analog Front End (AFE) boards that were essential for reading out the central fiber tracker and preshower detectors. In Summer 2001, only a very restrictive slice in ϕ was instrumented for CFT axial readout. During a shutdown in Nov. 2001, a large fraction of CFT axial AFE boards were installed and commissioned over the winter. Due to this missing readout, many commissioning tracking studies were performed with silicon-only tracking. The silicon SMT detector itself is operating very well with 95% of the barrel sensors, 96% of the small-z F-disks, and 87% of the larger-z H-disks operational.

Only by the end of winter 2002 were the CFT axial channels fully instrumented and CFT stereo fully instrumented by the end of April 2002, i.e., it is only until very recently that D0 has had its full tracking system available. Until May 2002, the Tevatron delivered approximately 35 pb^{-1} and the D0 detector recorded about

10 pb^{-1} of this in physics runs.

Paramount to being able to carry out the B physics program is good impact parameter resolution and the ability to form precise primary and secondary vertices. Using current data, comparisons between expectations and current performance are made. For high multiplicity primary vertices (e.g., $N_{\text{track}} \geq 14$), a primary vertex resolution of 46 μm has been measured in the transverse x-y plane. Other measurements indicate this resolution contains a convolution over a transverse beam size of approximately 30 μm. The impact parameter resolution measured with respect to this primary vertex is currently found to be 62 μm for global tracks (SMT and CFT point measurements) with transverse momentum $p_T > 0.5$ GeV as shown in Fig. 2(a). This asymptotically approaches a current value of 20 μm for high-p_T tracks and is compared to Monte Carlo expectations in Fig. 2(b). It is clear that progress on alignment of the tracking chambers has resulted in resolutions already approaching expected values.

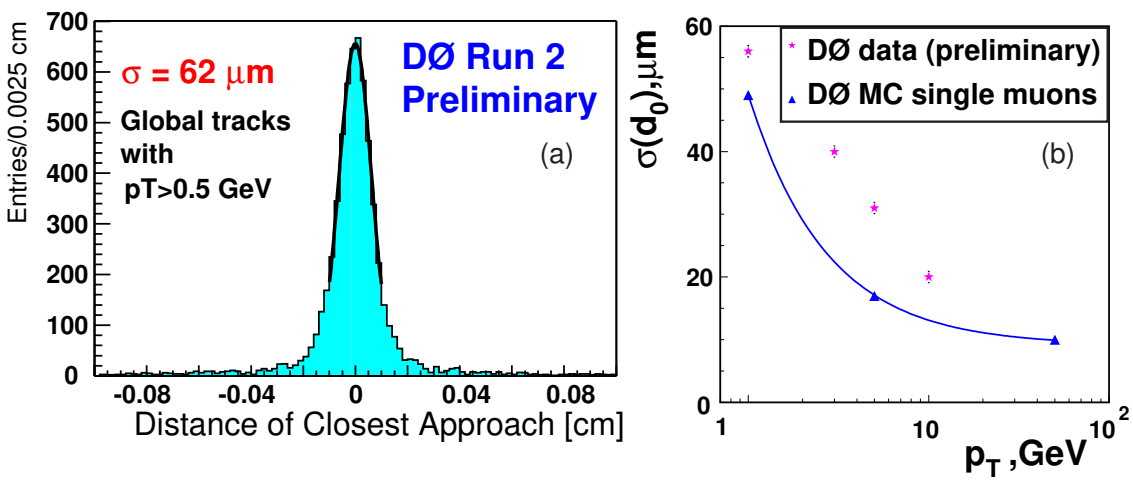

Figure 2: (a) Impact parameter resolution for D0 global tracks for $p_T > 0.5$ GeV and (b) behavior as a function of track p_T compared to Monte Carlo expectations.

5 Evidence for b production

One of the first systems to be reliably commissioned was the muon system and a benchmark analysis is the check of the muon plus jet rate due to $b \to \mu$. Muons reconstructed in only the muon system without a central track match (due to commissioning delays of the CFT) were associated with jets if close in angle: $\delta R = \sqrt{\delta\phi^2 + \delta\eta^2} < 0.7$. The measured differential cross section is shown in Fig. 3(a) for the indicated kinematic region. The shape is consistent with MC predictions as well as Run 1 D0

results [2]. Since the conference, the absolute rate has been measured as well and confirmed to be consistent with expectations.

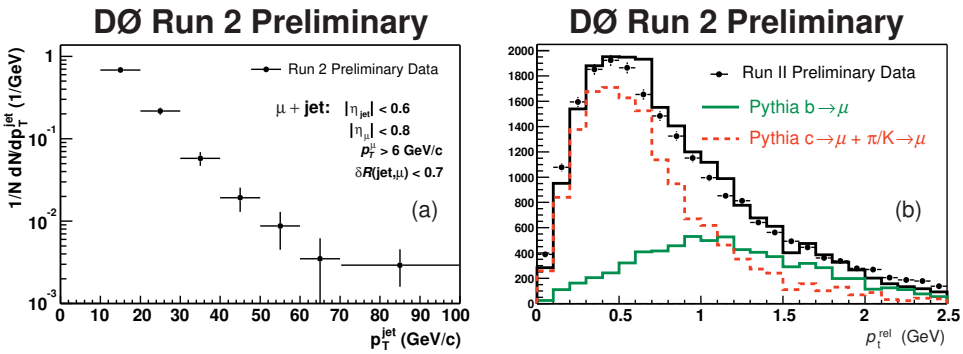

Figure 3: (a) Differential cross section for the rate of muons associated with jets (see text) in the range $|\eta_{\rm jet}| < 0.6$, $|\eta_\mu| < 0.8$, and $p_T^\mu > 6$ GeV; (b) fit to the transverse momentum of the muon with respect to the muon plus jet axis, i.e., $p_t^{\rm rel}$, to extract the b rate.

The muons in this sample will be due to $b \to \mu$, $b \to c \to \mu$, $c \to \mu$, and $\pi/K \to \mu$ decays in flight. The decay muon from the heavier b quark will tend to get a larger transverse momentum kick relative to the jet axis, $p_t^{\rm rel}$. Fig. 3(b) shows typical fits in this parameter to extract the b content. Entries at large values of $p_t^{\rm rel}$ are due to b hadrons, and also provide a method for identifying b jets. Current work using muons with a central track match shows substantial improvement in separation of $b \to \mu$ from backgrounds in the same parameter.

Using this muon plus jet sample and demanding $p_t^{\rm rel} > 1.5$ GeV to enhance the b content, tracks can be examined for evidence of b lifetime information. A signed impact parameter significance is formed where the sign is determined if the track in question crosses the jet axis upstream (positive) or downstream of the found primary vertex. Figure 4(a) shows the signed impact parameter significance (i.e., the distance of closest approach (dca) divided by its error) for an unbiased di-jet sample for $|\text{dca}| < 1.0$ mm to reduce contributions due to K_S^0 and Λ. The negative side of the distribution should be indicative of the resolution, and its mirror image is also superimposed on to the positive side of the distribution. The small excess is due to residual K_S^0 and Λ decays as well as small amounts of b jets in the sample. Figure 4 shows the same for the b-enhanced sample that shows a similar resolution as the di-jet sample, but a clear excess of tracks with significant impact parameters due to b content.

Using the di-jet sample, probability density functions can be formed for the observed resolution and Fig. 5(a) shows the resulting probability that tracks came from the interaction point (IP) or primary vertex. The spike on the positive side near zero shows that there is an excess of tracks with small probability of coming from the IP,

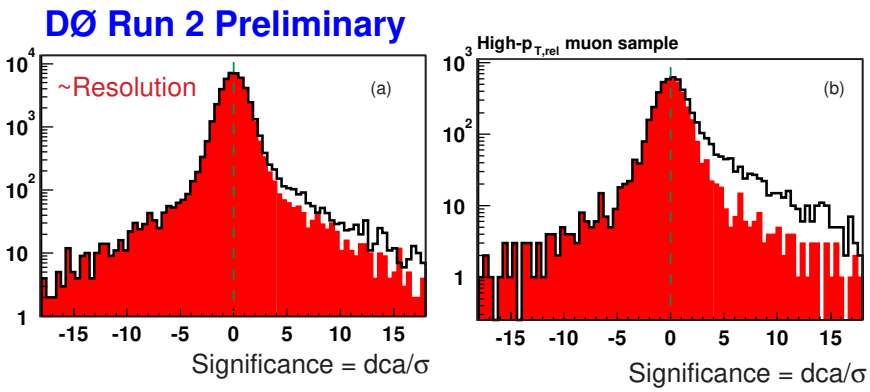

Figure 4: (a) Signed impact parameter significance (distance of closest approach (dca) divided by its error) for tracks in an unbiased di-jet sample with track $p_T > 1.5$ GeV, more than 10 total hits (SMT+CFT) and $|\text{dca}| < 1.0$ mm. The negative side of the distribution is also reflected to the positive side. (b) The same distribution in the muon plus jet sample with $p_t^{\text{rel}} > 1.5$ GeV to enhance the b-jet content.

i.e., tracks from secondary vertices carrying lifetime information. Taking the product of these track probabilities over the tracks in a jet, the probability that the jet is due to a light quark is shown in Fig. 5(b). This is the first time that lifetime information has been measured in the D0 detector.

The next step in utilizing lifetime information is the formation of secondary vertices. The important "golden" channel of $B^0 \to J/\psi K_S^0$ to measure the $\sin 2\beta$ parameter of CP violation serves as a useful benchmark to evaluate detector performance. The first physics objects reconstructed using both CFT axial and stereo tracks are two-prong secondary vertices from K_S^0 decays. The invariant mass as shown in Fig. 6(a) is found with a resolution of 5.1 MeV, close to MC expectations of 5.0 MeV demonstrating that the momentum resolution of the trackers is approaching nominal values.

Figure 6(b) shows the reconstruction of $J/\psi \to \mu^+\mu^-$ (and Υ's) where the muons have a CFT track match. The resultant mass resolution of 118 MeV improves to approximately 70 MeV if only tracks with both SMT and CFT hits are used. This can be compared to a resolution of 50–60 MeV expected from MC simulations. After the conference, decay lengths of reconstructed J/ψ secondary vertices due to $B \to J/\psi X$ as shown in Fig. 7 have been used to find a lifetime consistent with the PDG [3] value.

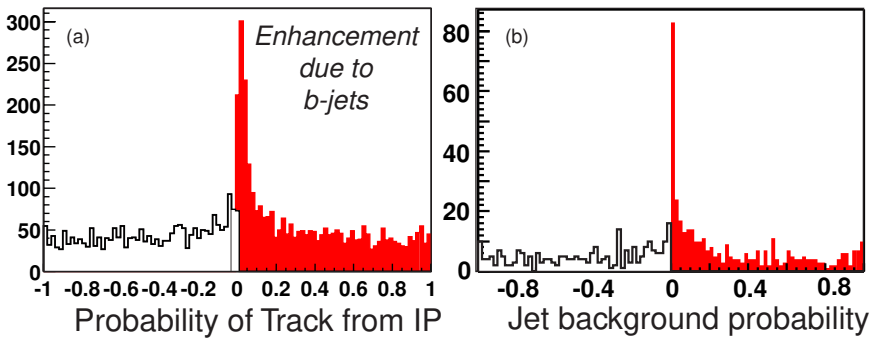

Figure 5: (a) From track significance values in the $p_t^{\rm rel} > 1.5$ GeV muon plus jet sample, probability that a track is from the interaction point or primary vertex; (b) normalized product of these track probabilities for the tracks in the jet. The peak is due to enhancement of b-jet content.

6 Some expectations for Run 2a

Continuing with expectations on the precision with which $\sin 2\beta$ could be measured using $B^0 \to J/\psi K_S^0$ events, the strengths of the D0 detector for such a B physics measurement are summarized in Table 2. One would measure the decay length of the B^0 decaying into $J/\psi K_S^0$, and tag the b quark flavor at production using a same-side tag of pion charge (from the primary) or an opposite-side tag by examining the lepton and/or jet charge. Defining tagging efficiency as $\epsilon = N_{\rm tag}/N_{\rm tot}$, and the dilution factor D as the asymmetry between "right" (R) and "wrong" (W) tags, $D = (N_R - N_W)/(N_R + N_W)$, the overall flavor tag quality can be quantified by ϵD^2. Although the D0 upgrade detector does not have kaon identification for opposite-side tagging, this is balanced by excellent muon and electron coverage for lepton tagging, and good forward tracking for determining jet charge. We also expect to be able to trigger on $J/\psi \to e^+e^-$ assisted by information from the preshower subdetectors.

Using these projections, and the expectation of 30–40k reconstructed events from the 2 fb^{-1} of Run 2a, an error of $\delta \sin 2\beta \approx 0.04$ is predicted [4].

Another high priority B physics analysis is the measurement of B_s^0 mixing. Current limits exclude $x_s = \Delta m_s/\Gamma_s > 21$ at 95% C.L. [3], while a global fit to a number of CKM triangle measurements in the framework of the Standard Model predicts [5] $x_s = 25.2^{+2.2}_{-1.0}$, although new physics can easily result in a much larger prediction. This very important measurement should therefore be in reach of the Tevatron experiments.

D0 has made Monte Carlo studies of both the semileptonic and hadronic decays of B_s^0 to extract this mixing. In the hadronic mode, which has the advantage of no missing neutrino, decays of $B_s^0 \to D_s^-\pi^+(\pi^+\pi^-)$; $D_s^- \to \phi\pi^-$, and $\phi \to K^+K^-$ can

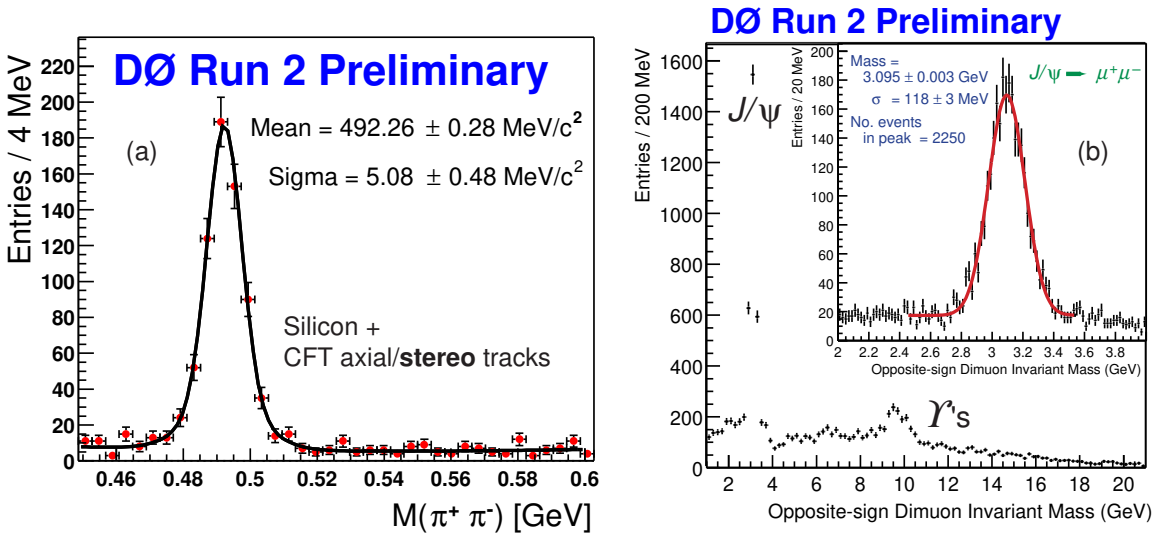

Figure 6: (a) Reconstructed $K_S^0 \to \pi^+\pi^-$ decays for tracks with both CFT axial and stereo tracks; (b) reconstruction of $J/\psi \to \mu^+\mu^-$ decays for muons with a CFT central track match.

be reconstructed. Triggers will be from leptons on the opposite side, and this lepton charge will tag the initial flavor. The final flavor will be tagged by the charge of the D_s. Approximately 2000 events are expected in 2 fb^{-1}, and with a signal-to-background ration of 0.5, and a pessimistic proper time resolution of 0.098 ps, the resulting projected reach on measuring x_s for this channel is shown in Fig. 8.

Tag	D0 Strength	Flavor Tag Quality, ϵD^2
Same side tag	–	2.0
Soft lepton tag	μ and e coverage and identification	3.1
Jet charge tag	forward tracking	4.7
Opposite-side kaon tag	*no K identification*	–
Combined		9.8

Table 2: Summary of predicted performance and strengths of flavor tagging in the CP violation channel $B^0 \to J/\psi K_S^0$.

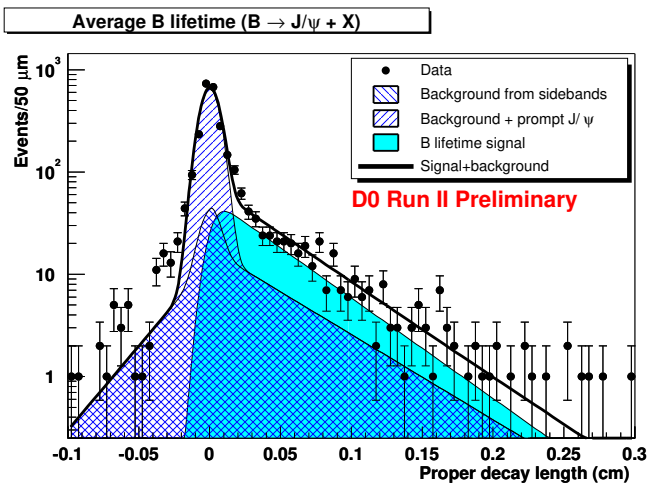

Figure 7: Proper decay length distribution for reconstructed J/ψ secondary vertices. The background is determined from J/ψ mass sidebands and prompt J/ψ Monte Carlo.

7 Future

The D0 upgrade detector with its tracking upgrades is much better suited for B physics than the Run 1 detector. The detector is still being commissioned, but we have observed lifetime information from b hadrons for the first time in the D0 detector, and are approaching data quality to soon allow preliminary B physics results.

Detector commissioning will continue with debugging, calibration, and alignment of the subdetectors and refinement of reconstruction algorithms to select physics objects. The full tracking system has just recently been available and secondary vertexing is rapidly improving as well as the prospects for tagging electrons (for b quark identification and $J/\psi \to e^+e^-$) using a road method and the preshower subdetectors.

The next large jump in performance will come from increasing the scope of the trigger system. The Level 2 trigger is coming online, a Level 1 central track trigger is expected at the end of summer 2002, and a Level 2 silicon track trigger able to fire on tracks with large impact parameter significance should be available fall 2002.

Of course, what is also needed is integrated luminosity and the Tevatron's performance has fallen short of expectations. Task forces at Fermilab have been addressing this low luminosity, and integrated luminosities of 300 pb^{-1} by the end of 2002 have been promised by laboratory management. The D0 collaboration eagerly looks forward to this data and the B physics that it holds for the future.

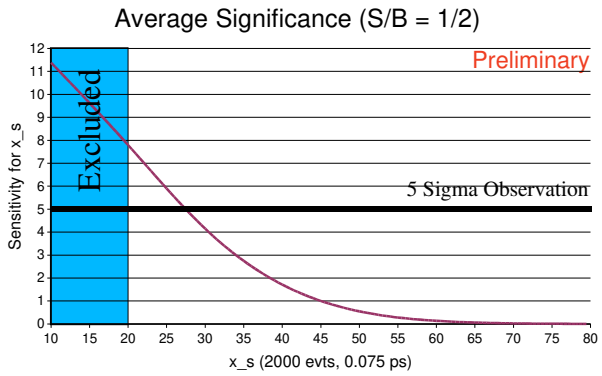

Figure 8: Projected reach on measuring x_s in Run 2a in the hadronic channel described in the text assuming a signal-to-background ratio of 0.5 and a proper decay time resolution of 0.098 ps.

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