B Tagging and Mixing at the Tevatron

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Abstract.
The measurement of the B_s mixing is one of the flagship analyses for the Run-II B physics program at Fermilab Tevatron. We report here preliminary results on key elements to the measurement including B_s event reconstruction, proper time resolution and initial B flavor tagging. The prospects on B_s mixing with the upgraded CDF and DØ detectors are also discussed.

INTRODUCTION

The measurements of the oscillation frequency of the neutral B meson, Δm_d for $B^0 - \bar{B}^0$ system and Δm_s for $B_s^0 - \bar{B}_s^0$ system, will be used to precisely determine the length of one side of the CKM unitarity triangle which is shown in Figure 1. The value of Δm_d is measured to a great precision [1], $\Delta m_d = 0.502 \pm 0.006\ ps^{-1}$. However, the Δm_s for the rapid oscillating $B_s^0 - \bar{B}_s^0$ system has not been resolved yet and its determination has a highest priority for the B physics program of Fermilab Tevatron experiments.

Key elements to the B_s mixing measurement include ability of collecting large B_s signal with small background, ability of initial B flavor tagging, and ability of precise determination of the proper decay time. We will discuss status and prospects of these key elements throughout this report.

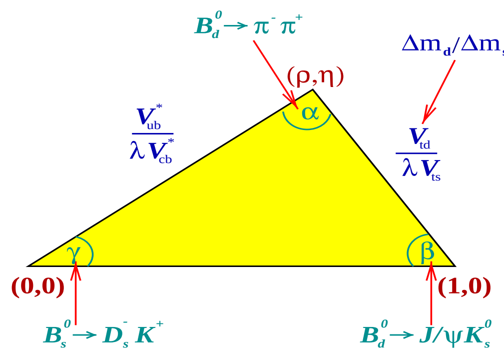

FIGURE 1. Experimental constrains on the CKM unitarity triangle.

B_S EVENT COLLECTIONS

Both CDF and DØ started taking Run-II data in March 2001. The strengths of the two detectors after upgrade efforts in the the 5 year shutdown are somewhat complementary to one another. Here we only briefly point out components most relevant to B physics and refer details to references listed in [2]. Both detectors have axial solenoidal magnetic fields, central tracking and silicon microvertex detectors. The DØ central tracking volume with the scintillating fibers covers the pesudorapidity region of $|\eta| \leq 1.7$. The DØ silicon detector has a barrel geometry interspersed with disk detectors to extend the tracking volume to $|\eta| \leq 3$. The CDF detector features a 1.4T solenoid surrounding a silicon microvertex detector and gas-wire drift chamber to provide excellent mass and vertex resolutions in the central region. The improved tracking coverages of both CDF and DØ, combined with muon detectors and calorimeters, allow for the excellent muon and electron identifications, as well as precise momentum and vertex measurements which are important for B physics. The late addition of a silicon layer very close to the beam spot (L00) and a Time Of Flight (TOF) system improves CDF's ability of vertex and flavor tagging dramatically.

Both experiments identify lepton at the trigger level to collect B events with leptons in the final state such as B semileptonic decay and $B \to J/\Psi X$. DØ has an inclusive muon trigger with large geometry coverage to allow them accumulate very large sample of semileptonic decays. Figure 2 shows the $B_s^0 \to D_s^- \mu^+ \nu X$ signal collected by DØ with the muon triggers. The CDF semileptonic trigger requires an additional displaced track associated with the lepton, providing cleaner samples with a somewhat smaller yields.

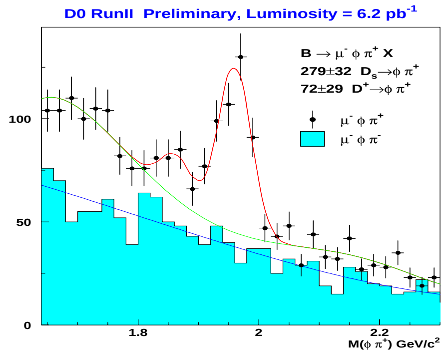

FIGURE 2. B_s events from semileptonic decays of $B_s^0 \to D_s^- \mu^+ \nu X$ with $D_s^- \to \phi\pi^-$ by the DØ experiment. The two peaks correspond to the D^+ and D_s^+ states, which can both decay to $\phi\pi^+$.

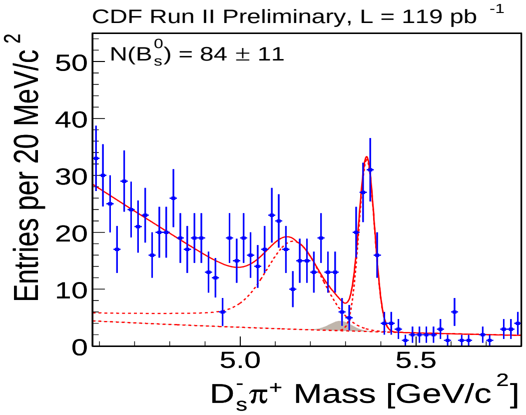

FIGURE 3. B_s^0 events from decay of $B_s^0 \to D_s^- \pi^+$ with $D_s^- \to \phi\pi^-$ collected using CDF's SVT trigger.

New to experiments at a hadron collider machine, CDF is using its new Silicon Vertex Tracker (SVT) to effectively collect events with large impact parameters. Tracks reconstructed by the eXtremely Faster Track (XFT) are passed to the SVT, which appends silicon hits to the track to measure the impact parameter of each track. The SVT has an impact parameter resolution of 47 μm for tracks with $p_T > 2GeV/c$. With this trigger, CDF collects B_s decays with at least two tracks having impact parameter $d_0 > 120\mu m$ and $p_T > 2GeV/c$. Figure 3 show the B_s^0 signal from $B_s^0 \to D_s^- \pi^+$ with $D_s^- \to \phi\pi^-$ using about 65 pb^{-1} data collected in the winter of 2002. In the plot, the narrow peak on the right is the B_s^0 signal and the broader bump on its left is background contributions from other B_s^0 channels other than $B_s^0 \to D_s^- \pi^+$.

There were many improvements on detector coverage and trigger optimization since this early data taking period where CDF was still in the process of commissioning for the silicon detector and SVT trigger. The live coverage of silicon detector reached above 90%. The SVT efficiency was improved greatly with a change of pattern recognition from requiring 4 hits in 4 silicon layers to 4 out 5. We also developed an optimized scheme to handle the L2 bandwidth to maximize useful trigger rate in different instantaneous luminosity scenarios. With these improvements, we were able to gain a factor of two increase for the B_s signal yield which corresponds to a rate of 1600 events per 1 fb^{-1} for $B_s^0 \to D_s^- \pi^+$ with $D_s^- \to \phi\pi^-$. Adding events from channels like $D_s^- \to K^* K^-, K_s K^-$ and $B_s^0 \to D_s^- \pi^+ \pi^- \pi^+$, a rate of B_s at 2000 events per 1 fb^{-1} is within the reach.

The ability of collecting the fully reconstructed B_s decay strengths our reach of much faster oscillation and makes the Tevatron the unique place for B_s mixing studies.

FLAVOR TAGGING

The initial flavor of a B meson at its production can be determined by using information of particles either produced on the same side together with the B meson or on the opposite of the B meson. The Same Side Tagging (SST) is to use the charge of an energetic track near the B meson to infer its production flavor. The opposite side tagging algorithms, such as Soft Lepton Tagging (SLT), Jet-Charge Tagging (JetQ) and Opposite Kaon Tagging (OKT), take advantage of the knowledge from $b\bar{b}$ production to infer the flavor of the B meson by the flavor of the other B hadron in the event.

The SST takes advantage of the correlation between the B flavor and the charge of a nearby track produced along B during b fragmentation. For a b quark to become a B_s^0 meson, it must grab an s quark from the vacuum, an $\bar{s}$ is popped with it, which could potentially turn into a K^+ meson in the B_s^0 case. Thus the correlation of $B_s^0 - K^+$ is the base for the SST tagging algorithm. Same is true for the $B^0 - \pi^+$ correlation. The B^{**} decay provides similar correlation.

The SLT algorithm uses the charge information of lepton produced from semileptonic decay, $b \to \ell^- X$ or $\bar{b} \to \ell^+ X$, to identify the B meson flavor. In JetQ algorithm, the weighted sum of charges for tracks recoiling against a B meson is used. The OKT uses the fact that there is more likely a K^- other than K^+ will be produced from a $\bar{B}$ decay in the dominated decay transition chain $b \to c \to s$. A K^- is a strong indication that it comes from a $\bar{B}$ meson. This tagging algorithm heavily relies on the kaon identification ability which CDF's TOF system will provide.

The power of a flavor tagging algorithm is determined by its tagging efficiency and its dilution. Tagging efficiency is measured as the fraction of the data events for

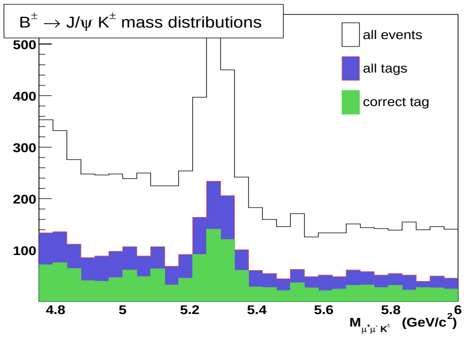

FIGURE 4. $B^+ \to J/\Psi K^+$ signal from DØ experiment. The open histogram with black line is all events. The histogram with blue line is events with a JetQ tagger. And the histogram with green line is events with a corrected tagger using JetQ.

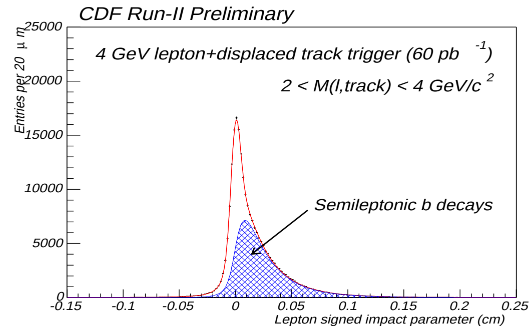

FIGURE 5. Signed impact parameter distribution of lepton with $2 < M(\ell, track) < 4GeV/c$.

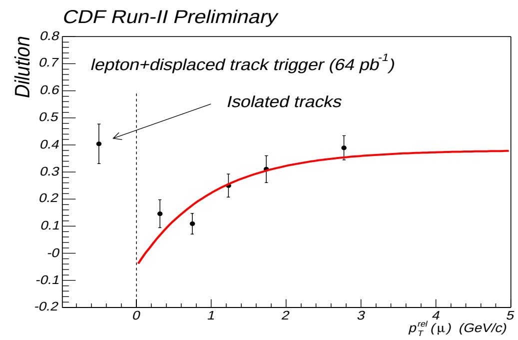

FIGURE 6. Dilution as a function of pT^{rel} of the tag muon : $D = A(1 - e^{(-p_T^{\mathrm{rel}} + B)})$. The p_T^{rel} is the component of the lepton's momentum that is transverse to the jet that it's associated with. The data points with $p_T^{\mathrm{rel}} < 0$ correspond to tracks not associated with a jet.

which the algorithm returns a decision: $\varepsilon \equiv N_{tag}/N_{total}$. The dilution, defined as $D \equiv (N_{RS} - N_{WS})/(N_{RS} + N_{WS})$ where N_{RS} and N_{WS} are respectively the number of correctly and incorrectly tagged events, reflects the purity of the tagging algorithm. The "effective tagging efficiency" is given by the quantity εD^2. In a B_s mixing measurement, the statistical power of the sample is directly proportional to εD^2. Tagging power is proportional to D^2 because incorrectly measuring the sign removes the event from the "correct" charge bin and puts the event into the "wrong" charge bin.

Using $B^+ \to J/\Psi K^+$ events, shown in Figure 4, DØ tested the performance of SST, SLT with muon and JetQ algorithms. The effective tagging efficiencies obtained from DØ are $\varepsilon D^2 = 5.5 \pm 2.0\%$ for SST, $1.6 \pm 1.1\%$ for SLT with muon, and $3.3 \pm 1.7\%$ for JetQ. The combined efficiency from DØ using these three tagging algorithms was estimated to be $\varepsilon D^2 \approx 10\%$[3].

CDF's strategy of flavor tagging for Run-II is as following. The algorithms are to be first optimized using a high statistics and high purity B sample such as semileptonic B decay events collected with the lepton+SVT trigger. Then performance of these taggers, in terms of value of εD^2, is measured using independent samples such as $B \to J/\Psi K^+$ and fully reconstructed B decays collected with SVT triggers. Finally these tagging algorithms will be applied directly to B_s mixing measurement without retuning to avoid potential bias.

In order to use the high statistics sample of lepton+SVT, we need to know its sample composition. First the B component is enriched by applying kinematic constrains such as the requirement of the invariant mass of lepton and the SVT track to be $2 < M(\ell, SVT) < 4$. Then the remaining backgrounds from charm and prompt decays can be subtracted using the the impact parameter distribution of the lepton, shown in Figure 5. In addition, the b-decay on the trigger side can mix and can also undergo wrong-sign sequential decays, $b \to c \to \ell$. These effects will reduce the 'raw' dilution measured for an opposite side tagging algorithm. We estimate the dilution on the trigger side using a Monte Carlo method and apply the correction factors obtained to determine the 'true' dilution of the opposite side tag. The overall correction factors of $D(trig) = 0.6412 \pm 0.002^{+0.014}_{-0.023}$, $D(trig) = 0.6412 \pm 0.002^{+0.022}_{-0.037}$ were obtained for μ+SVT and e+SVT sample respectively. Using these sample, we obtained the preliminary result on SLT performance with muon shown in Figure 6. The performance is a strong function of the lepton momentum. An averaged effective tagging efficiency was obtained $\varepsilon D^2 = 0.7 \pm 0.1\%$ which agrees well with projection using Run-I result.

The performance of SST algorithm at CDF was tested on two fully reconstructed charged B decay samples from $B^+ \to J/\Psi K^+$ and $B^+ \to D^0 \pi^+$ as shown in Figure 7 and 8. The dilution, shown in Figure 9 and 10, is again parameterized as function of the transverse momentum of B. The preliminary result of the tagging efficiency was obtained as $\varepsilon D^2 = 2.4 \pm 1.2\%$ and $\varepsilon D^2 =$

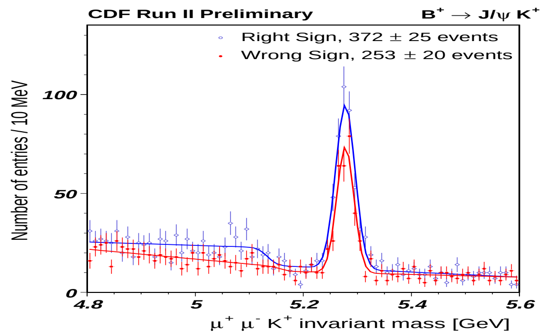

FIGURE 7. The invariant mass distribution of the Right Sign (blue line) and Wrong Sign (red line) $B^+ \to J/\Psi K^+$ candidates.

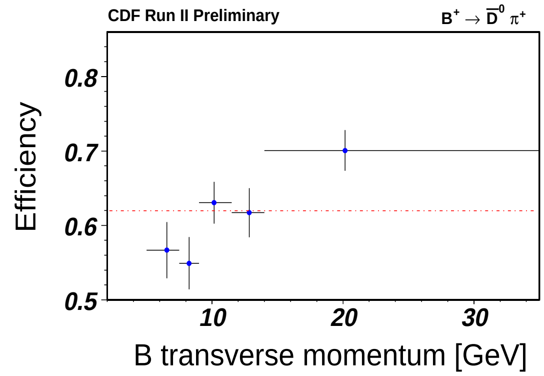

FIGURE 9. SST asymmetry as a function of pT for $B^+ \to J/\Psi K^+$; dot-dashed line denotes global value.

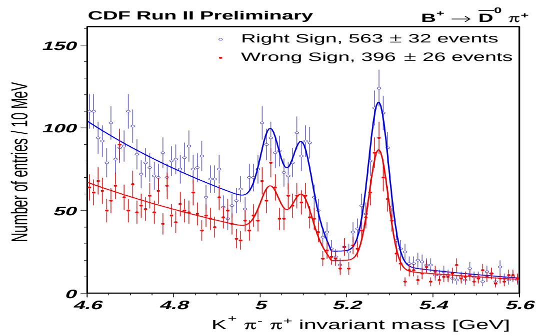

FIGURE 8. The invariant mass distribution of the Right Sign and Wrong Sign $B^+ \to \bar{D}^0 \pi^+$ candidates.

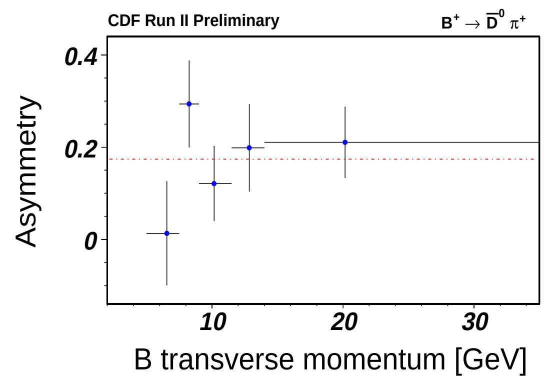

FIGURE 10. SST asymmetry as a function of pT for $B^+ \to \bar{D}^0 \pi^+$; dot-dashed line denotes global value.

$1.9 \pm 0.9\%$ independently from $B^+ \to J/\Psi K^+$ and $B^+ \to \bar{D}^0 \pi^+$ samples.

The Run-II preliminary result from CDF were summarized in Table 1. In the table, the Run-I CDF results and expected Run-II performance were also listed. Studies of JetQ and SLT electron algorithms are underway at CDF. Using the preliminary Run-II results and projections from Run-I, CDF expects a combined efficiency of $\varepsilon D^2 \approx 4\%$ from SLT, SST and JetQ algorithms. This is an estimation without taking into account of potential improvements from using the particle identification from TOF. The TOF provides a better than 2σ $K - \pi$ separation, shown in Figure 11, for tracks with $p < 1.6 GeV/c$. We expect the TOF system to increase improve both the OKT and SST efficiency dramatically.

PROPER TIME RESOLUTION

The $B_s^0 - \bar{B}_s^0$ oscillation is expected to have a very high frequency as the current limit, $\Delta m_s > 14.4\ ps^-1$[1], implies there are more than 4 oscillations in one lifetime cycle. Thus the B_s proper time reconstruction resolution play key roles in an experiment's sensitivity for the Δm_s measurement. At CDF and DØ , the transverse decay length L_{xy} and the transverse momentum p_T of the B meson are used to calculate the proper time

$$t = L/\beta\gamma = L_{xy} \cdot M/p_T.$$

L_{xy} is the two-dimensional flight distance between the beam spot where B is produced and the the point where the B decays. p_T is calculated from the B decay daughters. And M is the mass of B_s.

The uncertainty on the proper time is thus derived as

$$\sigma_t = \sqrt{(\sigma_{L_{xy}} \cdot M/p_T)^2 + (\sigma_{p_T}/p_T \cdot t)^2},$$

where $\sigma_{L_{xy}}$ and σ_{p_T} are measurement errors on the decay length and transverse momentum. There are two components to the decay length resolution, the uncertainty of beam spot position and the vertex fitting errors in determining the decay point. CDF estimates an error of $\sigma_{L_{xy}} \approx 50\mu m$ in the SVT triggered events. The spread of the beam spot contributes an error of $30\mu m$ to the decay length calculation. The beam spot was calculated on

TABLE 1. Summary of tagging algorithms performance at CDF

εD^2 (%)	Run-I	Run-II	Projection(no TOF)	Projection (with TOF)
SST	1.5 ± 0.4	2.1 ± 0.7	2.0	2.0-4.2
SLT-μ	0.6 ± 0.1	0.7 ± 0.1	1.0	1.0
SLT-e	0.3 ± 0.1	-	0.7	0.7
JetQ	1.0 ± 0.3	-	3.0	3.0
OKT	-	-	-	2.4

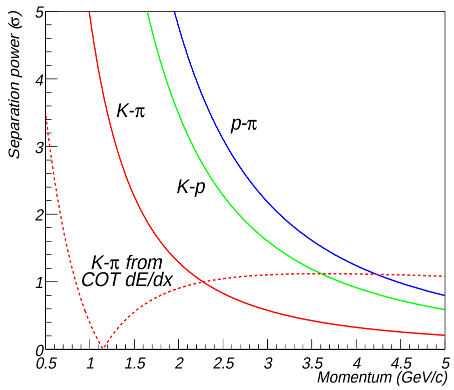

FIGURE 11. $K-\pi$ separation as function of track momentum from CDF TOF system.

a run averaged base at this time and improvement were under study. The uncertainty on the B transverse moment depends on the tracking resolution and on detail of event topologies which is very different for semileptonic decay events and the fully reconstructed hadronic decay events.

For fully reconstructed hadronic decay events, the uncertainty on B_s transverse momentum is negligible comparing to the uncertainty on the decay length due to excellent tracking resolutions. Therefore, decay length resolution which depends on the performance of the silicon systems is the most important issue to the precise measurement of proper time resolution and the ability for B_s mixing. From $B_s \to D_s\pi$ decay event reconstructed by CDF, a proper time resolution of $\sigma_t = 0.067ps$ was obtained. With further improvement on silicon tracking with L00 silicon hits and on beam spot calculation using tracks other than B daughter on an event-by-event base, CDF believes a resolution of $\sigma_t = 0.05ps$ is achievable.

For B_s semileptonic decay events, uncertainty on B_s transverse momentum dominates the resolution of proper time due to the unreconstructed neutrino. Monte Carlo method was used to estimate the B_s p_T by using kinematic correlation of the momenta of lepton and charm daughters of the B_s decays. This method results an error in the order of $10-15\%$. Method using the three-dimensional event topology information is being explored to improve the estimation [4]. In general, a sizable uncertainty introduced from B_s p_T calculation has to be overarmed in order to use B_s semileptonic decay event for B_s mixing measurements, especially if the Δm_s is indeed very large.

B_S MIXING SENSITIVITY

The sensitivity of B_s measurement is generally quantified as the significance of an observation of B_s mixing at certain value of Δm_s. Three key numbers, the B_s event yields, efficiency of flavors tagging and proper time resolution, determine an experiment's sensitivity for B_s mixing measurement. To a good approximation, the averaged significance $Sig(\Delta m_s)$, in number of standard deviations σ, is given as

$$Sig(\Delta m_s) = \sqrt{\frac{S\varepsilon D^2}{2}} e^{-\frac{(\Delta m_s \sigma_t)^2}{2}} \sqrt{\frac{S}{S+B}},$$

here S is the number of signal events, S/B is the signal to background ratio, and εD^2 and σ_t are the effective tagging efficiency and proper time resolution as discuss in the previous sections.

Both fully reconstructed and semileptonic samples will contribute to the measurement of Δm_s but at different Δm_s region. For lower value of Δm_s, the high statistics semileptonic sample could play key roles in the measurement. If the value of Δm_s is much higher than the current limit, the proper time resolution σ_t becomes the limiting factor in resolving the oscillations where we need to take advantage of the fully reconstructed samples.

Both DØ and CDF are using semileptonic B_s decay samples for the mixing study. DØ predicts a 15,000 signal yield from $B_s^0 \to D_s^- \mu^+ \nu X$ decay with a proper time resolution of 0.15 ps from 500 pb^{-1}. This results a sensitivity of 1.5σ for $\Delta m_s = 15\ ps^{-1}$ [3].

CDF's event rate of reconstructing $B_s \to D_s\pi$ decay is $S = 1600 events/fb^{-1}$ with $S/B = 2/1$ and proper time resolution of $\sigma_t = 0.067ps$. With a tagging efficiency of $\varepsilon D^2 = 4\%$, CDF will have a 2σ sensitivity for $\Delta m_s = 15\ ps^{-1}$ using $500pb^{-1}$ data. This will supersede the current world limit which combines contributions from 13 different measurements from LEP, SLD and CDF [1]. This sensitivity is predicted using numbers based on already achieved performance of the trigger, reconstruction and flavor tagging.

As discussed in previous sections, improvements are underway to increase the event yield from optimizing SVT trigger and by including more decay channels in the reconstruction. Proper time resolution is also improving with usage of hits from the innermost silicon layer and with an event-by-event beam spot calculation method. In addition, the flavor tagging efficiency will double with the help from kaon identification using TOF system. A higher sensitivity for CDF with the fully reconstructed B_s events can be derived taking into account these improvements using a set of numbers of $S = 2000 events/fb^{-1}$, $S/B = 2/1$, $\varepsilon D^2 = 5\%$ and $\sigma_t = 0.05ps$. It results a 5σ sensitivity for $\Delta m_s = 18 \rightarrow 24 ps^{-1}$ with $1.7 \rightarrow 3.2 fb^{-1}$ of data. This will cover the region of Δm_s that is currently preferred by the indirect fits using the world average [1]. To observe or exclude a value of Δm_s beyond this region will require additional data and improvement along with further progress on triggering, reconstruction and flavor tagging.

PROGRESS ON $\Delta\Gamma_S$ MEASUREMENT

A complementary method to Δm_s measurement in B_s mixing study is the measurement of the width difference $\Delta\Gamma_s$ of the the two CP eigenstates of $B_s^0\bar{B}_s^0$ system. Within the Standard Model, it is predicated that the ratio between $\Delta\Gamma_s$ and Δm_s is large [5]:

$$\frac{\Delta\Gamma_s}{\Delta m_s} = \frac{3\pi}{2} \cdot \frac{m_b^2}{m_t^2} \cdot \frac{\eta(\Delta\Gamma_s)}{\eta(\Delta m_s)} \approx (5.6 \pm 2.6) \times 10^{-3}.$$

If the value of Δm_s is indeed large, the width difference could be as much as $\Delta\Gamma_s/\Gamma_s$ 15% which will make its precision measurement possible using Run-II data.

Experimentally, three methods are being explored to extract the width difference. One can extract it by directly fitting the two lifetime components in events from a decay channel of a well define CP eigenstates, such as the $B_s^0 \rightarrow D_s^- \ell^+ \nu$ which is a 50-50 mixture of CP-even and CP-odd states. A modified method is to separate the CP-even and CP-odd states by a transversity analysis first then extract the width difference from the two states. $B_s \rightarrow J/\Psi\phi$ channel is expected to be dominated by CP-event state, as $\Gamma^{CP-even}/\Gamma = 0.778 \pm 0.090 \pm 0.012$ measured from CDF using Run-I data [6] and is being explored for this purpose. Both CDF and DØ are collecting sizable samples on this decay using the dimuon triggers. CDF's signal is shown in Figure 12. A precision of 0.05 on $\Delta\Gamma_s/\Gamma_s$ is predicated to be reachable using 4000 $B_s \rightarrow J/\Psi\phi$ events [4]. The third method involves B_s decay with a pure CP state such as $B_s^0 \rightarrow D_s^- D_s^+$ which is a pure CP-even states. The decay branching ratio can be related to $\Delta\Gamma_s$ by [7] $Br(B_s^0 \rightarrow D_s^- D_s^+) = \Delta\Gamma_s/[\Gamma_s(1 + \Delta\Gamma_s/2\Gamma_s)]$. CDF is studying the feasibility of the measurement using $B_s^0 \rightarrow D_s^- D_s^+$ decay events being collected using its SVT trigger.

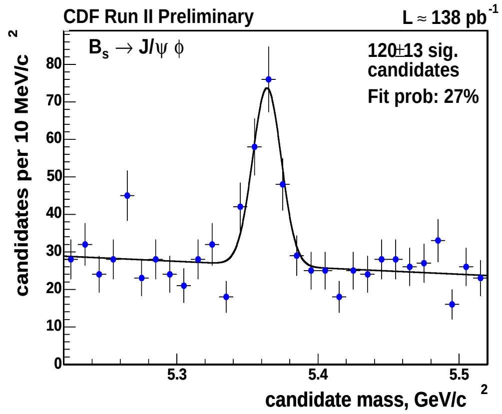

FIGURE 12. Invariant mass spectrum of the $B_s \rightarrow J/\Psi\phi$ candidates. The result is using about 138 pb^{-1} CDF data.

SUMMARY

Both CDF and DØ are collecting large samples of B_s decay events for the very challenging B mixing measurement. Many progresses have been made on flavor tagging and proper time reconstruction. Over the next few years, both experiments are expected to make significant contributions in the the determination of the mixing parameter Δm_s as well as the width difference $\Delta\Gamma_s$ for the $B_s^0\bar{B}_s^0$ system.

REFERENCES

1. Heavy Flavor Averaging Group, `http://www.slac.stanford.edu/xorg/hfag/index.html`.
2. D0 Collaboration, FERMILAB-Pub-96/357-E, 1996. CDF Collaboration, FERMILAB-Pub-96/390-E, 1996 and Fermilab-Proposal-909,1998.
3. V. Jain, these proceedings.
4. K.Anikeev,etal., "B physics at the Tevatron: Run II and Beyond", FERMILAB-pub-01/197.
5. M.Beneke,G.Buchala and I. Dunietz, "The width difference in the $B_s - \bar{B}_s$ system, hep-ph/9605259 (May 1996).
6. T. Affolder etal. (CDF collaboration),Phys. Rev. Lett. 85, 4668 (2000).
7. R.Aleksan, etal.,Phys. Lett. B316(1993)567.