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S. Recksiegel, A. Hoang, S. Paul

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B_s Lifetime Difference and Mixing @ the Tevatron

S. Hansmann-Menzemer
for the CDF II & D0 Collaboration
Physikalisches Institut Heidelberg
Philosophenweg 12
69120 Heidelberg, Germany

1 Introduction

The Tevatron collider at Fermilab, operating at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV has a huge $b\bar{b}$ production cross section (≈ 1 nb), which is about five orders of magnitude larger than the $b\bar{b}$ production rate at the B factories PEP and KEK, e^+e^- colliders running on the $Y(4S)$ resonance. In addition, only B^+ and B_d mesons are produced at $Y(4S)$, while higher mass b hadrons such as B_s, B_c, b baryons, B^* and p-wave B mesons are currently produced only at the Tevatron. In order to exploit the possibility to study those variety of heavy b hadrons in a busy hadronic environment, dedicated detector systems, triggers and reconstruction are crucial.
Both D0 and CDF are multipurpose detectors featuring high resolution tracking in a magnetic field and lepton identification. These detectors are symmetrical in polar and azimuthal angles around the interaction point, with approximate 4π coverage [1, 2]. The CDF and D0 experiments are able to trigger at hardware level on large track impact parameters. CDF exploits this trigger to collect a sample of fully reconstructed B mesons, enhancing the potential of its B physics program. At D0 the displaced track trigger is for the time being only used at lower bandwidth, e.g. for b tagging of potential Higgs candidates. CDF has a dedicated particle identification system composed of a time-of-flight detector and dE/dx measurements in the drift-chamber, which allows kaon-pion separation of at least 1.5 σ throughout the whole momentum range. D0 has an excellent muon system and a tracking coverage in the forward region up to a pseudo-rapidity of $\eta = 2.5$.
About 2 fb^{-1} of data has been collected in the meantime by each of the both experiments. About 8 fb^{-1} are expected till the shutdown of the Tevatron end of 2009. The results presented here are unless otherwise specified based on 1 fb^{-1} of data.

2 B_s Lifetime Difference & Mixing Phase

In the standard model (SM), the light (L) and heavy (H) eigenstates of the B_s system are expected to mix in such a way that the mass and decay width differences between them, $\Delta m_s = m_H - m_L$ and $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, are sizeable. The mixing phase ϕ_s^{SM} is within the SM predicted to be small [3], and thus to a good approximation the two mass eigenstates are expected to be CP eigenstates. New phenomena may introduce a non-vanishing mixing phase ϕ_s^{NP}, leading to a reduction of the observed $\Delta\Gamma_s$ compared to the SM prediction: $\Delta\Gamma_s = \Delta\Gamma_s^{SM} \times |\cos(\phi_s^{SM} + \phi_s^{NP})|$ [3]. While the mass difference Δm_s in the B_s system has been recently measured with a high precision, as it will be described in the following section, the mixing phase has remained unknown sofar.

Several analysis have been performed at the Tevatron, to access $\Delta\Gamma_s$ and/or ϕ_s:
$B_s \to K^+K^-$ is a pure CP even state. Assuming a small CP violating phase, the measurement of the lifetime in this final state directly corresponds to the measurement of the lifetime of the B_s(light), which can then be compared to measurements of lifetimes in flavor specific eigenstates [5].
The untagged decay rate asymmetry in semileptonic B_s decays (A^s_{SL}) is another handle on the mixing parameters of the B_s system [4]:

$$A^s_{SL} = \frac{\Delta\Gamma_s}{\Delta m_s}\tan(\phi_s) \tag{1}$$

Both analysis have been performed at the Tevatron and have been discussed in the talk from Cano Ay at this conference.
A third approach is the measurement of the branching ration of $B_s \to D_s^{(*)} D_s^{(*)}$. This decay is predominantly CP even [6] and gives the largest contribution in the lifetime difference between the B_s(heavy) and B_s(light). The following relation can be obtained [3]:

$$2 * BR(B_s \to D_s^{(*)} D_S^{(*)}) \approx \frac{\Delta\Gamma_s}{\cos(\phi_s)\Gamma_s}[1 + O(\frac{\Delta\Gamma}{\Gamma_s})], \tag{2}$$

where Γ_s is the average B_s decay width. This analysis is describe in more detail in the contribution from Manfred Paulini.

The decay $B_s \to J/\Psi\phi$, through the quark process $b \to c\bar{c}s$, gives rise to both CP even and CP odd final states. It is possible to separate the two CP components of this decay, and thus to measure the lifetime difference, through a simultaneous study of the time evolution and the angular distributions of the decay products of the J/Ψ and the ϕ mesons. Moreover, with a sizeable lifetime difference, there is a sensitivity to the mixing phase through the interference terms between the CP even and CP odd waves.

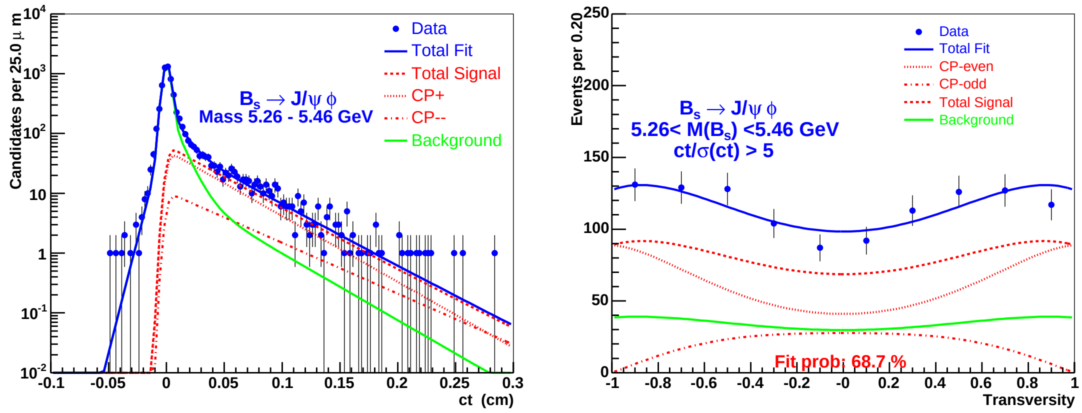

Figure 1: Lifetime and transversity angle distribution for CP even and CP odd $B_s \rightarrow J/\Psi\ \Phi$ decays of the D0 analysis.

Based on 1 fb^{-1} of D0 analyzes about 23.000 $B_s \rightarrow J/\Psi(\mu^+\mu^-)\phi(K^+K^-)$ candidates after selection cuts. A simultaneous unbinned likelihood fit is performed in terms of invariant mass, proper decay length and transversity angular variables, described in [7]. In Fig. 1 we show the projection of the fit result onto the proper decay time distribution and the onto $\cos\theta$, one of the transversity angles. Similar good agreement is observed in the projections onto the invariant mass and remaining transversity angles. A fit to the data has been performed in two ways. First the mixing phase ϕ_s has been fixed to zero, which assumes no significant New Physics contribution in ϕ_s. A non-zero decay width difference of $\Delta\Gamma_s = 0.12 \pm 0.08$ (stat.) $\pm$ 0.03 (syst.) has been obtained. This result has been compared to the result of the analysis of the $B_s \rightarrow K^+K^-$ lifetime and the branching ratio measurement, which have been briefly described above (Fig. 2). The plot contains as well the result of the angular analysis of the $B_s \rightarrow J/\Psi\phi$ mode performed by the CDF collaboration based on 380 pb^{-1} of data.
In a second fit to the D0 data, both the decay width difference $\Delta\Gamma_s$ and ϕ_s where floating parameters, which results in:

$$\Delta\Gamma_s = 0.17 \pm 0.09\ (\text{stat.}) \pm 0.03\ (\text{syst.})\ \text{ps}^{-1} \quad (3)$$
$$\phi_s = -0.79 \pm 0.56\ (\text{stat.}) \pm 0.01\ (\text{syst.}) \quad (4)$$

This is the first measurement of the mixing phase ϕ_s. The result is still dominated by statistical uncertainties. But with increasing data samples, this is a very promising analysis to probe the SM. Any sizeable phase would be a clear hint to New Physics. A combined fit of $\Delta\Gamma_s$ and ϕ_s both in the $B_s \rightarrow J/\Psi\phi$ decays and in the untagged semileptonic decay rate asymmetrie has been performed (Fig. 2).

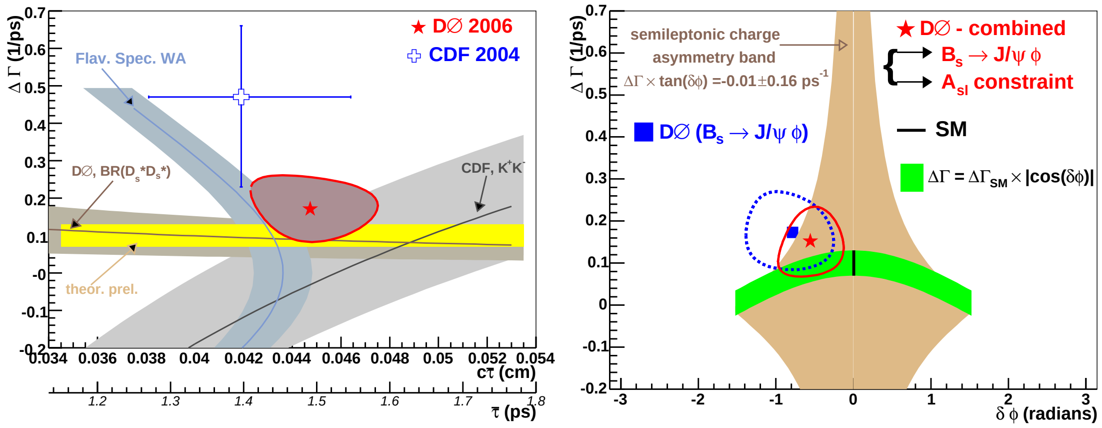

Figure 2: Left: Results of several Tevatron $\Delta\Gamma_s$ measurements superimposed with the SM theory predictions [3]. All measurements are performed under the SM assumption of a negligible CP violating phase ϕ_s. Right: D0 result for a common fit of the decay width difference $\Delta\Gamma_s$ and the CP violating phase ϕ_s superimposed with the SM expectations.

This combined fit slightly reduces the uncertainties on ϕ_s but still the analysis is at this stage statistical dominated:

$$\Delta\Gamma_s = 0.15^{+0.09}_{-0.08} \text{ ps}^{-1} \quad (5)$$

$$\phi_s = -0.56^{+0.44}_{-0.41} \quad (6)$$

For the moment all results are consistent with the SM expectations.

3 B_s Mixing

The precise determination of the $B_s - \overline{B_s}$ oscillation frequency Δm_s from a time-dependent analysis of the $B_s - \overline{B_s}$ system has been one of the most important goals for heavy flavor physics at the Tevatron. This frequency can be used to strongly improve the knowledge of the Cabbibo-Kobayashi-Maskawa (CKM) matrix, and to constraint contributions from New Physics.
The probability $\mathcal{P}$ for a B_s meson produced at time $t = 0$ to decays as a B_s ($\overline{B_s}$) at proper time t > 0 is, neglecting effects from CP violation as well as possible lifetime difference between the heavy and light B_s^0 mass eigenstates, given by

$$\mathcal{P}_\pm(t) = \frac{\Gamma_s}{2} e^{-\Gamma_s t}[1 \pm \cos \Delta m_s t)], \quad (7)$$

where the subscript "+" ("-") indicates that the meson decays as B_s ($\overline{B_s}$). Oscillation have been observed and well established in the B_d system. The mass difference Δm_d

is measured to be [5]

$$\Delta m_d = 0.505 \ \pm \ 0.005 \ ps^{-1}. \tag{8}$$

In the B_s system oscillation have also been established but till winter 2006 all attempts to measure Δm_s have only yielded a combined lower limit on the mixing frequency of $\Delta m_s > 14.5$ ps^{-1} at 95% confidence level (C.L.). Indirect fits constraint Δm_s to be below 24 ps^{-1} @ 95% C.L. within the SM. This spring the D0 experiment presented the first double sided 90% C.L. limit [8] and CDF shortly afterwards presented the first precision measurement on Δm_s, with a significance of the signal of about 3 σ at that time [9]. Just a few months later the CDF collaboration updated their result using the very same data, but improved analysis technics and where able to announce the observation of the $B_s - \overline{B_s}$ mixing frequency [10].
The canonical B mixing analysis proceeds as follows. The b flavor (b or $\bar{b}$ of the B meson at the time of decay) is determined from the charges of the reconstructed decay products in the final state. The proper time at which the decay occurred is determined from the transverse displacement of the B_s decay vertex with respect to the primary vertex, and the B_s transverse momentum with respect to the proton beam. Finally the production b flavor must be known in order to classify the B meson as being mixed (production and decay b flavor are different) or unmixed (production and decay b flavor are equal) at the time of its decay. Then the asymmetry can be measured and thus Δm_s be determined:

$$\mathcal{A}(t) \equiv \frac{N(t)_{unmixed} - N(t)_{mixed}}{N(t)_{unmixed} + N(t)_{mixed}} = \mathcal{D}\cos(\Delta m_s t), \tag{9}$$

where $N(t)$ are the time-dependent rates for mixed and unmixed B_s decays. $\mathcal{D}$ is the so-called dilution, a damping term which is related to the imperfect tagging. It is defined as $\mathcal{D} = 1 - P_w$, where P_w is the probability for a wrong tag.
The significance $\mathcal{S}$ of a mixing signal is given by:

$$\mathcal{S} = \sqrt{\frac{\epsilon\mathcal{D}^2}{2}}\sqrt{\frac{S}{S+B}}e^{-\frac{(\Delta m_s \sigma_{ct})^2}{2}} \tag{10}$$

S and B are the rates of signal and background events respectively. $\epsilon\mathcal{D}^2$ is the figure of merit for the flavor tagging, where ϵ is the efficiency to actually apply a tag to a given B_s candidate. σ_{ct} is the proper decay time resolution. Especially at large Δm_s values a small σ_{ct} resolution is crucial for this analysis.
We will in the following sections discuss those various ingredients to the mixing analysis and then present the result.

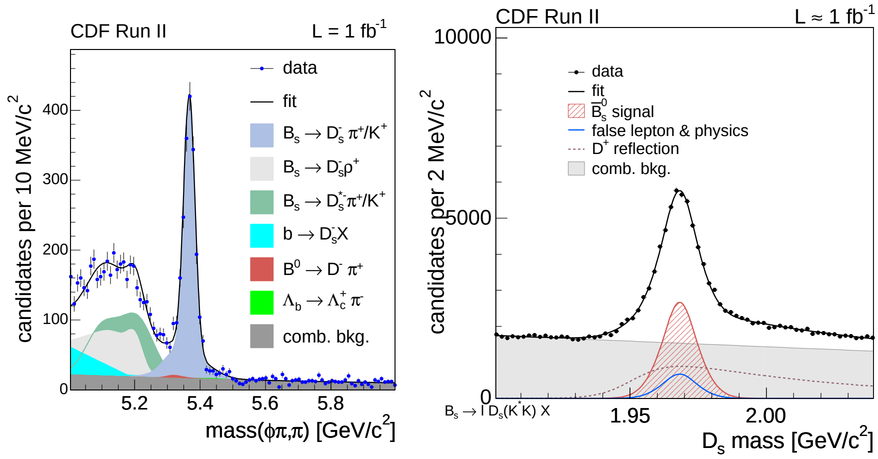

Figure 3: Left: Invariant mass distribution of $B_s \to D_s(\phi\pi)\pi$ candidates of the CDF mixing analysis. Right: D_s invariant mass distribution of $B_s \to \ell D_s X$ candidates.

3.1 Signal Yields

CDF analysis fully and partial reconstructed hadronic and semileptonic B_s candidates in events collected by the displaced track trigger. About 2000 candidates are fully reconstructed in the cleanest, so-called golden mode $B_s \to D_s(\phi\pi)\pi$. About 3200 partially reconstructed B_s candidates coming from $B_s \to D_s^*(\phi\pi)\pi$ and $B_s \to D_s^*(\phi\pi)\rho$ are reconstructed with the same signal signature. Those events have slightly worse proper decay time resolution than the fully reconstructed ones due to γ or π^0, which escaped reconstruction. 3600 B_s candidates are fully reconstructed in additional decay signatures such as $B_s \to D_s(K^*K)\pi$, $B_s \to D_s(3\pi)\pi$, $B_s \to D_s(\phi\pi)3\pi$, $B_s \to D_s(K^*K)3\pi$ and $B_s \to D_s(3\pi)3\pi$. Neural network technics have been used to enhance signal yield and to improve signal/background ratio.

A large sample of 61.500 semileptonic $B_s \to \ell D_s X$ candidates has been studied as well. Due to the missing momentum of the non reconstructed particles in this decay a correction factor derived in Monte Carlo, has been applied to scale the ℓD_s momentum to match the B_s momentum, which is needed to compute the proper decay time:

$$ct = \frac{L_{xy} M(B_s)}{p_T(B_s)} = \frac{L_{xy} M(B)}{p_T(\ell D_s)} * k. \tag{11}$$

It has turned out that the invariant ℓD_s mass is a good variable, both to reject background as well as to parameterize the k factor distribution. Low ℓD_s values are mainly background and the k factor distribution is rather broad which results in a large proper decay time uncertainty. Events with ℓD_s mass close to the B_s mass are more valuable events. They are suffering from less background and their k factor distribution is narrower.

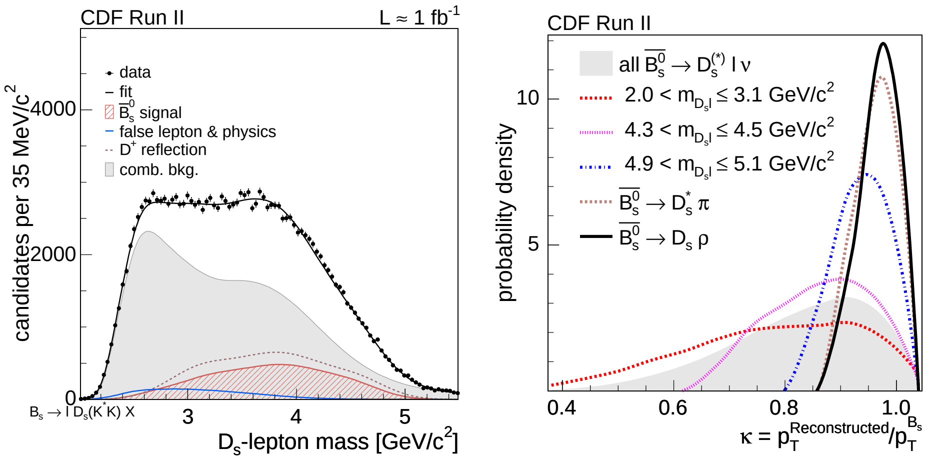

Figure 4: Left: ℓD_s invariant mass distribution of $B_s \to \ell D_s X$ candidates of the CDF analysis. K factor distribution for several ℓD_s mass values for semileptonic and partially reconstructed hadronic decays.

D0 studies exploits their excellent muon coverage and analyses a large sample of semi-muonic decays. About 27.000 $B_s \to \mu D_s(\phi\pi)X$, 12.600 $B_s \to \mu D_s(K^*K)X$ and 2.000 $B_s \to e D_s(\phi\pi)X$ candidates are analyzed. In order to get a handle on fully reconstructed candidates it is planed to use events triggered with a single muon as opposite-side tag and search for fully reconstructed B_s candidates on the non-trigger side.

3.2 Decay Length Resolution

One of the critical input to the analysis is the proper decay time resolution. It is the limiting factor of the sensitivity of the signal at large Δm_s values. For setting a limit a too optimistic proper decay time resolution estimate could potentially lead to the exclusion of Δm_s regions we are actually not sensitive to. Therefore σ_{ct} has been measured directly on data. CDF exploits prompt D decays plus tracks from the primary vertex to mimic all B decay topologies studied in this analysis. On an event-by-event basis, the decay time resolution is predicted, taking into account dependences on several variables, such as isolation, vertex χ^2 etc. D0 uses the negative tail of the lifetime distribution of prompt J/Ψ events to fit for one average σ_{ct} value applied to all events. The mean $< \sigma_{ct} >$ for hadronic events at CDF is 26 μm and for semileptonic events about 45 μm. The semileptonic events used in the D0 analysis have a resolution of a out 50-60 μm. The main difference between the D0

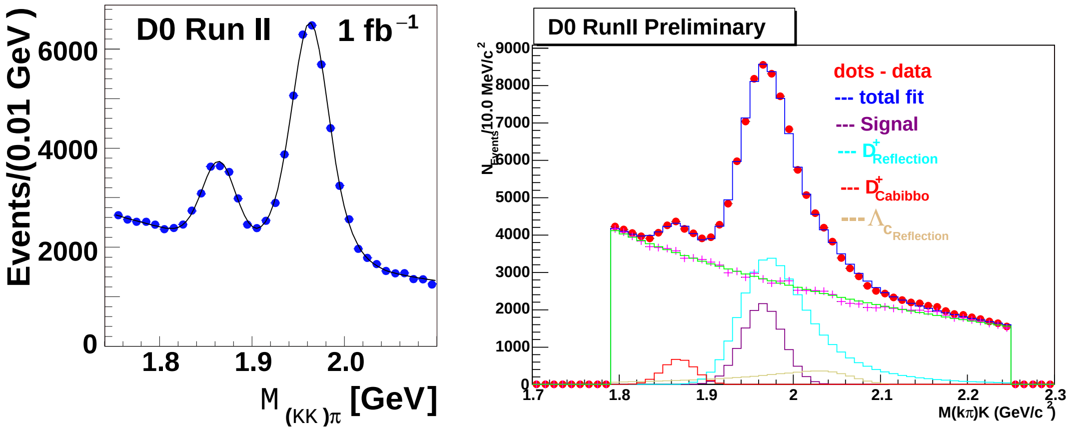

Figure 5: Left: D_s invariant mass distribution of $B_s \to \mu D_s(\phi\pi)X$ candidates of the D0 mixing analysis. Right: D_s invariant mass distribution of $B_s \to \mu D_s(K^*K)X$ candidates of the D0 mixing analysis.

and CDF semileptonic numbers is coming from the additional innermost silicon layer at a distance of about 1.2 cm from the collision point, in the CDF detector. D0 has added a similar layer to their detector recently, which is currently being commissioned. Therefore improvements in the D0 decay length resolution are expected to come soon.

3.3 Flavor Tagging

While the flavor of the B_s candidate at decay time is unambiguously defined by the charges of its daughter tracks, the flavor at production can be inferred, with a certain degree of uncertainty, by flavor tagging algorithms.
Two type of flavor tags can be applied: opposite-side and same-side flavor tags. Opposite-side tags infer the production flavor of the B_s from the decay products of the b hadron produced from the other b quark in the event. Lepton tagging algorithms are based on semileptonic b decays into an electron or muon ($b \to \ell^- X$). The charge of the lepton is thus correlated to the charge of the decaying b hadron. Jet charge tagging algorithms uses the fact that the charge of a b jet is correlated to the charge of the b quark. Kaon tagging are based on the CKM favored quark level decay sequence $b \to c \to s$. The charge of the kaon from opposite-side B decays is correlated to the b flavor. CDF combines this three tagging technics using a Neural Network approach. D0 exploits a combination of jet charge and lepton tags to determine the B_s production flavor. The performance of the opposite-side flavor tagging algorithm is measured in kinematically similar B_d and B^+ samples. The following Δm_d values have been found,

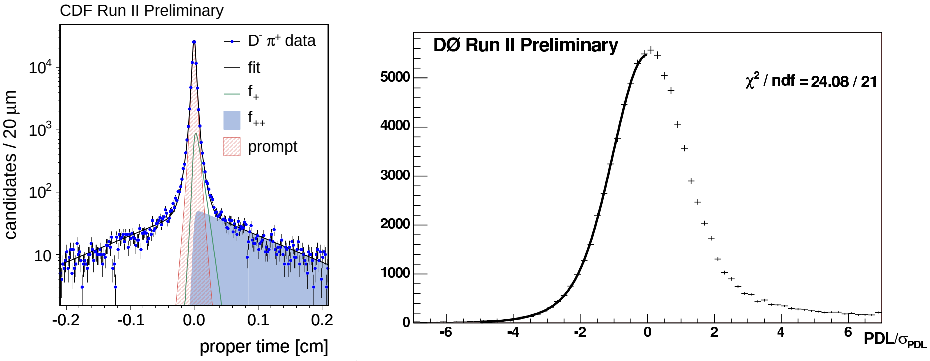

Figure 6: Left: CDF fits for vertex resolution of prompt charm decays to determine decay time resolution of B_s candidates.Right: D0 studies the negative side of the prompt J/Ψ decay time resolution.

$$\Delta m_d^{D0} = 0.506 \pm 0.020 \text{ (stat.)} \pm 0.016 \text{ (syst.) ps}^{-1} \quad (12)$$

$$\Delta m_d^{CDF} = 0.509 \pm 0.010 \text{ (stat.)} \pm 0.016 \text{ (syst.) ps}^{-1}, \quad (13)$$

which agree well with the world average [5].
CDF yields a combined opposite-side tagging performance of $\epsilon\mathcal{D}^2 = 1.8\%$. Mainly due to its excellent muon detector system, D0 yields a higher performance of $\epsilon\mathcal{D}^2 = 2.5\%$. Those values have to be compared to ϵD^2 of about 30% at the B factories. B flavor tagging in an hadronic environment is one of the main challenges of the Δm_s analysis. Same-side flavor tags are based on the charges of associated particles produced in the fragmentation of the b quark that produces the reconstructed B_s. Contrary to the opposite-side tagging algorithms, the performance of this tagging algorithm can not be calibrated on B_d and B^+ data, but we have to rely on Monte Carlo samples until a significant B_s mixing signal has been established.
CDF uses Neural Network technics to combined kaon particle-identification variables from dE/dx measurements in the drift-chamber and time-of-flight measurements with kinematic quantities of the kaon candidate into a single tagging variable. Tracks close in phase space to the B_s candidate are considered as same-side kaon tag candidates, and the track with the largest value of the tagging variable is selected as the tagging track. We predict the dilution of the same-side tag using simulated data samples generated with the PYTHIA [11] Monte Carlo program. Control samples of B^+ and B_d are used to validate the predictions of the simulation. The tagging power of this flavor tag is $\epsilon D^2 = 3.7/4.8\%$ for hadronic and semileptonic samples respectively. The same-side tags enlarges the CDF tagging power by a factor of 3-4. This was one of the key ingredients which pushed the analysis towards the observation of Δm_s. If both a same-side tag and an opposite-side tag are present, we combine the information from

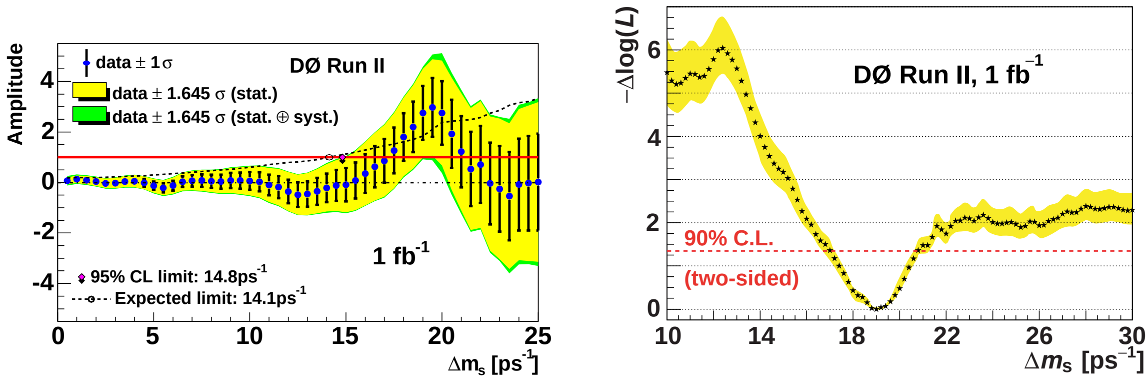

Figure 7: Left: Amplitude scan of $B_s \to \mu \mathcal{D}_s X$ candidates from D0. Right: $-\Delta \log \mathcal{L}$ distribution. The minimum is around 19 ps^{-1}, the two sided 90% C.L. is displayed.

both tags assuming they are independent.

3.4 Fit and Results

An unbinned maximum likelihood fit is utilized to search for $B_s - \overline{B_s}$ oscillations. The likelihood combines mass, proper decay time, proper decay time resolution and flavor tagging information for each candidate. Separate probability density functions are used to describe signal and each type of background. The amplitude scan method [12] was used to search for oscillations. The likelihood term describing the proper decay time of tagged B_s meson candidates in Eq. 7 is modified by introducing the amplitude $\mathcal{A}$:

$$\mathcal{L} \sim 1 \pm \mathcal{A} D \cos(\Delta m t). \quad (14)$$

Then, a scan in Δm is performed by fitting $\mathcal{A}$ for fixed values of Δm. The dilution $\mathcal{D}$ is fixed to the value obtained by the calibration process. This procedure corresponds to a Fourier transformation of the proper time space into the frequency space. In the case of infinite statistics and perfect resolution, it is expected to find $\mathcal{A} = 1$ for the true value of Δm and $\mathcal{A} = 0$ otherwise. In practice, the procedure consists in recording $(\mathcal{A}, \sigma_{\mathcal{A}})$ for each Δm hypothesis. A particular value of Δm is excluded at 95% C.L. if $\mathcal{A} + 1.645\ \sigma_{\mathcal{A}} < 1$ holds. The sensitivity of a mixing analysis is defined as the lowest Δm value for which 1.645 $\sigma_{\mathcal{A}}$ =1.

D0 Δm_s Results

The amplitude scan for the analysis of the semi-muonic $B_s \to D_s(\phi\pi)$ candidates is shown in Fig 7. The sensitivity is 14.1 ps^{-1}, the lower 95 % C.L. is 14.8 ps^{-1}. Around Δm_s = 19.0 ps^{-1} the amplitude $\mathcal{A}$ is consistent with 1 but not with 0. To assess the significance of this deviation, the negative logarithm of the ratio of the likelihood function for $\mathcal{A} = 1$ (mixing hypothesis) and $\mathcal{A} = 0$ (no-mixing hypothesis) was utilized ($\Lambda = -\log(\mathcal{L})$). D0 placed the first double sided limit on the mixing frequency of $17 < \Delta m_s < 21$ ps^{-1}. Toy Monte Carlo studies determined the probability to find a minimum that deep in the Λ distribution in the Δm_s range 17-21 ps^{-1} for a no-mixing sample. It is found to be 5%. A preliminary update of this analysis including as well $B_s \to \mu D_s(K^*K)X$ and $B_s \to e D_s(\phi\pi)X$ candidates was not able to confirm this result.

CDF Δm_s Results

The amplitude scans for the analysis of the hadronic and semileptonic B_s candidates and the combined result are shown separately in Fig 8. The combined sensitivity is 31.3 ps^{-1}. The value of the amplitude is consistent with unity around $\Delta m_s = 17.75$ ps^{-1}, where $\mathcal{A} = 1.21 \pm 0.20$. For all other Δm_s values, the amplitude is always consistent with zero (Fig. 8). The minimum likelihood ratio Λ is at $\Delta m_s = 17.77$ ps^{-1} and has a value of -17.26. The significance of the signal in the amplitude is the probability that randomly tagged data would produce a value of Λ lower than -17.26 at any value of Δm_s. Only 28 out of 350 million generated toy experiments yielded a Λ value lower than that. This results in a p-value of 8×10^{-8}, which corresponds to a 5.4 σ signal. The fit for Δm_s, with $\mathcal{A}$ fixed to unity, finds

$$\Delta m_s = 17.77 \ \pm \ 0.10 \text{ (stat.)} \ \pm \ 0.07 \text{ (syst) ps}^{-1}. \tag{15}$$

The dominant contributions to the systematic uncertainties comes from uncertainties on the absolute scale of the decay-time measurement.
The $B_s - \overline{B_s}$ oscillations are displayed in Fig. 9. Candidates in the hadronic sample are collected in five bins of proper decay time modulo $2\pi/\Delta m_s$. In each bin, a fit for $\mathcal{A}$ is performed and the result is plotted. The curve corresponds to a cosine wave with amplitude equal to 1.28, which is the fitted value in the hadronic sample. Data are well represented by the curve.

4 Summary

Both D0 and CDF have measured the width difference $\Delta\Gamma_s$ between the light and heavy B_s mass eigenstates, which in the limit of no CP violation, coincide with the CP even and CP odd eigenstates of the B_s system. A non-zero value of $\Delta\Gamma_s$ has been found. Additionally D0 has performed a simultaneous fit to $\Delta\Gamma_s$ and the CP violating phase ϕ_s. For the time being the result of the ϕ_s is completely dominated by statistical uncertainties and well consistent with the SM. Given the amount of data,

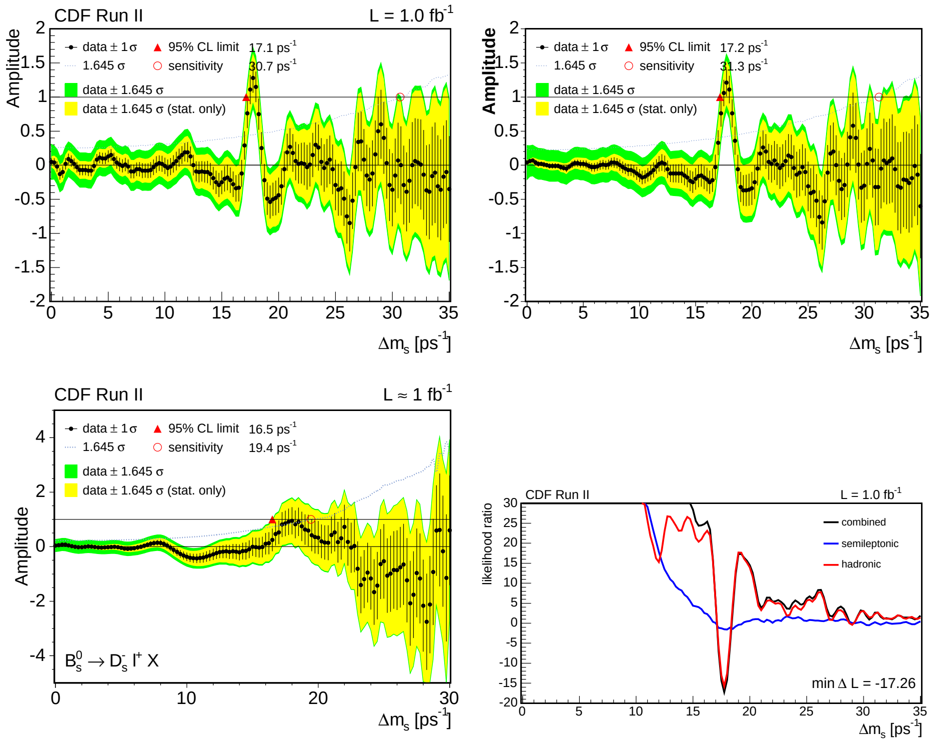

Figure 8: Left + top right: Amplitude scan of CDF hadronic and semileptonic modes separately and combined. While the semileptonic scan dominates at small Δm_s values due to its large static, the hadronic one takes over at large Δm_s values due to the better decay time resolution. Bottom right: Likelihood ration Λ distribution for combined CDF result.

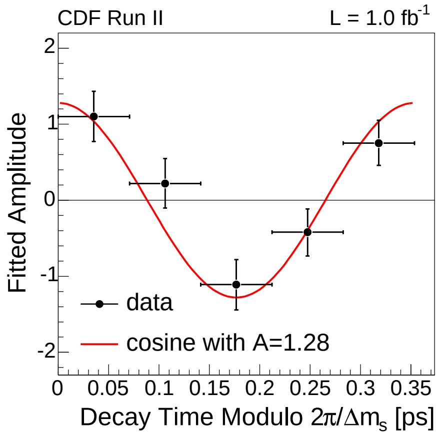

Figure 9: The CDF $B_s - \overline{B_s}$ oscillation signal (only hadronic decays) measured in five bins of proper decay time modulo the measured oscillation period $2\pi/\Delta m_s$. The curve shown is a cosine with an amplitude of 1.28, which corresponds to the observed value in the amplitude scan for the hadronic sample at $\Delta m_s = 17.77$ ps^{-1}. This plot does not represent the full statistic of the presented analysis.

expected to be collected in the next two years at the Tevatron, this analysis has the potential of being an interesting test of the SM and/or a window to New Physics.
D0 has performed a study of $B_s - \overline{B_s}$ oscillations using $B_s \to \mu^+ D_s^-(\phi\pi)X$ decays and opposite-side flavor tagging algorithms. The expected limit at 95% C.L. is 14.1 ps^{-1}. Assuming Gaussian uncertainties, a 90 % C.L. interval of $17 < \Delta m_s < 21$ ps^{-1} is set. A preliminary analysis on the same dataset including as well $B_s \to \mu^+ D_s^-(K^* K^+)X$ and $B_s \to e D_s(\phi\pi)X$ decays was not able to confirm this result.
CDF has searched for B_s flavor oscillations using hadronic and semileptonic decays. Opposite-side and for the first time at a hadron collider, same-side tags provide information about the B_s production flavor. A significant peak (probability for background fluctuation $< 8 \times 10^{-8}$) in the amplitude scan consistent with unity is observed. CDF measures the oscillating frequency to be

$$\Delta m_s = 17.77 \pm 0.10 \text{ (stat.)} \pm 0.07 \text{ (syst.) ps}^{-1} \tag{16}$$

The $B_s - \overline{B_s}$ oscillation frequency is used to derive the ratio of $|V_{td}/V_{ts}|$,

$$|\frac{V_{td}}{V_{ts}}| = \xi\sqrt{\frac{\Delta m_d M_{B_s}}{\Delta m_s M_{B_d}}} = 0.2061 \pm 0.0007 \text{ (exp.)} \ ^{+0.0081}_{-0.0060} \text{ (theo.)}, \tag{17}$$

where the following values have been used as inputs: $M_{B_d}/M_{B_s} = 0.98390$ [5] with negligible uncertainty, $\Delta m_d = 0.507 \pm 0.005$ ps^{-1} [5] and $\xi = 1.21^{+0.047}_{-0.035}$ [13].

5 Acknowledgments

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