Measurement of B_s oscillations at CDF

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The first precise measurement of the $B_s^0 - \bar{B}_s^0$ oscillation frequency Δm_s with the CDFII experiment is summarized in this talk. The measurement is performed with 1 fb^{-1} of data collected at the Fermilab Tevatron hadron collider. We find a signal consistent with flavour oscillations; the probability that such a signal is originated by random fluctuations is 0.2%. We measure $\Delta m_s = 17.31^{+0.33}_{-0.18}(stat.) \pm 0.07(syst.)ps^{-1}$ [1]. After a brief theoretical overview, I will describe the experimental technique and show the results of the CDF analysis and the $|V_{td}/V_{ts}|$ value we infer from this measurement.

1. Flavour oscillations

Flavour oscillations are a quantum phenomenon in the neutral meson systems. They occur via $\Delta F = 2$ flavour changing weak interactions; in the B meson sector ($b\bar{q}$, with $q = d, s$ for B_d^0, B_s^0) the amplitude of such a process is proportional to the mass difference Δm_q of the Hamiltonian eigenstates $B_{q,H}^0$ and $B_{q,L}^0$

$$\Delta m_q \sim m_{B_q} f_{B_q}^2 B_{B_q} |V_{tq}^* V_{tb}|^2 \tag{1}$$

where m_{B_q} is the meson mass, $f_{B_q}^2 B_{B_q}$ are parameters accounting for the hadron matrix elements; $|V_{tq}^* V_{tb}|$ is the product of the CKM matrix elements accounting for weak coupling of the b and q quark with the t quark essentially. Thus, the measurement of the Δm_q together with the theoretical calculation of the non perturbative parameters produces a constraint on the size of the unitarity triangle (UT) in the B sector. Furthermore, while in the Standard Model (SM) the only relevant coupling of the b quark is with the top quark, other theories beyond the SM, like Supersymmetry, predict the existence of new particles, some of which can interact with the b quark in the mixing phenomenon and contribute to give a Δm_q value away from SM predictions. The mixing frequency Δm_d in the B_d^0 sector is already well known [2]. Since the ratio $\xi = \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}}$ from lattice calculations is known with a better precision than the single factors, a measurement of the ratio $\Delta m_d / \Delta m_s$ is expected, that would produce a corresponding $|V_{td}/V_{ts}|$ measurement with a $\approx$ 4% error. The SM expectation for the frequency is $\Delta m_s \sim 20\ ps^{-1}$ (e.g. $\Delta m_s = 21.5 \pm 2.6\ ps^{-1}$ [3]); that is, the B_s are predicted to oscillate $\sim$ 40 times faster than the B_d.

2. Analysis outlook

The probability density P_+ (P_-) for a B_q^0 meson produced at a proper time $t = 0$ to decay with the same (opposite) flavour at a time t is expressed by

$$P_{\pm}(t) = \frac{\Gamma_q}{2} e^{-\Gamma_q t}[1 \pm cos(\Delta m_q t)] \tag{2}$$

Γ_q being the decay width of the two mass eigenstates. From this Probability Density Function (PDF) we extract the value of Δm_s in the B_s system using the method of maximum likelihood. We use 1 fb^{-1} of data collected by the CDF II detector in $p - \bar{p}$ collisions at $\sqrt{s} = 1.96\ TeV$ at the Fermilab Tevatron collider.
In order to perform a likelihood based fit in the proper time domain, we:

- reconstruct the B_s final states in hadronic ($\bar{B}_s^0 \to D_s^+ \pi^-, D_s^+ \pi^- \pi^+ \pi^-$) and semilep-

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tonic ($\bar{B}_s^0 \rightarrow D_s^{+(*)}\ell^-\bar{\nu}_\ell, \ell = e, \mu$) decay channels into charged particles only;

- calculate the proper decay time of each B_s from the distance of the production and decay vertices in the transverse plane, the reconstructed momentum and the meson mass $m(B_s) = 5.3696\ GeV/c^2$ [2];
- determine whether the meson contained a b or $\bar{b}$ quark when it was produced, using both the correlation of the flavour with the leading products of the fragmentation that originated the B_s and the flavour of the other b created.

The hadronic and semileptonic modes are complementary since while the first have a better proper-time resolution and thus provide us with a better sensitivity to rapid oscillations, the semileptonic sample is $\approx$ 10 times larger; their decay-time resolution is worsened due to the unmeasured ν momentum.

3. Final state selection

Both hadronic and semileptonic decay modes are selected using a dedicated 3-level trigger based on the Silicon Vertex Trigger: this exploits the kinematics of charm and bottom hadron decays and their feature to be long-lived particles. In particular, the main requirements are to have 2 tracks of opposite electric charge and an impact parameter $120\ \mu m \le |d_0| \le 1000\ \mu m$; together with that, both are required to have $p_t \ge 2.0\ GeV/c$ and $p_{t,1} + p_{t,2} \ge 5.5\ GeV/c$. We reconstruct several D_s final states: $D_s^+ \rightarrow \phi\pi^+, K^*(892)^0 K^+, \pi^+\pi^-\pi^+$, where the resonances decay as $\phi \rightarrow K^+K^-$ and $K^*(892)^0 \rightarrow K^+\pi^-$ respectively. They are also required to be compatible with the known mass and width values [2]. The resulting D_s mesons are then associated with other tracks to form $D_s^+\ell^-$, $D_s^+\pi^-$ and $D_s^+\pi^-\pi^+\pi^-$; a spatial constraint is introduced for them plus any other tracks associated to the B_s to originate from the same 3-D decay vertex. In the semileptonic case, muons and electrons are identified via a likelihood using muon chamber and electromagnetic calorimeter information.

3.1. Hadronic decays

A final yield of $\approx$ 3600 hadronic signal events is selected for the mixing analysis. An example distribution of the $B_s^0 \rightarrow D_s^-(\phi\pi^-)\pi^+$ is showed in fig.1. To remove contributions from partially reconstructed decays we require that the decay candidate have $M > 5.3\ GeV/c^2$. Candidates with $M > 5.5\, GeV/c^2$ are used to build PDF's for combinatorial background. The "shoulder" at lower mass values is mainly produced by decays of the kind $\bar{B}_s^0 \rightarrow D_s^{*+}(D_s^+\gamma)\pi^-$ or $\bar{B}_s^0 \rightarrow D_s^+\rho^-(\pi^-\pi^0)$, where the neutral particles have not been detected. CDF is presently working to include these modes in the mixing framework.

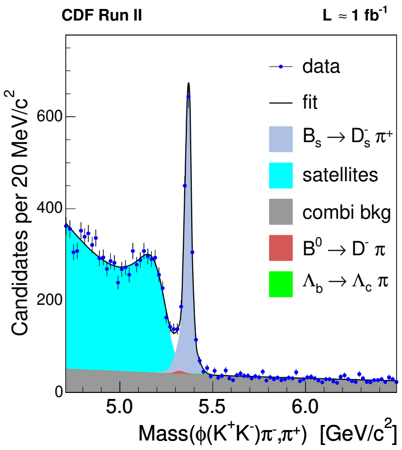

Figure 1. Invariant mass distribution of the $B_s^0 \rightarrow D_s^-(\phi\pi^-)\pi^+$ decay.

3.2. Semileptonic decays

A total of $\approx$ 37000 semileptonic B_s events have been selected. Due to the unmeasured momentum from neutral particles, no B_s mass can be reconstructed. Nevertheless, we see that the combined use of the D_s mass and the ℓD_s mass ($m(\ell D_s)$) is effective in rejecting most of the various sources of background present, among which the association of a signal D_s and a fake lepton coming from the primary vertex and the decays of the kind $\bar{B}_s^0 \to X D_s D(\to \ell \nu Y)$. The ℓD_s mass plot is showed in fig.2.

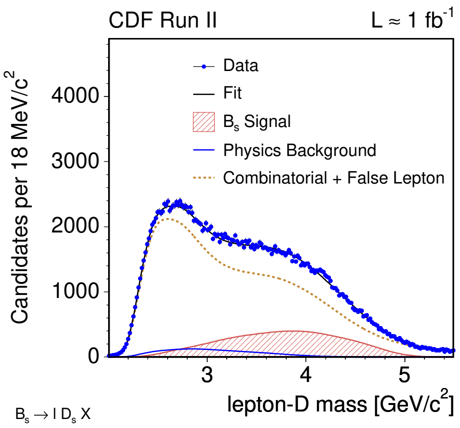

Figure 2. Mass distribution $\ell + D_s$.

4. Proper time determination

The decay time in the B_s rest frame is given by

$$t = k \times [L_T \ m(B_s)/p_T] \tag{3}$$

where L_T is the proper decay length of the B_s meson in the transverse plane; the factor k accounts for missing momentum in the semileptonic decays (that is, it is 1 for fully reconstructed events). The trigger lower cuts on the impact parameter and other proper decay time cuts introduce a bias on the proper time distribution. To correct for this and obtain an unbiased determination of the proper decay time of our B_s, a detailed simulation of the trigger and detector effects is performed. The parameterization of the trigger efficiency is then validated by performing a lifetime measurement of the various B mesons accordingly. The results are reported in tab.1. The associated systematic uncertainty is found to be negligible for mixing measurements.

4.1. Proper time resolution

The estimate of the decay-time resolution $\sigma(ct_i)$ is performed for each event starting from the measured track parameters and the relative uncertainties. We also calibrate such estimate on a large D^+ data sample combined with one or three prompt tracks to mimic the B^0-like decay topologies.
In the case of the fully reconstructed decays, the uncertainty on the absolute time scale is dominated by the resolution on the position of the primary vertex. In order to improve this contribution, we determine it on an event-by-event basis. The average decay time resolution obtained as such is $<\sigma(ct)>= 25.9\ \mu m$, which corresponds to $\frac{1}{5}$ an oscillation period at the lower limit on Δm_s ($14.5\ ps^{-1}$). Its distribution is showed in fig.3. For semileptonic decays, the distribution

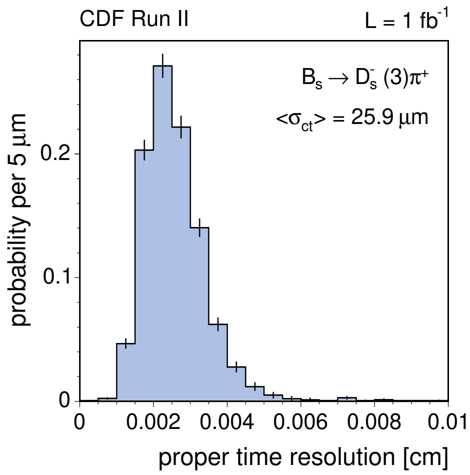

Figure 3. Proper time resolution for the fully reconstructed hadronic decays.

of the k factor is determined from Monte Carlo simulation. The fraction of B momentum carried by undetected particles is a relevant contribution to the final proper-time resolution and cannot be neglected with respect to the one coming from

Table 1
Lifetimes of the B mesons and comparison with the HFAG average values. The HFAG value for the B_s is measured from $B_s \to$ flavour specific modes only.

Decay mode	CDF $c\tau, \mu m$	HFAG $c\tau, \mu m$
$B^0_d \to D^- \pi^+$	452.1 ± 5.1 (stat.)	458.7 ± 2.7 (stat.)
$B^- \to D^0 \pi^-$	491.1 ± 5.1 (stat.)	491.1 ± 3.3 (stat.)
$B^0_s \to D^-_s(3)\pi^+$	461 ± 12 (stat.)	432 ± 20 (stat.)

The HFAG values are given in ref. [4].

vertex determination. To reduce this effect and increase the sensitivity of semileptonic modes to mixing, we determine the k factor distribution as a function of $m(\ell D_s)$.

5. Flavour tagging

The flavour of the B_s at production is determined using both opposite-side and same-side flavour tags. The tagging effectiveness is given by the figure-of-merit εD^2, where ε is the fraction of signal candidates with a tag associated, and $D = 1 - 2w$ the dilution; w is the probability that the tag is incorrect.

The Opposite Side Taggers infer the initial $b-$flavour of the mixing candidates by looking at the decay products of the *other* b produced in the incoherent $b - \bar{b}$ pair production at the Tevatron. We use lepton ($\ell = e, \mu$) charge and jet charge, whose sign is correlated with the flavour of the away b. The leptons are selected using a likelihood technique that exploits the muon detector and the electromagnetic calorimeter. The overall charge of the OS b-jet is calculated by weighting each track in a given cone around the jet axis for their p_t; three different types of jets are considered, according to the degree of displacement from the primary vertex of the jet tracks. The Opposite Side Taggers are combined exclusively such that the higher dilution taggers (lepton taggers) are preferred to the jet charge. The overall Opposite-Side tag dilution is measured on a mixed B^- and B^0_d sample, using a combined mass-lifetime fit that also returns a measurement of Δm_d. We find $\varepsilon D^2 = 1.47 \pm 0.10$ % on hadronic decays and $\varepsilon D^2 = 1.44 \pm 0.04$ % on semileptonic modes.

We also make use of Same-Side tags: those tag the flavour of the candidate B by looking at the charge of the leading product of the fragmentation process that produced the reconstructed B. In particular, a B^0_s ($\bar{B}^0_s$) is likely to be produced close to a K^- (K^+). The main advantage of such an algorithm is the large acceptance to the tagging tracks since they are spatially close to the triggered B. A combined Particle Identification technique is used to separate kaons from other particle species; this uses the specific ionization dE/dx in the COT and the particle's Time-Of-Flight. The track with the largest kaon likelihood is selected to tag the b flavour. Since the dilution depends specifically on the meson type, we cannot measure it using B^0_d and B^+ samples. Thus, we predict the dilution using a simulated sample generated with the `PYTHIA` Monte Carlo [5], after an extensive data-MC comparison of fragmentation-related quantities. Such a prediction is checked on other species and systematic uncertainties on the agreement are evaluated accordingly. We find $\varepsilon D^2 = 3.5 \pm 0.5$ % ($\varepsilon D^2 = 4.0 \pm 0.6$ %) for hadronic (semileptonic) decays.

6. Results

The search for B_s oscillations is performed using an unbinned maximum likelihood fit. The likelihood combines all the above ingredients: mass, decay-time, decay-time resolution and flavour tag for each candidate, distinguishing between the signal and the various types of background assessed for each decay mode. We perform an *amplitude scan* [6] by introducing a term $\mathcal{A}$ in the mixing part of the signal likelihood:

$$\mathcal{L} \sim \frac{1}{\tau} e^{-t/\tau} (1 \pm \mathcal{A} \cdot D \cdot (\Delta m_s t)) \quad (4)$$

and fitting for oscillations while fixing Δm_s at a probe value. $\mathcal{A}$ is expected to be consistent with unity at a given Δm_s if mixing is detected and with 0 elsewhere. The sensitivity is defined as the maximum value of Δm_s where $\mathcal{A} = 1$ is excluded at 95% C.L. if the measured value of $\mathcal{A}$ were 0. Fig.4 shows the result of the combined hadronic and semileptonic scan we perform with the 1 fb^{-1} data sample. CDF has a sensitivity of 25.8 ps^{-1} and exceeds the combined sensitivity of all previous experiments [2]. A value $\mathcal{A} = 1.03 \pm 0.28$ $(stat.)$ is found at $\Delta m_s = 17.3\ ps^{-1}$. The value is 3.7 σ away from 0. The significance of such a peak is evaluated by calculating the quantity $\Lambda = log(\mathcal{L}^{\mathcal{A}=0}/\mathcal{L}^{\mathcal{A}=1})$ for each probe frequency Δm_s. The likelihood ratio is shown again in fig.4. The minimum at $\Delta m_s = 17.3\ ps^{-1}$ has a value $\Lambda = -6.75$. Given this profile, we can evaluate the probability of null hypothesis $p = 0.2\%$, by producing a set of 50000 fits with random tag decision and counting how many times the fit would return a value ≤ -6.75. The p value corresponds to a significance $> 3\sigma$. In order to increase the significance of our measurement on this same set of data we are working toward the inclusion of partially reconstructed hadronic decays and a refinement of the selections of both hadronic and semileptonic decays. Finally, also our flavour tagging system is being enhanced by introducing a Neural Network to combine Opposite-side taggers and enhance Same Side Kaon Tagger; and an Opposite Side Kaon Tagger is now in place, with $\varepsilon D^2 = 0.23 \pm 0.02$ %. From the likelihood itself we measure $\Delta m_s = 17.31^{+0.33}_{-0.18}(stat.) \pm 0.07(syst.) ps^{-1}$, in the signal hypothesis. The only non-negligible systematic uncertainty comes from our knowledge of the absolute decay-time scale. This value agrees with the SM predictions (e.g.[3]) well within 2σ. This can also be translated into an estimate of the contribution of New Physics to the mixing hamiltonian, $C_{B_s} = \frac{\mathcal{H}^{SM+NP}}{\mathcal{H}^{SM}} = 0.97 \pm 0.27$ [3], which is compatible with unity (*SM-only* contributions) with an uncertainty already smaller than for the B_d system. Finally, using the input values $m(B^0)/m(B_s^0) = 0.98390$ [7], $\Delta m_d = 0.505 \pm 0.005$ [2] and $\xi = 1.210^{+0.047}_{-0.035}$ [8], we infer

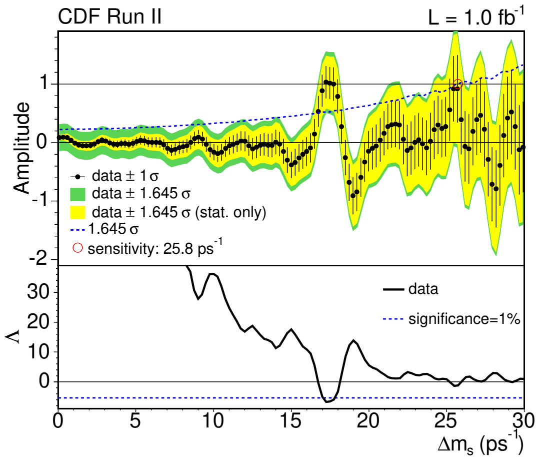

Figure 4. Upper: amplitude scan; the lighter band represents the statistical uncertainty, the darker band the statistical+systematic one. Lower: likelihood ratio profile with the line indicating a 1% null hypothesis probability.

$$|V_{td}/V_{ts}| = 0.208^{+0.001}_{-0.002}(exp.)^{+0.008}_{-0.006}(theo.).$$

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