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Bs Mixing at the Tevatron

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The measurement of the $B_s$mixing oscillation frequency, Δm_s, has been the main goal for both experiments CDF and D0 which are running at the Tevatron collider. With 1 $\text{fb}^{-1}$of data collected during the last four years D0 set a lower and upper limit on this frequency, $17 < \Delta m_s < 21$ ps^{-1}. CDF measured Δm_s with a precision better than 2% and the probability that the data could randomly fluctuate to mimic such a signature is 0.2%

1. Introduction

The Tevatron collider at Fermilab, operating at $\sqrt{1.96}$ TeV is a good B meson physics laboratory, where the properties of these particles can be studied with high precision thanks to the high b production cross section and the presence of all b-hadrons species. The usage of specialized triggers based on leptons or tracks significantly displaced from primary vertex [1] allows the selection of one B meson event out of 1000 QCD events. Both CDF and D0 are multipurpose 4π coverage detectors [2,3] featuring with high resolution tracking in a magnetic field, which is one of the key element for the mixing measurement as it will be discussed later.

Particle-antiparticle oscillation is described in the Standard Model [4] by Δm and $\Delta\Gamma$, mass and lifetime difference of the two mass eigenstates, B_q^H and B_q^L. In the B_d system Δm_d is measured to be $\Delta m_d = (0.505 \pm 0.005)$ ps^{-1} [5] while in the B_s system the world average limit is $\Delta m_s > 14.4$ ps^{-1} [5], which makes the measurement really challenging.

Experimentally the oscillation manifest itself in an asymmetry which depends on the time:

$$A(t) = \frac{N_{unmix}(t) - N_{mix}(t)}{N_{unmix}(t) + N_{mix}(t)} = cos\Delta m_s t \qquad (1)$$

In practice, it is necessary to identify the B meson flavor at the production and decay time and to determine the proper time at which the decay occurred to separate mixed from unmixed events as function of proper time. The B meson flavor at the decay time is obtained by exclusive reconstruction of final state. Large B_s samples with a good signal-to-noise ratio are needed to be sensitive to high mixing frequency.

The proper decay time, $t = L_T m_B / p_T c$, obtained from the transverse decay length L_T and the transverse momentum , p_T, has to be determined with high resolution in order to resolve high mixing frequencies. This implies an high precision tracking detector to measure the decay length and magnetic filed to evaluate the momentum.

The b flavor at the production time is evaluated with the so-called flavor tagging, which has a probability $\mathcal{P}_{tag}$ to tag correctly the b flavor, giving a dilution, $\mathcal{D} = 2\mathcal{P}_{tag}$- 1. This reduce the measured asymmetry:

$$A^{meas}(t) = \mathcal{D}A(t) = \mathcal{D}cos\Delta m_s t \qquad (2)$$

and for this reason many efforts have been put in optimizing algorithms to achieve the highest $\mathcal{D}$.

The analysis will proceed through the following steps:

- Reconstruct the B_s decays;
- Measure the proper decay time;
- Identify the b flavor at the production time.

2. B_s decay modes reconstructions

CDF exploits its trigger on tracks significantly displaced from primary vertex [1] to select fully reconstructed and semileptonic B_s decays. In the first case $B_s \to D_s^- \pi^+$ and $B_s \to D_s^- \pi^+ \pi^- \pi^+$ while in the second $B_s \to D_s^- l^+ X$ and in both $D_s^- \to \phi \pi^-$, $D_s^- \to K^{*0} K^-$ and $D_s^- \to \pi^+ \pi^- \pi^-$. Figure 1 shows the invariant mass for fully recon-

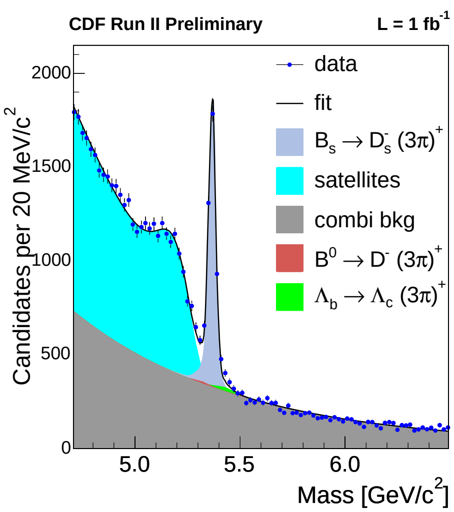

Figure 1. CDF: Invariant Mass for $B_s \to D_s^- \pi^+$ and $B_s \to D_s^- 3\pi^+$. The main signal is shown together with the contribution of partially reconstructed B decays.

structed decay modes, only events with masses greater than 5.3 GeV/c^2 are then used in the final fit in order to remove the contribution of partially reconstructed B while events with masses greater than 5.5 GeV/c^2 are taken to parametrize the combinatorial background contributions. CDF has $3,600$ signal events of hadronic B_s decays and $37,000$ semileptonic B_s decays.

D0 search for $B_s \to \mu^+ D_s^- X$ with $D_s^- \to \phi \pi^-$ in a sample of data collected with the muon trigger. In a cone around the muon a D_s is reconstructed first searching for a $\phi \to K^+ K^-$ and then attaching a pion to it. In figure 2 is shown the invariant mass of the D_s for event that satisfy the reconstruction requirements, corresponding to a total number of $27,000$ events.

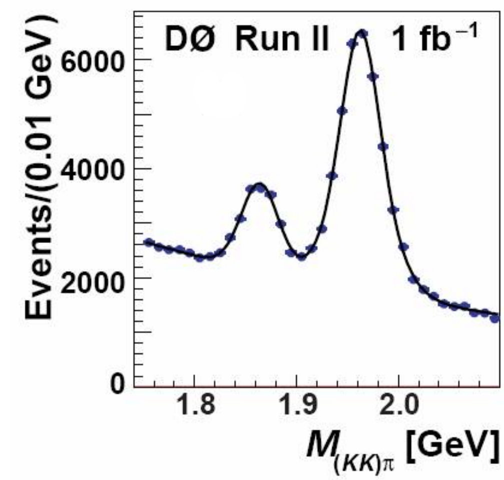

Figure 2. D0: $(K^+K^-)\pi^-$ invariant mass distribution for the untagged sample. The curve is the fit result used to evaluate the number of events.

3. Decay Length Reconstruction and Resolution

The proper decay time

$$t = \frac{L_T m_B}{p_T c}$$

is obtained directly from reconstructed quantities except m_B which is the B meson mass [5]. The transverse decay length, L_T, is defined as the displacement in the transverse plane from the primary event vertex to the reconstructed B meson decay vertex projected onto the B meson transverse momentum, $p_T(B)$. For semileptonic modes the undetected neutrino and other not-reconstructed particles like pions and photons, do not allow a precise determination of the B meson's momentum which is evaluated starting from $p_T(lD_s)$ and then corrected for the effects of the missing particles using $K = p_T(lD_s)/pT(B)$. The correction factor distribution is determined by using a Monte Carlo simulation for each of the decay channels. Both CDF and D0 found that the best correction is obtained when K is applied as function of the lepton-D_s mass which increases the proper time resolution.

The proper time scale is important for the correct determination of the of the oscillation frequency . This is checked looking at the B_s lifetime. Both experiments determined the meson lifetime in the sample used for the mixing analysis finding values compatible with world average. The proper decay time resolution, σ_t, affects the Δm_s sensitivity and, since it is part of the fitting procedure, need to be evaluated using control samples. CDF uses a large sample of D^+ mesons plus one or three charged particles from primary vertex, which mimic the the signal topologies, to measure t/σ_t. The correction is then applied on event-by event basis depending on the decay topology and on several kinematic quantities. For hadronic decays the average decay time resolution is 87 fs as can be seen in figure 3, while for the semileptonic is worse and depends on the proper time. For example at $t = 0$, $\sigma_t = 100$ fs and increases to $\sigma_t = 115$ at $t = 1.5$ ps.

D0 applies and overall correction on the time resolution with a double Gaussian distribution: the narrow Gaussian has width of 0.998σ and comprises 72% of the total and the second Gaussian has a width of 1.775σ where σ is the estimated error on the proper decay time of the candidate. The t/σ_t distribution is determined by using a sample of $J\psi \to \mu^+\mu^-$

4. Flavor tagging

The last component necessary for the mixing frequency measurement is the determination of the B meson flavor at the production time. This can be inferred from the flavor of the other B meson of the event (Opposite Side Taggers) or from the charge of the tracks produced in association with the primary reconstructed B meson (Same Side Tagger). The performance of the b flavor tag may be quantified by the so called tagger effectiveness $Q = \epsilon\mathcal{D}^2$, where ϵ is the efficiency, the fraction of signal candidates with a flavor tag, and $\mathcal{D} = 2\mathcal{P}_{tag} - 1$ is the dilution, with $\mathcal{P}_{tag}$ the probability that the tag is correct.

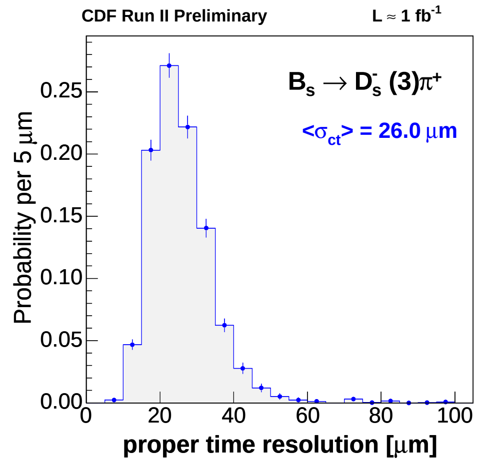

Figure 3. CDF proper time resolution for B_s^0 hadronic decays.

From the formula 2 and from section 5 can be understood that the knowledge of the flavor taggers performance is crucial. If the oscillation signal is evident then $\mathcal{D}$ can be treat as free parameter in the fit, but this can not be done when no signal is present and a limit has to be set. The dilution can be measured on B^0 and B^+ sample for the opposite side taggers but there are non data control samples for the same side tagger and the Monte Carlo, which must reproduce very well the data, is used.

4.1. Opposite Side Taggers

The OST exploit the fact that b quarks in hadron collider are produced in $b\bar{b}$ pairs and the fragmentation of the 2 quarks is expected to be independent. This means that the dilution is independent of the type of the B meson reconstructed on the decay side and can be evaluated in data using large samples of charged B mesons. An intrinsic dilution is expected due to the probability of oscillation between production and decay which depends on the type of the B meson, 0% for $B^{\pm}$,17.5% for B^0 and 50% for B_s^0.

Soft-lepton tagger

The soft lepton tagger is based on the semileptonic b decays into an electron or a muon ($b \to l^- X$), where the charge of the lepton is correlated to the flavor of the B meson. This method has a low efficiency because only 20% of the time the b decays semileptonically in either a muon or an electron. Beside the intrinsic dilution there is an additional source of miss-tag which comes fromthe transition $b \to c \to l^+ X$. Neverthless the dilution is higher with respect to other taggers because of the strong charge correlation.

Jet-charge tagger

The jet charge tagger exploits the fact that the hadronic charge of the B meson is correlated to the charge of the b-jet. Here the main challenge is to define and select the b-jet. Tracks belonging to a displaced vertex or tracks displaced from primary vertex are selected to help identify the b-jet. The efficiency of this method is high because of many tracks in the events but the dilution is low because of the selection of tracks not correlated to the B meson.

An event can be tag by more than one methods and in that case the tags are combined to maximize Q The combined OST effectiveness is $Q = 1.5 \pm 0.1\%$ for CDF and $Q = 2.48 \pm 0.22\%$ for D0 which has a better muon coverage.

4.2. Same Side Tagger

Tracks produced together with the B meson bring information on the fragmentation and it is possible to correlate the charge of these tracks with the B flavor. Basically a π^+ accompanies a B^- and B^0, π^- a B^+ and $\bar{B}^0$ and $K^-(K^+)$ accompanies a $\bar{B}_s^0(B_s^0)$. Hence, the charge of the track which pass the selection requirements and comes from the primary vertex gives the B meson flavor at production time if it is identified as kaon. The final algorithm selects the most likely kaon track using a combined particle identification likelihood based on the information coming from the energy loss in the central tracking chamber, dE/dx, and the time of flight. The performances of the SST can not be evaluated on data since it depends on the signal fragmentation process. CDF did an extensive Pythia Monte Carlo and data comparison to make the simulation reproduce the data and extract the dilution for the Monte Carlo. The average dilution obtained shows a very good agreement in high statistic $B^{\pm}$ and B^0 samples. The overall tagging performance as determined by Monte Carlo is $Q = 3.5\%$ for B_s hadronic decay modes and $Q = 4.0\%$ for the semileptonic ones.

5. Mixing Results

For each event the mass, decay time, decay time resolution and flavor tagging information are combined in a likelihood which is maximized to measure Δm_s. Samples composition is take into account by including terms for all types of signals and backgrounds. Instead fitting directly for Δm_s the "amplitude scan method", described in detail in [6], is used. This allows an easy combination among different measurements. The likelihood term for the signal is modified to include and addition parameter, $\mathcal{A}$, the so-called amplitude:

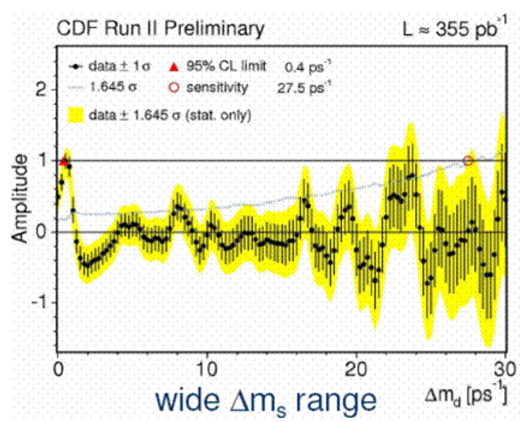

Figure 4. CDF amplitude scan as function of Δm_d in the hadronic decay mode.

$$\mathcal{L} \propto 1 \pm \mathcal{A}\mathcal{D}\cos(\Delta m_s t) \qquad (3)$$

The parameter $\mathcal{A}$ is let free in the fit while $\mathcal{D}$ is supposed to be known and fixed in the scan. The scan is performed as function of Δm_s, i.e. a fit for $\mathcal{A}$ is performed for each value of Δm_s. The parameter $\mathcal{A}$ is expected to be consistent with $\mathcal{A} = 1$ when Δm_s is equal to the true value and consistent $\mathcal{A} = 0$ if Δm_s is far from the true oscillation frequency.

In practice the output of this procedure is a list of ($\mathcal{A}$, $\sigma_{\mathcal{A}}$) for each Δm_s hypothesis. A particular value of Δm_s is exclude at 95% confidence level when $\mathcal{A} + 1.645\sigma_{\mathcal{A}} < 1$ and the sensitivity of a mixing measurement is defined as the lowest Δm_s value for which $1.645\sigma_{\mathcal{A}} = 1$

The plot in figure 4 shows the method applied to the B^0 data for CDF using only opposite side taggers on the same range used for B_s oscillation search.. The amplitude is expected to be one at the frequency $\Delta m_d = 0.5$ ps^{-1} and it is confirmed. This demonstrates that the all the ingredients used for the analysis are well understood and the fitting techniques well tested.

5.1. D0 Results

The D0 amplitude scan performed on 1fb^{-1} of data is shown in figure 5. The sensitivity is

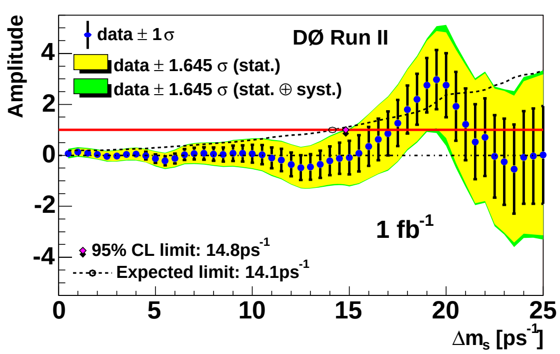

Figure 5. D0 amplitude scan as function of Δm_s. Dashed line shows the sensitivity while the solid line is $\mathcal{A} = 1$

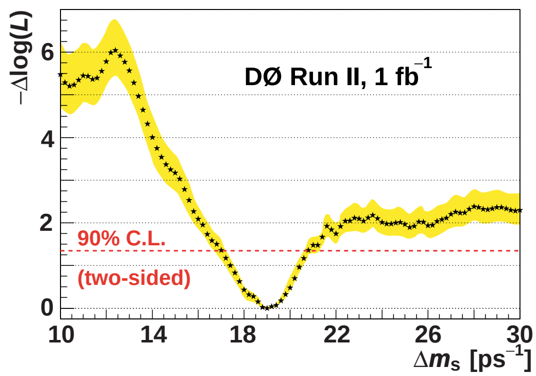

Figure 6. $-\Delta log\mathcal{L}$ as function of Δm_s. Dots represent data without the systematic uncertainties which are included in the shaded bands.

14.1 ps^{-1} and the 95% confidence level limit is $\Delta m_s >$ 14.8 ps^{-1}. At $\Delta m_s =$ 19 ps^{-1} the data deviates from the hypothesis $\mathcal{A} = 0$ ($\mathcal{A} = 1$) by 2.5.(1.6) standard deviations, corresponding to a two-sided confidence level of 1% (10%). Figure 6 shows the ratio of the *log* likelihood, $-\Delta log\mathcal{L}$, at $\mathcal{A} = 0$ and $\mathcal{A} = 1$ as function of Δm_s. If a signal is assumed at Δm_s=19 ps^{-1} a confidence limit interval at 90% can be extracted $17 < \Delta m_s < 21$ ps^{-1}.

5.2. CDF Results

The upper plot of figure 7 shows the CDF amplitude scan as function of Δm_s for the semileptonic and hadronic decay modes combined. The sensitivity is 25.8 ps^{-1}, better than the previous world combined average. [5]. B_s oscillations, i.e $\mathcal{A}$ consistent with unity, $\mathcal{A} = 1.03 \pm 0.28$(stat.) translates to an oscillation frequency Δm_s=17.3 ps^{-1}. At this value the amplitude is inconsistent with zero $\mathcal{A}/\sigma_{\mathcal{A}} = 3.7$. The significance of the signal is evaluated from Λ, the logarithm of the ratio of likelihoods in case of signal ($\mathcal{A} = 1$) at each given Δm_s and in case of no signal, ($\mathcal{A} = 0$) which is equivalent to having data with random flavor tags. Figure 7 (lower) shows Λ as function of Δm_s, where a minimum at Δm_s=17.3 ps^{-1} with value $\Lambda = -6.75$ is evident. The probability

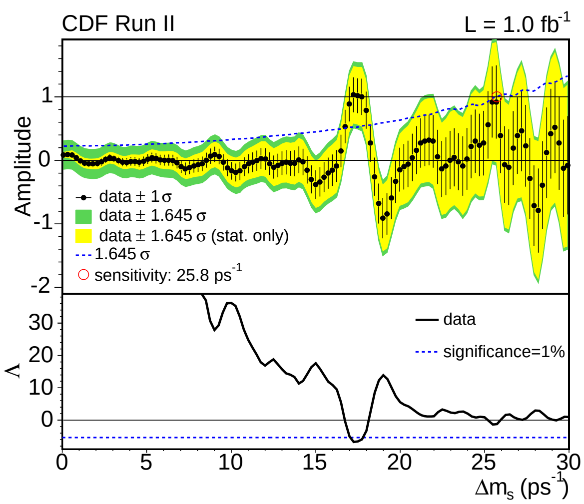

Figure 7. (Upper) Amplitude scan as function of Δm_s. Dots are data point and the dashed line shows the sensitivity. (Lower) Λ as function of Δm_s. The dashed line indicates the value of Λ that corresponds to a probability of 1% in case of no signal.

that the background fluctuated to produce a value of Λ lower than that is evaluated using a sample of data with random flavor tag and is 0.2%.

The oscillation mixing frequency is found fixing $\mathcal{A} = 1$ and fitting the data for Δm_s. The result is:

$$\Delta m_s = 17.31^{+0.33}_{-0.18}(stat.) \pm 0.07(syst.)ps^{-1}.$$

The 90% C.L. limit is $17.01 < \Delta m_s < 17.84$ ps^{-1}. The systematic uncertainties do not affect substantially the measurement except for the the absolute scale on the decay time which has been checked carefully as discussed before.

The measured oscillation frequency can be used to evaluate

$$\left|\frac{V_{td}}{V_{ts}}\right| = \xi\sqrt{\frac{\Delta m_d}{\Delta m_s}\frac{m_{B^0_s}}{m_{B^0}}}$$

The input values are: $m_{B^0_s}/m_{B^0} = 0.98390$[7] with negligible uncertainty, $\Delta m_d = 0.505 \pm 0.005$ ps^{-1} [5] and $\xi = 1.21^{+0.047}_{-0.035}$[8], which give

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

6. Conclusion

The two experiments currently running at the Tevatron collider have analyzed 1 fb^{-1} of data searching for $B^0_s - \bar{B}^0_s$ oscillations. D0 using a sample of $B^0_s \to \mu^+ D_s X$ decays with the production flavor tagged with opposite side method sets a limit $17 < \Delta m_s < 21$ ps^{-1} at 90% C.L.

CDF has used semileptonic and hadronic B^0_s decays with opposite side and same side flavor tagging to measure

$$\Delta m_s = 17.31^{+0.33}_{-18}(stat.) \pm 0.07(syst.)ps^{-1}$$

which allows to infer

$$\left|\frac{V_{td}}{V_{ts}}\right| = \xi\sqrt{\frac{\Delta m_d}{\Delta m_s}\frac{m_{B^0_s}}{m_{B^0}}} = 0.208^{+0.001}_{-0.002}(exp.)^{+0.008}_{-0.006}(theo.)$$

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