Prospects for B_s Mixing at CDF II

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The measurement of B_s mixing is one of the flagship analyses for the Tevatron Run II B physics program. The sensitivity of the measurement of the B_s oscillation frequency stronlgy depends on the tagging power and the number of reconstructed B_s mesons. The first samples of B_s mesons are available now. They are used to measure relative branching ratios, to understand the present yields and to give extrapolations for the B_s mixing sensitivity, which are presented here.

1 Introduction

After a 5 year shutdown with a major detector and accelerator upgrade, CDF restarted data taking in March 2001. Several detector systems have been replaced, such as the extended silicon vertex detector, consisting of 7-8 double-sided layers of silicon, the drift chamber and the forward calorimeters. A Time-of-Flight system (TOF), which is essential for particle identification and therefore very important for B physics, has been added. In addition to the upgraded detector devices, CDF II has a completely new trigger and data aquisition system. For the first time in an hadronic environment it has been possible to trigger on tracks with a large impact parameter at the hardware level (Secondary Vertex Trigger (SVT), fig. 1), and therefore to enrich the rate of events with displaced vertices, which is especially interesting for B physics (fig. 2).

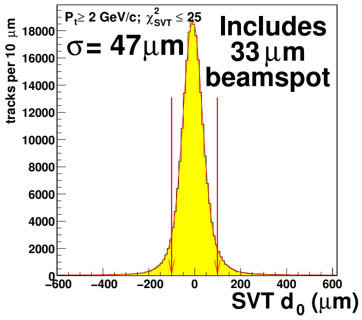

Fig. 1. Impact paramter resolution of the secondary vertex trigger.

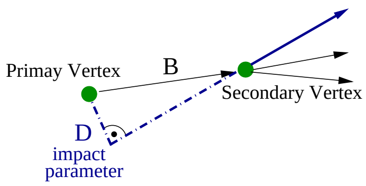

Fig. 2. Sketch of the impact parameter of tracks from secondary vertices.

Unlike the B factories, B harons produced at the Tevatron are not limited to B^+ and B^0, but also include heavier species such as, for example, the B_s meson. Thus the Tevatron experiments are currently the only ones which are able to produce and collect B_s mesons in order to measure the B_s mixing frequency, which is one of the most important measurements to probe the Standard Model.

2 B_s Mixing

The dominant Feynmann diagrams describing the mixing processes are shown in fig. 3. The probability that a B_s meson decays at proper time t and has or has not already mixed to the $\bar{B}_s$ state is given by:

$$P_{unmix}(t) = \frac{1}{2}(1 + \cos \Delta m_s t) \tag{1}$$

$$P_{mix}(t) = \frac{1}{2}(1 - \cos \Delta m_s t) \tag{2}$$

where the mixing frequency, Δm_s, is the mass difference between the heavy and the light mass eigenstate. The canonical B_s mixing analysis, in which oscillations are observed and the mixing fequency, Δm_s, is measured, proceeds as follows. The B_s meson flavour at the time of its decay is determined by exclusive reconstruction of the final state. The proper time, $t = m_{B_s} L/pc$, at which the decay ocurred is determined by measuring the decay length, L, and the B_s momentum, p. Finally the prodcution flavour must be tagged in order to classify the decay as being mixed or unmixed at the time of its decay.
Oscillation manifests itself in a time dependence of, for example, the mixed asymmetry:

$$A_{mix}(t) = \frac{N_{mixed}(t) - N_{unmixed}(t)}{N_{mixed}(t) + N_{unmixed}(t)} = -\cos \Delta m_s t \tag{3}$$

In practice, the production flavour will be correctly tagged with a probability P_{tag} which is significantly smaller than one but larger than one half (which corresponds to a random tag). The measured mixing asymmetry in terms of dilution, D, is

$$A_{mix}^{meas}(t) = DA_{mix} = -D \cos \Delta m_s t \tag{4}$$

where $D = 2P_{tag} - 1$. The mixing frequency is then determined by fitting the measured asymmetry to a function of this form.

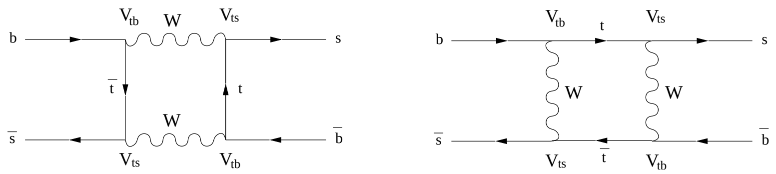

Fig. 3. Feynman diagrams for dominant B_s mixing processes.

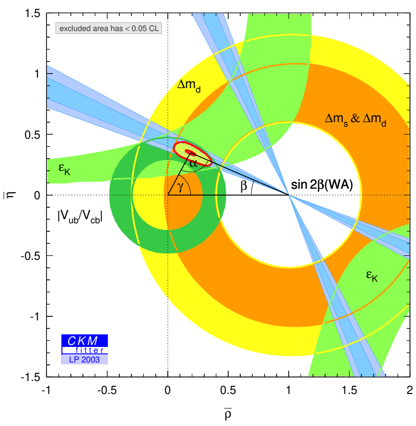

Fig. 4. Fit of the CKM unitarity triangle including all existing measurements. The measurement of Δm_s will shrink the size of the orange circle (centered at (1,0))[1]

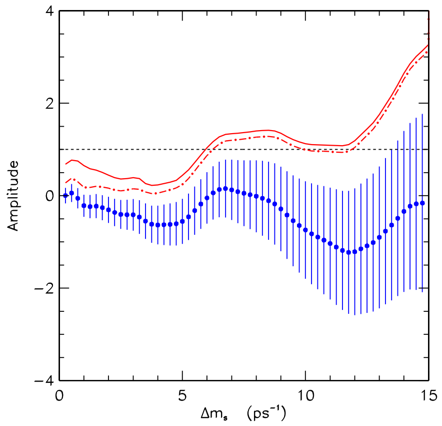

Fig. 5. CDF Run I B_s mixing result, the limit is $\Delta m_s \leq 6.3$ ps^{-1} @ 95 % CL.

The ratio $\frac{\Delta m_s}{\Delta m_d}$, where m_d is the already measured mass difference of the B_d system, is proportional to $|\frac{V_{ts}}{V_{td}}|^2$, which corresponds to the length of one of the sides of the CKM triangle (fig. 4). The advantage of taking the ratio of the mass differences is, that a lot of uncertainties cancel out, in particular those based on hard to calculate hadronic matrix elements. Thus this measurement is a crucial precession test of the unitarity of the CKM triangle an therfore of the Standard Model.
The current world average for the mass difference Δm_s is 14.4 ps^{-1} @ 95 % CL, which is a combination of 13 measurements form LEP, SLD and CDF I [2]. The best CDF Run I limit was based on the diplepton triger dataset, where semileptonic B_s events have been reconstructed and the second trigger lepton was used for the opposite side flavour tag. This resulted in a limit of $\Delta m_s \leq 6.3$ ps^{-1} @ 95 % CL [3] (fig.5).

3 B_s Mixing Sensitivity

The mixing frequency can be determined by calculating, for example, a likelihood function derived from the measured and expected asymmeteries and maximizing this function with respect to Δm_s. The significance of an observation of mixing is quantified in terms of the height of the maximum compared with the second highest maximum or some asymptotic value at large Δm_s. To a good approximation, the *average* significance is give as [4]:

$$\mathrm{Sig}(\Delta m_s) = \sqrt{\frac{(S+B)\epsilon D^2}{2}} e^{(\Delta m_s \sigma_t)^2/2} \sqrt{\frac{S}{S+B}} \tag{5}$$

where S/B is the singal-to-noise backround rato, ϵ is the efficiency for applying the flavour tag with associated dilution, D. σ_t is the average resolution with which the proper time is measured and it is a sum of the spatial resolution of the vertex detector and the product of the momentum resolution and the proper decay time:

$$\sigma_\tau = \frac{\sigma_{L_x y}}{c\gamma\beta} \oplus \frac{\sigma_{\gamma\beta}}{\gamma\beta} * \tau \tag{6}$$

where $\tau = \frac{L_{xy}}{c\gamma\beta}$ and $\gamma\beta = \frac{p_T(B_s}{M(B_s)}$. For fully reconstructed modes the momentum resolution is negligible (≈ 0.5 %) but for semileptonic modes it is of the order of 15 % due to the missing momentum from the neutrino.

4 Flavour Tagging Algorithms

There are two different kinds of flavour tagging algorithms, opposite side (OST) and same side tagging (SST), which are illustrated in fig. 6. OST algorithms use the fact that b quarks are always produced in $b\bar{b}$ pairs, therefore the flavour of the second (opposite side) b can be used to determine the flavour of the b quark on the signal side.

Jet-Charge-Tagging:
The weighted average charge of an opposite side b-jet is calcuted via

$$Q_{jet} = \frac{\sum_i q_i(\vec{p_i}\vec{a_i})}{\sum_i \vec{p_i}\vec{a_i}} \tag{7}$$

where i sums over all tracks in the jet, q_i is the charge of track i, $\vec{p_i}$ its momentum and $\vec{a_i}$ the jet axis. The sign of Q_{jet} is thus correlated to the sign of the charge of the opposite b at production time.

Soft-Lepton-Tagging:
In 20 % of cases the opposite b decays semileptonically either into an electron or a muon ($b \to l^- X$). The charge of the lepton is correlated to the charge of the deacying B meson. Depending on the type of the B meson there is a certain probability of oscillation between production and decay (0 % for $B^\pm$, 17.5 % for B^0 and 50 % for B_s). Therefore this tagging algorithm already contains an intrinsic dilution. Another potential source of miss-tag is the transition of the b quark into a c quark which then forms a D meson and subsequently decays semileptonically ($\bar{b} \to \bar{c} \to l^- X$). Due to the different decay length and momentum distribution of B and D meson decays this source of miss-tag can mostly be eliminated.

Kaon-Tagging:
Due to the transition chain $b \to c \to s$ it is more likely that a $\bar{B}$ meson contains a K^- than a K^+ in the final state. Therefore a K^- on the opposite side is a hint, that there was a $\bar{b}$ quark on the signal side. This tagging algorithm heavily relies on the kaon identification power of the TOF. It contains also an intrinsic dilution due to possible oscillation.

Same-Side-Tagging:
During fragmentation and the formation of the B_s meson there is a left over $\bar{s}$ quark which is likely to form a K^+ (fig. 6). So if there is a near by highly energetic charged particle, which is additionally identified as a kaon, it is quite likely that it is the leading fragmentation track and its charge is then correlated to the flavour of the B meson.

The previous estimates for the tagging power for B_s mixing was $\epsilon D^2 = 11.3$ % (for all tagging algorithms together) [4]. Although the TOF is working well (7), its efficiency is lower than expected and there are still problems with reconstruction due to large tails in the timing distribution. The kaon identification power will probably not be as good as hoped for, which has a significant impact on the same-side and opposite-side kaon tagging algorithms and therefore on the total ϵD^2 estimate. First measurements of the tagging power result in $\epsilon D^2 = 2.1 \pm 0.7$ % for same-side pion (B^+) tagging [5] and $\epsilon D^2 = 0.7 \pm 0.1$ % for opposite-side muon tagging [6]. A conservative estimate for the overall B_s tagging power currently is assumed to be $\epsilon D^2 = 4$ %.

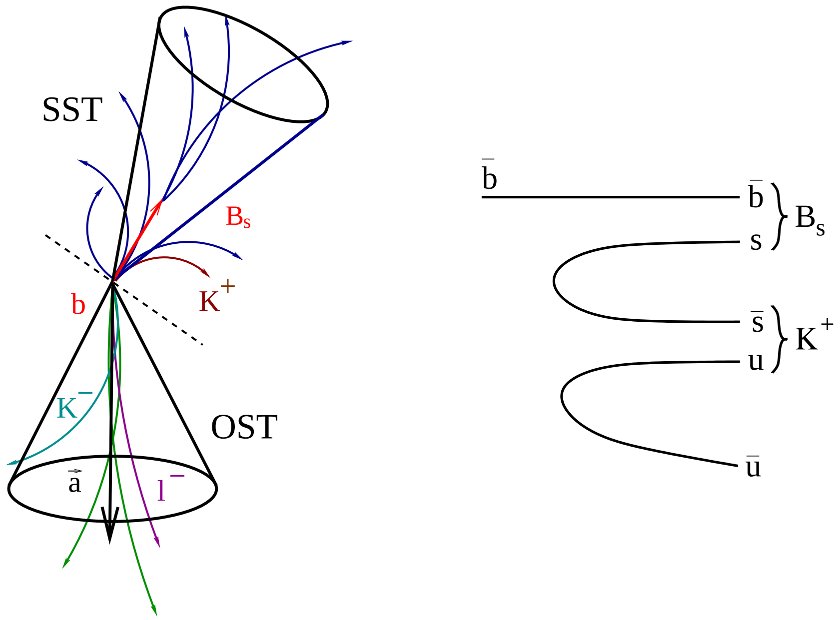

Fig. 6. Left: Sketch of different tagging algorithms; Right: Same-side kaon tagging.

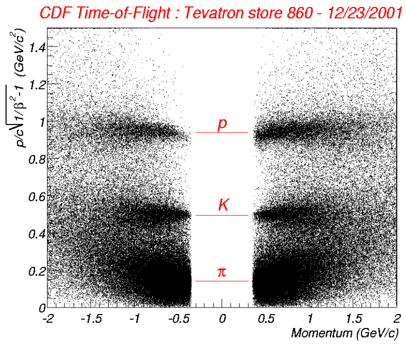

Fig. 7. TOF performance.

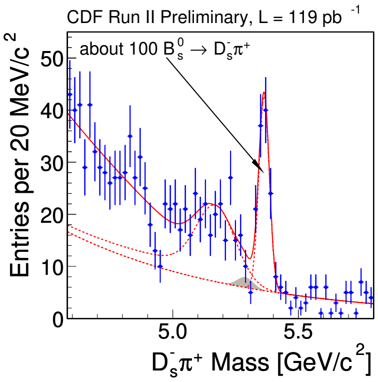

Fig. 8. $B_s \to D_s\pi$ candidates.

5 $B_s \to D_s\pi^-$ Yield

About 100 events in the decay mode $B_s \to D_s\pi^-(D_s \to \phi\pi^+, \phi \to KK)$ have been observed so far in 119 pb^{-1} of data (fig. 8). This mode is called "golden" for several reasons. It is decaying in only charged stable particles and is therefore fully reconstructable and further it has a very clean signature since the ϕ is in the final state. It can be extracted with a high rate based on the hadronic two track trigger, which requires two displaced SVT tracks. CDF II is for the first time able to measure the branching ratio. Previously only a limit set by OPAL existed ($BR(B_s \to D_s\pi^-) \leq 13\%$).
The principal guideline of this measurement is to compare the B_s decay to a very similar already well known decay mode $B_d \to D^-\pi^+, (D^- \to K^-\pi^+\pi^-)$ (fig. 9). The ratio of observed events then is:

$$\frac{N_{B_s}}{N_{B_d}} = \frac{f_s}{f_d}\frac{\epsilon_{B_s}}{\epsilon_{B_d}}\frac{BR(B_s \to D_s^-\pi^+)}{BR(B_d \to D^-\pi^+)}\frac{BR(D_s^- \to \phi\pi^-)BR(\phi \to K^-K^+)}{BR(D^- \to K^-\pi^=\pi^-)} \tag{8}$$

where f_s/f_d are the probabilities to form a B_s/B_d meson out of a b quark within the fragmentation process and $\epsilon_{B_s}/\epsilon_{B_d}$ are the trigger and reconstruction efficiencies for both decay chains. This ratio has been retrieved from studying a realistic Monte Carlo simulation. The advantage of determining the ratio is that a lot of systematics in trigger and reconstruction efficiencies cancel. For the unknown branching ratios, the PDG values are take [7]. The following result has been obtained based on 65 pb^{-1} of data [8]:

$$\frac{f_s}{f_d}\frac{BR(B_s \to D_s^-\pi^+}{BR(B_s \to D^-\pi^+)} = 0.42\ \pm\ 0.11\ (stat.)\ \pm\ 0.11\ (BR)\ \pm\ 0.07\ (sys.) \tag{9}$$

Taking the fragmentation ratio f_s/f_d and the branching ratio $BR(B_d \to D^-\pi^+)$ also from the PDG results in:

$$BR(B_s \to D_s\pi^\pm) = (4.8 \pm 1.2\ (stat.) \pm 1.8\ (BR) \pm 0.8\ (sys.) \pm 0.6\ (f_s/f_d)) \times 10^{-3} \tag{10}$$

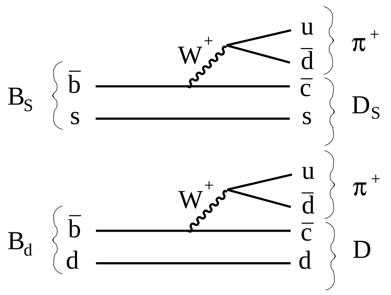

Fig. 9. Feynman diagrams for $B_s \to D_s \pi$ decay and $B_d \to D^0 \pi$ decay.

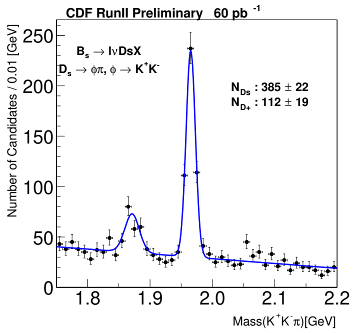

Fig. 10. $B_s \to D_s l\nu X$.

6 $B_s \to D_s l\nu X$ Channel

Thanks to the semileptonic trigger (lepton plus displaced SVT track) there is quite a clean semileptonic B_s sample ($B_s \to D_s l\nu X, D_s \to \phi\pi, \phi \to KK$). The yield per unit of luminosity for this mode is about 3 times higher as in Run I due to the different trigger tresholds and conditions. The signal to noise ratio is twice as good as in Run I. The reconstructed D_s and D^+ candidates in the semileptonic trigger sample are shown in fig. 10. The proper time resolution is a function of the momentum of the B_s meson. But only the momenta of the lepton and the D_s meson are reconstructed, thus a momentum dependent correction factor K, retrieved from Monte Carlo study, is applied:

$$ct = \frac{L_{xy}(B_s)M(B_s)}{p_T(B_s)} \tag{11}$$

$$= \frac{L_{xy}(B_s)M(B_s)}{p_T(lD_s)} * K \tag{12}$$

$$K = \frac{p_T(lD_s)}{p_T(B_s)} \tag{13}$$

$$\sigma_t = \sigma_{t_0} \oplus t * \frac{\sigma(K)}{K} \tag{14}$$

The proper time resolution of the semileptonic B_s decay is dominated by the error on K ($\sigma(K)/K \approx 15$ %). Due to the worse momentum resolution the semileptonic decay mode has only a limited B_s mixing sensitivity and serves as a high statistics back up sample.

7 B_s Sensitivity Esitmates

The current available prospects are limited to the hadronic decay mode described above. The following numbers based on the current detector and trigger performance are used to determine the B_s sensitivity:

$$1600 \text{ events/fb}^{-1},\ \text{S/B} = 2/1,\ \epsilon D^2 = 4\ \%,\ \sigma_t = 67 \text{ fs}.$$

This results in a 2σ sensitivity for $\delta m_s = 15$ ps $^{-1}$ with 0.5 fb^{-1} of data. This corresponds to the existing limit.
A more optimistic estimate takes some expected improvements into account. Among these are an improvment of the trigger rate via changing the SVT pattern recognition from requiring 4 hits in 4 silicon layers to 4 out of 5, the implementation of full silicon tracking in the level 3 filter (and thus the confirmation of the SVT trigger decision), and the use of a new data compression scheme for level 3 to avoid data transfer limitations. Additional improvements due to the reconstruction of more decay channels, better TOF reconstruction, resulting in improved kaon tagging, a higher spatial resolution due to an additional innermost silicon layer-hit and an event-by-event primary vertex are considered for the following numbers:

$$2000 \text{ events/fb}^{-1},\ \text{S/B} = 2/1,\ \epsilon D^2 = 5\ \%,\ \sigma_t = 50 \text{ fs}$$

We then obtain a 5σ sensitivity for $\Delta m_s = 18$ ps^{-1} with about 1.7 fb $^{-1}$ of data. To cover the entire Standard Model expected range based upon indirect fits ($\Delta m_s \leq$ 24 ps^{-1}) with a 5σ sensitivity, about 3.2 fb^{-1} of data are needed.

8 Conclusion

It has turned out that the measurement of the B_s oscillation frequency is a much more difficult issue than expected. Although there are still further improvements possible to increase the sensitivity of the B_s oscillation frequency measurement it will take time, luminosity and hard work.

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