DØ-Results on Neutral B Meson Flavor Oscillations

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Measuring the oscillation frequency in the B_s meson system and the mass difference Δm_s was one of the main goals in b-physics for the two experiments CDF and DØ at the Tevatron-Collider since the start of RunII in the year 2002. The DØ collaboration was the first experiment, which was able to give a two sided limit for the oscillation frequency of B_s^0 mesons in March 2006 within the interval $17\,\text{ps}^{-1} < \Delta m_s < 21\,\text{ps}^{-1}$ for the channel $B_s \to \mu\nu_\mu D_s(\phi\pi)$. Since than the three decay channels $B_s \to e\nu_e D_s(\phi\pi)$, $B_s \to \mu\nu_\mu D_s(K^*K)$ and $B_s \to \mu\nu_\mu D_s(K_s^0 K)$ have been added to this result. The observed limit for the combination of all channels has not changed, while the expected sensitivity for the amplitude scan has improved from $\Delta m_s > 14.8\,\text{ps}^{-1}$ (95% C. L.) to $\Delta m_s > 14.9\,\text{ps}^{-1}$ (95% C. L.). The expected limit has changed from $\Delta m_s = 14.1\,\text{ps}^{-1}$ to $\Delta m_s = 16.5\,\text{ps}^{-1}$.

I. INTRODUCTION

The CKM matrix describes the relation of weak and flavor eigenstates of the quarks. One of least known matrix elements is V_{td}. It is accessible by studying the transition of B-mesons to their anti-particles and vice versa. This behavior is also known as mixing. In principle this should be true for all neutral B-mesons and so for B_d^0 as well, as for B_s^0. Theoretically V_{td} is calculable by the equation:

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_{B_d^0} m_t^2 F\left(\frac{m_t^2}{m_W^2}\right) B_{B_d^0} f_{B_d^0}^2 |V_{tb}^* V_{td}|^2 \eta_{QCD} \quad (1)$$

As there are high uncertainties on hadronic correction terms the calculation of V_{td} is not trivial. These uncertainties are avoidable by measuring Δm_d and Δm_s and calculating the ratio to cancel out the hadronic corrections.
Since the first observation of flavor oscillations in the B_d^0-system by the ARGUS collaboration this topic has been studied intensively and was well measured at the B factories BaBar and Belle (PDG world-average: $\Delta m_d = (0.507 \pm 0.005)\ \text{ps}^{-1}$ [1]). The Tevatron-Collider at the Fermi National Accelerator Laboratories is currently the only place worldwide to study mixing in the B_s-system. Protons and Anti-Protons collide at $\sqrt{s}$=1.96 TeV with a bunching space of 396 ns.

II. DETECTOR AND TRIGGER-SYSTEM

At DØ a 4π multipurpose detector with a three level trigger system is used to record the physics relevant events on tape. The detector is described in detail elsewhere [3]. For the analysis presented here the excellent muon chamber coverage in pseudo-rapidity η up to $|\eta| < 2$ is mandatory and allows to detect semileptonic B decays highly efficient. Beside that the central tracking system is one of the most important components. It consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT). The tracking system provides charged particle tracking up to $|\eta| < 3$.
In contrast to e^+e^- colliders, there are many tracks per event for hadronic interactions. It is a big challenge to trigger on the interesting events as they are immersed in a large background. The DØ trigger system consists of a three level trigger system. While the first two stages are build in hardware and reduce the event rate from about 2.5 MHz to about 800 Hz, the last stage runs on a PC-farm, which has to reduce this rate again to 50 Hz for data acquisition. Due to the high computing power of 250 nodes, this cluster is fast enough to nearly fully reconstruct events and thus build physics objects like invariant masses of decaying particles.
Highly efficient triggers are needed to recognize signal events and record them for further analysis. As there is no particle identification built into the detector present muons are used to trigger on. As for higher luminosities the rate would increase very fast, there are different ways to suppress the background. As pre-scaling is a non-selective method and increasing the p_T-threshold of the muon would cut into the signal region, a more elegant way is needed to fulfill the requirements of rejecting unwanted processes, while keeping the signal efficiency high. Level-3 of the trigger system offers a very flexible way by calculating physics objects and cutting on their invariant masses, impact parameters etc. In the special case of the presented channel $B_s \to \mu\nu_\mu D_s(\phi\pi)$ a trigger was created, cutting on the invariant mass of the ϕ and cutting on the significance of the impact parameter.

III. PHYSICS ANALYSIS

The analysis steps for measuring the oscillation frequency include

- Tag final state flavor of the B-meson. This also includes reconstructing and selecting events.
- Measure the proper decay length

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- Initial state flavor tagging

With the help of these variables as input it is possible to do a Likelihood fit or amplitude scan and determine Δm_s.

A. Signal Selection

Most of the events were collected with single muon triggers, although no explicit trigger requirement was made. Beside cuts on the transverse momenta of the muons, hits in the tracking system and invariant masses, a likelihood ratio method was utilized for the different decay channels. As input for the likelihood function kinematic properties of the decaying particles like Kaon, D_s and B_s mass are used. The likelihood ratio variable y was chosen to maximize the predicted ratio of signal and background $S/\sqrt{S+B}$.

B. Flavor Tagging

Flavor Tagging is an important tool analyzing B meson oscillations. It is used to determine the initial and the final state of the B meson, i.e. whether it is a B or $\bar{B}$ and thus to clarify whether it has oscillated or not. Its performance is described by the combination of two quantities:

- the efficiency ϵ, which is the fraction of reconstructed B mesons, that are tagged divided by the total number:

$$\epsilon = \frac{N_{tag}}{N_{tot}} \tag{2}$$

- and the dilution $\mathcal{D}$, which is given by

$$\mathcal{D} = 2\eta - 1, \tag{3}$$

  where the purity η is given by the fraction of correct tagged events divided by the total number of tagged events:

$$\eta = \frac{N_{cor}}{N_{tag}} \tag{4}$$

For the initial state flavor tagging the opposite side tagging (OST) technique is used. To determine the flavor of the B meson, the b-Hadron on the non-decay side is used. As the tagging efficiency $\epsilon\mathcal{D}^2$ is independent of the analyzed channel, the tagging algorithm was developed for B_d decays, which give a significantly higher statistic. The OST could be achieved in three different ways:

- Charge of decay lepton: the charge of the lepton leads to the flavor of the b-Hadron and so to the flavor of the B meson on the signal side.
- Jet-charge tagging: Defining a cone with the condition

$$\Delta R = \sqrt{\phi^2 + \eta^2} \tag{5}$$

  and summing up all charges of this jet:

$$Q_J = \frac{\Sigma_i q^i p_T^i}{\Sigma_i p_T^i} \tag{6}$$

  leads to a charge, which allows to identify the flavor of the B meson. The tagging power was found to be

$$\epsilon\mathcal{D}^2 = (2.48 \pm 0.21\,(\text{stat.})\,^{+0.08}_{-0.06}\,(\,\text{syst.})\,\% \tag{7}$$

  As a consistency check the mass difference for the B_d system was extracted as

$$\Delta m_d = 0.506 \pm 0.020\,(\text{stat.})\ \pm 0.016\,(\,\text{syst.})\,\text{ps}^{-1} \tag{8}$$

  which is in perfect agreement with the well-measured world-average [1].

C. Proper Decay Length Measurement

A direct observable for a fully reconstructible event is the proper decay length given by

$$t_{B_s^0} = L_{xy}^B \cdot \frac{M_{B_s}^0}{p_T(B_s^0)}. \tag{9}$$

As in all semileptonic decays a ν is present, which can't be directly detected and measured only the visible proper decay length x^M is observable:

$$x^M \equiv L_{xy}^{\mu D_s} \cdot \frac{M_{B_s}^0}{p_T(B_s^0)} \cdot c \tag{10}$$

and so the decay time has to be corrected by the K-factor

$$t_{B_s^0} = \frac{x^M}{c} \cdot K, \text{with } K \equiv \frac{p_T(\mu D_s)}{p_T(B_s^0)} \tag{11}$$

To estimate the K-factor extensive MC studies were done to determine the smearing effect of the neutrino.

D. Fitting Procedure

All tagged events within a D_s mass range of $1.72 < m_{K^+K^-\pi^-} < 2.22\,GeV/c^2$ were used in the unbinned likelihood fitting procedure. The visible proper decay length x^M, its uncertainty σ_{x^M}, the D_s-meson candidate mass m_{D_s}, the predicted dilution d_{pr} and the selection variable y (which selects interesting events from the whole data sample) are used as input for the likelihood for an event to arise from a specific source. All of the quantities used in the unbinned likeklihood fitting procedure are known on an event-by-event basis. All signal and background sources were considered in a probability density function and the total probability density function was minimized using the MINUIT [2] program.

IV. RESULTS

Results for the studied decay channels will be shown here. This includes $B_s \rightarrow \mu\nu_\mu D_s(\phi\pi)$, $B_s \rightarrow e\nu_e D_s(\phi\pi)$, $B_s \rightarrow \mu\nu_\mu D_s(K^*K)$, a combination of these channels and the decay $B_s \rightarrow \mu\nu_\mu D_s(K^0_s K)$.

A. $B_s \rightarrow \mu\nu_\mu D_s(\phi\pi)$

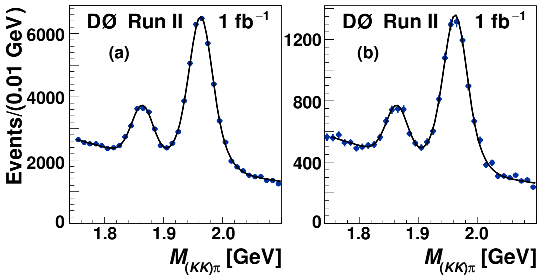

FIG. 1: Left-hand side: untagged event sample of the decay $B_s \rightarrow \mu\nu_\mu D_s(\phi\pi)$,Right-hand side: tagged event sample of same decay including 5601 ± 102 events.

The results for this channel were already published in PRL [4]. By the usage of this channel it was possible to set a two sided limit on Δm_s. Very high statistics can be obtained by the excellent muon coverage of the DØ-detector and its muon triggers. Figure 1 shows the event sample selection. While the left hand-side plot shows the untagged sample, the right-hand-side plot shows the already tagged event sample. From the channels presented it is the only one allowing to specify a two sided limit without taking into account the other decay modes as:

$$17\,\mathrm{ps}^{-1} < \Delta m_s < 21\,\mathrm{ps}^{-1} \quad (90\%\ \mathrm{C.\,L.}) \qquad (12)$$

The observed limit for the amplitude scan was found to be $\Delta m_s > 14.8\,\mathrm{ps}^{-1}$ (95% C. L.) with an expected limit of $\Delta m_s = 14.1\,\mathrm{ps}^{-1}$.

B. $B_s \rightarrow e\nu_e D_s(\phi\pi)$

This channel [5] is highly challenging, as it is not possible to build a single-electron trigger with low enough p_T threshold due to the high event rates. So the muon on "the other side" has to be used as trigger condition. This leads to lower statistics, but as it is possible to determine the initial flavor by this muon every recorded event is already tagged. Figure 2 shows the tagged event sample. A lower limit could be specified as:

$$\Delta m_s > 7.9\,\mathrm{ps}^{-1} \quad (95\%\ \mathrm{C.\,L.}) \qquad (13)$$

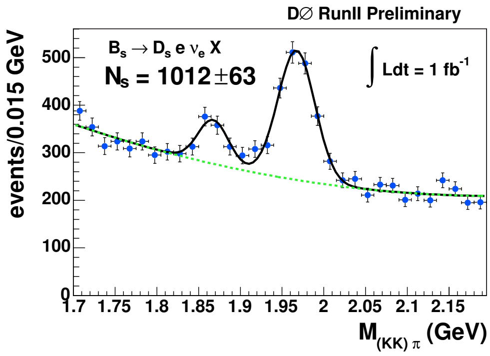

FIG. 2: Tagged event sample for the decay $B_s \rightarrow e\nu_e D_s(\phi\pi)$.

C. $B_s \rightarrow \mu\nu_\mu D_s(K^*K)$

As the signal region of this decay [6] is directly overlapping with reflections of miss-identified D$^+$-mesons and in addition to that with even higher statistics than the signal by itself the sensitivity of this channel is limited. Figure 5 shows this challenging channel.

$$\Delta m_s > 9.3\,\mathrm{ps}^{-1} \quad (95\%\ \mathrm{C.\,L.}) \qquad (14)$$

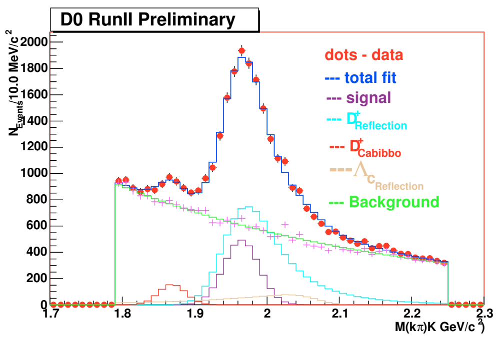

FIG. 3: Decay mode $B_s \rightarrow \mu\nu_\mu D_s(K^*K)$ and its tagged event sample with 2997 ± 146 events.

D. Combination of previous channels

Figure 4 shows the combination of the decay channels $B_s \rightarrow \mu\nu_\mu D_s(\phi\pi)$, $B_s \rightarrow e\nu_e D_s(\phi\pi)$ and $B_s \rightarrow \mu\nu_\mu D_s(K^*K)$. Compared to the results on the channel $B_s \rightarrow \mu\nu_\mu D_s(\phi\pi)$ no improvements on the limit

$$17\,\mathrm{ps}^{-1} < \Delta m_s < 21\,\mathrm{ps}^{-1} \quad (90\%\ \mathrm{C.\,L.}) \qquad (15)$$

could be made by adding these channels.

E. $B_s \rightarrow \mu\nu_\mu D_s(K^0_s K)$

[7] Like in $B_s \rightarrow \mu\nu_\mu D_s(K^*K)$ the signal region is

TABLE I: Overview of all decay channels.

Decay Channel	Tagged Events	S/N	Limit
$B_s \to \mu\nu_\mu D_s(\phi\pi)$	5601 ± 102	2.2	$17 < \Delta m_s < 21\,\mathrm{ps}^{-1}$ (90% C. L.)
$B_s \to e\nu_e D_s(\phi\pi)$	1012 ± 63	0.5	$\Delta m_s > 7.9\,\mathrm{ps}^{-1}$ (95% C. L.)
$B_s \to \mu\nu_\mu D_s(K^*K)$	2997 ± 146	0.16	$\Delta m_s > 9.3\,\mathrm{ps}^{-1}$ (95% C. L.)
$B_s \to \mu\nu_\mu D_s(K_s^0K)$	593 ± 102	0.17	$\Delta m_s > 1.09\,\mathrm{ps}^{-1}$ (95% C. L.)

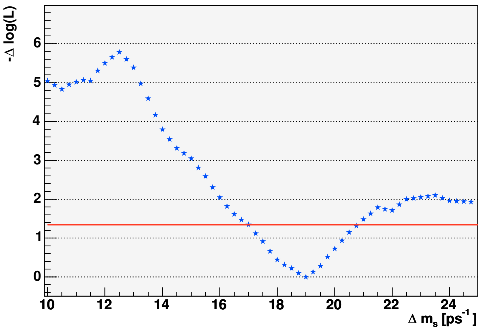

FIG. 4: Log-Likelihood function of Δm_s for the combination of the three channels $B_s \to \mu\nu_\mu D_s(\phi\pi)$, $B_s \to e\nu_e D_s(\phi\pi)$ and $B_s \to \mu\nu_\mu D_s(K^*K)$.

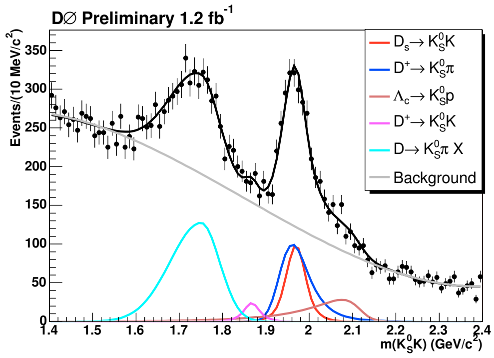

FIG. 5: Invariant $m_{K_s^0K}$ distribution of the tagged event sample for the decay $\mathrm{B_s} \to \mu\nu_\mu \mathrm{D_s}(\mathrm{K_s^0K})$ including 593 ± 102 events. The fit functions are drawn as solid lines.

overlapped by reflections (Figure 3). In addition it only provides small statistics. Because of the difficult K_s^0-selection a lower limit for Δm_s could be set as:

$$\Delta m_s > 1.09\,\mathrm{ps}^{-1} \quad (95\%\,\mathrm{C.\,L.}) \qquad (16)$$

V. CONCLUSION

An overview of all decay channels presented here can be found in table I. It shows the number of tagged events, the signal to background ratio and the expected limit per decay channel. The DØ-experiment was the first experiment presenting a two sided limit for Δm_s in the decay channel $B_s \to \mu\nu_\mu D_s(\phi\pi)$. Afterward the channels $B_s \to \mu\nu_\mu D_s(\phi\pi)$, $B_s \to e\nu_e D_s(\phi\pi)$, $B_s \to \mu\nu_\mu D_s(K^*K)$ and $B_s \to \mu\nu_\mu D_s(K_s^0K)$ were combined. The observed likelihood limit for Δm_s could not be reduced by adding this information compared to the previous allowed region using only the channel $B_s \to \mu\nu_\mu D_s(\phi\pi)$. The mass difference in the $\mathrm{B_s}$ system for all four channels is given as:

$$17\,\mathrm{ps}^{-1} < \Delta m_s < 21\,\mathrm{ps}^{-1} \quad (90\%\,\mathrm{C.\,L.}) \qquad (17)$$

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[6] V. M. Abazov *et al.* (DØ Collaboration), B_s Mixing studies with $B_s^0 \to D_s^-\mu^+X$ $(D_s^- \to K^{*0}K^-)$ Decay using Unbinned Fit, DØ note 5172-CONF.

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