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Study of B oscillations at the DØ Experiment

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We describe the study of B_d and B_s oscillations at the DØ experiment.

1. Introduction

B_d mixing was observed in 1987 by the ARGUS Collaboration [1], and gave first indication that the top quark was heavy which was discovered in 1995 at Tevatron [2,3], 8 years later. Following the observation of mixing, precise measurements of the B_d mixing parameter χ_d came from ARGUS [4] and CLEO [5] collaborations in 1992 and 1993 respectively.

The main motivation for performing the $B\bar{B}$ mixing measurement lies in the determination of the CKM matrix element V_{td}, that provides one of the constraints on the unitarity triangle. V_{td} is accessible experimentally through the box diagrams in Fig. 1, by measuring the mass difference Δm_d in B_d mixing. The relation between Δm_d and V_{td} can be seen in Eq. 1.

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_b m_t^2 F(\frac{m_t^2}{m_W^2}) \eta B_{B_d} f_{B_d}^2 \mid V_{tb}^* V_{td} \mid^2 \quad (1)$$

While Δm_d is measured with very good precision, the determination of V_{td} is limited by theoretical uncertainties in the decay constant f_{B_d} and the bag factor B_{B_d}. However, in the ratio $\Delta m_s/\Delta m_d$, most hadronic uncertainties cancel. With $\mid V_{ts} \mid \approx \mid V_{cb} \mid$, a precise measurement of both Δm_d and Δm_s provides a strong constraint on V_{td}. This underlines the importance of the B_s mixing measurements, as reviewed in number of papers [6,7].

Babar at SLAC and BELLE experiment at KEK, are producing a wealth of B physics studies and currently providing the most precise numbers on the B_d mixing. However, before the turn on of the Large Hadron Collider (LHC) at CERN, the Tevatron is the only place where we can study B_s mixing since all species of B hadrons are produced in $p\bar{p}$ collisions.

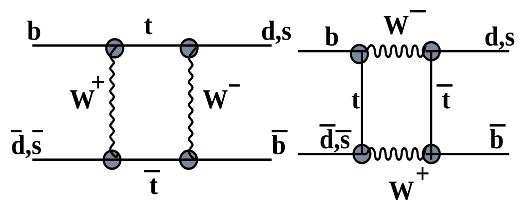

Figure 1. lowest-order Feynman diagrams describing $B_{d,s}$ mixing.

We present here results on B_d mixing using an integrated luminosity of 200 pb^{-1} and B_s mixing using an integrated luminosity of 460 pb^{-1}.

2. Detector and DØB Physics Trigger

We use mainly the central tracker and muon system to identify B decays. The central tracker consists of the silicon tracker (SMT) and the central fiber tracker (CFT). The CFT consists of eight thin coaxial barrels, each supporting two doublets of overlapping scintillating fibers providing measurement in z and $r-\phi$. Details can be found in [8]. The muon system consists of a layer of tracking detectors and scintillation trigger counters before 1.8 T toroids, followed by two additional layers after the toroids. Tracking at

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$\mid \eta \mid < 1$ relies on 10 cm wide drift tubes, while 1 cm wide mini drift tubes are used at $1 < \mid \eta \mid < 2$. A detailed description of the muon system can be found in [9,10]. We use a single inclusive muon trigger for B mixing studies. The trigger requires a good muon identified by the muon chamber with a matching track in the central tracker in the pseudorapidity range of $\mid \eta \mid < 2.0$. We use triggers with p_T cuts of $3-5$ GeV/c and the trigger is prescaled or turned off depending on the luminosity.

3. B_d Mixing

3.1. Semileptonic sample selection

We use the inclusive muon trigger to construct a sample of $B^0 \to D^{*-}\mu^+\nu_\mu X$, where $D^{*-} \to \bar{D}^0\pi^-$ and $\bar{D}^0 \to K^+\pi^-$. $B^+ \to \bar{D}^0\mu^+\nu_\mu X$ decays contaminate the sample and in order to take into account the cross talk between the two channels, we do a simultaneous fit to the asymmetry obtained from each sample. The $\bar{D}^0$ candidate was constructed from two oppositely charged displaced tracks (impact parameter significance $\sqrt{(d_T/\sigma(d_T))^2 + (d_L/\sigma(d_L))^2} > 2$), which should be in the same jet as the reconstructed muon. The two tracks were required to have $p_T > 0.7$ GeV/c and $|\eta| < 2.0$. The two track vertex was required to have mass between $1.4 <$ M$(K^+\pi^-)$ < 2.2 and a good vertex fit. The $\bar{D}^0$ candidate is then vertexed with a muon. The $\bar{D}^0$ and the B candidate vertex are required to be displaced.

If $1.75 < M_{D^0} < 1.95$ GeV/c^2 , we look for an additional soft pion (π^*), with momentum > 0.2 GeV/c . The three tracks are then vertex constrained to form the D^* candidate. The reconstructed D^* candidate is then vertexed with the muon.

The fit to the D^0 invariant mass distribution gives 92429 ± 815 signal events. Figure 2 shows the mass difference distribution of $\bar{D}^0$ and D^* candidates. We find a total of 20133 ± 173 D^* signal events.

3.2. Flavor Tagging

The tagging algorithms which are used for this analysis are soft muon tagger, opposite jet-charge tagger(JETQ) and soft pion tagger (same-side tagger (SST)). The dilution of the tag is defined as $\mathcal{D} = (N_{WS} - N_{RS})/(N_{WS} + N_{RS})$, where N_{WS} is wrong sign tags and N_{RS} is number of right sign tags. The efficiency of the tag is the ratio of the number of tagged events to the total number of reconstructed events $\epsilon = N_{tag}/N_{total}$. The taggers are calibrated using a sample of $B^+ \to J/\psi K^+$ and optimized to maximize the flavor tagging merit $\epsilon\mathcal{D}^2$.

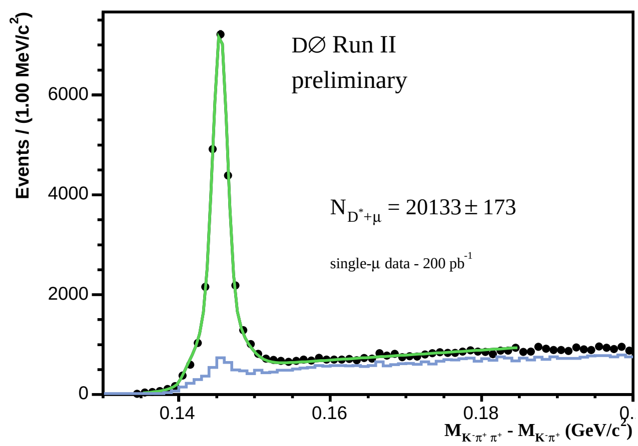

Figure 2. Mass difference between D^0 and D^* candidate.

The Soft muon tagger uses the fact that in a semileptonic (muonic) decay of a B hadron the muon charge correlates with the charge of the B hadron. A negative opposite-side muon corresponds to a $\bar{b}$ quark for the reconstructed B meson (i.e., B_d, B^+) and vice versa. However, mixing in the case of neutral B mesons, fakes and sequential decays give a wrong correlation between the B meson and the tag muon, and gives wrong sign tag, that contributes to the dilution of the tag and is taken into account in the asymmetry fit. The muon candidate is required to have $p_T > 2.2$ GeV/c and should be well separated from the reconstructed B meson ($\Delta\phi > 2.2$rad). The muon tag efficiency is found to be $(5.0\pm0.2)\%$ with a dilution of $(44.8 \pm 5.1)\%$ giving an $\epsilon\mathcal{D}^2$ of $(1.0 \pm 0.1)\%$.

For the opposite-side jet-charge tagger, we make a list of tracks lying in a cone and which are well separated from the reconstructed B meson ($\Delta\phi > 1.2$rad) and $p_T > 0.5$ GeV/c . The jet charge defined as the p_T weighted average charge $\frac{\sum p_T^i q^i}{\sum p_T^i}$, correlates with the charge of the B meson.

For the same-side tagger, we consider tracks within a cone of $\Delta R < 0.7$ centered around the reconstructed B candidate. Each track should have $p_T > 0.25$ GeV/c , have at least 3 hits in silicon tracker and 4 hits in the central tracker and not be identified as a muon. A positive pion corresponds to a $\bar{b}$ quark if the reconstructed B meson is neutral (B^0), while to a b quark if its charged (B^-).

The combined jetQ-SST algorithm has an efficiency of $(68.3 \pm 0.9)\%$ and a dilution of $(14.9 \pm 1.5)\%$ giving an $\epsilon\mathcal{D}^2 = (1.5 \pm 0.5)\%$.

3.3. Asymmetry Fit

The fit values of Δm_d, and dilutions in D* ($\mathcal{D}^0$) and D^0 ($\mathcal{D}^+$) were determined from the minimization of $\chi^2(\Delta m_d, \mathcal{D}^0, \mathcal{D}^+)$, defined in Eq. 2.

$$\chi^2 = \sum_i \frac{(A_i - A_i^e(\Delta m_d, \mathcal{D}^0, \mathcal{D}^+)^2}{\sigma^2(A_i)} \quad (2)$$

where A_i is the measured asymmetry and A_i^e is the expected asymmetry and index i corresponds to the i-th bin in VPDL (Visible Proper Decay Length), which is defined as $c\tau_B = \frac{L_{XY}^B}{(\beta\gamma)_T^B} = L_{XY}^B \cdot \frac{M_B}{p_T^B}$. L_{XY}^B is the transverse decay length of the B candidate vertex. The measured asymmetry is simply the ratio of the difference in opposite sign B's (non-oscillated) and same sign B's (oscillated) where the sign of the reconstructed B is given by the muon on one hand and by the flavor tag for the other B candidate.

3.3.1. Expected Asymmetry

The number of ideal non-oscillated and oscillated events for the B^0 meson is given as, $n_d^{nosc}(x) = \frac{K}{c\tau_{B_d}}\exp(-\frac{Kx}{c\tau_{B_d}}) \cdot 0.5 \cdot (1 + (2\mathcal{D}^0 - 1)\cos(\Delta m_d \cdot Kx/c))$ and $n_d^{osc}(x) = \frac{K}{c\tau_{B_d}}\exp(-\frac{Kx}{c\tau_{B_d}}) \cdot 0.5 \cdot (1 - (2\mathcal{D}^0 - 1)\cos(\Delta m_d \cdot Kx/c))$. Similar expressions can be written for the B^+ which will not have the oscillatory term and for the B_s meson, where we assume the oscillation frequency is infinite, so that the cosine term effectively disappears.

$K = p_T^{\mu \mathrm{D}^0}/p_T^B$ is a correction factor called the K-factor which is obtained from simulation and x is the visible proper decay length (VPDL).

Transition to the measured number of events as a function of measured VPDL, x^M is achieved by integration over K-factors and resolution function:

$$N_{(d,u,s),\ j}^{osc,\ nosc}(x^M) = \int dx\ Res_j(x - x^M) \cdot \epsilon_j^R(x) \int dK\ D_j(K) \cdot \theta(x) \cdot n_{(d,u,s),\ j}^{osc,\ nosc}(x, K) \quad (3)$$

Here $Res_j(x - x^M)$ is the detector resolution of the VPDL and $\epsilon_j^R(x)$ is the reconstruction efficiency for a given decay channel j of a B meson which contributes to the same final state. The step function $\theta(x)$ takes into account that only positive values of x are possible (x^M can have negative values due to resolution effects). The function $D_j(K)$ gives the normalized distribution of the K-factor in a given channel j.

One can then calculate the expected number of "oscillated events" ($N_i^{e,osc}$) and "non-oscillated" ($N_i^{e,nosc}$) events in the i-th bin of VPDL by summing the contributions from each type of B hadron and integrating over the measured VPDL over the given interval i.

The expected value A_i^e for interval i of the measured VPDL is given by:

$$A_i^e(\Delta m_d, \eta) = \frac{N_i^{e,non-osc} - N_i^{e,osc}}{N_i^{e,non-osc} + N_i^{e,osc}} \ . \quad (4)$$

3.3.2. Fit results

Doing a simultaneous asymmetry fit we get $\Delta m_d = 0.456 \pm 0.034(\text{stat.}) \pm 0.025(\text{syst.})\text{ps}^{-1}$. The asymmetries for the B^+ and B^0 candidates can be see in Fig. 3.

4. B_s mixing

4.1. Improvement in flavor tagging algorithm

Flavor tagging improvements have been made for the B_s mixing measurement. Different vari-

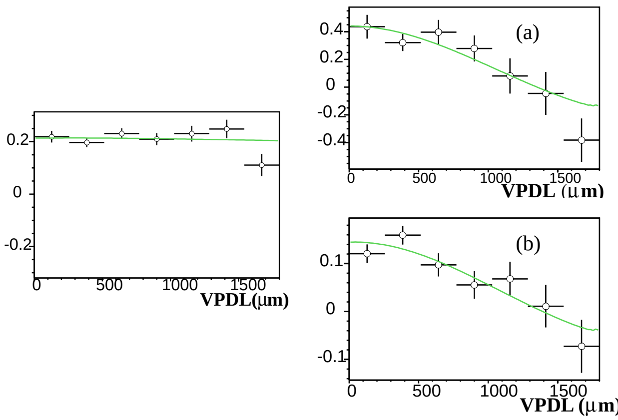

Figure 3. Asymmetry for B^+ candidates (left) and B^0 candidates (right). a) corresponds to soft muon tagger while b) corresponds to combined jetQ+SST tagger.

ables can be used to discriminate between b or $\bar{b}$ to determine the flavor of the reconstructed b hadron, and their combination into a single tagging variable gives a significantly better result. We obtain such a combination with the likelihood ratio method described below.

Some of the variables considered are for example, the muon jet charge defined as $\frac{\sum Q^j p_T^j}{\sum p_T^j}$, where j runs over all tracks in a cone of 0.5 around the muon, the p_T^{rel} which is the transverse momentum of the muon relative to the jet which contains it, etc. A complete description of the variables and figures can be found in [11]. For the initial b quark, the probability density function (PDF.) for a given variable x_i is denoted as $f_i^b(x_i)$, while for the initial $\bar{b}$ quark it is denoted as $f_i^{\bar{b}}(x_i)$. The combined tagging variable y is defined as: $y = \prod_{i=1}^n y_i$; $\quad y_i = \frac{f_i^{\bar{b}}(x_i)}{f_i^b(x_i)}$. When variable x_i is undefined, the corresponding variable y_i is set to 1. For an oscillation analysis, it is more convenient to define the tagging variable $d = (1-y)/(1+y)$. The variable d changes between -1 and 1. An event with $d > 0$ is tagged as coming from a b quark and with $d < 0$ as coming from $\bar{b}$ quark and a larger $|d|$ value corresponds to a better tagging purity. For uncorrelated variables $x_1, ...x_n$, and perfect modeling in the PDF, d gives the best possible tagging performance and its absolute value gives a dilution of a given event. For the subsequent B_s result, only soft muon tagger is used, which has a dilution of 0.448 ± 0.042 and efficiency of $4.76 \pm 0.19\%$. This dilution is used as an input for the asymmetry fit in the B_s sample.

4.2. B_s mixing limit

We use the decay mode $B_s^0 \rightarrow D_s^- \mu^+ \nu X$, $D_s^- \rightarrow \phi\pi^-$, $\phi \rightarrow K^+K^-$. We first fit the untagged sample in the VPDL bin -0.01 - 0.06 cm and then fix the mass and width of the D_s for the fits to the flavor-tagged sample. Figure 4 shows the D_s mass distribution before flavor tagging. The oscillated and non-oscillated candidates are grouped into seven VPDL bins and fitted to determine the asymmetry in each bin. Reconstruction efficiencies for the different channels contributing to the final state are calculated from simulation and variation of efficiency as a function of lifetime cut (VPDL) is also taken into account. Simulated events are used to determine the VPDL resolution. Tuning is applied to data and MC samples and an overall multiplicative correction factor to the resolution is found to be 1.095. The VPDL resolution can be seen in Fig. 5.

Since we don't observe significant asymmetry we proceed to set a limit on Δm_s. The χ^2 function is modified to the following equation:

$$\chi^2(\mathcal{A}) = \sum_i \frac{(A_i - A_i^e(\mathcal{A}))^2}{\sigma^2(\mathcal{A}_i)} \ . \qquad (5)$$

The values of Δm_s were changed from 1 ps^{-1} to 10 ps^{-1} with a step size of 1 ps^{-1} and for each value $\mathcal{A}$ and its error was determined. This can be seen in Fig. 6. We expect the amplitude A, to be equal to 1 at the true Δm_s and equal to 0 when frequency not equal to true Δm_s. The smallest value of Δm_s at which $A + 1.645\ \sigma_A = 1$ gives a 95% C.L. limit on Δm_s. All values below this are excluded. We obtain $\Delta m_s > 5.0$ ps^{-1} with a sensitivity of 4.6 ps^{-1}.

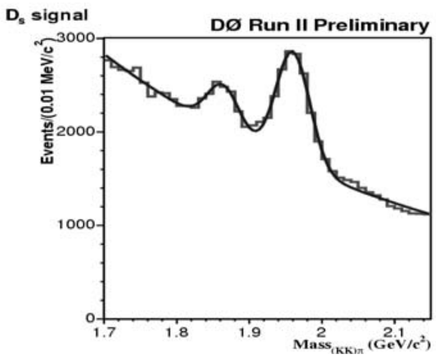

Figure 4. All B_s candidates for the untagged sample for $-0.01 <$VPDL < 0.06 cm.

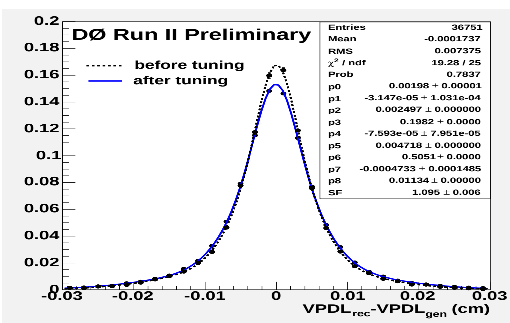

Figure 5. VPDL resolution

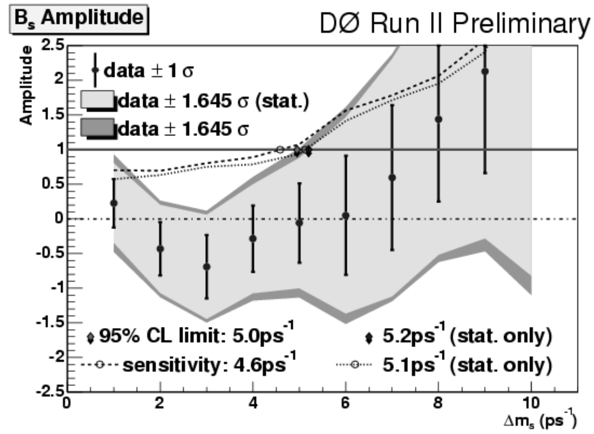

Figure 6. B_s mixing limit using amplitude scan method.

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REFERENCES

1. Observation of B0-B0bar Mixing,H. Albrecht *et. al.*, ARGUS Collaboration, *Phys. Lett.* **192B** (25 June 1987) 245.
2. Observation of the Top Quark, *Phys. Rev. Lett.***74**, 2632 (1995).
3. Observation of Top Quark Production in p anti-p Collisions with the Collider Detector at Fermilab F. Abe et al., The CDF Collaboration,*Phys. Rev. Lett.***74**, 2626 (1995)
4. H. Albrecht *et. al.*, *Z. Phys. C 55*, 357(1992),
5. Two Measurements of B0 Anti-B0 Mixing, *Phys.Rev.Lett.***71**:1680-1684,1993.
6. Review of BB-bar mixing results, Mourad Daoudi, SLAC-PUB-8278, Nov 1999. 12pp. (http://arxiv.org/pdf/hep-ex/9911027).
7. An analysis of quark mass matrices and b - anti-b mixing. ,Yosef Nir (Weizmann Inst. and SLAC), SLAC-PUB-4368, July 1987. 64pp. Published in *Nucl.Phys.***B 306**:14,1988.
8. The Upgraded DØ Detector, *hep-physics/0507191*; *Fermilab-Pub-05/341-E*
9. V. Abramov *et al.*, Forward Muon System for the DØDetector Upgrade,*Nucl. Instrum. Meth.* **A419**, 660-666 (1998).
10. C. Brown *et al.*, "DØ Muon System with Proportional Drift Tube Chambers, *Nucl. Instrum. Meth.* **A279**, 331-338 (1989).
11. http://www-d0.fnal.gov/Run2Physics/WWW/results/ b.htm,Combined Opposite side flavor tagging.