B_s^0 MIXING AT DØ EXPERIMENT

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In this report, we present a report on B_s^0 mixing studies at the DØ experiment. New results based on use of two additional decay modes are discussed and limits are given on the B_s^0 mixing parameter.

Keywords: B_s^0 meson; oscillation; flavor tagging.

1. Introduction

Particle-antiparticle oscillations are observed and well established in the B_d^0 system. The mass difference Δm_d is measured to be $\Delta m_d = 0.509 \pm 0.004$ ps^{-1} [1]. B_s^0 mesons are known to oscillate with a high frequency according to standard model predictions. Therefore, observing the oscillations in the B_s^0 system has been challenging. This has been an important focus of the B physics program at DØ experiment as well as in CDF experiment at Tevatron. Very recently DØ reported direct limits on the B_s^0 mixing parameter Δm_s [2] using the $B_s^0 \to D_s^- \mu^+ \nu X$, $D_s^- \to \phi\pi^-$ decay mode, and CDF reported a measurement of this parameter at 3.7 σ [3] [a]. The measurement of this parameter is an important test of the CKM (Cabibbo Kobayashi Maskawa) formalism of the standard model, and combining it with a measurement of Δm_d would allow us to reduce the error on V_{td} and constrain one side of the CKM triangle. The report described here adds two more B_s^0 decay modes and reports combined results using the new modes.

We use the central tracker, muon chambers and calorimeters to reconstruct the B decays. Details of the detector can be found elsewhere [4]. We use muons up-to a pseudo-rapidity $|\eta| < 2.0$ and $p_T > 1.0$ GeV/c and electrons only in the central region $|\eta| < 1.0$ with $p_T > 2.0$ GeV/c.

We use a single inclusive muon trigger or a di-muon trigger to accumulate samples for B_s^0 mixing studies. In the case of di-muon trigger the other muon acts as the tag muon used to identify the flavor of the B meson which we discuss later. The trigger requires a good muon identified by the muon chamber with a matching track in the central tracker in the pseudo-rapidity range of $|\eta| < 2.0$. We use triggers with p_T cuts of $3 - 5$ GeV/c and the trigger is prescaled or turned off depending on the luminosity. Hence for the $B_s^0 \to D_s^- e^+ \nu X$ decay mode, we have a tagged sample with the muon acting as a tag. We do not have a dedicated single electron trigger.

[a] Charge conjugated states are implied throughout the text

2. B_s^0 decays sample selection and reconstruction

DØ reported direct limits on B_s^0 oscillations using the decay mode $B_s^0 \to D_s^- \mu^+ \nu X$ decays with $D_s^- \to \phi\pi^-$ [2]. In this report, we present results with addition of two more decay modes, namely $B_s^0 \to D_s^- e^+ \nu X$ [5], and $B_s^0 \to D_s^- \mu^+ \nu X$ decays with $D_s^- \to K^{*0}K^-$, $K^{*0} \to K^+\pi^-$ [6]. The K^{*0} and the ϕ candidates are required to be consistent with known mass and width [7] of these two resonances.

Muons are required to have a $p_T > 1.5$ GeV/c and are identified in a pseudo-rapidity region of $|\eta| < 2.0$. Electrons are required to have $p_T > 2.0$ GeV/c and are identified in a pseudo-rapidity region of $|\eta| < 1.1$. The D_s^- and B_s^0 decay products are constrained to originate from a common vertex and the B_s^0 and D_s^- decay vertices are required to be significantly displaced from the $p\bar{p}$ collision vertex. Fig. 1 shows the mass distribution of the D_s candidate for the $B_s^0 \to D_s^- e^+ \nu X$ decay mode.

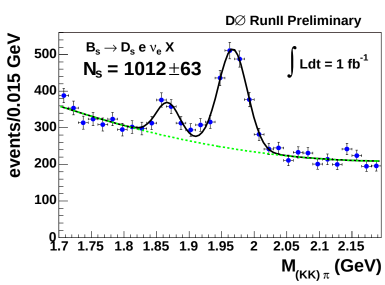

Fig. 1. The D_s invariant mass distribution where $D_s\phi\pi$ for $B_s^0 \to D_s^- e^+ \nu X$ decay mode

The $K^{*0} \to K^+\pi^-$ decay mode requires special treatment on account of large reflections, as both real physics processes and combinatorial background contribute to the signal peak. This is the signal mode, $D_s^- \to K^{*0}K^-$, $K^{*0} \to K^+\pi^-$, the physics processes, $D^+ \to K^-\pi^+\pi^+$ or $D^+ \to K^{*0}\pi^+(K^{*0} \to K^+\pi^-)$, $\Lambda_c^+ \to K^+\pi^-p^+$, $D^+ \to K^{*0}K^+(K^{*0} \to K^+\pi^-)$ (Cabibbo suppressed) and combinatorial background. One can fit for these contributions in an unbinned likelihood fit, which is discussed later. Fig. 2 shows the fit to the mass distribution of the $M_{K\pi K}$ system with the individual contributions superimposed.

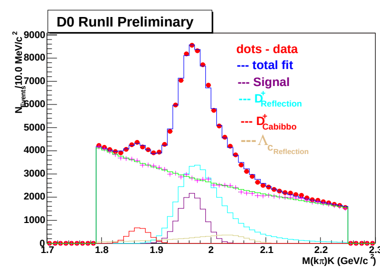

Fig. 2. The $M_{(K\pi)K}$ invariant mass distribution where $D_s \to K^{*0}K$ for $B_s^0 \to D_s^- \mu^+ \nu X$ decay mode

3. Flavor Tagging

The flavor of the initial state of the B_s^0 is determined using a likelihood ratio method, based on the properties of the other b-hadron in the event (opposite side tagging). The performance of any tagger is characterized by its efficiency and purity η_s or dilution defined as $\mathcal{D} = 2\eta_s - 1$. The efficiency is defined as $\epsilon = N_{tag}/N_{tot}$, where N_{tag} is the number of tagged B_s^0 mesons and N_{tot} is the total reconstructed B_s^0 mesons and the dilution is defined as $\mathcal{D} = \frac{N_{RS} - N_{WS}}{N_{tag}}$, where N_{RS} and N_{WS} are the right-sign and wrong-sign tags respectively. We calibrate the flavor tagger using $B \to \mu + \nu D^{*-}$ events, extracting the B_d oscillation parameter Δm_d and the dilution $\mathcal{D}$ as a function of a tag variable d (whose sign indicates a b or $\bar{b}$, and its value indicates the "b"-ness of the tag), to provide an event-by-event "predicted" dilution which is used in the unbinned likelihood fit, to be described later. More details can on the development of flavor tagging and results can be found here [8].

4. Proper decay time

In semileptonic decays the proper time gets smeared due to the presence of neutrino and other missing particles. To take this into account we introduce a K factor estimated from Monte Carlo (MC) simulation. It is defined as the distribution of $K = p_T(lD_s)/p_T(B)$ and it is estimated for each decay channel contributing to the B_s^0 candidates, where l stands for lepton(electron or muon). The real proper decay length is related to the measured or visible proper decay length (l_M), by the relation $ct(B_s^0) = l_M K$ where $l_M = M(B_s^0) \cdot (L_T)/(p_T(lD_s))$ is the measured visible proper decay length (l_M). L_T is the distance from the primary vertex to the B_s^0 decay vertex in the transverse plane projected onto the lD_s momentum, and $M(B_s^0)$ is the mass of the B_s^0 meson as obtained from PDG [7].

5. Unbinned likelihood fit

An unbinned likelihood fit is used to describe and fit for the B_s^0 oscillation. All flavor tagged events with $1.72 < M(D_s) < 2.22$ GeV/c^2 are used in the fit. The likelihood $\mathcal{L}$ for an event to arise from a specific source in the sample depends event-by-event on l_M, its uncertainty σ_{l_M}, the invariant mass of the candidate D_s candidate, the predicted dilution $\mathcal{D}(d)$ (d being the tag variable described in section 3), and the selection likelihood ratio variable y_{sel}. All the p.d.f's are determined from data, except for l_M which is determined from MC. But we introduce a scale factor determined from data which we discuss later.

The likelihood is given by $\mathcal{L} = -2\sum_n F_n$, where $F_n = f_{sig}F_{sig} + (1 - f_{sig})F_{bkg}$. The signal fraction is determined from the mass fit to the $M_{KK\pi}$ distribution. The signal p.d.f is given by the product of the individual p.d.f's as discussed above.

The p.d.f for the VPDL distribution is a sum of contributions from all species of B meson decays which can contribute to the signal peak and contribution from $c\bar{c}$ decays. The ideal expected p.d.f for the B_s^0 mesons for example is given by,

$$p_s^{nos(osc)}(x, K, d_{pr}) = \frac{K}{c\tau_{B_s}} exp(-\frac{Kx}{c\tau_{B_s}}) \cdot 0.5 \cdot (1 + (-)\mathcal{D}(d) cos(\Delta m_s \cdot Kx/c)) \quad (1)$$

For the other species of B mesons which can contribute to the same final state, one can write similar p.d.f's. We then take into account detector effects, by convoluting with a gaussian resolution function, and multiplying the reconstruction efficiency of each decay mode as a function of lifetime.

The background p.d.f's have contributions from prompt background, fake vertices and long lived background. The background fraction contributions to the VPDL and the B_s^0 lifetime were determined from a lifetime fit to the tagged data sample. The B_s^0 lifetime obtained was used in the unbinned likelihood fit.

In the case of $\phi\pi$ decay mode, the mass p.d.f's are parametrized by Gaussian or double Gaussian and an exponential background. In the case of $K^{*0}K$ decay mode, the individual fractions which contribute to the signal peak, can be parametrized in terms of a reflection variable R. This is defined below for the $D^- \to K^+\pi^-\pi^-$ mode, for example, where a π is assigned the mass of a kaon and a similar expression can be written for the Λ_c decay mode where a proton is assigned the mass of a kaon.

$$R = \frac{E_{K\pi}(E_K - E_\pi)}{M_K^2 - M_\pi^2} \quad (2)$$

and the shifted mass, M_R of the $K\pi$"K" system is related to the real mass M_D by the equation, $M_R^2 = M_D^2 + (1 + 2R)(M_K^2 - M_\pi^2)$.

The signal p.d.f for the mass distribution in the case of $K^{*0}K$ mode is then given as below:

$$P_i^j(M) = \frac{1}{\sqrt{2\pi}\sigma_j \; exp(-\frac{(M-M_i^j(R_i))^2}{2\sigma_j^2})}, \quad (3)$$

where M_i^j is the shifted mass.

6. VPDL scale factor

The VPDL uncertainty is determined by the vertex fitting procedure, track parameters, and track parameter uncertainties. To account for any imperfections in modeling of detector uncertainties, resolution scale factors are introduced by examining the pull distribution of $J/\psi \rightarrow \mu^+\mu^-$ ($B_s^0 \rightarrow D_s^-\mu^+\nu X$ mode) and $J/\psi \rightarrow e^+e^-$ ($B_s^0 \rightarrow D_s^- e^+\nu X$ mode) decays. The J/ψ mass distribution for the di-electron mode can be seen in Fig. 3.

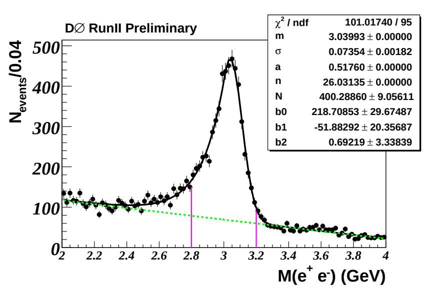

Fig. 3. The J/ψ mass distribution for the di-electron mode

7. Amplitude Scan

The likelihood term described above is modified by introducing an amplitude term $\mathcal{A}$ in front of the oscillatory cosine term, such that,

$$\mathcal{L} \propto 1 \pm \mathcal{A}\,\mathcal{D}\cos(\Delta m_s t) \quad (4)$$

More details on this method can be found in this report [9]. The parameter $\mathcal{A}$ is free in the fit while $\mathcal{D}$ is known and Δm_s is varied. The value of Δm_s where $\mathcal{A}$ is consistent with 1 and inconsistent with 0 would then give the Δm_s parameter. All values of Δm_s are for which $\mathcal{A}+1.645\,\sigma_{\mathcal{A}} < 1$ are then excluded at 95% confidence level. The sensitivity of the mixing measurement is defined as the Δm_s value for which $1.645\,\sigma_{\mathcal{A}} = 1$.

Using the $B_s^0 \rightarrow D_s^-\mu^+\nu X$, $D_s^- \rightarrow \phi\pi^-$ decay mode, we see an $\mathcal{A}$ consistent with unity at around 19 ps^{-1} as seen in Fig. 4. To assess the significance of the peak the deviation of -logL from the minimum is plotted as a function of Δm_s in Fig. 5. It shows a preferred value of 19 ps$^-$1, while the deviation from the minimum indicates an oscillation frequency of $17 < \Delta m_s < 21$ ps$^-$1 at the 90% confidence level (C.L.), the uncertainties being approximately gaussian inside this interval. To test the statistical significance of the observed minimum, an ensemble test was performed, assigning each candidate a random tag, which effectively simulates infinite B_s^0 oscillation frequency. The probability to observe such a minimum in the range $16 < \Delta m_s < 22$ ps$^-$1 is found to be (5.0 ± 0.3)%.

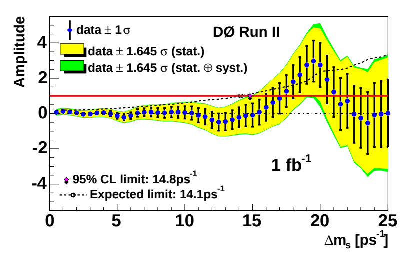

Fig. 4. The $\mathcal{A}$ vs Δm_s scan for $B_s^0 \rightarrow D_s^-\mu^+\nu X$, $D_s^- \rightarrow \phi\pi^-$ decay mode

The amplitude scans for the $B_s^0 \rightarrow D_s^- e^+\nu X$ and $B_s^0 \rightarrow D_s^-\mu^+\nu X$, $D_s^- \rightarrow K^{*0}K^-$ decay modes can be seen in Figs. 6 and 7.

The combination of the three modes [10] yields a 95% C.L. limit on the $B_s^0 - \bar{B}_s^0$ oscillation frequency $\Delta m_s > 15.0$ ps^{-1}. with the corresponding expected limit of 16.5 ps^{-1}. The combined scan can be seen in Fig. 8.

The program "combos" [11] developed at LEP is used for the combination. Uncertain-

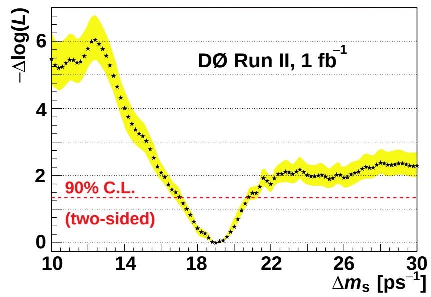

Fig. 5. The $\mathcal{A}$ vs Δm_s scan for $B_s^0 \to D_s^- \mu^+ \nu X$, $D_s^- \to \phi\pi^-$ decay mode

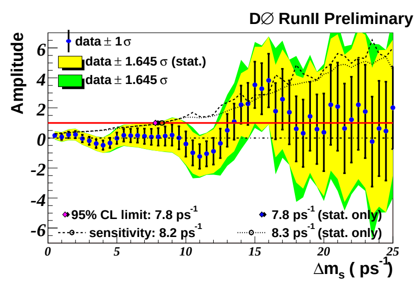

Fig. 6. The $\mathcal{A}$ vs Δm_s scan for $B_s^0 \to D_s^- e^+ \nu X$ decay mode

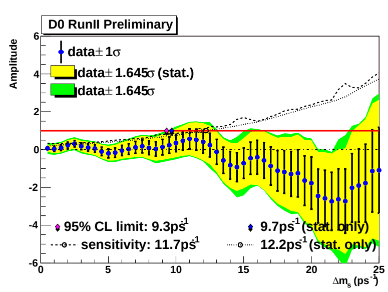

Fig. 7. The $\mathcal{A}$ vs Δm_s scan for $B_s^0 \to D_s^- \mu^+ \nu X$, $D_s^- \to K^{*0} K^-$ decay mode

ties in the following parameters are considered as correlated :

- Br $(B_s^0 \to D_s^- \mu^+ \nu X)$
- Br $(B_s^0 \to X D_s D_s)$
- Signal decay length resolution for $\mu\phi\pi$ and $\mu K^{*0} K$ decay modes.
- $\Delta\Gamma/\Gamma$.

The combined likelihood curve has a preferred value of $\Delta m_s = 19$ ps^{-1}, with a 90% confidence level interval of $17 < \Delta m_s < 21$ ps^{-1}, assuming Gaussian uncertainties. The probability for a background to produce a similar dip in the same interval is estimated to be 8 %.

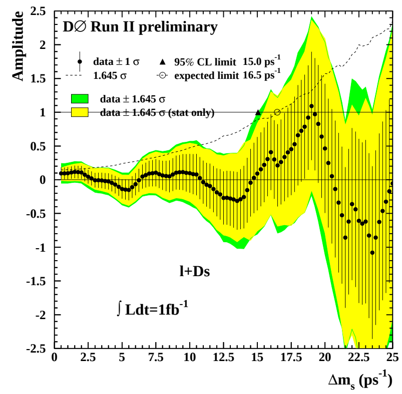

Fig. 8. The combined amplitude scan for three decay modes

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