Fermi National Accelerator Laboratory

FERMILAB-Conf-95/288

B_s Mixing Via ψK^*

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August 1995

From the Proceedings for *BEAUTY '95, 3rd International Workshop on B Physics at Hadron Machines*, Oxford, England, July 10-14, 1995

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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Abstract

The decay mode $B_s \to \psi \overline{K}^*$ is suggested as a very good way to measure the B_s mixing parameter x_s. These decays can be gathered using a $\psi \to \ell^+\ell^-$ trigger. This final state has a well resolved four track decay vertex, useful for good time resolution and background rejection.

Presented at
BEAUTY '95 - 3rd International Workshop on B-Physics at Hadron Machines

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1 Introduction

Measurement of B_s mixing would accurately determine one side of the so called "unitarity" triangle, because theoretical uncertainties mostly cancel when the ratio of B_s to B_d mixing is used [1].

Time dependent mixing measurements using dileptons at LEP have given precise values for the mixing parameter x_d, and have shown that $x_s > 8$ at 90% confidence level [2]. Standard model expectations are that $60 > x_s > 12$ [3]. In order to make these measurements the decay time is calculated according to:

$$t = \frac{L}{c\beta\gamma}, \tag{1}$$

where L is the decay length, c the speed of light and $\beta\gamma$ is equal to the momemtum divided by the mass. The error in t is given by

$$\sigma_t^2 = \left(\frac{\sigma_L}{c\beta\gamma}\right)^2 + \left(\frac{t\sigma_{\beta\gamma}}{\beta\gamma}\right)^2, \tag{2}$$

where the first term arises from the error in decay length and the second arises from the error in determining the B_s momentum.

Use of several modes have been suggested for measuring x_s with a D_s^+ in the final state. They are listed in Table 1 along with their predicted branching ratios [4].

Table 1: Branching Ratios for $B_s \to D_s$ Decays

Mode	B_s rate	Product branching fraction
$D_s^+\ell^-\overline{\nu}$	0.105	9×10^{-3}
$D_s^+\pi^-$	$(2.6 \pm 0.4) \times 10^{-3}$	1.1×10^{-4}
$D_s^+\pi^+\pi^-\pi^-$	$(6.3 \pm 2.6) \times 10^{-3}$	2.7×10^{-4}

The observable rate for $D_s^+ \to K^+K^-\pi^-$ through the intermeadiate states $\phi\pi^+$ and $K^{*o}K^-$ is taken as 4.3%.

Unfortunately, there are several problems with using these modes to measure x_s. The semileptonic decay has a large branching ratio, 21% for the sum of μ and electron modes, but the undetected neutrino causes the determination of the B_s momentum to have a relatively large uncertainty. This limits the maximum possible x_s reach to about 12.

The $D_s^+\pi^-$ mode has a relatively low branching ratio. Furthermore, the B decay vertex must be constructed by first forming a D_s decay vertex and then swimming back this vector to intersect with the π^-. There also may be combinatorial background problems as D_s production in B decays is substantial, about 12%. The background problems could be worse in the higher multiplicity $D_s^+\pi^+\pi^-\pi^-$ mode.

2 Use of $B_s \to \psi\overline{K}^*$, $\overline{K}^* \to K^\mp\pi^\pm$

The simplest B_s final states with ψ mesons are $\psi\eta$ and $\psi\phi$. Neither of these can be used to measure B_s mixing because they are not flavor specific, i.e. the final state can arise either from a B_s or a $\overline{B_s}$. Several years ago the Cabibbo suppressed decay $B_s \to \psi\overline{K}^*$, $\overline{K}^* \to K^\mp\pi^\pm$ was suggested as a possible way to investigate mixing phenomena [5]. Here the sign of the kaon charge distinguishes between B_s or $\overline{B}_s$.This mode would proceed via the diagram shown in Fig. 1. The recent CLEO observation of $B^- \to \psi\pi^-$ decays at the level expected from Cabibbo suppression is good evidence for the existance of such diagrams [6]. They measure

$$\frac{\mathcal{B}(B^- \to \psi\pi^-)}{\mathcal{B}(B^- \to \psi K^-)} = (5.2 \pm 2.6)\% \approx \lambda^2. \tag{3}$$

We predict the branching ratio

$$\mathcal{B}(B_s \to \psi\overline{K}^*) = \mathcal{B}(B_d \to \psi K^*) \times \lambda^2 = 1.7 \times 10^{-3} \times 0.05 = 8.5 \times 10^{-5}. \tag{4}$$

Another way of describing the yield of these decays is to form the ratio with respect to ψK_s. We have

$$\frac{\mathcal{N}(B_d \to \psi K_s)}{\mathcal{N}(B_s \to \psi\overline{K}^*)} = \frac{\mathcal{B}(B_d \to \psi K_s) \times \mathcal{B}(K_s \to \pi^+\pi^-) \times \mathcal{B}(\psi \to \mu^+\mu^-)}{\mathcal{B}(B_s \to \psi\overline{K}^*) \times \mathcal{B}(\overline{K}^* \to K^-\pi^+) \times \mathcal{B}(\psi \to \mu^+\mu^-)} = 5, \tag{5}$$

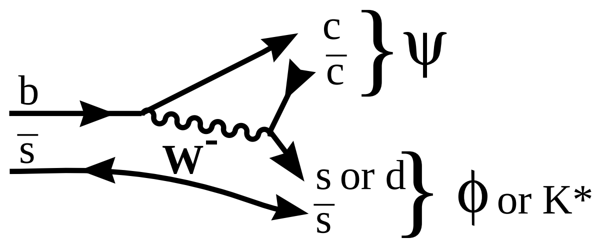

Figure 1: Weak decay diagrams for $\overline{B}_s \to \psi\phi$ and ψK^*. The K^* final state occurs when the virtual W^- materializes as a $\bar{c}d$ pair.

where $\mathcal{N}$ indicates the number of observed events, for an equal sample of B_d and B_s. We have assumed that the detection efficiency for $\overline{K}^* \to K^-\pi^+$ is equal to that for $K_s \to \pi^+\pi^-$. We expect, however, that the K_s efficiency is significantly lower due to the long decay distance of the K_s. We need to correct for the difference in the relative production ratio between B_d and B_s. An estimate is obtained from LEP data by using the measurement of the ratio of opposite sign dileptons to like sign dileptons and comparing with the same number found at the $\Upsilon(4S)$, where B_s aren't produced. Such a calculation gives 1/3-1/4 the number of B_s relative to the number of B_d. Therefore we expect about 1/15 the number of reconstructed and flavor tagged $B_s \to \psi\overline{K}^*$ as $B_d \to \psi K_s$. For hadron collider experiments several thousand tagged ψK_s events implies several hundred tagged $\psi\overline{K}^*$ events.

There are several significant advantages using the $\psi\overline{K}^*$ decay mode. A $\psi \to \ell^+\ell^-$ trigger can be used to select these events. Furthermore, this decay mode has a particularly useful topology, having four charged tracks emanating from a single decay vertex. This is important both for background reduction and for exquisite decay time resolution.

Let us consider the x_s sensitivity. With this fully reconstructed mode the momentum resolution can be made very good, so there is little effect from the error in γ (second term in equation 2). We have made estimates of the time resolution possible in both "forward" and "central" detectors at the FNAL collider. These detectors consist of silicon strips, tracking chambers and have a dipole field for the foward detector and a solenoidal field for the central detector. The simulation program is capable of correctly taking into account the track smearing due to multiple scattering and detector resolution, although the full pattern recognition is not attempted. While detailed resolutions are subject to exact detector configurations some clear conclusions have emerged. We show the time resolution as a function of pseudorapidity (η) for the forward and central geometries in Fig. 2. Similarly the time resolution is plotted as a function of $\beta\gamma$ in Fig 3.

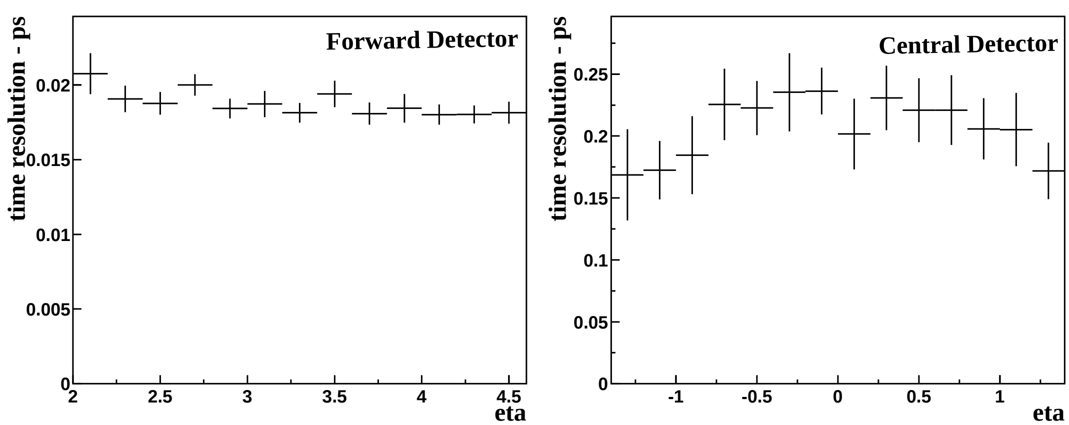

Figure 2: The time resolution plotted as a function of η for a forward detector ($2.0 < \eta < 4.5$) and a central detector ($|\eta| < 1.5$) for the decay $B_s \to \psi \overline{K}^*$ produced at a hadron collider with a center of mass energy of 1.8 TeV.

The time resolution, σ_t for the forward geometry is approximately 0.02 ps, while it is about a factor of 10 worse, 0.2 ps for the central geometry. σ_t appears to be independent of η and independent of γ for $\gamma > 2$. The latter can be understood as being a result of poorer decay length resolution in direct proportion to γ, a well

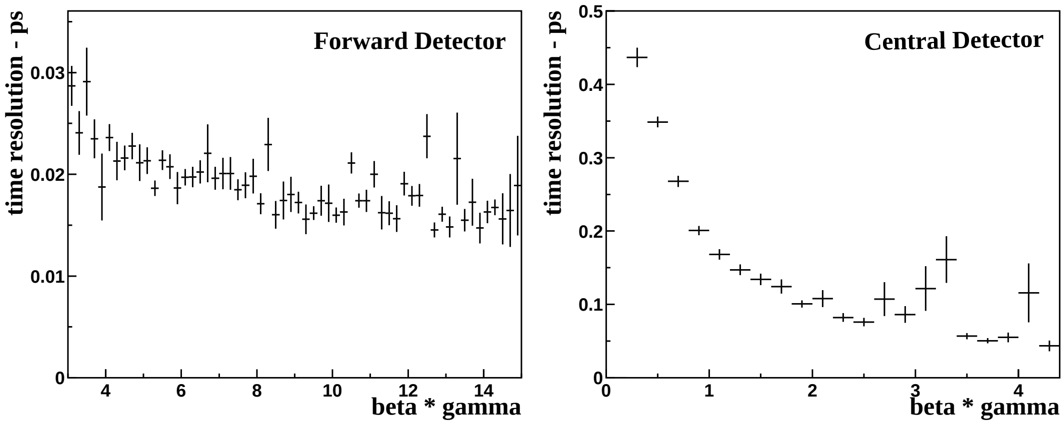

Figure 3: The time resolution plotted as a function of $\beta\gamma$ for a forward detector $(2.0 < \eta < 4.5)$ and a central detector $(|\eta| < 1.5)$ for the decay $B_s \to \psi \overline{K}^*$ produced at a hadron collider with a center of mass energy of 1.8 TeV.

know effect explained by the folding in spatial angle of the decay products as γ increases. The superiority of the forward geometry results from the decay tracks not being limited from multiple scattering and the ability to place detectors with inherent 10μm resolution inside the beam pipe.

The number of events as a function of decay time is given by

$$N(t) = N_o e^{-\frac{t}{\tau}} \left(1 + cos(x_s \frac{t}{\tau})\right) . \tag{6}$$

These oscillations are rather rapid on the scale of the B_s lifetime, τ. A picture is shown in Fig. 4, where we have also included a Gaussian showing the smearing caused by have a time resolution of 0.05 ps. This resolution was chosen from a naive formula, that the time resolution will cause degradation in the x_s measurement if it is poorer than $1/x_s$ (in units of ps). Thus, the good time resolution of the forward FNAL type detector in the ψK^* mode would allow a measurement of x_s up to values of approximately 50. The average γ for accepted decays is 9.5, giving an average decay length of 4.3 mm. For this γ the resolution in decay length is 50 μm.

To estimate the real reach in x_s for a particular experimental proposal requires studies not only of the vertex resolution, but of the backgrounds and fitting procedure

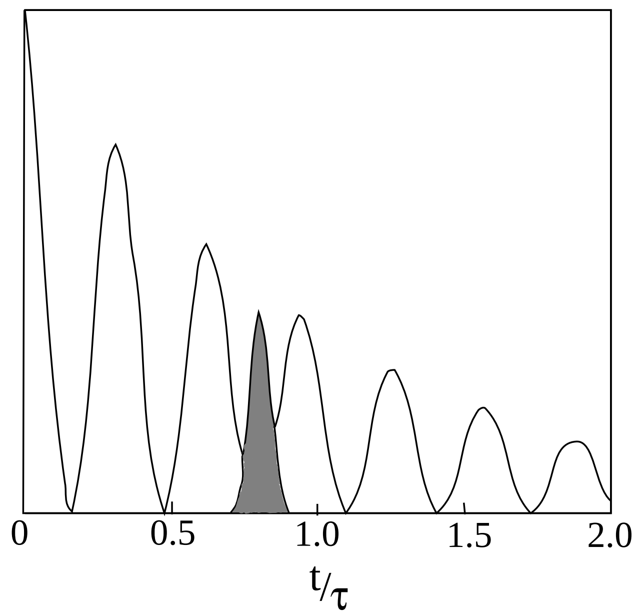

Figure 4: The time distribution $e^{-\frac{t}{\tau}}\{1 + cos\left(x_s\frac{t}{\tau}\right)\}$ for B_s decay for $x_s = 20$. The shaded region shows a Gaussian with time resolution of 0.05 ps.

as well. It is not the purpose of this paper to present such results. However, the measurement of this channel sets some requirements for a B detector. A detector with good vertex resolution will be able to take advantage of the clean J/ψ signal and the four track B decay vertex to significantly reduce the background from generic B decays. Excellent mass resolution will be needed to eliminate backgrounds from $B_d^0 \to J/\psi K^*$. Excellent particle identification will be required to identify the K and π in the K^* decay and to remove background from other channels such as $B_s \to J/\psi\phi$.

Previous attempts at comparing various experiments [7] have used a naive estimate that the number of tagged B_s required to measure x_s to 20% of its value (i.e. 5 σ requires a number of events:

$$N_{req} = \frac{5^2}{D^2 d_{time}^2}, \tag{7}$$

where D is the dilution from mistagging including away side mixing and d_{time} is the dilution from having finite time resolution. D is taken as approximately 0.5 for most experiments. For $x_s < 1/\sigma_t$, d_{time} is close to one. Therefore it appears that it only takes a few hundred fully reconstructed and tagged ψK^* events to measure x_s anywhere within the standard model range. We encourage a full Monte Carlo simulation of this process.

3 Conclusions

The decay mode $B_s \to \psi \overline{K}^*$ can be used to measure x_s. It is relatively easy to trigger on the $\psi \to \ell^+\ell^-$ decay. It has been shown that a forward detector in a hadron collider has excellent time resolution, of the order of 0.02 ps, which is sufficient to measure x_s within the standard model range should a few hundred tagged events be accumulated.

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[4] The B_s branching ratios are assumed to be equal to the B_d branching ratios. In the case of the three pion final state, it is also assumed that rate for $B_d \to D^{*+}\pi^+\pi^-\pi^-$ is equal to the rate for $B_d \to D^+\pi^+\pi^-\pi^-$.

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