\[ B_s \] lifetime measurement in the CP-odd channel
\[ B_s^0 \rightarrow J/\psi f_0(980) \] by the D0 experiment

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Abstract. The lifetime measurement of the \( B_s^0 \) meson in the decay channel \( B_s^0 \rightarrow J/\psi f_0(980) \) is reported, which is a CP-odd state. Using 10.4 fb\(^{-1}\) of data collected with the D0 detector in Run II of the Tevatron, the lifetime of the CP-odd component of the \( B_s^0 \) meson is measured to be \( \tau(B_s^0) = 1.70 \pm 0.14 \) (stat) \pm 0.05 (syst) ps.

1. Introduction
The \( B_s^0 \rightarrow J/\psi f_0(980) \) channel is a pure CP-odd eigenstate decay. Indeed, the \( B_s^0 \) is a spin 0 state, the resonance \( f_0(980) \) has \( J^{PC} = 0^{++} \) and the \( J/\psi \) has \( J^{PC} = 1^{--} \). For this reason, this channel is a very good alternative to the well known golden channel \( B_s^0 \rightarrow J/\psi \phi \) to study the \( B_s^0 \) mixing, because the last one requires an angular analysis to obtain the CP-even and CP-odd contributions of the eigenstates [1]. The \( B_s^0 \rightarrow J/\psi f_0(980) \) decay has been observed by the LHCb, Belle, CDF and D0 collaborations [2, 3, 4, 5]. Due to its CP-odd nature, in the absence of CP violation in mixing, the final state can be produced only by the decay of the \( B_s^0 \) heavy mass eigenstate, and the measurement of the \( B_s^0 \rightarrow J/\psi f_0(980) \) lifetime can be translated into a measurement of the heavy mass eigenstate lifetime. In 2011, the CDF collaboration reported a first measurement of the lifetime [4], obtaining \( c\tau = (510 \pm 36 \pm 9) \) \( \mu \)m. After that, the LHCb collaboration reported a lifetime of \( c\tau = (510 \pm 12 \pm 8) \) \( \mu \)m [6].

In this talk, a measurement by the D0 collaboration of the \( B_s^0 \) lifetime in the CP-odd channel \( B_s^0 \rightarrow J/\psi f_0(980) \) is reported.

2. \( B_s^0 \) mass and CP eigenstates
The \( B_s^0 \) (with quark content \( \bar{b}s \)) and \( \bar{B}_s^0 \) (quark content \( b\bar{s} \)) mesons are produced as flavor eigenstate at colliders. However, neither conservation law prevents \( B_s^0 \) and \( \bar{B}_s^0 \) from having transitions. Therefore, they oscillate between themselves. After the production, they propagate as mass eigenstates

\[ |B_L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle; \quad |B_H\rangle = p|\bar{B}_s^0\rangle - q|B_s^0\rangle, \]

being \( p \) and \( q \) complex parameters with the normalization condition \( |p|^2 + |q|^2 = 1 \). The state \( |B_H\rangle \) corresponds to the heavy mass eigenstate and the state \( |B_L\rangle \) to the light one.

On the other hand, CP transformation exchanges the \( B_s^0 \) and \( \bar{B}_s^0 \) states

\[ CP|B_s^0\rangle = e^{i\xi}|B_s^0\rangle; \quad CP|\bar{B}_s^0\rangle = e^{-i\xi}|\bar{B}_s^0\rangle. \]
Based on this, eigenstates of CP can be defined

\[ |B_\pm\rangle = \frac{1}{\sqrt{2}} (|B_s^0\rangle \pm e^{i\xi}|\bar{B}_s^0\rangle), \tag{3} \]

calling \(|B_+\rangle\) and \(|B_-\rangle\) the even and odd eigenstates, respectively. If CP violation is neglected in mixing, it can be shown that \(q/p = \pm e^{i\xi}\), giving

\[ CP|B_H\rangle = -|B_H\rangle; \quad CP|B_L\rangle = |B_L\rangle. \tag{4} \]

That is, the mass eigenstates are also eigenstates of CP [7]. The heavy mass eigenstate coincides with the odd eigenstate of CP, and the light mass eigenstate corresponds to the even eigenstate of CP.

So, a measurement of the \(B_s^0\) lifetime in a pure CP eigenstate gives information about the lifetime of the heavy or light mass eigenstates, which are important parameters to improve the understanding of the mixing process in the \(B_s^0\) system.

3. The D0 detector

The D0 detector is one of the two large particle physics experiments at Fermilab’s Tevatron collider. The D0 collaboration began in 1983 and involved hundreds of scientists from 77 institutions. The experiment was upgraded from 1996 to 2001 and ran until the Tevatron ceased operations in 2011.

The D0 detector is described in detail elsewhere [8]. The detector components most relevant to this analysis are the central tracking and the muon systems. Preshower detectors and electromagnetic and hadronic calorimeters surround the tracker. The muon system is located outside the calorimeter, and consists of multilayer drift chambers and scintillation counters inside 1.8 T iron toroidal magnets, and two similar layers outside the toroids.

4. Data selection

To reconstruct the \(B_s^0\) candidates, first a reconstruction of \(J/\psi \rightarrow \mu^+\mu^-\) candidates is performed looking for a pair of muon tracks with opposite charge and common vertex. Each \(J/\psi\) candidate must have a transverse momentum greater than 1.5 GeV/c and a mass inside the 2.80 – 3.35 GeV/c^2 window. After that, a search is made for \(\pi^+\pi^-\) tracks forming a common vertex with the \(J/\psi\) candidate. The invariant mass of the two pions is required to be in the mass interval 880 – 1080 MeV/c^2, consistent with the \(f_0(980)\) resonance. The \(B_s^0\) candidates are reconstructed by a constrained fit to a common vertex for the four charged tracks, requiring an invariant mass inside the range 5.1 – 5.8 GeV/c^2 and a \(P_T\) greater than 6.0 GeV/c.

Figure 1 shows the invariant mass distribution of the \(B_s^0\) candidates after the selection and cuts, in which several background sources are identified.

- Cross-feed contamination: mainly produced by the combination of \(J/\psi\) mesons from b hadron decays with another particles.
- Combinatorial background: coming from the random combinations of \(J/\psi\) mesons with additional tracks.
- \(B^+\) contamination: \(B^+ \rightarrow J/\psi K^+\) decays in which the kaon is misidentified as a pion, and an extra track accidentally forms a vertex with the \(J/\psi K^+\).
5. $B^0_s$ lifetime measurement

The lifetime measurement is based on the transverse decay length method. The transverse decay length is defined as

$$L_{xy} = \vec{L}_{xy} \cdot \vec{P}_T / P_T,$$

(5)

where $\vec{P}_T$ is the transverse momentum vector of the $B^0_s$, and $\vec{L}_{xy}$ is defined as figure 2 shows. The proper transverse decay length $\lambda$ is obtained applying a boost to $L_{xy}$. If $\beta$ and $\gamma$ are the Lorentz factors

$$\lambda = \frac{L_{xy}}{\langle \beta \gamma \rangle_T} = L_{xy} \frac{M_B}{P_T},$$

(6)

where $M_B$ is the mass of the $B^0_s$ taken from the world average reported in the Particle Data Group [9].

To measure the lifetime, a simultaneous likelihood fit to the mass and proper decay length distributions is performed. The mass distribution of the signal is modeled by a Gaussian. In the case of the mass distribution of the background components, the cross-feed contamination is modeled by a Gaussian function, the combinatorial background by an exponential function, and the $B^+$ contamination is modeled as a template determined by the following way: the events in the data sample are reconstructed as $B^+ \rightarrow J/\psi K^+$ to identify a peak associated with a $B^+$, the events inside the mass window are selected and reconstructed, adding an extra pion, as $B^0_s \rightarrow J/\psi \pi^+ \pi^-$, and the shape of the distribution is determined by a template. Details about the likelihood function and the models are described in Ref. [10].
The fit yields 494 ± 85 events and a lifetime of $c\tau = 504 \pm 42 \, \mu m$ for the signal component. Figures 3 and 4 show the distributions of the data with the fit result superimposed. To confirm the presence of the $f_0(980)$ resonance, the events within one $\sigma$ of the $B_0^s$ mass are selected, and the mass distribution of the $\pi^+\pi^-$ pairs is fit with a Flatté model [11].

![Figure 3](image3.png)  
**Figure 3.** Invariant mass distribution for $B_0^s$ candidates. The model obtained from the fit and each one of its components are superimposed [10].

![Figure 4](image4.png)  
**Figure 4.** Proper transverse decay length distribution for $B_0^s$ candidates. The model obtained from the fit and each one of its components are superimposed [10].

![Figure 5](image5.png)  
**Figure 5.** Invariant mass distribution of the $\pi^+\pi^-$ pairs coming from events within ±1$\sigma$ of the $B_0^s$ mass [10].

### 6. Systematic uncertainties

Several sources of systematic uncertainty are considered. Table 1 summarizes the uncertainties with its source and the total uncertainty, determined by combining individual uncertainties in quadrature. The uncertainty related to alignment has been previously determined. The $\pi^+\pi^-$ invariant mass window has is varied from its nominal width of 200 MeV/c^2 to between 160 and 240 MeV/c^2. The modeling and fitting method is tested with data generated in pseudoeexperiments, in which a bias of -4.4 $\mu m$ arises for an input lifetime of 500 $\mu m$ and 500 signal events. This bias is corrected in the nominal result. Finally, the parametrization of the models used to describe the distributions are changed, and the variation with respect to the nominal result is taken as a systematic uncertainty.
Table 1. Summary of systematic uncertainties.

| Source                    | Variation (µm) |
|---------------------------|---------------|
| Alignment                 | 5.4           |
| \(\pi^+\pi^-\) invariant mass window | 8.0          |
| Fit bias                  | 4.4           |
| Distribution models       | 12.5          |
| **Total (combining in quadrature)** | **16.4** |

7. Conclusions
In summary, the lifetime of the \(B^0_s\) is measured [10], obtaining:

\[
c\tau(B^0_s) = 508 \pm 42 \text{ (stat)} \pm 16 \text{ (syst) } \mu\text{m, (7)}
\]

from which:

\[
\tau(B^0_s) = 1.70 \pm 0.14 \text{ (stat)} \pm 0.05 \text{ (syst) } \text{ps, (8)}
\]

in the decay channel \(B^0_s \rightarrow J/\psi \pi^+\pi^-\) with \(880 \leq M_{\pi^+\pi^-} \leq 1080 \text{ MeV}/c^2\). Neglecting CP violation in this decay, the measurement can be translated into the width of the heavy mass eigenstate of the \(B_s^0\)

\[
\Gamma_H = 0.59 \pm 0.05 \text{ (stat)} \pm 0.02 \text{ (syst) } \text{ps}^{-1}. \quad (9)
\]

Our result is in good agreement with previous measurements from LHCb and CDF collaborations, and provides an independent confirmation of the longer lifetime for the CP-odd eigenstate of the \(B_s^0/\bar{B}_s^0\) system.

8. Acknowledgements
The D0 Collaboration thanks the staffs at Fermilab and collaborating institutions, and acknowledges support of the many international funding agencies which made these experimental programs possible.

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