Review of Heavy Flavor Physics at the Tevatron

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The D0 and CDF detectors at the Fermilab Tevatron have each accumulated more than 9 fb$^{-1}$ of integrated luminosity. The corresponding large datasets enable the two experiments to perform unprecedented studies of heavy flavor hadron properties. We present recent D0 and CDF measurements, focusing on rare decays and CP violation in $B$-meson decays.

1. Introduction

Flavor Physics probes new phenomena by either searching for small deviations from the Standard Model (SM) based theoretical predictions or by measuring quantities which are highly suppressed within the SM. Searching for small deviations from the SM are performed using large strange, charm or bottom hadron samples, mostly by kaon experiments of B factories. Measurements of highly suppressed quantities, such as CP violation phases and asymmetries in the neutral $B_s^0$-meson system or searches for rare $B$ decays, are performed with the hope that new physics effects would be large enough to significantly affect the measured quantities and so, lead to observations of deviations from the SM expectations.

The D0 and CDF detectors at the Fermilab Tevatron have each accumulated more than 9 fb$^{-1}$ of integrated luminosity. The corresponding large datasets enable the two experiments to perform unprecedented studies of heavy flavor hadron properties. We present recent D0 and CDF measurements, focusing on rare decays and CP violation in $B$-meson decays.

2. Search for $B^0_s \rightarrow \mu^+ \mu^-$ Decays

Processes involving Flavor Changing Neutral Currents (FCNC) provide excellent opportunities to search for evidence of new physics since in the SM they are forbidden at tree level and can only occur through higher order loop diagrams. Two such processes are the decays $B_{s/d} \rightarrow \mu^+ \mu^-$. In the SM, these decays are both Cabibbo and helicity suppressed. Their branching ratios are predicted with 10% accuracy $[1]$ as: $BR(B_s \rightarrow \mu^+ \mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ and $BR(B_d \rightarrow \mu^+ \mu^-) = (1.0 \pm 0.1) \times 10^{-10}$.

These predictions are one order of magnitude smaller than the current experimental sensitivity. Enhancements to the expected $B_s \rightarrow \mu^+ \mu^-$ branching fraction occur in a variety of different new physics models. For example, in supersymmetry (SUSY) models, new supersymmetric particles can increase the branching fraction $BR(B_s \rightarrow \mu^+ \mu^-)$ by several orders of magnitude at large $\tan(\beta)$, the ratio of vacuum expectation values of the Higgs doublets $[2]$. In the minimal supersymmetric standard model (MSSM), the enhancement is proportional to $\tan^6(\beta)$. For large $\tan(\beta)$, this search is one of the most sensitive probes of new physics available at the Tevatron experiments.

Using 6.1 fb$^{-1}$, the D0 experiment has published $[3]$ in 2010 an upper limit on the $B_s \rightarrow \mu^+ \mu^-$ branching ratio of $51 \times 10^{-9}$ at 95%CL. The CDF experiment has performed a recent update $[4]$ of the analysis using 7 fb$^{-1}$ of integrated luminosity which supersedes the previous CDF published result $[5]$ which used 2 fb$^{-1}$ of data.

In addition to increasing the size of the data set, the sensitivity of this analysis is improved another 20% by including events which cross regions of the tracker where the trigger efficiency is rapidly changing and by including events with muons in the forward regions. Other improvements include the use of a better neural network (NN) discriminant that provides approximately twice the background rejection for the same signal efficiency.

The events are collected using a set of dimuon triggers and must satisfy either of two sets of requirements corresponding to different topologies: CC events have both muon candidates detected in the central region (CMU), while CF events have one central muon and another muon detected in the forward region (CMX).

The baseline selection requires high quality muon candidates with transverse momentum relative to the beam direction of $p_T > 2.0 \times 2.2$ GeV/$c$ in the central (forward) region. The muon pairs are required to have an invariant mass in the range $4.669 < M(\mu \mu) < 5.969$ GeV/$c^2$ and are constrained to originate from a common well measured three-dimensional (3D) vertex. A likelihood method together with a energy loss based selection are used to further suppress contributions from hadrons misidentified as muons. A fraction of the total number
of background and simulated signal events are used to train a NN to discriminate signal from background events. The remainder are used to test for NN over-training and to determine the signal and background efficiencies.

To exploit the difference in the $M(\mu\mu)$ distributions between signal and background and the improved suppression of combinatorial background at large NN output ($\nu_{NN}$), the data is divided into sub-samples in the ($\nu_{NN}$, $M(\mu\mu)$) plane. The CC and CF samples are each divided into 40 sub-samples. There are eight bins in the $\nu_{NN}$. Within each $\nu_{NN}$ bin, five $M(\mu\mu)$ bins are employed, each 24 MeV/c$^2$ wide, centered on the world average $B_s$ ($B_d$) mass.

The number of observed events is compared to the number expected in all 80 sub-samples for the $B_d$ search region. The data are consistent with the background expectations and yield an observed limit of

$$BR(B_d \to \mu^+\mu^-) < 6.0 \times 10^{-9} \text{ at 95\% (90\%) C.L.}$$

The results for the $B_s$ region are shown in Fig. 1. There is an excess of events concentrated in the region with $\nu_{NN} > 0.97$. The p-value for background-only pseudo-experiments is 0.27\%. The excess in the 0.97 < $\nu_{NN}$ < 0.987 bin appears to be a statistical fluctuation of the background as there is no significant expectation of $B_s \to \mu^+\mu^-$ signal consistent with the observation in the two highest NN bins. The source of the data excess in the 0.97 < $\nu_{NN}$ < 0.987 range of the $B_s$ signal region is investigated. The same events, the same fits and the same methodologies are used for both $B_s$ and $B^0$ searches. Since the data in the $B^0$ search region shows no excess, problems with the background estimates are ruled out. The only peaking background in this mass region is from $B \to h^+h^-$ decays, whose contribution to the $B^0$ search window is ten times larger than to the $B_s$ search window. The NN studies find no evidence of over-training, $\nu_{NN} - m_{\mu\mu}$ correlations and no evidence for mis-modeling of the $\nu_{NN}$ shape. The most plausible explanation for the data excess in the 0.97 < $\nu_{NN}$ < 0.987 is a statistical fluctuation. If we consider only the two highest NN bins the p-value becomes 0.66\%. If $B_s \to \mu^+\mu^-$ events are included in the pseudo-experiments at the SM level ($BR = 3.2 \times 10^{-9}$) a p-value of 1.9\% (4.1\%) is obtained using all (only the highest 2) NN bins.

A log-likelihood fit is used to determine the $BR(B_s \to \mu^+\mu^-)$ most consistent with the data in the $B_s$ search region:

$$BR(B_s \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}.$$  

Additionally, 90\% C.L. bounds are set on the branching fraction:

$$4.6 \times 10^{-9} < BR(B_s \to \mu^+\mu^-) < 3.9 \times 10^{-8}.$$  

The Tevatron results are consistent with the recent measurements from the LHCb experiment, $BR(B_s \to \mu^+\mu^-) < 12(15) \times 10^{-9}$ at 90 (95\%) CL [6] and the CMS experiment $BR(B_s \to \mu^+\mu^-) < 16(19) \times 10^{-9}$ at 90 (95\%) CL [7].
3. Flavor Changing Neutral Currents in $b \to s \mu \mu$ Decays

Rare decays of bottom hadrons mediated by the flavor-changing neutral current (FCNC) process $b \to s \mu \mu$ occur in the SM through higher order amplitudes. A variety of beyond-the-standard-model (BSM) theories, on the other hand, favor enhanced rates for these FCNC decays. One can obtain rich information about the $b \to s \mu \mu$ dynamics by measuring of the branching ratios, their dependence on the di-lepton mass distributions, and the angular distributions of the decay products [8]. The CDF experiment has analyzed the following decays governed by the $b \to s \mu \mu$ transition:

$$
\Lambda_b^0 \to \Lambda^{\mu^+ \mu^-},
$$
$$
B_b^0 \to \phi^{\mu^+ \mu^-},
$$
$$
B^+ \to K^{+} \mu^+ \mu^-,
$$
$$
B^0 \to K^{*0} (892) \mu^+ \mu^-,
$$
$$
B^0 \to K^{0} \mu^+ \mu^- \text{ and }
$$
$$
B^+ \to K^{*+} (892) \mu^+ \mu^-.
$$

In addition to branching fractions and differential branching fractions of these decays, the angular distributions in $B \to K^{(*)} \mu^+ \mu^-$ decays are measured, as well. The analysis is based on a dataset corresponding to 6.8 fb$^{-1}$ of integrated luminosity. Previous iterations used 4.4 fb$^{-1}$ and 924 pb$^{-1}$, respectively [9].

The results include the first observation of the baryonic FCNC decay $\Lambda_b^0 \to \Lambda^{\mu^+ \mu^-}$ and the first measurement of its branching fraction and of the differential branching fraction as a function of squared dimuon mass. Fig. 1 shows the invariant mass distribution of $\Lambda^{\mu^+ \mu^-}$ from $\Lambda_b^0$ decays.

Most precise branching fraction measurements in $b \to s \mu \mu$ decays are determined as follows:

$$
BR(\Lambda_b^0 \to \Lambda^{\mu^+ \mu^-}) = [1.73 \pm 0.42(stat) \pm 0.55(syst)] \times 10^{-6}
$$
$$
BR(B_b^0 \to \phi^{\mu^+ \mu^-}) = [1.47 \pm 0.24(stat) \pm 0.46(syst)] \times 10^{-6}
$$
$$
BR(B^+ \to K^{+} \mu^+ \mu^-) = [0.46 \pm 0.04(stat) \pm 0.02(syst)] \times 10^{-6}
$$
$$
BR(B^0 \to K^{*0} (892) \mu^+ \mu^-) = [1.02 \pm 0.10(stat) \pm 0.06(syst)] \times 10^{-6}
$$
$$
BR(B^0 \to K^{0} \mu^+ \mu^-) = [0.32 \pm 0.10(stat) \pm 0.02(syst)] \times 10^{-6}
$$
$$
BR(B^+ \to K^{*+} (892) \mu^+ \mu^-) = [0.95 \pm 0.32(stat) \pm 0.08(syst)] \times 10^{-6}
$$

The full differential decay distribution for the decay $B \to K^{(*)} \mu^+ \mu^-$ is described by four independent kinematic variables: the di-muon invariant mass squared $q^2$, the angle $\theta_{\mu}$ between the muon $\mu^{+/−}$ direction and the direction opposite to the $B/\bar{B}$-meson in the di-muon rest frame, the angle $\theta_K$ between the kaon direction and the direction opposite to the $B$-meson in the $K^*$ rest frame, and the angle $\phi$ between the two planes formed by the di-muon and the $K−\pi$ systems. The distributions of $\theta_{\mu}$, $\theta_K$, and $\phi$ are projected from the full differential decay distribution and can be parametrized with four angular observables, $A_{FB}$, $F_{L}$, $A_{T}^{(2)}$ and $A_{in}$:

$$
\frac{d^2BR}{d\cos(\theta_{\mu})} = \frac{1}{2} F_{L} \cos^2\theta_{\mu} + \frac{1}{4} (1 - F_{L})(1 - \cos^2\theta_{K}),
$$
$$
\frac{d^2BR}{d\cos(\theta_{\mu})} = \frac{1}{2} F_{L} (1 - \cos^2\theta_{\mu}) + \frac{1}{4} (1 - F_{L})(1 + \cos^2\theta_{\mu}) + A_{FB} \cos\theta_{\mu},
$$
$$
\frac{d^2BR}{\sin2\phi} = \frac{1}{2} [1 + \frac{1}{2} (1 - F_{L}) A_{T}^{(2)} \cos2\phi + A_{in} \sin2\phi],
$$

Figure 2: Parameters $F_{L}$, $A_{FB}$ and $A_{T}^{(2)}$ as function of the di-muon invariant mass. The red curves represent the SM expectations [10] while the blue curves correspond to a supergravity model with large $\tan(\beta)$ [11].
where $\Gamma = \Gamma(B \rightarrow K^*\mu^+\mu^-)$, $A_{FB}$ is the muon forward-backward asymmetry, $F_L$ is the $K^*$ longitudinal polarization fraction, $A_T^{(2)}$ is the transverse polarization asymmetry, and $A_{IM}$ is the T-odd CP asymmetry of the transverse polarizations. Fig. 2 shows agreement between the $F_L$, $A_{FB}$ and $A_T^{(2)}$ as function of the dimuon invariant mass and the SM expectations [10]. The angular analysis results are among the most precise measurements to date. The right-handed current sensitive observables $A_T^{(2)}$ and $A_{IM}$ are measured for the first time.

4. Like-Sign Dimuon Asymmetry

The D0 collaboration presents an updated measurement [12] of the like-sign dimuon charge asymmetry in semi-leptonic decays of $b$-hadrons using a data sample corresponding to 9 fb$^{-1}$ of integrated luminosity. The like-sign dimuon asymmetry is defined as:

$$A_{sl}^b = \frac{N_{b^+}^- - N_{b^-}^+}{N_{b^+}^- + N_{b^-}^+} = C_d a_{sl}^d + C_s a_{sl}^s,$$

where $N_{b^+}^-$ and $N_{b^-}^+$ are the number of events containing two muons of same charge, produced in semi-leptonic decays of $b$-hadrons. The asymmetries $a_{sl}^q$, where $q = s/d$ are defined as:

$$a_{sl}^q = \frac{\Gamma(B_q^0 \rightarrow \mu^+X) - \Gamma(B_q^- \rightarrow \mu^-X)}{\Gamma(B_q^0 \rightarrow \mu^+X) + \Gamma(B_q^- \rightarrow \mu^-X)} = \frac{\Delta M_q}{\Delta M_q} \tan(\phi_q),$$

where $\phi_q$ is a CP violating phase and $\Delta M_q$ and $\Delta M_q$ are the mass and width difference between the eigenstates of the time propagation operator of the neutral $B^0_q$ systems. The coefficients $C_d$ and $C_s$ depend on the mean mixing probabilities and on the production rates of the $B^0$ and $B^0$ mesons [14]:

$$C_d = 0.594 \pm 0.022 \text{ and } C_s = 0.406 \pm 0.022.$$  

Using the SM predictions for $a_{sl}^q$ [15], one finds

$$A_{sl}^b (SM) = (-0.028^{+0.005}_{-0.006})\%.$$  

This theoretical uncertainties are negligible compared to the experimental sensitivity. A previous D0 analysis based on 6.1 fb$^{-1}$ of integrated luminosity [13] revealed a dimuon asymmetry of 3.2 standard deviations away from the SM expectation:

$$A_{sl}^b = (-0.00957 \pm 0.00251 (stat) \pm 0.00146 (syst)).$$  

The updated measurement not only uses an increased dataset due to increased integrated luminosity from 6.1 fb$^{-1}$ to 9 fb$^{-1}$, but also includes analysis improvements: 13% increase in data sample due to looser muon longitudinal momentum selection and 20% reduction in kaon and pion decay-in-flight backgrounds. In addition, muon impact parameter studies support the hypothesis that muons are indeed from B decays. New result is 3.9 standard deviations from the SM expectation

$$A_{sl}^b = (-0.787 \pm 0.172 (stat) \pm 0.093 (syst))\%,$$

and it represents one of the most interesting high energy physics results.

5. CP Violation in $B_s \rightarrow J/\psi\phi$ Decays

While CP violation has been well measured and found to agree with the SM expectations in kaon and in most B-meson decays, the study of CP violation in decays of $B_s$ mesons is still in its early stages, with the first results from $B_s \rightarrow J/\psi\phi$ decays reported by the CDF and D0 collaborations in the last couple of years [16–18]. In these decays, CP violation occurs through the interference between the decay amplitudes with and without mixing. In the SM the relative phase between the decay amplitudes with and without mixing is $\beta_s^{SM} = \arg(-V_{ts}V_{tb}^{\dagger}/V_{td}V_{tb}^{\dagger})$ and it is expected to be very small [19, 20]. New physics contributions manifested in the $B_s^0$ mixing amplitude may alter this mixing phase by a quantity $\phi_s^{NP}$ leading to an observed mixing phase $2\beta_s^{J/\psi\phi} = 2\beta_s^{SM} - \phi_s^{NP}$. Large values of the observed $\beta_s^{J/\psi\phi}$ would be an indication of physics beyond the SM [20–23]. It is interesting
to note that certain SUSY models with large \( \tan(\beta) \) predict enhanced \( BR(B_s \rightarrow \mu\mu) \) for large CP violating mixing phase in \( B_s \rightarrow J/\psi \phi \) decays \[24\].

Early measurements of the CP violation parameter \( \beta_s \) from the CDF \[17\] and D0 \[18\] collaborations showed small deviations from the SM \[19, 20\], however, a combination \[25\] of CDF and D0 analyzes, based on 2.8 fb\(^{-1}\) of integrated luminosity, revealed a deviation of slightly more than two standard deviations with respect to the SM predictions. More recent updates of this measurements were performed by both the CDF \[26\] and the D0 \[27\] experiments using data sample corresponding to 5.2 fb\(^{-1}\) and 8.0 fb\(^{-1}\) of integrated luminosity, respectively. The CDF experiment has a \( B_s \) yield of \( \approx 6500 \) signal events, while the D0 experiment reports a yield of \( \approx 5500 \) signal events, as shown in Fig. 3.

The updated measurements show better agreement with the SM expectation. The deviations are at one standard deviation level for each experiment. The CDF experiment finds \[26\] that the CP violation phase \( \beta_s \) is within the ranges \([0.02, 0.52]\) \( \pi \) [1.08, 1.55] radians at the 68% CL. The corresponding D0 result is \[27\] \( \beta_s = 0.28^{+0.19}_{-0.18} \) radians or \( \phi_s = -2\beta_s = -0.55^{+0.38}_{-0.36} \) radians. The two dimensional confidence regions in the \( \beta_s - \Delta \Gamma_s \) plane are shown in Fig. 4.

Apart from increasing the sample sizes, each experiment includes in the analysis the s-wave contribution from \( B_s \rightarrow J/\psi K^+ K^- \), where the \( K^+ K^- \) pair is in a s-wave state. The s-wave could be either the \( f_0(980) \) state or a non-resonant \( K^+ K^- \) state. The s-wave contribution to the CDF analysis is found to be less than 6.7% at the 95% CL while the corresponding D0 fraction is \( (17.3 \pm 3.6)\% \). The difference between the two s-wave contributions in the two analyzes is still to be understood.

The \( B_s \) mean lifetime, \( \tau_{B_s} \), as well and the decay width with difference between the \( B_s \) mass eigenstates, \( \Delta \Gamma_s \), the polarization fractions in the transversity basis \( |A_0(0)|^2 \) and \( |A_\parallel(0)|^2 \) and the strong phases are also measured. The CDF results are:

\[
\begin{align*}
\tau_{B_s} &= 458.6 \pm 7.6 \text{(stat)} \pm 3.6 \text{(syst)} \mu \text{m} \\
\Delta \Gamma_s &= 0.075 \pm 0.035 \text{(stat)} \pm 0.01 \text{(syst)} \text{ps}^{-1} \\
|A_\parallel(0)|^2 &= 0.231 \pm 0.014 \text{(stat)} \pm 0.015 \text{(syst)} \\
|A_0(0)|^2 &= 0.524 \pm 0.013 \text{(stat)} \pm 0.015 \text{(syst)} \\
\varphi_\perp &= 2.95 \pm 0.64 \text{(stat)} \pm 0.07 \text{(syst)}
\end{align*}
\]

and the corresponding D0 results, including both statistic and systematic uncertainties are:

\[
\begin{align*}
\tau_{B_s} &= 1.443^{+0.038}_{-0.035} \text{ps} \\
\Delta \Gamma_s &= 0.163^{+0.066}_{-0.064} \text{ps}^{-1} \\
|A_\parallel(0)|^2 &= 0.231^{+0.024}_{-0.030} \\
|A_0(0)|^2 &= 0.558^{+0.017}_{-0.019} \\
\delta_\parallel &= 3.15 \pm 0.22 \\
\cos(\delta_\perp - \delta_s) &= 0.11^{+0.27}_{-0.25}
\end{align*}
\]

Although less probable that the Tevatron experiments will be able to identify new physics using the remaining data, the analysis will be updated with the full datasets. Since the time of this presentation, the LCHb
experiment has presented [28] an updated analysis of $B_s \to J/\psi \phi$ decays, providing smaller uncertainties on the CP violation parameter $\beta_s$, which was found to be in agreement with the SM prediction.

6. Study of $B_s \to J/\psi f_0(980)$ Decays

Due to the small SM value of the phase $\phi_s = \arg(-M_{s2}^2/\Gamma_{s2}^2) = 0.22 \pm 0.06$ degrees [20], the $B_s$ mass eigenstates and the CP eigenstates coincide to a good approximation. Here $M_{s2}$ and $\Gamma_{s2}$ are the off-diagonal elements of the mass and decay matrices which describe the time evolution of the neutral $B_s$ system. The measurement of the mean $B_s$ lifetime decaying to a CP eigenstate provides directly the lifetime of the corresponding mass eigenstate. If new physics has large contributions to $\phi_s$, then the mass and CP eigenstates are no longer the same. In this case, the measured lifetime corresponds to the weighted average of the lifetimes of the two mass eigenstates, with weights depending on the size of the CP violating phase $\phi_s$ [23]. The measurement of the $B_s$ lifetime in a final state which is a CP eigenstate provides constraints on the width difference, $\Delta \Gamma_s$, and on the CP violating phase in $B_s$ mixing, $\phi_s$ [30].

Since the final state in the decay $B_s \to J/\psi f_0(980)$ with $f_0 \to \pi^+\pi^-$ is a CP eigenstate, this decay can be used to measure the CP violating phase $\beta_s = \arg([-V_{us}V_{ub}^*]/[V_{us}V_{ub}^*])$ without performing an angular analysis [29]. In case of large CP violation new physics effects, it holds that $\phi_s = -2\beta_s$. A measurement of the phase $\beta_s$ in $B_s \to J/\psi f_0(980)$, $f_0 \to \pi^+\pi^-$ decays was already performed by the LHCb experiment [28]. Further interest in the decay $B_s \to J/\psi f_0(980)$ with $f_0 \to K^+K^-$ is generated by the possibility of solving the $\beta_s$ ambiguity by using the interference between the p-wave in $B_s \to J/\psi \phi$ decays and the s-wave in $B_s \to J/\psi f_0(980)$ decays.

With a sample of $3.8 \text{ fb}^{-1}$ containing $502 \pm 37(\text{stat}) \pm 18(\text{syst})$ signal events, CDF experiment measures

$$R_{f_0/\phi} = \frac{BF(B_s \to J/\psi f_0(980)) \times BF(f_0(980) \to \pi^+\pi^-)}{BF(B_s \to J/\psi \phi) \times BF(\phi \to K^+K^-)} = 0.257 \pm 0.020(\text{stat}) \pm 0.014(\text{syst}),$$

from which

$$BF(B_s \to J/\psi f_0(980)) \times BF(f_0(980) \to \pi^+\pi^-) = (1.63 \pm 0.12(\text{stat}) \pm 0.09(\text{syst}) \pm 0.50(\text{pdg})) \times 10^{-4}$$

is derived. This is the most precise determination of $R_{f_0/\phi}$ to date. The corresponding D0 results, using $8 \text{ fb}^{-1}$ of integrated luminosity, with $498 \pm 74$ signal candidates, yields a relative branching fraction of

$$R_{f_0/\phi} = \frac{BF(B_s \to J/\psi f_0(980)) \times BF(f_0(980) \to \pi^+\pi^-)}{BF(B_s \to J/\psi \phi) \times BF(\phi \to K^+K^-)} = 0.210 \pm 0.032(\text{stat}) \pm 0.036(\text{syst}).$$

Fig. 5 shows the CDF and D0 $\mu^+\mu^-\pi^+\pi^-$ invariant mass from $B_s \to J/\psi f_0(980)$, $f_0(980) \to \pi^+\pi^-$ candidates. Both CDF and D0 results are in good agreement with the results from LHCb $R_{f_0/\phi} = 0.252^{+0.046}_{-0.037}(\text{stat})^{+0.027}_{-0.033}(\text{syst})$ [33] and from Belle $R_{f_0/\phi} = 0.206^{+0.055}_{-0.043}(\text{stat}) \pm 0.052(\text{syst})$ [34].

In addition to the relative branching fraction, $R_{f_0/\phi}$, the CDF experiment also measured the mean lifetime of the $B_s$ meson in $B_s \to J/\psi f_0(980)$ decays, $\tau(B_s \to J/\psi f_0(980)) = 1.70^{+0.11}_{-0.12}(\text{stat}) \pm 0.03(\text{syst})$ ps. This result is in good agreement with theoretical expectations as well as with other determinations of the $B_s^H$ lifetime.
7. Branching Fraction, Polarization and CP Violation in $B_s \to \phi \phi$ Decays

Studies of charmless $B_s \to \phi \phi$ decays, were first performed by the CDF experiment. We present first measurements of the branching ratio [35], of the polarization fractions [37] and a search for CP Violation [38] in these decays using data corresponding to 2.9 fb$^{-1}$ of integrated luminosity.

Charmless $B_s$ decays are still to be fully understood. They offer the possibility to test our current theoretical understanding and represent promising ways to search for physics beyond the Standard Model. The $B_s \to \phi \phi$ decay is part of the so called $B \to VV$ family in which the initial state $B$-meson is a pseudo-scalar (spin 0) and the final state $VV$ contains two vector mesons (spin 1). In the particular decay of $B_s$ to $\phi \phi$, the final state is a CP eigenstate. Such decays can be used to measure the $B_s$ decay width difference ($\Delta \Gamma_s$) and the phase responsible for CP violation in the interference between decays with and without mixing. To conserve the total angular momentum in $B_s \to \phi \phi$ decays, the relative orbital angular momentum between the two $\phi$ mesons in the final state must be either 0, 1 or 2. In the angular momentum space, there are various bases which can be used to analyze decays of pseudo-scalars to two vector mesons, but any formalism involves three independent amplitudes for the three different polarizations of the decay products in the final state. Measuring the polarization fractions amounts to an important test of the corresponding theoretical predictions.

Within the SM, the dominant process that contributes to the $B_s \to \phi \phi$ decay is the $b \to s s \bar{s}$ penguin diagram. The same penguin amplitude appears in other $B \to VV$ processes which exhibit significant discrepancies between the measured polarization fractions and the SM predictions. Explanations involving both new physics scenarios as well as newly accounted SM effects have been suggested to explain the observations. However, none of the existing scenarios is convincing enough. To solve this “polarization puzzle” it is important to study as many $B \to VV$ decays as available. The first polarization analysis of $B_s \to \phi \phi$ decays, performed by the CDF experiment is presented here together with an updated measurement of the $B_s \to \phi \phi$ branching fraction. The $B_s \to \phi \phi$ invariant mass distribution is shown in Fig. 6. The ratio of branching fractions is determined:

$$\frac{BR(B_s \to \phi \phi)}{BR(B_s \to J/\psi \phi)} = [1.78 \pm 0.14(stat) \pm 0.20(syst)] \times 10^{-2}$$

Using the experimental value of the $B_s \to J/\psi \phi$ branching ratio we obtain:

$$BR(B_s \to \phi \phi) = [2.40 \pm 0.21(stat) \pm 0.27(syst) \pm 0.82(BR)] \times 10^{-5}$$

where the last uncertainty ($BR$) is the dominant contribution and comes from the error on the $B_s \to J/\psi \phi$ branching ratio. This result is compatible with the initial observation [36], with substantial improvement on the statistical uncertainty. The result is also compatible with recent theoretical calculations [39] and [39].

The polarization fractions and strong phase $\delta|_{||}$ are measured as:
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Figure 6: Invariant mass of $\phi(\rightarrow K^+K^-)\phi(\rightarrow K^+K^-)$ (left). The $u$ (center) and $v$ (right) distributions in $B_s \rightarrow \phi\phi$ for side-bands subtracted signal event.

\[ |A_0|^2 = 0.348 \pm 0.041 \text{(stat)} \pm 0.021 \text{(syst)} \]
\[ |A_1|^2 = 0.287 \pm 0.043 \text{(stat)} \pm 0.011 \text{(syst)} \]
\[ |A_\perp|^2 = 0.365 \pm 0.044 \text{(stat)} \pm 0.027 \text{(syst)} \]
\[ \cos(\delta_1) = -0.91 \pm 0.13 \text{(stat)} \pm 0.09 \text{(syst)} \]

The longitudinal and transverse polarization fractions are:
\[ f_L = 0.348 \pm 0.041 \text{(stat)} \pm 0.021 \text{(syst)} , \]
\[ f_T = 0.652 \pm 0.041 \text{(stat)} \pm 0.021 \text{(syst)} \]

It is clear from this measurement that the SM expected amplitude hierarchy $|A_0| \gg |A_1| \sim |A_\perp|$ is not valid in $B_s \rightarrow \phi\phi$ decays. Instead, the observed relation between the polarization amplitudes is given by: $|A_0| \sim |A_1| > |A_\perp|$, which is similar to the measurements for the $b \rightarrow s$ penguin transition of $B \rightarrow \phi K^*$ decays [41] which were the origin of the polarization puzzle.

The results are compared with various theoretical predictions of the polarization amplitudes. We find that the central values are consistent within the uncertainty ranges with the expectations of the QCD factorization [39], while they are not in good agreement with the expectation of perturbative QCD [40] and QCD factorization [42].

Although the $B_s \rightarrow \phi\phi$ data sample size does not allow the investigation of the mixing induced CP-violation, a class of CP-violating effects which can reveal the presence of NP are the Triple Products ($TP$) correlations [43]. $TP$s are defined as: $TP = \vec{p} \cdot (\vec{q}_1 \times \vec{q}_2)$ where $\vec{p}$ is a momentum, and $\vec{q}_1$ and $\vec{q}_2$ can be either the spins or momenta of the decay particles. Triple products are odd variables under time reversal ($T$), therefore they constitute potential signals of CP violation. The $TP$ asymmetry is defined as:
\[ A_{TP} = \frac{\Gamma(TP>0) - \Gamma(TP<0)}{\Gamma(TP>0) + \Gamma(TP<0)} , \]

where $\Gamma$ is the decay rate of the process in question. Most of these $TP$ asymmetries are expected to be small in the SM, but can be enhanced in the presence of NP in the decay. In the untagged case the $TP$ asymmetries are proportional to the so-called "true" $TP$ asymmetry, that is a true CP violating effect. In what follows, for shortness, we refer to them as $TP$ only.

In the $B_s \rightarrow \phi\phi$ decays, there are two Triple Products: $TP_1$ is proportional to $Im(A_1A_\perp)$ and $TP_2$, related to $Im(A_0A_\perp)$. $TP_1$ can be probed through the observable $u = \cos \varphi \sin \varphi$, where $\varphi$ is the angle between the two $\phi$ meson decay planes. The asymmetry on $u$, $A_u$, is proportional to the asymmetry of $TP_1$ and is defined as: $A_u = (N^+ - N^-)/(N^+ + N^-)$, where $N^+ - N^-$ are the number of events with $u > 0$ ($u < 0$). In a similar way, we define an asymmetry $A_v$ for the variable $v = \sin \varphi < 0$ if $\cos \vartheta_1 \cos \vartheta_2 > 0$ and $v = \sin(-\varphi) < 0$ if $\cos \vartheta_1 \cos \vartheta_2 < 0$. The asymmetry $A_v$, which is proportional to the asymmetry of $TP_2$. The $u$ and $v$ distributions are shown in Fig. 6 for side-bands subtracted signal events.

The measured asymmetries of two T-odd helicity angles functions and the final results are:
\[ A_u = -0.007 \pm 0.064 \text{(stat)} \pm 0.018 \text{(syst)} , \]
\[ A_v = -0.120 \pm 0.064 \text{(stat)} \pm 0.016 \text{(syst)} . \]

The first asymmetry, $A_u$, is well consistent with zero within experimental uncertainties, while the second one, $A_v$, is 1.8 standard deviations from zero considering both statistical and systematic uncertainties. These asymmetries constrain the size of two T-violating true Triple Products asymmetries of the $B_s \rightarrow \phi\phi$ decay expected null in the SM.
8. CP Violation in $B \rightarrow DK$ Decays

The branching fractions and CP asymmetries of $B^- \rightarrow D^0 K^-$ modes allow a theoretically-clean way of measuring the CKM angle $\gamma$, which is the least well-known CKM angle, with uncertainties of about 10-20 degrees. In particular the "ADS method" [44, 45] makes use of modes where the $D^0$ decays in the Doubly Cabibbo Suppressed (DCS) mode: $D^0 \rightarrow K^+ \pi^-$. The large interference between the decays in which $B^-$ decays to $D^0 K^-$ through a Color Allowed $b \rightarrow c$ transition, followed by the DCS decay $D^0 \rightarrow K^+ \pi^-$, and the decay in which $B^-$ decays to $D^0 K^-$ through a Color Suppressed $b \rightarrow u$ transition, followed by the Cabibbo Favored (CF) decay $D^0 \rightarrow K^+ \pi^-$, can lead to measurable CP asymmetries, from which the $\gamma$ angle can be extracted.

The observables of the ADS method are:

$$R_{ADS}(K) = \frac{BR(B^- \rightarrow (K^+ \pi^-) D K^-) + BR(B^+ \rightarrow (K^- \pi^+) D K^-)}{BR(B^- \rightarrow (K^+ \pi^-) D K^-) + BR(B^+ \rightarrow (K^- \pi^+) D K^-)}$$

$$A_{ADS}(K) = \frac{BR(B^- \rightarrow (K^+ \pi^-) D K^-) - BR(B^+ \rightarrow (K^- \pi^+) D K^-)}{BR(B^- \rightarrow (K^+ \pi^-) D K^-) + BR(B^+ \rightarrow (K^- \pi^+) D K^-)}$$

$$R_{ADS}(K)$$ and $$A_{ADS}(K)$$ are related to the $\gamma$ angle through these relations:

$$R_{ADS}(K) = r_D^2 + r_B^2 + r_{BR} \cos \gamma \sin(\delta_B + \delta_D)$$

$$A_{ADS}(K) = 2 r_{BR} \sin \gamma \sin(\delta_B + \delta_D) / R_{ADS}(K)$$

where $r_B = |A(b \rightarrow u)/A(b \rightarrow c)|$ and $\delta_B = \arg[A(b \rightarrow u)/A(b \rightarrow c)]$. $r_D$ and $\delta_D$ are the corresponding amplitude ratio and strong phase difference of the $D$ meson decay amplitudes. As can be seen from the expressions above, $A_{ADS}(max) = 2 r_{BR} / (r_B^2 + r_D^2)$ is the maximum size of the asymmetry. For given values of $r_B(\pi)$ and $r_D$, sizeable asymmetries may be found also for $B^- \rightarrow D^0 \pi^-$ decays, so, interesting observables are:

$$R_{ADS}(\pi) = \frac{BR(B^- \rightarrow (K^+ \pi^-) D \pi^-) + BR(B^+ \rightarrow (K^- \pi^+) D \pi^-)}{BR(B^- \rightarrow (K^+ \pi^-) D \pi^-) + BR(B^+ \rightarrow (K^- \pi^+) D \pi^-)}$$

$$A_{ADS}(\pi) = \frac{BR(B^- \rightarrow (K^+ \pi^-) D \pi^-) - BR(B^+ \rightarrow (K^- \pi^+) D \pi^-)}{BR(B^- \rightarrow (K^+ \pi^-) D \pi^-) + BR(B^+ \rightarrow (K^- \pi^+) D \pi^-)}$$

$$R_{ADS}(\pi) = \frac{BR(B^- \rightarrow (K^+ \pi^-) D \pi^-) + BR(B^+ \rightarrow (K^- \pi^+) D \pi^-)}{BR(B^- \rightarrow (K^+ \pi^-) D \pi^-) + BR(B^+ \rightarrow (K^- \pi^+) D \pi^-)}$$

The CDF experiment presents an ADS analysis [46] on a data sample corresponding to 7 fb$^{-1}$ of integrated luminosity. An extended maximum likelihood fit that combines mass and particle identification information is used to separate statistically the $B^- \rightarrow DK^-$ contributions from the $B^- \rightarrow D \pi^-$ signals and from the combinatorial and physics backgrounds. The $B^- \rightarrow D \pi^-$ signal is reconstructed with a statistical significance of 3.6 Gaussian sigma. The suppressed signals $B^- \rightarrow DK^-$ are reconstructed with a significance of 3.2 sigma, including systematics. The plots in Fig. 7 show the B invariant mass distribution for positive and negative charges of the suppressed sample.

The ratios of the suppressed to favored branching fractions are measured as:
as well as the direct CP-violating asymmetry
\begin{align*}
A_{ADS}(K) &= -0.82 \pm 0.44(stat) \pm 0.09(syst), \\
A_{ADS}(\pi) &= -0.13 \pm 0.25(stat) \pm 0.02(syst).
\end{align*}

The results are in agreement and competitive with B-factories [47] and with the LHCb experiment [48].

9. Two Body Charmless B Decays

The decay modes of B-mesons into pairs of charmless pseudo-scalar mesons are effective probes of the quark-mixing (CKM) matrix and are sensitive to potential new physics effects. Their branching fractions and CP asymmetries can be predicted with good accuracy and compared to the rich experimental data available for \(B\) and \(B_d\) mesons, produced in large quantities in \(\Upsilon(4S)\) decays [49]. Measurements of similar modes predicted, for the \(B_s\) meson are important to supplement our understanding of \(B\)-meson decays. The measurement of observables from both strange and non-strange \(B\) hadron decays, when compared with other determinations of \(V\) of \(B\) be used in measuring \(B\) penguin-annihilation [52].

The decay modes of \(B^0 \to \pi^+\pi^-\) and \(B_s \to K^+K^-\) observables has been proposed as a way to directly determine the phase of the \(V_{ub}\) element of the CKM matrix (angle \(\gamma\)), or alternatively as a test of our understanding of the dynamics of \(B\) hadron decays, when compared with other determinations of \(\gamma\) [54]. The \(B_s \to K^-\pi^+\) mode can also be used in measuring \(\gamma\) [51], and its CP asymmetry is a powerful model-independent test [55] of the source of the direct CP asymmetry recently observed in the \(B^0 \to K^+\pi^-\) mode [56]. The \(B_s \to \pi^+\pi^-\) mode proceeds only through annihilation diagrams, which are currently poorly known and a source of significant uncertainty in many theoretical calculations [57]. Its features are similar to the \(B^0 \to K^+K^-\) mode, but it has a larger predicted branching fraction [58]; a measurement of both modes would allow a determination of the strength of penguin-annihilation [52].

Channels previously investigated by the CDF experiment are \(B_s \to K^+K^-\) [59], \(B_s \to K^-\pi^+\), \(\Lambda_b^0 \to p\pi^-\) and \(\Lambda_b^0 \to pK^-\) [60], and the corresponding asymmetries \(A_{CP}(B_s \to K^-\pi^+)\), \(A_{CP}(\Lambda_b^0 \to p\pi^-)\) and \(A_{CP}(\Lambda_b^0 \to pK^-)\) [61].

Recently, the CDF experiment has established [62] the first evidence for \(B_s \to \pi^+\pi^-\) decays and has set bounds on the branching fraction of the \(B^0 \to K^+K^-\) decay mode. Fig. 7 shows the invariant mass of \(\pi^+\pi^-\) from \(B \to h^+h^-\) candidates. The \(B_s \to \pi^+\pi^-\) and \(B^0 \to K^+K^-\) are 94 \pm 28(stat) \pm 11(syst) and 120 \pm 49(stat) \pm 42(syst), respectively. The branching fractions are measured as:
\begin{align*}
BR(B_s \to \pi^+\pi^-) &= (0.57 \pm 0.15(stat) \pm 0.10(syst)) \times 10^{-6}, \\
BR(B^0 \to K^+K^-) &= (0.23 \pm 0.10(stat) \pm 0.10(syst)) \times 10^{-5}, \\
BR(B^0 \to K^+K^-) &\in [0.05, 0.46] \times 10^{-6} at 90\% C.L.
\end{align*}

10. Observation of \(\Xi_b^0\)

The Tevatron experiments, D0 and CDF, have had major contribution to b-baryon spectroscopy, with the observations of the \(\Xi_b^0(dsb)\) [63], \(\Sigma_b((uwb, dlb))\) [64] and \(\Omega_b(ssb)\) [64] baryons.

We report the observation by the CDF experiment of an additional heavy baryon, \(\Xi_b^0(usbquarkcontent)\) [66] and the measurement of its mass. The measurement uses 4.2 fb\(^{-1}\) of integrated luminosity. The \(\Xi_b^0\) baryon is observed through it decay
\[\Xi_b^0 \to \Xi_b^+\pi^-,\text{ where } \Xi_b^+ \to \Xi^0\pi^+\pi^-, \Xi_b^- \to \Lambda\pi^-\text{ and } \Lambda \to p\pi^-\text{.}\]

In addition, the \(\Xi_b^-\) baryon is observed through the similar decay chain
\[\Xi_b^- \to \Xi_b^0\pi^-,\text{ where } \Xi_b^0 \to \Xi^0\pi^+\pi^-, \Xi^0 \to \Lambda\pi^-\text{ and } \Lambda \to p\pi^-\text{.}\]
The $\Xi^0_b$ and $\Xi^-_b$ candidate mass distributions are shown in Fig. 8. There are $25.3^{+5.6}_{-5.4} \Xi^0_b$ candidates and $25.8^{+5.5}_{-5.2} \Xi^-_b$ candidates with measured masses of $5787.8 \pm 5.0 \text{(stat)} \pm 1.3 \text{(syst)} \text{MeV}/c^2$ and $5796.7 \pm 5.1 \text{(stat)} \pm 1.4 \text{(syst)} \text{MeV}/c^2$, respectively. The $\Xi^0_b$ signal significance is greater than 6$\sigma$. Neither of these decay channels has been reported previously and the reconstruction of $\Xi^0_b$ is the first observation of this baryon in any channel.

11. Conclusions

The D0 and CDF experiments are continuing to produce a rich and exciting program in heavy flavor physics: interesting effects in same-sign di-muon asymmetry and $B_s \rightarrow \mu^+\mu^-$ decays, as well as the best measurements of CP violating phase, $\beta_s/\phi_s$. Many interesting results will benefit from increasing the data samples. It is anticipated that each of the two Tevatron experiments will accumulate approximately 10 fb$^{-1}$ of integrated luminosity by the end of the Tevatron run.

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