# Searches for BSM physics using flavor transitions at the Tevatron

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The CDF and DØ experiments at the Tevatron $p\bar{p}$ collider continue to produce important results on the benchmark channels for the indirect searches for Beyond Standard Model (BSM) physics using flavor transitions, now exploiting the full Run II dataset. We report three final CDF results: new bounds on the $B_s^0$ mixing phase and on the $B_s^0$ mass eigenstates decay width difference, a measurement of the difference of CP asymmetries in $K^+K^-$ and $\pi^+\pi^-$ decays of $D^0$ mesons, and an update of the search for $B_{(s)}^0$ mesons decaying into pairs of muons. We also present the $B_s \to D_s^{(*)+}D_s^{(*)-}$ decays brunching ratio measurements using 6.8 fb$^{-1}$ of data, and a search for CP violation in $D^0 \to K_S^0\pi^+\pi^-$decays in 6.0 fb$^{-1}$ of data.

## 1 Searches for BSM physics through CP violation

The understanding of CP violation in the $B_s$ sector still offers room for possible non-SM contributions, as indicated by the anomaly in the dimuon charge asymmetry reported by the DØ Collaboration [1]. CDF has updated the time-dependent $CP$ violation measurement in $B_s^0 \to J/\psi\phi$ decays, since this is widely recognized as the most effective experimental probe of New Physics (NP) entering $B_s$ mixing. Along with this result, we present the measurement of the $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$ brunching fractions, which helps to constrain the $B_s^0$ mass eigenstates decay width difference. In the case of charmed mesons, CP violation is not so well established as for $B$ mesons and kaons. The first evidence of CP violation in two-body singly-Cabibbo-suppressed $D^0$ decays has been recently reported by the LHCb Collaboration [2], suggesting a possible hint of NP. It is important both to have an independent confirmation of this result in a different environment such as $p\bar{p}$ collisions where no production asymmetries are expected, and to search for and measure CP violation in other charmed meson decays.

### 1.1 Measurement of the $B_s^0 \to J/\psi\phi$ time-evolution

New dynamics entering the $B_s^0$ sector would significantly alter the phase difference $\phi_s$ between the $B_s^0$–$\bar{B}_s^0$ mixing amplitude and the amplitude of $B_s^0$ and $\bar{B}_s^0$ decays into common final states, with respect to its nearly vanishing value expected in the SM. A non-CKM enhancement of $\phi_s$ can also decrease the decay width difference between the heavy and light mass-eigenstate of the $B_s^0$ meson, $\Delta\Gamma_s$. Since the decay is dominated by a single real amplitude, the phase difference equals the mixing phase to a good approximation. Early Tevatron measurements have shown a mild discrepancy of about $2\sigma$ with the SM expectation [3]. The latest updates by CDF and DØ are in better agreement with the SM, as well as first measurements provided by LHCb [4, 5, 6]. Here we report the new CDF update using the final dataset of 10 $\text{fb}^{-1}$ which includes about 11000 flavor-tagged $B_s^0 \to J/\psi\phi$ decays collected by a low-momentum dimuon trigger [7]. The decays are fully reconstructed through four tracks that fit to a common displaced vertex, two matched to muon pairs consistent with a $J/\psi$ decay, and two consistent with a $\phi \to K^+K^-$ decay. A joint fit that exploits the candidate-specific information given by the $B$ mass, decay time and production flavor, along with the decay angles of kaons and muons, is used to determine both $\phi_s$ and $\Delta\Gamma_s$. The analysis closely follows the previous measurement [4]. The only major difference is the use of an updated calibration of the tagging algorithm that uses information from the decay of the "opposite side" bottom hadron in the event to determine the flavor of the $B_s^0$ at its production, with tagging power $(1.39 \pm 0.01)\%$. The information of the tagger that exploits charge-flavor correlations of the neighboring kaon to the $B_s^0$ is instead restricted to only half of the sample, with tagging power $(3.2 \pm 1.4)\%$, degrading the statistical resolution on $\phi_s$ by no more than 15%. A decay resolution of $\sim 90$ fs allows resolving the fast $B_s^0$ oscillations to increase sensitivity on the mixing phase. The 68% and 95% confidence regions in the plane $(\phi_s, \Delta\Gamma_s)$ obtained from the profile-likelihood of the CDF data are reported in Fig. 1 (left). The confidence interval for the mixing phase is $\phi_s \in [-0.60, 0.12]$ rad at 68% C.L., in agreement with the CKM value and recent D0 and LHCb determinations [5, 8]. This is the final CDF measurement on the $B_s^0$ mixing phase, and provides a factor of 35% improvement in resolution with respect to the latest determination. CDF also reports $\Delta\Gamma_s = (0.068 \pm 0.026 \pm 0.007)$ $\text{ps}^{-1}$ under the hypothesis of a SM value for $\phi_s$, along with the measurement of the $B_s^0$ lifetime, $\tau_s = (1.528 \pm 0.019 \pm 0.009)$ ps, in agreement with other experiments' results [5, 8].

### 1.2 Measurement of $B_s \to D_s^{(*)+} D_s^{(*)-}$ brunching ratios

Using 6.8 $\text{fb}^{-1}$ of data collected by the displaced track trigger we performed the world's most precise measurement of $B_s \to D_s^{(*)+} D_s^{(*)-}$ brunching ratios [9], that could be used to infer indirect information about $\Delta\Gamma_s$. We measure the $B_s$ production rate times the $B_s \to D_s^{(*)+} D_s^{(*)-}$ brunching ratio relative to the normalization mode $B^0 \to D_s^+ D^-$. The relative brunching fractions are determined in a simultaneous mass fit to two signal and two normalization samples. The measured values depend on the yields observed on the four samples and the relative efficiency of signal and normalization modes. An accurate determination of the relative efficiencies is achieved by taking into account the Dalitz structure of the $D_s^+$ decay. Using measured values of production and relative brunching fractions, the following absolute brunching fractions are derived: $\mathcal{B}(B_s \to D_s^+ D_s^-) = (0.49 \pm 0.06 \pm 0.05 \pm 0.08)\%$ , $\mathcal{B}(B_s \to D_s^{*\pm} D_s^{\mp}) = (1.13 \pm 0.12 \pm 0.09 \pm 0.19)\%$, $\mathcal{B}(B_s \to D_s^{*+} D_s^{*-}) = (1.75 \pm 0.19 \pm 0.17 \pm 0.29)\%$, $\mathcal{B}(B_s \to D_s^{(*)+} D_s^{(*)-}) = (3.38 \pm 0.25 \pm 0.30 \pm 0.56)\%$. Statistical, systematic and normalization uncertainties are reported.

### 1.3 Measurement of CP violation in $D^0 \to h^+h^-$ decays

In singly-Cabibbo-suppressed transitions such as $D^0 \to h^+h^-$ ($h = K, \pi$) decays, any time-integrated CP asymmetry significantly larger than the 1% expected in the CKM hierarchy can be due to the presence of new dynamics that can enhance both the $D^0$–$\bar{D}^0$ mixing amplitude and the SM-suppressed penguin amplitude. In 2011, using 5.9 $\text{fb}^{-1}$ of data, CDF produced the world's most precise measurements of the CP asymmetries in $D^0 \to K^+K^-$ decays, $A_{CP}(KK) = (-0.24 \pm 0.22 \pm 0.09)\%$, and in $D^0 \to \pi^+\pi^-$ decays, $A_{CP}(\pi\pi) = (0.22 \pm 0.24 \pm 0.11)\%$ [10]. The difference between the individual asymmetries: $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$ is maximally sensitive to the presence of direct CP violation and highly suppresses systematic uncertainties from instrumental asymmetries. CDF presents the $\Delta A_{CP}$ measurement using the full CDF Run II dataset collected by the trigger on displaced tracks [11]. We use the charge of the soft pion in the $D^{\star+} \to D^0\pi^+$ decay to identify the $D^0$ flavor at production. The presence of the soft pion causes a bias in the measurement of the asymmetry induced by a few percent difference in reconstruction efficiency between positive and negative tracks at low momentum. However, provided that the relevant kinematic distributions are equalized in the two decay channels, this spurious asymmetry cancels to an excellent level of accuracy in $\Delta A_{CP}$. The cancellation of instrumental asymmetries allows a looser selection criteria with respect to the measurement of individual asymmetries and the larger statistics increases the sensitivity on $\Delta A_{CP}$. The number of decays for $D^0$ and $\bar{D}^0$ candidates has been determined with a simultaneous fit to the $D^0\pi$ mass distribution of positive and negative $D^*$ decays. Using final samples of 550 thousands $D^0 \to \pi^+\pi^-$ decays and 1.21 million $D^0 \to K^+K^-$ decays, CDF measures $\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$ which is $2.7\sigma$ from zero. Such a result provides a strong indication of CP violation in CDF charm data confirming the LHCb evidence [2] with the same resolution. The combination of CDF, LHCb and $B$-factory measurements deviates by approximately $3.8\sigma$ from the no CP violation point.

### 1.4 Search for CP violation in $D^0 \to K^0_S\pi^+\pi^-$decays

In a sample corresponding to an integrated luminosity of 6.0 fb$^{-1}$ of data we search for time-integrated CP asymmetries in the resonant substructure of the three-body decay $D^0 \to K^0_S\pi^+\pi^-$ decays. As the SM expectation of these CP asymmetries is of the order $10^{-6}$ and thus well below the experimental sensitivity, an observation of CP violation would be a clear hint for NP. The production flavor of the $D^0$ is determined, by the charge of the soft pion from the $D^{*+} \to D^0\pi^+$ decay. Two complementary approaches are used, namely a full Dalitz fit employing the isobar model for the involved resonances and a model-independent bin-by-bin comparison of the $D^0$ and $\bar{D}^0$ Dalitz plots. Our analysis represents a big improvement in terms of precision with respect to CLEO [12], but still no hints of any CP violating effects are found. Individual asymmetries are reported in [13]; the measured value for the overall integrated CP asymmetry is $A_{CP} = (-0.05 \pm 0.57 \pm 0.54)\%$.

## 2 Searches for BSM physics through rare $B$ decays

In the SM all neutral currents conserve flavor so transitions as $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$ can occur only through higher order loop diagrams. The brunching fractions are predicted in the SM to be $(3.2\pm0.2)\times10^{-9}$ and $(1.0\pm0.1)\times10^{-10}$ respectively for the $B^0_s$ and the $B^0$ mesons. A wide class of BSM theories predict significantly higher brunching ratio values. This makes these decays one of the most sensitive indirect searches for NP. Last summer CDF reported an intriguing $\sim2.5\sigma$ fluctuation over background in 7 fb$^{-1}$ of data. Even though compatible with the SM and other experiments' results, it allowed the first two-sided bound on the $B^0_s \to \mu^+\mu^-$ rate [14]. Here we report the CDF update of the analysis with the final 10 fb$^{-1}$ dataset [15]. The analysis methods are not changed from the previous iteration to ensure the unbiased inclusion

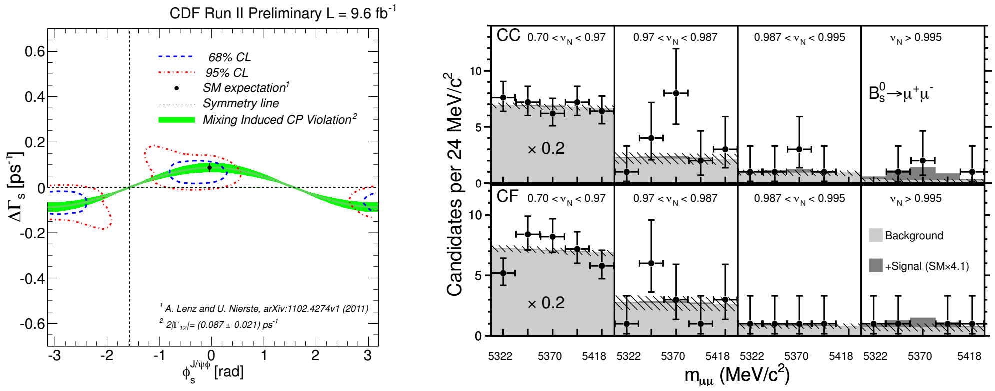


Figure 1: Left: 68% and 95% confidence regions in the plane $(\phi_s, \Delta\Gamma_s)$ from profile-likelihood of CDF data. Right: CDF $B_s^0 \to \mu^+\mu^-$ data compared with the expected background, for "Central Central (CC)" and "Central Forward (CF)" muons, according to the detector region.

of new data. Combinatorial and hadronic $B$-decay background predictions have been checked with many control samples and an optimized neural net (NN) has been used to eliminate these backgrounds while keeping the signal efficiency high. The search has been performed in mass and NN bins, and the observed signal has been normalized to the $B^+ \to J/\psi K^+$ channel. The data are found to be consistent with the background expectations for the $B^0 \to \mu^+\mu^-$ decay and yield the observed limit $< 4.6 \times 10^{-9}$ (expected limit: $< 4.2 \times 10^{-9}$ ). For $B_s^0 \to \mu^+\mu^-$ (Fig. 1 right) the summer 2011 deviation has not been reinforced by adding new data, the final double sided limit from CDF is $0.8 \times 10^{-9} < \mathcal{B}(B_s \to \mu^+\mu^-) < 3.4 \times 10^{-8}$ at 95% C.L., which is still compatible both with the SM expectation and the latest limits from LHC experiments. [16].

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