

## RECENT HEAVY FLAVOR RESULTS FROM THE TEVATRON

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The CDF and D0 experiments at the Tevatron  $p\bar{p}$  collider have pioneered and established the role of flavor physics in hadron collisions. A broad program is now at its full maturity. We report on three new results sensitive to physics beyond the standard model, obtained using the whole CDF dataset: a measurement of the difference of CP asymmetries in  $K^+K^-$  and  $\pi^+\pi^-$  decays of  $D^0$  mesons, new bounds on the  $B_s^0$  mixing phase and on the decay width difference of  $B_s^0$  mass-eigenstates, and an update of the summer 2011 search for  $B_{(s)}^0$  mesons decaying into pairs of muons. Finally, the D0 confirmation of the observation of a new hadron, the  $\chi_b(3P)$  state, is briefly mentioned.

### 1 Measurement of CP violation in charm in the final CDF dataset

Violation of the CP symmetry in tree-dominated decays  $D^0 \rightarrow \pi^+\pi^-$  and  $D^0 \rightarrow K^+K^-$  is a sensitive probe of physics beyond the standard model (SM). Both the  $D^0-\bar{D}^0$  mixing amplitude and the SM-suppressed penguin amplitude can be greatly enhanced by new dynamics, which can also increase the size of the CP violation over that expected from the Cabibbo-Kobayashi-Maskawa (CKM) hierarchy. Last year, using  $5.9 \text{ fb}^{-1}$  of data, CDF produced the world's most precise measurements of the CP asymmetries  $A_{\text{CP}}(KK) = (-0.24 \pm 0.22 \pm 0.09)\%$  and  $A_{\text{CP}}(\pi\pi) = (0.22 \pm 0.24 \pm 0.11)\%$ .<sup>1</sup> In spite of the hadronic uncertainties, there is broad consensus that direct CP asymmetries of  $D^0 \rightarrow K^+K^-$  and of  $D^0 \rightarrow \pi^+\pi^-$  should be of opposite sign. Therefore, a measurement of the difference between asymmetries of those decays is maximally sensitive to detect CP violation. Indeed, the LHCb collaboration reported recently the first evidence of CP violation in charm measuring  $\Delta A_{\text{CP}} = A_{\text{CP}}(KK) - A_{\text{CP}}(\pi\pi) = (-0.82 \pm 0.21 \pm 0.11)\%$ .<sup>2</sup> An independent measurement is crucial to establish the effect, and the  $10 \text{ fb}^{-1}$  sample of hadronic  $D$  decays collected by CDF is the only one currently available to attain sufficient precision.

The analysis follows closely the measurement of individual asymmetries.<sup>3</sup> The flavor of the  $D^0$  meson is tagged from the charge of the soft pion in the strong  $D^{*\pm} \rightarrow D^0\pi^\pm$  decay. Since  $D^{*+}$  and  $D^{*-}$  mesons are produced in equal number in strong  $p\bar{p}$  interactions, any asymmetry between the number of  $D^0$  and  $\bar{D}^0$  decays is due to either CP violation or instrumental effects. The latter can be induced only by the difference in reconstruction efficiency between positive and negative soft pions. Provided that the relevant kinematic distributions are equalized in the two decay channels, the instrumental asymmetry cancels to an excellent level of accuracy in the difference between the observed asymmetries between signal yields. Such cancellation allows one to increase the sensitivity on  $\Delta A_{\text{CP}}$  by loosening some selection criteria with respect to the measurement of individual asymmetries and double the signal yields. The trigger is fired by two charged particles with transverse momenta greater than  $2 \text{ GeV}/c$ . The excellent CDF momentum resolution yields precise mass resolution ( $\sim 8 \text{ MeV}/c^2$  for  $D$  mesons) which provides good signal-to-background. The typical resolution ( $50 \mu\text{m}$ ) on the impact parameter (IP) of the tracks is effective to trigger on good kaon or pion candidates, that are required to have  $\text{IP} > 100 \mu\text{m}$ . The offline selection adds some basic additional requirements on track and vertex quality. The numbers of  $D^0$  and  $\bar{D}^0$  decays are determined with a simultaneous fit to the  $D^0\pi$ -mass distribution of positive and negative  $D^*$  decays (see Fig. 1, left). About 1.21 million  $D^0 \rightarrow K^+K^-$  decays and 550 thousand  $D^0 \rightarrow \pi^+\pi^-$  decays are reconstructed, yielding the following observed asymmetries between signal yields,  $A_{\text{raw}}(KK) = (-2.33 \pm 0.14)\%$  and

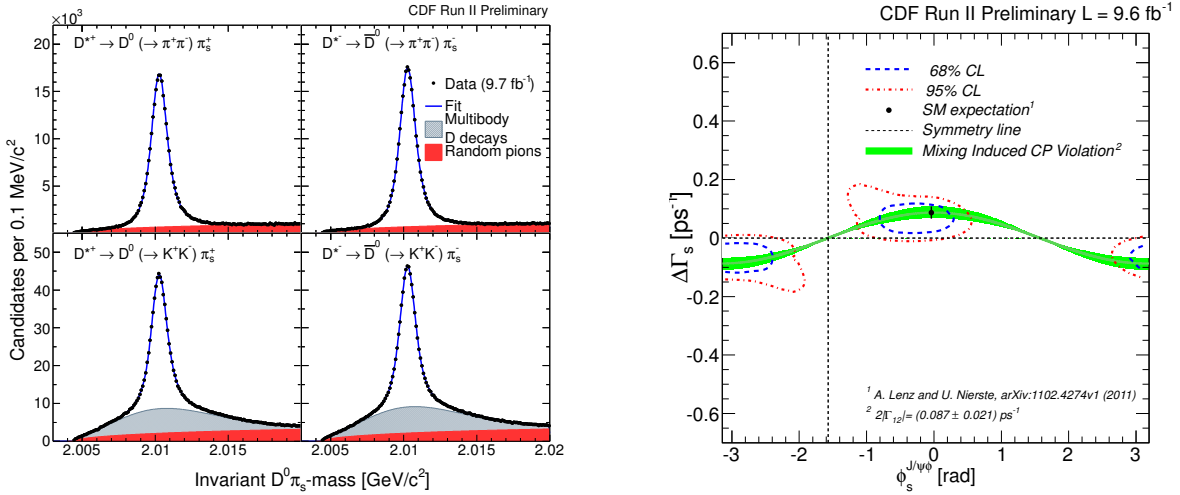


Figure 1: Left:  $D^0\pi$ -mass distributions of positive and negative  $D^*$  decays with fit projections overlaid. Right: 68% and 95% confidence regions in the plane  $(\phi_s, \Delta\Gamma_s)$  from profile-likelihood of CDF data.

$A_{\text{raw}}(\pi\pi) = (-1.71 \pm 0.15)\%$ . Residual systematic uncertainties total 0.10% and are driven by differences between distributions associated with charm and anticharm decays. The final result is  $\Delta A_{\text{CP}} = (-0.62 \pm 0.21 \pm 0.10)\%$ , which is  $2.7\sigma$  different from zero. This provides strong indication of CP violation in CDF charm data, supporting the LHCb earlier evidence with same resolution. The combination of CDF, LHCb and  $B$ -factories measurements deviates by approximately  $3.8\sigma$  from the no CP violation point.

## 2 Measurement of the $B_s^0 \rightarrow J/\psi\phi$ time-evolution in the final CDF dataset

The  $B_s^0-\bar{B}_s^0$  mixing is a promising process where to search for new physics (NP), given the D0  $3.9\sigma$  anomaly in dimuon charge asymmetry.<sup>4</sup> If the anomaly is due to new dynamics in the  $B_s^0$  sector, the phase difference 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,  $\phi_s$ , would be significantly altered 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,  $\Delta\Gamma_s$ . The analysis of the time evolution of  $B_s^0 \rightarrow J/\psi\phi$  decays is the most effective experimental probe of such a CP-violating phase. 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.<sup>5</sup> Latest updates by CDF and D0 are in better agreement with the SM, as well as first measurements provided by LHCb.<sup>6,7,8</sup>

Here we report the new CDF update using the final dataset of  $10 \text{ fb}^{-1}$  which comprises about 11000  $B_s^0 \rightarrow J/\psi\phi$  decays collected by a low-momenta dimuon trigger.<sup>9</sup> 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  $\phi \rightarrow K^+K^-$  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 obtained on a subset of the data.<sup>6</sup> 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 from 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, in which has tagging power  $(3.2 \pm 1.4)\%$ . This degrades 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 (right). 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.<sup>7,10</sup> This is the final CDF measurement on the  $B_s^0$  mixing phase, and provides a factor 35% improvement in resolution with respect to the latest determination. CDF also reports  $\Delta\Gamma_s = (0.068 \pm 0.026 \pm 0.007)$  ps<sup>-1</sup> 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.<sup>7,10</sup>

### 3 Final search for dimuon decays of $B$ mesons at CDF

The  $B_{(s)}^0 \rightarrow \mu^+\mu^-$  decays involve flavor changing neutral currents and the observation of an abnormal decay rate can provide excellent evidence of NP since in the SM they can occur only through high-order loop diagrams. Enhancements to the SM expectation of their branching ratios (BR) can indeed occur in a variety of different NP models. Last summer CDF reported an intriguing  $\sim 2.5\sigma$  fluctuation over background in 7 fb<sup>-1</sup> of data. Even if compatible with the SM and other experiments' results, it allowed the first two sided bound on the  $B_s^0 \rightarrow \mu^+\mu^-$  rate.<sup>11</sup>

Here we report the CDF update of the analysis with the final 10 fb<sup>-1</sup> dataset.<sup>12</sup> The analysis methods are not changed from the previous iteration to ensure the unbiased processing of new data. The events are collected using a set of dimuon triggers and are divided in two categories: “CC” events have both muon candidates in the central region of the detector, while “CF” events have one central muon and another muon in the forward region. The signal candidates are fully reconstructed with a secondary vertex due to the long  $B_s^0$  lifetime ( $\sim 450$   $\mu\text{m}$ ). They also feature a primary-to-secondary vertex vector aligned with the  $B_s^0$  candidate momentum and a very isolated  $B_s^0$  candidate. There are two sources of background: combinatorial background and peaking background. The former tends to be partially reconstructed and shorter-lived than signal. It is estimated by extrapolating the number of events in the sideband regions of the  $B$  mass distribution to the signal window using a linear fit. The peaking background are due to decays of  $B_s^0$  and  $B^0$  mesons to pions and kaons that are misreconstructed as muons, and it is ten times greater in the  $B^0$  search with respect to the  $B_s^0$  analysis. It is carefully taken into account with simulation (mass shape) and with  $D^0 \rightarrow K\pi$  decays from data (misidentification probability). A neural network (NN) classifier is optimized to reject the background using 14 event variables. The background estimates are checked to be consistent in many control samples. Finally, when the background is well understood, the number of observed events is compared to the number expected. The data are found to be consistent with the background expectations for the  $B^0 \rightarrow \mu^+\mu^-$  decay and yield an observed limit of  $\text{BR} < 4.6 \times 10^{-9}$  at 95% C.L (with expected limit  $4.2 \times 10^{-9}$ ). In the case of  $B_s^0 \rightarrow \mu^+\mu^-$  the summer 2011 excess is not reinforced, even though it is still present as shown in the most sensitive (top-right) bin of the NN in Fig. 2. The resulting bounds at 95% C.L. are  $0.8 \times 10^{-9} < \text{BR} < 3.4 \times 10^{-8}$ , which is still compatible both with the SM expectation and the latest limits from LHC experiments.<sup>13</sup> An upper limit at 95% C.L. of  $\text{BR} < 3.1 \times 10^{-8}$  (expected  $1.3 \times 10^{-8}$ ) is also derived.

### 4 A new state decaying into $\Upsilon(1S) + \gamma$

Using data corresponding to an integrated luminosity of 1.3 fb<sup>-1</sup>, the D0 collaboration observes a narrow mass state decaying into  $\Upsilon(1S) + \gamma$ , where the  $\Upsilon(1S)$  meson is detected by its decay

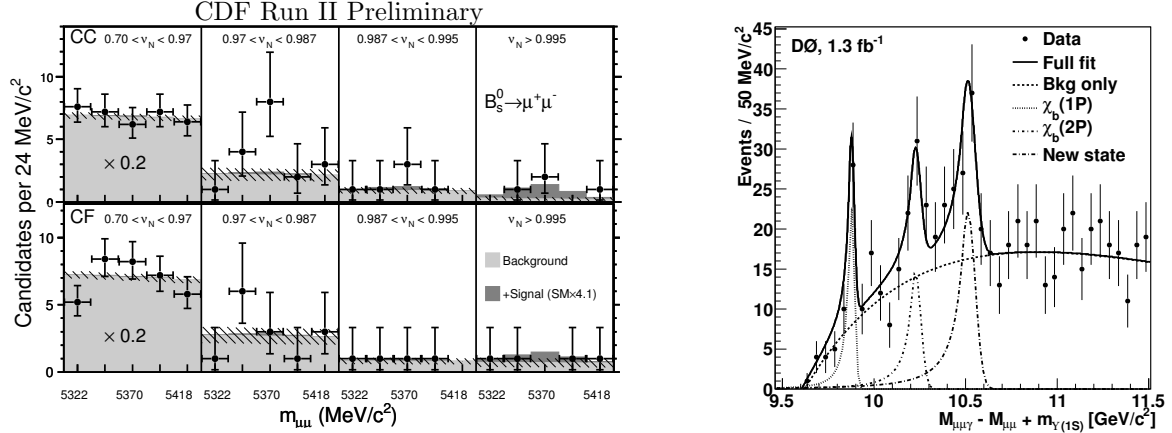


Figure 2: Left: comparison of the CDF  $B_s^0 \rightarrow \mu^+ \mu^-$  data (points) and expected background (solid grey) for CC and CF muons. Right: mass distribution of  $M_{\mu\mu\gamma} - M_{\mu\mu} + M_{\gamma(1S)}$  of D0 data with fit overlaid.

into a muons pair, and the photon through its conversion into an  $e^+e^-$  pair.<sup>14</sup> The fit to the mass spectrum in Fig. 2 (right) shows three structures above a smooth, threshold-like background. The one at the highest mass has a statistical significance of  $5.6\sigma$ . It is interpreted as the state  $\chi_b(3P)$  and is centered at  $10.551 \pm 0.014 \pm 0.017$  GeV/c<sup>2</sup>, consistent with the recent ATLAS observation.<sup>15</sup>

## 5 Conclusions

We reported the final CDF results on three flagship measurements in the indirect search for NP at Tevatron, and the confirmation of a new hadron ( $\chi_b(3P)$ ) by the D0 collaboration. The CP asymmetries of  $D^0$  meson decays reported by CDF confirm the first evidence of CP violation in charm reported by LHCb; in the  $B_s^0$  sector, tensions with SM predictions are now softened by latest updates of  $\phi_s$  and  $\Delta\Gamma_s$  bounds, making the D0  $A_{sl}$  anomaly even harder to depuzzle. The final CDF update on the  $B_s^0 \rightarrow \mu^+ \mu^-$  rate is concluding a decade-long program of Tevatron searches that improved the experimental bounds on the rate down to the  $10^{-8}$  range, nearing now the sensitivity to observe a SM signal. Analyses of the unique ( $p\bar{p}$  charge-symmetric), rich (*e.g.*, millions of charm decays), and well-understood (10-years expertise) data sample acquired by CDF and D0 are still in progress and may reserve interesting results in the near future.

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