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CP Violation in Hadronic B Decays at CDF

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I report recent measurements in b-hadron decays reconstructed in the full data set of $\sqrt{s} = 1.96$ TeV proton-antiproton collisions collected by the CDF experiment at the Tevatron. These include the final CDF results on: measurements of CP asymmetries in two-body charmless decays of the B^0, B_s^0, and Λ_b^0 hadrons; bounds on the B_s^0 mixing phase and on the decay width difference of B_s^0 mass eigenstates; and updated measurements of branching ratios of $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^{(\star)+} D_s^{(\star)-}$ decays. All measurements are among the most precise from a single experiment and in agreement with the standard model predictions.

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1. Direct *CP*-violation in charmless two-body *b*-hadron decays

Recently, the pattern of direct *CP* violation in charmless mesonic decays of *B* mesons has shown some unanticipated discrepancies from expectations that could be accommodated in several simple extensions of the standard model (SM) [1]. However, uncertainties on the contribution of higher-order SM amplitudes has prevented a firm conclusion. Redundant and precise measurements in similar decays related by flavor symmetries provide additional constraints to reduce the theoretical uncertainties and probe non-SM physics in the electro-weak amplitudes. Specifically, measurements of direct *CP* violation in $B_s^0 \to K^-\pi^+$ decays have been proposed as a nearly model-independent test for the presence of non-SM physics [2]. The Cabibbo-Kobayashi-Maskawa (CKM) mechanism predicts a well-defined hierarchy between direct *CP* violation in $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ decays, yielding a significant asymmetry for the latter, of about 30%. Supplementary information could come from *CP* violation in bottom baryons: *CP*-violating asymmetries in charmless Λ_b^0 decays could contribute additional insight.

The displaced vertex trigger of CDF is effective at selecting two-body *b*-hadron decays [3]. We report a recent measurement of *CP* asymmetries of such decays which uses all of the data from Run II of the Tevatron, corresponding to about $9.3\,\text{fb}^{-1}$ of integrated luminosity [4]. The offline selection is an unbiased and optimized set of requirements inherited from an earlier analysis [5], which relies on a more accurate determination of the same quantities used in the trigger (*e. g.*, two opposite-charged tracks with impact parameter between 0.1 and 1 mm; opening angles between tracks in the range 20° and 135°; *B* decay length in the transverse plane greater than 0.2 mm) with the addition of two further observables: the isolation of the *B* candidate and the quality of the three-dimensional fit of the decay point of the *B* candidate. No more than one *B* candidate per event is found after the selection, and a mass is assigned to each, using a charged pion mass assignment for both decay products. The resulting $\pi^+\pi^-$ spectrum is shown in Fig. 1 (left). Backgrounds include mis-reconstructed multibody *b*-hadron decays, causing the shoulder at $5.16\,\text{GeV}/c^2$, and random pairs of charged particles. In spite of the $25\,\text{MeV}/c^2$ mass resolution of CDF detector for two-body hadronic decays, the various signal modes overlap into an unresolved mass peak near the nominal B^0 mass, with a width of about $35\,\text{MeV}/c^2$.

We use an unbinned likelihood fit, incorporating kinematic and particle-identification (PID) information, to determine the fraction of each individual signal channel and the charge asymmetries, uncorrected for instrumental effects, of the flavor-specific decays $B^0 \to K^+\pi^-$, $B_s^0 \to K^-\pi^+$, $\Lambda_b^0 \to p\pi^-$, and $\Lambda_b^0 \to pK^-$. The decay flavor is inferred from the charges of final state particles assuming equal numbers of b and $\bar{b}$ quarks at production. Any effect from *CP* violation in *B*-meson flavor mixing is assumed to be negligible. The likelihood exploits the kinematic differences among the decay modes, enhancing statistical separation power between $\pi\pi$ and KK (or $K\pi$) final states. The kinematic information is summarized by three loosely correlated variables: the square of the invariant mass $m^2_{\pi\pi}$; the signed momentum imbalance $\beta = (p^+ - p^-)/(p^+ + p^-)$, where p^+ (p^-) is the the momentum of the positive (negative) particle; and the scalar sum of particle momenta $p = p^+ + p^-$. Kinematic fit templates are extracted from simulation for signal and physics background, while they are extracted from an independent sample for combinatorial background. Mass line shapes are accurately described for the non-Gaussian resolution tails and for the effects of the final state radiation of soft photons. This resolution model was checked against the observed shape of the 3.8 million $D^0 \to K^- \pi^+$ decays in a sample of $D^{\star +} \to D^0 \pi^+$ decays collected with a similar trigger selection. This sample was also used to calibrate the PID through the measurement of the specific ionization energy-loss (dE/dx) of kaons and pions in the drift chamber, using the charge of the $D^{\star +}$ pion to identify the D^0 decay products. The dE/dx response of protons was determined from a sample of about 0.3 million $\Lambda \to p\pi^-$ decays, where the kinematics and the momentum threshold of the trigger allow unambiguous identification of the decay products. The statistical separation between kaons and pions is about 1.4σ, while the ionization rates of protons and kaons are quite similar in the momentum range of interest. The signal yields from the fit are corrected for different detection efficiencies extracted from control samples in data to determine the physical asymmetries. Simulation is used only to account for small differences between the kinematics of decays and control signals. The corrections for decays into the $K^+\pi^-$ final state are extracted from a sample of about 30 million untagged $D^0 \to K^- \pi^+$ decays. For the $\Lambda_b^0 \to p\pi^-$ asymmetry, the factor is derived from a control sample of $\Lambda \to p\pi$ decays. The pK^- factor is extracted by combining the previous ones and assuming the trigger and reconstruction efficiency for two particles factorizes as the product of the single-particle efficiencies.

The final results are listed in Tab. 1. The asymmetry $\mathscr{A}_{CP}(B^0 \to K^+\pi^-)$ is consistent with results from B-factories and LHCb. The measured $\mathscr{A}_{CP}(B_s^0 \to K^-\pi^+)$ confirms the LHCb evidence with the same level of resolution. Systematic uncertainties on such asymmetries are largely due to variation of the fit results against different templates for combinatorial background, signal mass distributions and PID modeling. The observed asymmetries of the Λ_b^0 decays are consistent with zero. Their systematic uncertainty is dominated by the variation of unknown polarization amplitudes in the templates. They are in agreement with the previous results from CDF and supersede them [5].

2. Measurement of the $B_s^0 \to J/\psi\phi$ time-evolution and branching ratio in the complete CDF dataset

The B_s^0-$\bar{B}_s^0$ mixing is a promising process for searches for new physics (NP), given the D0 3.9σ anomaly in dimuon charge asymmetry [6]. 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, ϕ_s, would be significantly altered with respect to its nearly vanishing value expected in the SM. A non-CKM enhancement of ϕ_s can also decrease the decay width difference $\Delta\Gamma_s$ between the heavy and light mass-eigenstates of the B_s^0 meson. The analysis of the time evolution of $B_s^0 \to J/\psi\phi$ 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 2σ with the SM expectation [7]. Latest updates by CDF and D0 are in better agreement with the SM, as well as measurements provided by LHCb [8, 9, 10, 11].

Here we report the new CDF update using the complete dataset of 9.6 fb^{-1} which comprises about 11 000 $B_s^0 \to J/\psi\phi$ decays collected by the dimuon trigger [12]. The decays are fully reconstructed through four tracks that fit to a common decay point separated from the beam line, two matched to muon pairs consistent with a J/ψ 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 ϕ_s

and $\Delta\Gamma_s$. The analysis closely follows the previous determination obtained on a subset of the data [8]. 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 $(1.39 \pm 0.05)\%$. 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 $(3.5 \pm 1.4)\%$, because its calibration is feasible for early data only. This degrades the statistical resolution on ϕ_s by no more than 15%. A decay-time resolution of $\sim$90 fs allows resolving the fast B_s^0 oscillations to increase sensitivity on the mixing phase.

Included in the analysis is also the *CP*-odd *S*-wave component which originates from the non-resonant K^+K^- pair or from $f_0(980)$ decays. The fraction of *S*-wave in the K^+K^- mass range 1.009–1.028 GeV/c^2 is determined from the angular information to be consistent with zero with $\mathscr{O}(2\%)$ uncertainty, which is in agreement with our previous determination [8] and the LHCb [10] and ATLAS results [11], and inconsistent with the D0 determination [9]. An auxiliary simultaneous fit of the $J/\psi K^+K^-$ and K^+K^- mass distributions, which includes for the first time the full resonance structure of the $B^0 \to J/\psi K^+\pi^-$, determines a $(0.8 \pm 0.2(\text{stat}))\%$ K^+K^- *S*-wave contribution, in agreement with the central fit. The contamination from mis-identified B^0 decays is $(8.0 \pm 0.2(\text{stat}))\%$, which is significantly larger than the 2% values derived assuming only *P*-wave B^0 decays [8]. If neglected, this additional B^0 component could mimic a larger K^+K^- *S*-wave than is present.

The 68% and 95% confidence regions in the plane $(\phi_s, \Delta\Gamma_s)$ obtained using a profile-likelihood ratio ordering with frequentist inclusion of systematic uncertainties 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 other recent determinations [9, 10, 11]. This is the final CDF measurement on the B_s^0 mixing phase, and provides a factor 40% improvement in resolution with respect to the latest determination. In Tab. 1, we also report the measurements of $\Delta\Gamma_s$ and of the B_s^0 lifetime τ_s, under the hypothesis of a SM value for ϕ_s, which are in agreement with other experiments' results [9, 10, 11].

The Run II dimuon data set is also exploited for measuring the ratio of the $B_s^0 \to J/\psi\phi$ and $B^0 \to J/\psi K^\star(892)^0$ branching fractions, $R = (f_s/f_d)(\mathscr{B}(B_s^0 \to J/\psi\phi)/\mathscr{B}(B^0 \to J/\psi K^\star(892)^0))$, where $f_{s(d)}$ is the fragmentation fraction of the $s(d)$ quark [13]. We adopt an offline selection that differs from the selection for the ϕ_s measurement since it is optimized towards the measurement of R. We extract the B_s^0 and B^0 yields through a fit to the binned $J/\psi K^+K^-$ and $J/\psi K^+\pi^-$ invariant mass distributions. After application of a relative acceptance factor determined from simulation, we measure $R = 0.239 \pm 0.003(\text{stat}) \pm 0.019(\text{syst})$. Systematic uncertainties are dominated by the modeling of the background and signal templates in the fit and by the variation within uncertainties of the world average value of B lifetimes and polarization amplitudes in the simulation for the acceptance's estimation. Using the most recent CDF measurement [14] of $f_s/(f_u + f_d)\mathscr{B}(D_s \to \phi\pi)$ combined with the PDG value of $\mathscr{B}(D_s \to \phi\pi)$ [15] to extract (f_s/f_d) and the PDG value of $\mathscr{B}(B^0 \to J/\psi K^\star(892)^0)$ [15], we find the branching ratio $\mathscr{B}(B_s^0 \to J/\psi\phi)$ reported in Tab. 1, in agreement with and with similar resolution to Belle's latest result [16]. Using the latter, we also compute the ratio f_s/f_d (Tab. 1). The analysis is also performed in bins of B_s^0 transverse momentum in a range of $6 < p_T < 27$ GeV/c, showing no dependence of f_s/f_d versus p_T.

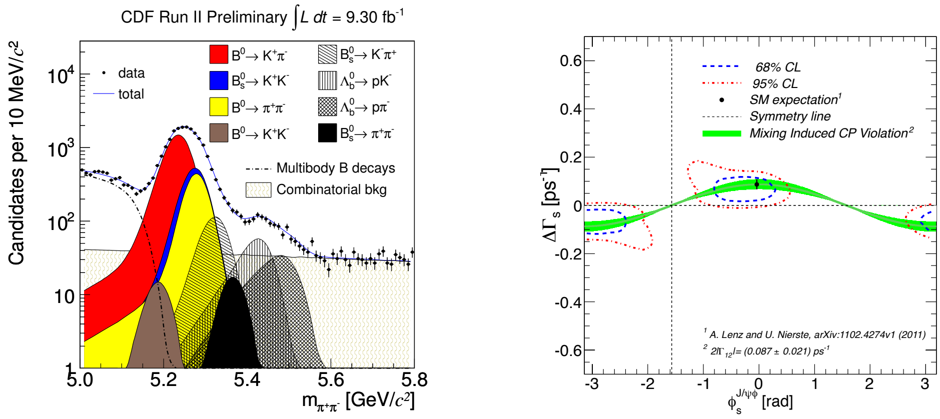

Figure 1: Distribution of $\pi^+\pi^-$ spectrum with fit projections overlaid (left); 68% and 95% confidence regions in the plane (ϕ_s,$\Delta\Gamma_s$) from profile-likelihood of CDF data (right).

3. Measurement of $B_s^0 \to D_s^{(\star)+} D_s^{(\star)-}$ branching ratios

A measurement of B_s^0 production rate times the $B_s^0 \to D_s^{(\star)+} D_s^{(\star)-}$ branching ratio relative to the normalization mode $B^0 \to D_s^+ D^-$ is perfomed using a data sample corresponding to an integrated luminosity of 6.8 fb^{-1} recorded by the displaced track trigger [17]. The decays $D_s^+ \to K^+ K^- \pi^+$ and $D^+ \to K^- \pi^+ \pi^+$ are reconstructed from combinations of three tracks with appropriate charge and mass hypothesis assignments, fitted to a common vertex and then combined into another vertex to form B_s^0 candidates. For the first time in this channel, the Dalitz structure of the intermediate states is exploited for an accurate evaluation of acceptances and efficiencies. The relative branching fractions are determined in a simultaneous maximum likelihood fit to mass distributions of two signal samples, $(\phi\pi^+)(\phi\pi^-)$ and $(\bar{K}^\star(892)^0 K^+)(\phi\pi^-)$, and two normalization samples, $(\phi\pi^+)(K^+\pi^-\pi^-)$ and $(\bar{K}^\star(892)^0 K^+)(K^+\pi^-\pi^-)$. Using measured values of production and relative branching fractions, the absolute branching fractions shown in Tab. 1 are derived. These results are the most precise to date from a single experiment and can provide information on the decay width difference $\Delta\Gamma_s$.

4. Conclusions

I have reported recent measurements in b-hadron decays which exploit the full CDF data set. The measured *CP* asymmetry of $B_s^0 \to K^-\pi^+$ decays confirms the LHCb result with similar resolution, providing strong evidence of direct *CP* violation in this decay mode. Unique measurements of *CP* asymmetries in Λ_b^0 decays are also presented. In the B_s^0-$\bar{B}_s^0$ mixing sector, tensions with SM predictions are now softened by latest updates of ϕ_s and $\Delta\Gamma_s$ bounds. From the large data set collected, we also gain a more precise measurement of the $B_s^0 \to J/\psi\phi$ branching ratio and investigation of dependences of the fragmentation fraction f_s/f_d on the B transverse momentum. Finally, we obtain the world's best measurement of $B_s^0 \to D_s^{(\star)+} D_s^{(\star)-}$ branching ratios to date. Analyses of the unique ($p\bar{p}$ charge-symmetric) and well-understood (10-years expertise) data sample acquired by CDF are still in progress and may provide interesting results in the near future.

$\mathscr{A}_{CP}(B^0 \to K^+\pi^-)$	$(-8.3\pm1.3(\text{stat})\pm0.3(\text{syst}))\%$
$\mathscr{A}_{CP}(B_s^0 \to K^-\pi^+)$	$(22\pm7(\text{stat})\pm2(\text{syst}))\%$
$\mathscr{A}_{CP}(\Lambda_b^0 \to p\pi^-)$	$(7\pm7(\text{stat})\pm3(\text{syst}))\%$
$\mathscr{A}_{CP}(\Lambda_b^0 \to pK^-)$	$(9\pm8(\text{stat})\pm4(\text{syst}))\%$
ϕ_s	$[-0.60,0.12]$ at 68% C.L.
$\Delta\Gamma_s$	$0.068\pm0.026(\text{stat})\pm0.009(\text{syst})\ \text{ps}^{-1}$
τ_s	$1.528\pm0.019(\text{stat})\pm0.009(\text{syst})$ ps
$\mathscr{B}(B_s^0 \to J/\psi\phi)$	$(0.118\pm0.002(\text{stat})\pm0.009(\text{syst})\pm0.015(\text{BR}))\%$
f_s/f_d	$0.254\pm0.003(\text{stat})\pm0.020(\text{syst})\pm0.044(\text{BR})$
$\mathscr{B}(B_s^0 \to D_s^+D_s^-)$	$(0.49\pm0.06(\text{stat})\pm0.05(\text{syst})\pm0.08(\text{BR}))\%$
$\mathscr{B}(B_s^0 \to D_s^{\star\pm}D_s^{\mp})$	$(1.13\pm0.12(\text{stat})\pm0.09(\text{syst})\pm0.19(\text{BR}))\%$
$\mathscr{B}(B_s^0 \to D_s^{\star+}D_s^{\star-})$	$(1.75\pm0.19(\text{stat})\pm0.17(\text{syst})\pm0.29(\text{BR}))\%$
$\mathscr{B}(B_s^0 \to D_s^{(\star)+}D_s^{(\star)-})$	$(3.38\pm0.25(\text{stat})\pm0.30(\text{syst})\pm0.56(\text{BR}))\%$

Table 1: Summary of results of the measurements described in this report.

References

[1] See, for instance, S. W. Lin *et al.* (Belle Collaboration), *Nature* **452**, 332 (2008) and references therein.

[2] M. Gronau and J. L. Rosner, *Phys. Lett.* B **482**, 71 (2008); H. J. Lipkin, *Phys. Lett.* B **621**, 126 (2005).

[3] L. Ristori and G. Punzi, Annu. Rev. Nucl. Part. Sci. **60**, 595 (2010).

[4] CDF Collaboration, CDF Note 10726 (2012).

[5] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **108**, 211803 (2012); *Phys. Rev. Lett.* **106**, 181802 (2011); *Phys. Rev. Lett.* **103**, 031801 (2009); *Phys. Rev. Lett.* **97**, 211802 (2006).

[6] V. M. Abazov *et al.* (D0 Collaboration), *Phys. Rev.* D **84**, 052007 (2011).

[7] CDF and D0 Collaborations, CDF Note 9787, D0 Note 5928 (2009); T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **100**, 161802 (2008);

[8] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev.* D **85**, 072002 (2012); *Phys. Rev. Lett.* **100**, 121803 (2008); *Phys. Rev. Lett.* **94**, 101803 (2005).

[9] V. M. Abazov *et al.* (D0 Collaboration), *Phys. Rev.* D **85**, 032006 (2012).

[10] R. Aaij *et al.* (LHCb Collaboration), LHCb-CONF-2012-002; *Phys. Rev. Lett.* **108**, 101803 (2012); *Phys. Rev. Lett.* **108**, 241801 (2012).

[11] G. Aad *et al.* (ATLAS Collaboration), arXiv:1208.0572.

[12] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **109**, 171802 (2012).

[13] CDF Collaboration, CDF Note 10795 (2012).

[14] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev.* D **77**, 072003 (2008).

[15] J. Beringer *et al.* (Particle Data Group), *Phys. Rev.* D **86**, 010001 (2012).

[16] F. Thorne (for the Belle Collaboration), talk at *Les Rencontres de Physique de la Vallée d'Aoste*, 2012.

[17] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **108**, 201801 (2012).