Heavy Flavor physics at Tevatron

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The study of CP violation and measurements of rare Flavor Changing Neutral Current (FCNC) processes play a key role in constraining CKM picture and nailing indirect contributions from new physics beyond the Standard Model. We present here recent results from CDF and D0 collaborations in this topics, including: direct CP violation studies in two-body charmless decays of neutral B mesons and in B_s^0 mixing with semi-leptonic B decays, the study of $b \to s\mu\mu$ transitions properties and an updated measurements of $B_s^0 \to \mu\mu$ search. The full Tevatron integrated luminosity dataset, corresponding to $10 fb^{-1}$, is used.

1 Introduction

In the electroweak interaction of the flavor sector, CP violation has been observed in the decay and mixing of neutral mesons containing strange, charm and bottom quarks. In the standard model, the flavour structure and quark flavor mixing is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1], [2] which has a single source of CP violation. Currently all measurements of CP violation, either in decay, mixing or in the interference between the two, have been consistent with the presence of a single phase in the CKM matrix. An observation of anomalously large CP violation in B mesons can indicate the existence of physics beyond the standard model (SM) and would lead to a tension in CKM picture. The Tevatron $p\bar{p}$ collider, exploits collisions at 1.96 TeV center of mass energy. At the Tevatron b quarks are produced in pairs with a sizable cross section [3] providing rich samples of bottom-flavored hadrons of all types and offer the opportunity to explore new territory in the field of B_s^0 mesons and b-flavored baryons. This provides privileged access to SM-suppressed processes such as FCNC rare transitions and CP violation in B hadron decays. Additional information coming from different decays yields further constraints on the possible explanations of previous findings, and may possibly reveal new deviations from expectations.

In this paper we focus on a selection of studies on B hadron CP violation and rare decays, performed or updated recently by CDF and D0 collaborations on the full Tevatron dataset.

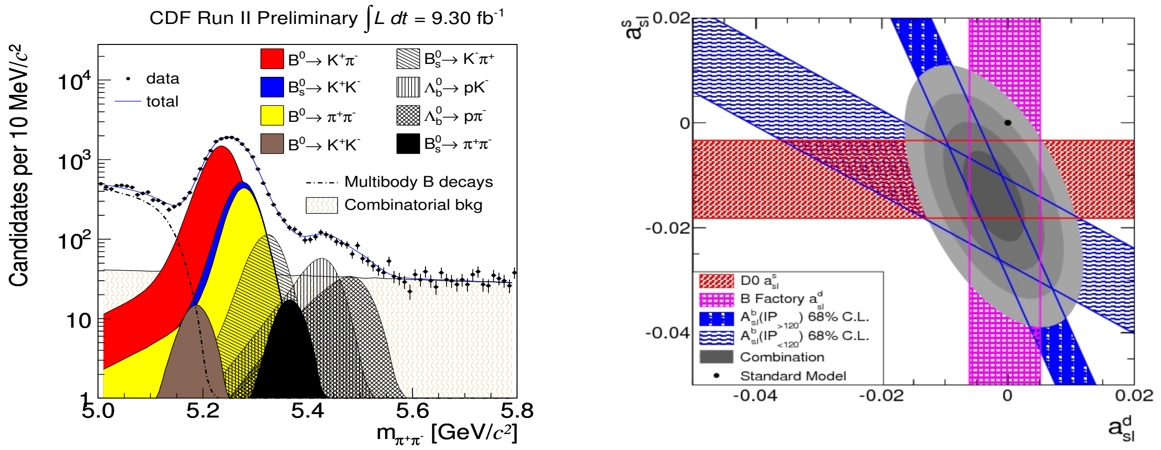

Figure 1: **Left**: CDF charmless hadronic $B \to hh'$ decay candidates, $m_{\pi\pi}$ distribution. The global fit projection is overlaid on data, different decay mode components are also shown. **Right**: Combination of D0 results for semi-leptonic CP asymmetries in the a^s_{sl}, a^d_{sl} plane. Error bands are $\pm 1\sigma$ uncertainties on individual measurement while ellipses are the 2-dimensional combined CL regions corresponding to 1,2,3 and 4 σ.

2 CP violation in charm-less $B_{s,d}$ decays at CDF

Direct CP violation is defined by the partial decay-width of a particle into a final state being different from the width of the corresponding antiparticle into the CP-conjugate final state. In recent times, the pattern of direct CP violation in charmless mesonic decays of B mesons has shown some unanticipated discrepancies from expectations. Under standard assumptions of isospin symmetry and smallness of contributions from higher-order processes, similar CP asymmetries are predicted for $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays refben. However, experimental data show a significant discrepancy, which has prompted intense experimental and theoretical activity. Several simple extensions of the standard model could accommodate the discrepancy, but uncertainty on the contribution of higher-order SM amplitudes has prevented a firm conclusion yet. High precision measurements of the violation of CP symmetry in charmless modes remains, therefore, a very interesting subject of study and may provide useful information to our comprehension of this discrepancy. Non-leptonic two-body charmless decays of neutral B mesons ($B \to hh'$, where h is a charged pion or kaon) allow to measure and constrain the parameters of the CKM matrix along with potential sensitivity to new physics. Asymmetries up to about 10% are predicted for $\Lambda_b^0 \to pK$ and $\Lambda_b^0 \to p\pi$ in the SM [5,6], and are accessible with current CDF data set corresponding to an integrated luminosity of 9.3 $fb^{?1}$. We select pairs of oppositely-charged particles with $p_T > 2Gev/c$ and $p_T(1) + p_T(2) > 5.5Gev/c$, that form B candidates. The CDF Silicon Vertex Trigger (SVT), directly selecting hadronic heavy flavor decays, requires also a transverse opening angle $20^o < \Delta\Phi < 135^o$ between the two tracks for background rejection. In addition, both charged particles were required to originate from a displaced vertex with a large impact parameter ($100\mu m < d_0(1,2) < 1mm$), while the b-hadron candidate was required to be produced in the primary $p\bar{p}$ interaction ($d_0 < 140\mu m$) and to have travelled a transverse distance $L_T > 200\mu m$. A Maximum Likelihood fit, including kinematics and PID information, was performed in order to disentangle the different components of the resulting mass peak Fig. 1 (left). The signal yields are calculated from the signal fractions returned by the likelihood fit. To determine the physical asymmetries these yields are corrected for detector-induced charge asymmetries extracted from control samples in data. The measurement of $A_{CP}(B^0 \to K^+\pi^-) = ?0.083 \pm 0.013 \pm 0.003$ is consistent with current results from asymmetric e+e colliders [?] and LHCb [8]. The $A_{CP}(B^0_s K^-\pi+) = 0.22 \pm 0.07 \pm 0.02$ result confirms the LHCb evidence [8]. An average value of the CDF and LHCb $A_{CP}(B^0_s \to K^-\pi+)$ results, $< A_{CP}(B^0_s \to K^+\pi^-) >= +0.242 \pm 0.054$, represents a strong evidence of CP violation in the B_s^0 mesons system with a 4.5σ significance. The observed asymmetry in the $\Lambda_b^0 \to pK$ decays, $A_{CP}(\Lambda_b^0 \to p\pi^-) = 0.07 \pm 0.07 \pm 0.03$, and in the $\Lambda_b^0 \to pK^-$ decays, $A_{CP}(\Lambda_b^0 \to pK^-) = -0.09 \pm 0.08 \pm 0.04$, are consistent with zero. However, the limited experimental precision does not allow a conclusive discrimination between the standard model prediction (8%) and much suppressed values (0.3%) expected in R-parity violating supersymmetric scenarios [6].

3 CP violation in B_s and B_d semi-leptonic decays at D0

An observation of anomalously large CP-violation in B_s^0 oscillations can indicate the existence of physics beyond the standard model [9]. Measurements of the like-sign di-muon asymmetry by the D0 Collaboration [10] show evidence of large CP-violating effects using data corresponding to $\sim 9fb^{-1}$ of integrated luminosity. Assuming that this asymmetry originates from mixed neutral B mesons, the measured value is $A_{sl}^b = C_d a_{sl}^d + C_s a_{sl}^s = [-0.787 \pm 0.172(stat) \pm 0.021(syst)]\%$ where $a_{sl}^{s(d)}$ is the time integrated flavor-specic semi-leptonic charge asymmetry in $B_s^0(B_d^0)$ decays that have undergone flavor mixing and $C_s(C_d)$ is the fraction of $B_s^0(B_d^0)$ events. The SM predicts a tiny value for $a_{sl}^s = (1.9 \pm 0.3) \times 10^{-5}$, [9] that is negligible compared with current experimental precision. However its value is extracted from the A_{sl}^b measurement and found to be $a_{sl}^s = (-1.81 \pm 1.06)\%$ [10]. D0 performed also an independent measurement of a_{sl}^s using the decay $B_s^0 \to D_s^- \mu^+ X$ where $D_s^- \to \phi\pi^-$ and $\phi \to K^+K^-$. The flavor of the B_s^0 meson at the time of decay is identified using the charge of the associated muon, and this analysis does not make use of initial-state tagging. The fraction of mixed events integrated over time is extracted using Monte Carlo simulations. We assume no production asymmetry between B_s^0 and $\bar{B}_s^0$ mesons, and that any CP violation only occurs in mixing. The analysis strategy is to extract a_{sl}^s by counting the number of reconstructed $B_s^0 \to \mu^+ D_s^- X$ decays, corrected for detector-related asymmetries and by the fraction of reconstructed $D_s^- \to \phi\pi^-$ decays (F^{osc}) that originate from the decay of a B_s^0 meson after oscillation in its antiparticle, hence $a_{sl}^s = (A - A_{det})/F^{osc}$. The data are collected with a suite of single and di-muon triggers. The selection and reconstruction of $\mu^+ D_s^- X$ decays requires tracks and muon with standard good quality requirements. In addition, muons are required to match tracks reconstructed in the central tracking system, with momentum $p > 3GeV/c$ and $2 < p_T < 25GeV/c$. The $\phi \to K^+K^-$, coming form the $D_s^- \to \phi\pi^-$ decay, is reconstructed if two tracks with $p_T > 0.7GeV/c$, opposite charge, and a mass $M(KK) < 1.07GeV/c^2$ are reconstructed in the kaon hypothesis. A third track is required with $0.5 < p_T < 25GeV/c$ to be consistent with a charged pion and to have opposite charge to the muons one. The three tracks are combined to create a common D_s^- decay vertex. This vertex is required to be displaced in the transverse plane from the $p\bar{p}$ interaction vertex, with a significance $(L_T/\sigma L_T)$ of at least 4 standard deviations. Kinematic requirements assure that the trajectories of the muon and D_s candidates originate from a common vertex (assumed to be the B_s^0 decay vertex). An effective mass consistent with B_s^0 semi-leptonic decays, is selected to be $2.6 < M(\mu^+ D_s^-) < 5.4GeV/c^2$. A $L_T/\sigma L_T > 4$ cut on the B_s^0 decay vertex is also applied. A likelihood ratio combining several discriminating variables, improves the significance of the B_s^0 selection. The number of events is extracted by fitting the $M(KK\pi)$ data distribution to an appropriate model. The resulting time-integrated flavor-specific semi-leptonic charge asymmetry is found to be $a_{sl}^s = [-1.12 \pm 0.74(stat) \pm 0.17(syst)]\%$ superseeding the previous D0 measurement [10], and in agreement with the SM prediction. A combination with the measurements of a_{sl}^d from B factories and di-muon asymmetries results from D0 collaborations [10] leads to the results in Fig. 1 (right). The results are $a_{sl}^s = (-1.42 \pm 0.57)\%$ and $a_{sl}^d = (-0.21 \pm 0.32)\%$ with a correlation of -0.53, which is a significant improvement on the previous measurement precision [10]. These results have a probability of agreement with the SM of 0.28×10^{-2} , which corresponds to 3.0 standard deviations from the SM prediction.

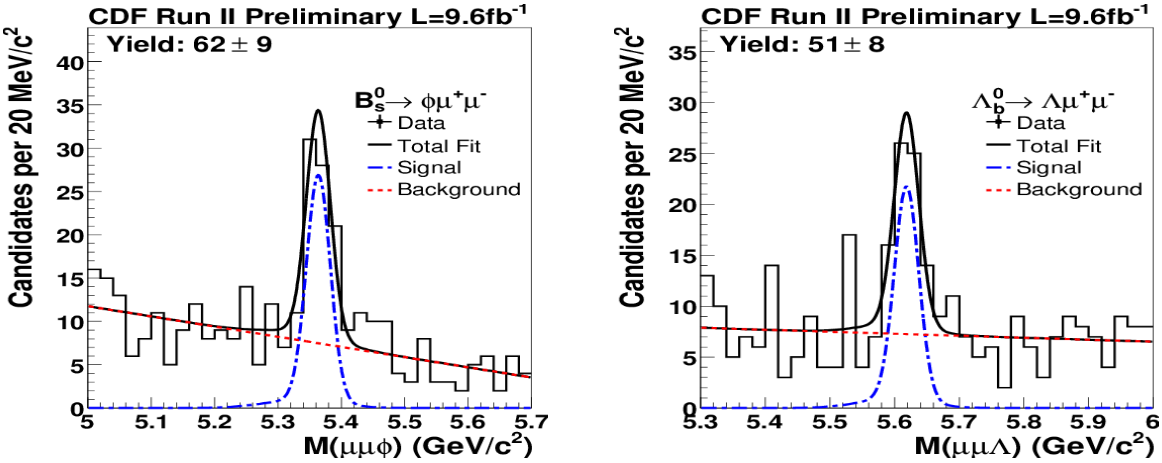

Figure 2: Signals of $b \to s\mu^+\mu^-$ transitions for $B_s^0 \to \phi\mu^+\mu^-$ (**Left**) and for $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ (**Right**) modes after selection, in 9.6 fb-1 of data collected by the CDF detector with di-muon trigger.

4 Studies on $b \to s\mu^+\mu^-$ decays at CDF

In the SM framework, $b \to s\mu^+\mu^-$ transitions are dominated by FCNC processes that are mediated by electroweak box and penguin type diagrams. A new physics process could enhance the decay amplitude and it might be seen as an interference with the SM amplitude. Therefore we measure various observables related to the magnitude or the complex phase, like branching ratio, polarization or forward-backward asymmetry, the isospin asymmetry between neutral and charged B mesons. CDF selects two oppositely charged muon candidates with a momentum transverse to the beam-line, p_T , greater than 1.5 or 2.0 GeV/c, depending on the trigger selection. $H_b \to h\mu^+\mu^-$ events are reconstructed as signal candidates and $H_b rightarrow J/\Psi h$ events as normalization channels, where H_b is a b-hadron $(B^0, B^+, B_s^0$ or $\Lambda_b^0)$ and h stands for a $K^+, K^{*0(+)}, K_S^0, \phi$ or Λ. For the $K^+, K^{*0(+)}, K_S^0, \phi$ and Λ, $K^+\pi^-, K_S^0\pi^+, K^+K^-$ and $p\pi^-$ combination are used respectively. The K_S^0 meson is reconstructed in the $\pi^+\pi^-$ decay mode. To enhance separation of signal from background we employ an artificial neural network (NN) technique. The signal yield is obtained by an un-binned maximum log-likelihood fit of the H_b invariant mass distribution. With $9.6fb^{-1}$ of data [11], the signal yields are: 323 ± 24 $(B^+ \to K^+\mu^+\mu^-)$, 228 ± 20 $(B^0 \to K^{?0}\mu^+\mu^-)$, 32 ± 8 $(B^0 \to K_S^0\mu^+\mu^-)$, 24 ± 6 $(B^+ \to K^{*+}\mu^+\mu^-)$, 62 ± 9 $(B_s^0 \to \phi\mu^+\mu^-)$ and 51 ± 8 $(\Lambda_b^0 \to \Lambda^0\mu^+\mu^-)$, with respectively 15.6σ, 16.8σ, 4.6σ, 4.2σ, 8.9σ and 7.6σ statistical significances. This is the first observation for the $\Lambda_b^0 \to \Lambda^0\mu^+\mu^-$ mode. In Fig. 2, signals for B_s (left) and Λ_b^0 (right) are shown. Obtained yields are consistent with theoretical expectations. Along with the branching fractions of rare decays, CDF measured a number of sensitive observables. We report here only the results of isospin asymmetry as example, see Fig. 3 (left), between neutral and charged B mesons, $A_I(B \to K\mu^+\mu^-) = [-0.11 \pm 0.13(stat) \pm 0.05(syst)] \times 10^{-6}$ and $A_I(B \to K^*\mu^+\mu^-) = [0.16 \pm 0.14(stat) \pm 0.06(syst)] \times 10^{-6}$. Other measurements are referenced in the original paper [11].

5 Search for $B_s \to \mu^+\mu^-$ decay at D0

The $B_s^0 \to \mu^+\mu^-$ rare decay is also dominated by FCNC process. The decay rate is further suppressed by the helicity factor, $(m_\mu/m_B)^2$. The SM expectations for the branching fraction is $\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$ [12]. As many new physics models can enhance the BR significantly, these decays provide sensitive probes for new physics. D0 selects two high-quality muon candidates with opposite-charge and a di-muon invariant mass window of $4.0 < m(\mu^+\mu^-) < 7.0GeV/c^2$. The muon candidates are required to have a $p_T > 1.5GeV/c$, a pseudorapidity $|\eta| < 2$ and to form a good three-dimensional vertex well separated from the

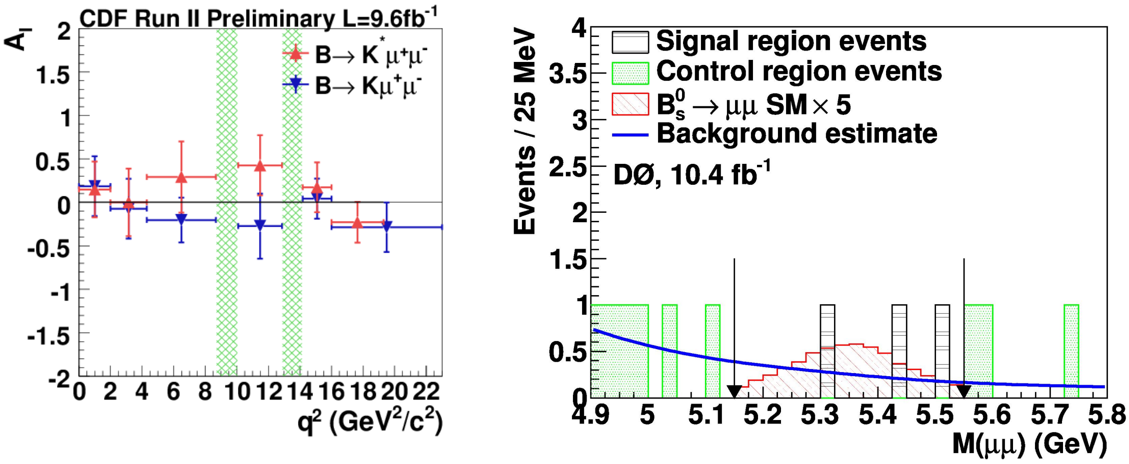

Figure 3: **Left**: CDF analysis of $b \to s\mu^+\mu^-$ Isospin Asymmetry as a function of $\mu^+\mu^-$ pair q^2 for charged B mesons. **Right**: D0 $\mu^+\mu^-$ invariant mass distribution after un-blinding in the search for rare $B_s \to \mu^+\mu^-$ decay.

primary $p\bar{p}$ interaction. These criteria are intended to be fairly loose to maintain high signal efficiency, with further discrimination provided by multivariate technique (Boosted Decision Tree, BDT). The event selection is checked with control samples of $B^{\pm}J/ \to J/\Psi K^{\pm}$. This analysis was performed within the relevant di-muon mass region (between 4.9 and 5.8 GeV/c^2) kept blinded until all analysis procedures were finalized, see Fig. 3 (right). Expectation in that region for a SM signal is of 1.23 ± 0.13 events and a background of 4.0 ± 1.5 events. After unblinding 3 events were observed which is compatible with background hypothesis. An upper limit on the branching fraction is set to BR$(B_s^0 \to \mu^+\mu^-) < 1.5 \times 10^{-8}$ at the 95% C.L. [13].

6 Summary and conclusions

This selection of results presented here, highlights the rich legacy in CP violation and search for new physics in heavy flavor from the Tevatron experiments. They successfully opened the way to experimental strategies now also in use at the LHC, to reach high precision in hadronic collision environment, producing results which were complementary and competitive to B factories in the last decade.

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