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Charmless and Penguin Decays at CDF

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Penguin transitions play a key role in the search of New Physics hints in the heavy flavor sector. During the last decade CDF has been exploring this opportunity with a rich study of two–body charmless decays of neutral B mesons into charged final–state particles. After briefly introducing the aspects of this physics peculiar to the hadron collision environment, I report on two interesting results: the first polarization measurement of the $B_s^0 \to \phi\phi$ decay and the update of the $B_{(s)}^0 \to h^+h'^-$ decays analysis.

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1 Introduction: the penguin role

Since the relevance of the penguin amplitudes was well established by the CLEO experiment about ten years ago [1], penguin–dominated processes become more and more attractive despite their theoretical complexity and experimental rareness. The possibility to access to New Physics (NP) through new virtual particles in the loops makes them an opportunity to be exploited rather than a limitation.

Non–leptonic two–body charmless decays of neutral B mesons, with their sensitivity to penguin amplitudes, play a major role. They can be used to determine the values of the CKM related quantities, which may differ from the ones extracted from tree-level dominated processes, possibly indicating non-Standard Model contributions. Comparison between γ determinations from charmed tree–dominated decays and from charmless $B^0_{(s)} \to h^+h'^-$ probes possible presence of NP in the penguin amplitude. Similarly, comparison of the mixing phase between the tree–process $B^0_s \to J/\psi\phi$ and the penguin $B^0_s \to \phi\phi$ charmless mode could allow to disentangle NP contribution in mixing and decay.

Usually optimal sensitivity is obtained through a full tagged and time–dependent analysis (as the case of $B^0_s \to J/\psi\phi$ above). However, this requires significant statistics of decays that are typically rare. Nevertheless, several strategies have been proposed that do not require identification of production flavor and provide already some sensitivity to NP contributions from measurements of averaged branching fractions, polarization amplitudes and time–integrated CP–asymmetries.

The CDF experiment provides a joint access to large samples of B^0 and B^0_s mesons, which allows to study charmless decays into charged final–state particles. This has been explored since the early 2000's with a pioneering and very rewarding program (for instance [2, 3]); here, the latest measurements of the $B^0_s \to \phi\phi$ decay and an overview of the results of the $B^0_{(s)} \to h^+h'^-$ analysis are reported, discussing finally some prospects. All conjugate modes are implied and branching fractions are CP–averages; for each result, the first uncertainty is statistical and the second one is the systematic error.

2 Charmless B decays in hadron collisions

CDF is a multipurpose solenoidal spectrometer with calorimeters and muon detectors, located at one of the two interaction points of the Tevatron collider. The good performances of the Tevatron (peak luminosity $\simeq 4 \times 10^{32}$ cm^{-2} s^{-1}) and the high data–taking efficiency allow to store on tape about 50 pb^{-1} of data every week.

Despite the higher production rate of B mesons with respect to the B–factories ($\mathcal{O}(10^3)$ more), the production cross section for a $b\bar{b}$ quarks pair at 1.96 TeV (the Tevatron center of mass energy) is a permille fraction of the total. Thus, a highly–

discriminating signature is needed to distinguish relevant events of b–physics. This is provided by the characteristic long lifetime of b–hadrons: they are typically produced with transverse momentum of a few GeV, thus flying about 0.5 mm in the detector and resulting in secondary vertices displaced from the $p\bar{p}$ collision point. Triggering on those vertices is challenging. First, it requires a high resolution tracking detector; this is given by double-sided silicon microstrips arranged in five cylindrical layers and an open cell drift chamber with 96 sense wires, all immersed in a 1.4 T solenoidal magnetic field [4]. Second, it needs to read out all the silicon detector (212 000 channels) and do pattern recognition and track fitting online. In CDF this is done by the Silicon Vertex Trigger in 25 μs with a resolution of the track impact parameter (IP), 48 μm, comparable with off-line measurements [5]. A sample enriched with b–flavor particles is then provided by a specific three–level trigger, based on the requirement of two displaced tracks (*i. e.*, with IP larger than $\mathcal{O}(120\ \mu\text{m})$) with opposite charge.

3 $B_s^0 \to \phi\phi$ Polarization

The $B_s^0 \to \phi\phi$ decay proceeds through a $b \to s\bar{s}s$ quark level process, whose dominant SM diagram is the $b \to s$ penguin. The rich dynamics of decay of pseudoscalar meson in two vector particles involves three different amplitudes corresponding to the polarization states. Hence, the $B_s^0 \to \phi\phi$ channel is attractive to test the theoretical predictions for these polarization amplitudes [6], which have shown several discrepancies with measurements of similar penguin decays [7], raising considerable attention on the so–called "polarization puzzle".

The first evidence for the $B_s^0 \to \phi\phi$ decay has been reported by CDF in 2005 with 8 events in a data sample corresponding to integrated luminosity of 180 pb^{-1} [3]. An updated analysis recently improved the measurement of branching fraction using 2.9 fb^{-1} of data and allows the world's first decay polarization measurement [8]. We reconstruct the $B_s^0 \to J/\psi\phi$ decay in the same dataset, and use this decay as a normalization for the branching ratio measurement and as a control sample for the polarization analysis.

Signal candidates are reconstructed by detecting $\phi \to K^+K^-$ and $J/\psi \to \mu^+\mu^-$ decays and are formed by fitting four tracks to a common vertex. Combinatorial background is reduced by exploiting several variables sensitive to the long lifetime and relatively hard p_T spectrum of B mesons. The requirements on the discriminating variables are optimized by maximizing $\mathcal{S}/\sqrt{\mathcal{S}+\mathcal{B}}$, where the signal ($\mathcal{S}$) is derived from a Monte Carlo (MC) simulation and the background ($\mathcal{B}$) is represented by appropriately normalized data sampled from the sideband mass regions. Two sources of background are expected for both $B_s^0 \to \phi\phi$ and $B_s^0 \to J/\psi\phi$: a dominant and smooth combinatorial background and a physics component, which is given by $B^0 \to \phi K^{*0}$ ($B^0 \to J/\psi K^{*0}$) decays in the case of $B_s^0 \to \phi\phi$ ($B_s^0 \to J/\psi\phi$) and it is estimated

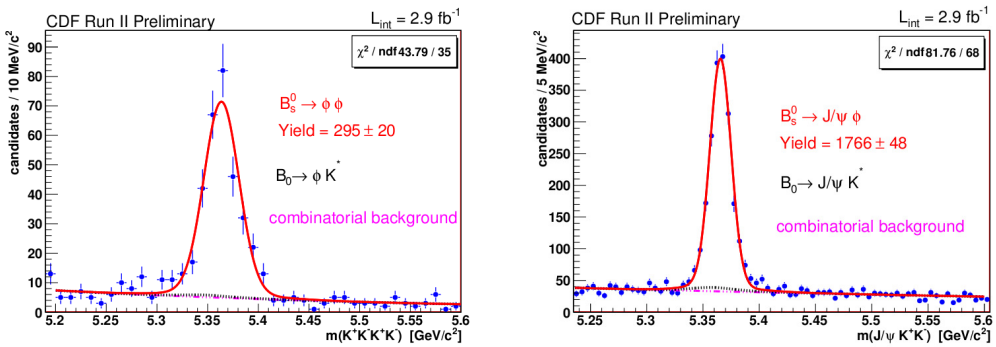

Figure 1: m_{KKKK} (left) and $m_{J/\Psi KK}$ (right) distributions for $B_s^0 \to \phi\phi$ and $B_s^0 \to J/\psi\phi$ candidates with fit projections overlaid.

by simulation not to exceed a 3% fraction of the signal. Signals of 295 ± 20 events of $B_s^0 \to \phi\phi$ and 1766 ± 48 events of $B_s^0 \to J/\psi\phi$ are obtained by fitting the mass distributions (see fig. 1).

The relative $B_s^0 \to \phi\phi$ decay rate is calculated using

$$\frac{\mathcal{B}\left(B_s^0 \to \phi\phi\right)}{\mathcal{B}\left(B_s^0 \to J/\psi\phi\right)} = \frac{N_{\phi\phi}}{N_{\psi\phi}} \frac{\mathcal{B}\left(J/\psi \to \mu^+\mu^-\right)}{\mathcal{B}\left(\phi \to K^+K^-\right)} \frac{\epsilon_{\psi\phi}}{\epsilon_{\phi\phi}} \epsilon^{\mu}_{\psi\phi} \ , \tag{1}$$

where $N_{\phi\phi}$ ($N_{\psi\phi}$) is the number of $B_s^0 \to \phi\phi$ ($B_s^0 \to J/\psi\phi$) events, $\epsilon_{\phi\phi}/\epsilon_{\psi\phi} = 0.939 \pm 0.030 \pm 0.009$ is the relative trigger and selection efficiency extracted from simulation; $\epsilon^{\mu}_{\psi\phi} = 0.8695 \pm 0.0044$, the efficiency for identifying a muon, is obtained from data using inclusive $J/\psi \to \mu^+\mu^-$ decays as a function of muon p_T. By using the known values for the branching fractions $\mathcal{B}(\phi \to K^+K^-)$, $\mathcal{B}(J/\psi \to \mu^+\mu^-)$ and $\mathcal{B}(B_s^0 \to J/\psi\phi)$ [9] (updated to current values of f_s/f_d), we determine $\mathcal{B}(B_s^0 \to \phi\phi) = (2.40 \pm 0.21 \pm 0.27 \pm 0.82) \times 10^{-5}$* in agreement with the previous determination [3].

We measure the polarization from the angular distributions of decay products, expressed as a function of helicity angles, $\vec{\omega} = (\cos\vartheta_1, \cos\vartheta_2, \Phi)$. The total decay width is composed of three polarization amplitudes: A_0, $A_\parallel$ and $A_\perp$. Taking the untagged decay rate integrated in time and neglecting CP-violating differences between $\bar{B}_s^0$ and B_s^0 both in mixing and in decay, the differential decay rate is a function of the helicity angles and depends on the polarization amplitudes at $t = 0$ and on the light and heavy B_s^0 mass-eigenstate lifetimes, τ_L and τ_H respectively, as follows:

$$\frac{d^3\Gamma}{d\vec{\omega}} \propto \tau_L(|A_0|^2 f_1 + |A_\parallel|^2 f_2 + |A_0||A_\parallel| \cos\delta_\parallel f_5) + \tau_H |A_\perp|^2 f_3, \tag{2}$$

where $\delta_\parallel = \arg(A_0^\star A_\parallel)$ and the $f_i = f_i(\vec{\omega})$ are functions of the helicity angles only.

*The last uncertainty is given by the uncertainty in $\mathcal{B}(B_s^0 \to J/\psi\phi)$.

We perform an unbinned maximum likelihood fit to the reconstructed mass m of the B_s^0 candidates and the helicity angles. The mass distribution provides discrimination between signal and background. At this stage only the combinatorial component is considered as background, accounting for the small contamination of other decays to the systematic uncertainties. Fixing τ_L and τ_H to the known values [9], the polarization amplitudes are extracted using directly Eq. 2 as the angular probability density function for the signal, corrected by an acceptance factor given by a full MC simulation. The angular background is modeled on sidebands data with polynomials and fitted in the whole mass range. The fitter is extensively tested and validated through statistical trials; the robustness and reliability of the approach is tested in data as well by measuring the polarization of the $B_s^0 \to J/\psi\phi$ in the sample used in the branching fraction update described above; the results, $|A_0|^2 = 0.534 \pm 0.019$ and $|A_\parallel|^2 = 0.220 \pm 0.025$, are in very good agreement with [10].

Several sources of systematic uncertainty are considered and only the main two are reported here. We account for the physics background effects through simulated samples. In addition to the $B^0 \to \phi K^{*0}$ decay, we consider other two contributions, the $B_s^0 \to \phi f_0$ decay and the non–resonant $B_s^0 \to \phi(K^+K^-)$: all the background decays give an additional 1.5% uncertainty on the polarization estimates. Then, the biases (1%) introduced by the time integration of the decay rate are examined with MC simulation. We check the tiny impact (0.2%) of our assumption of neglecting CP-violating effects.

The angular fit projections are shown in fig. 2. The results of the polarization observables for the $B_s^0 \to \phi\phi$ candidates are $|A_0|^2 = 0.348 \pm 0.041 \pm 0.021$, $|A_\parallel|^2 = 0.287 \pm 0.043 \pm 0.011$, $|A_\perp|^2 = 0.365 \pm 0.044 \pm 0.027$ and $\cos\delta_\parallel = -0.91^{+0.15}_{-0.13} \pm 0.09$. The measured amplitudes result in a smaller longitudinal fraction with respect to the naive expectation, $f_L = |A_0|^2/(|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2) = 0.348 \pm 0.041 \pm 0.021$, like previously found in other similar $b \to s$ penguin decays [7].

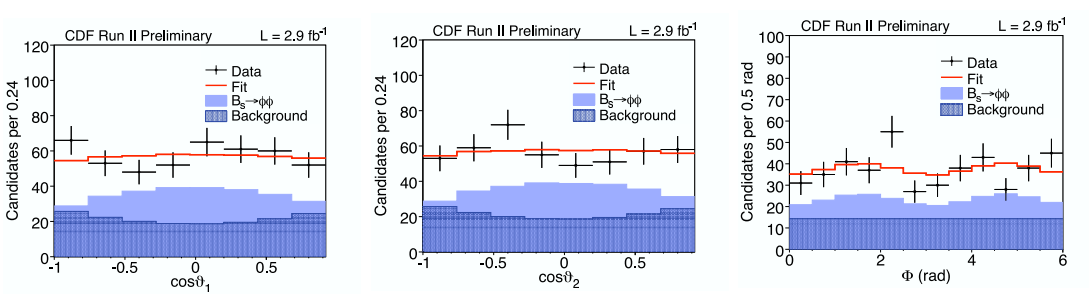

Figure 2: Projections of the fit for $B_s^0 \to \phi\phi$ onto the helicity angles.

4 $B^0_{(s)} \to h^+h'^-$ decays

Two-body decays mediated by the $b \to u$ quark level transition have amplitudes sensitive to γ CKM angle and to NP too, being affected by significant contributions from penguin transitions [11]. A variety of open channels with similar final states characterize this transition: this allow cancellation of many common systematic effects and provides key information to improve effective models of low–energy QCD. In 1 fb^{-1} of data, CDF observes four new modes of these decays and has unique access to direct CP violation in B^0_s and Λ^0_b decays; in addition, our measurements of direct CP violation in the B^0 sector are competitive with the B–factories.

An optimized offline selection isolates a clear signal of roughly 7000 events over a smooth background (fig. 3). A five-dimensional likelihood fit relying on kinematics differences between decays and particle identification from the measurement of specific ionization in the drift chamber allow statistical determination of the individual contributions. Event fractions for each channel are corrected for trigger and selection efficiencies (from simulation and data) to extract the decay–rates. We report the first observation of the decays $B^0_s \to K^-\pi^+$, $\Lambda^0_b \to p\pi^-$, $\Lambda^0_b \to pK^-$, and world-leading measurements of (upper limits on) the $B^0_s \to K^+K^-$ ($B^0_s \to \pi^+\pi^-$) branching fractions: in unit of 10^{-6}, $\mathcal{B}(B^0_s \to K^-\pi^+) = 5.0 \pm 0.7 \pm 0.8$, $\mathcal{B}(\Lambda^0_b \to p\pi^-) = 3.5 \pm 0.6 \pm 0.9$, $\mathcal{B}(\Lambda^0_b \to pK^-) = 5.6 \pm 0.8 \pm 1.5$, $\mathcal{B}(B^0 \to \pi^+\pi^-) = 5.02 \pm 0.33 \pm 0.35$, $\mathcal{B}(B^0_s \to K^+K^-) = 24.4 \pm 1.4 \pm 3.5$, and $\mathcal{B}(B^0_s \to \pi^+\pi^-) < 1.2$, $\mathcal{B}(B^0 \to K^+K^-) < 0.7$, both at 90% C.L. The measured ratio $\mathcal{B}(\Lambda^0_b \to p\pi^-)/\mathcal{B}(\Lambda^0_b \to pK^-) = 0.66 \pm 0.14 \pm 0.08$ shows that significant penguin contributions compensate the Cabibbo (and kinematic) suppression expected at tree level. We also report first measurements of the following direct CP–violating asymmetries: $A_{\mathsf{CP}}(B^0_s \to K^-\pi^+) = (39 \pm 15 \pm 8)\%$, $A_{\mathsf{CP}}(\Lambda^0_b \to p\pi^-) = (3 \pm 17 \pm 5)\%$, and $A_{\mathsf{CP}}(\Lambda^0_b \to pK^-) = (37 \pm 17 \pm 3)\%$. Direct CP violation in the $B^0 \to K^+\pi^-$ mode is measured as $A_{\mathsf{CP}}(B^0 \to K^+\pi^-) = (-8.6 \pm 2.3 \pm 0.9)\%$, consistent with the final B–factories results. The analysis of the 6 fb^{-1} sample is now in progress. We expect to have more than 16 000 $B^0_{(s)} \to h^+h'^-$ decays where new modes could be observed and CP-violating asymmetries measured with doubled precision.

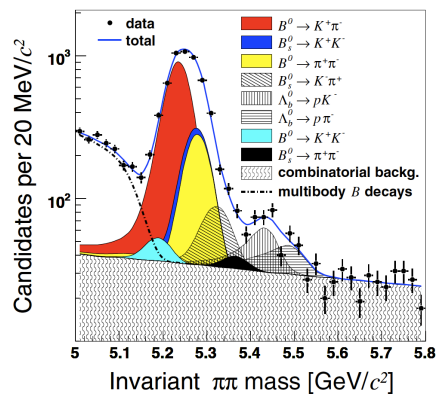

Figure 3: Distribution of $\pi\pi$–mass for $B^0_{(s)} \to h^+h'^-$ candidates with fit projections overlaid.

5 Conclusions and Outlook

Since the beginning of Run II, CDF is leading a rich program on B_s^0 meson physics, whose two–body charmless decays are a key part, given their sensitivity to NP through rare penguin transitions. We report the update of the branching fraction and the first polarization measurement for the $B_s^0 \to \phi\phi$ decay, which provides useful information on the puzzling scenario of B to vector–vector decays. Having a self-conjugate final state, the $B_s^0 \to \phi\phi$ can be used to measure the B_s^0 decay width difference ($\Delta\Gamma_s$), and it is sensitive to the CP violation in the decay and/or mixing, supplementing the analogous measurements in tree-dominated $B_s^0 \to J/\psi\phi$ decay. In the $B_{(s)}^0 \to h^+h'^-$ analysis, $B_s^0 \to K^-\pi^+$, $\Lambda_b^0 \to p\pi^-$, and $\Lambda_b^0 \to pK^-$ decays were newly observed and their branching fractions and CP-asymmetries measured. Updates beyond 1 fb^{-1} of this analysis will provide stringent model–independent constraints on non–SM contributions and exploration of time–dependent CP–asymmetries, increasing our knowledge of the γ angle. CDF collected to date 8 fb^{-1} of physics-quality data, which will reach 10 fb^{-1} by October 2011. Additional 6 fb^{-1} will be collected if the proposed three-year extension will be funded.

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