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Flavor Changing Neutral Current at the Tevatron

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Processes involving flavor changing neutral currents (FCNC) provide excellent signatures with which to search for evidence of new physics. They have very small branching fractions in the Standard Model since they are highly suppressed by Glashow-Iliopoulos-Maiani (GIM) mechanism. They occur only through higher order diagrams, and new particles contributions can provide a significant enhancements, which would be an uniquevocal signs of physics beyond the Standard Model. In this paper we present the most recent measurements on FCNC processes performed by CDF and DØ Collaborations, while last section is devote to the charm physics at CDF.

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1. Search for rare $B_s^0(B^0) \to \mu^+\mu^-$ decay modes

The FCNC decays $B_s^0(B^0) \to \mu^+\mu^-$ [1] occur in the Standard Model (SM) only through higher order diagrams and are further suppressed by the helicity factor, $(m_\mu/m_B)^2$. The B^0 decay is also suppressed with respect to the B_s^0 decay by the ratio of CKM elements, $|V_{td}/V_{ts}|^2$. The SM expectations for these branching fractions are $\mathscr{B}(B_s^0 \to \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$ and $\mathscr{B}(B^0 \to \mu^+\mu^-) = (1.00 \pm 0.14) \times 10^{-10}$ [2], which are one order of magnitude smaller than current experimental sensitivity. Enhancements to $B_s^0(B^0) \to \mu^+\mu^-$ occur in many new physics models [3]. In the absence of an observation, limits on $\mathscr{B}(B_s^0 \to \mu^+\mu^-)$ are complementary to those provided by other experimental measurements, and together would significantly constrain the allowed supersymmetric parameter space. In general, the search for these rare decays is central to exploring a large class of new physics models. In the following we will present recent results on the search of these very rare decays from CDF [4, 5] and DØ [6, 7] Collaborations. Since two analyses are very similar, we will shortly describe only CDF analysis. Details on CDF and DØ detectors can be found in [8].

At CDF in the offline analysis, the trigger selection [4, 5] is refined by applying a series of "baseline" requirements that substantially reduce the backgrounds while preserving the majority of the signal. We select two oppositely charged muon candidates within a dimuon invariant mass window of $4.669 < m_{\mu\mu} < 5.969\,\mathrm{GeV}/c^2$ around the B_s^0 and B^0 masses. Backgrounds from hadrons misidentified as muons are suppressed by selecting muon candidates using a likelihood function. This function tests the consistency of electromagnetic and hadronic energy with that expected for a minimum ionizing particle and the differences between extrapolated track trajectories and muon system hits [4]. In addition, backgrounds from kaons that penetrate through the calorimeter to the muon system or decay in flight outside the drift chamber are further suppressed by a loose selection based on the measurement of the ionization per unit path length, dE/dx [9, 10]. The inputs to the muon likelihood and the dE/dx performance are calibrated using samples of $J/\psi \to \mu^+\mu^-$, $D^0 \to K^-\pi^+$ and $\Lambda \to p\pi^-$ decays. To reduce combinatorial backgrounds the muon candidates are required to have transverse momentum relative to the beam direction $p_T > 2.0$ GeV$/c$, and $|\vec{p}_T^{\,\mu\mu}| > 4$ GeV$/c$, where $\vec{p}_T^{\,\mu\mu}$ is the transverse component of the sum of the muon momentum vectors. The remaining pairs of muon tracks are fit under the constraint that they come from the same three-dimensional (3D) space point. To achieve further separation of signal from background, we employ additional discriminating variables. These include the measured proper decay time, λ; the proper decay time divided by the estimated uncertainty, λ/σ_λ; the 3D opening angle between vectors $\vec{p}^{\,\mu\mu}$ and the displacement vector between the primary vertex and the dimuon vertex, $\Delta\Theta$; and the B-candidate track isolation, I [11]. We require that $\lambda/\sigma_\lambda > 2$, $\Delta\Theta < 0.7$ rad, and $I > 0.50$. The baseline selection reduces combinatorial backgrounds by a factor of 300 while keeping approximately 50% of the signal events that are within the acceptance (geometric and kinematic requirements) of the trigger. A sample of $B^+ \to J/\psi K^+$ events is collected to serve as a normalization mode using the same baseline requirements, but including a requirement of $p_T > 1$ GeV$/c$ for the kaon candidate and constructing the $B^+ \to J/\psi K^+ \to \mu^+\mu^-$ vertex using only the muon candidate tracks.

For the final event selection we use the following discriminating variables: $m_{\mu\mu}$, λ, λ/σ_λ, $\Delta\Theta$, I, $|\vec{p}_T^{\,\mu\mu}|$, and the p_T of the lower momentum muon candidate. To enhance signal and back-

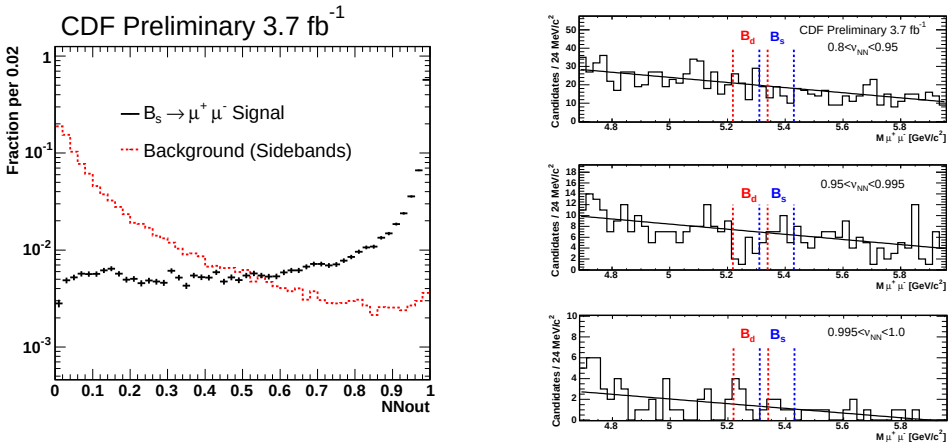

Figure 1: Distributions of ν_N for simulated $B_s^0 \to \mu^+\mu^-$ signal and observed sideband events (on the left). The $\mu^+\mu^-$ invariant mass distribution for events satisfying all selection criteria for the final three ranges of ν_N (on the right).

ground separation we construct a NN discriminant, ν_N, based on all the discriminating variables except $m_{\mu\mu}$, which is used to define signal and sideband background regions. The NN is trained using background events sampled from the sideband regions and signal events generated with a simulation described below. The ν_N distributions of B_s^0 signal and sideband background events are shown in fig. 1.

For measuring efficiencies, estimating backgrounds, and optimizing the analysis, samples of $B_s^0(B^0) \to \mu^+\mu^-$, $B^+ \to J/\psi K^+$, and $B \to h^+h^-$ (where $h^\pm$ are $\pi^\pm$ or $K^\pm$) are generated with the PYTHIA simulation program [12] and a CDF II detector simulation. The B-hadron p_T spectrum and the I distribution of the B-hadrons are weighted to match distributions measured in samples of $B^+ \to J/\psi K^+$ and $B_s^0 \to J/\psi\phi$ decays.

We use a relative normalization to determine the $B_s^0 \to \mu^+\mu^-$ branching fraction:

$$\mathscr{B}(B_s^0 \to \mu^+\mu^-) = \frac{N_s}{N_+} \cdot \frac{\alpha_+}{\alpha_s} \cdot \frac{\varepsilon_+}{\varepsilon_s} \cdot \frac{1}{\varepsilon_N} \cdot \frac{f_u}{f_s} \cdot \mathscr{B}(B^+), \quad (1)$$

where N_s is the number of $B_s^0 \to \mu^+\mu^-$ candidate events. We observe about $N_+ \approx 19,700$ $B^+ \to J/\psi K^+$ candidates. We use $\mathscr{B}(B^+) = \mathscr{B}(B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+) = (5.94 \pm 0.21) \times 10^{-5}$ [13] and the ratio of B-hadron production fractions $f_u/f_s = 3.86 \pm 0.59$ [13]. The parameter α_s (α_+) is the acceptance of the trigger and ε_s (ε_+) is the efficiency of the reconstruction requirements for the signal (normalization) mode. The reconstruction efficiency includes trigger, track, muon, and baseline selection efficiencies. The NN efficiency, ε_N, only applies to the signal mode. The expression for $\mathscr{B}(B^0 \to \mu^+\mu^-)$ is derived by replacing B_s^0 with B^0 and the fragmentation ratio with $f_u/f_d = 1$.

The ratio of acceptances α_+/α_s is measured using simulated events, and its uncertainty includes contributions from systematic variations of the modeling of the B-hadron p_T distributions, the longitudinal beam profile, and from the statistics of the simulated event samples. The ratio of reconstruction efficiencies $\varepsilon_+/\varepsilon_s$ is measured using simultaneously data and simulation. Muon reconstruction efficiencies are estimated as a function of muon p_T using observed event samples

of inclusive $J/\psi \to \mu^+\mu^-$ decays. Systematic uncertainties in this ratio largely cancel with the exception of the kaon efficiency from the B^+ decay. The uncertainty is dominated by kinematic differences between inclusive $J/\psi \to \mu^+\mu^-$ and $B_s^0(B^0) \to \mu^+\mu^-$ decays. The efficiency, ε_N, is estimated from the simulation. We assign a relative systematic uncertainty on ε_N of 6% based on comparisons of NN performance in simulated and observed $B^+ \to J/\psi K^+$ event samples and the statistical uncertainty on studies of the B_s^0 p_T and I distributions from observed $B_s^0 \to J/\psi\phi$ decays.

The expected background is obtained by summing contributions from the combinatorial continuum and from $B \to h^+h^-$ decays, which peak in the B_s^0 and B^0 invariant mass signal region and do not occur in the sidebands. The contribution from other heavy-flavor decays is negligible. We estimate the combinatorial background by linearly extrapolating from the sideband region to the signal region. The $B \to h^+h^-$ contributions are about a factor of ten smaller than the combinatorial background and are estimated using efficiencies taken from the simulation, probabilities of misidentifying hadrons as muons measured in a $D^0 \to \pi K$ data sample, and normalizations derived from branching fractions from refs. [9, 13]. The two-body invariant mass distribution of the simulated $B \to h^+h^-$ candidates is calculated from the momentum of the hadrons assuming the muon mass hypothesis. The background estimates are cross-checked using three independent control samples: $\mu^\pm\mu^\pm$ events, $\mu^+\mu^-$ events with $\lambda < 0$, and a misidentified muon-enhanced $\mu^+\mu^-$ sample in which we require one muon candidate to fail the muon quality requirements. We compare the predicted and observed number of events in these samples for a wide range of ν_N requirements and observe no significant discrepancies.

The $\mu^+\mu^-$ invariant mass distributions for the three different ν_N ranges are shown in fig. 1. The observed event rates are consistent with SM background expectations. Using a data sample of 3.7 fb^{-1} of integrated luminosity, collected by CDF II experiment, we extract 95% (90%) C.L. limits of $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 4.3 \times 10^{-8}$ (3.6×10^{-8}) [5] and $\mathscr{B}(B^0 \to \mu^+\mu^-) < 7.6 \times 10^{-8}$ (6.0×10^{-8}) [5], which are currently the world's best upper limits for both processes. Assuming $N_s = 1$, from eq. 1.1 we compute the single event sensitivity (SES) for the $B_s^0 \to \mu^+\mu^-$ decay mode as 3.2×10^{-9} for all mass and ν_N bins. The SES for the $B_s^0 \to \mu^+\mu^-$ is smaller than the expected SM branching fraction and we expect 1.2 events from $B_s^0 \to \mu^+\mu^-$ decays with 0.7 events occurring in the highest sensitivity ν_N bin. The result for $B_s^0 \to \mu^+\mu^-$ is slightly in excess of the expected limit, which is $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 3.3 \times 10^{-8}(2.7 \times 10^{-8})$ at 95(90)% C.L., and this was estimated with no signal hypothesis. We calculate the P-value of the excess as 23% corresponding to 0.73σ.

DØ performs a similar analysis. Latest results are based on a data sample of integrated luminosity of 2 fb^{-1}. The observed event rates are, also in this case, consistent with SM background expectations. We extract 95(90)% C.L. limit of $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 9.3 \times 10^{-8}$ (7.5×10^{-8}) [6]. With 5 fb^{-1} of data collected by the DØ experiment, we have studied the sensitivity to the branching fraction of $B_s^0 \to \mu^+\mu^-$ decays. An expected upper limit on the branching fraction is $\mathscr{B}(B_s^0 \to \mu^+\mu^-) < 5.3(4.3) \times 10^{-8}$ at the 95(90)% C.L. [7].

We observe no evidence for new physics and set limits that are the most stringent to date, improving the previous results [4, 6, 14] by a factor of 1.5 or more. These limits place further constraints on new physics models, and complement its direct searches. We expect the analysis sensitivity to continue to improve as we include larger data sets.

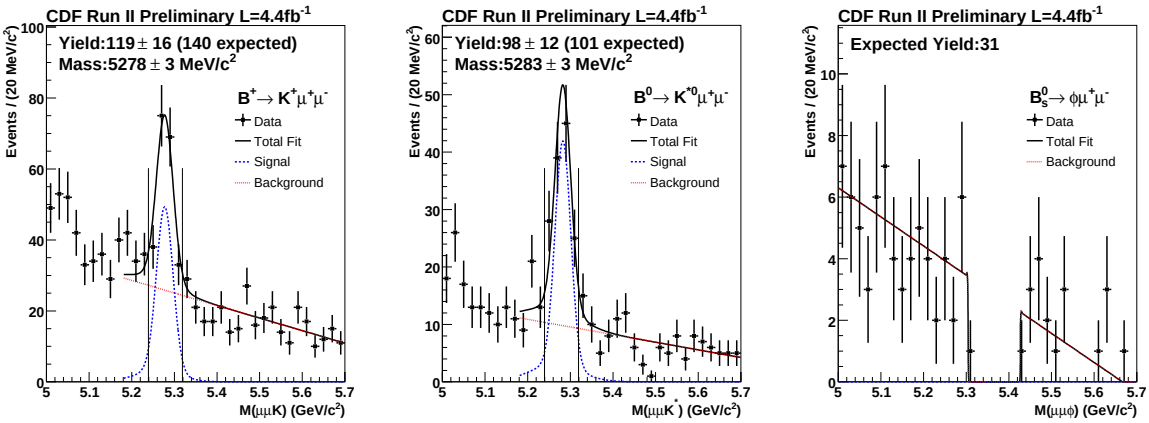

Figure 2: The B invariant mass of $B^+ \to K^+\mu^+\mu^-$(on the left), $B^0 \to K^{*0}\mu^+\mu^-$(center) and $B_s^0 \to \phi\ \mu^+\mu^-$(on the right) on a data sample of 4.4 fb^{-1} of integrated luminosity. Solid, dashed, and dotted line shows total fit, signal PDF and background PDF, respectively, while dots with error bars are data.

2. $b \to s\ \ell^+\ell^-$ transition at the Tevatron

The $b \to s\ \ell^+\ell^-$ transition is a FCNC process, which, in the SM, proceeds at lowest order via either a Z/γ penguin diagram or a W^+W^- box diagram, as the $B_s^0(B^0) \to \mu^+\mu^-$ decays. The effective Wilson coefficients C_7, C_9, and C_{10} describe the amplitudes from the electromagnetic penguin, the vector electroweak, and the axial-vector electroweak contributions, respectively. These amplitudes may interfere with the contributions from non-SM particles [15], therefore the transition can probe the presence of yet unobserved particles and processes. More specifically, the lepton forward-backward asymmetry (A_{FB}) and the differential branching fraction as functions of dilepton invariant mass ($M_{\ell\ell}$) in the decays $B \to K^*\ell^+\ell^-$ differ from the SM expectations in various extended models [16]. The former is largely insensitive to the theoretical uncertainties of the form factors describing the decay, and can hence provide a stringent experimental test of the SM. The latter has been already determined [17, 18], however the precision is still limited by statistics. It can be used to extract the information on the coefficients associated with the theoretical models as well. For more details see ref. [19].

Although the branching ratio of each $b \to\ s\ \mu^+\mu^-$ decay is quite small as $\mathscr{O}(10^{-7})$, the decay is experimentally clean due to opposite sign muons. Among many $b \to\ s\ \mu^+\mu^-$ decays, the exclusive channels $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$ have been observed and studied at Belle [17] and BaBar [18]. However, the analogous decays $B_s^0 \to \phi\ \mu^+\mu^-$ and $\Lambda_b^0 \to \Lambda\ \mu^+\mu^-$ have not been observed despite searches by CDF [20] and DØ [21]. Electrons can be reconstructed at the TeVatron, but they involve additional experimental difficulties and they will be treated in next iterations of the analysis.

CDF is currently updating the analysis on a data sample of 4.4 fb^{-1} of integrated luminosity [22]. We obtain a signal yield for the $B^0 \to K^{*0}\mu^+\mu^-$ decay mode equal to 98 ± 12 (101 expected), with a statistical significance of about 10σ and a signal yield for the $B^+ \to K^+\mu^+\mu^-$ equal to 119 ± 16 (140 expected), with a statistical significance of about 9σ. Significances are deterimined from the likelihood ratio to a null signal hypothesis. Search of the $B_s^0 \to \phi\ \mu^+\mu^-$ is still blind as shown in fig. 2. We expect a significant signal yield, also in this case, of about 31

events. Measurement of $\mathscr{B}(M^2_{\ell\ell})$ and A_{FB} is underway [23].

3. Search for rare $D^0 \to \mu^+\mu^-$ decay mode

The FCNC decay $D^0 \to \mu^+\mu^-$ is highly suppressed in the SM by the nearly exact Glashow-Iliopoulos-Maiani cancellation. SM expects the branching fraction to be about 10^{-18} [24] from short-distance processes, increasing to about 4×10^{-13} [24] by including long-distance processes. The prediction is many orders of magnitude beyond the reach of the present generation of experiments. The best published upper bound is 1.3×10^{-6} at the 90% C.L. from BaBar [25], while the world's best upper bound is 1.4×10^{-7} at the 90% C.L. from Belle [26].

However, new physics contributions can significantly enhance the branching ratio [24]. Some of these new scenarios could enhance the branching fraction to the range of 10^{-8} to 10^{-10} , and in particular R-parity violating SUSY could lift the branching fraction up to the level of the existing experimental bound. Similar enhancements can occur in K and B decays, but charm decays provide a unique laboratory to search for new physics couplings in the up-quark sector. Ref. [27] shows that, in some scenarios, new physics contributions to $D^0 - \overline{D}^0$ mixing can dominate, but yield a result consistent with the SM, the same new physics can contribute to $D^0 \to \mu^+\mu^-$, yielding a visible signal.

Using a data sample of 360 pb^{-1} of integrated luminosity CDF searches for $D^0 \to \mu^+\mu^-$ decays. A displaced-track trigger selects long-lived D^0 candidates in the $\mu^+\mu^-$, $\pi^+\pi^-$, and $K^-\pi^+$ decay modes. We use the kinematically similar $D^0 \to \pi^+\pi^-$ channel for normalization, and the Cabibbo-favored $D^0 \to K^-\pi^+$ channel to optimize the selection criteria in an unbiased manner. We set an upper limit on the branching fraction $\mathscr{B}(D^0 \to \mu^+\mu^-) < 3.0 \times 10^{-7}(2.1 \times 10^{-7})$ at the 95(90%) C.L. [28]. CDF is currently analyzing a data sample of about 5 fb^{-1} of data (already on tape), and it will integrate 8(10) fb^{-1} by the end of 2010(2011). We expect to significantly approach, by the end of Run II, the interesting region 10^{-8} for the $D^0 \to \mu^+\mu^-$ decay.

4. Charm Mixing

In the SM, the decay $D^0 \to K^+\pi^-$ proceeds through a doubly Cabibbo-suppressed (DCS) "tree" diagram, and may also result from a mixing process ($D^0 \leftrightarrow \overline{D}^0$), followed by a Cabibbo-favored (CF) decay ($\overline{D}^0 \to K^+\pi^-$). The DCS decay rate depends on Cabibbo-Kobayashi-Maskawa quark-mixing matrix elements and on the magnitude of SU(3) flavor symmetry violation [29]. Mixing may occur through two distinct types of second-order weak processes. In the first, the D^0 evolves into a virtual ("long-range") intermediate state such as $\pi^+\pi^-$, which subsequently evolves to a $\overline{D}^0$. The magnitude of the amplitude for long-range mixing has been estimated using strong interaction models [30], but has not been determined using a QCD calculation from first principles. The second type of second-order weak process is short-range [31], with either a "box" or "penguin" topology. Short-range mixing is negligible in the standard model. However, exotic weakly interacting particles could enhance the short-range mixing and provide a signature of new physics [32].

The ratio R of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ decay rates can be approximated as a simple quadratic function of t/τ, where t is the proper decay time and τ is the mean D^0 lifetime. This form

is valid assuming CP conservation and small values for the parameters $x = \Delta M/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where ΔM is the mass difference between the D^0 meson weak eigenstates, $\Delta\Gamma$ is the decay width difference, and Γ is the average decay width of the eigenstates. Under the assumptions stated above,

$$R(t/\tau) = R_D + \sqrt{R_D}y'\,(t/\tau) + \frac{x'^2 + y'^2}{4}\,(t/\tau)^2, \tag{4.1}$$

where R_D is the squared modulus of the ratio of DCS to CF amplitudes. The parameters x' and y' are linear combinations of x and y according to the relations

$$x' = x\cos\delta + y\sin\delta \quad \text{and} \quad y' = -x\sin\delta + y\cos\delta,$$

where δ is the strong interaction phase difference between the DCS and CF amplitudes. In the absence of mixing, $x' = y' = 0$ and $R(t/\tau) = R_D$.

We use a signal of 12.7×10^3 $D^0 \to K^+\pi^-$ decays with proper decay times between 0.75 and 10 mean D^0 lifetimes. The data sample was recorded with the CDF II detector and corresponds to an integrated luminosity of 1.5 fb^{-1}. We search for $D^0 - \overline{D}^0$ mixing and measure the mixing parameters to be $R_D = (3.04 \pm 0.55) \times 10^{-3}$, $y' = (8.5 \pm 7.6) \times 10^{-3}$, and $x'^2 = (-0.12 \pm 0.35) \times 10^{-3}$ [33]. Bayesian probability contours in the $x'^2 - y'$ plane shows that the data are inconsistent with the no-mixing hypothesis with a probability equivalent to 3.8σ [33]. This result is in agreement with the current B-factories measurements [34], and it has a comparable sensitivity.

Using the current data sample, corresponding to 4.4 fb^{-1} of integrated luminosity, we reconstruct about 24×10^3 $D^0 \to K^+\pi^-$ decays. This is approximately a factor 2 better in statistics with respect to the published results[33]. Assuming no analysis improvements and assuming as central values those published in [33], we expects to reach 5σ level of significance and to provide a precise measurement of mixing parameters x'^2 and y' at the next iteration of this analysis. CDF is currently taking data with the goal of integrating 8 fb^{-1} by the end of 2010. If the extension of Run II will be approved, CDF will collect on tape about 10 fb^{-1}, by the end of 2011, of good data for physics analysis. This scenario is very promising considering that CDF has already the world's largest data sample, and it is taking new charm data with an unprecedent rate.

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