

Rare decays / B_s CPV measurements at Tevatron

Hideki Miyake^{*†}

University of Tsukuba

E-mail: miyake@hep.px.tsukuba.ac.jp

Measurements of Flavor Changing Neutral Current (FCNC) processes (rare decays, flavor mixing) play a key role to pursue new physics beyond the Standard Model. We present recent analysis results about some FCNC transitions performed by CDF and D0 collaborations, including the first observation of the $B_s^0 \rightarrow \phi \mu^+ \mu^-$ mode, the forward-backward asymmetry measurement in $B \rightarrow K^{(*)} \mu^+ \mu^-$, and updated measurements of $B_s^0(B^0) \rightarrow \mu^+ \mu^-$, using data corresponding to integrated luminosities from 3.7fb^{-1} to 5fb^{-1} . We also show the CDF/D0 combined measurement of the B_s^0 mixing phase using 2.8fb^{-1} of data per experiment.

XXth Hadron Collider Physics Symposium

November 16 – 20, 2009

Evian, France

^{*}Speaker.

[†]On behalf of the CDF and DØ Collaborations.

1. Introduction

In order to pursue new physics beyond the Standard Model (SM), the Tevatron $p\bar{p}$ collider with $\sqrt{s} = 1.96\text{TeV}$ provides powerful approach with b hadrons. At the Tevatron b quarks are pair-produced with enormous cross section [1], which is three orders of magnitude higher than at e^+e^- colliders, and generate all sorts of b hadrons. This provides privileged access to SM-suppressed processes such as FCNC transitions and CP violation in B_s^0 mixing. These approaches from flavor sector at Tevatron are complementary to direct searches for BSM processes like Supersymmetry (SUSY) particles, and also B physics at the e^+e^- experiments. In this paper we focus on studies for some promising FCNC processes; $B \rightarrow K^{(*)}\mu^+\mu^-$, $B_s^0 \rightarrow \phi\mu^+\mu^-$, $B_s^0 \rightarrow \mu^+\mu^-$, and B_s^0 mixing, performed by CDF and D0 collaborations.

2. Rare decays

2.1 $B \rightarrow K^{(*)}\mu^+\mu^-$ and $B_s^0 \rightarrow \phi\mu^+\mu^-$

The $B \rightarrow K^{(*)}\mu^+\mu^-$ and $B_s^0 \rightarrow \phi\mu^+\mu^-$ decays are dominated by the FCNC $b \rightarrow s\ell\ell$ transition. In the SM framework, the quark transition is forbidden at the tree level. It may occur via Z/γ penguin diagram or a W^+W^- box diagram at the lowest order. 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.

CDF selects two oppositely charged muon candidates with a momentum transverse to the beamline, p_T , greater than 1.5 or 2.0 GeV/ c , depending on the trigger selection. We then reconstruct $B \rightarrow h\mu^+\mu^-$ signal candidates, where B stands for B^+ , B^0 , or B_s^0 , and h stands for K^+ , K^{*0} , or ϕ respectively. The K^{*0} is reconstructed in the mode $K^{*0} \rightarrow K^+\pi^-$, and the ϕ is reconstructed as $\phi \rightarrow K^+K^-$. To enhance separation of signal from background we employ an artificial neural network (NN) technique. Fig. 1 shows invariant mass distribution for each rare decay. The signal yield is obtained by an unbinned maximum log-likelihood fit of the B invariant mass distribution. From the B mass fit with 4.4fb^{-1} of data [2], we obtain 120 ± 16

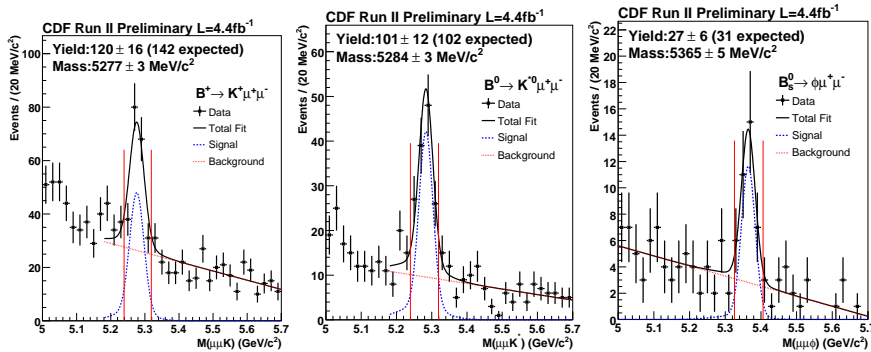


Figure 1: The B invariant mass of $B^+ \rightarrow K^+\mu^+\mu^-$ (left), $B^0 \rightarrow K^{*0}\mu^+\mu^-$ (middle), and $B_s^0 \rightarrow \phi\mu^+\mu^-$ (right) for 4.4fb^{-1} , respectively.

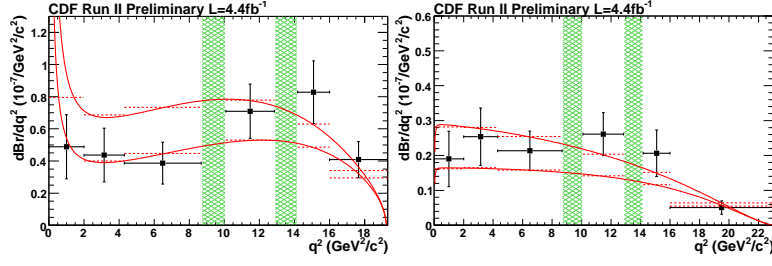


Figure 2: Differential BR of $B^0 \rightarrow K^{*0}\mu^+\mu^-$ (left) and $B^+ \rightarrow K^+\mu^+\mu^-$ (right). Hatched regions are charmonium veto regions. Solid lines are the SM expectation [4], which use maximum- and minimum-allowed form factor. Dashed line is the averaged theoretical curve in each q^2 bin.

($B^+ \rightarrow K^+\mu^+\mu^-$), 101 ± 12 ($B^0 \rightarrow K^{*0}\mu^+\mu^-$), and 27 ± 6 ($B_s^0 \rightarrow \phi\mu^+\mu^-$) signal yields, with 8.5σ , 9.7σ , and 6.3σ statistical significance, respectively. This is the first observation of the $B_s^0 \rightarrow \phi\mu^+\mu^-$ mode. Obtained yields are consistent with world average and theoretical expectations. We measure the branching fractions of rare decays relative to the corresponding reference channels, $J/\psi h$, which have same final states as rare decays but with an intermediate J/ψ resonance. Using PDG [3] values for BR of reference decays we obtain $\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-) = [0.38 \pm 0.05(\text{stat}) \pm 0.03(\text{syst})] \times 10^{-6}$, $\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-) = [1.06 \pm 0.14(\text{stat}) \pm 0.09(\text{syst})] \times 10^{-6}$, $\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-) = [1.44 \pm 0.33(\text{stat}) \pm 0.46(\text{syst})] \times 10^{-6}$.

We measure the differential decay rate with respect to the dimuon mass. The signal region is divided into six q^2 bins, where $q^2 \equiv M_{\mu\mu}^2 c^2$. To obtain the number of signal events in each q^2 bin we use the same procedure used in the global yield fit. Fig. 2 shows the differential branching fraction for $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and $B^+ \rightarrow K^+\mu^+\mu^-$.

The forward-backward asymmetry (A_{FB}) and K^{*0} longitudinal polarization (F_L) are extracted from $\cos\theta_\mu$ and $\cos\theta_K$ distributions, respectively, where θ_μ is the helicity angle between μ^+ (μ^-) direction and the opposite of the B (\bar{B}) direction in the dimuon restframe, and θ_K is the angle between the kaon direction and the direction opposite to the B meson in the K^{*0} rest frame. We measure F_L and A_{FB} for $B^0 \rightarrow K^{*0}\mu^+\mu^-$ and also A_{FB} for $B^+ \rightarrow K^+\mu^+\mu^-$. Fit results are shown in Fig. 3. Both F_L and A_{FB} are consistent with the SM and also an example of SUSY model. Our results are also consistent and competitive with B-factories measurements [5, 6].

2.2 $B_s^0(B^0) \rightarrow \mu^+\mu^-$

The $B_s^0(B^0) \rightarrow \mu^+\mu^-$ decays are also dominated by FCNC process. The decay rates 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 $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$ and $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.00 \pm 0.14) \times 10^{-10}$ [7]. As many new physics models can enhance the BR significantly, these decays provide sensitive probes for new physics.

CDF selects two oppositely charged muon candidates within a dimuon invariant mass windows of $4.669 < m_{\mu^+\mu^-} < 5.969 \text{ GeV}/c^2$. The muon candidates are required to have $p_T > 2.0 \text{ GeV}/c$, and $\vec{p}_T^{\mu^+\mu^-} > 4 \text{ GeV}/c$, where $\vec{p}_T^{\mu^+\mu^-}$ is the transverse component of the sum of the muon momentum vectors. For CDF analysis, we employ NN to select signal events. The event selection is checked

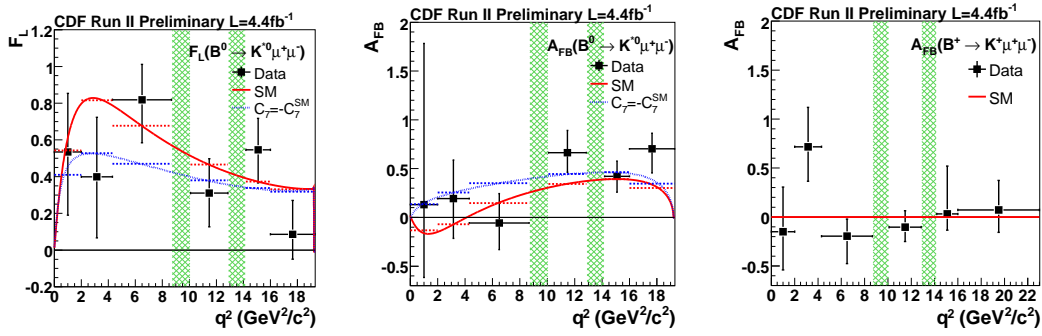


Figure 3: F_L (left) and A_{FB} (middle) fit results as a function of q^2 for $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ and A_{FB} (right) as a function of q^2 for $B^+ \rightarrow K^+ \mu^+ \mu^-$. The points show data. Solid (dotted) curve is the SM (an example of SUSY) expectation [4]. Dashed line is the averaged expectation in each q^2 bin. Hatched regions mean charmonium veto.

with control samples of $B^+ \rightarrow J/\psi K^+$ and sideband in data that the background estimates are correctly predicted. The $\mu^+ \mu^-$ invariant mass distributions for the three different NN ranges are shown in Fig. 4, using 3.7 fb^{-1} of data. In the absence of signal, we extract 95% (90%) C.L. limits of $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 4.3 \times 10^{-8}$ (3.6×10^{-8}) [8] and $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 7.6 \times 10^{-8}$ (6.0×10^{-8}) [8], which are currently the world's best upper limits for both processes.

D0 performs a similar analysis but employs a Boosted Decision Tree (BDT) instead of NN. With 5 fb^{-1} of data, D0 has studied the sensitivity to the branching fraction of $B_s^0 \rightarrow \mu^+ \mu^-$ decays. An expected upper limit on the branching fraction is $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 5.3(4.3) \times 10^{-8}$ at the 95(90)% C.L. [9].

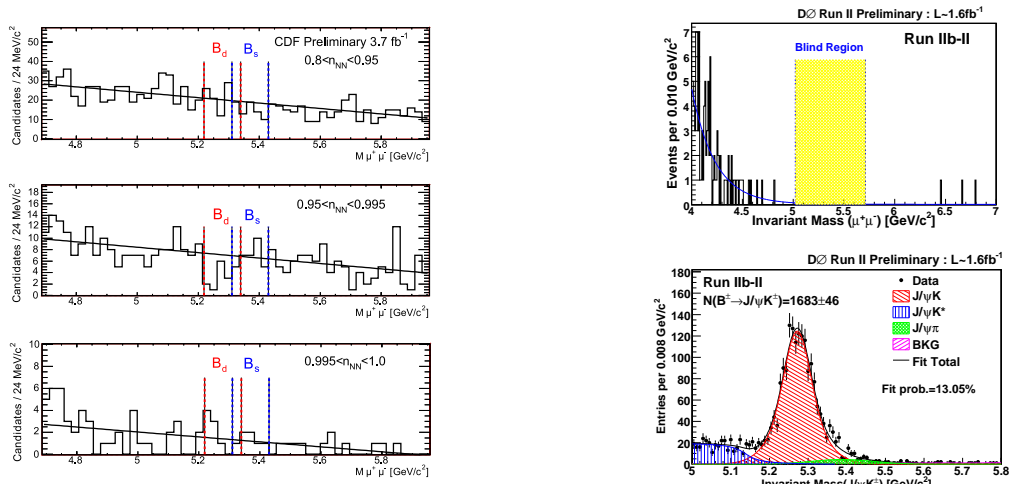


Figure 4: Left: Dimuon invariant mass distribution for CDF events satisfying all selection criteria for the three ranges of NN. Right top: Dimuon invariant mass distribution for D0 events after the BDT cut. Search box remains blinded. Right bottom: $J/\psi K^+$ events used as a control sample, in D0 data after applying the BDT cut.

3. Measurement of the B_s^0 mixing phase

Analogously to the neutral B^0 system, CP violation in B_s^0 system may occur also through interference of decays with and without the B_s^0 - \bar{B}_s^0 mixing. The $B_s^0 - \bar{B}_s^0$ mixing occurs via second order weak processes. It is described in the SM by Δm_s and $\Delta\Gamma_s$, mass and decay width difference of the two mass eigenstates, B_s^H and B_s^L . The quantity $\Delta\Gamma_s = 2|\Gamma_{12}|\cos(\phi_s)$ is sensitive to new physics effects that affect the phase $\phi_s = \arg(-M_{12}/\Gamma_{12})$, where Γ_{12} and M_{12} are the off-diagonal elements of the mass and decay matrices. In the SM, the ϕ_s^{SM} is predicted to be small as 0.004 [10]. If new physics has different phase ϕ_s^{NP} from the SM, the ϕ_s could be dominated by ϕ_s^{NP} . In this case we can access the phase by studying the time-evolution of $B_s^0 \rightarrow J/\psi\phi$ decays. The CP violating phase $\beta_s^{J/\psi\phi}$ is defined as the phase between the direct $B_s^0 \rightarrow J/\psi\phi$ decay amplitude and mixing followed by decay amplitude. The β_s^{SM} is described by CKM matrix elements as $\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ and predicted to be small, 0.02 [10]. Since ϕ_s^{NP} contributes to both ϕ_s and β_s , large β_s would indicate existence of new physics contribution.

To extract $\Delta\Gamma_s$ and β_s , an unbinned maximum likelihood is performed. The $B_s^0 \rightarrow J/\psi\phi$ consists of both CP -even and -odd final states. Although the observed CP asymmetry might be diluted by the opposite CP components, we can perform unbiased measurement taking into account time evolution of angular distributions of the decay products. Information about mixing is obtained from flavor tagging of B_s^0 meson, which is based on kaon tracks associated with the B_s^0 meson and the properties and decay tracks of the other B hadron in the event. Since there is an exact symmetry in the signal probability density function, which contains the strong phases among the three partial waves, the likelihood function shows two symmetric minima in the $\Delta\Gamma_s$ - $\beta_s^{J/\psi\phi}$ plane.

Both CDF and D0 have performed flavour tagged analysis on 2.8fb^{-1} of data [11, 12]. CDF selected about 3200 signal events with NN, while D0 selected about 2000 signal events with a cut based selection. Fig. 5 (top left) shows the confidence regions for CDF and Fig. 5 (top right) shows the fit result for D0. D0 updates the result from their previous publication result, which restricted the strong phases δ_{\parallel} and δ_{\perp} to the values measured in the $B^0 \rightarrow J/\psi K^{*0}$ system. D0 removes the constraints and also includes systematic uncertainties on Δm_s . Currently the compatibility with the SM point is 1.8σ for CDF and 1.2σ for D0. We then combine both profile likelihoods. Detail of combination is described in Ref. [13]. Fig. 5 (bottom) shows the combined results of CDF and D0, which exhibit a 2.1σ deviation from the SM.

4. Conclusion

At the Tevatron a rich B physics program is ongoing. CDF reports the first observation of $B_s^0 \rightarrow \phi\mu^+\mu^-$ and measures $A_{\text{FB}}(B \rightarrow K^{(*)}\mu^+\mu^-)$ in hadron collisions, which is competitive to e^+e^- B-factories. CDF updates the $B_s^0(B^0) \rightarrow \mu^+\mu^-$ analysis using 3.7fb^{-1} and continues to improve its world-leading upper limit. D0 continues to improve their $B_s^0 \rightarrow \mu^+\mu^-$ analysis and with 5fb^{-1} their expected limit is $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) < 5.3(4.3) \times 10^{-8}$ at the 95(90)% C.L.. Both CDF and D0 have updated their $\beta_s^{J/\psi\phi}$ measurements with $B_s^0 \rightarrow J/\psi\phi$ using 2.8fb^{-1} of data. Combined result of both experiments shows a 2.1σ deviation from the SM. The Tevatron is performing well with planed running through 2011 will provide double the datasets used for results presented here.

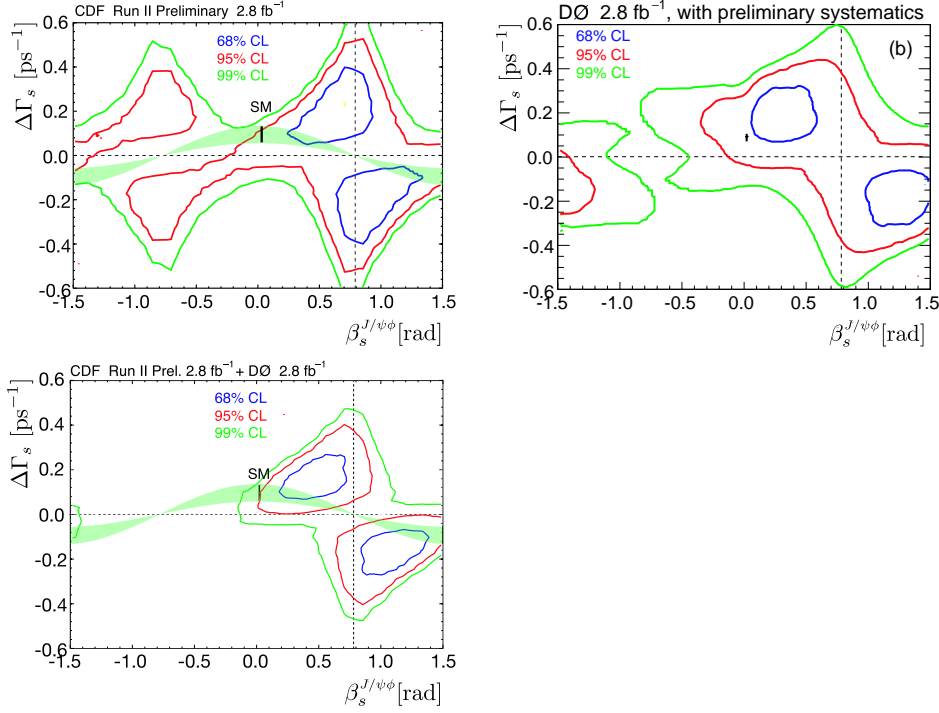


Figure 5: Two-dimensional profile likelihood as confidence contours of $\beta_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ for CDF's preliminary analysis using 2.8fb^{-1} of data (top left) and D0's published analysis using 2.8fb^{-1} of data, but allowing strong phases, δ_i to float and systematic uncertainties are included (top right), and the combined results (bottom). The SM expectation and uncertainty $(\beta_s^{\text{SM}}, \Delta\Gamma_s^{\text{SM}}) = (0.04, 0.088 \pm 0.017\text{ps}^{-1})$ [10] is indicated by the black line. The region allowed in new physics model given by $\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s$ is also shown (light green band).

References

- [1] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. **D79**, 092003 (2009), arXiv:0903.2403.
- [2] CDF Collaboration, Public Note 10047.
- [3] C. Amsler *et al.* (Particle Data Group), Phys. Lett. **B667**, 1 (2008).
- [4] A. Ali, P. Ball, L. T. Handoko, and G. Hiller, Phys. Rev. **D61**, 074024 (2000), arXiv:hep-ph/9910221.
- [5] J. T. Wei *et al.* (BELLE Collaboration), Phys. Rev. Lett. **103**, 171801 (2009), arXiv:0904.0770.
- [6] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. **D79**, 031102 (2009), arXiv:0804.4412.
- [7] A. J. Buras, Phys. Lett. **B566**, 115 (2003), arXiv:hep-ph/0303060.
- [8] CDF Collaboration, Public Note 8042.
- [9] D0 Collaboration, Conference Note 5906.
- [10] A. Lenz and U. Nierste, JHEP **06**, 072 (2007), arXiv:hep-ph/0612167.
- [11] CDF Collaboration, Public Note 9458.
- [12] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **101**, 241801 (2008), arXiv:0802.2255.
- [13] CDF and D0 Collaborations, CDF Public Note 9787 and D0 Conference Note 5928.