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# MEASUREMENTS OF B RARE DECAYS AT THE TEVATRON

F. SCURI
on behalf of the CDF and D0 collaborations.
*Istituto Nazionale di Fisica Nucleare, Sezione di Pisa,*
*Largo B. Pontecorvo 3, I-56127 Pisa, Italy*

A summary of recent results on B rare decays from the CDF and D0 experiments operating in Run II of the Fermilab Tevatron is given; analyzed decay modes are $B_{d,s} \rightarrow$ hh, $B_{d,s} \rightarrow \mu^+\mu^-$, and B $\rightarrow \mu^+\mu^-$ h. Data samples are relative to 1 fb$^{-1}$ or more integrated luminosity of $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV. All reported results are in agreement with Standard Model predictions and consistent with B-Factories analyzes.

## 1 Introduction

The large production of all kinds of $b$-hadrons at the Tevatron offers the opportunity to study rare decays also in the $B_s$ and $b$-baryon sectors, exploiting a physics program complementary to the B-Factories.

The bottom anti-bottom production cross-section $\sigma(b\bar{b})$ at the Tevatron is O($10^5$) larger than production in $e^+e^-$ colliders at the $\Upsilon(4s)$ or $Z^0$ energy scale; however, the inelastic cross-section is a factor $10^3$ larger than $\sigma(b\bar{b})$ and the branching ratios of rare $b$-hadron decays are O($10^{-5}$) or lower; therefore, interesting events must be extracted from a high track multiplicity environment and detectors need to have very good tracking and vertex resolution, wide acceptance and good particle identification, highly selective trigger. Both CDF and D0 detectors, whose detailed description can be found elsewhere [1], match those requirements.

The following decays modes are analyzed here: charmless $B_{d,s} \rightarrow h^+h-$, $B_{d,s} \rightarrow \mu^+\mu^-$, and B $\rightarrow \mu^+\mu^-$ h. All those rare decay modes are interesting in the search of New Physics contributions, each mode with its own peculiarity: charmless B $\rightarrow$ hh decays are a useful tool for probing CKM inferring on the $\alpha$ and $\gamma$ angles of the Unitarity Triangle; they are also sensitive to New Physics effects both in the Penguin diagram contributions to the process and via anomalies in the CP Asymmetry $A_{CP}$.

The Standard Model prediction of the Branching Ratio for flavor-changing neutral current (FCNC) processes like $B_s \rightarrow \mu^+\mu^-$ is very suppressed: $\mathcal{B}(B_s \rightarrow \mu^+\mu^-)^{SM} = (3.35\pm0.32)\times10^{-9}$ (M.Blanke *et al.* [2]); a slightly higher value for the BR upper limit was recently estimated in Constrained Minimal Flavor Violation [3]: $\mathcal{B}(B_s \rightarrow \mu^+\mu^-)^{CMFV} < 7.42 \times 10^{-9}$ (95% $C.L.$); the leptonic branching fraction of the $B_d$ decay is suppressed by a factor $\mid V_{td}/V_{ts} \mid^2$ in the CKM matrix elements leading to a SM predicted BR of O($10^{-10}$). The decay amplitude of $B_{d,s} \rightarrow \mu^+\mu^-$ can be significantly enhanced in some extensions of the SM, such as, for instance, the type-II two-Higgs-doublet-model (2HDM), where the BR depends only on $M_{H+}$ and on tan$\beta$, the ratio between the vacuum expectation values of the two neutral Higgs fields; in this case [4], $\mathcal{B}(B \rightarrow \mu^+\mu^-)^{2HDM} \propto (\tan\beta)^4$. In the minimal super-symmetric standard model (MSSM) the dependence on tan$\beta$ is even stronger, $\mathcal{B}(B \rightarrow \mu^+\mu^-)^{MSSM} \propto (\tan\beta)^6$, leading to an enhancement of orders of magnitude [5] in case of large values of tan$\beta$.

The $b \rightarrow s\ \mu^+\mu^-$ transition in the B$\rightarrow$ $s$-meson $\mu^+\mu^-$ modes allows the study of FCNC in more detail through additional observables, such as the dimuon invariant mass m($\mu^+\mu^-$), and the forward-backward asymmetry of the $s$-quark in the dimuon system.

A summary of recent results from the Tevatron experiments is given in the following section for all modes; quoted values refer to integrated luminosities varying from about 1 fb$^{-1}$ to about 2 fb$^{-1}$, depending on the specific analysis, and covering the Tevatron Run-II data taking period from 2002 to beginning of 2007.

## 2 Tevatron result summary for B rare decays

Hadronic decays of the B mesons into two charged tracks are studied in an efficient way by the CDF experiment, exploiting the high performances of its peculiar Secondary Vertex Trigger (SVT), designed to select events with vertexes displaced with respect to the primary vertex and whose full description can be found elsewhere [6]. Details of the event selection procedure and of the analysis method can be found in a recent CDF publication [7].

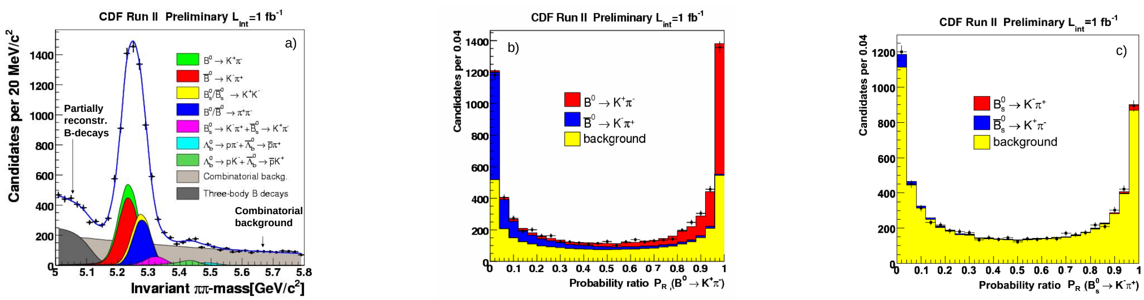


Figure 1: a): M($\pi\pi$) invariant mass distributions; b) Probability Ratio for $B^0 \to K^+\pi^-$; c) Probability ratio for $B_s \to K^-\pi^+$.

The invariant mass m($\pi\pi$) after cut optimization is shown in figure 1a); about 6500 signal events accumulate in the signal region; individual modes overlap in a single peak as shown by the signal composition (filled colored areas) estimated via Monte Carlo and including full detector simulation. The signal composition in real data is measured with a likelihood fit, combining information from kinematics (mass and momentum) and particle identification; details of the fit procedure can be found elsewhere [7].

Table 1: CDF results with 1 fb$^{-1}$ large sample for $\mathcal{B}(B \to h^+h^-)$.

| Decay mode | $BR \times 10^6$ |
|---|---|
| $B^0 \to \pi^+\pi^-$ | $5.10 \pm 0.33(stat.) \pm 0.36(syst.)$ |
| $B^0 \to K^+K^-$ | $0.39 \pm 0.16(stat.) \pm 0.12(syst.)$ |
| $B_s \to K^+K-$ | $24.4 \pm 1.4(stat.) \pm 4.6(syst.)$ |
| $B_s \to \pi^+K^-$ | $5.0 \pm 0.75(stat.) \pm 1.0(syst.)$ |
| $B_s \to \pi^+\pi^-$ | $0.53 \pm 0.31(stat.) \pm 0.40(syst.)$ |

Measured branching ratios for individual modes are summarized in table 1; values for the $B_d$ modes are consistent with the B-Factories results, while the $B_s$ modes are CDF exclusive.

The very good separation power between $B^0$ and $\bar{B^0}$ achieved with the likelihood fit is shown in figure 1b) for the raw asymmetry of the $B^0 \to K^+\pi^-$ mode ; the probability ratio $P_R = pdf(B^0)/[pdf(B^0) + pdf(\bar{B^0})]$ is based on probability density functions (pdf) using 5 observables ($M(\pi_1, \pi_2)$, $p_1 + p_2$, the charged pion momentum um-balancing [7], and the particle identification $ID_1$ and $ID_2$). With this method, the first measurement of direct CP asymmetry ($A_{CP}$) in the $B_s$ system was done, figure 1c). CDF results on $A_{CP}$ for the $K\pi$ modes are given in the following equations:

$$\begin{aligned} A_{CP}(B_d^0 \to K^+\pi^-) &= \frac{N(\bar{B}_d^0 \to K^-\pi^+) - N(B_d^0 \to K^+\pi^-)}{N(\bar{B}_d^0 \to K^-\pi^+) + N(B_d^0 \to K^+\pi^-)} &= -0.086 \pm 0.023(stat.) \pm 0.009(syst.) \\ A_{CP}(B_s^0 \to K^-\pi^+) &= \frac{N(\bar{B}_s^0 \to K^+\pi^-) - N(B_s^0 \to K^-\pi^+)}{N(\bar{B}_s^0 \to K^+\pi^-) + N(B_s^0 \to K^-\pi^+)} &= -0.39 \pm 0.15(stat.) \pm 0.08(syst.) \end{aligned} \quad (1)$$

Tevatron and B-Factories results on $A_{CP}(B_d^0 \to K^+\pi^-)$ agree; Tevatron confirms the difference in sign w.r.t. $A_{CP}(B^+ \to K^+\pi^0)$. The measured value of $A_{CP}(B_s^0 \to K^-\pi^+)$ (1) can be compared with the value obtained with the Lipkin test [8], based on minimal assumptions, just SM with SU(3) symmetry; in this case, the following equation holds:

$$A_{CP}(B_s^0 \to K^-\pi^+) = -A_{CP}(B_d^0 \to K^+\pi^-) \cdot \frac{\mathcal{B}(B_d^0 \to K^+\pi^-)}{\mathcal{B}(B_s^0 \to K^-\pi^+)} \cdot \frac{\tau(B_d^0)}{\tau(B_s^0)} \approx 0.37 \qquad (2)$$

In equation 2 the values of $A_{CP}(B_d^0 \to K^+\pi^-)$ and $\mathcal{B}(B_d^0 \to K^+\pi^-)$ are taken from the Heavy Flavor Averaging Group [9], $\mathcal{B}(B_d^0 \to K^+\pi^-)$ is the CDF resulted quoted in table 1, and the lifetime ratio is set equal to one.

The two Tevatron experiments adopt similar procedures to search for $B_s \to \mu^+\mu^-$ events; a blind cut optimization is made using signal Monte Carlo samples and signal sidebands for estimation of the background in the data sample. The $B^+ \to J/\psi\, K^+$ mode is used as normalization channel in the BR estimation. Similar discriminating observables (secondary vertex displacement, B pointing angle to the primary vertex, B isolation) are used to construct a Likelihood Ratio ($L_R$); optimal values of $L_R$ for event counting are obtained with different methods. The main difference in the two analyzes is the definition of the signal window in the $\mu-\mu$ invariant mass spectrum (figure 2); a 360 MeV/c$^2$ wide search region including $B_d$ and $B_s$ is defined by D0, two different regions, 120 MeV/$^2$ wide and centered in the $B_d$ and $B_s$ nominal masses are used by CDF, quoting separate limits; D0 assumes $\mathcal{B}(B_d \to \mu^+\mu^-) \ll \mathcal{B}(B_s \to \mu^+\mu^-)$ and quotes the overall value as a conservative limit on $\mathcal{B}(B_s \to \mu^+\mu^-)$.

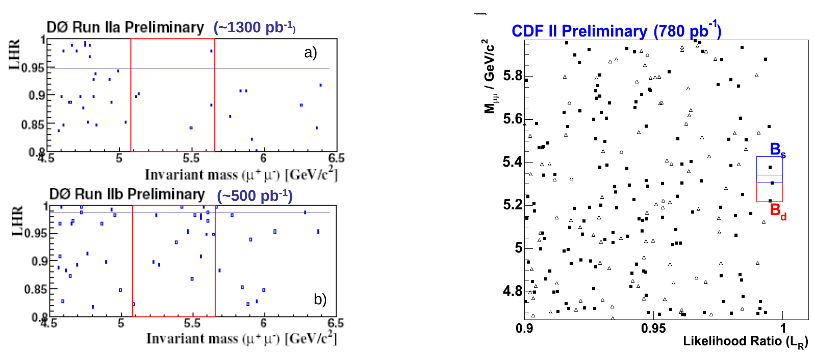


Figure 2: a), b): D0 Likelyhood Ratio $L_R$ vs. $\mu-\mu$ invariant mass; blue lines set the $L_R$ optimal value; c) CDF $\mu-\mu$ invariant mass vs. $L_R$; red and blue boxes define the search areas for $B_d$ and $B_s$ respectively.

Tevatron results on $B_s \to \mu^+\mu^-$ are summarized in table 2; a statistical combination is made by D0 to quote the overall limit from two data taking periods, before (run IIa) and after (run IIb) insertion of a new inner layer in silicon vertex detector.

Table 2: Tevatron result summary for $B_s \to \mu^+\mu^-$; (*) D0 run IIa and IIb combined result.

| Exp. | Int. Lum. $pb^{-1}$ | $B_s$ events | | $B_d$ events | | $\mathcal{B}(B_s \to \mu^+\mu^-)$ 90%(95%) C.L. | $\mathcal{B}(B_d \to \mu^+\mu^-)$ 90%(95%) C.L. |
|---|---|---|---|---|---|---|---|
| | | Expected | Obs. | Expected | Obs. | | |
| CDF | 780 | 1.27±0.37 | 1 | 2.45±0.40 | 2 | $< 8.0 \cdot 10^{-8}(10)$ | $< 2.3 \cdot 10^{-8}(3)$ |
| D0 | 1300 (run IIa) | 0.8 ±0.2 | 1 | - | - | $< 7.5 \cdot 10^{-8}(9.3)$(*) | - |
| | 500 (run IIb) | 1.5 ±0.5 | 2 | | | | |

CDF and D0 analyzes to reconstruct the B→ $\mu^+\mu^-\ h_s$ modes are similar; each signal is normalized to the analogous B→ $J/\psi\ h_s$ mode after a blind cut optimization and background estimation from the signal sidebands; details of the procedure can be found elsewhere [10].

CDF results for the $B_{u,d}$ modes, obtained with 1 $fb^{-1}$, are summarized in table 3; they are in good agreement with those from the B-Factories [11] and have similar uncertainty.

Table 3: CDF result summary for the $B_{u,d} \to h\ \mu^+\mu^-$ modes;

| Mode | Evts. in the signal region | Estimated bkg. | BR$\cdot 10^{-6}$ |
|---|---|---|---|
| $B^+ \to \mu^+\mu^- K^+$ | 90 | 45.3±5.8 | 0.60±0.15(stat.)±0.04(syst.) |
| $B_d \to \mu^+\mu^- K^{*0}$ | 35 | 16.5±3.6 | 0.82±0.31(stat.)±0.10(syst.) |

CDF and D0 limits for $\mathcal{B}(B_s \to \phi\ \mu^+\mu^-)$ are shown in table 4; CDF uses a Bayesian approach to extract its limit, while D0 confidence interval is constructed within the Feldman-Cousins scheme.

Table 4: Tevatron result summary for $B_s \to \phi\ \mu^+\mu^-$;

| Exp. | Int.Lum. | Observed events | Expected events | BR |
|---|---|---|---|---|
| CDF | 920 $pb^{-1}$ | 11 | 3.5±1.5 | $< 2.4 \cdot 10^{-6}$(90% C.L.) |
| D0 | 450 $pb^{-1}$ | 0 | 1.6±0.6 | $< 3.3 \cdot 10^{-6}$(90% C.L.) |

## 3 Conclusions

Tevatron is demonstrated to be a good place to study B rare decays offering different possibilities to constrain more and more New Physics in the $B_s \to \mu^+\mu^-$ and $b \to s\ \mu^+\mu^-$ modes; moreover, a physics program complementary to the B-Factories can be exploited in the $B_s \to h^+h^-$ sector. CDF made the first observation of the $B_s \to K^-\pi^+$ mode whose direct CP asymmetry appears to be large in agreement with expectation.

Tevatron current values for the limits on $\mathcal{B}(B_s \to \mu^+\mu^-)$ are entering the $10^{-8}$ territory; D0 current best limit is the first Tevatron result with 2 $fb^{-1}$ integrated luminosity. Any signal at Tevatron before its run II program end ($\int L\mathrm{dt} \sim 8\ fb^{-1}$) will be evidence of New Physics.

CDF and D0 are beginning the exploration of the $b \to s\ \mu^+\mu^-$ field; upper limits for $\mathcal{B}(B_s \to \phi\ \mu^+\mu^-)$ obtained with less than 1 $fb^{-1}$ are close to the SM prediction, CDF reported new results on $\mathcal{B}(B_{u,d} \to s\ \mu^+\mu^-)$ in general agreement with the B-Factories; significantly improved results will come soon.

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