

## Rare decay searches at CDF

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In the last decade the CDF experiment at the Tevatron clearly demonstrated that it is possible to study extensively heavy flavour physics in hadron collisions and achieve remarkable results, competitive and complementary to  $B$ -factories. In this paper we report on the indirect searches for physics beyond the standard model via measurements of rare  $b$ -hadron decays. The final limits, based on the analysis of the full CDF data set, on the branching fraction of the  $B_{(s)}^0$  decay into a pair of muons are presented and discussed. Moreover we review the latest measurements, with  $6.8 \text{ fb}^{-1}$  of collected data, of the total and differential branching fractions and angular observables of rare  $b$ -hadron decays proceeding via the flavour-changing neutral-current process  $b \rightarrow s\mu^+\mu^-$ .

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## 1. Introduction

Rare flavour-changing neutral-current (FCNC)  $B_{(s)}^0 \rightarrow \mu^+ \mu^-$  and  $b \rightarrow s \mu^+ \mu^-$  decays are considered among the most promising probes of the standard model (SM) and its extensions. The precise measurement of several observables (total and differential branching ratios, angular distributions of the decay products) of these decays might provide interesting clues for new physics (NP) phenomena, if any sizable deviation from the SM predictions is observed. In this paper we review the current status of these indirect searches at the Collider Detector at Fermilab (CDF II), which reached a sensitivity very close to SM predictions after a decade of Tevatron leadership in the exploration of  $B_s^0$  dynamics. The Tevatron  $p\bar{p}$  collider, whose operations ended in October 2011 after 20 years of operation, provided excellent opportunities to study  $B$  physics. CDF II is a multipurpose detector, consisting of a central charged particle tracking system, surrounded by calorimeters and muon chambers. It collected a final data set corresponding to about  $10 \text{ fb}^{-1}$  of integrated luminosity.

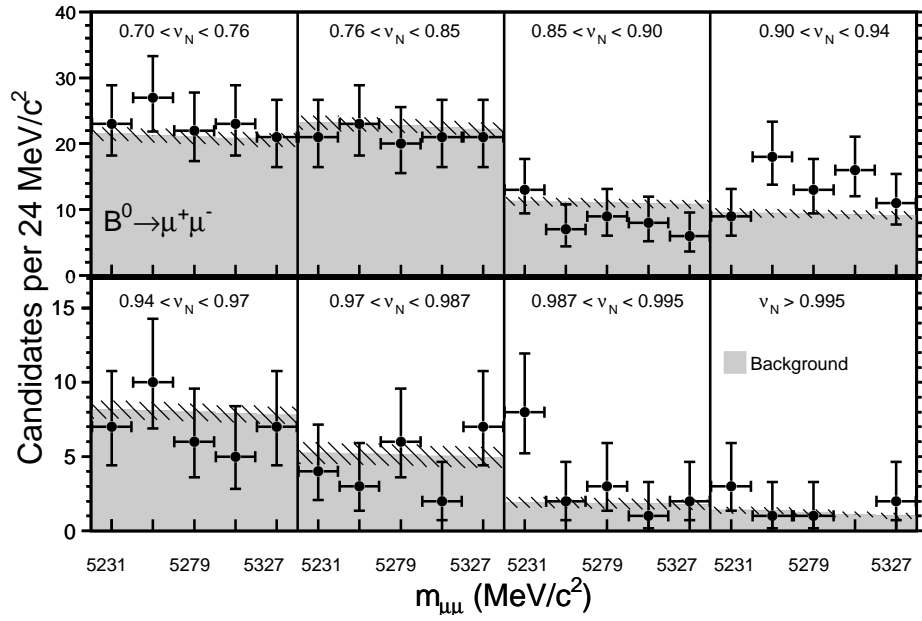
In the search for rare  $B$  decays, the experimental challenge is to reject a huge background while keeping the signal efficiency high. A dedicated dimuon trigger has been used to select events with a pair of muons in the final state in the pseudorapidity region  $|\eta| < 1.1$ . In the reconstruction and analysis of  $B$  hadron decays, CDF takes advantage of an excellent transverse momentum resolution,  $\frac{\sigma_{p_T}}{p_T} = 0.07\%$  ( $\text{GeV}/c$ ), which implies a resolution on the invariant dimuon mass of  $24 \text{ MeV}$  in the  $B_{(s)}^0 \rightarrow \mu^+ \mu^-$  decay, a vertex resolution of about  $30 \mu\text{m}$  in the transverse plane, and particle identification (PID) capability, based on multiple measurements of the ionization per unit of path length ( $dE/dx$ ) in the drift chambers.

## 2. Search for $B_{(s)}^0 \rightarrow \mu^+ \mu^-$

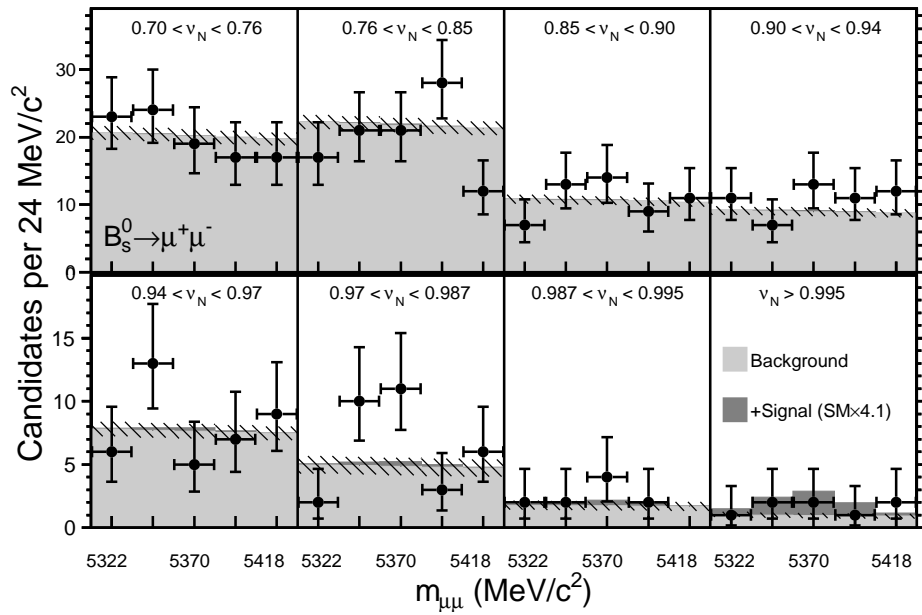
$B_{(s)}^0 \rightarrow \mu^+ \mu^-$  decays are mediated by FCNC and thus forbidden at first order in the SM. Moreover they are further suppressed by helicity factors  $(m_\mu/m_B)^2$  in the final dimuon state. They can only occur at second order through penguin and box diagrams. The SM predicts very low rates for these processes:  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.2 \pm 0.2) \times 10^{-9}$  and  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.0 \pm 0.1) \times 10^{-10}$  [1, 2]. However, a wide variety of beyond the standard model (BSM) theories predict enhancement of their branching ratios by several order of magnitudes, making these decays one of the most sensitive probes in indirect searches for NP.

In 2011, CDF observed an intriguing  $\sim 2.5\sigma$  excess over background in  $B_s^0 \rightarrow \mu^+ \mu^-$  using  $7 \text{ fb}^{-1}$  of data [3]. Though it was compatible with other experimental results (LHCb [4], CMS [5]) and the SM prediction, it could be interpreted as the first indication of a signal and allowed CDF to set a two-sided bound on the rate  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (1.8_{-0.9}^{+1.1}) \times 10^{-8}$ . To further investigate the nature of the excess, we repeated the analysis unchanged using the whole Run II data set, corresponding to  $9.7 \text{ fb}^{-1}$  of integrated luminosity, about 30% more data with respect to the 2011 analysis. Here we report on the final results of this search [6].

The baseline selection requires high quality muon candidates with opposite charge, transverse momentum  $p_T > 2 \text{ GeV}/c$ , and a dimuon invariant mass  $m_{\mu\mu}$  in the range  $4.669\text{--}5.969 \text{ GeV}/c^2$ . The muon pairs are constrained to originate from a common, well-measured reconstructed decay point. A likelihood-based muon identification method, is used to suppress contributions from hadrons



(a)



(b)

**Figure 1:** Dimuon mass distributions for the (a)  $B^0 \rightarrow \mu^+\mu^-$  and (b)  $B_s^0 \rightarrow \mu^+\mu^-$  signal region in the eight NN bins. The observed data (points) are compared to the total background expectation (light gray histogram). The hatched region is the total uncertainty on the background expectation. In (b) the dark gray histogram represents the SM signal expectation enhanced by a factor 4.1.

misidentified as muons. The branching ratios of  $B_{(s)}^0 \rightarrow \mu^+\mu^-$  are measured by normalizing to a sample of  $40225 \pm 267 B^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)K^+$  candidates, selected with the same baseline requirements. A Neural Network (NN) classifier is used to improve signal over background separation. Fourteen variables are used to construct the NN discriminant that ranges between 0 and 1. The six most discriminating variables include the 3D opening angle between the dimuon momentum and the displacement vector between the primary and secondary vertex; the isolation  $I^1$  of the candidate  $B_s^0$ ; the muon and  $B_{(s)}^0$  impact parameters; the  $B_{(s)}^0$  decay length significance; the vertex-fit  $\chi^2$ . The NN from the 2011 analysis was used with the same training. The final search region in the dimuon invariant mass has a half width of about 60 MeV corresponding to 2.5 times the dimuon mass resolution. The NN was validated with signal and background events. Careful checks for possible mass-biases of the NN output and overtraining show no anomalies.

Extensive and detailed background estimates and checks have been performed. Background is due to both combinatorial and peaking contributions in the signal region. Combinatorial background is estimated by fitting the sidebands to linear functions, after blinding the signal region in the dimuon mass distribution. The peaking background is due to  $B \rightarrow h^+h'^-$  decays where the hadrons ( $h, h'$  stand for  $\pi$  or  $K$ ) are misidentified as muons. This has been estimated from both MC and data. The misidentification probability is parametrized as a function of the track transverse momentum using  $D^*$ -tagged  $D^0 \rightarrow \pi^+K^-$  events. It turned out that the peaking background is about 10% of the combinatorial background in  $B_s^0 \rightarrow \mu^+\mu^-$  and about 50% of the total background in the  $B^0 \rightarrow \mu^+\mu^-$  channel. Background estimates have been cross-checked using independent background-dominated control samples, in which the muons have the same measured charge or the reconstructed dimuon candidate lifetime is negative. No significant discrepancies between the expected and observed number of events in the control samples have been found.

The data are divided into 8 bins of the NN discriminant to exploit the improved background suppression at high NN values, and five bins of mass in the search region. In the  $B^0$  search region data are consistent with the background prediction (Fig. 1(a)) and yield the limit of  $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 3.8(4.6) \times 10^{-9}$  at 90% (95%) C.L.. The significance of the background-only hypothesis expressed as a p-value, estimated from an ensemble of background-only pseudo-experiments, is 41%.

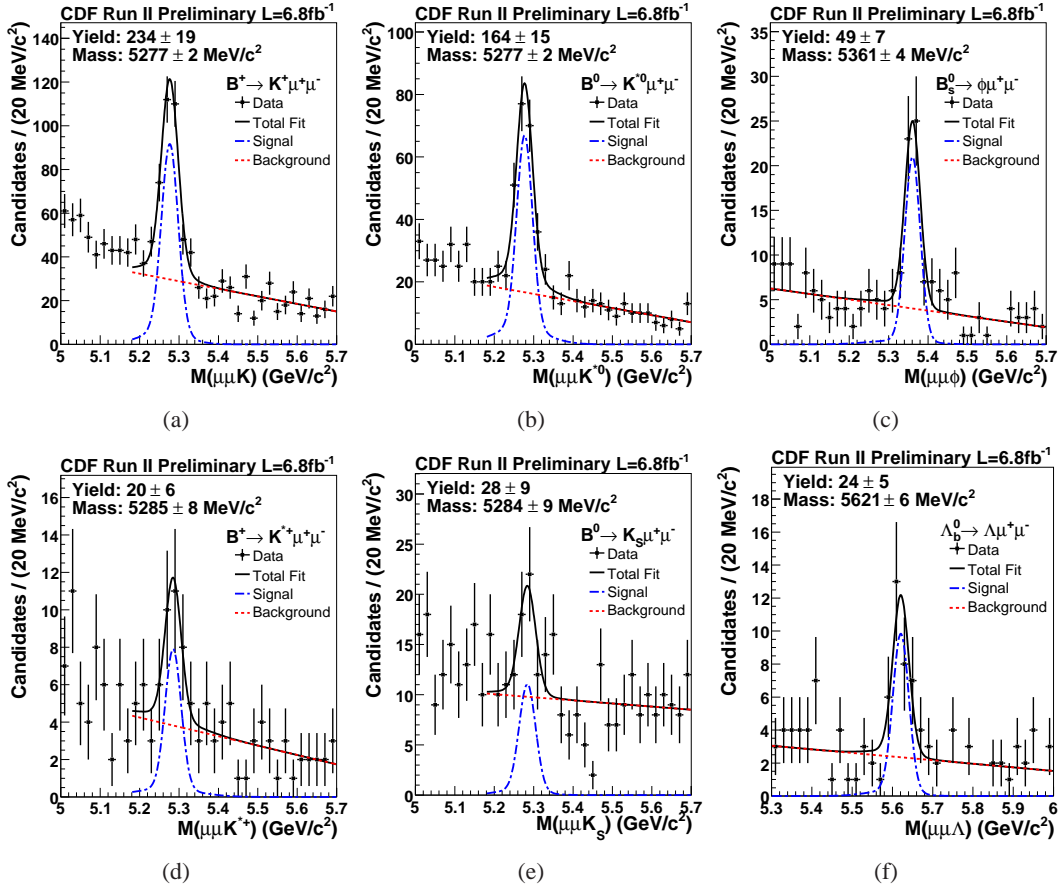
In the  $B_s^0$  search region, a moderate excess in the highest NN bins ( $>0.97$ ) is observed (Fig. 1(b)). The p-value for the background-only hypothesis is 0.94%. We also produce an ensemble of simulated experiments that includes a  $B_s^0 \rightarrow \mu^+\mu^-$  contribution at the expected SM branching fraction which yields a p-value of 7.1%. With respect to the previous CDF result with  $7 \text{ fb}^{-1}$  of data [3], the excess in the third significant NN bin (0.97-0.987) softened, as expected for a statistical fluctuation. Though the 2011 hint of signal is not reinforced by the new data, it is still present and remains  $>2\sigma$  significant over background. Assuming the observed excess in the  $B_s^0$  region is due to signal, CDF finds  $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (1.3_{-0.7}^{+0.9}) \times 10^{-8}$ , which is still compatible with both the SM expectation and the latest constraints from LHC experiments [7, 8].

### 3. $b \rightarrow s\mu^+\mu^-$ decays

Rare decays of bottom hadrons mediated by the FCNC process  $b \rightarrow s\mu^+\mu^-$  are suppressed

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<sup>1</sup> $I = |\vec{p}_T^{\mu\mu}| / (\sum_i p_T^i + |\vec{p}_T^{\mu\mu}|)$ , where  $\vec{p}^{\mu\mu}$  is the momentum of the dimuon pair; the sum is over all tracks with  $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} \leq 1$ ;  $\Delta\eta$  and  $\Delta\phi$  are the relative azimuthal angle and pseudorapidity of track  $i$  with respect to  $\vec{p}^{\mu\mu}$ .



**Figure 2:** Invariant mass of (a)  $B^+ \rightarrow K^+ \mu^+ \mu^-$ , (b)  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ , (c)  $B^0 \rightarrow \phi \mu^+ \mu^-$ , (d)  $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ , (e)  $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ , (f)  $\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$  with fit results overlaid.

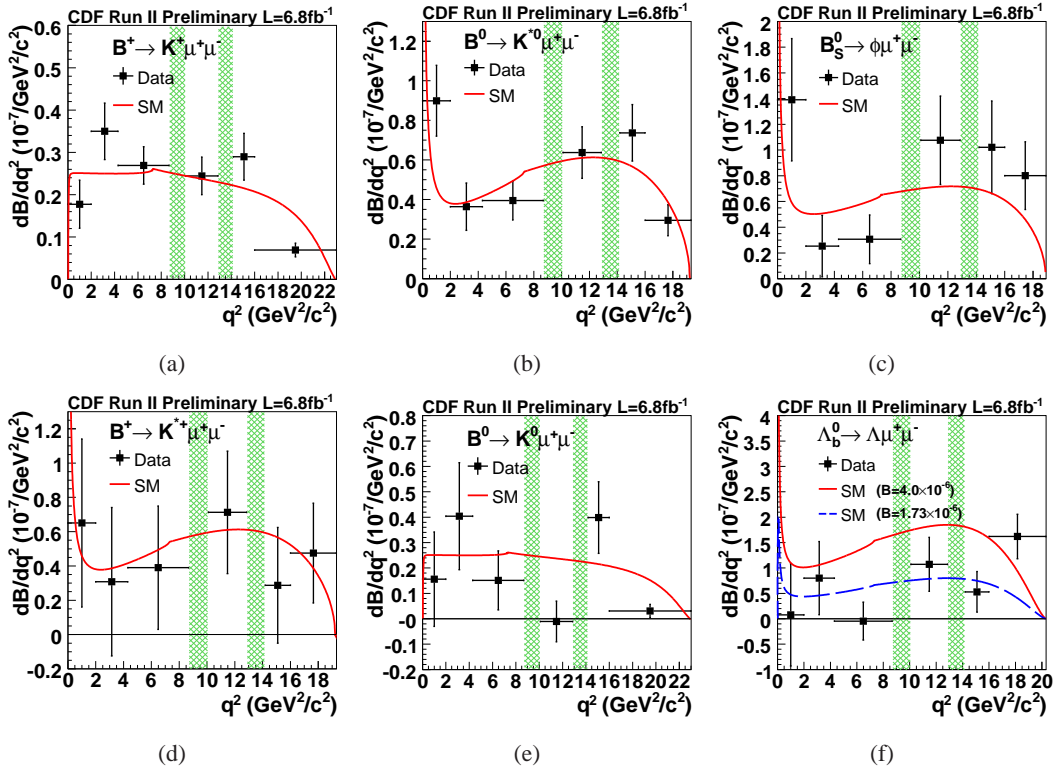
at tree level in the SM and must occur through higher-order loop amplitudes. Their expected branching ratios are of the order of  $10^{-6}$ . Because of their clean experimental signature and the reliable theoretical predictions for their rates, these are excellent channels for NP searches.

CDF has studied the FCNC  $H_b \rightarrow h \mu^+ \mu^-$  decays (where  $H_b$  and  $h$  indicate hadrons containing a  $b$  and  $s$  quark, respectively) listed in Table 1, using  $6.8 \text{ fb}^{-1}$  of data collected with the dimuon trigger [9]. Candidates for each decay have been selected by standard kinematics cuts and a NN optimized for best sensitivity. Signal yields are obtained by an unbinned maximum log-likelihood fit to the  $b$ -hadron mass distributions (Fig. 2), modelling the signal peak with a Gaussian, and the combinatorial background with a linear function. To cancel dominant systematic uncertainties, the branching ratio of each rare decay  $H_b \rightarrow h \mu^+ \mu^-$  is measured relative to the corresponding resonant channel  $H_b \rightarrow J/\psi h$ , used as a normalization and a cross-check of the whole analysis. The results of the total branching ratios are reported in Table 1 and include the first observation of the baryonic FCNC decay  $\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$ , and the first measurement of the  $B^+ \rightarrow K^{*+} \mu^+ \mu^-$  and  $B^0 \rightarrow K_S^0 \mu^+ \mu^-$  decays at a hadron collider.

Rich information about the  $b \rightarrow s \mu^+ \mu^-$  dynamics can be obtained by precise measurements of the differential branching ratio as a function of  $q^2 = m_{\mu\mu}^2 c^2$  and the angular distributions of

Decay mode	$\mathcal{B}(10^{-6})$
$B^+ \rightarrow K^+ \mu^+ \mu^-$	$0.46 \pm 0.04 \pm 0.02$
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$	$1.02 \pm 0.10 \pm 0.06$
$B_s^0 \rightarrow \phi \mu^+ \mu^-$	$1.47 \pm 0.24 \pm 0.46$
$B^+ \rightarrow K^{*+} \mu^+ \mu^-$	$0.95 \pm 0.32 \pm 0.08$
$B^0 \rightarrow K_S \mu^+ \mu^-$	$0.32 \pm 0.10 \pm 0.02$
$\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$	$1.73 \pm 0.42 \pm 0.55$

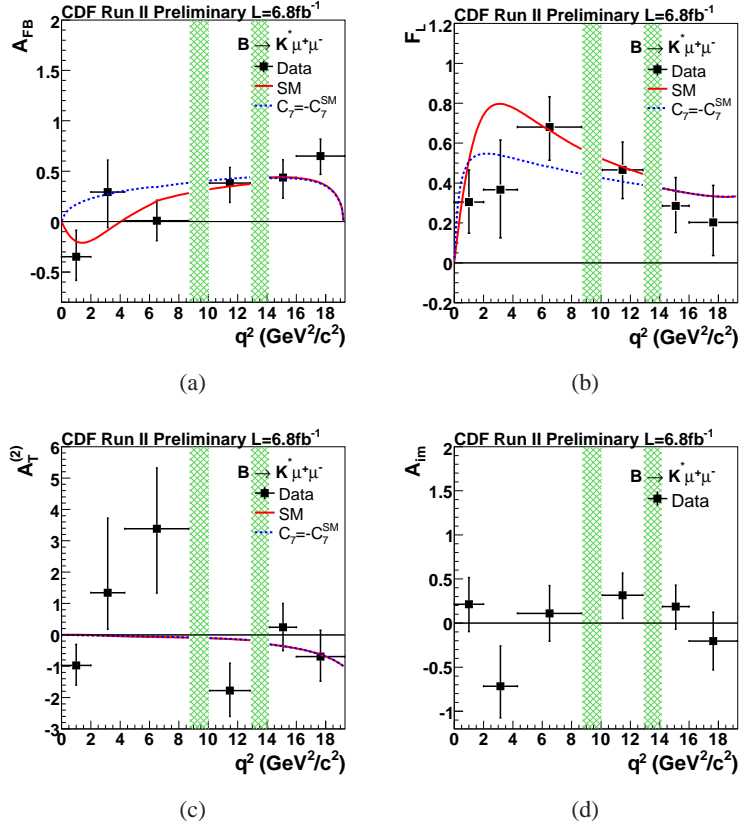
**Table 1:** Branching ratio of the  $H_b \rightarrow h \mu^+ \mu^-$  decays measured by CDF. The first quoted uncertainty is statistical, the second is systematic.



**Figure 3:** Differential branching ratios of (a)  $B^+ \rightarrow K^+ \mu^+ \mu^-$ , (b)  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ , (c)  $B_s^0 \rightarrow \phi \mu^+ \mu^-$ , (d)  $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ , (e)  $B^0 \rightarrow K_S \mu^+ \mu^-$ , (f)  $\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$ . The points are the fit result from data. The solid curves are the SM expectation [11, 12, 13, 14]. The dashed line in (f) is the SM prediction normalized to our total branching ratio measurement. The hatched regions are the charmonium veto regions.

the decay products. The differential branching ratios with respect to  $q^2$  have been measured by dividing the signal region into six bins in  $q^2$  and fitting the signal yield in each bin. In each fit, the mean of the  $H_b$  mass and the background slope were fixed to the value from the global fit, so that only the signal fraction was allowed to vary in the fit. The results are shown in Fig. 3. For  $B_s^0 \rightarrow \phi \mu^+ \mu^-$  and  $\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$  these are the first such measurements. At present no significant discrepancy from SM prediction is found.

The angular distributions of the combined  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  and  $B^+ \rightarrow K^{*+} \mu^+ \mu^-$  decays have



**Figure 4:** Measurements of angular observables (a)  $A_{FB}$ , (b)  $F_L$ , (c)  $A_T^{(2)}$ , and (d)  $A_{im}$  as a function of dimuon mass squared  $q^2$  in the combined decay mode  $B \rightarrow K^* \mu^+ \mu^-$ . The points are the fit results from data. The solid and dotted curves represent expectations from the SM and a particular BSM scenario, respectively.

been measured and parametrized to four angular observables: the muon forward-backward asymmetry  $A_{FB}$ , the  $K^*$  longitudinal polarization fraction  $F_L$ , the transverse polarization asymmetry  $A_T^{(2)}$ , the time-reversal-odd charge-and-parity asymmetry  $A_{im}$ , defined in [15, 16].  $A_T^{(2)}$  and  $A_{im}$  have been measured for the first time by CDF [10]. The results for these observables, shown in Fig. 4, are among the most precise to date and consistent with SM predictions and other experiments, but still statistically limited in providing stringent tests on various BSM models.

#### 4. Conclusion

We have summarized the recent updates on the searches of rare  $b$ -hadron decays at CDF. The intriguing excess in  $B_s^0 \rightarrow \mu^+ \mu^-$  reported in 2011 is confirmed with the full data set, though its significance is softened to the level of  $2\sigma$  over background. The measured  $B_s^0 \rightarrow \mu^+ \mu^-$  branching ratio is still compatible with the SM expectation and recent combined results from LHC experiments.

The dynamics of several rare decays mediated by the FCNC process  $b \rightarrow s \mu^+ \mu^-$  has been studied in detail extending the reach to new angular observables. The  $\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$  decay has

been observed for the first time. Analyses of the  $b \rightarrow s\mu^-\mu^-$  decays are still in progress and may yield interesting results in the near future.

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