

Heavy B Hadrons

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1 Introduction

The CDF and DO experiments have successfully collected data since start of the Run II at the Tevatron Collider in 2001. The large B-meson production cross-section and the possibility to produce all kind of B hadron states, opened to the two collaborations the possibility to study with high precision the tiny effects of CP-violation in the Heavy B hadrons system, and to search for new physics effects in rare decays, in a way unavailable to the previous generation experiments. A new and largely unknown sector of the Heavy Flavor physics, complementary to the one already tested with precision at the B-factories, as recently pointed out by I. Bigi [1], has begun to be explored in search of possible signs of new physics. In this short note a selection of the most recent results on heavy B hadrons (mostly B_s mesons) from the Fermilab Tevatron, and from the Belle experiment running at the $\Upsilon(5S)$ are reviewed.

2 CP Violation in B_s mesons at Tevatron

In the neutral B_s system, the CP asymmetry in $B_s^0 \rightarrow J/\psi\phi$ decay play the analogous role of the $B^0 \rightarrow J/\psi K_s^0$ for the B_d system. Decays of the B_s meson via $b \rightarrow c\bar{c}s$ transitions in fact can be used to probe, via interference effects in the mixing and decay amplitudes of the process, the β_s angle of the squashed (bs) unitarity triangle, defined as $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$. An important difference with respect to the B_d system is that in the Standard Model β_s is expected to be very small (~ 0.02), making the measurement of CP asymmetry in $B_s^0 \rightarrow J/\psi\phi$ decay very sensitive to new possible physics effects in the mixing phase of the $B_s^0 - \bar{B}_s^0$ system.

CDF and DO experiments have been able, for the first time, to perform a search for CP violation in the neutral B_s meson system, by measuring the time-dependent CP asymmetry in the $B_s^0 \rightarrow J/\psi\phi$ decay mode. The vector-vector final state $J/\psi\phi$ contains mixtures of polarization amplitudes: the CP-odd A_\perp , and the CP-even A_0 and A_\parallel amplitudes. These terms need to be disentangled, using the angular distributions, in order to extract β_s , and their interference provides additional sensitivity [2].

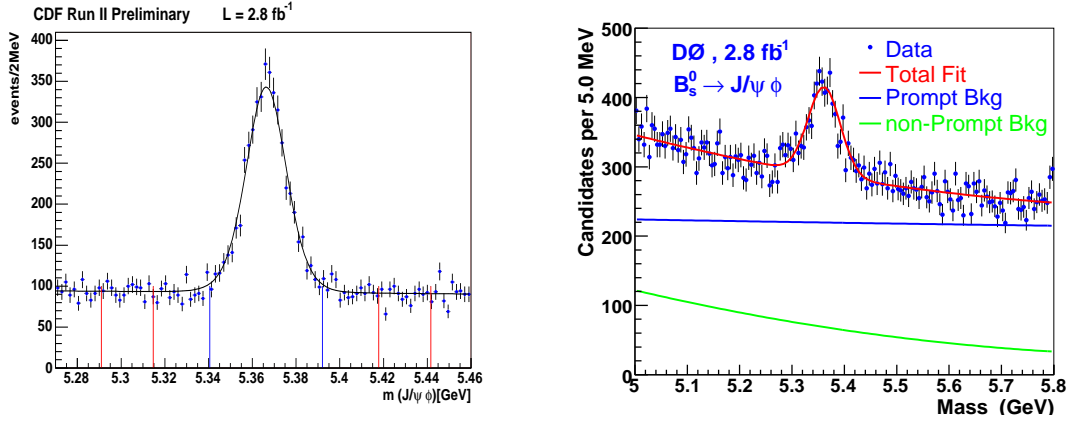


Figure 1: Data samples for the CDF and DO analyses of $B_s^0 \rightarrow J\psi\phi$ decay. The CDF experiment reports 3166 ± 56 events, while the DO experiment reports 1967 ± 65 events.

Very recently the CDF collaboration presented a new updated flavor-tagged, time-dependent, analysis, based on 2.8 fb^{-1} of integrated luminosity [3], that supersedes results from the previous 1.7 fb^{-1} untagged analysis [4], and 1.35 fb^{-1} flavor-tagged, time-dependent analysis [5]. The DO collaboration result is also based on a 2.8 fb^{-1} sample of flavor-tagged data, and is published in [6]. The $B_s^0 \rightarrow J/\psi\phi$ signals from the two experiments are shown in Fig. 1.

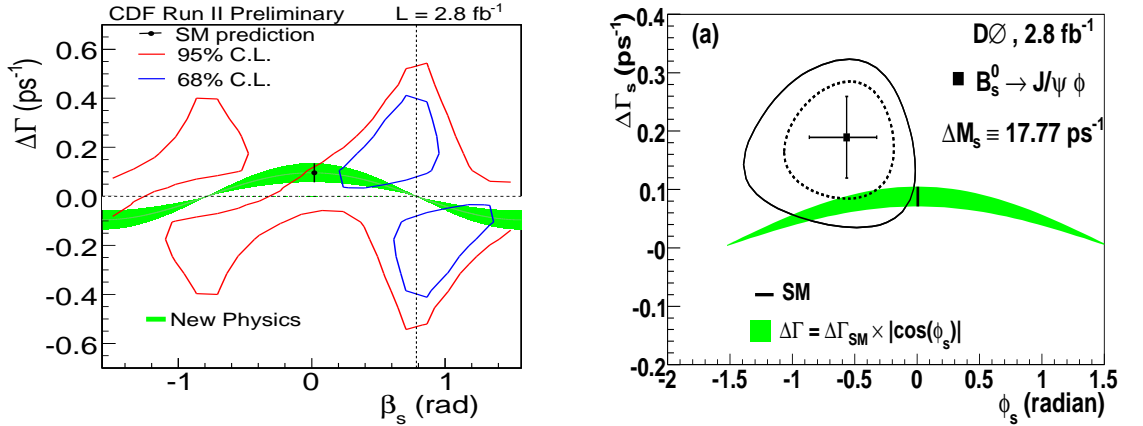


Figure 2: Confidence regions in the space of parameters $\Delta\Gamma_s$ and β_s for the CDF (left), and DO (right) analyses. The green band corresponds to new physics models, as described in the text.

In the CDF analysis two different fits have been performed, one without using flavor tagging and assuming the Standard Model, which fixes $\beta_s = 0$, and a second

one with flavor-tagging and letting β_s to be free. Assuming no CP violation ($\beta_s = 0$) the fit allows to simultaneously measure the decay width difference $\Delta\Gamma_s$ and the average lifetime of the B_s meson. The results are reported in Table 1.

Table 1: Standard Model fits in the CDF tagged analysis.

Parameter	CDF measurement (untagged)
$c\tau_s = 2c/(\Gamma_H + \Gamma_L)$	$459 \pm 12(stat) \pm 3(syst) \mu\text{m}$
$\Delta\Gamma_s = \Gamma_L - \Gamma_H$	$0.02 \pm 0.05(stat) \pm 0.01(syst) \text{ ps}^{-1}$
$ A_0 ^2$	$0.508 \pm 0.024 \pm 0.008$
$ A_{ }(0) ^2$	$0.241 \pm 0.019 \pm 0.007$

It is worth noticing here that the average B_s lifetime measurement is consistent with the HQET expectation of equal lifetimes for the B_s and B_d mesons. Table 1 reports also the measured polarization amplitudes for the $B_s^0 \rightarrow J/\psi\phi$ decay, that are consistent with those measured in the similar B_d decay $B^0 \rightarrow J/\psi K^{*0}$ [7]. For the CP fit, CDF does not report point estimates for any of the physics parameters, providing instead the confidence region in the $(\beta_s, \Delta\Gamma_s)$ plane shown in Fig. 2 (left), computed from Monte Carlo using Feldman-Cousins method for confidence intervals. Also shown in the same figure, is the theoretical expectation from the Standard Model (black point), and in presence of new physics (green band). The Standard Model p -value calculated using the likelihood ratio is of 7%, corresponding to 1.8 Gaussian standard deviations.

Treating $\Delta\Gamma_s$ as a nuisance parameter, CDF reports confidence intervals for β_s , and find that β_s is within $[0.28, 1.29]$ at 68% C.L., and within $[-\pi/2, -1.45] \cup [-1.01, -0.57] \cup [-0.13, \pi/2]$ at 95% CL.

To remove the two-fold ambiguity in the likelihood of the time-dependent, flavor tagged analysis, DO constrained the strong phases of the helicity amplitudes in the $B_s^0 \rightarrow J/\psi\phi$ decay to the world average values for the $B^0 \rightarrow J/\psi K^{*0}$ decay, measured at the B-factories [8]. Some justification of the constraint used has been recently showed in [9].

Results of the constrained fits are shown Table 2. In this case three types of fit have been performed: a Standard Model fit which fixes β_s to its expected value, a CP fit with β_s floating, and in addition, a CP fit with the further constraint that $\Delta\Gamma_s = 2|\Gamma_{12}^s| \cos\phi_s$, where $\phi_s = \text{arg}(-M_{12}^s/\Gamma_{12}^s)$, is the mixing phase of the B_s system¹, and M_{12}^s is the off-diagonal element of the mass matrix governing the flavor oscillations in the B_s system (related to the mixing frequency by $\Delta m_s = 2|M_{12}^s|$). The average

¹In the discussion the approximation $\phi_s \sim -2\beta_s$ has been made. This is a reasonable approximation since, although the equality does not hold in the Standard Model, both are much smaller than the current experimental resolution, whereas new physics contributions add a phase ϕ_{NP} to ϕ_s and subtract the same phase from $2\beta_s$, so that the approximation remains valid.

Table 2: CDF results from tagged $B_s^0 \rightarrow J/\psi\phi$ analysis.

Parameter	CP Fit (ϕ_s floating)	SM Fit ($\phi_s = 0$)	NP Fit ($\Delta\Gamma_s = 2 M_{12}^s \cos \phi_s$ constraint)
τ_s (ps)	1.52 ± 0.06	1.53 ± 0.06	1.49 ± 0.05
$\Delta\Gamma_s$ (ps $^{-1}$)	0.19 ± 0.07	0.14 ± 0.07	0.083 ± 0.018
$A_{\perp}(0)$	0.41 ± 0.04	0.44 ± 0.04	0.45 ± 0.03
$ A_0(0) ^2 - A_{\parallel}(0) ^2$	0.34 ± 0.05	0.35 ± 0.04	0.33 ± 0.04
$\phi_s = -2\beta_s$	$-0.57_{-0.30}^{+0.24}$	fixed (-0.04)	-0.46 ± 0.28

lifetime τ_s , and the decay amplitudes are consistent with expectations and with the CDF measurements. Confidence regions in the ($\phi_s(= -2\beta_s), \Delta\Gamma_s$) space are shown in Fig. 2 (right). The point estimate for the CP violation phase and $\Delta\Gamma_s$, obtained by DO are: $\phi_s = -0.57_{-0.30}^{+0.24}(stat)_{-0.02}^{+0.07}(syst)$ and $\Delta\Gamma_s = 0.19 \pm 0.07(stat)_{0.01}^{+0.02}(syst)$ ps $^{-1}$. The Standard Model p -value is of 6.6%, and the fluctuation respect to the Standard Model goes in the same direction as CDF.

Experimental sensitivity to new physics effects on the B_s mixing phase can also be obtained from charge asymmetry measurements in semi-leptonic B_s decays. The semi-leptonic asymmetry is in fact related to the mixing phase by the relation:

$$A_{SL}^s = \frac{N(\overline{B}_s \rightarrow f) - N(B_s \rightarrow \overline{f})}{N(\overline{B}_s \rightarrow f) + N(B_s \rightarrow \overline{f})} \sim \frac{\Delta\Gamma_s}{\Delta m_s} \tan \phi_s,$$

where f corresponds to direct B_s decays $B_s \rightarrow f$ (e.g. $D_s^- l^+ \nu_l$).

The Standard Model prediction for the semileptonic asymmetry in B_s decays is very small, at the level of few units in 10^{-5} [10].

At the Tevatron the semileptonic asymmetry has been measured both in inclusive di-muon samples, where $A_{SL}^s \sim \frac{N_{\mu^+\mu^+} - N_{\mu^-\mu^-}}{N_{\mu^+\mu^+} + N_{\mu^-\mu^-}}$, or by using the sequential decays sample $B_s^0 \rightarrow \mu\nu D_s$. The first method has very high statistical accuracy, but requires knowledge of asymmetries of other contributing processes in addition to the detector charge asymmetries. The second method has less statistical power but ensures that the major contribution to the asymmetry comes from the B_s decays. Combining the two measurements DO obtains: $A_{SL}^s = 0.0001 \pm 0.0090$ [11], while the CDF result based on 1.6 fb^{-1} di-muon pairs, is: $A_{SL}^s = 0.020 \pm 0.028$ [12]. At the current level of precision A_{SL}^s is not able to provide powerful constraints on new physics contributions on the mixing phase.

Both the CDF and DO analyses of the CP violation in $B_s^0 \rightarrow J/\psi\phi$ decay show a slight disagreement with the Standard Model prediction, and both results fluctuate in the same direction. Recently the DO collaboration has made public the results of the fit without the strong phase constraints, allowing the HFAG group to combine them

with the CDF results [13]. The combined contours are shown in Fig. 3. The p -value for the combined result is 3.1%, corresponding to 2.2 Gaussian standard deviations.

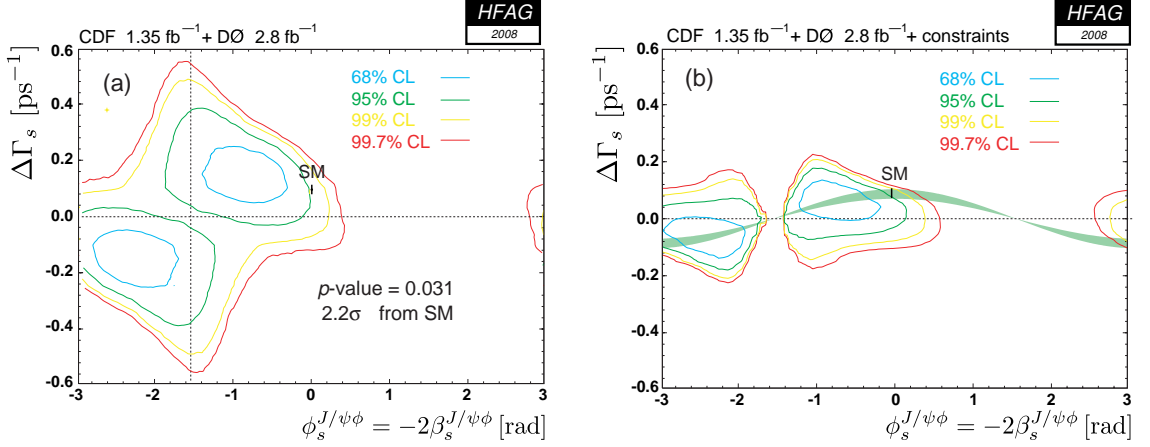


Figure 3: HFAG Combinations of the CDF and DO $B_s^0 \rightarrow J/\psi\phi$ tagged analyses. The plot on the right use additional experimental input from the CDF and DO measurements of A_{SL}^s .

3 Rare B_s decays at Tevatron and Belle

3.1 Leptonic Two-body Decays at Tevatron

The FCNC process $B_s^0 \rightarrow \mu^+\mu^-$ is predicted to have a branching ratio of $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.42 \pm 0.54) \times 10^{-9}$ in the Standard Model [14], well below the current experimental sensitivity of the Tevatron experiments. The $B^0 \rightarrow \mu^+\mu^-$ decay is further suppressed by $|V_{td}/V_{ts}|^2$, with a predicted branching ratio of $(1.00 \pm 0.14) \times 10^{-10}$. Significant enhancements are instead predicted by several new physics models. For example in the minimal super-symmetric standard model (MSSM) the B_s^0 branching ratio is proportional to $\tan^6 \beta$ where $\tan \beta$ is the ratio between the vacuum expectation values of the two neutral Higgs fields. In R -parity violating super-symmetric (SUSY) models an enhancement is possible even at low values of $\tan \beta$.

Both Tevatron experiments have dedicated triggers to collect $B \rightarrow \mu^+\mu^-$ events, and optimized selections for the $B_s^0 \rightarrow \mu^+\mu^-$ candidates based on sophisticated multivariate analysis techniques. DO combines the discriminant variables in a likelihood ratio, while CDF uses a neural network (NN) discriminant. Both experiments estimate the dominant combinatorial background by a fit to the mass sidebands, while contribution from decays of B mesons to two light hadrons, which could peak in the signal mass region, is estimated to be an order of magnitude lower than

the combinatorial background. Both experiments do not report any significant excess of signal candidates over the expected background, and set 90% C.L. limits calculated with a Bayesian method for a data sample of 2 fb^{-1} per experiment: $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 7.5 \times 10^{-8}$ (DO) [15] and $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 4.7 \times 10^{-8}$ (CDF) [16]. Because of the superior mass resolution of the tracking system CDF is able to separate B_s^0 and B^0 mesons and to quote a 90% C.L. limit separately for the B^0 decay of $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 1.5 \times 10^{-8}$.

Very recently the CDF experiment reported the results of a search for the $B_{s,d}^0 \rightarrow e^+ e^-$ channel and for the lepton-flavor violating mode $B_{s,d}^0 \rightarrow e^+ \mu^-$. In particular the latter decay modes are strongly suppressed within the Standard Model, in which leptons do not change flavor. These decays are allowed, however, in many models of new physics, such as Pati-Salam leptoquarks model, or in SUSY and Extra Dimension models, where the assumption of a local gauge symmetry between quarks and leptons at the lepton-flavor violation tree-level couplings leads to the prediction of a new force of Nature which mediates transitions between quarks and leptons [17].

Using a 2 fb^{-1} data sample, CDF find one event in the search window for the $B_s^0 \rightarrow e^+ \mu^-$, with estimated 0.81 ± 0.63 background events, and one event for $B_s^0 \rightarrow e^+ e^-$, with 2.8 ± 1.8 estimated background events. By using the $B^0 \rightarrow K^+ \pi^-$ decay mode as a relative normalization, CDF derives the upper limits at 90% C.L. on the decay branching ratios of $\mathcal{B}(B_s^0 \rightarrow e^+ \mu^-) < 2.0 \times 10^{-7}$, and $\mathcal{B}(B_s^0 \rightarrow e^+ e^-) < 2.8 \times 10^{-7}$ [16]. Finally from the decay branching ratio limits CDF calculate the corresponding lower bound on the Pati-Salam leptoquark mass: $M_{LQ}(B_s^0) > 47.7 \text{ TeV}/c^2$ at 90% C.L. (see Fig. 4).

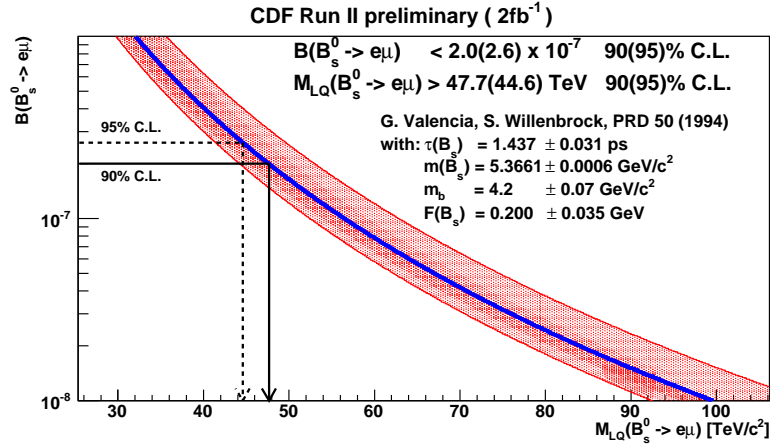


Figure 4: Leptoquark mass limit corresponding to the 90% C.L. on $\mathcal{B}(B_s^0 \rightarrow e^+ \mu^-)$.

3.2 Charmless Two-body Decays at Tevatron

Non-leptonic decays of b hadrons into pairs of charmless charged hadrons are effective probes of the CKM matrix, and sensitive to potential new physics effects. The large production cross section of b hadrons at Tevatron, and the ability of CDF to trigger on fully hadronic decays, allows extending such measurements to B_s^0 and Λ_b^0 decays, complementing the B^0 meson case, extensively studied at the B-factories.

CDF analyzed an integrated luminosity of $\sim 1 \text{ fb}^{-1}$ of pairs of oppositely-charged particles, selected by the displaced track trigger. A sample of 14500 $H_b^0 \rightarrow h^+ h'^-$ decay modes (where $H_b^0 = B^0, B_s^0$ or Λ_b^0 and $h = K, \pi, p$) was reconstructed after the off-line confirmation of trigger requirements. The invariant mass resolution and the particle identification separation power available in CDF, are not sufficient to disentangle the individual $H_b^0 \rightarrow h^+ h'^-$ decay modes on an event-by-event basis, therefore a Maximum Likelihood fit is performed to separate the different components. The fit combines kinematic and particle identification information, to statistically determine both the contribution of each mode, and the relative contributions to the CP asymmetries.

Significant signals are seen for $B^0 \rightarrow \pi^+ \pi^-$, $B^0 \rightarrow K^+ \pi^-$, and $B_s^0 \rightarrow K^+ K^-$, previously observed by CDF [19]. In addition to that, three new rare decay modes have been observed for the first time $B_s^0 \rightarrow K^- \pi^+$, $\Lambda_b^0 \rightarrow p \pi^-$ and $\Lambda_b^0 \rightarrow p K^-$, with a significance respectively of 8.2σ , 6.0σ and 11.5σ . No evidence was obtained for $B_s^0 \rightarrow \pi^+ \pi^-$ or $B^0 \rightarrow K^+ K^-$ mode.

Table 3: Branching fractions results. Absolute branching fractions are normalized to the the world-average values $\mathcal{B}(B^0 \rightarrow K^+ \pi^-) = (19.4 \pm 0.6) \times 10^{-6}$ and $f_s/f_d = 0.276 \pm 0.034$ and $f_\Lambda/f_d = 0.230 \pm 0.052$ [18].

Mode	BR(10^{-6})
$B^0 \rightarrow \pi^+ \pi^-$	$5.02 \pm 0.33 \pm 0.35$
$B_s^0 \rightarrow K^+ K^-$	$24.4 \pm 1.4 \pm 3.5$
$B_s^0 \rightarrow K^- \pi^+$	$5.0 \pm 0.7 \pm 0.8$
$\Lambda_b^0 \rightarrow p K^-$	$5.6 \pm 0.8 \pm 1.5$
$\Lambda_b^0 \rightarrow p \pi^-$	$3.5 \pm 0.6 \pm 0.9$
$B_s^0 \rightarrow \pi^+ \pi^-$	$0.49 \pm 0.28 \pm 0.36$
$B^0 \rightarrow K^+ K^-$	$0.39 \pm 0.16 \pm 0.12$

The absolute branching fractions obtained by CDF normalizing the measurements to the the world average value $\mathcal{B}(B^0 \rightarrow K^+ \pi^-) = (19.4 \pm 0.6) \times 10^{-6}$, are listed in Table 3, while the CP-related measurements are listed in Table 4, where f_d , f_s and f_Λ indicate the production fractions respectively of B^0 , B_s^0 and Λ_b^0 from fragmentation of a b quark in $\bar{p}p$ collisions.

Table 4: CP-violation related results.

Mode	Measurement
$A_{CP}(B^0 \rightarrow K^+ \pi^-)$	$-0.086 \pm 0.023 \pm 0.009$
$A_{CP}(B_s^0 \rightarrow K^- \pi^+)$	$0.39 \pm 0.15 \pm 0.08$
$A_{CP}(\Lambda_b^- \rightarrow p K^-)$	$-0.37 \pm 0.17 \pm 0.03$
$A_{CP}(\Lambda_b^0 \rightarrow p \pi^-)$	$-0.03 \pm 0.17 \pm 0.05$

The decays $\Lambda_b^0 \rightarrow p \pi^-$ and $\Lambda_b^0 \rightarrow p K^-$ are allowed at tree level in the Standard Model, but are suppressed by the small value of the involved CKM matrix element V_{ub} . Loop diagram processes can contribute at a magnitude that is comparable to the tree diagram process, leading to sizable direct CP violation. In the Standard Model a A_{CP} value of $\mathcal{O}(10\%)$ is predicted.

The measurement of the direct CP violation asymmetries in the b -baryon decays, presented by CDF, is the first such measurements in this sector. The statistical uncertainty still dominates the resolution and prevents a statement on the presence of asymmetry, whose measured value deviates from 0 at 2.1σ level in the $\Lambda_b^0 \rightarrow p K^-$ decay mode and is fully consistent with 0 in the $\Lambda_b^0 \rightarrow p \pi^-$ decay mode. In Fig. 5 the invariant mass spectrum in the $\pi^+ \pi^-$ mass hypothesis, and the relative probability density function for the $\Lambda_b^0 \rightarrow p K^-$ are shown, illustrating the good description of the data by the fit and the powerful $\Lambda_b^0/\bar{\Lambda}_b^0$ separation.

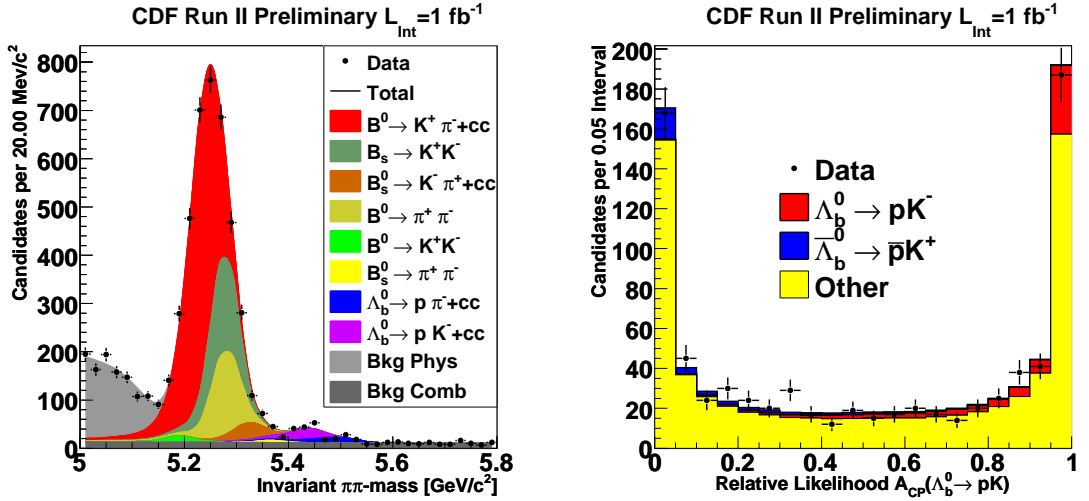


Figure 5: Invariant mass spectrum for $\pi^+ \pi^-$ mass assignment (left) and relative probability density function (pdf) of $\Lambda_b^0 \rightarrow p K^-$: $\text{pdf}(\Lambda_b^0)/[\text{pdf}(\Lambda_b^0) + \text{pdf}(\bar{\Lambda}_b^0)]$ (right).

3.3 Radiative B_s penguins at Belle

During the last several years the possibility of performing B_s^0 meson studies at the e^+e^- colliders running at the $\Upsilon(5S)$ resonance has been extensively explored. The first evidence for B_s^0 production at the $\Upsilon(5S)$ was found by the CLEO collaboration [26, 27] using a data sample of 0.42 fb^{-1} collected in 2003. This study indicated that practical B_s^0 measurements at the $\Upsilon(5S)$ are possible with at least 20 fb^{-1} , which can be easily collected at B-factories running with $\sim 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ luminosity. To test the feasibility of a B_s^0 physics program the Belle collaboration collected at the $\Upsilon(5S)$ a sample of 1.86 fb^{-1} of data in 2005, and a one of 21.7 fb^{-1} in 2006 [28, 29].

The collected samples have been used by Belle to perform searches for exclusive radiative decays of the B_s^0 mesons, that are of great interest, because sensitive to new physics effects and experimentally inaccessible to the Tevatron experiments (the presence of low energy photons in the final state makes these kind of decays too hard to be reconstructed in CDF and DO). In particular Belle searched for the decay modes $B_s^0 \rightarrow \phi\gamma$ and $B_s^0 \rightarrow \gamma\gamma$, using the full 23.6 fb^{-1} available data sample [30].



Figure 6: Diagrams describing the dominant SM processes for the $B_s^0 \rightarrow \phi\gamma$ (left) and $B_s^0 \rightarrow \gamma\gamma$ (right) decays.

Within the Standard Model (SM) the $B_s^0 \rightarrow \phi\gamma$ decay is described by the radiative penguin diagram shown in Fig. 6 (left). The branching fraction is predicted to be $\sim 4 \times 10^{-5}$ [31]. The $B_s^0 \rightarrow \gamma\gamma$ decay proceed via the penguin annihilation diagram shown in Fig. 6 (right) and is expected to have a much smaller branching ratio, in the range $(0.5 - 1.0) \times 10^{-6}$, that can be however enhanced by about an order of magnitude in various new physics models [32, 33, 34], reaching a level not far from the current sensitivity of the Belle experiment.

To extract the signal yields a multi-dimensional un-binned extended maximum likelihood fit is performed to the M_{bc} and ΔE variables. M_{bc} and ΔE are respectively the beam-energy-constrained mass, and the energy difference observable, defined as: $\Delta E = E_{B_s^0}^{\text{CM}} - E_{\text{beam}}^{\text{CM}}$ and $M_{bc} = \sqrt{(E_{\text{beam}}^{\text{CM}})^2 - (p_{B_s^0}^{\text{CM}})^2}$, where $E_{B_s^0}^{\text{CM}}$ and $p_{B_s^0}^{\text{CM}}$ are the energy and momentum of the B_s^0 candidate in the e^+e^- center-of-mass (CM) system, and $E_{\text{beam}}^{\text{CM}}$ is the CM beam energy.

Fig. 7 shows the M_{bc} and ΔE projections of the fit results of the data, together with the fitted functions. A clear signal of 18_{-5}^{+6} events is seen in the $B_s^0 \rightarrow \phi\gamma$ mode, with a significance of 5.5 standard deviations, providing the first observation of a B_s

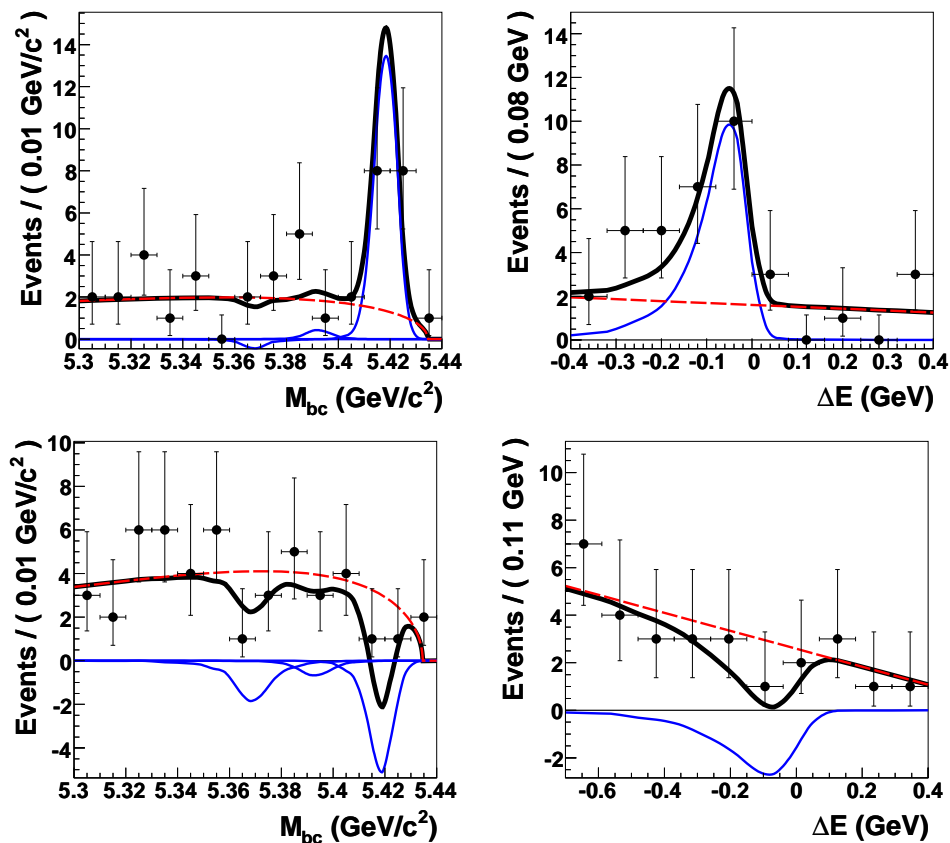


Figure 7: M_{bc} projection (left) and ΔE projection (right) for the $B_s^0 \rightarrow \phi\gamma$ (top) and $B_s^0 \rightarrow \gamma\gamma$ (bottom) modes. The thick solid curves are the fit functions (thin solid curves: signal functions, dashed curves: continuum contribution).

penguin radiative decay. The branching fraction is measured to be $\mathcal{B}(B_s^0 \rightarrow \phi\gamma) = (5.7^{+1.8}_{-1.5}(\text{stat.})^{+1.2}_{-1.1}(\text{syst.})) \times 10^{-5}$, in agreement with the SM predictions.

No significant signal is observed instead for the $B_s^0 \rightarrow \gamma\gamma$ mode, and an upper limit at the 90% C.L. of $\mathcal{B}(B_s^0 \rightarrow \phi\gamma) < 8.7 \times 10^{-6}$ is set.

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