



LATEST RESULTS ON ORBITALLY EXCITED STRANGE BOTTOM MESONS WITH THE CDF II DETECTOR

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We present the latest results on the spectroscopy of orbitally excited strange bottom mesons from $\sim 1 \text{ fb}^{-1}$ of CDF data. The measurements are performed with fully reconstructed B decays collected by the CDF II detector at $\sqrt{s} = 1.96 \text{ TeV}$ in both the di-muon and the fully hadronic trigger paths.

Keywords: spectroscopy; B-meson; bottom meson.

1. Introduction

Mesons containing one heavy quark are a useful laboratory to test QCD models. In the limit of heavy quark mass $m_Q \rightarrow \infty$, heavy mesons' properties are governed by the dynamics of the light quark. As such, these states become "hydrogen atoms" of hadron physics. In this Heavy Quark Symmetry approach (see references ¹) the quantum numbers of the heavy and light quarks are separately conserved by the strong interaction. For the bottom B -mesons the heavy bottom quark spin, $\mathbf{s}_Q = \frac{1}{2}^+$, couples with the light anti-quark momentum $\mathbf{j}_q = \mathbf{s}_q + \mathbf{L}$, where $\mathbf{s}_q = \frac{1}{2}^-$ is the spin of the light anti-quark and \mathbf{L} is its angular momentum. Hence for P -wave ($L = 1$) mesons we obtain two $j_q = \frac{3}{2}^+$ states, the $J^P = 2^+, 1^+$ states, and two $j_q = \frac{1}{2}^+$ states, the $J^P = 0^+, 1^+$ states. The sketch of the B_{sJ} -states with their possible strong decays to lower lying non-strange $B_{u,d}$ mesons and K -mesons are shown in Fig. 1. In our analysis we do not consider exotic modes (e.g. $B_{sJ} \rightarrow B_s \pi^0$) for which isospin is not conserved. The mass predictions from several authors are summarized in Table 1. The states B_{s0}^* and B_{s1}' decaying with the K -meson emitted in an S -wave are predicted

Table 1. Selected mass (in MeV/c^2) predictions of B_{sJ} states

Ref.	B_{s0}^*	B_{s1}'	B_{s1}	B_{s2}^*
2	5830.0	5860.0	5860.0	5888.0
3	5841.0	5859.0	5831.0	5844.0
4	-	-	5834.0	5846.0
5	-	-	5886.0	5899.0

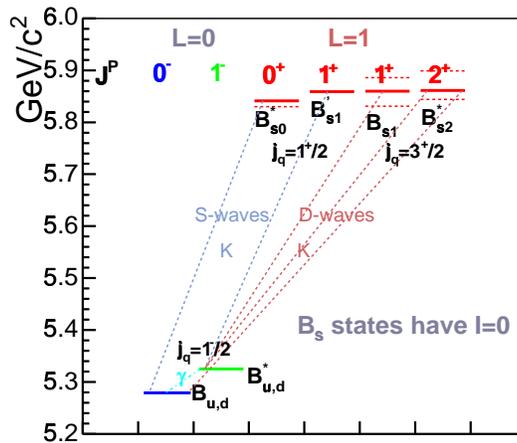


Fig. 1. Spectroscopy of orbital B_{sJ} Mesons

to have a large width of $(100 - 170) \text{ MeV}/c^2$ (see e.g. reference ²). These states are experimentally difficult to identify. The states B_{s1} and B_{s2}^* decaying via D -waves should have a narrow width predicted to be $(1 - 7) \text{ MeV}/c^2$ for B_{s2}^* and $(< 1.0 - 2.8) \text{ MeV}/c^2$ for B_{s1} (see references ^{2,4,5}).

The experimental results on orbital B_{sJ} mesons are limited by observation of only one narrow state. The first evidence of the state was made by the OPAL Collaboration ⁶ and later confirmed by the DELPHI experiment ⁷. Recently the DØ Collaboration ⁸ reported a narrow signal at the similar mass value as OPAL.

In this report we present results on the search for and observation of narrow $J^P = 1^+, 2^+$ states of strange bottom mesons.

2. Triggers and Datasets

Our results are based on data collected with the CDF II detector and corresponding to an integrated luminosity of $\sim 1 \text{ fb}^{-1}$. As $p\bar{p}$ collisions at 1.96 TeV have an enormous inelastic total cross-section of $\sim 60 \text{ mb}$, while b -hadron events comprise only $\approx 20 \mu\text{b}$ ($|\eta| < 1.0$), triggers selecting b -hadron events are of vital importance. The triggers set in the CDF II detector for b -physics studies are based on leptons and displaced tracks.

One of these is a dimuon trigger with a low muon transverse momentum threshold of $1.5 \text{ GeV}/c$. It reconstructs at Level 1 track pairs in the CDF central tracker COT. The tracks are then matched to hits in the CDF muon chambers. At Level 3 a full reconstruction is made and a dimuon mass cut $M(\mu^+\mu^-) \in [2.7, 4.0] \text{ GeV}/c^2$ around the mass of J/ψ is applied. This trigger saves B -mesons through the mode $B^+ \rightarrow J/\psi K^+, J/\psi \rightarrow \mu^+\mu^{-a}$.

^aUnless otherwise stated all references to the specific charge combination imply the charge conjugate combination as well.

The other is the Two displaced Track Trigger. It also reconstructs with the central tracker a pair of high p_T tracks at Level 1 and enables secondary vertex selection at Level 2 requiring each of these tracks to have impact parameter measured by the CDF silicon detector SVX II larger than $120 \mu\text{m}$. The excellent impact parameter resolution of SVX II makes this challenging task possible. The Two Track Trigger is efficient for heavy quark hadron decay modes. It triggers another fundamental mode used in this analysis, namely $B^+ \rightarrow \bar{D}^0\pi^+, \bar{D}^0 \rightarrow K^+\pi^-$.

3. Event Selection

To avoid absolute mass scale systematic uncertainties, we search for narrow signatures in a mass difference distribution $Q = M(B^+K^-) - M(B^+) - M(K^-)$, where $M(B^+K^-)$ is the invariant mass of the B^+K^- pair, $M(B^+)$ is the invariant mass of the B^+ candidate, and $M(K^-)$ is the PDG mass of the kaon. In the mode (see Fig. 1) $B_{s2}^* \rightarrow B^+K^-$, the signal is expected to appear at $70 \text{ MeV}/c^2 \lesssim Q \lesssim 130 \text{ MeV}/c^2$. If the mass of the state B_{s2}^* is above the $B^{*+}K^-$ threshold, an additional bump would emerge $45.78 \text{ MeV}/c^2$ below the other, due to the undetected γ from the radiative decay $B^{*+} \rightarrow B^+\gamma$. The same is true for $B_{s1} \rightarrow B^{*+}K^-$, which can appear as a narrow peak at $10 \text{ MeV}/c^2 \lesssim Q \lesssim 70 \text{ MeV}/c^2$, shifted due to the γ undetected.

For the candidates $B_{sJ} \rightarrow B^{(*)+}K^-$ the offline selections of reconstructed B^+K^- pairs have been done separately for B^+ decays in the $B^+ \rightarrow J/\psi K^+$ or $B^+ \rightarrow \bar{D}^0\pi^+$ modes. In both cases the charm candidates and bottom B^+ candidates have been subjected to 3-dimensional vertex fits. The candidates' topological quantities, kinematical variables, and particle identification information have also been analyzed by neural networks built separately for the B^+ and their parent B_{sJ} candidates ⁹. The neural net-

works have been trained on background patterns using experimental data. To train the neural network for a signal pattern we have used Monte-Carlo simulated data having the same invariant mass distribution as the experimental background events to avoid a bias to the signal. The distribution of the neural network output for the neural networks trained individually for two B_{sJ} decay modes is shown at Fig. 2. For the final selection we apply the cuts on the neural network output

\mathcal{NN} and on the number of B_{sJ} candidates in the event. The cuts on the \mathcal{NN} are chosen to maximize the figure of merit $S/\sqrt{S+B}$ for candidates with $Q \in (60, 70) \text{ MeV}/c^2$ when the numerator is obtained from Monte-Carlo and denominator is taken from data. The cut values are found to be $\mathcal{NN} > 0.5$ for $B_{sJ} \rightarrow B^+ K^-$, $B^+ \rightarrow J/\psi K^+$ and $\mathcal{NN} > 0.3$ for $B_{sJ} \rightarrow B^+ K^-$, $B^+ \rightarrow \bar{D}^0 \pi^+$. Only events with fewer than four B_{sJ} candidates are allowed, in order to suppress further the combinatorial background.

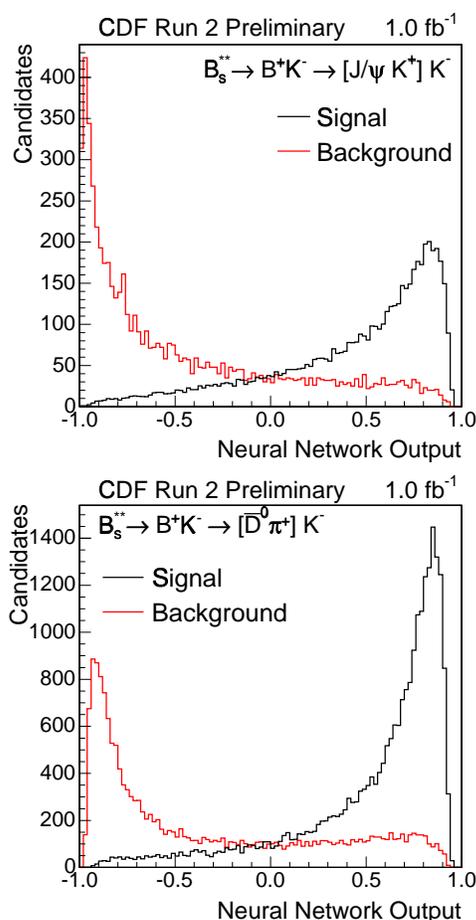


Fig. 2. Distribution of the neural network output for the signal and background events used for training of the neural network for the reconstructed decay modes $B_{sJ} \rightarrow B^+ K^-$, $B^+ \rightarrow J/\psi K^+$ and $B_{sJ} \rightarrow B^+ K^-$, $B^+ \rightarrow \bar{D}^0 \pi^+$.

4. Results

The Q -value spectra for every reconstructed decay mode of $B_{sJ} \rightarrow B^+ K^-$ with $B^+ \rightarrow J/\psi K^+$ or $\bar{D}^0 \pi^+$ are shown in Fig. 3 (two upper plots). The spectra have been fit using an unbinned maximum likelihood method. As

Table 2. Summary of fit results, errors are statistical only

State	$B_{s1} \rightarrow B^* K^-$	$B_{s2} \rightarrow B^* K^-$
B^+ Mode	$B^+ \rightarrow J/\psi K^+$	
$Q[\text{MeV}/c^2]$	10.87 ± 0.19	67.03 ± 0.44
$\sigma[\text{MeV}/c^2]$	0.64 ± 0.25	1.79 ± 0.42
N_{evts}	16.98 ± 5.14	44.15 ± 13.36
B^+ Mode	$B^+ \rightarrow \bar{D}^0 \pi^+$	
$Q[\text{MeV}/c^2]$	10.68 ± 0.46	66.85 ± 0.76
$\sigma[\text{MeV}/c^2]$	1.18 ± 0.56	2.88 ± 0.75
N_{evts}	20.66 ± 7.12	55.74 ± 19.20
Both B^+ Modes	Combined statistics	
$Q[\text{MeV}/c^2]$	$10.73 \pm 0.21(\text{stat})$	$66.96 \pm 0.39(\text{stat})$
N_{evts}	$36.4 \pm 9.0(\text{stat})$	$94.8 \pm 23.4(\text{stat})$

both decay modes have similar background shapes we add statistically both subsamples and proceed with the final fit, see the Fig. 3 bottom plot. The numerical results of the fits are summarized in Table 2. Using a ratio of the original likelihood to the one of the fit with the null hypothesis, $-2 \cdot \ln \mathcal{L}/\mathcal{L}_0$, we obtain a significance of 6.3σ for the peak at $10.73 \text{ MeV}/c^2$ and of 7.7σ for the peak at

66.96 MeV/ c^2 . The statistical experiments with background generated according to our data and the sole peak at 66.96 MeV/ c^2 yield a p-value of $2.13 \cdot 10^{-7}$ for the newly established signal at 10.73 MeV/ c^2 .

5. Summary

We have presented the observation of two narrow peaks in the mass difference $M(B^+K^-) - M(B^+) - M(K^-)$ distribution. The measured pattern of two peaks is interpreted as the signal of $B_{s2}^* \rightarrow B^+K^-$ previously observed by other experiments and confirmed by our data and the signal of $B_{s1} \rightarrow B^{*+}K^-$, reported here for the first time. Our measurements yielded:

- $M(B_{s1}) = 5829.41 \pm 0.21(\text{stat})$
 $\pm 0.14(\text{syst}) \pm 0.6(PDG) \text{ MeV}/c^2$
- $M(B_{s2}^*) = 5839.64 \pm 0.39(\text{stat})$
 $\pm 0.14(\text{syst}) \pm 0.5(PDG) \text{ MeV}/c^2$.

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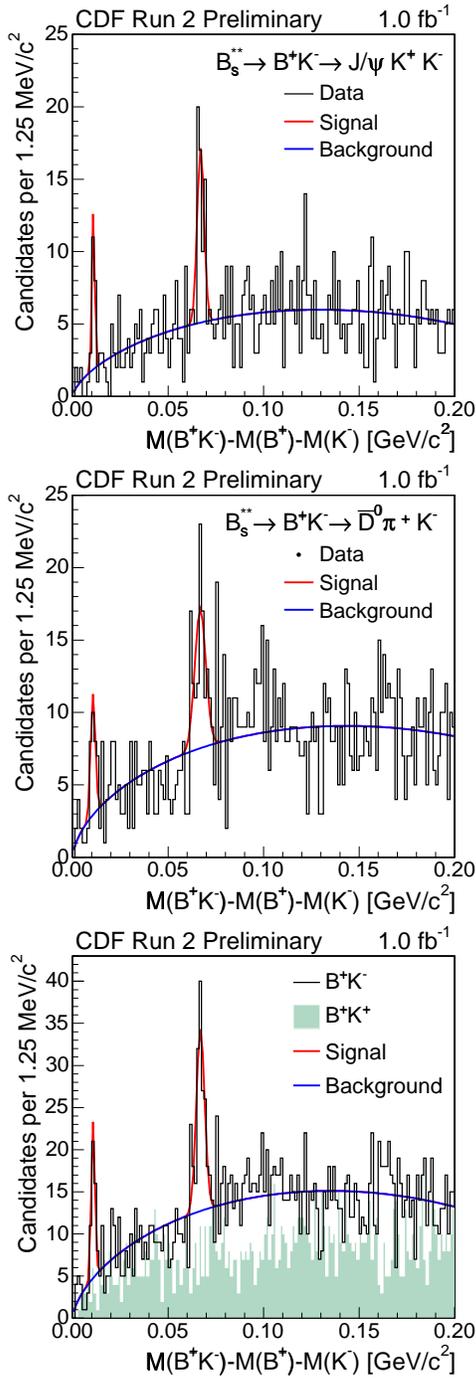


Fig. 3. The mass difference (Q-value) spectra for two modes $B_{sJ} \rightarrow B^+ K^-$, $B^+ \rightarrow J/\psi K^+$ or $\bar{D}^0 \pi^+$ (two upper plots). The statistics of both modes is added and the final result is shown at the bottom plot. The unbinned maximum likelihood fit projections are superimposed on each plot.