Observation of the B_s at CDF

CDF Collaboration
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Abstract

The CDF detector has observed for the first time the decay $B_s \rightarrow J/\psi\phi$. Using the statistics of 21 pb^{-1} a signal of 21 events is observed. Comparing this decay to the kinematically similar decay $B^0 \rightarrow J/\psi K^{*0}$, a branching ratio for the B_s decay was deduced: $BR(B_s \rightarrow J/\psi\phi) \times \frac{BR(b \rightarrow B_s)}{BR(b \rightarrow B_d)} = (3.6 \pm 0.8 \pm 1.0) \cdot 10^{-4}$.
This decay is also used for a mass determination of the B_s, giving $m_{B_s} = (5383.3 \pm 4.5 \pm 5.0)$ MeV/c^2. The semileptonic decay mode of the B_s was used to determine the lifetime $\tau_{B_s} = (1.54^{+0.42}_{-0.34}(stat.) \pm 0.10(sys.))$ ps.

1 Introduction

B meson decays used to be the domain of e^+e^- colliders. Recently, however, the UA1 and CDF collaborations have shown that it is also possible to reconstruct exclusive hadronic B meson decays at hadron colliders. Hadron colliders, compared to e^+e^- colliders have the advantage of a high b quark cross section, but have a very small signal to background ratio. This is illustrated in the following table:

	$\sigma_{b\bar{b}}/\sigma_{tot}$	$\sigma_{b\bar{b}}$
CESR	0.33	1 nb
LEP	0.2	7 nb
TEVATRON	10^{-3}	10 μb

The b cross section at the TEVATRON is for b quarks within the rapidity range of $|\eta| < 1.0$ and with a transverse momentum exceeding $p_t > 10$ GeV/c.
Consequently the reconstructed decays at hadron colliders so far have a higher background, but also higher statistics than the decays reconstructed at e^+e^- colliders. Moreover, hadron colliders so far have only been successful in reconstructing decays involving leptons. It will be a challenge for future upgrades to design clever trigger schemes which can also trigger on the decay length of the Bs and subsequently open up decays not involving leptons like $B^0 \rightarrow \pi^+\pi^-$.

B-physics is a rich field which opens a wide window into the world of the standard model and possibly beyond. The motivations to study the B_s meson are manifold.

- The B_s meson is a bound meson consisting of a $\bar{b}$ quark and an s quark. This state is firmly predicted by the standard model. Although it would be very surprising if this state did not exist, it is nevertheless very important to find it.
- As the top quark seems to be too heavy to form bound mesonic states, the beauty system remains the heaviest heavy-light meson system. Since the strong coupling constant at the scale of the b-quark is already small enough to make reliable QCD perturbative calculations, the B meson system is an ideal laboratory to test our understanding of weak decays, with sizable, but calculable QCD corrections.
- The study of B meson decays allows the measurement of several fundamental parameters of the standard model like V_{td}, V_{cb} etc., which would not be accessible otherwise.
- In the long run the study of penguin decays, and of CP violation in the B system also provide a window into a possible world beyond the standard model.

Hadron colliders have shown that they can successfully provide valuable information, partly complementary to e^+e^- colliders in this quest.

2 Evidence for the existence of the B_s

The first evidence for the existence of the B_s was seen by the CUSB collaboration looking at the γ spectrum running on the $\Upsilon(5S)$ resonance [1].

More direct evidence was obtained by the ALEPH collaboration at LEP. They observed the B_s meson in its semileptonic decay mode: $B_s \rightarrow D_s^- l^+ \nu X$, where they saw a D_s signal for $\phi\pi^- l^+$ combinations and not for $\phi\pi^+ l^+$ combinations [2].

The first observation of the decay $B_s \rightarrow J/\psi\phi$ was made by the CDF collaboration in June 1993. At that time, half of the currently available dataset was analyzed and 14.0 ± 4.7 events were observed in this decay channel [3].

3 The decay $B_s \rightarrow J/\psi\phi$

3.1 Observation

In order to reconstruct the B_s meson, the J/ψ and ϕ mesons must first be reconstructed. The J/ψ's are reconstructed at CDF in their dimuon mode. Opposite sign dimuons, which pass matching cuts between the muon chambers and the central drift chamber, and which have a transverse momentum exceeding $p_t^\mu > 1.4\ GeV/c$ are selected for the J/ψ reconstruction. Figure 1a shows the $\mu^+\mu^-$ invariant mass distribution. The current data sample contains 80,000 J/ψ candidates. The ϕ meson is reconstructed in its decay mode into two kaons. Every track with a transverse momentum exceeding $p_t^K > 400$ MeV/c is used as a kaon candidate and each two kaon candidates with a combined transverse momentum exceeding $p_t^\phi > 2.0\ GeV/c$ are used for the ϕ meson search. Figure 1b shows the resulting ϕ signal.

For the reconstruction of the B_s, the muon and kaon candidates falling within the following mass windows are considered as J/ψ and ϕ candidates: $|M(\mu^+\mu^-) - M(J/\psi)_{PDG}| < 3\sigma$

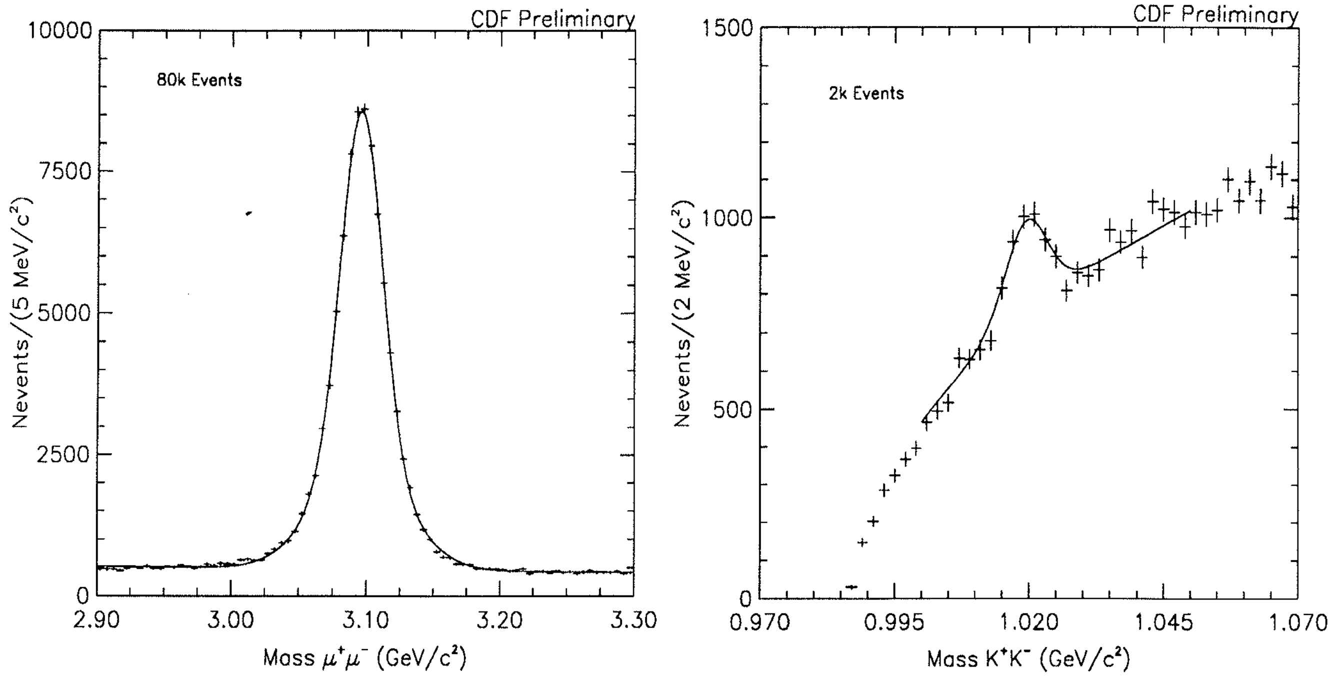


Figure 1: The invariant $\mu^+\mu^-$ and K^+K^- mass spectra

and $|M(KK) - M(\phi)_{PDG}| < 10$ MeV/c^2. Additionally, secondary vertex cuts are applied and a positive decay length is required. This means that the secondary vertex is in the direction of the B momentum. Furthermore, all $J/\psi\ \phi$ combinations are required to have a transverse momentum larger than $p_t^B > 8.0$ GeV/c. Figure 2 shows the resulting $J/\psi\phi$ invariant mass distribution. A signal of 21.1 ± 3.6 events is observed.

As a cross check, the analysis was done without a cut on the K^+K^- invariant mass. For $J/\psi K^+K^-$ combinations whose invariant mass is in the range from 5.34 to 5.40 MeV/c^2 we plot the K^+K^- invariant mass, shown in figure 3a. The observed ϕ peak contains 26 events. This is in agreement with the 21 B_s events seen, if the efficiency of the invariant mass cut on the ϕ meson is taken into account.

3.2 Branching ratio

The measurement of branching ratios of B meson decays at hadron colliders is thought to be very difficult and not competitive with the results of the cleaner e^+e^- environment. The various uncertainties, like the b quark cross section, fragmentations etc. will give large errors. CDF avoided this by measuring a relative branching ratio. The branching ratio of the decay $B_s \to J/\psi\phi$ is measured by comparing it to the kinematically very similar decay $B_d \to J/\psi K^{*0}$. Subsequently, by building the ratio of branching ratios most efficiencies together with their uncertainties will cancel out. The branching ratio is then calculated as follows:

$$BR(B_s \to J/\psi\phi) = \frac{N_{B_s} \cdot \epsilon_{B_d}}{N_{B_d} \cdot \epsilon_{B_s}} \cdot BRratios$$

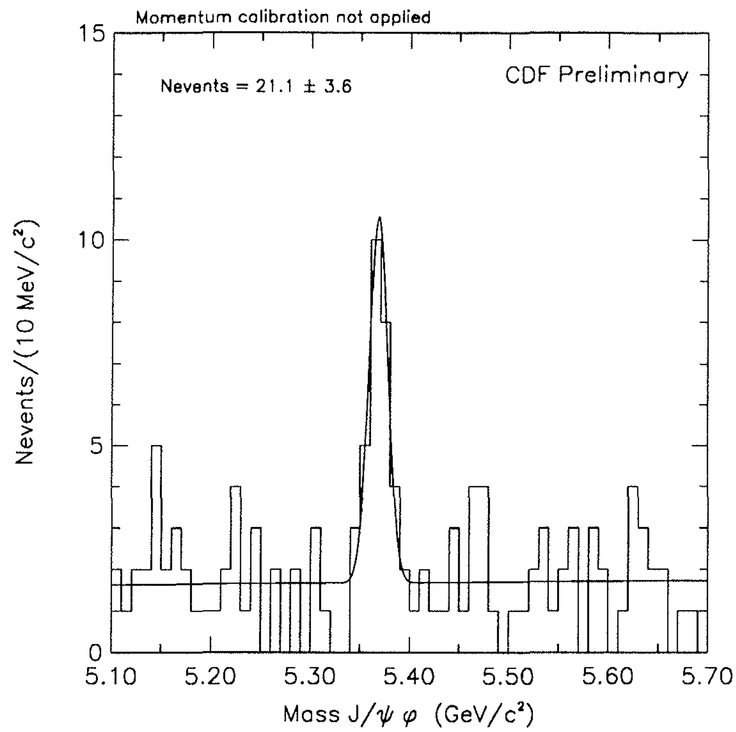
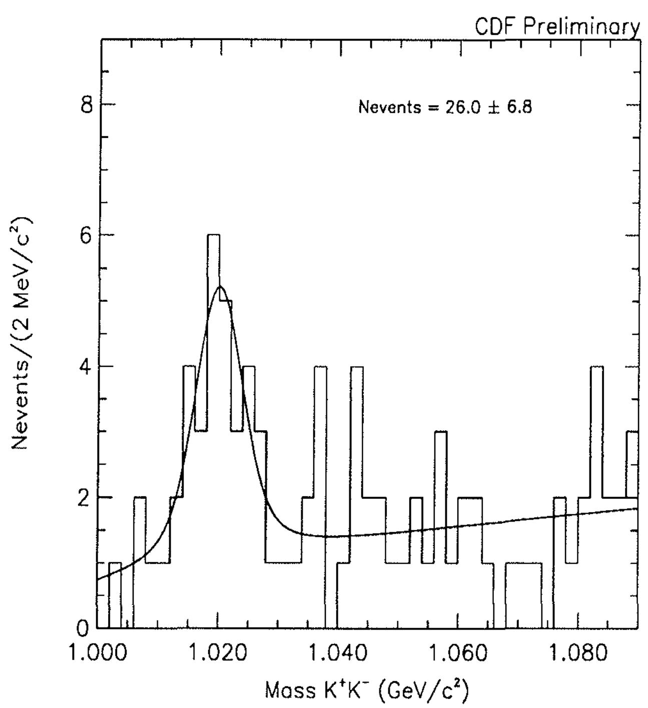


Figure 2: The invariant J/ψ ϕ mass spectrum



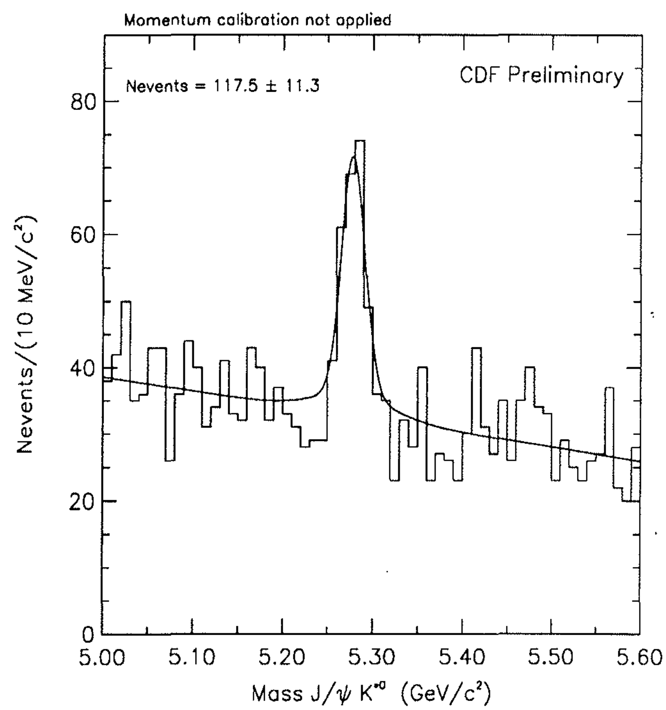


Figure 3: a) The invariant K^+K^- mass for $J/\psi K^+K^-$ combinations with invariant mass around the B_s mass. b) The $J/\psi K^{*0}$ invariant mass distribution.

with:

$$BRratios = \frac{BR(b \to B_d) \cdot BR(B_d \to J/\psi K^{*o}) \cdot BR(K^{*o} \to K^-\pi^+)}{BR(b \to B_s) \cdot BR(\phi \to K^+K^-)}$$

For the reconstruction of the B_d the same cuts were used as for the reconstruction of the B_s. Only the invariant mass window around the K^{*0} was 80 MeV/c^2 taking into account the large natural width of 50 MeV/c^2 of the K^{*0}. Figure 3b shows the invariant $J/\psi K^{*0}$ mass distribution. A B_d signal with 117 events is seen. The background in this plot is much larger than for the B_s because of the larger invariant mass cut around the K^{*0} compared to the mass cut around the ϕ.

The only efficiencies in the ratio that do not cancel out are:

- ϕ mass window cut; (84.5 ± 0.9) %.
- K^{*0} mass window cut; (80.3 ± 0.3) %.
- Efficiency of finding the second kaon before it decays; (96 ± 4) %.
- $\epsilon(B_d)/\epsilon(B_s)$ Momentum cut efficiency and acceptance; (95 ± 5) %.

The systematic error is dominated by the error on the B_d branching ratio measurement. The following table contains a summary of the systematic errors:

Two Mass window cuts	2×1%
Two Fits	2×4%
Two Prob(χ^2) vertex quality cuts	2×4%
$c\tau$ cut	2%
ϕ branching ratio	2%
Double counting in the $J/\psi K^{*o}$ case	6%
Polarization	5%
Decay in flight of kaons	4%
B_d branching ratio	24%
Total without B_d branching ratio	**13%**
Total	**27%**

The required branching ratios are taken from PDG 1992 [4], resulting in:

$$\frac{BR(B_s \to J/\psi\phi) \cdot BR(b \to B_s)}{BR(B_d \to J/\psi K^{*o}) \cdot BR(b \to B_d)} = 0.23 \pm 0.05 \pm 0.03$$

Using the B_d branching ratio as measured by the CLEO collaboration [5]:

$$BR(B_d \to J/\psi K^{*o}) = (0.156 \pm 0.034 \pm 0.017)\%$$

CDF obtains the following branching ratio:

$$BR(B_s \to J/\psi\phi) \times \frac{BR(b \to B_s)}{BR(b \to B_d)} = (3.6 \pm 0.8 \pm 1.0) \cdot 10^{-4}$$

The only remaining uncertainty is now the ratio of the fragmentation functions. From jet studies the following branching ratios are deduced: $BR(b \to B_s) = 0.15$ and $BR(b \to B_d) = 0.375$. Including these assumptions the following B_s branching ratio is obtained:

$$BR(B_s \to J/\psi\phi) = (9.0 \pm 2.0 \pm 2.5) \cdot 10^{-4}$$

No error due to the unknown fragmentation ratios is given. These fragmentation ratios, however, might be measurable by CDF in the future by comparing the semileptonic B_u, B_d and B_s decays .

3.3 Comparison with theory

This result for the branching ratio can now be compared with theoretical predictions. The branching ratios of B mesons are calculated in a factorization approach, which splits the short distance part of the decay from the long distance part.

- The short distance part consists of the weak decay of the b quark, including higher order QCD corrections. The QCD corrections can be reliably calculated in leading logarithmic approximation.
- The subsequent hadronization of the outgoing quarks is more model dependent. It involves mesonic form factors like $< 0|J_\mu|\pi >= if_\pi p_\mu$ and $< B|J_\mu|D >$. The Bauer, Stech and Wirbel model [6], for example, uses oscillator wavefunctions to calculate the latter matrix elements.

This approach has been highly successful in describing the B_u and B_d decays. Figure 4 shows the comparison of the data of the ARGUS collaboration (circles) for B_u and B_d decays with the predictions of this model (squares) [7]. The model describes the data fairly well.

A similar calculation for the B_s was done by Bijens and Hogeveen [8]. Scaling their result to the B_s lifetime as measured by the CDF collaboration ($\tau_{B_s} = 1.54 \pm 0.4$ ps) and the current value of $V_{cb} = 0.043 \pm 0.007$ [4] gives:

$$BR(B_s \to J/\psi\phi) = (12.5 \pm 5.0) \cdot 10^{-4}$$

A similar calculation by A.Deandrea et al. [9] leads to:

$$BR(B_s \to J/\psi\phi) = (17.8 \pm 7.1) \cdot 10^{-4}$$

The uncertainties in the branching ratios are due to the B_s lifetime measurement and the uncertainty in V_{cb}.

The branching ratio of the B_s decay can also be compared to the very similar decays of the B_u and B_d. The only difference is that the spectator quark is either a u, d or s quark. The measured branching ratios of these decays are [5]:

$$BR(B_d \to J/\psi K^{*\circ}) = (15.6 \pm 3.4 \pm 0.9) \cdot 10^{-4}$$

and

$$BR(B_u \to J/\psi K^{*-}) = (16.9 \pm 5.6 \pm 2.2) \cdot 10^{-4}$$

The B_s branching ratio seems to be a little bit lower than the theoretical predictions and the comparison to the similar B_u and B_d decays. However, more data is needed before one can draw any conclusions.

Figure 4: Comparison of data with the prediction of the BSW model

3.4 The B_s mass

The B_s mass so far has been determined using half of the data sample [3]. The following table gives the CDF mass in comparison with the LEP results [10]:

Experiment	Decay mode	B_s mass (MeV/c^2)
ALEPH	$\psi' \ \phi$ and $D_s \ X$	$5368.6 \pm 5.6 \pm 1.5$
DELPHI	$J/\psi \ \phi$ and $D_s \ X$	$5357 \pm 12 \pm 6$
OPAL	$J/\psi \ \phi$	5360 ± 70
CDF	$J/\psi \ \phi$	$5383.3 \pm 4.5 \pm 5.0$
Average		5373.1 ± 4.2

The mass difference between B_s and $B_{u,d}$ meson masses is then:

$$m_{B_s} - m_{B_{u,d}} = (94.5 \pm 4.6)\ \mathrm{MeV/c^2}$$

The SU(3) flavour splitting has the same magnitude as in the D meson system:

$$m_{D_s} - m_{D_{u,d}} = (99.5 \pm 0.6)\ \mathrm{MeV/c^2}$$

4 B_s lifetime measurement

Semileptonic decays of the B_s meson are partially reconstructed by identifying events with D_s^+ in association with a lepton ($B_s \rightarrow D_s^+ l^- X$). The displaced vertex of the $D_s^+ l^-$ system is used for the B_s lifetime determination. The analysis was done with 13 pb^{-1}, which is about half of currently available data. Details of the analysis can be found in [11].

The CDF result, which is in agreement with the measurements of the LEP detectors, is:

$$\tau_s = (1.54^{+0.42}_{-0.34}(stat.) \pm 0.10(sys))\ \mathrm{ps}.$$

5 Conclusions and Outlook

CDF has seen the B_s in a semileptonic mode and in the decay channel $B_s \to J/\psi\phi$. The following parameters were extracted:

- $m_{B_s} = (5383.3 \pm 4.5 \pm 5.0)$ MeV/c^2.
- $\tau_{B_s} = (1.54^{+0.42}_{-0.34}(stat.) \pm 0.10(sys.))$ ps.
- $BR(B_s \to J/\psi\phi) \times \frac{BR(b \to B_s)}{BR(b \to B_d)} = (3.6 \pm 0.8 \pm 1.0) \cdot 10^{-4}$
  or assuming a value of 0.4 for the fragmentation ratio:
  $BR(B_s \to J/\psi\phi) = (9.0 \pm 2.0 \pm 2.5) \times 10^{-4}$.

Apart from this results several studies still go on, like the search for more exclusive channels of the B_s (e.g. $B_s \to \psi'\phi$), or the determination of the helicity distribution in the decay $B_s \to J/\psi\phi$.
By the end of 1994 CDF is supposed to have quatrupeld its dataaset to 100 pb^{-1}, which will allow to study the properties of the B_s in much more detail.

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