B Spectroscopy at Tevatron

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Recent results on heavy flavor spectroscopy from the CDF and D0 experiments are reported in this contribution. Using up to 1 fb^{-1} of accumulated luminosity per experiment, properties of $X(3872)$, excited B^{**} states, and the B_c meson are measured. Also included are measurements of production rates for ground state b hadrons in $p\bar{p}$ collisions.

1. Introduction

In this paper we report the most recent results form the CDF and D0 experiments on heavy flavor spectroscopy. We start with the measurements of production fractions of ground state b hadrons in $p\bar{p}$ collisions in Sec. 2. Properties of the X(3872) are discussed in Sec. 3. Results on the B_c mesons are presented in Sec. 4. Finally, in the last two chapters the observation and measurement of masses and widths of B^{**} mesons is presented.

2. b hadron production

The process of transformation of b quarks produced in collisions into b hadrons is non-perturbative. It can not be easily calculated and has to be measured experimentally. In a recent analysis [1], CDF measures the probability of a b quark to end up as B^0, B^+, B_s or Λ_b. These probabilities are denoted as f_d, f_u, f_s and f_{Λ_b}, respectively.

Five final states are reconstructed in 360 pb^{-1} of data: ℓD^-, ℓD^0, ℓD^{*-}, ℓD_s and $\ell\Lambda_c$ where ℓ is either an electron or a muon. The invariant mass spectrum is then fit to obtain the signal yield for each signature. Two examples of such fits are shown in Fig. 1.

One of the difficulties in performing an analysis such as this is the fact that the final state does not in some cases uniquely identify the parent ground state b hadron. For example, both B^0 and B^+ can decay into the $\ell D^0 X$ final state. Therefore, the cross talk between the channels has to be taken into account. In this analysis it is assumed that the partial width into the semileptonic channels is equal for all ground state b hadrons.

The ratios of the f constants are measured. The "raw" ratios containing the branching fractions of the component decays are found to be the following:

$$\frac{f_s}{f_u+f_d} \times Br(D_s^+ \to \phi\pi^+) = (5.76 \pm 0.18(stat)^{+0.45}_{-0.42}(sys)) \times 10^{-3} ,$$

$$\frac{f_{\Lambda_b}}{f_u+f_d} \times Br(\Lambda_c^+ \to pK^-\pi^+) = (14.1 \pm 0.6(stat)^{+5.3}_{-4.4}(sys)) \times 10^{-3} ,$$

$$\frac{f_{\Lambda_b}}{f_u+f_d} \times Br(\Lambda_b^0 \to \ell\nu\Lambda_c) \times Br(\Lambda_c^+ \to pK^-\pi^+) = (12.9 \pm 0.6(stat) \pm 3.4(sys)) \times 10^{-4} .$$

From the above, using the best available values for branching fractions, CDF obtains:

$$\frac{f_u}{f_d} = 1.054 \pm 0.018(stat)^{+0.025}_{-0.045}(sys) \pm 0.058(Br) ,$$

$$\frac{f_s}{f_u+f_d} = 0.160 \pm 0.005(stat)^{+0.011}_{-0.010}(sys)^{+0.057}_{-0.034}(Br) ,$$

$$\frac{f_{\Lambda_b}}{f_u+f_d} = 0.281 \pm 0.012(stat)^{+0.058}_{-0.056}(sys)^{+0.128}_{-0.086}(Br) .$$

The ratios for the f_u and f_s agree well with the values from the LEP experiments [2], however the value of the f_{Λ_b} is currently different from the LEP result by approximately 2σ.

3. Angular analysis of the $X(3872)$

The discovery of a new particle $X(3872)$ was made by BELLE in 2003 [3]. Belle observed this particle in B decays reconstructing the $J/\psi\pi^+\pi^-$ decay channel of the X. CDF and D0 soon confirmed the discovery. The nature of the $X(3872)$ remained unclear and is not obvious from the mere observation of a bump in the $\mu^+\mu^-\pi^+\pi^-$ mass spectrum. Henceforth, the experiments capable of producing the X, and that includes BaBar in addition to the three mentioned above, embarked on the program of measuring properties of the X one by one, as the amount of reconstructed signal grew over the last years.

From Tevatron, first, came the mass measurement, then the production properties including kinematics as well as the prompt fraction have been measured which suggested similarity between the X and $\psi(2S)$ production in $p\bar{p}$ collisions [4].

One of the best approaches to figuring out the nature of the X is measuring its quantum numbers. The values of J^{PC} are the target of the latest analysis from CDF [5].

The J^{PC} is investigated by analyzing angular distributions of the decay. It turns out that the most sensitive angles to J^{PC} values are the two helicity angles $\theta_{\pi\pi}$, $\theta_{J/\psi}$ and the angle $\Delta\Phi$ between the decay planes of the $\mu\mu$ and the $\pi\pi$ systems. These angles are illustrated in Fig. 2.

In approximately 780 pb^{-1} of data approximately 3000 of the X particles are found. In order to reconstruct the angular distributions for the signal candidates, all reconstructed candidates are split into bins in three dimensions: three bins in $\Delta\Phi$, two bins in $\theta_{\pi\pi}$ and two bins in $\theta_{J/\psi}$ giving total of 3×2×2=12 bins. In each of these subsamples the invariant mass spectrum of the candidates is fit, and the signal yield is measured. The result for all 12 bins is drawn in Fig. 3.

The expected shape for the distribution is derived from theory. The amplitude is factorized according to the isobar model into the three factors for that describe the X, the J/ψ and the $\pi\pi$ systems as well as the two propagators for the J/ψ and $\pi\pi$. The angular momentum values $L = 0$ and $L = 1$ are considered for the $\pi\pi$ system. The correction to the shapes due to detector acceptance effects are applied. The shapes are derived for a variety of J^{PC} models.

For each model a χ^2-based probability of matching the 12 data points is calculated. The list of models and corresponding probabilities are found in Table I. The three best and the one least probable hypothesis are plotted over the data points in Fig. 3. It is immediately obvious that there are two possible combinations that fit the data quite well: $J^{PC} = 1^{++}$ and 2^{-+}. All others are excluded at $> 3\sigma$ level.

As the angular analysis at CDF can not distinguish between the two possibilities for the J^{PC}, one may consider examining the $\pi\pi$ invariant mass distribution. The shape of this distribution is different for the $L = 0$ case that corresponds to the 1^{++} and the $L = 1$ case corresponding to the 2^{-+}. This has been attempted by Belle [6] and the conclusion was, using a simple Breit-Wigner model, favoring 1^{++}. Later, CDF released an analysis of the dipion mass spectrum [7] using more sophisticated and generalized approach concluding that both $L = 0$ and $L = 1$ are possible. And thus, CDF results from both angular and dipion mass distributions allow either 1^{++} or 2^{-+} assignments for the $X(3872)$.

4. Properties of the B_c

Although discovered in 198 by CDF [8], the properties of the B_c remain poorly measured due to small samples of candidates available until recently. In Run II, CDF at D0 experiments have finally accumulated enough data to study the B_c in greater detail. Being the last discovered ground state B meson and the only meson with two heavy quarks of different flavor, the B_c is a great laboratory for potential models, HQET and lattice QCD. Its mass, lifetime, decay properties and production are all of interest as many precise predictions have been made by theorists.

Table I The list of hypotheses considered in the angular analysis of the X(3872) candidates as well as χ^2/probabilities from fits of the data.

hypothesis	3D χ^2 / 11 d.o.f.	χ^2 prob.
1^{++}	13.2	27.8%
2^{-+}	13.6	25.8%
1^{--}	35.1	0.02%
2^{+-}	38.9	$5.5{\cdot}10^{-5}$
1^{+-}	39.8	$3.8{\cdot}10^{-5}$
2^{--}	39.8	$3.8{\cdot}10^{-5}$
3^{+-}	39.8	$3.8{\cdot}10^{-5}$
3^{--}	41.0	$2.4{\cdot}10^{-5}$
2^{++}	43.0	$1.1{\cdot}10^{-5}$
1^{-+}	45.4	$4.1{\cdot}10^{-6}$
0^{-+}	103.6	$3.5{\cdot}10^{-17}$
0^{+-}	129.2	$\leq 1{\cdot}10^{-20}$
0^{++}	163.1	$\leq 1{\cdot}10^{-20}$

At the Tevatron, the B_c is reconstructed in several decay channels containing a J/ψ meson. It is seen in the semileptonic modes $B_c \to J/\psi e\nu X$ and $B_c \to J/\psi\mu\nu X$ by CDF, and in $B_c \to J/\psi e\mu\nu X$ by D0. The signal significance in all cases is over 5σ and the number of signal events (100+) is sufficient for a proper decay time measurement. D0 uses $J/\psi\mu$ while CDF uses $J/\psi e$ events. The measured values for the proper decay time are the following [9, 10]:

$$CDF : \tau_{B_c} = 0.474^{+0.073}_{-0.066} \pm 0.033 ps \ ,$$

$$D0 : \tau_{B_c} = 0.448^{+0.123}_{-0.096} \pm 0.121 ps \ .$$

Note, that only a fraction of available data is used by both experiments (CDF analyzed 360 pb^{-1} and D0 210 pb^{-1}), so significant improvements of the measurements are expected in near future.

The measured value agrees well with the theoretical prediction of 0.55 ± 0.15 found in [12].

In addition, CDF measures the B_c mass with high precision [11] analyzing a sample of fully reconstructed $B_c \to J/\psi\pi$ decays. In $0.8 fb^{-1}$ of data a clear peak with $> 5\sigma$ significance is seen in the invariant mass spectrum of $\mu\mu\pi$ candidates. A fit to this spectrum yields the mass measurement:

$$M(B_c) = 6275.2 \pm 4.3 \pm 2.3 MeV/c^2 \ .$$

which agrees moderately well with predictions from lattice QCD $M(B_c)_{LAT} = 6304 \pm 12^{+18}_{0} MeV/c^2$ [12].

5. Measurements of B^{**} narrow states

The spectroscopy of the $b\bar{q}$ system, where q is either u or d quark, is well understood theoretically. The HQET describes a heavy-light state and predicts that there are four P-wave states, collectively called B^{**} or B_J, see Fig. 4. It is expected that two of them, B_0^* and B_1^* are wide states as they decay via S-wave. On the other hand, the remaining to states are narrow because they decay via D-wave. The quantitative understanding is not nearly as good. Few experimental data are available on B^{**} properties. However, since recently we are starting to see progress in this area.

Both CDF and D0 seek to observe and measure the two of the B^{**} that have a narrow width, expected to be $O(10) MeV/c^2$ from theory. The other two P-wave states, the broad ones, are ignored as they are so wide that distinguishing them from combinatorial background is nearly impossible with the available data. B_1^0 decays only to $B^{*+}\pi^-$ while B_2^{*0} can decay to either $B^{*+}\pi^-$ or the ground state $B^+\pi^-$.

The analysis [13] from the D0 experiment searches for all three possible decays of the narrow states mentioned above. The final state $B^+\pi^-$ is reconstructed. The photon coming from $B^{*+} \to B^+\gamma$ decays is ignored, and leads to a shifted position of the mass peak for $B_1^0 \to B^{*+}\pi^-$ and $B_2^{*0} \to B^{*+}\pi^-$ signal events. The B^+ mesons are collected with dimuon trigger in the channel $B^+ \to J/\psi K^+$. The mass distribution of B^+ candidates for the full D0 sample (1 fb^{-1}) is shown in Fig. 5.

The mass difference $m(B\pi) - m(B)$ for the $B^+\pi^-$ candidates is shown in Fig. 6. This is the first observation of separate peaks for the narrow B^{**} states. D0 proceeds to fit this mass spectrum, assuming that the widths of the two narrow resonances are the same and fixing the mass difference between the B^* and B^+ to 45.78 MeV/c^2 [15]. The fit returns the masses and the width of these states:

$$M(B_1) = 5720.8 \pm 2.5 \pm 5.3\ MeV/c^2\ ,$$

$$M(B_2^*) - M(B_1) = 25.2 \pm 3.0 \pm 1.1\ MeV/c^2\ ,$$

$$\Gamma(B_1) = \Gamma(B_2^*) = 6.6 \pm 5.3 \pm 4.2\ MeV/c^2\ .$$

The D0 also reports the production rates for these resonances:

$$\frac{Br(b \to B_J^0 \to B\pi)}{Br(b \to B^+)} = 0.165 \pm 0.024 \pm 0.028\ ,$$

$$\frac{Br(B_2^* \to B^*\pi)}{Br(B_2^* \to B^{(*)}\pi)} = 0.513 \pm 0.092 \pm 0.115\ ,$$

$$\frac{Br(B_1 \to B^{*+}\pi)}{Br(B_J \to B^{(*)}\pi)} = 0.545 \pm 0.064 \pm 0.071\ .$$

The CDF experiment performs a similar analysis. The same three decays of the B_1^0 and B_2^{*0} are the subject of the measurement. The CDF sample of B^+ contains two signatures: $B^+ \to J/\psi K^+$ and $B^+ \to D^0\pi^+$ (see Fig. 7) where the combined yield on 374 pb^{-1} of data is order of 4000 signal candidates. The mass difference $m(B\pi) - m(B) - m(\pi)$ for the reconstructed B^{**} candidates is shown in Fig. 8. The fit of the mass spectrum is performed with the widths of both B^{**} fixed to the theoretical expectation $\Gamma = 16 \pm 6\ MeV/c^2$ [14], and the ratio $B_2^{*0} \to B^*\pi / B_2^{*0} \to B\pi$ is assumed to be 1.1 ± 0.3 [16]. The result of the fit is two mass measurements:

$$M(B_1) = 5734 \pm 3 \pm 2\ MeV/c^2\ ,$$

$$M(B_2^*) = 5738 \pm 5 \pm 1\ MeV/c^2\ .$$

6. Mass measurement of B_{s2}^{*0}

The heavy-light system $b\bar{s}$ is similar in its behavior to the $b\bar{u}$ and $b\bar{d}$ systems. As well, the HQET predicts two narrow and two wide B_s^{**} states. These are even more difficult to study because of lower production rates of B_s mesons in comparison to more common B^0 and B^+.

The D0 reports observation of a mass peak that is interpreted as B_{s2}^{*0}. Due to the isospin conservation the decays of B_s^{**} to $B_s\pi$ are highly suppressed, thus the D0 team is looking at the B^+K^- signature. In the analysis, the same sample of $B^+ \to J/\psi K^+$ events, as described in Sec. 5, is used. The invariant mass difference $m(BK) - m(B) - m(K)$ for the B_s^{**} candidates is shown in Fig. 9. A clear peak is observed with the significance over 5σ. The D0 asserts that the observed peak should be identified with the B_{s2}^{*0} (for longer discussion see [17]) and measures its mass to be

$$M(B_{s2}^{*0}) = 5839.1 \pm 1.4 \pm 1.5\ MeV/c^2\ .$$

7. Conclusions

With 1 fb^{-1} of data, many exciting results on heavy flavor physics are presently coming from the Tevatron experiments. In this paper we have seen interesting results on heavy flavor spectroscopy. CDF narrows the J^{PC} of the X(3872) down to 1^{++} and 2^{-+}. B^{**} states are now being resolved and precisely measured. The B_c properties are much more accessible than in the past. Overall, it is good time for flavor physics at the Tevatron as we are on the way to collecting multi-fb^{-1} of data.

Acknowledgments

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References

[1] CDF Collaboration, CDF Public Note 8140, "Relative B Hadron Fragmentation Fractions".
[2] D. Buskulic et al., ALEPH Collaboration, PL B**361**, 221 (1995),
P. Abreu et al., DELPHI Collaboration, PL B**298**, 199 (1992),
P. D. Acton et al., OPAL Collaboration, PL B**295**, 357 (1992).
[3] S. K. Choi et al. "Observation of a New Narrow Charmonium State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays", PRL 91, 262001 (2003).
[4] CDF Collaboration, PRL 93, 072001 2004,
D0 Collaboration, FERMILAB-Pub-04/061-E,
CDF Collaboration, CDF Public Note 7159.
[5] CDF Public Note 8201, "Analysis of the quantum numbers of the X(3872)".
[6] Belle Collaboration, hep-ex/0505038.
[7] A. Abulencia et al., "Measurement of the Dipion Mass Spectrum in $X(3872) \to J/\psi\pi\pi$ decay", PRL 96, 102002 (2006).
[8] F. Abe et al., PRL 81, 2432 (1998).
[9] CDF Collaboration, hep-ex/0603027.
[10] D0 Collaboration, D0 Public Note 4539-CONF.
[11] CDF Collaboration, CDF Public Note 8004.
[12] I. F. Allison et al., PRL 94, 172001 (2005).
[13] D0 Collaboration, D0 Public Note 5026-CONF.
[14] A. Falk et al., "Excited Heavy Mesons Beyond Leading Order in the Heavy Quark Expansion", JHU-TIPCAL-950008, hep-ph/9507311.
[15] Particle Data Group, S. Eidelman et al., PL B**592**, 1 2004.
[16] DELPHI Collaboration, DELPHI 2004-025 CONF 700.
[17] D0 Collaboration, D0 Public Note 5027-CONF.

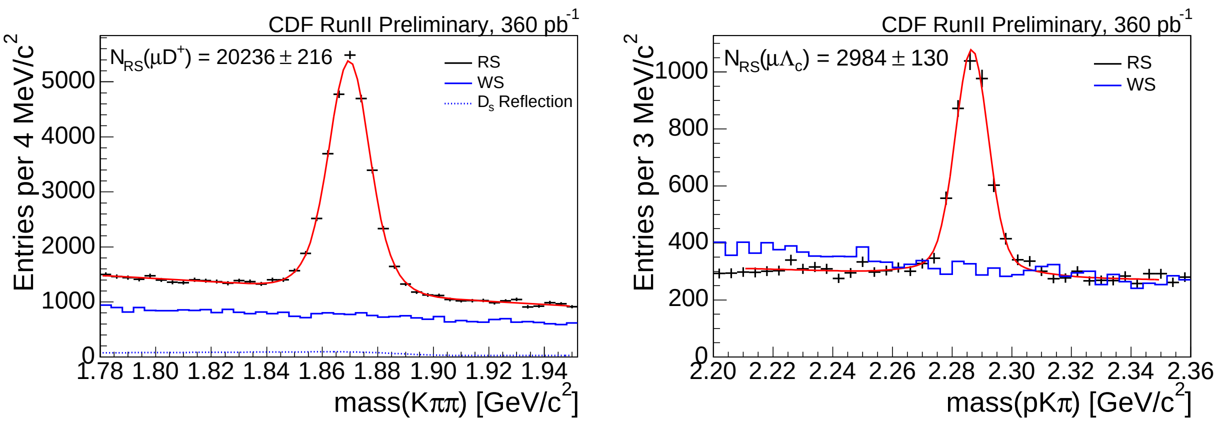

Figure 1: Mass spectra for two out of five final states used by CDF in determination of fragmentation fractions of ground state b-hadrons. The plot on the left hand side shows the $\mu D^+ X$ sample, and the plot on the right hand side shows the $\mu\Lambda_c X$ sample.

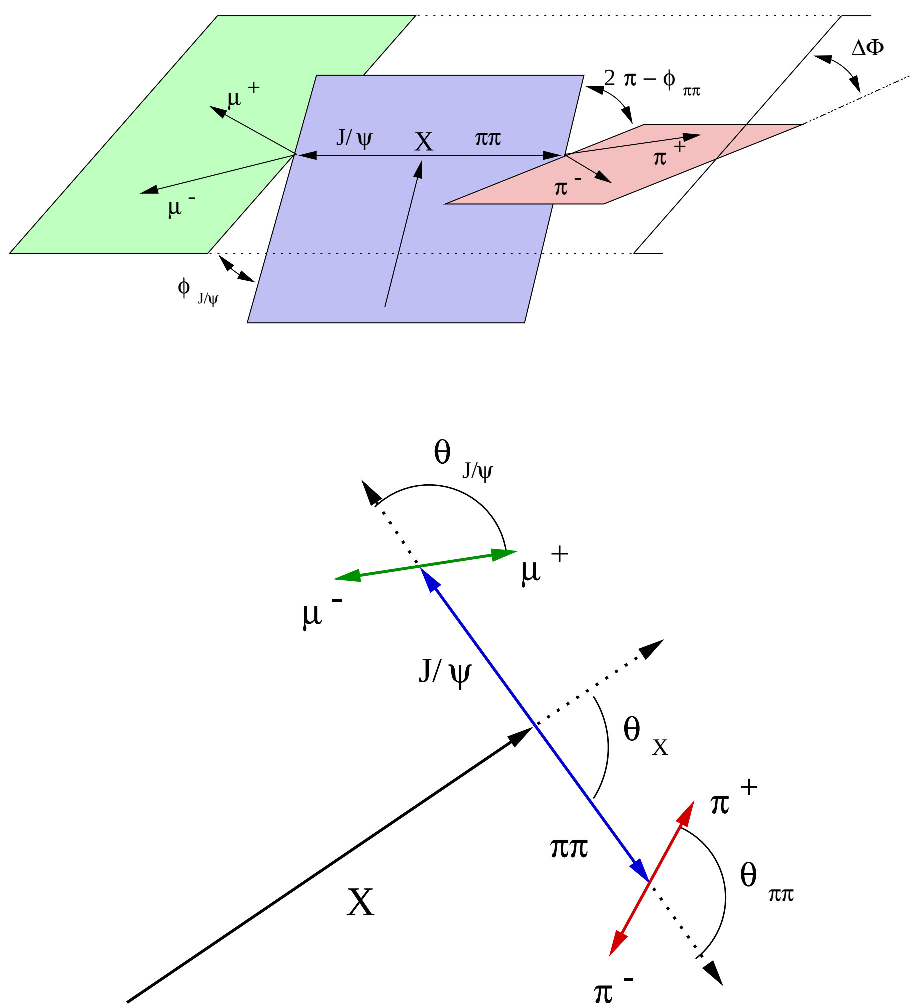

Figure 2: Definition of ϕ and θ angles for the analysis of angular decay properties of the X(3872).

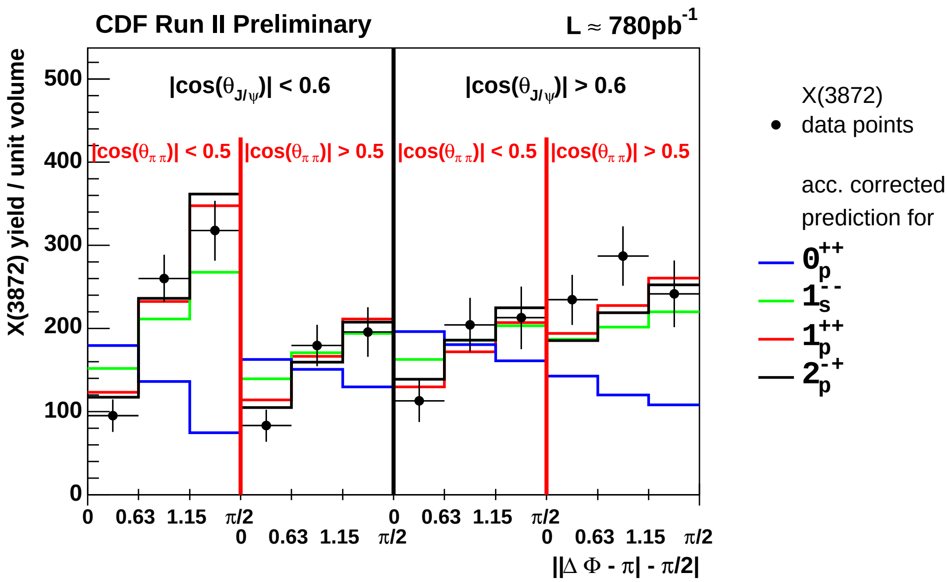

Figure 3: The number of the X(3872) signal candidates as a function of the two helicity angles and the angle between the decay planes of the $\pi\pi$ and $\mu\mu$ systems.

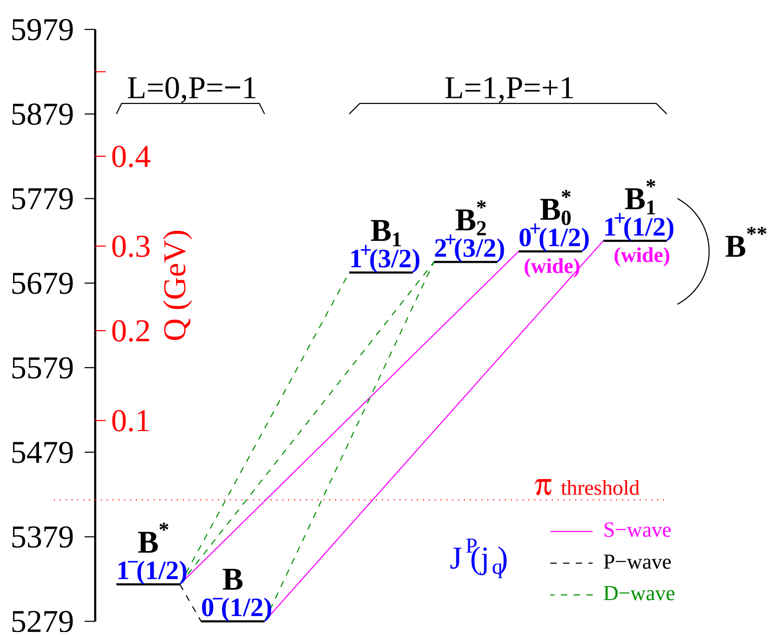

Figure 4: States of a $b\bar{q}$ system. The B, B^* and B^{**} states are shown as well as the allowed transitions.

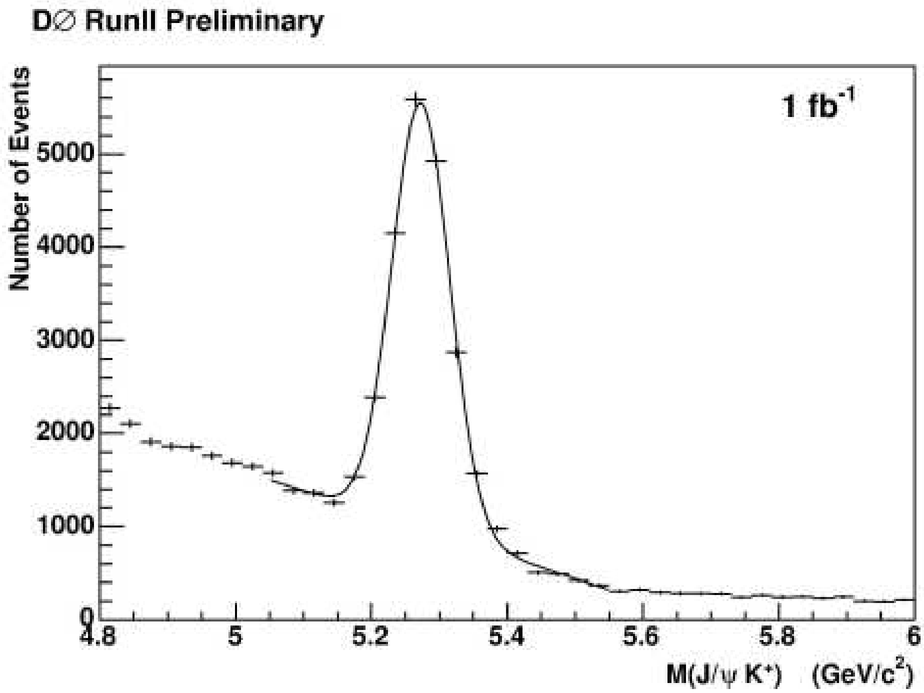

Figure 5: The $B^+ \rightarrow J/\psi K^+$ sample from D0 contains 16K of signal events and serves as the basis for all of their B^{**} measurements.

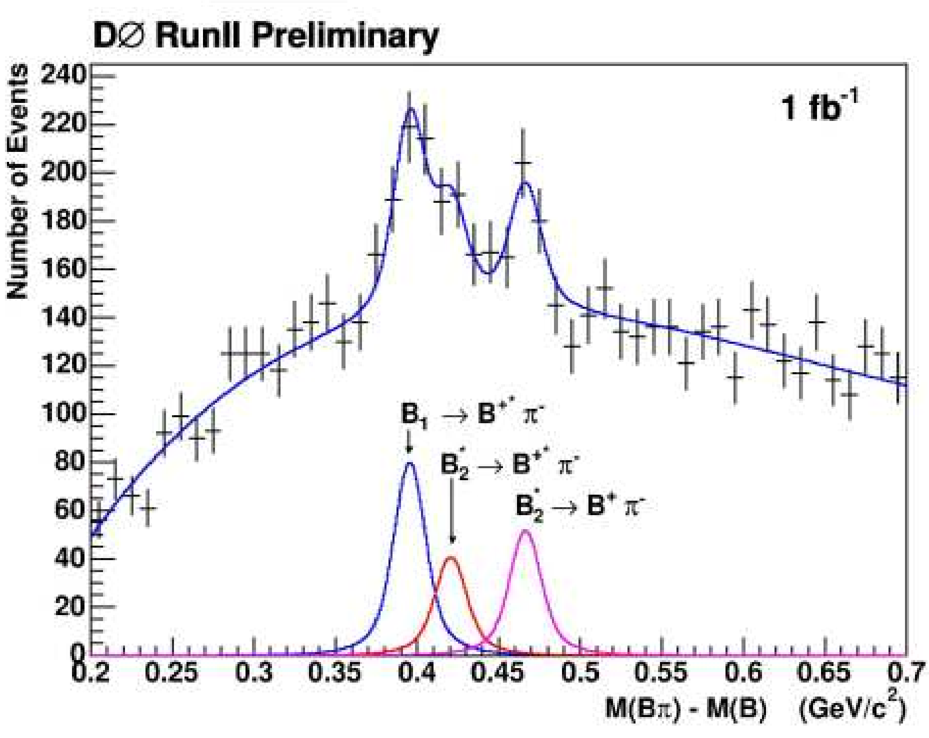

Figure 6: Invariant mass difference for the B^{**} candidates in the analysis from D0 with fit overlaid.

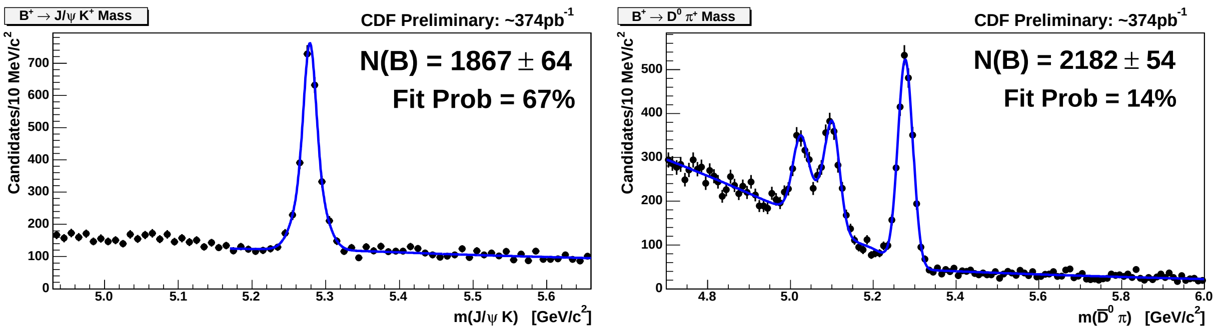

Figure 7: The $B^+ \to J/\psi K^+$ and $B^+ \to D^0\pi^+$ samples from CDF serve as the basis for all their B^{**} measurements.

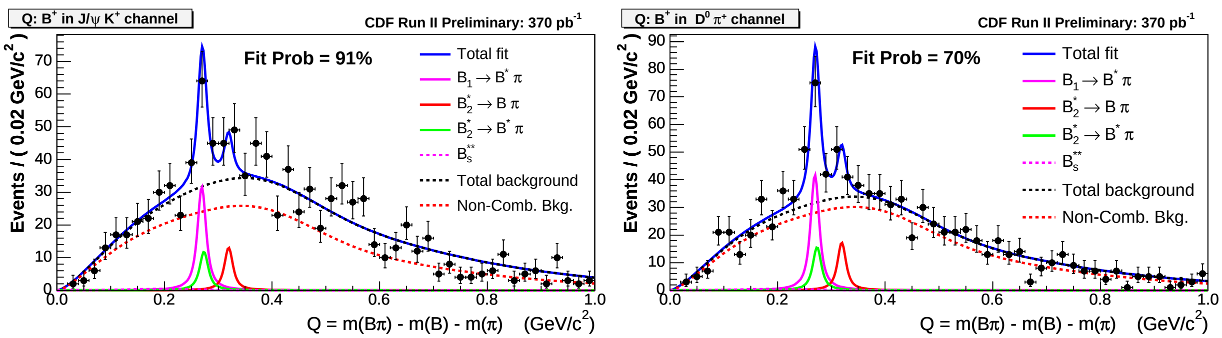

Figure 8: Invariant mass difference for the B^{**} candidates in the analysis from CDf with fit overlaid. The two plots correspond to the two B^+ samples shown in Fig. 7

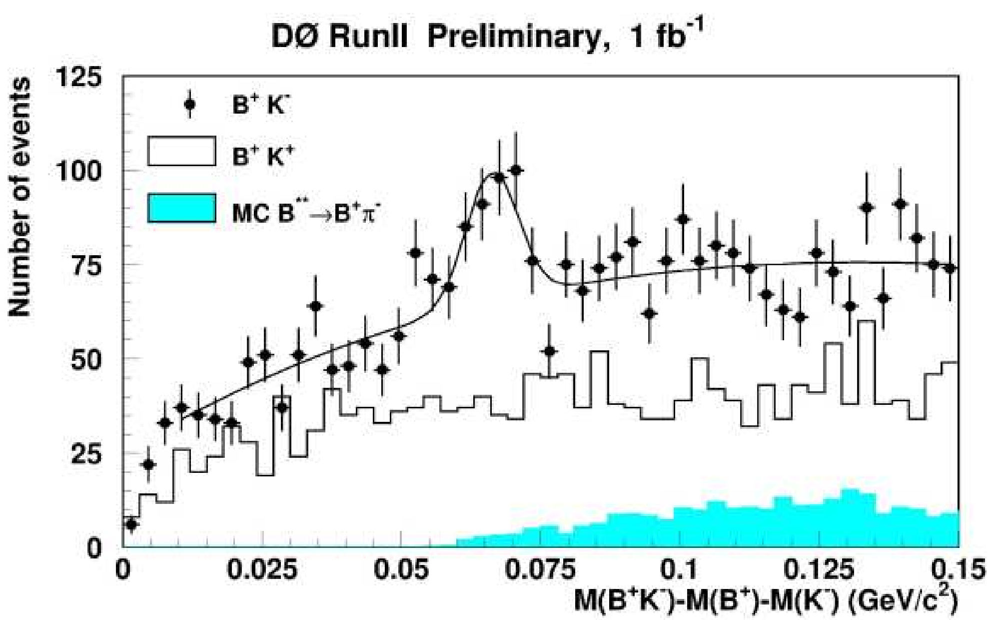

Figure 9: Invariant mass difference for the B_{s2}^{*0} candidates in the analysis from D0 with fit overlaid.