

Properties of Heavy Flavoured Hadrons at CDF

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We present recent CDF results on the properties of hadrons containing heavy quarks. These include the measurements of mass, lifetime and relative cross section of the B_c meson and an updated measurement of the B_s^0 and Λ_b^0 lifetime. We also summarize new measurements of the mass of the Σ_b baryon.

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1. Introduction

Hadrons containing bottom quarks can be classified according to their J^P quantum numbers. Among them, we find the ground state 0^- meson B_s^0 ($|bs\rangle$) and the B_c meson which contains a bottom and charm quark ($|bc\rangle$). Besides, there exist baryons containing b quarks like Λ_b^0 with quark content $|bdu\rangle$. Other bottom baryons are the Σ_b^- ($|bdd\rangle$) and the Σ_b^+ ($|buu\rangle$), with $J^P = 1/2^+$, plus their $3/2^+$ excited states Σ_b^{*-} ($|bdd\rangle$) and Σ_b^{*+} ($|buu\rangle$). All are considered as heavy hadrons in this paper. By properties we will touch lifetimes, masses as well as cross sections. The interaction between a b quark and the other quark(s) in a B hadron is based on the strong interaction or Quantum Chromodynamics (QCD). It is often stated that heavy quark hadrons are the hydrogen atom of QCD. The study of B hadron states is the study of (non-perturbative) QCD, providing sensitive test of potential models, heavy quark effective theory (HQET) and all aspects of QCD, including lattice gauge calculations. Thus measurements of B hadron lifetimes study the interplay between the strong and weak interaction and test the validity of HQE and the hierarchy of the B hadrons. The HQE technique is also used to supply input for the extraccion of elements of the Cabibbo-Kobayashi-Maskawa(CKM) quark mixing matrix [1, 2].

The Fermilab Tevatron Collider is currently the most copious source of B hadrons, thanks to the large $b\bar{b}$ production cross-section in 1.96 TeV $p\bar{p}$ collisions. With the statistics expected before the start-up of the Large Hadron Collider (6 fb^{-1} by the end of 2009, 8 fb^{-1} by the end of 2010) the Fermilab b Physics program allows for a wide range of measurements that are competitive or complementary with B -factories. We summarize here some of the recent experimental progress in the measurements related to heavy quark hadron properties. Precise microvertex detectors and online triggering of tracks from long-lived particles are good examples of the experimental techniques that make all these results possible.

2. The CDF detector

The CDF detector is a large multipurpose solenoidal magnetic spectrometer surrounded by 4π calorimetry and muon filters. It is axially and azimuthally symmetric around the interaction point. CDF features very precise tracking that provides excellent mass resolution and has strong particle identification capabilities. Additional details of the detector can be found elsewhere [3]. The elements of the CDF detector most relevant for b Physics analysis are the tracker, the particle identification detectors and the muon system. The CDF tracker is located within a 14.1 kG solenoidal magnetic field and it is composed of silicon detectors [4] surrounded by a drift chamber, COT [5]. The achieved performance of the integrated CDF tracker is a transverse momentum resolution $\sigma(p_t)/p_t^2 = 0.15\% (\text{GeV}/c)^{-1}$ and an impact parameter resolution $\sigma(d) = 35 \mu\text{m} @ 2 \text{ GeV}/c$. The CDF central muon detector [6] is located around the outside of the central calorimeter, which is 5.5 interaction lengths thick, at a radius of 347 cm from the beam axis. The pseudorapidity coverage of the muon detector is $|\eta| < 1$.

3. The CDF Trigger

At the Tevatron, B hadrons are mostly produced in pairs. The main $b\bar{b}$ production mechanism is flavor creation through gluon fusion. The $b\bar{b}$ production cross section of $\approx 30 \mu\text{b}$ [7]

is large compared to B -factories which enables rich b Physics programs at the Tevatron. However, the Tevatron cross section is orders of magnitude smaller than the total inelastic cross section of ≈ 50 mb. For this reason, CDF employs triggers that select events with signatures specific to various B decays. Thus, the trigger system is probably the single most important ingredient to pursue an effective b Physics program at the Tevatron. CDF has a multi-stage trigger organized in three Levels. The CDF experiment triggers on final states containing single or di-leptons to select high statistics samples of b -hadron decays. Semileptonic $B \rightarrow l\nu_l X$ plus charmonium $B \rightarrow J/\psi X \rightarrow [l^+l^-]X$ decays are of the order of 20% of the B meson widths. In addition CDF has a special trigger (hadronic trigger) to select events based upon track impact parameter (the minimum distance between the track and the beam), called SVT [8]. It is basically a trigger on events containing tracks originated in a vertex displaced from the primary. These events are enriched of heavy flavor contents, thanks to the higher mean-valued lifetimes of B hadrons.

4. The Physics Program on heavy quark hadron properties

4.1 B_c^\pm mass, lifetime and cross section

A recent update of the B_c^\pm mass [9] and lifetime [10] measurements with (4.7 fb^{-1}) is on progress. This new update keeps the same analysis framework but uses improved track parameter uncertainties with respect to previous results.

Results of the ratio of the production cross section times branching fraction of in $B_c^\pm \rightarrow J/\psi \mu^\pm \nu$ relative to $B^\pm \rightarrow J/\psi K^\pm$ for two $p_t(B)$ cuts have been presented for the first time [11]. The sources of background are the following: misidentified J/ψ , misidentified muon background with the doubly misidentified background subtracted, the contribution from muons of the other b in the event ($b\bar{b}$ background) and the contribution from the other decay modes. The ratio of the production cross section times branching fraction of in $B_c^\pm \rightarrow J/\psi \mu^\pm \nu$ relative to $B^\pm \rightarrow J/\psi K^\pm$ can be written as $N_{B_c^\pm} / N_{B^\pm} \times \epsilon_{rel}$, where N_{B^\pm} ($N_{B_c^\pm}$) is the number of observed decays $B^\pm \rightarrow J/\psi K^\pm$ ($B_c^\pm \rightarrow J/\psi \mu^\pm \nu$) respectively and ϵ_{rel} is the relative efficiency $\epsilon_{rel} = \epsilon_{B^\pm} / \epsilon_{B_c^\pm}$ obtained from simulations. The final cross section ratio is found to be 0.295 ± 0.040 (stat) $^{+0.033}_{-0.026}$ (syst) ± 0.036 (spectrum) for $p_t(B) > 4$ GeV and 0.227 ± 0.033 $^{+0.024}_{-0.017} \pm 0.014$ for $p_t(B) > 6$ GeV.

4.2 Λ_b^0 lifetime in $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$

New in 2008 is a preliminary CDF measurement of the Λ_b^0 lifetime using fully reconstructed $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ decays with $\Lambda_c^+ \rightarrow pK^+ \pi^-$ [12]. With a dataset of 1.2 fb^{-1} , CDF obtains a clean sample of about 3000 fully reconstructed signal event. From the lifetime distribution shown in Fig. 1, CDF measures $\tau(\Lambda_b^0) = (420.1 \pm 13.7 \pm 10.6) \mu\text{m}$ and reports a lifetime ratio $\tau(\Lambda_b^0)/\tau(B^0) =$

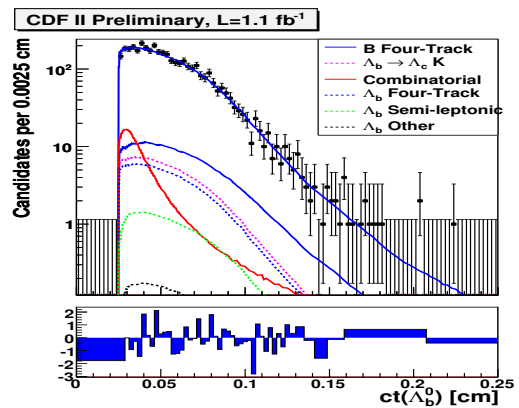


Figure 1: Λ_b^0 lifetime fit using CDF data.

0.916 ± 0.038 in good agreement with theoretical predictions. This measurement is also in good agreement with the current world average (PDG 2008).

4.3 B_s^0 lifetime

In the light of substantial width difference $\Delta\Gamma_s$, the B_s^0 system contains short- and long-lived components similar to the kaon system and various B_s^0 decay channels will have different proportions of the B_s^H and B_s^L eigenstates. Lifetime measurements of different final states have therefore different meaning and can be broken down into several categories. First, there are flavor specific decays, such as the semileptonic $B_s^0 \rightarrow D_s^- l^+ \nu$ decay and the $B_s^0 \rightarrow D_s^- \pi^+$ decay, which have equal fractions of B_s^H and B_s^L at proper time zero, from where both components will evolve with their specific lifetimes $\tau_H=1/\Gamma_H$ and $\tau_L=1/\Gamma_L$. Second, there is the CP specific measured in decays that are assumed to be either CP even or CP odd. For example, the exclusive decay $B_s^0 \rightarrow K^+ K^-$ is expected to be CP even within 5%. Finally, there are decays into a mixed CP final state where it is possible to disentangle the final state CP components. For example, an angular analysis can be used to decompose the CP components in the exclusive decay $B_s^0 \rightarrow J/\psi \phi$ [13] which is expected to be dominated by the CP even state and its lifetime.

The $B_s^0 \rightarrow J/\psi \phi$ decay is the transition of the spin-0 pseudo-scalar B_s^0 into two spin-1 vector particles. The orbital angular momenta of the vector mesons, J/ψ and ϕ , can be used to distinguish the CP even S-wave ($L=0$) and D-wave ($L=2$) final states from the CP odd P-wave ($L=1$) final state. Typically the set of decay angles $\rho=(\cos\theta_T, \phi_T, \cos\psi_T)$ defined in the transversity basis (see e.g. ref. [14]) is used to disentangle the CP mixture of the $J/\psi \phi$ final state. Such an angular decomposition reveals that the decay is dominated by the CP even state. CDF finds $3166 \pm 56 B_s^0$ signal events in 2.8 fb^{-1} of data. With these events we measure a mean B_s^0 lifetime $\tau_s=2/(\Gamma_L+\Gamma_H)=(1.53 \pm 0.04 \pm 0.01) \text{ ps}$. As can be seen in the lifetime distributions of Fig. 2, the lifetime distribution is mainly CP even while the CP odd component is much smaller.

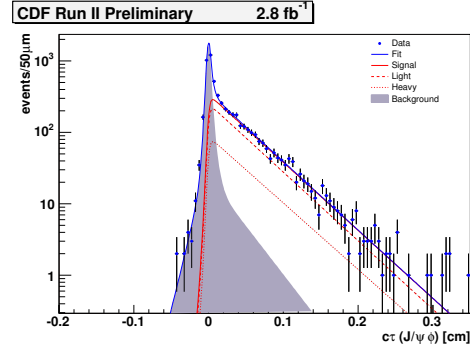


Figure 2: B_s^0 lifetime fit using CDF data.

4.4 Σ_b and Σ_b^* baryons [15]

Until recently only one bottom baryon, the Λ_b^0 , has been directly observed. The $\Sigma_b^{(*)}$ baryon has quark content $\Sigma_b^{(*)+} = |buu\rangle$ and $\Sigma_b^{(*)-} = |bdd\rangle$. In the Σ -type ground state, the light di-quark system has isospin $I = 1$ and $J^P = 1^+$. Together with the heavy quark, this leads to a doublet of baryons with $J^P = 1/2^+$ (Σ_b) and $J^P = 3/2^+$ (Σ_b^*). The ground state Σ -type baryons decay strongly to Λ -type baryons by emitting pions. In the limit $m_Q \rightarrow \infty$ the spin doublet Σ_b, Σ_b^* would be exactly degenerate since an infinitely heavy quark does not have a spin interaction with a light di-quark

system. As the heavy quark is not infinitely massive, there will be a small mass splitting between the doublet states resulting in an additional isospin splitting between the $\Sigma_b^{(*)-}$ and $\Sigma_b^{(*)+}$ states [16]. There exist a number of predictions for the masses and isospin splittings of these states using HQET, non-relativistic and relativistic potential models, $1/N_c$ expansion, sum rules and lattice QCD calculations [16, 17].

The CDF collaboration has accumulated a large data sample of Λ_b^0 baryons using the CDF SVT and the di-muon triggers. Using a 1.1 (3.8 fb⁻¹) data set of fully reconstructed $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ ($\Lambda_b^0 \rightarrow J/\psi \Lambda$) candidates, CDF searches for the decay $\Sigma_b^{*\pm} \rightarrow \Lambda_b^0 \pi^\pm$. The CDF analysis reconstructs a Λ_b^0 yield of approximately 2800 (1600) candidates in the signal region $m(\Lambda_b^0) \in [5.565, 5.670]$ GeV/c². To separate out the resolution on the mass of each Λ_b^0 candidate, CDF searches for narrow resonances in the mass difference distribution of $Q = m(\Lambda_b^0 \pi) - m(\Lambda_b^0) - m(\pi)$. Unless explicitly stated, $\Sigma_b^{(*)}$ refers to both the $J^P = 1/2^+$ (Σ_b^\pm) and $J^P = 3/2^+$ ($\Sigma_b^{(*)\pm}$) states while the analysis distinguishes between $\Sigma_b^{(*)-}$ and $\Sigma_b^{(*)+}$. There is no transverse momentum cut applied to the pion from the $\Sigma_b^{(*)}$ decay, since these tracks are expected to be very soft. The result of the $\Sigma_b^{(*)}$ search in the $\Lambda_b^0 \pi^+$ and $\Lambda_b^0 \pi^-$ subsamples is displayed in Figs. 3 and 4.

The top plot of Fig.3 shows the $\Lambda_b^0 \pi^+$ subsample, which contains $\Sigma_b^{(*)+}$, while the bottom plots shows the $\Lambda_b^0 \pi^-$ subsample, which contains $\Sigma_b^{(*)-}$. The signal fit is overlaid. A more than 5 σ with respect to no signal was found (the results can be found in [15]). Fig. 4 shows $\Lambda_b^0 \pi^+$ (top) and $\Lambda_b^0 \pi^-$ (bottom) for the $\Lambda_b^0 \rightarrow J/\psi \Lambda$ decay. The location of the peaks seems to be consistent with Fig. 3. The peculiarity of Fig. 4 is that the $\Lambda_b^0 \rightarrow J/\psi \Lambda$ decay is trigger unbiased and can be used to test the strong decay of Σ_b .

5. Conclusions

In this paper we have reviewed CDF results concerning properties of heavy quark hadrons. The CDF collaboration is very active in this area. The broad physics program includes measurements of mass, lifetime and cross section of B_c^\pm meson, lifetime measurements of B_s^0 and Λ_b^0 and finally the

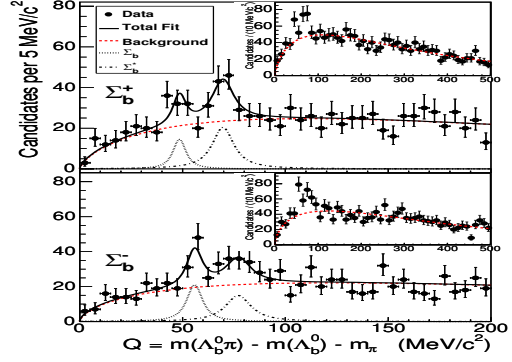


Figure 3: Q for $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ decay.

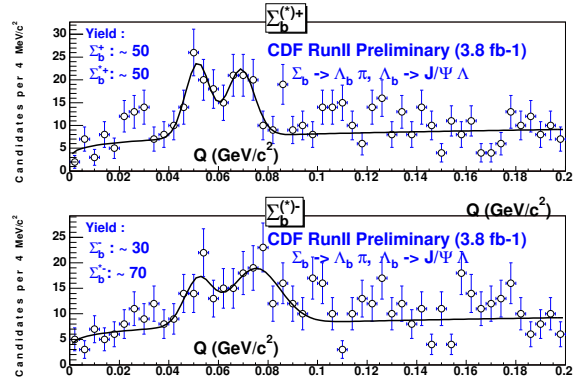


Figure 4: Q for $\Lambda_b^0 \rightarrow J/\psi \Lambda$ decay.

establishment of the $\Sigma_b^{(*)}$ states. We expect more results from the Tevatron which will accumulate more data until the end of Run II currently scheduled to conclude in 2010.

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