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CDF Results on Heavy Quarks

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Some recent CDF results on heavy quarks (mainly b) are presented, including baryon masses and lifetimes, CP violation in charmless baryon decays, B_c production, $A_{FB}(b\bar{b})$ at high $m(b\bar{b})$, and excited B mesons.

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1. Introduction

Precise vertex detection has enabled the CDF Detector at Fermilab to study a number of properties of mesons and baryons containing heavy quarks. This talk is a report on some of the most recent CDF results, primarily on bottom (b) quarks. All results are based on the full Run II (2001-2011) delivered sample of 12 fb^{-1}; recorded totals range from 8.7 to 9.6 fb^{-1}.

2. Baryon masses and lifetimes [1]

A $\mu^+\mu^-$ trigger ($p_T(\mu) > 1.5$ GeV/c) selects events with J/ψ, giving a sample unbiased with respect to b-hadron decay time, while a displaced two-track trigger, biased in favor of long decay times, selects events with b (and charm) decays. In the dimuon trigger, tracks in the outer μ chambers of CDF are matched with those in the central tracker. In the two-track trigger, drift chamber tracks provide "roads" to an inner silicon vertex detector [2]; events are selected with flight distance greater than 200 μm from the beam.

The ground-state $J^P = 1/2^+$ baryons with one b quark consist of $\Lambda_b = bud$, $\Sigma_b^{+,0,-} = b(uu,ud,dd)$, $\Xi_b^{0,-} = bs(u,d)$, and $\Omega_b^- = bss$. Previously [3] CDF had reported the discovery of four $\Sigma_b^{(*)\pm}$ states, all with the light quarks coupled up to $J_{\rm light} = 1$. Now CDF presents updated results on $\Xi_c^{(0,+)}, \Lambda_b, \Xi_b^{(-,0)}$, and Ω_b masses and lifetimes.

To illustrate the power of good vertex detection, the (top, bottom) plots in Fig. 1 denote mass distributions for charmed hyperon candidates (before, after) the demand that the negative hyperon be tracked in the silicon detector and the impact parameter with respect to the beam line be less than 100 μm. The signal-to-noise ratio is greatly improved with the addition of the silicon information, as shown in Table 1.

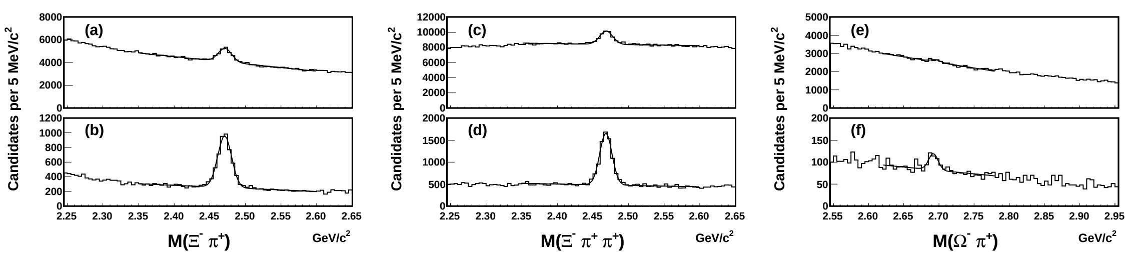

Figure 1: (a,b) Signal for $\Xi_c^0 \to \Xi^-\pi^+$ (before, after) imposition of vertex constraint; (c,d) same for $\Xi_c^0 \to \Xi^-\pi^+\pi^+$; (e,f) same for $\Omega_c \to \Omega^-\pi^+$.

Table 1: Purity of signals for some charmed baryons without and with information from silicon vertex detector.

	No silicon	With silicon
Ξ_c^0 purity	0.15 ± 0.01	0.63 ± 0.01
Ξ_c^+ purity	0.11 ± 0.01	0.61 ± 0.01
Ω_c purity	0.03 ± 0.01	0.22 ± 0.05

The Λ_b lifetime has been a long-standing problem. Theory has favored $\tau(\Lambda_b)/\tau(B^0)$ close to 1 [4, 5] while many experiments saw ratios closer to ~ 0.8. With more data and better vertex detection the observed lifetime has moved closer to theoretical predictions. The effective mass of Λ_b in the $J/\psi\Lambda$ mode has been plotted in four proper time bins and compared with reference plots for $B^+ \to J/\psi K^+$ and $B^0 \to (J/\psi K^{*0}, J/\psi K^0_S)$ which yield meson lifetimes within 1% or better of world averages.

Lifetimes of singly- and doubly-strange b-flavored baryons have also been measured by CDF. The corresponding mass distributions are shown in Figs. 2 and 3.

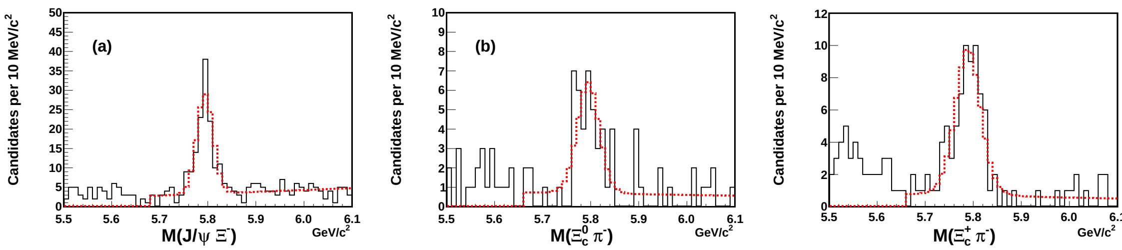

Figure 2: Signals for $\Xi_b^- \to J/\psi\Xi^-$ (left); $\Xi_b^- \to \Xi_c^0\pi^-$ (middle); $\Xi_b^0 \to \Xi_c^+\pi^-$ (right). Solid black curves denote data; dotted red curves are fits.

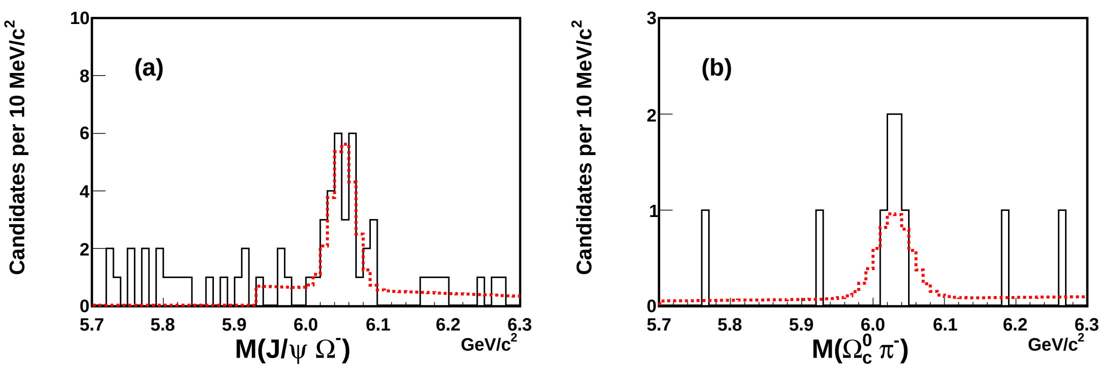

Figure 3: Signals for $\Omega_b^- \to J/\psi\Omega^-$ (left); $\Omega_b^- \to \Omega_c^0\pi^-$ (right). Curves as in Fig. 2.

The masses obtained by CDF in these channels (as well as some charmed-strange baryon masses) are shown in Table 2, while lifetimes are shown in Table 3. For reference, $\tau(B^0) = 1.519 \pm 0.005$ ps [6], while CDF and LHCb obtain $\tau(\Lambda_b)/\tau(B^0) = 1.021 \pm 0.024 \pm 0.013$ and $0.974 \pm 0.006 \pm 0.004$, respectively. A ratio within 1% of 1 is implied by the treatment of Ref. [4], while Ref. [5] finds 0.935 ± 0.054.

3. CP violation in charmless baryon decays

The signal for $\Lambda_b \to h^+h^-$ is a composite of contributions, as shown in Fig. 4. When plotted as if all charged particles are pions, it leads to displaced peaks when $h \neq \pi$. The ratio of branching fractions $\mathscr{B}(\Lambda_b \to p\pi^-)/\mathscr{B}(\Lambda_b \to pK^-)$ as measured by CDF and LHCb differs from that in

Table 2: Masses of charmed and b-flavored baryons.

Baryon	Mass (MeV/c^2) [1]	PDG 2012 [7]	Pred. [8]
Ξ_c^0	$2470.85 \pm 0.24 \pm 0.55$	$2470.88^{+0.34}_{-0.88}$	Input
Ξ_c^+	$2468.00 \pm 0.18 \pm 0.51$	$2467.8^{+0.4}_{-0.6}$	Input
Λ_b	$5620.15 \pm 0.31 \pm 0.47$	5619.4 ± 0.7	Input (vs. Λ_c)
Ξ_b^-	$5793.4 \pm 1.8 \pm 0.7$	5791.1 ± 2.2	5795 ± 5
Ξ_b^0	$5788.7 \pm 4.3 \pm 1.4$	5788 ± 5	(Chg. avg.)
Ω_b^-	$6047.5 \pm 3.8 \pm 0.6$	$(D0 \neq CDF)$	6052.1 ± 5.6
$M(\Xi_c^0) - M(\Xi_c^+)$	$2.85 \pm 0.30 \pm 0.04$	$3.1^{+0.4}_{-0.5}$	–
$M(\Xi_b^-) - M(\Xi_b^0)$	$4.7 \pm 4.7 \pm 0.7$	3 ± 6	6.24 ± 0.21

Table 3: Lifetimes of b-flavored baryons.

Baryon	CDF (ps) [1]	LHCb (ps) [9]
Λ_b	$1.565 \pm 0.035 \pm 0.020$	$1.468 \pm 0.009 \pm 0.008$
Ξ_b^-	$1.36 \pm 0.15 \pm 0.02$	$1.53^{+0.10}_{-0.09} \pm 0.03$
Ω_b^-	$1.66^{+0.53}_{-0.40} \pm 0.02$	$1.54^{+0.26}_{-0.31} \pm 0.05$

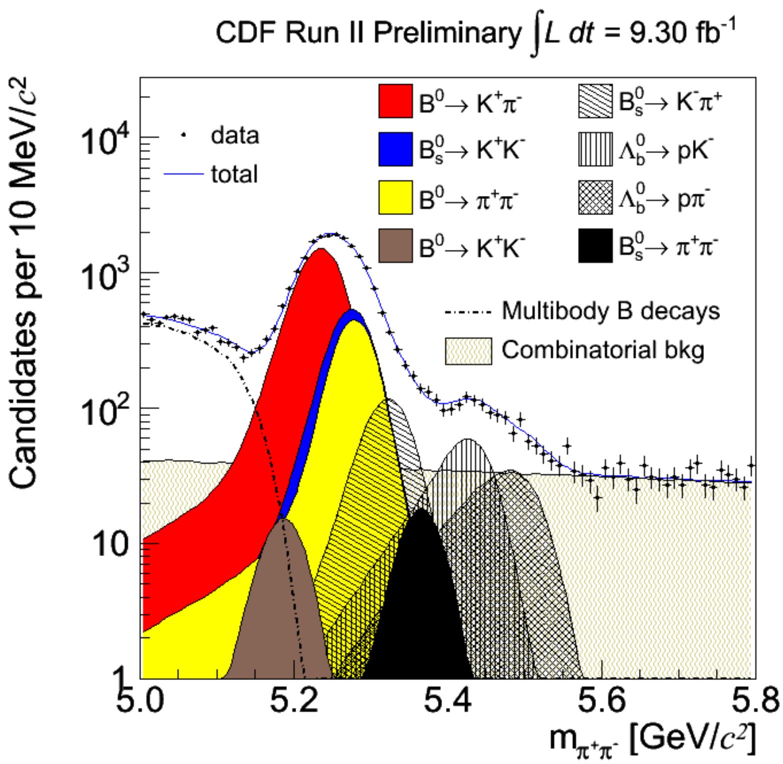

Figure 4: CDF spectrum of h^+h^- treating all h as π.

Table 4: Measured and predicted ratio $\mathscr{B}(\Lambda_b \to p\pi^-)/\mathscr{B}(\Lambda_b \to pK^-)$.

Source	Reference	Value
CDF	[10]	$0.66 \pm 0.14 \pm 0.08$
LHCb	[11]	$0.86 \pm 0.08 \pm 0.05$
pQCD	[12]	$2.6^{+2.0}_{-0.5}$

Table 5: CP asymmetry results from CDF [14].

Decay	$\mathscr{N}_{b\to f}$	$\mathscr{N}_{\bar{b}\to \bar{f}}$	$\mathscr{A}(b \to f)(\%)$
$B^0 \to K^+\pi^-$	5313 ± 109	6348 ± 117	$-8.3 \pm 1.3 \pm 0.4$
$B^0_s \to K^-\pi^+$	560 ± 51	354 ± 46	$+22 \pm 7 \pm 2$
$\Lambda^0_b \to p\pi^-$	242 ± 24	206 ± 23	$+6 \pm 7 \pm 3$
$\Lambda^0_b \to pK^-$	271 ± 30	324 ± 31	$-10 \pm 8 \pm 4$

one pQCD calculation (Table 4) which may underestimate penguin-dominated processes such as $\Lambda_b \to pK^-$ [13]. Other decays which might be penguin-dominated are $\Lambda_b \to \pi^\pm\Sigma^\mp$ and $\Lambda_b \to K\Xi$.

CDF's new results on CP violation [14] are shown in Table 5. The ratio of the first two asymmetries is as predicted by U-spin [15]. The difference between the last two asymmetries is measured to be (16 ± 12)%, to be compared with a pQCD prediction [12] of –26%.

4. B_c production

The CDF collaboration has measured $\sigma(p\bar{p} \to B_c + X)\mathscr{B}(B_c \to J/\psi\mu\nu)/\sigma(p\bar{p} \to B^+ + X)\mathscr{B}(B^+ \to J/\psi K^+)$ [16], with the B^+ decay as a normalization. The B_c decay invoves a missing neutrino, so the signal region is taken as $4 \leq M(J/\psi\mu) \leq 6$ GeV/c^2. Backgrounds include misidentified J/ψ plus a third muon (accounted for using J/ψ sidebands), $b\bar{b}$ giving rise to leptons, and modes involving $\psi(2S), \tau, \ldots$. The fitted $M(J/\psi\mu^+)$ spectrum is shown in Fig. 5. The turquoise histogram labeled "B_c Monte Carlo" is the fit to the $B_c \to J/\psi\mu^+\mu$ signal, with Monte Carlo shape. The results of this fit (and a corresponding one for $B^+ \to J/\psi K^+$) are shown in Table 6.

Table 6: Results of fits to $B_c \to J/\psi\mu^+\mu$ and $B^+ \to J/\psi K^+$

Quantity	Value
$N(B^+_c \to J/\psi\mu^+\nu)$	$739.5 \pm 39.6^{+19.8}_{-23.9}$
$N(B^+ \to J/\psi K^+)$	14338 ± 125 (stat. only)
Relative efficiency	$4.093 \pm 0.038^{+0.401}_{-0.359}$
$\frac{\sigma(B^+_c)*\mathscr{B}(B^+_c \to J/\psi\mu^+\nu)}{\sigma(B^+)*\mathscr{B}(B^+ \to J/\psi K^+)}$	$0.211 \pm 0.012^{+0.021}_{-0.020}$

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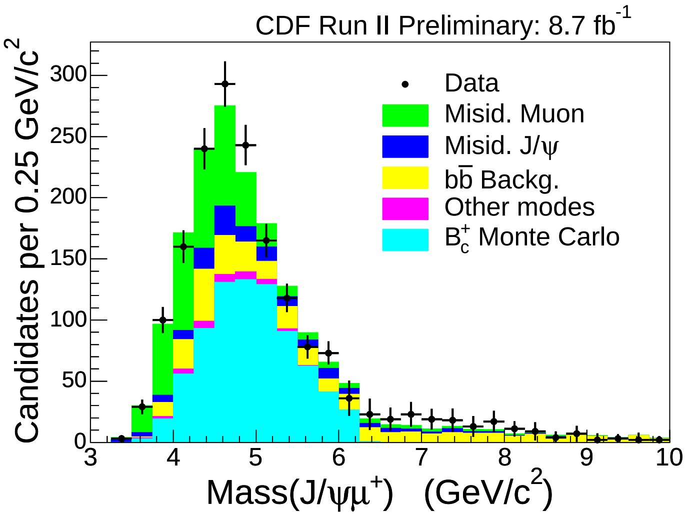

Figure 5: $M(J/\psi\mu^+)$ spectrum including signal for $B_c \to J/\psi\mu^+\nu$ and background contributions.

5. $A_{FB}(b\bar{b})$ at high $m(b\bar{b})$

The larger-than-expected A_{FB} in Tevatron top quark pair production [17] raises the question of whether $A_{FB}(b\bar{b})$ is observable. A proposed "string-drag" mechanism [18] gives too small an effect for $t\bar{t}$ production. An "axigluon" of mass 200 GeV/c^2 is one proposal [19] to account for the $t\bar{t}$ data. The corresponding asymmetry in $q\bar{q} \to b\bar{b}$ is best probed at high $M(b\bar{b})$. Expectations for this asymmetry in the standard model include that of Ref. [20], quoted in Fig. 6 along with the CDF results [21]. The CDF values of $A_{FB}(b\bar{b})$ are consistent with the standard model and with a 345 GeV/c^2 axigluon but not with a 200 GeV/c^2 axigluon.

6. Excited b mesons

CDF has measured the masses of orbitally-excited B mesons and presented evidence for a new state decaying to $B\pi$ at 5970 MeV, as shown in Table 7 [22]. The first six decays in Table 7 are most likely dominated by D-waves, accounting for the relative narrowness of these candidates for $L = 1$ $\bar{b}d$, $\bar{b}u$, and $\bar{b}s$ states. The spectra on which these measurements are based are shown in Fig. 7. In each of these figures, contributions to fits are listed in order of increasing Q-value.

Predicted B_1 masses range from 5700 to 5800 MeV/c^2, with B_2^* 5 to 20 MeV/c^2 higher. Predicted B_{s1} masses range from 5800 to 5900 MeV/c^2, with B_{s2}^* 10 to 20 MeV/c^2 higher. An unquenched lattice gauge theory calculation [23] gives $M(B_{s1,2*}) = (5889 \pm 52, 5901 \pm 52)$ MeV/c^2.

7. Conclusions

CDF has demonstrated unique capabilities for studying b physics. Baryon masses and lifetimes agree with standard model predictions. Charmless b baryon decays show no CP violation (yet!). The cross section times branching ratio for B_c production and decay to $J/\psi\mu\nu$ has been measured.

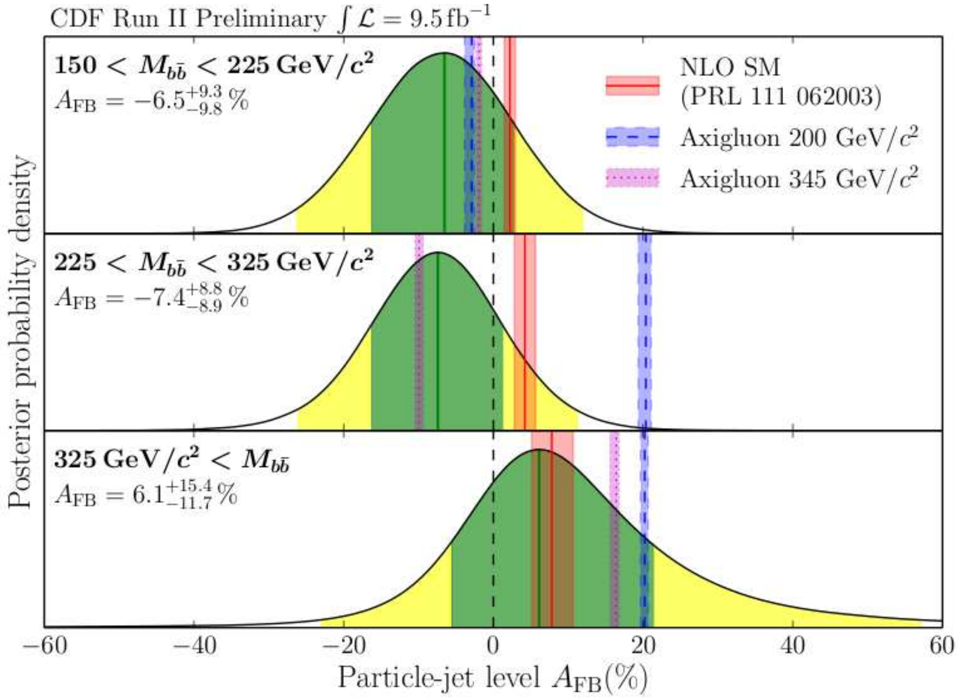

Figure 6: CDF results on $A_{FB}(b\bar{b})$ for three $M_{b\bar{b}}$ intervals. Pink bands: predictions of Ref. [20].

Table 7: Masses and widths of excited B mesons reported by CDF [22]. Subscripts denote total spin.

State	Mass (MeV/c^2)	Width (MeV/c^2)
B_1^0	$5726.6 \pm 0.9^{+1.1}_{-1.2} \pm 0.4$	$23 \pm 3 \pm 4$
B_2^{*0}	$5736.7 \pm 1.2^{+0.8}_{-0.9} \pm 0.2$	22^{+3+4}_{-2-5}
B_1^+	$5727 \pm 3^{+1}_{-3} \pm 2$	49^{+12+2}_{-10-13}
B_2^{*+}	$5736.9 \pm 1.2^{+0.3}_{-0.9} \pm 0.2$	11^{+4+3}_{-3-4}
B_{s1}^0	$5828.3 \pm 0.1 \pm 0.2 \pm 0.4$	$0.5 \pm 0.3 \pm 0.3$
B_{s2}^{*0}	$5839.7 \pm 0.1 \pm 0.1 \pm 0.2$	$1.4 \pm 0.4 \pm 0.4$
$B(5970)^0$	$5978 \pm 5 \pm 12$	$70^{+30}_{-20} \pm 30$
$B(5970)^+$	$5961 \pm 5 \pm 12$	$60^{+30}_{-20} \pm 40$

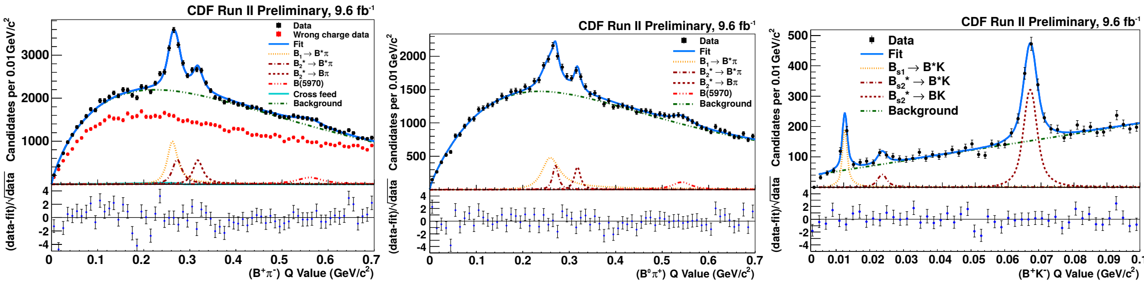

Figure 7: Q values for neutral $B\pi$ (left), charged $B\pi$ (middle), and B^+K^- (right) spectra.

The study of $A_{FB}(b\bar{b})$ has ruled out an axigluon of mass 200 GeV/c^2. CDF has measured the masses and widths of orbitally excited B mesons and observed a new state at 5970 MeV decaying to $B\pi$. All these results have exceeded expectations!

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