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Heavy flavor spectroscopy at the Tevatron

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During the last decade, the CDF and DØ experiments at the Tevatron have been pursuing an extensive heavy flavor spectroscopy program that provides significant advancements in the understanding of masses of ground state and orbitally excited b–hadrons, and phenomenology of exotic XYZ states. It also yields a breakthrough in our knowledge of bottom baryons with the first observation of the $\Sigma_b^{\pm(*)}$, Ξ_b^-, and Ω_b^- families. After briefly reviewing previous results, I will focus on the latest CDF measurements of $\Sigma_b^{\pm(*)}$ baryons and exotic $J/\psi\phi$ states, both updated to 6 fb^{-1} of data, and on a new analysis of charmed baryons.

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1. Spectroscopy at the Tevatron

The theory of strong interactions (QCD) is a pristine example of the success of quantum field theory as a paradigm to describe Nature at the microscopic level. However, when the energy regime approaches $\mathscr{O}(100)$ MeV, the theory becomes non perturbative and calculations are challenging. This prevents QCD from predicting the spectrum of the physical hadron states and their properties. And, more generally, it constrains seriously our understanding of the phenomenology of any process where soft QCD is involved, as transitions of heavy mesons sensitive to CP-violation. Numerical simulations in discretized space-time allow prediction of some quantities, and phenomenological *effective* models provide additional information by exploiting decoupling of dynamical degrees of freedom. But accurate experimental input is crucial to ensure adequate tuning of input parameters and constrain the approximations. The spectroscopy of heavy hadrons is particularly useful. It exploits the large mass difference between constituent quarks by approximating the heavy quark as a static color-field source for lighter partners, which simplifies the calculations.

The CDF and DØ experiments at the Tevatron are major contributors, owing to copious samples of all species of heavy hadrons available in $\sqrt{s} = 1.96$ TeV $\mathrm{p\bar{p}}$ collisions, well-understood triggers and detectors, and advanced analysis techniques. The experiments are similar, and focus on exclusive final states with charged particles. Since most recent result are from CDF, I only outline the CDF detector here. It is a multipurpose magnetic spectrometer surrounded by 4π calorimeters and muon detectors. Most relevant for heavy hadron spectroscopy are the tracking, particle-identification and muon detectors, and the trigger system. Six layers of double-readout silicon microstrip sensors between 2.5 and 22 cm from the beam, and a single-readout layer at 1.5 cm radius, provide precise vertex reconstruction, with approximately 15 (70) μm resolution in the azimuthal (longitudinal) direction. A drift chamber provides 96 samplings of three-dimensional charged-particles trajectories between 40 and 140 cm radii in $|\eta| < 1$, for a transverse momentum resolution of $\sigma_{p_T}/p_T^2 = 0.1\%/(\mathrm{GeV}/c)$. Specific ionization measurements allow 1.5σ separation between charged kaons (or protons) and pions, approximately constant at momenta larger than 2 GeV/c. A comparable identification is achieved at lower momenta by an array of scintillator bars at 140 cm radius, which measure the time-of flight (TOF). Muons with $p_T > 1.5(2.2)$ GeV/c are detected by planar drift chambers at $|\eta| < 0.6$ ($0.6 < |\eta| < 1.0$). Low-p_T dimuon triggers select charmonium decays, totaling approximately 40 millions J/ψ mesons in 5 fb^{-1} of data. These are used to reconstruct, for instance, 12 000 $X(3872) \to J/\psi\pi^+\pi^-$ decays. A trigger on charged particles displaced from the primary vertex collects hadronic long-lived decays reconstructing tracks in the silicon with offline-like (48 μm) impact parameter resolution, within 20 μs of the trigger latency. This yielded approximately 16 000 $\Lambda_b \to \Lambda_c^+\pi^-$ decays in 6 fb^{-1} of data.

Both experiments collected 8 fb^{-1} of physics-quality data, which will reach 10 fb^{-1} by October 2011. Additional 6 fb^{-1} will be collected if the proposed three-year extension will be funded.

Since the first Tevatron Run II publication [**?**], CDF and DØ have been steadily contributing to the understanding of heavy flavor spectroscopy. Both studied orbitally-excited mesons [**?**], observed exclusive B_c^+ decays [**?**], and studied exotic hadrons [**?**]; CDF provided the best measurements of b–hadron masses [**?**] and has evidence of a new exotic state, the $Y(4140)$ [**?**]. Both experiments extended significantly the knowledge of b–baryons, with the first observations of $\Sigma_b^{\pm(*)}$ [**?**], Ξ_b^- [**?**], and Ω_b^- [**?**] families. I report recent, world-leading results on $\Sigma_b^{\pm(*)}$ and charmed baryons

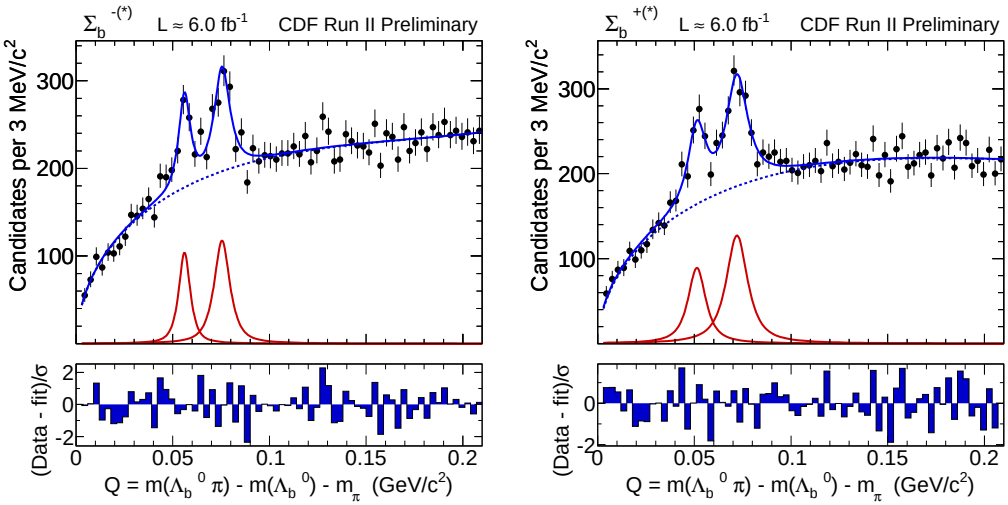

Figure 1: Q-value distributions for $\Sigma_b^{-(*)}$ (left) and $\Sigma_b^{+(*)}$ (right) candidates with fit overlaid.

properties, and an updated analysis of $J/\psi\phi$ final states in search for exotic mesons. Throughout the text, the first uncertainty is statistical, the second one is systematic, and charge-conjugate states are implied.

2. Improved measurement of $\Sigma_b^{\pm(*)}$ baryon resonance parameters

The CDF experiment reports an update of an earlier measurement of $\Sigma_b^{\pm(*)}$ (quark content *uub* or *ddb*) masses and widths using $\Sigma_b^{\pm(*)} \to \Lambda_b(\to \Lambda_c^+\pi^-)\pi^\pm$ decays followed by $\Lambda_c \to pK^-\pi^+$, fully reconstructed in 6.0 fb^{-1} of data collected by the hadronic trigger [**?**]. We reconstruct approximately 16 300 Λ_b candidates with good purity ($S/B \approx 1.8$) using the known Λ_c^+ mass as a constraint in the four-tracks fit. The long Λ_b lifetime is exploited by requiring at least two displaced tracks and the Λ_b vertex being significantly displaced from the $p\bar{p}$ vertex. The Λ_b candidates are then combined with a pion of $p_T > 0.2$ GeV/c into $\Sigma_b^{\pm(*)}$ candidates. We study the Q-value distributions, $Q = m(\Lambda_b\pi^\pm) - m(\Lambda_b) - m(\pi^\pm)$, to suppress the effects of Λ_b mass resolution (fig.**??**). We fit independently $\Sigma_b^{+(*)}$ and $\Sigma_b^{-(*)}$ distributions using a non-relativistic Breit-Wigner function with P–wave-modified width, convoluted with two Gaussian distributions for detector resolution. The background is described using a second-degree polynomial modulated by a threshold $\sqrt{(Q+m_\pi)^2 - \text{thr}}$ function. A Likelihood Ratio test (LR) against several null hypotheses yields statistical significances comfortably larger than 5.0σ. The difference in yield between $\Sigma_b^{+(*)}$ and $\Sigma_b^{-(*)}$ signals (tab. **??**, top) is due to the charge-asymmetric tracking efficiency for low-momentum particles. The limited knowledge of tracking resolutions for soft tracks dominates the systematic uncertainties. We estimated a 20% uncertainty on the widths by comparing the simulation with large samples of $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays, where the D^{*+} and $\Sigma_b^{(*)\pm}$ low-momentum pions have similar kinematics. Smaller contributions are due to tracking momentum scale, slightly biased width estimates, and the assumed models for signal and background. We determine masses with improved precision on the previous analysis (tab. **??**, top). We also provide the first measurement of widths and isospin mass splittings within I = 1 triplets, with precision

comparable with the one available for Σ_c states: $m(\Sigma_b^+) - m(\Sigma_b^-) = -4.2^{+1.1+0.07}_{-0.9-0.09}$ MeV/c^2, and $m(\Sigma_b^{*+}) - m(\Sigma_b^{*-}) = -3.0 \pm 0.9^{+0.12}_{-0.13}$ MeV/c^2.

State	Mass [MeV/c^2]	Width [MeV/c^2]	Yield
Σ_b^+	$5811.2^{+0.9}_{-0.8} \pm 1.7$	$9.2^{+3.8+1.0}_{-2.9-1.1}$	$468^{+110+18}_{-95-15}$
Σ_b^-	$5815.5^{+0.6}_{-0.5} \pm 1.7$	$4.3^{+3.1+1.0}_{-2.1-1.1}$	$333^{+93}_{-73} \pm 35$
Σ_b^{*+}	$5832.0 \pm 0.7 \pm 1.8$	$10.4^{+2.7+0.8}_{-2.2-1.2}$	$782^{+114+25}_{-103-27}$
Σ_b^{*-}	$5835.0 \pm 0.6 \pm 1.8$	$6.4^{+2.2+0.7}_{-1.8-1.1}$	$522^{+85}_{-76} \pm 29$
$\Sigma_c(2455)^{++}$	$2453.90 \pm 0.13 \pm 0.14$	$2.34 \pm 0.13 \pm 0.45$	$\approx 13\,800$
$\Sigma_c(2455)^0$	$2453.74 \pm 0.12 \pm 0.14$	$1.65 \pm 0.11 \pm 0.49$	$\approx 15\,900$
$\Sigma_c(2520)^{++}$	$2517.19 \pm 0.46 \pm 0.14$	$15.03 \pm 2.12 \pm 1.36$	$\approx 8\,800$
$\Sigma_c(2520)^0$	$2519.34 \pm 0.58 \pm 0.14$	$12.51 \pm 1.82 \pm 1.37$	$\approx 9\,000$
$\Lambda_c(2595)^+$	$2592.25 \pm 0.24 \pm 0.14$	$2.59 \pm 0.30 \pm 0.47$	$\approx 3\,500$
$\Lambda_c(2625)^+$	$2628.11 \pm 0.13 \pm 0.14$	< 0.97 at the 90% CL	$\approx 6\,200$

Table 1: Summary of baryon results.

3. Study of $\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Sigma_c(2455)^{++,0}$ and $\Sigma_c(2520)^{++,0}$ charmed baryons

In a new analysis of charmed baryons, CDF measure masses and widths of $\Lambda_c(2595)^+$, $\Lambda_c(2625)^+$, $\Sigma_c(2455)^{++,0}$ and $\Sigma_c(2520)^{++,0}$ states [**?**]. We study the largest available samples of Σ_c states in $\Lambda_c\pi$ decays, and Λ_c^{+*} in $\Lambda_c^+\pi^+\pi^-$ final states, through intermediate Σ_c resonances. Cross-contamination among channels requires careful treatment of the background because different sources populate different phase space regions. We exploit a sample of $\Lambda_c^+ \to pK^-\pi^+$ decays reconstructed in 5.2 fb^{-1} collected by the displaced track trigger. An artificial neural network classifier (NN) selects a pure subsample of approximately 55 000 Λ_c^+ decays (fig. **??**, top left) and another one optimizes the reconstruction of each signal from the Λ_c^+ candidates. Both NN are trained using data only. Masses and widths are measured through binned likelihood fits of distributions of masses subtracted by the Λ_c^+ mass, ΔM, to suppress effects of tracking resolution (fig.**??**). The $\Sigma_c(2455)^{++,0}$ and $\Sigma_c(2520)^{++,0}$ states are studied through the mass differences of $\Lambda_c^+\pi^+$ and $\Lambda_c^+\pi^-$. The distribution of $\Lambda_c^+\pi^+\pi^-$ is used for the $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$. Non-relativistic Breit-Wigner functions model the Σ_c states. For the $\Lambda_c(2595)^+$ we use a mass-dependent width to correct for the proximity of the $\Sigma_c(2455)\pi$ threshold and remove biases of the mass toward higher values [**?**]. The Breit-Wigner are convoluted with resolution functions from simulation, expanded in sum of Gaussians centered in zero with 1.6–2.6 MeV/c^2 mean widths, depending on the channel. The background is dominated by random combinations of tracks without a real Λ_c^+, which are modeled with empiric fits to the ΔM distribution of events from Λ_c^+ mass sidebands. Real Λ_c^+ combined with random tracks are modeled with polynomial functions determined by the fit. Non-resonant $\Lambda_c(2625)^+$ decays (in the Σ_c case) and real Σ_c combined with random tracks (Λ_c^{+*}) also contribute. Detector resolution at low-momentum drives the systematic uncertainties. As in the $\Sigma_b^{\pm(*)}$ case, this is constrained by using D^{*+} and $\psi(2S) \to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$ decays. Finite knowledge of the momentum scale, assumptions in the fit model and uncertainties on the external inputs to

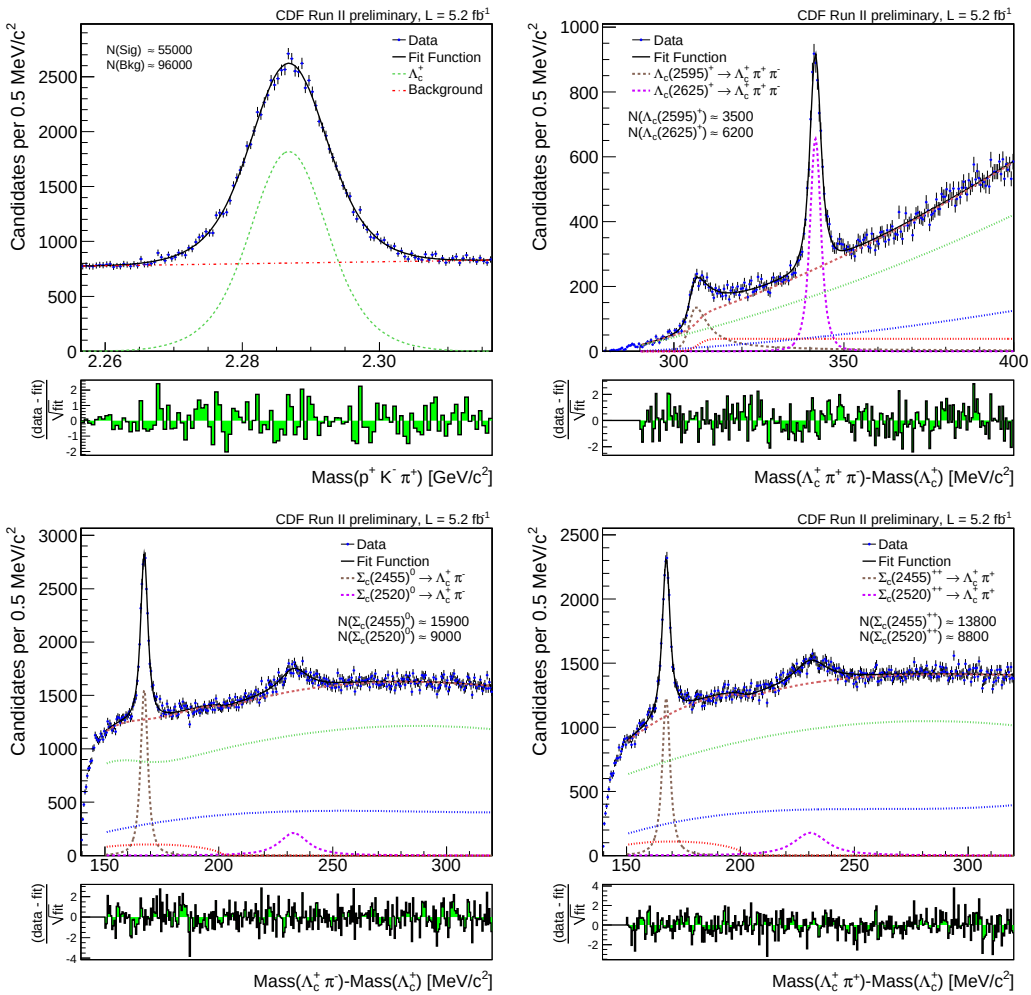

Figure 2: Mass distribution of Λ_c^+ candidates (top left). Mass difference for Λ_c^{+*} (top right) Σ_c^0 (bottom left), Σ_c^{++} (bottom right). Fit results are overlaid.

the fit add further contributions. All results (tab. **??**, bottom) agree with previous determinations except for the $\Lambda_c(2595)^+$ mass. Detailed treatment of threshold effects shifts it by 3.1 MeV/c^2 from the currently known value. We derive a 90% credibility Bayesian upper limit assuming a uniform positively-defined prior for the $\Lambda_c(2625)^+$ width because it is consistent with zero. The value $h_2^2 = 0.36 \pm 0.04 \pm 0.07$ for the squared pion decay-constant is derived from the $\Lambda_c(2595)^+$ width [**?**]. The precision of all results is comparable or superior to that of existing measurements.

4. Updated search for exotic $J/\psi\phi$ states

In 2009, CDF had an evidence for a $J/\psi\phi$ structure, dubbed $Y(4140)$, in exclusive $B^+ \to J/\psi\phi K^+$ decays reconstructed in 2.7 fb^{-1} collected by the dimuon trigger [**?**]. Belle and Babar, with lower acceptance for low-momentum charged particles, could not confirm or disprove. We report an update on 6.0 fb^{-1} with no changes in the candidate selection [**?**]. Candidates compatible with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ decays are combined with a charged particle with kaon mass

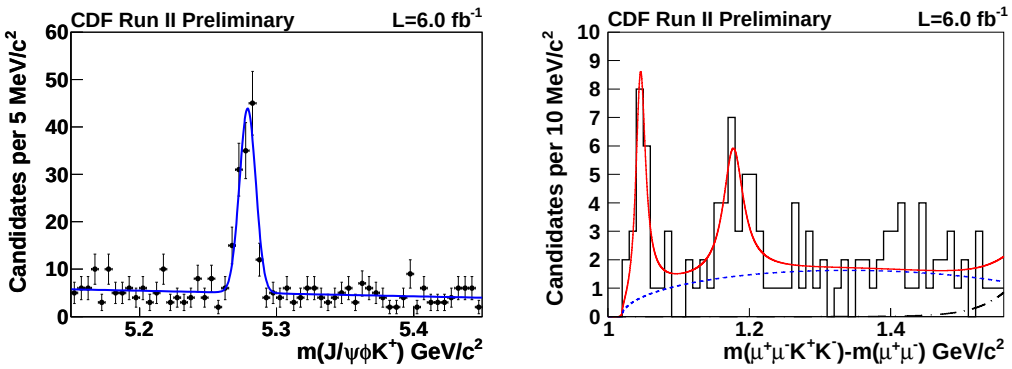

Figure 3: Distribution of $J/\psi\phi K^+$ mass (left) and Δm for events in the B^+ signal (right) with fit overlaid.

assignment in a kinematic fit to a displaced vertex. Vertex displacement and kaon identification (dE/dx and TOF) reduce the background by about five orders of magnitude. The combinatorial component is further reduced by requirements of the narrow B^+ mass window. Figure **??**, left, shows the mass spectrum where a signal of 115 ± 12 B^+ decays is visible. Despite the two-fold increase in integrated luminosity, this is only a 53% increase in signal yield over the previous analysis, because of trigger bandwidth limitation. A fit of the K^+K^- spectrum show no appreciable contribution from $f_0(980)$ or non-resonant K^+K^- decays. The $Y(4140)$ appears as a narrow near-threshold excess in the distribution of mass difference $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ (fig **??**, right). No structure is visible in the same spectrum sampled in B^+ mass sidebands. We exclude events with $\Delta m > 1.56$ GeV/c^2 to reject background from misidentified $B_s^0 \to \psi(2S)\phi \to (J/\psi\pi^+\pi^-)\phi$ decays, which are the only potential contaminants, as resulting from a simulation of all B decays with a J/ψ in the final state. We describe the enhancement as the convolution of an S-wave relativistic Breit-Wigner with a Gaussian resolution of 1.7 MeV/c^2 (from simulation) in an unbinned likelihood fit. We assume the background distributed as a three-body phase-space. We obtain a signal of 19 ± 6 ± 3 events with mass $m = 4143.4^{+2.9}_{-3.0} \pm 0.6$ MeV/c^2 and width $\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV/c^2, consistent with the previous analysis. The size of the width suggests a strong-interaction decay. The branching fraction relative to the non-resonant $B^+ \to J/\psi\ \phi K^+$ decay is $0.149 \pm 0.039 \pm 0.024$, with assumptions on the $Y(4140)$ J^{PC} quantum numbers. The significance is determined from the LR distribution in statistical trials of three-body phase space Δm distributions generated to mimic background. Only two out of ten millions trials show a structure with LR equal or higher than observed in data, corresponding to a statistical significance of 5.0σ. An additional excess appears at $\Delta m \approx 1.18$ MeV/c^2. Assuming the existence of the $Y(4140)$ and a three-body phase-space background, this enhancement is fit using a 3.0 MeV/c^2 Gaussian detector resolution. This yields a signal of 22 ± 8 signal events, located at $m = 4274.4^{+8.4}_{-6.7}$ MeV/c^2 mass, with $\Gamma = 32.3^{+21.9}_{-15.3}$ MeV/c^2 width and a significance of 3.1σ.

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