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Tevatron Results on Heavy Flavor Production and Decays

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ABSTRACT

The most recent results on heavy flavor production and decays from the Tevatron experiments CDF and D0 are summarized and compared with some LHC experiment results. The collected data sample refers to the full Tevatron run-II operation and it corresponds to about 10 fb^{-1} of integrated luminosity per experiment.

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1 Introduction

A wide heavy flavor physics program was done during the Tevatron Run II data taking thanks to the large b-hadron cross-section production, $\sigma(p\bar{p} \rightarrow b\bar{b}) \simeq 50 \mu\text{b}$ at $\sqrt{s} = 2 \text{ TeV}$, which is a factor $10^4 - 10^5$ larger than the production cross-section $\sigma(e^+e^- \rightarrow b\bar{b})$ at the B-factories [Y(4s)] active in the same decade.

All b-hadrons ($B^+, B^0, B_s, B_c, \Lambda_b, \Sigma_b, \Xi_b, \Omega_b$) are produced in $p\bar{p}$ collisions at Tevatron with production fractions $f_d : f_u : f_s : f_\Lambda \sim 4 : 4 : 1 : 1$, allowing a physics program complementary to the one of the B-Factories; however, the inelastic cross-section $\sigma(p\bar{p})_{inel.} \sim 100 \text{ mb}$ is a factor $10^3 - 10^4$ larger than $\sigma(p\bar{p} \rightarrow b\bar{b})$, and the branching ratios of rare b-hadron decays are $O(10^{-6})$ or lower; therefore, in order to efficiently reconstruct b-events, detectors need to have a very good tracking and vertex resolution, a wide acceptance and good particle identification for electrons and muons, and a highly selective trigger. The complete description of the CDF and D0 detectors can be found elsewhere [1]. Different trigger types are used at the Tevatron experiments to select events with b-hadron production; both CDF and D0 use dimuon (J/Ψ modes) triggers with $p_t(\mu) > 1.5 \text{ GeV}$, while CDF exploits also a special tool for secondary vertex reconstruction, the silicon vertex tracker (SVT) trigger, which reconstructs tracks displaced with respect to the primary vertex and having $p_t > 2 \text{ GeV}/c$ and impact parameter $d_0 > 100 \mu\text{m}$ [2]; with this trigger type fully hadronic b-decay modes can be also reconstructed.

Some recent results from the Tevatron experiments are presented here for b-hadrons; the analyzed data are relative to the full Tevatron Run II sample, corresponding to about 10 fb^{-1} of integrated luminosity per experiment. Results are grouped as it follows:

- section 2: B-mesons.
 - section 2.1: rare decays: $B_s \rightarrow \mu^+\mu^-$.
 - section 2.2: B_c semileptonic decays: $B_c^+ \rightarrow J/\Psi\mu^+\nu$.
 - section 2.3: orbitally excited B-mesons ($B_1^{0,+}, B_2^{*0,+}, B_{s1}^0, B_{s2}^{*0}$), and new $B\pi$ resonances: $B(5970)^{0,+}$.
- section 3: b baryons: $\Xi_b^{0,-}, \Omega_b^-$.
- section 4: Exotic resonances: $X(4140)$.

2 B-mesons

2.1 Rare decays: $B_s \rightarrow \mu^+\mu^-$

The long study of the $B_s \rightarrow \mu^+\mu^-$ decay is a clear example of a rich legacy left by Tevatron to the present and future hadron colliders; in more than 10 years, a variety of methods and tools was developed, having outlined the main road for the recent LHC evidence results [3].

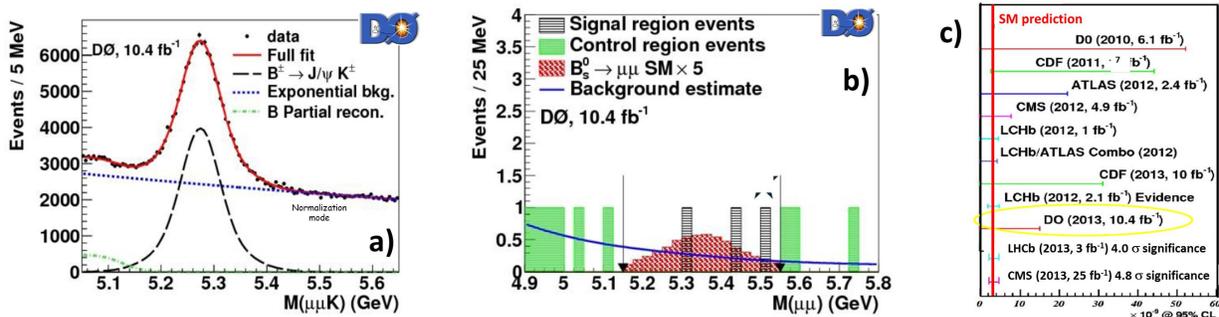


Figure 1: a): Normalization mode invariant mass; b): $M(\mu\mu)$ invariant mass after all selection cuts; c): Summary of the latest $BR(B_s^0 \rightarrow \mu\mu)$ measurements.

High purity and efficiency selection of dimuon vertex candidates is the first step of the procedure; efficient rejection of the background is obtained by applying multivariate analysis techniques such as Neural Network

(NN) and Boosted Decision Tree (BDT); the kinematic observables of the tracks and of the reconstructed vertexes as well as global event information are considered to select the event candidate sample and to deplete the background contributions (mainly $B \rightarrow h^+h^-$ decays and partially reconstructed B decays); the background level in the signal region is extrapolated from the sideband control regions; Single Event Sensitivity (SES) for the signal is determined from the abundant normalization mode $B^+ \rightarrow J/\Psi K^+ \rightarrow (\mu^+\mu^-)K^+$; Bayesian and frequentist approaches are used to set the expected (from SES) and observed limits at 90%(95%) confidence level. Details of the individual analyses can be found in the last Tevatron publications [4].

D0 set the best Tevatron limits: $BR(B_s^0 \rightarrow \mu^+\mu^-) < 15 \times 10^{-9}(12 \times 10^{-9})$ at 90% (95%) confidence level, only a factor 5 above the value predicted by the Standard Model and recently confirmed by the LHC experiment evidences. The invariant mass spectra of the normalization channel and of dimuon mass in the signal region are shown in figure 1a) and b) respectively, while the summary of most recent world results are shown in figure 1c).

2.2 B_c semileptonic decays: $B_c^+ \rightarrow J/\Psi\mu^+\nu$

The B_c^+ meson is the most massive bottom-flavored meson, apart from $b\bar{b}$, and it consists of a \bar{b} quark and a c quark in the ground state; it was discovered by CDF in the Tevatron Run I and it is an unique laboratory to study QCD and weak decays. The dominant production in $p\bar{p}$ collisions is through hard processes (figure 2a)) and the B_c^+ meson decays only weakly; the decay modes with b -quark spectator and c -quark spectator have different final states, so they do not interfere.

The CDF experiment has recently completed an analysis on the full Run II data set corresponding to 8.7 fb^{-1} of integrated luminosity; the measured observable is the B_c^+ production cross/section times the branching ratio in the $J/\Psi\mu^+\nu$ decay mode, normalized to the same quantity for the normalization mode $B^+ \rightarrow J/\Psi K^+$, and using the dimuon trigger type. Event selection is based on the association to the J/Ψ vertex of a third track that may be: the muon in the $B_c^+ \rightarrow J/\Psi\mu^+X$ decays; a charged kaon in the $B^+ \rightarrow J/\Psi K^+$ decay; a π^+, K^+ , or p in the background control samples. The invariant mass distribution of the $B_c^+ \rightarrow J/\Psi\mu^+\nu$ candidate events is shown in figure 2b).

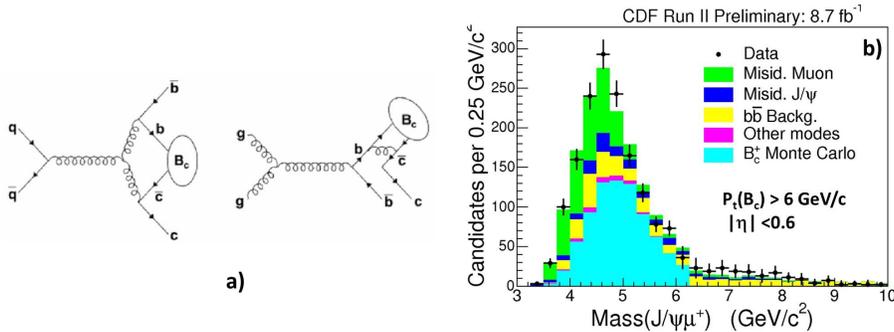


Figure 2: a): examples of B_c production hard processes; b): invariant mass of the $B_c^+ \rightarrow J/\Psi\mu^+\nu$ candidate events.

The new CDF results is:

$$\frac{\sigma(B_c^+) \times BR(B_c^+ \rightarrow J/\Psi\mu^+\nu)}{\sigma(B^+) \times BR(B^+ \rightarrow J/\Psi K^+)} = 0.211 \pm 0.012(stat.)_{-0.020}^{+0.021}(syst.); \quad (1)$$

the systematic error is dominated by the uncertainty on muon identification and the muon efficiency [5].

2.3 Orbitally excited B-mesons and new resonances

The study of the properties of orbitally excited B-mesons allows accurate tests of the predictions of the heavy-quark effective theory (HQET); assuming the bottom quark to be heavy, like the proton in the hydrogen

atom, the dynamics in HQET is dominated by the coupling between the light-quark's orbital momentum and spin, resulting in the total light-quark's momentum j ; additional contributions to system dynamics arise due to the coupling between the b-quark spin and j ; this results in two doublet states, corresponding to the fine and hyperfine splitting shown in figure 3a). Two states (B_1 and B_2^*) are *narrow* due to parity and angular momentum conservation; three decays per flavor mode ($B_{1(s1)} \rightarrow B^*\pi(K)$, $B_{2(s2)}^* \rightarrow B^*\pi(K)$, and $B_{2(s2)}^* \rightarrow B\pi(K)$) are observed by CDF; the other states have predicted widths of $150 \text{ MeV}/c^2$ and are too broad to be detected. The sum of the individual samples with a kaon and including B decays in the J/Ψ mode and in fully hadronic modes with a D-meson is shown in figure 3b); signals are described by non-relativistic Breit-Wigner functions convoluted with two Gaussians to account for the detector resolution.

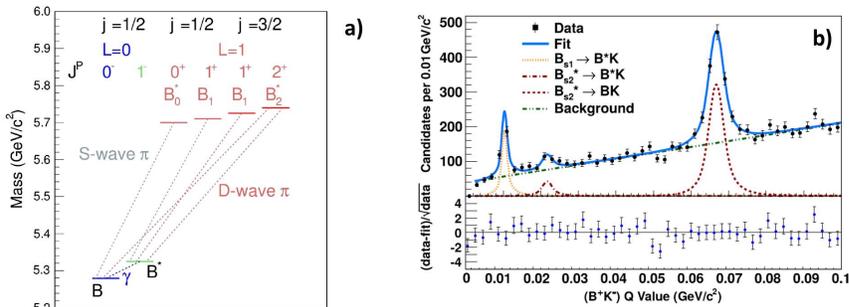


Figure 3: a): Spectrum of the allowed decays for the lowest orbitally excited B-states; b): Q value of the excited B-mesons: sum of all decay modes with a kaon.

The latest CDF updates for the masses of the observed excited B-mesons are listed in table 1 and compared with most recent results from other experiments and with the predictions of some HQET models.

| | B_1^0 | B_1^+ | B_2^{*0} | B_2^{*+} | B_{s1}^0 | B_{s2}^{*0} | Ref. |
|------|------------------|--------------|------------------|------------------|------------------|------------------|------|
| CDF | 5726.4 ± 1.6 | 5726 ± 5 | 5736.6 ± 1.7 | 5737.1 ± 1.4 | 5828.3 ± 0.4 | 5839.7 ± 0.2 | [6] |
| HQET | 5720 | 5720 | 5737 | 5737 | 5831 | 5847 | [7] |
| HQET | 5719 | 5719 | 5733 | 5733 | 5831 | 5844 | [8] |

Table 1: Excited B-meson masses; the total error on the CDF results includes statistical and systematic errors, and the uncertainty on the B-meson masses.

A broad structure is visible at Q value around $550 \text{ MeV}/c^2$ in both B^{**0} and B^{**+} invariant mass distributions (fig. 4); the properties of the previously unobserved resonances are measured for both neutral and charged final states; assuming a decay through the $B\pi$ channel, the mass values $m(B(5970)^0) = 5978 \pm 5 \pm 12$ and $m(B(5970)^+) = 5961 \pm 5 \pm 12$ are obtained with individual significances of 4.2σ and 3.7σ respectively.

3 b-baryons: $\Xi_b^{0,-}, \Omega_b^-$

The study of the properties of the b-baryons has been for a long time totally a Tevatron field; many elements of the $SU(4)$ (u,d,s,b) symmetry such as the $\Sigma^{(*)+}, \Sigma^{(*)-}, \Xi_b^-, \Omega_b^-$, and Ξ_b^0 baryons were first observed during the Tevatron Run II from 2006 to 2011. The b-baryons are reconstructed at the Tevatron experiments in the J/Ψ and fully hadronic modes; very recently, CDF made the first observation of the Ω_b^- in the fully hadronic mode; the invariant mass spectra of the Ω_b^- and Ξ_b^- baryons are shown in figures 5a) and 5b) respectively.

After more than two years from the collision end, Tevatron results on b-baryon properties are still almost competitive with the first LHC results; a comparison of CDF and LHCb recent results is shown in table 2.

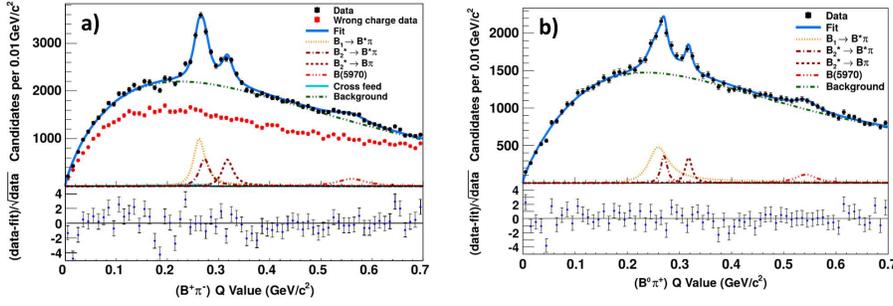


Figure 4: Distribution of the Q values of B^{**0} candidates (a) and B^{**+} candidates (b)

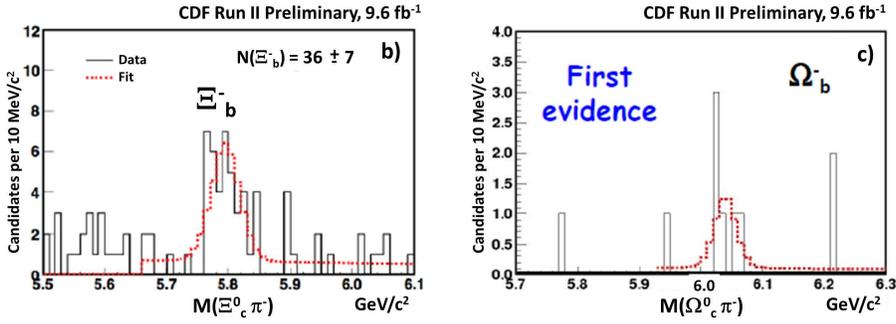


Figure 5: a): $M(\Xi_c^0 \pi^-)$ invariant mass; b): $M(\Omega_c^0 \pi^-)$ invariant mass.

| | CDF (ref. [9]) | | LHCb (ref. [10]) | |
|--------------|-----------------------------|---------------------------------|-----------------------------|---------------------------------|
| | Mass (MeV/c^2) | Lifetime (ps) | Mass (MeV/c^2) | Lifetime (ps) |
| Λ_b | $5620.15 \pm 0.31 \pm 0.47$ | $1.565 \pm 0.035 \pm 0.020$ | $5619.53 \pm 0.13 \pm 0.45$ | $1.482 \pm 0.18 \pm 0.12$ |
| Ξ_b^- | $5793.4 \pm 1.8 \pm 0.7$ | $1.32 \pm 0.14 \pm 0.02$ | $5795.8 \pm 0.9 \pm 0.4$ | $1.55^{+0.10}_{-0.09} \pm 0.03$ |
| Ξ_b^0 | $5788.7 \pm 4.3 \pm 1.4$ | | | |
| Ω_b^- | $6047.5 \pm 3.8 \pm 0.6$ | $1.66^{+0.53}_{-0.40} \pm 0.02$ | $6046.0 \pm 2.2 \pm 0.4$ | $1.54^{+0.26}_{-0.21} \pm 0.05$ |

Table 2: Summary of the latest results on b-baryon properties.

4 Exotic resonances: X(4140)

The study of narrow exotic resonances in the B decay product spectrum is important to infer on possible colorless bound quark states other than mesons and baryons; there are no theoretical reasons to exclude meson molecules, tetra-quark aggregates, or quark-gluon hybrids, but no definitive experimental evidence for any such states has been yet established.

The D0 experiment has recently studied the resonances in the $J/\Psi\phi$ system produced near threshold in the decay $B^+ \rightarrow J/\Psi\phi K^+$ (and charge conjugate) [11]. As shown in figure 6a), a 3.1σ evidence is obtained for the X(4140) resonance with mass $M_{X(4140)} = 4159 \pm 4.3(\text{stat.}) \pm 6.6(\text{syst.}) \text{ MeV}/c^2$ and width $\Gamma_{X(4140)} = 19.9 \pm 12.6(\text{stat.}) \pm 8(\text{syst.}) \text{ MeV}/c^2$ in agreement with the CDF first evidence and updated results [12], and with the CMS observation [13]. Debate on the existence of the narrow X(4140) resonance is not yet closed because of the non-observation results from Belle [14] and LHCb [15]. The interpretation of the observed resonance is also controversial; conventional charmonium should predominantly decay into $D\bar{D}$ pairs (not seen) with expected mass close to $3740 \text{ MeV}/c^2$, the open charm threshold, while the mode

$(c\bar{c}) \rightarrow J/\Psi \text{ hadrons}$ (e.g $\phi \rightarrow KK$) is OZI suppressed.

The summary of the experimental results on the search for narrow resonances in the $J/\Psi\phi$ invariant mass spectrum is shown in figure 6b); inconsistent results are found for the resonance around $4300 \text{ MeV}/c^2$.

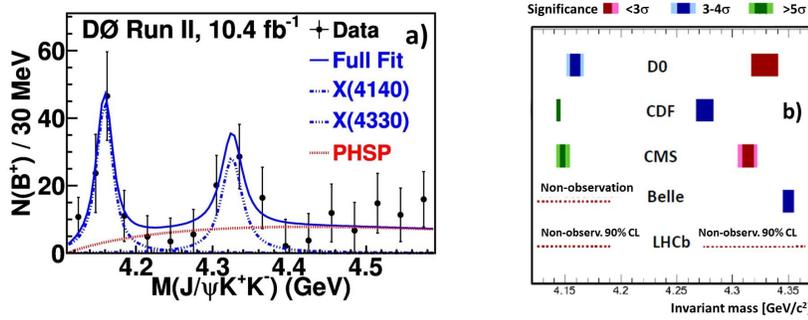


Figure 6: a): red dotted line is the fit result assuming three-body phase-space decays with no resonances; Breit-Wigner functions are used for the signal fit; b): summary of the resonance searches in the $J/\Psi\phi$ system.

5 Conclusions

Tevatron experiments produced high quality results in heavy flavor physics during the last two decades; the results have been complementary and competitive with the B-Factories, showing that precision measurements on heavy flavor physics are possible at the hadron colliders.

Many tools and methods were developed for a clean identification of events with b-hadron production; a rich legacy is left to LHC and to the future colliders and B-Factories.

The analysis of the full statistics samples collected by CDF and D0 is not yet completed; possible interesting results could be still obtained.

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