QCD and Heavy Quark Physics at the Tevatron

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1 Introduction

Recent results from the Tevatron experiments CDF and D0 in QCD and heavy quark measurements are summarized. These results include updates to earlier measurements. In many cases the analysis is based on the full Run 2 data set of approximately 10 fb^{-1}. QCD and heavy quark measurements in areas such as inclusive jet production, photon+heavy quark production, CP asymmetries, fragmentation studies, rare decays, and lifetimes are covered.

The Tevatron collider at Fermilab has been used to study proton-antiproton collisions at high energy from 1985 through September 30, 2011. This article discusses results from Run 2 of the collider, which ran from 2001 through 2011. The accelerator delivered about 12 fb^{-1} of luminosity to each experiment at a center of mass energy of 1.96 TeV.

2 QCD Physics

QCD analyses are used to study strong interactions in $p\overline{p}$ collisions. Some of the specific areas addressed are calculations of interaction probabilities at different orders of α_s, measurements of and comparisons to different parameterizations of parton distribution functions (pdf's), measurements at higher precision and in new kinematic regimes, processes now accessible because of increased statistics, and processes where the initial $p\overline{p}$ state allows for unique measurements.

D0 has measured inclusive jet cross sections in the kinematic range $-2.4 < \eta < 2.4$ and $50 < p_T < 600$ GeV/c [1]. The measurement provides information that can probe the quark and gluon structure of the proton. The differential cross section of inclusive jets is compared to theoretical predictions using a large variety of pdf's and good agreement is found in most cases. Figure 1(left) shows the cross sections for jets measured in bins of η.

CDF and D0 have measured the production of $\gamma + b$ jets and $\gamma + c$ jets at the Tevatron. The contributions to the production of $\gamma + b$ jets and $\gamma + c$ jets are Q+gluon ($Q = b, c$) and $q\overline{q}$ annihilation. The D0 measurement selects central ($|y| < 1$) or forward ($1.5 < |y| < 2.5$) photons with $30 < p_T < 300$ GeV and jets with $|y| < 1.5$ and uses 8.7 fb^{-1}. The b-jet fraction is determined by fitting the data

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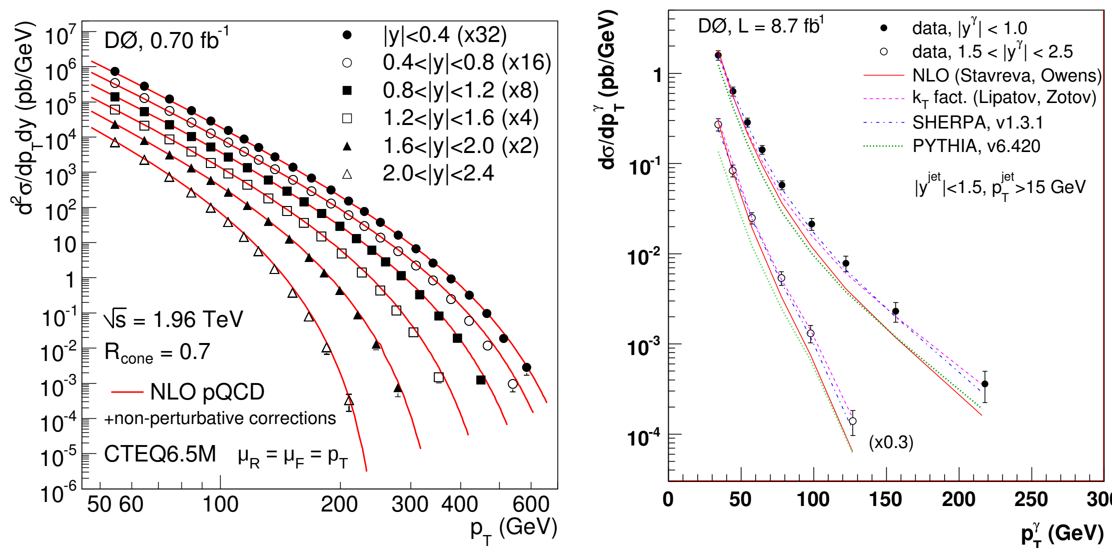

Figure 1: (left) Inclusive jet differential cross section; (right) γ + b jets inclusive cross section.

to templates of secondary vertex mass distribution shapes derived from simulation. The differential cross section as a function of p_T of the photon is compared to NLO calculations and is shown in figure 1(right). The calculations agree with data at $p_T < 70$ GeV but higher order QCD corrections are required to match the data at higher p_T where a contribution from $q\bar{q} \to \gamma + g(g \to Q\overline{Q})$ is dominating [2].

In the CDF measurements $\gamma + b$ jets and $\gamma + c$ jets are measured in the kinematic range $30 < E_T^\gamma < 300$ GeV, $|y^\gamma| < 1.0$ and $E_T^{jet} > 20$ GeV with $|y^{jet}| < 1.5$ using 9.1 fb^{-1} of integrated luminosity. The contributions from b, c and light quark jets are fit using templates from simulated events. Cross sections are calculated and compared to NLO predictions. As in the D0 analysis the calculations agree with data at low E_T and do not match at large E_T.

3 Heavy Quark Physics

The study of heavy quark production and decay in hadron colliders is an excellent technique for better understanding of the fundamental nature of matter and forces in particle physics. It provides an ideal laboratory for the study of beyond-standard-model physics at higher energy scales. Recent results in fragmentation, CP asymmetries, rare branching ratios, and lifetimes are discussed.

3.1 Fragmentation

CDF has performed a study [3] of fragmentation in D_s^+/D^+ meson production using the properties of associated $K^\pm$ mesons to measure the fragmentation chain in $p\overline{p}$ collisions. This study uses 360 pb^{-1} of data to study the same-sign and opposite-sign $K^\pm$ rate associated with D^+ and D_s^+ mesons. The rates show the expected qualitative behavior. When compared to model calculations from PYTHIA and HERWIG, some differences in the same-sign rates for both D^+ and D_s^+ are seen, indicating a need for further tuning of fragmentation in models.

3.2 CP Asymmetry in $D^0 \to h^+h^-$ and $D^0 \to K_S^0\pi^+\pi^-$ decays

Measuring CP asymmetries in the decays of charm mesons is a useful way to investigate physics effects beyond the standard model. CDF has measured the individual CP asymmetries in the decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ [4]. CDF also measured the difference in the CP asymmetries, defined as $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$. An update on ΔA_{CP} using the full Run 2 data set is presented. The selection criteria are relaxed to take advantage of the fact that many of the systematic errors cancel in the difference measurement. This leads to a significant increase in the number of signal events. The $D^0(\overline{D}^0)$ is tagged by the slow pion from the $D^{*\pm}$ decay. Approximately 550K $D^0 \to \pi^+\pi^-$ and 1.21M $D^0 \to K^+K^-$ decays are used in the analysis. Fits are made to identify signal, background from combinatorics, and background from multibody decays. The mass distributions are shown in Figure 2. The final result is $\Delta A_{CP} = (-0.62 \pm 0.21(\text{stat}) \pm 0.10(\text{syst}))\%$ [5]. This value is 2.7σ from zero and has similar precision and provides confirmation of the LHCb result of $\Delta A_{CP} = (-0.83 \pm 0.21(\text{stat}) \pm 0.11(\text{syst}))\%$ [6].

Additional understanding of CP asymmetry in charm decays can be investigated by measuring CP decay properties of many decay modes of the D^0 meson. A measurement of CP asymmetry was made by CDF in the $K_S^0\pi^+\pi^-$ decay mode. A D^* tag is used to identify the D^0 flavor. Two methods were used to measure the asymmetry; a full Dalitz fit using the isobar model and a model-independent bin-by-bin comparison. No CP asymmetry is found in any sub-resonance and integrating over all modes CDF measures $A_{CP} = -0.0005 \pm 0.0057(\text{stat}) \pm 0.0054(\text{syst})$ [7].

3.3 $B \to \mu^+\mu^-$ searches

Processes involving flavor-changing neutral currents are highly suppressed in the standard model and are therefore an excellent place to search for new physics that may increase measurable quantities such as decay rates. In the standard model the predictions for the neutral B meson branching ratios are $B^0 \to \mu^+\mu^- = (1.0 \pm 0.1) \times 10^{-10}$ and $B_s^0 \to \mu^+\mu^- = (3.2 \pm 0.2) \times 10^{-9}$.

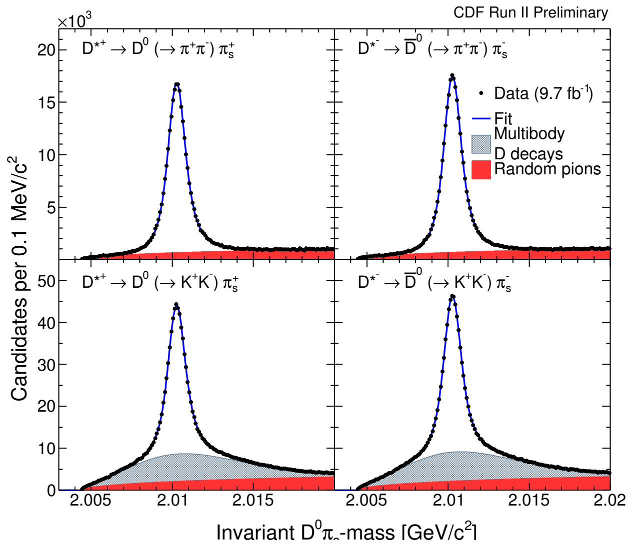

Figure 2: Fits to $D^0 \to \pi^+\pi^-, K^+K^-$

CDF published upper limits on both branching ratios using 7 fb^{-1} of data [8]. The analysis was extended to the full Run 2 data set of 9.7 fb^{-1} using the same analysis methods. A neural network (NN) is used to discriminate the signal-like events from background, and the branching ratio is normalized to the $B^+ \to J/\psi K^+$ decay. The challenge in this analysis is to reject a large background while keeping most of the signal. 14 discriminating variables were used to build an optimized neural net classifier. The combinatorial background is estimated from the mass sidebands and the fake muon peaking backgrounds are estimated from $B \to hh$ simulation and $B \to K\pi$ decays in data. The results are binned in NN ranges and from the data/background comparison the branching ratios are measured. The final results are $BR(B^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9}$, $BR(B_s^0 \to \mu^+\mu^-) < 3.1 \times 10^{-8}$, both at 95% C.L. Assuming that the observed excess in the B_s^0 is due to a signal, CDF finds $BR(B_s^0 \to \mu^+\mu^-) = 1.3^{+0.9}_{-0.7} \times 10^{-8}$.

The results are closer to the SM expectation and represents a big step in the program of measuring the branching ratio with better sensitivity.

3.4 B_s^0 decays and branching ratios

CDF has measured the branching ratios of B_s^0 decays to $D_s^{*+}D_s^{*-}$, $D_s^{*+}D_s^-$ and $D_s^+D_s^-$, where the D_s^+ decays to $\phi\pi^+$ or $K^{*0}K^+$ and the D_s^{*+} decays to $D_s^+\gamma$ or $D_s^+\pi^0$, with the γ or π^0 not detected. The measurement was made using a data sample of 6.8 fb^{-1}. A neural net was used to separate signal and background contributions, giving a total of approximately 750 $B_s^0 \to D_s^{(*)+}D_s^{(*)-}$ decays. Branching ratios were determined by normalizing to the well-measured $B^0 \to D_s^+ D^-$ decay branching ratio. The results, now the world's best measurements [9] are consistent with but lower than recent Belle results.

CDF uses the full Run 2 data set to measure BR($B_s^0 \to J/\psi\phi$) and to constrain the value of f_s/f_d, as well as to investigate f_s/f_d as a function of p_T. The $B_s^0 \to J/\psi\phi$ is normalized to the $B^0 \to J/\psi K^*$ decay mode. Approximately 11,000 B_s^0 and 57,000 B^0 events are used in the analysis. The final value for the ratio of the branching ratio multiplied by f_s/f_d is found to be $0.239 \pm 0.003 \pm 0.019$. Using the value of f_s/f_d measured by CDF and the PDG value [10] of BR($B^0 \to J/\psi K^*$), CDF finds $\mathrm{BR}(B_s^0 \to J/\psi\phi) = (1.18 \pm 0.02(\mathrm{stat}) \pm 0.09(\mathrm{syst}) \pm 0.014(\mathrm{frag}) \pm 0.05(\mathrm{pdg})) \times 10^{-3}$. This is the world's best measurement of the quantity. The analysis is also performed in bins of $p_T(B_s^0)$, showing no dependence on p_T within statistics. Using Belle's latest value of BR($B_s^0 \to J/\psi\phi$) a value of f_s/f_d can be computed and is found to be $f_s/f_d = 0.254 \pm 0.003(\mathrm{stat}) \pm 0.020(\mathrm{syst}) \pm 0.044(\mathrm{pdg})$.

D0 has performed a measurement of the relative branching ratio of the $B_s^0 \to J/\psi f_2'(1525)$ decay to the $B_s^0 \to J/\psi\phi$ decay. For this measurement the entire Run 2 data set of 10.4 fb^{-1} was used. Monte Carlo templates for decay modes with the same four-body final states were fit as a function of the K^+K^- mass to extract the $J/\psi f_2'(1525)$ contribution. A fit to the angular distributions of the decay show that the spin of the K^+K^- is consistent with a combination of spin 0 and spin 2 and is inconsistent with spin 1. The final result for the ratio of branching ratios is [11] $BR(B_s^0 \to J/\psi f_2')/BR(B_s^0 \to J/\psi\phi) = 0.22 \pm 0.05(\mathrm{stat}) \pm 0.04(\mathrm{syst})$.

3.5 $\chi_b \to \Upsilon(1S)\gamma$ studies

D0 combines $\Upsilon(1S)$ candidates in the mass range of $9.1 < M_{\mu^+\mu^-} < 9.7$ GeV with photons that have been identified by their conversion to e^+e^- pairs. The mass difference $\mathrm{M}_{\mu^+\mu^-\gamma}$ - $\mathrm{M}_{\mu^+\mu^-}$ is calculated for each event. Three clear states are seen, corresponding to the $\chi_b(1P)$, the $\chi_b(2P)$ and a new state. The mass of the third state is measured to be $10.551 \pm 0.014(\mathrm{stat}) \pm 0.017(\mathrm{syst})$ [12], consistent with the mass measured by ATLAS in the same decay mode [13].

3.6 Measurement of the Λ_b lifetime

The Λ_b lifetime measurements and predictions present a few puzzles. The measurements from various experiments and decay modes do not fully agree and the measurements are not all consistent with the theoretical predictions. This is an area where new measurements are needed to help resolve the mysteries.

D0 has made a new measurement of the Λ_b lifetime, using the full Run 2 data set of 10.4 fb^{-1} luminosity. In this analysis two topologically similar decay modes are measured, $\Lambda_b \to J/\psi\Lambda$ and $B^0 \to J/\psi K_s^0$. Separate fits are made to each decay mode. The results are $\tau(\Lambda_b) = (1.303 \pm 0.075(\text{stat}) \pm 0.035(\text{syst}))$ps, $\tau(B^0) = (1.508 \pm 0.025(\text{stat}) \pm 0.043(\text{syst}))$ps and $\tau(\Lambda_b)/\tau(B^0)) = 0.864 \pm 0.052(\text{stat}) \pm 0.033(\text{syst})$ [14]. These values can be compared to the PDG values and to the latest CDF values. Further measurements will be needed to help resolve the inconsistency.

4 Conclusions and Summary

The study of QCD and heavy quark physics in $p\overline{p}$ collisions at the Tevatron is a fruitful way to advance our knowledge of fundamental interactions and properties of matter. The results described provide interesting and novel information about parton distributions, parton interactions, quark decay properties, fragmentation, and CP asymmetries.

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