Charm and Beauty Production at the Tevatron

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CDF is now releasing measurements using data samples with integrated luminosities of up to $1\,\mathrm{fb}^{-1}$ enabling detailed studies of charm hadron production: Measurements of prompt charm meson pair production, spin alignment of the charmonium states J/ψ and $\psi(2S)$ and relative production of the $\chi_{c1}(P1)$ will be discussed. In addition recent measurements of the b-hadron and bottomonium production cross-section by CDF and DØ will be presented.

1 Introduction

The production and hadronization of long lived heavy quarks, c and b, in hadron hadron collisions is an active field of research in Quantum Chromo Dynamics (QCD). In the theoretical treatment of production and hadronization, the mass of the heavy quark provides a scale just at the transition between non-perturbative and perturbative regimes of QCD. Measurements of production cross-sections and polarization at production probe our understanding of QCD in this transition region.

Charm and beauty hadrons are produced in huge numbers in proton anti-proton collisions at a center-of-mass energy of $\sqrt{s} = 1.96\,\mathrm{TeV}$ at the Tevatron Collider at Fermilab. These collisions are recorded by the general purpose hadron collider detectors CDF [2] and DØ [3]. CDF's large tracking volume and precise silicon vertexing are key features in its very good performance for charm and beauty physics. Its trigger and data acquisition system, with a high bandwidth for track based triggers allows large samples to be recorded of up to several million fully reconstructed b and c hadron decays. DØ's excellent muon coverage enable measurements of b-hadrons over a wide range in rapidity y.

2 Charm meson pair production

With over $1\,\mathrm{fb}^{-1}$ of data collected by CDF, it is now possible to look for two fully reconstructed charm mesons to measure charm pair-production cross-sections in $p\bar{p}$ collisions.

For a first measurement of charm meson pair cross-sections only D^{*+} mesons, decaying to $D^0(\rightarrow K\pi)\pi$, are considered as candidates for the second charm hadron in the event, as the mass difference $\Delta m = m(K\pi\pi) - m(K\pi)$ provides a sufficient handle to suppress combinatorial background. More than 2000 signal pairs for both modes, D^0D^{*-} and D^+D^{*-} pairs, have been reconstructed.

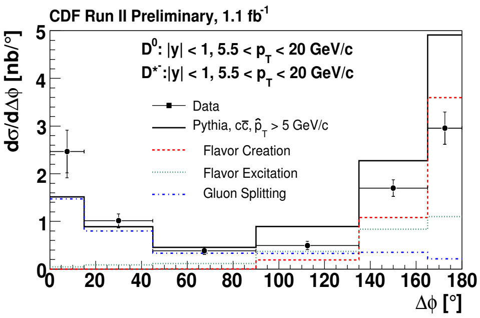

Figure 1: The D^0D^{*-} and pair cross-sections as a function of $\Delta\phi$.

Combinatorial background in the DD^{*-} sample is corrected for using a 2-dimensional sideband subtraction. The impact parameter distribution of the D^0 in the D^{*+} decay is used as a handle to extract the number of prompt pairs. The detector acceptance and reconstruction efficiencies are corrected for employing a detailed simulation of "realistic" $c\bar{c}$

events. Besides the charm mesons of interest, additional particles from fragmentation and the underlying event in the $p\bar{p}$ collision are incorporated. The simulation of pair events has been validated using large samples of inclusive D candidates from data.

Figure 1 displays the $D^0 D^{*-}$ pair cross-sections as a function of $\Delta\phi$. Collinear production is found to be as important as back-to-back production. The measurement is compared to the prediction derived from Pythia (Tune A) [4], which gives a fair estimate of the absolute pair cross-section, but underestimates (overestimates) collinear (back-to-back) production.

3 J/ψ and $\psi(2S)$ polarization

Both vector mesons are reconstructed in their decays into muon pairs, $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$. The distribution of the μ^+ in the vector meson rest frame relative to the flight direction of the vector meson in the $p\bar{p}$ rest frame, measured by the polar angle θ^* depends on the polarization parameter $\alpha \in [-1, 1]$: $\frac{dN}{d\Omega} \propto 1 + \alpha \cos^2\theta^*$, where $\alpha = +1$ (-1) for transversely (longitudinally) polarized vector mesons.

The samples of prompt J/ψ and $\psi(2S)$ are purged of the secondary J/ψ and $\psi(2S)$ from B-hadron decays by cutting on the combined impact parameter significance, d_0/σ_0, of the two μ-tracks: $S = (d_0^+/\sigma_{0+})^2 + (d_0^-/\sigma_{0-})^2 \leq 8$. Conversely the samples of secondary J/ψ and $\psi(2S)$ are enriched by requiring $S \geq 16$. Residual contributions of secondary (prompt) J/ψ and $\psi(2S)$ are taken into account in the polarization fits, from which α is extracted. The polarization fit employs a template method. The templates of fully-polarized vector mesons are generated using a Monte Carlo program which has been carefully validated to correctly reproduce the kinematic distributions of J/ψ and $\psi(2S)$ mesons in the CDF data. The polarization analysis is sensitive to any unknown apparatus response that could distort the decay angle distribution. The data used for the polarization analysis were taken from June, 2004 to February, 2006. Throughout this period, the COT operation was stable and the muon trigger efficiency did not change by more than 0.2% from the plateau value of 94.1%. The integrated luminosity of this data set is 800 pb^{-1}.

The polarization of the vector mesons from B-decays, α_B, is found to be independent of its p_T. CDF measures $\alpha_B(\psi(2S)) = 0.33 \pm 0.25$ and $\alpha_B(J/\psi) = -0.066 \pm 0.050$ consistent with the more precise results from the B-factories. Figure 2 shows the polarization of prompt vector mesons as a function of their transverse momentum p_T. With increasing p_T, both the J/ψ and the $\psi(2S)$ are increasingly longitudinally polarized. The measurement for the $\psi(2S)$ is less precise due to the smaller sample size. However, thanks to the absence of

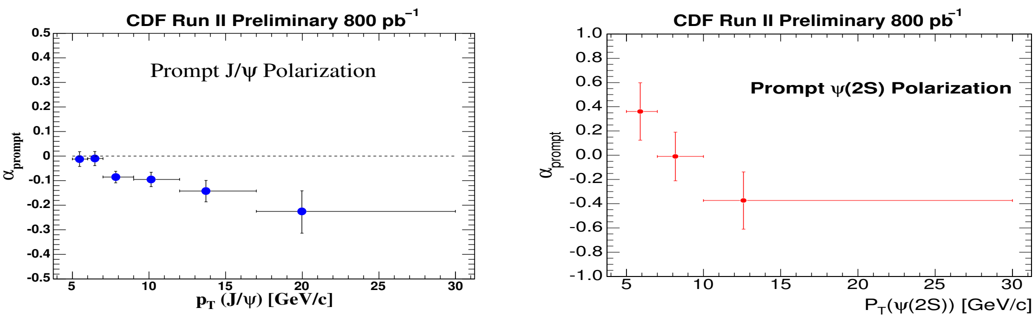

Figure 2: The polarization (α_{prompt}) of the vector meson as a function of its transverse momentum p_T, for prompt J/ψ (left) and prompt $\psi(2S)$ (right).

feed-down from χ_c states, the $\psi(2S)$ represents direct vector meson production more closely than in the case of the J/ψ.

4 Relative production of χ_{c1} and χ_{c2}

The reconstruction of the decay $\chi_{cJ} \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\gamma$ is challenging, due to the need to detect low energy photons within the environment of multi-particle final states. The large integrated luminosity delivered by the Tevatron allows CDF to reconstruct the low energy photons through conversion into e^+e^- pairs in sufficient quantity. As demonstrated in Fig. 3, such a reconstruction provides the mass resolution needed to distinguish the χ_{c1} from the χ_{c2}. The effective flight distance λ_{eff} of the J/ψ provides a handle to discriminate between prompt and secondary χ_{cJ}. By applying corrections for the relative efficiencies, $\epsilon(\chi_{c1})/\epsilon(\chi_{c2})$, and branching fractions, $Br(\chi_{c1} \rightarrow J/\psi\gamma)/Br(\chi_{c2} \rightarrow J/\psi\gamma)$, the yields of prompt χ_{cJ}, obtained from a simultaneous fit to λ_{eff} and $m(J/\psi\gamma)$, are converted into the ratio of production cross-sections $\sigma_{\chi_{c2}}/\sigma_{\chi_{c1}} = 0.70 \pm 0.04(\text{stat.}) \pm 0.03(\text{syst.}) \pm 0.06(\text{br})$, with no significant p_T dependence in the measured range of $5 < p_T < 14\,\text{GeV/c}$ [5].

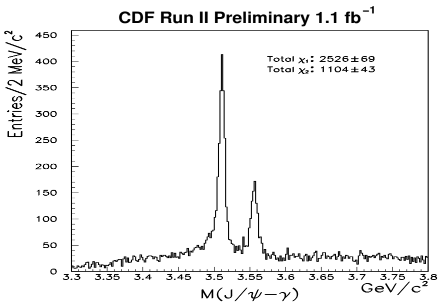

Figure 3: The $J/\psi\gamma$ invariant mass of all the χ_{cJ} candidates in the data sample.

The precision of this measurement sets a new standard. Models that predict production proportional to the number of spin states would expect this ratio to be $\frac{5}{3}$ [6]. Such models are ruled out by this measurement.

5 B-hadron production

To date, CDF has performed three measurements of the inclusive b-hadron (H_b) production cross-section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$. The first has been the measurement using $H_b \rightarrow J/\psi X,\ J/\psi \rightarrow \mu^+\mu^-$ decays, where the displacement of the J/ψ decay vertex from the beam line served as tag of the long lived H_b. Taking advantage of the low momentum J/ψ events accessible by the CDF muon triggers, this measurement has been the first one to map out the cross-section down to $p_T(H_b) = 0\,\text{GeV/c}$ [7]. Secondly CDF has performed a measurement of the B^+ meson cross-section for $p_T(B^+) > 6\,\text{GeV/c}$. For this measurement the decay chain $B^+ \rightarrow J/\psi K^+$ with $J/\psi \rightarrow \mu^+\mu^-$ has been fully reconstructed using a dataset of $800\,\text{pb}^{-1}$. With large statistics and a very clean fully reconstructed mode, the precision of this measurement is better than 10%. The third, most recent analysis takes advantage of the distinct semileptonic $H_b \rightarrow \mu^- D^0 X$, $D^0 \rightarrow K^-\pi^+$ decay signature. This measurement is superior to previous inclusive semileptonic measurements, $H_b \rightarrow \mu X$, thanks to the clear charm tag of the fully reconstructed D^0 meson, which provides an improved purity and therefore reduced systematic uncertainties.

Figure 4 shows a compilation of differential b-hadron cross-sections. There is good agreement between these complimentary measurements and the fixed order next-to-leading log (FONLL) [8] prediction is seen to be consistent with the data.

6 Bottomonium production

Using a dataset of 159 pb^{-1} DØ has measured the inclusive production cross-section of the $\Upsilon(1S)$ bottomonium state using the $\Upsilon(1S) \rightarrow \mu^+\mu^-$ decay mode [9]. For the central rapidity region ($|y(\Upsilon)| < 0.6$) the cross-section times branching ratio is $732 \pm 19(\text{stat}) \pm 73(\text{syst.}) \pm 46(\text{lumin.})$ pb. Measuring the ratios of cross-sections for the rapidity ranges $0.6 < |y(\Upsilon)| \leq 1.2$ and $1.2 < |y(\Upsilon)| \leq 1.8$ relative to the central rapidity allowed for determination of the $\Upsilon(1S)$ production cross-section in the extended rapidity ranges. As can be seen in Fig. 5 there is little variation between the rapidity regions in the shapes of the differential cross-sections, which agree reasonably well with theoretical predictions [10].

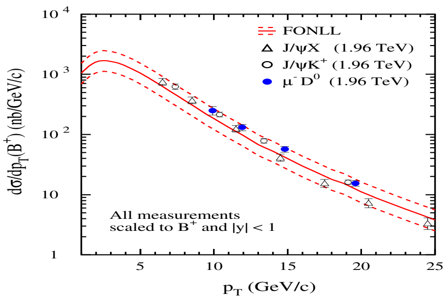

Figure 4: Differential b-hadron cross-sections compared to a FONLL [8] calculation.

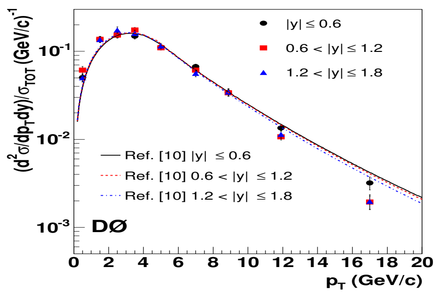

Figure 5: The normalized differential cross-section for $\Upsilon(1S)$ production.

7 Conclusion

The unprecedented integrated luminosity delivered by the Tevatron as well as the sustained excellent performance of the CDF and DØ detectors open a window of opportunity for detailed studies of the production of charm and beauty hadrons. Such studies have the potential to instigate new approaches to QCD models and calculations. The new results presented here will help improve our understanding of heavy quark production in proton (anti-)proton collisions.

References

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