Charm Production Studies at CDF

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The upgraded Collider Detector at Fermilab (CDF II) has a high bandwidth available for track based triggers. This capability in conjunction with the unprecedented integrated luminosity in excess of $1\,\mathrm{fb}^{-1}$ enables detailed studies of charm hadron production. CDF is now releasing first measurements of the prompt charm meson pair cross sections, which give access to QCD mechanisms by which charm quarks are produced in proton anti-proton collisions. Recent results on the spin alignment of J/ψ and $\psi(2S)$ as well as on the relative production of the $\chi_{c1}(P1)$ and $\chi_{c2}(1P)$ challenge our understanding of the fragmentation of charm quarks into charmonium states.

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. QCD, the theory of the strong force, describes one of the fundamental forces of nature. Therefore, such measurements are interesting in their own right. Furthermore, they provide important inputs to future experiments, such as production rates of calibration signals. In many essential measurements, such as top cross sections and top mass or searches for Higgs bosons and super-symmetric particles, the QCD production of heavy quarks is an important background and tagging of b quarks is a vital experimental technique. The efficiency and purity of the b-tags are studied in great detail by employing Monte Carlo simulation programs. For designing analysis strategies and control of systematic effects, an accurate modeling is very desirable.

Charm and beauty hadrons are produced in huge numbers in proton anti-proton collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV at the Tevatron Collider at Fermilab. The CDF II detector [1] is a general purpose hadron collider detector. Its large tracking volume and precise silicon vertexing are key features to its very good performance for B-Physics. Its trigger and data acquisition system, with a high bandwidth for track based triggers [2], allows the recording of large samples, up to several millions, of fully reconstructed beauty and charm hadrons.

In the following we present three recent measurements which offer new insights into open and hidden charm production.

2. CHARM MESON PAIRS

With only $5.8\,\mathrm{pb}^{-1}$ of early data in Run II, CDF measured the integrated and differential $d\sigma/dp_T$ cross sections of central, i.e. rapidity $|y| < 1$, D^0, D^+, D^{*+} and D_s^+ charm mesons in fully reconstructed hadronic decay modes [3]. In spite of the relatively small integrated luminosity of this early data sample, systematic uncertainties have been dominating the uncertainty of the measurement of inclusive cross sections.

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Comparing a fixed-order next-to-leading log calculation (FONLL) [4] to the measured cross sections, the cross sections were found to be underestimated by up to a factor of 2 at low transverse momentum p_T. However, measurement and prediction were still considered to be compatible owing to the large uncertainty due to scale variations in the theory calculation.

A more recent calculation in a next-to-leading order general-mass variable-flavor-number (GM-VFN) scheme [5] exhibits a smaller deviation from the measurement. Due to the reduced uncertainty of this calculation, the level of (in)compatibility between theory and measurement remains the same.

In QCD, flavor conservation implies that charm quarks are always produced in quark anti-quark pairs, $c\bar{c}$. A more detailed understanding of the underlying production process may be obtained from events in which both charm particles are detected. Correlations between the two charm particles, especially their opening angle in azimuth $\Delta\phi$, give access to different underlying production subprocesses [6]. For example, in a leading order plus parton shower model, as implemented in the event generator Pythia, prompt charm particles are produced back-to-back via flavor creation while collinear charm particles are due to gluon splitting. The centrality requirement, $|y| < 1$, leaves only a miniscule acceptance for the flavor excitation subprocess, which gives rise to a large separation Δy between the two charm particles.

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

Equations 1 and 2 give the expressions for the inclusive σ_i^D and pair $\sigma_{ij}^{D_1D_2}$ cross sections in p_T-bin $i(j)$,

$$\text{inclusive}: \ \sigma_i^D = \frac{N_i \cdot f_p}{\int \mathcal{L}\ \mathrm{d}t \cdot \epsilon_i \cdot Br}, \tag{1}$$

$$\text{pairs}: \ \sigma_{ij}^{D_1D_2} = \frac{N_{ij} \cdot f_p^{D_1D_2}}{\int \mathcal{L}\ \mathrm{d}t \cdot \epsilon_{ij} \cdot Br_1 Br_2}, \tag{2}$$

where $\int \mathcal{L}\ \mathrm{d}t$ is the integrated luminosity of the dataset, the $Br_{(1,2)}$ are the branching fractions of the reconstructed decay modes, N_i and N_{ij} are the numbers of signal inclusive D and D_1D_2 pairs, f_p and $f_p^{D_1D_2}$ are the fractions of these which are promptly produced, ϵ_i and ϵ_{ij} denote the efficiencies of inclusive D and D_1D_2 pairs.

A detailed study of simulated events verified that the pair efficiency can be written as product of efficiencies of the triggered charm meson and the second charm meson, $\epsilon_{ij} = \epsilon_i \cdot \epsilon_j$. Therefore, the pair cross section can be expressed relative to the inclusive cross section as

$$\sigma_{ij}^{D_1D_2} \quad = \quad \frac{N_{ij} \cdot f_p^{D_1D_2}}{N_i \cdot f_p \cdot \epsilon_j} \frac{\sigma_i^{D_1}}{Br_2}. \tag{3}$$

The published inclusive cross sections, measured in a relatively short, and thus well controlled in terms of trigger and reconstruction efficiencies, data taking period, can be exploited to give a normalization to the pair cross section.

The quantities related to the inclusive D mesons are extracted using methods already established for measurement of the inclusive cross section, i.e., fits to the candidate invariant mass distributions for the signal yields N_i and fits to the sideband subtracted candidate impact parameter distributions to obtain the prompt fractions f_p.

Only $D^{*+} \to D^0(\to K\pi)\pi$ are taken as second charm particles, as their mass difference $\Delta m = m(K\pi\pi) - m(K\pi)$ provides a sufficient handle to suppress combinatorial background in a loose selection of D^{*+}, which only employs cuts motivated by fiducial criteria and kinematic cuts of the CDF track reconstruction algorithms. A parameterization of the efficiency of the D^{*+}, the second charm meson in the pair (DD^{*-}), is obtained from 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 detector acceptance and reconstruction efficiencies of simulated pair events have been validated using the inclusive D candidates from data. Combinatorial background in the DD^{*-} sample is eliminated using a 2-dimensional sideband subtraction. The impact parameter distribution of the D^0 in the D^{*+} decay allows us to extract the number of prompt pairs.

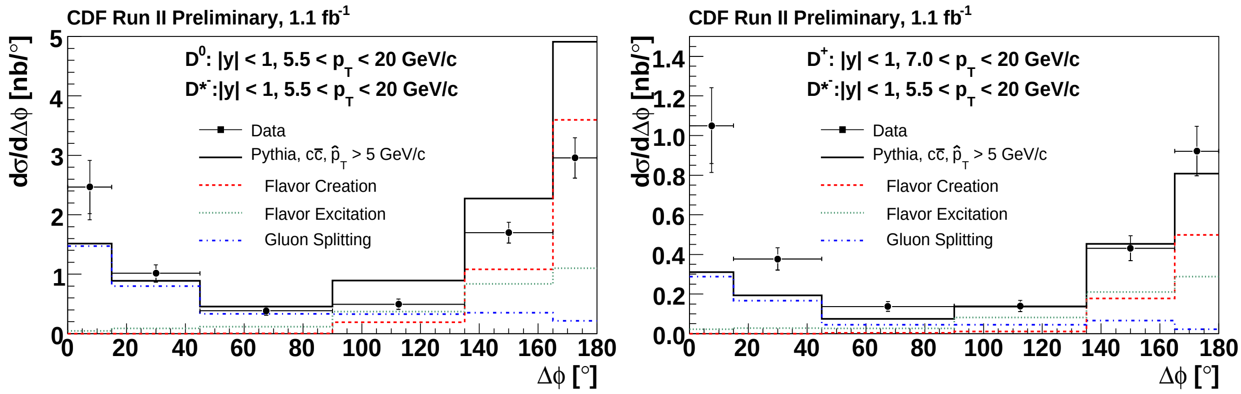

Figure 1. The D^0D^{*-} (left) and D^+D^{*-} (right) pair cross sections as a function of $\Delta\phi$. The measurements (points) are compared to the leading order matrix element plus parton shower event generator Pythia (Tune A) (black line). Also shown are the contributions of the leading order production mechanisms flavor creation (red), flavor excitation (green) and gluon splitting (blue).

More than 2000 signal pairs for both modes, D^0D^{*-} and D^+D^{*-} pairs, have been used for the first measurement of prompt charm meson pair production cross sections in $p\bar{p}$ collisions.

Figure 1 displays the D^0D^{*-} and D^+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, 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

Prior to the first measurements of J/ψ and $\psi(2S)$ cross sections at the Tevatron (Run I) [7], their production mechanism was described by the color singlet model (CSM) [8]. According to the CSM, the feed-down contribution from the higher mass charmonium states would dominate over the direct J/ψ production, and a larger fraction of prompt J/ψ would result from the decay of χ_c states. However, the Tevatron results show that the CSM underestimates the observed direct production cross section by an order of magnitude for J/ψ and nearly a factor of 50 for $\psi(2S)$, which has no feed-down contribution from χ_c states. To address this discrepancy, a color octet contribution was introduced [9]. Adjustable hadronization parameters of this model allow the amplitude and p_T-dependence of the production cross section to match the observation. The increase in cross section can be attributed to the contribution of high p_T gluons which give rise to transversely polarized J/ψ and $\psi(2S)$ [10]. Recently a different approach to the hadronization problem has been introduced, resulting in two new models, one model inspired by $\mathbb{P}$omeron ideas [11], and the other model known as k_T-factorization model [12]. Both models predict that at sufficiently large p_T of J/ψ and $\psi(2S)$, these vector mesons will exhibit longitudinal polarization.

Both vector mesons are reconstructed in their decays into muon pairs, J/ψ and $\psi(2S) \rightarrow \mu^+\mu^-$. The distribution of the μ^+ in the vector meson rest frame relative to the flight direction of the vector meson in $p\bar{p}$ rest frame, measured by the polar angle θ^* depends on the polarization parameter $\alpha \in [-1, 1]$: $\frac{dN}{d\Omega} \propto 1 + cos^2\theta^*$, 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, $\frac{d_0}{\sigma_0}$, of the two μ-tracks: $S = (\frac{d_0^+}{\sigma_{0+}})^2 + (\frac{d_0^-}{\sigma_{0-}})^2 \leq 8$. Conversely the samples of secondary J/ψ and $\psi(2S)$ are enriched by requiring $S \geq 16$. Residual contributions of sec-

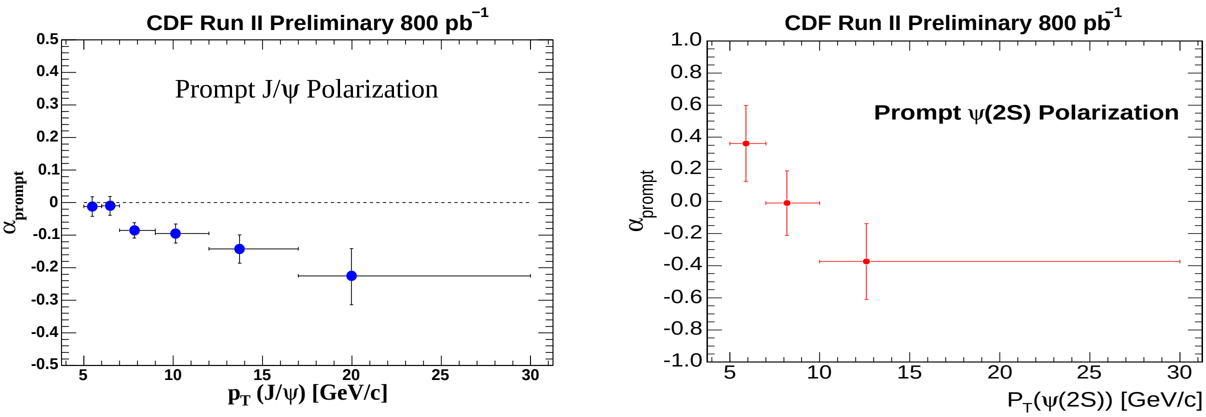

Figure 2. The polarization (α) of the vector meson as a function of its transverse momentum p_T, for prompt J/ψ (left) and prompt $\psi(2S)$ (right).

ondary (prompt) J/ψ and $\psi(2S)$ are taking 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 $\psi(2S)$ 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 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 $\mathcal{L} = 800$ pb^{-1}.

The polarization of the vector mesons from B-decays is found to be independent of p_T. Consistent with the more precise results from the B-factories, we measure $\alpha_B(J/\psi) = -0.066 \pm 0.050$. We also extract $\alpha_B(\psi(2S)) = 0.33 \pm 0.25$. 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 smaller sample size. However, thanks to the absence of feed-down from χ_c states, $\psi(2S)$ represents direct vector meson production more closely.

4. RELATIVE PRODUCTION OF χ_{c1} AND χ_{c2}

Recent approaches to understanding charmonium production make use of non-relativistic QCD [13]. It is known that a significant contribution of prompt J/ψ production is indirect, i.e. it results from feed-down of higher mass charmonium states [14]. In particular the radiative decay of χ_{cJ} accounts for a sizable fraction of the J/ψ production. Any calculation of J/ψ production must include χ_{cJ} production as well. The notation χ_{cJ} represents the states χ_{c0} χ_{c1} and χ_{c2}. Knowledge of the ratio of prompt χ_{c1} and χ_{c2} production cross sections is needed for any model that calculates J/ψ production through radiative χ_{cJ} decays, and may be an important standard for comparing production models.

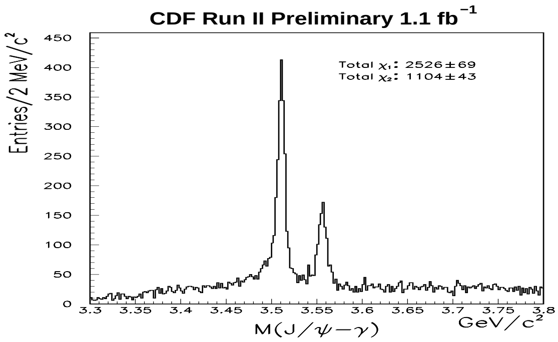

Figure 3. The $J/\psi\gamma$ invariant of the all χ_{cJ} candidates in the data sample.

The reconstruction of the decay $\chi_{cJ} \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\gamma$ is difficult,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 us 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 χ_{c1} from 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 in the ratio production cross section $\sigma_{\chi_{c2}}/\sigma\chi_{c1}$. Figure 4 displays the measurement of this ratio of production cross sections as a function of p_T. 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 $\frac{5}{3}$ [15]. Such models appear to be ruled out by this measurement.

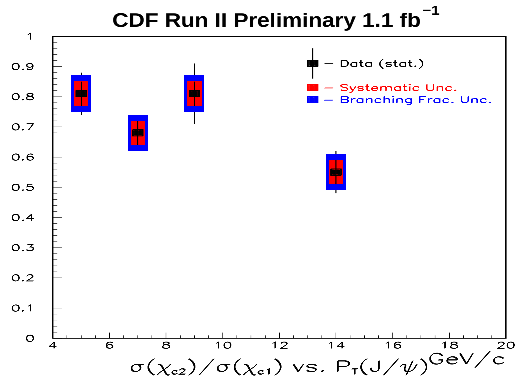

Figure 4. The ratio of χ_{cJ} production cross sections, $\sigma(\chi_{c2})/\sigma(\chi_{c1})$, as a function of the transverse momentum $p_T(J/\psi)$.

5. CONCLUSION

The unprecedented integrated luminosity delivered by the Tevatron as well as the sustained excellent performance of the CDF II detector and its ability to support a high bandwidth for track based triggers, in spite of ever increasing instantaneous luminosity, opens a window of opportunity for detailed studies of charm hadron production.This was not anticipated at the beginning of the CDF II program.

Unexpected results for open charm, e.g. charm meson pair cross sections, as well as for hidden charm production, e.g. J/ψ and $\psi(2S)$ polarization and relative production of $\chi_{c1}(P1)$ and $\chi_{c2}(1P)$, have the potential to instigate new approaches to QCD models and calculations. These new results will help improving our understanding of heavy quark production in proton (anti-)proton collisions.

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