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CHARM AND BEAUTY PRODUCTION AT CDF

PETER J. BUSSEY
FOR THE CDF COLLABORATION
Department of Physics and Astronomy
University of Glasgow, Glasgow G12 8QQ, UK
E-mail: p.bussey@physics.gla.ac.uk

A summary is presented of recent results from the CDF collaboration on the production of charm and beauty hadrons.

1 Introduction

The Tevatron at Fermilab is at present the world's highest energy particle accelerator. After extensive refurbishments, data taking for Run II started in 2001, and by the end of 2003 over 200 pb^{-1} of usable integrated luminosity had been accumulated by each Collider experiment, double the total for Run I.

In preparation for Run II, the CDF detector also underwent an extensive upgrade. Of special importance for the results presented here are the new Silicon Vertex Tracker, and a number of significant improvements to the trigger system. The Extremely Fast Tracker allows tracks in the central tracking system to be identified in the first-level trigger. In the second-level trigger, these tracks can be matched with tracking information from the SVT so as to identify events containing a displaced secondary vertex, by identifying tracks with a finite impact parameter relative to the beam line. The events are finally recorded after verification by the third-level trigger.

In this talk, recent measurements and analyses of charm and beauty states using the CDF detector are presented. The emphasis here is on production mechanisms; studies of the decay and lifetime properties of such particles are given in other contributions to these Proceedings.

2 Theoretical framework

Quantum Chromo-Dynamics is currently our most basic theory to describe the composition and production of hadrons. The study of particles containing c and b quarks provides important perspectives on our understanding of the application of this theory, because the heavy masses of these quarks allow perturbative calculations to be employed in ways that differ from the case of light partons.

The principal lowest-order QCD processes that contribute to the production of heavy quarks Q in $p\bar{p}$ collisions are the $q\bar{q} \to Q\bar{Q}$ and $gg \to Q\bar{Q}$, processes. When these so-termed *flavour creation* processes take place as hard scattering of the initial-state quarks or gluons in the (anti-)proton, two heavy quarks are produced at high transverse momentum p_T, and subsequently fragment into hadrons.

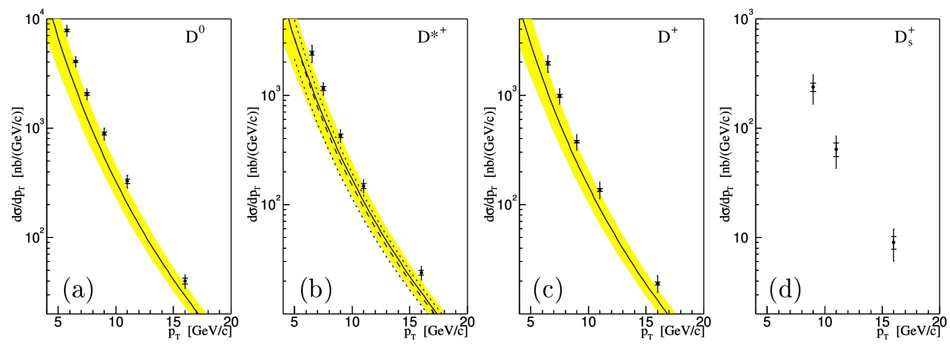


Figure 1. CDF inclusive cross sections for D^0, D^{*+}, D^+ and D_s^+ as a function of transverse momentum p_T. Comparison is made with the FONLL calculation of Cacciari and Nason [3] (a)–(c) and a similar NLO calculation from Kniehl et al (priv. comm.) (b). No calculation was available for the D_s case (d).

There is a further possibility that an initial-state gluon in the proton may split into a $Q\bar{Q}$ pair, and one of these may scatter at high p_T off a parton in the other incoming beam particle. This splitting may be calculated within perturbative QCD. Sometimes the unscattered heavy quark is formed at high p_T, but most often it will be at low p_T and will not be detected. In this case the heavy quark pair may be regarded as part of the parton structure of the proton. These are known as *flavour excitation* processes. A third type of process involves the production of a $Q\bar{Q}$ pair via the splitting of a gluon radiated within the fragmentation products of a final-state high-p_T parton. These may be referred to as *fragmentation* heavy quark pairs.

Many QCD calculations have been performed at LO and NLO to evaluate the various heavy quark production cross sections. Such cross sections normally need to be convoluted with a phenomenological fragmentation function to evaluate the cross section for producing a given charm or beauty particle at a given p_T value. At LO, the familiar leading-log Monte Carlo programs PYTHIA and HERWIG have long enabled the final-state hadronisation to be performed as part of the event generation. The recently-developed MC@NLO program (S. Frixione et al., see these Proceedings) does this also in next-to-leading order parton calculations.

3 Open charm production

The first published result from CDF II [1] consisted of a precision measurement of the mass difference between the D^+ and D_s^+ mesons, both observed in their decays to $\phi\pi^+$. (Throughout this article, the mention of a state will imply also the corresponding charge conjugate state.) Precision was enhanced by a careful treatment of the material through which the particles were tracked in the detector. The measured value of $\Delta m = 99.41 \pm 0.38 \pm 0.21\,\mathrm{MeV/c^2}$ improves on the previous PDG value.

Using just 6 pb^{-1} of integrated luminosity, CDF have published the first in-

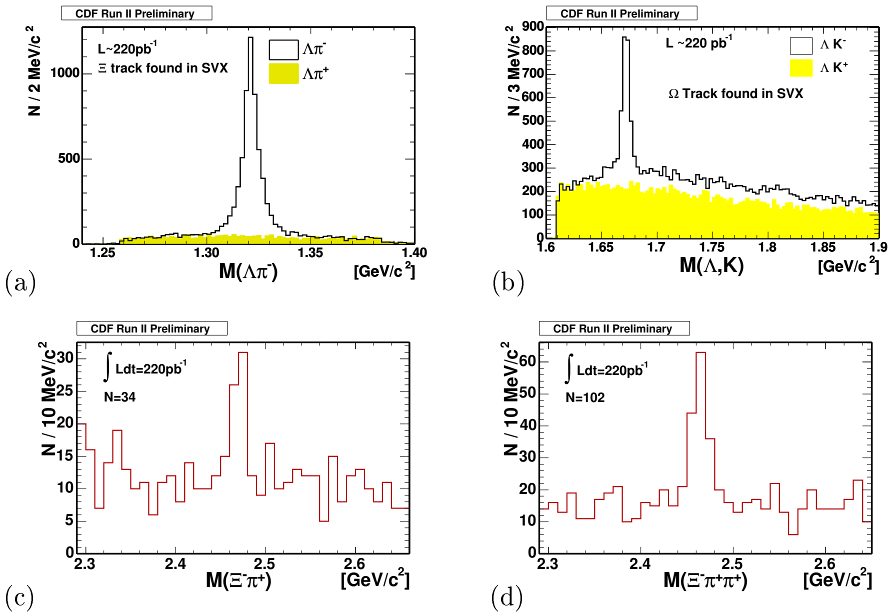


Figure 2. Hyperon mass spectra observed by CDF. In each case the charge-conjugate combination is included, and in the first two plots the wrong-sign combination is shown for comparison. (a) $\Lambda\pi^-$, (b) ΛK^-, (c) $\Xi^-\pi^+$, (d) $\Xi^-\pi^+\pi^+$.

clusive charm cross sections obtained at the Tevatron [2]. The results are shown in fig. 1, compared with the predictions from two NLO calculations. The FONLL model uses a fixed-order NLO calculation employing next-to-leading logarithms and a phenomenological D fragmentation function obtained from ALEPH data, with variable number of flavours. The cross sections refer to centrally produced D mesons with rapidity in the range $[-1,+1]$. The p_T distribution is accurately described in shape by the calculations, whose magnitude lies slightly lower than the data, though still just about within the error band due to the renormalisation and factorisation scale uncertainties. Further uncertainties from the mass of the charm quark are considered to be not larger than this. The Kniehl calculation uses a different fragmentation scheme and mass treatment from that of Cacciari et al. Overall, the agreement with theory appears satisfactory.

In baryon physics, CDF have demonstrated the observation of a variety of hyperon states, some of which contain charm as well as strangeness. The method is based first on the reconstruction of $\Lambda \to p\pi^-$ decays; the cascade baryon Ξ^- may then be reconstructed in its $\Lambda\pi^-$ decay mode, the CDF tracking algorithm having been modified to allow for the small kink in the observed track when the Ξ decays into the π. An extremely clean signal is observed (fig. 2(a)). The Ω^- particle is also prominently visible (fig. 2(b)).

The $\Xi^-\pi^+$ and $\Xi^-\pi^+\pi^+$ spectra now show clear peaks corresponding to the $\Xi_c(2470)$ in its neutral and singly-charged states respectively (figs. 2(c,d)). This is the first observation of these states in $p\bar{p}$ collisions.

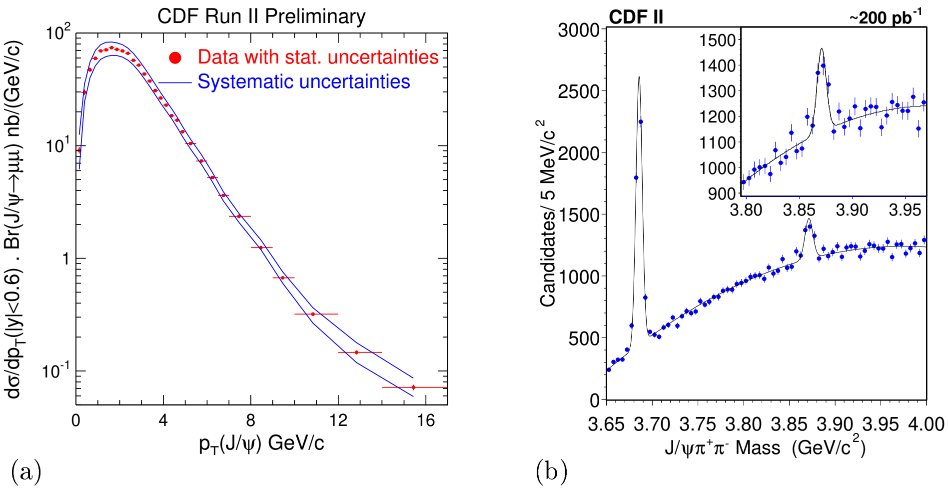


Figure 3. (a) J/ψ differential section observed by CDF as a function of p_T, (b) $J/\psi\pi^+\pi^-$ mass spectrum, showing peaks corresponding to the $J/\psi(4S)$ and $X(3872)$ states.

4 Charmonium production

The inclusive production of the J/ψ and other $c\bar{c}$ states was extensively studied at CDF I. The process is evaluated theoretically as a perturbative QCD calculation of the quark-antiquark state, together with a modelling of the subsequent hadronisation into the observed J/ψ. Both colour-singlet and colour-octet $Q\bar{Q}$ states may in principle be produced, and it is of interest to establish whether both mechanisms are required to account for the observations. On the basis of the p_T distributions, the Run I data demonstrated the need for both contributions. However the apparatus was then able to trigger only on J/ψ p_T values above 4 GeV/c, restricting the full comparison with theory. Using a new dimuon trigger, CDF is now able to record central $J/\psi \to \mu^+\mu^-$ production down to p_T=0. Preliminary results are shown in fig. 3(a). The measurable cross section is increased by a factor of approximately 14 compared to Run I.

In the summer of 2003 the BELLE experiment at KEK announced the observation of a new charmonium state at 3872 MeV/c^2, decaying into $J/\psi\pi^+\pi^-$. The physical nature of this state is unclear, since there is no very natural interpretation: a heavy $^3D_2$ state has been suggested, or possibly a $D^0\bar{D}^{*0}$ "molecule". CDF have confirmed this discovery [4]. J/ψ signals at $p_T > 4$ GeV/c were identified in the $\mu^+\mu^-$ decay mode, and combined with charged pions with $p_T > 0.4$ GeV/c. A clear peak at 3872 MeV/c^2 is seen, the $\psi'(4S)$ peak being very clean and serving as a control signal. A further cut at $\pi^+\pi^-$ masses above 500 MeV/c^2 enhances the signal, as also found by BELLE. This is shown in fig. 3(b). The width is consistent with the resolution of the apparatus; the fitted mass is 3871$\pm$0.7$\pm$0.4 MeV/c^2, in good agreement with BELLE's value of 3871.7$\pm$.6 MeV/c^2.

Subsequently CDF have shown that their signal is partly prompt and partly

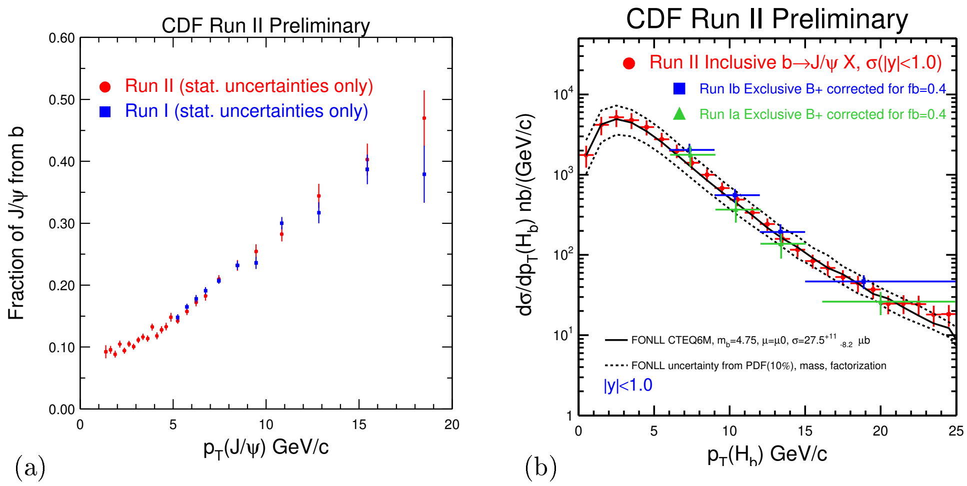


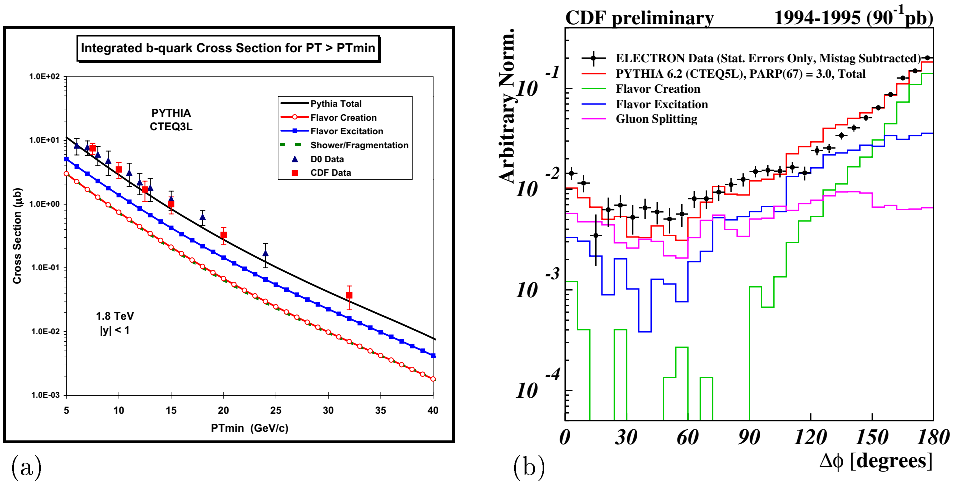
Figure 4. (a) Fraction of inclusive J/ψ which arise from the decay of a B hadron, as a function of p_T, (b) Differential cross section for inclusive B hadron production as a function of p_T.

arising from long-lived decays, presumably of B hadrons as must be the case in BELLE. The long-lived fraction is found to be 16±4.9±2 % (preliminary).

5 Beauty production

Both CDF and D0 published cross sections for inclusive B hadron production in Run I. The results from the two experiments were in agreement, but lay significantly above the existing QCD predictions, making an experimental confirmation in Run II an urgent necessity. From the CDF J/ψ cross sections described above, B cross sections have been extracted using an unfolding technique which incorporates information from the SVT to identify the displaced decay vertex of the B state. The fraction of J/ψ arising from initially produced b quarks is approximately 10% at p_T values around 2 GeV/c, rising to 50% at 20 GeV/c (fig. 4(a)). The resulting differential cross sections agree well with those of Run I, indicated in fig. 4(b) as the points with larger error bars. There is also agreement with the latest NLO QCD calculations represented by the FONLL predictions of Cacciari et al.[5], which are plotted with their uncertainty. A similarly good agreement is obtained with the MC@NLO Monte Carlo. Both data and theory are thus significantly improved. The areas of theory improvement lie especially in the proton PDF's that are employed, and in the description of the b quark hadronisation.

It is also found that PYTHIA can give a good description of the data, provided that the flavour creation, flavour excitation and fragmentation contributions are properly accounted for (fig. 5(a)). The three contributions are separately evaluated using PYTHIA 6.115 with the CTEQ3L proton PDF's and a hard scattering p_T threshold of 3 GeV/c. A further study of this topic has been performed using Run I data on $B\bar{B}$ correlations, The three contributions are plotted separately in a



(a) (b)

Figure 5. (a) CDF and D0 Run I unfolded cross sections for inclusive b-quark production vs. p_T. The lower curve is the (coincident) contributions from flavour creation and from fragmentation; the central curve is flavour creation and the top curve is the sum. All are evaluated using PYTHIA. (b) Azimuthal angle difference $\Delta\phi$ between B hadrons having p_T values of > 14 GeV/c (with an electron tag) and > 7 GeV/c. The upper histogram is the total predicted by PYTHIA from the three component heavy flavour production mechanisms, plotted as the lower histograms.

comparison of the azimuthal separation $\Delta\phi$ of the $B\bar{B}$ particles in fig. 5(b), where the initial-state gluon radiation generated by PYTHIA has also been optimally tuned. The flavour creation component is strongly back-to-back peaked, the excitation component less so, while the gluon splitting component is fairly flat in $\Delta\phi$. The proportions are fixed at their predicted values, but the overall normalisation is allowed to float. A plausible fit is obtained; however it is not perfect and more detailed studies will be valuable.

Summary

In Run II of the Tevatron, the CDF Collaboration has expanded its already flourishing programme of heavy flavour physics. This enables the latest theoretical models of heavy quark production to be tested from a number of viewpoints. Work is of course ongoing, but the improved agreement between NLO QCD and the data already represents a triumph both for theory and for experiment.

References

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