Parton Model Calculation of Inclusive Charm Production by a Low-energy Antiproton Beam

Pierre Artoisenet

Center for Particle Physics and Phenomenology,
Université Catholique de Louvain, B1348 Louvain-la-Neuve, Belgium

Eric Braaten

Physics Department, Ohio State University, Columbus, OH 43210, USA and

Bethe Center for Theoretical Physics,
Universität Bonn, 53115 Bonn, Germany

(Dated: June 22, 2009)

Abstract

The cross section for inclusive charm production by a low-energy antiproton beam is calculated using the parton model and next-to-leading order perturbative QCD. For an antiproton beam with a momentum of 15 GeV, the charm cross section at next-to-leading order in the QCD coupling constant changes by more than an order of magnitude as the charm quark mass is varied from 1.3 to 1.7 GeV. The variations can be reduced by demanding that the same value of the charm quark mass give the measured charm cross sections for fixed-target experiments with a proton beam. The resulting estimate for the charm cross section from a low-energy antiproton beam is large enough to allow the study of charm meson mixing.

PACS numbers: 12.38.-t, 12.39.St, 13.20.Gd, 14.40.Gx

Flavor physics in the charm sector is an aspect of elementary particle physics that has not been fully explored. The Standard Model of particle physics predicts the rates for charm meson mixing and for CP violation in charm meson decays to be very small, which makes the charm sector a promising window into new physics beyond the Standard Model [1]. Mixing of the neutral charm mesons D^0 and $\bar{D}^0$ was finally observed by several experiments in 2007 [3, 4, 5]. Searches for CP violation in the charm sector would require significantly larger data samples. One possible source of large data samples of flavor-tagged charm mesons is a low-energy antiproton beam, such as the High Energy Storage Ring (HESR) planned at the GSI laboratory. Quantitative predictions for the charm cross section at such a facility are needed in order to assess the prospects for studying charm flavor physics.

There have been very few previous estimates of the charm production rate by a low-energy antiproton beam. Braaten estimated the exclusive cross section for $D^{*0}\bar{D}^0$ in low-energy $\bar{p}p$ collisions by scaling measured cross sections for $K^{*-}K^+$ [5]. He obtained a surprisingly large cross section of 360 nb at a center-of-mass energy of 5.71 GeV. Titov and Kämpfer have used a Regge model based on baryon exchange to predict the differential cross sections and longitudinal asymmetries for the exclusive production of pairs of charm mesons [6], but they did not calculate cross sections integrated over angles. In this paper, we use the parton model and perturbative QCD to calculate the inclusive charm cross section from a low-energy antiproton beam.

The parton model and perturbative QCD have been used extensively to calculate cross sections for charm quarks, bottom quarks, and top quarks in hadron collisions. In the case of charm production, the applications have ranged from fixed-target experiments with proton beams with center-of-mass energy $\sqrt{s}$ below 10 GeV to Fermilab's Tevatron $\bar{p}p$ collider and CERN's Large Hadron Collider with $\sqrt{s} = 2$ TeV and 14 TeV, respectively. The parton model predictions for top quark production and for the transverse momentum distributions for bottom quarks and charm quarks are well tested at the Tevatron. The parton model was used to predict the charm cross section in pp collisions at $\sqrt{s} = 200$ GeV at Brookhaven's Relativistic Heavy Ion Collider (RHIC) [10]. We will use the parton model to make the much larger extrapolation down to $\bar{p}p$ collisions with center-of-mass energies as low as 5.5 GeV.

A convenient source of flavor-tagged charm mesons in high energy physics experiments is the production of the charm mesons $D^{*\pm}$. In the parton model, the inclusive cross section for producing D^{*+} in $\bar{p}p$ collisions can be expressed as

$$\sigma[\bar{p}(P_A)p(P_B) \to D^{*+} + X] = \sum_{ij} \int_0^1 dx_1\, f_{i/\bar{p}}(x_1) \int_0^1 dx_2\, f_{j/p}(x_2) \\ \times \hat{\sigma}[i(x_1 P_A) j(x_2 P_B) \to c + X]\, P_{c\to D^{*+}}, \qquad (1)$$

where $P_{c\to D^{*+}}$ is the fragmentation probability for a charm quark to hadronize into a D^{*+} meson. At low energies, the dominant contributions to the sums over the types of partons come from $(i,j) = (\bar{u}, u)$ and $(\bar{d}, d)$. The parton distributions $f_{i/\bar{p}}$ and $f_{j/p}$ depend on a factorization scale μ_f. The parton cross section $\hat{\sigma}$ can be calculated as a power series expansion in $\alpha_s(\mu_r)$, with coefficients that depend on μ_f and on the renormalization scale μ_r.

The lowest energy experiment in which the fragmentation probability $P_{c\to D^{*+}}$ has been measured accurately is e^+e^- annihilation at a center-of-mass energy of 10.6 GeV. The Belle Collaboration has made precise measurements of the inclusive cross sections for D^0, D^+, D_s^+, Λ_c^+, D^{*0}, and D^{*+} [15]. Using the constraint that the fragmentation probabilities for D^0, D^+, D_s^+, and Λ_c^+ add up to 1, we can determine the fragmentation probability for D^{*+}

at that energy scale to be $P_{c\to D^{*+}} = 24\%$. We will use this as an estimate of $P_{c\to D^{*+}}$ in low-energy $\bar{p}p$ collisions.

To assess whether the extrapolation of the parton model calculation to center-of-mass energies as low as 5.5 GeV is plausible, we first consider charm production in e^+e^- annihilation. From the charm meson threshold at $\sqrt{s} = 3.73$ GeV up to about 4.6 GeV, the cross section varies dramatically due to the charmonium resonances $\psi(3730)$, $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$. Only above 4.6 GeV is the cross section smooth enough to agree reasonably well with perturbative QCD. However *quark-hadron duality* can be exploited to extend the region of applicability of perturbative QCD to significantly lower energies by smearing over the energy [14]. The duality holds between the perturbative charm quark cross section and the sum of the cross sections for charm hadrons and for charmonium states below the charm threshold. Since the perturbative cross section is smooth without any local minima, the smeared hadron cross section should also be smooth. The minimum smearing interval is the spacing between radial excitations of the charmonium states, which is about 400 MeV. For the perturbative charm quark cross section to be a good approximation to the charm hadron cross section alone, the energy must be large enough that the smeared cross section receives no significant contributions from the charmonium states below the charm threshold and in particular from the $\psi(3686)$. This requires the energy at the center of the smearing interval to be greater than about 3.9 GeV.

We now compare inclusive charm production in $\bar{p}p$ collisions and e^+e^- annihilation. One difference is in the charmonium resonances that can be produced. The annihilation of e^+e^- can only produce resonances with quantum numbers 1^{--}. In contrast, $\bar{p}p$ collisions can produce charmonium resonances with any of the possible quantum numbers J^{PC}. Potential models predict the spacing between radial excitations in each angular momentum channel to be about 400 MeV. Thus smearing in the $\bar{p}p$ center-of-mass energy by that amount might be sufficient to get a smooth cross section above the $D\bar{D}$ threshold in each J^{PC} channel. The sum over J^{PC} will help to further smooth out the cross section. The parton model suggests that it may not be necessary to smear over the $\bar{p}p$ center-of-mass energy, because the integration over the momentum fractions x_1 and x_2 of the colliding partons automatically provides some smearing in the energy. To get a smooth cross section, it may be sufficient to demand that this integration provides smearing in the center-of-mass energy of the colliding partons by at least 400 MeV.

There is an important difference between e^+e^- annihilation and $\bar{p}p$ collisions in the parton processes that create the $c\bar{c}$ pair and therefore in the hadronization processes that produce the charm mesons. The annihilation of e^+e^- creates a $c\bar{c}$ pair and gluons whose overall color state is a singlet. In $\bar{p}p$ collisions, the colliding partons have color connections to the remnants of the $\bar{p}$ and p. The $c\bar{c}$ pair and the gluons that are created by the collision therefore also have color connections to the remnants of the p and $\bar{p}$. Part of the energy associated with the constituent mass of the light quark in the charm meson may be provided by those remnants. Thus it is possible for a parton collision with center-of-mass energy $\sqrt{\hat{s}}$ below the charm meson threshold to produce charm mesons.

Based on both the analogy with e^+e^- annihilation as well as the differences, we propose the following two conditions as plausible criteria for the validity of the parton model calculation of charm production:

A. The integration over parton momentum fractions should provide smearing of at least 400 MeV in the invariant mass $\sqrt{\hat{s}}$ of the colliding partons.

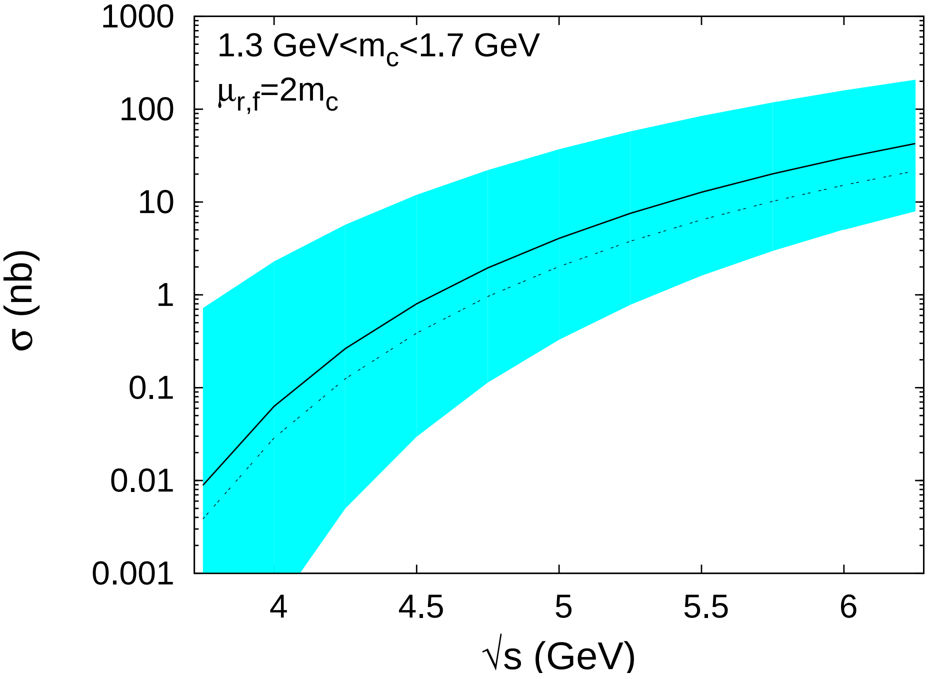

FIG. 1: Cross section for inclusive charm production in $\bar{p}p$ collisions as a function of the center-of-mass energy $\sqrt{s}$. The solid line is the NLO result for $m_c = 1.5$ GeV and $\mu_r = \mu_f = 2m_c$. The shaded band corresponds to varying m_c from 1.3 and 1.7 GeV. The dashed line is the LO result.

B. The dominant contributions should come from $\sqrt{\hat{s}}$ above the $D\bar{D}$ threshold at 3.73 GeV.

If the center-of-mass energy is too low for the criteria **A** and **B** to be satisfied, the parton model calculation can still be used as a phenomenological model for extrapolating the charm cross section to low energies.

To calculate the charm cross section in Eq. (1), we use the well-known next-to-leading order (NLO) calculations of the parton cross sections for heavy-quark production [7, 8, 9]. The parameters in the charm cross section are the charm quark mass and the renormalization and factorization scales. We do not carry out any resummation of logarithms of the transverse momentum, because these logarithms are not large at this low energy. We also do not carry out any resummation of the threshold logarithms of $\hat{s} - 4m_c^2$ [16, 17], where $\hat{s}$ is the invariant mass of the colliding partons, although these logarithms can be large. The inclusive cross section for $\bar{p}p \to c\bar{c} + X$ is calculated using the Monte-Carlo program MCFM [11]. The implementation of the cross section at NLO makes use of the matrix elements calculated in Ref. [7]. This computation is carried out in the $\overline{\text{MS}}$ scheme with $n_{\text{f}} = 3$ light flavors of quarks in the initial state. At LO and NLO, we use the parton distribution sets CTEQ6L1 and CTEQ6M, respectively [12]. These sets have been constructed for $n_{\text{f}} = 5$ initial flavors, which leads to a suppression of the gluon density compared to the case $n_{\text{f}} = 3$. At NLO accuracy, the correction term that must be added to compensate for the different number of flavors is proportional to the gluon-initiated Born-level cross section and depends logarithmically on the ratio μ_f/m_c [13]. Since our factorization scale is comparable to m_c, the correction term proves to be small and can be disregarded compared to other theoretical errors.

The parameters m_c, μ_r, and μ_f and their theoretical uncertainties are determined as

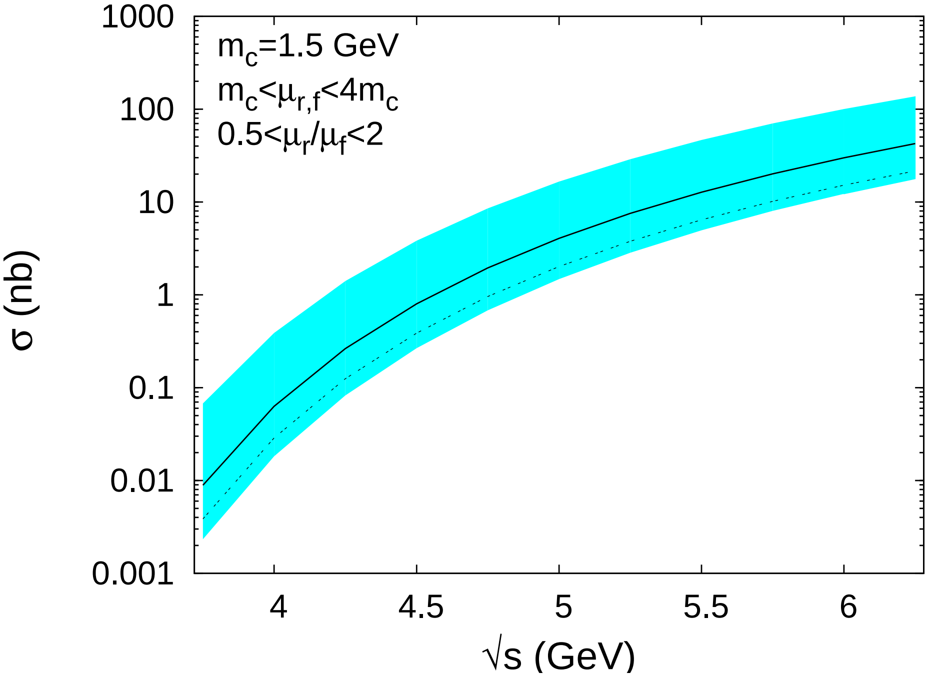

FIG. 2: Cross section for inclusive charm production in $\bar{p}p$ collisions as a function of the center-of-mass energy $\sqrt{s}$. The solid line is the NLO result for $m_c = 1.5$ GeV and $\mu_r = \mu_f = 2m_c$. The shaded band corresponds to varying μ_r and μ_f from m_c to $4m_c$ with $\frac{1}{2} < \mu_f/\mu_r < 2$. The dashed line is the LO result.

follows. We choose their central values to be $m_c = 1.5$ GeV and $\mu_r = \mu_f = 2m_c$. Our central value of $\mu_r = \mu_f$ is twice that used in Ref. [10], because this choice decreases the sensitivity to the scales at the low energies we consider. The scale $2m_c$ is a natural choice, because this is the minimal invariant mass of the virtual gluon in the dominant leading-order parton process $\bar{q}q \to c\bar{c}$. We obtain the error band from the charm quark mass by setting $\mu_r = \mu_f = 2m_c$ and allowing m_c to range from 1.3 to 1.7 GeV. We obtain the error band from the scales by setting $m_c = 1.5$ GeV and allowing μ_r and μ_f to range from m_c to $4m_c$ with $\frac{1}{2} < \mu_f/\mu_r < 2$.

Our results for the inclusive charm cross section are shown in Figs. 1 and 2 as functions of the center-of-mass energy $\sqrt{s}$. Two values of $\sqrt{s}$ that are of particular interest are 4.11 GeV, which corresponds to the maximum antiproton momentum of 8 GeV in Fermilab's accumulator ring, and 5.47 GeV, which corresponds to the maximum antiproton momentum of 15 GeV in the design of HESR. The central value of the cross section for $m_c = 1.5$ GeV and $\mu_r = \mu_f = 2m_c$ at $\sqrt{s} = 5.47$ GeV is 12 nb. The error band in Fig. 1 from varying the charm quark mass corresponds to a multiplicative factor of about $7.4^2 \approx 55$. The error band in Fig. 2 from varying μ_r and μ_f corresponds to a multiplicative factor of about $3.1^2 \approx 9.6$. The error band from varying m_c is significantly wider.

The reason for the large sensitivity to the charm quark mass is illustrated in Fig. 3, which shows the distributions at NLO of the invariant mass $\sqrt{\hat{s}}$ of the colliding partons for $\sqrt{s} = 5.47$ GeV and $m_c = 1.3$, 1.5, and 1.7 GeV. The full widths at half maximum of these distributions is about 500 MeV, which is large enough to provide the smearing required by our criterion **A** for the validity of the parton model calculation. However the peaks of

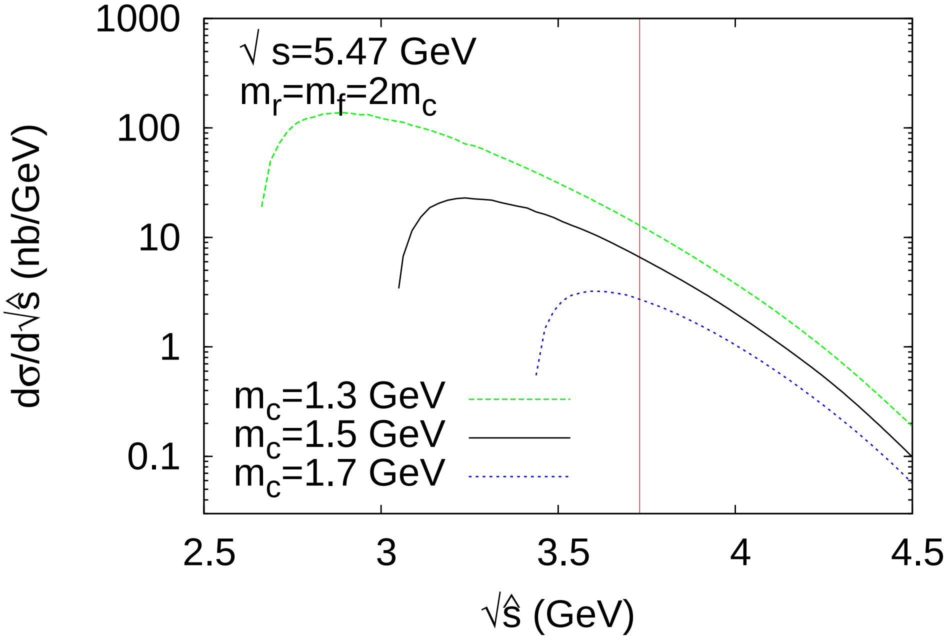

FIG. 3: Distribution of the invariant mass $\sqrt{\hat{s}}$ of the colliding partons at NLO for $\sqrt{s} = 5.47$ GeV, $\mu_r = \mu_f = 2m_c$, and $m_c = 1.3$, 1.5, and 1.7 GeV (left, middle, and right curves). The solid vertical line marks the position of the $D\bar{D}$ threshold.

the distributions are significantly below the $D\bar{D}$ threshold, which is indicated by the solid vertical line in Fig. 3. Thus our criterion **B** is not satisfied. This casts some doubt on the validity of the calculation for $\sqrt{s}$ as low as 5.47 GeV.

We can still regard the parton model calculation as a phenomenological model for the extrapolation of the charm cross section to low energies. To reduce the model to one with a single parameter, we fix the scales at $\mu_r = \mu_f = 2m_c$ and use the charm quark mass m_c as a phenomenological parameter. One way to determine m_c is to require that parton model calculations give the measured charm cross sections in low-energy fixed target experiments. The most recent data on inclusive charm production from a proton beam on a nuclear target with pp center-of mass-energy below 45 GeV are from the LEBC-MPS, ACCMOR, E743, E653, E769 and HERA-B Collaborations [18, 19, 20, 21, 22, 23].[1] Their beam energies range from 200 up to 920 GeV, which corresponds to pp center-of-mass energies from 19.4 up to 41.6 GeV. The six data points are plotted in Fig. 4 as a function of the center-of-mass energy $\sqrt{s}$. Also shown in Fig. 4 is the NLO calculation of the inclusive charm cross section as a function of $\sqrt{s}$. The solid line is for $m_c = 1.5$ GeV, while the shaded band is the range as m_c varies from 1.3 to 1.7 GeV. For $\sqrt{s} = 19.4$ GeV and $m_c = 1.5$ GeV, the distribution of

---

[1] In Ref. [24], the various charm meson cross sections published in Refs. [18, 19, 20, 21, 22] are converted into a common cross section which is denoted by $\sigma_{c\bar{c}}$ but is actually the inclusive cross section for D^0 and D^+ or, equivalently, the inclusive cross section for $\bar{D}^0$ and D^-. To obtain the inclusive charm cross section, this must be divided by the sum of the fragmentation probabilities for $c \to D^0$ and $c \to D^+$, which is approximately 0.81.

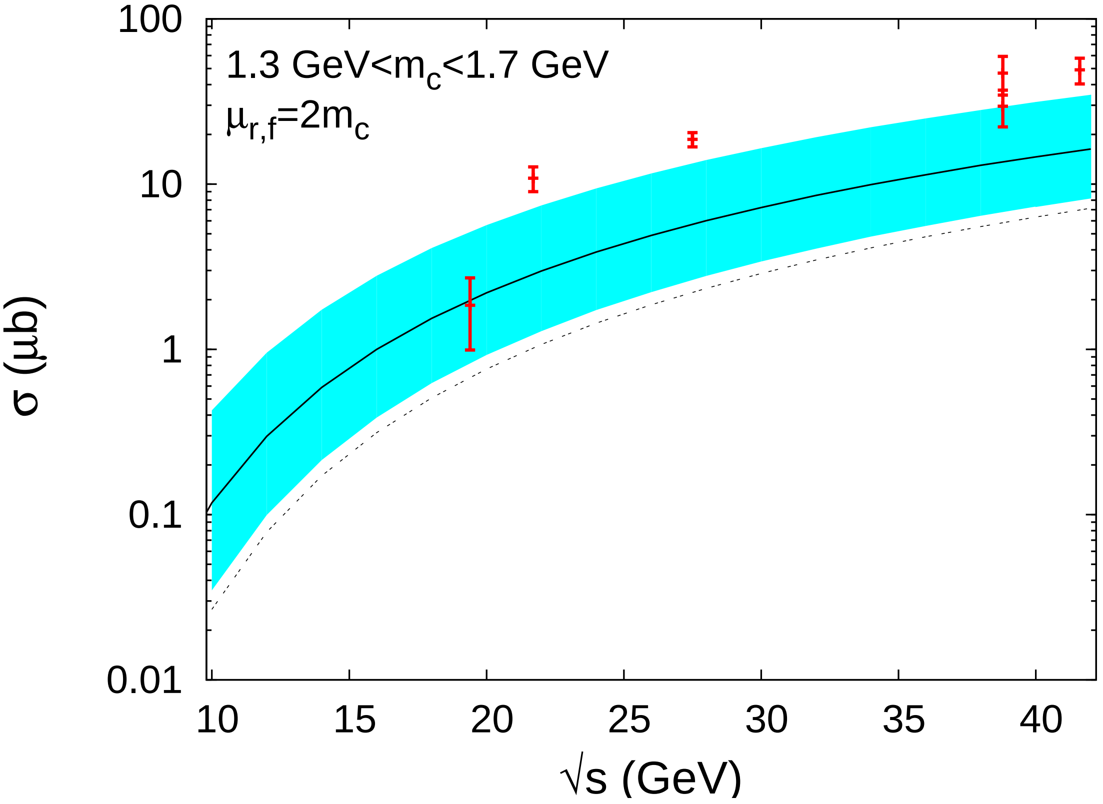

FIG. 4: Cross section for inclusive charm production in pp collisions as a function of the center-of-mass energy $\sqrt{s}$. The solid line is the NLO result for $m_c = 1.5$ GeV and $\mu_r = \mu_f = 2m_c$. The shaded band corresponds to varying m_c from 1.3 and 1.7 GeV. The dashed line is the LO result. The data points are the measurements from Refs. [18, 19, 20, 21, 22, 23].

the invariant mass $\sqrt{\hat{s}}$ of the colliding partons has a peak near 4.1 GeV and a full width at half maximum of greater than 2 GeV. Thus our criteria **A** and **B** for the validity of the parton model calculation are easily satisfied at this energy. The six data points in Fig. 4 are more compatible with the smaller values of m_c. The best fit to the six data points is $m_c = 1.29$ GeV.

We proceed to use our results to assess the prospects for the study of charm meson mixing at HESR. The maximum antiproton momentum is expected to be 15 GeV, which corresponds to a center-of-mass energy of 5.47 GeV. The NLO parton model with $m_c = 1.29$ GeV gives a cross section of 89 nb at this energy. The design luminosity of HESR is $2 \times 10^{32}/(\text{cm}^2\,\text{s})$. Using the NLO cross section, we find that 5.6×10^8 charm events could be produced in a year of dedicated running. Using our estimate $P_{c \to D^{*+}} = 24\%$ for the fragmentation probability, we obtain 2.7×10^8 D^{*+} or D^{*-} events. The tagging of the initial flavor of the charm meson as D^0 or $\bar{D}^0$ comes from the decay into $D^0\pi^+$ or $\bar{D}^0\pi^-$, which has a branching fraction of 68%. The simplest decay mode with which to observe mixing is the doubly-Cabbibo suppressed decay mode $D^0 \to K^+\pi^-$, which has a branching fraction 1.5×10^{-4}. Thus our estimate of the cross section corresponds to $27,000$ $D^0 \to K^+\pi^-$ events. To put this into context, the evidence for charm meson mixing at the Tevatron from the CDF Collaboration used 13,000 $D^0 \to K^+\pi^-$ events [4]. We conclude that the charm cross section at HESR could be large enough to study charm meson mixing.

There is also a proposal to use the antiproton source for Fermilab's Tevatron for low-energy $\bar{p}p$ collisions [25]. The maximum antiproton momentum in the accumulator ring at Fermilab is 8 GeV, which corresponds to a center-of-mass energy of only 4.11 GeV. The curves in Figs. 1 and 2 have been extended down to the $D\bar{D}$ threshold at 3.73 GeV, but this is too low for the model to be plausible, because the cross section must vanish at this threshold. A center-of-mass energy of 4.11 GeV may also be beyond the domain of plausibility of the model, because it is only a little above the $D^*\bar{D}^*$ threshold. If we ignore this problem, the NLO parton model with $m_c = 1.29$ GeV gives an inclusive charm cross section of 4.1 nb.

In summary, we have used the parton model and NLO perturbative QCD to calculate the cross section for inclusive charm production by a low-energy antiproton beam. At $\sqrt{s} = 5.47$ GeV, which corresponds to a $\bar{p}$ beam with momentum 15 GeV, the cross section can be increased or decreased by an order of magnitude by varying m_c, μ_r, and μ_f within reasonable ranges. Since the fundamental justification for the calculation is questionable at such low energies, we have proposed the parton model calculation as a phenomenological model for extrapolating the charm cross section. Treating m_c as a phenomenological parameter, we determined its value by fitting measured charm cross sections from fixed-target experiments with low-energy proton beams. The resulting estimate of the charm cross section at $\sqrt{s} = 5.47$ GeV is 89 nb. This cross section is large enough to allow the study of charm meson mixing in experiments with a 15 GeV antiproton beam.

P.A. was supported by the Fonds National de la Recherche Scientifique and by the Belgian Federal Office for Scientific, Technical and Cultural Affairs through the Interuniversity Attraction Pole No. P6/11. E.B. was supported in part by the Department of Energy under grant DE-FG02-91-ER40690 and by the Alexander von Humboldt Foundation.

---

[1] M. Artuso, B. Meadows and A. A. Petrov, Ann. Rev. Nucl. Part. Sci. **58**, 249 (2008) [arXiv:0802.2934 [hep-ph]].

[2] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **98**, 211802 (2007) [arXiv:hep-ex/0703020].

[3] M. Staric *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 211803 (2007) [arXiv:hep-ex/0703036].

[4] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **100**, 121802 (2008) [arXiv:0712.1567 [hep-ex]].

[5] E. Braaten, Phys. Rev. D **77**, 034019 (2008) [arXiv:0711.1854 [hep-ph]].

[6] A. I. Titov and B. Kampfer, Phys. Rev. C **78**, 025201 (2008) [arXiv:0807.1822 [hep-ph]].

[7] P. Nason, S. Dawson and R. K. Ellis, Nucl. Phys. B **303**, 607 (1988).

[8] W. Beenakker, H. Kuijf, W. L. van Neerven and J. Smith, Phys. Rev. D **40**, 54 (1989).

[9] W. Beenakker, W. L. van Neerven, R. Meng, G. A. Schuler and J. Smith, Nucl. Phys. B **351**, 507 (1991).

[10] M. Cacciari, P. Nason and R. Vogt, Phys. Rev. Lett. **95**, 122001 (2005) [arXiv:hep-ph/0502203].

[11] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999) [arXiv:hep-ph/9905386].

[12] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky and W. K. Tung, JHEP **0207**

(2002) 012 [arXiv:hep-ph/0201195].

[13] M. Cacciari, M. Greco and P. Nason, JHEP **9805**, 007 (1998) [arXiv:hep-ph/9803400].

[14] E. C. Poggio, H. R. Quinn and S. Weinberg, Phys. Rev. D **13**, 1958 (1976).

[15] R. Seuster *et al.* [Belle Collaboration], Phys. Rev. D **73**, 032002 (2006) [arXiv:hep-ex/0506068].

[16] N. Kidonakis, E. Laenen, S. Moch and R. Vogt, Phys. Rev. D **67**, 074037 (2003) [arXiv:hep-ph/0212173].

[17] N. Kidonakis and R. Vogt, Eur. Phys. J. C **36**, 201 (2004) [arXiv:hep-ph/0401056].

[18] S. Barlag *et al.* [ACCMOR Collaboration], Z. Phys. C **39**, 451 (1988).

[19] M. Aguilar-Benitez *et al.* [LEBC-EHS Collaboration], Z. Phys. C **40**, 321 (1988).

[20] R. Ammar *et al.*, Phys. Rev. Lett. **61**, 2185 (1988).

[21] K. Kodama *et al.* [E653 Collaboration], Phys. Lett. B **263**, 573 (1991).

[22] G. A. Alves *et al.* [E769 Collaboration], Phys. Rev. Lett. **77**, 2388 (1996) [Erratum-ibid. **81**, 1537 (1998)].

[23] I. Abt *et al.* [HERA-B Collaboration], Eur. Phys. J. C **52**, 531 (2007) [arXiv:0708.1443 [hep-ex]].

[24] S. Frixione, M. L. Mangano, P. Nason and G. Ridolfi, Adv. Ser. Direct. High Energy Phys. **15**, 609 (1998) [arXiv:hep-ph/9702287].

[25] D. M. Kaplan, arXiv:0809.2372 [hep-ex].