RECENT DEVELOPMENTS IN HEAVY QUARK AND QUARKONIUM PRODUCTION*

Thomas Mehen

Department of Physics, Duke University
Box 90305, Durham, NC 27708-0305, USA

(Received December 1, 2003)

Recent measurements of J/ψ production in e^+e^- colliders pose a challenge to the NRQCD factorization theorem for quarkonium production. Discrepancies between leading order calculations of color-octet contributions and the momentum distribution of J/ψ observed by Belle and BaBar are resolved by resumming large perturbative and nonperturbative corrections that are enhanced near the kinematic endpoint. The large cross sections for $J/\psi c\bar{c}$ and double quarkonium production remain poorly understood. Nonperturbative effects in fixed-target hadroproduction of open charm are also discussed. Large asymmetries in the production of charm mesons and baryons probe nonperturbative corrections to the QCD factorization theorem. A power correction called heavy-quark recombination can economically explain these asymmetries with a few universal parameters.

PACS numbers: 13.66.Bc, 13.85.Ni, 14.40.Gx, 14.65.Dw

1. Introduction

In the last couple of years there have been a number of interesting experimental results in the production of heavy particles, including measurements of J/ψ production in e^+e^- collisions at the $\Upsilon(4S)$ resonance [1–3] and charm meson production at the Tevatron [4]. This talk focuses on how these results impact theoretical understanding of heavy particle production. The spectrum of J/ψ observed in e^+e^- colliders disagrees with leading order calculations based on Non-Relativistic QCD (NRQCD) factorization theorems [5]. Better agreement is obtained in calculations which resum the large nonperturbative and perturbative corrections that arise near the kinematic endpoint [6]. However, large cross sections for $J/\psi c\bar{c}$ and exclusive double quarkonium production remain poorly understood. I also discuss heavy

* Presented at the XXXIII International Symposium on Multiparticle Dynamics, Kraków, Poland, September 5–11, 2003.

quark production. Calculations of charm and bottom production which resum large logarithms of $p_\perp/m_Q$ provide a consistent description of the production of these particles at the Tevatron [7–9]. Finally, I explain how the large asymmetries observed in fixed-target hadroproduction experiments can be explained by a power correction to the QCD factorization theorem called heavy-quark recombination [10, 11].

2. J/ψ production at the $\Upsilon(4S)$

The current theoretical framework for understanding the production of heavy quarkonia is NRQCD [5]. NRQCD solves important theoretical and phenomenological problems in quarkonium theory. Color-singlet model calculations of χ_c decay suffer from infrared divergences [12]. NRQCD provides a generalized factorization theorem that includes nonperturbative corrections to the color-singlet model, including color-octet decay and production mechanisms. Infrared divergences are factored into nonperturbative matrix elements, so calculations of inclusive production and decay rates are infrared safe [13]. Color-octet production mechanisms are necessary for understanding the production of J/ψ at large transverse momentum, $p_\perp$, at the Tevatron [14]. Convincing evidence for color-octet mechanisms has recently been seen in $\gamma\gamma$ collisions, where color-singlet mechanisms underestimate the cross section by an order of magnitude while calculations including color-octet mechanisms describe the data well [15].

However, there are many unsolved problems in quarkonium physics [16]. Perhaps the most puzzling is the polarization of J/ψ and ψ', which is predicted to be transverse at very large $p_\perp$ in hadron colliders [17]. The theoretical prediction is consistent with the data at intermediate $p_\perp$ but at the largest $p_\perp$ measured the J/ψ and ψ' are observed to be slightly longitudinally polarized.

This talk focuses on new puzzles arising from recent measurements of J/ψ production in e^+e^- colliders [1–3]. The leading color-octet contribution to this process was expected to dramatically enhance the cross section for maximally energetic J/ψ as well as modify their angular distribution [18]. If $\cos\theta$ is the angle of the J/ψ relative to the axis defined by the e^+e^- beams and $z = E_{J/\psi}/E_{J/\psi}^{\max}$, then the differential cross section is

$$\frac{d\sigma}{dz\, d\cos\theta} = S(z)(1 + A(z)\cos^2\theta)\,. \tag{1}$$

The function $A(z)$ tends to -1 as $z \to 1$ for color-singlet production. The leading color-octet diagram contributes only at $z = 1$ and gives $A(1) \approx 1$. The total color-singlet cross section is predicted to be 0.4-0.9 pb [19], while the total cross section from the leading color-octet mechanism is expected to be $\approx$ 1 pb. A substantial rise in the cross section near the kinematic endpoint accompanied by a change in angular distribution was predicted to be a robust signal of the color-octet mechanism [18].

Experimental data does not agree with these expectations [1–3]. One problem is that a sharp rise in the cross section near the kinematic endpoint is not observed. On the other hand, the cross section is larger than predicted by the color-singlet model and $A(z) \approx 1$ for $0.7 < z < 1$. Another puzzle is the production of open charm with J/ψ. Belle observes that a large fraction of J/ψ are produced with an additional $c\bar{c}$ [1]:

$$\frac{\sigma(e^+e^- \to J/\psi\, c\bar{c})}{\sigma(e^+e^- \to J/\psi\, X)} = 0.59^{+0.15}_{-0.13} \pm 0.12. \qquad (2)$$

(Preliminary results described by P. Pakhlov in this conference suggest that the ratio is even larger [20].) Leading order color-singlet model calculations predict the ratio to be ≈ 0.2 [19] and a large color-octet contribution will make the ratio even smaller.

The resolution of the first problem lies in a careful analysis of the perturbative and nonperturbative corrections that appear near the kinematic endpoint of quarkonia production [6, 21]. The J/ψ production cross section in NRQCD is

$$\frac{d\sigma}{dz}(e^+e^- \to J/\psi + X) = \sum_n \frac{d\hat{\sigma}}{dz}(e^+e^- \to c\bar{c}[n] + X)\langle \mathcal{O}_n^{J/\psi}\rangle\,, \qquad (3)$$

where $\langle \mathcal{O}_n^{J/\psi}\rangle$ are NRQCD matrix elements and $d\hat{\sigma}(e^+e^- \to c\bar{c}[n] + X)$ are perturbatively calculable short-distance cross sections. The label n denotes the angular momentum and color quantum numbers of the $c\bar{c}$. The NRQCD scaling rules show that $\langle \mathcal{O}_n^{J/\psi}\rangle$ scales as some power of v, where v is the typical velocity of the heavy quarks inside the bound state.

The leading Feynman diagrams which contribute to color-octet production give $d\hat{\sigma}(e^+e^- \to c\bar{c}[n]+X)/dz$ proportional to $\delta(1-z)$. This is the first in an infinite series of terms that are singular at $z = 1$. There are higher order nonperturbative corrections that scale as $v^{2n}/(1-z)^n$ [21] as well as perturbative corrections that go like $\alpha_{\rm s}^n \ln^m(1-z)/(1-z)$, $m \leq 2n-1$. For charmonium, $v^2 \sim \alpha_{\rm s} \sim 0.3$ so for $z \geq 0.7$ perturbation theory and the NRQCD v expansion both break down.

Near the kinematic endpoint, the final state consists of two kinds of quanta: energetic collinear particles with light-like momenta in the jet against which the J/ψ is recoiling and particles which are soft as viewed from the rest frame of the J/ψ. NRQCD breaks down because the theory does not explicitly include these degrees of freedom. The problem can be fixed by using the Soft-Collinear Effective Theory (SCET) [22] which explicitly includes both collinear and soft degrees of freedom. By combining SCET and NRQCD one finds that in the endpoint region Eq. (3) is replaced with the following factorization theorem: [6]

$$\frac{d\sigma^{[n]}}{dz} = \sigma_0^{[n]} \int_z^1 d\xi\, S^{[n]}(\xi)\, J(\xi - z)\,. \tag{4}$$

Here $\sigma_0^{[n]}$ is a short distance cross section which is perturbatively calculable. The shape function $S^{[n]}(\xi)$ is a universal nonperturbative distribution that resums the large nonperturbative corrections. $J(\xi - z)$ is a calculable function that describes the propagation of the collinear particles in the energetic gluon jet. Large perturbative corrections can be resummed by solving the SCET renormalization group equations for $\sigma_0^{[n]}, S^{[n]}(\xi)$ and $J(\xi - z)$.

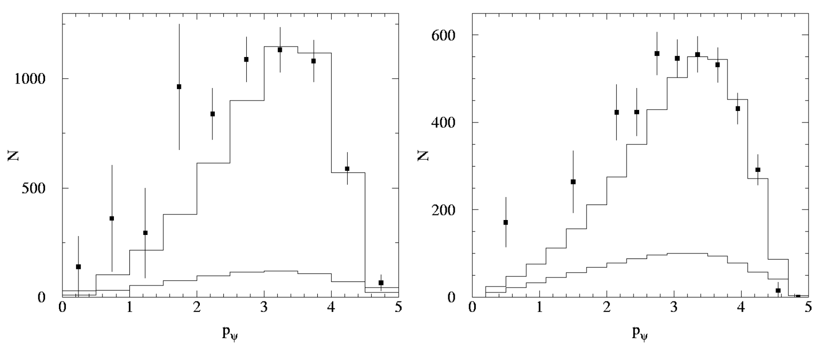

Fig. 1. The sum of the resummed color-octet and leading order color-singlet contributions are plotted as the upper line. The lower line is the leading order color-singlet contribution only, and the data are from the BaBar collaboration [2] (left) and Belle collaboration [3] (right).

Comparison of this calculation with data from BaBar [2] and Belle [3] is shown in Fig. 1 [6]. The number of events is plotted as a function of the J/ψ momentum, p_ψ. The lower line in both plots is the leading color-singlet contribution which falls well below data. The upper line includes the resummed color-octet cross section. The leading order calculation of the color-octet contribution (not shown) gives an integrated cross section comparable to that of the resummed calculation shown here, but the entire cross section is located in the very last bin of p_ψ. This also does not agree with data. Fig. 1 demonstrates that when large perturbative and nonperturbative corrections are included the momentum spectrum of the J/ψ produced by the color-octet mechanism is significantly broadened. The agreement with data is good in the endpoint region where the calculation is most reliable.

The calculation is not predictive because the shape function is fitted to available data. However, the moments of the shape function can be estimated using the NRQCD scaling rules and the shape function used in Ref. [6] satisfies these constraints. The universality of the shape function can be tested by applying the methods of Ref. [6] to other J/ψ production processes.

While resolving the discrepancy between leading order color-octet calculations and the observed p_ψ distribution, the calculation does not help explain the large cross section for $J/\psi c\bar{c}$ observed by the Belle collaboration. The Belle collaboration also observes a large cross section for exclusive $J/\psi + \eta_c$ and $J/\psi + \chi_c$ [3]. An NRQCD analysis of exclusive cross sections appears in Ref. [23]. Because the helicity conservation rules for exclusive QCD processes suppress the leading QCD contribution, the purely QED contributions are surprisingly large ($\approx 20\%$). The leading relativistic corrections give large corrections which unfortunately are difficult to estimate reliably. For instance, Ref. [23] quotes $\sigma(J/\psi + \eta_c) = 5.5^{+10.6}_{-3.5}$ fb, with the uncertainty dominated by relativistic corrections. For comparison Belle measures $\sigma(J/\psi+\eta_c)\times \mathrm{Br}[\eta_c \to 4\,\text{charged particles}] = 33^{+7}_{-6}\pm 9$ fb. Clearly a mechanism for enhancing the $J/\psi c\bar{c}$ and double charmonium cross sections is needed. Proposals for nonperturbative mechanisms responsible for this enhancement appear in Ref. [24].

3. Open charm and bottom production

The QCD factorization theorem states that the production cross section for a heavy particle H containing a heavy quark Q is [25]

$$d\sigma[AB \;\to\; HX] = \sum_{i,j} f_{i/A} \otimes f_{j/B} \otimes d\hat{\sigma}[ij \to Q\bar{Q}X] \otimes D_{Q\to H} + \dots \,. \quad (5)$$

Here $f_{i/A}$ is a parton distribution function, $D_{Q\to H}$ is a fragmentation function, $d\hat{\sigma}[ij \to Q\bar{Q}X]$ is a short-distance cross section and the ellipsis represents corrections which are suppressed by $\Lambda_{\mathrm{QCD}}/m_Q$ or $\Lambda_{\mathrm{QCD}}/p_\perp$.

Perturbative aspects of Eq. (5) are tested by measurements of charm and bottom production at collider experiments. Experimental reviews of heavy quark production at LEP, HERA and the Tevatron are described in the talks of Sciaba [26], Olivier [27] and Rinnert [28], respectively. At the Tevatron, discrepancies between NLO calculations of bottom production and experimental cross sections have been known for a long time [29]. Recently CDF has extended measurements to include charm as well as bottom [4]. Resummation of large logarithms of $p_\perp/m_Q$ is needed to obtain better agreement with both charm and bottom cross sections [7–9]. It is also important to treat fragmentation functions carefully as the total cross section is sensitive to the fragmentation function used [9]. Though the existing calculations differ in how finite mass corrections are handled they are consistent numerically and agree with data within the theoretical uncertainties estimated by varying factorization and renormalization scales.

Nonperturbative power corrections to Eq. (5) are probed in lower energy fixed-target experiments. Production asymmetries are an incisive test of these corrections. At leading order in perturbation theory, charm particles and antiparticles are produced symmetrically because the partonic processes $gg \to c\bar{c}$ and $q\bar{q} \to c\bar{c}$ produce charm and anticharm symmetrically and $D_{c\to H} = D_{\overline{c}\to\overline{H}}$ due to charge conjugation invariance. At next-to-leading order, the asymmetry, $\alpha[H] = (\sigma[H] - \sigma[\,\overline{H}\,])/(\sigma[H] + \sigma[\,\overline{H}\,])$, is only a few percent [30]. Fixed-target hadroproduction [31–34] and photoproduction [35, 36] experiments observe much larger asymmetries. In hadroproduction the asymmetries are known as the "Leading Particle Effect". Cross sections for charm particles sharing a valence quark with the beam hadron are enhanced in the forward direction of the beam. Hadroproduction asymmetries can be quite large. For example, in the most forward region measured in $\pi^- N$ collisions, the ratio of D^- to D^+ is ≈ 6.

Charm asymmetries are conventionally explained by nonperturbative models of hadronization [37]. These models suffer from a lack of predictive power, since they depend on a number of nonperturbative functions, such as the distribution of spectator quarks in hadron remnants. The most commonly used model is the Lund string fragmentation model [39] which can be implemented using PYTHIA [40]. The PYTHIA Monte Carlo with default parameters rarely predicts the asymmetries correctly [31] and in the case of Λ_c asymmetries in πN collisions [32] and γN collisions [36] gets the sign of the asymmetry wrong.

A novel mechanism for generating charm hadron asymmetries called heavy-quark recombination has recently been introduced in Ref. [10]. Similar mechanisms for production of light hadrons were considered in Ref. [41]. An important difference between the production of heavy hadrons and light hadrons is that in the former case heavy quark symmetry [42] can be used to simplify the structure of nonperturbative factors appearing in the calculation. Heavy-quark recombination is an $O(\Lambda_{\rm QCD}/m_c)$ suppressed power correction to the factorization theorem of Eq. (5). In this process, a light anti-quark, $\overline{q}$, from the incident hadron participates in a hard-scattering process which produces a c and $\overline{c}$ quark. Following the hard scattering the $\overline{q}$ and the c recombine to form a D meson. A similar mechanism in which a light quark recombines with the c quark is the dominant recombination contribution to charm baryon production [11]. Heavy-quark recombination differs from previous nonperturbative models in that the asymmetry is generated in the short-distance process so cross sections are calculable up to an overall normalization that is set by a few universal parameters. The short-distance cross section is strongly peaked in the forward direction of the light quark or antiquark, naturally leading to an asymmetric cross section.

Heavy-quark recombination accounts for the D meson asymmetries observed in photoproduction and hadroproduction experiments. Fig. 2 shows asymmetries for D^+ and D^{*+} mesons produced in 500 GeV πN collisions [33] and asymmetries for D_s mesons produced in 600 GeV $\Sigma^- N$ collisions [34]. There are four universal parameters in the theory. The theory curves in Fig. 2 correspond to fits with one, two and three of these parameters. (A four parameter fit yields identical results as the three parameter fit.) The heavy-quark recombination mechanism correctly describes asymmetries for different types of D mesons in experiments with different beams with a minimal set of universal parameters. The heavy-quark recombination also correctly describes Λ_c asymmetries in both πN and pN collisions [11].

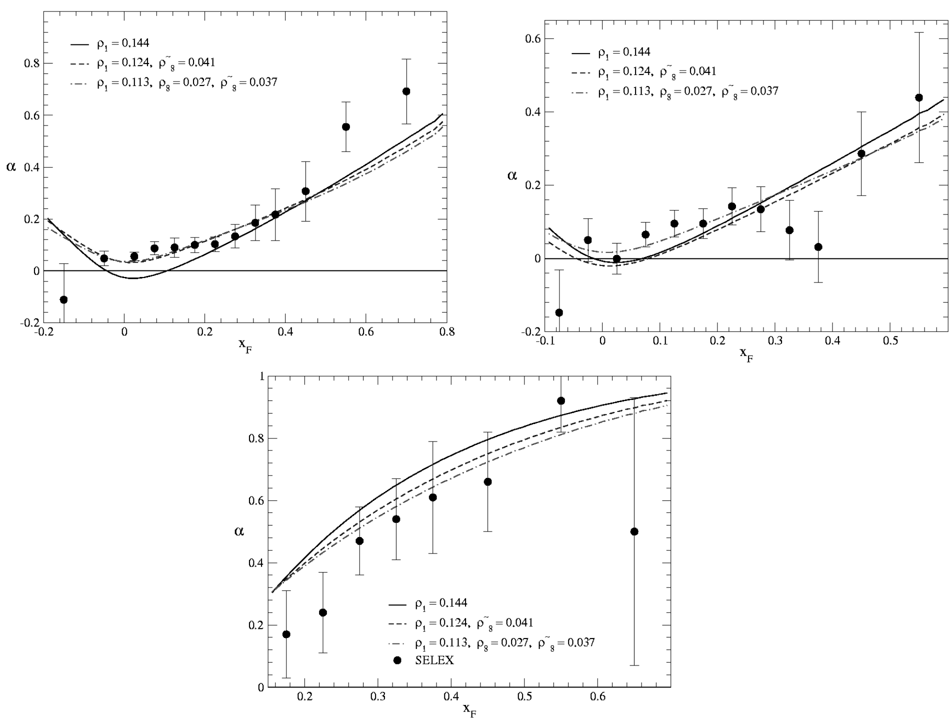

Fig. 2. Asymmetry as a function of x_F for D^+ mesons (top left) and D^{*+} mesons (top right) produced in 500 GeV πN collisions [33] and D_s^+ mesons produced in 600 GeV $\Sigma^- N$ collisions [34] (bottom). Theory curves are explained in text.

REFERENCES

[1] K. Abe *et al.* [Belle Collaboration], *Phys. Rev. Lett.* **89**, 142001 (2002).

[2] B. Aubert *et al.* [BABAR Collaboration], *Phys. Rev. Lett.* **87**, 162002 (2001).

[3] K. Abe *et al.* [BELLE Collaboration], *Phys. Rev. Lett.* **88**, 052001 (2002).

[4] D. Acosta *et al.* [CDF Collaboration], *Phys. Rev. Lett.* **91**, 241804 (2003).

[5] W.E. Caswell, G.P. Lepage, *Phys. Lett.* **B167**, 437 (1986); G.T. Bodwin, E. Braaten, G.P. Lepage, *Phys. Rev.* **D51**, 1125 (1995); **D55**, 5853 (1997); M.E. Luke, A.V. Manohar, I.Z. Rothstein, *Phys. Rev.* **D61**, 074025 (2000).

[6] S. Fleming, A.K. Leibovich, T. Mehen, *Phys. Rev.* **D68**, 094011 (2003).

[7] J. Binnewies, B.A. Kniehl, G. Kramer, *Phys. Rev.* **D58**, 034016 (1998).

[8] M. Cacciari, P. Nason, *Phys. Rev. Lett.* **89**, 122003 (2002).

[9] M. Cacciari, P. Nason, *J. High Energy Phys.* **0309**, 006 (2003).

[10] E. Braaten, Y. Jia, T. Mehen, *Phys. Rev. Lett.* **89**, 122002 (2002); *Phys. Rev.* **D66**, 034003 (2002); **D66**, 014003 (2002).

[11] E. Braaten, M. Kusunoki, Y. Jia, T. Mehen, `hep-ph/0304280`.

[12] R. Barbieri, R. Gatto, E. Remiddi, *Phys. Lett.* **B61**, 465 (1976); *Phys. Lett.* **B106**, 497 (1981); R. Barbieri, M. Caffo, R. Gatto, E. Remiddi, *Nucl. Phys.* **B192**, 61 (1981).

[13] G.T. Bodwin, E. Braaten, G.P. Lepage, *Phys. Rev.* **D46**, 1914 (1992).

[14] E. Braaten, S. Fleming, *Phys. Rev. Lett.* **74**, 3327 (1995); P.L. Cho, A.K. Leibovich, *Phys. Rev.* **D53**, 150 (1996); *Phys. Rev.* **D53**, 6203 (1996).

[15] M. Klasen, B.A. Kniehl, L.N. Mihaila, M. Steinhauser, *Phys. Rev. Lett.* **89**, 032001 (2002).

[16] G.T. Bodwin, `hep-ph/0212203`.

[17] P.L. Cho, M.B. Wise, *Phys. Lett.* **B346**, 129 (1995); A.K. Leibovich, *Phys. Rev.* **D56**, 4412 (1997); M. Beneke, M. Kramer, *Phys. Rev.* **D55**, 5269 (1997); E. Braaten, B.A. Kniehl, J. Lee, *Phys. Rev.* **D62**, 094005 (2000).

[18] E. Braaten, Y.Q. Chen, *Phys. Rev. Lett.* **76**, 730 (1996).

[19] P.L. Cho, A.K. Leibovich, *Phys. Rev.* **D54**, 6690 (1996); F. Yuan, C.F. Qiao, K.T. Chao, *Phys. Rev.* **D56**, 321 (1997); S. Baek, P. Ko, J. Lee, H.S. Song, *J. Korean Phys. Soc.* **33**, 97 (1998); G.A. Schuler, *Eur. Phys. J.* **C8**, 273 (1999); J.H. Kuhn, H. Schneider, *Phys. Rev.* **D24**, 2996 (1981); *Z. Phys.* **C11**, 263 (1981); V.M. Driesen, J.H. Kuhn, E. Mirkes, *Phys. Rev.* **D49**, 3197 (1944).

[20] P. Pakhlov, *Acta Phys. Pol. B* **35**, 97 (2004), these Proceedings.

[21] M. Beneke, I.Z. Rothstein, M.B. Wise, *Phys. Lett.* **B408**, 373 (1997).

[22] C.W. Bauer, S. Fleming, M.E. Luke, *Phys. Rev.* **D63**, 014006 (2001). C.W. Bauer, S. Fleming, D. Pirjol, I.W. Stewart, *Phys. Rev.* **D63**, 114020 (2001); C.W. Bauer, I.W. Stewart, *Phys. Lett.* **B516**, 134 (2001); C.W. Bauer, D. Pirjol, I.W. Stewart, *Phys. Rev. Lett.* **87**, 201806 (2001); *Phys. Rev.* **D65**, 054022 (2002); *Phys. Rev.* **D66**, 054005 (2002).

[23] E. Braaten, J. Lee, *Phys. Rev.* **D67**, 054007 (2003).

[24] B.L. Ioffe, D.E. Kharzeev, hep-ph/0306062, A.B. Kaidalov, *JETP Lett.* **77**, 349 (2003) [*Pisma Zh. Eksp. Teor. Fiz.* **77**, 417 (2003)].

[25] J.C. Collins, D.E. Soper, G. Sterman, *Nucl. Phys.* **B263**, 37 (1986).

[26] A. Sciaba, *Acta Phys. Pol. B* **35**, 101 (2004), these Proceedings.

[27] B. Olivier, *Acta Phys. Pol. B* **35**, 107 (2004), these Proceedings.

[28] K. Rinnert, *Acta Phys. Pol. B* **35**, 115 (2004), these Proceedings.

[29] D. Acosta *et al.* [CDF Collaboration], *Phys. Rev.* **D65**, 052005 (2002).

[30] P. Nason, S. Dawson, R.K. Ellis, *Nucl. Phys.* **B327**, 49 (1989); W. Beenakker, H. Kuijf, W.L. van Neerven, J. Smith, *Phys. Rev.* **D40**, 54 (1989); W. Beenakker, W.L. van Neerven, R. Meng, G.A. Schuler, J. Smith, *Nucl. Phys.* **B351**, 507 (1991).

[31] M. Adamovich *et al.* [WA82 Collaboration], *Phys. Lett.* **B305**, 402 (1993); G.A. Alves *et al.* [E769 Collaboration], *Phys. Rev. Lett.* **72**, 812 (1994); **77**, 2392 (1996); E.M. Aitala *et al.* [E791 Collaboration], *Phys. Lett.* **B411**, 230 (1997); M. Adamovich *et al.* [BEATRICE Collaboration], *Nucl. Phys.* **B495**, 3 (1997); M.I. Adamovich *et al.* [WA89 Collaboration], *Eur. Phys. J.* **C8**, 593 (1999); F.G. Garcia *et al.* [SELEX Collaboration], *Phys. Lett.* **B528**, 49 (2002).

[32] E.M. Aitala *et al.* [E791 Collaboration], *Phys. Lett.* **B495**, 42 (2000).

[33] E.M. Aitala *et al.* [E791 Collaboration], *Phys. Lett.* **B539**, 218 (2002); **371**, 157 (1996);

[34] M. Kaya *et al.* [SELEX Collaboration], *Phys. Lett.* **B558**, 34 (2003).

[35] J.C. Anjos *et. al.* [Tagged Photon Spectrometer Collaboration], *Phys. Rev. Lett.* **62**, 513 (1989); *M.P. Alvarez et. al.* [NA14/2 Collaboration], *Z. Phys.* **C60**, 53 (1993); P.L. Frabetti *et. al.* [E687 Collaboration], *Phys. Lett.* **B370**, 222 (1996); J.C. Anjos, E. Cuautle [FOCUS Collaboration], *AIP Conf. Proc.* **531**, 172 (2000).

[36] J.M. Link *et. al.* [FOCUS Collaboration], hep-ex/0311022.

[37] R. Vogt, S.J. Brodsky, *Nucl. Phys.* **B478**, 311 (1996); E. Norrbin, T. Sjöstrand, *Phys. Lett.* **B442**, 407 (1998); A.K. Likhoded, S.R. Slabospitsky, *Phys. Atom. Nucl.* **62**, 693 (1999) [*Yad. Fiz.* **62**, 742 (1999)]; O.I. Piskounova, hep-ph/0202005; R.C. Hwa, *Phys. Rev.* **D51**, 85 (1995); R. Rapp, E.V. Shuryak, *Phys. Rev.* **D67**, 074036 (2003); T. Tashiro, S. Nakariki, H. Noda, K. Kinoshita, *Eur. Phys. J.* **C24**, 573 (2002); E. Cuautle, G. Herrera, J. Magnin, *Eur. Phys. J.* **C2**, 473 (1998).

[38] G. Herrera, J. Magnin, *Eur. Phys. J.* **C2**, 477 (1998).

[39] H.-U. Bengtsson, T. Sjöstrand, *Comput. Phys. Commun.* **46**, 43 (1987).

[40] T. Sjostrand, L. Lonnblad, S. Mrenna, hep-ph/0108264.

[41] K.P. Das, R.C. Hwa, *Phys. Lett.* **B68**, 459 (1977) [Erratum-ibid. **73B**, 504 (1978)]; E.L. Berger, T. Gottschalk, D.W. Sivers, *Phys. Rev.* **D23**, 99 (1981).

[42] N. Isgur, M.B. Wise, *Phys. Lett.* **B232**, 113 (1989); **237**, 527 (1990).