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PHENOMENOLOGY OF QUARKONIA PRODUCTION IN FIXED TARGET EXPERIMENTS AND AT THE TEVATRON AND HERA COLLIDERS[†]

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Abstract

The phenomenology of heavy quarkonia production in fixed target experiments and at the Tevatron and HERA colliders is reviewed. The latest theoretical results are presented and compared with data, with emphasis on the predictions of the factorization approach by Bodwin, Braaten and Lepage.

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1 Introduction

The production of heavy quarkonia has been subjected to intense study in the last two or three years, with tens of papers having being produced on the problem of J/ψ's, χ's and Υ's production in e^+e^-, γp, $p\bar{p}$, pN, πN collisions and also B decays.

The reason for such a surge in interest was the appearance of a theoretical framework, the so called Factorization Approach (FA) by Bodwin, Braaten and Lepage [1], which seems able to solve the theoretical problems that quarkonia production models faced in the past, and also to reconcile theoretical predictions with experimental data, previously in disagreement up to factors of fifty in some instances.

In this talk I shall not review the Factorization approach in detail, leaving this theoretical introduction to other sources (see for instance [2, 3, 4]). I shall also not discuss in detail the Color Singlet Model (CSM) [5] and the Color Evaporation Model (CEM)[6] (the latter has also been recently compared to data and found able to describe at least some of them [7, 8]).

I shall just recall how the factorization approach writes the quarkonium state H production cross section in the following form:

$$\sigma(ij \to Q\bar{Q} \to H) = \sum_n \hat{\sigma}(ij \to Q\bar{Q}[n])\langle \mathcal{O}^H(n)\rangle. \tag{1}$$

According to this equation, the cross section for producing the observable quarkonium state H is factorized into two steps. In the short distance part a $Q\bar{Q}$ pair of heavy quarks is produced in the spin/color/angular momentum state ${}^{2S+1}L_J^{(c)} \equiv n$ by the scattering of the two light partons i and j. Successively this pair hadronizes into the quarkonium H, and $\langle \mathcal{O}^H(n)\rangle$ is formally a Non Relativistic QCD (NRQCD) matrix element describing this non perturbative transition.

An important feature of this equation is that also $Q\bar{Q}$ pairs in a color octet state are allowed to contribute to the production of a color singlet quarkonium H: their color is neutralized via a non perturbative emission of soft gluons. While the corresponding matrix elements are suppressed by the need of such an emission, the short distance coefficients can on the other hand be large, perhaps overcompensating the suppression of the non perturbative term. This explains why color octet contributions can play a very important role in predicting the total size of quarkonia production cross sections.

Many theoretical items would be worth discussing about the Factorization Approach. Actually, they would probably be worth a seminar (or more) by themselves. As I said, I shall however skip such a detailed discussion and rather concentrate on some selected phenomenological outcomes of the theoretical investigations which have been carried on so far. I shall restrict myself to analyses of experimental data coming from $p\bar{p}$ collisions at the Tevatron, γp collisions at HERA and fixed target experiment, reviewing the results of these investigations. References will be provided to the theoretical papers, leaving to them the task of properly citing the experimental ones.

The aim of the game will be to check whether the non perturbative matrix elements which can be extracted from these experimental data are mutually consistent with each other. In other words, we shall check whether the factorization approach can properly describe all the data with matrix elements truly universal and independent from the underlying short distance process, as they should.

2 The Tevatron data in $p\bar{p}$ collisions

Beginning with the Tevatron data looks appropriate as the explanation of its anomalously large ψ' production rate (a factor of fifty above the Color Singlet Model prediction) was the first phenomenological breakthrough of the FA. Braaten and Fleming [9] explained this large rate by assuming it was due to a color octet $Q\bar{Q}$ pair originating via perturbative splitting from a large p_T gluon. While the non perturbative matrix element for such a color octet pair to produce a ψ' is predicted by NRQCD to be about two order of magnitudes suppressed with respect to the one for a color singlet, the production rate of gluons (and hence of such pairs) is however so large that it can more than compensate for the suppression. Indeed, Braaten and Fleming could successfully describe the data fitting a value for the matrix element in good agreement with the theoretically predicted two-orders-of-magnitude suppression.

This apparent success of the factorization approach on the ψ' anomaly problem made immediately clear the potential importance of color octet mediated channels and stimulated similar research in other reactions: by the time of this Conference, the Braaten and Fleming's paper has received more than 120 citations.

Cross sections for large p_T J/ψ's and χ's production at the Tevatron have been analyzed, and a more detailed study of ψ' has also been performed. It was found the theoretical curves could describe the shape of the data pretty well. The following matrix elements values were returned by the fits, performed either within the fragmentation approximation [10, 11] or evaluating the full leading order matrix elements [12, 13]:

$$\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle \simeq (1.5\ [11], 1.1\ [14], 1.06\ [13]) \times 10^{-2}\ \mathrm{GeV}^3 \quad (2)$$

$$\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle + \frac{3}{m^2}\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle \simeq 9 \times 10^{-2}\ \mathrm{GeV}^3 \quad [14] \quad (3)$$

$$\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle + \frac{3.5}{m^2}\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle \simeq 4.38 \times 10^{-2}\ \mathrm{GeV}^3 \quad [13] \quad (4)$$

$$\langle \mathcal{O}_8^{\psi'}(^3S_1)\rangle \simeq (4.3\ [11], 3.8\ [14], 4.4\ [13]) \times 10^{-3}\ \mathrm{GeV}^3 \quad (5)$$

$$\langle \mathcal{O}_8^{\psi'}(^1S_0)\rangle + \frac{3}{m^2}\langle \mathcal{O}_8^{\psi'}(^3P_0)\rangle \simeq 3 \times 10^{-2}\ \mathrm{GeV}^3 \quad [14] \quad (6)$$

$$\langle \mathcal{O}_8^{\psi'}(^1S_0)\rangle + \frac{3.5}{m^2}\langle \mathcal{O}_8^{\psi'}(^3P_0)\rangle \simeq 1.8 \times 10^{-2}\ \mathrm{GeV}^3 \quad [13] \quad (7)$$

$$\langle \mathcal{O}_8^{\chi_J}(^3S_1)\rangle \simeq (2J+1)m^2 \times 3.6 \times 10^{-3}\ \mathrm{GeV}^5 \quad [11] \quad (8)$$

m is the charm mass, usually taken equal to 1.5 GeV. Figure 1 shows the CDF data from the Tevatron and the curves which fit them with these parameters.

The uncertainties on these fits are certainly not smaller than a factor of two, due to the many systematics entering their determination: parton distribution functions (responsible for the difference between [14] and [13]), charm quark mass, α_s value, higher order QCD corrections, etc. They could, however, even be larger. Indications in this direction come from a fit [15] which makes use of PYTHIA for simulating the effect of initial state radiations from the partons before they collide to produce the $Q\bar{Q}$ pair: this changes the slope of the theoretical predictions and

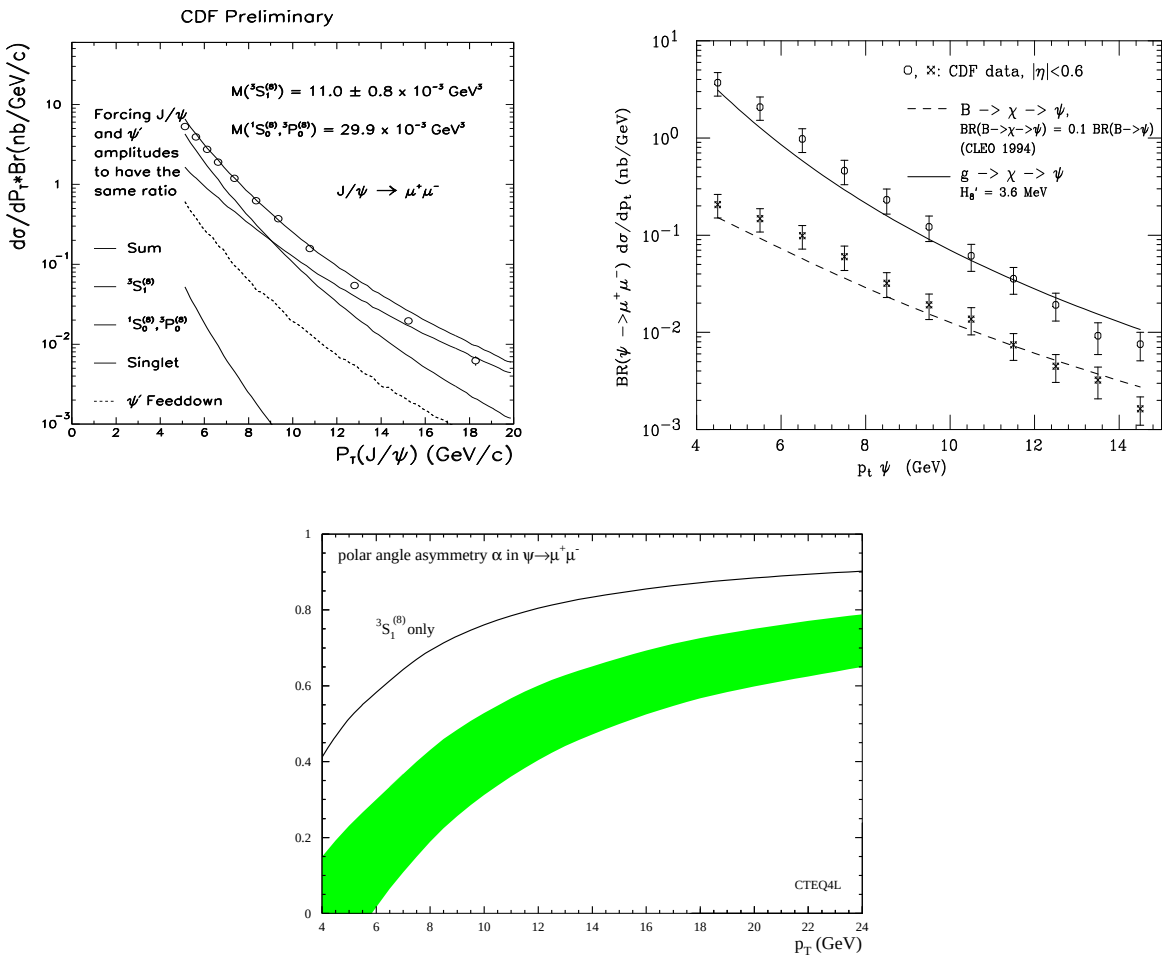

Figure 1: Fits to production of direct J/ψ (left) [12] and χ (right) [11] at CDF. The J/ψ plot also shows by how much the Color Singlet Model underestimates the data. Also shown (below) is the J/ψ polarization pattern predicted [13] by the factorization approach.

hence the result of the fit:

$$\langle \mathcal{O}_8^{J/\psi}(^3S_1)\rangle \simeq 3 \times 10^{-3}\ \mathrm{GeV}^3 \qquad [15] \tag{9}$$

$$\langle \mathcal{O}_8^{J/\psi}(^1S_0)\rangle + \frac{3}{m^2}\langle \mathcal{O}_8^{J/\psi}(^3P_0)\rangle \simeq 1.2 \times 10^{-2}\ \mathrm{GeV}^3 \qquad [15] \tag{10}$$

The effect can be seen to be large, the results being significantly smaller. While such a reduction would actually be welcome in the light of other data which will be presented further on, one should however for the time being only take this as an indication of the size of the uncertainty which may still lay hidden in their determination.

Other than the size of the production cross section, the polarization of the quarkonia is an observable with great discriminating power for the various approaches to quarkonia production. It can be measured by analyzing the angular distribution of the quarkonium decay products (muons) in its rest frame, and parametrizing it as

$$\frac{d\sigma(\psi \to \mu^+\mu^-)}{d\cos\theta} \propto 1 + \alpha(\psi)\cos^2\theta \tag{11}$$

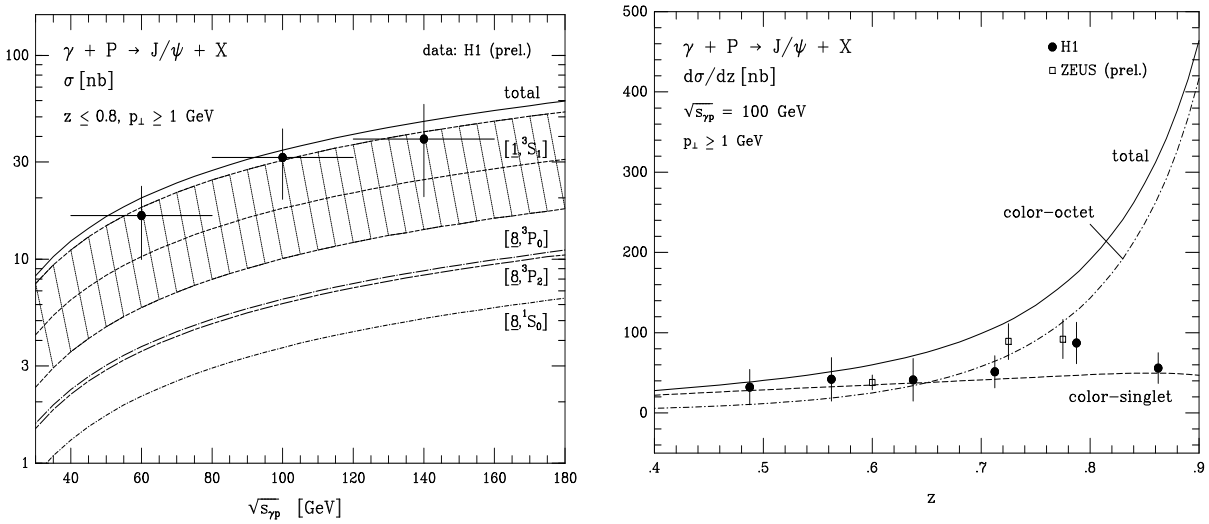

Figure 2: Total cross section (left) and inelasticity distribution (right) in photoproduction at HERA [18]. Color octet curves with parameters fitted to Tevatron data in [12].

J/ψ's produced at the Tevatron at large p_T are predicted to be almost fully transversely polarized, i.e. $\alpha(J/\psi) \simeq 1$ [16], as a result of the production via gluon fragmentation into ${}^3S_1^{(8)}$ states being largely dominant. At smaller p_T, on the other hand, non-fragmentation channels involving ${}^1S_0^{(8)}$ and ${}^3P_J^{(8)}$ become important: the J/ψ's are then predicted to be produced essentially unpolarized in the low transverse momentum region, around $p_T \simeq 5$ GeV [13]. The observation of such a polarization pattern, shown in figure 1, would provide great support for the factorization approach to quarkonia production.

3 The HERA data in γp collisions

Within γp collisions J/ψ's can be produced in leading order at non-zero p_T via the color singlet channel $\gamma p \to {}^3S_1^{(1)} g \to J/\psi X$ ([5], first reference). Next-to-leading order QCD corrections to this channel have been recently computed [17], and the results have been found in fairly good agreement with the experimental results from the ZEUS and H1 experiments: the absolute normalization of the total cross section agrees within the theoretical uncertainties, and the shape of the inelasticity distribution of the J/ψ (usually denoted by z, with $z = E_{J/\psi}/E_\gamma$ in the proton rest frame) is well described by the calculation.

Color octet contributions to J/ψ photoproduction have been investigated in leading order [18, 19]. In the non-zero p_T region the five $\gamma p \to ({}^1S_0{}^{(8)}, {}^3S_1{}^{(8)}, {}^3P_J{}^{(8)}) g$ channels contribute. Figure 2 shows the results for the total cross section and the inelasticity distribution with the inclusion of these channels: matrix elements *of the order* of the ones fitted to the Tevatron data without using PYTHIA have been employed in these plots, taking $\langle \mathcal{O}_8^{J/\psi}({}^3S_1)\rangle = \langle \mathcal{O}_8^{J/\psi}({}^1S_0)\rangle = \langle \mathcal{O}_8^{J/\psi}({}^3P_J)\rangle/(2J+1)m^2 = 1 \times 10^{-2}$ GeV^3.

One can see from the plots how the data do not need any octet contributions: the color singlet channel by itself can describe them well. More than this, the octet terms evaluated

with the Tevatron parameters look at variance with the data, suggesting a non-universality of these NRQCD matrix elements. We have however seen how indications exist [15] that the fits to the Tevatron data may be a significant overestimate: if we reduce the value of the matrix elements used in the photoproduction calculation by a factor of three, to bring them in line with the smaller Tevatron fits returned by using PYTHIA, the discrepancy in the inelasticity distribution is greately reduced. Further unaccounted for contributions, like higher orders near the phase space end point, could easily provide large corrections and bring the prediction in agreement with the data. See refs. [4, 20] for a more detailed discussion about this point.

An analysis of photoproduction data within the factorization approach has also been attempted in the elastic region, by fitting experimental results with the leading order prediction given by the octet channels $\gamma g \to {}^1S_0^{(8)}, {}^3P_0^{(8)}, {}^3P_2^{(8)}$. This gives the result [21]

$$\langle \mathcal{O}_8^{J/\psi}({}^1S_0)\rangle + \frac{7}{m^2}\langle \mathcal{O}_8^{J/\psi}({}^3P_0)\rangle \simeq 2 \times 10^{-2}\ \mathrm{GeV}^3 \qquad [21] \tag{12}$$

This looks smaller than some of the Tevatron fits but, as we shall see in the next Section, in line with fits to fixed target data. This result should however be taken with great care, due to the many subtleties surrounding elastic vector meson production and to the large theoretical uncertainties.

4 Quarkonia in fixed target experiments

Fixed target experiments were of course the first to produce data on quarkonia production. Large normalization discrepancies between, say, J/ψ production data and theoretical predictions based on the Color Singlet Model had been observed but, lacking a detailed understanding of the problem, usually dealt with by scaling the theoretical curves by very large K-factors, of order ten or more. Nowadays, the FA offers the possibility to give a theoretically sound interpretation of these data, possibly in line with the one which seems to successfully describe the Tevatron data. Color octet contributions to total J/ψ and ψ' production in a fixed target set-up have been evaluated, and compared to data obtained in pN and πN collisions. Fitting pN data with leading order short distance cross sections (a next-to-leading order calculation is in preparation [22]) the following values for the matrix elements have been found [23]:

$$\langle \mathcal{O}_8^{J/\psi}({}^1S_0)\rangle + \frac{7}{m^2}\langle \mathcal{O}_8^{J/\psi}({}^3P_0)\rangle \simeq 3 \times 10^{-2}\ \mathrm{GeV}^3 \qquad [23] \tag{13}$$

$$\langle \mathcal{O}_8^{\psi'}({}^1S_0)\rangle + \frac{7}{m^2}\langle \mathcal{O}_8^{\psi'}({}^3P_0)\rangle \simeq 5.2 \times 10^{-3}\ \mathrm{GeV}^3 \qquad [23] \tag{14}$$

Figure 3 shows how such values for the color octet matrix elements allows for a good description on the data in a wide beam energy range, whereas the singlet contribution alone clearly underestimates them. A similar analysis has also been performed in [24]. It is to be noted that the fitted values are not fully consistent with the Tevatron ones, looking at least a factor of three smaller (notice that the linear combination of the two matrix elements is not exactly the same): this can be taken as a further indication that the Tevatron fits might be an overestimate).

These parameters fitted in pN collisions have been tested by predicting J/ψ and ψ' production in πN collisions: they provide a fairly good description of the data, though they seem to underestimate them by about a factor of two [23].

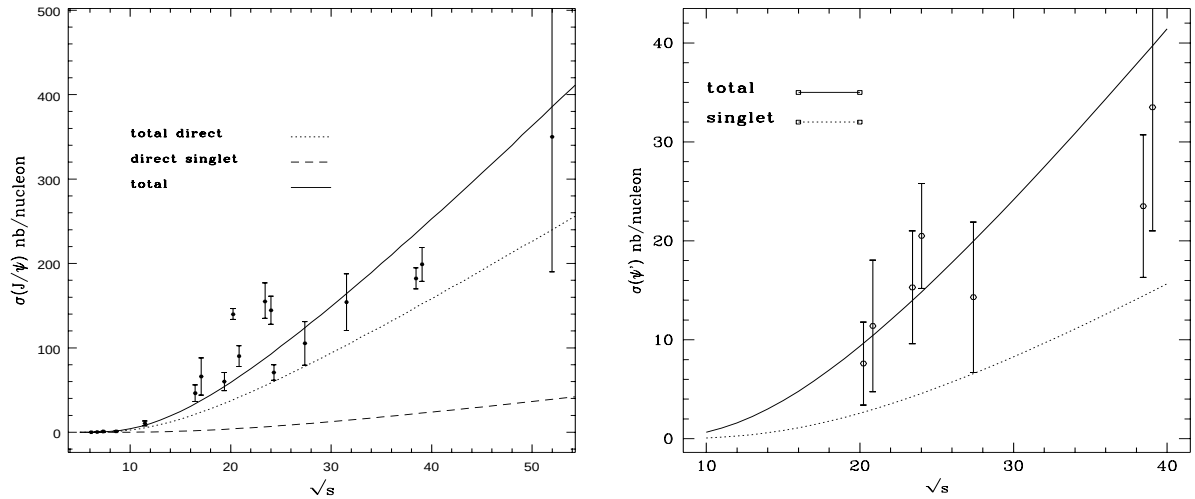

Figure 3: J/ψ (left) and ψ' (right) production in pN fixed target experiments, compared with theoretical fits with the color octet contributions [23].

A few more observables can offer a good handle on the validity of a given quarkonium production framework, namely χ's production, relative fraction of ψ's and χ's, and polarization of the produced quarkonium. Let us consider them in turn.

The ratio $\sigma(\chi_1)/\sigma(\chi_2)$ has been measured in many experiments, both in pN and in πN collisions. An average value for πN is about 0.6, while two pN experiments give smaller values (0.34 ± 0.16 for E771, 0.24 ± 0.3 for E673) but with large errors. A new preliminary result, 0.45 ± 0.2, has been presented by E771 at this Conference [25].

These experimental results have to be compared with a theoretical prediction, within the FA, of about 0.08 [23]. The reason for such a small prediction is that at leading order the $gg \to {}^3P_1^{(1)} \to \chi_1$ process vanishes in the FA, and the color octet channel $q\bar{q} \to {}^3S_1^{(8)} \to \chi_J$ only contributes a small fraction. One should however consider that more color octet channels can contribute to both χ_1 and χ_2 production. These processes go through the octet states ${}^1S_0^{(8)}$, ${}^3P_J^{(8)}$ and ${}^3D_J^{(8)}$, and an accurate assessment of their relevance is prevented by our ignorance of the values of the NRQCD matrix elements weighing their transition to the observable χ states. A very crude estimate of their effect [23, 4] returns a value around 0.3, in good agreement with the pN data but smaller that the πN ones[1].

One more interesting observable is the fraction of J/ψ coming from χ's decays, $\sigma(J/\psi \leftarrow \chi)/\sigma(J/\psi)$, which is of course also a part of the ratio of J/ψ and χ's cross sections. The experimental data, both in fixed target experiments in pN and πN collisions and also in $p\bar{p}$ collisions at the Tevatron, gather around a central value of 0.3–0.4. The FA, making use of fits to Tevatron data for the χ's matrix elements and to fixed target data for J/ψ ones predicts a value of about 0.3 [23], thus in good agreement with the experiment.

What's special about this observable is that its value is strikingly different in γp collisions.

[1]Of course this disagreement between the two sets of data, if found to persist and become more significant, would by itself be pretty puzzling.

This is because the leading order reaction $\gamma g \to \chi_J g$ is forbidden due to charge conjugation invariance. Indeed, no experimental data exist for $\sigma(J/\psi \leftarrow \chi)/\sigma(J/\psi)$ in photoproduction, due to the vanishingly small χ's yield, but only an upper limit by NA14 [26]: $\sigma(J/\psi \leftarrow \chi)/\sigma(J/\psi) < 0.08$. The reason why this is important is that the Color Evaporation Model, in that it is not concerned with the details of the particles initiating the reaction, would predict the same ratio for hadro- and photoproduction. Hence, one could say that the CEM is ruled out by this result, though more independent confirmations of the photoproduction experimental result would actually be welcome.

One further key observable is the polarization of the quarkonium, measured according to eq. (11). One finds, experimentally,

$$\alpha(J/\psi) = 0.02 \pm 0.14 \tag{15}$$

$$\alpha(\psi') = 0.028 \pm 0.004 \tag{16}$$

That is, the quarkonia are found to be produced essentially unpolarized.

This is in contrast with theoretical calculations within the FA, which predict instead a sizeable degree of polarization, returning $0.31 < \alpha(J/\psi) < 0.62$ and $0.15 < \alpha(\psi') < 0.44$ [23], the large band taking into account the very approximate knowledge we have of the NRQCD matrix elements' values.

Such a discrepancy is certainly disturbing, and if confirmed would be a serious problem for the factorization approach. At the present stage of our understanding we must however be aware that many unaccounted for contributions may still play an important role here. For instance, a proper inclusion of effects which would lead to off-shell rather than on-shell colliding gluons could significantly change the picture presented above. I therefore think it would not be wise to bury the factorization approach at this stage and because of this discrepancy.

5 Conclusions

With this brief survey of a few of the phenomenological consequences of the factorization approach to quarkonia production (which I should urge you *not* to call "Color Octet Model"!) we have seen how it looks able to describe in a satisfactory way experimental results previously at great variance with the Color Singlet Model, both in fixed target experiments and at the Tevatron.

Problems appear in photoproduction at HERA, where the color singlet contribution alone appears on the other hand to well describe the data. But the uncertainties are still large and can accomodate for the discrepancy.

Polarization data are also troublesome for the factorization approach (as they are for the CSM, while the CEM cannot give a prediction at all). But I feel, once again, the uncertainties to be still too large for an assessment of the validity of this approach based on these data.

Surely enough, the factorization approach appears superior to both the CSM (of which it is an extension) and the CEM. One could say the CSM approximation still appears to work fairly well when few gluons are involved (in photoproduction), whereas the CEM can work when very many gluons are around (in hadron-hadron collisions). But neither of them can even attempt

to describe the whole yield of data: for instance, the CSM can be ruled out by the Tevatron data alone, and the CEM could possibly be ruled out by χ_J photoproduction.

It is quite a widespread belief (though by no means universal!) that the factorization approach *is* the right theory for heavy quarkonia production and decay. As a matter of fact, the NRQCD lagrangian on which it is based is nothing but a limit of the QCD lagrangian itself, and not an *ad hoc* model.

If anything, a problem of the FA is not of being inadequate, but rather of being perhaps even too general. Many different NRQCD matrix elements enter the phenomenological predictions (because the corresponding operators enter the nonrelativistic limit of the QCD lagrangian), and it is difficult to produce accurate numerical results with so many unknown parameters. These matrix elements are on the other hand rigorously defined and in principle calculable by lattice QCD, so it is possible they will be more precisely determined in the future either this way or by global analyses of experimental data.

Given the reasonable correctness of the underlying lagrangian, discrepancies of the theoretical predictions with experimental data may still be originated by the approximations included in the calculations.

Higher twist corrections to the factorization approximation can be large, especially for charmonium (one should never forget that $\Lambda/m_c \simeq 0.3$, not really a negligibly small number). Higher order corrections, both in the strong coupling ($\alpha_s(m_c) \simeq 0.3$) and in the velocity of the heavy quarks (again, $v^2 \simeq 0.3$ for charm), can also be large. The value of v^2 (and higher powers) determines – via scaling rules [27] – which matrix elements are dominant, and also how accurately – via spin symmetry – different matrix elements can be equated to each other. These approximations are widely used in the phenomenological predictions, to truncate the series and to decrease the number of independent parameters. How reliable they are is therefore extremely important for the accuracy of the theoretical result: the fairly large value of v^2 for charmonium systems may help explaining discrepancies between nowadays predictions and experimental data.

The situation should be much better for bottomonium systems, for which all the expansion parameters I mentioned take significantly smaller values, around 0.1. All the approximations should therefore be much better justified, and one should expect a better agreement between theory and data. A detailed study of such systems, both theoretically and experimentally, will therefore greatly help finally confronting the factorization approach to quarkonia production and decay with the real world.

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References

[1] G.T. Bodwin, E. Braaten, and G.P. Lepage, Phys. Rev. **D51** (1995) 1125, erratum *ibid.* **D55** (1997) 5853

[2] E. Braaten, S. Fleming and T.C. Yuan, Ann. Rev. Nucl. Part. Sci. **46** (1996) 197

[3] E. Braaten, Talk given at 3rd International Workshop on Particle Physics Phenomenology, Taipei, Taiwan, 14-17 Nov 1996, OHSTPY-HEP-T-97-004, hep-ph/9702225

[4] M. Beneke, Lecture at the XXXIV SLAC Summer Institute on Particle Physics (August 1996), CERN-TH/97-55 (hep-ph/9703429)

[5] E.L. Berger and D. Jones, Phys. Rev. **D23** (1981) 1521; R. Baier and R. Rückl, Phys. Lett. **102B** (1981) 364; for a recent review see also G.A. Schuler, CERN-TH.7170/94 (hep-ph/9403387)

[6] H. Fritzsch, Phys. Lett. **67B** (1977) 217; F. Halzen, Phys. Lett. **69B** (1977) 105; F. Halzen and S. Matsuda, Phys. Rev. **D17** (1978) 1344; M. Glück, J. Owens and E. Reya, Phys. Rev. **D17** (1978) 2324; A. Bramon, E. Etim and M. Greco, Phys. Lett. **41B** (1972) 609

[7] G. Schuler and R. Vogt, Phys. Lett. **B387** (1996) 181

[8] J.F. Amundson, O.J.P. Eboli, E.M. Gregores, F. Halzen, Phys. Lett. **B390** (1997) 323; Phys. Lett. **B372** (1996) 127

[9] E. Braaten and S. Fleming, Phys. Rev. Lett. **74** (1995) 3327

[10] M. Cacciari and M. Greco, Phys. Rev. Lett. **73** (1994) 1586; E. Braaten, M.A. Doncheski, S. Fleming, and M.L. Mangano, Phys. Lett. **B333** (1994) 548; D.P. Roy and K. Sridhar, Phys. Lett. **B339** (1994) 141

[11] M. Cacciari, M. Greco, M.L. Mangano and A. Petrelli, Phys. Lett. **B356** (1995) 553

[12] P. Cho and A.K. Leibovich, Phys. Rev. **D53** (1996) 150; Phys. Rev. **D53** (1996) 6203

[13] M. Beneke and M. Krämer,Phys. Rev. **D55** (1997) 5269

[14] S.M. Tkaczyk, for the CDF and D0 Collaborations, hep-ex/9611009, theoretical curves taken from [12]

[15] B. Cano-Coloma and M.A. Sanchis-Lozano, hep-ph/9701210

[16] P. Cho and M.B. Wise, Phys. Lett. **B346** (1995) 129; Beneke and I.Z. Rothstein, Phys. Lett. **B372** (1996) 157, erratum *ibid.* **B389** (1996) 769

[17] M. Krämer, Nucl. Phys. **B459** (1996) 3

[18] M. Cacciari and M. Krämer, Phys. Rev. Lett. **76** (1996) 4128

[19] P. Ko, J. Lee and H.S. Song, Phys. Rev. **D54** (1996) 4312

[20] M. Beneke, I.Z. Rothstein and M. Wise, CERN-TH/97-86 (hep-ph/9705286)

[21] J. Amundson, S. Fleming and I. Maksymyk, UTTG-10-95 (hep-ph/9601298)

[22] M. Cacciari, M. Greco, F. Maltoni, M.L. Mangano and A. Petrelli, in preparation

[23] M. Beneke and I.Z. Rothstein, Phys. Rev. **D54** (1996) 2005, erratum *ibid.* 7082

[24] S. Gupta and K. Sridhar, Phys. Rev. **D54** (1996) 5545; Phys. Rev. **D55** (1997) 2650

[25] K.E. Gollwitzer, these Proceedings

[26] R. Barate et al. (NA14 Coll.) Z. Phys. **C33** (1987) 505; P. Rodeau et al. (NA14 Coll.), Nucl. Phys. Proc. Suppl. **7B** (1989) 273

[27] G.P. Lepage, L. Magnea, C. Nakhleh, U. Magnea, and K. Hornbostel, Phys. Rev. **D46** (1992) 4052