$J/\psi$ and $\psi(2S)$ Production and Polarization at the Tevatron*

Michael Krämer

Department of Physics and Astronomy
The University of Edinburgh
Edinburgh EH9 3JZ, Scotland

The NRQCD factorization approach for quarkonium production at hadron colliders is reviewed. The prediction of $J/\psi$ and $\psi(2S)$ transverse polarization at large transverse momentum is confronted with recent experimental data, and potential shortcomings of the theoretical analysis are discussed.

1. Introduction

The production of charmonium states at high-energy colliders has been the subject of considerable interest during the past few years. New results from $p\bar{p}$, $ep$, and $e^+e^-$ experiments have become available, some of which revealed dramatic shortcomings of earlier quarkonium production models. In theory, progress has been made on the factorization between the short distance physics of heavy-quark creation and the long-distance physics of bound state formation. The colour-singlet model [1] has been superseded by a consistent and rigorous framework, based on the use of non-relativistic QCD (NRQCD) [2], an effective field theory that includes the so-called colour-octet mechanisms. On the other hand, the colour evaporation model [3] of the early days of quarkonium physics has been revived [4]. However, despite the recent theoretical and experimental developments the range of applicability of the different approaches is still subject to debate, as is the quantitative verification of factorization. Because the charmonium mass is still not very large with respect to the QCD scale, non-factorizable corrections [5] may not be suppressed enough and the expansions in NRQCD may not converge very well.

In this situation cross checks between various processes, and predictions of observables such as quarkonium polarization and differential cross sections, are crucial in order to assess the importance of different quarkonium production mechanisms, as well as the limitations of a particular theoretical approach. Among the specific predictions of NRQCD, transverse polarization of direct (i.e. not from $B$ and $\chi_c$ decays) $J/\psi$ and $\psi(2S)$ hadroproduction at large transverse momentum has emerged as the most distinct and most accessible signature [6]. Transverse polarization also discriminates NRQCD from other approaches, like the colour evaporation model which predicts the quarkonium to be produced unpolarized. In the following, I will briefly review the general mechanism of quarkonium production at hadron colliders in the NRQCD factorization approach. The prediction of $J/\psi$ and $\psi(2S)$ transverse polarization at large transverse momentum is confronted with recent experimental data from the Tevatron, and potential shortcomings of the theoretical analysis are discussed.

2. Quarkonium production at hadron colliders

In the NRQCD approach, the cross section for producing a quarkonium state $H$ at a hadron collider is written as a sum of factorizable terms,

\[
    d\sigma(p\bar{p} \to H + X) = \sum_n d\sigma(p\bar{p} \to QQ^n[n] + x) \langle O^H[n] \rangle,
\]

as quarkonium polarization and differential cross sections, are crucial in order to assess the importance of different quarkonium production mechanisms, as well as the limitations of a particular theoretical approach. Among the specific predictions of NRQCD, transverse polarization of direct (i.e. not from $B$ and $\chi_c$ decays) $J/\psi$ and $\psi(2S)$ hadroproduction at large transverse momentum has emerged as the most distinct and most accessible signature [6]. Transverse polarization also discriminates NRQCD from other approaches, like the colour evaporation model which predicts the quarkonium to be produced unpolarized. In the following, I will briefly review the general mechanism of quarkonium production at hadron colliders in the NRQCD factorization approach. The prediction of $J/\psi$ and $\psi(2S)$ transverse polarization at large transverse momentum is confronted with recent experimental data from the Tevatron, and potential shortcomings of the theoretical analysis are discussed.

* Talk presented at the 4th International Conference on Hyperons, Charm and Beauty Hadrons, Valencia, Spain, 27-30 June 2000. To be published in the proceedings.
where \( n \) denotes the colour, spin and angular momentum state of an intermediate \( Q\bar{Q} \) pair. The short-distance cross section \( \sigma \) can be calculated perturbatively in the strong coupling \( \alpha_s \). The NRQCD matrix elements \( \langle O^H[n] \rangle \) (see \[2\] for their definition) are related to the non-perturbative transition probabilities from the \( Q\bar{Q} \) state \( n \) into the quarkonium \( H \). They scale with a definite power of the intrinsic heavy-quark velocity \( v \) \[7\]. \( (v^2 \sim 0.3 \) for charmonium and \( v^2 \sim 0.1 \) for bottomonium.) The general expression \[2\] is thus a double expansion in powers of \( \alpha_s \) and \( v \).

The NRQCD formalism implies that so-called colour-octet processes associated with higher Fock state components of the quarkonium wave function must contribute to the cross section. Heavy quark pairs that are produced at short distances in a colour-octet state can evolve into a physical quarkonium through radiation of soft gluons at late times in the production process, when the quark pair has already expanded to the quarkonium size.

The production of \( S \)-wave charmonium in \( pp \) collisions at the Tevatron has attracted considerable attention and has stimulated much of the recent theoretical development in quarkonium physics. The CDF collaboration has measured cross sections for the production of \( J/\psi \) and \( \psi(2S) \) states not coming from \( B \) or radiative \( \chi_c \) decays, for a wide range of transverse momenta \( 5 \text{GeV} \lesssim p_t(\psi) \lesssim 20 \text{GeV} \) \[8,9\]. Surprisingly, the experimental cross sections were found to be orders of magnitudes larger than the theoretical expectation based on the leading-order colour-singlet model \[10\]. This result is particularly striking because the data extends out to large transverse momenta where the theoretical analysis is rather clean and non-factorizable corrections should be suppressed. The shortcoming of the colour-singlet model can be understood by examining a typical Feynman diagram contributing to the leading-order parton cross section, Fig.1(a).

At large transverse momentum, the two internal quark propagators are off-shell by \( \sim p_t^2 \) so that the parton differential cross section scales like \( d\sigma/dp_t^2 \sim 1/p_t^4 \), as indicated in the figure. On the other hand, when \( p_t \gg 2m_c \) the quarkonium mass can be considered small and the inclusive charmonium cross section is expected to scale like any other single-particle inclusive cross section \( \sim 1/p_t^4 \). The dominant production mecha-

\[
\begin{align*}
\text{(a) leading-order colour-singlet:} & \\
g + g & \rightarrow \alpha_s^3 \psi^{(1)} + g \\
& + \ldots \sim \alpha_s^3 (2m_c)^4 \frac{1}{p_t^6} \\
\text{(b) colour-singlet fragmentation:} & \\
g + g & \rightarrow [\alpha_s^3 \psi^{(1)}] + gg + g \\
& + \ldots \sim \alpha_s^3 \frac{1}{p_t^6} v^4 \\
\text{(c) colour-octet fragmentation:} & \\
g + g & \rightarrow \alpha_s^3 \psi^{(8)} + g \\
& + \ldots \sim \alpha_s^3 \frac{1}{p_t^6} v^4 \\
\text{(d) colour-octet fusion:} & \\
g + g & \rightarrow \alpha_s^3 S_0^{(8)}, S_J^{(8)} + g \\
& + \ldots \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4 
\end{align*}
\]
mechanism for charmonium at sufficiently large \( p_t \) must thus be via fragmentation \([1]\), the production of a parton with large \( p_t \) which subsequently decays into charmonium and other partons. A typical fragmentation contribution to colour-singlet \( J/\psi \) production is shown in Fig.1(b). While the fragmentation contributions are of higher order in \( \alpha_s \) compared to the fusion process Fig.1(a), they are enhanced by a power \( p_t^3/(2m_c)^3 \) at large \( p_t \) and thus overtake the fusion contribution at \( p_t \gg 2m_c \). When colour-singlet fragmentation is included, the \( p_t \) dependence of the theoretical prediction is in agreement with the Tevatron data but the normalization is still underestimated by about an order of magnitude \([2]\), indicating that an additional fragmentation contribution is still missing. It is now generally believed that gluon fragmentation into colour-octet \( ^3S_1 \) charm quark pairs \([3]\), as shown in Fig.1(c), is the dominant source of \( J/\psi \) and \( \psi(2S) \) at large \( p_t \) at the Tevatron. The probability of forming a \( J/\psi(\psi(2S)) \) particle from a pointlike \( c\bar{c} \) pair in a colour-octet \( ^3S_1 \) state is given by the NRQCD matrix element 
\[ \langle \mathcal{O}^f/\psi(\psi(2S))|^{3S_1^{(8)}} \rangle \]
which is suppressed by \( v^4 \) relative to the non-perturbative factor of the leading colour-singlet term. However, this suppression is more than compensated by the gain in two powers of \( \alpha_s/\pi \) in the short-distance cross section for producing colour-octet \( ^3S_1 \) charm quark pairs as compared to colour-singlet fragmentation. At \( \mathcal{O}(v^4) \) in the velocity expansion, two additional colour-octet channels have to be included, Fig.1(d), which do not have a fragmentation interpretation at order \( \alpha_s^3 \) but which become significant at moderate \( p_t \sim 2m_c \) \([4]\). The importance of the \( ^1S_0^{(8)} \) and \( ^3P_j^{(8)} \) contributions cannot be estimated from naive power counting in \( \alpha_s \) and \( v \) alone, but rather follows from the dominance of \( t \)-channel gluon exchange, forbidden in the leading-order colour-singlet cross section.

The different contributions to the \( J/\psi \) transverse momentum distribution are compared to the CDF data \([5]\) in Fig.2. As mentioned above, the colour-singlet model at lowest order in \( \alpha_s \) fails dramatically when confronted with the experimental results. When colour-singlet fragmentation is included, the prediction increases by more than an order of magnitude at large \( p_t \), but it still falls below the data by a factor of \(~30\). The CDF results on charmonium production can be explained by including the leading colour-octet contributions and adjusting the unknown non-perturbative parameters to fit the data. Numerically one finds the non-perturbative matrix elements to be of \( \mathcal{O}(10^{-2} \text{ GeV}^3) \), see e.g. \([6]\), perfectly consistent with the \( v^4 \) suppression expected from the velocity scaling rules. Similar conclusions can be drawn for \( \psi(2S) \) production at the Tevatron.

![Figure 2](image.png)

**Figure 2.** Colour-singlet and colour-octet contributions to direct \( J/\psi \) production in \( pp \rightarrow J/\psi + X \) at the Tevatron together with experimental data from CDF \([7]\). Parameters and NRQCD matrix elements as specified in \([8]\).

### 3. \( J/\psi \) and \( \psi(2S) \) polarization at the Tevatron

The analysis of the CDF data \([8]\) alone, although very encouraging, does not strictly prove the phenomenological relevance of colour-octet contributions because free parameters have to be introduced to fit the data. However, if factorization holds the non-perturbative matrix elements extracted from the \( J/\psi \) and \( \psi(2S) \) cross sections are universal and can be used to make predictions for various processes and observables. The single most crucial test of the NRQCD approach to charmonium production at hadron colliders is
the analysis of $\psi(2S)$ polarization at large transverse momentum. Recall that at large $p_t$, $\psi(2S)$ production should be dominated by gluon fragmentation into a colour-octet $^3S_1$ charm quark pair, Fig.1(c). When $p_t \gg 2m_c$, the fragmenting gluon is effectively on-shell and transverse. The intermediate $c\bar{c}$ pair in the colour-octet $^3S_1$ state inherits the gluon’s transverse polarization and so does the quarkonium, because the emission of soft gluons during hadronization does not flip the heavy quark spin at leading order in the velocity expansion. Consequently, at large transverse momentum one should observe transversely polarized $\psi(2S)$.

The polarization can be measured through the angular distribution in the decay $\psi \rightarrow l^+l^-$, given by $d\Gamma/d\cos\theta \propto 1 + \alpha \cos^2 \theta$, where $\theta$ denotes the angle between the lepton three-momentum in the $\psi$ rest frame and the $\psi$ three-momentum in the lab frame. Pure transverse polarization implies $\alpha = 1$. Corrections to this asymptotic limit due to higher order fragmentation contributions have been estimated to be small [17]. The dominant source of depolarization comes from the colour-octet fusion diagrams, Fig.1(d), which are important at moderate $p_t$. Still, at $\mathcal{O}(v^4)$ in the velocity expansion, the polar angle asymmetry $\alpha$ can be unambiguously calculated within NRQCD [18,19] in terms of the non-perturbative matrix elements that have been determined from the unpolarized cross section. In Fig.3 we display the theoretical prediction [18] (shaded band) for $\alpha$ in $\psi(2S)$ production at the Tevatron as function of the $\psi(2S)$ transverse momentum, taking into account the $^1S_0^{(8)}$ and $^3P_j^{(8)}$ fusion channels and higher-order corrections to the fragmentation contributions. No transverse polarization is expected at $p_t \sim 5$ GeV, but the angular distribution is predicted to change drastically as $p_t$ increases. A first measurement from CDF [20] does not support this prediction, but the experimental errors are too large to draw definite conclusions.

The analysis of $J/\psi$ polarization is complicated by the fact that the experimental data sample [21] includes $J/\psi$ that have not been produced directly but come from decays of $\chi_c$ and $\psi(2S)$ mesons. The contribution from the radiative decays of the higher excited states decreases, but does not eliminate, the transverse $J/\psi$ polarization at large $p_t$ [21]. Again, the NRQCD factorization prediction is not supported by the experimental data, see Fig.4.
4. Discussion

The absence of transversely polarized $J/\psi$ and $\psi(2S)$ at large transverse momentum, if confirmed at the Tevatron Run II, represents a challenge for the application of NRQCD factorization to charmonium production. In the following, I will discuss some possible uncertainties and potential shortcomings of the present theoretical analysis:

- **Higher-order QCD effects** in the short-distance cross section should be included to improve the accuracy of the theoretical prediction, in particular in the intermediate $p_t$ region. While no attempt has been made to estimate the impact of higher-order corrections on the spin-dependence of the cross section, preliminary studies indicate large NLO effects for the unpolarized $p_t$-distributions. These corrections could strongly affect the determination of the NRQCD matrix elements from the Tevatron data. A full NLO analysis is however needed before quantitative conclusions can be drawn. The impact of non-vanishing transverse momentum of the incoming partons on the determination of the NRQCD matrix elements has been analyzed using a Gaussian smearing of the $p_t$ distribution. Monte Carlo event generators and, most recently, the $k_t$-factorization formalism. The actual size of the effect, however, turns out to be very different for the different approaches studied in the literature.

- The uncertainty in the determination of NRQCD matrix elements translates into an uncertainty in the predicted yield of transversely polarized $J/\psi$ and $\psi(2S)$. The extraction of NRQCD matrix elements from the unpolarized cross section at the Tevatron is affected by large theoretical uncertainties which have not yet been fully quantified, see e.g. [14, 10]. In Fig.3 we also show the polarization prediction for the extreme choices of vanishing $\langle O^{0[3S_0^{(8)}], 3P_0^{(8)}} \rangle$ matrix elements (upper dashed line) and a very small $\langle O^{0[3S_1^{(8)}]} \rangle$ matrix element (lower dotted line, see Figure caption). The latter choice is motivated by the recent analyses of $J/\psi$ and $\psi(2S)$ production at the Tevatron in the $k_t$-factorization approach which predict a strongly enhanced colour-singlet contribution and a substantially decreased value of $\langle O^{0[3S_1^{(8)}]} \rangle$. A decreased value of the $\langle O^{0[3S_1^{(8)}]} \rangle$ matrix element, relative to $\langle O^{0[1S_0^{(8)}], 3P_0^{(8)}]} \rangle$, would delay the onset of transverse polarization and reduce the discrepancy between NRQCD predictions and data. However, such extreme values for the NRQCD matrix elements would indicate a flaw in our understanding of the velocity scaling rules which imply that all three matrix elements are of approximately equal size $O(v) \approx O(10^{-2} \text{GeV}^3)$.

- **Heavy quark spin-symmetry** is violated by higher-order terms in the NRQCD lagrangian and longitudinal polarization can arise if the binding of the charm quark pair into $J/\psi$ and $\psi(2S)$ proceeds through two chromo-magnetic dipole transitions. According to the velocity scaling rules these transitions are suppressed by $v^4$ and the corresponding corrections to transverse polarization should not exceed $\approx 5\%$. Predictions of heavy quark spin-symmetry for radiative charmonium decays agree quite well with experimental data and there is no obvious reason why spin-symmetry should fail when applied to charmonium production. Still, the estimate of the spin-symmetry breaking corrections to transverse polarization relies on the conventional velocity scaling rules which have not been firmly established for the case of charmonium. Alternative velocity scaling rules imply a hierarchy of NRQCD matrix elements different from the standard counting and might indicate larger spin-symmetry violating corrections.

- Finally, charmonium production mechanisms beyond NRQCD could be responsible for $J/\psi$ and $\psi(2S)$ depolarization. For example, the leading-twist formalism of NRQCD factorization does not include possible rescattering interactions between the intermediate heavy quark pair and a comoving colour field. It has been shown that such rescattering corrections could yield unpolarized quarkonium. The analysis, however, relies on several simplifying assumptions, and further work is needed to establish the importance of comover interactions for charmonium production at large $p_t$. 

}\end{verbatim}
5. Conclusion

The absence of a transverse polarization in $J/\psi$ and $\psi(2S)$ hadroproduction at large $p_t$ represents a serious challenge for the application of the NRQCD factorization approach to charmonium production. Several potential problems with the current theoretical analysis have been discussed but no conclusive picture has emerged yet. If no transverse polarization is observed with higher statistics at larger values of $p_t$ in Run II of the Tevatron, one might have to conclude that the charm quark mass is not large enough for a non-relativistic approach to work in all circumstances.

Note added
After submission of this proceedings contribution, charmonium polarization at the Tevatron has been addressed in the $k_t$-factorization approach [30]. The authors argue that the $1S(8)_0$ production channel could be the dominant source of $J/\psi$ and $\psi(2S)$ in the experimentally accessible region of transverse momentum, which implies that quarkonium be produced mainly unpolarized.

Acknowledgements
I would like to thank Martin Beneke for his collaboration and the conference organizers for creating a pleasant and stimulating atmosphere. A conference grant by the Royal Society is gratefully acknowledged.

REFERENCES

1. E. L. Berger and D. Jones, Phys. Rev. D23 (1981) 1521; R. Baier and R. Rückl, Phys. Lett. B102 (1981) 364.
2. G. T. Bodwin, E. Braaten and G. P. Lepage, Phys. Rev. D51 (1995) 1125; erratum ibid. D55 (1997) 5853.
3. H. Fritzsch, Phys. Lett. 67B (1977) 217; F. Halzen, Phys. Lett. 69B (1977) 105; M. Glück, J. F. Owens and E. Reya, Phys. Rev. D17 (1978) 2324.
4. G. A. Schuler and R. Vogt, Phys. Lett. B387 (1996) 181; J. F. Amundson, O. J. Eboli, E. M. Gregores and F. Halzen, Phys. Lett. B390 (1997) 323; A. Edin, G. Ingelman and J. Rathsman, Phys. Rev. D56 (1997) 7317.
5. S. J. Brodsky, Int. J. Mod. Phys. A12 (1997) 4087; P. Hoyer, Nucl. Phys. Proc. Suppl. 75B (1999) 153.
6. P. Cho and M. B. Wise, Phys. Lett. B346 (1995) 129.
7. G. P. Lepage, L. Magnea, C. Nakhleh, U. Magnea and K. Hornbostel, Phys. Rev. D46 (1992) 4052.
8. F. Abe et al. [CDF Collaboration], Phys. Rev. Lett. 69 (1992) 3704.
9. F. Abe et al. [CDF Collaboration], Phys. Rev. Lett. 79 (1997) 572.
10. R. Baier and R. Rückl, Z. Phys. C19 (1983) 251; R. Gastmans, W. Troost and T. T. Wu, Nucl. Phys. B291 (1987) 731.
11. E. Braaten and T. C. Yuan, Phys. Rev. Lett. 71 (1993) 1673.
12. 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.
13. E. Braaten and S. Fleming, Phys. Rev. Lett. 74 (1995) 3327.
14. P. Cho and A. K. Leibovich, Phys. Rev. D53 (1996) 150; Phys. Rev. D55 (1996) 6203.
15. M. Krämer, F. Maltoni and M. A. Sanchis Lozano, in 'Bottom Production', P. Nason, G. Ridolfi, O. Schneider, G. F. Tartarelli, P. Vikas et al., hep-ph/0003142, published in CERN-YR-2000/01, G. Altarelli and M. L. Mangano editors.
16. A. K. Leibovich, these proceedings [hep-ph/0008236].
17. M. Beneke and I. Z. Rothstein, Phys. Lett. B372 (1996) 157.; erratum ibid. D54 (1997) 7082.
18. M. Beneke and M. Krämer, Phys. Rev. D55 (1997) 5269.
19. A. K. Leibovich, Phys. Rev. D56 (1997) 4412.
20. T. Affolder et al. [CDF Collaboration], Phys. Rev. Lett. 85 (2000) 2886.
21. E. Braaten, B. A. Kniehl and J. Lee, Phys. Rev. D62 (2000) 094005; B. A. Kniehl and J. Lee, hep-ph/0007292.
22. A. Petrilli, Nucl. Phys. Proc. Suppl. 86 (2000) 533.
23. B. Cano-Coloma and M. A. Sanchis-Lozano, Nucl. Phys. B508 (1997) 753.
24. F. Yuan and K. Chao, hep-ph/0008302.
25. P. Hägler et al., hep-ph/0008316.
26. A. Pineda, these proceedings [hep-ph/0008327].
27. M. Beneke, hep-ph/9703425.
28. G. A. Schuler, Int. J. Mod. Phys. A12 (1997) 3951.
29. N. Marchal, S. Peigne and P. Hoyer, hep-ph/0004234.
30. P. Yuan and K. Chao, hep-ph/0009224.