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A possible resolution of the CDF ψ' anomaly

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ABSTRACT

We consider the contribution of radially excited $2^3P_{1,2}$ states to ψ' production at the Tevatron energy. Production of these states *via* the conventional gluon fusion mechanism and *via* gluon and charm quark fragmentation processes is considered. We find that it is possible to account for the data on ψ' production from the CDF experiment, by taking into account the decays of these $2^3P_{1,2}$ states into ψ' .

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The CDF measurement [1] of J/ψ and ψ' production at large transverse momentum (p_T) in 1.8 TeV $\bar{p}p$ collisions at the Tevatron is one of the most challenging experimental results of recent times. There is a huge discrepancy between the experimental data and theoretical predictions of conventional models, much larger than the uncertainties that are typical of such theoretical predictions.

The production of quarkonia at large p_T is usually described by the parton-fusion mechanism in the framework of the colour-singlet model [2, 3, 4]. In this model, the wave-function at the origin for a S -wave (or its derivative for a P -wave) quarkonium is convoluted with the cross-section for producing a heavy quark pair with the proper spin, parity and charge-conjugation assignments. There is an uncertainty in the determination of the wave-function parameters, and taken in quadrature with that due to choice of scale, an overall uncertainty of a factor ~ 3 is expected in the predicted normalisation of the quarkonium cross-section. Within this normalisation uncertainty, the colour-singlet model prediction agrees with the J/ψ hadroproduction data from fixed-target and ISR experiments over a reasonable range of p_T [3, 5, 6].

At higher energies where b -quark production becomes important, the decay of b quarks is a mechanism that contributes to J/ψ and ψ' production, in addition to the parton-fusion mechanism of the colour-singlet model [6]. In the CDF experiment, however, the secondary vertex information has been used to separate out the b -quark decay contribution. The remainder are presumably produced directly by the fusion mechanism: therefore, the discrepancy between the large J/ψ and ψ' cross-sections measured by CDF and the theoretical predictions shows that the fusion mechanism grossly under-estimates the direct J/ψ and ψ' production cross-sections.

The above discrepancy calls for a new mechanism of quarkonium production at large p_T . At high-energy colliders, where gluons and charm quarks are copiously produced, the fragmentation of these particles into quarkonium states has been suggested as an important mechanism for large- p_T quarkonium production [7]. Even though the fragmentation process is of higher order in the strong coupling constant, α_s , it can dominate over the direct quarkonium production *via* fusion at large p_T , where terms of the order of p_T^2/m_Q^2 can easily compensate for the suppression due to the extra power of α_s . The validity of this suggestion is borne out by the explicit computation of the fusion and fragmentation contributions for the Tevatron energy, presented in Refs. [8, 9, 10]. In these papers, it was shown that the fragmentation contribution is the dominant contribution at the Tevatron energy; the largest contribution comes from gluons fragmenting into χ 's, which subsequently decay into J/ψ 's. Together with the fusion contribution it can explain the large cross-section measured by the CDF experiment to within a factor of 2-3, which is also the typical uncertainty in the predicted normalisation. In Ref. [8], the energy dependence of the fragmentation and fusion contributions was studied as well. It was shown that at ISR energies the fusion

contribution dominates over the p_T range of interest, although the inclusion of the fragmentation contribution helps to improve the quantitative agreement with the ISR data.

In Refs. [8, 9], the production of ψ' by fragmentation was also studied. Unlike J/ψ production, ψ' production does not involve the P -state contribution. Consequently, the fragmentation contribution is comparatively smaller. The total predicted ψ' cross-section is more than an order of magnitude smaller than the cross-section measured by CDF.

In this letter, we explore the possibility that radially excited P -state charmonia contribute *via* their electromagnetic decays to ψ' production. Some authors [11, 12] have recently suggested the possibility of a large contribution of the $2^3P_{1,2}$ states to ψ' production at the Tevatron energy. These $2P$ states have been predicted [13] to lie about 200-300 MeV above the open charm threshold, but their $D\bar{D}$ decay width is expected to be suppressed due to $L = 2$ phase-space as well as dynamical effects [11, 14]. Consequently, the branching ratios due to the decays $2^3P_{1,2} \rightarrow 2^3S_1 + \gamma$ can be substantial, and, hence, the $2P$ states could potentially contribute a significant fraction of the measured ψ' cross-section¹ [11, 12]. We present the first quantitative estimate of this contribution.

The theoretical set-up which we need to compute the p_T distributions has been discussed in detail in Ref. [8]. We will compute the contributions from the fusion and the fragmentation processes to the direct production of ψ' as well as to that of the $2P$ states. The large- p_T production cross-section for the fusion process is given as

$$\frac{d\sigma}{dp_T}(AB \rightarrow (2S, 2P_{1,2})X) = \sum \int dy dx_1 x_1 G_{a/A}(x_1) x_2 G_{b/B}(x_2) \frac{4p_T}{2x_1 - \bar{x}_T e^y} \frac{d\hat{\sigma}}{dt}(ab \rightarrow (2S, 2P_{1,2})c), \quad (1)$$

where the sum, in the above equation, runs over all the partons contributing to the subprocesses $ab \rightarrow (2S, 2P_{1,2})c$. $G_{a/A}$ and $G_{b/B}$ are the distributions of the partons a and b in the hadrons A and B with momentum fractions x_1 and x_2 , respectively, and x_2 is given as

$$x_2 = \frac{x_1 \bar{x}_T e^{-y} - 2\tau}{2x_1 - \bar{x}_T e^y}, \quad (2)$$

where $\tau = M^2/s$, with M the mass of the resonance, s the centre-of-mass energy and y the rapidity at which the resonance is produced.

$$\bar{x}_T = \sqrt{x_T^2 + 4\tau} \equiv \frac{2M_T}{\sqrt{s}}, \quad x_T = \frac{2p_T}{\sqrt{s}} \quad (3)$$

¹The contribution of the 1D_2 state to the ψ' yield is expected to be small. For a discussion, see Ref. [11].

The expressions for the subprocess cross-sections, $d\hat{\sigma}/d\hat{t}$, are explicitly given in Refs. [3] and [16].

The dominant fragmentation contribution comes from the fragmentation of gluons and charm quarks. It is computed by factorising the cross-section for the process $AB \rightarrow (2S, 2P_{1,2})X$ into a part containing the hard-scattering cross-section for producing a gluon or a charm quark and a part which specifies the fragmentation of the gluon (or the charm quark) into the required charmonium state, i.e.

$$d\sigma(AB \rightarrow (2S, 2P_{1,2})X) = \sum \int_0^1 dz d\sigma(AB \rightarrow cX) D_{c \rightarrow (2S, 2P_{1,2})}(z, \mu), \quad (4)$$

where c is the fragmenting parton (either a gluon or a charm quark) and the sum in the above equation runs over the contributing partons. $D(z, \mu)$ is the fragmentation function. The fragmentation function which is computed perturbatively at an initial scale of the order of the charm quark mass is evolved to the scale typical of the fragmenting parton which is of the order of p_T/z , using the Altarelli-Parisi equation. For the production cross-sections of the gluons and charm quarks we will use the lowest-order cross-sections, $d\hat{\sigma}/d\hat{t}(ab \rightarrow cd)$, just as in the case of the fusion contribution. The full set of initial fragmentation functions that we need to obtain the $2S$ and $2P$ contributions are : $D_{g \rightarrow 2S}$ [7], $D_{g \rightarrow 2P}$ [17], $D_{c \rightarrow 2S}$ [18] and $D_{c \rightarrow 2P}$ [19, 20]. The final cross-section for the fragmentation process is given by a formula similar to Eq. 1 but with an extra integration over z , or equivalently over x_2 .

As mentioned earlier, a major uncertainty in these calculations is due to the wave-functions. In the computation of the fusion contribution these appear in the subprocess cross-sections, whereas for the fragmentation contribution, the fragmentation functions at the initial scale are proportional to the wave-function factors. The wave function factor R_0^2 for ψ' is reasonably well-determined [5], but we have to make assumptions for the parameters that describe the $2P$ states. In Ref. [17] the fragmentation function for $g \rightarrow \chi$ is written in terms of two parameters H_1 and H'_8 , where H_1 is related to R'_1 , and H'_8 is a parameter that describes the $g \rightarrow \chi$ fragmentation *via* a S -wave $c\bar{c}$ colour-octet state. We assume that the H_1 for the $2P$ states is about the same magnitude as that of the $1P$ states [13]. The parameter H'_8 has a large range of uncertainty even for the $1P$ states. On general grounds one expects the H'_8 parameter for the $2P$ state to lie in the same range [11]. Firstly the H_1 and H'_8 contributions to any P -wave quarkonium production are expected to be comparable in size. Secondly the wave function factor R_0^2 , which is the colour singlet analogue of H'_8 , is similar in size for the $1S$ and $2S$ states. Therefore we assume the same H'_8 parameter for the $2P$ state as for $1P$; whether or not they are exactly equal is immaterial in view of the large uncertainty in this parameter. The parameter values used are $R_0^2 = 0.49 \text{ GeV}^3$ [5], $H_1 = 15.0 \text{ MeV}$ and $H'_8 = 3.0 \text{ MeV}$ [7, 17]. We take the masses of the 2^3P_1 and the 2^3P_2 states to be 3.95 GeV and 3.98 GeV, respectively [13]. In our computations, we use [21] the

updated MRSD-' parametrisations [22] for the parton densities in the nucleon, evolved to a scale $Q^2 = \mu^2/4$, where μ is chosen to be M_T for the fusion process, and equal to $p_T^{g,c} = p_T/z$ for the fragmentation process. The fragmentation functions are evolved to the scale p_T/z .

Finally, we come to the branching ratios for the radiative decay $2^3P_{1,2} \rightarrow 2^3S_1 + \gamma$. The absolute value of these widths have been estimated by rescaling the known values for the bottomonium system [11]. One gets $\Gamma(2^3P_{1,2} \rightarrow 2^3S_1 + \gamma) \sim 0.1 - 0.2$ MeV. The corresponding total widths have been estimated, assuming phase-space and dynamical suppressions into open charm states, to be $\sim 2 - 5$ MeV each [11]. The resulting branching ratios for $2^3P_{1,2} \rightarrow 2^3S_1 + \gamma$ lie in the range 2 - 10%. The results presented below are based on the optimistic value of the branching ratios = 10%.

In Fig. 1 we present our results for $Bd\sigma/dp_T$ for ψ' production in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV and integrated over a pseudo-rapidity interval $|\eta| \leq 0.5$, and compare our predictions to the data from the CDF experiment [1]. $B = 7.7 \times 10^{-3}$ is the ψ' branching ratio into leptons. As in the case of J/ψ production [8], we find the $g \rightarrow P$ -state fragmentation contribution to be dominant. The inclusion of the contribution of the $2P$ states increases the ψ' cross-section significantly, and assuming a value of 10% for the branching ratios this is capable of explaining the bulk of the observed cross-section. It should be noted of course that this choice of the $2P \rightarrow 2S$ branching ratios corresponds to the upper end of the estimated range. Within the latitude of this range the cross-section can go down by a factor of 5. Further there is an uncertainty of a factor of 3 on either side in the production cross-section of the $2P$ states, arising largely from the H_1 and H'_8 parameters. Consequently the predicted normalisation of the ψ' cross-section can be anywhere between the experimentally observed range and an order of magnitude below. Thus it is premature to rule out the necessity of more exotic contributions, e.g. from the hybrid states suggested in [11]. It is remarkable nonetheless that the inclusion of the $2P$ contributions can push up the predicted ψ' cross-section by the required factor of ~ 30 within the latitude of the model parameters.

In conclusion, we find the $2^3P_{1,2}$ contribution to ψ' production at CDF to be very important. We have computed the fusion and fragmentation contributions to these $2P$ -states and to the $2S$ ψ' state, and find that with an optimistic choice of the $2P \rightarrow 2S$ branching, it is possible to explain the anomalously large cross-section for ψ' production reported by at the CDF experiment.

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Figure captions

Fig. 1 The cross-section $Bd\sigma/dp_T$ (integrated over the pseudorapidity range $-0.5 < \eta < 0.5$) for the process $\bar{p}p \rightarrow \psi' X$ as a function of p_T at $\sqrt{s} = 1.8$ TeV. The data are taken from Ref. [1]. The different curves correspond to the direct production via fusion (dashed line), the gluon fragmentation contribution (dashed-dotted line), the charm quark fragmentation term (dotted line) and the sum of all contributions (solid line).

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