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Prompt J/ψ production at the LHC

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Abstract: Models with essential non-perturbative QCD dynamics for the production of charmonium are extrapolated to give predictions of prompt J/ψ production at the LHC. Differences of up to an order of magnitude occurs, although the different models all describe the Tevatron data on high-$p_\perp$ charmonium. An important point is here the treatment of higher order perturbative QCD effects. We also discuss the large rate of prompt J/ψ from these models as a background to CP violation studies.

Keywords: CP violation, QCD, Phenomenological Models.

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1. Introduction

The important interplay of hard, perturbative QCD (pQCD) and soft, non-perturbative QCD effects has recently been clearly demonstrated in the production of heavy quarkonia in hadron collisions. The Tevatron data [1] for high-$p_\perp$ J/ψ, ψ' and Υ is up to factors of 50 above the pQCD prediction in the Colour Singlet Model (CSM) [2], where a colour singlet $c\bar{c}$ pair is produced at the parton level and gives a charmonium state with the same quantum numbers. This deficit can be explained by letting a fraction of the more abundant $c\bar{c}$ pairs in a colour octet state be transformed to a singlet state through some soft, non-perturbative QCD dynamics. Lacking a proper understanding of non-pQCD, this has been described in different models: the Colour Octet Model (COM) [3], the Colour Evaporation Model (CEM) [4], the Soft Colour Interaction model (SCI) [5] and the Generalized Area Law model (GAL) [6]. All these models can be made to fit these Tevatron data.

In this paper we study the extrapolation of these models to the LHC energy and examine the theoretical uncertainty in the charmonium production rate. Future LHC data may then discriminate between the models and provide an improved understanding of the non-pQCD mechanism they involve.

Prompt J/ψ production is also of importance as a background to CP-violation studies based on B meson decays into $J/\psi X$, with X being K_s^0, ϕ etc. The B production cross section at the LHC is very high in comparison with e^+e^- colliders, but its fraction of the total inelastic cross section is small (0.7%). The trigger for B physics has therefore to be very selective and is typically based on the leptons from a J/ψ decay. Studies of such triggers have shown that prompt J/ψ is indeed a source of background [7]. The prompt J/ψ, which emerge from the primary interaction vertex, can to a large extent be distinguished from J/ψ from B decays, which are produced at a secondary vertex typically located a few hundred micrometers from the primary vertex. There is, however, a remaining prompt charmonium background that affects B-physics analyses and the associated CP-violation studies, such as measurements of $\sin 2\beta$.

In section 2 the models and their normalisation to the Tevatron data are discussed. The extrapolation to the LHC energy is made in section 3, where also the observed differences are analysed and prompt J/ψ as a background for CP-violation studies is considered. We end with some conclusions in section 4.

2. Models and tuning to Tevatron data

In the Colour Octet Model the cross section is factorised in a short distance part, where a $c\bar{c}$ pair is produced in a well defined quantum number state $({}^{2S+1}L_J)$, and a long distance part, giving the probability that this state will convert non-perturbatively into a charmonium state. These probabilities are given by non-relativistic QCD (NRQCD) matrix elements, which are assumed to be universal and in practice are free parameters obtained from fits to experimental data. For high-$p_\perp$ J/ψ production at the Tevatron, the main subprocesses are $gg \to J/\psi g$ and $gq \to J/\psi q$, which are next-to-leading order in the hard pQCD $c\bar{c}$ production process. The extraction of the NRQCD matrix elements from the Tevatron data has been performed in several steps where perturbative effects and intrinsic transverse momenta have successively been taken better into account explicitly instead of being absorbed into the fitted matrix elements [8].

The CEM, SCI and GAL models are based on a similar phenomenological approach, where soft colour interactions can change the colour state of a $c\bar{c}$ pair from an octet to a singlet. They employ the same hard pQCD processes to produce a $c\bar{c}$ pair regardless of its spin state. The leading order (LO) processes are $gg \to c\bar{c}$ (figure 1a) and $q\bar{q} \to c\bar{c}$. Heavy quark production is, however, known to have large contributions from next-to-leading order (NLO) diagrams [9]. Virtual corrections to the leading order processes together with soft and collinear gluon emissions give an increase of the cross section, which can be approximately described as an overall K-factor multiplying the leading order cross-section. The LO processes and these NLO processes cannot produce a J/ψ at high-$p_\perp$ since there is nothing to compensate its $p_\perp$ to give the essentially zero $p_\perp$ of the initial partons. Of importance for high-$p_\perp$ J/ψ production is instead NLO tree diagrams with a third hard parton that balances the $p_\perp$ of the $c\bar{c}$ pair. The most important contribution is given by the diagram in figure 1b. Although this is an $\mathcal{O}(\alpha_s)$ correction in terms of a gluon splitting $g \to c\bar{c}$ applied to the basic $2 \to 2$ process of $gg \to gg$, it is numerically large since $gg \to gg$ has a much larger $\mathcal{O}(\alpha_s^2)$ cross section than the LO $c\bar{c}$ production processes. Matrix elements with non-zero quark masses are only available up to NLO. Still higher orders can be expected to be important at the Tevatron and LHC. The reason is that at these energies many gluons can be emitted and their virtuality need not be very large in order to

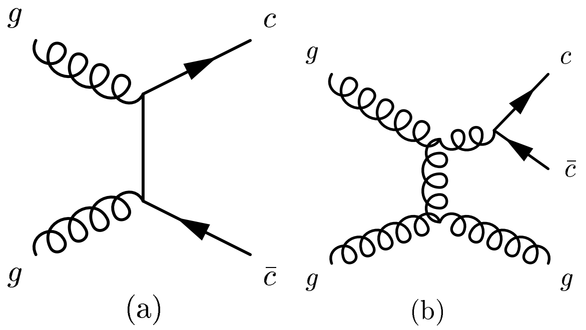

Figure 1: Illustration of $c\bar{c}$ production processes in (a) leading order (α_s^2) and (b) next-to-leading order (α_s^3).

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allow a split into a $c\bar{c}$ pair. The higher order processes can be approximately described by the parton shower approach available in the PYTHIA [10] Monte Carlo, where in all basic QCD $2 \to 2$ processes the incoming and outgoing partons may branch as described by the DGLAP equations [11].

In CEM the exchange of soft gluons is assumed to give a randomisation of the colour state. This implies a probability 1/9 that a $c\bar{c}$ pair is in a colour singlet state and produces charmonium if its mass is below the threshold for open charm production, $m_{c\bar{c}} < 2m_D$. The fraction of charmonium giving a J/ψ is given by an additional non-perturbative parameter $\rho_{J/\psi} = 0.43 - 0.5$ [4]. This model was recently implemented in PYTHIA such that higher order pQCD processes could be included in terms of parton showers and events be Monte Carlo simulated. It was found [12] that this model reproduced quite well x_F and $p_\perp$ distributions, both in shape and normalisation, of J/ψ produced in fixed target experiments.

In the Soft Colour Interaction model [5] it is assumed that colour-anticolour, corresponding to non-perturbative gluons, can be exchanged between partons emerging from a hard scattering and hadron remnants. This can be viewed as the partons interacting softly with the colour medium, or colour background field, of the initial hadron as they propagate through it. This should be a natural part of the process in which 'bare' partons are 'dressed' into non-perturbative ones and the confining colour flux tube between them is formed. The hard parton level interactions are given by standard perturbative matrix elements and parton showers, which are not altered by softer non-perturbative effects. The unknown probability to exchange a soft gluon between parton pairs is given by a phenomenological parameter R, which is the only free parameter of the model. These colour exchanges lead to different topologies of the confining colour force fields (strings) and thereby to different hadronic final states after hadronisation. This model gives a novel explanation of rapidity gap events in deep inelastic scattering and in hard $p\bar{p}$ processes at the Tevatron [5, 13], which are well reproduced with $R = 0.5$. Applying the same Monte Carlo implementation in PYTHIA (with the same R-value), it was found that the Tevatron data on high-$p_\perp$ charmonium and bottomonium are also well reproduced [14]. The increased production rate is here given by the possibility for a perturbatively produced $Q\bar{Q}$ pair in a colour octet state to be transformed to a singlet state as a result of these soft colour interactions. The mapping of $c\bar{c}$ pairs, with mass below the threshold for open charm production, is here made based on spin statistics which avoids introducing further free parameters. This was also found to give a correct description of the different onium states observed at the Tevatron [14].

An alternative to SCI is the later developed Generalised Area Law model [6], where modified colour string-field topologies are obtained by interactions between the strings in the event instead of the partons. A generalisation of the area law suppression e^{-bA}, with A the area swept out by the string in energy-momentum space, gives a dynamic probability $R = R_0(1 - e^{-b\Delta A})$ for two string pieces to interact depending on the area difference ΔA resulting from the changed string topology. This favours making shorter strings and thereby favours quarkonium production. The parameter R_0 and some hadronisation model parameters, e.g. b, are obtained from a fit to data from both deep inelastic scattering and e^+e^- annihilation [6].

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The comparison of the CEM, SCI and GAL models with the Tevatron data is shown in figure 2. As can be seen, all models give a quite decent description of the data. Although the shape is not perfect in the tail of the distribution, it is quite acceptable given the simplicity of the models. The overall normalisation is correctly given by the models. For the CEM this is obtained by setting $\rho_{J/\psi} = 0.43$ and the charm quark mass to 1.5 GeV. As parameterisations of the parton density functions we have used CTEQ4L [15], but we have checked that the result does not change much if we use GRVHO or CTEQ2L (e.g. CTEQ2L reduces the normalisation by a few percent). The SCI and GAL models have not been tuned to these data, but the result is also sensitive to the charm quark mass (taken as default $m_c = 1.35$ GeV in Pythia 5.7). The parton densities are here kept the same as used in other applications of these models, namely CTEQ3L [16] for SCI and CTEQ4L [15] for GAL. The values of the essential parameters R and R_0 in SCI and GAL are, as discussed, given by the rate of rapidity gap events in deep inelastic scattering. The SCI model is, however, quite stable such that R can be chosen in the range 0.2–0.5. One should note that an arbitrary K factor is not needed in any of the models, since higher order pQCD processes were included through the parton showers.

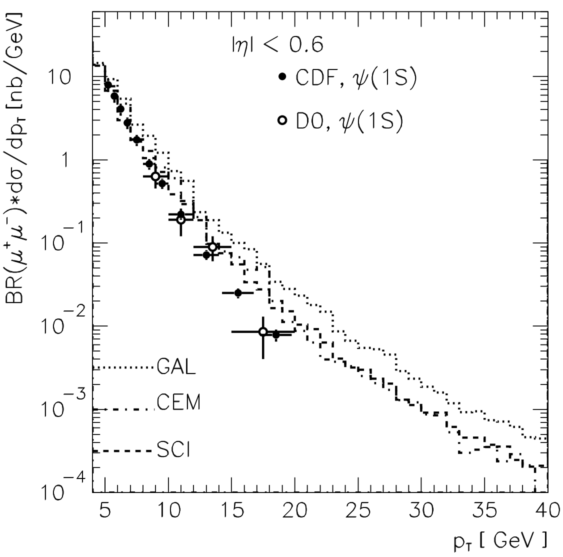

Figure 2: Distribution in transverse momentum of prompt J/ψ as observed by CDF and D0 [1] in $p\bar{p}$ interactions at the Tevatron and obtained in the CEM, SCI and GAL models.

In view of the Tevatron running with increased luminosity one can expect forthcoming J/ψ data extending to higher $p_\perp$, which would test and constrain the models further. We therefore include in figure 2 model predictions for $p_\perp$ up to 40 GeV, which show that the CEM and SCI models are quite close, whereas the GAL model gives a somewhat higher cross section in the high-$p_\perp$ tail. New data could help in discriminating or improving the models resulting in reduced uncertainties in the model predictions.

Based on the ability of these models to reproduce, in a reasonable way, the presently available Tevatron data, we now extrapolate them to the LHC energy.

3. Extrapolation to the LHC energy

Applying these models also for the larger energy at the LHC, i.e. $\sqrt{s} = 14$ TeV, should be appropriate since they include a reasonable energy dependence. The production of the $c\bar{c}$ pair is given by hard pQCD processes with a well-defined energy dependence. The soft interactions that change colour octet states to singlet states have no explicit energy

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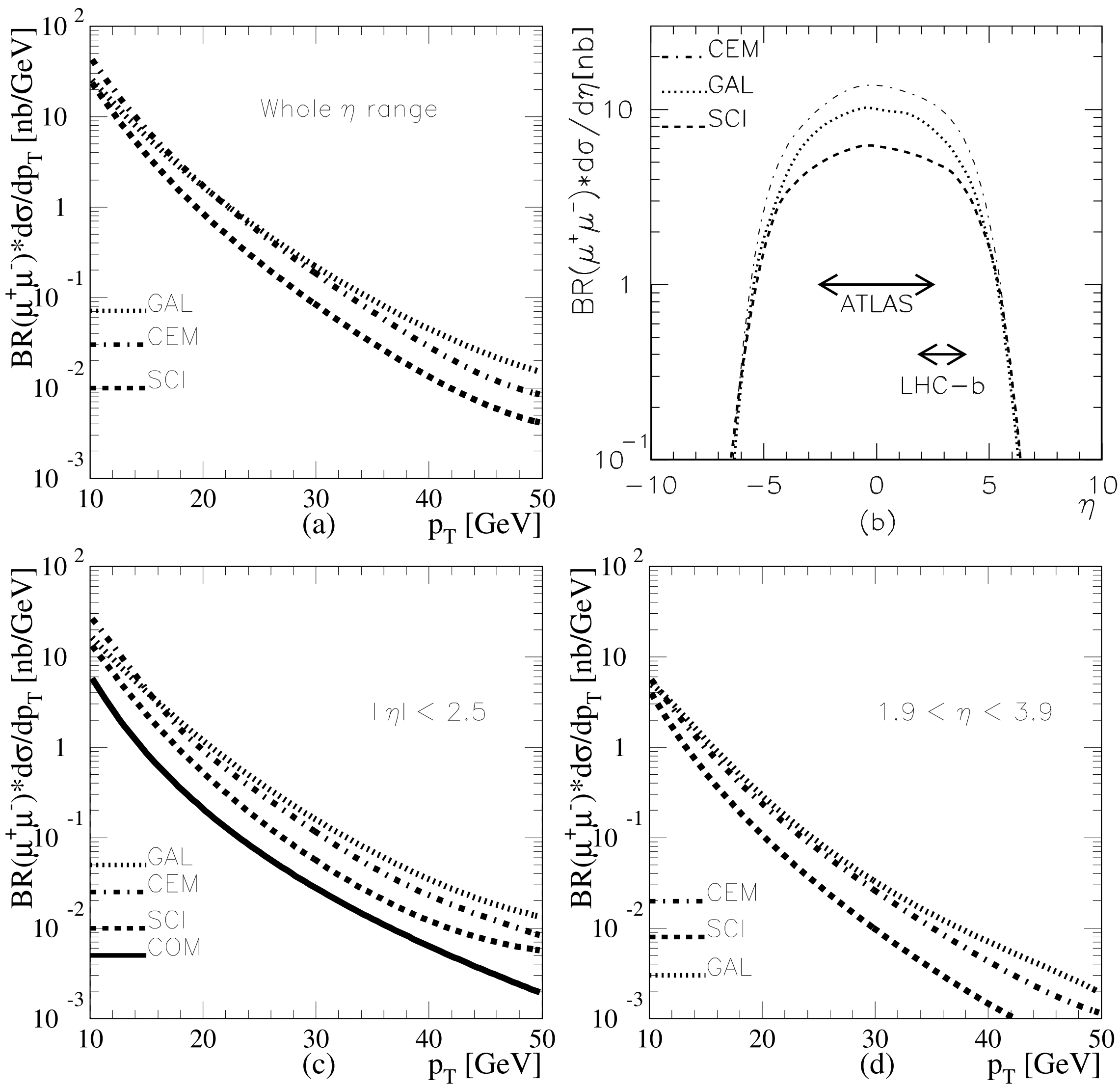

Figure 3: Differential cross sections in transverse momentum and rapidity for J/ψ in pp collisions at $\sqrt{s} = 14$ TeV based on the CEM, SCI and GAL models. In all cases only J/ψ with $p_\perp^{J/\psi} > 10$ GeV and decaying into $\mu^+\mu^-$, which in (c, d) are required to be within the indicated rapidity coverage of the ATLAS and LHC-b detectors, respectively. For comparison, the COM results from [8] is included in (c).

dependence, similar to the normal hadronisation process. The SCI and GAL models will, however, have an implicit energy dependence since they act on a parton state or string topology that depend on the collision energy.

Results of the models, keeping all parameters fixed from the comparison with the Tevatron data, are shown figure 3. The $p_\perp$ distribution in figure 3a is quite similar for the three models, although they differ somewhat in the high-$p_\perp$ tail and GAL has a somewhat less steep slope. These predictions should, however, not be taken as very precise in view of the simplicity of these models that attempt to describe unknown non-perturbative QCD phenomena. The overall normalisation, which e.g. is sensitive to the value of the charm quark mass, should not be considered to be better than within about a factor two.

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In order to consider what can realistically be measured, we show in figure 3*b* the distribution in pseudorapidity of J/ψ and the acceptance regions of the LHC experiments. Requiring the muons from the J/ψ decay to be within these regions we obtain the results in figure 3*cd*, which show lower effective cross sections with slightly more separated model curves. Thus, figure 3 shows a slightly different behaviour of the models as function of rapidity and transverse momentum, but a more detailed study of this is premature until some data are available to show that the models give a reasonable overall description of J/ψ production at the LHC energy. A retuning of the models may then reduce these differences and it is therefore not clear to what extent these model differences can be exploited to discriminate among the models and disentangle details of the charmonium production mechanism. In any case, this would require data of quite high precision.

Here we can make an interesting comparison with a previous calculation of the prompt J/ψ production in the COM model [8]. As can be seen in figure 3*c*, the COM result is significantly lower than the other models. The COM result is based on using pQCD matrix elements in NLO. At high $p_\perp$ the dominant process is, as discussed above, the order $\mathcal{O}(\alpha_s^3)$ process $gg \to c\bar{c}g$ in figure 1*b*. A shift of the momentum distribution of this $c\bar{c}$ pair has been made in order to account for the effect of higher order gluon emissions as estimated based on the parton shower. Since $g \to c\bar{c}$ in the parton shower is here not included, the applied higher order correction does not change the normalisation of the $c\bar{c}$ cross section, but only the shape of the momentum distribution which becomes somewhat softer due to gluon radiation.

Our calculations with the CEM, SCI and GAL models use leading order matrix elements and include the full parton shower evolution, including $g \to c\bar{c}$ in any branching. This gives an estimate of the $c\bar{c}$ production cross section including all higher orders. To find out to what extent this is the reason for the observed difference, we mimic the $\mathcal{O}(\alpha_s^3)$ matrix elements by including only those $c\bar{c}$ pairs coming from the first branching of the parton shower (cf. figure 1*b*) giving the results shown in figure 4. Since we want to explicitly show the effect of omitting higher order $c\bar{c}$ production we have here not changed any parameters in the models (which could be done to partly compensate for the loss of higher orders). As compared to the standard result, including $c\bar{c}$ from any branching, this 'first branching' approximation does indeed give a lower J/ψ cross section. At the Tevatron energy the difference is not large and could at least partly be absorbed into a tuning of parameters such as m_c and α_s. Nevertheless, in the region of lower $p_\perp$ where the data are more precise, some preference for the all order result is indicated. At LHC, where more energy is available to build up a more extended parton shower, the difference is larger and becomes an order of magnitude at high $p_\perp$. As can be seen in figure 4*b*, this reduction of the J/ψ yield in the first branching approximation brings the CEM and SCI models closer to the COM result [8]. This COM result was based on the older parameterisation CTEQ2L of parton densities, but we have checked that this causes a reduction in the overall normalisation which is much smaller than omitting higher order $g \to c\bar{c}$ in the parton shower. Thus, we conclude that $c\bar{c}$ production in orders higher than $\mathcal{O}(\alpha_s^3)$ are important at the LHC energy.

As discussed in the introduction, we also consider the prompt J/ψ production as background for CP-violation studies based on B meson decays such as $B_d^0 \to J/\psi K_s^0$,

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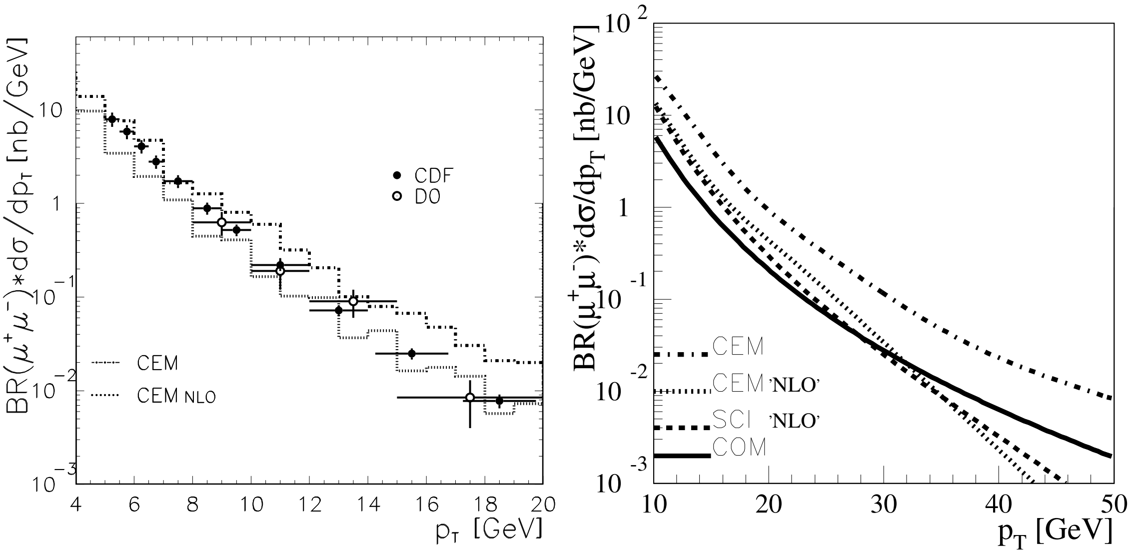

Figure 4: Distribution in transverse momentum of prompt J/ψ at (a) the Tevatron and (b) LHC ($|\eta| < 2.5$ as for ATLAS) for the colour octet model (COM) based on NLO $\mathcal{O}(\alpha_s^3)$ matrix elements (from [8]) and for the colour evaporation model (CEM) including $g \to c\bar{c}$ to all orders in the parton shower and in the 'NLO' approximation where only $c\bar{c}$ pairs from the first branching have been included. The result of this 'first branching' approximation applied to the soft colour interaction model (SCI) is also shown in (b).

$B_s^0 \to J/\psi\phi$, etc. A detailed analysis has been made for ATLAS [17], taking into account trigger conditions, acceptance cuts, off-line selection criteria and reconstruction methods. This resulted in the signal-to-background ratio of 4.1 for the case of $B_s^0 \to J/\psi\phi$. The estimated contamination from $pp \to J/\psi X$ on the level of 3% was here entirely due to prompt J/ψ produced by the COM model implemented in the ATLAS Monte Carlo package. Although other backgrounds were found to be more important, this signal-to-background ratio may be somewhat too optimistic in view of our finding that COM gives a lower prompt J/ψ cross section than the CEM, SCI and GAL models.

At this stage one cannot decide which of these models is most reliable and gives the best prediction for the prompt J/ψ production. The variation between them should therefore be taken as an estimate of the theoretical uncertainty. From figure 3*c* we find cross sections that are almost an order of magnitude larger than in COM. The signal-to-background does not, however, decrease by the full amount of this factor since other backgrounds are also present. Nevertheless, this indicates that the prompt J/ψ production could be an important background giving a lower signal-to-background ratio than previously estimated. A proper study of this is beyond the scope of this paper, but our results show that the prompt J/ψ production is a background for CP-violation studies that should not be neglected.

4. Conclusions

Charmonium production provides an interesting testing ground for QCD, including both perturbative and non-perturbative effects. Several models (COM, CEM, SCI, GAL) have been developed to account for the possibility that a perturbatively produced $c\bar{c}$ pair in

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a colour octet state is transformed into a singlet state through soft interactions. This enhances the rate of charmonium production by more than an order of magnitude, as compared to conventional expectations based on the Colour Singlet Model. All these new models can account for the observed rate of high-$p_\perp$ prompt J/ψ at the Tevatron, and are thereby normalised at this energy. Since the models tend to differ more at higher $p_\perp$, we have extended our model calculations to give predictions for a region of higher $p_\perp$ which may be reached in the high luminosity runs at the Tevatron. Forthcoming high statistics data may then discriminate among the models or help in reducing the uncertainties in results of the models.

Extrapolating the COM, CEM, SCI and GAL models to the LHC energy, we find significant differences in the predicted prompt J/ψ cross sections; up to almost an order of magnitude. In particular, the COM result is lower than the others. Part of this difference is related to the fact that COM is based on NLO matrix elements, whereas the other models include still higher order $c\bar{c}$ production through the parton shower approximation in pQCD.

Prompt J/ψ is also a background for studies of B meson decays into J/ψ, which are important for studies of CP-violation. An earlier estimate of the signal-to-background ratio based on COM gave the favourable result of 4.1. Using the larger rate of prompt J/ψ from the other models, will reduce the signal-to-background ratio. Prompt J/ψ production must therefore be better understood in order to control it as a background for CP-violation studies.

Improving our understanding of the mechanism for prompt J/ψ production is also important in its own right. It involves an interplay of hard, perturbative and soft, non-perturbative QCD dynamics which is closely connected with the more general problem of understanding QCD.

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