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Total J/ψ and Υ production cross section at the LHC: theory vs. experiment

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We evaluate the production cross section for direct J/ψ and Υ integrated in P_T for various collision energies in the QCD-based Colour-Singlet Model (CSM). We consider the LO contribution from gluon fusion whose P_T-integrated cross section shows a very good agreement with the Tevatron and LHC data, both for J/ψ and Υ. The rapidity distribution of this yield is evaluated in the central region relevant for the ATLAS and CMS detectors, as well as in the more forward region relevant for the ALICE and LHCb detectors. The results obtained here are compatible with those of other approaches within the range of the theoretical uncertainties which are admittedly very large. This suggests that the "mere" measurements of the yield at the LHC will not help disentangle between the different possible quarkonium production mechanisms. Yet, the comparison with the first LHC results by ALICE, ATLAS, CMS and LHCb confirms that the CSM correctly accounts for the P_T-integrated yield at $\sqrt{s} = 7$ TeV.

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1. Introduction

In 2007, the first evaluations of QCD corrections to quarkonium-production rates at hadron colliders became available. It is now widely accepted that α_s^4 and α_s^5 corrections to the CSM [1] are fundamental for understanding the P_T spectrum of J/ψ and Υ produced in high-energy hadron collisions [2, 3, 4, 5, 6, 7], while the difficulties of predicting these observables had been initially attributed to non-perturbative effects associated with channels in which the heavy quark and antiquark are produced in a colour-octet state [8, 9, 10, 11]. Further, the effect of QCD corrections is also manifest in the polarisation predictions. While the J/ψ and Υ produced inclusively or in association with a photon are predicted to be transversally polarised at LO, it has been recently emphasised that their polarisation at NLO is increasingly longitudinal when P_T gets larger [4, 5, 12, 13, 14].

In a recent work [15], we have also shown that hard subprocesses based on colour singlet $Q\bar{Q}$ configurations alone are sufficient to account for the observed magnitude of the P_T-integrated cross section. In particular, the predictions for the J/ψ yield at LO [1] and NLO [2, 3, 4] accuracy are both compatible with the measurements by the PHENIX collaboration at RHIC [16] within the present uncertainties. This also pointed at a reduced impact of the s-channel cut contributions [17] as well as of some specific colour-octet mediated channels relevant for the low P_T region (${}^1S_0^{[8]}$ and ${}^3P_J^{[8]}$). The latter are anyway very strongly constrained by very important recent e^+e^- analyses [18] which leave in some cases no room at all for colour octets of any kind.

The compatibility between the LO and NLO yields provided some indications that the computations are carried in a proper perturbative regime, at least at RHIC energies. The agreement with the data is improved when hard subprocesses involving the charm-quark distribution of the colliding protons are taken into consideration. These constitute part of the LO (α_S^3) rate and can be responsible for a significant fraction of the observed yield [15, 20].

We proceed here to the evaluation the P_T-integrated yield at higher energies both in the central and forward rapidity regions. At large energies, our study shows that the theoretical uncertainties on the J/ψ yield for become very large –close to one decade– reminiscent of the case of total charm production [19]. Both for the J/ψ and the Υ, we find a very good agreement with the CDF measurements [21] and the first LHC ones. Finally, we shortly discuss the impact of higher QCD corrections and the comparison with other approaches.

2. Total J/ψ and Υ cross section at the LHC[1]

The P_T integrated cross sections obtained here have been evaluated along the same lines as our previous study [15]. The uncertainty bands have been evaluated following exactly the same procedure using the same values for m_c (m_b), μ_R and μ_F.

In Fig. 1, we show $d\sigma^{direct}_{J/\psi}/dy|_{y=0} \times \mathrm{Br}$ as function of $\sqrt{s}$ from 200 GeV up to 14 TeV compared to the PHENIX [16], the CDF [21] and ALICE [22] data multiplied by the direct fraction[2][3]

[1] Note that we have not depicted the systematic uncertainties attached the unknown J/ψ and Υ polarisation produced at the LHC . They can be as high as 50 % at very low P_T for extreme configurations.

[2] We employ this makeshift, although the χ_c yield can now be computed at NLO accuracy [23], since one cannot extend these computations to low P_T.

[3] Note that the measurement of the prompt yield by CDF went only down to P_T = 1.25 GeV. We have assumed a fraction of non-prompt J/ψ of 10% below. We have assumed the same fraction at $\sqrt{s}$ = 7 TeV for the ALICE data.

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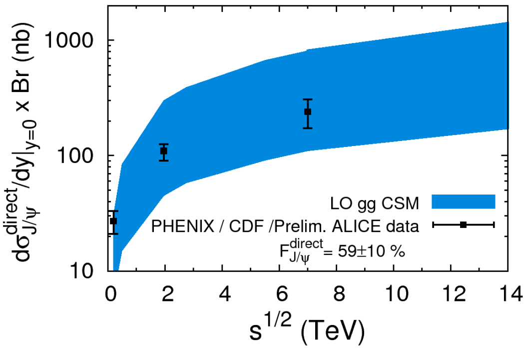

Figure 1: $d\sigma^{direct}_{J/\psi}/dy|_{y=0} \times \mathrm{Br}$ from gg fusion in pp collisions for $\sqrt{s}$ from 200 GeV up to 14 TeV compared to the PHENIX [16], CDF [21] and ALICE [22] data multiplied by the direct fraction (see text).

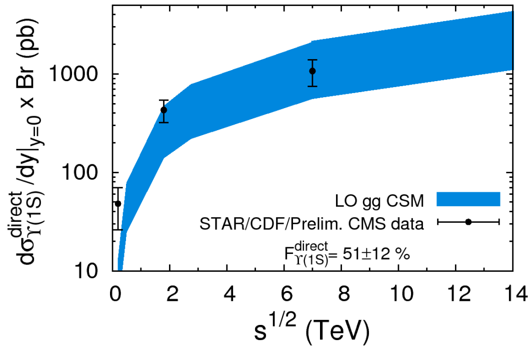

Figure 2: $d\sigma^{direct}_{\Upsilon}/dy|_{y=0} \times \mathrm{Br}$ from gg fusion in pp collisions for $\sqrt{s}$ from 200 GeV up to 14 TeV compared to the STAR [27], CDF [28] and CMS [29] data multiplied by the direct fraction (see text).

measured by CDF at $\sqrt{s}$ = 1.8 TeV [24]. We have found a good agreement. At larger energies, these results at 7 TeV (100 to 800 nb) and at 14 TeV (200 to 1400 nb) are in the same range as those of the Colour Evaporation Model [25] with central (upper) values of 140 nb (400 nb) at 7 TeV and 200 nb (550 nb) at 14 TeV. They are also compatible with the results of the "gluon tower model" (GTM) [26], 300 nb at 7 TeV and 480 nb at 14 TeV, which takes into account some NNLO contributions shown to be enhanced by log(s). Quoting the authors [26], "the expected accuracy of the prediction is about a factor of 2-3 in either direction or even worse." In Fig. 2, we show the same predictions for direct Υ for $\sqrt{s}$ from 200 GeV up to 14 TeV compared to the STAR [27], CDF [28] and CMS [29] data multiplied by the direct fraction measured by CDF [30] at $\sqrt{s}$ = 1.8 TeV. While there seems to be some tension between the CSM predictions and the data at $\sqrt{s}$ = 200 GeV, the agreement is very good with the preliminary CMS data.

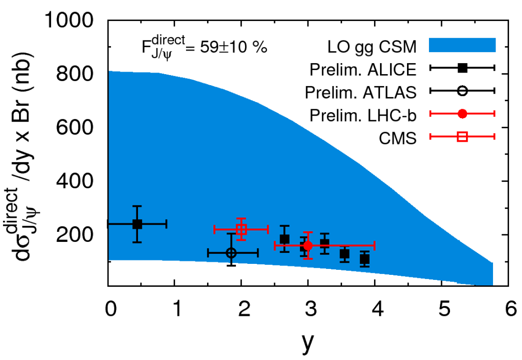

Figure 3: $d\sigma^{direct}_{J/\psi}/dy \times \mathrm{Br}$ from gg fusion LO contributions in pp collisions at $\sqrt{s}$ = 7 TeV compared to ALICE [22], ATLAS [32], CMS [31] and LHCb [33] results multiplied by the direct fraction (and the prompt fraction (10 %) if applicable).

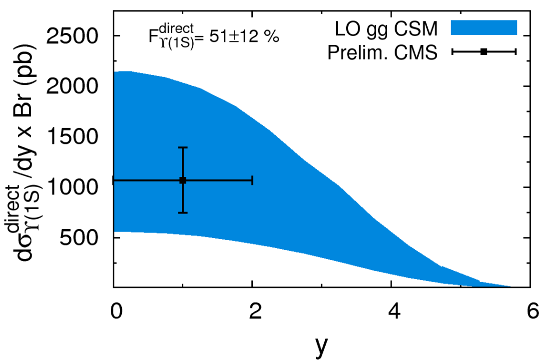

Figure 4: $d\sigma^{direct}_{\Upsilon}/dy \times \mathrm{Br}$ from LO CSM via gg fusion in pp collisions at $\sqrt{s}$ = 7 TeV compared to the preliminary CMS results [29] multiplied by the direct fraction (see text).

In Fig. 3, we show the cross section differential in rapidity at $\sqrt{s}$ = 7 TeV compared to the ALICE [22], ATLAS [32], CMS [31] and LHCb [33] results multiplied by the direct fraction (and the prompt fraction (10 %) if applicable) as done for Fig. 1. The region $y < 0$ is not plotted since it does not contain any additional physical information. Similarly, experimental measurements for $y > 0$ or $y < 0$ are physically strictly equivalent. In Fig. 4, we show the same plot for the direct Υ yield along the only public results available so far, from CMS [29], multiplied by the direct fraction from CDF. In both cases, the agreement is found to be very good.

3. Discussion and conclusion

Let us now briefly discuss the expectations for the results when QCD corrections are taken into account. First, we would like to stress that, although NLO results [2] are perfectly well behaved in nearly all of the phase-space region at RHIC energies [15], it does not seem to be so for larger s for the J/ψ. One observes that the region where the differential cross section in P_T and/or y is negative (i.e. very low P_T and large y) widens for increasing s. Negative differential cross sections at low P_T are a known issue. Nonetheless, for $\sqrt{s}$ above a couple of TeV, and for some (common) choices of μ_F and μ_R, the P_T-integrated "yield" happens to become negative, even in the central region. This can of course be explained by a larger contribution from the virtual corrections at α_S^4 –which can be negative– compared to the real emission contributions –which are positive–. Naturally, such results cannot be compared to experimental ones. This also points at virtual NNLO contributions at low P_T which are likely large but which are not presently known. Yet, as already mentioned, specific NNLO contributions were shown [26] to be enhanced by $\log(s)$. We also note that this issue of negative cross sections at LHC energies does not seem as critical for the Υ, whose production is initiated by gluons with larger x_{Bj}.

As we have discussed above, one may try to compare the LO CSM with other theoretical approaches such as the CEM [25] and the GTM [26]. They all qualitatively agree, as well as with existing measurements. For all approaches, one expects a significant spread –up to a factor of ten – of the results when the scales and the mass are varied.

Owing to these uncertainties, it will be difficult to discriminate between different mechanisms [8, 34] by only relying on the yield integrated in P_T and even, to a less extent, on its P_T dependent counterpart. This is a clear motivation to study at the LHC other observables related to the production of J/ψ such as its production in association with a single charm (or lepton) [15], with a prompt isolated photon [12, 13] or even with a pair of $c\bar{c}$ [3].

Yet, the good agreement at the level of the P_T-integrated cross section between the CSM and the available measurements from $\sqrt{s} = 200$ GeV to $\sqrt{s} = 7$ TeV confirms the little –if not negligible– impact of colour-octet contributions at low P_T, at least for the J/ψ, in accordance to recent e^+e^- analyses [18].

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