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A change of perspective in quarkonium production: All data are equal, but some are more equal than others

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Abstract

Quarkonium polarization data, usually considered a difficult challenge for the QCD description of quarkonium production and relegated to an *a posteriori* test of predictions exclusively driven by cross-section measurements, with *puzzling* results, provide, in reality, the most fundamental, direct and model-independent connection to the production mechanisms. We have simultaneously fitted the $\psi(2S)$ and $\Upsilon(3S)$ differential cross sections and polarizations, reliably measured at the LHC up to higher transverse momentum p_T values than ever before, as a superposition of colour-singlet and colour-octet contributions perturbatively calculated up to next-to-leading order. We show that, except for the lowest p_T cross-section data, where factorization between short-distance and long-distance QCD effects is not expected to be applicable, all the measurements are very well reproduced. Besides providing a straightforward solution to the "quarkonium polarization puzzle", our study shows that quarkonium production is dominated by the unpolarized ${}^1S_0^{[8]}$ octet term, an observation that opens new paths towards the understanding of bound-state formation in QCD.

Keywords: Quarkonium; Polarization; NRQCD; QCD; Hadron formation

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Traditional studies of quarkonium production ignore polarization measurements, probably because most of the results published before 2011 are incomplete and ambiguous [1]. The CMS [2] and LHCb [3] polarization measurements reflect much improved analysis techniques [4]. The good quality of these results and their reach into transverse momentum p_T regions extending well beyond previous data, allow us to perform reliable "global fits" of quarkonium data, considering the polarization measurements at the same level as the cross sections. This is a far-reaching change of strategy, given that the different colour channels contributing to $Q\overline{Q}$ production have similar (exponential-like) cross sections but remarkably distinctive polarization patterns. Furthermore, past studies included low-p_T data, even lower than the mass of the quarkonium state, where the short-distance and long-distance phases of the quarkonium production process are not expected to factorize [5]. This approach, probably justified by the fear that rejecting such data would lead to under-constrained fits, gave birth to the famous "quarkonium polarization puzzle", by predicting that quarkonia should be transversely polarized at high-p_T, contrary to the observations. The availability of (high-p_T) LHC data allows us to progressively reject the lowest p_T measurements while retaining well-constrained fits.

Assuming that short- and long-distance effects can be factorized, the cross section for the inclusive production of a quarkonium is given by a sum of (kinematics-dependent) short-distance coefficients (SDC), proportional to the parton-level cross sections for the production of the pre-resonance $Q\overline{Q}$ in a given angular momentum and colour configuration, scaled by the corresponding long-distance matrix elements (LDME), constants proportional to the probability of the bound-state formation. While the LDMEs are free parameters in the fits to the data, the SDCs are calculable in perturbative QCD, presently up to next-to-leading order (NLO). In our analysis we use the colour-singlet (${}^3S_1^{[1]}$) and colour-octet (${}^1S_0^{[8]}$, ${}^3S_1^{[8]}$) SDCs reported in Ref. [6]. The NLO ${}^3P_J^{[8]}$ SDC has been neglected because of its strange properties [7]: the polarization parameter λ_ϑ exceeds $+1$ (even diverging for a certain p_T value), the $Q\overline{Q}$ yield is *negative* in a broad p_T range, and both change dramatically from leading to next-to-leading order.

Our analysis is inspired and guided by two data-driven considerations. The first is illustrated in Fig. 1-left, which shows the ATLAS [8] and CMS [9] differential cross sections for the production of seven different quarkonia. The shapes of all these p_T/M distributions (where the mass rescaling equalizes the kinematic effects of different average parton momenta and phase spaces) are well described (at least for $p_T/M > 3$) by a single power-law function. The easiest conjecture explaining this common behaviour is that a single mechanism dominates the production of all quarkonia. If several mechanisms were at play, we would expect to see variations of their mixture because differences in the quark masses and in the binding energy of the hadrons should affect the non-perturbative effects. Furthermore, some of these states are almost pure S-wave ($\psi(2S)$ and $\Upsilon(3S)$), others P-wave (χ_{c1} and χ_{c2}) and others a mixture of the two (J/ψ, $\Upsilon(1S)$, $\Upsilon(2S)$, significantly affected by feed-down decays). The observed p_T/M scaling indicates, independently of theoretical calculations, that colour-singlet processes play a negligible role, given that their kinematics necessarily depends on the angular momentum of the observed state.

The second, even stronger, observation is shown in Fig. 1-right: the polarizations of the S-wave quarkonia recently measured at the LHC [2,3,11] cluster around the unpolarized limit, with no significant changes with kinematics, from directly-produced states to those affected by P-wave feed-down decays, and between charmonia and bottomonia. Besides strengthening the conjecture that all quarkonia are dominantly produced by a single mechanism, this unpolarized