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Quarkonium production at the LHC: A data-driven analysis of remarkably simple experimental patterns

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ABSTRACT

The LHC quarkonium production data reveal a startling observation: the J/ψ, $\psi(2S)$, χ_{c1}, χ_{c2} and $\Upsilon(nS)$ p_T-differential cross sections in the central rapidity region are compatible with one universal momentum scaling pattern. Considering also the absence of strong polarizations of directly and indirectly produced S-wave mesons, we conclude that there is currently no evidence of a dependence of the partonic production mechanisms on the quantum numbers and mass of the final state. The experimental observations supporting this universal production scenario are remarkably significant, as shown by a new analysis approach, unbiased by specific theoretical calculations of partonic cross sections, which are only considered a posteriori, in comparisons with the data-driven results.

1. Introduction, motivation and conceptual remarks

A large fraction of the recent publications based on LHC data are devoted to theory-driven analyses, aimed at seeing if the measurements agree with hypotheses derived in the context of specific theory models. Such analyses give the primary role to the theoretical predictions, which are based on calculations with a certain level of accuracy (often incorporating approximations) and precision (e.g., only up to a given fixed order in a perturbative series). In the case of heavy quarkonium production, non-relativistic quantum chromodynamics (NRQCD) [1] is the theory commonly-considered in "global fits" of experimental data. While being the most sophisticated, complex, and conceptually profound theory presently available in this chapter of physics, it remains "work in progress", with new improvements frequently taking place. The significant changes seen in some calculations from leading order (LO) to next-to-leading order (NLO) are a good example of the transient nature of the theoretical predictions.

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It has been previously shown [2] that global fits of quarkonium production data in the framework of NRQCD can lead to puzzling results, if one assumes that a certain superposition of the presently available NLO perturbative QCD calculations of short-distance coefficients (SDCs) is able to describe the measured differential cross sections down to very low quarkonium transverse momentum (p_T). The highest (statistical) precision of the lowest-p_T data drives the result of the fit and leads to what has been historically considered an inescapable prediction: quarkonium production must be transversely polarized, already at not-so-high p_T values. The puzzling nature of the measured (absence of) quarkonium polarizations, in clear contradiction with the predictions, disappears by considering that the existing calculations are not sufficiently accurate at low p_T. Indeed, Ref. [2] shows that the NLO SDCs are perfectly able to simultaneously describe, with a very good fit quality, the cross section and polarization data, provided we avoid the lowest p_T region. This example clearly shows that fitting (a suited word) experimental measurements within a given theoretical mould might lead to results determined by the theoretical corset, that forces the data into predetermined shapes, preventing us from exploring a richer spectrum of options and, worse, potentially blinding us from simpler and more natural interpretations.

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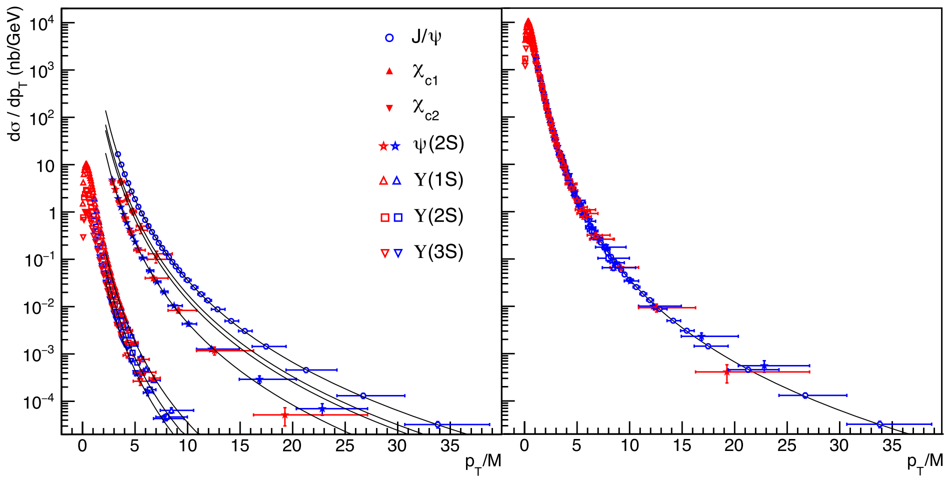

Fig. 1. Mid-rapidity prompt quarkonium cross sections measured in pp collisions at $\sqrt{s} = 7$ TeV by ATLAS (red markers) [3–5] and CMS (blue markers) [6,7], as a function of p_T/M. The curves represent a single empirical function, with shape parameters determined by a simultaneous fit to all data (of $p_T/M > 2$) and normalizations specific to each state (left panel) or adjusted to the J/ψ points (right panel) to directly illustrate the universality of the kinematic dependences. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The study reported in the present Letter goes one step further in our data-driven approach: perturbative calculations of the production kinematics are not used as ingredients anywhere in our analysis, the outcome of the fit being exclusively determined by the measurements, which are already sufficiently precise to provide stable and significant results; the theory calculations are only used a posteriori, in comparisons with the distributions determined by the fit. Remarkably, the (high-p_T) quarkonium measurements made at the LHC provide strong model-independent indications regarding the mechanisms of prompt quarkonium production, allowing us to explore a broader landscape than in previous phenomenological analyses, presumably because the crystal-clear experimental patterns are obscured when seen through theoretically-driven perspectives. These considerations have physical and methodological consequences. On one hand, such indications should provide inspiration for developments in the theoretical description of quarkonium production. On the other hand, the quality reached by the experimental information suggests a new strategy for theory-data comparisons, where fits to measurements are performed with minimal theoretical ingredients and the results are compared only a posteriori with theory predictions based on fixed-order perturbative calculations.

In Section 2 we present our central observation, brought forth by a comparative analysis of prompt quarkonium cross section and polarization measurements in proton-proton collisions at the LHC, with no recourse to model considerations: the data are compatible with a remarkably simple scenario, where all quarkonium states, despite their different quantum numbers, follow an almost universal production trend. This observation raises the central physics question of this Letter: can we derive significant statements, from the experimental observations, regarding possible differences in the production mechanisms behind $^3S_1$ and ^3P_J quarkonium production? In Section 3 we describe the details of our original data-fitting approach, where the individual physical contributions to quarkonium production are exclusively discriminated by their characteristic polarizations, while the p_T distributions and relative normalizations are parametrized by an empirical function. The cross-section measurements are complemented by the corresponding polarizations and all the relevant feed-down decays are properly accounted for, using general kinematic relations for the modelling of the momentum distributions and polarizations of the indirectly produced states. Section 4 shows the results of the analysis, restricted to the charmonium family given the lack of experimental information on bottomonium feed-down fractions. We then discuss, in Section 5, how the seemingly universal data patterns compare to the NRQCD theory framework, with its relatively complex structure of hierarchies and constraints, and differences in the calculated kinematic behaviours of the participating processes.

2. The universality of the measured patterns

Fig. 1 shows the first of the two interesting observations we want to discuss: a seemingly universal pattern in the shapes of the p_T distributions of all prompt quarkonia. Indeed, when presented as p_T/M distributions, where M is the mass of the quarkonium state, the prompt J/ψ, χ_{c1}, χ_{c2}, ψ(2S) and Υ(nS) production cross sections are all compatible with a single kinematic dependence, at least for mid-rapidity ($|y| \lesssim 1$) and for not-too-small p_T/M. This observation confirms, with higher-p_T data, a trend first noticed in Ref. [2]. Fig. 2 offers a linear representation of the p_T/M scaling, in the form of pulls, i.e. the differences between each data point and the function shown in Fig. 1-right, normalized to the measurement uncertainty. Only a small fraction of all the data points depart from the universal function by more than two standard deviations, fluctuating without any systematic trends. The good fit quality, expressed by the normalized χ^2 of 1.11 for 193 degrees of freedom (ndf), provides a quantitative measure of the p_T/M universality.

Fig. 3 presents a clearer view of the χ_c measurements, also adding χ_b data: the χ_{c2}/χ_{c1} and χ_{b2}/χ_{b1} yield ratios, as well as the ratio of J/ψ from χ_c decays to prompt J/ψ yield, show a flat dependence vs. p_T/M. Since the prompt ψ(2S) mesons are fully directly produced while the J/ψ and Υ(nS) states are significantly affected by feed-down contributions from χ_c and χ_b decays ($\simeq 25\%$ [5] and $\simeq 40\%$ [12], respectively), the perfect compatibility of their p_T/M shapes is another observation supporting the similarity of P- and S-wave quarkonium production, even in p_T/M ranges uncovered by the existing χ data.

The universality of the production kinematics could indicate that a single parton-level process (or mixture of processes) describes the production of all states, irrespectively of their masses and quantum numbers. Indeed, the kinematic dependence of the partonic cross section of a given process is invariant by simultaneous rescaling of all energy-related variables. This translates to an