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η_c' hadroproduction at next-to-leading order and its relevance to ψ' production

Jean-Philippe Lansberg [a,*], Hua-Sheng Shao [b,c], Hong-Fei Zhang [d]

[a] IPNO, CNRS-IN2P3, Univ. Paris-Sud, Université Paris-Saclay, 91406 Orsay Cedex, France
[b] Sorbonne Universités, UPMC Univ. Paris 06, UMR 7589, LPTHE, F-75005 Paris, France
[c] CNRS, UMR 7589, LPTHE, F-75005 Paris, France
[d] College of big data statistics, Guizhou university of finance and economics, Guiyang 550025, China

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ABSTRACT

We proceed to the first phenomenological study of η_c' prompt hadroproduction at next-to-leading order in α_s. Based on heavy-quark-spin symmetry, which is systematically used in quarkonium-production phenomenology, we demonstrate that prompt η_c' can be studied at the LHC with the existing data. We emphasise its relevance to constrain ψ' production, in the same way as the first prompt η_c data at the LHC lately strongly impacted the phenomenology of J/ψ studies.

1. Introduction

Heavy-quark-spin symmetry (HQSS), whereby soft nonperturbative gluon emissions do not flip the spin of heavy quarks, is, at the heart of all phenomenological studies (see [1–3] for reviews) of quarkonium production in nonrelativistic QCD (NRQCD) [4] since more than 20 years. This symmetry sets stringent constraints between the amplitudes of different nonperturbative transitions at work in quarkonium production, encapsulated in the NRQCD Long Distance Matrix Elements (LDMEs). For the colour-singlet (CS) transitions, one knows that the spin-triplet and spin-singlet states have the same spatial wave function and hence their LDME are related. Prime examples are the $\eta_c - J/\psi$ and the $\chi_{c0} - \chi_{c1} - \chi_{c2}$ systems for which the CS LDMEs are identical up to a $2J+1$ factor. Another well known example, central to J/ψ and ψ' phenomenology, is that of the P-wave LDMEs for the Colour-Octet (CO) transitions, $\langle\mathcal{O}(^3P_J^{[8]})\rangle$, which are also equal up to a $2J+1$ factor.

Besides, HQSS also very strongly constrains the polarisation of the produced quarkonium. Indeed, a heavy-quark pair produced at short distances in a given spin state will remain, by virtue of HQSS, in this very spin state until its hadronisation in a quarkonium. Based on this, as early as in 1994, it has been predicted [5] by Cho and Wise that a high-P_T ψ' produced by gluon fragmentation should fully inherit its mother-gluon polarisation and thus be transversely polarised in the helicity frame. The reason why current state-of-the-art NRQCD predictions [6–8] do not follow this simple trend is not due to an assumed violation of HQSS but to large QCD corrections in the short distance production of the heavy-quark pair, which is not necessarily produced in a spin ±1 state, even at large P_T as earlier expected based on Leading-Order (LO) arguments. To conclude, all the Next-to-Leading-Order (NLO) polarisation predictions [6–21] heavily rely on HQSS.

Moreover, HQSS lately has attracted back the attention of many, following the first experimental study of η_c hadroproduction at the LHC [22]. Indeed, the cross section measured by LHCb was found to be compatible with a negligible contribution of CO transitions. This, in conjunction with HQSS, in turn set extremely stringent constraints on the corresponding CO transitions at work on J/ψ production [23–26], to such an extent that only one fit [23] currently survives these constraints with a slight tension with the CDF polarisation data [27] though.[1]

These η_c production results potentially cast doubts onto both the universality of the LDMEs and the validity of the factorisation conjecture of NRQCD [28–30]. As such, it is of paramount importance to further explore the $2S$ charmonium sector to see whether similar tensions occur.

In the present Letter, through a complete NLO computation, we demonstrate that such a first study of prompt η_c' production is within the reach of the LHCb collaboration. We even show that it

* Corresponding author.
E-mail address: Jean-Philippe.Lansberg@in2p3.fr (J.-P. Lansberg).

[1] To be complete, let us add that polarisation data are not included in the PKU fit [23]. Such a more global fit including polarisation data and feed-down altogether remains to be done.

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is the case for a couple of decay channels. We also emphasise how important such a measurement is to advance our understanding of ψ' production for which, contrary to the J/ψ case, no *ep* and e^+e^- data are available to feed in NRQCD fits.

2. η_c' studies at hadron colliders: where do we stand?

Before discussing our evaluation of the η_c' production cross section and how its measurement can constrain that of ψ', let us address first how η_c''s can be studied at the LHC. Indeed, unlike the quarkonium spin-triplet vector states, which can decay into an easily detectable lepton pair, the study of the spin-singlet pseudoscalar states, such as the η_c and the η_c', its radial excitation, currently relies on hadronic decay channels. This makes their detection a real challenge at hadron colliders. As aforementioned, η_c hadroproduction was first studied by LHCb [22]. To do so, they used the decay channel into $p\bar{p}$ with a branching on the order of 1.5×10^{-3} [31]; that is 40 times smaller than the corresponding di-muon decay branching of the J/ψ. Beside a smaller branching, such hadronic channels are much more complicated to deal with because of the high level of the combinatorial background to be suppressed by stringent requirements on the particle identification and by limiting the accessible P_T range, already at the level of the trigger system. In its study, LHCb simultaneously reported on the nonprompt and prompt yields, *i.e.* the η_c from a b-hadron decay or not. The former are significantly easier to study since the $p\bar{p}$ pair is displaced with respect to the primary vertex from which emerges most of the particles constituting the combinatorial background.

More recently, LHCb pioneered again with the first study of η_c' [32] production in exclusive b decay via the $\eta_c' \to p\bar{p}$ decay channel. From the above argument, such a *nonprompt* η_c' detection is notably simpler than that of *prompt* η_c' which we wish to motivate in the present Letter. Yet, this first η_c' production study is very encouraging and gives us reliable indications on the order of magnitude of some η_c' branchings. This is crucial in order to assess the feasibility of prompt η_c' cross-section measurements as we wish to do here.

Let us first discuss the baryon–antibaryon channels. With their measurement [32] of

$$\frac{\mathcal{B}(B^+ \to \eta_c' K^+) \times \mathcal{B}(\eta_c' \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} \tag{1}$$

giving $(1.58 \pm 0.33 \pm 0.09) \times 10^{-2}$ and knowing that [31]

$$\mathcal{B}(B^+ \to \eta_c' K^+) = (3.4 \pm 1.8) \times 10^{-4}, \tag{2}$$

$$\mathcal{B}(B^+ \to J/\psi K^+) = (1.026 \pm 0.031) \times 10^{-3}, \tag{3}$$

$$\mathcal{B}(J/\psi \to p\bar{p}) = (2.120 \pm 0.029) \times 10^{-3}, \tag{4}$$

one can obtain that

$$\mathcal{B}(\eta_c' \to p\bar{p}) = (1.0 \pm 0.5) \times 10^{-4}. \tag{5}$$

The ratio $\mathcal{B}(\eta_c' \to p\bar{p})/\mathcal{B}(\eta_c \to p\bar{p})$ is thus likely as high as 10%, which gives us great confidence that prompt η_c' studies are within the reach of the LHCb detector with data on tape or to be recorded soon. Moreover, it is reasonable to suppose that the corresponding ratios for the heavier final states $\Lambda\bar{\Lambda}$, $\Lambda^*\bar{\Lambda}^*$, $\Xi\bar{\Xi}$ would be on the same order as for the η_c, if not larger, since, in general, the phase space is relatively larger for η_c' compared to η_c. Given that $\mathcal{B}(\eta_c \to \Lambda\bar{\Lambda}) = (1.09 \pm 0.24) \times 10^{-3}$ and $\mathcal{B}(\eta_c \to \Xi\bar{\Xi}) = (8.9 \pm 2.7) \times 10^{-4}$, one can infer that the corresponding branchings for the η_c' are expected to also be on the order of 10^{-4}. As discussed in [33], the latter channels, in spite of the request to find 4(6) tracks, are also promising owing to the presence of 2(4) secondary vertices which drastically reduces the combinatorial background.

Beside these baryon–antibaryon channels, the $\phi\phi$ decay channel is also of interest given the large ϕ branching to charged K pairs resulting in two narrow and clean peaks [33]. This channel is indeed the first via which η_c' production in inclusive b decay was observed by LHCb [34] with

$$\frac{\mathcal{B}(b \to \eta_c' X)\mathcal{B}(\eta_c' \to \phi\phi)}{\mathcal{B}(b \to \eta_c X)\mathcal{B}(\eta_c \to \phi\phi)} = (4.0 \pm 1.1 \pm 0.4) \times 10^{-2}. \tag{6}$$

Along with $\mathcal{B}(\eta_c \to \phi\phi) = (1.75 \pm 0.20) \times 10^{-3}$ [31][2] and assuming[3] that the $2S/1S$ ratio of the partial b width for the spin-singlet states ($\eta_c(nS)$) is similar to that of the spin-triplet states ($\psi(nS)$), we expect $\mathcal{B}(\eta_c' \to \phi\phi)$ to be 6–7 times smaller, that is on the order of 2.5×10^{-4}. To phrase it differently, the di-ϕ channel is another serious alternative.

Finally, the $K\bar{K}\pi$ channel with a branching of about 2% [31] or the $K^+K^-\pi^+\pi^-$ one, which should be of a similar magnitude, could be used to increase the reach to large P_T where the combinatorial background is getting less problematic and the statistics small. As we shall explain below, the large P_T region is probably the most interesting. The di-photon channel ($\mathcal{B}(\eta_c' \to \gamma\gamma) = (1.9 \pm 1.2) \times 10^{-4}$ [31]) is a further option to be explored. Yet another method would be to look for η_c or η_c' in the already recorded J/ψ sample as suggested in [20]. This would allow one to bypass most of the triggering constraints. Table 1 summarises the aforementioned channels and their status.

Table 1
Summary of tractable η_c' decay channels in hadroproduction studies.

Channel	η_c' Partial width	Status
$p\bar{p}$	$(1.0 \pm 0.5) \times 10^{-4}$	measured
$\gamma\gamma$	$(1.9 \pm 1.2) \times 10^{-4}$	measured
$K\bar{K}\pi$	$(1.9 \pm 1.2) \times 10^{-2}$	measured
$\phi\phi$	$(1 \div 4) \times 10^{-4}$	extrapolated
$\Lambda\bar{\Lambda}$	$\mathcal{O}(10^{-4})$	estimated
$\Xi\bar{\Xi}$	$\mathcal{O}(10^{-4})$	estimated

3. Theoretical framework

Within NRQCD, one factorises any differential cross section to produce a quarkonium into calculable coefficients related to the production at short distances of the heavy-quark pair in different Fock states and the LDMEs encoding the nonperturbative transitions between these states and the final-state quarkonium. Generally, the partonic quarkonium-production cross section reads

$$\sigma(\mathcal{Q} + X) = \sum_n \hat{\sigma}(Q\bar{Q}[n] + X)\langle O^{\mathcal{Q}}(n)\rangle, \tag{7}$$

where n labels the different Fock states of the $Q\bar{Q}$ pair which is produced in the partonic scattering. Correspondingly, the $\hat{\sigma}(Q\bar{Q}[n] + X)$ are the short-distance coefficients (SDC), which are perturbatively calculable using usual Feynman graphs. $\langle O^{\mathcal{Q}}(n)\rangle$ denotes the nonperturbative – but universal – NRQCD LDMEs. The hadronic cross section is then obtained by folding $\sigma(\mathcal{Q} + X)$ with the parton distribution functions (PDFs) as usually done in collinear factorisation.

[2] We take the "fit" PDG value, rather than the "average" PDG which is much less precise.

[3] And approximately accounting for the different feed-down structure.