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# Study of charmonium production with the LHCb

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This contribution is devoted to understanding charmonium production mechanism using data from the LHCb experiment. It also suggests an exploration of new observables and proposes a series of new approaches on charmonia studies in LHCb. It will describe a possible extension of a series of breakthrough studies, performed at IJCLab (former LAL) and UCAS within the LHCb collaboration and documented in Refs. [1, 2, 3, 4].

The most precise charmonium studies employ decays into experimentally clean dimuon final state, which is possible for $J^{PC} = 1^{--}$ charmonia, such as $J/\psi$ and $\psi(2S)$ states. In addition, $\chi_{cJ}$ states can be reconstructed via their radiative decays to $J/\psi$, which, however, requires a reconstruction of a low-energy photon. Other charmonium states are accessible via hadronic decays. Therefore the decays to such final states as $p\bar{p}$, $\phi\phi$, $\Lambda\bar{\Lambda}$ allow to study simultaneously multiple charmonium states. The LHCb experiment is well positioned for these studies due to its precise vertex reconstruction, momentum measurements, and powerful particle-identification performance, which allows suppressing high combinatorial background.

The next-to-leading order (NLO) calculations in NRQCD successfully describe the measurements of $J/\psi$ and $\psi(2S)$ production rates in, however, a limited range of transverse momentum. While NRQCD provides a good description of the $J/\psi$ production and polarization, a consistent description of the $J/\psi$ production and polarization together with the production of the $\eta_c(1S)$, described by linked long-distance matrix elements (LDMEs), remains challenging [5]. This judgment is based on a factorization approach and linking of the LDMEs corresponding to the $J/\psi$ and $\eta_c(1S)$ production within a heavy-quark spin symmetry assumption. The first $\eta_c(1S)$ production measurement by LHCb [2] triggered a major revisiting of the theoretical framework and yielded new approaches capable to describe simultaneously the three observables, however, in a limited $p_T$ range.
The recent $\eta_c(1S)$ production measurement [4] further constrains the theory and indicates another fundamental consistency problem to be solved in the coming years. Meanwhile, J.-P. Lansberg, H.-S. Shao and H.-F. Zhang outlined that the studies of the first excited state of $\eta_c(1S)$, the \eta_c(2S) meson, will allow clear and unambiguous interpretation and estimated the expected $\eta_c$ meson hadroproduction cross-section in the LHCb acceptance at 13 TeV [6]. Theory suggests the same relations between parameters for $\eta_c(2S)$ and $\psi(2S)$ states, as for $\eta_c$ and $J/\psi$. Moreover, a pair of excited states is expected to be free from feed-down contributions. Therefore, a measurement of their production cross section will provide a possibility to further test main NRQCD assumptions. Further lacking important measurements of charmonia hadroproduction are those for $h_c$ and $\chi_{cJ}$ states. Using a dedicated 2D fit technique and reconstructing charmonia via their decays to two phi mesons, LHCb measured [3] the branching fractions of $b$-hadron inclusive decays to the $\chi_{cJ}$ states providing first or most precise results.

A new technique has recently been proposed to constrain theory using results of both charmonia hadroproduction and charmonia production in $b$-hadron inclusive decays under the assumptions of factorization, LDME universality, and heavy-quark spin symmetry, where different charmonium states are involved. Using the LHCb measurements, this technique allowed a first direct comparison between the LDMEs, responsible for the $J/\psi$ and $\eta_c(1S)$ hadronization, as determined from hadroproduction and from $b$-hadron decays. In addition, it allowed to strongly constrain the corresponding matrix elements and revealed a clear problem in theory description of $b$-hadron inclusive decays to the $\chi_{cJ}$ states. Alternatively, once hadroproduction and production in $b$-decays will be measured for charmonium states with linked LDMEs, the most basic theory assumptions can be tested quantitatively.

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