New measurements in the quarkonia sector

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An overview of recent measurements by the LHC experiments in the quarkonia sector is presented in this proceedings. Selected results on differential production cross-section, P-wave charmonia polarization and associated quarkonia production are discussed.

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1. Introduction

Quarkonium is a bound state of a quark and its own antiquark, composed only of heavy quarks q which mass m_q is bigger than the binding energy. It plays an important role in the understanding of strong interaction. In pp collisions, quarkonium state can be produced directly from hard collisions of partons (hadroproduction), through the feed-down of excited states, or via decays of b-hadrons. The quarkonia from the first two sources originate from the primary vertex of the pp collision, and are called prompt, while those from the last source originate from b-decay vertices, which are typically displaced from the primary vertex, and are called charmonia from-b. At present, the effective quantum field theory of non-relativistic Quantum Chromodynamics (NRQCD) constitutes the most powerful approach to describe quarkonium production.

The simplest approach assumes that only heavy quark pairs produced in the dominant Fock state form a physical quarkonium. It considers that the colour of the $q\bar{q}$ can be the same as the physical final state H, and the colourless state is then called a color singlet state. Therefore, the model which describes this process is called Colour-Singlet model.

The NRQCD approach provides a natural solution by generalizing Colour-Singlet model (CS) to Colour-Octet (CO) model. In this model, heavy quark pairs that are produced at short distances in a colour-octet state can emit soft gluons at a later stage of the production process, when the quark pair has already expanded to the quarkonium size. According to the power counting rules, CO matrix elements for S-wave quarkonia are suppressed by power of the velocity compared to the CS contribution. Nevertheless, the CO processes can be dominant in case of enhanced production of $q\bar{q}$ in a CO state.

This proceeding focuses on the selected quarkonia production and polarization measurements in pp collisions from the ALICE, ATLAS, CMS and LHCb experiments. The LHC experiments have complementary acceptance ranges. The ATLAS, CMS and ALICE experiments perform measurements in midrapidity range, at the same time ALICE and LHCb experiments cover forward-rapidity. All the experiments can access dimuon ($\mu^+\mu^-$) final state, when the LHCb experiment can also perform precise measurements via hadronic final states.

2. Quarkonia production

The most precise charmonium studies employ decays into experimentally clean dilepton final states, which is possible for $J^{PC} = 1^{--}$ charmonia, such as J/ψ and $\psi(2S)$ states. The ATLAS experiment reported a measurement of J/ψ and $\psi(2S)$ prompt production cross-section and production from b-decays at $\sqrt{s} = 13$ TeV [1]. The charmonia yields are measured for rapidity $|y| < 2.0$ and transverse momentum $60 < p_T < 360$ GeV/c in the dimuon channel. J/ψ inclusive production was also studied by the ALICE experiment at $\sqrt{s} = 5.02$ TeV in $|y| < 0.9$ (Fig. 1) [2]. At the same time the LHCb experiment reported $\psi(2S)$ production measurement at $\sqrt{s} = 7$ and 13 TeV in a complementary kinematical region: $2.0 < |y| < 4.5$ and $p_T < 20$ GeV/c (Fig. 2) [3]. For the J/ψ and $\psi(2S)$ prompt production rates, the next-to-leading order (NLO) calculations in NRQCD can successfully describe the measurements in, however, a limited range of transverse momentum. The measured charmonium production in b-decays is is well-described by FONLL predictions [4].

The first measurement of the η_c meson hadroproduction at $\sqrt{s} = 7$ TeV [5] revealed a lack of comprehensive theoretical model able to simultaneously describe a production cross-section of the
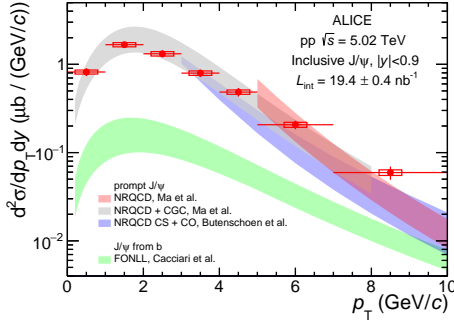
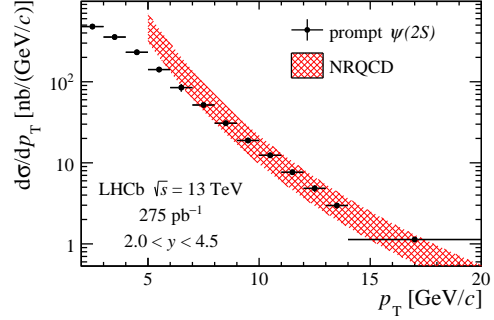**Figure 1:** Inclusive J/ψ p_T-differential cross-sections [2].

Figure 2: Prompt $\psi(2S)$ p_T-differential cross-sections at 13 TeV [3].

J/ψ and $\eta_c(1S)$ states and a polarisation of the J/ψ meson. The $\eta_c(1S)$ production measurement by the LHCb Collaboration 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 LHCb experiment published a measurement of the $\eta_c(1S)$ production at $\sqrt{s} = 13$ TeV for $6.5 < p_T < 14$ GeV/c and $2.0 < |y| < 4.5$ [6]. It shows that $\eta_c(1S)$ prompt production can be described by CS contribution (Fig. 3 (b)). New studies in the extended p_T region will provide an improved sensitivity to a possible CO contribution.

3. Quarkonia polarization

Another important observable is charmonia polarization. The CMS Collaboration reported the χ_{c2}/χ_{c1} polarization ratio as a function of $|\cos\theta^{HX}|$ and ϕ^{HX} [7]. The χ_c states are reconstructed via their radiative decays $\chi_c \to J/\psi\gamma$, with the photons being measured through conversions, which allows the two states to be well resolved. While azimuthal decay angle distributions show no differences between the two states, polar anisotropies are observed to be significantly different. A scenario where both states are unpolarized along the helicity quantization axis was excluded at a 99.7% confidence level. This is the first measurement of significantly polarized quarkonia produced at high transverse momentum and it shows good agreement with NRQCD predictions (Fig. 4).
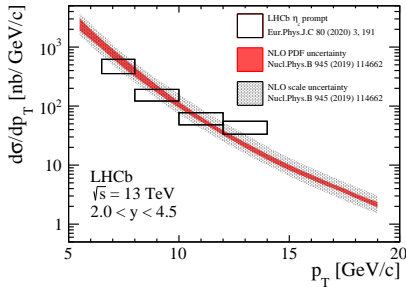

Figure 3: Relative $\eta_c/J/\psi$ prompt production cross-section (boxes), NLO NRQCD prediction with PDF (red band) and scale (grey band) uncertainties.
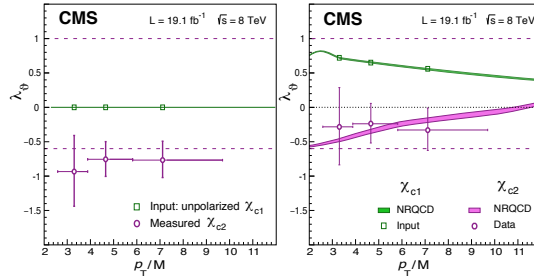

Figure 4: The χ_{c2} polarization values (circles) measured when the χ_{c1} polarization values (squares) are fixed to the unpolarized (left) or the NRQCD (right) scenarios (green curves), as a function of p_T/M of the J/ψ [7].

4. Associated production

In order to test the charmonium hadronization mechanism, the CMS experiment studied J/ψ production inside jets at $\sqrt{s} = 8$ TeV [8]. The analysis combines the experimental measurement of J/ψ mesons contained in jets with a theoretical approach based on the fragmenting jet function (FJF) model [9]. The FJF model postulates that the $c\bar{c}$ pair is produced in fragmentation of a high-p_T jet. The cross-section contributions for all relevant $^{2S+1}L_J^n$ terms are computed using the NRQCD methodology. Each cross-section term has a characteristic relation between the jet energy E_{jet} and its fraction carried by the J/ψ meson: $z = E_{J/\psi}/E_{jet}$. The differential cross-section as a function of E_{jet} is measured in three ranges of z and compared to the FJF prediction for this quantity, using three different long-distance matrix elements (LDME) parameter sets. The FJF prediction using the BCKL [10] LDME parameters shows the best agreement with the data for all three z ranges.

The ATLAS experiment measured the ratio of the associated prompt J/ψ and $W^{\pm}$ production cross-section to the inclusive $W^{\pm}$ boson production cross-section at $\sqrt{s} = 8$ TeV [11]. The cross-section ratios are reported for $8.5 < p_T^{J/\psi} < 150$ GeV/c and $|y| < 2.1$. Study of the opening angle $\Delta\phi(J/\psi, W^{\pm})$ for prompt $J/\psi + W^{\pm}$ candidates suggest presence of both single- and double-parton-scattering contributions (SPS and DPS). The result is compared with a theoretical prediction at NLO for CO prompt production processes. Two different values of the effective DPS cross-section σ_{eff} are used. However, neither of them can correctly describe J/ψ p_T-dependence.

The CMS experiment reported another important probe of QCD processes using quarkonium pair production. The $\Upsilon(1S)$ pair production was measured at $\sqrt{s} = 13$ TeV with four muons in the final state and where both $\Upsilon(1S)$ have an absolute rapidity $|y| < 2.0$ [12]. The DPS contribution to the total inclusive pair production cross-section is estimated for the first time to be $(39 \pm 14)\%$. This analysis also aims at searching for narrow resonances decaying to $\Upsilon(1S)\mu^+\mu^-$. No excess of events compatible with a signal is observed in the four-muon invariant mass spectrum. Upper limits at 95% confidence level on the product of the signal cross-section and branching fraction to four muons via an intermediate resonance are set for different signal models, expanding the kinematic and mass coverage of previous searches [13].

A similar study of J/ψ pair production was performed by the LHCb experiment at $\sqrt{s} = 7$ and 8 TeV in order to search for a possible tetraquark candidate [14]. A narrow structure, $X(6900)$, matching the lineshape of a resonance and a broad structure next to the di-J/ψ mass threshold are found. The global significance of both structures is estimated to be larger than five standard deviations. The narrow $X(6900)$ structure is a possible four-charm tetraquark candidate. The broad structure close to the di-J/ψ mass threshold could originate from a mixture of multiple four-charm quark states or have contributions from feed-down decays of four-charm states through heavier quarkonia. Additional study with more data and spin-parity determination are required to understand the nature of the observed structure.

5. Summary

The summary of recent measurements in the quarkonia sector performed at LHC has been presented. It covers studies of different observables important for understanding the quarkonia production mechanism. The LHC experiments provide measurements in complementary kinematical ranges and different final states. Improved statistics and new datasets would allow to improve the precision of the existing measurements and access new observables for the quarkonia studies.

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