PROCEEDINGS OF SCIENCE

Associated Production of Quarkonium Pairs at LHC

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The study of heavy quarkonium production has long been an intriguing topic in quantum chromodynamics. The associated production of two quarkonia adds unique value to our understanding of quarkonium production and has been extensively studied by the LHC experiments. These proceedings present two recent measurements at the LHC in pp collisions at the centre-of-mass energy of $\sqrt{s} = 13$ TeV, which are the inclusive J/ψ pair production study by ALICE, and the associated prompt J/ψ and Υ production study by LHCb. The presence of double-parton interactions in these processes is implicated.

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1. Introduction

Heavy quarkonium production mechanism has been studied ever since J/ψ was observed in 1974 [1, 2]. The production of quarkonia can be factorised into the production of quark-antiquark pairs and the hadronisation of quark pairs into quarkonia. While the first step can be calculated in a perturbative approach, the second cannot and thus needs experimental inputs to test or constrain the models. Several models have been developed to describe the hadronisation process, yet each has problems. The colour singlet model (CSM) [3–5] considers only the colour-singlet intermediate state with the same quantum numbers as the final-state quarkonium. It effectively describes production cross-sections at low energies but fails at higher energies. The non-relativistic QCD (NRQCD) [6] takes into consideration both colour-singlet and colour-octet intermediate states, and assumes process-independent long-distance matrix elements (LDMEs) describing the transition probabilities from quark pairs to quarkonia. It is the most successful model by far as it can predict differential quarkonium production cross-sections with respect to the transverse momentum. However, LDMEs measured in different processes seem to contradict the assumption of its universality. The model also has difficulty simultaneously describing the polarisations and production cross-sections of quarkonia.

Quarkonium pair production serves as a unique input for the development of the quarkonium production models. The quarkonium pair can be produced either from single-parton scattering (SPS) or double-parton scattering (DPS). While the SPS is instrumental in improving the understanding of quarkonium production mechanisms, the DPS can provide information on the parton transverse profile and parton correlations in the colliding hadrons [7]. Under the assumption that the transverse and longitudinal components of parton distributions are factorisable and there is no correlation between two partons, the DPS cross-section can be written as

$$\sigma_{Q_1Q_2} = \frac{1}{1+\delta_{Q_1Q_2}} \frac{\sigma_{Q_1}\sigma_{Q_2}}{\sigma_{\text{eff}}}, \tag{1}$$

where σ_{Q_1} and σ_{Q_2} are single quarkonium inclusive production cross-sections, and the effective cross-section σ_{eff} is a factor that is expected to be universal for all processes [8–10]. A selection of results measuring the σ_{eff} is summarised in Fig. 1. Its universality remains to be tested [11].

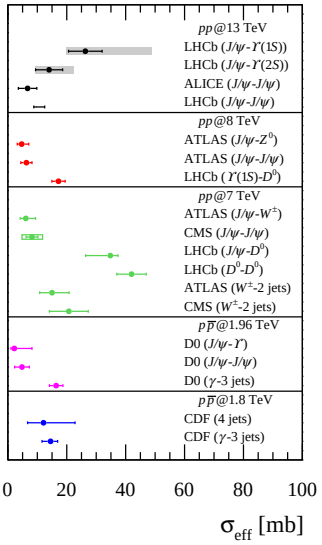

Figure 1: Effective cross-sections measured in different particle production processes by various experiments, reproduced from Ref. [12].

2. Double charmonium production

The LHC experiments have been investigating double charmonium production in the past years at different collision energies. The J/ψ-pair production was measured by the CMS experiment [13] in pp collisions at $\sqrt{s} = 7\,\text{TeV}$, by the ATLAS experiment [14] and the LHCb experiment [15] at $\sqrt{s} = 8\,\text{TeV}$, and by the LHCb experiment at $\sqrt{s} = 13\,\text{TeV}$ [16, 17]. The associated production of J/ψ and $\psi(2S)$ is recently measured by the LHCb experiment at $\sqrt{s} = 13\,\text{TeV}$ [18].

The ALICE experiment recently measured the cross-section of inclusive J/ψ pair production in pp collisions at a centre-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$ with both J/ψ mesons in the rapidity range of $2.5 < y < 4.0$ and for transverse momentum $p_{\text{T}} > 0$ [19]. The two-dimensional invariant-mass distribution of J/ψ pairs is fitted to extract the signal yields as shown in Fig. 2. The inclusive cross-section of J/ψ pairs is measured to be $10.3 \pm 2.3\,(\text{stat}) \pm 1.3\,(\text{syst})\,\text{nb}$. The contribution of nonprompt J/ψ pair production is evaluated. Assuming the cross-section is completely contributed by DPS, the effective cross-section as defined in Eq. 1 is measured to be $6.7 \pm 1.6\,(\text{stat}) \pm 2.7\,(\text{syst})\,\text{mb}$. As shown in Fig. 1, the results are consistent with the LHCb measurements which is performed in a slightly different kinematic interval [15, 16].

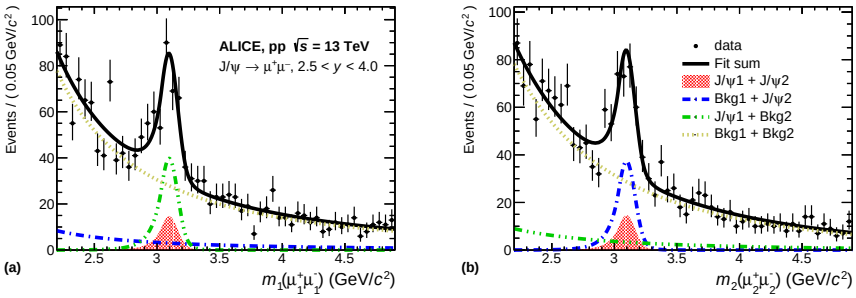

Figure 2: Results of the two-dimensional fit to the invariant mass of the J/ψ–J/ψ candidates projected on the invariant masses (left) $m(\mu_1^+\mu_1^-)$ and (right) $m(\mu_2^+\mu_2^-)$, Ref. [19].

3. Associated production of charmonium and bottomonium

The associated production of prompt J/ψ–Υ pairs in pp collisions at a centre-of-mass energy of $\sqrt{s} = 13\,\text{TeV}$ was measured by the LHCb experiment, for J/ψ (Υ) mesons with a transverse momentum $p_{\text{T}} < 10\,(30)\,\text{GeV}/c$ in the rapidity range $2.0 < y < 4.5$. An unbinned extended maximum-likelihood fit is performed to the two-dimensional J/ψ–Υ invariant-mass distribution to extract the signal yield. The fit result is shown in Fig. 3. The associated production of J/ψ–$\Upsilon(1S)$ pairs is observed with a significance of $7.9\,\sigma$, and an evidence is found for the J/ψ–$\Upsilon(2S)$ process.

The cross-section for J/ψ–$\Upsilon(1S)$ production is measured to be $133 \pm 22\,(\text{stat}) \pm 7\,(\text{syst}) \pm 3\,(\mathcal{B})\,\text{pb}$ and that for J/ψ–$\Upsilon(2S)$ production $76 \pm 21\,(\text{stat}) \pm 4\,(\text{syst}) \pm 7\,(\mathcal{B})\,\text{pb}$. The effective cross-sections are $26 \pm 5\,(\text{stat}) \pm 2\,(\text{syst})^{+22}_{-3}\,(\text{theo})\,\text{mb}$ for J/ψ–$\Upsilon(1S)$ production and $14 \pm 5\,(\text{stat}) \pm 1\,(\text{syst})^{+7}_{-1}\,(\text{theo})\,\text{mb}$ for J/ψ–$\Upsilon(2S)$ process. Distributions of variables sensitive to kinematic correlations between the J/ψ and $\Upsilon(1S)$ mesons are investigated to study the contributions of SPS and DPS. The distributions of the J/ψ-$\Upsilon(1S)$ invariant mass, the transverse momentum of the J/ψ–$\Upsilon(1S)$ system, and the relative azimuthal angle between the J/ψ and $\Upsilon(1S)$ particles are shown in Fig. 4. The DPS

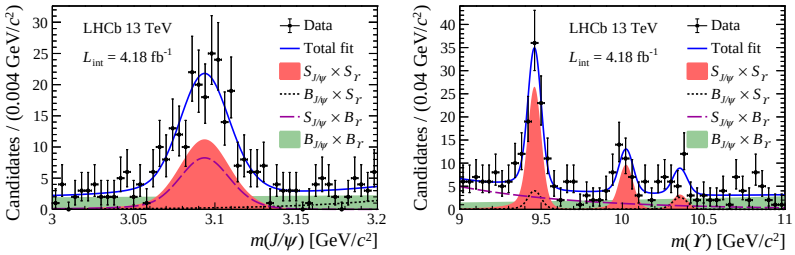

Figure 3: Two-dimensional invariant-mass distribution of the J/ψ–Υ candidates projected on (left) the J/ψ invariant mass $m(J/\psi)$ and (right) the Υ invariant mass $m(\Upsilon)$, Ref. [12].

contribution is modelled with pseudoexperiments using previously measured single-J/ψ and -Υ kinematic distributions as input [20, 21], given that in DPS process the kinematic distribution of each associated-produced meson is expected to be similar to that in a single meson production. The SPS distribution is taken from calculations in Ref. [22]. As shown in Fig. 4, the kinematic correlations between the J/ψ and $\Upsilon(1S)$ mesons are found to be consistent between the measurement and pseudoexperiments either assuming only the DPS contribution or also adding the SPS contribution calculated in Ref. [22].

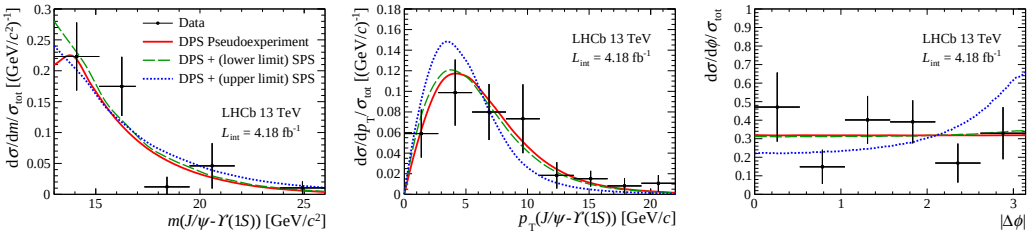

Figure 4: Distributions of (left) the invariant mass $m(J/\psi$–$\Upsilon(1S))$, (middle) the transverse momentum $p_{\mathrm{T}}(J/\psi$–$\Upsilon(1S))$, (right) the azimuthal angle difference $|\Delta\phi|$ for data and the pseudodata, Ref. [12].

4. Summary

The associated production of heavy quarkonium pairs is actively studied by the LHC experiments. These proceedings summarise two latest results measuring associated quarkonium pair production cross-sections by the LHC experiments, both imply that DPS contributes to these processes.

With upgrade data coming soon, LHC experiments will be able to extend the studies to rarer processes, for example, triple quarkonium production which could be sensitive to the triple-parton scattering process. Using Run 2 data, CMS has observed triple-J/ψ production which is found to be dominated by DPS and the triple-parton scattering [23]. Measurements of cross-sections of quarkonium pairs are also synergistic with spectroscopy studies. Peaking states with high statistical significance are seen in the double-J/ψ invariant-mass spectrum of the dataset collected by the LHCb [24], CMS [25] and ATLAS [26] experiments. These peaking states are candidates of fully charmed tetraquarks. The discussion about their nature is still ongoing.

Currently, all such measurements are limited by the statistics. Improvements in distinguishing contributions from SPS and DPS processes are expected with the forthcoming LHC Run 3 dataset and advancements in theoretical calculations.

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