Associated Quarkonium Hadroproduction at High-Energy Colliders

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Quarkonium production in proton-proton collision is interesting in profiling the partons inside the nucleon. Recently, the impact of double parton scatterings (DPSs) was suggested by experimental data of associated quarkonium production ($J/\psi + Z$, $J/\psi + W$, and $J/\psi + J/\psi$) at the LHC and Tevatron, in addition to single parton scatterings (SPSs). In this proceedings contribution, we review the extraction of the effective parameter of the DPS ($\sigma_{\text{eff}}$) through the evaluation of the SPS contributions under quark-hadron duality.

KEYWORDS: Nucleon structure, double parton scattering, quarkonia

1. Introduction

The prime motivation to study quarkonium production is to unveil novel nonperturbative and perturbative features of QCD [1–4]. In this context, an interesting class of processes is that of the associated quarkonium production, which is being studied to probe double parton scatterings (DPS) [5–7] and even triple parton scatterings [8]. A representative case is di-$J/\psi$ production, which was measured in many experiments (NA3 [9], D0 [10], CMS [11], ATLAS [12], and LHCb [13, 14]), and was studied in many theoretical works [15–18]. Recently, experimental data of associated production with vector bosons were released by the ATLAS Collaboration ($J/\psi + W$ [19] and $J/\psi + Z$ [20]). The single parton scattering (SPS) contributions to these processes were theoretically computed in NRQCD [21–26], and the predictions have difficulties in explaining the yields in several regions of the phase space. This proceedings contribution summarizes the results of the calculations of the SPS of $J/\psi + W$, $J/\psi + Z$, and $J/\psi + J/\psi$ [18, 27–29] production in the color evaporation model (CEM) which provides us indirect informations about the DPS.

2. The double parton scattering

Let us parametrize the DPS. If we assume two uncorrelated parton scatterings, the DPS cross section can be written as

$$\sigma_{\text{DPS}}(A + B) = \frac{1}{1 + \delta_{AB}} \frac{\sigma(A)\sigma(B)}{\sigma_{\text{eff}}},$$

with $\delta_{AB} = 1$ for the case where we have $A = B$ in the final state, where $A$ or $B$ (or both) is a quarkonium.
3. The color evaporation model

The CEM is a model to calculate heavy quarkonium production processes based on quark-hadron duality [4,30–33]. In this model, the quarkonium $Q$ is produced as a quark-antiquark pair $Q \bar{Q}$ having its invariant mass below the open-heavy flavor threshold $2m_{\text{thr}}$. The cross section in the model is given by

$$\sigma_Q^{(NLO, \text{direct \ prompt})} = \mathcal{P}_Q^{(NLO, \text{direct \ prompt})} \int_{2m_{\text{thr}}}^{\infty} \frac{d\sigma_Q^{(NLO)}}{dm_Q \bar{Q}} dm_Q \bar{Q},$$

where we assume universal parameters $\mathcal{P}_Q^{(NLO, \text{prompt})}$. For $J/\psi$, we have $\mathcal{P}_{J/\psi}^{(NLO, \text{prompt})} = 0.014$ (LO), $0.009$ (NLO) [34], obtained from the fit of the single inclusive $J/\psi$ production data. A caveat is that the single-quarkonium production cross section predicted by the model overshoots the experimental data at high transverse momentum $p_T$ [2, 4, 34]. It is understood that the dominance of the gluon fragmentation in the model yields too hard a $p_T$ spectrum, which should also apply to the associated quarkonium production with vector bosons, discussed in the next section.

4. Analysis of the ATLAS data for $J/\psi + Z$ and $J/\psi + W$ productions in the CEM

Let us now consider the $J/\psi + Z$ and $J/\psi + W$ productions. As we mentioned in the previous section, the single quarkonium production in the CEM is dominated by the gluon fragmentation topologies at large $p_T$, which also happens for the cases of $J/\psi + Z$ and $J/\psi + W$. Since the CEM predictions overshoot the experimental data at high $p_T$, we can set conservative upper limits to the SPS contribution of both these processes. The SPS is evaluated at NLO in $\alpha_s$ with MadGraph5_AMC@NLO [35].

|   | ATLAS | NLO CEM |
|---|-------|---------|
| $J/\psi + Z$ | $1.6 \pm 0.4$ pb [20] | $0.19^{+0.10}_{-0.04}$ pb [34] |
| $J/\psi + W$ | $4.5^{+1.9}_{-1.4}$ pb [19] | $0.28 \pm 0.07$ pb [36] |

Table I shows the results of the associated $J/\psi$ productions with vector bosons. We see that the NLO CEM SPS predictions alone are smaller than the ATLAS experimental data (see also Fig. 1).

Let us now fit $\sigma_{\text{eff}}$ by assuming that the DPS fills the gap between the SPS and the measured total cross section. The result is shown in Fig. 1. We obtain $\sigma_{\text{eff}} = (4.7^{+2.4}_{-1.5})$ mb [34] ($J/\psi + Z$) and $\sigma_{\text{eff}} = (6.1^{+3.3}_{-1.9})$ mb [36] ($J/\psi + W$).

5. Analysis of di-$J/\psi$ production in the CEM

Let us now evaluate the di-$J/\psi$ production in the CEM. The regions of the phase space of interest are at the large invariant mass $M_{\psi\psi}$ and rapidity separation $\Delta y$, where the experimental data of CMS and ATLAS are overshooting the color singlet model SPS prediction [11, 12, 18, 27].

By computing the SPS contribution to the di-$J/\psi$ production at LO, we obtain the result of Fig. 2. No particular enhancements at large $M_{\psi\psi}$ and $\Delta y$ are seen in the CEM. Our result is suggesting the dominance of the DPS in these regions of the di-$J/\psi$ production. By assuming the dominance of the DPS, the $\sigma_{\text{eff}}$ value extracted from the CMS [11] ($\sigma_{\text{eff}} = (8.2 \pm 2.0_{\text{stat}} \pm 2.9_{\text{sys}})$ mb [18]), D0
Fig. 1. The $p_T$ distribution of the $J/\psi$ in the $J/\psi + Z$ [34] (left panel) and $J/\psi + W$ [36] (right panel) production cross section in the CEM. The ATLAS experimental data [19, 20] are also displayed for comparison.

Fig. 2. The invariant mass (left panel) and $\Delta y$ (right panel) differential cross sections of di-$J/\psi$ production (CMS setup, $\sqrt{s} = 7$ TeV).

$(\sigma_{\text{eff}} = (4.8 \pm 0.5_{\text{stat}} \pm 2.5_{\text{sys}}) \text{ mb})$ [10], and ATLAS Collaborations $(\sigma_{\text{eff}} = (6.3 \pm 1.6_{\text{stat}} \pm 1.0_{\text{sys}}) \text{ mb})$ [12] are all consistent with each other, as well as with those of the $J/\psi + W$ and $J/\psi + Z$ productions. In Fig. 3, we summarize the extractions of $\sigma_{\text{eff}}$ from different processes and experimental data.

Fig. 3. Summary of several extractions of $\sigma_{\text{eff}}$. Quarkonium related extractions are shown in color (see Ref. [36]).
6. Conclusion

To summarize, we analyzed the production processes of \( J/\psi + W/Z \) (NLO) and \( J/\psi + J/\psi \) (LO) in the CEM. For the case of \( J/\psi + W/Z \), it is possible to extract the DPS yield from the experimental data by setting an upper limit on the SPS contribution. We obtained \( \sigma_{\text{eff}} = (4.7^{+2.4}_{-1.5}) \text{mb} (J/\psi + Z) \), and \( \sigma_{\text{eff}} = (6.1^{+3.3}_{-1.9}) \text{mb} (J/\psi + W) \), which emphasizes the importance of the DPS and is compatible with other extractions from other central rapidity quarkonium data. This \( \sigma_{\text{eff}} \) is also in agreement with the enhancement of the di-\( J/\psi \) production at large \( \Delta y \) and invariant mass.

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