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Di-J/ψ production at the Tevatron and the LHC

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We briefly review recent results which we have obtained in the study of J/ψ-pair production at the Tevatron and the LHC. We claim that the existing data set from CMS and D0 point at a significant double-parton-scattering contributions with an effective cross section smaller than that for jet-related observables. We have also derived simple relations involving feed-down fractions from excited states which can help in disentangling the single from the double scatterings.

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1. Introduction

The observation of the associated production of a quarkonium with a vector boson or a heavy quark as well as of a pair of quarkonia is now quasi the bread and butter of quarkonium physics at the LHC and the Tevatron with nearly a dozen of experimental analyses [1, 2, 3, 4, 5, 6, 7, 8, 9, 10] accompanied by many relevant theoretical works[1] providing predictions before these analysis [15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27] or interpretations of these results [28, 29, 30, 31, 32, 33, 34]. We focus here on J/ψ-pair production at the LHC and the Tevatron.

2. J/ψ-pair production and the "CMS puzzle"

As a matter of fact, J/ψ-pair hadroproduction is not a new subject of investigations. 30 years ago, NA3 [35, 36] analysed it at the CERN-SPS. At the LHC, it has been measured by LHCb [1] with an admittedly small data sample but which covers low P_T and more recently by the CMS [4] and ATLAS [10] collaborations with a P_T cut of 4 to 8 GeV depending of the rapidity. At the Tevatron, the D0 collaboration [5] analysed it with a P_T cut of 3 GeV.

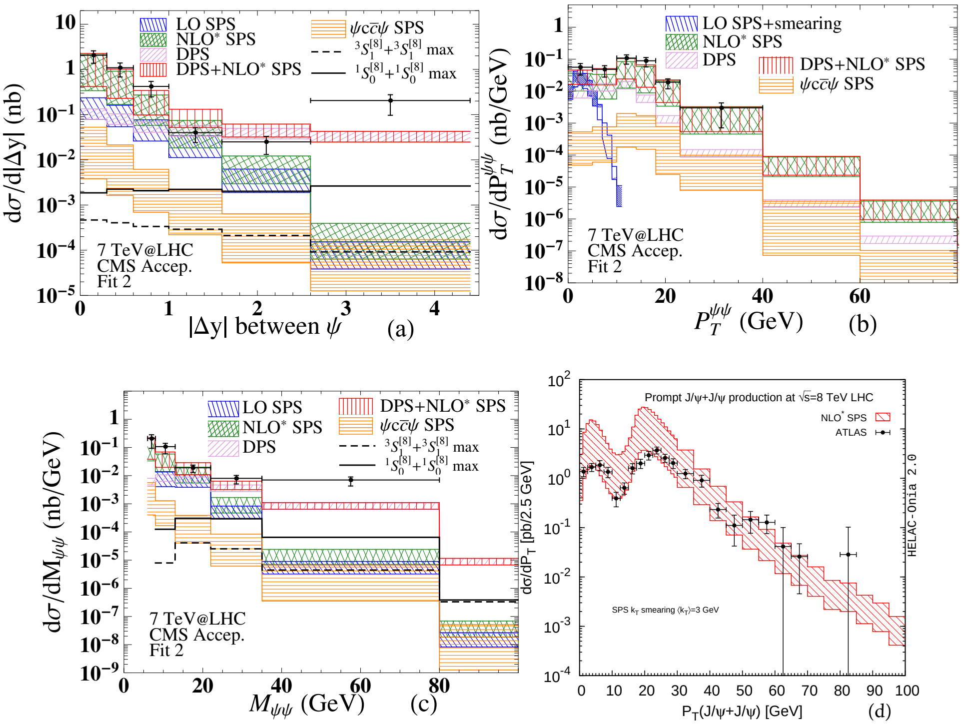

Figure 1: Comparisons of different theoretical contributions with the CMS measurement: (a) absolute-rapidity difference ; (b) pair transverse momentum; (c) pair invariant mass. Idem with the ATLAS data: pair transverse momentum.

Our claim is that all these data sample are compatible with Colour Singlet (CS) contributions only (known up to Next-to-Leading-Order (NLO) accuracy [23, 28, 27]) at small rapidity separations, Δy, whereas they point at a significant Double Parton Scattering (DPS) contributions for increasing Δy, compatible with a σ_{eff} below 10 mb. We guide the reader to [29] for a detailed

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[1] Let us stress here that a number of these theoretical works benefited from automated tools tailored for quarkonium production. Let us cite MADONIA [11], HELAC-ONIA [12, 13] and FDC [14].

discussion of these different results and to [30, 31] for recent LO NRQCD studies. We find it worth recalling that the D0 and ATLAS J/ψ-pair analyses [5, 10] are the only ones among those of quarkonium associated production (including with a heavy quark or a vector boson) where the DPS and Single Parton Scattering (SPS) contributions were separated based on kinematical variables[2].

Fig. 1 summarises well the situation for data with P_T cuts:

- the rapidity separation, Δy, dependence (Fig. 1a), agrees very well with the NLO CS contributions (green band) – contrary to the LO CS ones (blue band)– but for the two last points for $\Delta y \geq 2$. This has been referred to the *CMS puzzle* and was first discussed in [28]. We claimed in [29] that the puzzle is very naturally solved by the inclusion of DPS contributions in an amount compatible with the D0 extraction [5] (purple band). Higher QCD corrections at Next-to-Next-to-Leading Order (NNLO) are not expected to be significant (the orange band shows one of the dominant ones). Contrary to the claim made in [30], we do not find the CO contributions relevant here (black lines) unless unphysical[3] LDME values are used. If we fit them to this distribution, we obtain $\langle \mathcal{O}^{J/\psi}(^3S_1^{[8]})\rangle = 0.42 \pm 0.12$ GeV^3 & $\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle = 0.91 \pm 0.22$ GeV^3. Only unexpectedly large QCD corrections could make these values significantly smaller as to become realistic.
- the pair $P_T^{\psi\psi}$ dependence (Fig. 1b) is very well accounted by the NLO CS contributions. As expected, the LO contribution cannot account for it since large-$P_T^{\psi\psi}$ configurations arise from a hard parton with a significant P_T recoiling on the J/ψ pair[4]. A typical k_T smearing of a couple of GeV from initial-state radiations is not enough to account for the entire spectrum. We note that the CS contributions (as always without any tuned/fit parameters) agree with the data up to the last bin where $P_T^{\psi\psi}$ is as large as 30 GeV. The DPS contributions (purple band) are a bit softer and are only relevant at low $P_T^{\psi\psi}$. The CO contributions are not shown since they are simply negligible whatever the LDME set used is.
- the invariant-mass dependence (Fig. 1c) essentially displays the same information as the Δy dependence. It is normal since, for the majority of the events, $M_{\psi\psi} \simeq 2m_T^{\psi} \cosh \frac{\Delta y}{2}$. The inclusion of the DPS contribution removes the gap with the data in the 4th bin and reduces it for the last bin which probably contains the exact same events as in the two last bins of the Δy distribution. The maximum allowed CO contributions are still too low to matter.
- Fig. 1d shows the corresponding plot of Fig. 1b but for the ATLAS acceptance and with their preliminary data. The predicted NLO CS contribution (still no tuning) is in good agreement with the experimental points.

3. Di-J/ψ production involving feed-down from χ_c and ψ'

Under the simplistic, yet widely used, approach of the DPS mechanism using the so-called pocket formula, one can derive general formulae relating the feed-down fractions of the DPS yields

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[2] We wish to stress that, following the widespread practice, all the DPS contributions will be understood under the fully factorised "pocket formula" approach whereby $\sigma_{AB}^{\rm DPS} \propto \sigma_A \sigma_B$. This amounts to consider that the parton scattering producing the particle A is completely uncorrelated with that producing the particle B.

[3] Not only would they violate the velocity-scaling rules of NRQCD, they would generate single-J/ψ cross sections one or two orders of magnitude larger than all the existing data.

[4] The impact of the QCD corrections to the P_T spectrum of quarkonium-pair production was first discussed in [23].

for di-J/ψ production to those for single-J/ψ production. These are useful for two reasons. First, one can employ them to evaluate the feed-down size and thereby improving theoretical predictions. Second, one can also use them to test a possible hypothesis of DPS-dominance, if hinted at by some typical kinematical distributions, by measuring the cross section for pair productions involving the excited states.

To derive them, one first define specific feed-down fractions for di-J/ψ inspired from those for single J/ψ. These are $F_{\psi}^{\rm direct}$, $F_{\psi}^{\chi_c}$ and $F_{\psi}^{\psi'}$, respectively for direct production, for production from χ_c decay or from ψ' decay. For $J/\psi+J/\psi$, there are more possibilities. Yet, since it is experimentally challenging to measure (and subtract) the $\chi_c+\chi_c$ or even $\chi_c+\psi'$ yields, we restrict our definition to $F_{\psi\psi}^{\chi_c}$ (resp. $F_{\psi\psi}^{\psi'}$) as the $J/\psi+J/\psi$-event fraction from the feed-down of *at least* a χ_c (or resp. a ψ') decay. To phrase it differently, $F_{\psi\psi}^{\chi_c}$ is the fraction of events which include a prompt J/ψ (*i.e.* direct or from χ_c and ψ' feed-down) plus a J/ψ which is identified as from a χ_c. Since it is easier to predict and in spite of being probably very difficult to measure, we also define $F_{\psi\psi}^{\rm direct}$ as being the pure direct component, excluding all the possible feed-downs.

Starting from the factorised pocket formula, one easily gets (see [29] for details)

$$F_{\psi\psi}^{\chi_c}=F_{\psi}^{\chi_c}\times(F_{\psi}^{\chi_c}+2F_{\psi}^{\rm direct}+2F_{\psi}^{\psi'}),\ F_{\psi\psi}^{\psi'}=F_{\psi}^{\psi'}\times(F_{\psi}^{\psi'}+2F_{\psi}^{\rm direct}+2F_{\psi}^{\chi_c}),\ F_{\psi\psi}^{\rm direct}=(F_{\psi}^{\rm direct})^2. \quad (3.1)$$

Using the world average values, $F_{\psi}^{\rm direct}$, $F_{\psi}^{\chi_c}$ and $F_{\psi}^{\psi'}$ are close to 60%, 30% and 10% we have $F_{\psi\psi}^{\chi_c}\simeq 50\%$, $F_{\psi\psi}^{\psi'}\simeq 20\%$ and $F_{\psi\psi}^{\rm direct}\simeq 35\%$.

If SPSs dominate, the feed-down are significantly different; one expects a larger feed-down from ψ' in the CSM. $F_{\psi\psi}^{\psi'}/F_{\psi\psi}^{\rm direct}$ is expected to be as large as 0.85. As for SPS to $\sigma(\chi_c+J/\psi)$, we have checked that it is indeed suppressed although it can be kinematically enhanced at large P_T [27] (as for $\sigma(J/\psi+\eta_c)$ [23]). $F_{\psi\psi}^{\chi_c}$ should thus be small. In turn, we also have $F_{\psi\psi}^{\psi'}\simeq 0.85/(1+0.85)\simeq 46\%$ at any order in α_s. $F_{\psi\psi}^{\rm direct}$ should also be close to 55 %. We stress that the value of $\sigma_{\rm eff}$ does not appear in Eq. (3.1).

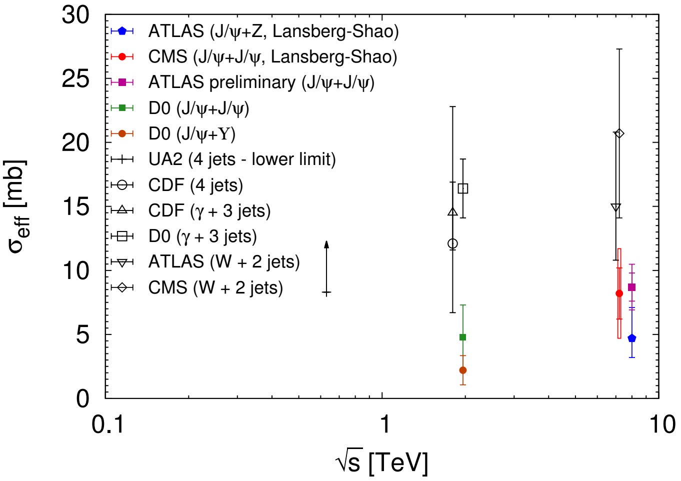

Figure 2: Our ranges for $\sigma_{\rm eff}$ extracted from the $J/\psi+Z$ data ($4.7^{+2.4}_{-1.5}$ mb) [34] and from di-J/ψ data [29] ($8.2\pm2.0\pm2.9$ mb) compared to other extractions [37, 38, 39, 40, 41, 42, 43, 5, 10].

4. Conclusion

Many recent experimental studies of associated-production of quarkonia have been lately carried out. We have reviewed one of them: J/ψ-pair production, for which we have found that DPS contributions are indispensable with a somewhat small σ_{eff} compared to jet-related observables as illustrated on Fig. 2. Yet, this value is well within the ballpark of the D0 extraction $J/\psi+\Upsilon$ production and another we have done from $J/\psi+Z$.

We have derived simple relations for the feed-down fractions from an excited charmonium state with a J/ψ in the case of the dominance of DPSs, which significantly deviate from those for SPSs. Such relations can be used to disentangle the DPS and SPS regimes.

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