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Triple Parton Scattering at the Compact Muon Solenoid experiment

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Summary. — In 2021, the CMS Collaboration observed a triple J/ψ production from the same event: the result excited large interest in Triple Parton Scattering (TPS) in proton-proton interactions. This has driven us to investigate a new charmed final state with two J/ψ and a D^* in the CMS experimental framework. The preliminary work that lays the foundation for a complete analysis will be discussed here.

1. – Introduction

Multi-Parton Interaction (MPI) identifies the class of events with simultaneous interactions between partons (quarks and gluons). MPIs stand out for the energy involved in hard and soft processes: Double Parton Scattering (DPS) and Triple Parton Scattering (TPS) belong to the former. A DPS occurs if in the same proton-proton collision two couples of partons initiate two separate hard scattering processes. The generic DPS cross section reads

$$\begin{aligned}\sigma^{DPS}_{pp\longrightarrow q\bar{q}q\bar{q}} =& \frac{m}{2!}\int \Gamma^{gg}_{p}(x_1,x_2;\vec{b_1},\vec{b_2};\mu_1^2,\mu_2^2)\times\hat{\sigma}^{gg}_{q\bar{q}}(x_1,x_1',\mu_1^2)\hat{\sigma}^{gg}_{q\bar{q}}(x_2,x_2',\mu_2^2)\\ &\times\,\Gamma^{gg}_{p}(x_1',x_2';\vec{b_1}-\vec{b},\vec{b_2}-\vec{b};\mu_1^2,\mu_2^2)\times \mathrm{d}x_1\mathrm{d}x_2\mathrm{d}x_1'\mathrm{d}x_2'\mathrm{d}^2b_1\mathrm{d}^2b_2\mathrm{d}^2b,\end{aligned} \tag{1}$$

where $\hat{\sigma}^{gg}_{q\bar{q}}(x_i,x_i',\mu_i^2)$ are the partonic cross sections for the $gg\rightarrow q\bar{q}$ mechanism, x_i, $x\prime_i$ are the longitudinal momentum fractions, μ_i are the renormalization/factorization scales, $m/2!$ is the combinatorial factor with $m=1$ or 2 depending on the multiplicity of the final state and $\Gamma^{gg}_{p}(x_1\prime,x_2\prime;\vec{b_1},\vec{b_2};\mu_1^2,\mu_2^2)$ is the double-gluon distribution function [1]. Using a factorized ansatz, the longitudinal and transverse degrees of freedom of the double gluon distribution can be considered independent and the correlations between partons can be neglected [1]. Therefore, a DPS process can be seen as two simultaneous single parton scattering (SPS) and one can write the so-called pocket formula,

$$\sigma_{DPS}^{pp\to ab} = \left(\frac{m}{2!}\right)\frac{\sigma_{SPS}^{pp\to a}\cdot\sigma_{SPS}^{pp\to b}}{\sigma_{\text{eff},DPS}}, \tag{2}$$

where m is the same combinatorial factor described above, $\sigma_{SPS}^{pp\to X}$ is the cross section for a specific final state and the $\sigma_{\text{eff},DPS}$'s role is to summarize all the unknown effects. Similarly to the DPS case, the TPS cross section, under the hypothesis illustrated below, can be simplified to the pocket formula

$$\sigma_{TPS}^{pp\to abc} = \left(\frac{n}{3!}\right)\frac{\sigma_{SPS}^{pp\to a}\cdot\sigma_{SPS}^{pp\to b}\cdot\sigma_{SPS}^{pp\to c}}{\sigma_{\text{eff},TPS}^{2}}, \tag{3}$$

where n is a combinatorial factor (1, 3 or 6), $\sigma_{SPS}^{pp\to X}$ is the cross section for a specific final state and the $\sigma_{\text{eff},TPS}$ is the sigma effective [1]. While in the DPS case the σ_{eff} can be extrapolated from the data, that is not the case for the $\sigma_{\text{eff},TPS}$. However, the $\sigma_{\text{eff},TPS}$ is closely connected to the $\sigma_{\text{eff},DPS}$ from a geometrical point of view: from existing measurements of $\sigma_{\text{eff},DPS}$ and realistic proton profiles, it is possible to derive a numerical value of $\sigma_{\text{eff},TPS}$: $\sigma_{\text{eff},TPS} = 12.5 \pm 4.5\,\text{mb}$ [2].

2. – State of art

In 2021, the CMS Collaboration published the first evidence of TPS processes in a triple J/ψ production [3], with each meson decaying in $\mu^+\mu^-$. The charmed mesons are forecasted to be the golden final states for TPS studies, [2] while the SPS is expected to be suppressed for these final states. The total integrated luminosity considered was of $133\,\text{fb}^{-1}$ at a centre of mass energy $\sqrt{s} = 13\,\text{TeV}$. Five signal events, consistent with the production via SPS ($\approx 6\%$), DPS($\approx 74\%$) and TPS($\approx 20\%$), have been found: the SPS seems to be negligible with respect to the other mechanisms, as expected. A novel value for the $\sigma_{\text{eff},DPS}$ has been extrapolated from the triple J/ψ analysis: $\sigma_{\text{eff},DPS} = 2.7^{+1.4}_{-1.0}(\text{exp})^{+1.5}_{-1.0}(\text{theo})\,\text{mb}$. From a theoretical standpoint, σ_{eff} should be constant; this, however, seems to be contradicted by experimental results (see fig. 3 in [3]). The dependence of the $\sigma_{\text{eff},DPS}$ from the process might be linked to the different parton transverse profiles and/or correlations present [3].

3. – Charmed mesons as a probe for TPS

To enlarge the cross section and increment the statistics, in principle, the triple J/ψ could be replaced with three opened charmed mesons, *i.e.*, D mesons. However, the detector's performance must be taken into account. While the CMS detector excels in muon detection, which ensures high efficiency in the J/ψ reconstruction, the D mesons identification has typically a low purity, since a proper particle ID detector is missing. The D^* mesons, among all the open charmed states, are the ones that CMS can reconstruct with the highest purity, as it can be tagged by the low energy pion in its golden decay channel: $D^{*\pm} \to D^0\pi^{\pm}_{slow}$. Taking into account all these considerations, the choice

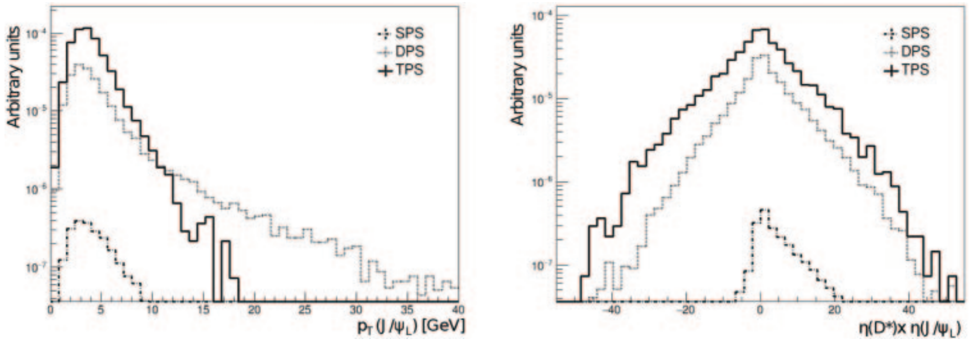

Fig. 1. – Left: the graph shows the p_T distributions for the leading J/ψ_L. Right: the graph shows the $\eta(D^*) \times \eta(J/\psi_L)$ distributions. All the contributions have been renormalized with the corresponding cross section.

of the final state fell on: $pp \to J/\psi + J/\psi + D^{*\pm} + X$, where the J/ψs decay in $\mu^+\mu^-$ and the D^* in $D^{*\pm} \to D^0\pi^{\pm}_{slow} \to K^{\mp}\pi^{\pm}\pi^{\pm}_{slow}$.

The first step of the analysis is the Monte Carlo (MC) study. Given the novelty of the to-be-simulated processes, employing an *ad hoc* procedure for the sample production required a deep knowledge of the logic behind it. We used two generators: HELAC-Onia [4, 5] for the samples production and PYTHIA 8.3 [6] for their hadronization. In addition to the TPS mechanism, also the two possible productions via DPS and SPS had to be taken into account. The cross sections for the overall reproduced processes are

$$\sigma_{SPS} = \sigma_{SPS}^{(J/\psi + J/\psi + c\bar{c} + X)}, \tag{4}$$

$$\sigma_{DPS} = \frac{\sigma_{SPS}^{(J/\psi + J/\psi + X)} \cdot \sigma_{SPS}^{(c\bar{c} + X)}}{\sigma_{\text{eff},DPS}} + \frac{1}{2}\frac{\sigma_{SPS}^{(J/\psi + c\bar{c} + X)} \cdot \sigma_{SPS}^{(J/\psi + X)}}{\sigma_{\text{eff},DPS}}, \tag{5}$$

$$\sigma_{TPS} = \frac{3}{3!}\frac{\sigma_{SPS}^{(J/\psi + X)} \cdot \sigma_{SPS}^{(J/\psi + X)} \cdot \sigma_{SPS}^{(c\bar{c} + X)}}{\sigma^2_{\text{eff},TPS}}. \tag{6}$$

The SPS cross sections have been computed by HELAC-Onia and then, using the pocket formulae (eqs. (5) and (6)), we have calculated the DPS and TPS cross sections. The following values were obtained: $\sigma_{SPS} = 0.229 \times 10^{-6}$ mb, $\sigma_{DPS} = 0.349 \times 10^{-4}$ mb and $\sigma_{TPS} = 0.549 \times 10^{-3}$ mb. The analysis of the D^* and the two J/ψ allowed us to forecast a possible set of kinematic and relationship variables useful to distinguish the different production mechanisms. From the plot on the left in fig. 1, we learn that, for the most energetic quarkonia of the two (indicated with the label L), the low-transverse momentum (p_T) region is expected to be more populated by TPS events, while the high-p_T one, by DPS events. The graph on the right in fig. 1 shows the product of the pseudorapidity $\eta_i \times \eta_j$ which can create a correlation between the mother particles: in the SPS, the correlation is the strongest, while in the TPS, according to the hypothesis, it seems to be absent. Although this is a preliminary result, it suggests that some variables will perform well as discriminators with the introduction of a neural network analysis. Given the detector acceptance, to estimate the efficiency ϵ for each mechanism we set some fiducial cuts for $|\eta| < 2.5$: $p_{T,\pi_{\text{slow}}} > 0.3\,\text{GeV}$, $p_{T,\pi} > 0.5\,\text{GeV}$, $p_{T,K} > 0.5\,\text{GeV}$, for μ_1 and μ_2, $p_T > 2.5\,\text{GeV}$ and for μ_3 and μ_4, $p_T > 1\,\text{GeV}$, where the labels 1, 2, 3 and 4 are used to indicate the muons from the most energetic to the least energetic one. Hence, given $N = \mathcal{L} \cdot \sigma \cdot \epsilon$, where $\mathcal{L}$ is the integrated luminosity of Run 2, we got: SPS contribution seems negligible (0.30 ± 0.03 events), while DPS (191 ± 16 events) should prevail over the TPS (81 ± 3 events), reproducing the same hierarchy as in [3].

4. – Summary

In this paper, we reported a preliminary study on the Triple Parton Scattering in the $J/\psi + J/\psi + D^*$ final state. This study led to some interesting observations: the hierarchy of SPS, DPS and TPS production agrees with the one in [3]. The σ_{TPS} for the final state with two J/ψ and a D^* (0.55×10^{-3} mb) is two orders of magnitude larger than σ_{TPS} for the triple J/ψ (0.06×10^{-5} mb). Finally, some of the investigated variables suggest possible discrimination between TPS and DPS. All the reasons above led us to conclude that the final state $J/\psi + J/\psi + D^*$ might be a good probe for studying the TPS with the CMS experiment using the Run 2 data and, possibly, the data from the ongoing Run 3.

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