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Observation of triple J/ψ meson production in proton-proton collisions at $\sqrt{s} = 13$ TeV

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The first observation of the three J/ψ meson production in proton-proton collisions at a center-of-mass energy of 13 TeV in final states with three $\mu^+\mu^-$ pairs is reported. The analysis is based on a data sample recorded by the CMS experiment at the CERN LHC corresponding to an integrated luminosity of $133\,\mathrm{fb}^{-1}$. The $\mathrm{pp} \to \mathrm{J}/\psi\,\mathrm{J}/\psi\,\mathrm{J}/\psi\,\mathrm{X}$ process is observed with a significance in excess of five standard deviations. The fiducial cross section for this process is found to be $\sigma(\mathrm{pp} \to \mathrm{J}/\psi\,\mathrm{J}/\psi\,\mathrm{J}/\psi\,\mathrm{X}) = 272^{+141}_{-104}(\mathrm{stat}) \pm 17(\mathrm{syst})\,\mathrm{fb}$. The result is compared to theoretical expectations for the production of three J/ψ mesons in single (SPS), double- (DPS), and triple- (TPS) parton scattering processes. Under the most economical assumption of factorization of multiple hard scattering probabilities in terms of SPS cross sections, the measured final state is found to be dominated by DPS and TPS contributions. A value of the associated DPS effective cross section parameter of $\sigma_{\mathrm{eff,DPS}} = 2.7^{+1.4}_{-1.0}(\mathrm{exp})^{+1.5}_{-1.0}(\mathrm{theo})\,\mathrm{mb}$, related to the transverse distribution of partons in the proton, is derived.

Keywords: CMS; QCD; triple parton scattering; J/ψ meson.

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1. Introduction

Thanks to the remarkable performance of the Large Hadron Collider (LHC) at CERN, a large dataset of proton-proton collisions was made available to all experiments, making the search of rare processes and decay modes possible [1–5]. Such rare processes are the simultaneous production of various particles in multiple hard scatterings which can be used to probe the generalised parton densities of the proton [6], determine the unknown energy evolution of the proton parton profile as a function of the collision impact parameter (b), and study the role of partonic correlations in the hadronic wave functions.

Ignoring parton correlations, the probability to produce two or three particles in double- (DPS) and triple- (TPS) parton scatterings is proportional to the square and cube of the corresponding single-parton-scattering (SPS) probabilities [8]. The cross section to produce two particles ψ_1 and ψ_2 in a DPS can be written as

$$\sigma_{\mathrm{DPS}}^{\mathrm{pp}\to\psi_1\,\psi_2+X} = \binom{m}{2}\,\frac{\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_1+X}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\psi_2+X}}{\sigma_{\mathrm{eff,DPS}}}, \quad (1)$$

where, m is a combinatorial factor to avoid double counting the same process, $m = 1\,(2)$ if $\psi_1 = \psi_2$ ($\psi_1 \neq \psi_2$), and $\sigma_{\mathrm{eff,DPS}}$ is the effective interaction area known as "effective cross section" [8]. Interestingly, using different final states, the $\sigma_{\mathrm{eff,DPS}}$ is found to be $\sigma_{\mathrm{eff,DPS}} \approx 3-10$ mb from J/ψJ/ψ [9–13], J/$\psi\Upsilon$ [14], and $\Upsilon\Upsilon$ [15,16] studies, and $\sigma_{\mathrm{eff,DPS}} \approx 15$mb from final states involving pairs of high-p_{T} jets and/or electroweak bosons [17–24].

Using the dataset collected in Run-2 with the CMS detector [25], the triple-J/ψ production is studied [26]. The equivalent of the equation above for this process can be written as:

$$\sigma_{\mathrm{TPS}}^{\mathrm{pp}\to\mathrm{J}/\psi_1\,\mathrm{J}/\psi_2\,\mathrm{J}/\psi_3+X} = \binom{m}{3!} \times \frac{\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\mathrm{J}/\psi_1+X}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\mathrm{J}/\psi_2+X}\,\sigma_{\mathrm{SPS}}^{\mathrm{pp}\to\mathrm{J}/\psi_3+X}}{\sigma_{\mathrm{eff,TPS}}^2}, \quad (2)$$

where $m = 1$ and the effective cross section $\sigma_{\mathrm{eff,TPS}}$ is closely related to its DPS counterpart via $\sigma_{\mathrm{eff,TPS}} = \kappa\,\sigma_{\mathrm{eff,DPS}}$ with $\kappa = 0.82 \pm 0.11$ [27]. This analysis offers a very clean experimental signature for triple-J/ψ production, including prompt and nonprompt J/ψ mesons, with all the combinations displayed in Fig. 1.

The analysis requires six muons to be reconstructed by combining information from the silicon tracker and the muon system. They are required to have $p_{\mathrm{T}} > 3.5$ GeV for $|\eta| < 1.2$ (barrel) and $p_{\mathrm{T}} > 2.5$ GeV for $1.2 < |\eta| < 2.4$ (endcap). Muons must be oppositely charged, have a dimuon invariant mass between 2.8 and 3.35 GeV, and have to originate from a common vertex with a probability greater than 0.5%. The total luminosity collected with the J/ψ+μ trigger used, amounts to 133 fb^{-1}. Monte Carlo simulations are used to determine the J/ψ acceptance and trigger efficiency. Simulated events are generated using HELAC-ONIA (v.2.6.6) [28, 29] and PYTHIA 8 (v2.05) for the hadronization and decay.

After applying the selection criteria discussed above, six triple-J/ψ events are observed. The signal is extracted with a three-dimensional unbinned extended maximum likelihood fit, in the three dimuon invariant mass $m_{\mu^+\mu^-}[1, 2, 3]$. The derived signal components are shown by the shaded areas in Fig. 2. The extracted signal yield corresponds to $N_{\mathrm{sig}}^{3\mathrm{J}/\psi} = 5.0^{+2.6}_{-1.9}$ triple-J/ψ events. The statistical significance of the signal is evaluated to be greater than $5\,\sigma$.

For the prompt and nonprompt separation of the J/ψ mesons the proper decay length variable is used, defined as $L^{\mathrm{J}/\psi} = (m/p_{\mathrm{T}}^{\mathrm{J}/\psi})\,L_{xy}^{\mathrm{J}/\psi}$, where $L_{xy} = (\vec{r_{\mathrm{T}}}\vec{p_{\mathrm{T}}}^{\,\mathrm{J}/\psi})/|p_{\mathrm{T}}^{\mathrm{J}/\psi}|$ is

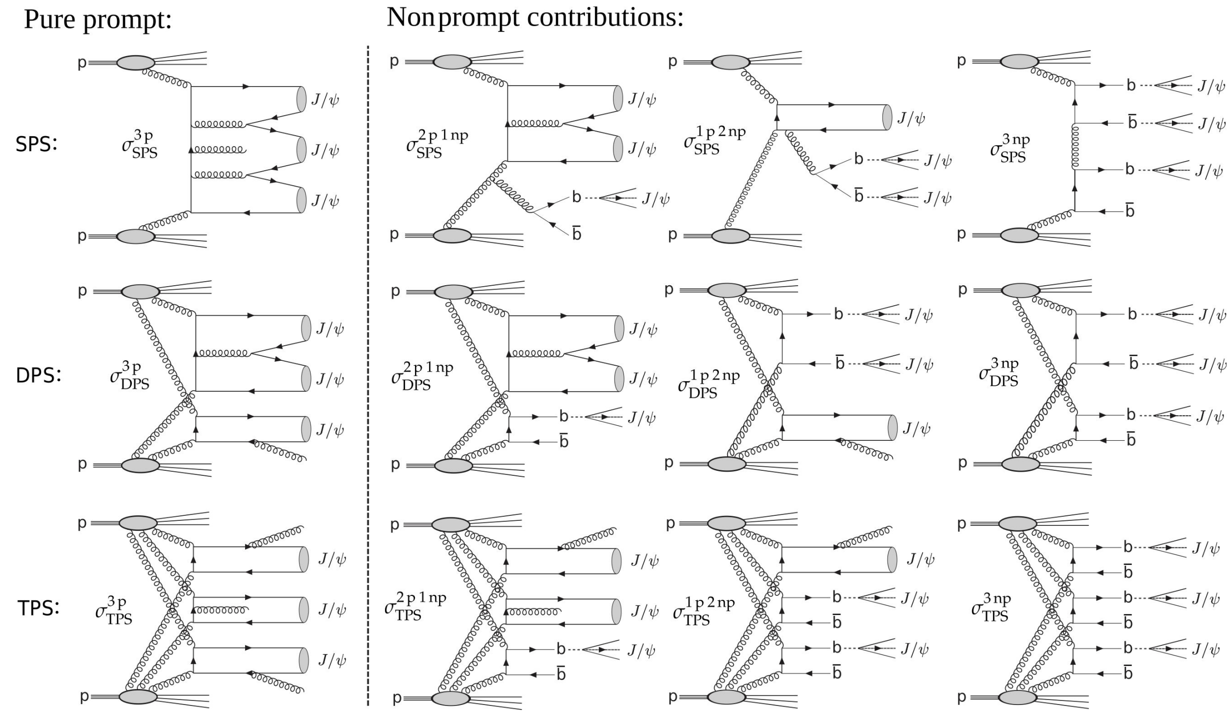

FIGURE 1. Leading-order diagrams for triple-J/ψ production in pp collisions via SPS (upper), DPS (middle), and TPS (lower) processes. The leftmost diagrams show the triple prompt-J/ψ processes. The remaining diagrams show (left to right) final states with increasing contributions of nonprompt J/ψ's from B meson decays. The symbols $\sigma^{i\mathrm{p}j\mathrm{np}}_{\mathrm{NPS}}$ identify the number (i and j) of prompt (p) and nonprompt (np) contributions to the cross section of each diagram.

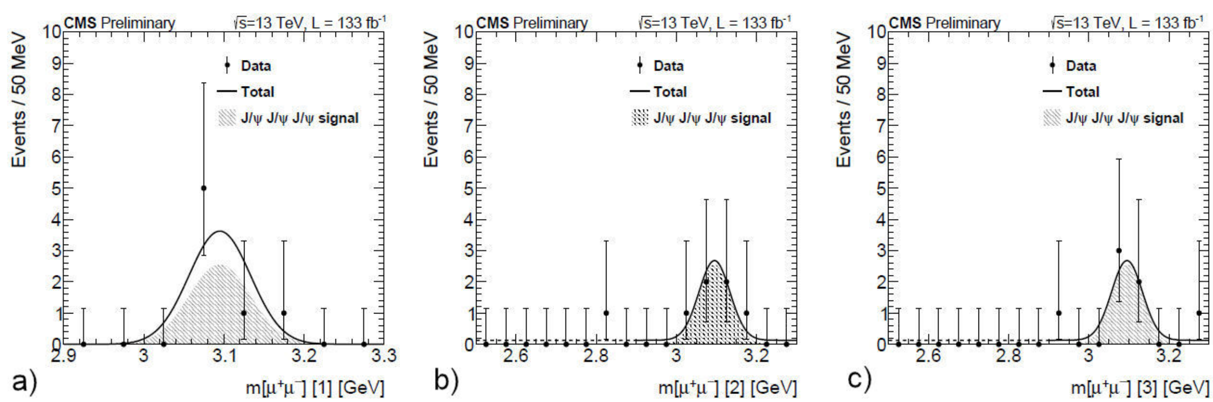

FIGURE 2. Invariant mass distributions for the three J/ψ muon pairs, ordered (left to right) by increasing transverse momentum of the $\mu^+\mu^-$ system. In each panel, the data are represented by the points, with the vertical bars showing the statistical uncertainties, and the solid curve the overall fit to the data. The shaded region corresponds to the fitted signal yield.

the transverse distance between the J/ψ vertex and the PV ($\vec{r_\mathrm{T}}$ is the transverse vector pointing along both vertices), and m and $p_\mathrm{T}^{\mathrm{J}/\psi}$ are the world-average J/ψ mass [30] and candidate transverse momentum, respectively. The five measured triple-J/ψ signal events can be classified as two events being consistent with "2 nonprompt + 1 prompt J/ψ", plus one event each with either "1 nonprompt + 2 prompt J/ψ", "3 nonprompt J/ψ", or "3 prompt J/ψ" respectively.

The fiducial cross section for triple-J/ψ production, is obtained via $\sigma(\mathrm{pp} \rightarrow \mathrm{J}/\psi\,\mathrm{J}/\psi\,\mathrm{J}/\psi\,\mathrm{X}) = N_{\mathrm{sig}}^{3\mathrm{J}/\psi}/(\epsilon\,\mathcal{L}_{\mathrm{int}}\,\mathcal{B}^3_{\mathrm{J}/\psi\rightarrow\mu^+\mu^-})$, where $N_{\mathrm{sig}}^{3\mathrm{J}/\psi}$ is the number of extracted signal events, $\mathcal{L}_{\mathrm{int}}$ the total integrated luminosity, and $\epsilon = \epsilon_{\mathrm{trig}}\,\epsilon_{\mathrm{id}}\,\epsilon_{\mathrm{reco}}$ the total efficiency composed of trigger, reconstruction, and identification components. Systematic uncertainties include the signal and background modelling, the detector's muon reconstruction and trigger efficiency and luminosity measurement uncertainty, the size of the MC sample used for the efficiency studies and the $\mathrm{J}/\psi\rightarrow\mu^+\mu^-$ branching fraction uncertainty. The total systematic uncertainty is 6.2% and the fiducial triple J/ψ cross section $\sigma(\mathrm{pp} \rightarrow \mathrm{J}/\psi\mathrm{J}/\psi\mathrm{J}/\psi\,\mathrm{X}) = 272^{+141}_{-104}(\mathrm{stat}) \pm 17(\mathrm{syst})$ fb.

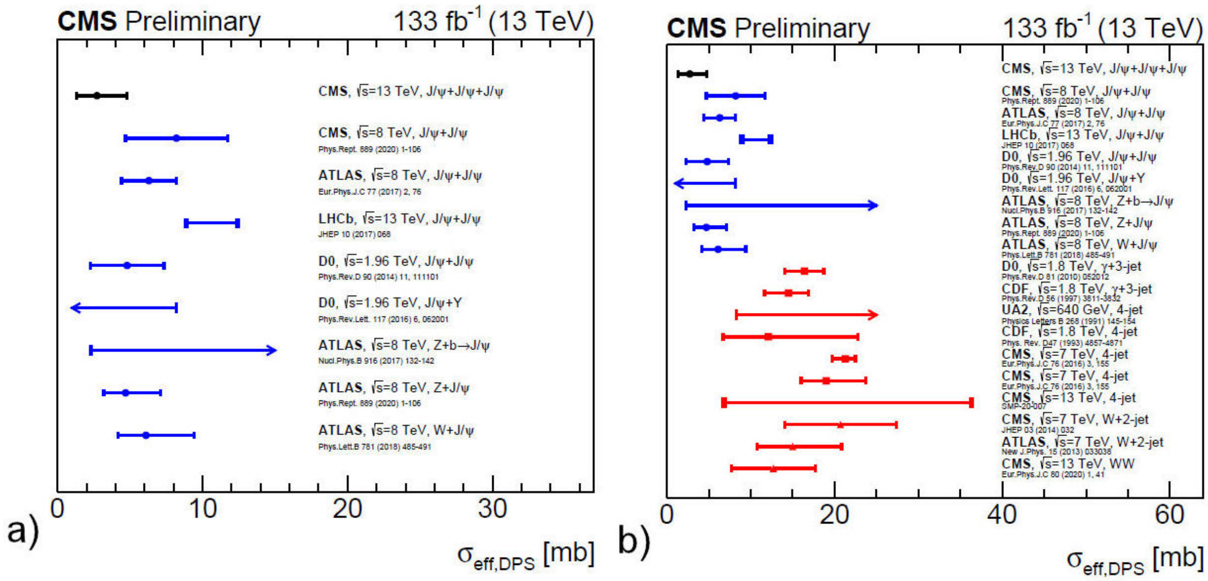

FIGURE 3. a) Comparison of the effective DPS cross sections $\sigma_{\rm eff,DPS}$ extracted in this work a) (data point in both panels) to the same parameter derived in measurements of double-quarkonium and electroweak boson plus quarkonium production alone, b) as well as also in final states with jets, $\gamma+$jets, W+jets, and same-sign W bosons.

The total triple-J/ψ cross section is expected to correspond to the sum of the contributions from the SPS, DPS, and TPS processes schematically shown in Fig. 1, each of which contains various combinations of prompt (p) and nonprompt (np) J/ψ contributions,

$$\begin{aligned}\sigma^{3{\rm J}/\psi}_{\rm tot} &= \sigma^{3{\rm J}/\psi}_{\rm SPS} + \sigma^{3{\rm J}/\psi}_{\rm DPS} + \sigma^{3{\rm J}/\psi}_{\rm TPS} \\ &= \left(\sigma^{3\,\rm p}_{\rm SPS} + \sigma^{2\rm p1np}_{\rm SPS} + \sigma^{1\rm p2np}_{\rm SPS} + \sigma^{3\,\rm np}_{\rm SPS}\right) \\ &+ \left(\sigma^{3\,\rm p}_{\rm DPS} + \sigma^{2\rm p1np}_{\rm DPS} + \sigma^{1\rm p2np}_{\rm DPS} + \sigma^{3\,\rm np}_{\rm DPS}\right) \\ &+ \left(\sigma^{3\,\rm p}_{\rm TPS} + \sigma^{2\rm p1np}_{\rm TPS} + \sigma^{1\rm p2np}_{\rm TPS} + \sigma^{3\,\rm np}_{\rm TPS}\right). \qquad (3)\end{aligned}$$

The DPS and TPS contributions to triple-J/ψ production (last row of Eq. (3)) can be written through Eqs. (1) and (2) as a combination of products of single- and double-J/ψ SPS cross sections as follows,

$$\begin{aligned}\sigma^{3{\rm J}/\psi}_{\rm dps+tps} &= m_0\left(\sigma^{3{\rm J}/\psi}_{\rm dps}\right) = m_1\Big(\sigma^{2\rm p}_{\rm SPS}\sigma^{1\rm p}_{\rm SPS} + \sigma^{2\rm p}_{\rm SPS}\sigma^{1\rm np}_{\rm SPS} \\ &+ \sigma^{1\rm p}_{\rm SPS}\sigma^{1\rm p1np}_{\rm SPS} + \sigma^{1\rm p1np}_{\rm SPS}\sigma^{1\rm np}_{\rm SPS} + \sigma^{1\rm p}_{\rm SPS}\sigma^{2\rm np}_{\rm SPS} \\ &+ \sigma^{2\rm np}_{\rm SPS}\sigma^{1\rm np}_{\rm SPS}\Big)/\sigma_{\rm eff,DPS}, \\ \sigma^{3{\rm J}/\psi}_{\rm tps} &= m_3\Big(\left[\sigma^{1\rm p}_{\rm SPS}\right]^3 + \left[\sigma^{1\rm np}_{\rm SPS}\right]^3\Big) \\ &+ m_2\left(\left[\sigma^{1\rm p}_{\rm SPS}\right]^2\sigma^{1\rm np}_{\rm SPS} + \sigma^{1\rm p}_{\rm SPS}\left[\sigma^{1\rm np}_{\rm SPS}\right]^2\right)\Big/\sigma^2_{\rm eff,TPS}, \quad (4)\end{aligned}$$

with combinatorial prefactors $m_1 = 2/2 = 1, m_2 = 3/3! = 1/2$, and $m_3 = 1/3! = 1/6$. Therefore, from the eight individual SPS cross sections for single-, double-, and triple-J/ψ cross sections one can determine the total 3-J/ψ production cross section via Eqs. (3) and (4). Obtaining values of the SPS single, double and triple prompt-J/ψ and nonprompt cross sections and using the Eq. (4) the value $\sigma_{\rm eff,DPS} = 2.7^{+1.4}_{-1.0}({\rm exp})^{+1.5}_{-1.0}({\rm theo})$ mb is derived.

In Fig. 3, the $\sigma_{\rm eff,DPS}$ value extracted in this work is compared to the world-data of effective DPS cross sections derived from double-quarkonium and electroweak boson plus quarkonium production measurements (top), as well as also from processes with jets, photons, and W bosons (bottom).

The first observation of the concurrent production of three J/ψ mesons in pp collisions is reported. The fiducial triple J/ψ cross section is measured to be $\sigma({\rm pp} \rightarrow {\rm J}/\psi{\rm J}/\psi{\rm J}/\psi\,{\rm X}) = 272^{+141}_{-104}({\rm stat}) \pm 17({\rm syst})$ fb and the DPS effective cross section $\sigma_{\rm eff,DPS} = 2.7^{+1.4}_{-1.0}({\rm exp})^{+1.5}_{-1.0}({\rm theo})$ mb is derived.

1. CMS Collaboration, Observation of a new excited beauty strange baryon decaying to $\Xi_b^- \pi^+ \pi^-$, *Phys. Rev. Lett.*, **126** (2021) 252003, https://doi.org/10.1103/PhysRevLett.126.252003.
2. CMS Collaboration, Measurement of properties of $B_s^0 \to \mu^+\mu^-$ decays and search for $B^0 \to \mu^+\mu^-$ with the CMS experiment, *JHEP* **2020** (2020) 188, https://doi.org/10.1007/JHEP04(2020)188.
3. CMS Collaboration, Observation of the $B_s^0 \to$X(3872)ϕ decay, *Phys. Rev. Lett.* **125** (2020) 152001, https://doi.org/10.1103/PhysRevLett.125.152001.
4. CMS Collaboration, Observation of Two Excited B_c^+ States and Measurement of the B_c^+(2S) Mass in pp Collisions at $\sqrt{s}$ = 13 TeV, *Phys. Rev. Lett.* **122** (2019) 132001, https://doi.org/10.1103/PhysRevLett.122.132001.
5. CMS Collaboration, Observation of the Z$\to \psi\ell^+\ell^-$ decay in pp collisions at $\sqrt{s}$ = 13 TeV, *Phys. Rev. Lett.* **121** (2018) 141801, https://doi.org/10.1103/PhysRevLett.121.141801.
6. M. Diehl, and D. Ostermeier, and A. Schafer, Elements of a theory for multiparton interactions in QCD, *JHEP* **03** (2012) 089, https://doi.org/10.1007/JHEP03(2012)089.
7. P. Bartalini, and J. R. Gaunt, Multiple Parton Interactions at the LHC, (WSP, **vol. 29**, Singapore, 2019).
8. D. d'Enterria, and A. Snigirev, Double, triple, and n-parton scatterings in high-energy proton and nuclear collisions, *Adv. Ser. Direct. High Energy Phys.* **29** (2018) 159. https://doi.org/10.1142/97898132277670009.
9. LHCb Collaboration, Observation of J/ψ pair production in pp collisions at $\sqrt{s}$ = 7 TeV, *Phys. Lett. B* **707** (2012) 52, https://doi.org/10.1016/j.physletb.2011.12.015.
10. D0 Collaboration, Observation and Studies of Double J/ψ Production at the Tevatron, *Phys. Rev. D* **90** (2014) 111101, https://doi.org/10.1103/PhysRevD.90.111101.
11. CMS Collaboration, Measurement of prompt J/ψ pair production in pp collisions at $\sqrt{s}$ = 7 TeV *JHEP* **2014** (2014) 094, https://doi.org/10.1007/JHEP09(2014)094.
12. ATLAS Collaboration, Measurement of the prompt J/ψ pair production cross-section in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Eur. Phys. J. C* **77** (2017) 76, https://doi.org/10.1140/epjc/s10052-017-4644-9.
13. LHCb Collaboration, Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s}$ = 13 TeV, *JHEP* **06** (2017) 047, https://doi.org/10.1007/JHEP06(2017)047.
14. D0 Collaboration, Evidence for simultaneous production of J/ψ and Υ mesons, *Phys. Rev. Lett.* **116** (2016) 082002, https://doi.org/10.1103/PhysRevLett.116.082002.
15. CMS Collaboration, Observation of Υ(1S) pair production in proton-proton collisions at $\sqrt{s} = 8$ TeV, *JHEP* **05** (2017) 013, https://doi.org/10.1007/JHEP05(2017)013.
16. CMS Collaboration, Measurement of the Υ(1S) pair production cross section and search for resonances decaying to Υ(1S)$\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s}$ = 13 TeV, *Phys. Lett. B* **808** (2020) 135578, https://doi.org/10.1016/j.physletb.2020.135578.
17. ATLAS Collaboration, Measurement of hard double-parton interactions in W($\to l\nu$)+ 2 jet events at $\sqrt{s}$ = 7 TeV with the ATLAS detector, *New J. Phys.* **15** (2013) 033038, https://doi.org/10.1088/1367-2630/15/3/033038.
18. CMS Collaboration, Study of Double Parton Scattering Using W + 2-Jet Events in Proton-Proton Collisions at $\sqrt{s}$ = 7 TeV, arXiv:1312.5729, *JHEP* **03** (2014) 032, https://doi.org/10.1007/JHEP03(2014)032.
19. ATLAS Collaboration, Study of hard double-parton scattering in four-jet events in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS experiment, *JHEP* **11** (2016) 110, https://doi.org/10.1007/JHEP11(2016)110.
20. CMS Collaboration, Constraints on the double-parton scattering cross section from same-sign W boson pair production in proton-proton collisions at $\sqrt{s} = 8$ TeV, *JHEP* **02** (2018) 032, https://doi.org/10.1007/JHEP02(2018)032.
21. ATLAS Collaboration, Study of the hard double-parton scattering contribution to inclusive four-lepton production in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector, *Phys. Lett. B* **790** (2019) 595, https://doi.org/10.1016/j.physletb.2019.01.062.
22. CMS Collaboration, Evidence for WW production from double-parton interactions in proton-proton collisions at $\sqrt{s}$ = 13 TeV, *Eur. Phys. J. C* **80** (2020) 41, https://doi.org/10.1140/epjc/s10052-019-7541-6.
23. CMS Collaboration, Measurement of double-parton scattering in inclusive production of four jets with low transverse momentum in proton-proton collisions at $\sqrt{s}$ = 13 TeV, arXiv:2109.13822.
24. ATLAS Collaboration, Observation and measurements of the production of prompt and non-prompt J/ψ mesons in association with a Z boson in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector, *Eur. Phys. J. C* **75** (2015) 229. https://doi.org/10.1140/epjc/s10052-015-3406-9.
25. CMS Collaboration, The CMS experiment at the CERN LHC, *JINST* **3** (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.
26. CMS Collaboration, Observation of triple J/ψ meson production in proton-proton collisions at $\sqrt{s}$ = 13 TeV, CMS-PAS-BPH-21-004, 2021, arXiv:2111.05370[hep-ex].
27. D. d'Enterria, and A. M. Snigirev, Triple parton scatterings in high-energy proton-proton collisions, *Phys. Rev. Lett.* **118** (2017) 122001, https://doi.org/10.1103/PhysRevLett.118.122001.
28. H.-S. Shao, HELAC-Onia: An automatic matrix element generator for heavy quarkonium physics, *Comput. Phys. Commun.* **184** (2013) 2562, https://doi.org/10.1016/j.cpc.2013.05.023.
29. H.-S. Shao, HELAC-Onia 2.0: an upgraded matrix-element and event generator for heavy quarkonium physics, arXiv:1507.03435, *Comput. Phys. Commun.* **198** (2016) 238. https://doi.org/10.1016/j.cpc.2015.09.011.
30. Particle Data Group, Review of Particle Physics, *Phys. Rev. D* **98** (2018) 030001, https://doi.org/10.1103/PhysRevD.98.030001.