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

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## Abstract

The first observation of the simultaneous production of three  $J/\psi$  mesons in proton-proton (pp) collisions is presented, based on a data sample collected by the CMS experiment at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of  $133 \text{ fb}^{-1}$ . The  $pp \rightarrow J/\psi J/\psi J/\psi X$  process is observed with a significance above five standard deviations in final states with three  $\mu^+ \mu^-$  pairs. The measured inclusive fiducial cross section of  $\sigma(pp \rightarrow J/\psi J/\psi J/\psi X) = 272_{-104}^{+141} \text{ (stat)} \pm 17 \text{ (syst)} \text{ fb}$  is compared to theoretical expectations for the production of three  $J/\psi$  mesons in single- (SPS), double- (DPS), and triple- (TPS) parton scatterings. Assuming factorization of multiple hard-scattering probabilities in terms of SPS cross sections, the measured process is found to be dominated by DPS and TPS contributions, and an effective DPS cross section, related to the transverse distribution of partons in the proton, of  $\sigma_{\text{eff,DPS}} = 2.7_{-1.0}^{+1.4} \text{ (exp)}_{-1.0}^{+1.5} \text{ (theo)} \text{ mb}$  is determined.

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## Introduction

High-energy particle accelerators are unique tools to study the structure of matter at the shortest distances. The most powerful accelerator today is the CERN Large Hadron Collider (LHC) that has so far collided beams of protons with energies of up to 6.5 TeV, resulting in center-of-mass energies of up to 13 TeV. Protons are used in energy-frontier colliders because they are relatively easy to accelerate and keep in a circular orbit to enable high collision rates. However, protons are not fundamental particles and, in fact, have a complicated quantum mechanical structure. In the modern picture known as the parton model [1], individual “parts” of the two protons undergo a hard scattering with one another, with the remainders of each proton only slightly disturbed in the process. Protons consist of three quarks, two up-type and one down-type, and gluons, which hold together the three valence quarks, as well as of a “sea” of virtual quark-antiquark pairs, which are fundamental elements of the quantum vacuum. All these components are referred to as “partons”. As the energy of the colliding protons increases, the collisions probe shorter and shorter distances within the proton, and the density of gluons and sea quarks grows rapidly. Thus, at high enough energies, more than one pair of partons can undergo a hard scattering in a single proton-proton (pp) collision, leading to the simultaneous and independent production of two or more particles with large transverse momentum ( $p_T$ ) and/or mass ( $m$ ), above a few GeV. Double-parton scatterings (DPS) were first observed at the CERN Intersecting Storage Rings some 35 years ago [2, 3] and have been a subject of intense theoretical and experimental investigations ever since [4]. Numerous DPS processes have been studied in measurements with many combinations of pairs of heavy and/or high- $p_T$  produced particles [4]. Triple-parton scatterings (TPS), where three hard parton interactions take place simultaneously, have only been proposed for study recently [5] and have not been experimentally explored yet.

Studies of  $n$ -parton scattering (NPS) processes are important to elucidate the complicated inner structure of the proton and its evolution with energy [6, 7]. Many of these features, e.g., the parton density profile in the plane transverse to the colliding beams, as well as the various correlations (in position, momentum, flavor, color, spin, etc.) between individual partons, are very difficult to calculate theoretically, and can only be mapped out through experimental studies of NPS in different systems and for different numbers  $n$  of simultaneous scatterings [4]. Measurements of such processes not only allow for a deeper understanding of the proton structure, but are also of relevance at the LHC to predict backgrounds in rare standard model processes, and in searches for new physics, in final states where multiple heavy particles are produced [8, 9]. The first study of TPS via triple- $J/\psi$  production, which is the subject of this article, provides novel input for further theoretical and experimental progress in understanding the NPS dynamics. This work is also the first experimental study of the simultaneous production of three particles in NPS, and the first observation of triple  $J/\psi$  meson production, making it an important step in a half-a-century old quest towards understanding the proton structure.

In the simplest approach, ignoring any correlations between the individual partons, the probability to produce  $n$  high- $p_T$  particles in a given pp collision must be proportional to the  $n^{\text{th}}$ -product of probabilities to independently produce each of them. Thus, the probability to produce two or three high- $p_T$  particles in DPS and TPS scales with the square and cube, respectively, of the corresponding single-parton scattering (SPS) probabilities [10]. The occurrence of DPS and TPS processes is therefore more likely for final states with large SPS cross sections, such as quarkonia states (e.g.,  $J/\psi$  and  $Y$  mesons), than for rarer heavier particles such as, e.g., electroweak (EW) bosons [11]. In the DPS case, the cross section to produce, e.g., two charmonium mesons  $\psi_1$  and  $\psi_2$  can be written as the product of the SPS cross sections for the production of each individual meson divided by an effective cross section to warrant the proper units

of the final result,

$$\sigma_{\text{DPS}}^{\text{pp} \rightarrow \psi_1 \psi_2 + X} = \left( \frac{m}{2} \right) \frac{\sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_1 + X} \sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_2 + X}}{\sigma_{\text{eff,DPS}}}. \quad (1)$$

Here,  $m$  is a combinatorial factor to avoid double counting,  $m = 1$  ( $2$ ) if  $\psi_1 = \psi_2$  ( $\psi_1 \neq \psi_2$ ), and  $\sigma_{\text{eff,DPS}}$  is an effective cross section that, in a purely geometric approach, can be determined from the pp transverse overlap [10]. A *smaller* value of  $\sigma_{\text{eff,DPS}}$ , which is proportional to the average (squared) transverse separation of the partons participating in the two hard scatterings, implies *larger* DPS yields.

For the proton form factors typically implemented in the PYTHIA 8 [12] and HERWIG++ [13] event generators commonly used in collider physics, values of  $\sigma_{\text{eff,DPS}} \approx 20\text{--}30$  mb are expected. Such estimates are, however, about a factor of two larger than those experimentally derived via the ratio  $\sigma_{\text{eff,DPS}} = (\sigma_{\text{SPS}}^{\text{pp} \rightarrow X_1} \sigma_{\text{SPS}}^{\text{pp} \rightarrow X_2}) / \sigma_{\text{DPS}}^{\text{pp} \rightarrow X_1 X_2}$  for processes involving pairs of high- $p_T$  jets and/or EW bosons, which are found to lie in the range  $\sigma_{\text{eff,DPS}} \approx 10\text{--}20$  mb [14–20]. This discrepancy has been mostly explained as evidence of parton correlations in the collision not accounted for in the purely geometrical approaches [21]. In addition, significantly lower  $\sigma_{\text{eff,DPS}} \approx 3\text{--}10$  mb values have been extracted from measurements of quarkonium pair production ( $J/\psi J/\psi$  [22–26],  $J/\psi Y$  [27], and  $YY$  [9, 28]) that have been interpreted as due to the different dominant species (mostly gluons for quarkonia, and quarks for EW bosons) in the parton distribution functions (PDFs) probed in the different scatterings [4], but can be also attributed in some cases to poorly controlled subtractions of SPS contributions [11].

The study of TPS via triple- $J/\psi$  production can help solve all the issues mentioned above. The equivalent of Eq. (1) for the production of three charmonium mesons in a TPS process reads

$$\sigma_{\text{TPS}}^{\text{pp} \rightarrow \psi_1 \psi_2 \psi_3 + X} = \left( \frac{m}{3!} \right) \frac{\sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_1 + X} \sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_2 + X} \sigma_{\text{SPS}}^{\text{pp} \rightarrow \psi_3 + X}}{\sigma_{\text{eff,TPS}}^2}, \quad (2)$$

where  $m = 1, 3$ , or  $6$  (depending on whether all three, two, or none of the  $\psi_i$  states are identical), and the effective cross section  $\sigma_{\text{eff,TPS}}$  is closely related to its DPS counterpart via  $\sigma_{\text{eff,TPS}} = \kappa \sigma_{\text{eff,DPS}}$ , with  $\kappa$  of order unity. In the absence of parton correlations, a value of  $\kappa = 0.82 \pm 0.11$  has been derived in [5] for a variety of proton transverse parton profiles. A theoretical study of the production of three prompt- $J/\psi$  mesons [29], based on the nonrelativistic quantum chromodynamics (NRQCD) approach at leading-order (LO) accuracy as implemented in the HELAC-ONIA code [30, 31], has demonstrated that the pure SPS contributions are negligible compared to those from DPS and TPS. Namely, the upper left diagram of Fig. 1 is irrelevant compared to the two other diagrams in the left column of the figure. The experimental measurement of  $\text{pp} \rightarrow J/\psi J/\psi J/\psi X$  is thus a golden channel for the study of TPS and, in addition, provides an alternative extraction of  $\sigma_{\text{eff,DPS}}$ , thereby shedding new light into the underlying dynamics of hard NPS. The production of  $J/\psi$  states can also proceed nonpromptly through the decay of a beauty-quark ( $b$ ) hadron. Notwithstanding a small branching fraction,  $\mathcal{B}_{b \rightarrow J/\psi X} \approx 1\%$  [32], the cross section to produce  $b\bar{b}$  pairs is large at the LHC,  $\sigma(\text{pp} \rightarrow b\bar{b} X) \approx 0.5$  mb [5]. The contributions of such processes to inclusive triple- $J/\psi$  production are schematically shown in Fig. 1 (diagrams to the right of the vertical dashed line).

This Letter presents the first observation of the simultaneous production of three  $J/\psi$  mesons in pp collisions. The analysis is based on a data sample collected at  $\sqrt{s} = 13$  TeV by the CMS experiment, corresponding to an integrated luminosity of  $133 \text{ fb}^{-1}$ . The  $J/\psi$  mesons are reconstructed in their dimuon decay mode over a fiducial phase space in transverse momenta and (pseudo)rapidities ( $p_T^{\mu, J/\psi}$ ,  $|\eta^\mu|$ , and  $|y^{J/\psi}|$ ) defined to maximize the signal purity and the detec-

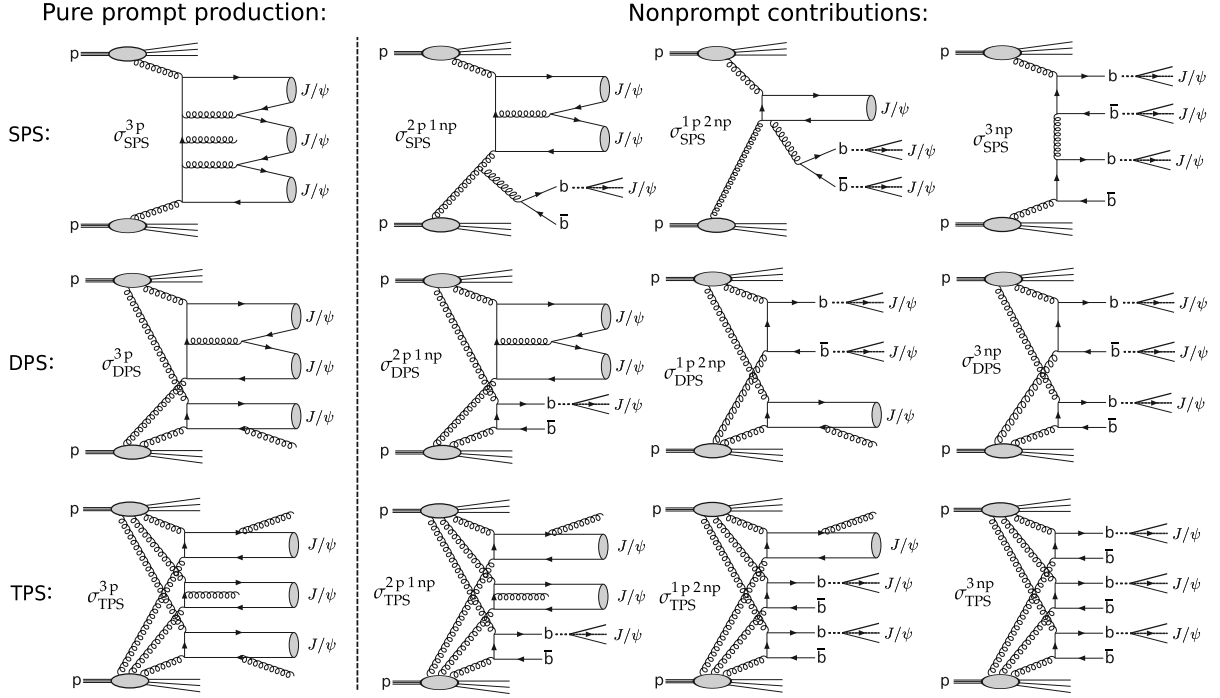


Figure 1: Leading-order diagrams for inclusive triple- $J/\psi$  production in  $pp$  collisions via SPS (upper), DPS (middle), and TPS (lower) processes. The leftmost diagrams show triple prompt- $J/\psi$  processes. The remaining diagrams show (left to right) final states with increasing contributions of nonprompt  $J/\psi$  mesons from beauty hadron decays. The symbols  $\sigma_{NPS}^{ipjnp}$  identify the number ( $i$  and  $j$ ) of prompt (p) and nonprompt (np) contributions to the cross section of each diagram.

tor acceptance and efficiency. The analysis of the  $6\mu$  final state offers a very clean experimental signature for inclusive triple- $J/\psi$  production, comprising prompt and nonprompt components.

## Experimental setup

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the  $\eta$  coverage provided by the barrel and endcap detectors. Muons are measured over the range  $|\eta| < 2.4$  in gas-ionization detectors, embedded in the steel flux-return yoke outside the solenoid, made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. A more detailed description of the CMS detector can be found in Ref. [33].

Events of interest are selected using a two-tiered trigger system. The first trigger level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz with a fixed latency of about  $4\ \mu\text{s}$  [34]. The second level (or high-level trigger, HLT) consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [35]. The present analysis employs an HLT that requires three muons, each having  $p_T > 3.5\ \text{GeV}$  for  $|\eta| < 1.2$  (barrel) or  $p_T > 2.5\ \text{GeV}$  for  $1.2 < |\eta| < 2.4$  (endcap). In addition, the event must have at least one pair of oppositely charged muons with invariant mass between 2.80 and 3.35 GeV that originate from a common vertex with a

probability greater than 0.5%, as determined by a Kalman vertex fit [36], thus suppressing random combinations of muons from unrelated sources. Monte Carlo (MC) simulations are used to determine the trigger efficiency. Simulated events are generated using HELAC-ONIA (v.2.6.6) with the NNPDF3.0 PDF set [37], and PYTHIA 8.205 for the hadronization and decay with the CUETP8M1 underlying event tune [38]. Triple- $J/\psi$  events are simulated by combining events with single and double prompt- $J/\psi$  meson production following Ref. [29]. The generated events are then processed through a detailed GEANT4 simulation [39] of the CMS detector response.

## Event reconstruction and selection

Muons are reconstructed by combining information from the silicon tracker and the muon system [40]. The matching between tracks reconstructed in each of the subsystems proceeds either outside-in, starting from a track in the muon system, or inside-out, starting from a track provided by the silicon tracker. Matching muons to tracks measured in the silicon tracker leads to a relative  $p_T$  resolution of 1% in the barrel and 3% in the endcaps for muons with  $p_T$  up to 100 GeV [40]. The candidate vertex with the largest value of summed physics-object  $p_T^2$  in the event is taken to be the primary pp interaction vertex (PV) [41].

The offline data analysis starts by selecting events with six or more reconstructed muons, each passing the  $p_T$  and  $\eta$  criteria implemented at the HLT. The muons are combined into opposite-sign (OS) pairs, and are considered for further study if their invariant mass is  $2.9 < m_{\mu^+\mu^-} < 3.3$  GeV (corresponding to about  $\pm 7$  times the  $J/\psi$  mass resolution discussed below) and originate from a common vertex with a probability greater than 0.5%. All selected muon pairs are further required to share the same PV (including the possibility that they originate from secondary vertices associated to a common PV) to eliminate accidental combinations of muons from different pp collisions in the same or neighboring bunch crossings. The analysis thereby includes prompt- $J/\psi$  mesons coming directly from the pp interaction (or from feed-down decays of promptly produced and decayed resonances), and nonprompt ones coming from the decays of beauty hadrons. In order to ensure high purity and reconstruction efficiency, the  $J/\psi$  candidates are required to have  $p_T > 6$  GeV and  $|\eta| < 2.4$ .

After applying the selection criteria discussed above, six triple- $J/\psi$  events are observed. No alternative pairings among the OS muons in these six events are found to satisfy the analysis requirements. In all events, the  $J/\psi$  meson with highest  $p_T$  (“leading”  $J/\psi$ ) is found to correspond to the muon pair that passed the online trigger selection. In inclusive  $J/\psi$  measurements [24, 42–45], a continuum background is present in the  $m_{\mu^+\mu^-}$  distribution due to random combinations of OS muons originating from semileptonic beauty- and charm-quark hadron decays,  $b \rightarrow \mu + X$  and  $c \rightarrow \mu + X$ , and Drell–Yan events, which pass the trigger and data analysis criteria. To monitor the sideband background population, the mass windows corresponding to the two subleading  $J/\psi$  mesons are extended well below the  $J/\psi$  mass region. The corresponding dimuon invariant mass distributions are shown in Fig. 2 ordered (left to right) by decreasing  $p_T$  of the  $\mu^+\mu^-$  system. Only one additional background event is found in the extended mass region indicated by the dotted curves, confirming that the combinatorial continuum is suppressed by the requirement of having three reconstructed  $J/\psi$  candidates in the same event.

## Cross section measurement

The signal yield is extracted with a three-dimensional unbinned extended maximum likelihood fit of the  $m_{\mu^+\mu^-}$  distributions of all  $J/\psi$  candidates in the event over the  $2.9 < m_{\mu^+\mu^-} < 3.3$  GeV range. The expected  $J/\psi$  mass peaks are modeled with a Gaussian function with mean fixed to their nominal value ( $m^{J/\psi} = 3.097$  GeV) [32] and the root-mean-square (RMS) width fixed to the resolution derived from the MC simulation ( $\sigma_m \approx 30$  MeV). Given the very low number of events passing the selection, the mass mean and RMS width of the  $J/\psi$  mesons cannot be left as free parameters in the fit. The dimuon background is described with an exponential function [24, 42–45]. The fit has eight free parameters for the yields given by the combination of each of the three  $J/\psi$  candidates as being either signal or background. The extracted signal yield (red shaded areas in the  $m_{\mu^+\mu^-}$  distributions of Fig. 2) corresponds to  $N_{\text{sig}}^{3J/\psi} = 5.0_{-1.9}^{+2.6}$  triple- $J/\psi$  events, with  $1.0_{-0.8}^{+1.4}$  background events. The statistical significance of the signal is evaluated using various methods. From the likelihood ratio of two fits (background-only imposing  $N_{\text{sig}}^{3J/\psi} = 0$ , and the default signal-plus-background), with the standard asymptotic formula [46] assuming that the conditions to apply Wilks' theorem [47] are satisfied, a significance of 6.7 standard deviations (std. dev.) is obtained. The significance derived assuming a Poisson counting experiment yields 5.8 std. dev., and it is found to be above 5.5 std. dev. by using MC pseudoexperiments.

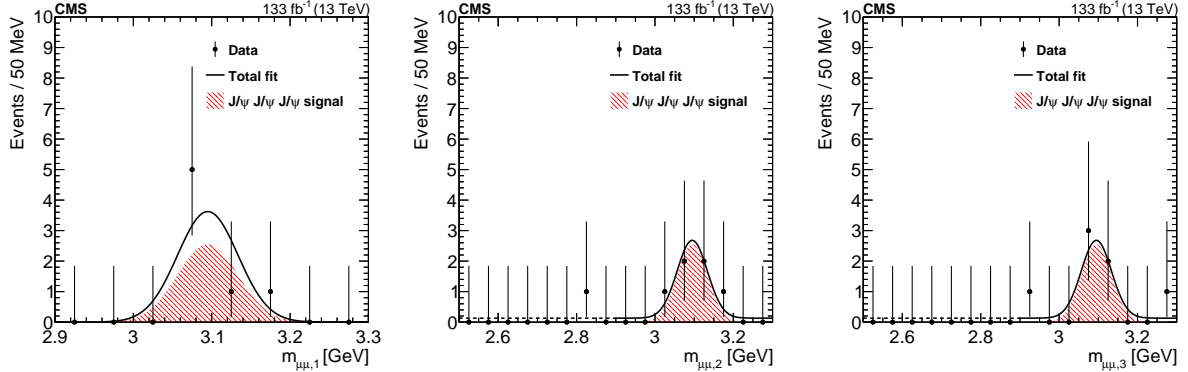


Figure 2: Invariant mass distributions for the three  $\mu^+\mu^-$  pairs, ordered (left to right) by decreasing pair  $p_T$ , in the selected events. The data are represented by the points with the vertical bars showing the (Poisson) statistical uncertainties. The solid (dotted) curve shows the overall fit to the data (in the extended mass range), and the red shaded area the fitted signal yield.

To cross-check the size of the combinatorial background derived from the fit, two tests are carried out. First, the fit is repeated over the extended dimuon mass range [2.5–3.3] GeV for the two subleading  $J/\psi$  mesons (dotted curves in Fig. 2). This mass range corresponds to an asymmetric window of about  $[-20\sigma_m, +7\sigma_m]$  around the  $J/\psi$  nominal mass that, as aforementioned, covers lower dimuon masses where the background, if any, should be larger. The obtained signal yield is fully consistent with the default result. A second test is performed whereby the OS requirement is removed to allow also for same-sign dimuon combinations ( $\mu^\pm\mu^\pm$ ) for the two subleading pairs. After applying the rest of the selection criteria of the default analysis, no triplet events containing same-sign muon pairs are observed.

In order to estimate the average prompt and nonprompt contributions in the triple- $J/\psi$  events, the proper decay-length of each  $J/\psi$  is calculated as  $L^{J/\psi} = (m^{J/\psi} / p_T^{J/\psi}) L_{xy}^{J/\psi}$ , where  $L_{xy}^{J/\psi} = (\vec{r} \cdot \vec{p}_T^{J/\psi}) / |p_T^{J/\psi}|$  is the transverse distance between the  $J/\psi$  decay vertex and the PV ( $\vec{r}$  is the vector from the PV to the  $J/\psi$  vertex). Prompt  $J/\psi$  mesons are defined as those having  $L^{J/\psi} < 60$   $\mu\text{m}$ .

A signal-only subset of events is defined based on all  $J/\psi$  candidates found in a narrower invariant mass region, within  $\pm 3$  std. dev. around  $m^{J/\psi}$ , than that used in the default signal extraction. In this range, five triple- $J/\psi$  events are found that can be classified as two events being consistent with the “2 nonprompt + 1 prompt  $J/\psi$ ” hypothesis, and one event each in the “1 nonprompt + 2 prompt  $J/\psi$ ”, “3 nonprompt  $J/\psi$ ”, and “3 prompt  $J/\psi$ ” categories. Such a classification is confirmed with a second method where prompt and nonprompt weights are extracted with the SPLOT technique [48], exploiting an unbinned maximum likelihood fit of the  $L^{J/\psi}$  distributions.

Detailed information of the kinematic properties of the  $J/\psi$  candidates passing the triple- $J/\psi$  selection criteria are shown in Table 1. The kinematic distributions of all six  $J/\psi$  triplets do not show any local peak, which could be indicative of, e.g., a resonance decaying into three  $J/\psi$  mesons, but are distributed featureless over triple- $J/\psi$  mass,  $p_T$ , and  $\eta$ .

Table 1: Dimuon invariant mass, proper decay-length, transverse momentum, rapidity, and azimuthal angle of each of the three  $J/\psi$  candidates measured in the six triple- $J/\psi$  events passing our selection criteria.

Event	$m^{J/\psi,1}$ (GeV)	$m^{J/\psi,2}$ (GeV)	$m^{J/\psi,3}$ (GeV)	$L^{J/\psi,1}$ (mm)	$L^{J/\psi,2}$ (mm)	$L^{J/\psi,3}$ (mm)
1	3.08	3.10	3.07	1.77	0.24	-0.01
2	3.15	3.06	3.09	0.05	0.36	0.02
3	3.10	3.14	3.11	-0.04	0.03	0.05
4	3.07	3.03	3.09	0.48	0.81	0.82
5	3.12	3.14	3.14	-0.25	0.13	-0.02
6	3.06	3.17	2.94	0.11	0.38	0.61

Event	$p_T^{J/\psi,1}$ (GeV)	$p_T^{J/\psi,2}$ (GeV)	$p_T^{J/\psi,3}$ (GeV)	$y^{J/\psi,1}$	$y^{J/\psi,2}$	$y^{J/\psi,3}$
1	17.64	17.50	8.68	-2.25	-0.39	1.53
2	91.50	54.04	11.81	1.99	0.81	-0.71
3	11.29	10.29	6.98	-0.50	-0.37	-1.64
4	15.46	10.61	7.84	-0.83	-2.24	-1.78
5	8.67	7.71	6.75	2.03	-1.14	-1.87
6	60.70	19.09	17.03	1.59	2.29	1.58

Event	$\phi^{J/\psi,1}$	$\phi^{J/\psi,2}$	$\phi^{J/\psi,3}$
1	-1.98	2.06	-1.56
2	2.60	-2.14	-0.38
3	-0.87	-1.50	0.66
4	1.00	-2.07	-1.77
5	-1.77	1.99	2.91
6	-1.98	-1.74	-2.17

The cross section for inclusive triple- $J/\psi$  production measured in the fiducial region defined in Table 2 is obtained via  $\sigma(\text{pp} \rightarrow J/\psi J/\psi J/\psi X) = N_{\text{sig}}^{3J/\psi} / (\epsilon \mathcal{L}_{\text{int}} \mathcal{B}_{J/\psi \rightarrow \mu^+ \mu^-}^3)$ , where  $N_{\text{sig}}^{3J/\psi}$  is the number of signal events,  $\mathcal{L}_{\text{int}}$  the total integrated luminosity,  $\mathcal{B}_{J/\psi \rightarrow \mu^+ \mu^-}$  the dimuon branching fraction, and  $\epsilon = \epsilon_{\text{trig}} \epsilon_{\text{id}} \epsilon_{\text{reco}}$  the total efficiency composed of trigger, identification, and reconstruction components. The  $J/\psi$  muon identification and reconstruction efficiencies

are extracted with the tag-and-probe method using correction factors from the large inclusive  $J/\psi \rightarrow \mu^+\mu^-$  data samples used in Ref. [40]. Since they depend on the  $p_T$  and  $\eta$  of the muons, the corrections are propagated to the final cross section via two-dimensional maps, yielding  $\epsilon_{\text{id}} \epsilon_{\text{reco}} = 0.78$ . The trigger efficiency is found to be  $\epsilon_{\text{trig}} = 0.84$  from a study of the MC samples.

Table 2: Definition of the fiducial phase space for the triple- $J/\psi$  cross section measurement.

For all muons	$p_T > 3.5 \text{ GeV}$ for $ \eta  < 1.2$ $p_T > 2.5 \text{ GeV}$ for $1.2 <  \eta  < 2.4$
For all $J/\psi$ mesons	$p_T > 6 \text{ GeV}$ and $ y  < 2.4$ $2.9 < m_{\mu^+\mu^-} < 3.3 \text{ GeV}$

The impact on the extracted cross section of the choice of functions used to reproduce the shapes of the signal and background dimuon invariant masses is studied. For the signal, the Gaussian distribution is changed to a Crystal-Ball function [49] as well as to a Gaussian function with the RMS width left to vary in the fit. The background shape is changed from the default exponential to first- and zeroth-order polynomials. The relative differences in the cross sections obtained from the alternative modeling for signal and background are 0.8 and 3.4%, respectively, and are assigned as corresponding systematic uncertainties. Uncertainties arising from the muon reconstruction and identification efficiencies are derived by allowing the tag-and-probe correction factors for each  $(p_T, \eta)$  bin to vary within their precision, and checking the effect on the extracted cross section. The maximal variation observed is  $\pm 1.0\%$ . Varying the relative composition of double- and single- $J/\psi$  meson production in the MC event sample used for the determination of the trigger efficiency leads to a 3.4% propagated uncertainty. Uncertainties of 1.6% and 3.0% are added from the integrated luminosity measurement [50–52], and from the simulated signal sample size, respectively. The uncertainty in the  $\mathcal{B}_{J/\psi \rightarrow \mu^+\mu^-} = (5.961 \pm 0.033)\%$  value [32] propagates into a 1.7% uncertainty in the cross section. The total systematic uncertainty of the measured cross section is 6.2%, obtained by adding all individual sources in quadrature (Table 3). The measured cross section for triple- $J/\psi$  production, within the fiducial region defined in Table 2, is  $\sigma(\text{pp} \rightarrow J/\psi J/\psi J/\psi X) = 272_{-104}^{+141}$  (stat)  $\pm 17$  (syst) fb.

Table 3: Relative contributions to the systematic uncertainty of the  $\sigma(\text{pp} \rightarrow J/\psi J/\psi J/\psi X)$  measurement. The last row gives the sum in quadrature of all components.

Source	Relative uncertainty
$J/\psi$ meson signal shape	0.8%
Dimuon continuum background shape	3.4%
Muon reconstruction and identification	1.0%
Trigger efficiency	3.4%
MC sample size	3.0%
Integrated luminosity	1.6%
Dimuon branching fraction	1.7%
Total	6.2%

## Discussion

The total inclusive triple- $J/\psi$  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)  $J/\psi$  contributions,

$$\begin{aligned}\sigma_{\text{tot}}^{3J/\psi} &= \sigma_{\text{SPS}}^{3J/\psi} + \sigma_{\text{DPS}}^{3J/\psi} + \sigma_{\text{TPS}}^{3J/\psi} \\ &= \left( \sigma_{\text{SPS}}^{3p} + \sigma_{\text{SPS}}^{2p1np} + \sigma_{\text{SPS}}^{1p2np} + \sigma_{\text{SPS}}^{3np} \right) \\ &\quad + \left( \sigma_{\text{DPS}}^{3p} + \sigma_{\text{DPS}}^{2p1np} + \sigma_{\text{DPS}}^{1p2np} + \sigma_{\text{DPS}}^{3np} \right) + \left( \sigma_{\text{TPS}}^{3p} + \sigma_{\text{TPS}}^{2p1np} + \sigma_{\text{TPS}}^{1p2np} + \sigma_{\text{TPS}}^{3np} \right).\end{aligned}\quad (3)$$

Under the simplest assumption of factorization of multiple hard-scattering probabilities in terms of SPS cross sections, the DPS and TPS contributions to triple- $J/\psi$  production (last row of Eq. (3)) can be written through Eqs. (1) and (2) as a combination of products of single- and double- $J/\psi$  SPS cross sections as

$$\begin{aligned}\sigma_{\text{DPS}}^{3J/\psi} &= \frac{\mathbf{m}_1 \left( \sigma_{\text{SPS}}^{2p} \sigma_{\text{SPS}}^{1p} + \sigma_{\text{SPS}}^{2p} \sigma_{\text{SPS}}^{1np} + \sigma_{\text{SPS}}^{1p} \sigma_{\text{SPS}}^{1p1np} + \sigma_{\text{SPS}}^{1p1np} \sigma_{\text{SPS}}^{1np} + \sigma_{\text{SPS}}^{1p} \sigma_{\text{SPS}}^{2np} + \sigma_{\text{SPS}}^{2np} \sigma_{\text{SPS}}^{1np} \right)}{\sigma_{\text{eff,DPS}}}, \quad \text{and} \\ \sigma_{\text{TPS}}^{3J/\psi} &= \frac{\mathbf{m}_3 \left( \left( \sigma_{\text{SPS}}^{1p} \right)^3 + \left( \sigma_{\text{SPS}}^{1np} \right)^3 \right) + \mathbf{m}_2 \left( \left( \sigma_{\text{SPS}}^{1p} \right)^2 \sigma_{\text{SPS}}^{1np} + \sigma_{\text{SPS}}^{1p} \left( \sigma_{\text{SPS}}^{1np} \right)^2 \right)}{\sigma_{\text{eff,TPS}}^2},\end{aligned}\quad (4)$$

with combinatorial prefactors  $\mathbf{m}_1 = 2/2 = 1$ ,  $\mathbf{m}_2 = 3/3! = 1/2$ , and  $\mathbf{m}_3 = 1/3! = 1/6$ . Therefore, from the eight individual SPS cross sections for single-, double-, and triple- $J/\psi$  production, one can determine the total triple- $J/\psi$  production cross section via Eqs. (3) and (4). The values of the relevant SPS cross sections, each within the fiducial phase space defined in Table 2, are computed as described next and listed in Table 4.

Table 4: Predictions for single-, double-, and triple- $J/\psi$  production cross sections in SPS processes, which pass the fiducial criteria listed in Table 2, derived from the HELAC-ONIA (HO) and MADGRAPH5\_aMC@NLO (MG5NLO) matrix element calculators, complemented with the PYTHIA 8 (PY8) parton shower, as described in the text.

SPS single- $J/\psi$ production		SPS double- $J/\psi$ production			SPS triple- $J/\psi$ production			
HO(DATA)	MG5NLO+PY8	HO(NLO*)	HO(LO)+PY8	MG5NLO+PY8	HO(LO)	HO(LO)+PY8	HO(LO)+PY8	MG5NLO+PY8
$\sigma_{\text{SPS}}^{1p}$	$\sigma_{\text{SPS}}^{1np}$	$\sigma_{\text{SPS}}^{2p}$	$\sigma_{\text{SPS}}^{1p1np}$	$\sigma_{\text{SPS}}^{2np}$	$\sigma_{\text{SPS}}^{3p}$	$\sigma_{\text{SPS}}^{2p1np}$	$\sigma_{\text{SPS}}^{1p2np}$	$\sigma_{\text{SPS}}^{3np}$
$570 \pm 57$ nb	$600^{+130}_{-220}$ nb	$40^{+80}_{-26}$ pb	$24^{+35}_{-16}$ fb	$430^{+95}_{-130}$ pb	$< 5$ ab	$5.2^{+9.6}_{-3.3}$ fb	$14^{+17}_{-8}$ ab	$12 \pm 4$ fb

The values of the SPS single, double, and triple prompt- $J/\psi$  cross sections ( $\sigma_{\text{SPS}}^{1p}$ ,  $\sigma_{\text{SPS}}^{2p}$ ,  $\sigma_{\text{SPS}}^{3p}$ ) are obtained with HELAC-ONIA at LO or at approximately next-to-leading-order (NLO\*) accuracy [53, 54]. For the single prompt- $J/\psi$  prediction ( $\sigma_{\text{SPS}}^{1p}$ ), the theoretical calculations HO(DATA) in Table 4 are normalized with a parameterization [55] that reproduces the data measured in pp collisions at 7 TeV [44, 56], including all feed-down contributions from decays of heavier charmonium resonances. For the double and triple prompt- $J/\psi$  processes, the HELAC-ONIA calculations include only the  $\psi(2S)$  feed-down because the  $\chi_c$  decay contribution is only a few percent. All predictions for cross sections of nonprompt  $J/\psi$  meson production in beauty hadron decays ( $\sigma_{\text{SPS}}^{1np}$ ,  $\sigma_{\text{SPS}}^{2np}$ ,  $\sigma_{\text{SPS}}^{3np}$ ) have been obtained with MADGRAPH5\_aMC@NLO (v.2.6.6) [57] matrix elements, scaled by a factor of 1.15 to account for next-to-next-to-leading-order  $b\bar{b}$  cross section corrections [5], combined with the PYTHIA 8.244 generator for parton shower and decays (including all feed-down quarkonium contributions) [54]. The uncertainties include the (dominant) theoretical scale dependence and the (subdominant) PDF uncertainties of the CT14NLO set [58], except for the single prompt- $J/\psi$  predictions that have a better precision because they are determined with an explicit fit of the NRQCD predictions to the LHC data [55] and have an

associated 10% uncertainty of experimental origin. All these sources are treated as uncorrelated and the corresponding uncertainties are added in quadrature.

Using Eq. (4) with the SPS cross sections listed in Table 4, and assuming that the effective DPS and TPS cross sections are related by  $\sigma_{\text{eff,TPS}} = (0.82 \pm 0.11) \sigma_{\text{eff,DPS}}$  [5] in a baseline approach that ignores parton correlations, one can extract the value of the effective DPS cross section that yields the experimentally measured  $\sigma_{\text{tot}}^{3J/\psi}$  value. Following such a procedure, the value  $\sigma_{\text{eff,DPS}} = 2.7^{+1.4}_{-1.0} (\text{exp})^{+1.5}_{-1.0} (\text{theo}) \text{ mb}$  is derived, where the first uncertainty is due to the experimental  $\sigma_{\text{tot}}^{3J/\psi}$  precision and the second is due to the propagation of all sources of theoretical uncertainties in the ingredients of Eqs. (3) and (4).

Table 5: Central values of the predictions for triple- $J/\psi$  production cross sections (in fb) and yields from SPS, DPS (for  $\sigma_{\text{eff,DPS}} = 2.7 \text{ mb}$ ), and TPS (for  $\sigma_{\text{eff,TPS}} = 0.82 \sigma_{\text{eff,DPS}} = 2.2 \text{ mb}$ ) processes, and their total sum. The values are given in columns for combinations of  $n$  prompt and  $(3 - n)$  nonprompt  $J/\psi$  mesons, the last column giving their corresponding sums. The DPS and TPS results are derived via Eqs. (3) and (4) from the SPS cross sections listed in Table 4 with  $\sigma_{\text{eff,DPS}}$  chosen so that the sum of contributions yields a total cross section equal to the experimental value of  $\sigma_{\text{tot}}^{3J/\psi}$ . The expected yield,  $N_{\text{NPS}}^{3J/\psi}$ , is given for an effective integrated luminosity of  $\epsilon \mathcal{L}_{\text{int}} = 87 \text{ fb}^{-1}$  for each contributing process. The last column lists the total cross sections and yields for SPS, DPS, TPS and their sums.

Process:	3 prompt	2 prompt+1 nonprompt	1 prompt+2 nonprompt	3 nonprompt	Total
$\sigma_{\text{SPS}}^{3J/\psi}$ (fb)	< 0.005	5.7	0.014	12	18
$N_{\text{SPS}}^{3J/\psi}$	0.0	0.10	0.0	0.22	0.32
$\sigma_{\text{DPS}}^{3J/\psi}$ (fb)	8.4	8.9	90	95	202
$N_{\text{DPS}}^{3J/\psi}$	0.15	0.16	1.65	1.75	3.7
$\sigma_{\text{TPS}}^{3J/\psi}$ (fb)	6.1	19.4	20.4	7.2	53
$N_{\text{TPS}}^{3J/\psi}$	0.11	0.36	0.38	0.13	1.0
$\sigma_{\text{tot}}^{3J/\psi}$ (fb)	15	34	110	114	272
$N_{\text{tot}}^{3J/\psi}$	0.3	0.6	2.0	2.1	5.0

The inclusive triple- $J/\psi$  theoretical cross sections and yields for each individual process contributing to the total production are listed in Table 5. The expected contributions from SPS, DPS, and TPS processes to the total triple- $J/\psi$  cross section amount to about 6, 74, and 20%, respectively. This confirms the conclusion of Ref. [29] that triple- $J/\psi$  production is a golden channel to study DPS and TPS, with minimal SPS contamination. The largest contributors to the triple- $J/\psi$  cross section are  $\sigma_{\text{DPS}}^{3\text{np}}$  and  $\sigma_{\text{DPS}}^{1\text{p}2\text{np}}$  accounting for  $\approx 33\%$  each,  $\sigma_{\text{TPS}}^{2\text{p}1\text{np}}$  and  $\sigma_{\text{TPS}}^{1\text{p}2\text{np}}$  amounting to about 7% each, and  $\sigma_{\text{SPS}}^{3\text{np}}$  representing about 4% of the total production. In terms of prompt and nonprompt contributions, the theoretical expectation for the production of three promptly produced  $J/\psi$  mesons is  $\approx 5\%$  of the total yield, whereas the percentage expected for three nonprompt  $J/\psi$  mesons is  $\approx 45\%$ . The remaining half of the triple- $J/\psi$  events are expected to be due to the combination of  $J/\psi$  mesons produced promptly and from beauty hadron decays. This result is consistent, within the large statistical uncertainties of the present data set, with the combination of prompt and nonprompt  $J/\psi$  mesons derived from the decay length of each dimuon candidate.

In Fig. 3, the  $\sigma_{\text{eff,DPS}}$  value extracted here (red circle) is compared to the world data on effective DPS cross sections derived from midrapidity measurements with quarkonium final states [23,

25–27, 59] (blue circles), as well as from processes with jets, photons, and/or W bosons [14–20, 60–63] (black squares and triangles). A few of the  $\sigma_{\text{eff,DPS}}$  values plotted have been derived by more advanced phenomenological studies [64–67] of the experimental quarkonium data. The effective cross sections obtained from quarkonium measurements favor a smaller value of  $\sigma_{\text{eff,DPS}} \approx 3\text{--}10\text{ mb}$  compared to the  $\sigma_{\text{eff,DPS}} \approx 10\text{--}20\text{ mb}$  derived from harder or heavier final states. Such an apparent process-dependent  $\sigma_{\text{eff,DPS}}$  value is suggestive of different parton transverse profiles, and/or correlations present, probed inside the proton at varying fractional momenta, given by  $x = \sqrt{p_{T,V}^2 + m_V^2} e^\eta / \sqrt{s}$ , for  $V = J/\psi, Y, W, Z$ . At midrapidity ( $|\eta| < 2.5$ ), quarkonia are produced mostly in gluon-gluon scatterings carrying a fraction  $x \approx 5 \times 10^{-4}$  of the proton momentum, whereas mostly quarks around  $x \approx 10^{-2}$  intervene in the production of EW bosons. The fact that LHCb measurements of double-quarkonia and quarkonia-plus-charm [26, 68] at *forward* rapidities ( $\eta \approx 2\text{--}4.5$ ), processes that originate in parton scatterings with asymmetric fractional momenta  $x_1 \approx 10^{-4}$  and  $x_2 \approx 10^{-2}$ , lead to values of  $\sigma_{\text{eff,DPS}} \approx 15\text{ mb}$ , larger than those measured at midrapidity for similar final states, seems to confirm the dependence of the effective DPS cross section on the relevant parton species and  $x$  fractions probed.

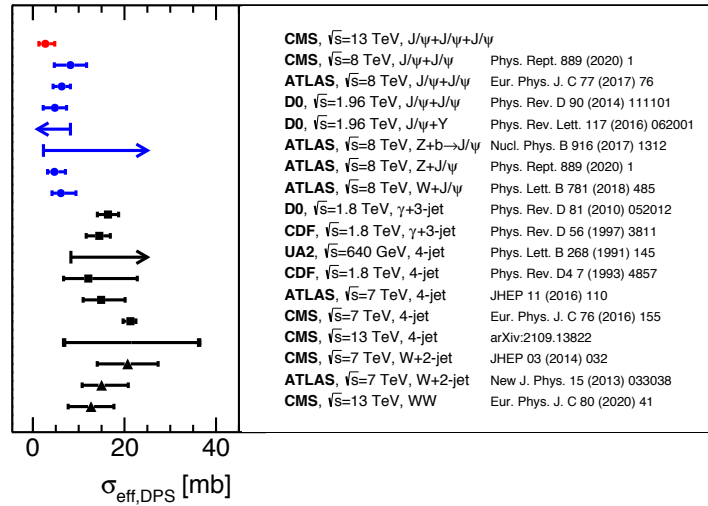


Figure 3: Comparison of the  $\sigma_{\text{eff,DPS}}$  parameter extracted here (upper red circle) to those derived in midrapidity measurements of double-quarkonium and EW boson plus quarkonium production [23, 25, 26, 64–67] (blue circles), as well as in final states with jets [20, 38, 60, 61],  $\gamma$ +jets [62, 63],  $W$ +jets [14, 15], and same-sign  $W$  bosons [19] (black squares and triangles). The arrows indicate lower limits at 95% confidence level.

## Summary

In summary, the first observation of the simultaneous production of three  $J/\psi$  mesons in proton-proton (pp) collisions has been reported. Events with three reconstructed  $J/\psi$  mesons, each decaying into two muons, are selected from a data sample collected at  $\sqrt{s} = 13\text{ TeV}$  corresponding to an integrated luminosity of  $133\text{ fb}^{-1}$ . After all selection requirements, five events are found consistent with triple- $J/\psi$  production, plus one event assigned to combinatorial background, through a three-dimensional unbinned extended maximum likelihood fit of the measured dimuon invariant mass distributions. The statistical significance of the signal, including prompt as well as nonprompt (i.e., coming from beauty hadron decays) contributions, relative to the background-only expectation, is above five standard deviations. The cross section

for inclusive triple- $J/\psi$  production, within the fiducial region defined in Table 2, is  $\sigma(\text{pp} \rightarrow J/\psi J/\psi J/\psi X) = 272_{-104}^{+141}$  (stat)  $\pm 17$  (syst) fb. This result is compared to the theoretical expectations for triple- $J/\psi$  production via a sum of contributions from single- (SPS), double- (DPS), and triple- (TPS) parton scatterings. Under the simplest assumption of factorization of multiple hard-scattering probabilities in terms of SPS cross sections, the measured triple- $J/\psi$  cross section is consistent with the production via DPS ( $\approx 74\%$ ), TPS ( $\approx 20\%$ ), and SPS ( $\approx 6\%$ ) processes for a value of the effective DPS cross section parameter, closely related to the transverse distribution of partons in the proton, of  $\sigma_{\text{eff,DPS}} = 2.7_{-1.0}^{+1.4}$  (exp)  $_{-1.0}^{+1.5}$  (theo) mb. Within its large uncertainty, this parameter is consistent with those extracted from double-quarkonium measurements, but significantly smaller than the  $\sigma_{\text{eff,DPS}}$  values derived from DPS studies based on high- $p_T$  jets and/or electroweak bosons. This work presents a novel approach to study multiple hard-scatterings in pp collisions exploiting, for the first time, the simultaneous production of three heavy particles.

## Data availability

Tabulated results are provided in the HEPData record for this analysis [69].

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


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











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

























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






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











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**Indian Institute of Science (IISc), Bangalore, India**

S. Choudhury, J.R. Komaragiri , D. Kumar, L. Panwar , P.C. Tiwari 








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H. Bakhshiansohi<sup>40</sup> , E. Khazaie, M. Zeinali<sup>41</sup>




























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S. Chenarani<sup>42</sup>, S.M. Etesami , M. Khakzad , M. Mohammadi Najafabadi 
























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




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















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



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











A. Benaglia<sup>a</sup> , G. Boldrini , F. Brivio<sup>a,b</sup>, F. Cetorelli<sup>a,b</sup>, F. De Guio<sup>a,b</sup> , M.E. Dinardo<sup>a,b</sup> , P. Dini<sup>a</sup> , S. Gennai<sup>a</sup> , A. Ghezzi<sup>a,b</sup> , P. Govoni<sup>a,b</sup> , L. Guzzi<sup>a,b</sup> , M.T. Lucchini<sup>a,b</sup> , M. Malberti<sup>a</sup>, S. Malvezzi<sup>a</sup> , A. Massironi<sup>a</sup> , D. Menasce<sup>a</sup> , L. Moroni<sup>a</sup> , M. Paganoni<sup>a,b</sup> , D. Pedrini<sup>a</sup> , B.S. Pinolini, S. Ragazzi<sup>a,b</sup> , N. Redaelli<sup>a</sup> , T. Tabarelli de Fatis<sup>a,b</sup> , D. Valsecchi<sup>a,b,21</sup>, D. Zuolo<sup>a,b</sup> 

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



S. Buontempo<sup>a</sup> , F. Carnevali<sup>a,b</sup>, N. Cavallo<sup>a,c</sup> , A. De Iorio<sup>a,b</sup> , F. Fabozzi<sup>a,c</sup> , A.O.M. Iorio<sup>a,b</sup> , L. Lista<sup>a,b,46</sup> , S. Meola<sup>a,d,21</sup> , P. Paolucci<sup>a,21</sup> , B. Rossi<sup>a</sup> , C. Sciacca<sup>a,b</sup> 

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







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
























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












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















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




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






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











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











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











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












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

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









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L. Ceard, Y. Chao, K.F. Chen , P.H. Chen , P.s. Chen, H. Cheng , W.-S. Hou , Y.y. Li, R.-S. Lu, E. Paganis , A. Psallidas, A. Steen, H.y. Wu, E. Yazgan , P.r. Yu



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B. Asavapibhop , C. Asawatangtrakuldee , N. Srimanobhas 





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B. Isildak<sup>74</sup>, G. Karapinar, K. Ocalan<sup>75</sup> , M. Yalvac<sup>76</sup> 





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B. Akgun, I.O. Atakisi , E. Gülmez , M. Kaya<sup>77</sup> , O. Kaya<sup>78</sup>, Ö. Özçelik, S. Tekten<sup>79</sup>, E.A. Yetkin<sup>80</sup> 

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L. Levchuk 



















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D. Anthony, E. Bhal , S. Bologna, J.J. Brooke , A. Bundock , E. Clement , D. Cussans , H. Flacher , J. Goldstein , G.P. Heath, H.F. Heath , L. Kreczko , B. Krikler , S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou<sup>83</sup> , K. Walkingshaw Pass, R. White





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






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







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R. Bartek , A. Dominguez , R. Uniyal , A.M. Vargas Hernandez




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S. Sagir<sup>90</sup> , F. Simpson, E. Usai , W.Y. Wong, X. Yan , D. Yu , W. Zhang







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







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M. Bachtis , R. Cousins , A. Datta , D. Hamilton, J. Hauser , M. Ignatenko, M.A. Iqbal, T. Lam, W.A. Nash, S. Regnard , D. Saltzberg , B. Stone, V. Valuev 










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K. Burt, Y. Chen, R. Clare , J.W. Gary , M. Gordon, G. Hanson , G. Karapostoli , O.R. Long , N. Manganeli, M. Olmedo Negrete, W. Si , S. Wimpenny, Y. Zhang













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


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A. Bornheim , O. Cerri, I. Dutta , J.M. Lawhorn , N. Lu , J. Mao, H.B. Newman , T.Q. Nguyen , M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , Z. Zhang , R.Y. Zhu 















**Carnegie Mellon University, Pittsburgh, Pennsylvania, USA**

J. Alison , S. An , M.B. Andrews, P. Bryant , T. Ferguson , A. Harilal, C. Liu, T. Mudholkar , M. Paulini , A. Sanchez, W. Terrill


























**University of Colorado Boulder, Boulder, Colorado, USA**

J.P. Cumalat , W.T. Ford , A. Hassani, G. Karathanasis, E. MacDonald, R. Patel, A. Perloff , C. Savard, K. Stenson , K.A. Ulmer , S.R. Wagner 

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J. Alexander , S. Bright-Thonney , X. Chen , Y. Cheng , D.J. Cranshaw , S. Hogan, J. Monroy , J.R. Patterson , D. Quach , J. Reichert , M. Reid , A. Ryd, W. Sun , J. Thom , P. Wittich , R. Zou 

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L. Spiegel, S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk, N.V. Tran , L. Uplegger , E.W. Vaandering , H.A. Weber 







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D. Acosta , P. Avery, D. Bourilkov , L. Cadamuro , V. Cherepanov, F. Errico , R.D. Field, D. Guerrero, B.M. Joshi , M. Kim, E. Koenig, J. Konigsberg , A. Korytov, K.H. Lo, K. Matchev , N. Menendez , G. Mitselmakher , A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, J. Rotter, K. Shi , J. Wang , E. Yigitbasi , X. Zuo














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T. Adams , A. Askew , R. Habibullah , V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg , G. Martinez, H. Prosper , C. Schiber, O. Viazlo , R. Yohay , J. Zhang








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M.R. Adams, H. Becerril Gonzalez , R. Cavanaugh , S. Dittmer, O. Evdokimov , C.E. Gerber , D.A. Hangal , D.J. Hofman , A.H. Merrit, C. Mills , G. Oh , T. Roy, S. Rudrabhatla, M.B. Tonjes , N. Varelas , J. Viinikainen , X. Wang, Z. Wu , Z. Ye 

















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M. Alhusseini , K. Dilsiz<sup>91</sup> , L. Emediato, R.P. Gandrajula , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili<sup>92</sup>, J. Nachtman, H. Ogul<sup>93</sup> , Y. Onel , A. Penzo, C. Snyder, E. Tiras<sup>94</sup> 




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O. Amram , B. Blumenfeld , L. Corcodilos , J. Davis, M. Eminizer , A.V. Gritsan , S. Kyriacou, P. Maksimovic , J. Roskes , M. Swartz, T.Á. Vámi 

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






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E. Adams, A. Baden, O. Baron, A. Belloni , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer , M. Seidel , A. Skuja , L. Wang, K. Wong 




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A. Baty , T. Carnahan, M. Decaro, S. Dildick , K.M. Ecklund , S. Freed, P. Gardner, E.J.M. Geurts , A. Kumar , W. Li, B.P. Padley , R. Redjimi, W. Shi , A.G. Stahl Leiton , S. Yang , L. Zhang<sup>95</sup>, Y. Zhang 

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B. Chiarito, J.P. Chou , A. Gandrakota , Y. Gershtein , E. Halkiadakis , A. Hart, M. Heindl , O. Karacheban<sup>25</sup> , I. Laflotte, A. Lath , R. Montalvo, K. Nash, M. Osherson, S. Salur , S. Schnetzer, S. Somalwar , R. Stone, S.A. Thayil , S. Thomas, H. Wang 




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




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