Measurement of the Y(1S) pair production cross section and search for resonances decaying to Y(1S)μ⁺μ⁻ in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration *

CERN, Switzerland

ABSTRACT

The fiducial cross section for Y(1S) pair production in proton-proton collisions at a center-of-mass energy of 13 TeV in the region where both Y(1S) mesons have an absolute rapidity below 2.0 is measured to be $79 \pm 11\,(\text{stat}) \pm 6\,(\text{syst}) \pm 3\,(\mathcal{B})$ pb assuming the mesons are produced unpolarized. The last uncertainty corresponds to the uncertainty in the Y(1S) meson dimuon branching fraction. The measurement is performed in the final state with four muons using proton-proton collision data collected in 2016 by the CMS experiment at the LHC, corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$. This process serves as a standard model reference in a search for narrow resonances decaying to Y(1S)μ⁺μ⁻ in the same final state. Such a resonance could indicate the existence of a tetraquark that is a bound state of two b quarks and two b̄ antiquarks. The tetraquark search is performed for masses in the vicinity of four times the bottom quark mass, between 17.5 and 19.5 GeV, while a generic search for other resonances is performed for masses between 16.5 and 27 GeV. No significant excess of events compatible with a narrow resonance is observed in the data. Limits on the production cross section times branching fraction to four muons via an intermediate Y(1S) resonance are set as a function of the resonance mass.

1. Introduction

Quarkonium pair production is an important probe of both perturbative and nonperturbative processes in quantum chromodynamics. Experimental studies of this process can provide valuable information about the underlying mechanisms of particle production and improve our understanding of numerous physics processes that are treated as backgrounds in searches and measurements. Quarkonium pairs may originate from single-parton scattering (SPS) or double-parton scattering (DPS). These production mechanisms can be separated experimentally since the DPS production is characterized, among other features, by more forward and separated mesons. The analysis of nonperturbative effects is easier for quarkonium states composed of b quarks, as their large masses allow them to be approximated as nonrelativistic systems [1]. The CMS Collaboration observed for the first time the production of a pair of Y(1S) mesons, using proton-proton data collected at a center-of-mass energy of 8 TeV [2]. This Letter presents a measurement of the Y(1S) pair production cross section at a center-of-mass energy of 13 TeV. The cross section is measured in the fiducial region where both Y(1S) mesons have an

absolute rapidity below 2.0, using the final state with four muons. Additionally, the DPS contribution to the process is measured for the first time.

The Y(1S) pair production can serve as a reference in searches for tetraquarks or generic resonances with masses close to twice the Y(1S) meson mass. A light resonance decaying to a Y(1S) meson and a pair of leptons might be the signature of a tetraquark characterized as a bound state of two b quarks and two b̄ antiquarks, especially if its mass is below twice the η_b mass [3–13]. In this Letter, in addition to the measurement of the Y(1S) pair production cross section, we describe a search for tetraquarks with masses between 17.5 and 19.5 GeV, since bbb̄b̄ tetraquarks would be expected to have a mass around four times that of the bottom quark. A generic search for narrow resonances with mass between 16.5 and 27 GeV and decaying to a Y(1S) meson and a pair of muons is also presented. The final state is the same as for the measurement of the Y(1S) pair production cross section, and a similar event selection is used. The Y(1S) pair production is a background to the resonance search.

The LHCb Collaboration searched for bbb̄b̄ tetraquarks using data collected at center-of-mass energies of 7, 8, and 13 TeV, without finding any hint of a signal [14]. This analysis probes a kine-

* *E-mail address:* cms-publication-committee-chair@cern.ch.

matic region that is not accessible with the LHCb detector and extends the covered mass range in the context of the generic search.

The Y(1S) pair production fiducial cross section measurement and the resonance search are based on proton-proton collision data collected in 2016 at a center-of-mass energy of 13 TeV by the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$.

2. The CMS detector

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, there 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 pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system [15]. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [16].

Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution in the range 0.8–3.0% for muons with p_T less than 10 GeV [17].

3. Simulated samples

The Y(1S) pair production signal is simulated using the PYTHIA 8.226 generator [18], separately for the SPS and DPS mechanisms, under the assumption that the mesons are produced unpolarized. The DPS sample is produced by generating two hard interactions with color-singlet production of bottomonium states via $gg \rightarrow b\bar{b}$ or color-octet production of bottomonium states via $qq \rightarrow b\bar{b}$. The invariant mass distribution of the meson pair and of the rapidity separation between the mesons are used to extract the fraction of DPS production, as detailed in Section 5. For this measurement, the distributions of these variables for the SPS process are taken from the next-to-leading-order (NLO*) calculation with a cutoff color-singlet mechanism (CSM) [19–21] using HELAC-ONIA 2.0.1 [22,23].

The signal of a narrow resonance decaying to a Y(1S) meson and a pair of muons is modeled using different physics assumptions depending on the nature of the resonance:

- a bottomonium state with the properties of the $\chi_{b1}(1P)$, assuming a phase-space decay to a Y(1S) meson and a pair of muons, using the PYTHIA 8.226 generator;
- a scalar particle produced in gluon fusion, using the JHUGEN generator [24–27];
- a pseudoscalar particle produced in gluon fusion, using the JHUGEN generator;
- a spin-2 particle produced in gluon fusion, using the JHUGEN generator.

The signals are generated assuming the narrow-width approximation. The $\chi_{b1}(1P)$ sample is used to model the tetraquark signal, for which no dedicated generator exists. The other samples correspond to the signals in the generic search over an extended mass range. For each model, four resonance mass values are simulated: 14, 18, 22, and 26 GeV. Since the signal acceptance falls steeply around and below 14 GeV in the simulated samples, the probed mass range in this analysis is restricted to stay well above this

mass threshold. The different mass points are used to interpolate and extrapolate the signal model over the whole mass range.

The PYTHIA generator with the tune CUETP8M1 [28] is used to model the parton shower and hadronization processes. Generated events are processed through a simulation of the CMS detector based on GEANT4 [29].

4. Event selection criteria

The event reconstruction is based on the particle-flow algorithm [30], which identifies individual particle candidates using information from all the individual subdetectors. Muons are reconstructed by combining information from the silicon tracker and the muon system [17].

Events are selected with a trigger that requires the presence of three muons. Among these muons, two must have an invariant mass compatible with a Y resonance ($8.5 < m_{2\mu} < 11.4$ GeV) at trigger level, and the dimuon vertex fit probability, calculated using the χ^2 and the number of degrees of freedom of the fit, must be greater than 0.5%.

Offline, we require each event to have four reconstructed muons with $p_T > 2$ GeV and $|\eta| < 2.4$. These muons are required to satisfy the global or particle-flow muon identification criteria described in Ref. [17]. About 25% of simulated signal events and about 30% of data events have more than four such muons. Possible combinations of four muon tracks are refit with a constraint to come from a common vertex, and the χ^2 probability of the fit is determined. The combination of four muons with the largest χ^2 probability is chosen. For simulated signal events with more than four reconstructed muons, the correct muons are chosen in about 98% of cases. Among the four muons, at least three need to be associated with the trigger-level objects. At least two muons must be associated with the objects that passed the Y mass compatibility and vertex criteria of the trigger, and they are paired together. If there are more than two such muons, which happens for 2 to 35% of simulated signal events depending on the resonance mass, those that have opposite-sign (OS) charges and an invariant mass closest to the world-average Y(1S) mass [31] are paired together.

After selecting the best combination of four muons with $p_T > 2$ GeV, the p_T threshold is raised to 2.5 GeV for the selected muons. The final selection requiring $p_T > 2.5$ GeV reduces the background from misidentified muons by about a factor of two. The muons are required to satisfy the medium muon identification criteria described in Ref. [17]. Both pairs of muons have to be composed of OS muons. The vertex fit χ^2 probability of the four muons is required to be greater than 5%, whereas that of the Y(1S) candidate is required to be above 0.5%, similar to the requirement already imposed at trigger level. The muons are required to be separated from each other by at least $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.02$, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle between the muons. The positively (negatively) charged muon from one of the pairs can be paired with the negatively (positively) charged muon of the other pair to form so-called alternative pairs of OS muons. If one of these alternative pairs has an invariant mass compatible with a J/ψ particle within two standard deviations of the experimental resolution, which ranges between about 0.03 and 0.12 GeV depending on the muon pair kinematics, the event is discarded from the analysis. Events are also discarded if they contain two OS pairs of muons with invariant mass less than 4 GeV.

The selection criteria detailed above are common for the measurement of the Y(1S) pair production cross section and the search for a resonant signal. The criteria that differ between the measurement and the search are described in the following. In the measurement of the Y(1S) pair fiducial cross section, the reconstructed absolute rapidity of both muon pairs is required to be

less than 2.0. In addition, for muons with $|\eta| < 0.9$, the p_T threshold is raised to 3.5 GeV. Central muons with transverse momentum below 3.5 GeV have a high probability of being absorbed in the calorimeter or undergoing significant multiple scattering before reaching the muon detectors. This selection criterion reduces the systematic uncertainty in the muon reconstruction related to the detector simulation. It is, however, not used in the resonant search because it would strongly reduce the signal acceptance for the lower-mass signal range. In the resonance search, the invariant mass of the Y(1S) candidate is required to be within two standard deviations of the experimental resolution from the Y(1S) mass [31], where the resolution varies between about 0.06 and 0.15 GeV depending on the event.

The mass range of interest is known a priori for the search of a $b\bar{b}b\bar{b}$ tetraquark signal. In this case, all the selection criteria described above have been determined and fixed in a blinded way, using simulation and without looking at data events with four muons having an invariant mass between 17.5 and 19.5 GeV.

5. Measurement of the Y(1S) pair production cross section

The methodology used to measure the Y(1S) pair production cross section is detailed in Section 5.1. After discussing the systematic uncertainties in Section 5.2, the results of the measurement of the inclusive Y(1S) pair production fiducial cross section are presented in Section 5.3. Nonisotropic decays of the Y(1S) mesons would change the measured cross section. Section 5.4 describes how the cross section would vary for nonzero values of the polarization parameters. Finally, the DPS and SPS mechanisms can be separated experimentally by measuring the Y(1S) pair production cross section in bins of the rapidity difference between the mesons, $|\Delta y(\text{Y(1S)}, \text{Y(1S)})|$, and of the invariant mass of the meson pairs, $m_{\text{Y(1S)Y(1S)}}$. A measurement of the DPS-to-inclusive cross section ratio in the fiducial region is presented in Section 5.5.

5.1. Methodology

The Y(1S) pair production cross section is measured in the fiducial region where both mesons have an absolute rapidity below 2.0. No other requirement is applied to define the fiducial region. The fiducial cross section, σ_{fid}, can be expressed as:

$$\sigma_{\text{fid}} = \frac{N^{\text{corr}}}{\mathcal{L}\mathcal{B}^2},\qquad(1)$$

where N^{corr} is the number of signal events corrected for the acceptance and efficiency of the selection, $\mathcal{L}$ is the integrated luminosity, and $\mathcal{B}$ stands for $\mathcal{B}(\text{Y(1S)} \to \mu^+\mu^-) = (2.48 \pm 0.05)\%$ [31], which is the branching fraction of the Y(1S) meson decay to a pair of muons. To extract N^{corr} from the data, we perform an extended unbinned two-dimensional (2D) maximum likelihood fit of the invariant mass distributions of two OS muon pairs, where all events are weighted for the acceptance and efficiency on an event-by-event basis by the weight ω, defined as:

$$\omega = \left[A_1 A_2 \epsilon_1^{\text{reco}} \epsilon_2^{\text{reco}} \left(1 - (1 - \epsilon_1^{\text{vtx}})(1 - \epsilon_2^{\text{vtx}})\right) \epsilon^{\text{evt}}\right]^{-1},\qquad(2)$$

where the different terms are described below:

- A, the probability for a Y(1S) meson with an absolute rapidity below 2.0 and decaying to a pair of muons to have two muons in the geometrical acceptance of the detector (muon $|\eta| < 2.4$); No strong correlation between the acceptance values of the two mesons are found with a closure test described in Section 5.2, and the total acceptance is therefore computed as the product of the per-meson weights;

- ϵ^{reco}, the probability for a Y(1S) meson with an absolute rapidity below 2.0 and decaying to a pair of muons each with $|\eta| < 2.4$ to have two reconstructed muons passing the identification and kinematic criteria listed in Section 4;
- ϵ^{vtx}, the probability for a Y(1S) meson passing the acceptance reconstruction criteria outlined in items 2 and 3 to have a vertex fit χ^2 probability above 0.5%;
- ϵ^{evt}, the probability for an event where both Y(1S) candidates pass all the criteria of items 2 and 3, and at least one of them passes the vertex fit χ^2 probability criterion of item 4, to pass the following event-level criteria: the trigger requirements, the four-muon vertex fit χ^2 probability above 5%, and the absence of OS dimuon pairs with an invariant mass within two standard deviations of the world-average J/ψ meson mass [31].

The first three items in the above list are calculated as a function of the Y(1S) rapidity and p_T. The values of A, ϵ^{reco}, and ϵ^{vtx}, range between 0.47 and 1.00, 0.23 and 0.88, and 0.81 and 0.98, respectively, depending on the Y(1S) rapidity and p_T. The factor ϵ^{evt} is calculated as a function of the p_T of both Y(1S) candidates, and ranges between 0.33 and 0.65. The subscript indices in Eq. (2) indicate the Y(1S) candidate to which the weight corresponds. The factor ϵ^{vtx} enters the formula differently from the other acceptance and efficiency terms because the dimuon vertex fit χ^2 probability criterion needs to be satisfied by at least one of the two Y(1S) candidates, but not necessarily by both. The weight ω is computed on an event-by-event basis, using the kinematic quantities of the reconstructed Y(1S) candidates in data. They are estimated from simulation as efficiency maps and are similar for the SPS and DPS production modes, despite different correlations between the mesons. Data-to-simulation corrections for the trigger and muon identification efficiencies are taken into account in the computation of N^{corr}.

In about 3% of cases, the four reconstructed muons are not correctly paired in the SPS and DPS Y(1S) pair simulations. These events cannot be identified as part of the signal by the 2D fit since their distribution is similar to that of the floating combinatorial background. Therefore, the value N^{corr} extracted from the fit is corrected by +3% to take into account these mispairings.

In the 2D fit, the muons are paired as described in Section 4, and the invariant masses of the two pairs are randomly denoted m_{12} and m_{34}. The signal model corresponds to Y(1S) + Y(1S) events, whereas the background model is the sum of the following physics processes:

- Y(2S) + Y(2S);
- Y(3S) + Y(3S);
- Y(2S) + Y(1S);
- Y(3S) + Y(1S);
- Y(1S) + combinatorial background;
- Y(2S) + combinatorial background;
- Y(3S) + combinatorial background;
- combinatorial background + combinatorial background.

The shape of the invariant mass distribution for the Y(1S) component is determined from a 2D fit of the two dimuon invariant masses in the Y(1S) pair SPS simulation. The results are verified to be compatible with those of a fit performed using the simulated DPS events, even if the muon rapidity distributions differ between production modes. The m_{12} and m_{34} distributions are fitted with the sum of two same-mean Crystal Ball functions, which correspond to a power law tail added to a Gaussian core. This allows the radiative tails of the distributions to be well modeled. Fig. 1 shows the projection of the 2D fit on the m_{12} axis for Y(1S)Y(1S) simulated events. The projection on the m_{34} axis is statistically identical and therefore not shown. The fitted mean of the Crys-
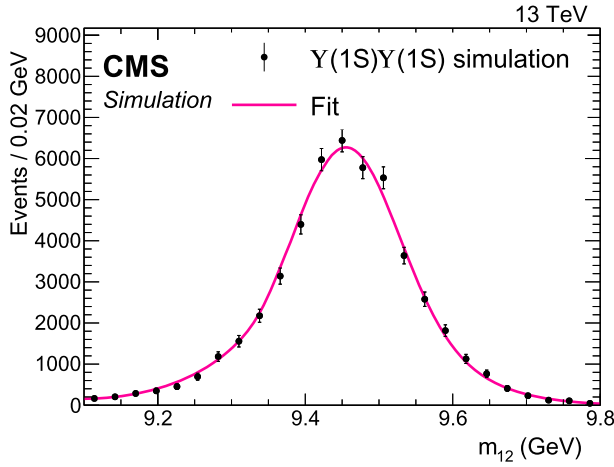
Fig. 1. Projection of the 2D fit (line) to the m_{12} invariant mass distribution (points) for the SPS Y(1S)Y(1S) simulation. The vertical bars on the points show the statistical uncertainty only. The mass distribution is modeled with the sum of two Crystal Ball functions with the same mean.

Table 1
Systematic uncertainties considered in the Y(1S) pair production cross section measurement. The last column gives the associated absolute uncertainty in the measurement of σ_{fid}.

Uncertainty source	Uncertainty (%)	Impact on σ_{fid} (pb)
Integrated luminosity	2.5	2.0
Muon identification	2.0	1.6
Trigger	6.0	4.7
Vertex probability	1.0	0.8
$\mathcal{B}(Y(1S) \to \mu^+\mu^-)$	4.0	3.2
Signal and background models	1.2	1.0
Method closure	1.5	1.2
Total	8.1	6.4

tal Ball functions in simulation is compatible within one standard deviation with the world-average mass of the Y(1S) meson, while the full width at half maximum is about 0.19 GeV, which is several orders of magnitude larger than the world-average width of the Y(1S) meson [31] because of the limited detector resolution.

The contributions from Y(2S) and Y(3S) mesons are small, and the dimuon invariant mass distributions for these mesons are taken from a control region in data with events with two muons and two additional tracks that do not correspond to muon candidates. Both processes are modeled with a Gaussian function.

The combinatorial background components in the m_{12} and m_{34} distributions are modeled with second-order Chebychev polynomials with identical parameters. The number of degrees of freedom has been determined with a Fisher F-test [32], where the distribution of the combinatorial background is found by inverting the muon pair association in the signal region. The parameters of the polynomial are free to float in the 2D fit to data in the signal region, detailed in Section 5.3.

In the 2D fit to the data performed in the signal region, the free parameters are the normalizations of all the processes and the parameters of the combinatorial background mass distribution. The function parameters of the Y(1S), Y(2S), and Y(3S) signal shapes are constrained within their uncertainties.

5.2. Systematic uncertainties

The normalization uncertainties that affect the measurement are the following:

- 2.5% uncertainty in the integrated luminosity for the 2016 running period [33], which appears in Eq. (1).
- 0.5% uncertainty per muon in the efficiency of the muon identification and tracking, measured with a tag-and-probe method [17]. It sums up to 2% per event because the uncertainties are assumed to be correlated for the four muons since they mostly originate from the same source. This uncertainty is related to the term ϵ^{reco} in the weight ω.
- 1% uncertainty in the vertex fit χ^2 probability criterion, determined by comparing background-subtracted observed and simulated distributions of the vertex fit χ^2 probability for events with a Y(1S) meson and two nearby tracks. This uncertainty is related to the term ϵ^{vtx} in the weight ω.
- 2% uncertainty per muon matched to trigger objects in the trigger efficiency, measured with a tag-and probe method,

summing up to 6% per event because the uncertainties are assumed to be correlated for the three muons required at trigger level. This uncertainty is related to the term ϵ^{evt} in the weight ω.

These normalization uncertainties propagate directly into identical uncertainties in the Y(1S) pair production cross section. Additionally, the uncertainty of 2% in the $\mathcal{B}(Y(1S) \to \mu^+\mu^-)$ branching fraction, which is used to compute N^{corr} based on Eq. (1), results in a 4% uncertainty in the Y(1S) pair production cross section measurement.

The parameters of the combinatorial background are freely floating, while the parameters of the Y(1S)Y(1S) distributions are constrained within the uncertainties obtained from the fit to simulated events. An uncertainty of 0.2% in the muon momentum scale is propagated as an uncertainty in the mean of the Y(1S) model. These uncertainties in the signal and background model together contribute an uncertainty of 1.5% in the Y(1S) pair production cross section measurement.

The consistency of the method to obtain N^{corr} is checked by applying the efficiency and acceptance weights to the events selected in simulation, and comparing the computed N^{corr} to the number of events generated in the fiducial region before applying any selection criterion. This test is performed for both the SPS and DPS simulations using the correction maps derived from one sample, the other one, or their combination. Using the combined map, the weighted DPS yield has a deviation of $(-1.3 \pm 3.7)\%$ with respect to the generated yield, and the corresponding deviation for the SPS sample is $(-0.6 \pm 1.5)\%$. The level of closure is similarly good for both production modes despite average event weights differing by more than a factor of 3 because of the kinematic differences. The weighted number of data events used to compute the Y(1S) pair production cross section is increased by 1% to allow for a potential nonclosure, and an uncertainty of 1.5% is associated with this correction.

The systematic uncertainties are summarized in Table 1.

5.3. Measurement of the fiducial cross section

The 2D unbinned fit to the m_{12} vs. m_{34} distribution yields $N^{\text{corr}} = 1740 \pm 240$ for the Y(1S)Y(1S) process. The projections on both dimensions with all the fit components are shown in Fig. 2. This number of events can be translated into an inclusive cross section for the Y(1S)Y(1S) process in the fiducial region defined such that both Y(1S) mesons have an absolute rapidity below 2.0. Taking into account the statistical and systematic uncertainties described in Section 5.2, and assuming unpolarized Y(1S) mesons, the inclusive fiducial cross section is measured to be:

$$\sigma_{\text{fid}} = 79 \pm 11\,(\text{stat}) \pm 6\,(\text{syst}) \pm 3\,(\mathcal{B})\ \text{pb},\qquad(3)$$

where the last uncertainty comes from the uncertainty in the Y(1S) dimuon branching fraction.
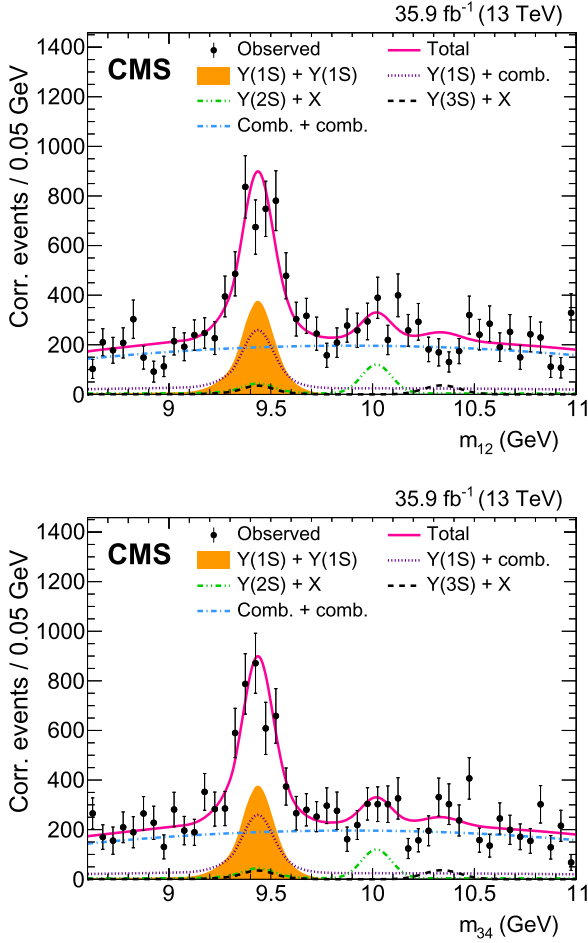
Fig. 2. The two projections and the result of the 2D fit to the muon pair invariant masses. Each event is corrected for acceptance and efficiency. The Y(1S) pair production signal is shown as a filled area. The contributions from the combinatorial background, and from events with a Y(1S) meson and a pair of combinatorial muons, with a Y(2S) meson and two reconstructed muons from any origin, and with a Y(3S) meson and two reconstructed muons from any origin, are overlaid.

Table 2
The unweighted number of events for each of the processes from the fit to the m_{12} and m_{34} distributions without acceptance nor efficiency corrections.

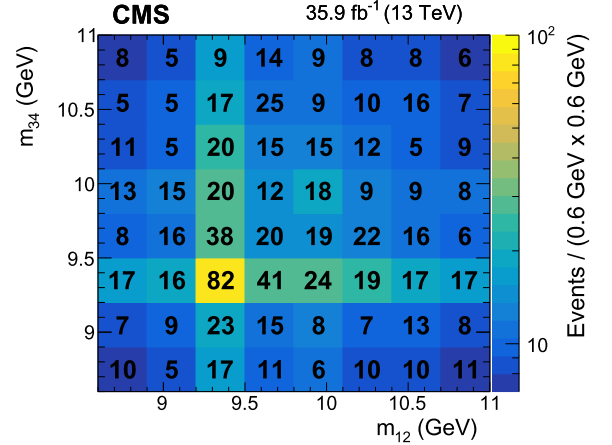| Process	Uncorrected yield
Y(1S) + Y(1S)	111 ± 16
Y(2S) + Y(2S)	$3.6^{+4.4}_{-3.6}$
Y(3S) + Y(3S)	$1.1^{+1.4}_{-1.1}$
Y(1S) + combinatorial	166 ± 33
Y(2S) + combinatorial	25 ± 18
Y(3S) + combinatorial	$1.1^{+11}_{-1.1}$
Y(2S) + Y(1S)	19 ± 10
Y(3S) + Y(1S)	17 ± 11
Combinatorial + combinatorial	561 ± 41

Fig. 3. The number of data events in each 0.6 GeV × 0.6 GeV bin of the m_{12} vs. m_{34} distribution is shown. The results of the maximum-likelihood fit to the signal+background model are given by the colors, using the color scale to the right of the plot.

The CMS Collaboration previously measured, in the same fiducial region, the Y(1S)Y(1S) production cross section at a center-of-mass energy of 8 TeV to be $69 \pm 13\,(\text{stat}) \pm 7\,(\text{syst}) \pm 3\,(\mathcal{B})$ pb [2]. Assuming all uncertainties are uncorrelated with those in the result presented in this Letter except that in the branching fraction of the Y(1S) meson to muons, the measured ratio of the cross section at a center-of-mass of 13 TeV to that at 8 TeV is 1.14 ± 0.32, where the uncertainty includes both the statistical and systematic components. The PYTHIA generator predicts a ratio of 2.1 for DPS production, and 1.6 for the SPS production. Taking the fraction of the DPS mechanism in the total cross section $f_{\text{DPS}} = (39 \pm 14)\%$ at a center-of-mass energy of 13 TeV, as measured in Section 5.5, the cross section ratio predicted by PYTHIA is 1.79 ± 0.27. Combining the uncertainties in quadrature, the prediction is within two standard deviations of the measurement.

Another unbinned extended maximum likelihood fit is performed to extract the number of Y(1S)Y(1S) events observed in data after the selection. The Y(1S)Y(1S) unweighted signal yield is obtained from a fit where all observed events have a weight of 1.0. For this fit, a separate signal shape is determined by fitting the m_{12} and m_{34} distributions in the unweighted simulation. The absence of weighting does not significantly modify the signal distribution. The unweighted event yields are given for all processes in Table 2. There is no evidence for the simultaneous production of two excited states of the Y meson, but excesses with a significance

lower than two standard deviations indicate the possible presence of Y(1S)Y(2S) and Y(1S)Y(3S) events. The number of events from data in the m_{12} vs. m_{34} distribution is shown in Fig. 3, along with the results of the fit to the signal+background model, using the color scale to the right of the plot.

5.4. Effect of the polarization

The acceptance and efficiency corrections have been computed assuming negligible polarization of the Y(1S) mesons. A different assumption on the polarization can change the measured fiducial cross section. The polarization of the Y(1S) states affects the angular distributions of the leptons produced in the Y(1S) → $\mu^+\mu^-$ decays through the following formula [34]:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}\cos\theta\,\mathrm{d}\phi} \propto \frac{1}{3 + \lambda_\theta}(1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi),$$

where θ and ϕ are the polar and azimuthal angles, respectively, of the positively charged muon with respect to the z axis of a polarization frame, and λ_θ, λ_ϕ, and $\lambda_{\theta\phi}$ are the angular distribution parameters. To estimate the effect of the polarization on the measurement of the Y(1S)Y(1S) fiducial cross section, we choose to use the helicity frame, where the polar axis coincides with the direction of the Y(1S) momentum. Measurements performed by the CMS and LHCb Collaborations on single Y production indicate compatibility of all the angular distribution parameters with zero over a large phase space [35,36]. However, the same may not be true for Y(1S) pair production. To estimate the effect of polarization on the Y(1S) pair production cross section, simulated events are

Table 3
Variation of the measured fiducial Y(1S) pair production cross section for several λ_θ coefficient values.

λ_θ	−1.0	−0.5	−0.3	−0.1	+0.1	+0.3	+0.5	+1.0
$\Delta\sigma_{\text{fid}}$	−60%	−22%	−12%	−3.7%	+3.4%	+9.4%	+14%	+25%

reweighted to have the angular distributions corresponding to various λ_θ values, without changing the overall simulated yield. The same efficiency and acceptance corrections as in Eq. (2) are used to calculate N^{corr} for these different polarization scenarios. The variations in the measured Y(1S) pair production cross section are given for different λ_θ coefficients in Table 3. The effect of different polarizations can be substantial, changing the measured cross section by −60 to +25%.

5.5. Measurement of the DPS-to-inclusive fraction

The DPS and SPS mechanisms lead to different kinematic distributions for the Y(1S)Y(1S) events. The DPS production is characterized by a larger separation in rapidity between the mesons, $|\Delta y(Y(1S), Y(1S))|$, as they are largely uncorrelated, and by a larger invariant mass of the meson pairs, $m_{Y(1S)Y(1S)}$. The distributions of $\Delta\phi(Y(1S), Y(1S))$, $\Delta R(Y(1S), Y(1S))$, and $p_T(Y(1S)Y(1S))$ also differ for the SPS and DPS mechanisms, but they are very sensitive to the choice of model parameters in the simulation and are subject to large theoretical uncertainties [37]. Measuring the Y(1S)Y(1S) fiducial cross section in bins of $|\Delta y(Y(1S), Y(1S))|$ or of $m_{Y(1S)Y(1S)}$ can give a measurement of the fraction of DPS events, f_{DPS}, defined as:

$$f_{\text{DPS}} = \frac{\sigma_{\text{fid}}^{\text{DPS}}}{\sigma_{\text{fid}}^{\text{SPS}} + \sigma_{\text{fid}}^{\text{DPS}}}, \qquad (4)$$

where $\sigma_{\text{fid}}^{\text{DPS}}$ and $\sigma_{\text{fid}}^{\text{SPS}}$ are, respectively, the DPS and SPS cross sections in the fiducial region. We measure the fiducial cross section in five bins of $|\Delta y(Y(1S), Y(1S))|$ and five bins of $m_{Y(1S)Y(1S)}$. The signal and background models are the same as for the inclusive measurement, except that the width of the function describing the Y(1S) invariant mass shape is allowed to float between its best-fit values for the inclusive selection and for the selection in the relevant exclusive bin. This allows for a potential degradation (improvement) of the muon momentum resolution at high (low) pseudorapidity to be taken into account, since the muon pseudorapidity is correlated with both $|\Delta y(Y(1S), Y(1S))|$ and $m_{Y(1S)Y(1S)}$. The systematic uncertainties are identical to those presented in Section 5.2.

The extracted fiducial cross sections as a function of $|\Delta y(Y(1S), Y(1S))|$ and $m_{Y(1S)Y(1S)}$ are compared to the expected distributions for SPS and DPS production, as obtained in the fiducial region using PYTHIA for the DPS process, and from HELAC-ONIA with the NLO* CSM predictions for the SPS process. The fraction f_{DPS} is measured with a binned maximum-likelihood fit of these two simulated distributions with floating normalizations to the measured fiducial cross sections in bins of $|\Delta y(Y(1S), Y(1S))|$ and $m_{Y(1S)Y(1S)}$. As determined from pseudo-experiments, the best precision is expected to be achieved using $|\Delta y(Y(1S), Y(1S))|$. Theoretical uncertainties coming from the choice of parton distribution functions and the factorization and renormalization scales are taken into account for both the SPS and DPS predicted distributions. The fraction f_{DPS} is measured to be $(39 \pm 14)\%$ using $|\Delta y(Y(1S), Y(1S))|$ as the discriminative distribution. This results includes both statistical and systematic uncertainties, where the former strongly dominates. The result using $m_{Y(1S)Y(1S)}$ is compatible with this measurement, but with much lower precision: $(27 \pm 22)\%$. The uncertainties are strongly dominated by the
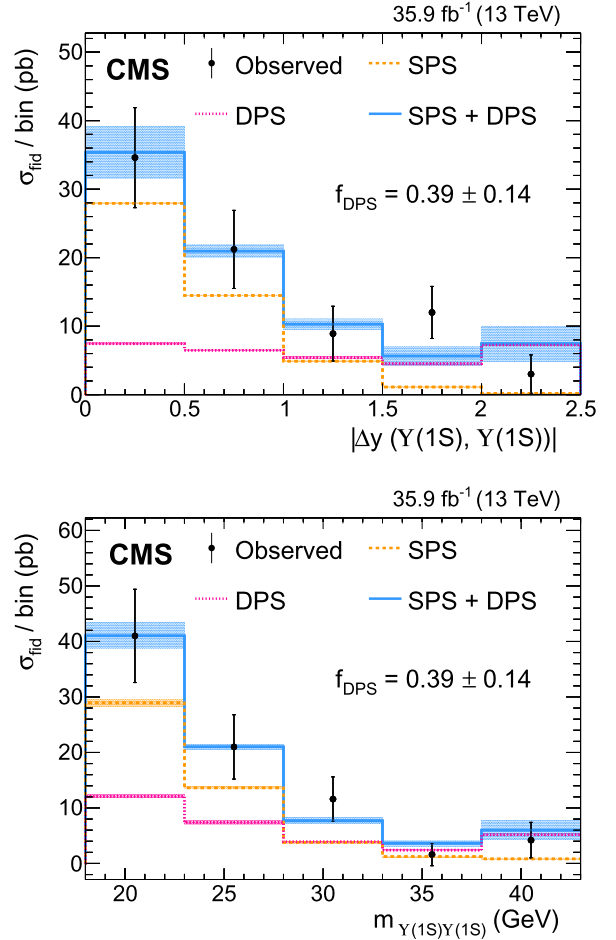

Fig. 4. Measured fiducial cross section (black dots) in bins of $|\Delta y(Y(1S), Y(1S))|$ (upper) or $m_{Y(1S)Y(1S)}$ (lower). The last bin includes the overflow. The SPS and DPS distributions predicted from simulation are overlaid using the f_{DPS} value extracted from the fit to the $|\Delta y(Y(1S), Y(1S))|$ distribution. The shaded areas around the SPS and DPS predictions indicate the theoretical uncertainties, which are often smaller than the thickness of the dashed lines. The shaded area around the total distribution corresponds to the uncertainty in the measurement of f_{DPS}. The solid line shows the sum of the SPS and DPS contributions with the best-fit f_{DPS}.

uncertainties in the measurements of the cross section in the $|\Delta y(Y(1S), Y(1S))|$ and $m_{Y(1S)Y(1S)}$ bins, with theoretical uncertainties in the predicted SPS and DPS distributions playing a role at the percent level. The measured differential fiducial cross sections are shown in Fig. 4, together with the SPS and DPS predictions.

6. Search for resonances

6.1. Methodology

We search for a narrow excess of events above an expected smooth four-muon invariant mass spectrum. Assuming that the resonant state decays into two muons and a Y(1S) meson that further decays to a pair of muons, the signal mass resolution can be improved by using a mass-difference observable [38]:

$$\widetilde{m}_{4\mu} = m_{4\mu} - m_{\mu\mu} + m_{Y(1S)}, \qquad (5)$$

where $m_{4\mu}$ is the invariant mass of the four leptons, $m_{\mu\mu}$ the invariant mass associated with the Y(1S) candidate, and $m_{Y(1S)}$ the nominal mass of the Y(1S) particle (9.46 GeV [31]). This estimated mass, denoted as $\widetilde{m}_{4\mu}$, has a resolution about 50% better than the four-muon invariant mass $m_{4\mu}$ for signal events. The $m_{4\mu}$ and $\widetilde{m}_{4\mu}$ distributions are similar for the combinatorial background.

The results are extracted by performing an unbinned maximum-likelihood fit to the $\widetilde{m}_{4\mu}$ spectrum. The signal and background components are modeled by several functional forms in the fit, as described in the next paragraphs.

The signal distributions are parameterized by the sum of two Gaussian functions with the same mean. The parameters are extracted for the four mass points available in simulation. The signal modeling needs to be interpolated for masses between 16.5 and 26 GeV and extrapolated to masses up to 27 GeV to search for narrow resonances with any mass between 16.5 and 27 GeV. This is done by fitting with polynomials the different parameters of the two Gaussian functions as a function of the generated resonance mass. The same procedure is repeated for every signal model. The full width at half maximum is about 0.2 GeV for a resonance mass of 18 GeV.

The background is separated into two components: the Y(1S)Y(1S) process, which was the signal in Section 5 and is characterized by a sharp rising edge in the $\widetilde{m}_{4\mu}$ spectrum at twice the Y(1S) meson mass, and the combinatorial background, which is described by a smooth function as explained below.

The $\widetilde{m}_{4\mu}$ spectrum for the Y(1S)Y(1S) process is obtained from simulation, and is modeled as the product of a sigmoid function and an exponential function with a negative exponent. The nominal model for the Y(1S)Y(1S) background is taken as an average between the DPS and SPS templates, which is consistent with the measurement of the DPS fraction presented in Section 5.3. Fig. 5 shows the $\widetilde{m}_{4\mu}$ models obtained from simulated DPS and SPS events, together with the average fit model. The number of Y(1S)Y(1S) events in the signal region is extracted, as detailed in Section 5, using the selection designed for the resonance search and without applying the acceptance and efficiency corrections from Eq. (2). In this case, only events with $13 < \widetilde{m}_{4\mu} < 28$ GeV are retained and no rapidity criteria are applied for the reconstructed Y(1S) candidates. The yield is measured to be 78 ± 13 events. The requirement that the mass of a dimuon pair is compatible with the mass of a Y(1S) meson within two standard deviations is enforced in the resonance search but is not applied to extract the yield because the 2D fit relies on the mass tails to estimate the combinatorial background. Since the efficiency of this criterion is 95% in both the SPS and DPS Y(1S)Y(1S) simulations, the Y(1S)Y(1S) yield in the signal region is corrected to 74 ± 13. The normalization of the Y(1S) pair production process and its uncertainty are extracted from the same data as in the signal region of the resonance search, but this does not lead to a significant overconstraint of the uncertainty in the maximum-likelihood fit of the $\widetilde{m}_{4\mu}$ distribution because the latter can determine the Y(1S) pair normalization only with poor precision.

The $\widetilde{m}_{4\mu}$ spectrum for the combinatorial background is obtained in the fit to the data in the signal region. Several generic functions are used to parameterize this smooth background:

- Chebychev polynomials of various orders;
- the sum of a Gaussian function and a Chebychev polynomial;
- the sum of a Breit–Wigner function and a Chebychev polynomial.

The widths of the Gaussian and Breit–Wigner functions are constrained to be above 2 GeV to avoid fitting narrow structures due to statistical fluctuations. We verify, using a control region where the vertex fit χ^2 probability of the four muons is in the range 10^{-10}–10^{-3}, that these three functional forms describe the smooth $\widetilde{m}_{4\mu}$ spectrum of the combinatorial background with a good χ^2 probability. Muons with a vertex probability in this range are likely to be associated with processes from the same primary vertex, but can originate from decays in flight or displaced secondary vertices. This control region is shown in Fig. 6 for illustrative purposes. The
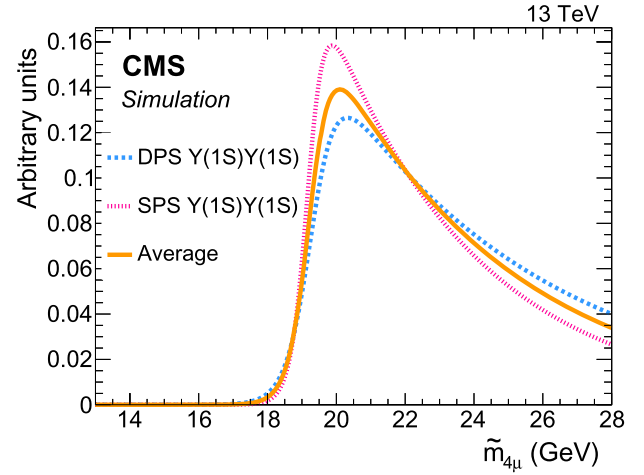

Fig. 5. Distributions of $\widetilde{m}_{4\mu}$ for simulated Y(1S)Y(1S) events. The dashed lines are the best-fit models for the SPS and DPS simulations. The solid line is the average of the SPS and DPS models, which is taken as the nominal model for the Y(1S)Y(1S) background in the resonance search.
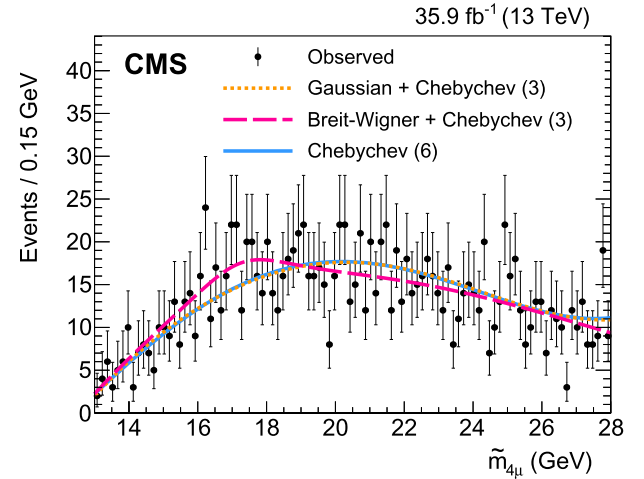

Fig. 6. Distributions of $\widetilde{m}_{4\mu}$ for the combinatorial background in a control region with the vertex fit χ^2 probability of the four muons in the range 10^{-10}–10^{-3}. The parameters obtained in this fit are not used as an input for the fit in the signal region. The functional forms for the combinatorial background shown by the lines are all considered as possible shapes for the background model in the likelihood fit. The order of the polynomials is indicated in parentheses in the legend.

parameters of the functions determined from the fit are not used in the signal region, where the parameters of the combinatorial background, as well as the choice of the functional form, are freely floating.

6.2. Systematic uncertainties

The systematic uncertainties are to a large extent similar to those used in the measurement of the Y(1S)Y(1S) cross section and introduced in Section 5.2. In this section, only the differences are highlighted. They arise from slightly different selection criteria, a different choice of observable, the treatment of the Y(1S)Y(1S) process as a background, and the introduction of a new signal process.

The uncertainty per muon in the muon identification and tracking is increased from 0.5% to 1% because poorly reconstructed muons with $p_T < 3.5$ GeV in the barrel are included in the resonance search to increase the signal acceptance for light resonances. In addition, in the resonance search, the signal is affected by a 1% yield uncertainty related to the requirement that the Y(1S) can-
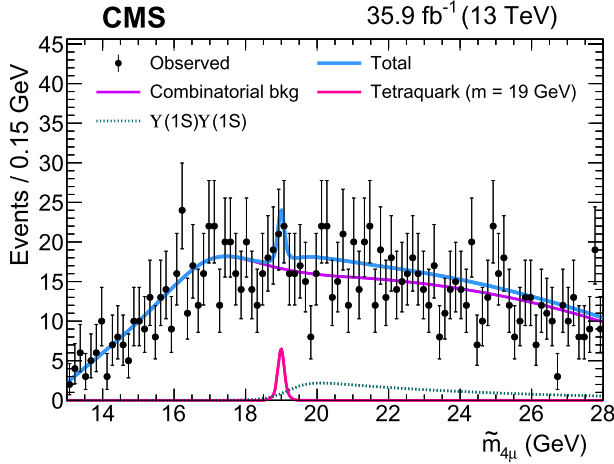
Fig. 7. The $\widetilde{m}_{4\mu}$ distribution from data and the results of the fit in the resonance search. An example signal is shown for the tetraquark model with a mass of 19 GeV, which has a significance of about one standard deviation.

didate has an invariant mass compatible with the nominal Y(1S) meson mass within two standard deviations. This uncertainty is determined by comparing the dimuon invariant mass resolution distributions in Y(1S)Y(1S) simulated events and in Y(1S) events in data. The modeling of the signal process with a resonance mass other than those for which simulated samples were generated leads to a 2% uncertainty in the signal normalization for the resonance search.

The discrete profiling method [39] is used to model the combinatorial background. This allows the choice of the fit functions among those provided to be considered as a discrete nuisance parameter. The parameters of these fit functions are freely floating.

The normalization of the Y(1S)Y(1S) background in the resonance search is extracted from the 2D unbinned fit to the invariant mass of the dimuon pairs in the Y(1S) mass region. The uncertainty in the yield obtained from the fit is considered as a log-normal uncertainty in the fit to the $\widetilde{m}_{4\mu}$ distribution. The $\widetilde{m}_{4\mu}$ distribution of the Y(1S)Y(1S) background is allowed to float between the predictions for the SPS and DPS simulations.

Uncertainties in the $\widetilde{m}_{4\mu}$ distribution of the resonant signal take into account the limited size of the simulated samples, and the limited precision of the description of the signal for masses not available in simulations. The uncertainty in the mean mass of the signal is 0.2%, corresponding to the uncertainty in the muon momentum scale. The other parameters describing the shape of the signal have an uncertainty between 5 and 15%, which leads to a combined impact on the final upper limits of less than 2%.

The uncertainty in the Y(1S) dimuon branching fraction is not considered, since the limits are set on the product of the resonance production cross section and its branching fraction to four muons via an intermediate Y(1S) resonance.

6.3. Results

The binned $\widetilde{m}_{4\mu}$ distribution in the signal region of the resonance search is shown in Fig. 7. The background and example signal components are shown using their best-fit shapes and normalizations. Using the number of Y(1S)Y(1S) events observed in data as a reference, a resonance with a mass around 19 GeV and having a similar production cross section and branching fraction to four muons as the Y(1S)Y(1S) production, would produce about 100 events in our sample, given the similarity between the kinematic distributions of both processes. No significant narrow excess of events is observed above the background expectation. The largest excess is observed for a resonance mass of 25.1 GeV, and

has a local significance of 2.4 standard deviations for the scalar signal hypothesis.

Upper limits on the product of the production cross section of a resonance and the branching fraction to a final state of four muons via an intermediate Y(1S) resonance are set at 95% confidence level (CL) using the modified frequentist construction CL_s in the asymptotic approximation [40–44], separately for each signal model. The upper limits are extracted using unbinned distributions. The cross section is defined in the entire phase space without fiducial requirements, and the branching fraction used is the product of the branching fraction of the resonant state to a Y(1S) meson and two muons, and the branching fraction of the Y(1S) meson to two muons. Masses between 17.5 and 19.5 GeV are probed in the context of the tetraquark search, using the bottomonium model, whereas the limits in the extended mass range 16.5–27 GeV are set for the generic search, using the JHUGEN models. The corresponding upper limits are given in Fig. 8. They range between 5 and 380 fb, depending on the mass and signal model. The patterns in the limits are broader for the spin-2 signal than for the scalar and pseudoscalar states because the signal is characterized by softer and more forward muons, leading to a worse $\widetilde{m}_{4\mu}$ resolution.

7. Summary

The cross section for Y(1S) pair production is measured in the fiducial region where both Y(1S) mesons have an absolute rapidity below 2.0. The measurement is performed using proton-proton collision data collected at a center-of-mass energy of 13 TeV by the CMS detector in 2016 and corresponding to an integrated luminosity of 35.9 fb^{-1}. Assuming that the Y(1S) mesons are produced unpolarized, the fiducial Y(1S) pair production cross section is determined to be $79 \pm 11\,(\text{stat}) \pm 6\,(\text{syst}) \pm 3\,(\mathcal{B})$ pb, where the last uncertainty comes from the uncertainty in the Y(1S) dimuon branching fraction. The result can change if the Y(1S) mesons are produced with a nonzero polarization. Changing the polarization coefficient λ_θ from -1 to $+1$, the resulting Y(1S) pair production cross section measurement varies by -60 to $+25\%$.

The contribution of double-parton scattering to the total inclusive Y(1S) pair production cross section is determined for the first time. It is measured to be $(39 \pm 14)\%$ in the same fiducial region as described above, where the uncertainty includes both statistical and systematic components, with the statistical uncertainty dominating.

The results of a search are also presented for a light narrow resonance, such as a tetraquark or a bound state beyond-the-standard model, decaying to a Y(1S) and a pair of opposite-sign muons. No excess of events compatible with a signal is observed in the four-muon invariant mass spectrum. Upper limits at 95% confidence level on the product of the signal cross section and branching fraction to four muons via an intermediate Y(1S) resonance are set for different signal models, expanding the kinematic and mass coverage of previous searches.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
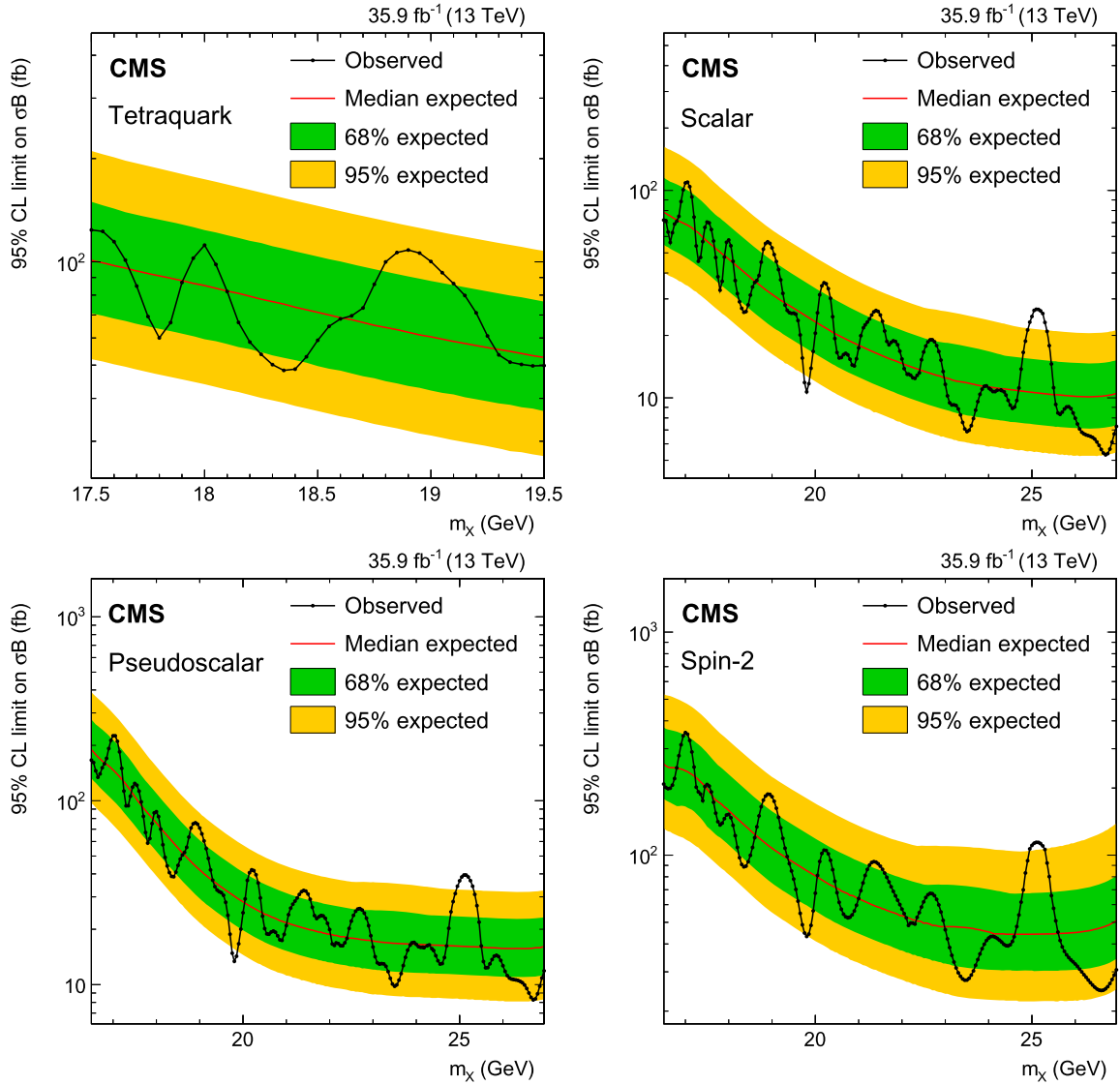
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Fig. 8. Upper limits at 95% CL on the product of the cross section and branching fraction for a tetraquark (upper left), scalar (upper right), pseudoscalar (lower left), and spin-2 (lower right) states. The symbol σ denotes the production cross section of the resonance, and the symbol $\mathcal{B}$ denotes the product of the branching fraction for the decay of the resonance to a Y(1S) meson and two muons, and the Y(1S) meson dimuon branching fraction. The line with the points on it shows the observed upper limits and the thin red line is the median of the expected upper limits. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.

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The CMS Collaboration

A.M. Sirunyan [†], A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambrogi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth [1], M. Jeitler [1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, J. Schieck [1], R. Schöfbeck, M. Spanring, W. Waltenberger, C.-E. Wulz [1], M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Drugakov, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

M.R. Darwish, E.A. De Wolf, D. Di Croce, X. Janssen, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, L. Moureaux, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, I. Khvastunov [2], M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Ghent University, Ghent, Belgium

O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, V. Lemaitre, J. Prisciandaro, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato [3], E. Coelho, E.M. Da Costa, G.G. Da Silveira [4], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, J. Martins [5], D. Matos Figueiredo, M. Medina Jaime [6], M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote [3], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

C.A. Bernardes [a], L. Calligaris [a], T.R. Fernandez Perez Tomei [a], E.M. Gregores [b], D.S. Lemos, P.G. Mercadante [b], S.F. Novaes [a], Sandra S. Padula [a]

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

University of Sofia, Sofia, Bulgaria

W. Fang [7], X. Gao [7], L. Yuan

Beihang University, Beijing, China

M. Ahmad, Z. Hu, Y. Wang

Department of Physics, Tsinghua University, Beijing, China

G.M. Chen [8], H.S. Chen [8], M. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang [8], J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Q. Wang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

M. Xiao

Zhejiang University, Hangzhou, China

C. Avila, A. Cabrera, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

Universidad de Antioquia, Medellin, Colombia

D. Giljanović, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov [9], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

University of Cyprus, Nicosia, Cyprus

M. Finger [10], M. Finger Jr. [10], A. Kveton, J. Tomsa

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

Y. Assran [11,12], S. Elgammal [12]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

F. Garcia, J. Havukainen, J.K. Heikkilä, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini,
S. Laurila, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud,
P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, B. Lenzi, E. Locci, J. Malcles, J. Rander,
A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro [13], M. Titov, G.B. Yu

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

S. Ahuja, C. Amendola, F. Beaudette, M. Bonanomi, P. Busson, C. Charlot, B. Diab, G. Falmagne,
R. Granier de Cassagnac, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini,
J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Paris

J.-L. Agram [14], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte [14],
J.-C. Fontaine [14], D. Gelé, U. Goerlach, C. Grimault, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

S. Gadrat

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, R. Chierici, D. Contardo, P. Depasse,
H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage,
M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

T. Toriashvili [15]

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze [10]

Tbilisi State University, Tbilisi, Georgia

C. Autermann, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz,
M. Teroerde

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

M. Erdmann, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo,
M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook,
A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma,
S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

G. Flügge, W. Haj Ahmad [16], O. Hlushchenko, T. Kress, T. Müller, A. Nowack, C. Pistone, O. Pooth, D. Roy,
H. Sert, A. Stahl [17]

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Aldaya Martin, P. Asmuss, I. Babounikau, H. Bakhshiansohi, K. Beernaert, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras [18], V. Botta, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo [19], A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, A. Jafari, N.Z. Jomhari, H. Jung, A. Kasem [18], M. Kasemann, H. Kaveh, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann [20], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, R.E. Sosa Ricardo, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev, R. Zlebcik

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, T. Dreyer, A. Ebrahimi, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, T. Lange, A. Malara, J. Multhaup, C.E.N. Niemeyer, A. Reimers, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald, I. Zoi

University of Hamburg, Hamburg, Germany

M. Akbiyik, M. Baselga, S. Baur, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann [17], C. Heidecker, U. Husemann, M.A. Iqbal, S. Kudella, S. Maier, S. Mitra, M.U. Mozer, D. Müller, Th. Müller, M. Musich, A. Nürnberg, G. Quast, K. Rabbertz, D. Schäfer, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, C. Wöhrmann, R. Wolf, S. Wozniewski

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

M. Diamantopoulou, G. Karathanasis, P. Kontaxakis, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas, F.A. Triantis, D. Tsitsonis

University of Ioánnina, Ioánnina, Greece

M. Bartók [21], R. Chudasama, M. Csanad, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath [22], F. Sikler, V. Veszpremi, G. Vesztergombi [†]

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [21], J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, D. Teyssier, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo, W.J. Metzger, F. Nemes, T. Novak

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati [24], C. Kar, G. Kole, P. Mal, V.K. Muraleedharan Nair Bindhu, A. Nayak [25], D.K. Sahoo [24], S.K. Swain

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra [26], R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi

Panjab University, Chandigarh, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

University of Delhi, Delhi, India

R. Bhardwaj [27], M. Bharti [27], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep [27], D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber [28], M. Maity [29], K. Mondal, S. Nandan, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh [27], S. Thakur [27]

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, P.R. Pujahari, A. Sharma, A.K. Sikdar

Indian Institute of Technology Madras, Madras, India

D. Dutta, V. Jha, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, Ravindra Kumar Verma

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo, S. Sawant

Tata Institute of Fundamental Research-B, Mumbai, India

S. Dube, B. Kansal, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chenarani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], R. Aly [a,b,30], C. Calabria [a,b], A. Colaleo [a], D. Creanza [a,c], L. Cristella [a,b], N. De Filippis [a,c], M. De Palma [a,b], A. Di Florio [a,b], W. Elmetenawee [a,b], L. Fiore [a], A. Gelmi [a,b], G. Iaselli [a,c], M. Ince [a,b], S. Lezki [a,b], G. Maggi [a,c], M. Maggi [a], J.A. Merlin [a], G. Miniello [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a], A. Ranieri [a], G. Selvaggi [a,b], L. Silvestris [a], F.M. Simone [a,b], R. Venditti [a], P. Verwilligen [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*

ᶜ *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], C. Battilana [a,b], D. Bonacorsi [a,b], L. Borgonovi [a,b], S. Braibant-Giacomelli [a,b],
R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], C. Ciocca [a], G. Codispoti [a,b], M. Cuffiani [a,b],
G.M. Dallavalle [a], F. Fabbri [a], A. Fanfani [a,b], E. Fontanesi [a,b], P. Giacomelli [a], C. Grandi [a], L. Guiducci [a,b],
F. Iemmi [a,b], S. Lo Meo [a,31], S. Marcellini [a], G. Masetti [a], F.L. Navarria [a,b], A. Perrotta [a], F. Primavera [a,b],
A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b], N. Tosi [a]

ᵃ *INFN Sezione di Bologna, Bologna, Italy*
ᵇ *Università di Bologna, Bologna, Italy*

S. Albergo [a,b,32], S. Costa [a,b], A. Di Mattia [a], R. Potenza [a,b], A. Tricomi [a,b,32], C. Tuve [a,b]

ᵃ *INFN Sezione di Catania, Catania, Italy*
ᵇ *Università di Catania, Catania, Italy*

G. Barbagli [a], A. Cassese, R. Ceccarelli, V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], F. Fiori [a], E. Focardi [a,b],
G. Latino [a,b], P. Lenzi [a,b], M. Meschini [a], S. Paoletti [a], G. Sguazzoni [a], L. Viliani [a]

ᵃ *INFN Sezione di Firenze, Firenze, Italy*
ᵇ *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo [a,b], F. Ferro [a], R. Mulargia [a,b], E. Robutti [a], S. Tosi [a,b]

ᵃ *INFN Sezione di Genova, Genova, Italy*
ᵇ *Università di Genova, Genova, Italy*

A. Benaglia [a], A. Beschi [a,b], F. Brivio [a,b], V. Ciriolo [a,b,17], M.E. Dinardo [a,b], P. Dini [a], S. Gennai [a],
A. Ghezzi [a,b], P. Govoni [a,b], L. Guzzi [a,b], M. Malberti [a], S. Malvezzi [a], D. Menasce [a], F. Monti [a,b], L. Moroni [a],
M. Paganoni [a,b], D. Pedrini [a], S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b], D. Valsecchi [a,b,17], D. Zuolo [a,b]

ᵃ *INFN Sezione di Milano-Bicocca, Milano, Italy*
ᵇ *Università di Milano-Bicocca, Milano, Italy*

S. Buontempo [a], N. Cavallo [a,c], A. De Iorio [a,b], A. Di Crescenzo [a,b], F. Fabozzi [a,c], F. Fienga [a], G. Galati [a],
A.O.M. Iorio [a,b], L. Layer [a,b], L. Lista [a,b], S. Meola [a,d,17], P. Paolucci [a,17], B. Rossi [a], C. Sciacca [a,b],
E. Voevodina [a,b]

ᵃ *INFN Sezione di Napoli, Napoli, Italy*
ᵇ *Università di Napoli 'Federico II', Napoli, Italy*
ᶜ *Università della Basilicata, Potenza, Italy*
ᵈ *Università G. Marconi, Roma, Italy*

P. Azzi [a], N. Bacchetta [a], D. Bisello [a,b], A. Boletti [a,b], A. Bragagnolo [a,b], R. Carlin [a,b], P. Checchia [a],
P. De Castro Manzano [a], T. Dorigo [a], U. Dosselli [a], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a],
S.Y. Hoh [a,b], M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a,b], M. Presilla [b], P. Ronchese [a,b], R. Rossin [a,b],
F. Simonetto [a,b], A. Tiko [a], M. Tosi [a,b], M. Zanetti [a,b], P. Zotto [a,b], A. Zucchetta [a,b], G. Zumerle [a,b]

ᵃ *INFN Sezione di Padova, Padova, Italy*
ᵇ *Università di Padova, Padova, Italy*
ᶜ *Università di Trento, Trento, Italy*

A. Braghieri [a], D. Fiorina [a,b], P. Montagna [a,b], S.P. Ratti [a,b], V. Re [a], M. Ressegotti [a,b], C. Riccardi [a,b],
P. Salvini [a], I. Vai [a], P. Vitulo [a,b]

ᵃ *INFN Sezione di Pavia, Pavia, Italy*
ᵇ *Università di Pavia, Pavia, Italy*

M. Biasini [a,b], G.M. Bilei [a], D. Ciangottini [a,b], L. Fanò [a,b], P. Lariccia [a,b], R. Leonardi [a,b], E. Manoni [a],
G. Mantovani [a,b], V. Mariani [a,b], M. Menichelli [a], A. Rossi [a,b], A. Santocchia [a,b], D. Spiga [a]

ᵃ *INFN Sezione di Perugia, Perugia, Italy*
ᵇ *Università di Perugia, Perugia, Italy*

K. Androsov [a], P. Azzurri [a], G. Bagliesi [a], V. Bertacchi [a,c], L. Bianchini [a], T. Boccali [a], R. Castaldi [a], M.A. Ciocci [a,b], R. Dell'Orso [a], S. Donato [a], L. Giannini [a,c], A. Giassi [a], M.T. Grippo [a], F. Ligabue [a,c], E. Manca [a,c], G. Mandorli [a,c], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], G. Rolandi [a,c], S. Roy Chowdhury [a,c], A. Scribano [a], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], N. Turini, A. Venturi [a], P.G. Verdini [a]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

F. Cavallari [a], M. Cipriani [a,b], D. Del Re [a,b], E. Di Marco [a], M. Diemoz [a], E. Longo [a,b], P. Meridiani [a], G. Organtini [a,b], F. Pandolfi [a], R. Paramatti [a,b], C. Quaranta [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b], L. Soffi [a,b], R. Tramontano [a,b]

[a] *INFN Sezione di Roma, Rome, Italy*
[b] *Sapienza Università di Roma, Rome, Italy*

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], A. Bellora [a,b], C. Biino [a], A. Cappati [a,b], N. Cartiglia [a], S. Cometti [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], J.R. González Fernández [a], B. Kiani [a,b], F. Legger [a], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], E. Monteil [a,b], M. Monteno [a], M.M. Obertino [a,b], G. Ortona [a], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], G.L. Pinna Angioni [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Salvatico [a,b], V. Sola [a], A. Solano [a,b], D. Soldi [a,b], A. Staiano [a], D. Trocino [a,b]

[a] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale, Novara, Italy*

S. Belforte [a], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], A. Da Rold [a,b], G. Della Ricca [a,b], F. Vazzoler [a,b], A. Zanetti [a]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

B. Francois, T.J. Kim, J. Park

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, Y. Roh, J. Yoo

Korea University, Seoul, Republic of Korea

J. Goh

Kyung Hee University, Department of Physics, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, H. Lee, K. Lee, S. Lee, K. Nam, M. Oh, S.B. Oh, B.C. Radburn-Smith, U.K. Yang, H.D. Yoo, I. Yoon

Seoul National University, Seoul, Republic of Korea

D. Jeon, J.H. Kim, J.S.H. Lee, I.C. Park, I.J. Watson

University of Seoul, Seoul, Republic of Korea

Y. Choi, C. Hwang, Y. Jeong, J. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Veckalns [33]

Riga Technical University, Riga, Latvia

V. Dudenas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

F. Mohamad Idris [34], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [35], R. Lopez-Fernandez, A. Sanchez-Hernandez

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

J. Mijuskovic [2], N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler, P. Lujan

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, M.I.M. Awan, Q. Hassan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

V. Avati, L. Grzanka, M. Malawski

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk [36], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

M. Araujo, P. Bargassa, D. Bastos, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, G. Strong, O. Toldaiev, J. Varela

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev [37,38], P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

L. Chtchipounov, V. Golovtcov, Y. Ivanov, V. Kim [39], E. Kuznetsova [40], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko [41], V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

O. Bychkova, R. Chistov [42], M. Danilov [42], S. Polikarpov [42], E. Tarkovskii

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin [43], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Barnyakov [44], V. Blinov [44], T. Dimova [44], L. Kardapoltsev [44], Y. Skovpen [44]

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

A. Babaev, A. Iuzhakov, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

Tomsk State University, Tomsk, Russia

P. Adzic [45], P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic, M. Stojanovic

University of Belgrade, Faculty of Physics and VINCA Institute of Nuclear Sciences, Serbia

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, C.F. Bedoya, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez,

J.M. Hernandez, M.I. Josa, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, C. Willmott

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, S. Sanchez Cruz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Russo [46], L. Scodellaro, I. Vila, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

D.U.J. Sonnadara

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna, N. Wickramage

University of Ruhuna, Department of Physics, Matara, Sri Lanka

T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, A. Caratelli, G. Cerminara, E. Chapon, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, O. Davignon, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita [47], D. Fasanella, S. Fiorendi, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, Y. Iiyama, V. Innocente, T. James, P. Janot, O. Karacheban [20], J. Kaspar, J. Kieseler, M. Krammer [1], N. Kratochwil, C. Lange, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo [17], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas [48], J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada [49], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, R.A. Manzoni, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

ETH Zurich – Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

C. Amsler [50], C. Botta, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, K. Schweiger, Y. Takahashi, S. Wertz

Universität Zürich, Zurich, Switzerland

C.M. Kuo, W. Lin, A. Roy, T. Sarkar [29], S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

A. Bat, F. Boran, A. Celik [51], S. Damarseckin [52], Z.S. Demiroglu, F. Dolek, C. Dozen [53], I. Dumanoglu [54], G. Gokbulut, Emine Gurpinar Guler [55], Y. Guler, I. Hos [56], C. Isik, E.E. Kangal [57], O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir [58], S. Ozturk [59], A.E. Simsek, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

B. Isildak [60], G. Karapinar [61], M. Yalvac [62]

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya [63], O. Kaya [64], Ö. Özçelik, S. Tekten [64], E.A. Yetkin [65]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak [54], Y. Komurcu, S. Sen [66]

Istanbul Technical University, Istanbul, Turkey

S. Cerci [67], B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci [67]

Istanbul University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

E. Bhal, S. Bologna, J.J. Brooke, D. Burns [68], E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [69], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, Gurpreet Singh Chahal [70], D. Colling, P. Dauncey, G. Davies, M. Della Negra, P. Everaerts, G. Hall, G. Iles, M. Komm, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, A. Morton, J. Nash [71], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, T. Strebler, A. Tapper, K. Uchida, T. Virdee [17], N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

Brunel University, Uxbridge, United Kingdom

A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, C. Madrid, B. McMaster, N. Pastika, C. Smith

Baylor University, Waco, USA

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

Catholic University of America, Washington, DC, USA

A. Buccilli, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

A. Albert, D. Arcaro, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, D. Sperka, D. Spitzbart, I. Suarez, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, B. Burkle, X. Coubez [18], D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan [72], K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir [73], R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

Brown University, Providence, USA

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko [†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Los Angeles, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, B.R. Yates, Y. Zhang

University of California, Riverside, Riverside, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, J. Duarte, R. Gerosa, D. Gilbert, B. Hashemi, D. Klein, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, J. Richman, U. Sarica, D. Stuart, S. Wang

University of California, Santa Barbara – Department of Physics, Santa Barbara, USA

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

California Institute of Technology, Pasadena, USA

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, Y. Cheng, J. Chu, A. Datta, A. Frankenthal, K. Mcdermott, J.R. Patterson, D. Quach, A. Ryd, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, R. Heller, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, J. Lewis, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena [43], F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, R. Vidal, M. Wang, H.A. Weber, A. Woodard

Fermi National Accelerator Laboratory, Batavia, USA

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

University of Florida, Gainesville, USA

Y.R. Joshi

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

M.M. Baarmand, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, V. Kumar, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, H. Wang, X. Wang, Z. Wu

University of Illinois at Chicago (UIC), Chicago, USA

M. Alhusseini, B. Bilki [55], K. Dilsiz [74], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili [75], A. Moeller, J. Nachtman, H. Ogul [76], Y. Onel, F. Ozok [77], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

The University of Iowa, Iowa City, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, A.V. Gritsan, W.T. Hung, S. Kyriacou, P. Maksimovic, C. Mantilla, J. Roskes, M. Swartz, T.Á. Vámi

Johns Hopkins University, Baltimore, USA

C. Baldenegro Barrera, P. Baringer, A. Bean, S. Boren, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, D. Majumder, W. Mcbrayer, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

The University of Kansas, Lawrence, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg,
A.C. Mignerey, S. Nabili, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, G. Gomez Ceballos,
M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier,
A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi,
G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

R.M. Chatterjee, A. Evans, S. Guts [†], P. Hansen, J. Hiltbrand, Sh. Jain, Y. Kubota, Z. Lesko, J. Mans,
M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, R. Kamalieddin, I. Kravchenko, J.E. Siado,
G.R. Snow [†], B. Stieger, W. Tabb

University of Nebraska-Lincoln, Lincoln, USA

G. Agarwal, C. Harrington, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, A. Parker, J. Pekkanen,
S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, B. Marzocchi, D.M. Morse,
T. Orimoto, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, J. Bueghly, G. Fedi, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung,
M. Velasco

Northwestern University, Evanston, USA

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon,
W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, Y. Musienko [37], R. Ruchti, P. Siddireddy, G. Smith,
S. Taroni, M. Wayne, A. Wightman, M. Wolf

University of Notre Dame, Notre Dame, USA

J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, W. Ji, A. Lefeld, T.Y. Ling, B.L. Winer

The Ohio State University, Columbus, USA

G. Dezoort, P. Elmer, J. Hardenbrook, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, S. Kwan, D. Lange,
M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, D.H. Miller, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, N. Trevisani, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA

A. Baty, U. Behrens, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton, Z. Tu, A. Zhang

Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

University of Rochester, Rochester, USA

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, S. Stone, S. Thomas

Rutgers, The State University of New Jersey, Piscataway, USA

H. Acharya, A.G. Delannoy, S. Spanier

University of Tennessee, Knoxville, USA

O. Bouhali [78], M. Dalchenko, M. De Mattia, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon [79], H. Kim, S. Luo, S. Malhotra, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa

Wayne State University, Detroit, USA

K. Black, T. Bose, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, T. Ruggles, A. Savin, V. Sharma, W.H. Smith, D. Teague, S. Trembath-Reichert

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.

[1] Also at Vienna University of Technology, Vienna, Austria.

[2] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

[3] Also at Universidade Estadual de Campinas, Campinas, Brazil.

[4] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

[5] Also at UFMS, Nova Andradina, Brazil.

[6] Also at Universidade Federal de Pelotas, Pelotas, Brazil.

[7] Also at Université Libre de Bruxelles, Bruxelles, Belgium.

[8] Also at University of Chinese Academy of Sciences, Beijing, China.

[9] Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia.

[10] Also at Joint Institute for Nuclear Research, Dubna, Russia.

[11] Also at Suez University, Suez, Egypt.

[12] Now at British University in Egypt, Cairo, Egypt.

[13] Also at Purdue University, West Lafayette, USA.

[14] Also at Université de Haute Alsace, Mulhouse, France.

[15] Also at Tbilisi State University, Tbilisi, Georgia.

[16] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.

[17] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

[18] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

[19] Also at University of Hamburg, Hamburg, Germany.

[20] Also at Brandenburg University of Technology, Cottbus, Germany.

[21] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

[22] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

[23] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

[24] Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India.

[25] Also at Institute of Physics, Bhubaneswar, India.

[26] Also at G.H.G. Khalsa College, Punjab, India.

[27] Also at Shoolini University, Solan, India.

[28] Also at University of Hyderabad, Hyderabad, India.

[29] Also at University of Visva-Bharati, Santiniketan, India.

[30] Now at INFN Sezione di Bari ^{a}, Università di Bari ^{b}, Politecnico di Bari ^{c}, Bari, Italy.

[31] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.

[32] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.

[33] Also at Riga Technical University, Riga, Latvia.

[34] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

[35] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.

[36] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

[37] Also at Institute for Nuclear Research, Moscow, Russia.

[38] Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.

[39] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

[40] Also at University of Florida, Gainesville, USA.

[41] Also at Imperial College, London, United Kingdom.

[42] Also at P.N. Lebedev Physical Institute, Moscow, Russia.

[43] Also at California Institute of Technology, Pasadena, USA.

[44] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.

[45] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

[46] Also at Università degli Studi di Siena, Siena, Italy.

[47] Also at INFN Sezione di Pavia ^{a}, Università di Pavia ^{b}, Pavia, Italy, Pavia, Italy.

[48] Also at National and Kapodistrian University of Athens, Athens, Greece.

[49] Also at Universität Zürich, Zurich, Switzerland.

[50] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.

[51] Also at Burdur Mehmet Akif Ersoy University, BURDUR, Turkey.

[52] Also at Şırnak University, Sirnak, Turkey.

[53] Also at Department of Physics, Tsinghua University, Beijing, China.

[54] Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey.

[55] Also at Beykent University, Istanbul, Turkey.

[56] Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey.

[57] Also at Mersin University, Mersin, Turkey.

[58] Also at Piri Reis University, Istanbul, Turkey.

[59] Also at Gaziosmanpasa University, Tokat, Turkey.

[60] Also at Ozyegin University, Istanbul, Turkey.

[61] Also at Izmir Institute of Technology, Izmir, Turkey.

[62] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.

[63] Also at Marmara University, Istanbul, Turkey.

[64] Also at Kafkas University, Kars, Turkey.

[65] Also at Istanbul Bilgi University, Istanbul, Turkey.

[66] Also at Hacettepe University, Ankara, Turkey.

[67] Also at Adiyaman University, Adiyaman, Turkey.

[68] Also at Vrije Universiteit Brussel, Brussel, Belgium.

[69] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

[70] Also at IPPP Durham University, Durham, United Kingdom.
[71] Also at Monash University, Faculty of Science, Clayton, Australia.
[72] Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA.
[73] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[74] Also at Bingol University, Bingol, Turkey.
[75] Also at Georgian Technical University, Tbilisi, Georgia.
[76] Also at Sinop University, Sinop, Turkey.
[77] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[78] Also at Texas A&M University at Qatar, Doha, Qatar.
[79] Also at Kyungpook National University, Daegu, Republic of Korea.