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Search for high-mass exclusive $\gamma\gamma \to \mathrm{WW}$ and $\gamma\gamma \to \mathrm{ZZ}$ production in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS and TOTEM Collaborations*

Abstract

A search is performed for exclusive high-mass $\gamma\gamma \to \mathrm{WW}$ and $\gamma\gamma \to \mathrm{ZZ}$ production in proton-proton collisions using intact forward protons reconstructed in near-beam detectors, with both weak bosons decaying into boosted and merged jets. The analysis is based on a sample of proton-proton collisions collected by the CMS and TOTEM experiments at $\sqrt{s} = 13\,\mathrm{TeV}$, corresponding to an integrated luminosity of $100\,\mathrm{fb}^{-1}$. No excess above the standard model background prediction is observed, and upper limits are set on the $\mathrm{pp} \to \mathrm{pWWp}$ and $\mathrm{pp} \to \mathrm{pZZp}$ cross sections in a fiducial region defined by the diboson invariant mass $m(\mathrm{VV}) > 1\,\mathrm{TeV}$ (with $\mathrm{V} = \mathrm{W}, \mathrm{Z}$) and proton fractional momentum loss $0.04 < \xi < 0.20$. The results are interpreted as new limits on dimension-6 and dimension-8 anomalous quartic gauge couplings.

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*See Appendix A for the list of collaboration members

1 Introduction

A class of proton-proton scattering events at the CERN LHC exists in which the incoming protons radiate high-energy quasireal photons and remain intact, whereas only the two photons interact, as shown in Fig. 1. The protons lose a small fraction of their initial 6.5 TeV energy and are scattered at very small angles. In the CMS experiment, the scattered protons are measured with the Precision Proton Spectrometer (PPS), a set of near-beam detectors located on both sides of the central elements of the CMS detector at around 200 m from the interaction point (IP) [1, 2]. The trajectories of the scattered protons are bent by the LHC magnets between the interaction point and the PPS detectors, which makes it possible to measure their momenta. By reconstructing both protons, the center-of-mass energy of the two-photon collision is determined on an event-by-event basis.

In the present paper, a search is presented for the exclusive production of gauge boson pairs (WW or ZZ) from $\gamma\gamma$ interactions using the PPS. The final state consists solely of the two bosons and the scattered protons, which are reconstructed using PPS. The fully hadronic decay modes of the W and Z bosons are studied. When the gauge bosons are produced with a large boost, as expected in many scenarios beyond the standard model (BSM), decay products of each of the bosons are merged into a single large-area jet.

The branching fraction of the fully hadronic channel for W and Z bosons is the highest (67–70%), but this mode is not accessible without the proton detection because of the very large background from jet production in quantum chromodynamics (QCD) processes. For exclusive production when the protons are measured, the kinematics of the final-state bosons can be independently reconstructed both with the central part of the CMS detector and with PPS. Therefore, for signal events that are correctly identified, the entire 13 TeV collision energy can be reconstructed in the four-body pWWp or pZZp system.

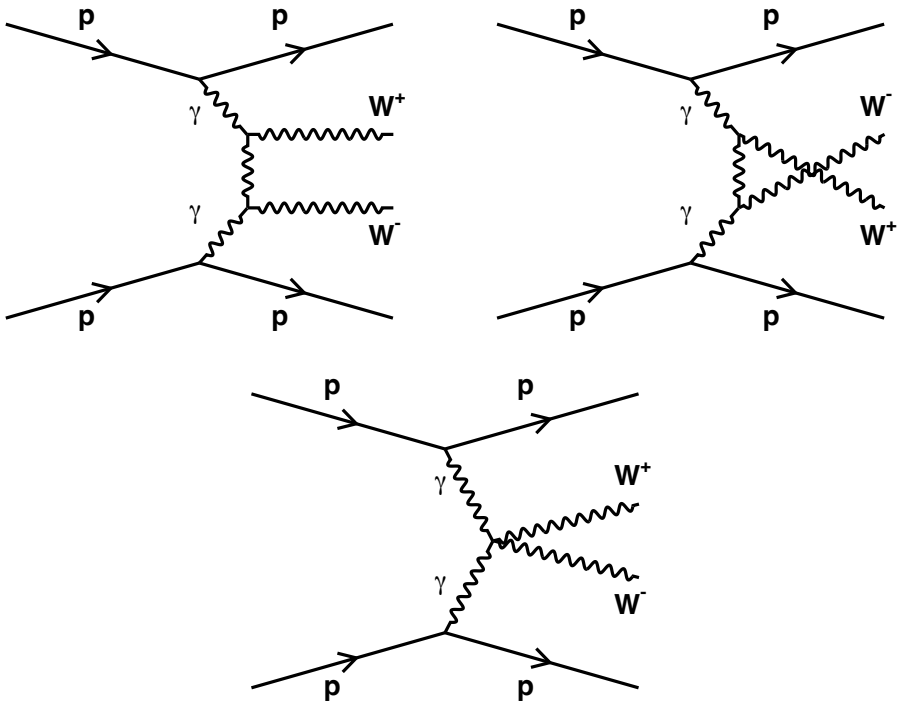

Figure 1: Schematic diagrams of exclusive $\gamma\gamma \to$ WW production with intact protons according to the standard model (SM).

Within the SM, quartic couplings involving two-photon production of charged ($W^{\pm}$) gauge bosons are allowed at tree level, as illustrated in Fig. 1. Because of gauge invariance, the strength of these couplings is related to the triple gauge couplings, which enter through t- and u-channel $\gamma\gamma \to WW$ production, and is fully specified in the SM. The SM cross sections for the $\gamma\gamma \to WW$ and $\gamma\gamma \to ZZ$ processes with both protons intact are expected to be around 50 fb and 0.05 fb, respectively, at $\sqrt{s} = 13\,\text{TeV}$ [3–6], and are concentrated at low values of the VV invariant mass, $m(VV)$. Any significant signal over the prediction, particularly in the high $m(VV)$ tails where the expected SM cross section is small, could indicate BSM physics.

BSM effects on $\gamma\gamma \to VV$ processes are predicted in a variety of models, with both resonant and nonresonant signals [3, 4, 7–13]. A common approach to quantify deviations from the SM with minimal assumptions involves anomalous quartic gauge couplings (AQGCs). Two formalisms commonly used in electroweak studies at the LHC exploit dimension-6 nonlinear operators, and dimension-8 linear operators [14–18], where the terms linear and nonlinear refer to the realization of the broken electroweak symmetry. In the case of the dimension-6 operators, the most general formulation, which was used in the analysis of e^+e^- collisions at LEP [19], has four independent operators. The a_0^W/Λ^2 and a_C^W/Λ^2 operators, where Λ is an energy scale characterizing new physics, will modify the $\gamma\gamma \to WW$ process if they have values different from the SM value of zero. Similarly, nonzero values of the a_0^Z/Λ^2 and a_C^Z/Λ^2 operators will modify the $\gamma\gamma \to ZZ$ process. The detailed definitions of these operators are reported in Refs. [14, 15].

The $\gamma\gamma \to WW$ process without the measurement of the outgoing protons was among several processes used to place the first LHC bounds on such AQGCs using 7 and 8 TeV data [20–24]; constraints were also obtained from 1.96 TeV data at the Tevatron [25]. The cross section was also measured at 13 TeV, using the leptonic channel without proton detection [26]. Recently, strong constraints have been placed on AQGCs using a variety of scattering [23, 24, 27–30] and triple boson production [31] processes at 13 TeV. The first limits on anomalous couplings using forward protons measured with PPS were obtained in searches for high-mass $\gamma\gamma \to \gamma\gamma$ scattering [32].

2 Experimental setup

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) 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. 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. [33].

The Precision Proton Spectrometer is a system of near-beam tracking and timing detectors, located in Roman pots (RPs) at about 200 m from the CMS interaction point [1]. The Roman pots are movable near-beam devices that allow the detectors to be brought very close (within a few mm) to the beam without affecting the vacuum, beam stability, or other aspects of the accelerator operation. The PPS makes it possible to measure the 4-momentum of the scattered protons, along with their time-of-flight from the IP. The proton momenta are measured by two tracking stations on each arm of the spectrometer. The timing, not used for the present

analysis, can be exploited to suppress background from other collisions in the same bunch crossing (pileup).

Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [34]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [35]. The forward proton information from the PPS detector is available in the HLT, but is not used in the HLT selection.

3 Data samples and simulation

The data used for the present analysis were collected at $\sqrt{s} = 13\,\text{TeV}$ in the years 2016–2018. The data are required to pass quality criteria for both PPS and other CMS subdetectors. In the case of PPS, these criteria require the Roman pots to be fully inserted in the data-taking position. Compared with CMS analyses that do not use forward protons, the requirement of having the RPs inserted removes a fraction of data at the beginning and end of each LHC fill. During the first year of operation (2016), a significant amount of time was also devoted to the commissioning of PPS, so the integrated luminosity available for the analysis for that year is only 9.9 fb^{-1}. In the 2017 and 2018 samples, the integrated luminosities of the data meeting the PPS quality criteria are 37.2 fb^{-1} and 52.9 fb^{-1}, respectively, corresponding to nearly 90% of the luminosity available for CMS analyses without forward protons. In total, the three years' data combined correspond to a luminosity of 100 fb^{-1} [36–38].

Signal events are simulated at leading order with the FPMC [5] Monte Carlo (MC) generator, for both the $\gamma\gamma \to \text{WW}$ and $\gamma\gamma \to \text{ZZ}$ channels. The dominant nonexclusive backgrounds from QCD multijet production are simulated at leading order with the PYTHIA 8.205 [39] MC generator with the CUETP8M1 [40] tune for the 2016 samples, and PYTHIA 8.230 with the CP5 [41] tune for the 2017–2018 samples. Backgrounds arising from the production of a W or Z boson in association with jets are simulated at next to leading order (NLO) in QCD with MADGRAPH5_aMC@NLO [42]. The background from pair production of top quarks is simulated at NLO in QCD with POWHEG [43–45]. The parton shower and hadronization for the $\text{W} + \text{jets}$, $\text{Z} + \text{jets}$, and $\text{t}\bar{\text{t}}$ samples are performed with PYTHIA. The SM contribution to the $\gamma\gamma \to \text{WW}$ and $\gamma\gamma \to \text{ZZ}$ processes is expected to be negligible within the kinematic region considered in this analysis.

All of the generated signal and background samples are passed through a detailed GEANT4 [46] simulation of the central part of the CMS detector, extending to $|\eta| < 5$, and reconstructed in the same way as the data. For the signal samples, the forward protons are passed through a "direct" simulation [47], which propagates the protons from the IP to the RP positions, simulates hits in the detector planes, and reconstructs the tracks and proton kinematics in the same way as done for the data. In the background samples, protons from pileup events are not simulated and their effect is estimated from the data, as described later. A realistic mix of beam crossing angles and aperture limitations along the beam line is used when simulating the protons.

4 Event reconstruction

Events are selected online by means of several jet triggers. These are based on either the highest transverse momentum (p_T) jet in the event, or the scalar sum of the p_T values of all jets, H_T.

In some cases, additional requirements on the "trimmed" mass [48] of the jets are imposed, to select jet masses above 30 or 50 GeV. The triggers are identical to those used in the analysis of Ref. [49], where a more detailed description is reported.

The primary vertex (PV) is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [50].

The particle-flow algorithm [51] reconstructs and identifies each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

For each event, hadronic jets are clustered from these reconstructed particles using the infrared and collinear safe anti-k_{T} algorithm [52], as implemented in the FASTJET package [53], with a distance parameter of 0.8. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5 to 10% of the true momentum over the whole p_{T} spectrum and detector acceptance. Additional proton-proton interactions from pileup can contribute with additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, charged particles identified to be originating from pileup vertices are discarded and an offset correction is applied to remove any remaining contributions. Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle-level jets on average. In situ measurements of the momentum balance in dijet, $\gamma +$ jet, Z + jet, and multijet events are used to account for any residual differences in the jet energy scale between data and simulation [54]. The jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [54]. Standard CMS quality criteria are applied to each jet to remove jets potentially dominated by spurious contributions from various subdetector components or reconstruction failures.

Hadronic decays of W and Z bosons are identified using the ratio between 2-subjettiness and 1-subjettiness [55], $\tau_{21} = \tau_2/\tau_1$, and the jet mass $m(\mathrm{j})$ after applying a "pruning" algorithm to reduce the contributions of soft gluon radiation and pileup [56, 57]. The pruning algorithm is a procedure to repeat the initial jet clustering, removing the softest and largest angle components at each step. For each pair of jet constituents the hardness z is defined as the ratio of the minimum p_{T} of the pair to the p_{T} of their combination. The constituent with the lower p_{T} is removed if the hardness is below the threshold $z_{\mathrm{c}} = 0.1$, and if the angular distance relative to the axis of the combination of the two constituents is larger than $D_{\mathrm{c}} = 0.5m/p_{\mathrm{T}}$ (where m and p_{T} are the mass and transverse momentum of the original jet). If neither constituent is removed, they are merged into a new constituent. This procedure is repeated iteratively until all constituents have either been removed or merged. The pruned mass obtained from this final jet is then used in the remainder of the analysis.

The τ_N subjettiness variables are defined by the p_{T} weighted ΔR distance between each jet constituent particle and the nearest subjet. When all constituent particles are close to a correctly identified subjet, τ_N will have a small value indicating the jet is consistent with containing $\leq N$ subjets. The ratio $\tau_{21} = \tau_2/\tau_1$ will then be smaller if the jet is more consistent with con-

taining two subjets, as expected for a W or Z boson, instead of one subjet, as expected for a quark or gluon jet. Since τ_{21} may have an undesirable correlation with the jet mass and p_T, a "Designed Decorrelated Taggers" (DDT) approach [49, 58] was developed to reduce this. Simulated samples are used to extract the slope M of the mean value of τ_{21} vs. ρ', where $\rho' = \ln(m^2_{jet}/(p_T \times 1\,\text{GeV}))$. The slope M is then used to define the decorrelated subjettiness variable $\tau_{21}^{DDT} = \tau_{21} - M\rho'$.

Forward protons are reconstructed using a "multi-RP" algorithm, which combines tracks reconstructed in both of the tracking Roman pots in each arm of PPS. The lever arm between the two RPs allows the reconstruction of the proton scattering angles θ^* (where the superscript "*" indicates an angle defined at the IP) and proton fractional momentum loss ξ:

$$\xi = (p_{nom} - p)/p_{nom}, \tag{1}$$

where p_{nom} and p are the nominal beam momentum and the scattered proton momentum, respectively. PPS provides a ξ resolution of $\leq$5% over the full acceptance [47]. Additional selections are applied to ensure that the protons are within the acceptance of the sensors, and within the aperture constraints defined by the LHC collimators. The LHC conditions and the PPS tracking detector configuration were different for each of the three data-taking years. For this reason, the 2016, 2017, and 2018 samples are analyzed separately, and the results are combined at the end. Further details of the proton reconstruction, including the determination of the beam optics and the detector alignment, are presented in [47, 59, 60].

5 Event selection

Events are selected based on the properties of the jets, the protons, and the correlation between protons and jets.

5.1 Jet selection

The jets are first required to have $p_T > 200\,\text{GeV}$, $|\eta| < 2.5$, and, if more than two pass these criteria, the two with the highest p_T are chosen. In the following, these are labeled j1 and j2, corresponding to the jet with the highest and second-highest p_T, respectively. The pair of jets is required to have a dijet invariant mass $m(jj) > 1126\,\text{GeV}$, where the efficiency of the trigger is >99% relative to the offline selection [49]. The two jets are further required to have a pseudorapidity difference of $|\Delta\eta| < 1.3$ to reduce the QCD multijets background. Figure 2 shows the dijet invariant mass distribution in data and simulation for each of the three years of data taking in the range of interest.

To enhance the exclusive production, the jets are required to be balanced in azimuthal angle and transverse momentum. This is implemented by requiring the acoplanarity ($a = |1 - |(\phi_{j1} - \phi_{j2})|/\pi|$) is < 0.01, and the ratio ($p_T(j1)/p_T(j2)$) is < 1.3. The ϕ resolution for single jets in the region of interest is approximately 0.004 radians, and the resulting efficiency of the $a < 0.01$ requirement is 99% for simulated AQGC signal events.

Finally, the jet substructure properties are exploited to enrich the sample with merged jets from boosted W or Z decays. The pruned mass of the jets is required to be between 60 and 107 GeV, i.e., compatible with the W or Z mass. The constraint retains almost all signal events. The τ_{21}^{DDT} discriminator must be smaller than 0.75, compatible with that expected for two quark jets originating from one boson decay and merged into a single high-momentum jet. From simulation, this requirement retains approximately 85% of anomalous $\gamma\gamma \to WW$ events passing all other jet selection criteria, while rejecting ≈65% of high mass QCD multijet background events.

5.2 W and Z selection

The reconstructed pruned mass of the jets discriminates between the WW and ZZ final states, due to the mass difference between the W and Z bosons. To reduce the two-dimensional space of the pruned jet masses (denoted by $m(\mathrm{j1})$ and $m(\mathrm{j2})$) into a single variable, a simple discriminant based on the sum of $m(\mathrm{j1}) + m(\mathrm{j2})$ is used. The result is shown for simulated signal events in Fig. 3, with two distinct distributions visible, corresponding to the WW and ZZ samples. The resolution of the resulting variable is ≈8 GeV for the WW and 10 GeV for the ZZ sample, correspondingly. The optimal value to separate the two channels is then chosen by first treating one of the channels as signal and the other as background, and then inverting their roles. A single constraint is chosen that maximizes the sum (S(WW)+S(ZZ))/(B(WW)+B(ZZ)), where S indicates that the WW or ZZ candidates are reconstructed in the correct mass region (i.e. the one containing the peak of the WW or ZZ distribution, respectively), and B indicates that they are reconstructed outside that region. A value of $m(\mathrm{j1}) + m(\mathrm{j2}) = 166.6$ GeV provides the best separation between WW and ZZ events; this retains more than 80% of signal for each channel, and corresponds to a signal to background ratio of ≈4.8, with no significant dependence on the anomalous coupling values assumed.

5.3 Proton selection

Only protons with a ξ value greater than 0.05 are retained for the analysis to avoid the region of large radiation-induced inefficiencies of the PPS detectors near the beam. For signal events, the $\xi > 0.05$ requirement is less restrictive than the $m(\mathrm{jj}) > 1126$ GeV condition imposed on the jets. For background events, where the protons are uncorrelated with the jets, the $\xi > 0.05$ and $m(\mathrm{jj}) > 1126$ GeV requirements are independent. The upper bounds imposed by the collimators are different for each of the two arms of the spectrometer, each data-taking period, and each beam crossing angle. The exact upper ξ requirements therefore vary with the data-taking period, generally lying within the range $0.12 \leq \xi \leq 0.20$. The upper mass limit of the centrally produced system (dijet in this analyis) correspondingly varies between 1.55 and 2.01 TeV (for a proton scattering angle of $\theta^* = 0$).

In the 2016 and 2017 data samples, only one proton per event can be reconstructed in each arm of the spectrometer. When multiple protons are present, the pattern recognition is unable to find a unique solution, and no protons are reconstructed in that arm. With improved detectors in 2018, multiple protons can be reconstructed. This leads to an increase in both the expected number of observed signal events S, and the expected number of observed background events B. In terms of the expected significance, estimated as $S/\sqrt{B}$, the use of up to three tracks in each arm leads to ≈7% improvement over using only events with one track. No additional improvement is seen by using events with more than three tracks, where the effect of showers and noncollision backgrounds becomes significant. Therefore, only events with up to three protons per arm are used, and the proton with the largest value of ξ is chosen for the analysis. This is motivated because the anomalous signal cross section is rising with ξ, whereas the SM backgrounds are generally decreasing with ξ. When a simulated signal proton is within the acceptance of the detectors, this choice results in the correct proton being selected 63 to 77% of the time, depending on the arm of the spectrometer. In simulated signal events where both protons are within the acceptance, the probability of correctly selecting at least one of the two is 92%. The use of multiple-proton events leads to both a significantly larger signal efficiency and a larger combinatorial background in the 2018 data, compared with the 2016 or 2017 data.

5.4 Proton-jet matching and signal region

The matching between the proton and jet kinematics for exclusive signal is based on the variables $1 - m(\mathrm{VV})/m(\mathrm{pp})$ and $y(\mathrm{pp}) - y(\mathrm{VV})$. Here $m(\mathrm{VV})$ and $y(\mathrm{VV})$ represent the invariant mass and rapidity of the WW or ZZ system, as reconstructed from the merged jets. The variables $m(\mathrm{pp})$ and $y(\mathrm{pp})$ are the expected invariant mass and rapidity of the central system, calculated from the proton information:

$$m(\mathrm{pp}) = \sqrt{s}\sqrt{\xi_{\mathrm{p1}}\xi_{\mathrm{p2}}}, \qquad y(\mathrm{pp}) = -\frac{1}{2}\ln\left(\frac{\xi_{\mathrm{p1}}}{\xi_{\mathrm{p2}}}\right). \tag{2}$$

The resolution of $m(\mathrm{pp})$ is estimated to be 2.3% from simulation. Two signal regions are defined by comparing the invariant mass and rapidity of the WW or ZZ system obtained from the jets with the same quantities inferred from the two protons. A diamond-shaped area in the $y(\mathrm{pp}) - y(\mathrm{VV})$ vs. $1 - m(\mathrm{VV})/m(\mathrm{pp})$ plane, centered around zero, contains the bulk of the signal when both protons are correctly associated to the jets ("region δ"). In case one of the signal protons is missed and a pileup proton is used instead, the events tend to fall in one of the two diagonal bands of Fig. 4. A second signal region ("region o") is therefore defined based on these bands. The dimensions of the two regions are optimized to provide the best expected signal significance, estimated as $S/\sqrt{B}$. Of the simulated signal events passing all other selections, typically between 19 and 25% are contained in region δ, and a similar fraction in region o. The area with $|1 - m(\mathrm{VV})/m(\mathrm{pp})| < 1.0$ and $|y(\mathrm{pp}) - y(\mathrm{VV})| < 0.5$, encompassing both signal regions, remained blinded and was not examined until the selection criteria and background estimation methods were fixed.

6 Background estimation

The background is mainly due to jets produced in one pp collision combined with unrelated protons from pileup interactions in the same bunch crossing. The largest source of jets is QCD multijet production, with smaller contributions from W or Z bosons in association with jets, and $\mathrm{t\bar{t}}$ production. The protons predominantly arise from diffractive pileup interactions, which are not expected to be well modeled by simulations. For this reason, we rely mainly on data to estimate the background.

The nominal background estimate is derived by inverting the dijet acoplanarity requirements, and/or the dijet-proton matching requirements, to define three independent sideband regions. The first (region B) is defined by acoplanarity $a > 0.01$, with the signal region selection applied in $|1 - m(\mathrm{WW})/m(\mathrm{pp})|$ and $|y(\mathrm{pp}) - y(\mathrm{WW})|$. The second region (region C) has $a < 0.01$, and $|1 - m(\mathrm{WW})/m(\mathrm{pp})| > 1.0$ or $|y(\mathrm{pp}) - y(\mathrm{WW})| > 0.5$. The third (region D) is defined by $a > 0.01$, and $|1 - m(\mathrm{WW})/m(\mathrm{pp})| > 1.0$ or $y(\mathrm{pp}) - y(\mathrm{WW}) > 0.5$. If the numbers of events in each of these regions are N_{B}, N_{C}, and N_{D}, respectively, the expected number of events in the signal region is then $N_{\mathrm{A}} = (N_{\mathrm{B}}\, N_{\mathrm{C}})/N_{\mathrm{D}}$.

Figure 5 illustrates the distribution of data in these regions for the 2018 data with the WW selection. Data selected with the acoplanarity requirement $a > 0.01$ (referred to as the anti-acoplanarity region/method in the following) are compared with the predicted background from simulation in Fig. 6, for each of the years and in both the WW and ZZ mass regions. In general, the data are well reproduced by the simulation, apart from a small excess at low masses in the 2016 WW sample. Since the final background estimate is obtained entirely from the data, such minor discrepancies do not impact the results. For values of the anomalous couplings near

the expected sensitivity of the analysis, the signal contamination in the sideband regions ranges from < 0.1 to $< 2.7\%$, where we have conservatively used a 95% CL limit in the various data-taking periods and regions where zero signal MC events actually pass the sideband constraints.

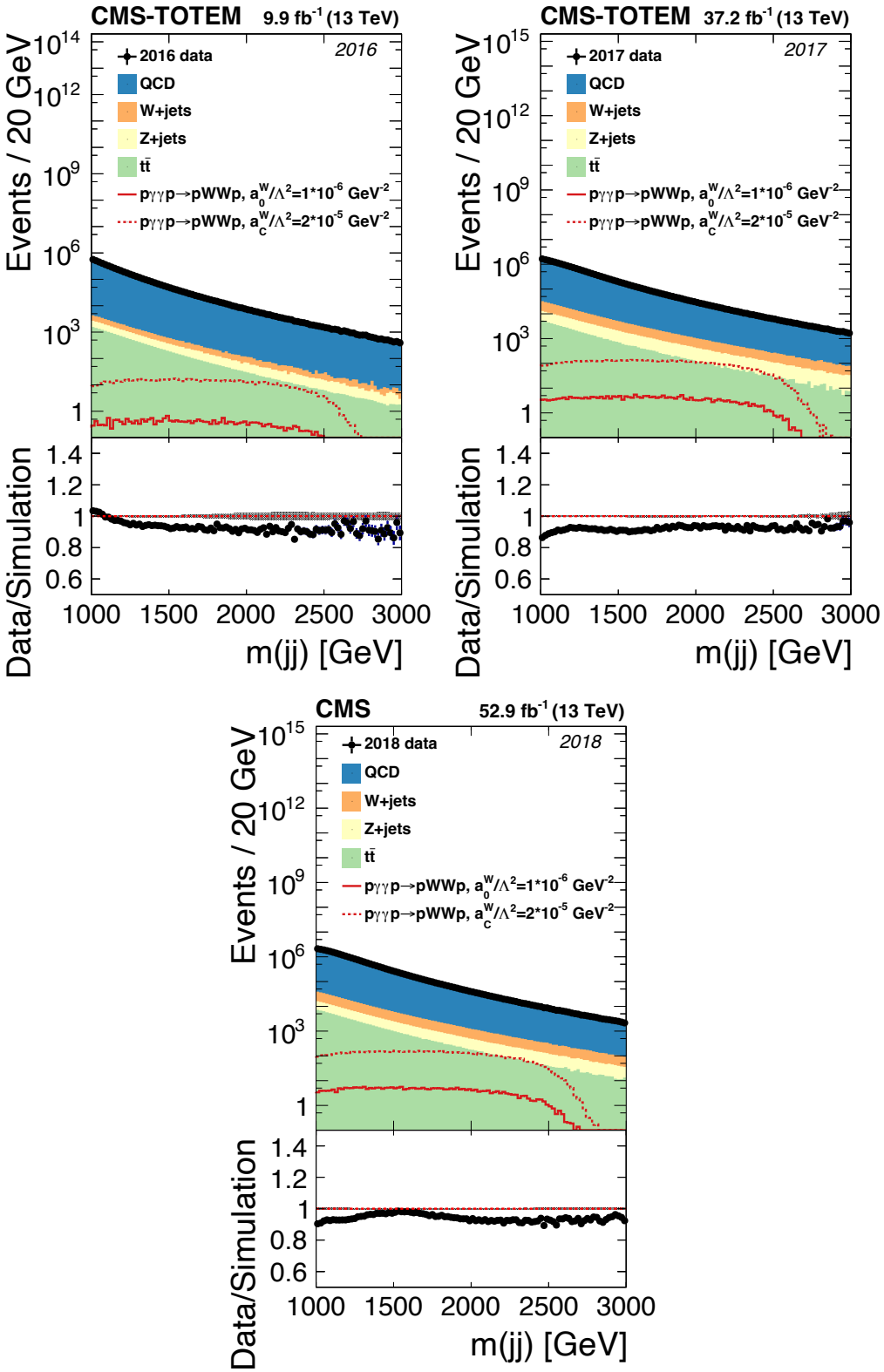

Figure 2: Dijet invariant mass spectra in data and simulation, for the years 2016 (upper left), 2017 (upper right), and 2018 (lower). The distributions of number of events show data compared with the stacked background predictions from simulation, with the corresponding ratios of data to the sum of simulated backgrounds, shown below them. The plots are shown at the preselection level, with no requirements on the protons, jet substructure, or dijet balance. Examples of simulated signals are shown for protons generated in the range of $0.01 \leq \xi \leq 0.20$. Only statistical uncertainties (dashed grey bands) are shown.

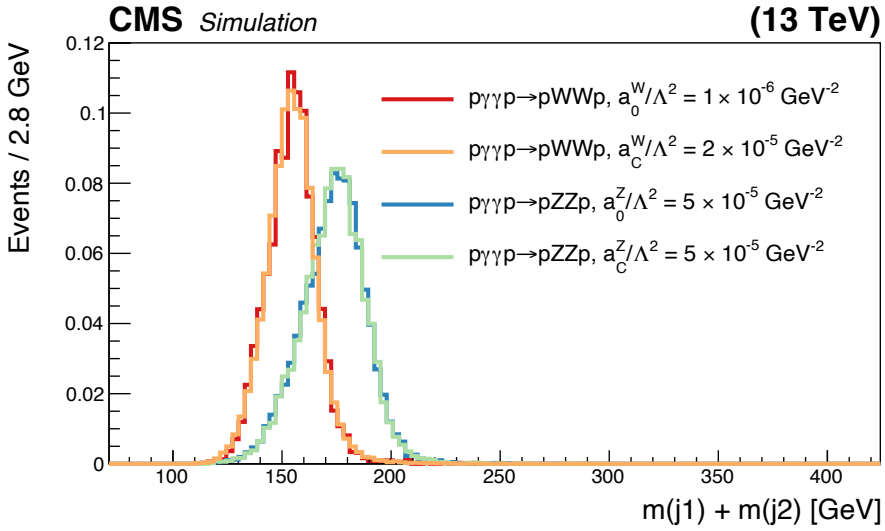

Figure 3: Event distribution as a function of the discriminant described in the text for simulated WW and ZZ signal events.

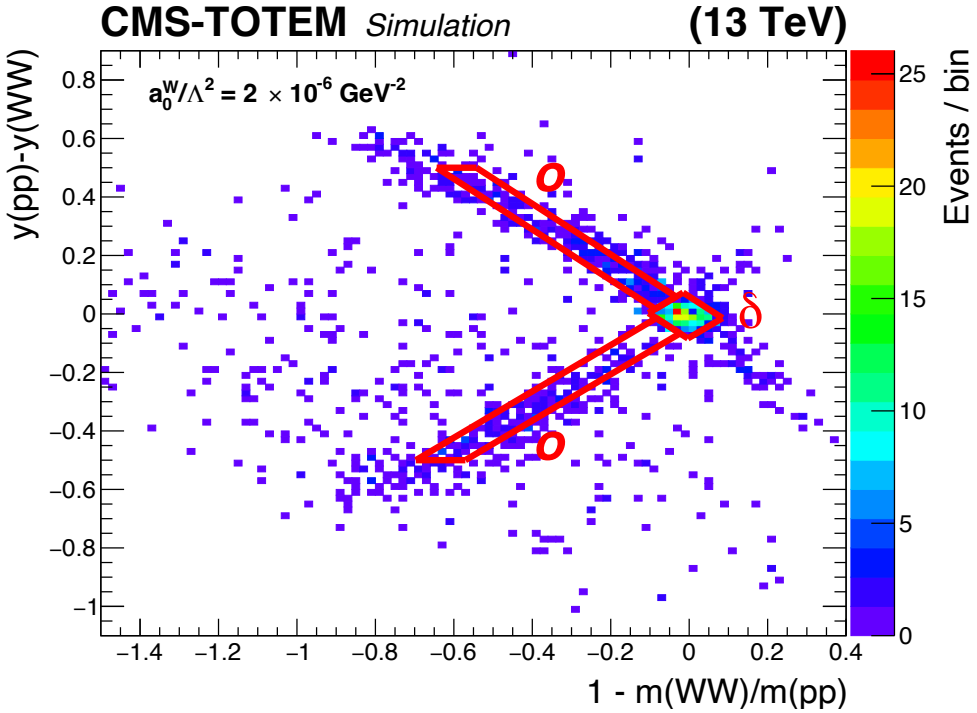

Figure 4: Matching between the jets and the protons, in invariant mass and rapidity, for simulated WW exclusive signal events. The red diamond-shaped area near the origin (signal region δ) corresponds to the case where both protons are correctly matched to the jets. The areas within the red diagonal bands (signal region o) correspond to the case where one proton is correctly matched, and the second proton originates from a pileup interaction.

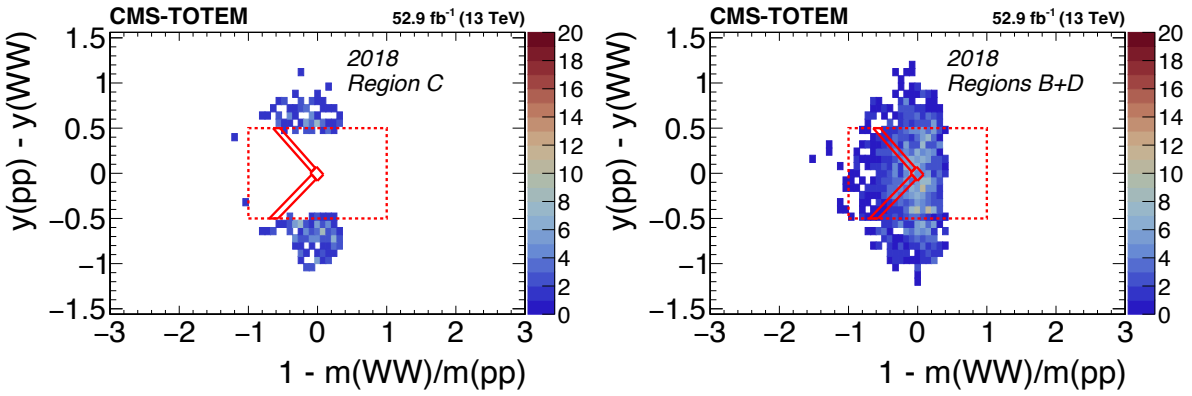

Figure 5: Distribution of the 2018 data in the $y(\mathrm{pp}) - y(\mathrm{VV})$ vs $1 - m(\mathrm{VV})/m(\mathrm{pp})$ plane in the WW mass region. On the left, the sample with all selections applied is shown, except that the region inside the dashed lines remains blinded. On the right, the region with the acoplanarity requirement inverted is shown. The solid lines indicate the same signal regions as shown in Fig. 4. In the right plot the area inside the solid lines corresponds to "region B", while the area outside the dashed lines corresponds to "region D". The color scale on the z axis indicates the number of events in each bin.

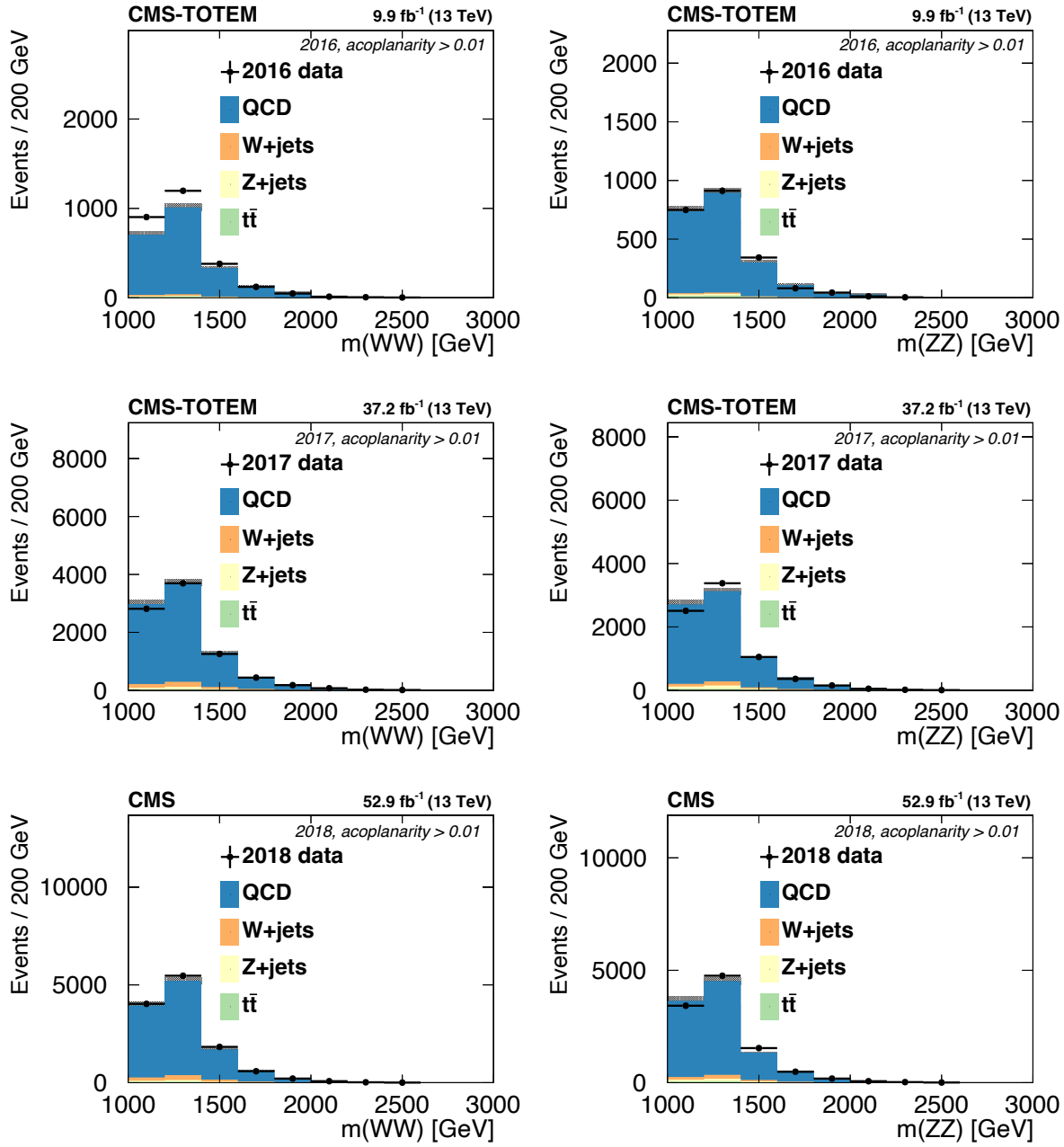

Figure 6: Diboson invariant mass distributions in data and simulation in the anti-acoplanarity region ($a > 0.01$), with no requirement on the proton matching. The plots from top to bottom are for the 2016, 2017, and 2018 data, respectively, with the WW region in the left column and the ZZ region in the right column. Only statistical uncertainties (dashed grey bands) are shown.

As an alternative background model, we perform the same procedure, except that the selection on the pruned masses of both jets is inverted ($m(\mathrm{j}) < 60\,\mathrm{GeV}$ or $m(\mathrm{j}) > 107\,\mathrm{GeV}$), rather than that on the acoplanarity. This method is used only to derive systematic uncertainties.

Finally, as a cross-check we also estimate the background using an event-mixing approach, in which the simulated background events for the central detectors are mixed with protons from real data, randomly drawn from the jet-triggered data sample. This procedure is repeated 1000 times, and the mean and root-mean-square (RMS) of the resulting number of events selected in these pseudoexperiments are taken as the background estimate and uncertainty. In the δ region of the 2016 and 2017 data, the number of expected background events is near zero, and the RMS uncertainties can extend to cover negative values. In these cases we instead consider only the mean and upper limit on the background prediction, where the upper limit is determined by finding the value that contains 95% of the pseudoexperiment results. This procedure has the drawback of relying on simulation for the central jet samples, and explicitly assumes that the protons always originate from different interactions than the jets. Thus, it is not used in the final background estimate, but only as an independent cross-check. Additionally, we use the simulation to perform a closure test of the nominal background estimation method, by using the yields in regions B, C, and D to predict the background in region A, and comparing that prediction with the actual number of simulated background events in region A. No statistically significant differences are observed.

The resulting background estimates and statistical uncertainties, for all years and signal regions, are shown in Tables 1 and 2 for the default method and the alternative method, based on inversions of the acoplanarity and pruned mass requirements, respectively. In these approaches, the origin of the statistical uncertainties is mainly the limited number of events failing the central detector selections but passing the dijet-proton matching ("region B"). The results of the event mixing method are also shown, with statistical uncertainties dominated by the limited number of simulated QCD events. When the event mixing method predicts a small number of background events, only the mean and upper limit are shown.

In general, the estimates obtained from the different methods are compatible, given the statistical uncertainties. In all methods the background is dominated by QCD multijet production, with other backgrounds contributing $\leq$8% of the total, according to the Monte Carlo simulation. The background and expected AQGC signal levels in 2018 are much larger than for the other years. In addition to the increase in integrated luminosity, this reflects the improvements in the PPS tracking detectors and ability to reconstruct multiple protons, which significantly improves the signal efficiency but also increases the number of observed background proton tracks. For all years and regions the expected SM $\gamma\gamma \to \mathrm{WW}$ signal is less than 0.07 events (Table 1). This is primarily due to the high dijet invariant mass requirement of $m(\mathrm{jj}) > 1126\,\mathrm{GeV}$ imposed at the preselection level, which reduces the expected signal by more than three orders of magnitude. The less boosted W bosons from the SM signal are also less likely to be reconstructed as merged jets, which further reduces the acceptance compared with the AQGC signals. In the case of $\gamma\gamma \to \mathrm{ZZ}$, the theoretical SM signal is smaller by an additional three orders of magnitude.

7 Systematic uncertainties

We estimate systematic uncertainties in the signal prediction due to the jet energy scale, proton ξ measurement, proton reconstruction efficiency, and integrated luminosity. The effect of the jet energy scale is evaluated by shifting the energy of both jets in the event up or down by the uncertainty, and recomputing the expected signal yields. The resulting uncertainties in

Table 1: Number of background events (N_{evt} with statistical uncertainties) expected for all methods in the different WW analysis regions with reconstruction of both signal protons (region δ) or only one signal proton (region o). The mean value of the expected number of signal events for one anomalous coupling point ($a_0^{\text{W}}/\Lambda^2 = 5 \times 10^{-6}\,\text{GeV}^{-2}$) and for the SM are also shown for comparison. In cases where zero simulated SM events pass the final selection, the value is displayed as a 95% confidence level upper limit.

Number of events	region	N_{evt} (2016)	N_{evt} (2017)	N_{evt} (2018)
Anti-acoplanarity sideband	δ	0.4 ± 0.4	1.6 ± 1.0	11.6 ± 2.6
Anti-pruned mass sideband	δ	0.5 ± 0.2	1.5 ± 0.3	11.3 ± 0.8
Event mixing	δ	0.5 (<2.2)	1.8 (<4.2)	14.3 ± 8.9
Expected signal ($a_0^{\text{W}}/\Lambda^2 = 5 \times 10^{-6}\,\text{GeV}^{-2}$)	δ	1.7	2.2	16.1
Expected signal (SM)	δ	0.006	< 0.05	0.03
Anti-acoplanarity sideband	o	1.4 ± 0.9	10.0 ± 3.2	41.4 ± 5.7
Anti-pruned mass sideband	o	2.5 ± 0.8	7.1 ± 1.3	43.0 ± 3.0
Event mixing	o	2.4 ± 1.9	8.4 ± 6.3	49 ± 13
Expected signal ($a_0^{\text{W}}/\Lambda^2 = 5 \times 10^{-6}\,\text{GeV}^{-2}$)	o	1.5	1.7	16.8
Expected signal (SM)	o	0.005	<0.05	<0.07

the signal yield depend on the data-taking period and sample, but typically range from a few percent up to 10%. Possible discrepancies between data and MC regarding the pruned mass and the τ_{21} variable are found to be negligible (below 1%) using a tag and probe method.

The systematic uncertainties related to the proton ξ reconstruction in the two arms are assumed to be uncorrelated. There are two reasons for this assumption: (i) the RP alignment relative to the beam, and the uncertainty in the LHC magnet strengths that determine the optics, are independent for the two colliding beams; and (ii) a significant part of the uncertainty is related to the stability over time. In the case of the alignment, this is a fill-by-fill effect, that fluctuates in both directions around the mean whenever the Roman pots are moved in or out. The optics uncertainty includes a component related to the LHC crossing angle, which was adjusted several times per fill (in 2017) or continuously throughout the fill (in 2018). An approximation is made that the expected signal is less than 1 event per fill (which is the expected case for the present analysis), and therefore these components of the uncertainty are not correlated event-by-event.

The effect of the proton reconstruction uncertainty is evaluated by shifting the value of ξ for each simulated signal proton by an amount drawn from a Gaussian distribution with width equal to the uncertainty [47], and recomputing the expected signal yield. Because of the tight matching requirements between protons and jets, this is one of the largest systematic uncertainties in the analysis, with values typically of the order of 30% of the expected signal yield. The proton reconstruction efficiency uncertainties are based on comparing results obtained with different control samples and efficiency estimation procedures [47]. The total efficiency uncertainty per arm is 10% in 2016; in 2017 and 2018 the improved detectors and methods led to uncertainties between 2 and 3% per arm [47]. The efficiency uncertainties for the two arms are assumed uncorrelated, and are summed in quadrature to obtain the event uncertainty. The integrated luminosity uncertainties are estimated as 1.2% [36], 2.3% [37], and 2.5% [38] for the

Table 2: Number of background events (N_{evt} with statistical uncertainties) expected for all methods in the different ZZ analysis regions with reconstruction of both signal protons (region δ) or only one signal proton (region o). The mean value of the expected number of the expected signal for one anomalous coupling point ($a_0^Z/\Lambda^2 = 1 \times 10^{-5}\,\text{GeV}^{-2}$) is also shown for comparison.

Number of events	region	N_{evt} (2016)	N_{evt} (2017)	N_{evt} (2018)
Anti-acoplanarity sideband	δ	1.5 ± 1.1	1.6 ± 0.8	14.2 ± 3.0
Anti-pruned mass sideband	δ	0.4 ± 0.2	0.9 ± 0.2	9.9 ± 0.9
Event mixing	δ	0.5 (< 2.1)	1.5 (< 3.6)	11.6 ± 9.4
Expected signal ($a_0^Z/\Lambda^2 = 1 \times 10^{-5}\,\text{GeV}^{-2}$)	δ	1.3	1.4	9.0
Anti-acoplanarity sideband	o	1.5 ± 1.1	3.7 ± 1.5	37.4 ± 5.6
Anti-pruned mass sideband	o	2.1 ± 0.8	5.4 ± 1.3	41.7 ± 3.1
Event mixing	o	2.0 ± 1.8	6.3 ± 5.1	42 ± 16
Expected signal ($a_0^Z/\Lambda^2 = 1 \times 10^{-5}\,\text{GeV}^{-2}$)	o	1.0	1.6	12.8

2016, 2017, and 2018 samples, respectively. The uncertainty includes both a part that is uncorrelated between years, and parts that are correlated between 2016 and 2017, and between 2016, 2017, and 2018. The overall uncertainty for the 2016–2018 period for data collected with PPS is 1.8%.

The theoretical uncertainty in the signal prediction includes contributions from the simulation sample size, and from the proton survival probability, i.e., the probability that the colliding protons do not break up due to soft interactions between their spectator partons. The statistical uncertainty in the simulation varies with the assumed anomalous coupling value and year simulated. For the points closest to the expected sensitivity, which determine the numerical value of the limits, it is typically in the range of 2–10%. For the smallest coupling values simulated, which are far from the expected sensitivity, it is typically 25% in the 2016 samples where the integrated luminosity of the data is low. The uncertainty in the proton survival probability is assumed to be 10% [61].

The systematic uncertainty in the background has two contributions. The first is the statistical uncertainty in the normalization, based on the nominal acoplanarity sideband method. The second is the dependence of the background estimate on the choice of the sideband region. This is estimated as the full difference between the central values of the acoplanarity sideband method, and the pruned mass sideband method. The first uncertainty, which depends mainly on the amount of sideband data, ranges from $\approx 15 - 20\%$ in the 2018 data, to $>100\%$ in the 2016 data. The second uncertainty also has a significant statistical component, which ranges from a few percent in the 2018 data, to 80% in the 2016 data.

8 Signal extraction and results

The high-mass exclusive $\gamma\gamma \to \text{WW}$ and $\gamma\gamma \to \text{ZZ}$ signals are extracted using a binned maximum-likelihood fit in a total of twelve bins: one for each of the three years of data taking, times two for the WW and ZZ regions, times two for the events with either reconstruction

Table 3: Limits on LEP-like dimension-6 anomalous quartic gauge coupling parameters [19], with and without unitarization via a clipping [27] procedure.

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert a_0^W/\Lambda^2\rvert$	$4.3\ (3.9) \times 10^{-6}\,\mathrm{GeV}^{-2}$	$5.2\ (5.1) \times 10^{-6}\,\mathrm{GeV}^{-2}$
$\lvert a_C^W/\Lambda^2\rvert$	$1.6\ (1.4) \times 10^{-5}\,\mathrm{GeV}^{-2}$	$2.0\ (2.0) \times 10^{-5}\,\mathrm{GeV}^{-2}$
$\lvert a_0^Z/\Lambda^2\rvert$	$0.9\ (1.0) \times 10^{-5}\,\mathrm{GeV}^{-2}$	—
$\lvert a_C^Z/\Lambda^2\rvert$	$4.0\ (4.5) \times 10^{-5}\,\mathrm{GeV}^{-2}$	—

of both signal protons (region δ) or only one signal proton (region o). In most cases, systematic uncertainties are included as log-normal nuisance parameters [62]. When the estimate of the systematic uncertainty is based on a sample with less than 10 events, Poisson nuisances are used instead; this applies to some of the background statistical uncertainties derived from sideband regions, and some of the simulation statistical errors for very small couplings. The signal is estimated for each of the anomalous couplings, with all other couplings fixed to zero.

Figure 7 shows the number of observed events compared with the expected background and a hypothetical signal, in each bin of the analysis. The backgrounds and observed data are compared with a signal having nonzero WW anomalous couplings, slightly above the expected sensitivity of the analysis. Small ($\leq 1\sigma$) excesses are seen in "region o" of the WW for all years, while small deficits are seen in the ZZ channel. None of these excesses or deficits in the data is significant.

8.1 AQGC limits

The resulting expected and observed 95% confidence level (CL) upper limits on the AQGC operators are shown in Fig. 8.

For large values of anomalous couplings, the predicted cross section becomes unphysically large at high masses of the produced diboson system, and violates partial wave unitarity. We estimate the sensitivity of the limits to this effect by calculating the energy of $\gamma\gamma$ collisions at which unitarity is violated for the expected limits [17], and then apply a "clipping" procedure [63] to remove the simulated signal above that value. The background estimate and the data are left unchanged in this procedure. In Ref. [27] the SM contribution to the signal was retained above the clipping threshold; in the current analysis the total SM signal is negligible, and is not included. We then rederive the limits with the clipping applied.

In the WW channel, unitarity violation occurs at a diboson mass of $\Lambda \approx 1.4\,\mathrm{TeV}$. By clipping the signal model at that value, we obtain new expected limits that are approximately 30 to 40% higher than the unitarity-violating limits. In the ZZ channel, where the expected limits are higher, unitarity violation occurs at approximately 1.1 TeV for both a_0^Z/Λ^2 and a_C^Z/Λ^2. In this case, because of the invariant mass threshold imposed by the jet triggers, there is no value of clipping for which unitarity is preserved. The full list of 95% CL upper limits with and without clipping is shown in Table 3.

We also obtain limits in the two-dimensional planes of a_0^W/Λ^2 vs. a_C^W/Λ^2 and a_0^Z/Λ^2 vs. a_C^Z/Λ^2 by fitting the limits on the ratio of observed to predicted cross sections to an analytical model

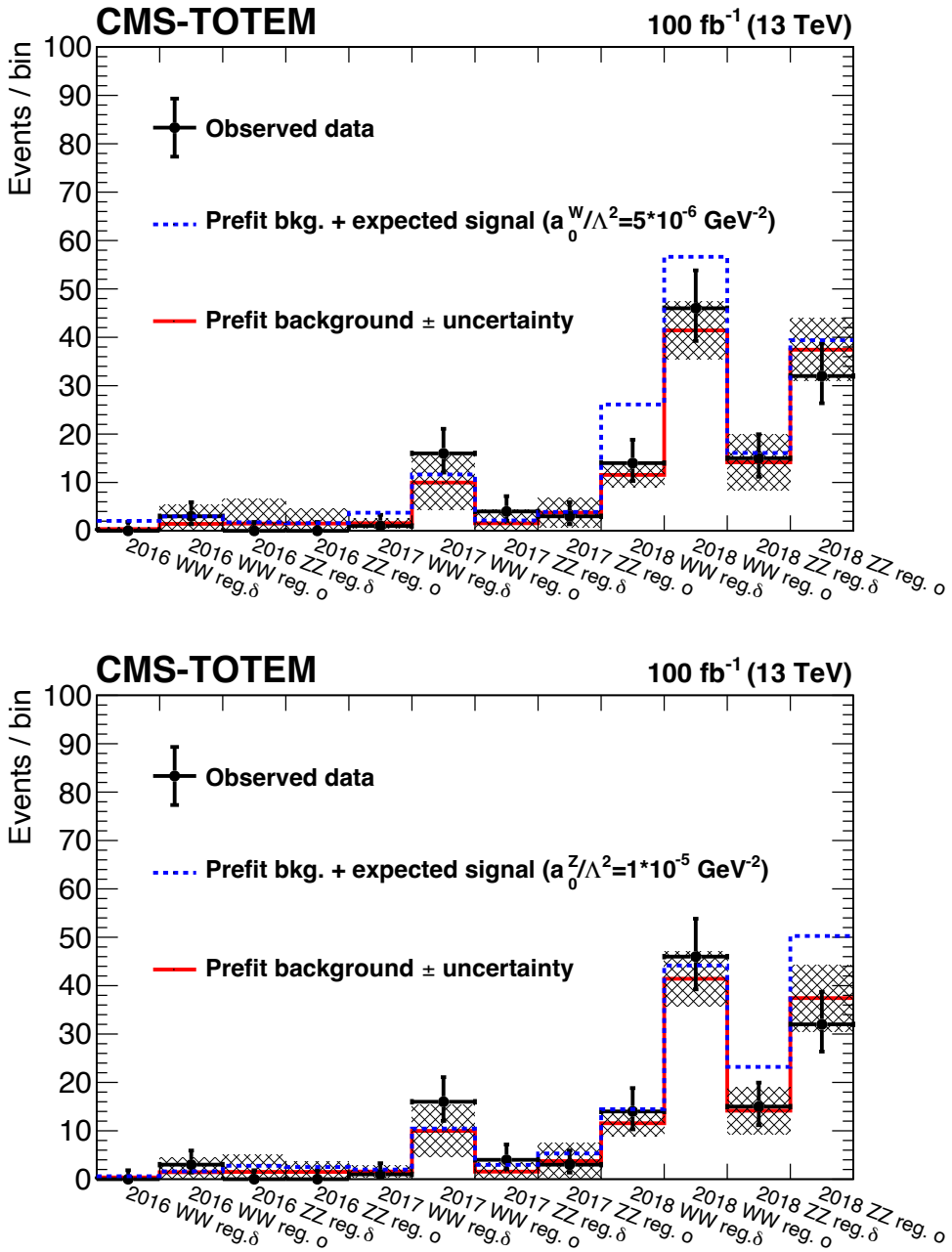

Figure 7: Observed data and expected number of background events in each signal region. Hypothetical AQGC signals are also shown. The histogram with solid lines indicates the number expected for only background, with uncertainties shown by the shaded band. The dashed-line histogram shows the number for background plus assumed signals with $a_0^W/\Lambda^2 = 5 \times 10^{-6}\,\text{GeV}^{-2}$ (upper) or $a_0^Z/\Lambda^2 = 1 \times 10^{-5}\,\text{GeV}^{-2}$ (lower). The histograms and uncertainties are shown prior to the binned maximum-likelihood fit described in the text. The shaded band indicates the uncertainty in the background estimate, while the vertical bars on the points represent the statistical uncertainty in the observed data.

for the dependence of the cross section on the AQGC values. The results are shown in Fig. 9. The a_0^W/Λ^2 vs. a_C^W/Λ^2 limits are shown with and without clipping the signal model at 1.4 TeV. Compared with the limits on the $|a_0^W/\Lambda^2|$ and $|a_C^W/\Lambda^2|$ couplings obtained with LHC Run 1

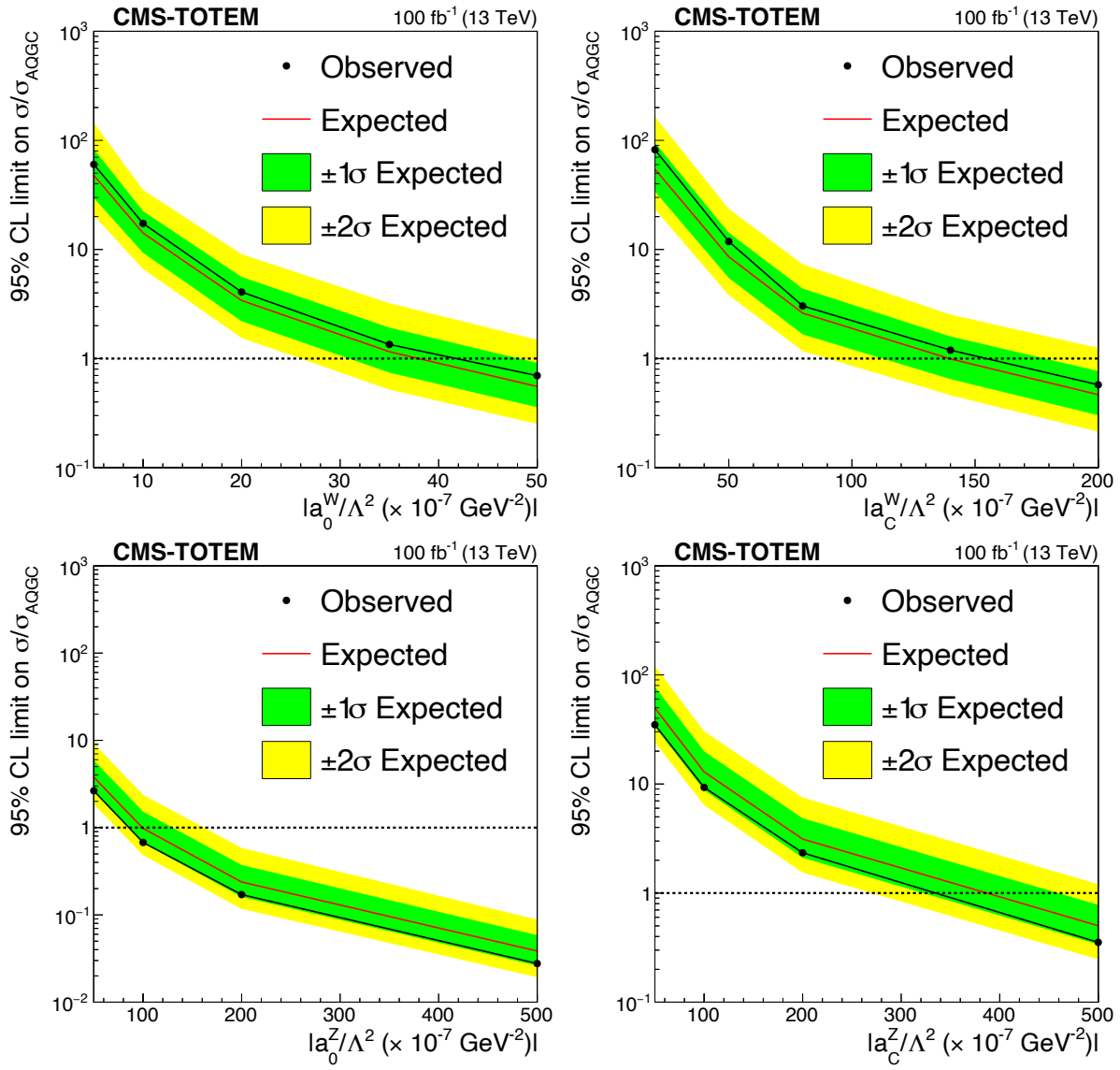

Figure 8: Expected and observed upper limits on the AQGC operators a_0^W/Λ^2 (upper left), a_C^W/Λ^2 (upper right), a_0^Z/Λ^2 (lower left), a_C^Z/Λ^2 (lower right), with no unitarization. The y axis shows the limit on the ratio of the observed cross section to the cross section predicted for each anomalous coupling value (σ_{AQGC}). The graphs are not fully representative close to the values of the 95limit due to technical plotting features; the 95% CL upper limits quoted in Table 3 correspond to the exact values.

data [20, 22], where unitarization was imposed via a dipole form factor, the unitarized limits obtained here represent an improvement by a factor ≈15–20.

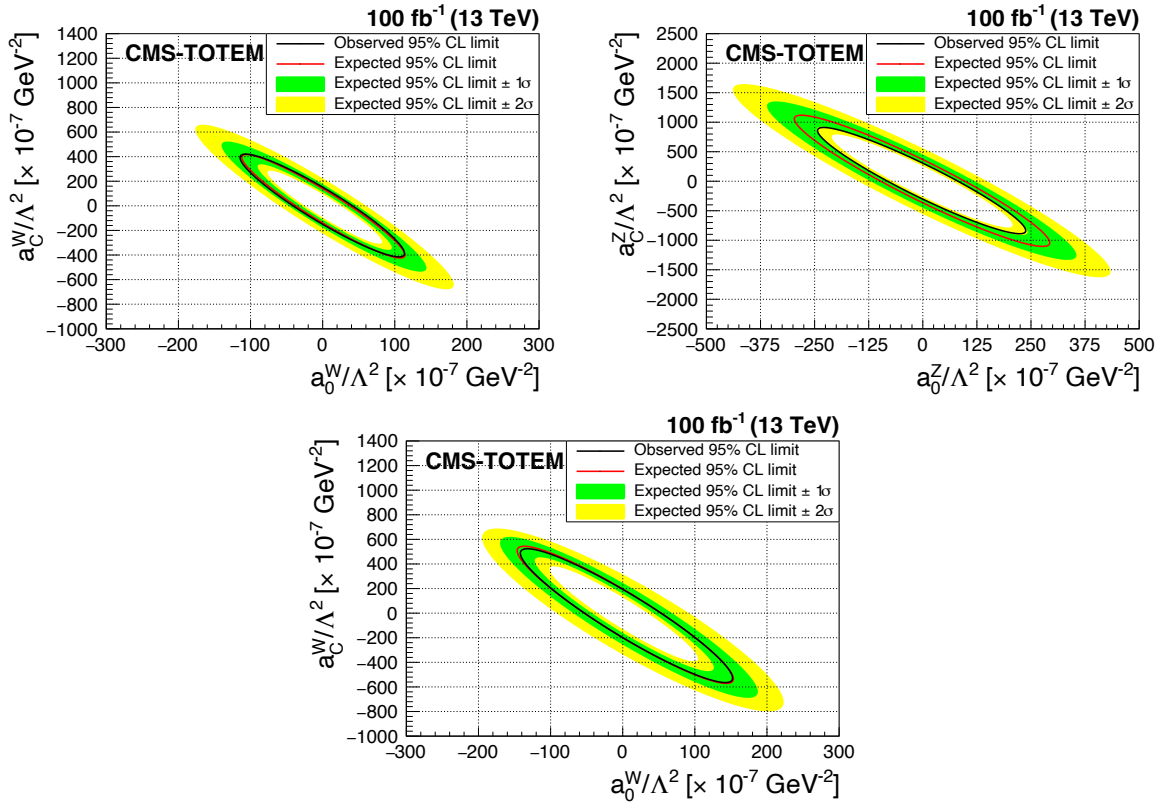

Figure 9: Expected and observed limits in the two-dimensional plane of a_0^W/Λ^2 vs a_C^W/Λ^2 (upper left), a_0^Z/Λ^2 vs. a_C^Z/Λ^2 (upper right), and a_0^W/Λ^2 vs. a_C^W/Λ^2 with unitarization imposed by clipping the signal model at 1.4 TeV (lower).

8.2 Translation to linear dimension-8 AQGCs

Many recent anomalous coupling searches quote limits on dimension-8 linear operators alone. These operators are classified in several categories, depending on whether they contain only covariant derivatives of the Higgs field, only field strength tensors, or both ("mixed" operators, with couplings denoted f_M) [18]. In the case of processes involving photons, the $a_{0,C}^{W,Z}$ operators can be translated into a linear combination of "mixed" dimension-8 $f_{M,i}$ $(i = 0\text{–}7)$ operators [18]. For the a_0^W coupling, the relationship reads [18]:

$$a_0^W = -\frac{m_W}{\pi\alpha_{em}}\left[s_w^2\frac{f_{M,0}}{\Lambda^2} + 2c_w^2\frac{f_{M,2}}{\Lambda^2} + s_w c_w\frac{f_{M,4}}{\Lambda^2}\right]. \tag{3}$$

Here m_W is the W boson mass, α_{em} is the fine structure constant, and s_w and c_w represent the sine and cosine of the weak mixing angle, respectively. By further assuming that anomalous contributions to WWZγ vanish, an additional constraint of $f_{M,0} + 2f_{M,2}$ is obtained [14, 64], allowing a_0^W to be written in terms of only $f_{M,0}$ and $f_{M,4}$. In order to compare with other results, we scan the values of $f_{M,0}$ and $f_{M,4}$ for which the limit on a_0^W is satisfied. We find the results shown in Table 4, evaluated at the point where the other coupling is zero.

Table 4: Conversion of limits on a_0^W to dimension-8 $f_{M,i}$ operators, using the assumption of vanishing WWZγ couplings to eliminate some parameters. When quoting limits on one of the operators, the other is fixed to zero. The results for $|f_{M,0}/\Lambda^4|$ and $|f_{M,4}/\Lambda^4|$ are shown with and without clipping of the signal model at 1.4 TeV, when the other parameter is fixed to the SM value of zero.

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert f_{M,0}/\Lambda^4\rvert$	16.2 (14.7) TeV^{-4}	19.5 (19.2) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4\rvert$	90.9 (82.6) TeV^{-4}	110 (108) TeV^{-4}

The results are compared with other vector boson scattering studies at 13 TeV that are sensitive to the same operators [28]. When the conversion is performed assuming vanishing WWZγ couplings, the unitarity-violating limits on $|f_{M,0}/\Lambda^4|$ and $|f_{M,4}/\Lambda^4|$ are several times looser than those quoted in other measurements. After the clipping, the results for $|f_{M,0}/\Lambda^4|$ are similar to the best limits obtained from vector boson scattering in the same sign $W^\pm W^\pm$ and WZ final states in CMS [27]. The milder effect of the unitarization in this analysis is due to the upper mass limit of $\approx$2 TeV for reconstructing the protons, imposed by the LHC collimator apertures. This already suppresses most of the unphysical high-mass part of the signal model, before applying any unitarization procedure.

Alternatively, all dimension-8 $f_{M,i}$ except one are set equal to zero. In this case, the results of the conversion are shown in Table 5. When the conversion is performed by setting all other couplings to zero, the limits on $|f_{M,0}/\Lambda^4|$ are significantly looser, the limits on $|f_{M,4}/\Lambda^4|$ are somewhat more restrictive, and tight constraints are obtained on $|f_{M,2}/\Lambda^4|$.

Table 5: Conversion of limits on a_0^W and a_C^W to dimension-8 $f_{M,i}$ operators, using the assumption that all $f_{M,i}$ except one are equal to zero. The results are shown with and without clipping of the signal model at 1.4 TeV.

Coupling	Observed (expected) 95% CL upper limit No clipping	Observed (expected) 95% CL upper limit Clipping at 1.4 TeV
$\lvert f_{M,0}/\Lambda^4\rvert$	66.0 (60.0) TeV^{-4}	79.8 (78.2) TeV^{-4}
$\lvert f_{M,1}/\Lambda^4\rvert$	245.5 (214.8) TeV^{-4}	306.8 (306.8) TeV^{-4}
$\lvert f_{M,2}/\Lambda^4\rvert$	9.8 (9.0) TeV^{-4}	11.9 (11.8) TeV^{-4}
$\lvert f_{M,3}/\Lambda^4\rvert$	73.0 (64.6) TeV^{-4}	91.3 (92.3) TeV^{-4}
$\lvert f_{M,4}/\Lambda^4\rvert$	36.0 (32.9) TeV^{-4}	43.5 (42.9) TeV^{-4}
$\lvert f_{M,5}/\Lambda^4\rvert$	67.0 (58.9) TeV^{-4}	83.7 (84.1) TeV^{-4}
$\lvert f_{M,7}/\Lambda^4\rvert$	490.9 (429.6) TeV^{-4}	613.7 (613.7) TeV^{-4}

8.3 Fiducial cross sections

In addition to the limits on different anomalous coupling parameters, we derive upper limits on the cross section for an AQGC-like signal in the $\text{pp} \to \text{pWWp}$ and $\text{pp} \to \text{pZZp}$ channels. The limits are obtained for a fiducial region of $0.04 < \xi < 0.20$ and diboson invariant mass $m(\text{VV}) > 1\,\text{TeV}$, and correspond to the diboson production cross section before decays into hadrons. The signal simulation is used to extrapolate from the measurement region to the fiducial region. As with the AQGC limits, the cross section limits are obtained for each channel separately, assuming zero signal in the other channel. After verifying that the signal efficiency and acceptance do not depend strongly on the exact value of the AQGCs, for $0.04 < \xi < 0.20$ and $m(\text{VV}) > 1000\,\text{GeV}$ we measure the following upper exclusion limits at 95% CL: $\sigma(\text{pp} \to \text{pWWp}) < 67(53^{+34}_{-19})\,\text{fb}$ and $\sigma(\text{pp} \to \text{pZZp}) < 43(62^{+33}_{-20})\,\text{fb}$, where the expected limit and its one standard deviation uncertainty are shown in parentheses. Since the simulation is used to extrapolate the results from the measurement region to the fiducial region, the cross section limits given are valid for signals with an AQGC-like ξ and mass dependence. The limits cannot therefore be applied to models with a very different mass and ξ behaviour.

9 Summary

A first search for exclusive high-mass $\gamma\gamma \to \text{WW}$ and $\gamma\gamma \to \text{ZZ}$ production with reconstructed forward protons has been performed, in final states with hadronically decaying W or Z bosons, using $100\,\text{fb}^{-1}$ of data collected in 13 TeV proton-proton collisions. No significant excess is found over the standard model background prediction. The resulting limits are interpreted in terms of nonlinear dimension-6 and linear dimension-8 anomalous quartic gauge couplings (AQGC).

The unitarized dimension-6 $\gamma\gamma\text{WW}$ AQGC limits are approximately 15–20 times more stringent than those obtained from the $\gamma\gamma \to \text{WW}$ process without proton detection using the LHC Run 1 data [20, 22]. In the analyses without proton detection [20, 22, 26], larger SM signals were measured at lower invariant WW masses. However, since enhancements due to AQGCs come mainly from the high energy region of $\gamma\gamma$ interactions, the analysis described here is

more sensitive than the limits obtained in those publications. In addition, the use of proton detectors results in a theoretically cleaner result, by reducing the dependency on the unitarization scheme, and reducing the contribution of signal events where the protons dissociate. The derived dimension-8 limits are close to those obtained from same-sign WW and WZ scattering at 13 TeV after unitarization, for the case when the WWZγ coupling is suppressed. The limits on $\gamma\gamma$ZZ anomalous couplings are the first obtained from the exclusive $\gamma\gamma \to$ ZZ channel. New limits are placed on the cross section in a fiducial region of $0.04 < \xi < 0.20$ and diboson invariant mass $m(\mathrm{VV}) > 1$ TeV of $\gamma\gamma \to$ WW and $\gamma\gamma \to$ ZZ production with intact forward protons.

Tabulated results are provided in HEPData [65].

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, P.S. Hussain, M. Jeitler[2], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck[2], R. Schöfbeck, D. Schwarz, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[3], T. Janssen, T. Kello[4], H. Rejeb Sfar, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
E.S. Bols, J. D'Hondt, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, G. De Lentdecker, L. Favart, D. Hohov, J. Jaramillo, K. Lee, M. Mahdavikhorrami, I. Makarenko, A. Malara, S. Paredes, L. Pétré, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Rendón, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, N. Van Den Bossche, B. Vermassen, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, T.T. Tran, P. Vischia, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, E. Coelho, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, J. Martins[7], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[8], A. Vilela Pereira

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

Beihang University, Beijing, China
T. Cheng, T. Javaid[9], M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, G. Bauer[10], Z. Hu, S. Lezki, K. Yi[10,11]

Institute of High Energy Physics, Beijing, China
G.M. Chen[9], H.S. Chen[9], M. Chen[9], F. Iemmi, C.H. Jiang, A. Kapoor, H. Liao, Z.-A. Liu[12], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. An, Y. Ban, C. Chen, A. Levin, C. Li, Q. Li, X. Lyu, Y. Mao, S.J. Qian, X. Sun, D. Wang, J. Xiao, H. Yang

Sun Yat-Sen University, Guangzhou, China
M. Lu, Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[4], D. Leggat, H. Okawa, Y. Zhang

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, B.K. Chitroda, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov[13], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr., A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian

Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[14,15], E. Salama[16,17]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M.A. Mahmoud, Y. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, R.K. Dewanjee, K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott, M.m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, P. Jarry, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[18], P. Simkina, M. Titov

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damas, O. Davignon, B. Diab, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, G. Liu, J. Motta, M. Nguyen, C. Ochando, L. Portales, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[19], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
S. Beauceron, C. Bernet, B. Blancon, G. Boudoul, A. Carle, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen[20], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, L. Torterotot, M. Vander Donckt, P. Verdier, S. Viret

Georgian Technical University, Tbilisi, Georgia
D. Chokheli, I. Lomidze, Z. Tsamalaidze[13]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, M. Erdmann, P. Fackeldey,

D. Fasanella, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, M.y. Lee, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, S. Mondal, S. Mukherjee, D. Noll, A. Novak, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, H. Reithler, A. Schmidt, S.C. Schuler, A. Sharma, L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[21], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, A. Stahl[22], T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, F. Blekman[23], K. Borras[24], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[23], A. Geiser, A. Giraldi, G. Greau, A. Grohsjean, V. Guglielmi, M. Guthoff, A. Jafari[25], N.Z. Jomhari, B. Kaech, A. Kasem[24], M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka, W. Lohmann[26], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, G. Milella, M. Mormile, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham[27,24], V. Scheurer, S. Schnake[24], P. Schütze, C. Schwanenberger[23], M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, N. Tonon[†], M. Van De Klundert, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Walter, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[24], C. Wissing, S. Wuchterl, Y. Yang, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, M. Bonanomi, P. Connor, K. De Leo, M. Eich, K. El Morabit, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, M. Hajheidari, J. Haller, A. Hinzmann, H.R. Jabusch, G. Kasieczka, R. Klanner, W. Korcari, T. Kramer, V. Kutzner, J. Lange, A. Lobanov, C. Matthies, A. Mehta, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, M. Rieger, O. Rieger, P. Schleper, M. Schröder, J. Schwandt, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
J. Bechtel, S. Brommer, M. Burkart, E. Butz, R. Caspart, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann[22], M. Horzela, U. Husemann, P. Keicher, M. Klute, R. Koppenhöfer, S. Maier, S. Mitra, Th. Müller, M. Neukum, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, N. Trevisani, R. Ulrich, J. van der Linden, R.F. Von Cube, M. Wassmer, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, D. Karasavvas, P. Kontaxakis, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
K. Farkas, M.M.A. Gadallah[28], S. Lökös[29], P. Major, K. Mandal, G. Pásztor, A.J. Rádl[30], O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[31], G. Bencze, C. Hajdu, D. Horvath[32,33], F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[31], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, B. Ujvari[34]

Panjab University, Chandigarh, India
J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[35], R. Gupta, A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, P. Kumari, M. Meena, K. Sandeep, T. Sheokand, J.B. Singh[36], A. Singla, A. K. Virdi

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, B.C. Choudhary, M. Gola, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, S. Saumya, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Baradia, S. Barman[37], S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber[38], M. Maity[37], P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, P. Kalbhor, J.R. Komaragiri[39], D. Kumar[39], A. Muhammad, L. Panwar[39], R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar, P.C. Tiwari[39], S. Verma

Bhabha Atomic Research Centre, Mumbai, India
K. Naskar[40]

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, I. Das, S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[41], A.K. Das, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[42], A. Nayak[42], P. Saha, S.K. Swain, D. Vats[42]

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[43], E. Khazaie, M. Zeinali[44]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[45], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,c,14], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], W. Elmetenawee[a,b], F. Errico[a,b], L. Fiore[a], G. Iaselli[a,c], M. Ince[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], D. Ramos[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], A. Stamerra[a], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], L. Brigliadori[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,46], L. Lunerti[a,b], 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]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,47], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,47], C. Tuve[a,b]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
G. Barbagli[a], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], R. Seidita[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[22], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
F. Ferro[a], R. Mulargia[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], G. Boldrini[a], F. Brivio[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], B.S. Pinolini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Università G. Marconi[d], Roma, Italy
S. Buontempo[a], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,48], P. Paolucci[a,22], B. Rossi[a], C. Sciacca[a,b]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy
P. Azzi[a], N. Bacchetta[a,49], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], T. Dorigo[a], F. Gasparini[a,b], G. Grosso[a], L. Layer[a,50], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], M. Sgaravatto[a], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], S. Ventura[a], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
S. Abu Zeid[a,17], C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
P. Asenov[a,51], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,51], A. Piccinelli[a,b], M. Presilla[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy
P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], R. Bhattacharya[a], L. Bianchini[a,b], T. Boccali[a], D. Bruschini[a,c], R. Castaldi[a], M.A. Ciocci[a,b], V. D'Amante[a,d], R. Dell'Orso[a], M.R. Di Domenico[a,d], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], G. Mandorli[a,c], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[a,b], F. Palla[a], S. Parolia[a,b], G. Ramirez-Sanchez[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,c], T. Sarkar[a,37], N. Shafiei[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Barria[a], M. Campana[a,b], F. Cavallari[a], 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], R. Tramontano[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, 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], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], M. Grippo[a,b], B. Kiani[a,b], F. Legger[a], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], E. Migliore[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], M. Ruspa[a,c], K. Shchelina[a], F. Siviero[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], M. Tornago[a,b], D. Trocino[a], G. Umoret[a,b], A. Vagnerini[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], G. Sorrentino[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, M.S. Ryu, S. Sekmen, Y.C. Yang

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

H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
E. Asilar, T.J. Kim, J. Park

Korea University, Seoul, Korea
S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh

Sejong University, Seoul, Korea
H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, W. Jun, J. Kim, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, J. Lee, S. Lee, B.H. Oh, M. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, Y. Kang, D. Kim, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, J.A. Merlin, I.C. Park, Y. Roh, D. Song, Watson, I.J., S. Yang

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, Y. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia
K. Dreimanis, A. Gaile, A. Potrebko, M. Seidel, T. Torims, V. Veckalns

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Carvalho Antunes De Oliveira, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, S.Y. Hoh[52], I. Yusuff[52], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, I. Heredia-De La Cruz[53], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro

I. Bubanja, J. Mijuskovic[54], N. Raicevic

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, M. Gul, H.R. Hoorani, W.A. Khan, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, J. Varela

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
P. Adzic[55], M. Dordevic, P. Milenovic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, D.D. Redondo Ferrero, L. Romero, S. Sánchez Navas, J. Sastre, L. Urda Gómez, J. Vazquez Escobar, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, A. García Alonso, G. Gomez, C. Lasaosa García, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy[56], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, B. Bilin, A. Bocci, E. Brondolin, C. Caillol, T. Camporesi, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury,

M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita[57], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kieseler, N. Kratochwil, S. Laurila, P. Lecoq, E. Leutgeb, A. Lintuluoto, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[58], A.G. Stahl Leiton, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk[59], K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[60], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[60], L. Noehte[60], T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, K. Androsov[59], M. Backhaus, P. Berger, A. Calandri, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, A. Mascellani[59], M.T. Meinhard, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, J. Steggemann[59], D. Valsecchi[22], R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[61], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

National Central University, Chung-Li, Taiwan
C. Adloff[62], C.M. Kuo, W. Lin, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, Y. Chao, K.F. Chen, P.s. Chen, H. Cheng, W.-S. Hou, R. Khurana, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[63], E. Eskut, Y. Guler[64], E. Gurpinar Guler[64], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[65], A. Polatoz, A.E. Simsek, B. Tali[66], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
G. Karapinar[67], K. Ocalan[68], M. Yalvac[69]

Bogazici University, Istanbul, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[70], O. Kaya[71], Ö. Özçelik, S. Tekten[72]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[63], Y. Komurcu, S. Sen[63]

Istanbul University, Istanbul, Turkey
O. Aydilek, S. Cerci[66], B. Hacisahinoglu, I. Hos[73], B. Isildak[74], S. Ozkorucuklu, C. Simsek, D. Sunar Cerci[66]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, E. Bhal, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[75], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[76], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[77], J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, C.E. Brown, O. Buchmuller, V. Cacchio, V. Cepaitis, G.S. Chahal[78], D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, D.G. Monk, J. Nash[79], M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[22], M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
A. Buccilli, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio[80], C. West

Boston University, Boston, Massachusetts, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, C. Erice,

E. Fontanesi, D. Gastler, S. May, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan

Brown University, Providence, Rhode Island, USA
G. Benelli, B. Burkle, X. Coubez[24], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[81], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, M. Narain, N. Pervan, S. Sagir[82], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, California, USA
J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, Y. Yao, F. Zhang

University of California, Los Angeles, California, USA
M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, W.A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, California, USA
Y. Chen, R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, W. Si, S. Wimpenny

University of California, San Diego, La Jolla, California, USA
J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
N. Amin, C. Campagnari, M. Citron, G. Collura, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, A.J. Li, P. Masterson, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, P. Siddireddy, D. Stuart, S. Wang

California Institute of Technology, Pasadena, California, USA
A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T. Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, S. Murthy, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, F. Marini, R. Patel, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper

Cornell University, Ithaca, New York, USA
J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, D. Gadkari, S. Hogan, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry,

J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, K.F. Di Petrillo, J. Dickinson, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[83], F. Ravera, A. Reinsvold Hall[84], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, I. Zoi

University of Florida, Gainesville, Florida, USA
P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R.D. Field, D. Guerrero, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Askew, R. Habibullah, V. Hagopian, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, O. Viazlo, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
M.M. Baarmand, S. Butalla, T. Elkafrawy[17], M. Hohlmann, R. Kumar Verma, M. Rahmani, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, Illinois, USA
M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, S. Dittmer, O. Evdokimov, C.E. Gerber, D.J. Hofman, D. S. Lemos, A.H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, X. Wang, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, K. Dilsiz[85], L. Emediato, R.P. Gandrajula, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[86], J. Nachtman, O. Neogi, H. Ogul[87], Y. Onel, A. Penzo, C. Snyder, E. Tiras[88]

Johns Hopkins University, Baltimore, Maryland, USA
O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, J. Roskes, S. Sekhar, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, P. Baringer, A. Bean, Z. Flowers, S. Khalil, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, C. Rogan, R. Salvatico, S. Sanders, C. Smith, Q. Wang, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, S. Duric, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam, J. Natoli, D. Roy

Lawrence Livermore National Laboratory, Livermore, California, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, USA

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

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
D. Abercrombie, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, P. Harris, M. Hu, D. Kovalskyi, J. Krupa, Y.-J. Lee, K. Long, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, Minnesota, USA
R.M. Chatterjee, B. Crossman, A. Evans, J. Hiltbrand, Sh. Jain, B.M. Joshi, C. Kapsiak, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, Mississippi, USA
L.M. Cremaldi

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, M. Bryson, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, C. Joo, I. Kravchenko, I. Reed, J.E. Siado, G.R. Snow†, W. Tabb, A. Wightman, F. Yan, A.G. Zecchinelli

State University of New York at Buffalo, Buffalo, New York, USA
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, M. Morris, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Krishna, J. Li, J. Lidrych, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, Illinois, USA
S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, K.A. Hahn, Y. Liu, N. Odell, M.H. Schmitt, M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA
R. Band, R. Bucci, S. Castells, M. Cremonesi, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko[13], H. Nelson, R. Ruchti, A. Townsend, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA
B. Bylsma, M. Carrigan, L.S. Durkin, B. Francis, C. Hill, A. Lesauvage, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA
F.M. Addesa, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, Indiana, USA
A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic, J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, Indiana, USA
J. Dolen, N. Parashar

Rice University, Houston, Texas, USA
D. Acosta, A. Baty, T. Carnahan, M. Decaro, S. Dildick, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Rotter, W. Shi, S. Yang, E. Yigitbasi, L. Zhang[89], Y. Zhang, X. Zuo

University of Rochester, Rochester, New York, 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, G.P. Van Onsem

The Rockefeller University, New York, New York, USA
K. Goulianos

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, D. Jaroslawski, O. Karacheban[26], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, Tennessee, USA
H. Acharya, A.G. Delannoy, S. Fiorendi, T. Holmes, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA
O. Bouhali[90], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[91], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, V. Hegde, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara, B. Tannenwald

Wayne State University, Detroit, Michigan, USA
P.E. Karchin, N. Poudyal

University of Wisconsin - Madison, Madison, Wisconsin, USA
S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, A. Loeliger, R. Loveless,

J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov[92], E. Boos, D. Budkouski, V. Bunichev, O. Bychkova, M. Chadeeva[92], V. Chekhovsky, A. Dermenev, T. Dimova[92], I. Dremin, M. Dubinin[83], L. Dudko, V. Epshteyn, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, Y. Ivanov, V. Kachanov, L. Kardapoltsev[92], V. Karjavine, A. Karneyeu, V. Kim[92], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, V. Klyukhin, O. Kodolova[93], D. Konstantinov, V. Korenkov, A. Kozyrev[92], N. Krasnikov, E. Kuznetsova[94], A. Lanev, P. Levchenko, A. Litomin, O. Lukina, N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev[92], V. Murzin, A. Nikitenko[95], S. Obraztsov, V. Okhotnikov, I. Ovtin[92], V. Palichik, P. Parygin, V. Perelygin, M. Perfilov, G. Pivovarov, V. Popov, E. Popova, O. Radchenko[92], V. Rusinov, M. Savina, V. Savrin, D. Selivanova, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen[92], S. Slabospitskii, V. Smirnov, A. Snigirev, D. Sosnov, A. Stepennov, V. Sulimov, A. Terkulov, O. Teryaev, I. Tlisova, M. Toms, A. Toropin, L. Uvarov, A. Uzunian, E. Vlasov, A. Vorobyev, N. Voytishin, B.S. Yuldashev[96], A. Zarubin, I. Zhizhin, A. Zhokin

†: Deceased

[1]Also at Yerevan State University, Yerevan, Armenia

[2]Also at TU Wien, Vienna, Austria

[3]Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt

[4]Also at Université Libre de Bruxelles, Bruxelles, Belgium

[5]Also at Universidade Estadual de Campinas, Campinas, Brazil

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

[7]Also at UFMS, Nova Andradina, Brazil

[8]Also at The University of the State of Amazonas, Manaus, Brazil

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

[10]Also at Nanjing Normal University Department of Physics, Nanjing, China

[11]Now at The University of Iowa, Iowa City, Iowa, USA

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

[13]Also at an institute or an international laboratory covered by a cooperation agreement with CERN

[14]Also at Helwan University, Cairo, Egypt

[15]Now at Zewail City of Science and Technology, Zewail, Egypt

[16]Also at British University in Egypt, Cairo, Egypt

[17]Now at Ain Shams University, Cairo, Egypt

[18]Also at Purdue University, West Lafayette, Indiana, USA

[19]Also at Université de Haute Alsace, Mulhouse, France

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

[21]Also at Erzincan Binali Yildirim University, Erzincan, Turkey

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

[23]Also at University of Hamburg, Hamburg, Germany

[24]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[25]Also at Isfahan University of Technology, Isfahan, Iran
[26]Also at Brandenburg University of Technology, Cottbus, Germany
[27]Also at Forschungszentrum Jülich, Juelich, Germany
[28]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[29]Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
[30]Also at Wigner Research Centre for Physics, Budapest, Hungary
[31]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
[32]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[33]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[34]Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
[35]Also at Punjab Agricultural University, Ludhiana, India
[36]Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
[37]Also at University of Visva-Bharati, Santiniketan, India
[38]Also at University of Hyderabad, Hyderabad, India
[39]Also at Indian Institute of Science (IISc), Bangalore, India
[40]Also at Indian Institute of Technology (IIT), Mumbai, India
[41]Also at IIT Bhubaneswar, Bhubaneswar, India
[42]Also at Institute of Physics, Bhubaneswar, India
[43]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[44]Also at Sharif University of Technology, Tehran, Iran
[45]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[46]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[47]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[48]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[49]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[50]Also at Università di Napoli 'Federico II', Napoli, Italy
[51]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[52]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[53]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[54]Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[55]Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
[56]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[57]Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
[58]Also at National and Kapodistrian University of Athens, Athens, Greece
[59]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[60]Also at Universität Zürich, Zurich, Switzerland
[61]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[62]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[63]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[64]Also at Konya Technical University, Konya, Turkey
[65]Also at Izmir Bakircay University, Izmir, Turkey
[66]Also at Adiyaman University, Adiyaman, Turkey
[67]Also at Istanbul Gedik University, Istanbul, Turkey

[68]Also at Necmettin Erbakan University, Konya, Turkey
[69]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[70]Also at Marmara University, Istanbul, Turkey
[71]Also at Milli Savunma University, Istanbul, Turkey
[72]Also at Kafkas University, Kars, Turkey
[73]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[74]Also at Yildiz Technical University, Istanbul, Turkey
[75]Also at Vrije Universiteit Brussel, Brussel, Belgium
[76]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[77]Also at University of Bristol, Bristol, United Kingdom
[78]Also at IPPP Durham University, Durham, United Kingdom
[79]Also at Monash University, Faculty of Science, Clayton, Australia
[80]Also at Università di Torino, Torino, Italy
[81]Also at Bethel University, St. Paul, Minnesota, USA
[82]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[83]Also at California Institute of Technology, Pasadena, California, USA
[84]Also at United States Naval Academy, Annapolis, Maryland, USA
[85]Also at Bingol University, Bingol, Turkey
[86]Also at Georgian Technical University, Tbilisi, Georgia
[87]Also at Sinop University, Sinop, Turkey
[88]Also at Erciyes University, Kayseri, Turkey
[89]Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
[90]Also at Texas A&M University at Qatar, Doha, Qatar
[91]Also at Kyungpook National University, Daegu, Korea
[92]Also at another institute or international laboratory covered by a cooperation agreement with CERN
[93]Also at Yerevan Physics Institute, Yerevan, Armenia
[94]Now at University of Florida, Gainesville, Florida, USA
[95]Also at Imperial College, London, United Kingdom
[96]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan

B The TOTEM Collaboration

G. Antchev[a], P. Aspell[8], I. Atanassov[a], V. Avati[7,8], J. Baechler[8], C. Baldenegro Barrera[10], V. Berardi[4a,4b], M. Berretti[2a], V. Borshch[11], E. Bossini[6a], U. Bottigli[6c], M. Bozzo[5a,5b], H. Burkhardt[8], F.S. Cafagna[4a], M.G. Catanesi[4a], M. Csanád[3a,b], T. Csörgő[3a,3b], M. Deile[8], F. De Leonardis[4a,4c], M. Doubek[1c], D. Druzhkin[8,11], K. Eggert[9], V. Eremin[e], A. Fiergolski[8], F. Garcia[2a], V. Georgiev[1a], S. Giani[8], L. Grzanka[7], J. Hammerbauer[1a], T. Isidori[10], V. Ivanchenko[11], M. Janda[1c], A. Karev[8], J. Kašpar[1b,8], B. Kaynak[c], J. Kopal[8], V. Kundrát[1b], S. Lami[6a], R. Linhart[1a], C. Lindsey[10], M.V. Lokajíček[†,1b], L. Losurdo[6c], F. Lucas Rodríguez[8], M. Macrí[†,5a], M. Malawski[7], N. Minafra[10], S. Minutoli[5a], K. Misan[7], T. Naaranoja[2a,2b], F. Nemes[3a,3b,8], H. Niewiadomski[9], T. Novák[3b], E. Oliveri[8], F. Oljemark[2a,2b], M. Oriunno[d], K. Österberg[2a,2b], P. Palazzi[8], V. Passaro[4a,4c], Z. Peroutka[1a], J. Procházka[1b], M. Quinto[4a,4b], E. Radermacher[8], E. Radicioni[4a], F. Ravotti[8],

C. Royon[10], G. Ruggiero[8], H. Saarikko[2a,2b], V.D. Samoylenko[e], A. Scribano[6a,10], J. Široký[1a], J. Smajek[8], W. Snoeys[8], R. Stefanovitch[8], J. Sziklai[3a], C. Taylor[9], E. Tcherniaev[11], N. Turini[6c], O. Urban[1a], V. Vacek[1c], O. Vavroch[1a], J. Welti[2a,2b], J. Williams[10], J. Zich[1a]

†Deceased
[1a]University of West Bohemia, Pilsen, Czech Republic
[1b]Institute of Physics of the Academy of Sciences of the Czech Republic, Prague, Czech Republic
[1c]Czech Technical University, Prague, Czech Republic
[2a]Helsinki Institute of Physics, University of Helsinki, Helsinki, Finland
[2b]Department of Physics, University of Helsinki, Helsinki, Finland
[3a]Wigner Research Centre for Physics, RMKI, Budapest, Hungary
[3b]MATE Institute of Technology KRC, Gyöngyös, Hungary
[4a]INFN Sezione di Bari, Bari, Italy
[4b]Dipartimento Interateneo di Fisica di Bari, University of Bari, Bari, Italy
[4c]Dipartimento di Ingegneria Elettrica e dell'Informazione — Politecnico di Bari, Bari, Italy
[5a]INFN Sezione di Genova, Genova, Italy
[5b]Università degli Studi di Genova, Genova, Italy
[6a]INFN Sezione di Pisa, Pisa, Italy
[6c]Università degli Studi di Siena and Gruppo Collegato INFN di Siena, Siena, Italy
[7]Akademia Górniczo-Hutnicza (AGH) University of Science and Technology, Krakow, Poland
[8]CERN, Geneva, Switzerland
[9]Case Western Reserve University, Department of Physics, Cleveland, Ohio, USA
[10]The University of Kansas, Lawrence, Kansas, USA
[11]Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

[a] INRNE-BAS, Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
[b] Department of Atomic Physics, Eötvös Loránd University, Budapest, Hungary
[c] Istanbul University, Istanbul, Turkey
[d] SLAC, Stanford University, California, USA
[e] Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN