Search for new physics in high-mass diphoton events from proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS collaboration

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

ABSTRACT: Results are presented from a search for new physics in high-mass diphoton events from proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$. The data set was collected in 2016–2018 with the CMS detector at the LHC and corresponds to an integrated luminosity of $138\,\text{fb}^{-1}$. Events with a diphoton invariant mass greater than $500\,\text{GeV}$ are considered. Two different techniques are used to predict the standard model backgrounds: parametric fits to the smoothly-falling background and a first-principles calculation of the standard model diphoton spectrum at next-to-next-to-leading order in perturbative quantum chromodynamics calculations. The first technique is sensitive to resonant excesses while the second technique can identify broad differences in the invariant mass shape. The data are used to constrain the production of heavy Higgs bosons, Randall-Sundrum gravitons, the large extra dimensions model of Arkani-Hamed, Dimopoulos, and Dvali (ADD), and the continuum clockwork mechanism. No statistically significant excess is observed. The present results are the strongest limits to date on ADD extra dimensions and RS gravitons with a coupling parameter greater than 0.1.

Contents

1 Introduction

While the standard model (SM) of particle physics has been a remarkably successful framework, it is widely expected to be incomplete. A leading motivation for beyond-the-SM (BSM) physics has been the SM hierarchy problem [1, 2], whereby quantum corrections to the Higgs boson mass must be fine-tuned to $\sim(M_{\rm EW}/M_{\rm Pl})^2$ to keep it at the observed electroweak scale, where $M_{\rm Pl}$ and $M_{\rm EW}$ are the Planck and electroweak scales, respectively.

Large extra spatial dimensions have been proposed to resolve this problem by modifying the fundamental Planck scale. Should the modified scale be of the same order as the electroweak scale, then little fine-tuning would be needed. In the model proposed by Arkani-Hamed, Dimopoulos, and Dvali (ADD) [3–5], the SM fields are constrained to the usual 3+1 spacetime dimensions, while gravity can also propagate in $n_{\rm ED}$ extra, compactified spatial dimensions. The effective strength of gravity is thus reduced by a Gauss's law reduction in the flux.

In the model proposed by Randall and Sundrum (RS) [6, 7], there is just one additional dimension but with a warped geometry, described by a curvature parameter k. The effective strength of gravity is exponentially suppressed by the curvature over the distance in the extra dimension between the Planck "brane" where gravity originates and the SM brane, to which SM fields are constrained. In both the ADD and RS scenarios, Kaluza-Klein (KK) modes of the graviton couple to the SM through the stress-energy tensor and decay into two SM particles. In ADD extra dimensions, the KK modes are closely spaced and result in a continuum excess of diphoton events over the expected SM background. In the RS graviton model, the KK modes are on-shell and appear as resolvable resonances in the diphoton mass spectrum.

Another proposed solution to the SM hierarchy problem is the continuum clockwork mechanism [8]. In the continuum limit of the clockwork, the massless graviton is accompanied by an infinite tower of massive spin-2 graviton KK modes with a characteristic pattern of masses and couplings. Like in the ADD extra dimension scenario, an approximately continuous distribution of KK modes results in a continuum excess [9, 10]; however, in the clockwork scenario, the KK modes are all on-shell, while in the ADD case, virtual contributions to the diphoton spectrum are significant [11–13].

Finally, in addition to the above models that could address the hierarchy problem, high-mass diphoton events are also potentially sensitive to other BSM physics, such as the decays of heavy spin-0 resonances. These spin-0 resonances could arise from extended Higgs sectors [14–16].

Searches for BSM physics in high-mass diphoton events from Run 2 of the CERN LHC were performed by the ATLAS and CMS experiments using proton-proton (pp) collisions at a center-of-mass energy $\sqrt{s} = 13\,\text{TeV}$ [17–23]. Prior searches have also been performed by both experiments in Run 1 of the LHC [24–28], at $\sqrt{s} = 7$ and $8\,\text{TeV}$, and also at the Fermilab Tevatron by the CDF [29–31] and D0 [32–35] experiments using $p\overline{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$.

We present the results of a search for BSM physics in high-mass diphoton events from pp collisions at $\sqrt{s} = 13\,\text{TeV}$, using data collected with the CMS detector during the LHC Run 2 period of 2016–2018, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$. To search for both resonant and nonresonant deviations from the SM, we make use of two complementary background estimation techniques. In the search for resonant excesses from both the RS and heavy Higgs boson models, we implement a technique where the diphoton spectrum is fit to a parameterized functional form, allowing for a description of the shape based exclusively on data. In the search for nonresonant excesses that arise from the ADD and clockwork models, we use a next-to-next-to-leading order (NNLO) calculation in quantum chromodynamics of the SM diphoton background, and we estimate the background from jets being misidentified as photons using control samples in data. In addition to using a larger sample of data, this search improves upon the previous CMS analysis [18] in a variety of ways, including better photon identification and calibrations, more precise modelling of the background from jets in the case of the nonresonant analysis, and, in the case of the resonant analysis, improved statistical inference techniques.

The rest of the document is organized as follows. The CMS detector is described in section 2. Event selection and reconstruction is summarized in section 3. Section 4 describes the simulation of the new physics signal models in this analysis, while section 5 describes the background determination for both resonant and nonresonant excesses. Section 6 discusses the sources of systematic uncertainties. We present our results in section 7 and summarize the paper in section 8.

Tabulated results are provided in the HEPData record for this analysis [36].

2 The CMS detector

The CMS detector [37] is a multipurpose, nearly hermetic detector, designed to trigger on [38, 39] and identify electrons, muons, photons, and charged and neutral hadrons [40–42].

A global "particle-flow" algorithm [43] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic (ECAL) and brass-scintillator hadron (HCAL) calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build tau leptons, jets, and missing transverse momentum [44–46]. Within the solenoid volume are a silicon pixel and a strip tracker.

The ECAL consists of 75 848 PbWO$_4$ crystals, each with a transverse dimension approximately matching the Molière radius of the material and 25 radiation lengths in depth. The ECAL barrel (EB) covers the pseudorapidity range $|\eta| < 1.48$, and the two endcap (EE) sections cover $1.48 < |\eta| < 3.00$. In the EB, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The energy resolution of the remaining, converted barrel photons is about 1.3% up to $|\eta| = 1$, changing to about 2.5% at $|\eta| = 1.4$. In the endcaps, the energy resolution is about 2.5% for unconverted or late-converting photons, and between 3 and 4% for the other ones [40, 47]. The diphoton mass resolution, as measured in H $\to \gamma\gamma$ decays, is typically in the 1–2% range, depending on the measurement of the photon energies in the ECAL and the topology of the photons in the event [48].

Events of interest are selected using a two-tiered trigger system. The first level, 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 [38]. The second level, known as the high-level trigger, 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 [39]. The integrated luminosities for the 2016, 2017, and 2018 data-taking years have 1.2–2.5% individual uncertainties [49–51], while the overall uncertainty for the 2016–2018 period is 1.6%. 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. [37].

3 Event selection

Photon candidates are reconstructed from energy deposits in the ECAL, referred to as superclusters, using a clustering algorithm to associate deposits that are compatible with the expected electromagnetic shower shape along the azimuthal direction and allowing for energy recovery from electron bremsstrahlung and photon conversions. Since the clustering algorithm does not distinguish whether the electromagnetic shower originates from a photon or an electron, it can also be applied to Z $\to$ e$^+$e$^-$ events, which are then used to assess the photon energy scale and resolution, and the efficiency of the photon selection criteria. A more detailed documentation of photon reconstruction in the CMS detector is given in refs. [40, 47].

To suppress backgrounds from jets or electrons, additional selection criteria are applied to photon candidates, based on observables sensitive to the electromagnetic shower shape and any additional activity surrounding the shower. The hadronic energy captured along the photon direction in the HCAL must be $< 5\%$ of the total energy of the photon. Isolation variables are based on the total transverse momentum of particles reconstructed within a

cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the photon candidate, where ϕ is the azimuthal angle. Two different isolation variables are constructed, summing the transverse momenta of either charged hadrons or photons. The charged-hadron isolation is required to be less than 5.0 GeV. The photon isolation is required to be less than 2.75 (2.0) GeV in the EB (EE), where the isolation is corrected by the average energy density in the event to account for contributions of the photon and other interactions inside the isolation region. The second-order moment of the log-weighted crystal energies of the photon candidate in the η direction, $\sigma_{i\eta i\eta}$, is used to measure the electromagnetic shower shape [40]. Hits in the silicon pixel and strip trackers are used to reject electrons, with a further check to ensure that photon candidates associated with electron tracks are incompatible with those resulting from photon conversions. Finally, a selection on the shower shape variable $R_9 > 0.8$ is imposed [40], where R_9 is defined as the energy sum of the 3×3 crystals centered on the most energetic crystal in the supercluster divided by the energy of the supercluster. The per photon reconstruction efficiency is approximately 90% (82%) in the EB (EE) and depends only weakly on the photon p_{T} in the signal region.

Events are selected online by a trigger that requires at least two reconstructed photon candidates, each with transverse momentum $p_{\mathrm{T}} > 60\,(70)$ GeV, for the 2016 (2017–2018) data sets. In events with more than two photon candidates, the two photons leading in p_{T} are chosen. The trigger photon candidates are required to have a ratio of hadronic/electromagnetic energy of less than 0.15. With these selections, the trigger efficiency is close to 100% for two photons reconstructed offline with $p_{\mathrm{T}} > 125$ GeV.

Two diphoton event categories are considered in this analysis: the first category is where both photons are reconstructed in the fiducial region of the EB with $|\eta| < 1.44$ (denoted EBEB), while the second category consists of events with one photon in the EB and the other photon in the fiducial region of the EE, $1.57 < |\eta| < 2.50$ (EBEE). Photons in the overlap region between $1.44 < |\eta| < 1.57$ have low reconstruction efficiency and hence are not used. The EBEE category typically provides an increase of approximately 10% to the signal sensitivity, whereas events where both photons are in the EE are not considered because this category is dominated by SM backgrounds and has negligible sensitivity to the considered signal models. The minimum reconstructed invariant mass of the diphoton system is required to be $m_{\gamma\gamma} > 500$ GeV. Photon pairs must additionally satisfy $\Delta R_{\gamma\gamma} > 0.45$ to be consistent with the calculation used for SM diphoton production described in section 5.

The energy scale and resolution of photons are inferred from measurements of electrons in $\mathrm{Z} \to \mathrm{e^+e^-}$ events. The energy of the photons is typically corrected by approximately 0.5% and varies with the p_{T} and η of the photon, while the additional Gaussian smearing needed in simulation to match the measured energy resolution in data varies between 0.8 and 1.5% for photon candidates in the EB region and between 2 and 2.5% for photon candidates in the EE region.

The interaction vertex associated with the diphoton system is selected using the algorithm described in refs. [52, 53], which uses a multivariate classifier to enhance the probability that the correct vertex is assigned. Variables that enter this classifier include the p_{T}^2 sum of the charged-particle tracks associated with the vertex, and two variables that quantify the vector and scalar balance of p_{T} between the diphoton system and the tracks associated with

the vertex. In addition, if either photon has an associated track that has been identified as originating from a photon conversion to an electron-positron pair, the conversion information is used in the classifier. For signal events with diphoton invariant masses above 500 GeV, the fraction of events in which the interaction vertex is correctly assigned is approximately 90%.

4 Signal simulation

Signals predictions are computed at leading order (LO) using the PYTHIA 8.230 program [54], and the detector response is simulated with GEANT4 [55]. The signal Monte Carlo (MC) events use the NNPDF2.3 [56] LO set of parton distribution functions (PDFs) and the CUETP8M1 [57] underlying event tune for the 2016 data set and the NNPDF3.1 [58] LO set of PDFs and underlying event tune CP2 [59] for the 2017 and 2018 data sets. In addition to the hard process, simulated events include the effects of additional pp interactions from within the same or nearby bunch crossings (pileup). The simulation is reweighted such that the pileup profile matches the one observed in data, based on measurements of the luminosity and assuming that the pp inelastic cross section is 69.2 mb [60]. The photon identification efficiency and resolution are corrected based on known differences between data and MC simulation as measured in $Z \to e^+e^-$ events.

In the resonant analysis, two values of intrinsic spin are considered: a spin-0 ($J = 0$) signal, which corresponds to a heavy SM-like Higgs boson, and a spin-2 ($J = 2$) signal, which corresponds to the RS graviton in the warped extra dimension model. Three signal width hypotheses are considered for both the spin-0 and spin-2 cases, corresponding to a width that is narrower than, comparable to, and wider than the detector resolution. In the $J = 0$ case, these widths are $\Gamma_X/m_X = 1.4 \times 10^{-4}$, 1.4×10^{-2}, and 5.6×10^{-2}, where Γ_X is the natural width of the resonance, and m_X is the resonance mass. In the $J = 2$ case, these same intrinsic widths correspond to a relative $\widetilde{k} = 0.01$, 0.1, and 0.2, where $\widetilde{k} = \sqrt{8\pi}\, k/\overline{M}_{Pl}$. Events with various mass point values are generated for each signal width in both EBEB and EBEE categories, and binned histograms in $m_{\gamma\gamma}$ are used as the shape template. To interpolate between generated points, a linear interpolation of the cumulative distribution functions of the $m_{\gamma\gamma}$ shapes are used.

The signal normalization is determined by the product of the acceptance and the event selection efficiency. The acceptance is estimated at the generator-level, whereas the efficiency is estimated after the full event reconstruction and selection. The signal normalization is interpolated between each mass point with a cubic spline fit as a function of the generated mass. In the case of the heavy Higgs boson resonance, gluon fusion is the dominant production mechanism so the off-shell production can overwhelm the on-shell signal, producing significant low-mass tails. Thus a fiducial acceptance is quoted such that the generated diphoton invariant mass is within 20% of the pole mass. Figure 1 shows the product of the acceptance and selection efficiency of the narrow signal width hypothesis for both $J = 0$ and $J = 2$, as a function of m_X; the product of the acceptance and efficiency are very similar for the other width scenarios. This figure demonstrates that the signal becomes more central as the resonance mass increases.

In the nonresonant analysis, ADD signals are generated at LO together with the SM diphoton process to account for the interference effects. An additional SM-only sample is
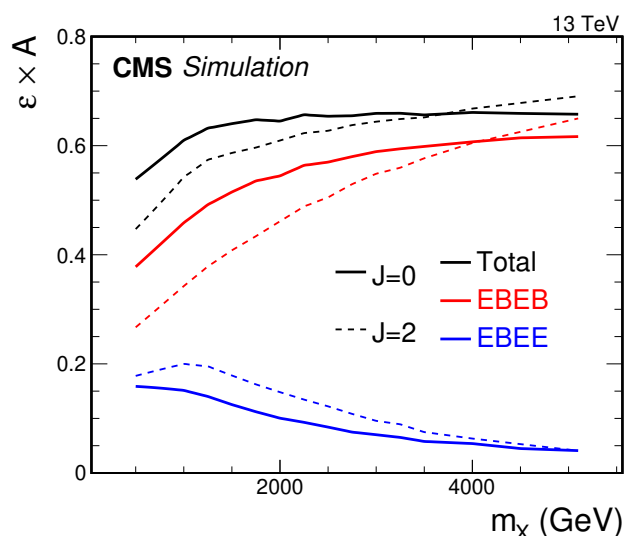
Figure 1. The product of the acceptance (A) and the event selection efficiency (ϵ) is shown as a function of the signal resonance mass m_X for the narrow signal width hypothesis ($\Gamma_X/m_X = 1.4 \times 10^{-4}$ for $J = 0$ and $\widetilde{k} = 0.01$ for $J = 2$). The total (black), EBEB (red), and EBEE (blue) curves are shown for spin hypotheses $J = 0$ (solid) and $J = 2$ (dashed).

generated such that the difference between signal samples and the SM-only sample isolates the total effect of the ADD process. The ADD model is parametrized by the scale variable M_S, which is the ultraviolet cutoff parameter for the virtual graviton exchange process in the Giudice-Rattazzi-Wells (GRW) convention [61]. The generated diphoton spectra are therefore truncated at the value of M_S. Translations to the Hewett [62] and Han-Lykken-Zhang (HLZ) [63] conventions are performed by noting that the total cross section for the ADD signal is given by

$$\sigma_{\text{total}} = \sigma_{\text{SM}} + \frac{\mathcal{F}}{M_S^4}\sigma_{\text{int}} + \frac{\mathcal{F}^2}{M_S^8}\sigma_{\text{ADD}}, \tag{4.1}$$

where σ_{SM}, σ_{int}, and σ_{ADD} are the cross sections for the SM-only, the interference term, and the direct term, respectively. The variable $\mathcal{F}$ transforms the predictions into the different conventions,

$$\mathcal{F} = \begin{cases} 1 & \text{(GRW)}, \\[2mm] \left. \begin{array}{ll} \log\left(\dfrac{M_S^2}{\hat{s}}\right), & \text{if } n_{\text{ED}} = 2 \\[3mm] \dfrac{2}{n_{\text{ED}} - 2}, & \text{if } n_{\text{ED}} > 2 \end{array} \right\} & \text{(HLZ)} \\[8mm] \pm\dfrac{2}{\pi} & \text{(Hewett)} \end{cases} \tag{4.2}$$

where $\sqrt{\hat{s}}$ is the center-of-mass energy of the colliding partons.

Predictions for the clockwork model can be obtained via a reinterpretation of the ADD signal samples. In the clockwork model, the KK modes are all on-shell and narrow, so there

is no interference effect. Using the generated signal samples, the direct term (corresponding to σ_{ADD}) can be isolated by taking a linear combination of samples with positive interference, negative interference, and the SM diphoton process. The direct term can then be rescaled by the expression, provided by the authors of ref. [10]:

$$\theta(m_{\gamma\gamma} - k)\frac{30\Lambda_{\text{T}}^8}{283\pi M_5^3}\sqrt{1 - \frac{k^2}{m_{\gamma\gamma}^2}}\frac{1}{m_{\gamma\gamma}^5}\left[1 + \frac{2975}{283 \cdot 2^8}\left(1 - \frac{k}{m_{\gamma\gamma}}\right)^9\sqrt{\frac{m_{\gamma\gamma}}{k}}\right]^{-1}, \qquad (4.3)$$

to generate the clockwork model prediction, where Λ_{T} is equal to M_{S} in the GRW convention, M_5 is the fundamental scale of the gravitational interactions, and θ is the Heaviside step function. The clockwork spring parameter k sets the inverse size of the extra dimension; phenomenologically, it controls the energy scale at which the KK modes can be excited. Imposing perturbativity of the theory constrains $k < M_5$. Because the direct term is a relatively small contribution to the overall cross section σ_{total} at low $m_{\gamma\gamma}$, large statistical fluctuations in the clockwork template construction at low mass are common. To avoid being sensitive to these fluctuations the search for the clockwork model only begins at $m_{\gamma\gamma}$ above $1\,\text{TeV}$.

5 Background determination

The two dominant backgrounds in this analysis are the irreducible SM diphoton production and an additional reducible background from jets that mimic prompt photons (called "misID") in the detector. We use two different methods to estimate the SM background. The resonant background technique uses a functional fit to extract the background shape and is optimal for identifying narrow resonances. The drawback of a functional fit is that it can be insensitive to shape differences that do not produce a peak, especially if the deviation lies in the tail of the distribution. The nonresonant background technique uses a combination of higher-order MC predictions and techniques predicting the background shape from control samples in data and is best suited for identifying nonresonant deviations in the tail of the distribution. This technique can produce large single-bin statistical fluctuations due to the misidentified-photon background, which requires a coarser binning to mitigate this effect, thus reducing the sensitivity to a narrow resonant excess.

5.1 Resonant search background

For the resonant signal search, parametrized functions are fit to the $m_{\gamma\gamma}$ spectrum. Localized excesses in the form of a peak are distinguishable from the smoothly-falling background. Four functions of the dimensionless variable $x = m_{\gamma\gamma}/\sqrt{s}$ are given equal consideration in the statistical analysis:

$$\begin{aligned} f_1(x) &= p_0 x^{p_1 + p_2 \log(x)}, \\ f_2(x) &= p_0 \mathrm{e}^{p_1 x} x^{p_2}, \\ f_3(x) &= p_0 (1 + x p_1)^{p_2}, \\ f_4(x) &= p_0 (1 + x p_1)^{p_2 + p_3 x}, \end{aligned} \qquad (5.1)$$

where p_i are unconstrained nuisance parameters in the hypothesis test. During the likelihood scan of the signal strength (a numerical multiplier of the signal normalization), a discrete-profiling technique is used wherein the function that yields the maximum likelihood value is chosen in the evaluation of the likelihood. Variable-size binning is adopted for the $m_{\gamma\gamma}$ spectrum, so that bin widths vary from 10 GeV at low $m_{\gamma\gamma}$ to 150 GeV at high $m_{\gamma\gamma}$, where the bin width is chosen to be comparable to the resolution of the reconstructed signal mass.

Tests are performed to estimate the potential bias introduced because of the background parameterization, as was done in ref. [18]. Pseudo-experiments are generated for all background functions with different choices of assumed signal strength. The parameterizations are considered unbiased and accurate because the mean of the measured signal strength is within ± 0.5 standard deviations of the injected value for all signal strengths tested.

5.2 Nonresonant search background

For the nonresonant signal search, the SM diphoton production spectrum is first computed at LO with the SHERPA 2.2.4 [64] MC event generator, which includes up to three extra partons in the final state computed at tree level. The detector response is again simulated with GEANT4. A K factor, defined as the generator-level ratio of the $m_{\gamma\gamma}$ spectrum predicted by MCFM v8.0 [65] at NNLO to the spectrum predicted by SHERPA, is calculated as a function of $m_{\gamma\gamma}$ to incorporate higher-order corrections to this process. The renormalization, factorization, and fragmentation scales in the MCFM calculation are set to the invariant mass of the diphoton pair, $m_{\gamma\gamma}$. The NNPDF30_nnlo_as_0118 PDF set is used in both calculations [58]. Events with $\Delta R_{\gamma\gamma} < 0.45$ are rejected to avoid infrared divergences. The K factor values vary as a function of $m_{\gamma\gamma}$ and range from 1.3 (1.4) to 2.0 (2.2) for EBEB (EBEE) events with $m_{\gamma\gamma} < 4$ TeV. The simulated SHERPA events are then reweighted by the appropriate K factor to produce an NNLO prediction with the full detector simulation.

The secondary background from γ+jet and multijet events occurs when either one or two jets are misidentified as photons. This misidentification frequently occurs when a neutral meson decays into photons at sufficiently high momentum that the photons overlap in the detector. If there is simultaneously little hadronic energy surrounding them, these photons can look like a single, isolated photon. A method based on control samples in data, which is similar to the one described in ref. [18], is used to estimate the rate in each $m_{\gamma\gamma}$ bin.

This method computes a transfer ratio in two reference samples, a jet-triggered data set and a double-muon-triggered data set. The two samples are enriched in jets produced through the strong interaction and in association with a Z boson, respectively, and have different quark-gluon compositions that are used to bound the uncertainty in the misID rate. The numerator of this ratio is the number of jets that are misidentified as photons. The denominator is the number of jets that are reconstructed as 'photon-like' objects, where photon-like means that the object passes a less-strict version of the photon identification criteria and also fails at least one of the isolation or shower shape requirements. The contamination of the numerator of the transfer ratio by prompt photons is estimated statistically by fitting the shower shape variable $\sigma_{i\eta i\eta}$ to two templates. The contamination of the denominator by prompt photons is negligibly small. The transfer ratio can thus be used to estimate the number of jets misidentified as photons in a signal sample from the number of photon-like jets in that same sample.

This transfer ratio is measured as a function of the photon object p_T, the number of reconstructed primary vertices, and in three $|\eta|$ regions: the EB and two ranges in the EE, corresponding to $1.57 < |\eta| < 2.03$ and $2.03 < |\eta| < 2.50$. The final estimate of the misID background sources is calculated by measuring the number of events that pass the final event selection but with either one or two photon-like objects replacing one or two photons and applying the transfer ratio to those events. This is performed for each $m_{\gamma\gamma}$ bin separately for the EBEB and EBEE categories.

6 Systematic uncertainties

Sources of systematic uncertainty held in common by the two background treatments include a 1.6% uncertainty in the signal normalization, stemming from the uncertainty in the total integrated luminosity. Uncertainties in the signal shape come from the photon identification efficiency, the photon energy scale, and the photon energy resolution. In the range $1 < m_{\gamma\gamma} < 3\,\text{TeV}$, the maximum effect of these uncertainties in the rate per bin are approximately 7–15% for the photon identification efficiency and 2–4% for the photon energy scale. The uncertainty in the energy resolution, including the vertex assignment accuracy, is $<1\%$, and its effect is negligible for the nonresonant analysis. The uncertainty due to the pileup is assigned by changing the total inelastic cross section by $\pm 4.6\%$ in the pileup reweighting procedure [66].

In the resonant analysis, there is an additional 6% uncertainty in the signal normalization in order to account for the variation in the kinematic acceptance of the signal that comes from the use of alternative PDF sets. The resonant analysis also treats the background shape parameters described in section 5.1 as unconstrained nuisance parameters.

In the nonresonant analysis, there are several sources of uncertainty associated with the backgrounds. The diphoton background has a 1.6% uncertainty in its normalization due to the uncertainty associated with the integrated luminosity, which is assumed to be fully correlated with the luminosity uncertainty in the signal. It also has an additional 5% normalization uncertainty from potential higher-order corrections beyond the NNLO calculation. Uncertainties that modify the background shape arise from both theoretical and experimental sources. The PDFs are treated as 50 independent eigenvectors with uncorrelated uncertainties. Uncertainties in the K factors arise from changing the renormalization, factorization, and fragmentation scales simultaneously between $m_{\gamma\gamma}/2$ and $2m_{\gamma\gamma}$. Uncertainties due to pileup, as well as the photon efficiency and energy scale, are applied to background in the same way as for signal events. For the misID photon background contribution, an uncertainty in the shape as well as an overall 30% uncertainty in the normalization is assigned to cover variations observed in the rates measured in the different data sets and from closure studies based on simulation samples.

The systematic uncertainties are treated as nuisance parameters in the calculation of the final results. They are assumed to have a log-normal shape profile, unless otherwise stated.

7 Results

The results of the resonant search are obtained assuming two kinds of signals, RS gravitons and heavy Higgs bosons. A composite hypothesis test is conducted to compare the agreement
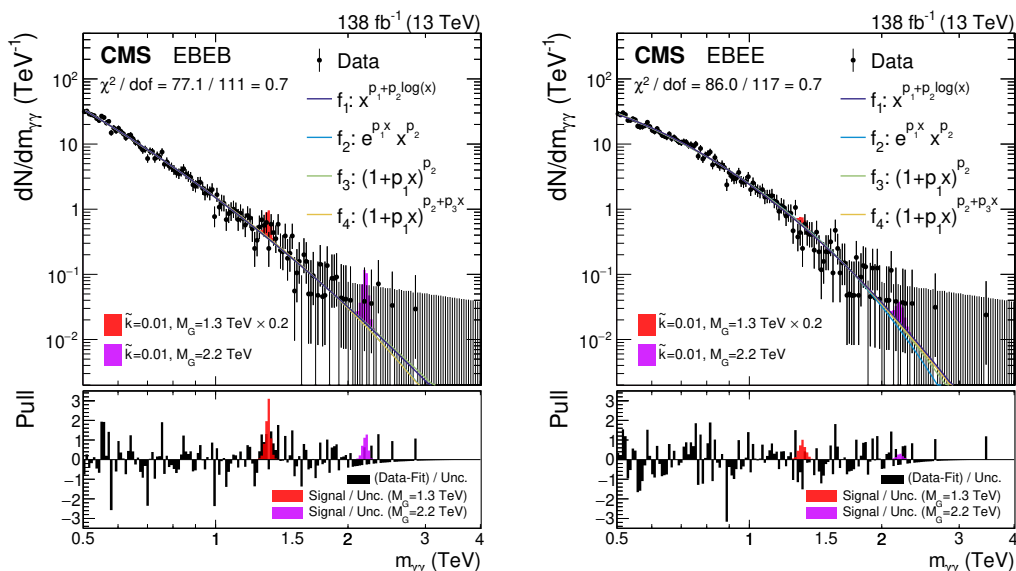
Figure 2. Observed diphoton invariant mass spectra for the EBEB (left) and EBEE (right) categories for the 2016–2018 data are shown. Also shown are the results of a likelihood fit to the background-only hypothesis. The black, blue, green, and yellow lines indicate the result of the fit functions f_1, f_2, f_3, and f_4, respectively. The predicted excesses from narrow RS gravitons at masses 1.3 and 2.2 TeV are shown based on the theoretical LO cross sections, with the 1.3 TeV signal scaled by an additional factor of 0.2. The lower panels show the difference between the data and the f_1 fit, divided by the statistical uncertainty in the data points. The indicated χ^2 in the plot is also given with respect to the f_1 fit.

of observed data with the null and alternative hypotheses, which are the background-only and the signal-plus-background hypotheses, respectively. A simultaneous fit is performed to the $m_{\gamma\gamma}$ spectrum in 6 event categories, EBEB and EBEE, separately for each of the three years of data taking. The test statistics are based on the profile likelihood ratio:

$$q(\mu) = -\log \frac{L(\mu S + B|\hat{\theta}_\mu)}{L(\hat{\mu} S + B|\hat{\theta})}, \tag{7.1}$$

where S and B are the probability distribution functions for the signal and SM background processes, respectively, μ is the signal strength parameter, and θ are the nuisance parameters of the model. The "hat" notation indicates the best-fit value of the parameters. The result of the fits, combining the 2016, 2017, and 2018 data sets, using bin sizes chosen for the narrow width hypothesis are shown in figure 2.

No statistically significant excess is observed in the data. To set the upper limit on the signal cross section, the modified frequentist method, commonly known as CL_s, is used according to the prescriptions of ref. [67], in conjunction with the use of asymptotic formulas [68]. The 95% confidence level (CL) upper limits on the production cross sections are reported in figure 3, as a function of the resonance mass. Figure 4 reports the same expected and observed upper limits but as a function of the resonance mass and width. The largest excess over the SM expectation is found at 1320 GeV with a width of $\Gamma_X/m_X = 5.6 \times 10^{-2}$, and the local significance is 2.6 standard deviations. The global significance, computed
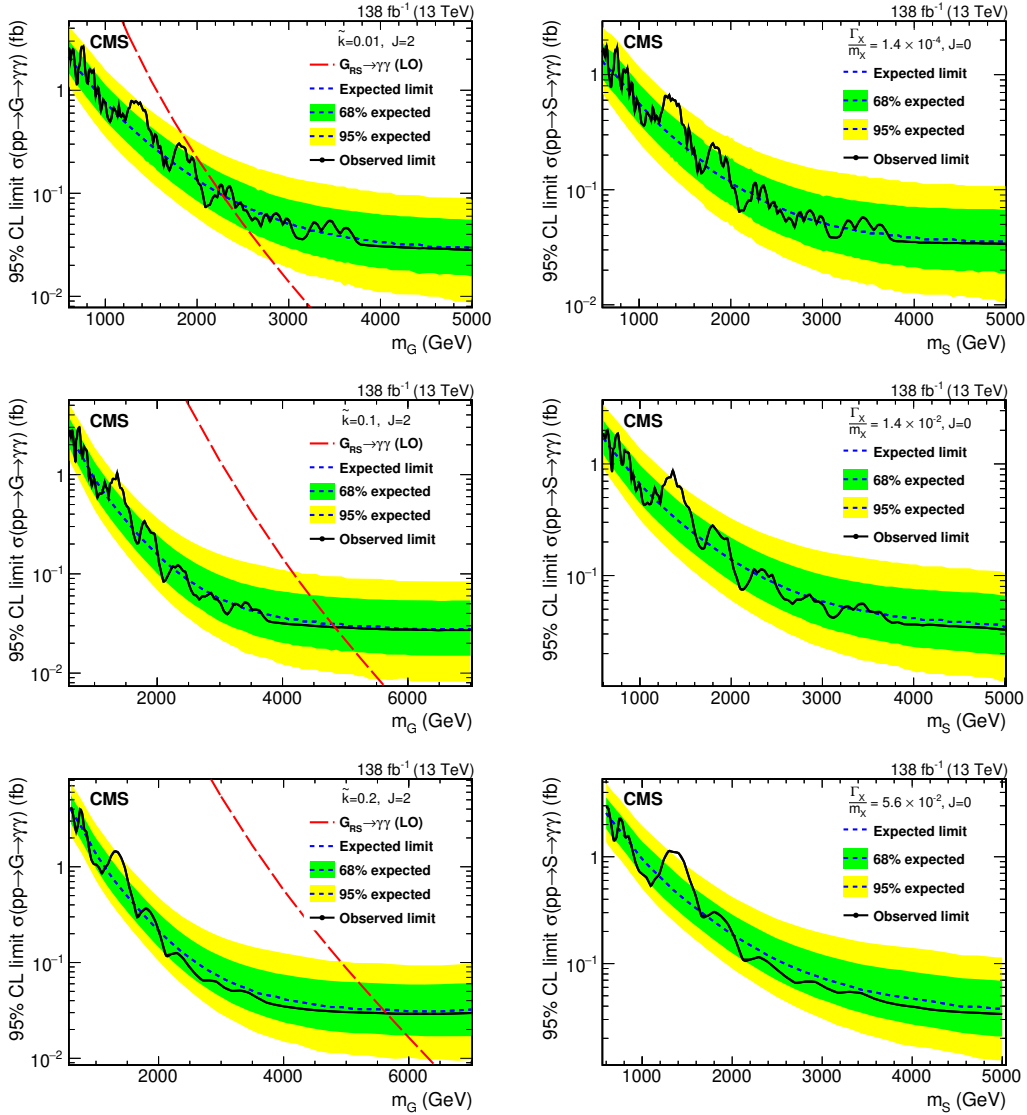
Figure 3. Expected and observed 95% CL upper limits on the product of the production cross section and branching fraction as a function of the RS graviton mass m_G (left) and heavy Higgs boson mass m_S (right) for the full Run 2 data set. The dotted red line is the LO theoretical cross section for the RS graviton. The rows correspond to different resonance widths. Expected 68% and 95% limit bands are shown in green and yellow, respectively.

by considering resonance mass hypotheses from 0.6–2.5 TeV and widths from 1.4×10^{-4} to 5.6×10^{-2}, is 0.8 standard deviations.

For the nonresonant analysis, constant bin widths of 100 GeV are used. Similar to the resonant analysis, a simultaneous fit to the $m_{\gamma\gamma}$ spectrum in six event categories, EBEB and EBEE for each of the three years of data collection, is performed. The $m_{\gamma\gamma}$ spectrum begins at 500 GeV for the ADD interpretation, while this threshold is raised to 1 TeV in the clockwork mechanism analysis to avoid statistical fluctuations in the template construction described in section 4. A Bayesian statistical approach was taken to constrain the signal
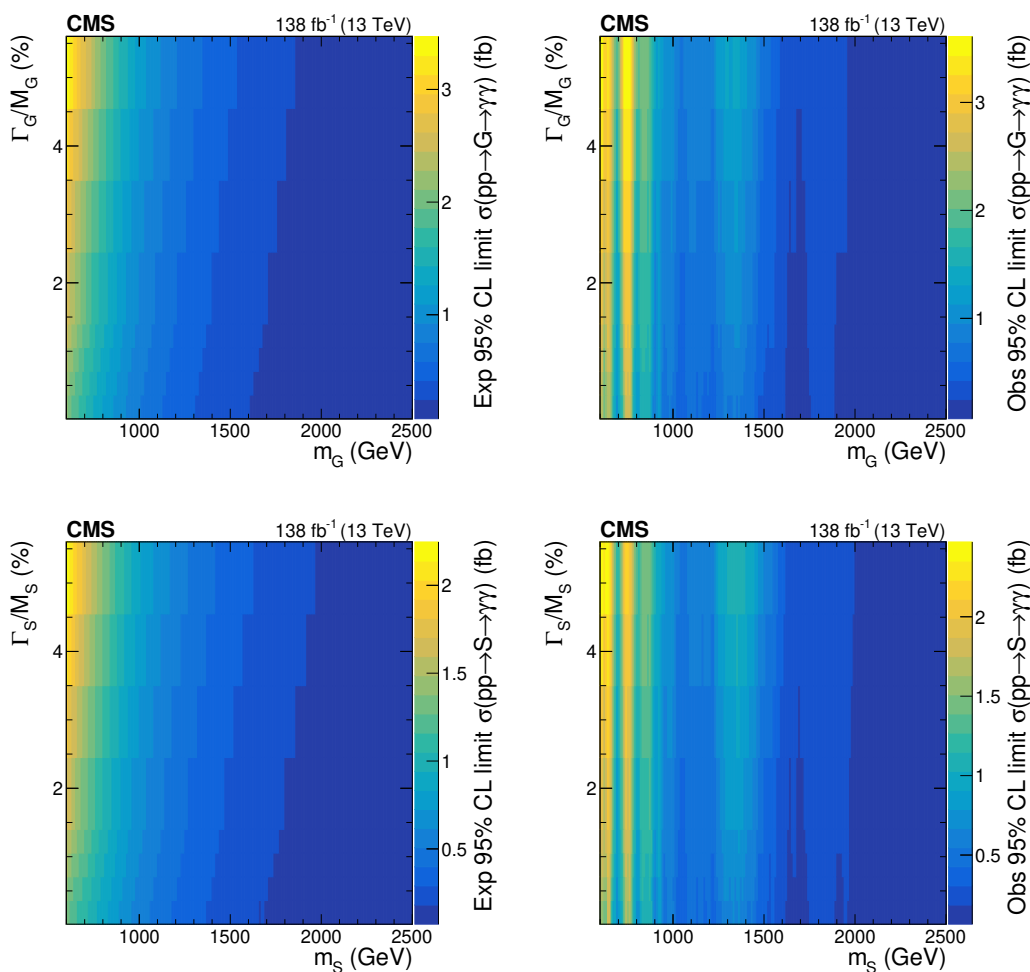
Figure 4. Expected (left) and observed (right) 95% CL upper limits on the product of the cross section and branching fraction as a function of the RS graviton mass m_G (upper) and heavy Higgs boson mass m_S (lower) versus the resonance width for the 2016–2018 data.

parameters with a flat prior on the signal strength, which is constrained to be positive, and a Markov chain MC method [69] is used to marginalize the nuisance parameters.

Figure 5 presents the data and background prediction before the marginalization of the nuisance parameters, combined for each of the three years. The shaded bands show the systematic uncertainties, neglecting the normalization of the diphoton prediction. Both the previous analysis [18] and the pre-fit predictions in the low-$m_{\gamma\gamma}$, background-dominated region give evidence that the NNLO predicts the overall normalization well. The data and background prediction after the nuisance parameters have been marginalized are shown in figure 6.

For the ADD model, upper limits are set at the 95% CL on the signal strength, which are translated into lower limits on the mass scale M_S. Table 1 summarizes the results for all ADD model conventions probed. The excluded values of M_S range from 7.1 to 11.1 TeV, depending on the convention.
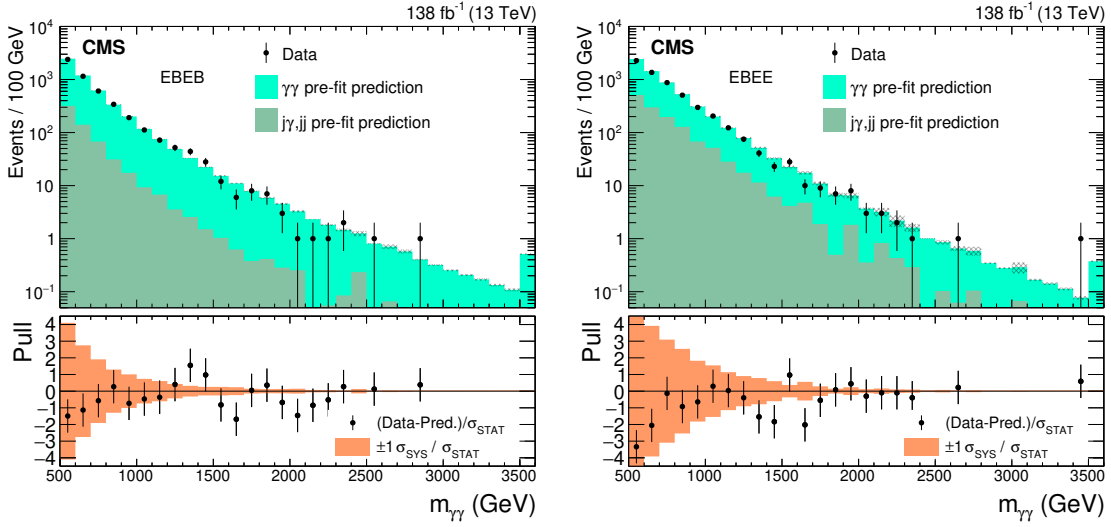
Figure 5. The $m_{\gamma\gamma}$ spectra and the background estimate before nuisance parameter marginalization ("pre-fit") due to SM diphoton production ($\gamma\gamma$) and misidentified photon production ($j\gamma$, jj) for the EBEB (left) and EBEE (right) cases, combining the 2016, 2017, and 2018 data sets. The pull distributions, defined as the data minus prediction divided by the statistical uncertainty, are shown in the lower panel. The shaded bands show the systematic uncertainties, neglecting the normalization of the diphoton prediction. The last bin contains the overflow of events with $m_{\gamma\gamma} > 3.5\,\mathrm{TeV}$.
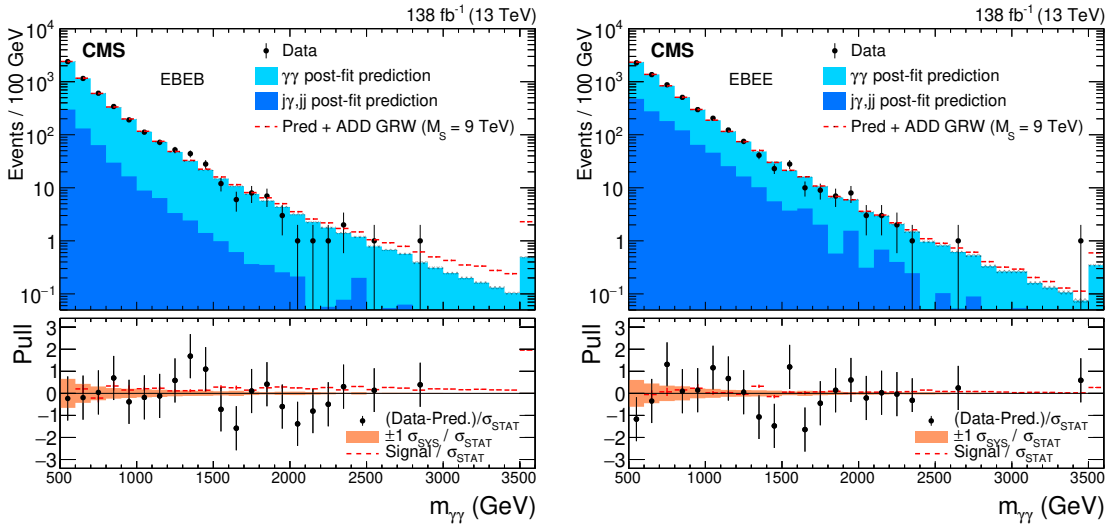
Figure 6. The $m_{\gamma\gamma}$ spectra and background prediction after nuisance parameter marginalization ("post-fit") due to SM diphoton production ($\gamma\gamma$) and misidentified photon production ($j\gamma$, jj) for the EBEB (left) and EBEE (right) cases, combining the 2016, 2017, and 2018 data sets. The prediction with an ADD signal (GRW convention with $M_{\mathrm{S}} = 6\,\mathrm{TeV}$) is also shown. The pull distributions, defined as the data minus prediction divided by the statistical uncertainty, are shown in the lower panel. The shaded bands show the systematic uncertainties, neglecting the normalization of the diphoton prediction. The last bin contains the overflow of events with $m_{\gamma\gamma} > 3.5\,\mathrm{TeV}$.

Signal:	GRW	Hewett		HLZ				
		negative	positive	$n_{\mathrm{ED}} = 3$	$n_{\mathrm{ED}} = 4$	$n_{\mathrm{ED}} = 5$	$n_{\mathrm{ED}} = 6$	$n_{\mathrm{ED}} = 7$
Expected:	$8.7^{+0.7}_{-0.6}$	$7.3^{+0.3}_{-0.3}$	$7.8^{+0.6}_{-0.5}$	$10.3^{+0.8}_{-0.7}$	$8.7^{+0.7}_{-0.6}$	$7.9^{+0.6}_{-0.5}$	$7.3^{+0.6}_{-0.5}$	$6.9^{+0.6}_{-0.5}$
Observed:	9.3	7.1	8.3	11.1	9.3	8.4	7.8	7.4

Table 1. The observed and expected lower limits on M_{S} in TeV at the 95% CL for different theoretical conventions of the ADD extra dimension model.
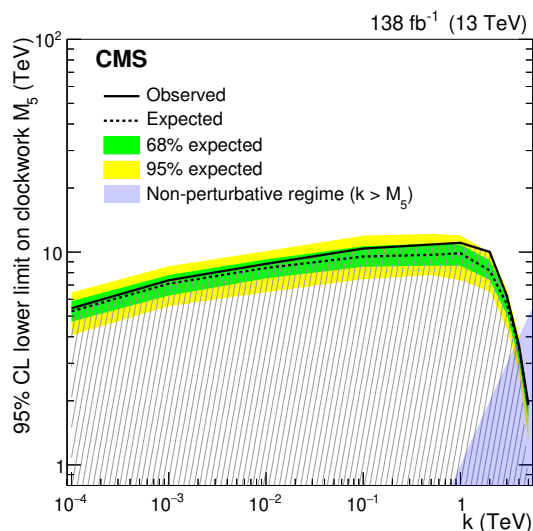
Figure 7. The exclusion limit for the clockwork framework over the k–M_5 parameter space. The darker shaded region denotes where the theory becomes nonperturbative. The region below the solid line constitutes the excluded region. Expected 68% and 95% limit bands are shown in green and yellow, respectively.

The limit-setting strategy for the clockwork model is similar to that for the ADD model. Figure 7 shows the 95% CL exclusion limits in the k–M_5 plane. Values of M_5 lower than 8.0 TeV are excluded for k values in the range of 0.2 GeV to 2.0 TeV.

As described above, the two different background estimation approaches in this paper are sensitive to different types of deviations from the SM expectation. Despite the different techniques used, the two methods agree bin-by-bin typically well within the statistical uncertainties, with relative deviations as large as 7% for $m_{\gamma\gamma} < 1500$ GeV in both the EBEB and EBEE spectra.

8 Summary

A search has been performed for new physics in high-mass diphoton events from proton-proton collisions at a center-of-mass energy of 13 TeV. The data used correspond to an integrated luminosity of $138\,\mathrm{fb}^{-1}$ collected with the CMS detector in 2016–2018. No statistically significant excess, either resonant or nonresonant, is observed in the spectra. Masses below 2.2 to 5.6 TeV are excluded at the 95% confidence level for the excited state of the Randall-

Sundrum (RS) graviton, for coupling parameters between $0.01 < \widetilde{k} < 0.2$. Limits are also set on the production of scalar Higgs boson like resonances. In the model with large extra spatial dimensions by Arkani-Hamed, Dimopoulos, and Dvali (ADD), exclusion limits on the mass scale M_S range between 7.1 to 11.1 TeV, depending on the specific convention. Additionally, exclusion limits are set in the two-dimensional space of the continuum clockwork model, with the fundamental scale M_5 excluded at the 95% confidence level below 8.0 TeV for k values between 0.2 GeV and 2.0 TeV. The present results are the strongest limits to date on ADD extra dimensions and RS gravitons with $\widetilde{k} \geq 0.1$.

Acknowledgments

References

[1] S. Weinberg, *Implications of Dynamical Symmetry Breaking*, *Phys. Rev. D* **13** (1976) 974 [INSPIRE].

[2] L. Susskind, *Dynamics of Spontaneous Symmetry Breaking in the Weinberg-Salam Theory*, *Phys. Rev. D* **20** (1979) 2619 [INSPIRE].

[3] N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, *The Hierarchy problem and new dimensions at a millimeter*, *Phys. Lett. B* **429** (1998) 263 [hep-ph/9803315] [INSPIRE].

[4] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, *New dimensions at a millimeter to a Fermi and superstrings at a TeV*, *Phys. Lett. B* **436** (1998) 257 [hep-ph/9804398] [INSPIRE].

[5] N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, *Phenomenology, astrophysics and cosmology of theories with submillimeter dimensions and TeV scale quantum gravity*, *Phys. Rev. D* **59** (1999) 086004 [hep-ph/9807344] [INSPIRE].

[6] L. Randall and R. Sundrum, *A Large mass hierarchy from a small extra dimension*, *Phys. Rev. Lett.* **83** (1999) 3370 [hep-ph/9905221] [INSPIRE].

[7] L. Randall and R. Sundrum, *An Alternative to compactification*, *Phys. Rev. Lett.* **83** (1999) 4690 [hep-th/9906064] [INSPIRE].

[8] G.F. Giudice and M. McCullough, *A Clockwork Theory*, *JHEP* **02** (2017) 036 [arXiv:1610.07962] [INSPIRE].

[9] M. Baryakhtar, *Graviton Phenomenology of Linear Dilaton Geometries*, *Phys. Rev. D* **85** (2012) 125019 [arXiv:1202.6674] [InSPIRE].

[10] G.F. Giudice, Y. Kats, M. McCullough, R. Torre and A. Urbano, *Clockwork/linear dilaton: structure and phenomenology*, *JHEP* **06** (2018) 009 [arXiv:1711.08437] [InSPIRE].

[11] G.F. Giudice and A. Strumia, *Constraints on extra dimensional theories from virtual graviton exchange*, *Nucl. Phys. B* **663** (2003) 377 [hep-ph/0301232] [InSPIRE].

[12] G.F. Giudice, T. Plehn and A. Strumia, *Graviton collider effects in one and more large extra dimensions*, *Nucl. Phys. B* **706** (2005) 455 [hep-ph/0408320] [InSPIRE].

[13] R. Franceschini, P.P. Giardino, G.F. Giudice, P. Lodone and A. Strumia, *LHC bounds on large extra dimensions*, *JHEP* **05** (2011) 092 [arXiv:1101.4919] [InSPIRE].

[14] G.C. Branco, P.M. Ferreira, L. Lavoura, M.N. Rebelo, M. Sher and J.P. Silva, *Theory and phenomenology of two-Higgs-doublet models*, *Phys. Rep.* **516** (2012) 1 [arXiv:1106.0034] [InSPIRE].

[15] T.D. Lee, *A Theory of Spontaneous T Violation*, *Phys. Rev. D* **8** (1973) 1226 [InSPIRE].

[16] N. Craig, J. Galloway and S. Thomas, *Searching for Signs of the Second Higgs Doublet*, arXiv:1305.2424 [InSPIRE].

[17] ATLAS collaboration, *Search for periodic signals in the dielectron and diphoton invariant mass spectra using* $139\,fb^{-1}$ *of pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, *JHEP* **10** (2023) 079 [arXiv:2305.10894] [InSPIRE].

[18] CMS collaboration, *Search for physics beyond the standard model in high-mass diphoton events from proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, *Phys. Rev. D* **98** (2018) 092001 [arXiv:1809.00327] [InSPIRE].

[19] ATLAS collaboration, *Search for resonances decaying into photon pairs in* $139\,fb^{-1}$ *of pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, *Phys. Lett. B* **822** (2021) 136651 [arXiv:2102.13405] [InSPIRE].

[20] ATLAS collaboration, *Search for new phenomena in high-mass diphoton final states using* $37\,fb^{-1}$ *of proton-proton collisions collected at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, *Phys. Lett. B* **775** (2017) 105 [arXiv:1707.04147] [InSPIRE].

[21] CMS collaboration, *Search for high-mass diphoton resonances in proton-proton collisions at* 13 *TeV and combination with* 8 *TeV search*, *Phys. Lett. B* **767** (2017) 147 [arXiv:1609.02507] [InSPIRE].

[22] ATLAS collaboration, *Search for resonances in diphoton events at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, *JHEP* **09** (2016) 001 [arXiv:1606.03833] [InSPIRE].

[23] CMS collaboration, *Search for Resonant Production of High-Mass Photon Pairs in Proton-Proton Collisions at* $\sqrt{s} = 8$ *and* 13 *TeV*, *Phys. Rev. Lett.* **117** (2016) 051802 [arXiv:1606.04093] [InSPIRE].

[24] ATLAS collaboration, *Search for high-mass diphoton resonances in pp collisions at* $\sqrt{s} = 8$ *TeV with the ATLAS detector*, *Phys. Rev. D* **92** (2015) 032004 [arXiv:1504.05511] [InSPIRE].

[25] CMS collaboration, *Search for diphoton resonances in the mass range from* 150 *to* 850 *GeV in pp collisions at* $\sqrt{s} = 8$ *TeV*, *Phys. Lett. B* **750** (2015) 494 [arXiv:1506.02301] [InSPIRE].

[26] ATLAS collaboration, *Search for Extra Dimensions in diphoton events using proton-proton collisions recorded at* $\sqrt{s} = 7$ *TeV with the ATLAS detector at the LHC*, *New J. Phys.* **15** (2013) 043007 [arXiv:1210.8389] [InSPIRE].

[27] CMS collaboration, *Search for signatures of extra dimensions in the diphoton mass spectrum at the Large Hadron Collider*, *Phys. Rev. Lett.* **108** (2012) 111801 [arXiv:1112.0688] [INSPIRE].

[28] CMS collaboration, *Search for Large Extra Dimensions in the Diphoton Final State at the Large Hadron Collider*, *JHEP* **05** (2011) 085 [arXiv:1103.4279] [INSPIRE].

[29] CDF collaboration, *Search for New Dielectron Resonances and Randall-Sundrum Gravitons at the Collider Detector at Fermilab*, *Phys. Rev. Lett.* **107** (2011) 051801 [arXiv:1103.4650] [INSPIRE].

[30] CDF collaboration, *Limits on Extra Dimensions and New Particle Production in the Exclusive Photon and Missing Energy Signature in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV*, *Phys. Rev. Lett.* **89** (2002) 281801 [hep-ex/0205057] [INSPIRE].

[31] CDF collaboration, *Search for Randall-Sundrum Gravitons in the Diphoton Channel at CDF*, *Phys. Rev. D* **83** (2011) 011102 [arXiv:1012.2795] [INSPIRE].

[32] D0 collaboration, *Search for Randall-Sundrum Gravitons in the Dielectron and Diphoton Final States with $5.4\,fb^{-1}$ of Data from $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. Lett.* **104** (2010) 241802 [arXiv:1004.1826] [INSPIRE].

[33] D0 collaboration, *Search for large extra dimensions in dielectron and diphoton production*, *Phys. Rev. Lett.* **86** (2001) 1156 [hep-ex/0008065] [INSPIRE].

[34] D0 collaboration, *Search for Large extra spatial dimensions in the dielectron and diphoton channels in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. Lett.* **102** (2009) 051601 [arXiv:0809.2813] [INSPIRE].

[35] D0 collaboration, *Search for Randall-Sundrum gravitons in dilepton and diphoton final states*, *Phys. Rev. Lett.* **95** (2005) 091801 [hep-ex/0505018] [INSPIRE].

[36] HEPData record for this analysis, DOI:10.17182/hepdata.150677, (2024).

[37] CMS collaboration, *The CMS Experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [INSPIRE].

[38] CMS collaboration, *Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV*, 2020 *JINST* **15** P10017 [arXiv:2006.10165] [INSPIRE].

[39] CMS collaboration, *The CMS trigger system*, 2017 *JINST* **12** P01020 [arXiv:1609.02366] [INSPIRE].

[40] CMS collaboration, *Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC*, 2021 *JINST* **16** P05014 [arXiv:2012.06888] [INSPIRE].

[41] CMS collaboration, *Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV*, 2018 *JINST* **13** P06015 [arXiv:1804.04528] [INSPIRE].

[42] CMS collaboration, *Description and performance of track and primary-vertex reconstruction with the CMS tracker*, 2014 *JINST* **9** P10009 [arXiv:1405.6569] [INSPIRE].

[43] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, 2017 *JINST* **12** P10003 [arXiv:1706.04965] [INSPIRE].

[44] CMS collaboration, *Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV*, 2018 *JINST* **13** P10005 [arXiv:1809.02816] [INSPIRE].

[45] CMS collaboration, *Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV*, 2017 *JINST* **12** P02014 [arXiv:1607.03663] [INSPIRE].

[46] CMS collaboration, *Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13\,TeV$ using the CMS detector*, 2019 *JINST* **14** P07004 [arXiv:1903.06078] [inSPIRE].

[47] CMS collaboration, *Performance of Photon Reconstruction and Identification with the CMS Detector in Proton-Proton Collisions at $\sqrt{(s)} = 8\,TeV$*, 2015 *JINST* **10** P08010 [arXiv:1502.02702] [inSPIRE].

[48] CMS collaboration, *A measurement of the Higgs boson mass in the diphoton decay channel*, *Phys. Lett. B* **805** (2020) 135425 [arXiv:2002.06398] [inSPIRE].

[49] CMS collaboration, *Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13\,TeV$ in 2015 and 2016 at CMS*, *Eur. Phys. J. C* **81** (2021) 800 [arXiv:2104.01927] [inSPIRE].

[50] CMS collaboration, *CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13\,TeV$*, CMS-PAS-LUM-17-004 (2018).

[51] CMS collaboration, *CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13\,TeV$*, CMS-PAS-LUM-18-002 (2019).

[52] CMS collaboration, *Observation of the Diphoton Decay of the Higgs Boson and Measurement of Its Properties*, *Eur. Phys. J. C* **74** (2014) 3076 [arXiv:1407.0558] [inSPIRE].

[53] CMS collaboration, *Measurements of Higgs boson properties in the diphoton decay channel in proton-proton collisions at $\sqrt{s} = 13\,TeV$*, *JHEP* **11** (2018) 185 [arXiv:1804.02716] [inSPIRE].

[54] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [arXiv:1410.3012] [inSPIRE].

[55] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [inSPIRE].

[56] NNPDF collaboration, *Parton distributions with LHC data*, *Nucl. Phys. B* **867** (2013) 244 [arXiv:1207.1303] [inSPIRE].

[57] CMS collaboration, *Event generator tunes obtained from underlying event and multiparton scattering measurements*, *Eur. Phys. J. C* **76** (2016) 155 [arXiv:1512.00815] [inSPIRE].

[58] NNPDF collaboration, *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040 [arXiv:1410.8849] [inSPIRE].

[59] CMS collaboration, *Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements*, *Eur. Phys. J. C* **80** (2020) 4 [arXiv:1903.12179] [inSPIRE].

[60] CMS collaboration, *Pileup mitigation at CMS in 13 TeV data*, 2020 *JINST* **15** P09018 [arXiv:2003.00503] [inSPIRE].

[61] G.F. Giudice, R. Rattazzi and J.D. Wells, *Quantum gravity and extra dimensions at high-energy colliders*, *Nucl. Phys. B* **544** (1999) 3 [hep-ph/9811291] [inSPIRE].

[62] J.A.L. Hewett, *Indirect collider signals for extra dimensions*, *Phys. Rev. Lett.* **82** (1999) 4765 [hep-ph/9811356] [inSPIRE].

[63] T. Han, J.D. Lykken and R.-J. Zhang, *On Kaluza-Klein states from large extra dimensions*, *Phys. Rev. D* **59** (1999) 105006 [hep-ph/9811350] [inSPIRE].

[64] E. Bothmann et al., *Event Generation with Sherpa 2.2*, *SciPost Phys.* **7** (2019) 034 [arXiv:1905.09127] [inSPIRE].

[65] J.M. Campbell, R.K. Ellis, Y. Li and C. Williams, *Predictions for diphoton production at the LHC through NNLO in QCD*, *JHEP* **07** (2016) 148 [`arXiv:1603.02663`] [InSPIRE].

[66] CMS collaboration, *Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13\,TeV$*, *JHEP* **07** (2018) 161 [`arXiv:1802.02613`] [InSPIRE].

[67] ATLAS, CMS collaborations and LHC HIGGS COMBINATION Group, *Procedure for the LHC Higgs boson search combination in Summer 2011*, CMS-NOTE-2011-005 (2011) [ATL-PHYS-PUB-2011-11].

[68] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [*Erratum ibid.* **73** (2013) 2501] [`arXiv:1007.1727`] [InSPIRE].

[69] N. Metropolis, A.W. Rosenbluth, M.N. Rosenbluth, A.H. Teller and E. Teller, *Equation of state calculations by fast computing machines*, *J. Chem. Phys.* **21** (1953) 1087 [InSPIRE].

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. Hayrapetyan, A. Tumasyan [1]

Institut für Hochenergiephysik, Vienna, Austria

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, P.S. Hussain, M. Jeitler [2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck [2], R. Schöfbeck, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz [2]

Universiteit Antwerpen, Antwerpen, Belgium

M.R. Darwish [3], T. Janssen, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium

N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat [4], G.P. Van Onsem, S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium

B. Bilin, B. Clerbaux, A.K. Das, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, J. Jaramillo, A. Khalilzadeh, F.A. Khan, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium

M. De Coen, D. Dobur, G. Gokbulut, Y. Hong, J. Knolle, L. Lambrecht, D. Marckx, K. Mota Amarilo, A. Samalan, K. Skovpen, N. Van Den Bossche, J. van der Linden, L. Wezenbeek

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

A. Benecke, A. Bethani, G. Bruno, C. Caputo, J. De Favereau De Jeneret, C. Delaere, I.S. Donertas, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, M. Alves Gallo Pereira, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, A. Moraes, P. Rebello Teles, M. Soeiro, A. Vilela Pereira [5]

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

W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato [6], E.M. Da Costa, G.G. Da Silveira [7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, M. Macedo, J. Martins [8], C. Mora Herrera, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes [7], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

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

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

University of Sofia, Sofia, Bulgaria

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

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

S. Keshri 🆔, S. Thakur 🆔

Beihang University, Beijing, China

T. Cheng 🆔, T. Javaid 🆔, L. Yuan 🆔

Department of Physics, Tsinghua University, Beijing, China

Z. Hu 🆔, Z. Liang, J. Liu, K. Yi 🆔 [9,10]

Institute of High Energy Physics, Beijing, China

G.M. Chen 🆔 [11], H.S. Chen 🆔 [11], M. Chen 🆔 [11], F. Iemmi 🆔, C.H. Jiang, A. Kapoor 🆔 [12], H. Liao 🆔, Z.-A. Liu 🆔 [13], R. Sharma 🆔 [14], J.N. Song [13], J. Tao 🆔, C. Wang [11], J. Wang 🆔, Z. Wang [11], H. Zhang 🆔, J. Zhao 🆔

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

A. Agapitos 🆔, Y. Ban 🆔, S. Deng 🆔, B. Guo, C. Jiang 🆔, A. Levin 🆔, C. Li 🆔, Q. Li 🆔, Y. Mao, S. Qian, S.J. Qian 🆔, X. Qin, X. Sun 🆔, D. Wang 🆔, H. Yang, L. Zhang 🆔, Y. Zhao, C. Zhou 🆔

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China

S. Yang 🆔

Sun Yat-Sen University, Guangzhou, China

Z. You 🆔

University of Science and Technology of China, Hefei, China

K. Jaffel 🆔, N. Lu 🆔

Nanjing Normal University, Nanjing, China

G. Bauer [15], B. Li, J. Zhang 🆔

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

X. Gao 🆔 [16]

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 ⓘ, J.A. Reyes Vega

Universidad de Antioquia, Medellin, Colombia

F. Ramirez ⓘ, C. Rendón, M. Rodriguez ⓘ, A.A. Ruales Barbosa ⓘ, J.D. Ruiz Alvarez ⓘ

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

D. Giljanovic ⓘ, N. Godinovic ⓘ, D. Lelas ⓘ, A. Sculac ⓘ

University of Split, Faculty of Science, Split, Croatia

M. Kovac ⓘ, A. Petkovic, T. Sculac ⓘ

Institute Rudjer Boskovic, Zagreb, Croatia

P. Bargassa ⓘ, V. Brigljevic ⓘ, B.K. Chitroda ⓘ, D. Ferencek ⓘ, K. Jakovcic, S. Mishra ⓘ, A. Starodumov ⓘ[17], T. Susa ⓘ

University of Cyprus, Nicosia, Cyprus

A. Attikis ⓘ, K. Christoforou ⓘ, A. Hadjiagapiou, C. Leonidou, J. Mousa ⓘ, C. Nicolaou, L. Paizanos, F. Ptochos ⓘ, P.A. Razis ⓘ, H. Rykaczewski, H. Saka ⓘ, A. Stepennov ⓘ

Charles University, Prague, Czech Republic

M. Finger ⓘ, M. Finger Jr. ⓘ, A. Kveton ⓘ

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

Y. Assran[18,19], B. El-mahdy, S. Elgammal[19]

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

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

H. Kirschenmann ⓘ, K. Osterberg ⓘ, M. Voutilainen ⓘ

Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar ⓘ, N. Bin Norjoharuddeen ⓘ, E. Brücken ⓘ, F. Garcia ⓘ, P. Inkaew ⓘ, K.T.S. Kallonen ⓘ, T. Lampén ⓘ, K. Lassila-Perini ⓘ, S. Lehti ⓘ, T. Lindén ⓘ, L. Martikainen ⓘ, M. Myllymäki ⓘ, M.m. Rantanen ⓘ, H. Siikonen ⓘ, J. Tuominiemi ⓘ

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

P. Luukka ⓘ, H. Petrow ⓘ

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

M. Besancon ⓘ, F. Couderc ⓘ, M. Dejardin ⓘ, D. Denegri, J.L. Faure, F. Ferri ⓘ, S. Ganjour ⓘ, P. Gras ⓘ, G. Hamel de Monchenault ⓘ, M. Kumar ⓘ, V. Lohezic ⓘ, J. Malcles ⓘ, F. Orlandi ⓘ, L. Portales ⓘ, A. Rosowsky ⓘ, M.Ö. Sahin ⓘ, A. Savoy-Navarro ⓘ[20], P. Simkina ⓘ, M. Titov ⓘ, M. Tornago ⓘ

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

F. Beaudette ⓘ, G. Boldrini ⓘ, P. Busson ⓘ, A. Cappati ⓘ, C. Charlot ⓘ, M. Chiusi ⓘ, F. Damas ⓘ, O. Davignon ⓘ, A. De Wit ⓘ, I.T. Ehle ⓘ, B.A. Fontana Santos Alves ⓘ, S. Ghosh ⓘ, A. Gilbert ⓘ, R. Granier de Cassagnac ⓘ, A. Hakimi ⓘ, B. Harikrishnan ⓘ, L. Kalipoliti ⓘ, G. Liu ⓘ, M. Nguyen ⓘ, C. Ochando ⓘ, R. Salerno ⓘ, J.B. Sauvan ⓘ, Y. Sirois ⓘ, L. Urda Gómez ⓘ, E. Vernazza ⓘ, A. Zabi ⓘ, A. Zghiche ⓘ

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

J.-L. Agram ⓘ[21], J. Andrea ⓘ, D. Apparu ⓘ, D. Bloch ⓘ, J.-M. Brom ⓘ, E.C. Chabert ⓘ, C. Collard ⓘ, S. Falke ⓘ, U. Goerlach ⓘ, R. Haeberle ⓘ, A.-C. Le Bihan ⓘ, M. Meena ⓘ, O. Poncet ⓘ, G. Saha ⓘ, M.A. Sessini ⓘ, P. Van Hove ⓘ, P. Vaucelle

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

A. Di Florio ⓘ

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

D. Amram, S. Beauceron ⓘ, B. Blancon ⓘ, G. Boudoul ⓘ, N. Chanon ⓘ, D. Contardo ⓘ, P. Depasse ⓘ, C. Dozen ⓘ[22], H. El Mamouni, J. Fay ⓘ, S. Gascon ⓘ, M. Gouzevitch ⓘ, C. Greenberg, G. Grenier ⓘ, B. Ille ⓘ, E. Jourd'huy, I.B. Laktineh, M. Lethuillier ⓘ, L. Mirabito, S. Perries, A. Purohit ⓘ, M. Vander Donckt ⓘ, P. Verdier ⓘ, J. Xiao ⓘ

Georgian Technical University, Tbilisi, Georgia

I. Lomidze ⓘ, T. Toriashvili ⓘ[23], Z. Tsamalaidze ⓘ[17]

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

V. Botta ⓘ, S. Consuegra Rodríguez ⓘ, L. Feld ⓘ, K. Klein ⓘ, M. Lipinski ⓘ, D. Meuser ⓘ, A. Pauls ⓘ, D. Pérez Adán ⓘ, N. Röwert ⓘ, M. Teroerde ⓘ

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

S. Diekmann ⓘ, A. Dodonova ⓘ, N. Eich ⓘ, D. Eliseev ⓘ, F. Engelke ⓘ, J. Erdmann ⓘ, M. Erdmann ⓘ, P. Fackeldey ⓘ, B. Fischer ⓘ, T. Hebbeker ⓘ, K. Hoepfner ⓘ, F. Ivone ⓘ, A. Jung ⓘ,

M.y. Lee ©, F. Mausolf ©, M. Merschmeyer ©, A. Meyer ©, S. Mukherjee ©, D. Noll ©, F. Nowotny,
A. Pozdnyakov ©, Y. Rath, W. Redjeb ©, F. Rehm, H. Reithler ©, V. Sarkisovi ©, A. Schmidt ©,
A. Sharma ©, J.L. Spah ©, A. Stein ©, F. Torres Da Silva De Araujo [24], S. Wiedenbeck ©, S. Zaleski

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

C. Dziwok ©, G. Flügge ©, T. Kress ©, A. Nowack ©, O. Pooth ©, A. Stahl ©, T. Ziemons ©,
A. Zotz ©

Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen ©, M. Aldaya Martin ©, J. Alimena ©, S. Amoroso, Y. An ©, J. Bach ©,
S. Baxter ©, M. Bayatmakou ©, H. Becerril Gonzalez ©, O. Behnke ©, A. Belvedere ©,
S. Bhattacharya ©, F. Blekman ©[25], K. Borras ©[26], A. Campbell ©, A. Cardini ©, C. Cheng,
F. Colombina ©, M. De Silva ©, G. Eckerlin, D. Eckstein ©, L.I. Estevez Banos ©, O. Filatov ©,
E. Gallo ©[25], A. Geiser ©, V. Guglielmi ©, M. Guthoff ©, A. Hinzmann ©, L. Jeppe ©, B. Kaech ©,
M. Kasemann ©, C. Kleinwort ©, R. Kogler ©, M. Komm ©, D. Krücker ©, W. Lange,
D. Leyva Pernia ©, K. Lipka ©[27], W. Lohmann ©[28], F. Lorkowski ©, R. Mankel ©,
I.-A. Melzer-Pellmann ©, M. Mendizabal Morentin ©, A.B. Meyer ©, G. Milella ©,
K. Moral Figueroa ©, A. Mussgiller ©, L.P. Nair ©, J. Niedziela ©, A. Nürnberg ©, Y. Otarid,
J. Park ©, E. Ranken ©, A. Raspereza ©, D. Rastorguev ©, J. Rübenach, L. Rygaard, A. Saggio ©,
M. Scham ©[29,26], S. Schnake ©[26], P. Schütze ©, C. Schwanenberger ©[25], D. Selivanova ©,
K. Sharko ©, M. Shchedrolosiev ©, D. Stafford, F. Vazzoler ©, A. Ventura Barroso ©, R. Walsh ©,
D. Wang ©, Q. Wang ©, Y. Wen ©, K. Wichmann, L. Wiens ©[26], C. Wissing, Y. Yang ©,
A. Zimermmane Castro Santos ©

University of Hamburg, Hamburg, Germany

A. Albrecht ©, S. Albrecht ©, M. Antonello ©, S. Bein ©, L. Benato ©, S. Bollweg, M. Bonanomi ©,
P. Connor ©, K. El Morabit ©, Y. Fischer ©, E. Garutti ©, A. Grohsjean ©, J. Haller ©,
H.R. Jabusch ©, G. Kasieczka ©, P. Keicher, R. Klanner ©, W. Korcari ©, T. Kramer ©, C.c. Kuo,
V. Kutzner ©, F. Labe ©, J. Lange ©, A. Lobanov ©, C. Matthies ©, L. Moureaux ©, M. Mrowietz,
A. Nigamova ©, Y. Nissan, A. Paasch ©, K.J. Pena Rodriguez ©, T. Quadfasel ©, B. Raciti ©,
M. Rieger ©, D. Savoiu ©, J. Schindler ©, P. Schleper ©, M. Schröder ©, J. Schwandt ©,
M. Sommerhalder ©, H. Stadie ©, G. Steinbrück ©, A. Tews, M. Wolf ©

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer ©, M. Burkart, E. Butz ©, T. Chwalek ©, A. Dierlamm ©, A. Droll, N. Faltermann ©,
M. Giffels ©, A. Gottmann ©, F. Hartmann ©[30], R. Hofsaess ©, M. Horzela ©, U. Husemann ©,
J. Kieseler ©, M. Klute ©, R. Koppenhöfer ©, J.M. Lawhorn ©, M. Link, A. Lintuluoto ©,
B. Maier ©, S. Maier ©, S. Mitra ©, M. Mormile, Th. Müller ©, M. Neukum, M. Oh ©,
E. Pfeffer ©, M. Presilla ©, G. Quast ©, K. Rabbertz ©, B. Regnery ©, N. Shadskiy ©, I. Shvetsov ©,
H.J. Simonis ©, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms ©, N. Trevisani ©, R.F. Von Cube ©,
M. Wassmer ©, S. Wieland ©, F. Wittig, R. Wolf ©, X. Zuo ©

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

G. Anagnostou, G. Daskalakis ©, A. Kyriakis, A. Papadopoulos[30], A. Stakia ©

National and Kapodistrian University of Athens, Athens, Greece

P. Kontaxakis ⓘ, G. Melachroinos, Z. Painesis ⓘ, I. Papavergou ⓘ, I. Paraskevas ⓘ, N. Saoulidou ⓘ, K. Theofilatos ⓘ, E. Tziaferi ⓘ, K. Vellidis ⓘ, I. Zisopoulos ⓘ

National Technical University of Athens, Athens, Greece

G. Bakas ⓘ, T. Chatzistavrou, G. Karapostoli ⓘ, K. Kousouris ⓘ, I. Papakrivopoulos ⓘ, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou ⓘ, C. Foudas, C. Kamtsikis, P. Katsoulis, P. Kokkas ⓘ, P.G. Kosmoglou Kioseoglou ⓘ, N. Manthos ⓘ, I. Papadopoulos ⓘ, J. Strologas ⓘ

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

C. Hajdu ⓘ, D. Horvath ⓘ[31,32], K. Márton, A.J. Rádl ⓘ[33], F. Sikler ⓘ, V. Veszpremi ⓘ

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

M. Csanád ⓘ, K. Farkas ⓘ, A. Fehérkuti ⓘ[34], M.M.A. Gadallah ⓘ[35], Á. Kadlecsik ⓘ, P. Major ⓘ, G. Pásztor ⓘ, G.I. Veres ⓘ

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

B. Ujvari ⓘ, G. Zilizi ⓘ

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

T. Novak ⓘ

Panjab University, Chandigarh, India

J. Babbar ⓘ, S. Bansal ⓘ, S.B. Beri, V. Bhatnagar ⓘ, G. Chaudhary ⓘ, S. Chauhan ⓘ, N. Dhingra ⓘ[36], A. Kaur ⓘ, A. Kaur ⓘ, H. Kaur ⓘ, M. Kaur ⓘ, S. Kumar ⓘ, K. Sandeep ⓘ, T. Sheokand, J.B. Singh ⓘ, A. Singla ⓘ

University of Delhi, Delhi, India

A. Ahmed ⓘ, A. Bhardwaj ⓘ, A. Chhetri ⓘ, B.C. Choudhary ⓘ, A. Kumar ⓘ, A. Kumar ⓘ, M. Naimuddin ⓘ, K. Ranjan ⓘ, M.K. Saini, S. Saumya ⓘ

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia ⓘ, S. Barman ⓘ[37], S. Bhattacharya ⓘ, S. Das Gupta, S. Dutta ⓘ, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India

M.M. Ameen ⓘ, P.K. Behera ⓘ, S.C. Behera ⓘ, S. Chatterjee ⓘ, G. Dash ⓘ, P. Jana ⓘ, P. Kalbhor ⓘ, S. Kamble ⓘ, J.R. Komaragiri ⓘ[38], D. Kumar ⓘ[38], P.R. Pujahari ⓘ, N.R. Saha ⓘ, A. Sharma ⓘ, A.K. Sikdar ⓘ, R.K. Singh, P. Verma, S. Verma ⓘ, A. Vijay

Tata Institute of Fundamental Research-A, Mumbai, India

S. Dugad, G.B. Mohanty [ORCID], B. Parida [ORCID], M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India

A. Bala [ORCID], S. Banerjee [ORCID], R.M. Chatterjee, M. Guchait [ORCID], Sh. Jain [ORCID], A. Jaiswal, S. Kumar [ORCID], G. Majumder [ORCID], K. Mazumdar [ORCID], S. Parolia [ORCID], A. Thachayath [ORCID]

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Bahinipati [ORCID][39], C. Kar [ORCID], D. Maity [ORCID][40], P. Mal [ORCID], T. Mishra [ORCID], V.K. Muraleedharan Nair Bindhu [ORCID][40], K. Naskar [ORCID][40], A. Nayak [ORCID][40], S. Nayak, K. Pal, P. Sadangi, S.K. Swain [ORCID], S. Varghese [ORCID][40], D. Vats [ORCID][40]

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

S. Acharya [ORCID][41], A. Alpana [ORCID], S. Dube [ORCID], B. Gomber [ORCID][41], P. Hazarika [ORCID], B. Kansal [ORCID], A. Laha [ORCID], B. Sahu [ORCID][41], S. Sharma [ORCID], K.Y. Vaish [ORCID]

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi [ORCID][42], A. Jafari [ORCID][43], M. Zeinali [ORCID][44]

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

S. Bashiri, S. Chenarani [ORCID][45], S.M. Etesami [ORCID], Y. Hosseini [ORCID], M. Khakzad [ORCID], E. Khazaie [ORCID][46], M. Mohammadi Najafabadi [ORCID], S. Tizchang [ORCID][47]

University College Dublin, Dublin, Ireland

M. Felcini [ORCID], M. Grunewald [ORCID]

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy

M. Abbrescia [ORCID][a,b], A. Colaleo [ORCID][a,b], D. Creanza [ORCID][a,c], B. D'Anzi [ORCID][a,b], N. De Filippis [ORCID][a,c], M. De Palma [ORCID][a,b], W. Elmetenawee [ORCID][a,b,48], L. Fiore [ORCID][a], G. Iaselli [ORCID][a,c], L. Longo [ORCID][a], M. Louka[a,b], G. Maggi [ORCID][a,c], M. Maggi [ORCID][a], I. Margjeka [ORCID][a], V. Mastrapasqua [ORCID][a,b], S. My [ORCID][a,b], S. Nuzzo [ORCID][a,b], A. Pellecchia [ORCID][a,b], A. Pompili [ORCID][a,b], G. Pugliese [ORCID][a,c], R. Radogna [ORCID][a,b], D. Ramos [ORCID][a], A. Ranieri [ORCID][a], L. Silvestris [ORCID][a], F.M. Simone [ORCID][a,c], Ü. Sözbilir [ORCID][a], A. Stamerra [ORCID][a,b], D. Troiano [ORCID][a,b], R. Venditti [ORCID][a,b], P. Verwilligen [ORCID][a], A. Zaza [ORCID][a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy

G. Abbiendi [ORCID][a], C. Battilana [ORCID][a,b], D. Bonacorsi [ORCID][a,b], P. Capiluppi [ORCID][a,b], [ORCID][†], F.R. Cavallo [ORCID][a], M. Cuffiani [ORCID][a,b], G.M. Dallavalle [ORCID][a], T. Diotalevi [ORCID][a,b], F. Fabbri [ORCID][a], A. Fanfani [ORCID][a,b], D. Fasanella [ORCID][a], P. Giacomelli [ORCID][a], L. Giommi [ORCID][a,b], C. Grandi [ORCID][a], L. Guiducci [ORCID][a,b], S. Lo Meo [ORCID][a,49], M. Lorusso [ORCID][a,b], L. Lunerti [ORCID][a], S. Marcellini [ORCID][a], G. Masetti [ORCID][a], F.L. Navarria [ORCID][a,b], G. Paggi [ORCID][a,b], A. Perrotta [ORCID][a], F. Primavera [ORCID][a,b], A.M. Rossi [ORCID][a,b], S. Rossi Tisbeni [ORCID][a,b], T. Rovelli [ORCID][a,b], G.P. Siroli [ORCID][a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy

S. Costa [ORCID][a,b,50], A. Di Mattia [ORCID][a], A. Lapertosa [ORCID][a], R. Potenza[a,b], A. Tricomi [ORCID][a,b,50], C. Tuve [ORCID][a,b]

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

P. Assiouras ![ORCID]^a, G. Barbagli ![ORCID]^a, G. Bardelli ![ORCID]^{a,b}, B. Camaiani ![ORCID]^{a,b}, A. Cassese ![ORCID]^a, R. Ceccarelli ![ORCID]^a, V. Ciulli ![ORCID]^{a,b}, C. Civinini ![ORCID]^a, R. D'Alessandro ![ORCID]^{a,b}, E. Focardi ![ORCID]^{a,b}, T. Kello^a, G. Latino ![ORCID]^{a,b}, P. Lenzi ![ORCID]^{a,b}, M. Lizzo ![ORCID]^a, M. Meschini ![ORCID]^a, S. Paoletti ![ORCID]^a, A. Papanastassiou^{a,b}, G. Sguazzoni ![ORCID]^a, L. Viliani ![ORCID]^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi ![ORCID], S. Bianco ![ORCID], S. Meola ![ORCID]^{51}, D. Piccolo ![ORCID]

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

P. Chatagnon ![ORCID]^a, F. Ferro ![ORCID]^a, E. Robutti ![ORCID]^a, S. Tosi ![ORCID]^{a,b}

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

A. Benaglia ![ORCID]^a, F. Brivio ![ORCID]^a, F. Cetorelli ![ORCID]^{a,b}, F. De Guio ![ORCID]^{a,b}, M.E. Dinardo ![ORCID]^{a,b}, P. Dini ![ORCID]^a, S. Gennai ![ORCID]^a, R. Gerosa ![ORCID]^{a,b}, A. Ghezzi ![ORCID]^{a,b}, P. Govoni ![ORCID]^{a,b}, L. Guzzi ![ORCID]^a, M.T. Lucchini ![ORCID]^{a,b}, M. Malberti ![ORCID]^a, S. Malvezzi ![ORCID]^a, A. Massironi ![ORCID]^a, D. Menasce ![ORCID]^a, L. Moroni ![ORCID]^a, M. Paganoni ![ORCID]^{a,b}, S. Palluotto ![ORCID]^{a,b}, D. Pedrini ![ORCID]^a, A. Perego ![ORCID]^{a,b}, B.S. Pinolini^a, G. Pizzati^{a,b}, S. Ragazzi ![ORCID]^{a,b}, T. Tabarelli de Fatis ![ORCID]^{a,b}

INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^{b}, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Scuola Superiore Meridionale (SSM)^d, Napoli, Italy

S. Buontempo ![ORCID]^a, A. Cagnotta ![ORCID]^{a,b}, F. Carnevali^{a,b}, N. Cavallo ![ORCID]^{a,c}, F. Fabozzi ![ORCID]^{a,c}, A.O.M. Iorio ![ORCID]^{a,b}, L. Lista ![ORCID]^{a,b,52}, P. Paolucci ![ORCID]^{a,30}, B. Rossi ![ORCID]^a

INFN Sezione di Padova^a, Università di Padova^b, Padova, Italy; Università di Trento^c, Trento, Italy

R. Ardino ![ORCID]^a, P. Azzi ![ORCID]^a, N. Bacchetta ![ORCID]^{a,53}, D. Bisello ![ORCID]^{a,b}, P. Bortignon ![ORCID]^a, G. Bortolato^{a,b}, A. Bragagnolo ![ORCID]^{a,b}, A.C.M. Bulla ![ORCID]^a, R. Carlin ![ORCID]^{a,b}, P. Checchia ![ORCID]^a, T. Dorigo ![ORCID]^a, F. Gasparini ![ORCID]^{a,b}, E. Lusiani ![ORCID]^a, M. Margoni ![ORCID]^{a,b}, G. Maron ![ORCID]^{a,54}, A.T. Meneguzzo ![ORCID]^{a,b}, M. Migliorini ![ORCID]^{a,b}, J. Pazzini ![ORCID]^{a,b}, P. Ronchese ![ORCID]^{a,b}, R. Rossin ![ORCID]^{a,b}, F. Simonetto ![ORCID]^{a,b}, M. Tosi ![ORCID]^{a,b}, A. Triossi ![ORCID]^{a,b}, S. Ventura ![ORCID]^a, M. Zanetti ![ORCID]^{a,b}, P. Zotto ![ORCID]^{a,b}, A. Zucchetta ![ORCID]^{a,b}, G. Zumerle ![ORCID]^{a,b}

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

C. Aimè ![ORCID]^a, A. Braghieri ![ORCID]^a, S. Calzaferri ![ORCID]^a, D. Fiorina ![ORCID]^a, P. Montagna ![ORCID]^{a,b}, V. Re ![ORCID]^a, C. Riccardi ![ORCID]^{a,b}, P. Salvini ![ORCID]^a, I. Vai ![ORCID]^{a,b}, P. Vitulo ![ORCID]^{a,b}

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

S. Ajmal ![ORCID]^{a,b}, M.E. Ascioti^{a,b}, G.M. Bilei ![ORCID]^a, C. Carrivale^{a,b}, D. Ciangottini ![ORCID]^{a,b}, L. Fanò ![ORCID]^{a,b}, M. Magherini ![ORCID]^{a,b}, V. Mariani ![ORCID]^{a,b}, M. Menichelli ![ORCID]^a, F. Moscatelli ![ORCID]^{a,55}, A. Rossi ![ORCID]^{a,b}, A. Santocchia ![ORCID]^{a,b}, D. Spiga ![ORCID]^a, T. Tedeschi ![ORCID]^{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

C.A. Alexe ![ORCID]^{a,c}, P. Asenov ![ORCID]^{a,b}, P. Azzurri ![ORCID]^a, G. Bagliesi ![ORCID]^a, R. Bhattacharya ![ORCID]^a, L. Bianchini ![ORCID]^{a,b}, T. Boccali ![ORCID]^a, E. Bossini ![ORCID]^a, D. Bruschini ![ORCID]^{a,c}, R. Castaldi ![ORCID]^a, M.A. Ciocci ![ORCID]^{a,b}, M. Cipriani ![ORCID]^{a,b},

V. D'Amante [a,d], R. Dell'Orso [a], S. Donato [a], A. Giassi [a], F. Ligabue [a,c], A.C. Marini [a], D. Matos Figueiredo [a], A. Messineo [a,b], M. Musich [a,b], F. Palla [a], A. Rizzi [a,b], G. Rolandi [a,c], S. Roy Chowdhury [a], T. Sarkar [a], A. Scribano [a], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], N. Turini [a,d], F. Vaselli [a,c], A. Venturi [a], P.G. Verdini [a]

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

C. Baldenegro Barrera [a,b], P. Barria [a], C. Basile [a,b], M. Campana [a,b], F. Cavallari [a], L. Cunqueiro Mendez [a,b], D. Del Re [a,b], E. Di Marco [a,b], M. Diemoz [a], F. Errico [a,b], E. Longo [a,b], J. Mijuskovic [a,b], 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]

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], C. Borca [a,b], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], L. Finco [a], M. Grippo [a,b], B. Kiani [a,b], F. Legger [a], F. Luongo [a,b], C. Mariotti [a], L. Markovic [a,b], S. Maselli [a], A. Mecca [a,b], L. Menzio [a,b], P. Meridiani [a], E. Migliore [a,b], M. Monteno [a], R. Mulargia [a], M.M. Obertino [a,b], G. Ortona [a], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], M. Ruspa [a,c], F. Siviero [a,b], V. Sola [a,b], A. Solano [a,b], A. Staiano [a], C. Tarricone [a,b], D. Trocino [a], G. Umoret [a,b], R. White [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], K. De Leo [a], G. Della Ricca [a,b]

Kyungpook National University, Daegu, Korea

S. Dogra, J. Hong, C. Huh, B. Kim, J. Kim, D. Lee, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, B. Tae, Y.C. Yang

Department of Mathematics and Physics - GWNU, Gangneung, Korea

M.S. Kim

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

G. Bak, P. Gwak, H. Kim, D.H. Moon

Hanyang University, Seoul, Korea

E. Asilar, J. Choi, D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

Korea University, Seoul, Korea

S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, S. Lee, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh, S. Yang

Sejong University, Seoul, Korea

H. S. Kim, Y. Kim, S. Lee

Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi [iD], J. Choi, W. Jun [iD], J. Kim [iD], S. Ko [iD], H. Kwon [iD], H. Lee [iD], J. Lee [iD], J. Lee [iD], B.H. Oh [iD], S.B. Oh [iD], H. Seo [iD], U.K. Yang, I. Yoon [iD]

University of Seoul, Seoul, Korea

W. Jang [iD], D.Y. Kang, Y. Kang [iD], S. Kim [iD], B. Ko, J.S.H. Lee [iD], Y. Lee [iD], I.C. Park [iD], Y. Roh, I.J. Watson [iD]

Yonsei University, Department of Physics, Seoul, Korea

S. Ha [iD], H.D. Yoo [iD]

Sungkyunkwan University, Suwon, Korea

M. Choi [iD], M.R. Kim [iD], H. Lee, Y. Lee [iD], I. Yu [iD]

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait

T. Beyrouthy, Y. Gharbia

Riga Technical University, Riga, Latvia

K. Dreimanis [iD], A. Gaile [iD], G. Pikurs, A. Potrebko [iD], M. Seidel [iD], D. Sidiropoulos Kontos

University of Latvia (LU), Riga, Latvia

N.R. Strautnieks [iD]

Vilnius University, Vilnius, Lithuania

M. Ambrozas [iD], A. Juodagalvis [iD], A. Rinkevicius [iD], G. Tamulaitis [iD]

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

I. Yusuff [iD][56], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez [iD], A. Castaneda Hernandez [iD], H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello [iD], J.A. Murillo Quijada [iD], A. Sehrawat [iD], L. Valencia Palomo [iD]

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

G. Ayala [iD], H. Castilla-Valdez [iD], H. Crotte Ledesma, E. De La Cruz-Burelo [iD], I. Heredia-De La Cruz [iD][57], R. Lopez-Fernandez [iD], J. Mejia Guisao [iD], C.A. Mondragon Herrera, A. Sánchez Hernández [iD]

Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera [iD], D.L. Ramirez Guadarrama, M. Ramírez García [iD]

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bautista [iD], I. Pedraza [iD], H.A. Salazar Ibarguen [iD], C. Uribe Estrada [iD]

University of Montenegro, Podgorica, Montenegro

I. Bubanja [iD], N. Raicevic [iD]

University of Canterbury, Christchurch, New Zealand

P.H. Butler

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

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan

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

V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, 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, A. Muhammad

Warsaw University of Technology, Warsaw, Poland

K. Pozniak, W. Zabolotny

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

M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, T. Niknejad, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia

P. Adzic, P. Milenovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic

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

J. Alcaraz Maestre, Cristina F. Bedoya, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, 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, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, S. Sánchez Navas, J. Sastre, J. Vazquez Escobar

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, P. Leguina, E. Palencia Cortezon,

J. Prado Pico, C. Ramón Álvarez 📀, V. Rodríguez Bouza 📀, A. Soto Rodríguez 📀, A. Trapote 📀,
C. Vico Villalba 📀, P. Vischia 📀

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

S. Bhowmik 📀, S. Blanco Fernández 📀, J.A. Brochero Cifuentes 📀, I.J. Cabrillo 📀, A. Calderon 📀,
J. Duarte Campderros 📀, M. Fernandez 📀, G. Gomez 📀, C. Lasaosa García 📀, R. Lopez Ruiz 📀,
C. Martinez Rivero 📀, P. Martinez Ruiz del Arbol 📀, F. Matorras 📀, P. Matorras Cuevas 📀,
E. Navarrete Ramos 📀, J. Piedra Gomez 📀, L. Scodellaro 📀, I. Vila 📀, J.M. Vizan Garcia 📀

University of Colombo, Colombo, Sri Lanka

B. Kailasapathy 📀[58], D.D.C. Wickramarathna 📀

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

W.G.D. Dharmaratna 📀[59], K. Liyanage 📀, N. Perera 📀

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo 📀, C. Amendola 📀, E. Auffray 📀, G. Auzinger 📀, J. Baechler, D. Barney 📀,
A. Bermúdez Martínez 📀, M. Bianco 📀, A.A. Bin Anuar 📀, A. Bocci 📀, L. Borgonovi 📀, C. Botta 📀,
E. Brondolin 📀, C. Caillol 📀, G. Cerminara 📀, N. Chernyavskaya 📀, D. d'Enterria 📀, A. Dabrowski 📀,
A. David 📀, A. De Roeck 📀, M.M. Defranchis 📀, M. Deile 📀, M. Dobson 📀, G. Franzoni 📀,
W. Funk 📀, S. Giani, D. Gigi, K. Gill 📀, F. Glege 📀, J. Hegeman 📀, J.K. Heikkilä 📀, B. Huber,
V. Innocente 📀, T. James 📀, P. Janot 📀, O. Kaluzinska 📀, O. Karacheban 📀[28], S. Laurila 📀,
P. Lecoq 📀, E. Leutgeb 📀, C. Lourenço 📀, L. Malgeri 📀, M. Mannelli 📀, M. Matthewman,
A. Mehta 📀, F. Meijers 📀, S. Mersi 📀, E. Meschi 📀, V. Milosevic 📀, F. Monti 📀, F. Moortgat 📀,
M. Mulders 📀, I. Neutelings 📀, S. Orfanelli, F. Pantaleo 📀, G. Petrucciani 📀, A. Pfeiffer 📀,
M. Pierini 📀, H. Qu 📀, D. Rabady 📀, B. Ribeiro Lopes 📀, M. Rovere 📀, H. Sakulin 📀,
S. Sanchez Cruz 📀, S. Scarfi 📀, C. Schwick, M. Selvaggi 📀, A. Sharma 📀, K. Shchelina 📀, P. Silva 📀,
P. Sphicas 📀[60], A.G. Stahl Leiton 📀, A. Steen 📀, S. Summers 📀, D. Treille 📀, P. Tropea 📀,
D. Walter 📀, J. Wanczyk 📀[61], J. Wang, S. Wuchterl 📀, P. Zehetner 📀, P. Zejdl 📀, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

T. Bevilacqua 📀[62], L. Caminada 📀[62], A. Ebrahimi 📀, W. Erdmann 📀, R. Horisberger 📀, Q. Ingram 📀,
H.C. Kaestli 📀, D. Kotlinski 📀, C. Lange 📀, M. Missiroli 📀[62], L. Noehte 📀[62], T. Rohe 📀

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

T.K. Aarrestad 📀, K. Androsov 📀[61], M. Backhaus 📀, G. Bonomelli, A. Calandri 📀, C. Cazzaniga 📀,
K. Datta 📀, P. De Bryas Dexmiers D'archiac 📀[61], A. De Cosa 📀, G. Dissertori 📀, M. Dittmar,
M. Donegà 📀, F. Eble 📀, M. Galli 📀, K. Gedia 📀, F. Glessgen 📀, C. Grab 📀, N. Härringer 📀,
T.G. Harte, D. Hits 📀, W. Lustermann 📀, A.-M. Lyon 📀, R.A. Manzoni 📀, M. Marchegiani 📀,
L. Marchese 📀, C. Martin Perez 📀, A. Mascellani 📀[61], F. Nessi-Tedaldi 📀, F. Pauss 📀, V. Perovic 📀,
S. Pigazzini 📀, C. Reissel 📀, T. Reitenspiess 📀, B. Ristic 📀, F. Riti 📀, R. Seidita 📀,
J. Steggemann 📀[61], A. Tarabini 📀, D. Valsecchi 📀, R. Wallny 📀

Universität Zürich, Zurich, Switzerland

C. Amsler [63], P. Bärtschi, M.F. Canelli, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, U. Molinatti, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

National Central University, Chung-Li, Taiwan

C. Adloff [64], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari [38], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, K.F. Chen, P.s. Chen, Z.g. Chen, A. De Iorio, W.-S. Hou, T.h. Hsu, Y.w. Kao, S. Karmakar, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, X.f. Su, J. Thomas-Wilsker, L.s. Tsai, H.y. Wu, E. Yazgan

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

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

D. Agyel, F. Boran, F. Dolek, I. Dumanoglu [65], E. Eskut, Y. Guler [66], E. Gurpinar Guler [66], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir [67], A. Polatoz, B. Tali [68], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey

G. Sokmen, M. Yalvac [69]

Bogazici University, Istanbul, Turkey

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

Istanbul Technical University, Istanbul, Turkey

A. Cakir, K. Cankocak [65,73], G.G. Dincer [65], Y. Komurcu, S. Sen [74]

Istanbul University, Istanbul, Turkey

O. Aydilek [75], B. Hacisahinoglu, I. Hos [76], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey

S. Cerci [68], B. Isildak [77], D. Sunar Cerci, T. Yetkin

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

A. Boyaryntsev, B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

D. Anthony ⓘ, J.J. Brooke ⓘ, A. Bundock ⓘ, F. Bury ⓘ, E. Clement ⓘ, D. Cussans ⓘ, H. Flacher ⓘ, M. Glowacki, J. Goldstein ⓘ, H.F. Heath ⓘ, M.-L. Holmberg ⓘ, L. Kreczko ⓘ, S. Paramesvaran ⓘ, L. Robertshaw, S. Seif El Nasr-Storey, V.J. Smith ⓘ, N. Stylianou [78], K. Walkingshaw Pass

Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball, K.W. Bell ⓘ, A. Belyaev ⓘ[79], C. Brew ⓘ, R.M. Brown ⓘ, D.J.A. Cockerill ⓘ, C. Cooke ⓘ, A. Elliot ⓘ, K.V. Ellis, K. Harder ⓘ, S. Harper ⓘ, J. Linacre ⓘ, K. Manolopoulos, D.M. Newbold ⓘ, E. Olaiya, D. Petyt ⓘ, T. Reis ⓘ, A.R. Sahasransu ⓘ, G. Salvi ⓘ, T. Schuh, C.H. Shepherd-Themistocleous ⓘ, I.R. Tomalin ⓘ, K.C. Whalen ⓘ, T. Williams ⓘ

Imperial College, London, United Kingdom

I. Andreou ⓘ, R. Bainbridge ⓘ, P. Bloch ⓘ, C.E. Brown ⓘ, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya ⓘ, G.S. Chahal ⓘ[80], D. Colling ⓘ, J.S. Dancu, I. Das ⓘ, P. Dauncey ⓘ, G. Davies ⓘ, J. Davies, M. Della Negra ⓘ, S. Fayer, G. Fedi ⓘ, G. Hall ⓘ, M.H. Hassanshahi ⓘ, A. Howard, G. Iles ⓘ, M. Knight ⓘ, J. Langford ⓘ, J. León Holgado ⓘ, L. Lyons, A.-M. Magnan ⓘ, S. Mallios, M. Mieskolainen ⓘ, J. Nash ⓘ[81], M. Pesaresi ⓘ, P.B. Pradeep, B.C. Radburn-Smith ⓘ, A. Richards, A. Rose ⓘ, K. Savva ⓘ, C. Seez ⓘ, R. Shukla ⓘ, A. Tapper ⓘ, K. Uchida ⓘ, G.P. Uttley ⓘ, L.H. Vage, T. Virdee ⓘ[30], M. Vojinovic ⓘ, N. Wardle ⓘ, 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 ⓘ, E. Collins ⓘ, J. Dittmann ⓘ, K. Hatakeyama ⓘ, J. Hiltbrand ⓘ, B. McMaster ⓘ, J. Samudio ⓘ, S. Sawant ⓘ, C. Sutantawibul ⓘ, J. Wilson ⓘ

Catholic University of America, Washington, DC, USA

R. Bartek ⓘ, A. Dominguez ⓘ, C. Huerta Escamilla, A.E. Simsek ⓘ, R. Uniyal ⓘ, A.M. Vargas Hernandez ⓘ

The University of Alabama, Tuscaloosa, Alabama, USA

B. Bam ⓘ, A. Buchot Perraguin ⓘ, R. Chudasama ⓘ, S.I. Cooper ⓘ, C. Crovella ⓘ, S.V. Gleyzer ⓘ, C. Henderson ⓘ, E. Pearson, C.U. Perez ⓘ, P. Rumerio ⓘ[82], E. Usai ⓘ, C. West ⓘ, R. Yi ⓘ

Boston University, Boston, Massachusetts, USA

A. Akpinar ⓘ, C. Cosby ⓘ, G. De Castro, Z. Demiragli ⓘ, C. Erice ⓘ, C. Fangmeier ⓘ, C. Fernandez Madrazo ⓘ, E. Fontanesi ⓘ, D. Gastler ⓘ, F. Golf ⓘ, S. Jeon, J. O'cain, I. Reed ⓘ, J. Rohlf ⓘ, K. Salyer ⓘ, D. Sperka ⓘ, D. Spitzbart ⓘ, I. Suarez ⓘ, A. Tsatsos ⓘ, A.G. Zecchinelli ⓘ

Brown University, Providence, Rhode Island, USA

G. Benelli ⓘ, D. Cutts ⓘ, L. Gouskos ⓘ, M. Hadley ⓘ, U. Heintz ⓘ, J.M. Hogan ⓘ[83], T. Kwon ⓘ, G. Landsberg ⓘ, K.T. Lau ⓘ, D. Li ⓘ, J. Luo ⓘ, S. Mondal ⓘ, M. Narain ⓘ[†], N. Pervan ⓘ, T. Russell, S. Sagir ⓘ[84], F. Simpson ⓘ, M. Stamenkovic ⓘ, N. Venkatasubramanian, X. Yan ⓘ

University of California, Davis, Davis, California, USA

S. Abbott ⬝, C. Brainerd ⬝, R. Breedon ⬝, H. Cai ⬝, M. Calderon De La Barca Sanchez ⬝,
M. Chertok ⬝, M. Citron ⬝, J. Conway ⬝, P.T. Cox ⬝, R. Erbacher ⬝, F. Jensen ⬝, O. Kukral ⬝,
G. Mocellin ⬝, M. Mulhearn ⬝, S. Ostrom ⬝, W. Wei ⬝, Y. Yao ⬝, S. Yoo ⬝, F. Zhang ⬝

University of California, Los Angeles, California, USA

M. Bachtis ⬝, R. Cousins ⬝, A. Datta ⬝, G. Flores Avila ⬝, J. Hauser ⬝, M. Ignatenko ⬝,
M.A. Iqbal ⬝, T. Lam ⬝, E. Manca ⬝, A. Nunez Del Prado, D. Saltzberg ⬝, V. Valuev ⬝

University of California, Riverside, Riverside, California, USA

R. Clare ⬝, J.W. Gary ⬝, M. Gordon, G. Hanson ⬝, W. Si ⬝

University of California, San Diego, La Jolla, California, USA

A. Aportela, A. Arora ⬝, J.G. Branson ⬝, S. Cittolin ⬝, S. Cooperstein ⬝, D. Diaz ⬝, J. Duarte ⬝,
L. Giannini ⬝, Y. Gu, J. Guiang ⬝, R. Kansal ⬝, V. Krutelyov ⬝, R. Lee ⬝, J. Letts ⬝,
M. Masciovecchio ⬝, F. Mokhtar ⬝, S. Mukherjee ⬝, M. Pieri ⬝, M. Quinnan ⬝,
B.V. Sathia Narayanan ⬝, V. Sharma ⬝, M. Tadel ⬝, E. Vourliotis ⬝, F. Würthwein ⬝, Y. Xiang ⬝,
A. Yagil ⬝

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

A. Barzdukas ⬝, L. Brennan ⬝, C. Campagnari ⬝, K. Downham ⬝, C. Grieco ⬝, J. Incandela ⬝,
J. Kim ⬝, A.J. Li ⬝, P. Masterson ⬝, H. Mei ⬝, J. Richman ⬝, S.N. Santpur ⬝, U. Sarica ⬝,
R. Schmitz ⬝, F. Setti ⬝, J. Sheplock ⬝, D. Stuart ⬝, T.Á. Vámi ⬝, S. Wang ⬝, D. Zhang

California Institute of Technology, Pasadena, California, USA

A. Bornheim ⬝, O. Cerri, A. Latorre, J. Mao ⬝, H.B. Newman ⬝, G. Reales Gutiérrez,
M. Spiropulu ⬝, J.R. Vlimant ⬝, C. Wang ⬝, S. Xie ⬝, R.Y. Zhu ⬝

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison ⬝, S. An ⬝, P. Bryant ⬝, M. Cremonesi, V. Dutta ⬝, T. Ferguson ⬝,
T.A. Gómez Espinosa ⬝, A. Harilal ⬝, A. Kallil Tharayil, C. Liu ⬝, T. Mudholkar ⬝, S. Murthy ⬝,
P. Palit ⬝, K. Park, M. Paulini ⬝, A. Roberts ⬝, A. Sanchez ⬝, W. Terrill ⬝

University of Colorado Boulder, Boulder, Colorado, USA

J.P. Cumalat ⬝, W.T. Ford ⬝, A. Hart ⬝, A. Hassani ⬝, G. Karathanasis ⬝, N. Manganelli ⬝,
A. Perloff ⬝, C. Savard ⬝, N. Schonbeck ⬝, K. Stenson ⬝, K.A. Ulmer ⬝, S.R. Wagner ⬝,
N. Zipper ⬝, D. Zuolo ⬝

Cornell University, Ithaca, New York, USA

J. Alexander ⬝, S. Bright-Thonney ⬝, X. Chen ⬝, D.J. Cranshaw ⬝, J. Fan ⬝, X. Fan ⬝, S. Hogan ⬝,
P. Kotamnives, J. Monroy ⬝, M. Oshiro ⬝, J.R. Patterson ⬝, M. Reid ⬝, A. Ryd ⬝, J. Thom ⬝,
P. Wittich ⬝, R. Zou ⬝

Fermi National Accelerator Laboratory, Batavia, Illinois, USA

M. Albrow ⬝, M. Alyari ⬝, O. Amram ⬝, 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 , G. Cummings , J. Dickinson , I. Dutta , V.D. Elvira ,
Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer ,
S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , R. Heller , T.C. Herwig ,
J. Hirschauer , 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 , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro ,
C. Pena [85], F. Ravera , A. Reinsvold Hall [86], L. Ristori , M. Safdari , E. Sexton-Kennedy ,
N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk ,
N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi

University of Florida, Gainesville, Florida, USA

C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, E. Koenig ,
M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher ,
K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , Y. Takahashi ,
J. Wang

Florida State University, Tallahassee, Florida, USA

T. Adams , A. Al Kadhim , A. Askew , S. Bower , R. Habibullah , V. Hagopian ,
R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P.R. Prova,
M. Wulansatiti , R. Yohay , J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani, M.M. Baarmand , S. Butalla , S. Das , T. Elkafrawy [87], M. Hohlmann ,
M. Rahmani, E. Yanes

University of Illinois Chicago, Chicago, USA

M.R. Adams , A. Baty , C. Bennett, R. Cavanaugh , R. Escobar Franco , O. Evdokimov ,
C.E. Gerber , M. Hawksworth, A. Hingrajiya, D.J. Hofman , J.h. Lee , D. S. Lemos ,
A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti,
T. Roy , S. Rudrabhatla , M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo

The University of Iowa, Iowa City, Iowa, USA

M. Alhusseini , D. Blend, K. Dilsiz [88], L. Emediato , G. Karaman , O.K. Köseyan ,
J.-P. Merlo, A. Mestvirishvili [89], O. Neogi, H. Ogul [90], Y. Onel , A. Penzo , C. Snyder,
E. Tiras [91]

Johns Hopkins University, Baltimore, Maryland, USA

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou ,
P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz

The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean ,
Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu ,
J. Marquez , M. Murray , M. Nickel , M. Pitt , S. Popescu [92], C. Rogan , C. Royon ,
R. Salvatico , S. Sanders , C. Smith , G. Wilson

Kansas State University, Manhattan, Kansas, USA

B. Allmond ©, R. Gujju Gurunadha ©, A. Ivanov ©, K. Kaadze ©, Y. Maravin ©, J. Natoli ©, D. Roy ©, G. Sorrentino ©

University of Maryland, College Park, Maryland, USA

A. Baden ©, A. Belloni ©, J. Bistany-riebman, Y.M. Chen ©, S.C. Eno ©, N.J. Hadley ©, S. Jabeen ©, R.G. Kellogg ©, T. Koeth ©, B. Kronheim, Y. Lai ©, S. Lascio ©, A.C. Mignerey ©, S. Nabili ©, C. Palmer ©, C. Papageorgakis ©, M.M. Paranjpe, L. Wang ©

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

J. Bendavid ©, I.A. Cali ©, P.c. Chou ©, M. D'Alfonso ©, J. Eysermans ©, C. Freer ©, G. Gomez-Ceballos ©, M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi ©, J. Krupa ©, L. Lavezzo ©, Y.-J. Lee ©, K. Long ©, C. Mcginn, A. Novak ©, C. Paus ©, C. Roland ©, G. Roland ©, S. Rothman ©, G.S.F. Stephans ©, Z. Wang ©, B. Wyslouch ©, T. J. Yang ©

University of Minnesota, Minneapolis, Minnesota, USA

B. Crossman ©, B.M. Joshi ©, C. Kapsiak ©, M. Krohn ©, D. Mahon ©, J. Mans ©, B. Marzocchi ©, M. Revering ©, R. Rusack ©, R. Saradhy ©, N. Strobbe ©

University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom ©, D.R. Claes ©, G. Haza ©, J. Hossain ©, C. Joo ©, I. Kravchenko ©, J.E. Siado ©, W. Tabb ©, A. Vagnerini ©, A. Wightman ©, F. Yan ©, D. Yu ©

State University of New York at Buffalo, Buffalo, New York, USA

H. Bandyopadhyay ©, L. Hay ©, H.w. Hsia, I. Iashvili ©, A. Kalogeropoulos ©, A. Kharchilava ©, M. Morris ©, D. Nguyen ©, S. Rappoccio ©, H. Rejeb Sfar, A. Williams ©, P. Young ©

Northeastern University, Boston, Massachusetts, USA

G. Alverson ©, E. Barberis ©, J. Bonilla ©, J. Dervan, Y. Haddad ©, Y. Han ©, A. Krishna ©, J. Li ©, M. Lu ©, G. Madigan ©, R. Mccarthy ©, D.M. Morse ©, V. Nguyen ©, T. Orimoto ©, A. Parker ©, L. Skinnari ©, D. Wood ©

Northwestern University, Evanston, Illinois, USA

J. Bueghly, S. Dittmer ©, K.A. Hahn ©, Y. Liu ©, Y. Miao ©, D.G. Monk ©, M.H. Schmitt ©, A. Taliercio ©, M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA

G. Agarwal ©, R. Band ©, R. Bucci, S. Castells ©, A. Das ©, R. Goldouzian ©, M. Hildreth ©, K.W. Ho ©, K. Hurtado Anampa ©, T. Ivanov ©, C. Jessop ©, K. Lannon ©, J. Lawrence ©, N. Loukas ©, L. Lutton ©, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley ©, C. Mcgrady ©, C. Moore ©, Y. Musienko ©[17], H. Nelson ©, M. Osherson ©, A. Piccinelli ©, R. Ruchti ©, A. Townsend ©, Y. Wan, M. Wayne ©, H. Yockey, M. Zarucki ©, L. Zygala ©

The Ohio State University, Columbus, Ohio, USA

A. Basnet ©, B. Bylsma, M. Carrigan ©, L.S. Durkin ©, C. Hill ©, M. Joyce ©, M. Nunez Ornelas ©, K. Wei, B.L. Winer ©, B. R. Yates ©

Princeton University, Princeton, New Jersey, USA

H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, S. Kwan, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, A. Shevelev, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik

Purdue University, West Lafayette, Indiana, USA

A.S. Bakshi, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, V. Scheurer, J.F. Schulte, M. Stojanovic, J. Thieman, A. K. Virdi, F. Wang, W. Xie

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen, N. Parashar, A. Pathak

**Rice University, Houston, Texas, USA**

D. Acosta, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, W. Li, J. Lin, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[93], E. Popova[93], R. Taus

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

B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, J. Reichert, H. Routray, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

University of Tennessee, Knoxville, Tennessee, USA

D. Ally, A.G. Delannoy, S. Fiorendi, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA

D. Aebi, M. Ahmad, T. Akhter, O. Bouhali[94], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[95], H. Kim, S. Luo, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA

N. Akchurin, J. Damgov, N. Gogate, V. Hegde, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, A. Mankel, T. Peltola, I. Volobouev

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA

B. Cardwell⬚, B. Cox⬚, J. Hakala⬚, R. Hirosky⬚, A. Ledovskoy⬚, C. Neu⬚

Wayne State University, Detroit, Michigan, USA

S. Bhattacharya⬚, P.E. Karchin⬚

University of Wisconsin - Madison, Madison, Wisconsin, USA

A. Aravind, 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, R. Loveless⬚,
J. Madhusudanan Sreekala⬚, A. Mallampalli⬚, A. Mohammadi⬚, S. Mondal, G. Parida⬚,
L. Pétré⬚, D. Pinna, A. Savin, V. Shang⬚, V. Sharma⬚, W.H. Smith⬚, D. Teague, H.F. Tsoi⬚,
W. Vetens⬚, A. Warden⬚

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

S. Afanasiev⬚, V. Alexakhin⬚, V. Andreev⬚, Yu. Andreev⬚, T. Aushev⬚, M. Azarkin⬚,
A. Babaev⬚, V. Blinov[96], E. Boos⬚, V. Borshch⬚, D. Budkouski⬚, V. Bunichev⬚, V. Chekhovsky,
R. Chistov⬚[96], M. Danilov⬚[96], A. Dermenev⬚, T. Dimova⬚[96], D. Druzhkin⬚[97], M. Dubinin⬚[85],
L. Dudko⬚, A. Ershov⬚, G. Gavrilov⬚, V. Gavrilov⬚, S. Gninenko⬚, V. Golovtcov⬚,
N. Golubev⬚, I. Golutvin⬚[†], I. Gorbunov⬚, A. Gribushin⬚, Y. Ivanov⬚, V. Kachanov⬚,
V. Karjavine⬚, A. Karneyeu⬚, V. Kim⬚[96], M. Kirakosyan, D. Kirpichnikov⬚, M. Kirsanov⬚,
V. Klyukhin⬚, O. Kodolova⬚[98], D. Konstantinov⬚, V. Korenkov⬚, A. Kozyrev⬚[96],
N. Krasnikov⬚, A. Lanev⬚, P. Levchenko⬚[99], N. Lychkovskaya⬚, V. Makarenko⬚,
A. Malakhov⬚, V. Matveev⬚[96], V. Murzin⬚, A. Nikitenko⬚[100,98], S. Obraztsov⬚, V. Oreshkin⬚,
V. Palichik⬚, V. Perelygin⬚, M. Perfilov, S. Polikarpov⬚[96], V. Popov⬚, O. Radchenko⬚[96],
M. Savina⬚, V. Savrin, V. Shalaev⬚, S. Shmatov⬚, S. Shulha⬚, Y. Skovpen⬚[96],
S. Slabospitskii⬚, V. Smirnov⬚, D. Sosnov⬚, V. Sulimov⬚, A. Terkulov⬚, O. Teryaev⬚,
I. Tlisova⬚, A. Toropin, L. Uvarov⬚, A. Uzunian⬚, A. Vorobyev[†], G. Vorotnikov⬚,
N. Voytishin⬚, B.S. Yuldashev[101], 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 Ghent University, Ghent, Belgium*

[5] *Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

[6] *Also at Universidade Estadual de Campinas, Campinas, Brazil*

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

[8] *Also at UFMS, Nova Andradina, Brazil*

[9] *Also at Nanjing Normal University, Nanjing, China*

[10] *Now at The University of Iowa, Iowa City, Iowa, USA*

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

[12] *Also at China Center of Advanced Science and Technology, Beijing, China*

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

[14] *Also at China Spallation Neutron Source, Guangdong, China*

[15] *Now at Henan Normal University, Xinxiang, China*

[16] *Also at Université Libre de Bruxelles, Bruxelles, Belgium*

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

[18] *Also at Suez University, Suez, Egypt*

[19] *Now at British University in Egypt, Cairo, Egypt*

[20] *Also at Purdue University, West Lafayette, Indiana, USA*

[21] *Also at Université de Haute Alsace, Mulhouse, France*

[22] *Also at Istinye University, Istanbul, Turkey*

[23] *Also at Tbilisi State University, Tbilisi, Georgia*

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

[25] *Also at University of Hamburg, Hamburg, Germany*

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

[27] *Also at Bergische University Wuppertal (BUW), Wuppertal, Germany*

[28] *Also at Brandenburg University of Technology, Cottbus, Germany*

[29] *Also at Forschungszentrum Jülich, Juelich, Germany*

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

[31] *Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

[32] *Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania*

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

[34] *Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary*

[35] *Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt*

[36] *Also at Punjab Agricultural University, Ludhiana, India*

[37] *Also at University of Visva-Bharati, Santiniketan, India*

[38] *Also at Indian Institute of Science (IISc), Bangalore, India*

[39] *Also at IIT Bhubaneswar, Bhubaneswar, India*

[40] *Also at Institute of Physics, Bhubaneswar, India*

[41] *Also at University of Hyderabad, Hyderabad, India*

[42] *Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany*

[43] *Also at Isfahan University of Technology, Isfahan, Iran*

[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 Department of Physics, Isfahan University of Technology, Isfahan, Iran*

[47] *Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran*

[48] *Also at Helwan University, Cairo, Egypt*

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

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

[51] *Also at Università degli Studi Guglielmo Marconi, Roma, Italy*

[52] *Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy*

[53] *Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA*

[54] *Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy*

[55] *Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy*

[56] *Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia*

[57] *Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico*

[58] *Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka*

[59] *Also at Saegis Campus, Nugegoda, Sri Lanka*

[60] *Also at National and Kapodistrian University of Athens, Athens, Greece*

[61] *Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland*

[62] *Also at Universität Zürich, Zurich, Switzerland*

[63] *Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria*

[64] *Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France*

[65] *Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey*

[66] *Also at Konya Technical University, Konya, Turkey*

[67] Also at Izmir Bakircay University, Izmir, Turkey

[68] Also at Adiyaman University, Adiyaman, 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] Now at Istanbul Okan University, Istanbul, Turkey

[74] Also at Hacettepe University, Ankara, Turkey

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

[76] Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey

[77] Also at Yildiz Technical University, Istanbul, Turkey

[78] Also at Vrije Universiteit Brussel, Brussel, Belgium

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

[80] Also at IPPP Durham University, Durham, United Kingdom

[81] Also at Monash University, Faculty of Science, Clayton, Australia

[82] Also at Università di Torino, Torino, Italy

[83] Also at Bethel University, St. Paul, Minnesota, USA

[84] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

[85] Also at California Institute of Technology, Pasadena, California, USA

[86] Also at United States Naval Academy, Annapolis, Maryland, USA

[87] Also at Ain Shams University, Cairo, Egypt

[88] Also at Bingol University, Bingol, Turkey

[89] Also at Georgian Technical University, Tbilisi, Georgia

[90] Also at Sinop University, Sinop, Turkey

[91] Also at Erciyes University, Kayseri, Turkey

[92] Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania

[93] Now at an institute or an international laboratory covered by a cooperation agreement with CERN

[94] Also at Texas A&M University at Qatar, Doha, Qatar

[95] Also at Kyungpook National University, Daegu, Korea

[96] Also at another institute or international laboratory covered by a cooperation agreement with CERN

[97] Also at Universiteit Antwerpen, Antwerpen, Belgium

[98] Also at Yerevan Physics Institute, Yerevan, Armenia

[99] Also at Northeastern University, Boston, Massachusetts, USA

[100] Also at Imperial College, London, United Kingdom

[101] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan