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Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two muons and two b quarks in pp collisions at 13 TeV

The CMS Collaboration*

Abstract

A search for exotic decays of the Higgs boson to a pair of light pseudoscalar particles a_1 is performed under the hypothesis that one of the pseudoscalars decays to a pair of opposite sign muons and the other decays to $b\bar{b}$. Such signatures are predicted in a number of extensions of the standard model (SM), including next-to-minimal supersymmetry and two-Higgs-doublet models with an additional scalar singlet. The results are based on a data set of proton-proton collisions corresponding to an integrated luminosity of 35.9 fb^{-1}, accumulated with the CMS experiment at the CERN LHC in 2016 at a centre-of-mass energy of 13 TeV. No statistically significant excess is observed with respect to the SM backgrounds in the search region for pseudoscalar masses from 20 GeV to half of the Higgs boson mass. Upper limits at 95% confidence level are set on the product of the production cross section and branching fraction, $\sigma_h \mathcal{B}(h \to a_1 a_1 \to \mu^+\mu^- b\bar{b})$, ranging from 5 to 36 fb, depending on the pseudoscalar mass. Corresponding limits on the branching fraction, assuming the SM prediction for σ_h, are (1–6) $\times 10^{-4}$.

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*See Appendix A for the list of collaboration members

1 Introduction

The discovery of the particle now identified as the Higgs boson by the ATLAS and CMS experiments [1–3] at the CERN LHC [4] has opened a new era in the history of particle physics. So far, precise measurements of the Higgs boson spin, parity, width, and couplings in production and decay have been consistent with the expectations for the standard model (SM) Higgs boson [5–9]. However the possibility of exotic Higgs boson decays to new lighter bosons is not excluded. The LHC combination of the SM Higgs boson measurements at 7 and 8 TeV allows Higgs boson decays to states beyond the SM (BSM) with a rate of up to 34% [7] at 95% confidence level (CL). The LHC data at 13 TeV have been used to place an upper limit of about 40% for the Higgs boson branching fraction ($\mathcal{B}$) to BSM particles at 95% CL [10].

Several searches for exotic decays of the Higgs boson have been performed at the LHC, using the data at 8 TeV [11–14] and 13 TeV [15–20]. Such decays occur in the context of the next-to-minimal supersymmetric standard model, NMSSM, and other extensions to two-Higgs-doublet models (2HDM) where the existence of a scalar singlet is hypothesised (2HDM+S) [21–24]. The 2HDM, and hence 2HDM+S, are categorised into four types depending on the interaction of SM fermions with the Higgs doublet structure [14]. All SM particles couple to the first Higgs doublet, Φ_1, in type I models. In type II models, which include the NMSSM, up-type quarks couple to Φ_1 while leptons and down-type quarks couple to the second Higgs doublet, Φ_2. Quarks couple to Φ_1 and leptons couple to Φ_2 in type III models. In type IV models, leptons and up-type quarks couple to Φ_1, while down-type quarks couple to Φ_2. After electroweak symmetry breaking, the 2HDM predicts a pair of charged Higgs bosons $\mathrm{H}^{\pm}$, a neutral pseudoscalar A, and two neutral scalar mass eigenstates, H and h. In the decoupling limit the lighter scalar eigenstate, h, is the observed boson with $m_{\mathrm{h}} \approx 125$ GeV. In 2HDM+S models, a complex scalar singlet $S_{\mathrm{R}} + iS_{\mathrm{I}}$ that has no direct Yukawa couplings is introduced. Hence, it is expected to decay to SM fermions by virtue of mixing with the Higgs sector. This mixing is small enough to preserve the SM-like nature of the h boson.

In this Letter we consider the Higgs boson decay to a pair of a_1 particles where a_1 is a pseudoscalar mass eigenstate mostly composed of S_{I}. We perform a search for the decay chain $\mathrm{h} \to \mathrm{a}_1\mathrm{a}_1 \to \mu^+\mu^-\mathrm{b}\overline{\mathrm{b}}$. The gluon gluon fusion (ggF) and the vector boson fusion (VBF) production mechanisms are considered, with production cross sections of 48.58 ± 1.89 pb (at next-to-next-to-next-to-leading order) and 3.93 ± 0.08 pb (at next-to-next-to-leading order), respectively [25]. As a benchmark, the branching fraction of $\mathrm{h} \to \mathrm{a}_1\mathrm{a}_1$ is assumed to be 10%. The branching fractions of a_1 to SM particles depend on the type of 2HDM+S, on the pseudoscalar mass m_{a_1}, and on $\tan\beta$, defined as the ratio of the vacuum expectation values of the second and first doublets. The $\tan\beta$ parameter is assumed to be 2 which implies $2\mathcal{B}(\mathrm{a}_1 \to \mathrm{b}\overline{\mathrm{b}})\mathcal{B}(\mathrm{a}_1 \to \mu^+\mu^-) = 1.7 \times 10^{-3}$ for $m_{\mathrm{a}_1} = 30$ GeV in type-III 2HDM+S [21]. For the set of parameters under discussion and with $20 \leq m_{\mathrm{a}_1} \leq 62.5$ GeV, no strong dependence on m_{a_1} is expected for $\mathcal{B}(\mathrm{a}_1 \to \mathrm{b}\overline{\mathrm{b}})$ and $\mathcal{B}(\mathrm{a}_1 \to \mu^+\mu^-)$ [21]. The product of the cross section and branching fraction is therefore approximated to be about 8 fb for all m_{a_1} values considered in this analysis.

The present search for the exotic a_1 particle in the $\mu^+\mu^-\mathrm{b}\overline{\mathrm{b}}$ final state is sensitive to the mass range of $20 \leq m_{\mathrm{a}_1} \leq 62.5$ GeV. The sensitivity of the search largely decreases towards $m_{\mathrm{a}_1} \approx 20$ GeV and lower because a_1 gets boosted and the two b quark jets tend to merge [26]. The upper bound is imposed by the Higgs boson mass. The analysis is performed using the proton-proton collision data at 13 TeV collected with the CMS detector during 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}. Though the signal selection is optimised for the $\mathrm{h} \to \mathrm{a}_1\mathrm{a}_1 \to \mu^+\mu^-\mathrm{b}\overline{\mathrm{b}}$ process, decays of $\mathrm{h} \to \mathrm{a}_1\mathrm{a}_1 \to \mu^+\mu^-\tau^+\tau^-$ can contribute to the selected sample if hadronically decaying τ leptons are misidentified as b quark jets. Such a contribution is found to be negligible using the benchmark scenario, although in some parts of the parameter space the enhancement in $\mathcal{B}(\mathrm{a}_1 \to \tau^+\tau^-)$ can lead to a nonnegligible fraction of these events surviving the selection. This is taken into account in the scan over the $(m_{\mathrm{a}_1}, \tan\beta)$ plane in the type III 2HDM+S, as for certain values, the increase in $\mu^+\mu^-\tau^+\tau^-$ signal can affect the sensitivity. The signal from $\mathrm{a}_1\mathrm{a}_1 \to \mathrm{b}\bar{\mathrm{b}}\tau^+\tau^-$ with $\tau \to \mu$ leads to $m_{\mu\mu}$ significantly smaller than m_{a_1} and is not considered in the search.

The CMS detector is briefly described in Section 2. The data and simulated samples are introduced in Section 3. Section 4 is devoted to the event selection and categorisation. The signal and background modelling is discussed in Section 5, while in Section 6, different sources of systematic uncertainties are described. Results are presented in Section 7, and the paper is summarised in Section 8.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and endcap sections. Forward calorimeters, made of steel and quartz-fibres, extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionisation chambers embedded in the steel flux-return yoke outside the solenoid. They are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum (p_{T}) resolution, for muons with p_{T} up to 100 GeV, of 1% in the barrel and 3% in the endcaps [27]. 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. [28].

3 Simulated samples

The NMSSMHET model [21] is used to generate signal samples with the Monte Carlo (MC) event generator MADGRAPH5_aMC@NLO [29] at leading order (LO). Background processes with dominant contributions are the Drell–Yan production in association with additional b quarks and $\mathrm{t\bar{t}}$ in the dimuon final state. Simulated samples for background processes are used in this analysis to optimise the selection and for validation purposes in those selection steps that yield reasonable statistical precision. The contribution of backgrounds to the selected sample is directly extracted from data with no reference to simulation. The Drell–Yan process, $\mathrm{Z}/\gamma^*(\to \ell^+\ell^-) +$ jets with a minimum dilepton mass threshold of 10 GeV, is modelled with the same event generator at LO, exclusive in number of additional partons (up to 4). The reference cross section for the Drell–Yan process is computed using FEWZ 3.1 [30] at next-to-next-to-leading order. The top quark samples, $\mathrm{t\bar{t}}$ and single top quark production, are produced with POWHEG2.0 [31–34] at next-to-leading order (NLO). Backgrounds from diboson (WW, WZ, ZZ) production are generated at NLO with the same program and settings as that of the Drell–Yan samples. The only exception is the WW process that is generated at LO. The set of parton distribution functions (PDFs) is NLO NNPDF3.0 for NLO samples, and LO NNPDF3.0 for LO samples [35]. For all samples, PYTHIA 8.212 [36] with tune CUETP8M1 [37, 38] is used for the modelling of the parton showering and fragmentation. The full CMS detector simulation based on GEANT4 [39] is implemented for all generated event samples. In order to model the effect of additional interactions per bunch crossing (pileup), generated minimum bias events are added to the simulated samples. The number of additional interactions are scaled to agree with that observed in data [40].

4 Event selection and categorisation

Events are filtered using a high-level trigger requirement based on the presence of two muons with $p_{\mathrm{T}} > 17$ and 8 GeV. For offline selection, events must contain at least one primary vertex, considered as the vertex of the hard interaction. At least four tracks must be associated with the selected primary vertex. The longitudinal and radial distances of the vertex from the centre of the detector must be smaller than 24 and 2 cm, respectively. The vertex with the largest sum of p_{T}^2 of the physics objects is chosen for the analysis. The physics objects are the jets, clustered using the jet finding algorithm [41, 42] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_{T} of those jets. Extra selection criteria are applied to leptons and jets, reconstructed using the CMS particle-flow algorithm [43].

The selection requires two muons with opposite electric charge in $|\eta| < 2.4$, originating from the selected primary vertex. Events with the leading (subleading) muon $p_{\mathrm{T}} > 20\,(9)$ GeV are selected. A relative isolation variable I_{rel} is calculated by summing the transverse energy deposited by other particles inside a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the muon with ϕ being the azimuthal angle measured in radians, divided by the muon p_{T},

$$I_{\mathrm{rel}} = \frac{I^{\mathrm{ch.\,h}} + \max((I^{\gamma} + I^{\mathrm{n.\,h}} - 0.5\, I^{\mathrm{PU\,ch.\,h}}), 0)}{p_{\mathrm{T}}}, \tag{1}$$

where $I^{\mathrm{ch.\,h}}$, I^{γ}, $I^{\mathrm{n.\,h}}$ and $I^{\mathrm{PU\,ch.\,h}}$ are, respectively, the scalar p_{T} sums of stable charged hadrons, photons, neutral hadrons, and charged hadrons associated with pileup vertices. The contribution $0.5\, I^{\mathrm{PU\,ch.\,h}}$ accounts for the expected pileup contribution from neutral particles. The neutral-to-charged particle ratio is taken to be approximately 0.5 from isospin invariance. Only muons with the isolation variable satisfying $I_{\mathrm{rel}} < 0.15$ are considered in the analysis. The efficiencies for muon trigger, reconstruction, and selection in simulated events are corrected to match those in data. In case more muons in the event pass the selection requirements, the two with the largest p_{T} are chosen.

Jets are reconstructed by clustering charged and neutral particles using the anti-k_{T} algorithm [41] with a distance parameter of 0.4. The reconstructed jet energy is corrected for effects from the detector response as a function of the jet p_{T} and η. Contamination from pileup, underlying event, and electronic noise are subtracted [44, 45]. Extra η-dependent smearing is performed on the jet energy in simulated events as prescribed in Refs. [44, 45].

Events are required to have at least two jets with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 20$ (leading) and 15 GeV (subleading), with both jets separated from the selected muons ($\Delta R > 0.5$). A combined secondary vertex algorithm is used to identify jets that are likely to originate from b quarks. The algorithm uses the track-based lifetime information together with the secondary vertices inside the jet to provide a multivariate discriminator for the b jet identification [46]. Working points "loose" (L), "medium" (M), and "tight" (T) are defined. They correspond to thresholds on the discriminator, for which the misidentification probability is around 10, 1, and 0.1%, respectively, for jets originating from light quarks and gluons [46]. The misidentification probability for jets originating from c quarks is around 30, 10, and 2%, respectively, for the loose, medium, and tight working points. The efficiencies for correctly identifying b jets are ≈80% for the loose,

≈60% for the medium, and ≈40% for the tight working point. The jet with maximum discriminator value must pass the tight working point of the algorithm, while the second is required to pass the loose one. The correction factors for b jet identification are applied to simulated events to reproduce the data distribution of the b tagging discriminator. In events with more jets passing the selection criteria, the two with the largest p_T are taken.

The imbalance in the transverse momentum in signal events is not expected to be large, as the contribution from neutrinos from semileptonic decays in b jets is typically small. The missing transverse momentum, p_T^{miss} is defined as the magnitude of the negative vector sum of the transverse momenta of all reconstructed particles. The jet energy calibration introduces corrections to the p_T^{miss} measurement [45]. Events are required to have $p_T^{miss} < 60$ GeV.

Assuming the b quark jets and muons are the decay products of the pseudoscalar a_1, it is expected to have $m_{bb} \approx m_{\mu\mu} \approx m_{a_1}$ in signal events. Moreover, the system of muons and b quark jets is expected to have an invariant mass close to 125 GeV. A χ^2 variable is introduced as $\chi^2_{bb} + \chi^2_h$, where

$$\chi_{bb} = \frac{(m_{bb} - m_{\mu\mu})}{\sigma_{bb}} \quad \text{and} \quad \chi_h = \frac{(m_{\mu\mu bb} - 125)}{\sigma_h}. \tag{2}$$

Here σ_{bb} and σ_h are, respectively, the mass resolutions of the di-b-quark jet system and the Higgs boson candidate, derived from simulation. The mass resolution of the di-b-quark jet system increases linearly with m_{a_1}. It is evaluated on an event-by-event basis, where $m_{\mu\mu}$ is assumed to be equal to m_{a_1}. The distribution of χ^2 in the signal sample with $m_{a_1} = 40$ GeV is compared with that in backgrounds in Fig. 1. Events are selected with $\chi^2 < 5$. In Fig. 2, χ_{bb} and χ_h are shown in 2D histograms for backgrounds and for the signal with $m_{a_1} = 40$ GeV, where the contour of $\chi^2 < 5$ is also presented. This selection has a signal efficiency up to 64% while rejecting more than 95% of backgrounds. Events with $m_{\mu\mu}$ values not in [20, 62.5] GeV are discarded.

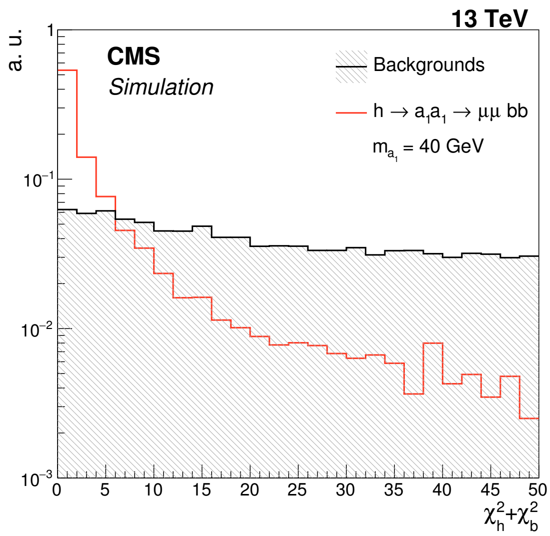

Figure 1: The distribution of χ^2 in simulated background processes and the signal process with $m_{a_1} = 40$ GeV. The samples are normalized to unity.

A method that fully relies on data is used to estimate the background, as described in Section 5. Simulated background samples are however used to optimise the selection. Figure 3 shows distributions, in data and simulation, for events passing the selection requirements except those of p_T^{miss} and χ^2. In this figure, expected number of simulated events is normalised

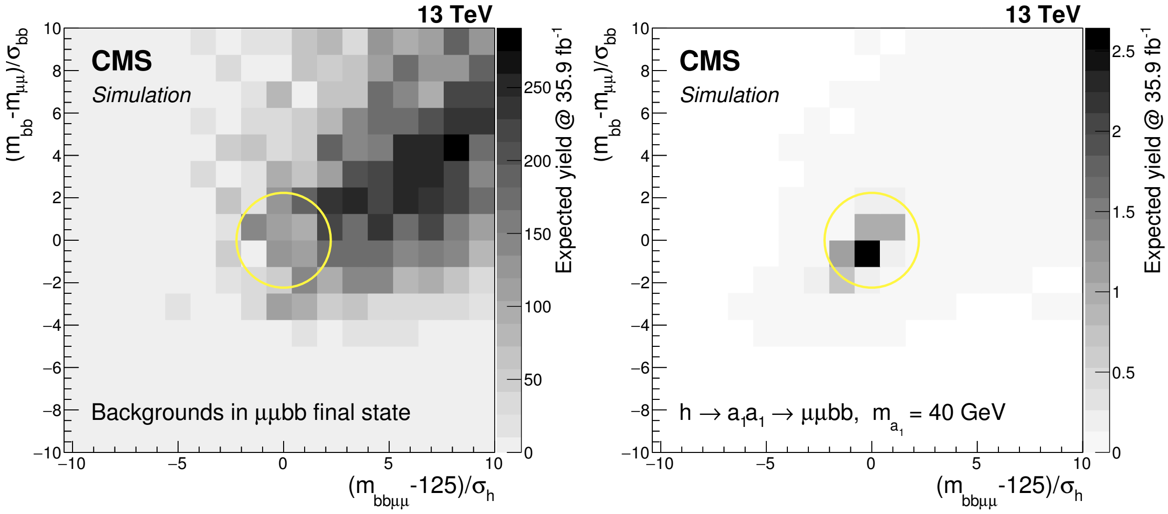

Figure 2: The distribution of χ_{bb} versus χ_{h} as defined in Eq. (2) for (left) simulated background processes and (right) the signal process with $m_{a_1} = 40\,\text{GeV}$. The contours encircle the area with $\chi^2 < 5$. The grey scale represents the expected yields at $35.9\,\text{fb}^{-1}$.

to the integrated luminosity of $35.9\,\text{fb}^{-1}$. Data and simulation are compared for the p_{T} of the dimuon system, and the mass and p_{T} of the di-b-jet system. Using the same selected muon and jet pairs, Fig. 3 also illustrates the distributions of the invariant mass $m_{\mu\mu bb}$ and the transverse momentum $p_{T}^{\mu\mu bb}$ of the four-body system. The distributions for simulated events follow reasonably those in the data, within the statistical uncertainties presented in the figure. The yield in data and the expected yields in simulation are presented in Table 1. The expected yield from a signal of $h \to a_1 a_1 \to \mu^+\mu^-\tau^+\tau^-$ is found to be around 0.01 with the model parameters used in this table.

Table 1: Event yields for simulated processes and data after requiring two muons and two b jets ($\mu^+\mu^- b\bar{b}$ selection) and after the final selection. The expected number of simulated events is normalised to the integrated luminosity of $35.9\,\text{fb}^{-1}$. Uncertainties are only statistical.

Process	$\mu^+\mu^- b\bar{b}$ selection	Final selection
Top ($t\bar{t}$, single top quark)	$33\,730 \pm 120$	198 ± 9
Drell–Yan	5237 ± 77	399 ± 21
Diboson	51 ± 4	1 ± 0.1
Total expected background	$39\,015 \pm 140$	598 ± 23
Data	36 360	610
Signal for $\sigma_h \mathcal{B} \approx 8\,\text{fb}$		
$m_{a_1} = 20\,\text{GeV}$	14.0 ± 0.1	6.0 ± 0.1
$m_{a_1} = 40\,\text{GeV}$	14.8 ± 0.1	7.5 ± 0.1
$m_{a_1} = 60\,\text{GeV}$	16.7 ± 0.1	10.1 ± 0.1

To enhance the sensitivity, an event categorisation is employed: different categorisation schemes are tried, and the one resulting in the highest expected significance is chosen. The data in a sideband region are used to determine the categorization that is most sensitive for this analysis. The sideband region is constructed using the same selection as that for the signal region except that $5 < \chi^2 < 11$. In simulated background samples, the correlations between χ^2 and $m_{\mu\mu}$ and the variables used for categorisation are found to be small. The best sensitivity is found with categorisation according to the b tagging discriminator value of the loose b-tagged jet. The tight-tight (TT) category contains events with both jets passing the tight requirements of the b

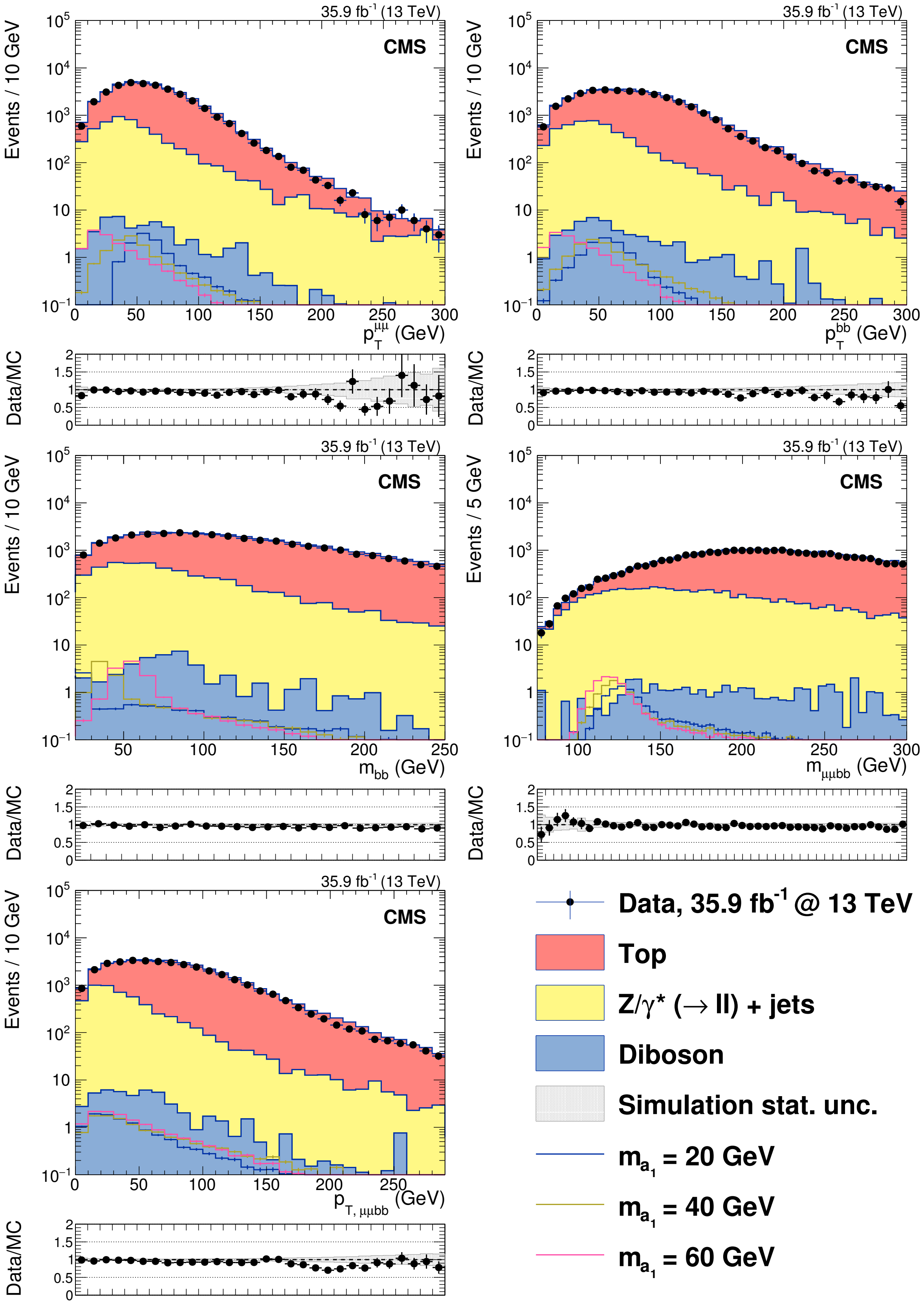

Figure 3: The distribution of the p_T of the (top left) dimuon and (top right) di-b-jet system, the mass of the (middle left) di-b-jet and (middle right) $\mu\mu$bb system, and (bottom left) the p_T of the $\mu\mu$bb system, all after requiring two muons and two b-tagged jets in the event. Simulated samples are normalised to an integrated luminosity of 35.9 fb^{-1} using their theoretical cross sections.

jet identification algorithm. Events in which the loose b-tagged jet passes the medium b tagging requirements but fails the tight conditions fall into the tight-medium (TM) category. The remaining events with the loose b-tagged jet failing the medium requirements of the b jet identification algorithm belong to the tight-loose (TL) category. On average, 41% of signal events pass the TL selection, while 32% fulfil the TM requirements and 27% belong to the TT category. According to the data in the sideband region, the majority of background events (≈70%) fall into the TL category whereas about 20% pass the TM requirements and less than 10% can meet the TT criteria.

5 Signal and background modelling

The search is performed using an unbinned fit to the $m_{\mu\mu}$ distribution in data, simultaneously in the TT, TM, and TL categories. The signal shape is modelled with a weighted sum of Voigt profile [47] and Crystal Ball (CB) functions [48], where the mean values of the two are bound to be the same. The initial values for the signal model parameters are extracted from a simultaneous fit of the model to a number of simulated signal samples, spanning the m_{a_1} search region in 5 GeV steps. All parameters in the signal model are found to be independent of m_{a_1}, except for the resolution parameter of the Voigt profile and CB functions, σ_v and σ_{cb}, respectively. These parameters depend linearly on m_{a_1} and only their slopes, respectively α and β, float in the final fit within their uncertainties,

$$\begin{aligned} \sigma_v &= \sigma_{v,0} + \alpha\, m_{\mu\mu}, \\ \sigma_{cb} &= \sigma_{cb,0} + \beta\, m_{\mu\mu}. \end{aligned} \tag{3}$$

The $m_{\mu\mu}$ distribution in data is used to evaluate the contribution of backgrounds. The uncertainty associated with the choice of the background model is treated in a similar way as other uncertainties for which there are nuisance parameters in the fit. The unbinned likelihood function for the signal-plus-background fit has the form

$$\mathcal{L}(\text{data}|s(p, m_{\mu\mu}) + b(m_{\mu\mu})), \tag{4}$$

where $s(p, m_{\mu\mu})$ is the parametric signal shape with the set of parameters indicated by p, and $b(m_{\mu\mu})$ is the background model. The shape for the background is modelled, independently in each category, with a set of analytical functions using the discrete profiling method [49–51]. In this approach the choice of the functional form of the background shape is considered as a discrete nuisance parameter, for which the best fit value can vary as the trial value of the parameter of interest ($m_{\mu\mu}$) varies. The background parameter space therefore contains multiple models, each including its own parameters.

To provide the input background models to the discrete profiling method, the data are modelled with different parametrisations of polynomials. The degrees of the polynomials are determined through statistical tests (F-test) [52] to ensure the sufficiency of number of parameters and to avoid over-fitting the data. The input background functions are tried in the minimisation of the negative logarithm of the likelihood with a penalty term added to account for the number of free parameters in the background model. The discrete profiling method can choose a different best-fit functional form for the background as the physics parameter of interest varies, thus effectively incorporating the systematic uncertainty on the background functional form: in the present analysis the result is to yield expected upper limits that are about 10% less stringent than those obtained with a single functional form for the background. The likelihood ratio for the penalised likelihood function $\widetilde{\mathcal{L}}$ can be written as

$$-2\ln\frac{\widetilde{\mathcal{L}}(\text{data}|\mu, \hat{\theta}_\mu, \hat{b}_\mu)}{\widetilde{\mathcal{L}}(\text{data}|\hat{\mu}, \hat{\theta}, \hat{b})}, \tag{5}$$

where μ is the measured quantity. The numerator is the maximum penalised likelihood for a given μ, at the best fit values of nuisance parameters, $\hat{\theta}_{\mu}$ and of the background function, $\hat{b}_{\mu}$. The denominator is the global maximum for $\widetilde{\mathcal{L}}$, achieved at $\mu = \hat{\mu}$, $\theta = \hat{\theta}$ and $b = \hat{b}$. A confidence interval for μ is obtained with the background function maximising $\widetilde{\mathcal{L}}$ for any value of μ [49].

6 Systematic uncertainties

The statistical interpretation of the analysis takes into account several sources of systematic uncertainties related to the accuracy in the signal modelling and uncertainties in the signal acceptance. The imprecise knowledge of the background contributions is taken into account by the discrete profiling method described in Section 5.

Theoretical uncertainties: to evaluate the upper limit on $\mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1} \to \mu^+\mu^-\mathrm{b\bar{b}})$, the Higgs boson production cross section is set to the SM prediction where an uncertainty of 3.6% is considered for the sum of the ggF and VBF production cross sections, accounting for PDF and α_s uncertainties [25].

Uncertainties in signal shape and acceptance modelling: an uncertainty of 2.5% is assigned to the integrated luminosity of the CMS 13 TeV data collected in 2016 [40]. The uncertainty in the number of pileup interactions per event is estimated by varying the total inelastic ppcross section by $\pm 4.6\%$ [53]. The simulation-to-data correction factors for the trigger efficiency, muon reconstruction, and selection efficiencies are estimated using a "tag-and-probe" method [54] in Drell–Yan data and simulated samples. These uncertainties include the pileup dependence of the correction factors. For the jet energy scale (JES), the variations are made according to the η- and p_{T}-dependent uncertainties and propagated to the $p_{\mathrm{T}}^{\mathrm{miss}}$ of the event. An additional uncertainty, arising from unclustered energies in the event, is assessed for $p_{\mathrm{T}}^{\mathrm{miss}}$. For the jet energy resolution, the smearing corrections are varied within their uncertainties [44]. Systematic uncertainty sources that affect the simulation-to-data corrections of the b tagging discriminator distribution are JES, the contaminations from light flavor (LF) jets in the b-jet sample, the contaminations from heavy flavor (HF) jets in the light-flavor jet sample, and the statistical fluctuations in data and MC. The uncertainties due to JES and light-flavor jet contamination in b-jet samples are found to be dominant [46]. Finally, uncertainties arising from the limited understanding of the PDFs [55] are taken into account. These uncertainties have a negligible effect on the shape of the signal. Their effects on the yield are taken into account by introducing nuisance parameters with log-normal distributions into the fit.

7 Results

The analysis yields no significant excess of events over the SM background prediction. Figure 4 shows the $m_{\mu\mu}$ distribution in the data of all categories together with the best fit output for the background model, including uncertainties.

The upper limit on $\sigma_{\mathrm{h}}\mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1} \to \mu^+\mu^-\mathrm{b\bar{b}})$ is obtained at 95% CL using the $\mathrm{CL_s}$ criterion [56, 57] and an asymptotic approximation to the distribution of the profiled likelihood ratio test statistic [58]. Assuming the SM cross sections for the Higgs boson production processes within the theoretical uncertainties, an upper limit is placed on $\mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1} \to \mu^+\mu^-\mathrm{b\bar{b}})$ using the same procedure. Limits are evaluated as a function of $m_{\mathrm{a_1}}$. The observed and expected limits are illustrated in Fig. 5 for both cases. Dominant systematic uncertainties are those associated with the b jet identification. For $m_{\mathrm{a_1}} = 40\,\mathrm{GeV}$, the b tagging uncertainties arising from LF

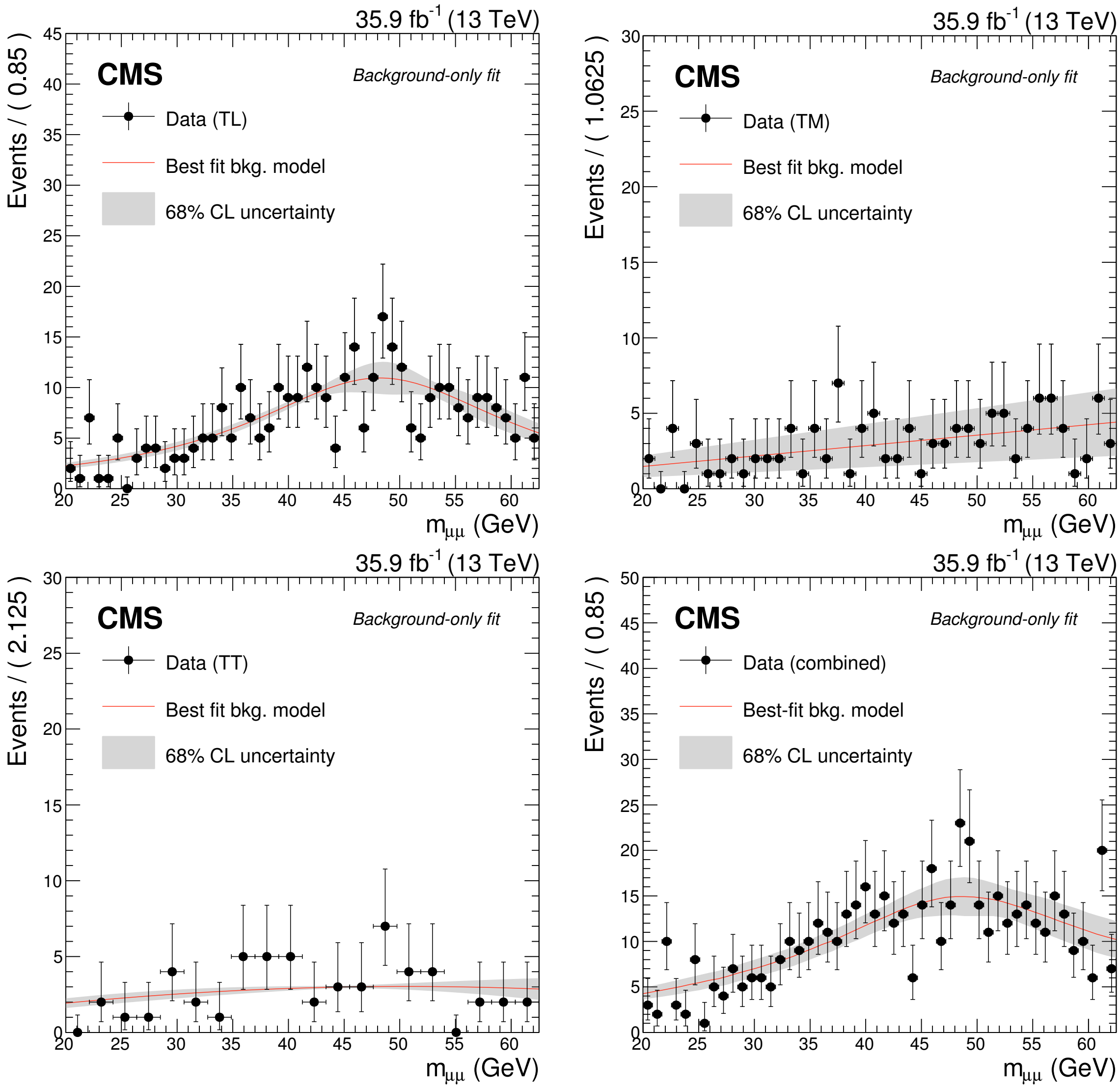

Figure 4: The best fit output to the data under the background-only hypothesis for the (top-left) TL category, (top right) TM category, (bottom left) TT category and (bottom right) all categories, presented together with 68% CL uncertainty band for the background model.

contamination and JES amount to 17 and 14%, respectively. Other uncertainties are below 5%.

At 95% CL, the observed limits on $\mathcal{B}(\mathrm{h} \to \mathrm{a}_1\mathrm{a}_1 \to \mu^+\mu^-\mathrm{b}\bar{\mathrm{b}})$ are $(1\text{–}6) \times 10^{-4}$ for the mass range 20 to 62.5 GeV, whilst the expected limits are $(1\text{–}2) \times 10^{-4}$. A similar search from CMS in Run I [14] led to observed upper limits of $(2\text{–}8) \times 10^{-4}$ at 95% CL, considering the ggF Higgs boson production and the mass range $25 \leq m_{\mathrm{a}_1} \leq 62.5$ GeV. The corresponding expected limits on the branching fraction at 95% CL are $(3\text{–}4) \times 10^{-4}$. At 13 TeV, the ggF Higgs boson production cross section has increased by a factor of about 2.3 over that at 8 TeV, while the production cross section of main backgrounds, Drell–Yan and $\mathrm{t}\bar{\mathrm{t}}$, has increased by a factor of 1.5 and 3.3, respectively. Despite the relative increase in backgrounds, better sensitivity is achieved using improved analysis techniques in Run II.

Observed limits on $\mathcal{B}(\mathrm{h} \to \mathrm{a}_1\mathrm{a}_1)$ are shown in Fig. 6 in the plane of $(m_{\mathrm{a}_1}, \tan\beta)$ for type-III and type-IV 2HDM+S, using only the $\mu^+\mu^-\mathrm{b}\bar{\mathrm{b}}$ signal. The allowed ranges for $\mathcal{B}(\mathrm{h} \to \mathrm{a}_1\mathrm{a}_1) \leq 1$ and $\mathcal{B}(\mathrm{h} \to \mathrm{a}_1\mathrm{a}_1) \leq 0.34$ are also presented. Constraints from Run I Higgs boson measurements at

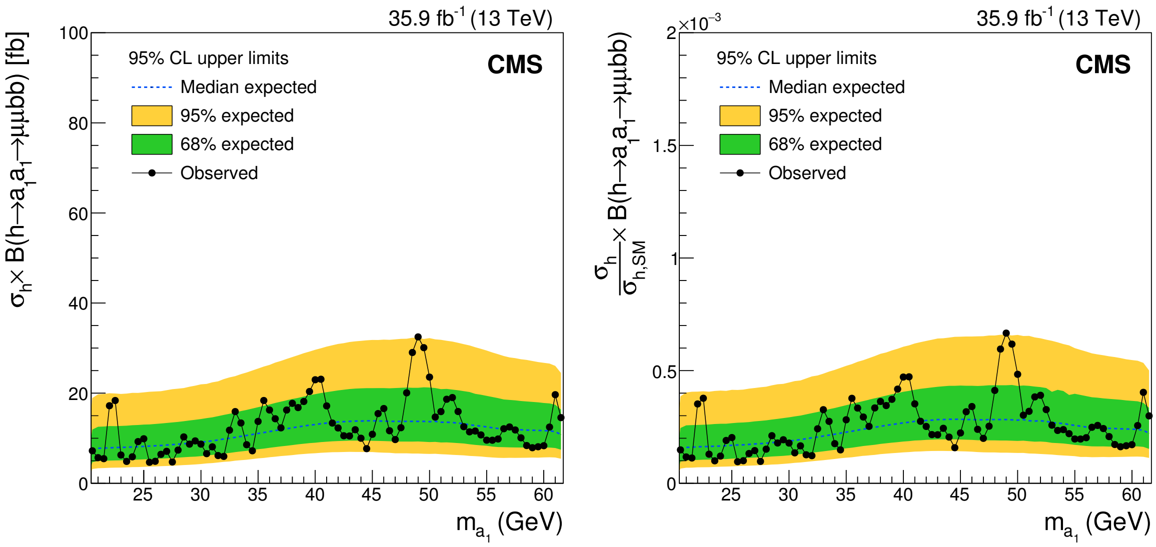

Figure 5: Observed and expected upper limits at 95% CL on the (left) product of the Higgs boson production cross section and $\mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1} \to \mu^+\mu^-\mathrm{b\bar{b}})$ and (right) the branching fraction as a function of $m_{\mathrm{a_1}}$. The inner and outer bands indicate the regions containing the distribution of limits located within 68 and 95% confidence intervals, respectively, of the expectation under the background–only hypothesis.

the LHC allow $\mathcal{B}(\mathrm{h} \to \mathrm{BSM})$ up to 0.34 [7].

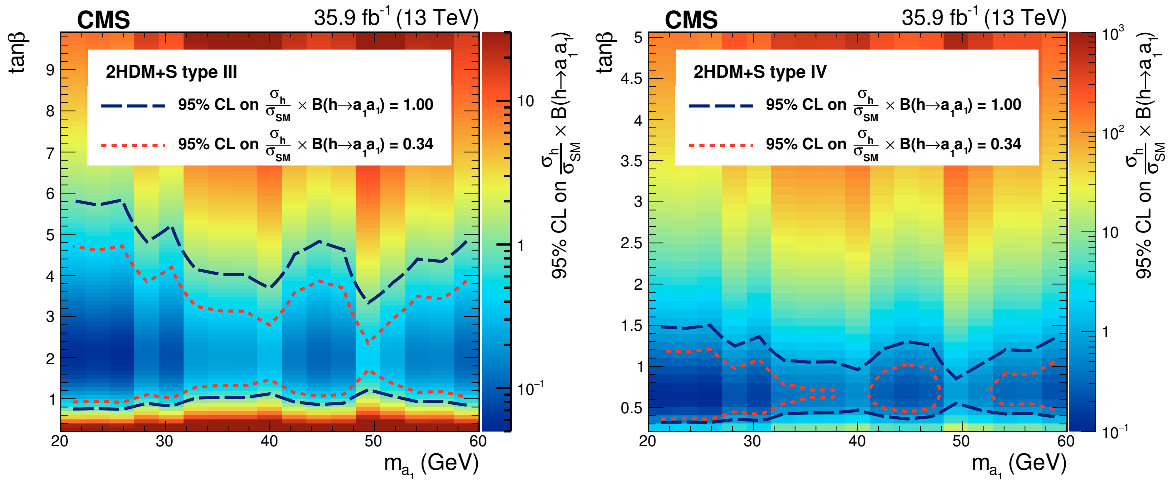

Figure 6: Observed upper limits at 95% CL on $\mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1})$ in the plane of $(m_{\mathrm{a_1}}, \tan\beta)$ for (left) type-III and (right) type-IV 2HDM+S, using only the $\mu^+\mu^-\mathrm{b\bar{b}}$ signal.

The effect of including the $\mu^+\mu^-\tau^+\tau^-$ signal is studied in the $(m_{\mathrm{a_1}}, \tan\beta)$ plane for the four types of 2HDM+S. For a given $(m_{\mathrm{a_1}}, \tan\beta)$ the relevance of $\mu^+\mu^-\tau^+\tau^-$ depends on the ratio $\mathcal{B}(\mathrm{a_1} \to \tau\tau)\epsilon^{\text{sel.}}_{\mu\mu\tau\tau}/\mathcal{B}(\mathrm{a_1} \to \mathrm{bb})\epsilon^{\text{sel.}}_{\mu\mu\mathrm{bb}}$ as well as the sensitivity of the analysis. Here $\epsilon^{\text{sel.}}$ refers to the acceptance and the selection efficiency of the process. The ratio $\epsilon^{\text{sel.}}_{\mu\mu\tau\tau}/\epsilon^{\text{sel.}}_{\mu\mu\mathrm{bb}}$ is about 1% in the TL category while it reduces to 0.3 and 0.1% in the TM and TT categories, respectively. However, because of the increase in the relative branching fraction, the contribution of the $\mu^+\mu^-\tau^+\tau^-$ signal becomes nonnegligible in the type-III 2HDM+S with $\tan\beta \approx 5$. Figure 7 shows the observed limits on $\mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1})$ in the $(m_{\mathrm{a_1}}, \tan\beta)$ plane, including the contribution of $\mu^+\mu^-\tau^+\tau^-$ signal for type-III 2HDM+S. The observed limit contours of $\mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1}) = 1.00$ and $\mathcal{B}(\mathrm{h} \to \mathrm{a_1 a_1}) = 0.34$ are generally extended compared with Fig. 6 (left).

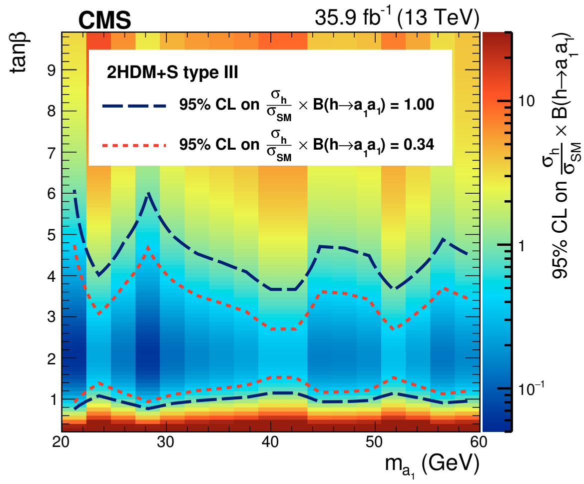

Figure 7: Observed upper limits at 95% CL on $\mathcal{B}(\mathrm{h} \to \mathrm{a}_1\mathrm{a}_1)$ in the plane of $(m_{\mathrm{a}_1}, \tan\beta)$ for type-III 2HDM+S, including $\mu^+\mu^-\tau^+\tau^-$ signal that is misidentified as $\mu^+\mu^-\mathrm{b}\overline{\mathrm{b}}$.

8 Summary

A search for the Higgs boson decay to a pair of new pseudoscalars $\mathrm{h} \to \mathrm{a}_1\mathrm{a}_1 \to \mu^+\mu^-\mathrm{b}\overline{\mathrm{b}}$, motivated by the next-to-minimal supersymmetric standard model and other extensions to two-Higgs-doublet models, is carried out using a sample of proton-proton collision data corresponding to an integrated luminosity of 35.9 fb^{-1} at 13 TeV centre-of-mass energy. No statistically significant excess is found in data with respect to the background prediction. The results of the analysis are presented in the form of upper limits, at 95% confidence level, on the product of the Higgs boson production cross section and branching fraction, $\sigma_\mathrm{h}\mathcal{B}(\mathrm{h} \to \mathrm{a}_1\mathrm{a}_1 \to \mu^+\mu^-\mathrm{b}\overline{\mathrm{b}})$ as well as on the Higgs boson branching fraction assuming the SM prediction of σ_h. The former ranges between 5 to 36 fb, depending on m_{a_1}. The corresponding limits on the branching fraction are $(1\text{–}6) \times 10^{-4}$ for the mass range of $20 \leq m_{\mathrm{a}_1} \leq 62.5$ GeV. In an analysis performed by ATLAS [18], the limits on the branching fraction range between 2×10^{-4} and 10^{-3}. Compared with the similar analysis in Run I [14], the expected upper limits on the branching fraction are improved by more than a factor of two.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth[1], V.M. Ghete, J. Hrubec, M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, A. Lelek, M. Pieters, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D'Hondt, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov[2], D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, K. Piotrzkowski, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

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

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

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

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang[5], X. Gao[5], L. Yuan

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, S.M. Shaheen[6], A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang[6], J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang

Tsinghua University, Beijing, China
Y. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov[7], T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic
M. Finger[8], M. Finger Jr.[8]

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[9,10], S. Elgammal[11], S. Khalil[10]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

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

Helsinki Institute of Physics, Helsinki, Finland
J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam[12], C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[13], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte[13], J.-C. Fontaine[13], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, A. Popov[14], V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze[8]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[8]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, A. Pozdnyakov, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, O. Hlushchenko, T. Kress, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[15]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras[16], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo[17], A. Geiser, J.M. Grados Luyando, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Leonard, K. Lipka, W. Lohmann[18], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saibel, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, M. Van De Klundert, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, T. Dreyer, A. Ebrahimi, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, C.E.N. Niemeyer, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann[15], S.M. Heindl, U. Husemann, I. Katkov[14], S. Kudella, S. Mitra, M.U. Mozer, Th. Müller, M. Musich, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki

National and Kapodistrian University of Athens, Athens, Greece
A. Agapitos, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Vellidis

National Technical University of Athens, Athens, Greece
K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Bartók[19], M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[20], Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi[19], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[22], C. Kar, P. Mal, K. Mandal, A. Nayak[23], S. Roy Chowdhury, D.K. Sahoo[22], S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi, G. Walia

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj[24], M. Bharti[24], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[24], D. Bhowmik, S. Dey, S. Dutt[24], S. Dutta, S. Ghosh, M. Maity[25], K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar[25], M. Sharan, B. Singh[24], S. Thakur[24]

Indian Institute of Technology Madras, Madras, India
P.K. Behera, A. Muhammad

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla, P. Suggisetti

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, N. Sahoo

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[26], E. Eskandari Tadavani, S.M. Etesami[26], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh[27], M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], F. Errico[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], A. Sharma[a], L. Silvestris[a], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], S.S. Chhibra[a,b], G. Codispoti[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi, P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,28], S. Marcellini[a], G. Masetti[a], A. Montanari[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

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

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], K. Chatterjee[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino, P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], L. Russo[a,29], G. Sguazzoni[a], D. Strom[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

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

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], A. Beschi[b], F. Brivio[a,b], V. Ciriolo[a,b,15], S. Di Guida[a,b,15], M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], M. Malberti[a,b], S. Malvezzi[a], D. Menasce[a], F. Monti, L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Zuolo[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], A. Di Crescenzo[a,b], F. Fabozzi[a,c], F. Fienga[a], G. Galati[a], A.O.M. Iorio[a,b], L. Lista[a], S. Meola[a,d,15], P. Paolucci[a,15], C. Sciacca[a,b], E. Voevodina[a,b]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], A. Boletti[a,b], A. Bragagnolo, R. Carlin[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S.Y. Hoh, S. Lacaprara[a], P. Lujan, M. Margoni[a,b], A.T. Meneguzzo[a,b], J. Pazzini[a,b], M. Presilla[b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko, E. Torassa[a], M. Tosi[a,b], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
A. Braghieri[a], A. Magnani[a], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], C. Cecchi[a,b], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], E. Manoni[a], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], L. Bianchini[a], T. Boccali[a], L. Borrello, R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], F. Fiori[a,c], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], G. Rolandi[30], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Sapienza Università di Roma [b], Rome, Italy
L. Barone[a,b], F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], S. Gelli[a,b], E. Longo[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], C. Biino[a], A. Cappati[a,b], N. Cartiglia[a], F. Cenna[a,b], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], R. Salvatico[a,b], K. Shchelina[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a]

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

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

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
B. Francois, J. Goh[31], T.J. Kim

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Sejong University, Seoul, Korea
H.S. Kim

Seoul National University, Seoul, Korea
J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea
D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, J. Lee, I. Yu

Riga Technical University, Riga, Latvia
V. Veckalns[32]

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
Z.A. Ibrahim, M.A.B. Md Ali[33], F. Mohamad Idris[34], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz[35], R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, M. Ramirez-Garcia, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

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

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

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

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

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[36], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, J. Seixas, G. Strong, O. Toldaiev, J. Varela

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

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[39], E. Kuznetsova[40], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, A. Shabanov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
R. Chistov[41], M. Danilov[41], S. Polikarpov[41], E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin[38], M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[42], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia
A. Barnyakov[43], V. Blinov[43], T. Dimova[43], L. Kardapoltsev[43], Y. Skovpen[43]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, S. Baidali, V. Okhotnikov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[44], P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic[45], J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi

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

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

University of Ruhuna, Department of Physics, Matara, Sri Lanka
N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita[46], D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Gruchala, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, V. Innocente, G.M. Innocenti, A. Jafari, P. Janot, O. Karacheban[18], J. Kieseler, A. Kornmayer, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo[15], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[47], A. Stakia, J. Steggemann, D. Treille, A. Tsirou, A. Vartak, M. Verzetti, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[48], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Reichmann, C. Reissel, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler[49], D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, S. Leontsinis, V.M. Mikuni, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, S. Wertz, A. Zucchetta

National Central University, Chung-Li, Taiwan
T.H. Doan, R. Khurana, C.M. Kuo, W. Lin, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
A. Bat, F. Boran, S. Cerci[50], S. Damarseckin, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos[51], C. Isik, E.E. Kangal[52], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[53], S. Ozturk[54], D. Sunar Cerci[50], B. Tali[50], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[55], G. Karapinar[56], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya[57], O. Kaya[58], S. Ozkorucuklu[59], S. Tekten, E.A. Yetkin[60]

Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen[61]

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

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
F. Ball, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold[62], S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[63], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, P. Everaerts, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash[64], A. Nikitenko[7], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee[15], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, T. Bose, Z. Demiragli, D. Gastler, S. Girgis, D. Pinna, C. Richardson, J. Rohlf, D. Sperka, I. Suarez, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, B. Burkle, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan[65], K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir[66], R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, USA
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, S. Erhan, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA
E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, San Diego, La Jolla, USA
J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, D. Olivito, S. Padhi, M. Pieri, V. Sharma, M. Tadel, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, R. Bhandari, C. Campagnari, M. Citron, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, H. Mei, A. Ovcharova, H. Qu, J. Richman, D. Stuart, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, J.M. Lawhorn, N. Lu, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, F. Ravera, A. Reinsvold, L. Ristori, A. Savoy-Navarro[67], B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, USA
Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA
A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, C. Schiber, R. Yohay

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, M.B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
M. Alhusseini, B. Bilki[68], W. Clarida, K. Dilsiz[69], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul[70], Y. Onel, F. Ozok[71], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao

The University of Kansas, Lawrence, USA
A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi

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

University of Maryland, College Park, USA
A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, M. Seidel, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

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

University of Minnesota, Minneapolis, USA
A.C. Benvenuti[†], R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, S. Kalafut, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, R. Rusack, M.A. Wadud

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, G. Madigan, D.M. Morse, T. Orimoto, A. Tishelman-charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, O. Charaf, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

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

The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer

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

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

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, Arun Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, Z. Tu, A. Zhang

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, E. Ranken, P. Tan, R. Taus

Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen

University of Tennessee, Knoxville, USA
H. Acharya, A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A&M University, College Station, USA
O. Bouhali[72], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[73], S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

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

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gomber[74], M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W.H. Smith, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at University of Chinese Academy of Sciences, Beijing, China
7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
8: Also at Joint Institute for Nuclear Research, Dubna, Russia
9: Also at Helwan University, Cairo, Egypt
10: Now at Zewail City of Science and Technology, Zewail, Egypt
11: Now at British University in Egypt, Cairo, Egypt
12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
13: Also at Université de Haute Alsace, Mulhouse, France
14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India

23: Also at Institute of Physics, Bhubaneswar, India
24: Also at Shoolini University, Solan, India
25: Also at University of Visva-Bharati, Santiniketan, India
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT, Bologna, Italy
29: Also at Università degli Studi di Siena, Siena, Italy
30: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
31: Also at Kyunghee University, Seoul, Korea
32: Also at Riga Technical University, Riga, Latvia
33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
40: Also at University of Florida, Gainesville, USA
41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
42: Also at California Institute of Technology, Pasadena, USA
43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
45: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
46: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
47: Also at National and Kapodistrian University of Athens, Athens, Greece
48: Also at Universität Zürich, Zurich, Switzerland
49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
50: Also at Adiyaman University, Adiyaman, Turkey
51: Also at Istanbul Aydin University, Istanbul, Turkey
52: Also at Mersin University, Mersin, Turkey
53: Also at Piri Reis University, Istanbul, Turkey
54: Also at Gaziosmanpasa University, Tokat, Turkey
55: Also at Ozyegin University, Istanbul, Turkey
56: Also at Izmir Institute of Technology, Izmir, Turkey
57: Also at Marmara University, Istanbul, Turkey
58: Also at Kafkas University, Kars, Turkey
59: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
60: Also at Istanbul Bilgi University, Istanbul, Turkey
61: Also at Hacettepe University, Ankara, Turkey
62: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
63: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
64: Also at Monash University, Faculty of Science, Clayton, Australia
65: Also at Bethel University, St. Paul, USA
66: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

67: Also at Purdue University, West Lafayette, USA
68: Also at Beykent University, Istanbul, Turkey
69: Also at Bingol University, Bingol, Turkey
70: Also at Sinop University, Sinop, Turkey
71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
72: Also at Texas A&M University at Qatar, Doha, Qatar
73: Also at Kyungpook National University, Daegu, Korea
74: Also at University of Hyderabad, Hyderabad, India