



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*

CERN, Switzerland

ARTICLE INFO

Article history:

Received 15 December 2018
 Received in revised form 2 May 2019
 Accepted 11 June 2019
 Available online 13 June 2019
 Editor: M. Doser

Keywords:

CMS
 Physics
 BSM Higgs physics

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, $\sigma_h \mathcal{B}(h \rightarrow a_1 a_1 \rightarrow \mu^+ \mu^- b\bar{b})$, ranging from 5 to 33 fb, depending on the pseudoscalar mass. Corresponding limits on the branching fraction, assuming the SM prediction for σ_h , are $(1-7) \times 10^{-4}$.

© 2019 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

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 [5–8]. However, the possibility of exotic Higgs boson decays to new lighter bosons is not excluded, and is proposed in various theories beyond the SM (BSM) [9]. The LHC combination of the SM Higgs boson measurements at 7 and 8 TeV allows Higgs boson decays to BSM states 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 [15–21]. 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) [9,22–24]. 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 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 $m_h \approx 125 \text{ GeV}$. In 2HDM+S models, a complex scalar singlet $S_R + iS_I$ 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 $h \rightarrow a_1 a_1 \rightarrow \mu^+ \mu^- b\bar{b}$. The gluon gluon fusion (ggF) and the vector boson fusion (VBF) production mechanisms are considered, with production cross sections of $48.58 \pm 2.45 \text{ pb}$ (at next-to-next-to-

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

next-to-leading order in QCD) and 3.78 ± 0.08 pb (at next-to-next-to-leading order in QCD), respectively [25]. As a benchmark, the branching fraction of $h \rightarrow a_1 a_1$ 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 $2\mathcal{B}(a_1 \rightarrow b\bar{b})\mathcal{B}(a_1 \rightarrow \mu^+\mu^-) = 1.7 \times 10^{-3}$ for $m_{a_1} = 30$ GeV in type-III 2HDM+S [9]. For the set of parameters under discussion and with $20 \leq m_{a_1} \leq 62.5$ GeV, no strong dependence on m_{a_1} is expected for $\mathcal{B}(a_1 \rightarrow b\bar{b})$ and $\mathcal{B}(a_1 \rightarrow \mu^+\mu^-)$ [9]. 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 $\mu^+\mu^-b\bar{b}$ final state is sensitive to the mass range of $20 \leq m_{a_1} \leq 62.5$ GeV. The sensitivity of the search largely decreases towards $m_{a_1} \approx 20$ 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 $h \rightarrow a_1 a_1 \rightarrow \mu^+\mu^-b\bar{b}$ process, decays of $h \rightarrow a_1 a_1 \rightarrow \mu^+\mu^-\tau^+\tau^-$ 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 $\mathcal{B}(a_1 \rightarrow \tau^+\tau^-)$ can lead to a nonnegligible fraction of these events surviving the selection. This is taken into account in the scan over the $(m_{a_1}, \tan\beta)$ 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 $a_1 a_1 \rightarrow b\bar{b}\tau^+\tau^-$ with $\tau \rightarrow \mu$ 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 [9] is used to generate signal samples with the Monte Carlo (MC) event generator MADGRAPH5_AMC@NLO [29] at leading order (LO). The signal samples span the m_{a_1} search region in 5 GeV steps. Background processes with dominant contributions are the Drell–Yan production in association with additional b quarks and $t\bar{t}$ 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, $Z/\gamma^*(\rightarrow \ell^+\ell^-) + \text{jets}$ 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, $t\bar{t}$ 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 $p_T > 17$ 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 $p_T > 20$ (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 ,

$$I_{\text{rel}} = \frac{I^{\text{ch,h}} + \max((I^\gamma + I^{\text{n,h}} - 0.5 I^{\text{PU ch,h}}), 0)}{p_T}, \quad (1)$$

where $I^{\text{ch,h}}$, I^γ , $I^{\text{n,h}}$ and $I^{\text{PU ch,h}}$ are, respectively, the scalar p_T sums of stable charged hadrons, photons, neutral hadrons, and charged hadrons associated with pileup vertices. The contribution $0.5 I^{\text{PU ch,h}}$ 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 $I_{\text{rel}} < 0.15$ 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 $p_{\text{T}} > 20$ (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 $\approx 80\%$ for the loose, $\approx 60\%$ for the medium, and $\approx 40\%$ 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, $p_{\text{T}}^{\text{miss}}$ 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 $p_{\text{T}}^{\text{miss}}$ measurement [45]. Events are required to have $p_{\text{T}}^{\text{miss}} < 60$ GeV.

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

$$\chi_{\text{bb}} = \frac{(m_{\text{bb}} - m_{\mu\mu})}{\sigma_{\text{bb}}} \quad \text{and} \quad \chi_{\text{h}} = \frac{(m_{\mu\mu\text{bb}} - m_{\text{h}})}{\sigma_{\text{h}}}. \quad (2)$$

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 decay width of a_1 is negligible compared with the experimental mass resolutions in the analysis. 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. The tails in the χ_{bb} and χ_{h} distributions, arising from the imperfect energy estimation of b jets as

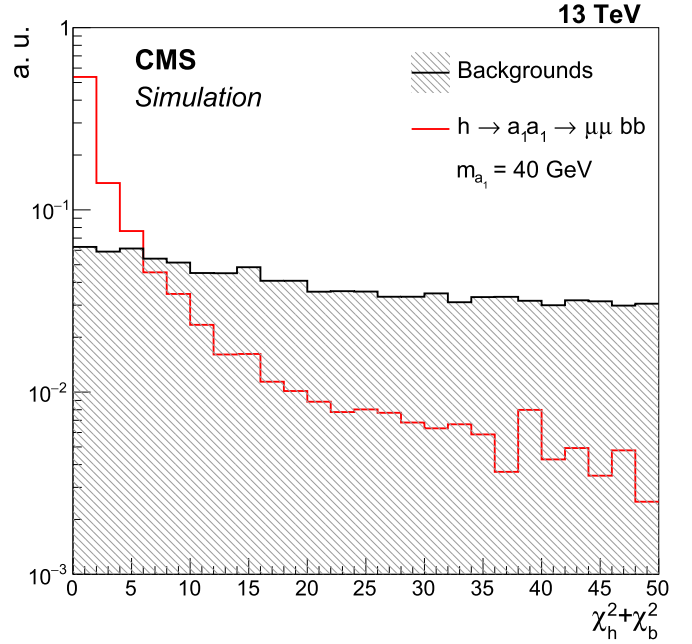


Fig. 1. The distribution of χ^2 in simulated background processes and the signal process with $m_{a_1} = 40$ GeV. The samples are normalised to unity.

well as combinatorics of the di-b-jet system, are more populated in background processes. The search for the new particle a_1 is performed within $20 \leq m_{a_1} \leq 62.5$ GeV. A slightly wider range, driven by the narrow width of a_1 and the high resolution of $m_{\mu\mu}$, is used for the event selection; thus events with $m_{\mu\mu}$ values not in [19.5, 63.5] GeV are discarded. This ensures the full signal selection efficiency and the proper background modelling at the boundaries.

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. Fig. 3 shows distributions, in data and simulation, for events passing the selection requirements except those of $p_{\text{T}}^{\text{miss}}$ and χ^2 . In this figure, expected number of simulated events is normalised to the integrated luminosity of 35.9 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 $m_{\mu\mu\text{bb}}$ and the transverse momentum $p_{\text{T}}^{\mu\mu\text{bb}}$ 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 $h \rightarrow a_1 a_1 \rightarrow \mu^+ \mu^- \tau^+ \tau^-$ is found to be around 0.01 with the model parameters used in this table.

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 categorisation 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 jet identification algorithm. Events in which the loose b-tagged jet passes the medium b tagging requirements but fails the tight conditions fall

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 fb^{-1} . Uncertainties are statistical only.

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

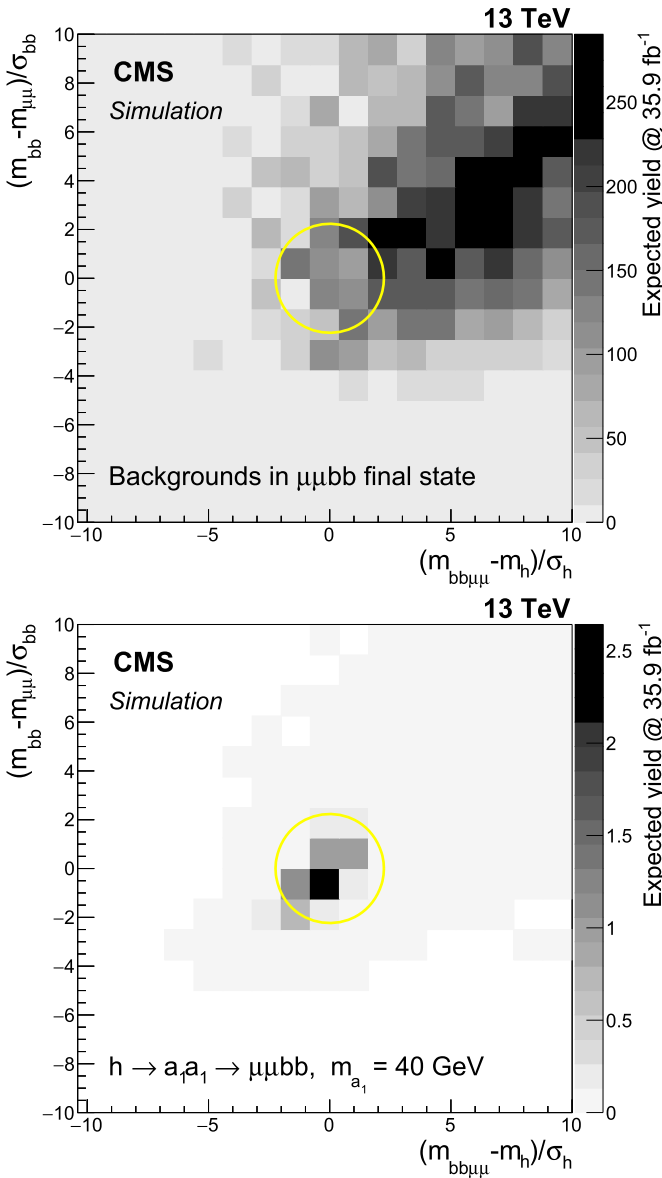


Fig. 2. The distribution of χ_{bb} versus χ_h as defined in Eq. (2) for (upper) simulated background processes and (lower) the signal process with $m_{a_1} = 40 \text{ GeV}$. The contours encircle the area with $\chi^2 < 5$. The grey scale represents the expected yields at 35.9 fb^{-1} .

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 ($\approx 70\%$) 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 the simulated signal samples described in Section 3. Almost all parameters in the signal model are found to be independent of m_{a_1} and are fixed in the final fit. The only exceptions are 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,

$$\sigma_v = \sigma_{v,0} + \alpha m_{\mu\mu}, \quad (3)$$

$$\sigma_{cb} = \sigma_{cb,0} + \beta m_{\mu\mu}.$$

The expected signal efficiency and acceptance are interpolated for m_{a_1} values not covered by simulation. 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

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

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 analytic 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.

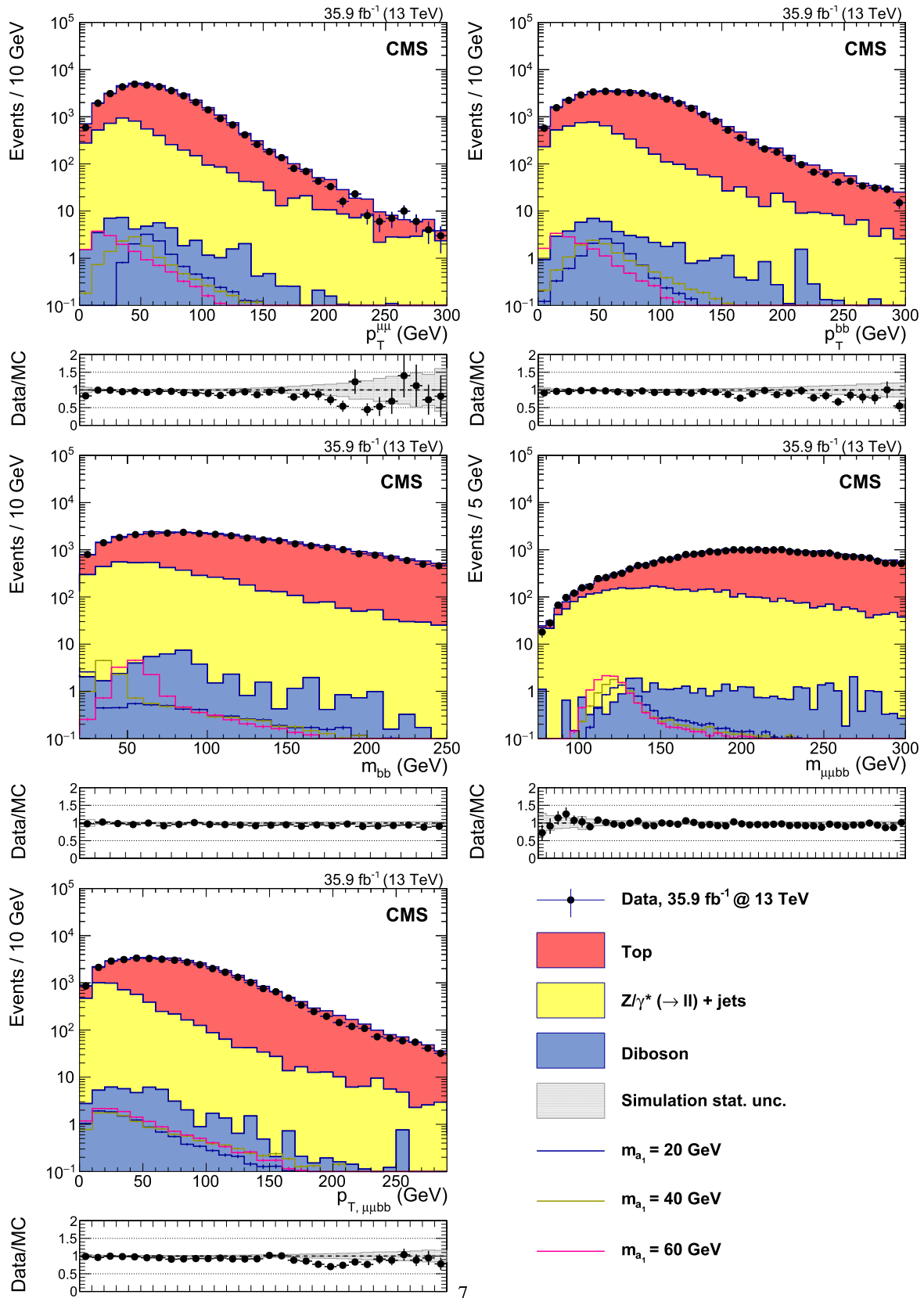


Fig. 3. The distribution of the p_T of the (top left) dimuon and (top right) di-b-jet system, the mass of the (middle left) di-b-jet and (middle right) $\mu\mu bb$ system, and (bottom left) the p_T of the $\mu\mu bb$ system, all after requiring two muons and two b-tagged jets in the event. Simulated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

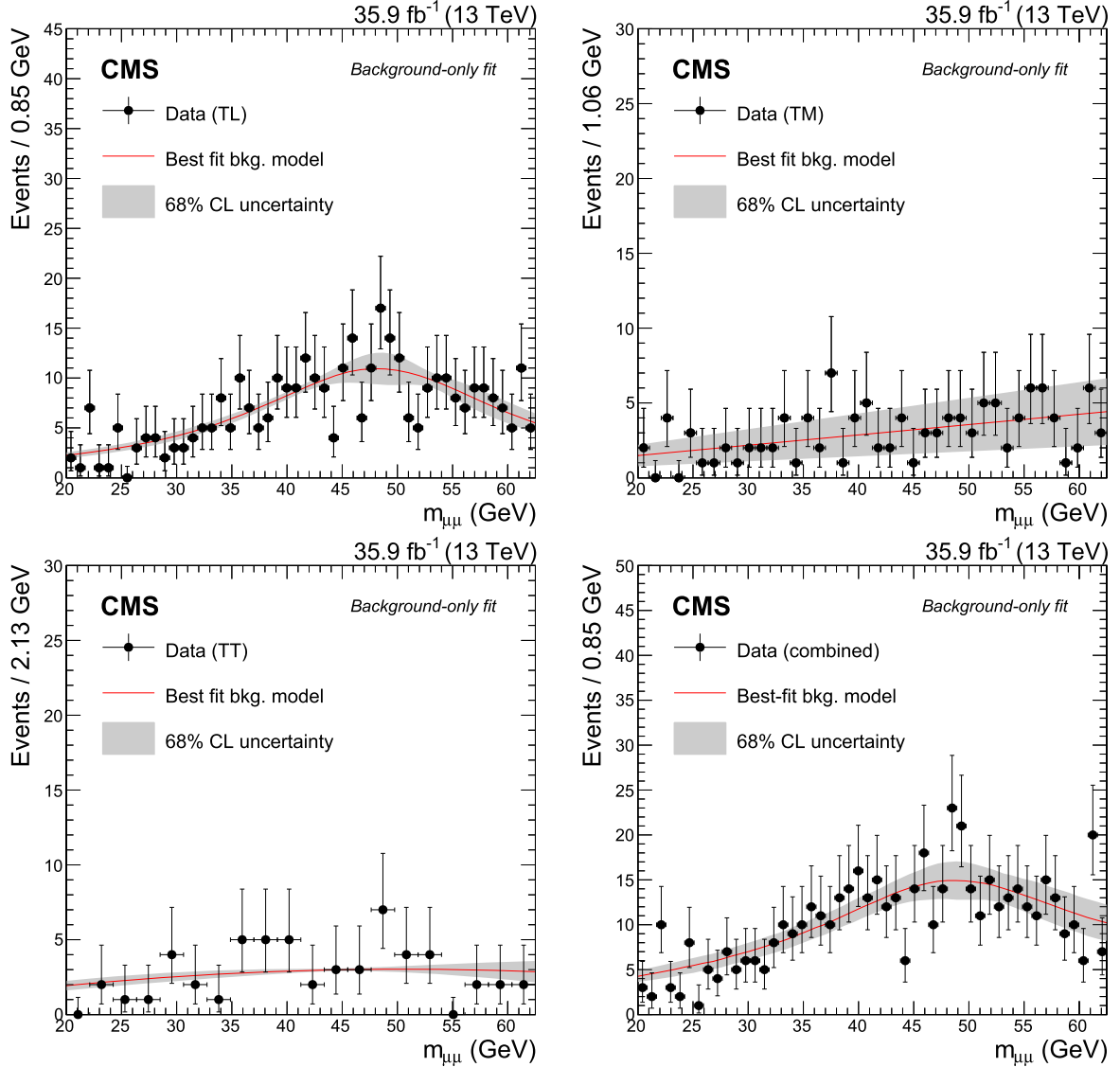


Fig. 4. The best fit output to the data under the background-only hypothesis for the (top left) TL category, (top right) TM category, (bottom left) TT category and (bottom right) all categories, presented together with 68% CL uncertainty band for the background model.

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 $\tilde{\mathcal{L}}$ can be written as

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

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}_μ . The denominator is the global maximum for $\tilde{\mathcal{L}}$, achieved at $\mu = \hat{\mu}$, $\theta = \hat{\theta}$ and $b = \hat{b}$. A confidence interval for μ is obtained with the background function maximising $\tilde{\mathcal{L}}$ 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 $\mathcal{B}(h \rightarrow a_1 a_1 \rightarrow \mu^+ \mu^- b \bar{b})$, the Higgs boson production cross section is set to the SM prediction where an uncertainty of 4.7% 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_T^{miss} of the event. An additional uncertainty, arising from unclustered energies in the event, is assessed for p_T^{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]. Uncertainties in the choice of the renormalisation, μ_r , and factorisation, μ_f , scales are estimated by doubling and halving μ_r and μ_f simultaneously in the signal sample. To estimate the uncertainties associated with the parton showering and fragmentation model, additional signal samples are produced using HERWIG ++ [55] and compared to PYTHIA. Finally, uncertainties arising from the limited understanding of the PDFs [56] 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. Fig. 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 $\sigma_h \mathcal{B}(h \rightarrow a_1 a_1 \rightarrow \mu^+ \mu^- b\bar{b})$ is obtained at 95% CL using the CL_s criterion [57,58] and an asymptotic approximation to the distribution of the profiled likelihood ratio test statistic [59]. Assuming the SM cross sections for the Higgs boson production processes within the theoretical uncertainties, an upper limit is placed on $\mathcal{B}(h \rightarrow a_1 a_1 \rightarrow \mu^+ \mu^- b\bar{b})$ using the same procedure. Limits are evaluated as a function of m_{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, followed by the modelling of parton shower and fragmentation. For $m_{a_1} = 40$ GeV, the b tagging uncertainties arising from LF contamination and JES amount to 17 and 14%, respectively. The uncertainty arising from the parton shower and fragmentation models is about 7%. Other uncertainties are below 5%.

At 95% CL, the observed upper limits on $\mathcal{B}(h \rightarrow a_1 a_1 \rightarrow \mu^+ \mu^- b\bar{b})$ are $(1-7) \times 10^{-4}$ for the mass range 20 to 62.5 GeV, whilst the expected limits are $(1-3) \times 10^{-4}$. A similar search from CMS in Run I [14] led to observed upper limits of $(2-8) \times 10^{-4}$ at 95% CL, considering the ggF Higgs boson production and the mass range $25 \leq m_{a_1} \leq 62.5$ GeV. The corresponding expected limits on the branching fraction at 95% CL are $(3-4) \times 10^{-4}$. 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 $t\bar{t}$, 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.

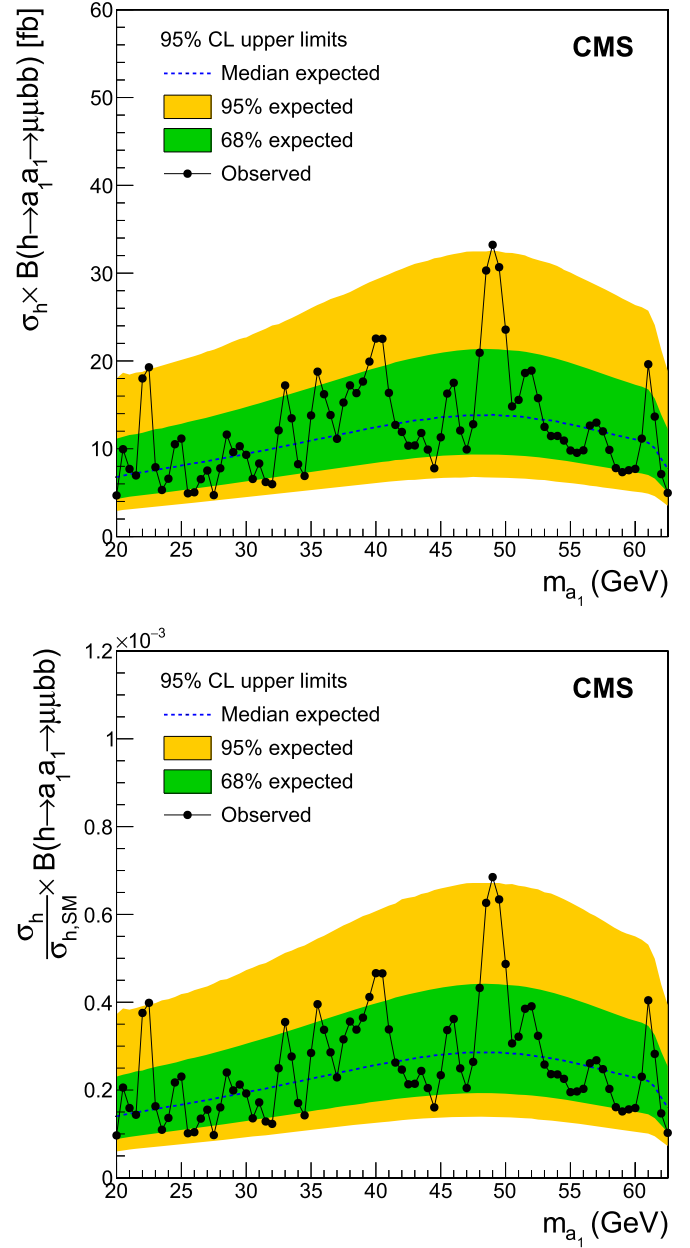


Fig. 5. Observed and expected upper limits at 95% CL on the (upper) product of the Higgs boson production cross section and $\mathcal{B}(h \rightarrow a_1 a_1 \rightarrow \mu^+ \mu^- b\bar{b})$ and (lower) the branching fraction as a function of m_{a_1} . The inner and outer bands indicate the regions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

Observed limits on $\mathcal{B}(h \rightarrow a_1 a_1)$ are shown in Fig. 6 in the plane of $(m_{a_1}, \tan \beta)$ for type-III and type-IV 2HDM+S, using only the $\mu^+ \mu^- b\bar{b}$ signal. The allowed ranges for $\mathcal{B}(h \rightarrow a_1 a_1) \leq 1$ and $\mathcal{B}(h \rightarrow a_1 a_1) \leq 0.34$ [7] are also presented.

The effect of including the $\mu^+ \mu^- \tau^+ \tau^-$ signal is studied in the $(m_{a_1}, \tan \beta)$ plane for the four types of 2HDM+S. For a given $(m_{a_1}, \tan \beta)$ the relevance of $\mu^+ \mu^- \tau^+ \tau^-$ depends on the ratio $\mathcal{B}(a_1 \rightarrow \tau\tau) \epsilon_{\mu\mu\tau\tau}^{\text{sel.}} / \mathcal{B}(a_1 \rightarrow b\bar{b}) \epsilon_{\mu\mu b\bar{b}}^{\text{sel.}}$ 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 $\epsilon_{\mu\mu\tau\tau}^{\text{sel.}} / \epsilon_{\mu\mu b\bar{b}}^{\text{sel.}}$ 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 $\mu^+ \mu^- \tau^+ \tau^-$ sig-

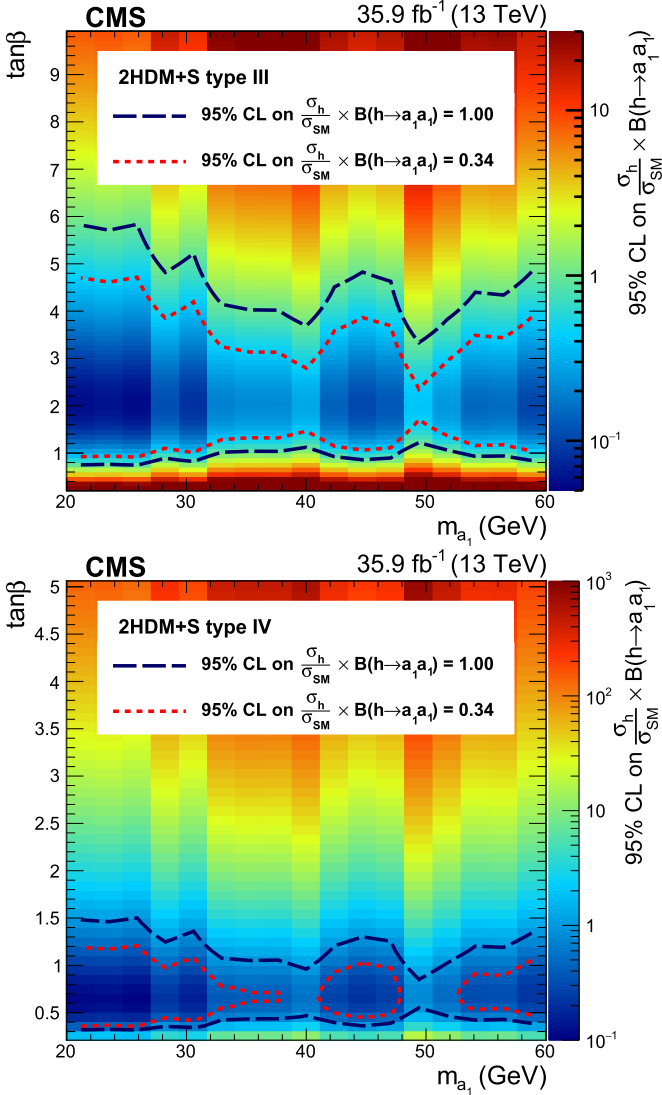


Fig. 6. Observed upper limits at 95% CL on $\mathcal{B}(h \rightarrow a_1 a_1)$ in the plane of $(m_{a_1}, \tan \beta)$ for (upper) type-III and (lower) type-IV 2HDM+S, using only the $\mu^+ \mu^- b \bar{b}$ signal.

nal becomes nonnegligible in the type-III 2HDM+S with $\tan \beta \approx 5$. Fig. 7 shows the observed limits on $\mathcal{B}(h \rightarrow a_1 a_1)$ in the $(m_{a_1}, \tan \beta)$ plane, including the contribution of $\mu^+ \mu^- \tau^+ \tau^-$ signal for type-III 2HDM+S. The observed limit contours of $\mathcal{B}(h \rightarrow a_1 a_1) = 1.00$ and $\mathcal{B}(h \rightarrow a_1 a_1) = 0.34$ are generally extended compared with Fig. 6 (upper).

8. Summary

A search for the Higgs boson decay to a pair of new pseudoscalars $h \rightarrow a_1 a_1 \rightarrow \mu^+ \mu^- b \bar{b}$, 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, $\sigma_h \mathcal{B}(h \rightarrow a_1 a_1 \rightarrow \mu^+ \mu^- b \bar{b})$ as well as on the Higgs boson branching fraction assuming the SM prediction of σ_h . The former

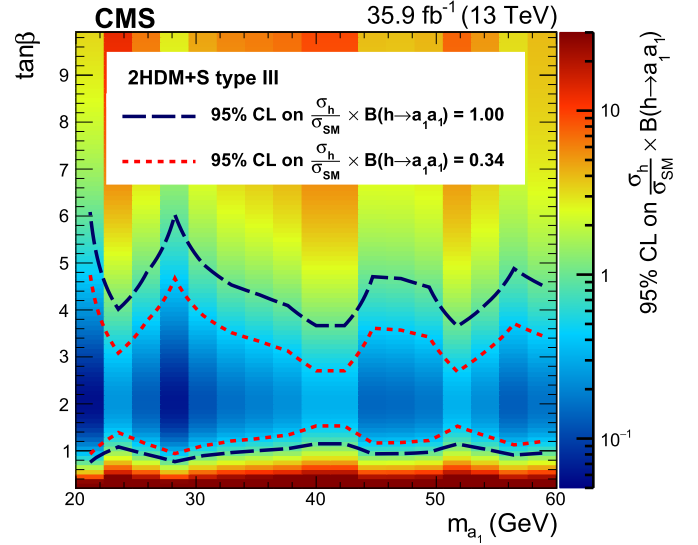


Fig. 7. Observed upper limits at 95% CL on $\mathcal{B}(h \rightarrow a_1 a_1)$ in the plane of $(m_{a_1}, \tan \beta)$ for type-III 2HDM+S, including $\mu^+ \mu^- \tau^+ \tau^-$ signal that is misidentified as $\mu^+ \mu^- b \bar{b}$.

ranges between 5 and 33 fb, depending on m_{a_1} . The corresponding upper limits on the branching fraction are $(1-7) \times 10^{-4}$ for the mass range of $20 \leq m_{a_1} \leq 62.5$ GeV. In an analysis performed by ATLAS [19], the upper limits on the branching fraction are $(1.2-8.4) \times 10^{-4}$. Compared with the similar analysis in Run I [14], the expected upper limits on the branching fraction are improved by a factor between 1.4 and 1.8 for $25 \leq m_{a_1} \leq 62.5$ GeV.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFI (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt

Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science – EOS” – be.h project n. 30820817; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület (“Momentum”) Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NK-FIA research grants 123842, 123959, 124845, 124850, and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] ATLAS Collaboration, Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, *Phys. Lett. B* 716 (2012) 1, <https://doi.org/10.1016/j.physletb.2012.08.020>, arXiv:1207.7214.
- [2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, *Phys. Lett. B* 716 (2012) 30, <https://doi.org/10.1016/j.physletb.2012.08.021>, arXiv:1207.7235.
- [3] CMS Collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV, *J. High Energy Phys.* 06 (2013) 081, [https://doi.org/10.1007/JHEP06\(2013\)081](https://doi.org/10.1007/JHEP06(2013)081), arXiv:1303.4571.
- [4] L. Evans, P. Bryant, LHC machine, *J. Instrum.* 3 (2008) S08001, <https://doi.org/10.1088/1748-0221/3/08/S08001>.
- [5] ATLAS Collaboration, Measurement of the Higgs boson coupling properties in the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay channel at $\sqrt{s} = 13$ TeV with the ATLAS detector, *J. High Energy Phys.* 03 (2018) 095, [https://doi.org/10.1007/JHEP03\(2018\)095](https://doi.org/10.1007/JHEP03(2018)095), arXiv:1712.02304.
- [6] CMS Collaboration, Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* 11 (2017) 047, [https://doi.org/10.1007/JHEP11\(2017\)047](https://doi.org/10.1007/JHEP11(2017)047), arXiv:1706.09936.
- [7] ATLAS and CMS Collaborations, Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV, *J. High Energy Phys.* 08 (2016) 045, [https://doi.org/10.1007/JHEP08\(2016\)045](https://doi.org/10.1007/JHEP08(2016)045), arXiv:1606.02266.
- [8] CMS Collaboration, Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs, *Phys. Rev. Lett.* 110 (2013) 081803, <https://doi.org/10.1103/PhysRevLett.110.081803>, arXiv:1212.6639.
- [9] D. Curtin, R. Essig, S. Gori, P. Jaiswal, A. Katz, T. Liu, Z. Liu, D. McKeen, J. Shelton, M. Strassler, Z. Surujon, B. Tweedie, Y.-M. Zhong, Exotic decays of the 125 GeV Higgs boson, *Phys. Rev. D* 90 (2014) 075004, <https://doi.org/10.1103/PhysRevD.90.075004>, arXiv:1312.4992.
- [10] CMS Collaboration, Combined measurements of Higgs boson couplings in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* 79 (2019) 421, <https://doi.org/10.1140/epjc/s10052-019-6909-y>.
- [11] ATLAS Collaboration, Search for Higgs bosons decaying to aa in the $\mu\mu\tau\tau$ final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS experiment, *Phys. Rev. D* 92 (2015) 052002, <https://doi.org/10.1103/PhysRevD.92.052002>, arXiv:1505.01609.
- [12] CMS Collaboration, A search for pair production of new light bosons decaying into muons, *Phys. Lett. B* 752 (2016) 146, <https://doi.org/10.1016/j.physletb.2015.10.067>, arXiv:1506.00424.
- [13] CMS Collaboration, Search for a very light NMSSM Higgs boson produced in decays of the 125 GeV scalar boson and decaying into τ leptons in pp collisions at $\sqrt{s} = 8$ TeV, *J. High Energy Phys.* 01 (2016) 079, [https://doi.org/10.1007/JHEP01\(2016\)079](https://doi.org/10.1007/JHEP01(2016)079), arXiv:1510.06534.
- [14] CMS Collaboration, Search for light bosons in decays of the 125 GeV Higgs boson in proton-proton collisions at $\sqrt{s} = 8$ TeV, *J. High Energy Phys.* 10 (2017) 076, [https://doi.org/10.1007/JHEP10\(2017\)076](https://doi.org/10.1007/JHEP10(2017)076), arXiv:1701.02032.
- [15] ATLAS Collaboration, Search for the Higgs boson produced in association with a W boson and decaying to four b-quarks via two spin-zero particles in pp collisions at 13 TeV with the ATLAS detector, *Eur. Phys. J. C* 76 (2016) 605, <https://doi.org/10.1140/epjc/s10052-016-4418-9>, arXiv:1606.08391.
- [16] ATLAS Collaboration, Search for Higgs boson decays to beyond-the-Standard-Model light bosons in four-lepton events with the ATLAS detector at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* 06 (2018) 166, [https://doi.org/10.1007/JHEP06\(2018\)166](https://doi.org/10.1007/JHEP06(2018)166), arXiv:1802.03388.
- [17] ATLAS Collaboration, Search for Higgs boson decays into pairs of light (pseudo)scalar particles in the $\gamma\gamma j$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 782 (2018) 750, <https://doi.org/10.1016/j.physletb.2018.06.011>, arXiv:1803.11145.
- [18] ATLAS Collaboration, Search for the Higgs boson produced in association with a vector boson and decaying into two spin-zero particles in the $H \rightarrow aa \rightarrow 4b$ channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *J. High Energy Phys.* 10 (2018) 031, [https://doi.org/10.1007/JHEP10\(2018\)031](https://doi.org/10.1007/JHEP10(2018)031), arXiv:1806.07355.
- [19] ATLAS Collaboration, Search for Higgs boson decays into a pair of light bosons in the $bb\mu\mu$ final state in pp collision at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* 790 (2019) 1, <https://doi.org/10.1016/j.physletb.2018.10.073>, arXiv:1807.00539.
- [20] CMS Collaboration, Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two b quarks and two τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Lett. B* 785 (2018) 462, <https://doi.org/10.1016/j.physletb.2018.08.057>, arXiv:1805.10191.
- [21] CMS Collaboration, Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state of two muons and two τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* 11 (2018) 018, [https://doi.org/10.1007/JHEP11\(2018\)018](https://doi.org/10.1007/JHEP11(2018)018), arXiv:1805.04865.
- [22] M. Dine, W. Fischler, M. Srednicki, A simple solution to the strong CP problem with a harmless axion, *Phys. Lett. B* 104 (1981) 199, [https://doi.org/10.1016/0370-2693\(81\)90590-6](https://doi.org/10.1016/0370-2693(81)90590-6).
- [23] J.E. Kim, H.P. Nilles, The μ -problem and the strong CP-problem, *Phys. Lett. B* 138 (1984) 150, [https://doi.org/10.1016/0370-2693\(84\)91890-2](https://doi.org/10.1016/0370-2693(84)91890-2).
- [24] U. Ellwanger, C. Hugonie, A.M. Teixeira, The next-to-minimal supersymmetric standard model, *Phys. Rep.* 496 (2010) 1, <https://doi.org/10.1016/j.physrep.2010.07.001>, arXiv:0910.1785.
- [25] D. de Florian, et al., Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector, CERN Report CERN-2017-002-M, 2016, <https://doi.org/10.23731/CYRM-2017-002>, arXiv:1610.07922.
- [26] D. Curtin, R. Essig, Y.-M. Zhong, Uncovering light scalars with exotic Higgs decays to $bb\mu^+\mu^-$, *J. High Energy Phys.* 06 (2015) 025, [https://doi.org/10.1007/JHEP06\(2015\)025](https://doi.org/10.1007/JHEP06(2015)025), arXiv:1412.4779.
- [27] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. Instrum.* 13 (2018) P06015, <https://doi.org/10.1088/1748-0221/13/06/P06015>, arXiv:1804.04528.
- [28] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* 3 (2008) S08004, <https://doi.org/10.1088/1748-0221/3/08/S08004>.
- [29] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* 07 (2014) 079, [https://doi.org/10.1007/JHEP07\(2014\)079](https://doi.org/10.1007/JHEP07(2014)079), arXiv:1405.0301.
- [30] Y. Li, F. Petriello, Combining QCD and electroweak corrections to dilepton production in fewz, *Phys. Rev. D* 86 (2012) 094034, <https://doi.org/10.1103/PhysRevD.86.094034>, arXiv:1208.5967.
- [31] E. Re, Single-top Wt-channel production matched with parton showers using the powhcg method, *Eur. Phys. J. C* 71 (2011) 1547, <https://doi.org/10.1140/epjc/s10052-011-1547-z>, arXiv:1009.2450.
- [32] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the powhcg BOX, *J. High Energy Phys.* 06 (2010) 043, [https://doi.org/10.1007/JHEP06\(2010\)043](https://doi.org/10.1007/JHEP06(2010)043), arXiv:1002.2581.
- [33] S. Alioli, P. Nason, C. Oleari, E. Re, NLO single-top production matched with shower in POWHEG: s- and t-channel contributions, *J. High Energy Phys.* 09 (2009) 111, <https://doi.org/10.1088/1126-6708/2009/09/111>, arXiv:0907.4076, Erratum: [https://doi.org/10.1007/JHEP02\(2010\)011](https://doi.org/10.1007/JHEP02(2010)011).
- [34] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the powhcg method, *J. High Energy Phys.* 11 (2007) 070, <https://doi.org/10.1088/1126-6708/2007/11/070>, arXiv:0709.2092.
- [35] R.D. Ball, et al., NNPDF, Parton distributions for the LHC Run II, *J. High Energy Phys.* 04 (2015) 040, [https://doi.org/10.1007/JHEP04\(2015\)040](https://doi.org/10.1007/JHEP04(2015)040), arXiv:1410.8849.

- [36] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to pythia 8.2, *Comput. Phys. Commun.* 191 (2015) 159, <https://doi.org/10.1016/j.cpc.2015.01.024>, arXiv:1410.3012.
- [37] P. Skands, S. Carrazza, J. Rojo, Tuning pythia 8.1: the Monash 2013 tune, *Eur. Phys. J. C* 74 (2014) 3024, <https://doi.org/10.1140/epjc/s10052-014-3024-y>, arXiv:1404.5630.
- [38] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, *Eur. Phys. J. C* 76 (2016) 155, <https://doi.org/10.1140/epjc/s10052-016-3988-x>, arXiv:1512.00815.
- [39] S. Agostinelli, et al., GEANT4, Geant4—a simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip.* 506 (2003) 250, [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8).
- [40] CMS Collaboration, CMS Luminosity Measurements for the 2016 Data Taking Period, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017, URL: <http://cds.cern.ch/record/2257069>.
- [41] M. Cacciari, G.P. Salam, G. Soyez, The anti- k_T jet clustering algorithm, *J. High Energy Phys.* 04 (2008) 063, <https://doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [42] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, *Eur. Phys. J. C* 72 (2012) 1896, <https://doi.org/10.1140/epjc/s10052-012-1896-2>, arXiv:1111.6097.
- [43] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, *J. Instrum.* 12 (2017) P10003, <https://doi.org/10.1088/1748-0221/12/10/P10003>, arXiv:1706.04965.
- [44] CMS Collaboration, Jet Algorithms Performance in 13 TeV Data, CMS Physics Analysis Summary CMS-PAS-JME-16-003, 2017, URL: <http://cds.cern.ch/record/2256875>.
- [45] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, *J. Instrum.* 6 (2011) P11002, <https://doi.org/10.1088/1748-0221/6/11/P11002>, arXiv:1107.4277.
- [46] CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV, *J. Instrum.* 13 (2018) P05011, <https://doi.org/10.1088/1748-0221/13/05/P05011>, arXiv:1712.07158.
- [47] G. Pagnini, R.K. Saxena, A note on the Voigt profile function, arXiv:0805.2274, 2008.
- [48] M.J. Oreglia, A Study of the Reactions $\psi' \rightarrow \gamma\gamma\psi$, Ph.D. thesis, Stanford University, 1980, URL: <http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-r-236.pdf>, SLAC Report SLAC-R-236.
- [49] P.D. Dauncey, M. Kenzie, N. Wardle, G.J. Davies, Handling uncertainties in background shapes: the discrete profiling method, *J. Instrum.* 10 (2015) P04015, <https://doi.org/10.1088/1748-0221/10/04/P04015>, arXiv:1408.6865.
- [50] CMS Collaboration, Observation of the diphoton decay of the Higgs boson and measurement of its properties, *Eur. Phys. J. C* 74 (2014) 3076, <https://doi.org/10.1140/epjc/s10052-014-3076-z>, arXiv:1407.0558.
- [51] ATLAS and CMS Collaborations, Combined measurement of the Higgs boson mass in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS experiments, *Phys. Rev. Lett.* 114 (2015) 191803, <https://doi.org/10.1103/PhysRevLett.114.191803>, arXiv:1503.07589.
- [52] F. James, *Statistical Methods in Experimental Physics*, second ed., World Scientific, Singapore, 2007.
- [53] CMS Collaboration, Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* 07 (2018) 161, [https://doi.org/10.1007/JHEP07\(2018\)161](https://doi.org/10.1007/JHEP07(2018)161), arXiv:1802.02613.
- [54] CMS Collaboration, Measurements of inclusive W and Z cross sections in pp collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* 01 (2011) 080, [https://doi.org/10.1007/JHEP01\(2011\)080](https://doi.org/10.1007/JHEP01(2011)080), arXiv:1012.2466.
- [55] M. Bähr, S. Gieseke, M.A. Gigg, D. Grellscheid, K. Hamilton, O. Latunde-Dada, S. Plätzer, P. Richardson, M.H. Seymour, A. Sherstnev, B.R. Webber, herwig++ physics and manual, *Eur. Phys. J. C* 58 (2008) 639, <https://doi.org/10.1140/epjc/s10052-008-0798-9>, arXiv:0803.0883.
- [56] J. Butterworth, et al., PDF4LHC recommendations for LHC Run II, *J. Phys. G* 43 (2016) 023001, <https://doi.org/10.1088/0954-3899/43/2/023001>, arXiv:1510.03865.
- [57] T. Junk, Confidence level computation for combining searches with small statistics, *Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip.* 434 (1999) 435, [https://doi.org/10.1016/S0168-9002\(99\)00498-2](https://doi.org/10.1016/S0168-9002(99)00498-2), arXiv:hep-ex/9902006.
- [58] A.L. Read, Presentation of search results: the CL_s technique, *J. Phys. G* 28 (2002) 2693, <https://doi.org/10.1088/0954-3899/28/10/313>.
- [59] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* 71 (2011) 1554, <https://doi.org/10.1140/epjc/s10052-011-1554-0>, arXiv:1007.1727, Erratum: <https://doi.org/10.1140/epjc/s10052-013-2501-z>.

The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambroggi, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, V.M. Ghete, J. Hrubec, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck¹, R. Schöfbeck, M. Spanring, D. Spitzbart, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, 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

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov², D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, O. Bondu, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, A. Giammanco, G. Krintiras, V. Lemaître, A. Magitteri, K. Piotrkowski, A. Saggio, M. Vidal Marono, P. Vischia, J. Zobel

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

F.L. Alves, G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, 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 Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, 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, Sandra S. Padula^a

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

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

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

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang⁵, X. Gao⁵, L. Yuan

Beihang University, 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. Shaheen⁶, A. Spiezia, J. Tao, E. Yazgan, H. Zhang, S. Zhang⁶, J. Zhao

Institute of High Energy Physics, Beijing, China

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

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

Y. Wang

Tsinghua University, Beijing, China

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

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

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, M. Roguljic, A. Starodumov⁷, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger⁸, M. Finger Jr.⁸

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A.A. Abdelalim^{9,10}, S. Elgammal¹¹, S. Khalil¹⁰

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, 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

Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

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

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

A. Abdulsalam¹², 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 Leitner, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

J.-L. Agram¹³, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte¹³, J.-C. Fontaine¹³, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, 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. Popov¹⁴, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

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

A. Khvedelidze⁸

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze⁸

Tbilisi State University, Tbilisi, Georgia

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, I. Physikalisches Institut, 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 A, Aachen, Germany

G. Flügge, O. Hlushchenko, T. Kress, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁵

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

M. Aldaya Martin, T. Arndt, C. Asawatrangkuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras¹⁶, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranichis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁷, 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. Lohmann¹⁸, 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

Deutsches Elektronen-Synchrotron, 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. Multhaupt, 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

University of Hamburg, Hamburg, 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. Hartmann¹⁵, S.M. Heindl, U. Husemann, I. Katkov¹⁴, 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

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

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

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

A. Agapitos, G. Karathanasis, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Vellidis

National and Kapodistrian University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Giannelios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

University of Ioánnina, Ioánnina, Greece

M. Bartók¹⁹, M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

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

G. Bencze, C. Hajdu, D. Horvath²⁰, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi¹⁹, A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

Institute of Physics, University of Debrecen, Debrecen, Hungary

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

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati²¹, C. Kar, P. Mal, K. Mandal, A. Nayak²², S. Roy Chowdhury, D.K. Sahoo²¹, S.K. Swain

National Institute of Science Education and Research, HBNI, Bhubaneswar, 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. Viridi, G. Walia

Panjab University, Chandigarh, 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

University of Delhi, Delhi, India

R. Bhardwaj²³, M. Bharti²³, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²³, D. Bhowmik, S. Dey, S. Dutt²³, S. Dutta, S. Ghosh, M. Maity²⁴, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, G. Saha, S. Sarkar, T. Sarkar²⁴, M. Sharan, B. Singh²³, S. Thakur²³

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, A. Muhammad

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, D.K. Mishra, P.K. Netrakanti, L.M. Pant, P. Shukla, P. Suggisetti

Bhabha Atomic Research Centre, Mumbai, India

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

Tata Institute of Fundamental Research-A, Mumbai, India

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

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

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

S. Chenarani²⁵, E. Eskandari Tadavani, S.M. Etesami²⁵, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh²⁶, M. Zeinali

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

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

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borghonovi^{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,27}, 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

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, 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,28}, G. Sguazzoni^a, D. Strom^a, L. Viliani^a

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

F. Ferro^a, R. Mulargia^{a,b}, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

A. Benaglia^a, A. Beschi^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}

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

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. De Iorio^{a,b}, A. Di Crescenzo^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a, G. Galati^a, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,15}, P. Paolucci^{a,15}, C. Sciacca^{a,b}, E. Voevodina^{a,b}

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, Italy

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, A. Boletti^{a,b}, A. Bragagnolo, R. Carlin^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^{a,b}, 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}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, 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}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, 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

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, 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. Rolandi²⁹, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

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}

^a INFN Sezione di Roma, Rome, Italy

^b Sapienza Università di Roma, Rome, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, 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

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

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

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

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

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon, G. Oh

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

B. Francois, J. Goh³⁰, T.J. Kim

Hanyang University, Seoul, Republic of 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

Korea University, Seoul, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of 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

Seoul National University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

V. Veckalns³¹

Riga Technical University, Riga, Latvia

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

Z.A. Ibrahim, M.A.B. Md Ali³², F. Mohamad Idris³³, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz³⁴, R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, M. Ramirez-Garcia, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

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 Physics, Quaid-I-Azam University, Islamabad, Pakistan

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

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk³⁵, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

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

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

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{36,37}, P. Moiseenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim³⁸, E. Kuznetsova³⁹, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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

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

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepanov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

R. Chistov⁴⁰, M. Danilov⁴⁰, S. Polikarpov⁴⁰, E. Tarkovskii

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

V. Andreev, M. Azarkin, I. Dremin³⁷, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴¹, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin

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

A. Barnyakov⁴², V. Blinov⁴², T. Dimova⁴², L. Kardapoltsev⁴², Y. Skovpen⁴²

Novosibirsk State University (NSU), Novosibirsk, 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

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

A. Babaev, S. Baidali, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

P. Adzic⁴³, P. Cirkovic, D. Devetak, M. Dordevic, P. Milenovic⁴⁴, J. Milosevic

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

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

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

C. Albajar, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, 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

Universidad de Oviedo, Oviedo, 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

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

N. Wickramage

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

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. Fallavollita⁴⁵, 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. Karacheban¹⁸, J. Kieseler, A. Kornmayer, M. Krammer¹, 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. Pantaleo¹⁵, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabaday, A. Racz, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁶, A. Stakia, J. Steggemann, D. Treille, A. Tsiros, A. Vartak, M. Verzetti, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada⁴⁷, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, 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. Luster mann, 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

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

T.K. Aarrestad, C. Amsler⁴⁸, 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

Universität Zürich, Zurich, Switzerland

T.H. Doan, R. Khurana, C.M. Kuo, W. Lin, S.S. Yu

National Central University, Chung-Li, 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

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

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

A. Bat, F. Boran, S. Cerci⁴⁹, S. Damarseekin, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos⁵⁰, C. Isik, E.E. Kangal⁵¹, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵², S. Ozturk⁵³, D. Sunar Cerci⁴⁹, B. Tali⁴⁹, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Isildak⁵⁴, G. Karapinar⁵⁵, M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁵⁶, O. Kaya⁵⁷, S. Ozkorucuklu⁵⁸, S. Tekten, E.A. Yetkin⁵⁹

Bogazici University, Istanbul, Turkey

M.N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen⁶⁰

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

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

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. Newbold⁶¹, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁶², 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

Rutherford Appleton Laboratory, Didcot, 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. Nash⁶³, A. Nikitenko⁷, 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. Virdee¹⁵, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

R. Bartek, A. Dominguez

Catholic University of America, Washington, DC, USA

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

The University of Alabama, Tuscaloosa, 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

Boston University, Boston, USA

G. Benelli, B. Burkle, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶⁴, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir⁶⁵, R. Syarif, E. Usai, D. Yu

Brown University, Providence, 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, Davis, Davis, 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, Los Angeles, 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, Riverside, Riverside, 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, San Diego, La Jolla, 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

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

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, 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

Cornell University, Ithaca, 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-Navarro⁶⁶, 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

Fermi National Accelerator Laboratory, Batavia, 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

University of Florida, Gainesville, USA

Y.R. Joshi, S. Linn

Florida International University, Miami, 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 State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, M. Saunders, F. Yumiceva

Florida Institute of Technology, Melbourne, 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

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

M. Alhusseini, B. Bilki ⁶⁷, W. Clarida, K. Dilsiz ⁶⁸, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul ⁶⁹, Y. Onel, F. Ozok ⁷⁰, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

The University of Iowa, Iowa City, 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

Johns Hopkins University, Baltimore, 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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, 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

University of Maryland, College Park, 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

Massachusetts Institute of Technology, Cambridge, 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 Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, 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

University of Nebraska-Lincoln, Lincoln, USA

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁶, M. Planer, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, 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

The Ohio State University, Columbus, 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

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, 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, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, 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

Rice University, Houston, 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

University of Rochester, Rochester, 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

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

H. Acharya, A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

University of Tennessee, Knoxville, USA

O. Bouhali⁷¹, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷², S. Luo, D. Marley, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

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

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, 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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, I. De Bruyn, L. Dodd, B. Gomber⁷³, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W.H. Smith, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.

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

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

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

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

⁵ Also at 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 Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.

²² Also at Institute of Physics, Bhubaneswar, India.

²³ Also at Shoolini University, Solan, India.

²⁴ Also at University of Visva-Bharati, Santiniketan, India.

²⁵ Also at Isfahan University of Technology, Isfahan, Iran.

²⁶ Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

²⁷ Also at ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT, Bologna, Italy.

²⁸ Also at Università degli Studi di Siena, Siena, Italy.

²⁹ Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.

³⁰ Also at Kyunghee University, Seoul, Republic of Korea.

³¹ Also at Riga Technical University, Riga, Latvia.

³² Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.

³³ Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

³⁴ Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.

³⁵ Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

³⁶ Also at Institute for Nuclear Research, Moscow, Russia.

³⁷ Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.

³⁸ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

³⁹ Also at University of Florida, Gainesville, USA.

⁴⁰ Also at P.N. Lebedev Physical Institute, Moscow, Russia.

⁴¹ Also at California Institute of Technology, Pasadena, USA.

⁴² Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.

⁴³ Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.

⁴⁴ Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

⁴⁵ Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy.

⁴⁶ Also at National and Kapodistrian University of Athens, Athens, Greece.

⁴⁷ Also at Universität Zürich, Zurich, Switzerland.

⁴⁸ Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.

⁴⁹ Also at Adiyaman University, Adiyaman, Turkey.

⁵⁰ Also at Istanbul Aydin University, Istanbul, Turkey.

⁵¹ Also at Mersin University, Mersin, Turkey.

⁵² Also at Piri Reis University, Istanbul, Turkey.

- 53 Also at Gaziosmanpasa University, Tokat, Turkey.
- 54 Also at Ozyegin University, Istanbul, Turkey.
- 55 Also at Izmir Institute of Technology, Izmir, Turkey.
- 56 Also at Marmara University, Istanbul, Turkey.
- 57 Also at Kafkas University, Kars, Turkey.
- 58 Also at Istanbul University, Faculty of Science, Istanbul, Turkey.
- 59 Also at Istanbul Bilgi University, Istanbul, Turkey.
- 60 Also at Hacettepe University, Ankara, Turkey.
- 61 Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- 62 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- 63 Also at Monash University, Faculty of Science, Clayton, Australia.
- 64 Also at Bethel University, St. Paul, USA.
- 65 Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- 66 Also at Purdue University, West Lafayette, USA.
- 67 Also at Beykent University, Istanbul, Turkey.
- 68 Also at Bingol University, Bingol, Turkey.
- 69 Also at Sinop University, Sinop, Turkey.
- 70 Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- 71 Also at Texas A&M University at Qatar, Doha, Qatar.
- 72 Also at Kyungpook National University, Daegu, Republic of Korea.
- 73 Also at University of Hyderabad, Hyderabad, India.