EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

Search for beyond the standard model Higgs bosons bearch for beyond the standard moder ringgs bosons
decaying into a $b\overline{b}$ pair in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration[∗](#page-0-0)

Abstract

A search for Higgs bosons that decay into a bottom quark-antiquark pair and are accompanied by at least one additional bottom quark is performed with the CMS detector. The data analyzed were recorded in proton-proton collisions at a centre-of- α detector. The data analyzed were recorded in proton-proton collisions at a centre-oi-
mass energy of $\sqrt{s} = 13$ TeV at the LHC, corresponding to an integrated luminosity of 35.7 fb⁻¹. The final state considered in this analysis is particularly sensitive to signatures of a Higgs sector beyond the standard model, as predicted in the generic class of two Higgs doublet models (2HDMs). No signal above the standard model background expectation is observed. Stringent upper limits on the cross section times branching fraction are set for Higgs bosons with masses up to 1300 GeV. The results are interpreted within several MSSM and 2HDM scenarios.

Published in the Journal of High Energy Physics as [doi:10.1007/JHEP08\(2018\)113.](http://dx.doi.org/10.1007/JHEP08(2018)113)

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[∗]See Appendix [C](#page-26-0) for the list of collaboration members

1 Introduction

In the standard model (SM), a Higgs boson at a mass of 125 GeV has a large coupling to b quarks via Yukawa interactions. Its production in association with b quarks and subsequent decay into b quarks at the CERN LHC is, however, difficult to detect because of the high rate of heavy-flavour multijet production. There are, nevertheless, models beyond the SM that predict an enhancement of Higgs boson production in association with b quarks, which motivate the search for such processes.

Prominent examples of models beyond the SM are the two Higgs doublet model (2HDM) [\[1\]](#page-17-0), which contains two scalar Higgs doublets, as well as one particular realization within the minimal supersymmetric extension of the SM (MSSM) [\[2\]](#page-17-1). These result in two charged Higgs bosons, H^{\pm} and three neutral ones, jointly denoted as ϕ . Among the latter are, under the assumption that *CP* is conserved, one *CP*-odd (A), and two *CP*-even (h, H) states, where h usually denotes the lighter *CP*-even state. For the purpose of this analysis, the boson discovered in 2012 with a mass near 125 GeV [\[3–](#page-17-2)[6\]](#page-17-3) is interpreted as h, whose mass is thus constrained to the measured value. The two heavier neutral states, H and A, are the subject of the search presented here.

In the 2HDM, flavour changing neutral currents at tree level can be suppressed by introducing discrete symmetries, which restrict the choice of Higgs doublets to which the fermions can couple. This leads to four types of models with natural flavour conservation at tree level:

- **type-I**: all charged fermions couple to the same doublet;
- **type-II**: up-type quarks (u, c, t) couple to one doublet, down-type fermions (d, s, b, e, μ , τ) couple to the other. This structure is also implemented in the MSSM;
- **lepton-specific**: all charged leptons couple to one doublet, all quarks couple to the other;
- **flipped**: charged leptons and up-type quarks couple to one doublet, down-type quarks to the other.

While until now the type-I and -II models have been most intensively tested, the flipped model is remarkably unexplored from the experimental side. The $A/H \rightarrow bb$ decay mode is ideally suited to constrain this model due to the large branching fraction of the Higgs boson into b quarks.

The *CP*-conserving 2HDMs have seven free parameters. They can be chosen as the Higgs boson masses (m_h , m_H , m_A , $m_{H^{\pm}}$), the mixing angle between the *CP*-even Higgs bosons (α), the ratio of the vacuum expectation values of the two doublets (tan $\beta = v_2/v_1$), and the parameter that potentially mixes the two Higgs doublets (m_{12}) . For $\cos(\beta - \alpha) \rightarrow 0$, the light *CP*-even Higgs boson (h) obtains properties indistinguishable from the SM Higgs boson with the same mass in all four types of models listed above [\[1\]](#page-17-0).

The MSSM Higgs sector has the structure of a type-II 2HDM. The additional constraints given by the fermion-boson symmetry fix all mass relations between the Higgs bosons and the angle *α* at tree level, reducing the number of parameters at this level to only two. These parameters are commonly chosen as the mass of the pseudoscalar Higgs boson, m_A , and tan β. After the Higgs boson discovery at the LHC, MSSM benchmark scenarios have been refined to match the experimental data and to reveal characteristic features of certain regions of the parameter space [\[7,](#page-17-4) [8\]](#page-17-5). Considered in this analysis are the $m_h^{\text{mod}+}$, the hMSSM [\[9\]](#page-17-6), the light stau ($\tilde{\tau}$), and the light stan ($\tilde{\tau}$) consrige [7] the light stop \tilde{t}) scenarios [\[7\]](#page-17-4).

The $m_h^{\text{mod+}}$ scenario is a modification of the m_h^{max} scenario, which was originally defined to give conservative exclusion bounds on tan β in the LEP Higgs boson searches [\[10–](#page-18-0)[12\]](#page-18-1). It has been modified such that the mass of the lightest *CP*-even state, *m*h, is compatible with the mass of the observed boson within ± 3 GeV [\[13,](#page-18-2) [14\]](#page-18-3) in a large fraction of the considered parameter space [\[7\]](#page-17-4). The hMSSM approach [\[9,](#page-17-6) [15,](#page-18-4) [16\]](#page-18-5) describes the MSSM Higgs sector in terms of just m_A and tan *β*, given the experimental knowledge of *m*_Z and *m*_h. It defines a largely model-independent scenario, because the predictions for the properties of the MSSM Higgs bosons do not depend on the details of the supersymmetric sector [\[17\]](#page-18-6). Further variations of the supersymmetric sector are implemented in the light $\tilde{\tau}$ and light \tilde{t} scenarios [\[7\]](#page-17-4), which are also designed such that the light scalar h is compatible with the measured Higgs boson mass [\[18\]](#page-18-7).

For tan β values larger than one, the couplings of the Higgs fields to b quarks are enhanced both in the flipped and the type-II models, and thus also in the MSSM. Furthermore, there is an approximate mass degeneracy between the A and H bosons in the MSSM for the studied range of m_A . For the 2HDM scenarios considered in this paper, such a degeneracy will be imposed. These effects enhance the combined cross section for producing these Higgs bosons in association with b quarks by a factor of up to 2 tan² β with respect to the SM. The decay $A/H \rightarrow b\overline{b}$ is expected to have a high branching fraction, even at large values of the Higgs boson mass and $|\cos(\beta - \alpha)|$ [\[19\]](#page-18-8).

The most stringent constraints on the MSSM parameter tan *β* so far, with exclusion limits in the range 4–60 in the mass interval of 90–1600 GeV, have been obtained in measurements at the LHC in the $\phi \to \tau \tau$ decay mode [\[20](#page-18-9)[–25\]](#page-19-0). Preceding limits have been obtained by the LEP [\[10\]](#page-18-0) and the Tevatron experiments [\[26–](#page-19-1)[28\]](#page-19-2). The $\phi \to \mu\mu$ decay mode has been investigated as well [\[21,](#page-18-10) [29,](#page-19-3) [30\]](#page-19-4).

In the $\phi \rightarrow b\overline{b}$ decay mode, searches have initially been performed at LEP [\[10\]](#page-18-0) and by the CDF and D0 Collaborations [\[31\]](#page-19-5) at the Tevatron collider. At the LHC, the only analyses in this channel with associated b jets have also been performed by the CMS Collaboration using the 7 and 8 TeV data [\[32,](#page-19-6) [33\]](#page-19-7). In the absence of any signal, limits on the pp \rightarrow b $\phi(\rightarrow b\overline{b}) + X$ cross section have been derived in the 90–900 GeV mass range. The combined 7 and 8 TeV data analyses translate into upper bounds on tan *β* between 14 and 50 in the Higgs boson mass range of 100–500 GeV, assuming the $m_h^{\text{mod}+}$ scenario of the MSSM.

The ATLAS and CMS Collaborations have performed extensive 2HDM interpretations of measurements in different production and decay channels, in particular also in the A \rightarrow Zh, h \rightarrow bb decay mode [\[34](#page-19-8)[–36\]](#page-19-9). The ATLAS interpretation [\[35\]](#page-19-10) also covers the flipped scenario, and the 2HDM interpretations reported in this paper are compared to these.

With the proton-proton (pp) collision data set corresponding to an integrated luminosity of 35.7 fb^{−1} collected at a centre-of-mass energy of \sqrt{s} = 13 TeV in 2016, the sensitivity to key model parameters with respect to previous CMS searches is significantly extended. The analysis focuses on neutral Higgs bosons A and H with masses $m_{A/H} \geq 300$ GeV that are produced in association with at least one b quark and decay to $b\overline{b}$, as shown by the diagrams in Fig. [1.](#page-4-0) The signal signature therefore comprises final states characterized by at least three b quark jets ("b jets"), and the dominant background is multijet production. A fourth b jet is not explicitly required, since due to the process topology the majority of the signal events are found to have at most three b jets within the acceptance of this analysis. Events are selected by dedicated triggers that identify b jets already during data taking. This helps significantly to suppress the large rate of multijet production, while maintaining sensitivity to the signal process. The analysis searches for a peak in the invariant mass distribution, M_{12} , of the two b jets with the highest transverse momentum p_T values, which originate from the Higgs boson decay in about

66% of all cases at $m_{A/H} = 300$ GeV, increasing up to 75% for $m_{A/H} \ge 700$ GeV. The dominant background is the production of heavy-flavour multijet events containing either three b jets, or two b jets plus a third jet originating from either a charm quark, a light-flavour quark, or a gluon, which is misidentified as a b jet.

Figure 1: Example Feynman diagrams for the signal processes.

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 field volume, the inner tracker is formed by a silicon pixel and strip tracker. It measures charged particles within the pseudorapidity range $|\eta|$ < 2.5. The tracker provides a transverse impact parameter resolution of approximately 15 μ m and a resolution on p_T of about 1.5% for particles with $p_T = 100$ GeV. Also inside the field volume are a crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Forward calorimetry extends the coverage provided by the barrel and endcap detectors up to $|\eta|$ < 5. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke, in the range $|\eta|$ < 2.4, with detector planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching muons to tracks measured in the silicon tracker results in a p_T resolution between 1 and 10%, for p_T values up to 1 TeV. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [\[37\]](#page-20-0).

3 Event reconstruction and simulation

A particle-flow algorithm [\[38\]](#page-20-1) aims to reconstruct and identify all particles in the event, i.e. electrons, muons, photons, and charged and neutral hadrons, with an optimal combination of all CMS detector systems.

The reconstructed vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex. The physics objects chosen are those that have been defined using information from the tracking detector, including jets, the associated missing transverse momentum, which is taken as the negative vector sum of the p_T of those jets, and charged leptons.

Jets are clustered from the reconstructed particle-flow candidates using the anti- k_T algorithm [\[39,](#page-20-2) [40\]](#page-20-3) with a distance parameter of 0.4. Each jet is required to pass dedicated quality criteria to suppress the impact of instrumental noise and misreconstruction. Contributions from additional pp interactions within the same or neighbouring bunch crossing (pileup) affect the jet momentum measurement. To mitigate this effect, charged particles associated with other vertices than the reference primary vertex are discarded before jet reconstruction [\[41\]](#page-20-4), and residual contributions (e.g. from neutral particles) are accounted for using a jet-area based correction [\[42\]](#page-20-5). Subsequent jet energy corrections are derived from simulation, and are confirmed with in situ measurements of the energy balance in dijet, multijet, and Z/γ + jet events [\[43\]](#page-20-6).

For the offline identification of b jets, the combined secondary vertex (CSVv2) algorithm [\[44\]](#page-20-7) is used. This algorithm combines information on track impact parameters and secondary vertices within a jet into an artificial neural network classifier that provides separation between b jets and jets of other flavours.

Simulated samples of signal and background events were produced using different event generators and include pileup events. The MSSM Higgs boson signal samples, $pp \rightarrow b\overline{b}\phi + X$ with $\phi \rightarrow$ bb, were produced at leading order (LO) in the 4-flavour scheme with PYTHIA 8.212 [\[45\]](#page-20-8). Comparing this prediction to computationally expensive next-to-leading order (NLO) calculations [\[46\]](#page-20-9) generated using MADGRAPH5 aMC@NLO in version 2.3.0 [\[47,](#page-20-10) [48\]](#page-20-11), we find a very good agreement in the shapes of the leading dijet invariant mass distribution, *M*12, while the selection efficiency is up to 10% lower when using the NLO prediction. We correct the NLO effect by applying mass-dependent correction factors to the LO signal samples and assign a corresponding systematic uncertainty in the final results. Multijet background events from quantum chromodynamics (QCD) processes have been simulated with the MADGRAPH5 aMC@NLO event generator [\[49,](#page-20-12) [50\]](#page-20-13) using the 5-flavour scheme and MLM merging [\[51\]](#page-20-14); they are used for studying qualitative features but not for a quantitative background prediction. The NNPDF 3.0 [\[52\]](#page-20-15) parton distribution functions (PDFs) are used in all generated samples. For all generators, fragmentation, hadronization, and the underlying event have been modelled using PYTHIA with tune CUETP8M1 [\[53\]](#page-21-0). The response of the CMS detector is modelled with the GEANT4 toolkit [\[54\]](#page-21-1).

4 Trigger and event selection

A major challenge to this search is posed by the huge hadronic interaction rate at the LHC. This is addressed with a dedicated trigger scheme [\[55\]](#page-21-2), especially designed to suppress the multijet background. Only events with at least two jets in the range of $|\eta| \leq 2.4$ are selected. The two leading jets are required to have $p_T > 100 \text{ GeV}$, and an event is accepted only if the absolute value of the difference in pseudorapidity, $\Delta \eta$, between any two jets fulfilling the p_T and *η* requirements, is less than or equal to 1.6. The tight online requirements on the opening angles between jets are introduced to reduce the trigger rates, while preserving high efficiency in the probed mass range of the Higgs bosons. At trigger level, b jets are identified using the CSVv2 algorithm with slightly tighter requirements than for the offline analysis. At least two jets in the event must satisfy the online b tagging criteria.

The efficiency of the jet p_T requirements in the trigger is derived from data collected with prescaled single-jet triggers with lower threshold. The efficiency in data and simulation is measured as a function of jet p_T and η . The differences between the two are corrected for in the analysis of the simulated samples. The online b tagging efficiencies relative to the offline b tagging selection are obtained from data using prescaled dijet triggers with a single b-tag requirement. A tag-and-probe method is employed to determine the efficiency as a function of p_T and η of the jets. Both leading jets are required to pass offline selection criteria including b tagging requirements similar to the final event selection described below. The second-leading b jet must always pass the online b tagging requirement to ensure that it has fired the trigger. The fraction of the first leading b jets that also satisfy the online b tagging requirements is a direct measure of the relative online b tagging efficiency. Relative efficiencies are found to range from above 80% for $p_T \approx 100$ GeV to around 50% for $p_T \approx 900$ GeV, averaged over η .

The offline selection requires at least two jets with $p_T > 100$ GeV and another one with $p_T > 100$ 40 GeV, which all need to satisfy |*η*| ≤ 2.2. The *η* selection is applied to benefit from optimal b tagging performance. The three leading jets have to pass the CSVv2 b tagging requirement of the medium working point [\[44\]](#page-20-7). This working point features a 1% probability for light-flavour jets (attributed to u, d, s, or g partons) to be misidentified as b jets, and has a b jet identification efficiency of about 70%. The separation between the two leading jets in *η* has to be less than 1.55, and a minimal pairwise separation of ∆*R* > 1 between each two of the three leading jets is imposed to suppress background from $b\overline{b}$ pairs arising from gluon splitting. This sample is referred to as "triple b tag" sample in the following.

5 Signal modeling

A signal template for the M_{12} distribution is obtained for each Higgs boson mass considered by applying the full selection to the corresponding simulated signal data set, for nominal masses in the range of 300–1300 GeV. The sensitivity of this analysis does not extend down to cross sections as low as that of the SM Higgs boson. Thus, a signal model with a single mass peak is sufficient. This is in contrast to the $\phi \to \tau\tau$ analysis [\[25\]](#page-19-0), where the signal model comprises the three neutral Higgs bosons of the MSSM, one of which is SM-like.

The signal efficiency for each Higgs boson mass point is obtained from simulation and shown in Fig. [2.](#page-6-0) A scale factor for the efficiency of the kinematic trigger selection has been derived with data from control triggers, as described in Section [4,](#page-5-0) and is applied as a weight for each event. Correction factors to account for the different b tagging efficiencies in data and simulation [\[44\]](#page-20-7) are also applied. The total signal efficiency ranges between 0.5 and 1.4% and peaks around 500 GeV. The efficiency first increases due to the kinematic selection and then decreases for masses beyond 500 GeV due to the requirement of three b-tagged jets, and the fact that the b tagging efficiency decreases at high jet p_T .

Figure 2: Signal efficiency as a function of the Higgs boson mass after different stages of event selection.

For nominal masses between 300 and 500 GeV, each signal shape is parameterized by a bifurcated Gaussian function, which has different widths on the right- and left-hand side of the peak position, continued at higher masses with an exponential function to describe the tail. The function has five parameters. The signal of the 600 GeV mass point requires one additional Gaussian function on each side of the peak position to be able to describe the tails of the distribution. This function has nine parameters in total. For nominal masses in the range 700–1300 GeV, a Bukin function as defined in Appendix [A,](#page-23-0) which has five parameters, is used. All parameterizations provide a very good modelling of the M_{12} spectra.

Figure 3: Invariant mass distributions of the two leading b jets in simulated signal events and their parameterizations for three different A/H masses, normalized to unity.

The distributions of the invariant mass of the two leading b jets, *M*12, of the signal templates and parameterizations of the probability density function for different Higgs boson masses are shown in Fig. [3.](#page-7-0) The natural width expected for an MSSM Higgs boson in the considered mass and tan *β* region is negligible compared to the detector resolution. For example, in the $m_h^{\text{mod}+}$ scenario at a mass of 600 GeV and tan $\beta = 60$, the natural width of the mass peak is found to be only about 19% of the full width at half maximum of the reconstructed mass distribution. The shape of the mass distribution is thus dominated by the experimental resolution, and the possibility of the two leading jets used to compute *M*¹² not being the daughters of the Higgs boson, which we refer to as wrong jet pairing. Pronounced tails towards lower masses are attributed to cases of incomplete reconstruction of the Higgs daughter partons, for example due to the missing momentum of neutrinos in semileptonic decays of hadrons containing bottom and charm quarks. The wrong jet pairing gives rise to tails in both directions. For the lower mass points, however, the tails towards lower masses are suppressed because of the jet p_T threshold.

6 Background model

The main background for this analysis originates from multijet production, with at least two energetic jets containing b hadrons, and a third jet that satisfies the b tagging selection but possibly as a result of a mistag. Top quark-antiquark production exhibits a shape very similar to the multijet process. It is found to be negligible, but nevertheless is implicitly covered by our background model.

The relevant features of the multijet background are studied in a suitable control region (CR) in data, which is obtained from the triple b tag selection by imposing a b-tag veto on the third leading jet. This veto rejects jets that would satisfy a loose b tagging requirement, defined by a 10% probability for light-flavour jets to be misidentified as b jets, and has a b jet identification efficiency of about 80%. This CR has no overlaps with the triple b tag signal region (SR), while it preserves similar kinematic distributions for the three leading jets. In addition, the signal contamination in the CR is negligible.

A suitably chosen analytic function is used to model the multijet background. This function is extensively validated in the b tag veto CR. In order to improve the background description and reduce the potential bias related to the choice of the background model, the *M*¹² distribution is divided into the three overlapping subranges [200, 650], [350, 1190], and [500, 1700] GeV. Their borders are chosen to largely cover the signal shapes of the associated mass points of [300, 500], [500, 1100], and [1100, 1300] GeV, respectively (as discussed in Section [5\)](#page-6-1).

In the first subrange, the selection criteria introduce a kinematic edge (turn-on) in the *M*¹² distribution. The chosen function is a product of two terms. The first term is a turn-on function, represented by a Gaussian error function in the form of:

$$
f(M_{12}) = 0.5 \left[erf(p_0[M_{12} - p_1]) + 1 \right], \tag{1}
$$

where

$$
erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt,
$$
\n(2)

and the parameters p_0 and p_1 describe the slope and point of the turn-on, respectively.

The falling part of the spectrum is described by an extension of the Novosibirsk function originally used to describe a Compton spectrum [\[56\]](#page-21-3), defined as:

$$
g(M_{12}) = p_2 \exp\left(-\frac{1}{2\sigma_0^2} \ln^2[1 - \frac{M_{12} - p_3}{p_4} p_5 - \frac{(M_{12} - p_3)^2}{p_4} p_5 p_6] - \frac{\sigma_0^2}{2}\right),\tag{3}
$$

where p_2 is a normalization parameter, p_3 the peak value of the distribution, p_4 and p_5 are the parameters describing the asymmetry of the spectrum, and p_6 is the parameter of the extended term. The variable σ_0 is defined as:

$$
\sigma_0 = \frac{2}{\xi} \sinh^{-1}(p_5 \xi/2), \text{ where } \xi = 2\sqrt{\ln 4}.
$$
 (4)

In the second and third subranges, we choose a nonextended Novosibirsk function ($p_6 \equiv 0$) without turn-on factor.

Figure [4](#page-9-0) shows the fits of the chosen functions to the CR data, which have been prescaled to give similar event count as in the SR. In the first subrange, $M_{12} = [200, 650]$ GeV, the turnon effect due to the jet p_T threshold at trigger level is clearly visible. In the other two mass subranges, the spectrum shows only the expected falling behaviour with *M*12. The values of the parameters p_0 and p_1 used to model the turn-on obtained in the CR are also used for the SR fit since the turn-on behaviour in the two regions is found to be very similar. The other function parameters are allowed to vary independently in the CR and SR fits.

Different families of alternative probability density functions such as Bernstein polynomials and the so-called dijet function as defined in Ref. [\[57\]](#page-21-4) are studied to estimate the possible bias from the choice of the background model. For each family, a systematic bias on the extraction of a signal with mass $m_{A/H}$ is determined: the alternative function is fit to the observed data, from which toy experiments are drawn. Using the nominal background model in the respective

subrange, a maximum-likelihood fit of signal and background is performed for each pseudoexperiment. The difference in the extracted and injected number of signal events is divided by the statistical uncertainty of the fit. The resulting pull distribution is considered to represent the systematic bias on the signal strength due to the choice of the background function and our insufficient knowledge of the background processes. We infer a bias of 100, 20, and 25% in units of the statistical uncertainty of the signal strength for the first, second, and third subranges, respectively.

Figure 4: Distributions of the dijet invariant mass *M*12, obtained from the b tag veto CR as described in the text in the three subranges used for the fit: $M_{12} = [200, 650]$ GeV (upper left) in linear scale, $M_{12} = [350, 1190]$ GeV (upper right) and $M_{12} = [500, 1700]$ GeV (lower) in logarithmic scale. The dots represent the data. The full line is the result of the fit of the background parameterizations described in the text. In the bottom panel of each plot, the normalized difparameterizations described in the
ference [(Data-Fit)/√Fit] is shown.

7 Systematic uncertainties

The following systematic uncertainties in the expected signal and background estimation affect the determination of the signal yield or its interpretation within the MSSM or generic 2HDM models.

The signal yields are affected by the following uncertainties:

- a 2.5% uncertainty in the estimated integrated luminosity of the data sample [\[58\]](#page-21-5);
- the uncertainty in the online b tagging efficiency scale factor, which results in an overall uncertainty in the range of 0.8–1.3% for Higgs boson masses of 300–1300 GeV;
- a 5% uncertainty in the correction of the selection efficiency comparing to the NLO prediction;
- the effect due to the choice of PDFs and the value of α_s (1–6%), following the recommendations of the LHC Higgs Cross Section Working Group [\[59\]](#page-21-6) when interpreting the results in benchmark models;
- the uncertainty in the normalization and factorization scales (1–10%) when interpreting the results in benchmark models.

Uncertainties affecting the shape as well as the normalization of the signal templates are:

- the uncertainty in the jet trigger efficiencies, ranging between subpercent values and 7% per jet depending on its η and p_T ;
- the uncertainty in the offline b tagging efficiency (2–5% per jet depending on its transverse momentum) and the mistag scale factors $(<0.3\%)$;
- the jet energy scale (JES) and jet energy resolution (JER) uncertainties $(1-6%)$: their impact is estimated by varying the JES and JER in the simulation within the measured uncertainties;
- the uncertainty in the total inelastic cross section of 4.6% assumed in the pileup simulation procedure [\[60\]](#page-21-7).

For the background estimation, the bias on the extracted signal strength, as reported in Section [6,](#page-7-1) is considered as an additional bias term to the background fitting function. This poses the largest uncertainty for the analysis.

8 Results

The number of potential signal events is extracted by performing a maximum-likelihood fit of the signal plus background parameterizations to the *M*¹² data distribution. Initially, a fit with only the background parameterizations is performed. Results of this background-only fit in all three subranges are given in Fig. [5.](#page-11-0) A good description of the data is observed. The normalized differences between data and fit together with the post-fit uncertainties are shown for each subrange.

In a second step, a combined fit of signal and background to the data is performed. No significant excess over the background-only distribution is observed and upper limits at 95% confidence level (CL) on the cross section times branching fraction σ (pp \rightarrow bA/H + X) $\mathcal{B}(A/H \rightarrow b\bar{b})$ are derived. For the calculation of exclusion limits, the modified frequentist criterion CL^s [\[61–](#page-21-8)[63\]](#page-21-9) is adopted using the ROOSTATS package [\[64\]](#page-21-10). The test statistic is based on the profile likelihood ratio. Systematic uncertainties are treated as nuisance parameters and profiled in the statistical interpretation using log-normal priors for

Figure 5: Distribution of the dijet invariant mass *M*¹² in the data triple b tag sample showing the three subranges together with the corresponding background-only fits. The shaded area shows the post-fit uncertainty. For illustration, the expected signal contribution for three representative mass points is shown, scaled to cross sections suitable for visualization. The change of slope around 350 GeV of the 300 GeV signal shape is caused by wrong jet pairing. In the bottom panels the normalized difference ((Data-Bkg)/ $\sqrt{\mathrm{Bkg}}$), where Bkg is the background as estimated by the fit, for the three subranges is shown.

uncertainties affecting the signal yield, while Gaussian priors are used for shape uncertainties.

Model-independent upper cross section times branching fraction limits are shown as a function of the mass of the A/H bosons in Fig. [6](#page-12-0) up to a mass of 1300 GeV. The visible steps in the expected and observed limits at 500 and 1100 GeV are due to the transitions between the mass subranges as explained in Section [6.](#page-7-1) The limits range from about 20 pb at 300 GeV, to about 0.4 pb at 1100 GeV. The limits are also summarized in Table [1](#page-23-1) in Appendix [B.](#page-23-2)

Figure 6: Expected and observed upper limits on $\sigma(pp \to bA/H + X) \mathcal{B}(A/H \to bb)$ at 95% CL as a function of the Higgs boson mass $m_{A/H}$. The inner and the outer bands indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The dashed horizontal lines illustrate the borders between the three subranges in which the results have been obtained.

8.1 Interpretation within the MSSM

The cross section limits shown in Fig. [6](#page-12-0) are translated into exclusion limits on the MSSM parameters tan β and m_A . The cross sections for $b + A/H$ associated production as obtained with the four-flavour NLO [\[65,](#page-21-11) [66\]](#page-21-12) and the five-flavour NNLO QCD calculations implemented in BBH@NNLO [\[67\]](#page-22-0) were combined using the Santander matching scheme [\[68\]](#page-22-1). The branching fractions were computed with FEYNHIGGS version 2.12.0 [\[13,](#page-18-2) [69–](#page-22-2)[71\]](#page-22-3) and HDECAY [\[72,](#page-22-4) [73\]](#page-22-5) as described in Ref. [\[19\]](#page-18-8).

The observed and expected 95% CL median upper limits on tan β versus m_A are shown in Fig. [7](#page-14-0) (upper row). They were computed within the MSSM $m_h^{\text{mod}+}$ $h_{\rm h}^{\rm moa+}$ benchmark scenario [\[8\]](#page-17-5) with the higgsino mass parameter $\mu = +200$ GeV and in the hMSSM scenario [\[9,](#page-17-6) [15,](#page-18-4) [16\]](#page-18-5). In the former scenario, the observed upper limits range from tan β of about 25 at $m_A = 300$ GeV to about 60 scenario, the observed upper limits range from tan *p* of about 25 at $m_A = 500$ GeV to about 60 at $m_A = 750$ GeV. These results considerably extend the preceding measurements at $\sqrt{s} = 7$

and 8 TeV [\[32,](#page-19-6) [33\]](#page-19-7). The model interpretation is not extended beyond tan β values of 60, as theoretical predictions are not considered reliable for much higher values. Additional model interpretations for m_A vs. tan β in the light $\tilde{\tau}$ and the light t benchmark scenarios are given in Fig. [7](#page-14-0) (lower), and in Tables [2–](#page-24-0)[5](#page-24-1) in Appendix [B.](#page-23-2)

8.2 Interpretation within the 2HDM

Cross sections and branching fractions for the bbH and bbA processes within different 2HDM models have been computed at NNLO using SUSHI version 1.6.1 [\[74\]](#page-22-6), 2HDMC version 1.7.0 [\[75\]](#page-22-7) and LHAPDF version 6.1.6 [\[76\]](#page-22-8). The 2HDM parameters have been set according to the "Scenario G" proposed in Ref. [\[77\]](#page-22-9). Specifically, the heavier Higgs bosons are assumed to be degenerate in mass ($m_A = m_H = m_{H^{\pm}}$), and the mixing term has been set to $m_{12}^2 = 0.5 m_A^2 \sin 2\beta$. The choice of such an MSSM-like parameterization allows using the same signal samples as for the MSSM analysis.

The results for the type-II and flipped models are displayed in Fig. [8](#page-15-0) as upper limits for tan *β* as a function of $cos(\beta - \alpha)$. Observed upper limits derived from the ATLAS A \rightarrow Zh analysis [\[24\]](#page-19-11) at a centre-of-mass energy of 13 TeV are shown as well. The results for the flipped model presented here provide competitive upper limits in the central region of $cos(\beta - \alpha)$ and strong unique constraints on tan *β*. Figure [9](#page-16-0) shows the upper limits for tan *β* as a function of $cos(\beta - \alpha)$ in the type-II and flipped models for $m_{A/H} = 500$ GeV.

9 Summary

A search for a heavy Higgs boson decaying into a bottom quark-antiquark pair and accompanied by at least one additional bottom quark has been performed. The data analyzed correspond to an integrated luminosity of 35.7 fb $^{-1}$, recorded in proton-proton collisions at a *cespond to an integrated funtifiestry of 33.7 to* θ , recorded in proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV at the LHC. For this purpose, dedicated triggers using all-hadronic jet signatures combined with online b tagging were developed. The signal is characterized by events with at least three b-tagged jets. The search has been performed in the invariant mass spectrum of the two leading jets that are also required to be b-tagged.

No evidence for a signal is found. Upper limits on the Higgs boson cross section times branching fraction are obtained in the mass region 300–1300 GeV at 95% confidence level. They range from about 20 pb at the lower end of the mass range, to about 0.4 pb at 1100 GeV, and extend to considerably higher masses than those accessible to previous analyses in this channel.

The results are interpreted within various benchmark scenarios of the minimal supersymmetric extension of the standard model (MSSM). They yield upper limits on the model parameter tan *β* as a function of the mass parameter m_A . The observed limit at 95% confidence level for tan β is as low as about 25 at the lowest m_A value of 300 GeV in the $m_h^{\text{mod+}}$ scenario with a higgsino mass parameter of $\mu = +200$ GeV. In the hMSSM, scenarios with tan β values above 22 to 60 for Higgs boson masses from 300 to 900 GeV are excluded at 95% confidence level. The results are also interpreted in the two Higgs doublet model (2HDM) type-II and flipped scenarios. In the flipped 2HDM scenario, similar upper limits on tan *β* as for the hMSSM are set over the full $\cos(\beta - \alpha)$ range and for Higgs boson masses from 300 to 850 GeV. The limits obtained for the flipped scenario provide competitive upper limits in the region around zero of $cos(\beta - \alpha)$ and provide strong unique constraints on tan *β*.

Figure 7: Expected and observed upper limits at 95% CL for m_A vs. the MSSM parameter $\tan \beta$ in the (upper left) $m_{\rm h}^{\rm mod+}$ $\mu_{\rm h}^{\rm mod+}$ benchmark scenario with $\mu = +200$ GeV, in the (upper right) hMSSM, the (lower left) light $\tilde{\tau}$, and the (lower right) light \tilde{t} benchmark scenarios. The inner and outer bands indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis. The excluded parameter space is indicated by the red shaded area. The hashed area is excluded because $m_{h,H}$ would deviate by more than ± 3 GeV from the mass of the observed Higgs boson at 125 GeV. Since theoretical calculations for tan $\beta > 60$ are not reliable, no limits are set beyond this value. To illustrate the improvement in sensitivity, the observed and expected upper limits from the preceding CMS miprovement in sensitivity, the observed and expected upper limits from the prece
analyses at $\sqrt{s} = 7$ and 8 TeV [\[32,](#page-19-6) [33\]](#page-19-7) are also shown as solid and dashed black lines.

Figure 8: Upper limits for the parameter tan *β* at 95% CL for the flipped (upper) and type-II (lower) models, as a function of $cos(\beta - \alpha)$ in the range of [-0.5, 0.5] for the mass $m_H = m_A$ = 300 GeV (left) and as a function of $m_{A/H}$ when $cos(\beta - \alpha) = 0.1$ (right). The observed limits from the ATLAS A \rightarrow Zh analysis [\[24\]](#page-19-11) at 95% CL, which are provided up to tan $\beta = 50$, are also shown as blue shaded area for comparison.

Figure 9: Upper limits for the parameter tan *β* at 95% confidence level for the flipped (left) and type-II (right) models as a function of $cos(\beta - \alpha)$ in the full range of $[-1.0, 1.0]$, for the mass $m_H = m_A = 500$ GeV. The inner and outer bands indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.

Acknowledgments

The authors would like to thank Stefan Liebler and Oscar Stål for their help with the interpretation of the results in the 2HDM models. 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: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, 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); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEP-Center, 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 a 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 NKFIA 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 Thalis 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).

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A Definition of Bukin function

The Bukin function as implemented in ROOT version 6.06/01 [\[78\]](#page-22-10) is defined as:

$$
f(M_{12}) = A_p \exp\left[-\ln 2 \frac{\ln^2\left(1 + \sqrt{2}\xi\sqrt{\xi^2 + 1} \frac{(M_{12} - x_p)}{\sqrt{\ln 2}\sigma_p}\right)}{\ln^2\left(1 + 2\xi(\xi - \sqrt{\xi^2 + 1})\right)}\right],
$$

\nif $x_1 < M_{12} < x_2$,
\n
$$
f(M_{12}) = A_p \exp\left[\pm \frac{\xi\sqrt{\xi^2 + 1}(M_{12} - x_i)\sqrt{2\ln 2}}{\sigma_p \ln(\sqrt{\xi^2 + 1} + \xi)\left(\sqrt{\xi^2 + 1} + \xi\right)^2} + \rho_i \left(\frac{M_{12} - x_i}{x_p - x_i}\right)^2 - \ln 2\right],
$$
\nif $M_{12} \le x_1$ or $M_{12} \ge x_2$, (6)

where $\rho_i = \rho_1$ and $x_i = x_1$ for $M_{12} \le x_1$, $\rho_i = \rho_2$ and $x_i = x_2$ when $M_{12} \ge x_2$, and:

$$
x_{1,2} = x_p + \sigma_p \sqrt{2 \ln 2} \left(\frac{\xi}{\sqrt{\xi + 1}} \mp 1 \right). \tag{7}
$$

The parameters x_p and σ_p are the peak position and width, respectively, and ζ is an asymmetry parameter.

B Exclusion limits

The model-independent 95% CL limits on $\sigma(pp \to bA/H + X) \mathcal{B}(A/H \to b\overline{b})$ are listed in Table [1](#page-23-1) for different Higgs boson masses $m_{A/H}$. The 95% CL limits of (tan *β*, m_A) are listed in Tables [2](#page-24-0) to [5](#page-24-1) for different MSSM benchmark scenarios.

Table 1: Expected and observed 95% CL upper limits on $\sigma(pp \to bA/H + X) \mathcal{B}(A/H \to b\overline{b})$ in pb as a function of $m_{A/H}$.

Mass [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Observed
300	10.8	14.3	19.7	27.5	36.5	19.1
350	6.3	8.4	11.7	16.3	21.7	14.0
400	3.6	4.8	6.7	9.2	12.3	5.7
500	1.7	2.2	3.1	4.4	5.9	1.9
600	$1.0\,$	1.4	1.9	2.7	3.7	2.1
700	0.7	0.9	1.3	1.8	2.4	1.5
900	0.4	0.6	0.8	1.2	1.6	0.9
1100	0.36	0.49	0.68	0.96	1.36	0.40
1300	0.36	0.48	0.68	0.96	1.31	0.50

Mass [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Observed
300	19.3	22.0	25.8	30.6	35.7	25.4
350	21.5	24.4	28.5	33.6	39.0	31.2
400	22.6	25.5	29.4	34.4	39.7	27.3
500	26.9	30.2	34.9	40.9	47.4	28.3
600	32.9	37.1	43.0	50.6	58.5	44.5
700	39.0	44.2	51.7			55.9
900	58.5					

Table 2: Expected and observed 95% CL upper limits on $\tan \beta$ as a function of m_A in the $m_h^{\text{mod+}}$, $\mu = +200$ GeV, benchmark scenario. Since theoretical predictions for tan $\beta > 60$ are not reliable, entries for which tan β would exceed this value are indicated by —.

Table 3: Expected and observed 95% CL upper limits on tan β as a function of m_A in the hMSSM benchmark scenario. Since theoretical predictions for tan *β* > 60 are not reliable, entries for which tan β would exceed this value are indicated by —.

Mass [GeV]	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Observed
300	16.8	19.3	22.6	26.7	30.9	22.3
350	17.5	20.2	23.8	28.2	32.5	26.1
400	17.6	20.3	23.8	28.1	32.4	21.9
500	19.6	22.6	26.7	31.6	36.9	20.9
600	23.6	27.2	32.1	38.0	44.3	33.2
700	27.9	32.2	38.0	45.1	52.4	41.2
900	42.8	49.4	58.4			

Table 4: Expected and observed 95% CL upper limits on tan β as a function of m_A in the light $\tilde{\tau}$ benchmark scenario. Since theoretical predictions for tan $\beta > 60$ are not reliable, entries for which tan β would exceed this value are indicated by —.

Mass [GeV]			-2σ -1σ Median			$+1\sigma$ $+2\sigma$ Observed
300	19.9	23.6	28.8	35.8	43.7	28.2
350	21.0	25.0	30.8	38.4	47.5	34.7
400	21.7	25.5	31.2	38.8	47.9	28.0
500	25.0	29.8	37.2	47.8		27.0
600	31.5	38.0	48.5			51.5
700	40.0	48.8				

Table 5: Expected and observed 95% CL upper limits on tan β as a function of m_A in the light t benchmark scenario. Since theoretical predictions for tan $\beta > 60$ are not reliable, entries for which tan β would exceed this value are indicated by —.

C The CMS Collaboration

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

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, 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, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Universit´e Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

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

Universit´e Catholique de Louvain, Louvain-la-Neuve, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

E. Belchior Batista Das Chagas, W. Carvalho, J. 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 Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

S. Ahuja^a, C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante*^b* , S.F. Novaes*^a* , SandraS. Padula*^a* , D. Romero Abad*^b*

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

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

University of Sofia, Sofia, Bulgaria

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

Beihang University, Beijing, China W. Fang⁵, X. Gao⁵, L. Yuan

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

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

Tsinghua University, Beijing, China Y. Wang

Universidad de Los Andes, Bogota, Colombia

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

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

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

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

Institute Rudjer Boskovic, Zagreb, Croatia V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov⁶, T. Susa

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

Charles University, Prague, Czech Republic M. Finger⁷, M. Finger Jr.⁷

Escuela Politecnica Nacional, Quito, Ecuador E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt H. Abdalla 8 , A.A. Abdelalim 9,10 , S. Khalil 10

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

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

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland T. Tuuva

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

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

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

A. Abdulsalam¹¹, C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Universit´e de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

J.-L. Agram¹², J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte¹², J.-C. Fontaine¹², D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

Universit´e de Lyon, Universit´e Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucl´eaire de Lyon, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹³, V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Georgian Technical University, Tbilisi, Georgia A. Khvedelidze⁷

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁷

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

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov¹³

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

A. Albert, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, A. Schmidt, D. Teyssier, S. Thuer ¨

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

G. Flügge, O. Hlushchenko, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, H. Sert, A. Stahl¹⁴

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras¹⁵, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁶, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krucker, ¨ W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann¹⁷, 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, M. Savitskyi, P. Saxena, P. Schutze, C. Schwanenberger, R. Shevchenko, A. Singh, ¨ N. Stefaniuk, H. Tholen, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, A. Benecke, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, 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, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

Karlsruher Institut fuer Technology

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁴, S.M. Heindl, U. Husemann, F. Kassel¹⁴, I. Katkov¹³, S. Kudella, H. Mildner, S. Mitra, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wohrmann, ¨ R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece

G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, N. Saoulidou, E. Tziaferi, K. Vellidis

National Technical University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece

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

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

M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Suranyi, G.I. Veres ´

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath¹⁸, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi†

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²⁰, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary M. Bartók¹⁹, P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri

National Institute of Science Education and Research, HBNI, Bhubaneswar, India S. Bahinipati²¹, P. Mal, K. Mandal, A. Nayak²², D.K. Sahoo²¹, S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, S. Sharma, J.B. Singh, G. Walia

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj²³, M. Bharti, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²³, D. Bhowmik, S. Dey, S. Dutt²³, S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, S. Thakur²³

Indian Institute of Technology Madras, Madras, India

P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India

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

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, B. Mahakud, G.B. Mohanty, N. Sur, B. Sutar, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁴, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar²⁴

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

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

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

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

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari *^a* **, Universit`a di Bari** *^b* **, Politecnico di Bari** *^c* **, Bari, Italy**

M. Abbrescia^{a,*b*}, C. Calabria^{a,*b*}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,*b*}, N. De Filippis^{a,c}, M. De Palma*a*,*^b* , A. Di Florio*a*,*^b* , F. Errico*a*,*^b* , L. Fiore*^a* , A. Gelmi*a*,*^b* , G. Iaselli*a*,*^c* , 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,14}, R. Venditti^a, P. Verwilligen*^a* , G. Zito*^a*

INFN Sezione di Bologna *^a* **, Universit`a di Bologna** *^b* **, Bologna, Italy**

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b},

L. Brigliadori^{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}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta*^a* , A.M. Rossi*a*,*^b* , T. Rovelli*a*,*^b* , G.P. Siroli*a*,*^b* , N. Tosi*^a*

INFN Sezione di Catania *^a* **, Universit`a di Catania** *^b* **, Catania, Italy** S. Albergo*a*,*^b* , A. Di Mattia*^a* , R. Potenza*a*,*^b* , A. Tricomi*a*,*^b* , C. Tuve*a*,*^b*

INFN Sezione di Firenze *^a* **, Universit`a di Firenze** *^b* **, Firenze, Italy**

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, G. Latino, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,27}, G. Sguazzoni^a, D. Strom^a, L. Viliani*^a*

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁴

INFN Sezione di Genova *^a* **, Universit`a di Genova** *^b* **, Genova, Italy** F. Ferro*^a* , F. Ravera*a*,*^b* , E. Robutti*^a* , S. Tosi*a*,*^b*

INFN Sezione di Milano-Bicocca *^a* **, Universit`a di Milano-Bicocca** *^b* **, Milano, Italy**

A. Benaglia^a, A. Beschi^b, L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,14}, S. Di Guida^{a,d,14}, 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, R.A. Manzoni^{a,b}, A. Massironi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini*^a* , S. Ragazzi*a*,*^b* , T. Tabarelli de Fatis*a*,*^b*

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

S. Buontempo^a, N. Cavallo^{a,c}, A. Di Crescenzo^{a,b}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, G. Galati^{a,b}, A.O.M. Iorio^{a,*b*}, W.A. Khan^a, L. Lista^a, S. Meola^{a,d,14}, P. Paolucci^{a,14}, C. Sciacca^{a,*b*}, E. Voevodina*a*,*^b*

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

P. Azzi^a, N. Bacchetta^a, M. Bellato^a, L. Benato^{a,b}, 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, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, P. Lujan, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, N. Pozzobon*a*,*^b* , P. Ronchese*a*,*^b* , R. Rossin*a*,*^b* , F. Simonetto*a*,*^b* , A. Tiko, E. Torassa*^a* , M. Zanetti*a*,*^b* , P. Zotto*a*,*^b*

INFN Sezione di Pavia *^a* **, Universit`a di Pavia** *^b* **, Pavia, Italy**

A. Braghieri^a, A. Magnani^a, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b}, C. Riccardi^{a,b}, P. Salvini*^a* , I. Vai*a*,*^b* , P. Vitulo*a*,*^b*

INFN Sezione di Perugia *^a* **, Universit`a di Perugia** *^b* **, Perugia, Italy**

L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,*b*}, E. Manoni^a, G. Mantovani^{a,*b*}, V. Mariani^{a,*b*}, M. Menichelli^a, A. Rossi^{a,*b*}, A. Santocchia*a*,*^b* , D. Spiga*^a*

INFN Sezione di Pisa *^a* **, Universit`a di Pisa** *^b* **, Scuola Normale Superiore di Pisa** *^c* **, Pisa, Italy** K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, L. Bianchini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, 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}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli*a*,*^b* , A. Venturi*^a* , P.G. Verdini*^a*

INFN Sezione di Roma *^a* **, Sapienza Universit`a di Roma** *^b* **, Rome, Italy**

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, N. Daci^a, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, S. Gelli*a*,*^b* , E. Longo*a*,*^b* , B. Marzocchi*a*,*^b* , P. Meridiani*^a* , G. Organtini*a*,*^b* , F. Pandolfi*^a* , R. Paramatti*a*,*^b* , F. Preiato*a*,*^b* , S. Rahatlou*a*,*^b* , C. Rovelli*^a* , F. Santanastasio*a*,*^b*

INFN Sezione di Torino *^a* **, Universit`a di Torino** *^b* **, Torino, Italy, Universit`a del Piemonte Orientale** *^c* **, Novara, Italy**

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, 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* , K. Shchelina*a*,*^b* , V. Sola*^a* , A. Solano*a*,*^b* , A. Staiano*^a*

INFN Sezione di Trieste *^a* **, Universit`a di Trieste** *^b* **, Trieste, Italy**

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

Kyungpook National University

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

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

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

Hanyang University, Seoul, Korea J. Goh, T.J. Kim

Korea University, Seoul, Korea

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

Sejong University, Seoul, Korea H. Kim

Seoul National University, Seoul, Korea

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

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

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

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

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

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali²⁸, F. Mohamad Idris²⁹, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

M.C. Duran-Osuna, H. Castilla-Valdez, E. De La Cruz-Burelo, G. Ramirez-Sanchez, I. Heredia-De La Cruz³⁰, R.I. Rabadan-Trejo, R. Lopez-Fernandez, J. Mejia Guisao, R Reyes-Almanza, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

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

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

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

University of Auckland, Auckland, New Zealand D. Krofcheck

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

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

A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland K. Bunkowski, A. Byszuk³¹, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadruccio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

V. Alexakhin, A. Golunov, I. Golutvin, N. Gorbounov, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev^{32,33}, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim³⁴, E. Kuznetsova³⁵, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev, A. Bylinkin³³

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

R. Chistov³⁶, M. Danilov³⁶, P. Parygin, D. Philippov, S. Polikarpov³⁶, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³³, I. Dremin³³, M. Kirakosyan³³, S.V. Rusakov, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin³⁷, L. Dudko, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov³⁸, T. Dimova³⁸, L. Kardapoltsev³⁸, D. Shtol³⁸, Y. Skovpen³⁸

State Research Center of Russian Federation, Institute for High Energy Physics of NRC 'Kurchatov Institute', Protvino, Russia

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

National Research Tomsk Polytechnic University, Tomsk, Russia A. Babaev

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

P. Adzic39, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

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

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

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

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

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita⁴⁰, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁷, J. Kieseler, V. Knünz, A. Kornmayer,

M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴¹, F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, F. Pantaleo¹⁴, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, G. Rolandi⁴², M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴³, A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsirou, V. Veckalns⁴⁴, M. Verweij, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl[†], L. Caminada⁴⁵, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

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

M. Backhaus, L. Bani, P. Berger, B. Casal, N. Chernyavskaya, G. Dissertori, M. Dittmar, ¨ M. Donega, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Lustermann, ` M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Quittnat, M. Reichmann, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴⁶, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

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

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

C¸ ukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

A. Bat, F. Boran, S. Cerci⁴⁷, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos⁴⁸, E.E. Kangal⁴⁹, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵⁰, S. Ozturk⁵¹, D. Sunar Cerci⁴⁷, B. Tali⁴⁷, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey B. Isildak⁵², G. Karapinar⁵³, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁵⁴, O. Kaya⁵⁵, S. Tekten, E.A. Yetkin⁵⁶

Istanbul Technical University, Istanbul, Turkey M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen⁵⁷

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

B. Grynyov

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

University of Bristol, Bristol, United Kingdom

T. Alexander, F. Ball, L. Beck, 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. Newbold⁵⁸, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁵⁹, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom

G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash⁶⁰, A. Nikitenko⁶, V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee¹⁴, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. Mcmaster, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

D. Arcaro, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA

G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶¹, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir⁶², R. Syarif, D. Yu

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli,

E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, San Diego, La Jolla, USA

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶³, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Bornheim, J. Bunn, J.M. Lawhorn, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

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

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], 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, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro⁶⁴, 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, A. Whitbeck

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, M. Carver, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, J. Wang, S. Wang

Florida International University, Miami, USA

Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

Florida Institute of Technology, Melbourne, USA

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

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

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA

M. Alhusseini, B. Bilki⁶⁵, W. Clarida, K. Dilsiz⁶⁶, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁶⁷, Y. Onel, F. Ozok⁶⁸, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

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

Northeastern University, Boston, USA

G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³², M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA

S. Cooperstein, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroue, J. Salfeld-Nebgen, ´ D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

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

Purdue University Northwest, Hammond, USA

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

University of Rochester, Rochester, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, R. Taus, M. Verzetti

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

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

A.G. Delannoy, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA

O. Bouhali⁶⁹, A. Castaneda Hernandez⁶⁹, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷⁰, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Pernie, D. Rathjens, A. Safonov, A. Tatarinov `

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

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

University of Wisconsin - Madison, Madison, WI, USA

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

†: Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at IRFU, CEA, Universite 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 Institute for Theoretical and Experimental Physics, Moscow, Russia
- 7: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 8: Also at Cairo University, Cairo, Egypt
- 9: Also at Helwan University, Cairo, Egypt
- 10: Now at Zewail City of Science and Technology, Zewail, Egypt
- 11: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
- 12: Also at Université de Haute Alsace, Mulhouse, France

13: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

14: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

15: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

- 16: Also at University of Hamburg, Hamburg, Germany
- 17: Also at Brandenburg University of Technology, Cottbus, Germany
- 18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

- 20: Also at Institute of Physics, University of Debrecen, 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 Universita degli Studi di Siena, Siena, Italy `
- 28: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 29: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 30: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 31: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 32: Also at Institute for Nuclear Research, Moscow, Russia
- 33: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 34: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 35: Also at University of Florida, Gainesville, USA
- 36: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 37: Also at California Institute of Technology, Pasadena, USA
- 38: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 39: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 40: Also at INFN Sezione di Pavia *^a* , Universita di Pavia ` *b* , Pavia, Italy

41: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

- 42: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 43: Also at National and Kapodistrian University of Athens, Athens, Greece
- 44: Also at Riga Technical University, Riga, Latvia
- 45: Also at Universität Zürich, Zurich, Switzerland
- 46: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 47: Also at Adiyaman University, Adiyaman, Turkey
- 48: Also at Istanbul Aydin University, Istanbul, Turkey
- 49: Also at Mersin University, Mersin, Turkey
- 50: Also at Piri Reis University, Istanbul, Turkey
- 51: Also at Gaziosmanpasa University, Tokat, Turkey
- 52: Also at Ozyegin University, Istanbul, Turkey
- 53: Also at Izmir Institute of Technology, Izmir, Turkey
- 54: Also at Marmara University, Istanbul, Turkey
- 55: Also at Kafkas University, Kars, Turkey
- 56: Also at Istanbul Bilgi University, Istanbul, Turkey
- 57: Also at Hacettepe University, Ankara, Turkey
- 58: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 59: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 60: Also at Monash University, Faculty of Science, Clayton, Australia
- 61: Also at Bethel University, St. Paul, USA
- 62: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 63: Also at Utah Valley University, Orem, USA
- 64: Also at Purdue University, West Lafayette, USA
- 65: Also at Beykent University, Istanbul, Turkey
- 66: Also at Bingol University, Bingol, Turkey
- 67: Also at Sinop University, Sinop, Turkey
- 68: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 69: Also at Texas A&M University at Qatar, Doha, Qatar

70: Also at Kyungpook National University, Daegu, Korea