Search for neutral MSSM Higgs bosons decaying into a pair of bottom quarks

The CMS collaboration

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

ABSTRACT: A search for neutral Higgs bosons decaying into a $b\bar{b}$ quark pair and produced in association with at least one additional $b$ quark is presented. This signature is sensitive to the Higgs sector of the minimal supersymmetric standard model (MSSM) with large values of the parameter $\tan\beta$. The analysis is based on data from proton-proton collisions at a center-of-mass energy of 8 TeV collected with the CMS detector at the LHC, corresponding to an integrated luminosity of 19.7 fb$^{-1}$. The results are combined with a previous analysis based on 7 TeV data. No signal is observed. Stringent upper limits on the cross section times branching fraction are derived for Higgs bosons with masses up to 900 GeV, and the results are interpreted within different MSSM benchmark scenarios, $m_{h_{\text{max}}}$, $m_{h_{\text{mod}^+}}$, $m_{h_{\text{mod}^-}}$, light-stau and light-stop. Observed 95% confidence level upper limits on $\tan\beta$, ranging from 14 to 50, are obtained in the $m_{h_{\text{mod}^+}}$ benchmark scenario.

KEYWORDS: Supersymmetry, Hadron-Hadron Scattering, Beyond Standard Model, Higgs physics

ArXiv ePrint: 1506.08329
Contents

1 Introduction
2 The CMS detector
3 Event reconstruction and simulation
4 Trigger and event selection
5 Background model
6 Signal modeling
  6.1 Signal templates
  6.2 Signal efficiency
  6.3 Fitting procedure
7 Systematic uncertainties
8 Results
  8.1 Background-only fit
  8.2 Combined fit of signal and background templates
  8.3 Upper limits on cross sections times branching fractions
  8.4 Interpretation within the MSSM
9 Summary
A Signal efficiency
B Exclusion limits

The CMS collaboration

1 Introduction

The discovery of a Higgs boson with a mass around 125 GeV [1–3] marked a milestone for elementary particle physics. While the measured properties of the observed boson are in agreement with the expectations of the standard model (SM) with the current experimental precision, this particle could well be the first visible member of an extended Higgs sector, which would be a direct indication of new physics. Extended Higgs sectors are possible in various theoretical models, such as Supersymmetry [4–7], which relates fermionic and bosonic degrees of freedom and in consequence requires the introduction of additional Higgs
bosons as well as a superpartner to each SM particle. The superpartners provide potential dark-matter candidates [8], and their contribution to quantum-loop corrections can lead to a unification of the gauge couplings at higher energies [9]. Moreover, the problem of the quadratic divergence of the Higgs boson mass at high energies [10] is solved naturally through cancellation of loop terms by the superpartners.

The minimal supersymmetric extension of the SM (MSSM) [5] contains two scalar Higgs doublets, which result in two charged Higgs bosons, $H^\pm$, and three neutral ones, jointly denoted as $\phi$. Among the latter are two CP-even ($h, H$) and one CP-odd state ($A$). The recently discovered boson with a mass near 125 GeV might then be interpreted as one of the neutral CP-even states. Two parameters, generally chosen as the mass of the pseudoscalar Higgs boson $m_A$ and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan \beta = v_2/v_1$, define the properties of the Higgs sector in the MSSM at tree level. For $\tan \beta$ values larger than one, the couplings of the Higgs field to down-type fermions are enhanced relative to those to the up-type fermions. Furthermore, the $A$ boson is nearly degenerate in mass with either the $h$ or $H$ boson. These effects enhance the combined cross section for producing these Higgs bosons in association with b quarks by a factor of $\approx 2 \tan^2 \beta$. The decay $\phi \to b\bar{b}$ is expected to have a high branching fraction ($\approx 90\%$), even at large values of the Higgs boson mass [11].

Measurements at the CERN LHC in the $\phi \to \tau\tau$ decay mode [12–15] have lead to the most stringent constraints on $\tan \beta$ so far, with exclusion limits in the range $4–60$ in the mass interval of $90–1000$ GeV. Preceding limits had been obtained by the LEP [16] and Tevatron experiments [17–19]. Also the $\phi \to \mu\mu$ decay mode has been investigated [13, 20]. Besides extending the MSSM Higgs boson search to an independent channel, the $\phi \to b\bar{b}$ decay mode is particularly sensitive to the higgsino mass parameter $\mu$ [21], and thus to the bottom quark Yukawa coupling. In the $\phi \to \tau\tau$ channel, the sensitivity to $\mu$ is much smaller due to a partial cancellation of the respective radiative corrections between the contributions to the production and decay processes [21]. Beyond the MSSM interpretation, lepton-specific two-Higgs-doublet models (2HDM) [22] may allow for enhanced couplings of down-type quarks relative to leptons. The $b\bar{b}$ decay mode is also relevant in the more general context of exotic resonance searches, motivated for example by dark-matter models involving mediator particles with a large coupling to b quarks [23, 24].

Searches in the $\phi \to b\bar{b}$ decay mode have initially been performed at LEP [16] and by the CDF and D0 experiments [25] at the Tevatron collider. The first and so far the only analysis at the LHC in this channel has been performed by the CMS experiment, using the 7 TeV data, and set significantly more stringent bounds in the mass range $90–350$ GeV [26].

In this article, the CMS search is extended by adding the data set comprising 19.7 fb$^{-1}$ of proton-proton collision data, collected at a center-of-mass energy of 8 TeV, and by the use of a refined methodology. The higher integrated luminosity as well as the greater center-of-mass energy allow extension of the search up to a mass of 900 GeV.

The search is performed for neutral MSSM Higgs bosons $\phi$ with masses $m_\phi \geq 100$ GeV that are produced in association with at least one b quark and decay to $b\bar{b}$; an illustration of the signal process is given by the diagrams in figure 1. The signal is thus searched for in final states characterized by at least three b-tagged jets. No requirement of a fourth b-tagged
jet is made, since its kinematic distributions extend significantly beyond the available acceptance, and the resulting signal efficiency would be very low. Events are selected by specialized triggers that identify b jets already at the online level. This is important to suppress the large rate of multijet production at the LHC. The analysis searches for a peak in the invariant mass distribution of the two b jets with the highest $p_T$ values, which are assumed to originate from the Higgs boson decay. The dominant background is the production of heavy-flavor multijet events containing either three b jets, or two b jets plus a third jet originating from either a charm quark, a light-flavor quark or a gluon, which is misidentified as a b quark jet. For the final limits, the results of the 8 TeV analysis are combined with the previous 7 TeV analysis \cite{26}.

2 The CMS detector

The central feature of the CMS detector 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 $\mu$m and a resolution on $p_T$ of about 1.5% for 100 GeV particles. Also inside the field volume are a crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke, in the pseudorapidity 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 5%, for $p_T$ values up to 1 TeV. Forward calorimetry extends the coverage provided by the barrel and endcap detectors up to $|\eta| < 5$. 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. \cite{27}.

3 Event reconstruction and simulation

A particle-flow algorithm \cite{28,29} is used to reconstruct and identify all particles in the event, i.e. electrons, muons, photons, charged hadrons, and neutral hadrons, with an optimal combination of all CMS detectors systems.
The reconstructed primary vertex with the largest $p_T^2$-sum of its associated tracks is chosen as the vertex of the hard interaction and used as reference for the other physics objects.

Jets are clustered from the reconstructed particle candidates using the anti-$k_T$ algorithm [30] with a distance parameter of $R = 0.5$, and each jet is required to pass dedicated quality criteria to suppress the impact of instrumental noise and misreconstruction. Contributions from additional proton-proton interactions within the same 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 in the jet reconstruction, and residual contributions (e.g. from neutral particles) are accounted for using a jet-area based correction [31]. Jets originating entirely from pileup interactions are identified and rejected based on vertex and jet-shape information [32]. Jet energy corrections are derived from simulation, and are confirmed with in situ measurements of the energy balance in dijet and $Z/\gamma+\text{jet}$ events [33].

For the offline identification of $b$ jets, the combined secondary vertex (CSV) algorithm [34] is used. This algorithm combines information on track impact parameters and secondary vertices within a jet in a single likelihood discriminant that provides a good separation between $b$ jets and jets of other flavors. Secondary-vertex reconstruction is performed with an inclusive vertex search amongst the tracks associated with a jet [35].

Simulated samples of signal and background events, also referred to as Monte Carlo (MC) samples, were produced using the pythia [36] and MadGraph [37] event generators and include pileup events. The response of the CMS detector is modeled with Geant4 [38]. The MSSM Higgs signal samples, $p p \to b\bar{b}\phi+X$ with $\phi \to b\bar{b}$, were produced at leading order in the 4-flavor scheme with PYTHIA version 6.4.12. The $p_T$ and $\eta$ distributions of the leading associated $b$ jet are in good agreement with the next-to-leading order (NLO) calculations [39]. The multijet background from quantum chromodynamics (QCD) processes has been produced with PYTHIA, while for $t\bar{t} + \text{jets}$ events the MadGraph event generator was used in its version 5.1.5.11. For all generators, fragmentation, hadronization, and the underlying event have been modeled using PYTHIA with tune $Z2^*$. The most recent PYTHIA 6 $Z2^*$ tune is derived from the Z1 tune [40], which uses the CTEQ5L parton distribution functions (PDF) set, whereas $Z2^*$ adopts the CTEQ6L [41] PDF set.

4 Trigger and event selection

A major challenge to this analysis is posed by the huge hadronic interaction rate at the LHC, and it is addressed with a dedicated trigger scheme, designed especially to suppress the QCD multijet background. Only events with at least two jets in the pseudorapidity range of $|\eta| \leq 1.74$ are selected. The leading jet (here and in the following the jets are ordered by decreasing $p_T$) is required to have $p_T > 80 \text{ GeV}$, while the subleading jet must have $p_T > 70 \text{ GeV}$. Furthermore, the event is only accepted if the absolute value of the difference in pseudorapidity between any two jets fulfilling the $p_T$ and $\eta$ requirements is less than or equal to 1.74. The tight online requirements on the angular variables of the jets are introduced to reduce the trigger rates while preserving the signal significances in the probed mass range of
the Higgs bosons. At the trigger level, b jets are identified using an algorithm that requires at least two tracks with high 3D impact parameter significance to be associated with the jet. At least two jets within the event must meet the online b tagging criteria to be accepted by the trigger. The efficiency of the jet-$p_T$ requirements in the trigger are derived from the data with zero-bias triggered events. The online b tagging efficiencies relative to the offline b tagging selection are obtained from simulations of QCD events generated with PYTHIA and scaled to account for the different b tagging efficiencies between data and simulation. The total trigger efficiency for events satisfying the offline selection requirements detailed below ranges from 46–62% over the Higgs boson mass range of 100–900 GeV.

The offline selection requires events to have the two leading jets within $|\eta| \leq 1.65$ to be fully within the pseudorapidity windows of the trigger, and the third leading jet within $|\eta| \leq 2.2$. The three leading jets must also pass $p_T$ thresholds of 80, 70 and 20 GeV, respectively. In addition, the two leading jets must have a pseudorapidity difference of $|\Delta\eta_{12}| \leq 1.4$, because the QCD multijet background increases significantly with respect to the expected signal with increasing $|\Delta\eta_{12}|$. A minimal pairwise separation of $\Delta R > 1$ between the three leading jets, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and azimuthal angle differences (in radians) between the two jets, is imposed to suppress background from b quark pairs arising from gluon splitting.

In the following, “triple-b-tag” and “double-b-tag” samples are introduced, which play crucial roles in the analysis. The triple-b-tag sample is the basis for the signal search. It is defined by requiring all three leading jets to satisfy a tight CSV b tagging selection requirement at a working point characterized by a misidentification probability for light-flavor jets (attributed to u, d, s, or g partons) of about 0.1% at an average jet $p_T$ of 80 GeV. The typical corresponding efficiency for b jets is about 50–60% in the central pseudorapidity region. The total number of events passing the trigger and offline selections is approximately 69 k.

The double-b-tag sample plays a key role in the estimation of the multijet background. In this selection, only two of the three leading jets must pass the tight CSV b tagging requirement. The total number of double-b-tag events remaining after the trigger and offline selections is about 2.4 M. While this definition does not explicitly exclude the triple-b-tag events, the potential signal contribution is negligible due to the size of the QCD multijet background in the double-b-tag sample, and a veto would lead to distortions in the background model described in section 5.

An additional flavor-sensitive quantity, the secondary vertex mass sum of a jet, $\Sigma M_{SV,j}$, is introduced to further improve the separation between jets of different flavor on top of the CSV b tagging requirement. It is defined as the sum of the invariant masses calculated from the tracks forming secondary vertices inside a jet, and thus provides additional separation power. The extension of the signal mass range compared to the previous 7 TeV analysis implies that the jets can have larger $p_T$, with the consequence that b-tagged jets from background events have a higher probability to contain two heavy flavor quarks instead of at most one. This can occur for example if a very energetic gluon splits into a pair of b or c quarks with a narrow opening angle. For this reason, b and c quark pairs merged into the same jet, labeled as “b2” and “c2”, respectively, are treated separately from the cases of unmerged b and c quarks, labeled “b1” and “c1”, respectively.
Table 1. Left: definition of the index $B_j$ according to the value of the secondary vertex mass sum of the jet. Right: definition of the values of the combined event $b$ tagging estimator $X_{123}$ for all combinations of the secondary vertex mass sum indices $B_1$, $B_2$, and $B_3$.

The subsequent analysis will use the secondary vertex mass information to categorize events and to build background templates. Therefore, the secondary vertex mass sums of the three leading jets are combined into a condensed event $b$ tagging estimator, $X_{123}$. The construction of this estimator is shown in table 1. Each selected jet $j$, where $j$ is the rank of the jet in order of decreasing $p_T$, is assigned an index $B_j$, which can take one of the four possible integer values from 0-3 according to its secondary vertex mass sum value, as shown in table 1 (left). For jets with no reconstructed secondary vertex, $B_j$ is also set to zero. The definition of these index regions is motivated by the population of the secondary vertex mass sum by the different jet flavors. From the three indices $B_1$, $B_2$, and $B_3$, a combined event $b$ tagging variable $X_{123}$ is constructed as shown in table 1 (right). By definition, the event $b$ tagging variable $X_{123}$ can assume nine possible values ranging from 0 to 8. The events are then categorized according to the value of $X_{123}$, with the rationale of having sufficient statistics in each bin. The signal is searched for in the two-dimensional spectrum formed by the invariant mass of the two leading jets, $M_{12}$, and the event $b$ tagging variable $X_{123}$.

5 Background model

The main background for this analysis originates from QCD multijet production, with at least two energetic jets actually containing $b$ hadrons, and a third jet that passes the $b$ tagging selection but possibly as a result of a mistag. Since this type of background cannot be accurately predicted by MC simulation, it is estimated from the data using control samples. The chosen method is similar to the one used in ref. [42]. The background is modeled by a combination of templates, which are constructed from the double-b-tag sample. Only the shape of these background templates is relevant, since the normalization will be determined by the fit to the data.

Three categories of events are distinguished in the double-b-tag sample, which are denoted as xbb, bxb and bbx depending on whether the jet with the highest, second-highest or third-highest $p_T$ is exempt from the $b$-tag requirement. In this notation the three jets are referred to in order of decreasing $p_T$.

From these three double-b-tag categories, background templates are constructed by weighting each untagged jet with the $b$ tagging probability according to its assumed flavor. In the template nomenclature, the convention is to indicate the assumed flavor with a
capital letter, and it can be one of the five options Q, C1, B1, C2, and B2, where Q refers to light quarks or gluons, while C1 and C2 refer to a jet with a single charm quark and a pair of charm quarks, respectively. Similarly, B1 and B2 refer to jets assumed to contain a single bottom quark and a pair of bottom quarks, respectively. The total number of templates is therefore 15. Each background template is a binned distribution in the two-dimensional space spanned by $M_{12}$, the dijet mass of the two leading jets, and the event $b$ tagging variable $X_{123}$. For the construction of each template, each event is weighted with the $b$ tagging probability corresponding to the assumed flavor of the untagged jet. This weight accounts for the effect of the $b$ tagging discriminant threshold. The $b$ tagging probability for each flavor is determined with simulated QCD multijet events, where the flavor selection is based on Monte Carlo truth information. Data/MC scale factors for the $b$ tagging efficiencies are applied where appropriate [34]. Since the $b$ tagging efficiency has a characteristic dependence on $p_T$ and $\eta$ for each flavor, the weighting results in different shapes of the $M_{12}$ distributions. The $X_{123}$ dimension of the templates is modeled in the following way: in a given $M_{12}$ bin, an event can contribute to different $X_{123}$ bins depending on the flavor of its jets and its kinematics. For the two $b$-tagged jets, the secondary vertex mass sum information is taken as measured. For the untagged jet, each of the four possible values of the secondary vertex mass sum index is taken into account with a weight according to the probability that a jet with given flavor, $p_T$ and $\eta$, will assume this value. These probabilities, parametrized as a function of the jet $p_T$ and $\eta$, were determined from simulated events, and validated in control data samples.

Two additional corrections are applied to the templates. The first correction addresses a contamination in the double-$b$-tag sample from non-$bb$ events at the level of a few percent. This contamination is estimated directly from the data using a negative $b$ tagging discriminator [34] constructed with a track counting algorithm based on the negative im-
impact parameter of the tracks, ordered from the most negative impact parameter significance upward. A second correction is required since the online b tagging patterns are different in the double- and the triple-b-tag samples. In double-b-tag events, the two online b tags usually coincide with the offline b tags, while in triple-b-tag events the online b tags can be assigned to any two-jet subset of the three leading jets. The correction is computed from simulated QCD multijet events, and is applied in the form of additional weights to the events in the double-b-tag sample.

Similarity in shape between some templates leads to unnecessary redundancy. For this reason, similar templates are combined using a $\chi^2$-based metric to guide the decisions. The relative weights in a combination are taken from MC. In the cases where one of the two leading jets is untagged, and the flavor assumption is the same, e.g. Qbb, and bQb, the templates are combined, resulting in a merged template $(Q,b)b = Qbb + bQb$. By analogy, also (C1,b)b, (B1,b)b, (C2,b)b, and (B2,b)b are obtained. The resulting set of ten templates still shows many similarities. For this reason, (B1,b)b, (B2,b)b, and (C2,b)b are combined into a single template; bbB1, bbB2, and bbC2 into a second; and bbC1 and bbQ into a third. The total number of templates to be fitted in combination to the data is thus reduced to five, namely (B2+B1+C2)b, (C1,b)b, (Q,b)b, bb(B2+B1+C2), and bb(C1+Q). The projections of the $M_{12}$ and $X_{123}$ variables are shown in figure 2 for these five background templates.

Beyond QCD multijet production, top-quark pair ($t\bar{t}$) events pose the largest potential background to the signal topology. The requirement of three b-tagged jets reduces this background substantially, since only two highly energetic b-tagged jets are expected from the decays of the top quarks. However, one of the W bosons can decay into a c\bar{s} pair, and the c jet can be mistagged as b jet. Using the $t\bar{t}$ Monte Carlo sample, the $t\bar{t}$ contribution is found to be relatively small; the number of $t\bar{t}$ events passing the selections of the double- and triple-b-tag datasets it estimated to be about a factor of 70 smaller than the total amount of data in these samples. The invariant mass spectrum from $t\bar{t}$ is very similar to the one from the QCD multijet background, and does not show any narrow peaks. Since the $t\bar{t}$ events contribute to the double-b-tag sample, they are also taken into account in the background model.

6 Signal modeling

6.1 Signal templates

A signal template is obtained for each MSSM Higgs boson mass considered by applying the full selection to the corresponding simulated signal data set, for nominal masses in the range of 100–900 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, in contrast to the $\phi \to \tau\tau$ analysis [14], where the signal model comprises the three neutral Higgs bosons of the MSSM, one of which is SM-like. The projections for the $M_{12}$ and $X_{123}$ distributions of the signal templates for three different Higgs boson masses are shown in figure 3. The shape of the mass distribution is dominated by the experimental resolution and the combinatorial background. The natural width expected for a MSSM
Higgs boson in the considered mass and tan $\beta$ region is negligible in comparison with the detector resolution. At a mass of 500 GeV and $\tan \beta = 50$, for example, the natural width of the mass peak is found to be 13 GeV, which is only $\approx 14\%$ of the RMS of the reconstructed mass distribution. The $X_{123}$ distributions show little variation with the MSSM Higgs boson mass; they reflect the triple-b-quark signature.

### 6.2 Signal efficiency

The signal efficiency for each MSSM Higgs mass point is obtained from the simulated data sets. The efficiency of the kinematic trigger selection has been derived with data from control triggers and is applied by weighting. Scale factors to account for the different $b$ tagging efficiencies in data and MC [34] are also applied. The efficiency ranges between 0.17 and 6.38 per mille and peaks around 300 GeV. The detailed mass dependence is shown in appendix A. The decrease of the efficiency for masses beyond 300 GeV is due to the degradation of the $b$ tagging efficiency at high jet $p_T$. For masses around 300 GeV the kinematic selections give rise to an efficiency of approximately 0.12, which is reduced to approximately 0.0065 when triple $b$ tagging is required.

### 6.3 Fitting procedure

The overall two-dimensional distribution in the variables $M_{12}$ and $X_{123}$ is fitted by a model combining the background templates and optionally a signal template. A binned likelihood technique is used. The relative contribution of each template is determined by the fit. The systematic uncertainties are represented by nuisance parameters that are varied in the fit according to their probability density functions.
Table 2. Systematic uncertainties and their relative impact on the expected limit. The values represent an average over the mass range from 100–900 GeV, except for the template statistical and the offline b tagging (bc) uncertainties, where ranges are given.

7 Systematic uncertainties

The following systematic uncertainties in the expected signal and background estimates affect the determination of the signal yield and/or its interpretation within the MSSM.

Uncertainties in the yields of the signal contributions include the uncertainty in the luminosity estimate [43], the statistical uncertainties in the signal MC samples, and the uncertainties of the relative online b tagging corrections. Also taken into account are the QCD renormalization and factorization scale ($\mu_r, \mu_f$) uncertainties, the uncertainties due to the parton distribution functions (PDF) and the strong coupling constant $\alpha_s$, and the uncertainties in the underlying event and parton shower modeling, which all only affect the translation of the signal cross section into $\tan \beta$ in the MSSM interpretation. The impact of these uncertainties on the signal acceptance is not significant.

The rate as well as the shape of the signal contributions are also affected by the uncertainties in the trigger efficiencies, the jet energy scale, the jet energy resolution, and the pileup modeling, as well as the scale factors for the b-tag efficiency, the mistag rate, and the secondary vertex mass scale. The last three also affect the shapes of the background templates (recall that only the shape is relevant for the background templates). The statistical uncertainty in the template shape, due to the limited size of the double-b-tag sample and due to the uncertainty in the offline b-tag efficiencies and mistag rates, are propagated into the templates and accounted for in the fitting procedure. Additional systematic uncertainties in the shapes of the background-templates arise from the impurity of the double-b-tag sample and the online b tag correction to the templates. The sources and types of systematic uncertainties and their impact on the expected limit are summarized in table 2.
Figure 4. Projections of the dijet mass $M_{12}$ (left) and event b-tag variable $X_{123}$ (right) in the triple-b-tag sample, together with the corresponding projections of the fitted background templates. The hatched area shows the total bin-by-bin background uncertainty of the templates prior to the fit, which takes into account the limited size of the double-b-tag sample and the uncertainties of the offline b-tag efficiencies and mistag rates. For illustration, the signal contribution expected in the $m_{\phi}^{\text{max}}$ benchmark scenario of the MSSM with $m_A = 350$ GeV, $\tan \beta = 30$, and $\mu = +200$ GeV is overlayed, scaled by a factor 10 for better readability. In addition, the ratio of data to the background estimate is shown at the bottom.

8 Results

8.1 Background-only fit

In the first step, an unconstrained fit is performed without inclusion of a signal template, involving a linear combination of the background templates only. Results are shown in figure 4 and table 3. The template-based background model describes the data well within the uncertainty of the template fits with a goodness-of-fit of $\chi^2/N_{\text{dof}} = 207.9/209$, where $N_{\text{dof}}$ is the number of degrees of freedom, corresponding to a $p$-value of 0.51. As expected, the fit is dominated by templates involving triple b-jet signatures, whose fitted total contributions amount to $\approx 82\%$.

8.2 Combined fit of signal and background templates

In the second step, a signal template is included together with the background templates in the fit, with the relative fractions of signal and background templates allowed to vary freely. The fit is performed for all considered Higgs boson masses from 100 to 900 GeV. None of the fits shows any significant signal excess. Results for a Higgs boson mass of 350 GeV are shown in figure 5 and table 3. At this mass point, the highest fluctuation in the fitted Higgs boson production cross section is observed, corresponding to a local significance of approximately 1.5 standard deviations. The goodness-of-fit is $\chi^2/N_{\text{dof}} = 205.2/208$, corresponding to a $p$-value of 0.54.
Figure 5. Results from the combined fit of signal and background templates in the triple-b-tag sample, at the 350 GeV mass point. The left plot shows the projections of the dijet mass $M_{12}$, the right plot the projections of the event b-tag variable $X_{123}$. The red graph represents the fitted Higgs signal contribution. The hatched area shows the total bin-by-bin background uncertainty of the templates prior to the fit, which takes into account the limited size of the double-b-tag sample and the uncertainties of the offline b-tag efficiencies and mistag rates. In addition, the ratio of data to the background estimate is shown at the bottom.

| Template                  | Background-only fit fraction [%] | Signal+background fit fraction [%] |
|---------------------------|----------------------------------|-----------------------------------|
| (B2+B1+C2,b)b            | 51.3 ± 3.5                      | 49.5 ± 3.9                       |
| (C1,b)b                  | 1.3 ± 2.3                       | 1.7 ± 3.1                        |
| (Q,b)b                   | 1.2 ± 2.0                       | 1.1 ± 1.5                        |
| bb(B2+B1+C2)             | 31.2 ± 3.2                      | 32.2 ± 3.4                       |
| bb (C1+Q)                | 15.1 ± 0.9                      | 15.0 ± 0.9                       |
| $bb\phi(m = 350$ GeV)    | —                               | 0.5 ± 0.3                        |

Table 3. Relative contributions of the individual templates as determined by the background-only and by the signal+background fit for a Higgs boson mass hypothesis of 350 GeV.

8.3 Upper limits on cross sections times branching fractions

Cross sections are obtained from the fractions determined by the fit multiplied by the total number of data events after the selection in the signal region, and divided by the corresponding signal efficiencies (section 6.2) and the integrated luminosity of 19.7 fb$^{-1}$.

In the absence of any significant signal, the results are translated into upper limits on the cross section times the branching fraction, $\sigma(pp \to b\phi + X) B(\phi \to b\bar{b})$, of a generic Higgs-like state in the mass range 100–900 GeV. For calculations of exclusion limits, the modified frequentist construction $CL_s$ [44, 45] is adopted using the RooStats package [46].
The chosen test statistic, used to determine how signal- and background-like the data are, is based on the profile likelihood ratio. Systematic uncertainties are incorporated in the analysis via nuisance parameters and treated as pseudo-observables, following the frequentist paradigm. These uncertainties have been listed in section 7.

The observed and the median expected 95% confidence level (CL) limits as a function of the Higgs boson mass are shown in figure 6 and listed in table 5 in appendix B. The 1σ and 2σ bands of the test statistic, including systematic uncertainties, are also shown.

8.4 Interpretation within the MSSM

The cross section limits shown in figure 6 are further translated into exclusion limits on the MSSM parameters tan β and m_A. The cross sections obtained with the four-flavor NLO QCD calculation [47, 48] and the five-flavor NNLO QCD calculation as implemented in bbh@nnlo [49] for b + h/H/A associated production have been combined using the Santander matching scheme [50]. The branching fractions were computed with the FeynHiggs [51–54] and HDECAY [55, 56] programs as described in ref. [11].

The observed and expected 95% CL median upper limits on tan β versus m_A, together with the 1σ and 2σ bands, are shown in figure 7 (left). They have been computed within the traditional MSSM m^\text{max}_h benchmark scenario [57] with the higgsino mass parameter μ = +200 GeV. The observed upper limits range from tan β about 20 in the low-m_A region to about 50 at m_A = 500 GeV, and extend the existing measurement at 7 TeV [26] into the hitherto unexplored m_A region beyond 350 GeV. The model interpretation is not extended to higher masses above 500 GeV because the theoretical predictions are not reliable for tan β much higher than 60.

While the cross section limits obtained from the 2011 and 2012 data cannot be combined directly due to the different center-of-mass energies, such a combination is possible for the model-dependent interpretation. The resulting upper limits on tan β versus m_A ...
Figure 7. Expected and observed upper limits at 95% CL for the MSSM parameter \( \tan \beta \) versus \( m_A \) in the \( m_{\text{max}}^h \) benchmark scenario with \( \mu = +200 \text{ GeV} \). The excluded parameter space (observed limit) is indicated by the shaded area. Regions where the mass of neither of the CP-even MSSM Higgs bosons \( h \) or \( H \) is compatible with the discovered Higgs boson of 125 GeV within a range of \( 3 \text{ GeV} \) are marked by the hatched areas. The left plot shows the result obtained with the 8 TeV data only, the right plot shows the result obtained after a combination with the 7 TeV data. For comparison, the expected limit of the 7 TeV data analysis [26] is overlayed.

from both data periods are shown in figure 7 (right). While the sensitivity is significantly enhanced compared to the 7 TeV analysis [26] already up to 350 GeV, the addition of the 7 TeV result visibly improves the sensitivity in the low-mass area below 200 GeV. The observed limit for \( \tan \beta \) ranges down to about 14 at the lowest \( m_A \) value considered.

Association of one of the CP-even MSSM Higgs bosons \( h \) and \( H \) with the measured state at a mass of 125 GeV within a margin of \( \pm 3 \text{ GeV} \) that reflects the theoretical uncertainties [21] leads to an indirect constraint on \( \tan \beta \). The incompatible regions in the parameter space are illustrated by the hatched areas in both plots in figure 7. In the \( m_{\text{max}}^h \) scenario, the MSSM parameters beyond tree level have been tuned such that \( m_h \) becomes as large as possible. As a result, large \( m_A \) and already moderate values of \( \tan \beta \) lead to \( m_h \) values that are higher than the measured Higgs boson mass. This apparent exclusion of large \( \tan \beta \) values is, however, an artificial consequence of the assumptions in the \( m_{\text{max}}^h \) scenario. Recently, several new MSSM benchmark scenarios have been proposed, which are more naturally compatible with the observed Higgs boson at 125 GeV [21], and among them the \( m_{\text{mod}+}^h \), \( m_{\text{mod}^-}^h \), light-stop, and light-stau scenarios are also used in the following for the interpretation of the results of this analysis. The observed and expected 95% CL exclusion limits in these scenarios with \( \mu = +200 \text{ GeV} \), obtained with the combined 7 and 8 TeV data, are shown in figure 8. (The term “stop” refers to the supersymmetric partner of the top quark throughout this paper. Results for the \( \tau \)-phobic and low-\( m_H \) scenarios are not shown because the analysis has sensitivity in a limited mass region only.) The limits obtained in all MSSM benchmark scenarios are listed in tables 6 to 11 in appendix B.
The aforementioned sensitivity of the $\phi \to b\bar{b}$ channel to the higgsino mass parameter $\mu$ is evident in figure 9, where the limit in the $m_{h^{\text{mod}+}}$ scenario is compared for different values of $\mu$. The dependence is particularly pronounced at higher $m_A$; for example, the observed upper limit on $\tan \beta$ varies from 30 for $\mu = -500$ GeV to beyond 60 for $\mu = +500$ GeV for $m_A = 500$ GeV. The limits are also listed in table 12 in appendix B.

9 Summary

A search for a Higgs boson decaying into a pair of $b$ quarks and accompanied by at least one additional $b$ quark has been performed in proton-proton collisions at a center-of-mass energy of 8 TeV at the LHC, corresponding to an integrated luminosity of 19.7 fb$^{-1}$. The data were taken with dedicated triggers using all-hadronic jet signatures combined with online $b$ tagging. A selection of events with three $b$-tagged jets has been performed in the offline analysis. A signal has been searched for in the two-dimensional spectrum formed by the invariant mass of the two leading jets and a condensed event $b$-tag estimator.
Figure 9. Expected and observed upper limits at 95% CL for the MSSM parameter $\tan \beta$ versus $m_A$ for four different values of the higgsino mass parameter $\mu$ (left) and versus $\mu$ for three different values of $m_A$ (right) in the $m_h^{\text{mod+}}$ scenario.

No evidence for a signal is found. The observed distributions are well described by a background model constructed from events in which only two of the three leading jets are required to be $b$ tagged. Upper limits on the Higgs boson cross section times branching fraction are obtained in the mass region from 100–900 GeV, thus extending the search to considerably higher masses than those accessed by the previous 7 TeV analysis. The upper limits range from about 250 pb at the lower end of the mass range, to about 1 pb at 900 GeV.

The results are interpreted within the MSSM in the benchmark scenarios $m_{h^{\text{max}}}$, $m_h^{\text{mod+}}$, $m_h^{\text{mod-}}$, light-stau and light-stop, and lead to upper limits for the model parameter $\tan \beta$ as a function of the mass parameter $m_A$. In combination with the 7 TeV data, the observed limit for $\tan \beta$ ranges down to about 14 at the lowest $m_A$ value of 100 GeV in the $m_h^{\text{mod+}}$ scenario with a higgsino mass parameter of $\mu = +200$ GeV. The limit depends significantly on $\mu$, varying from $\tan \beta = 30$ for $\mu = -500$ GeV to beyond 60 for $\mu = +500$ GeV at $m_A = 500$ GeV.

Acknowledgments

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 centers 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); MoER, ERC IUT and
The total signal efficiency in per mille as a function of the Higgs boson mass $m_\phi$, for a center-of-mass energy of 8 TeV.

| $m_\phi$ [GeV] | Efficiency [per mille] |
|----------------|------------------------|
| 100            | 0.17                   |
| 140            | 0.57                   |
| 160            | 1.03                   |
| 200            | 2.85                   |
| 300            | 6.38                   |
| 350            | 6.32                   |
| 400            | 6.08                   |
| 500            | 5.07                   |
| 600            | 3.85                   |
| 700            | 2.90                   |
| 900            | 1.39                   |

Table 4. The total signal efficiency in per mille as a function of the Higgs boson mass $m_\phi$, for a center-of-mass energy of 8 TeV.

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (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 Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; and Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand).

A Signal efficiency

The signal efficiencies are summarized in table 4 and shown in figure 10 as a function of the Higgs boson mass.
Figure 10. The signal efficiency as a function of the Higgs boson mass $m_{\phi}$, for a center-of-mass energy of 8 TeV.

![Plot showing signal efficiency as a function of Higgs boson mass](image)

Table 5. Expected and observed 95% CL upper limits on $\sigma(pp \to b\phi + X) B(\phi \to b\bar{b})$ in pb as a function of $m_{\phi}$, where $\phi$ denotes a generic Higgs-like state, as obtained from the 8 TeV data.

| Mass [GeV] | $-2\sigma$ | $-1\sigma$ | Median | $+1\sigma$ | $+2\sigma$ | Observed |
|------------|------------|------------|--------|------------|------------|----------|
| 100        | 160.7      | 221.0      | 330.4  | 518.8      | 811.2      | 251.9    |
| 140        | 49.4       | 68.0       | 101.6  | 161.2      | 254.7      | 158.8    |
| 160        | 25.9       | 35.6       | 52.5   | 81.6       | 126.1      | 68.7     |
| 200        | 13.7       | 19.0       | 28.2   | 44.1       | 68.6       | 17.8     |
| 300        | 3.0        | 4.1        | 6.1    | 9.4        | 14.5       | 10.5     |
| 350        | 1.9        | 2.7        | 3.9    | 6.1        | 9.3        | 7.1      |
| 400        | 1.3        | 1.8        | 2.7    | 4.2        | 6.4        | 2.4      |
| 500        | 0.8        | 1.2        | 1.7    | 2.7        | 4.2        | 1.5      |
| 600        | 0.6        | 0.9        | 1.3    | 2.0        | 3.2        | 0.7      |
| 700        | 0.5        | 0.7        | 1.1    | 1.8        | 2.8        | 1.3      |
| 900        | 0.4        | 0.6        | 1.0    | 1.6        | 2.7        | 0.8      |

Table 5. Expected and observed 95% CL upper limits on $\sigma(pp \to b\phi + X) B(\phi \to b\bar{b})$ in pb as a function of $m_{\phi}$, where $\phi$ denotes a generic Higgs-like state, as obtained from the 8 TeV data.

### B Exclusion limits

The model-independent 95% CL limits on $\sigma(pp \to b\phi + X) B(\phi \to b\bar{b})$ are listed in table 5 for different Higgs boson masses $m_{\phi}$. The 95% CL limits of $(\tan \beta, m_A)$ are listed in tables 6 to 11 for different MSSM benchmark scenarios with $\mu = +200$ GeV and for different values of $\mu$ in the $m_{h}^{\text{mod+}}$ scenario in table 12.
| Mass [GeV] | $-2\sigma$ | $-1\sigma$ | Median | $+1\sigma$ | $+2\sigma$ | Observed |
|-----------|-----------|-----------|--------|-----------|-----------|----------|
| 100       | 14.4      | 17.4      | 22.0   | 29.3      | 39.4      | 18.8     |
| 140       | 15.5      | 18.4      | 22.9   | 30.1      | 40.1      | 29.4     |
| 160       | 13.6      | 16.2      | 20.2   | 26.4      | 34.9      | 23.5     |
| 200       | 15.2      | 18.1      | 22.8   | 29.9      | 40.0      | 17.7     |
| 300       | 18.0      | 21.0      | 25.9   | 33.4      | 43.9      | 34.9     |
| 350       | 21.8      | 25.4      | 31.0   | 39.7      | 52.2      | 42.6     |
| 400       | 25.1      | 29.3      | 36.0   | 46.2      | —         | 33.9     |
| 500       | 36.4      | 42.7      | 52.9   | —         | —         | 49.4     |

Table 6. Expected and observed 95% CL upper limits on $\tan \beta$ as a function of $m_A$ in the $m_h^{\text{max}}$, $\mu = +200\text{ GeV}$, benchmark scenario obtained from the 8 TeV data only.

| Mass [GeV] | $-2\sigma$ | $-1\sigma$ | Median | $+1\sigma$ | $+2\sigma$ | Observed |
|-----------|-----------|-----------|--------|-----------|-----------|----------|
| 100       | 13.1      | 15.6      | 19.4   | 24.6      | 31.2      | 13.9     |
| 140       | 13.8      | 16.1      | 19.5   | 24.2      | 29.8      | 22.3     |
| 160       | 12.3      | 14.5      | 17.6   | 22.0      | 27.2      | 17.8     |
| 200       | 13.2      | 15.5      | 18.8   | 23.3      | 28.5      | 14.5     |
| 300       | 17.3      | 20.1      | 24.4   | 30.5      | 38.5      | 33.5     |
| 350       | 21.1      | 24.5      | 29.6   | 36.9      | 46.4      | 36.5     |
| 400       | 25.1      | 29.3      | 36.0   | 46.2      | —         | 33.9     |
| 500       | 36.4      | 42.7      | 52.9   | —         | —         | 49.4     |

Table 7. Expected and observed 95% CL upper limits on $\tan \beta$ as a function of $m_A$ in the $m_h^{\text{max}}$, $\mu = +200\text{ GeV}$, benchmark scenario obtained from a combination of the 7 and 8 TeV data.

| Mass [GeV] | $-2\sigma$ | $-1\sigma$ | Median | $+1\sigma$ | $+2\sigma$ | Observed |
|-----------|-----------|-----------|--------|-----------|-----------|----------|
| 100       | 13.4      | 16.0      | 19.8   | 25.1      | 31.9      | 14.2     |
| 140       | 13.8      | 16.2      | 19.6   | 24.3      | 30.1      | 22.4     |
| 160       | 12.6      | 14.8      | 18.0   | 22.4      | 27.7      | 18.2     |
| 200       | 13.5      | 15.8      | 19.2   | 23.8      | 29.1      | 14.8     |
| 300       | 17.6      | 20.5      | 24.8   | 31.1      | 39.2      | 34.1     |
| 350       | 21.4      | 24.8      | 30.0   | 37.5      | 47.1      | 37.1     |
| 400       | 25.5      | 29.8      | 36.5   | 46.9      | —         | 34.4     |
| 500       | 36.8      | 43.2      | 53.5   | —         | —         | 50.0     |

Table 8. Expected and observed 95% CL upper limits on $\tan \beta$ as a function of $m_A$ in the $m_h^{\text{mod+}}$, $\mu = +200\text{ GeV}$, benchmark scenario obtained from a combination of the 7 and 8 TeV data.
| Mass [GeV] | $-2\sigma$ | $-1\sigma$ | Median | $+1\sigma$ | $+2\sigma$ | Observed |
|-----------|-----------|-----------|--------|-----------|-----------|----------|
| 100       | 12.7      | 15.0      | 18.3   | 22.8      | 28.3      | 13.4     |
| 140       | 13.1      | 15.2      | 18.1   | 22.2      | 26.9      | 20.6     |
| 160       | 11.9      | 13.9      | 16.7   | 20.5      | 24.9      | 16.9     |
| 200       | 12.8      | 14.9      | 17.9   | 21.7      | 26.1      | 13.9     |
| 300       | 16.5      | 18.9      | 22.6   | 27.7      | 33.9      | 30.1     |
| 350       | 19.8      | 22.7      | 26.9   | 32.7      | 39.7      | 32.4     |
| 400       | 23.2      | 26.7      | 32.0   | 39.7      | 49.7      | 30.4     |
| 500       | 32.3      | 37.1      | 44.4   | 55.1      | —         | 41.9     |

Table 9. Expected and observed 95% CL upper limits on $\tan \beta$ as a function of $m_A$ in the $m_{h^0}^{m_{A}}$, $\mu = +200$ GeV, benchmark scenario obtained from a combination of the 7 and 8 TeV data.

| Mass [GeV] | $-2\sigma$ | $-1\sigma$ | Median | $+1\sigma$ | $+2\sigma$ | Observed |
|-----------|-----------|-----------|--------|-----------|-----------|----------|
| 100       | 14.4      | 17.4      | 22.2   | 29.1      | 38.6      | 15.4     |
| 140       | 15.0      | 17.8      | 22.0   | 28.2      | 36.2      | 25.7     |
| 160       | 13.5      | 16.1      | 20.0   | 25.6      | 32.9      | 20.2     |
| 200       | 14.4      | 17.2      | 21.4   | 27.4      | 34.8      | 15.9     |
| 300       | 17.8      | 21.6      | 27.6   | 36.7      | 48.9      | 41.4     |
| 350       | 21.0      | 25.7      | 33.1   | 44.8      | —         | 44.1     |
| 400       | 25.7      | 31.8      | 42.4   | —         | —         | 39.0     |
| 500       | 40.3      | 52.1      | —      | —         | —         | —        |

Table 10. Expected and observed 95% CL upper limits on $\tan \beta$ as a function of $m_A$ in the light-stau, $\mu = +200$ GeV, benchmark scenario obtained from a combination of the 7 and 8 TeV data.

| Mass [GeV] | $-2\sigma$ | $-1\sigma$ | Median | $+1\sigma$ | $+2\sigma$ | Observed |
|-----------|-----------|-----------|--------|-----------|-----------|----------|
| 100       | 15.3      | 18.9      | 24.7   | 34.1      | 49.2      | 16.5     |
| 140       | 15.9      | 19.1      | 24.3   | 32.6      | 44.9      | 29.1     |
| 160       | 14.4      | 17.4      | 22.1   | 29.6      | 40.2      | 22.4     |
| 200       | 15.5      | 18.8      | 24.2   | 32.3      | 43.8      | 17.3     |
| 300       | 19.7      | 24.5      | 32.7   | 47.6      | —         | 56.8     |
| 350       | 23.6      | 29.9      | 41.4   | —         | —         | —        |
| 400       | 29.7      | 39.0      | 58.6   | —         | —         | 51.7     |
| 500       | 52.5      | —         | —      | —         | —         | —        |

Table 11. Expected and observed 95% CL upper limits on $\tan \beta$ as a function of $m_A$ in the light-stop, $\mu = +200$ GeV, benchmark scenario obtained from a combination of the 7 and 8 TeV data.
Table 12. Observed (expected) 95% CL upper limits on $\tan \beta$ as a function of $m_A$ in the $m_{\tilde{h}}^{mod+}$ benchmark scenario for different values of the higgsino mass parameter $\mu$ obtained from a combination of the 7 and 8 TeV data.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

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 (2013) 1 [arXiv:1207.7214] [INSPIRE].

[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 [arXiv:1207.7235] [INSPIRE].

[3] CMS collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV, JHEP 06 (2013) 081 [arXiv:1303.4571] [INSPIRE].

[4] J. Wess and B. Zumino, Supergauge transformations in four-dimensions, Nucl. Phys. B 70 (1974) 39 [INSPIRE].

[5] H.P. Nilles, Supersymmetry, supergravity and particle physics, Phys. Rept. 110 (1984) 1 [INSPIRE].

[6] S.P. Martin, A supersymmetry primer, hep-ph/9709356 [INSPIRE].

[7] D.J.H. Chung, L.L. Everett, G.L. Kane, S.F. King, J.D. Lykken and L.-T. Wang, The soft supersymmetry breaking Lagrangian: theory and applications, Phys. Rept. 407 (2005) 1 [hep-ph/0312378] [INSPIRE].

[8] G. Bertone, D. Hooper and J. Silk, Particle dark matter: evidence, candidates and constraints, Phys. Rept. 405 (2005) 279 [hep-ph/0404175] [INSPIRE].

[9] S. Dimopoulos, S. Raby and F. Wilczek, Supersymmetry and the scale of unification, Phys. Rev. D 24 (1981) 1681 [INSPIRE].

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Mass [GeV] & $\mu = -500$ GeV & $\mu = -200$ GeV & $\mu = +200$ GeV & $\mu = +500$ GeV \\
\hline
100 & 12.9 (16.6) & 13.7 (18.1) & 14.2 (19.8) & 16.1 (22.7) \\
140 & 18.2 (16.4) & 19.9 (17.8) & 22.4 (19.6) & 26.1 (22.5) \\
160 & 15.5 (15.4) & 16.7 (16.6) & 18.2 (18.0) & 20.8 (20.6) \\
200 & 13.1 (16.2) & 14.0 (17.5) & 14.8 (19.2) & 16.6 (21.9) \\
300 & 24.2 (16.4) & 27.6 (21.3) & 34.1 (24.8) & 41.0 (27.8) \\
350 & 15.5 (15.4) & 16.7 (16.6) & 18.2 (18.0) & 20.8 (20.6) \\
400 & 13.1 (16.2) & 14.0 (17.5) & 14.8 (19.2) & 16.6 (21.9) \\
500 & 30.3 (31.8) & 37.8 (39.6) & 50.0 (53.5) & — (—) \\
600 & 33.2 (41.0) & 42.3 (52.8) & 57.5 (—) & — (—) \\
700 & 54.3 (51.3) & — (—) & — (—) & — (—) \\
\hline
\end{tabular}
\caption{Observed (expected) 95\% CL upper limits on $\tan \beta$ as a function of $m_A$ in the $m_{\tilde{h}}^{mod+}$ benchmark scenario for different values of the higgsino mass parameter $\mu$ obtained from a combination of the 7 and 8 TeV data.}
\end{table}
[10] E. Witten, *Mass hierarchies in supersymmetric theories*, Phys. Lett. B 105 (1981) 267 [inSPIRE].

[11] LHC Higgs Cross Section Working Group collaboration, J.R. Andersen et al., *Handbook of LHC Higgs cross sections: 3. Higgs properties*, CERN-2013-004, CERN, Geneva Switzerland (2013) [FERMILAB-CONF-13-667-T] [arXiv:1307.1347] [inSPIRE].

[12] CMS collaboration, *Search for neutral Higgs bosons decaying to τ pairs in pp collisions at √s = 7 TeV*, Phys. Lett. B 713 (2012) 68 [arXiv:1202.4083] [inSPIRE].

[13] ATLAS collaboration, *Search for the neutral Higgs bosons of the minimal supersymmetric Standard Model in pp collisions at √s = 7 TeV with the ATLAS detector*, JHEP 02 (2013) 095 [arXiv:1211.6956] [inSPIRE].

[14] CMS collaboration, *Search for neutral MSSM Higgs bosons decaying to a pair of τ leptons in pp collisions*, JHEP 10 (2014) 160 [arXiv:1408.3316] [inSPIRE].

[15] ATLAS collaboration, *Search for neutral Higgs bosons of the minimal supersymmetric Standard Model in pp collisions at √s = 8 TeV with the ATLAS detector*, JHEP 11 (2014) 056 [arXiv:1409.6064] [inSPIRE].

[16] DELPHI, OPAL, ALEPH, LEP Working Group for Higgs Boson Searches and L3 collaborations, S. Schael et al., *Search for neutral MSSM Higgs bosons at LEP*, Eur. Phys. J. C 47 (2006) 547 [hep-ex/0602042] [inSPIRE].

[17] CDF collaboration, T. Aaltonen et al., *Search for Higgs bosons predicted in two-Higgs-doublet models via decays to τ lepton pairs in 1.96 TeV pp collisions*, Phys. Rev. Lett. 103 (2009) 201801 [arXiv:0906.1014] [inSPIRE].

[18] D0 collaboration, V.M. Abazov et al., *Search for Higgs bosons decaying to τ pairs in pp collisions with the D0 detector*, Phys. Rev. Lett. 101 (2008) 071804 [arXiv:0805.2491] [inSPIRE].

[19] D0 collaboration, V.M. Abazov et al., *Search for Higgs bosons of the minimal supersymmetric Standard Model in pp collisions at √s = 1.96 TeV*, Phys. Lett. B 710 (2012) 569 [arXiv:1112.5431] [inSPIRE].

[20] CMS collaboration, *Search for neutral MSSM Higgs bosons decaying to μ⁺μ⁻ in pp collisions at √s = 7 and 8 TeV*, arXiv:1508.01437 [inSPIRE].

[21] M. Carena, S. Heinemeyer, O. Stål, C.E.M. Wagner and G. Weiglein, *MSSM Higgs boson searches at the LHC: benchmark scenarios after the discovery of a Higgs-like particle*, Eur. Phys. J. C 73 (2013) 2552 [arXiv:1302.7033] [inSPIRE].

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

[23] E. Izaguirre, G. Krnjaic and B. Shuve, *The galactic center excess from the bottom up*, Phys. Rev. D 90 (2014) 055002 [arXiv:1404.2018] [inSPIRE].

[24] A. Berlin, D. Hooper and S.D. McDermott, *Simplified dark matter models for the galactic center gamma-ray excess*, Phys. Rev. D 89 (2014) 115022 [arXiv:1404.0022] [inSPIRE].

[25] CDF and D0 collaborations, T. Aaltonen et al., *Search for neutral Higgs bosons in events with multiple bottom quarks at the Tevatron*, Phys. Rev. D 86 (2012) 091101 [arXiv:1207.2757] [inSPIRE].
CMS collaboration, *Search for a Higgs boson decaying into a b-quark pair and produced in association with b quarks in proton-proton collisions at 7 TeV*, Phys. Lett. B 722 (2013) 207 [arXiv:1302.2892] [insPIRE].

CMS collaboration, *The CMS experiment at the CERN LHC, 2008 JINST 3 S08004* [insPIRE].

CMS collaboration, *Particle-flow event reconstruction in CMS and performance for jets, taus and MET, CMS-PAS-PFT-09-001*, CERN, Geneva Switzerland (2009).

CMS collaboration, *Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector, CMS-PAS-PFT-10-001*, CERN, Geneva Switzerland (2010).

M. Cacciari, G.P. Salam and G. Soyez, *The anti-$k_t$ jet clustering algorithm*, JHEP 04 (2008) 063 [arXiv:0802.1189] [insPIRE].

M. Cacciari and G.P. Salam, *Pileup subtraction using jet areas*, Phys. Lett. B 659 (2008) 119 [arXiv:0707.1378] [insPIRE].

CMS collaboration, *Pileup jet identification, CMS-PAS-JME-13-005*, CERN, Geneva Switzerland (2013).

CMS collaboration, *Determination of jet energy calibration and transverse momentum resolution in CMS, 2011 JINST 6 P11002 [arXiv:1107.4277]* [insPIRE].

CMS collaboration, *Identification of b-quark jets with the CMS experiment, 2013 JINST 8 P04013 [arXiv:1211.4462]* [insPIRE].

W. Waltenberger, *Adaptive vertex reconstruction, CMS-NOTE-2008-033*, CERN, Geneva Switzerland (2008).

T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 physics and manual, JHEP 05 (2006) 026 [hep-ph/0603175]* [insPIRE].

J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, *MadGraph 5: going beyond, JHEP 06 (2011) 128 [arXiv:1106.0522]* [insPIRE].

GEANT4 collaboration, S. Agostinelli et al., *GEANT4: a simulation toolkit, Nucl. Instrum. Meth. A 506 (2003) 250* [insPIRE].

S. Dittmaier et al., *Handbook of LHC Higgs cross sections: 2. Differential distributions, CERN-2012-002, CERN, Geneva Switzerland (2012) [arXiv:1201.3084]* [insPIRE].

R. Field, *Early LHC underlying event data — findings and surprises, arXiv:1010.3558* [insPIRE].

J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P.M. Nadolsky and W.K. Tung, *New generation of parton distributions with uncertainties from global QCD analysis, JHEP 07 (2002) 012 [hep-ph/0201195]* [insPIRE].

CDF collaboration, T. Aaltonen et al., *Search for Higgs bosons produced in association with b-quarks, Phys. Rev. D 85 (2012) 032005 [arXiv:1106.4782]* [insPIRE].

CMS collaboration, *CMS luminosity based on pixel cluster counting — summer 2013 update, CMS-PAS-LUM-13-001, CERN, Geneva Switzerland (2013).*

T. Junk, *Confidence level computation for combining searches with small statistics, Nucl. Instrum. Meth. A 434 (1999) 435 [hep-ex/9902006]* [insPIRE].
[45] A.L. Read, *Presentation of search results: the CL$_s$ technique*, J. Phys. G 28 (2002) 2693 [inSPIRE].

[46] L. Moneta et al., *The RooStats project*, in 13th International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT2010), SISSA, Trieste Italy (2010) [PoS(ACAT2010)057] [arXiv:1009.1003] [inSPIRE].

[47] S. Dittmaier, M. Krämer and M. Spira, *Higgs radiation off bottom quarks at the Tevatron and the CERN LHC*, Phys. Rev. D 70 (2004) 074010 [hep-ph/0309204] [inSPIRE].

[48] S. Dawson, C.B. Jackson, L. Reina and D. Wackeroth, *Exclusive Higgs boson production with bottom quarks at hadron colliders*, Phys. Rev. D 69 (2004) 074027 [hep-ph/0311067] [inSPIRE].

[49] R.V. Harlander and W.B. Kilgore, *Higgs boson production in bottom quark fusion at next-to-next-to leading order*, Phys. Rev. D 68 (2003) 013001 [hep-ph/0304035] [inSPIRE].

[50] R. Harlander, M. Krämer and M. Schumacher, *Bottom-quark associated Higgs-boson production: reconciling the four- and five-flavour scheme approach*, arXiv:1112.3478 [inSPIRE].

[51] G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, *Towards high precision predictions for the MSSM Higgs sector*, Eur. Phys. J. C 28 (2003) 133 [hep-ph/0212020] [inSPIRE].

[52] M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak and G. Weiglein, *The Higgs boson masses and mixings of the complex MSSM in the Feynman-diagrammatic approach*, JHEP 02 (2007) 047 [hep-ph/0611326] [inSPIRE].

[53] S. Heinemeyer, W. Hollik and G. Weiglein, *FeynHiggs: a program for the calculation of the masses of the neutral CP even Higgs bosons in the MSSM*, Comput. Phys. Commun. 124 (2000) 76 [hep-ph/9812320] [inSPIRE].

[54] S. Heinemeyer, W. Hollik and G. Weiglein, *The masses of the neutral CP-even Higgs bosons in the MSSM: accurate analysis at the two loop level*, Eur. Phys. J. C 9 (1999) 343 [hep-ph/9812472] [inSPIRE].

[55] A. Djouadi, J. Kalinowski and M. Spira, *HDECAY: a program for Higgs boson decays in the Standard Model and its supersymmetric extension*, Comput. Phys. Commun. 108 (1998) 56 [hep-ph/9704448] [inSPIRE].

[56] A. Djouadi, M.M. Mühlleitner and M. Spira, *Decays of supersymmetric particles: the program SUSY-HIT (Suspect-SdecaY-HDECAY-InTerface)*, Acta Phys. Polon. B 38 (2007) 635 [hep-ph/0609292] [inSPIRE].

[57] M. Carena, S. Heinemeyer, C.E.M. Wagner and G. Weiglein, *MSSM Higgs boson searches at the Tevatron and the LHC: impact of different benchmark scenarios*, Eur. Phys. J. C 45 (2006) 797 [hep-ph/0511023] [inSPIRE].
The CMS collaboration

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

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth\(^1\), V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler\(^1\), V. Knünz, A. König, M. Krammer\(^1\), I. Krätschmer, D. Likò, T. Matsushita, I. Mikulec, D. Rabady\(^2\), B. Rahbaran, H. Rohringer, J. Schieck\(^1\), R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz\(^1\)

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez González

Universiteit Antwerpen, Antwerpen, Belgium
S. Alderweireldt, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D’Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous, J. Keaveney, S. Lowette, L. Moreels, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
P. Barria, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, D. Dobur, G. Fasanella, L. Favart, A.P.R. Gay, A. Grebenyuk, T. Lenzi, A. Léonard, T. Maerschalk, A. Marinov, L. Perniè, A. Randle-conde, T. Reis, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang\(^3\)

Ghent University, Ghent, Belgium
K. Beernaert, L. Bennuci, A. Cinminno, S. Crucy, A. Fagot, G. Garcia, M. Gul, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva, M. Sigamani, N. Strobbe, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, C. Beluffi\(^4\), O. Bondu, S. Brochet, G. Bruno, R. Castello, A. Caudron, L. Cead, G.G. Da Silveira, C. Delaere, D. Favart, L. Forthomme, A. Giammanco\(^5\), J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Mertens, C. Nuttens, L. Perrini, A. Pin, K. Piotrzkowski, A. Popov\(^6\), L. Quertenmont, M. Selvaggi, M. Vidal Marono

Université de Mons, Mons, Belgium
N. Beliy, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, C. Hensel, C. Mora Herrera, 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. Chinellato⁷, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guatava, H. Malbouisson, D. Matos Figueirêdo, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Szajdner, E.J. Tonelli Manganote⁷, A. Vilela Pereira

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
S. Ahuja a, C.A. Bernardes b, A. De Souza Santos b, S. Dogra a, T.R. Fernandez Perez Tomei a, E.M. Gregores b, P.G. Mercadante b, C.S. Moon a, S.F. Novaes a, Sandra S. Padula a, D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, V. Genchev†, R. Hadjiiska, P. Iaydjiev, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

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

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina⁹, F. Romeo, S.M. Shaheen, J. Tao, C. Wang, Z. Wang, H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, L. Sudic

University of Cyprus, Nicosia, Cyprus
A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rylaczewski

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger¹⁰, M. Finger Jr.¹⁰
Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
R. Aly, E. El-khateeb, T. Elkafrwy, A. Lotfy, A. Mohamed, A. Radi, E. Salama, A. Sayed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kadastik, M. Murumaa, M. Raidal, A. Tiko, C. Veelken

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

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbrro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, M. Machet, J. Malec, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, T. Dahms, O. Davignon, N. Filipovic, A. Florent, R. Granier de Cassagnac, S. Lisniak, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte, X. Coubez, J.-C. Fontaine, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, J.A. Merlin, K. Skovpen, P. Van Hove

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

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao
Georgian Technical University, Tbilisi, Georgia
T. Toriashvili

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, S. Beranek, M. Edelhoff, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, T. Verlage, H. Weber, B. Wittmer, V. Zhukov

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padelen, P. Papacz, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teysssier, S. Thié

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, F. Hoehle, B. Kargoll, T. Kress, Y. Kussel, A. Künsken, J. Lingemann, A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Footh, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, I. Asin, N. Bartosik, O. Behnke, U. Behrens, A.J. Bell, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, E. Gallo, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel, H. Jung, A. Kalogeropoulos, O. Karacheban, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussiger, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, B. Roland, M. Sahin, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, K.D. Trippkewitz, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfe, E. Garutti, K. Goebel, D. Gonzalez, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, D. Nowatschin, J. Ott, F. Pantaleo, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, J. Schwandt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer
Institut für Experimentelle Kernphysik, Karlsruhe, Germany
M. Akbiyik, C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Descroix, A. Dierlamnn, M. Feindt, F. Freusch, M. Giefsls, A. Gilbert, F. Hartmann\textsuperscript{2}, U. Husemann, F. Kassel\textsuperscript{2}, I. Katkov\textsuperscript{6}, A. Kormayer\textsuperscript{2}, P. Lobelle Pardo, M.U. Mozer, T. Müller, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Markou, A. Psallidas, I. Topsis-Giotis

University of Athens, Athens, Greece
A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

University of Ioánnina, Ioánnina, Greece
I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, A. Haiz, P. Hidas, D. Horvath\textsuperscript{19}, F. Sikler, V. Veszpremi, G. Vesztergombi\textsuperscript{20}, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi\textsuperscript{21}, J. Molnar, Z. Szillasi

University of Debrecen, Debrecen, Hungary
M. Bartók\textsuperscript{22}, A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
P. Mal, K. Mandal, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, R. Gupta, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, A. Mehta, M. Mittal, N. Nishu, J.B. Singh, G. Walia

University of Delhi, Delhi, India
Ashok Kumar, Arun Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutta, S. Jain, Sh. Jain, R. Khurana, N. Majumdar, A. Modak, K. Mondal, S. Mukherjee, S. Mukhopadhyay, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulhassim, R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty\textsuperscript{2}, L.M. Pant, P. Shukla, A. Topkar

{ 29 }
INFN Sezione di Milano-Bicocca \textsuperscript{a}, Università di Milano-Bicocca \textsuperscript{b}, Milano, Italy

M.E. Dinardo\textsuperscript{a,b}, S. Fiorendi\textsuperscript{a,b}, S. Gennai\textsuperscript{a,b}, R. Gerosa\textsuperscript{a,b}, A. Ghezzi\textsuperscript{a,b}, P. Govoni\textsuperscript{a,b}, S. Malvezzi\textsuperscript{a}, R.A. Manzoni\textsuperscript{a,b}, B. Marzocchi\textsuperscript{a,b,2}, D. Menasce\textsuperscript{a}, L. Moroni\textsuperscript{a}, M. Paganoni\textsuperscript{a,b}, D. Pedrini\textsuperscript{a}, S. Ragazzi\textsuperscript{a,b}, N. Redaelli\textsuperscript{a}, T. Tabarelli de Fatis\textsuperscript{a,b}

INFN Sezione di Napoli \textsuperscript{a}, Università di Napoli 'Federico II' \textsuperscript{b}, Napoli, Italy, Università della Basilicata \textsuperscript{c}, Potenza, Italy, Università G. Marconi \textsuperscript{d}, Roma, Italy

S. Buontempo\textsuperscript{a}, N. Cavallo\textsuperscript{a,c}, S. Di Guida\textsuperscript{a,d,2}, M. Esposito\textsuperscript{a,b}, F. Fabozzi\textsuperscript{a,c}, A.O.M. Iorio\textsuperscript{a,b}, G. Lanza\textsuperscript{a}, L. Lista\textsuperscript{a}, S. Meola\textsuperscript{a,d,2}, M. Merola\textsuperscript{a}, P. Paolucci\textsuperscript{a,2}, C. Sciacca\textsuperscript{a,b}, F. Thyssen

INFN Sezione di Padova \textsuperscript{a}, Università di Padova \textsuperscript{b}, Padova, Italy, Università di Trento \textsuperscript{c}, Trento, Italy

P. Azzi\textsuperscript{a,2}, N. Bacchetta\textsuperscript{a}, M. Bellato\textsuperscript{a}, D. Bisello\textsuperscript{a,b}, A. Branca\textsuperscript{a,b}, R. Carlin\textsuperscript{a,b}, P. Checchia\textsuperscript{a}, M. Dall’Oss\textsuperscript{a,b,2}, T. Dorigo\textsuperscript{a}, U. Dosselli\textsuperscript{a}, F. Gasparini\textsuperscript{a,b}, U. Gasparini\textsuperscript{a,b}, A. Gozzelino\textsuperscript{a}, M. Gulmini\textsuperscript{a,20}, K. Kanishchev\textsuperscript{a,c}, S. Lacaprara\textsuperscript{a}, M. Margoni\textsuperscript{a,b}, A.T. Meneguzzo\textsuperscript{a,b}, J. Pazzini\textsuperscript{a,b}, N. Pozzobon\textsuperscript{a,b}, P. Ronchese\textsuperscript{a,b}, E. Torassa\textsuperscript{a}, M. Tosi\textsuperscript{a,b}, S. Ventura\textsuperscript{a}, M. Zanetti, P. Zotto\textsuperscript{a,b,2}, A. Zucchetta

INFN Sezione di Pavia \textsuperscript{a}, Università di Pavia \textsuperscript{b}, Pavia, Italy

A. Braghieri\textsuperscript{a}, A. Magnani\textsuperscript{a}, S.P. Ratti\textsuperscript{a,b}, V. Re\textsuperscript{a}, C. Riccardi\textsuperscript{a,b}, P. Salvini\textsuperscript{a}, I. Vai\textsuperscript{a}, P. Vitulo\textsuperscript{a,b}

INFN Sezione di Perugia \textsuperscript{a}, Università di Perugia \textsuperscript{b}, Perugia, Italy

L. Alunni Solestizi\textsuperscript{a,b}, M. Biasini\textsuperscript{a,b}, G.M. Bilei\textsuperscript{a}, D. Ciangottini\textsuperscript{a,b,2}, L. Fanò\textsuperscript{a,b}, P. Lariccia\textsuperscript{a,b}, G. Mantovani\textsuperscript{a,b}, M. Menichelli\textsuperscript{a}, A. Saha\textsuperscript{a}, A. Santocchia\textsuperscript{a,b}, A. Spiezia\textsuperscript{a,b}

INFN Sezione di Pisa \textsuperscript{a}, Università di Pisa \textsuperscript{b}, Scuola Normale Superiore di Pisa \textsuperscript{c}, Pisa, Italy

K. Androsov\textsuperscript{a,30}, P. Azzurri\textsuperscript{a}, G. Bagliesi\textsuperscript{a}, J. Bernardini\textsuperscript{a}, T. Boccali\textsuperscript{a}, G. Broccolo\textsuperscript{a,c}, R. Castaldi\textsuperscript{a}, M.A. Ciocci\textsuperscript{a,30}, R. Dell’Orso\textsuperscript{a}, S. Donato\textsuperscript{a,c,2}, G. Fedi, L. Foà\textsuperscript{a,c}, A. Giassi\textsuperscript{a}, M.T. Grippo\textsuperscript{a,30}, F. Ligabue\textsuperscript{a,c}, T. Lomtadze\textsuperscript{a}, L. Martini\textsuperscript{a,b}, A. Messineo\textsuperscript{a,b}, F. Palla\textsuperscript{a}, A. Rizzii\textsuperscript{a,b}, A. Savoy-Navarro\textsuperscript{a,31}, A.T. Serban\textsuperscript{a}, P. Spagnolo\textsuperscript{a}, P. Squillacioti\textsuperscript{a,30}, R. Tenchini\textsuperscript{a}, G. Tonelli\textsuperscript{a,b}, A. Venturi\textsuperscript{a}, P.G. Verdini

INFN Sezione di Roma \textsuperscript{a}, Università di Roma \textsuperscript{b}, Roma, Italy

L. Barone\textsuperscript{a,b}, F. Cavallari\textsuperscript{a}, G. D’imperio\textsuperscript{a,b,2}, D. Del Re\textsuperscript{a,b}, M. Diemoz\textsuperscript{a}, S. Gelli\textsuperscript{a,b}, C. Jordà\textsuperscript{a}, E. Longo\textsuperscript{a,b}, F. Margaroli\textsuperscript{a,b}, P. Meridiani\textsuperscript{a}, F. Micheli\textsuperscript{a,b}, G. Organtini\textsuperscript{a,b}, R. Paramatti\textsuperscript{a}, F. Preiato\textsuperscript{a,b}, S. Rahatlou\textsuperscript{a,b}, C. Rovelli\textsuperscript{a}, F. Santanastasio\textsuperscript{a,b}, P. Traczyk\textsuperscript{a,b,2}

INFN Sezione di Torino \textsuperscript{a}, Università di Torino \textsuperscript{b}, Torino, Italy, Università del Piemonte Orientale \textsuperscript{c}, Novara, Italy

N. Amapane\textsuperscript{a,b}, R. Arcidiacono\textsuperscript{a,c,2}, S. Arigo\textsuperscript{a,b}, M. Arneodo\textsuperscript{a,c}, R. Bellan\textsuperscript{a,b}, C. Biino\textsuperscript{a}, N. Cartiglia\textsuperscript{a}, M. Costa\textsuperscript{a,b}, R. Covarelli\textsuperscript{a,b}, A. Degano\textsuperscript{a,b}, N. Demaria\textsuperscript{a}, L. Fineo\textsuperscript{a,b,2},
B. Kiani\textsuperscript{a,b}, C. Mariotti\textsuperscript{a}, S. Maselli\textsuperscript{a}, E. Migliore\textsuperscript{a,b}, V. Monaco\textsuperscript{a,b}, E. Monteil\textsuperscript{a,b}, M. Musich\textsuperscript{a}, M.M. Obertino\textsuperscript{a,b}, L. Pacher\textsuperscript{a,b}, N. Pastrone\textsuperscript{a}, M. Pelliccioni\textsuperscript{a}, G.L. Pinna Angioni\textsuperscript{a,b}, F. Ravera\textsuperscript{a,b}, A. Romero\textsuperscript{a,b}, M. Ruspa\textsuperscript{a,c}, R. Sacchi\textsuperscript{a,b}, A. Solano\textsuperscript{a,b}, A. Staiano\textsuperscript{a}, U. Tamponi\textsuperscript{a}

INFN Sezione di Trieste \textsuperscript{a}, Università di Trieste \textsuperscript{b}, Trieste, Italy

S. Belforte\textsuperscript{a}, V. Candelise\textsuperscript{a,b,2}, M. Casarsa\textsuperscript{a}, F. Cossutti\textsuperscript{a}, G. Della Ricca\textsuperscript{a,b}, B. Gobbo\textsuperscript{a}, C. La Licata\textsuperscript{a,b}, M. Marone\textsuperscript{a,b}, A. Schizzi\textsuperscript{a,b}, T. Umer\textsuperscript{a,b}, A. Zanetti\textsuperscript{a}

Kangwon National University, Chunchon, Korea
S. Chang, A. Kropivnitskaya, S.K. Nam

Kwangju National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea
J.A. Brochero Cifuentes, H. Kim, T.J. Kim, M.S. Ryu

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

Korea University, Seoul, Korea
S. Choi, Y. Go, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea
H.D. Yoo

University of Seoul, Seoul, Korea
M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

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

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali\textsuperscript{32}, F. Mohamad Idris\textsuperscript{33}, W.A.T. Wan Abdullah

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz\textsuperscript{34}, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia
M. De Gruttola, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, T. du Pree, N. Dupont, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, H. Kirschenmann, M.J. Kortelainen, K. Kousouris, K. Krajcjar, P. Lecoq, C. Lourenço, M.T. Lucchini, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, A. Martelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, M.V. Nemallapudi, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, D. Piparo, A. Racz, G. Rolandi, M. Rovere, M. Ruan, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Silva, M. Simon, P. Spigas, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres, N. Wardle, H.K. Wöhri, A. Zagozdzinska, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, M. Düser, P. Eller, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, M. Rossini, A. Starodumov, M. Takahashi, V.R. Tavolaro, K. Theofilatos, R. wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler, L. Caminada, M.F. Canelli, V. Chiochia, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, D. Salerno, S. Taroni, Y. Yang

National Central University, Chung-Li, Taiwan

M. Cardaci, K.H. Chen, T.H. Doan, C. Ferro, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

R. Bartek, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, U. Grundler, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, J.F. Tsai, Y.M. Tseng

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

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gürpınar, I. Hos, E.E. Kangal, G. Onengut, K. Özdemir, A. Polatoz, D. Sunar Cerci, M. Vergili, C. Zorbilmez
Fermi National Accelerator Laboratory, Batavia, U.S.A.
S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, Z. Hu, S. Jindariani, M. Johnson, U. Joshi, A.W. Jung, B. Klina, B. Kreis, S. Kwan\textsuperscript{t}, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O’Dell, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, A. Whitbeck, F. Yang, H. Yin

University of Florida, Gainesville, U.S.A.
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Carnes, M. Carver, D. Curry, S. Das, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, J.F. Low, P. Ma, K. Matchev, H. Mei, P. Milenovic\textsuperscript{63}, G. Mitselmakher, L. Muniz, D. Rank, R. Rossin, L. Shchutska, M. Snowball, D. Sperka, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, U.S.A.
S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, U.S.A.
A. Ackert, J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, U.S.A.
V. Bhopatkar, M. Hohlmann, H. Kalakhety, D. Mareskas-palcek, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, U.S.A.
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O’Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas, Z. Wu, M. Zakaria

The University of Iowa, Iowa City, U.S.A.
B. Bilki\textsuperscript{64}, W. Clarida, K. Diliz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya\textsuperscript{65}, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok\textsuperscript{54}, A. Penzo, C. Snyder, P. Tan, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, U.S.A.
I. Anderson, B.A. Barnett, B. Blumenfeld, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, K. Nash, M. Osherson, M. Swartz, M. Xiao, Y. Xin

The University of Kansas, Lawrence, U.S.A.
P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, D. Noonan, S. Sanders, R. Stringer, Q. Wang, J.S. Wood
The Ohio State University, Columbus, U.S.A.
L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, B. Liu, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, U.S.A.
O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, C. Palmer, P. Piroué, X. Quan, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

Purdue University, West Lafayette, U.S.A.
V.E. Barnes, D. Benedetti, D. Bortoletto, L. Gutay, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D.H. Miller, N. Neumeister, F. Primavera, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

Purdue University Calumet, Hammond, U.S.A.
N. Parashar, J. Stupak

Rice University, Houston, U.S.A.
A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, U.S.A.
B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, M. Galanti, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, O. Hindrichs, A. Khukhunaishvili, G. Petrillo, M. Verzetti

The Rockefeller University, New York, U.S.A.
L. Demortier

Rutgers, The State University of New Jersey, Piscataway, U.S.A.
S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, A. Lath, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, U.S.A.
M. Foerster, G. Riley, K. Rose, S. Spanier, A. York

Texas A&M University, College Station, U.S.A.
O. Bouhali, A. Castaneda Hernandez, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon, V. Krutelyov, R. Montalvo, R. Mueller, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Saforov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, U.S.A.
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, S. Undleeb, I. Volobouev
Vanderbilt University, Nashville, U.S.A.
E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, Y. Mao, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, U.S.A.
M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood, F. Xia

Wayne State University, Detroit, U.S.A.
C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin, Madison, U.S.A.
D.A. Belknap, D. Carlsmit, M. Cepeda, A. Christian, S. Dasu, L. Dodd, S. Duric, E. Friis, B. Gomber, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Ruggles, T. Sarangi, A. Savin, A. Sharma, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
4: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
5: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
6: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
7: Also at Universidade Estadual de Campinas, Campinas, Brazil
8: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Now at Helwan University, Cairo, Egypt
12: Now at Ain Shams University, Cairo, Egypt
13: Now at Fayoum University, El-Fayoum, Egypt
14: Also at Zewail City of Science and Technology, Zewail, Egypt
15: Also at British University in Egypt, Cairo, Egypt
16: Also at Université de Haute Alsace, Mulhouse, France
17: Also at Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at Eötvös Loránd University, Budapest, Hungary
21: Also at University of Debrecen, Debrecen, Hungary
22: Also at Wigner Research Centre for Physics, Budapest, Hungary
23: Also at University of Visva-Bharati, Santiniketan, India
24: Now at King Abdulaziz University, Jeddah, Saudi Arabia
25: Also at University of Ruhuna, Matara, Sri Lanka
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
29: Also at Laboratori Nazionali di Legnaro dell’INFN, Legnaro, Italy
30: Also at Università degli Studi di Siena, Siena, Italy
31: Also at Purdue University, West Lafayette, U.S.A.
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 TECNOLOGIA, MEXICO, Mexico
35: Also at Institute for Nuclear Research, Moscow, Russia
36: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
37: Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
38: Also at California Institute of Technology, Pasadena, U.S.A.
39: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
40: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
41: Also at National Technical University of Athens, Athens, Greece
42: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
43: Also at University of Athens, Athens, Greece
44: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
45: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
46: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
47: Also at Gaziosmanpasa University, Tokat, Turkey
48: Also at Mersin University, Mersin, Turkey
49: Also at Cag University, Mersin, Turkey
50: Also at Piri Reis University, Istanbul, Turkey
51: Also at Adiyaman University, Adiyaman, Turkey
52: Also at Ozyegin University, Istanbul, Turkey
53: Also at Izmir Institute of Technology, Izmir, Turkey
54: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
55: Also at Marmara University, Istanbul, Turkey
56: Also at Kafkas University, Kars, Turkey
57: Also at Yildiz Technical University, Istanbul, Turkey
58: Also at Hacettepe University, Ankara, Turkey
59: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
60: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
61: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
62: Also at Utah Valley University, Orem, U.S.A.
63: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
64: Also at Argonne National Laboratory, Argonne, U.S.A.
65: Also at Erzincan University, Erzincan, Turkey
66: Also at Texas A&M University at Qatar, Doha, Qatar
67: Also at Kyungpook National University, Daegu, Korea