Search for a light pseudoscalar Higgs boson in the dimuon decay channel in pp collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration

Abstract

The dimuon invariant mass spectrum is searched in the range between 5.5 and 14 GeV for a light pseudoscalar Higgs boson $a$, predicted in a number of new physics models, including the next-to-minimal supersymmetric standard model. The data sample used in the search corresponds to an integrated luminosity of 1.3 fb$^{-1}$ collected in pp collisions at $\sqrt{s} = 7$ TeV with the CMS detector at the LHC. No excess is observed above the background predictions and upper limits are set on the cross section times branching fraction $\sigma \cdot B(\text{pp} \rightarrow a \rightarrow \mu^+ \mu^-)$ in the range of 1.5–7.5 pb. These results improve on existing bounds on the $ab\bar{b}$ coupling for $m_a < m_{\Upsilon(1S)}$ and are the first significant limits for $m_a > m_{\Upsilon(3S)}$. Constraints on the supersymmetric parameter space are presented in the context of the next-to-minimal model.

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*See Appendix A for the list of collaboration members*
Low energy supersymmetry (SUSY) is an elegant solution to the hierarchy problem that arises in the Standard Model (SM), provides a candidate for dark matter, and allows for the unification of gauge couplings at the grand-unified-theory (GUT) scale \[1,2\]. However, the minimal supersymmetric model (MSSM) has an ad hoc Higgs superfield mixing parameter \(\mu\) and requires very large masses for the supersymmetric partner of the top quark (stop) in order for the lightest CP-even Higgs boson to be heavier than 122 GeV without large stop mixing \[3\].

Both problems are solved in the next-to MSSM (NMSSM) (a review can be found in Ref. \[4\]), which extends the MSSM by introducing a complex singlet superfield which necessarily contains a scalar field component. Associated super- and scalar-potential terms generate an effective \(\mu\) parameter and easily raise the mass of the light Higgs boson without requiring a heavy stop \[5\].

The added scalar field expands the Higgs sector to three CP-even scalars \(h_1, h_2, h_3\), two CP-odd scalars \(a_1, a_2\) and two charged scalars \(H^+, H^-\). The \(a_1\) is a superposition of the MSSM doublet pseudoscalar \(a_{\text{MSSM}}\) and the additional singlet pseudoscalar of the NMSSM \(a_3\): \(a_1 = \cos \theta_A a_{\text{MSSM}} + \sin \theta_A a_3\), where \(\theta_A\) is the mixing angle. The NMSSM has two symmetries that, if imposed (e.g. at the GUT scale), imply that small \(\tan \beta\) is a very natural possibility \[10\]. However, the couplings \(C_{a_1\bar{b}b} = C_{a_1\mu^+\mu^-} = C_{a_1\tau^+\tau^-} = \tan \beta \cos \theta_A\) can be sizeable for large values of \(\tan \beta\), the ratio of neutral Higgs field vacuum expectation values, even if \(\cos \theta_A\) is small. More generally, superstring modeling suggests the possibility of many light \(a\) particles, at least some of which couple to \(\mu^+\mu^-\), \(\tau^+\tau^-\) and \(b\bar{b}\) \[11\]. In the following, \(a\) \((a_1)\) denotes a general (NMSSM) light pseudoscalar Higgs boson.

Searches for a light \(a\) are mainly sensitive to \(C_{\mu b\bar{b}}\) \[12,13\]. For \(m_a < m_{\chi(1 \text{S})}\), the strongest constraints on \(C_{\mu b\bar{b}}\) are those from BaBar \[14,15\]. For \(m_a > m_{\chi(1 \text{S})}\), only the Tevatron and Large Hadron Collider (LHC) have sensitivity \[16\], using production via \(gg \rightarrow a\), where the coupling \(C_{gg}\) derives from quark (especially bottom and top) triangle loops. This process, plus higher-order corrections, leads to a large cross section due to the large \(gg\) parton luminosity at small gluon momentum fractions, provided the \(C_{a\bar{q}q}\) \((q = t, b\) in particular) couplings are not too suppressed. This large cross section will typically lead to a significant number of \(gg \rightarrow a \rightarrow \mu^+\mu^-\) events even though \(B(a \rightarrow \mu^+\mu^-)\) is small.

In the NMSSM context, where \(C_{\mu b\bar{b}} = \tan \beta \cos \theta_A\), the existing limits \[17,18\] translate to rather modest limits on \(|\cos \theta_A|\). Such bounds do not strongly constrain NMSSM models of interest for possibly hiding a light Higgs boson because of \(h \rightarrow aa\) decays \(\text{(with } a \rightarrow 2\tau, 2g, 2c, 2s \text{ decays being dominant [19]) that are not excluded by large electron-positron (LEP) collider experiments [20].}

At tree level, the branching fraction for \(a \rightarrow \mu^+\mu^-\) depends on \(m_a\) and on \(\tan \beta\), but not on \(\cos \theta_A\) \[16\]. It is nearly constant for \(m_a > 5\) GeV and ranges from \(10^{-3}\) to \(4 \times 10^{-3}\) for \(\tan \beta = 1\) to \(\tan \beta = 50\), changing very little once \(\tan \beta > 2\). In contrast, \(\sigma(gg \rightarrow a)\) increases rapidly with \(\tan \beta\) due to the fact that \(C_{\mu b\bar{b}} \propto \tan \beta\). However, top-quark loop contributions and higher-order corrections imply a slower \(\sigma(gg \rightarrow a)\) increase than \(\tan^2 \beta\). In the context of the NMSSM, all \(q\bar{q}\) couplings of the \(a_1\) are proportional to \(\cos \theta_A\), implying that \(\sigma(gg \rightarrow a_1) \propto \cos^2 \theta_A\).

This Letter presents the results of a search in pp collisions for a light \(a\) with a mass near the \(Y\) resonances decaying into two oppositely charged muons. Data used for this analysis were recorded by the Compact Muon Solenoid (CMS) detector in pp collisions at a center-of-mass energy of 7 TeV, between August and November 2011. The sample corresponds to a total integrated luminosity of 1.3 fb\(^{-1}\), collected with a dedicated trigger. As estimated in Ref. \[16\] and explicitly demonstrated here, CMS has sensitivity beyond the BaBar and CDF limits, for the latter due to the higher production yield \([\sigma_{\text{LHC}}(pp \rightarrow a) \sim 4.5 \sigma_{\text{Tevatron}}(p\bar{p} \rightarrow a)]\) and the higher...
acceptance and efficiency of the muon detector. Furthermore, the CMS analysis can extend the limits into the $m_a > m_{\Upsilon(3S)}$ mass range.

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 are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter and the brass/scintillator hadron calorimeter. Muons are measured by gas-ionization detectors embedded in the steel return yoke in the pseudorapidity range $|\eta| < 2.4$, ($\eta \equiv -\ln(\tan(\theta/2))$, where $\theta$ is the polar angle of the trajectory of a particle with respect to the direction of the counterclockwise proton beam) using three detector technologies: drift tubes (DT) (for the range $|\eta| < 1.2$), resistive plate chambers (RPC) (for $|\eta| < 1.6$) and cathode strip chambers (CSC) (for $0.9 < |\eta| < 2.4$). The DT and RPC are indicated as the central “barrel” while the CSC comprises the “endcaps”. A more detailed description of the CMS detector can be found in [21].

We search the dimuon invariant mass distribution between 5.5 and 8.8 GeV (defined as “mass range 1”) and between 11.5 and 14 GeV (“mass range 2”) for a narrow resonance $a$, with a decay width $\sim$ MeV, natural in the NMSSM context. We avoid the range between 9 and 11 GeV because the abundant contributions of the bottomonium resonances to the mass spectrum makes this search unfeasible. Selection criteria are applied to reduce backgrounds from QCD continuum, and we perform a mass scan in mass ranges 1 and 2 to determine a potential contribution from an $a$ signal. Given the better mass resolution in the barrel part of the detector than in the endcaps, we also separate the mass scan into two acceptance regions, based on the dimuon $\eta$, in order to improve the sensitivity.

We analyze events collected with an online selection that requires the detection of two oppositesign muons with transverse momenta $p_T > 3.5$ GeV and additional requirements imposed at the high level trigger (HLT). All three muon systems, DT, CSC, and RPC, take part in the trigger decision. A good primary vertex is also required, as defined in Ref. [22]. The additional HLT requirements include $p_T(\mu^+\mu^-) > 6$ GeV, $5.5 < m_{\mu^+\mu^-} < 14$ GeV, and a distance of closest approach of the muon tracks to the beam axis compatible with that expected for prompt decays. A prescale factor of two was imposed on the trigger to maintain a reasonable trigger rate.

The main backgrounds arise from QCD processes and, in the lower invariant mass range, from a residual tail of the $\Upsilon(1S)$ resonance. We determine the background shape in the invariant mass directly from data, and use simulated events as a cross-check. Signal samples, QCD, and $\Upsilon$ resonances are simulated with PYTHIA 6.4.24, Tune D6T [23], and CTEQ6 parton distribution functions [24]. Tune Z2 gives compatible results. As the NMSSM is not fully implemented in PYTHIA, we generate the MSSM pseudoscalar A boson in the mass range of 5.5 to 14 GeV and require dimuon decays. These samples also contain a simulation of the effects on the number of primary vertices from overlapping pp interactions in the same bunch crossing.

To select the best dimuon candidate in each event, quality criteria are applied to the tracks which reject misidentified muons and muons from kaon and pion decays. Muons are required to be within the geometrical acceptance ($|\eta| \leq 2.4$) and to be in the plateau of the trigger efficiency, with $p_T > 5.5$ GeV. Muon tracks are required to have at least 11 hits in the silicon tracker, at least one of which must be in the pixel detector, and a track fit $\chi^2$/dof < 1.8. This value is chosen to maximize the signal significance with respect to the QCD continuum, which is extracted directly from data.

Isolation requirements suppress misidentified leptons from jets and non-prompt muons from hadron decays. Muons are required to be isolated within a cone of radius $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.3$ around the muon direction, where $\phi$ is the azimuthal angle. The muon isolation, $I_{rel}$, is
Figure 1: Dimuon invariant mass distribution for the barrel (upper) and endcaps (lower) after the event selection. The invariant mass distributions are fitted accounting for the three $\Upsilon$ resonances and QCD continuum. Hypothetical signals from pseudoscalar Higgs bosons $a$ at 7 and 12 GeV are shown.

Defined as the sum of the $p_T$ (as measured in the silicon tracker) and transverse energy (as measured in the calorimeters) of all objects within this cone (excluding the muon itself), divided by the muon $p_T$ as measured by the tracker. We require $I_{rel} < 0.2$. This requirement is optimized by comparing the simulated signal with opposite-sign dimuons from data, and we verify that this value is appropriate for both the barrel and endcap dimuon pairs. This isolation requirement rejects a large fraction of the background arising from QCD production of jets.

Dimuon candidates consist of two opposite-sign muons [25] with an invariant mass between 5.5 and 14 GeV. If more than one dimuon candidate is present, that with the highest $\chi^2$ probability associated to the kinematic fit of the dimuon vertex is retained.

The invariant mass spectrum in the search range has two main contributions: the QCD continuum and the bottomonium resonances. To characterize these shapes for use in the mass scan, we perform a binned maximum likelihood fit to the total invariant mass distribution. For the QCD continuum, we use a first-order polynomial probability density function (PDF). Each $\Upsilon$ resonance is parametrized via a double Crystal Ball (CB) function [26, 27]. The resolution of one of the CB functions is left free in the fit but is constrained to be the same for all the three resonances. The resolution of the second CB function is determined from the fit of the $\Upsilon(1S)$ peak, and forced to scale with the mass of the other two resonances. As the resonances overlap, we fit for the presence of all three $\Upsilon$ states simultaneously using three double CB functions. The mean of the CB of the $\Upsilon(1S)$ is left free in the fit to accommodate a possible bias in the
momentum scale calibration. The number of free parameters is reduced by fixing the $Y(2S)$ and $Y(3S)$ mass differences, relative to $Y(1S)$, to their world average values [6].

The fits to the $Y$ shape and continuum background are performed in the barrel and endcap regions separately, shown in Fig. and the fitted numbers of events are given in Table. Outside the $Y$ peak range, corresponding to the signal search mass ranges, the data are well-described by a first-order polynomial. Figure also shows hypothetical signals from pseudoscalar Higgs bosons $a$ with masses 7 and 12 GeV, and 2 pb cross sections, scaled by a factor of 10 for visibility. We perform mass scans of the invariant mass spectra, dividing mass range 1 into 110 steps and mass range 2 into 100 steps of 30 MeV each, and treating the barrel and endcap spectra separately. At each step, we build a signal Gaussian PDF with a mean fixed to the center of the step and a width determined by the mass resolution, use a first-order polynomial to characterize the background, and perform an unbinned maximum likelihood fit to search for a possible contribution from the $a$. For each signal mass point, we determine the resolution by fitting the $a$ invariant mass spectrum with two CB functions (similar to that for the $Y$) and the mass resolution is calculated as the weighted average of the widths of the two functions. The resulting dimuon invariant mass resolution ranges from 50 to 120 MeV (90 to 190 MeV) in the barrel (endcaps) for the mass range 5.5 to 14 GeV. These agree well with the resolution obtained from the $Y$ resonances in data and MC. We fit the resolution as a function of mass using the simulated signal samples, and use this to extract the values of the dimuon mass resolution for each mass bin needed in the scan to determine the upper limit.

In mass range 1, we take into account the radiative tail of the $Y(1S)$ by including its shape determined from the full invariant mass spectrum fit. No significant discrepancy with SM background predictions is observed, and we proceed to set cross section limits, as described below.

Table 1: Fitted numbers of $Y$ and continuum background events in the invariant mass range 5.5–14 GeV. The $Y$ contributions are summed over the three resonances.

| Contribution | events (barrel) | events (endcaps) |
|--------------|----------------|------------------|
| $Y$          | $93753 \pm 396$ | $95876 \pm 454$  |
| Continuum    | $41210 \pm 320$ | $45792 \pm 385$  |

The efficiency for the selection is factorized into three contributions, $\epsilon = \epsilon_{\text{acc}} \times \epsilon_{\text{trig}} \times \epsilon_{\text{sel}}$, where $\epsilon_{\text{acc}}$ is the kinematic acceptance for the $a$, $\epsilon_{\text{trig}}$ is the efficiency of the muon trigger, and $\epsilon_{\text{sel}}$ is the efficiency of the selection applied to the dimuon candidates. We use PYTHIA 6 to simulate the $a$ signal and to determine $\epsilon_{\text{acc}}$. The trigger and selection efficiencies ($\epsilon_{\text{trig}}$ and $\epsilon_{\text{sel}}$) are measured with $J/\psi$ events in data using the tag-and-probe technique [27]. We perform this study in bins of $\eta$ and $p_T$ of the probe muon. The efficiency values extracted from data are compared with those obtained from the simulation of prompt $J/\psi \rightarrow \mu^+ \mu^-$. The difference between the efficiency in data and Monte Carlo (MC) simulation is evaluated in bins of $p_T$ and $\eta$ and used as a correction to weight the MC events in order to accommodate possible discrepancies. These corrections are typically on the order of a few percent. For each dimuon candidate, the weight is the product of the corrections for the two muons.

The isolation requirement efficiency that contributes to $\epsilon_{\text{sel}}$ cannot be measured using the $J/\psi$ dataset as one of the main production mechanisms for $J/\psi$ is through B-meson decays, resulting in non-isolated muons. This is not well accounted for in simulation, and would result in biased data/MC efficiency corrections. In order to estimate this correction, we use $Z \rightarrow \mu^+ \mu^-$ events and consider the lower $p_T$ spectrum of the probe muon.
The total efficiency $\epsilon$ is defined for each $a$ mass sample as the fraction of generated signal events, weighted by the appropriate data/MC corrections, that satisfy all the selection requirements. This ranges from 1–3.5% for the $a$ mass range of 5.5–14 GeV, and we fit the $\epsilon$ distributions with second (third) order polynomial functions in the barrel (endcaps) to use in the mass scan. The increase in the efficiency as a function of the invariant mass is mainly due to the $p_T$ requirements on the muons at the HLT level.

Several sources of systematic uncertainty affect these results, including a 2.2% uncertainty on the integrated luminosity [28]. The efficiency corrections are determined using the tag-and-probe results described above. We determine, event-by-event, the uncertainty on the total efficiency corrections by propagating the uncertainties on the single muon corrections. This total event efficiency uncertainty is largely independent of mass, with a maximum value of 12%. We apply this value as a systematic uncertainty for every bin in the scan.

The isolation efficiency is uncertain at the 5% level, corresponding to the largest discrepancy between data and MC simulation in the entire relevant $p_T$ range. We evaluate the systematic uncertainty on the resolution of the $a$ as the quadrature sum of the difference between the mass resolution of the $a$ with a mass of 10 GeV and the resolution of the $\Upsilon(2S)$ (which has the same mass) in MC simulation, and the difference between the latter and the mass resolution obtained for the $\Upsilon(2S)$ from data. Additionally, the finite statistics for the determination of the mass resolution as a function of the dimuon mass contributes a source of uncertainty. We consider the mass ranges separately and include these systematic uncertainties in the calculation of the upper limit on the cross section times branching fraction. Overall, this adds a 11% (4%) effect for the barrel (endcaps).

Systematic uncertainties on the background description include the shape uncertainty of the first-order polynomial fit of the background PDF. We fit the background with alternative functions (a second-order polynomial and an exponential function), generate MC pseudo-experiments using these functions, and fit the distributions using the first-order polynomial. The resulting systematic uncertainties, from the distribution of the fitted parameters, is of the order of a few percent.

No significant signal is observed, and we determine 95% confidence level (CL) upper limits on $\sigma \cdot B(pp \to a \to \mu^+\mu^-)$ as a function of the dimuon mass using the CLs approach [29–31]. A small number of steps at the edges of the mass scans where the fitting procedure fails to converge are not used. Figure 2 shows the upper limit results for the two mass ranges including the systematic uncertainties discussed above. These limits are significant in the context of the NMSSM, and can be presented in terms of upper limits on $|\cos \theta_A|$. The larger the value of $\tan \beta$, the stronger is the constraint. Figure 3 presents upper limits, $|\cos \theta_A|^{\text{max}}$ as a function of $m_{a_1}$ for $\tan \beta = 1, 2, 3, 10, 30, 50$. Our upper limits are compared to an earlier analysis of the BaBar $\Upsilon(1S)$ and $\Upsilon(3S)$ data [32], and are superior for $m_{a_1} \geq 7.5$ GeV for $\tan \beta = 50$, decreasing to $m_{a_1} \geq 6$ GeV for $\tan \beta = 2$, and are superior for all masses at $\tan \beta = 1$. Further, these are the first significant limits for $m_{a_1} > m_{\Upsilon(3S)}$.

In conclusion, we performed a search for a narrow, low mass pseudoscalar $a$, which is produced by $gg \to a$ and decays via $a \to \mu^+\mu^-$ in the mass ranges 5.5–8.8 GeV and 11.5–14 GeV, using a data sample corresponding to an integrated luminosity of 1.3 fb$^{-1}$ collected with the CMS detector. No significant signal is observed, and we set upper limits on $\sigma \cdot B(pp \to a \to \mu^+\mu^-)$. These upper limits are applied in the context of the light pseudoscalar $a_1$ of the NMSSM to yield upper limits on the NMSSM parameter $|\cos \theta_A|$. These limits are superior to existing constraints for a significant portion of the $m_{a_1} < m_{\Upsilon(1S)}$ mass range, and are the first significant limits available in the $m_{a_1} > m_{\Upsilon(3S)}$ mass range.
Figure 2: Upper limits at 95% CL on $\sigma \cdot B(pp \rightarrow a \rightarrow \mu^+\mu^-)$ in the two mass ranges including systematic uncertainties. The dotted lines correspond to the expected limits, and the bands correspond to 1- and 2-$\sigma$ level uncertainties on the expected limits.
Figure 3: Upper limits on the NMSSM parameter $|\cos\theta_A|$ as a function of $m_{a_1}$ in the two mass ranges. The solid curves correspond to different $\tan\beta$ values: from top to bottom, $\tan\beta = 1$, $\tan\beta = 2$, $\tan\beta = 3$, $\tan\beta = 10$, $\tan\beta = 30$, and $\tan\beta = 50$. For each $\tan\beta$ value in mass range 1 the second, dotted curve shows the limits from the BaBar $\Upsilon$ analysis. There are no BaBar limits for $\tan\beta = 1$ in mass range 1, or for any $\tan\beta$ in mass range 2. The line at $|\cos\theta_A|_{\text{max}} = 1$ is equivalent to no limit. Results from CDF are not shown as they are less stringent than the BaBar limits.
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A The CMS Collaboration

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

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan1, M. Friedl, R. Frühwirth1, V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler1, W. Kiesenhofer, V. Knünz, M. Krammer1, D. Liko, I. Mikulec, M. Pernicka1, B. Rahbaran, C. Rohringer, H. Rohringer, R. Schönbeck, J. Strauss, A. Taurok, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz1

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

Universiteit Antwerpen, Antwerpen, Belgium
S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeek

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, S. Blyweert, J. D’Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Derienck, P. Van Mulders, G.P. Van Onsem, I. Villeda

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, T. Reis, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium
V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. McCartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, G. Bruno, R. Castello, A. Caudron, L. Cerdà, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco2, J. Hollar, V. Lemaître, J. Liao, O. Militaru, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrzkowski, N. Schul, J.M. Vizan Garcia

Université de Mons, Mons, Belgium
N. Beliy, T. Caebers, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldan Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznaier

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
C.A. Bernardes3, F.A. Dias4, T.R. Fernandez Perez Tomei, E. M. Gregores3, C. Lagana, F. Marinho, P.G. Mercadante3, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev5, P. Iaydjiev5, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova
University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, S. Wang, B. Zhu, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, R. Plestina, D. Polic, I. Puljak

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

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

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran, S. Elgamal, A. Ellithi Kamel, S. Khalil, M.A. Mahmoud, A. Radi

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
M. Kadastik, M. Muinlo, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland
V. Azzolini, P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Harikonen, A. Heikkinen, V. Karimaki, R. Kinnunen, M.J. Kortelainen, T. Lampen, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenaier, P. Miné, C. Mironov, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Siros, C. Veelken, A. Zabi
Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte, F. Drouhin, C. Ferro, J.-C. Fontaine, D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, N. Beaufere, O. Bondou, G. Boudoul, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

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

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teissier, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M. Bontenackels, V. Cherepanov, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
C. Autermann, V. Blobel, S. Bobrovskyi, J. Draeger, H. Enderle, J. Erle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, H. Stadie, G. Steinbrück, J. Thomsen
Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff, C. Hackstein, F. Hartmann, T. Hauth, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov, J.R. Komaragiri, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, A. Scheurer, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece
G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

University of Athens, Athens, Greece
L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
G. Bencze, C. Hajdu, P. Hidas, D. Horvath, F. Sikler, V. Veszpremi, G. Vesztergombi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czeizel, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary
J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India
S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J. Singh

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

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, S. Ganguly, M. Guhait, M. Maity, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India
S. Banerjee, S. Dugad

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Arfaei, H. Bakhshiansoohi, S.M. Etesami, A. Fahim, M. Hashemi, A. Jafari, M. Khakzad, A. Mohammadi, M. Mohammadi Najafabadi, S. Paktinat Mehdizadeh, B. Safarzadeh, M. Zeinali
A The CMS Collaboration

INFIN Sezione di Roma $^a$, Università di Roma “La Sapienza” $^b$, Roma, Italy
L. Barone$^{a,b}$, F. Cavallari$^b$, D. Del Re$^{a,b,5}$, M. Diemoz$^a$, M. Grassi$^{a,b,5}$, E. Longo$^{a,b}$, P. Meridiani$^{a,5}$, F. Micheli$^{a,b}$, S. Nourbakhsh$^{a,b}$, G. Organtini$^{a,b}$, R. Paramatti$^a$, S. Rahatlou$^{a,b}$, M. Sigamani$^a$, L. Soffi$^{a,b}$

INFIN Sezione di Torino $^a$, Università di Torino $^b$, Università del Piemonte Orientale (Novara) $^c$, Torino, Italy
N. Amapane$^{a,b}$, R. Arcidiacono$^{a,c}$, S. Argiro$^{a,b}$, M. Arneodo$^{a,c}$, C. Biino$^a$, N. Cartiglia$^a$, M. Costa$^{a,b}$, N. Demaria$^a$, A. Graziano$^{a,b}$, C. Mariotti$^{a,5}$, S. Maselli$^a$, E. Migliore$^{a,b}$, V. Monaco$^{a,b}$, M. Musich$^{a,5}$, M.M. Obertino$^{a,c}$, N. Pastrone$^a$, M. Pelliccioni$^a$, A. Potenza$^{a,b}$, A. Romero$^{a,b}$, M. Ruspa$^{a,c}$, R. Sacchi$^{a,b}$, V. Sola$^{a,b}$, A. Solano$^{a,b}$, A. Staiano$^a$, A. Vilela Pereira$^a$

INFIN Sezione di Trieste $^a$, Università di Trieste $^b$, Trieste, Italy
S. Belforte$^a$, V. Candelise$^{a,b}$, F. Cossutti$^a$, G. Della Ricca$^{a,b}$, B. Gobbo$^a$, M. Marone$^{a,b,5}$, D. Montanino$^{a,b,5}$, A. Penzo$^a$, A. Schizzi$^{a,b}$

Kangwon National University, Chunchon, Korea
S.G. Heo, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea
S. Chang, J. Chung, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
J.Y. Kim, Zero J. Kim, S. Song

Korea University, Seoul, Korea
S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

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

Sungkyunkwan University, Suwon, Korea
Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania
M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood
National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoab

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland
H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
N. Almeida, P. Bargassa, A. David, P. Faccioli, M. Fernandes, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
I. Belotelov, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia
S. Evtuhykhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

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

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov³, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴, L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M.Perfilov, S. Petrushanko, A. Popov, L. Sarycheva†, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin⁵, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourchanovich, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic³¹, M. Djordjevic, M. Ekmedzic, D. Krpic³¹, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo
Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. García-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

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

Universidad de Oviedo, Oviedo, Spain
H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, C. Bernet, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D’Enterría, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, T. Maki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimià, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi, T. Rommerskirchen, C. Rovelli, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Spichalski, D. Spiga, M. Spiropulu, M. Stoye, A. Tsirou, G.I. Veres, J.R. Vlimant, H.K. Wöhri, S.D. Worm, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Dürrser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov, B. Stieger, M. Takahashi, L. Tauscher, A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Universität Zürich, Zurich, Switzerland
E. Aguilo, C. Amsler, V. Chiocchia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otioougoua, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

National Central University, Chung-Li, Taiwan
Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci, S. Cerci, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, G. Karapinar, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk, A. Polatoz, K. Sogut, D. Sunar Cerci, B. Tali, H. Topakli, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, B. Isildak, M. Kaya, O. Kaya, S. Ozkorucuklu, N. Sonmez

Istanbul Technical University, Istanbul, Turkey
K. Cankocak

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

University of Bristol, Bristol, United Kingdom
F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso, K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom
R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futhan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko, A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi, D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Brunel University, Uxbridge, United Kingdom
M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA
O. Charaf, C. Henderson, P. Rumerio
Boston University, Boston, USA
A. Avetisyan, T. Bose, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA
J. Alimena, S. Bhattacharya, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, J. Gunion, R. Houtz, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, F. Ricci-tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Los Angeles, Los Angeles, USA
V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein1, J. Tucker, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng51, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA
W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech52, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, R. Bellan, C. Campagnari, M. D’Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lovette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA
A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
B. Akgun, R. Carroll, T. Ferguson, Y. liyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA
J.P. Cumalat, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA
D. Winn
Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko53, C. Newman-Holmes, V. O’Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Updegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, M. Chen, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic54, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA
V. Gaultney, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
J.R. Adams, T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, C. Dragoiu, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O’Brien, C. Silkworth, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki55, W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermekkaya56, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA
B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA
A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA
A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn,
T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA
G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar57, W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephens, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA
S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, University, USA
L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA
A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA
L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

The Ohio State University, Columbus, USA
B. Bylsma, L.S. Durkin, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

Princeton University, Princeton, USA
N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA
J.G. Acosta, E. Brownson, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyan

Purdue University, West Lafayette, USA
E. Alagöz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng
Purdue University Calumet, Hammond, USA
S. Guragain, N. Parashar

Rice University, Houston, USA
A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, A. Garcia-Bellido, P. Goldenzwieg, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA
A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

Rutgers, the State University of New Jersey, Piscataway, USA
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, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA
G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA
R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Sook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA
M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood, R. Yohay

Wayne State University, Detroit, USA
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, USA
M. Anderson, M. Bachits, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
3: Also at Universidade Federal do ABC, Santo Andre, Brazil
4: Also at California Institute of Technology, Pasadena, USA
5: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
6: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
7: Also at Suez Canal University, Suez, Egypt
8: Also at Zewail City of Science and Technology, Zewail, Egypt
9: Also at Cairo University, Cairo, Egypt
10: Also at Fayoum University, El-Fayoum, Egypt
11: Also at Ain Shams University, Cairo, Egypt
12: Now at British University, Cairo, Egypt
13: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
14: Also at Université de Haute-Alsace, Mulhouse, France
15: Now at Joint Institute for Nuclear Research, Dubna, Russia
16: Also at Moscow State University, Moscow, Russia
17: Also at Brandenburg University of Technology, Cottbus, Germany
18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
19: Also at Eötvös Loránd University, Budapest, Hungary
20: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
21: Also at University of Visva-Bharati, Santiniketan, India
22: Also at Sharif University of Technology, Tehran, Iran
23: Also at Isfahan University of Technology, Isfahan, Iran
24: Also at Shiraz University, Shiraz, Iran
25: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
26: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
27: Also at Università della Basilicata, Potenza, Italy
28: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
29: Also at Università degli studi di Siena, Siena, Italy
30: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania
31: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
32: Also at University of Florida, Gainesville, USA
33: Also at University of California, Los Angeles, Los Angeles, USA
34: Also at Scuola Normale e Sezione dell’ INFN, Pisa, Italy
35: Also at INFN Sezione di Roma; Università di Roma “La Sapienza”, Roma, Italy
36: Also at University of Athens, Athens, Greece
37: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
38: Also at The University of Kansas, Lawrence, USA
39: Also at Paul Scherrer Institut, Villigen, Switzerland
40: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
41: Also at Gaziosmanpasa University, Tokat, Turkey
42: Also at Adiyaman University, Adiyaman, Turkey
43: Also at The University of Iowa, Iowa City, USA
44: Also at Mersin University, Mersin, Turkey
45: Also at Ozyegin University, Istanbul, Turkey
46: Also at Kafkas University, Kars, Turkey
47: Also at Suleyman Demirel University, Isparta, Turkey
48: Also at Ege University, Izmir, Turkey
49: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
50: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
51: Also at University of Sydney, Sydney, Australia
52: Also at Utah Valley University, Orem, USA
53: Also at Institute for Nuclear Research, Moscow, Russia
54: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
55: Also at Argonne National Laboratory, Argonne, USA
56: Also at Erzincan University, Erzincan, Turkey
57: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
58: Also at Kyungpook National University, Daegu, Korea