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Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-muon final states

The CMS Collaboration*

Abstract

Results are reported from a search for non-standard-model Higgs boson decays to pairs of new light bosons, each of which decays into the $\mu^+\mu^-$ final state. The new bosons may be produced either promptly or via a decay chain. The data set corresponds to an integrated luminosity of $5.3\,\mathrm{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$, recorded by the CMS experiment at the LHC. Such Higgs boson decays are predicted in several scenarios of new physics, including supersymmetric models with extended Higgs sectors or hidden valleys. Thus, the results of the search are relevant for establishing whether the new particle observed in Higgs boson searches at the LHC has the properties expected for a standard model Higgs boson. No excess of events is observed with respect to the yields expected from standard model processes. A model-independent upper limit of $0.78 \pm 0.05\,\mathrm{fb}$ on the product of the cross section times branching fraction times acceptance is obtained. The results are applicable to a broad spectrum of models and are also compared with the predictions of two benchmark scenarios as functions of a Higgs boson mass within the range 86–150 GeV/c^2 and of a new light boson mass within the range 0.25–3.55 GeV/c^2.

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*See Appendix A for the list of collaboration members

The observation of a new particle [1, 2] with a mass near 125 GeV/c^2 in searches for the standard model (SM) Higgs boson [3–5] at the Large Hadron Collider (LHC) raises the critical question of whether the new particle is in fact the SM Higgs boson. The precision of the comparisons of the new particle's production and decay properties with the final states predicted by the SM will improve with additional data. However, distinguishing a true SM Higgs boson from a non-SM Higgs bosons with couplings moderately different from the SM values will remain a challenge. Searches for non-SM Higgs boson production and decay modes are therefore particularly timely as they provide a complementary path, which in many cases can allow a discovery or rule out broad ranges of new physics scenarios with existing data.

This Letter presents a search for the production of a non-SM Higgs boson (h) decaying into a pair of new light bosons (a) of the same mass, which subsequently decay to pairs of oppositely charged muons (*dimuons*) isolated from the rest of the event activity ($\mathrm{h} \to 2\mathrm{a} + \mathrm{X} \to 4\mu + \mathrm{X}$, where X denotes possible additional particles from cascade decays of a Higgs boson). This sequence of decays is predicted in several classes of models beyond the SM. One example is the next-to-minimal supersymmetric standard model (NMSSM) [6–14], which extends of the minimal supersymmetric standard model (MSSM) [15–17] by an additional field (gauge singlet under new $U(1)_{PQ}$ symmetry) in the Higgs sector of the superpotential. Compared to the MSSM, the NMSSM resolves the so-called μ-problem (generation of the mass parameter μ in the Higgs superpotential at the electroweak scale [18]) and significantly reduces the amount of fine tuning required [19–21].

In the NMSSM, the CP-even Higgs bosons h_1 and h_2 (one of them is the SM-like Higgs boson) can decay via $\mathrm{h}_{1,2} \to 2\mathrm{a}_1$, where a_1 is a new CP-odd light Higgs boson [22–26]. The Higgs boson production cross section may differ substantially from that of the SM, depending on the parameters of a specific model: e.g., a high singlet fraction in h_1 (or h_2) suppresses its couplings to SM particles. The new light boson a_1 couples weakly to SM particles, with the coupling to fermions proportional to the fermion mass, and can have a substantial branching fraction $\mathcal{B}(\mathrm{a}_1 \to \mu^+\mu^-)$ if its mass is within the range $2m_\mu < m_{\mathrm{a}_1} < 2m_\tau$ [27, 28].

Pair production of light bosons can also occur in supersymmetric models with additional hidden (or *dark*) valleys [29–31], which can be motivated by the excesses in positron spectra observed by satellite experiments [32, 33]. These dark-SUSY models predict cold dark matter with a mass scale of ~ 1 TeV/c^2, which can provide the right amount of relic density due to the Sommerfeld enhancement in the annihilation cross section arising from a new $U(1)_D$ symmetry [34, 35]. In these models, $U(1)_D$ is broken, giving rise to light but massive dark photons γ_D that weakly couple to the SM particles via a small kinetic mixing [36–38] with photons. The lightest neutralino n_1 in the *visible* (as opposed to *hidden*) part of the SUSY spectrum is no longer stable and can decay via e.g. $\mathrm{n}_1 \to \gamma_D + \mathrm{n}_D$, where n_D is a light dark fermion (dark neutralino) that escapes detection. The SM-like Higgs boson can decay via $\mathrm{h} \to 2\mathrm{n}_1$, if $m_\mathrm{h} > 2m_{\mathrm{n}_1}$. The branching fraction $\mathcal{B}(\mathrm{h} \to 2\mathrm{n}_1)$ can vary from very small to large (bounded by the LHC measurements of the $\mathrm{h} \to \mathrm{ZZ}$ decay branching fraction). The lack of an anti-proton excess in the measurements of the cosmic ray spectrum constrains the mass of γ_D to be $\leq \mathcal{O}(1)$ GeV/c^2 [39]. Assuming that γ_D can only decay to SM particles, the branching fraction $\mathcal{B}(\gamma_D \to \mu^+\mu^-)$ can be as large as 45%, depending on m_{γ_D} [31]. The Higgs boson production cross section may or may not be enhanced compared to the SM, depending on the specific parameters of the model. The search described in this Letter was designed to be independent of the details of specific models, and the results can be interpreted in the context of other models predicting the production of the same final states.

Previous searches for the pair production of new light bosons decaying into dimuons were performed at the Tevatron with a 4.2 fb^{-1} data sample [40] and more recently at the LHC with a 35 pb^{-1} data sample [41]. Associated production of the light CP-odd scalar bosons has been searched for at e^+e^- colliders [42, 43] and the Tevatron [44]. Direct production of the a_1 has been studied at the LHC [45], but in the framework of NMSSM the sensitivity of these searches is limited by the typically very weak coupling of the a_1 to SM particles. The most stringent limits on NMSSM are provided by the WMAP data [46] and LEP searches [47–49] ($m_{h_1} > 86\,\mathrm{GeV}/c^2$). In the framework of dark SUSY, experimental searches for γ_D have focused on the production of dark photons at the end of SUSY cascades at the Tevatron [50–52] and the LHC [41]. Furthermore, if the newly observed particle at the LHC [1, 2] is indeed a Higgs boson, the studies of its SM decays will provide additional constraints on the allowed branching fractions for the non-SM decays.

The analysis presented in this Letter uses experimental data collected by the Compact Muon Solenoid (CMS) experiment at the LHC. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. The inner tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the direction of the counterclockwise proton beam that is the z-axis of the CMS reference frame. The tracker provides an impact parameter resolution of $\sim$15 μm and a transverse momentum (p_T) resolution of about 1.5% for 100 GeV/c particles. Muons are measured in gas-ionization detectors embedded in the steel return yoke. The detectors are made using the following technologies: drift tubes ($|\eta| < 1.2$), cathode strip chambers ($0.9 < |\eta| < 2.4$), and resistive-plate chambers ($|\eta| < 1.6$). Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution between 1and 5% for p_T values up to 1 TeV/c. A more detailed description can be found in Ref. [53].

The search is performed as a "blind" analysis (the signal region was not used to define the reconstruction and selection procedures) based on a data sample corresponding to an integrated luminosity of 5.3 fb^{-1} collected with a trigger selecting events containing at least two muons, one with $p_T > 17\,\mathrm{GeV}/c$ and one with $p_T > 8\,\mathrm{GeV}/c$. In the offline analysis, events are selected by requiring at least one primary vertex reconstructed with at least four tracks and with its z coordinate within 24 cm of the nominal collision point. Offline muon candidates are built using tracks reconstructed in the inner tracker matched to track segments in the muon system, using an arbitration algorithm [54]. The candidates are further required to have at least eight hits in the tracker, with the $\chi^2/\mathrm{Ndof} < 4$ for the track fit in the inner tracker (where Ndof is the number of degrees of freedom), and at least two matched segments in the muon system. The data are further selected by requiring at least four offline muon candidates with $p_T > 8\,\mathrm{GeV}/c$ and $|\eta| < 2.4$; at least one of the candidates must have $p_T > 17\,\mathrm{GeV}/c$ and be reconstructed in the central region, $|\eta| < 0.9$. Application of the selection requirements described above yields 1,745 events in the data. The trigger efficiency for the selected events is high (96–97%) and is nearly independent of the p_T and η of any of the four muons. The $|\eta| < 0.9$ requirement is tighter than that imposed by the trigger, but eliminates significant model dependence attributable to the reduced trigger performance in the forward region in the presence of multiple spatially close muons. This η requirement causes an overall reduction in the analysis acceptance of about 20%, as obtained in a simulation study with one of the NMSSM benchmark samples used in the analysis.

Next, oppositely charged muons are grouped into dimuons (a muon may be shared between several dimuons) if their pairwise invariant mass satisfies $m_{\mu\mu} < 5\,\mathrm{GeV}/c^2$ and if either the fit of the two muon tracks for a common vertex has a χ^2 fit probability greater than 1% or the two muon tracks satisfy the cone size requirement $\Delta R(\mu^+,\mu^-) = \sqrt{(\eta_{\mu^+} - \eta_{\mu^-})^2 + (\phi_{\mu^+} - \phi_{\mu^-})^2} < 0.01$, where ϕ is the azimuthal angle in radians. The ΔR requirement compensates for the reduced efficiency of the vertex probability requirement for dimuons with very low mass ($m_{\mu\mu} \gtrsim 2m_\mu$), in which the two muon tracks are nearly parallel to each other at the point of closest approach.

Once all dimuons are constructed, only events with exactly two dimuons not sharing common muons are selected for further analysis. There is no restriction on the number of ungrouped *(orphan)* muons. Assuming that each dimuon is a decay product of a new light boson, we require that the two dimuons have invariant masses in the range 0.25–3.55 GeV/c^2. We reconstruct $z_{\mu\mu}$, the z coordinate of the dimuon system at the point of the closest approach to the beam line, using the dimuon momentum measured at the common vertex and the vertex position. We ensure that the two dimuons originate from the same pp interaction by requiring $|z_{\mu\mu_1} - z_{\mu\mu_2}| < 1$ mm. This selection yields 139 events in data and it is fully efficient for signal events while reducing the probability of selecting rare events with dimuons from two separate primary interactions.

To suppress SM background, we require that the dimuons be isolated from other activity in the event, using the criterion $I_{\text{sum}} < 3$ GeV/c, where the isolation parameter of the dimuon system I_{sum} is defined as the scalar sum of the transverse momenta of all additional charged tracks with $p_{\text{T}} > 0.5$ GeV/c within a cone of size $\Delta R = 0.4$ centered on the momentum vector of the dimuon system. Tracks used in the calculation of I_{sum} must also have a z coordinate at the point of the closest approach to the beam line that lies within 1 mm of the z coordinate of the dimuon system. The I_{sum} selection yields three events in data and it suppresses the contamination from $\text{b}\bar{\text{b}}$ production by about a factor of 40 (measured in data) while rejecting less than 10% of the signal events (obtained from the simulation study).

Finally, we require that the invariant masses of the two reconstructed dimuons are compatible with each other within the detector resolution $|m_1 - m_2| < 0.13\,\text{GeV}/c^2 + 0.065 \times (m_1 + m_2)/2$, where $m_1 = m_{\mu\mu_1}$ and $m_2 = m_{\mu\mu_2}$. The numerical parameters in this last requirement correspond to at least five times the size of the core resolution in dimuon mass, including the differences in resolution in the central and forward regions. The inefficiency of this $m_1 \simeq m_2$ selection is less than 5% per event; it is due to QED final-state radiation and is unrelated to the detector resolution.

To illustrate the performance of the analysis to select possible signal, we use the two benchmark models introduced earlier. The NMSSM samples are simulated with the PYTHIA 6.4.26 event generator [55] using MSSM Higgs boson production via gluon-gluon fusion $\text{gg} \to \text{H}^0_{\text{MSSM}}$, where the Higgs bosons are forced to decay via $\text{H}^0_{\text{MSSM}} \to 2\text{A}^0_{\text{MSSM}}$. The masses of H^0_{MSSM} and A^0_{MSSM} are set to the desired values for the h_1 mass (within the range 86–150 GeV/c^2) and a_1 mass (within the range 0.25–3.55 GeV/c^2), respectively. Both A^0_{MSSM} bosons are forced to decay to a pair of muons. The dark-SUSY samples are simulated with the MADGRAPH 4.5.2 event generator [56] using SM Higgs boson production via gluon-gluon fusion $\text{gg} \to \text{h}_{\text{SM}}$, where the mass of h_{SM} is set to the desired value for the h mass (within the range 90–150 GeV/c^2). The BRIDGE software [57] was used to implement the new physics model that forces the Higgs bosons h_{SM} to undergo a non-SM decay to a pair of neutralinos n_1, each of which decays $\text{n}_1 \to \text{n}_D + \gamma_D$, where $m_{\text{n}_1} = 10$ GeV/c^2, $m_{\text{n}_D} = 1$ GeV/c^2 and $m_{\gamma_D} = 0.4$ GeV/c^2. Both dark photons γ_D are forced to decay to two muons, while both dark neutralinos n_D escape detection. In each case the narrow width approximation is imposed by setting the widths of the Higgs bosons and dark photons to a small value (10^{-3} GeV/c^2).

Table 1: Event selection efficiencies $\epsilon(m_{h_1}, m_{a_1})$ with statistical uncertainties for the NMSSM benchmark scenario, as obtained from simulation.

m_{h_1} [GeV/c^2]	90	100	100	100	100	100	125	150
m_{a_1} [GeV/c^2]	2	0.25	0.5	1	2	3	2	2
ϵ_{full} [%]	12.1 ± 0.1	34.9 ± 0.2	18.1 ± 0.2	15.5 ± 0.1	14.7 ± 0.1	14.5 ± 0.1	20.0 ± 0.1	24.0 ± 0.1
α_{gen} [%]	16.6 ± 0.1	47.0 ± 0.2	24.2 ± 0.3	20.9 ± 0.1	20.0 ± 0.1	19.9 ± 0.1	27.5 ± 0.1	33.2 ± 0.1
$\epsilon_{full}/\alpha_{gen}$ [%]	73.0 ± 0.3	74.2 ± 0.2	74.5 ± 0.6	73.9 ± 0.3	73.5 ± 0.3	72.6 ± 0.3	72.6 ± 0.3	72.2 ± 0.2

Table 2: Event selection efficiencies $\epsilon(m_h, m_{\gamma_D})$ with statistical uncertainties for a dark-SUSY benchmark model, as obtained from simulation.

m_h [GeV/c^2]	90	125	150
m_{γ_D} [GeV/c^2]	0.4	0.4	0.4
ϵ_{full} [%]	2.7 ± 0.1	7.6 ± 0.1	11.4 ± 0.1
α_{gen} [%]	3.6 ± 0.1	10.1 ± 0.1	15.2 ± 0.1
$\epsilon_{full}/\alpha_{gen}$ [%]	76.1 ± 0.8	75.5 ± 0.5	74.9 ± 0.4

All events of the benchmark signal samples are processed through a detailed simulation of the CMS detector based on GEANT4 [58] and are reconstructed with the same algorithms used for data analysis. Tables 1 and 2 show the event selection efficiencies ϵ_{full} obtained using the simulated signal events for these two benchmark scenarios. To provide a simple recipe for future reinterpretations of the results in the context of other models, we separately determine α_{gen}, the geometric and kinematic acceptance of this analysis calculated using generator level information only. It is defined with the criteria that an event contains at least four muons with $p_T > 8\,\text{GeV}/c$ and $|\eta| < 2.4$, with at least one of these muons having $p_T > 17\,\text{GeV}/c$ and $|\eta| < 0.9$. Tables 1 and 2 also show α_{gen} along with the ratio $\epsilon_{full}/\alpha_{gen}$. The systematic uncertainty for the ratio $\epsilon_{full}/\alpha_{gen}$ is 7.4%, for α_{gen} is 3.0% and for ϵ_{full} is 8.0% as described below. The model independence of the ratio permits an estimate of the full event selection efficiency of this analysis for an arbitrary model predicting the same signature with two pairs of muons. The acceptance α_{gen} is calculated using a suitable event generator. The full efficiency ϵ_{full} is then calculated by multiplying α_{gen} by the ratio $\epsilon_{full}/\alpha_{gen} = 0.74 \pm 0.05$.

The background contributions after final selections include $b\bar{b}$ and direct J/ψ pair production events. The leading part of the $b\bar{b}$ contribution is due to b-quark decays to pairs of muons via double semileptonic decays or resonances, i.e. ω, ρ, ϕ, J/ψ. A smaller contribution comes from events with one real dimuon and a second dimuon with a muon from a semileptonic b-quark decay and a charged hadron misidentified as another muon, due to the incorrect association of the track of the charged hadron with the track segments from a real muon in the muon system. The contribution of other SM processes has been found to be negligible, e.g. the low mass Drell–Yan production is heavily suppressed by the requirement of additional muons.

The direct J/ψ pair production contribution is estimated using the simulation scaled to data in a few regions of the invariant mass of the J/ψ pair. The comparison yields an estimate for the number of direct J/ψ pair produced events satisfying all analysis criteria of 0.3 ± 0.3 events.

The $b\bar{b}$ background contribution is modeled as a two dimensional (2D) template $B_{b\bar{b}}(m_1, m_2)$ in the plane of the invariant masses of the two dimuons in the selected events, where m_1 always refers to the dimuon containing a muon with $p_T > 17\,\text{GeV}/c$ and $|\eta| < 0.9$. For events with

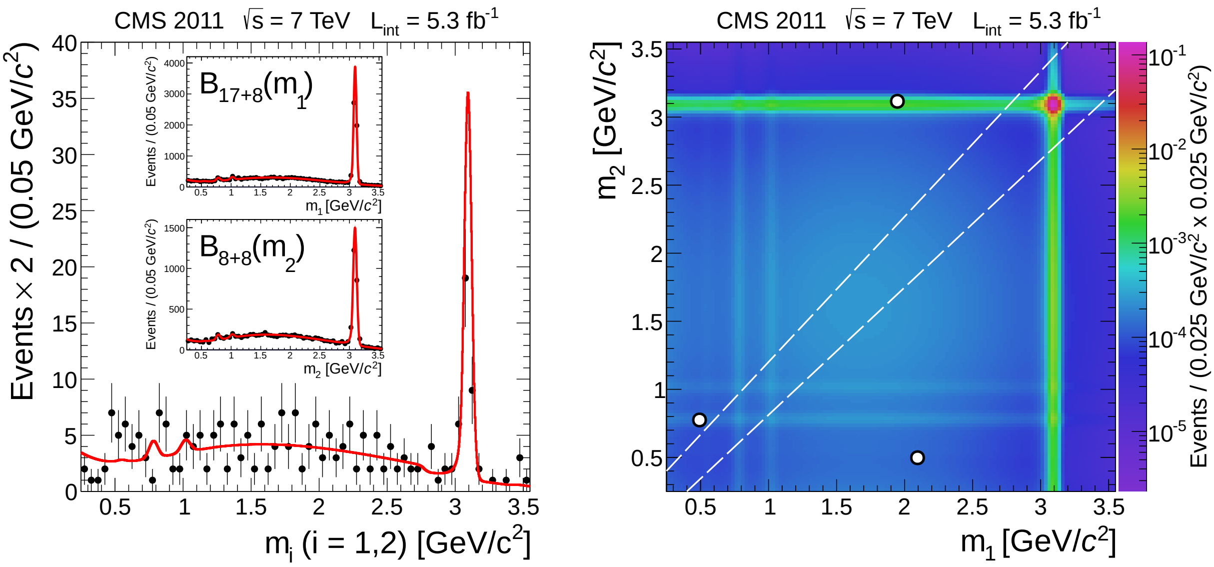

Figure 1: Left: Comparison of the data (solid circles) failing the $m_1 \simeq m_2$ requirement in the control sample (no isolation requirement is applied to reconstructed dimuons) with the prediction of the background shape model (solid line) scaled to the number of entries in the data. The insets show the B_{17+8} and B_{8+8} templates (solid lines) for dimuons obtained with background-enriched data samples. Right: Distribution of the invariant masses m_1 vs. m_2 for the isolated dimuon systems for the three events in the data (shown as empty circles) surviving all selections except the requirement that these two masses fall into the diagonal signal region $m_1 \simeq m_2$ (outlined with dashed lines). The background expectation (as indicated by the intensity (color online) of the shading) is a sum of the $\mathrm{b\bar{b}}$ and the direct J/ψ pair production contributions.

both dimuons containing such a muon, the assignment of m_1 and m_2 is random. As each b quark fragments independently, we construct the template describing the 2D probability density function as a Cartesian product $B_{17+8}(m_1) \times B_{8+8}(m_2)$, where the B_{17+8} and B_{8+8} templates model the invariant-mass distributions for dimuons with or without the requirement that the dimuon contains at least one muon satisfying $p_\mathrm{T} > 17\,\mathrm{GeV}/c$ and $|\eta| < 0.9$. This distinction is necessary as the shape of the dimuon invariant mass distribution depends on the transverse momentum thresholds used to select muons and whether the muons are in the central ($|\eta| < 0.9$) or in the forward ($0.9 < |\eta| < 2.4$) regions, owing to the differences in momentum resolution of the barrel and endcap regions of the tracker. The B_{17+8} shape is measured using a data sample enriched in $\mathrm{b\bar{b}}$ events with exactly one dimuon and one orphan muon under the assumption that one of the b quarks decays to a dimuon containing at least one muon with $p_\mathrm{T} > 17\,\mathrm{GeV}/c$ and $|\eta| < 0.9$, while the other b quark decays semileptonically resulting in an orphan muon with $p_\mathrm{T} > 8\,\mathrm{GeV}/c$. For the B_{8+8} shape, we use a similar sample and procedure but only require the dimuon to have both muons with $p_\mathrm{T} > 8\,\mathrm{GeV}/c$, while the orphan muon has to have $p_\mathrm{T} > 17\,\mathrm{GeV}/c$ and $|\eta| < 0.9$. Both data samples used to measure background shapes are collected with the same trigger and with kinematic properties similar to those $\mathrm{b\bar{b}}$ events passing the selections of the main analysis. These event samples do not overlap the sample containing two dimuons that is used for the main analysis, and they have negligible contributions from non-$\mathrm{b\bar{b}}$ backgrounds. The B_{17+8} and B_{8+8} distributions, fitted with a parametric analytical function using a combination of Bernstein polynomials [59] and Crystal Ball functions [60] describing resonances, are shown as insets in Fig. 1 (left). Once the $B_{\mathrm{b\bar{b}}}(m_1, m_2)$ template is constructed, it is used to provide a proper description of the $\mathrm{b\bar{b}}$ background shape in the main analysis.

To validate the constructed $B_{b\bar{b}}(m_1, m_2)$ template, we compare its shape with the distribution of the invariant masses m_1 vs. m_2 from events obtained with all standard selections except the requirement that each of the two reconstructed dimuons is isolated. Omitting the isolation requirement provides a high-statistics control sample of events with two dimuons highly enriched with $b\bar{b}$ events. To avoid unblinding the search, the diagonal signal region is excluded in both the data and the template, i.e. the comparison has been limited to the data events that satisfy all analysis selections but fail the $m_1 \simeq m_2$ requirement. Distributions of m_1 and m_2 are consistent with the projections of the $B_{b\bar{b}}(m_1, m_2)$ template on the respective axes normalized to the number of events in the data control sample. The sum of the m_1 and m_2 distributions agrees well with the sum of the template projections as shown in Fig. 1 (left).

Another cross-check has been performed using data events which satisfy all analysis selections except that the isolation parameters of each dimuon system have been required to satisfy $3\,\text{GeV}/c < I_{\text{sum}} < 8\,\text{GeV}/c$, which removes potential signal events (the signal selections require $I_{\text{sum}} < 3\,\text{GeV}/c$ for each dimuon). These selections yield four events in the off-diagonal sideband region of (m_1, m_2) plane. Normalizing the background distribution to these four observed events, we predict 0.9 ± 0.4 $b\bar{b}$ events in the diagonal region, consistent with no events being observed there.

To normalize the constructed $B_{b\bar{b}}(m_1, m_2)$ template, we use the data events that satisfy all analysis selections except for the $m_1 \simeq m_2$ requirement. These selections yield three events in the off-diagonal sideband region of (m_1, m_2) plane, which corresponds to an expected number of 0.7 ± 0.4 $b\bar{b}$ events in the diagonal signal region. This result is shown in Fig. 1 (right) where the three events in the off-diagonal sidebands of the (m_1, m_2) plane are shown as empty circles. The distribution of the total background expectation in the (m_1, m_2) plane (a sum of the $b\bar{b}$ and the direct J/ψ pair production contributions) is also shown by the intensity of the shading in Fig. 1 (right).

Selection efficiencies of muon and dimuon reconstruction, trigger, and isolation criteria are obtained with the simulation and have been corrected by using the scale factor of 0.91 (per event), obtained by comparing data and simulation. Systematic uncertainties include the uncertainty in the LHC integrated luminosity of the data sample (2.2%) [61], uncertainties related to parton distribution functions (PDF) and the knowledge of the strong coupling constant α_s (3%), offline muon reconstruction (5.7%), dimuon reconstruction that accounts for effects related to overlaps of muon trajectories in the tracker and in the muon system (3.5%), trigger (1.5%), and the dimuon mass shape, which affects the efficiency of the requirement that the two dimuon masses are compatible (1.5%). All uncertainties quoted are relative to the final analysis selection efficiency per signal event. The PDF uncertainties are estimated by comparing the CTEQ6.6 [62] with NNPDF2.0 [63] and MSTW2008 [64] sets following the PDF4LHC recommendations [65]. Varying the QCD renormalization/factorization scales has been found to have a negligible effect. The total systematic uncertainty in the selection efficiency is 8.0%.

When the final data was unblinded, no events were observed in the signal diagonal region, as illustrated in Fig. 1 (right). The expected number of background events in the signal diagonal region is 1.0 ± 0.5. This number includes contributions from the $b\bar{b}$ and the direct J/ψ pair production.

We interpret these results in the context of the dark-SUSY and the NMSSM scenarios and obtain 95% confidence level (CL) upper limits, using a Bayesian prescription. For the dark-SUSY model, the limit is set on $\sigma(pp \to h \to 2n_1 \to 2\gamma_D + 2n_D) \times \mathcal{B}^2(\gamma_D \to 2\mu)$ as a function of m_h. This limit is shown in Fig. 2 (left) for $m_{\gamma_D} = 0.4\,\text{GeV}/c^2$, which yields the branching fraction $\mathcal{B}(\gamma_D \to 2\mu)$ close to its maximum, reaching approximately 45% [31]. In the case of the

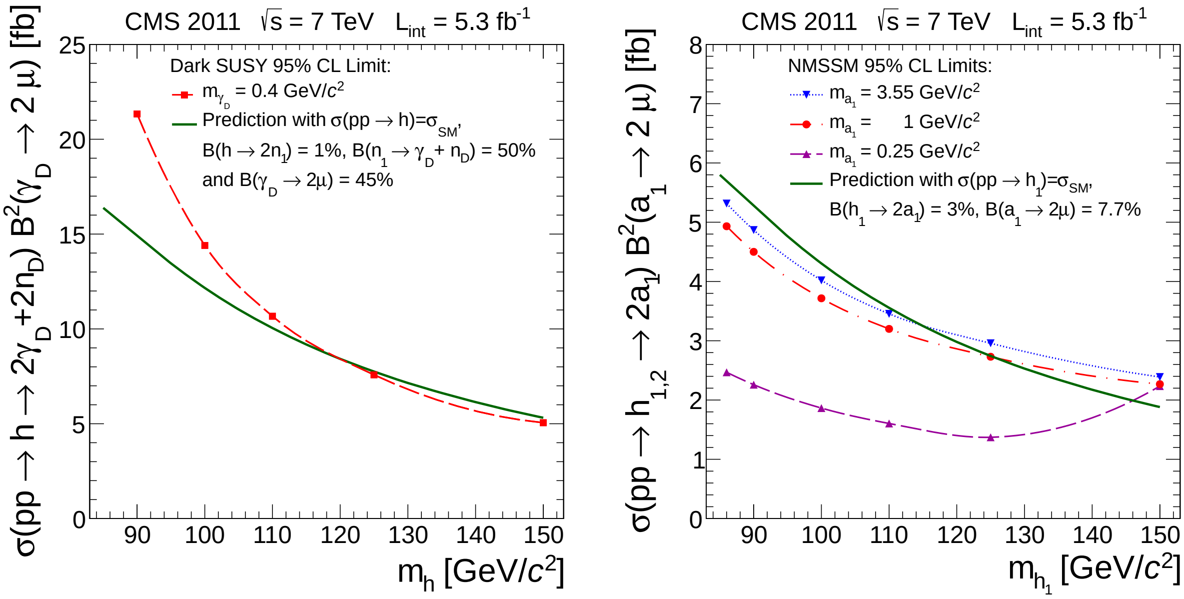

Figure 2: Left: The 95% CL upper limit as a function of m_{h}, for the dark-SUSY scenario, on $\sigma(\mathrm{pp} \to \mathrm{h} \to 2\gamma_D + 2\mathrm{n}_D) \times \mathcal{B}^2(\gamma_D \to 2\mu)$ with $m_{\gamma_D} = 0.4\,\mathrm{GeV}/c^2$ (dashed curve). As an illustration, the limit is compared to the rate obtained using a toy model with SM Higgs boson production cross section $\sigma(\mathrm{pp} \to \mathrm{h}) = \sigma_{\mathrm{SM}}$, $\mathcal{B}(\mathrm{h} \to 2\mathrm{n}_1) = 1\%$, $\mathcal{B}(\mathrm{n}_1 \to \gamma_D + \mathrm{n}_D) = 50\%$, and $\mathcal{B}(\gamma_D \to 2\mu) = 45\%$ (solid curve). The chosen $\mathcal{B}(\gamma_D \to 2\mu)$ is taken from [31]. Right: The 95% CL upper limits as functions of m_{h_1}, for the NMSSM case, on $\sigma(\mathrm{pp} \to \mathrm{h}_{1,2} \to 2\mathrm{a}_1) \times \mathcal{B}^2(\mathrm{a}_1 \to 2\mu)$ with $m_{\mathrm{a}_1} = 0.25\,\mathrm{GeV}/c^2$ (dashed curve), $m_{\mathrm{a}_1} = 1\,\mathrm{GeV}/c^2$ (dash-dotted curve) and $m_{\mathrm{a}_1} = 3.55\,\mathrm{GeV}/c^2$ (dotted curve), compared to the rate obtained using a toy model with $\sigma(\mathrm{pp} \to \mathrm{h}_1) = \sigma_{\mathrm{SM}}$, $\mathcal{B}(\mathrm{h}_1 \to 2\mathrm{a}_1) = 3\%$, and $\mathcal{B}(\mathrm{a}_1 \to 2\mu) = 7.7\%$ (solid curve). The chosen $\mathcal{B}(\mathrm{a}_1 \to 2\mu)$ is taken from [28].

NMSSM, the 95% CL upper limit is set for $\sigma\,(\mathrm{pp} \to \mathrm{h}_{1,2} \to 2\mathrm{a}_1) \times \mathcal{B}^2(\mathrm{a}_1 \to 2\mu)$ as a function of m_{h_1} for three choices of m_{a_1} as shown in Fig. 2 (right) and as a function of m_{a_1} for three choices of m_{h_1} as shown in Fig. 3 (left). We also set the 95% CL upper limit for $\mathcal{B}\,(\mathrm{h}_{1,2} \to 2\mathrm{a}_1) \times \mathcal{B}^2(\mathrm{a}_1 \to 2\mu)$ as a function of m_{a_1} for three choices of m_{h_1} assuming $\sigma(\mathrm{pp} \to \mathrm{h}_1) = \sigma(\mathrm{pp} \to \mathrm{h}_2) = \sigma_{\mathrm{SM}}(125\,\mathrm{GeV}/c^2)$ as shown in Fig. 3 (right). As m_{h_2} is unrestricted for any given m_{h_1}, we use $\epsilon_{\mathrm{full}}(m_{\mathrm{h}_2}) = \epsilon_{\mathrm{full}}(m_{\mathrm{h}_1})$ to simplify the interpretation. This is conservative since $\epsilon_{\mathrm{full}}(m_{\mathrm{h}_2}) > \epsilon_{\mathrm{full}}(m_{\mathrm{h}_1})$ if $m_{\mathrm{h}_2} > m_{\mathrm{h}_1}$, for any m_{a_1}.

In the representative scenarios, for any fixed combinations of m_{h} and m_{a} both the Higgs boson production cross section and the branching fractions can vary significantly, depending on the model parameters. In the absence of broadly accepted "model slopes" for the NMSSM or the dark-SUSY scenarios, we compare the obtained experimental limits with a few benchmark "toy" models, assuming the SM Higgs boson production cross section as a function of the Higgs boson mass [66]. We further use $\mathcal{B}(\gamma_D \to 2\mu) = 45\%$ [31] for the dark-SUSY model and we assume $\mathcal{B}(\mathrm{n}_1 \to \gamma_D + \mathrm{n}_D) = 50\%$, allowing for other possible decays. We use $\mathcal{B}(\mathrm{a}_1 \to 2\mu)$ as a function of m_{a_1}, obtained using the NMSSM calculation (hadronization effects in region of low m_{a_1} are not included) in [28] for $\tan\beta = 20$. The branching fraction $\mathcal{B}(\mathrm{a}_1 \to 2\mu)$ is equal to 7.7% for $m_{\mathrm{a}_1} \approx 2\,\mathrm{GeV}/c^2$. Finally, we choose $\mathcal{B}(\mathrm{h} \to 2\mathrm{n}_1) = 1\%$ and $\mathcal{B}(\mathrm{h}_{1,2} \to 2\mathrm{a}_1) = 3\%$, which yields the toy model predictions for rates of the dimuon pair events comparable to the experimental limits. With these parameter values, the branching fractions include the Higgs boson couplings to the new light bosons as well as the reduced couplings of Higgs bosons to

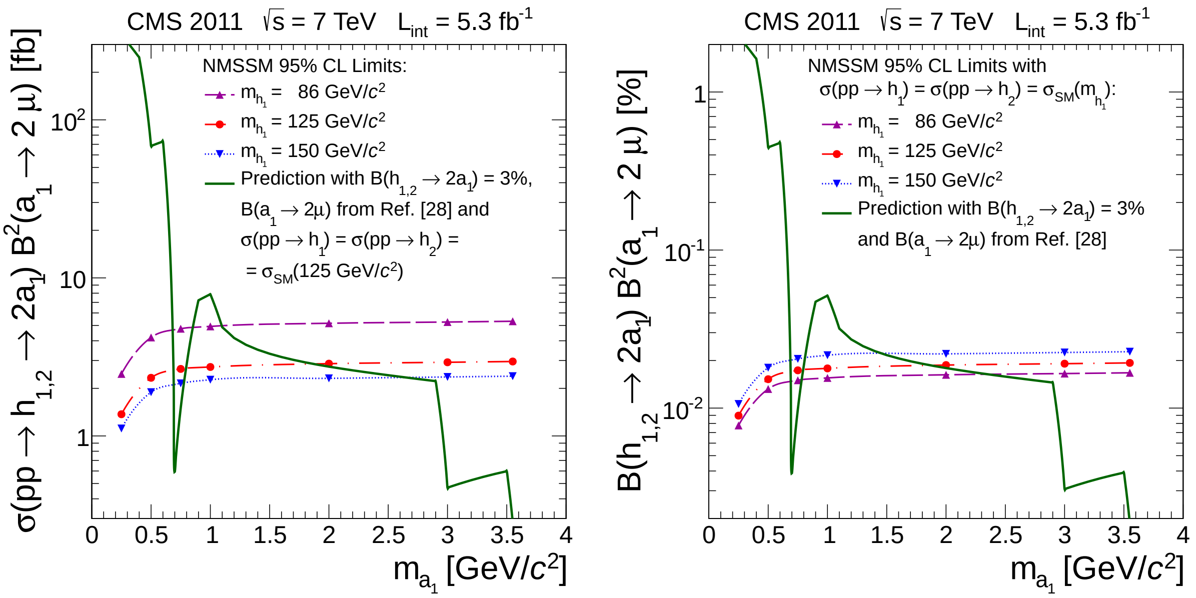

Figure 3: Left: The 95% CL upper limits as functions of m_{a_1}, for the NMSSM case, on $\sigma(pp \to h_{1,2} \to 2a_1) \times \mathcal{B}^2(a_1 \to 2\mu)$ with $m_{h_1} = 86\,\text{GeV}/c^2$ (dashed curve), $m_{h_1} = 125\,\text{GeV}/c^2$ (dash-dotted curve) and $m_{h_1} = 150\,\text{GeV}/c^2$ (dotted curve). The limits are compared to the rate (solid curve) obtained using a toy model with $\sigma(pp \to h_1) = \sigma(pp \to h_2) = \sigma_{SM}(125\,\text{GeV}/c^2)$, $\mathcal{B}(h_{1,2} \to 2a_1) = 3\%$, and $\mathcal{B}(a_1 \to 2\mu)$ as a function of m_{a_1} which is taken from [28] for NMSSM parameter $\tan\beta = 20$. Right: The 95% CL upper limits on $\mathcal{B}(h_{1,2} \to 2a_1) \times \mathcal{B}^2(a_1 \to 2\mu)$ with $m_{h_1} = 86\,\text{GeV}/c^2$ (dashed curve), $m_{h_1} = 125\,\text{GeV}/c^2$ (dash-dotted curve) and $m_{h_1} = 150\,\text{GeV}/c^2$ (dotted curve) assuming $\sigma(pp \to h_1) = \sigma(pp \to h_2) = \sigma_{SM}(125\,\text{GeV}/c^2)$. The limits are compared to the branching fraction (solid line) obtained using $\mathcal{B}(h_{1,2} \to 2a_1) = 3\%$ and $\mathcal{B}(a_1 \to 2\mu)$ as a function of m_{a_1} which is taken from [28].

the SM particles in these models, which affect the Higgs boson production cross section. The sensitivity of this search can be compared to that of a similar analysis performed at the Tevatron [40] after rescaling with the ratio of the Higgs boson cross sections at the LHC and the Tevatron. If plotted in Fig. 2 and Fig. 3 (left), the Tevatron results would have excluded rates above ~ 130 fb, an order of magnitude in sensitivity less.

For an arbitrary non-SM scenario predicting the signature investigated in this Letter, the results can be presented as the 95% CL limit $\sigma(pp \to 2a + X) \times \mathcal{B}^2(a \to 2\mu) \times \alpha_{gen} < 0.78 \pm 0.05\,\text{fb}$, where α_{gen} is the generator level kinematic and geometric acceptance described earlier. The calculation uses integrated luminosity $\mathcal{L} = 5.3\,\text{fb}^{-1}$ and takes the ratio $\epsilon_{full}/\alpha_{gen} = 0.74 \pm 0.05$, which includes the systematic uncertainties and covers the variation in the ratio over all of the benchmark points used (see Tables 1 and 2). The limit is not applicable to models where the new light bosons are typically non-isolated or have substantial lifetime. The efficiency of the selections in this analysis abruptly deteriorates if the light boson's decay vertex is more than ~ 4 cm away from the beamline.

In summary, no excess is observed in the data with respect to the SM predictions. We find no evidence of non-SM decay modes of a Higgs boson into pairs of new light bosons of the same mass, which subsequently decay to pairs of oppositely charged muons ($h \to 2a + X \to 4\mu + X$) for Higgs boson masses in the range $86 < m_h < 150\,\text{GeV}/c^2$ and for the new light-boson masses in the range $0.25 < m_a < 3.55\,\text{GeV}/c^2$ using data collected by the CMS experiment in proton-proton collisions at $\sqrt{s} = 7\,\text{TeV}$, corresponding to an integrated luminosity of $5.3\,\text{fb}^{-1}$. The analysis has been designed as a quasi-model-independent search allowing interpretation of its results in the context of a broad range of non-SM scenarios predicting this type of signature. In the context of the NMSSM and one of the SUSY models with hidden valleys this search provides the best experimental limits to date, significantly surpassing the sensitivity of earlier similar searches performed at the Tevatron.

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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, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan[1], M. Friedl, R. Frühwirth[1], V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler[1], W. Kiesenhofer, V. Knünz, M. Krammer[1], I. Krätschmer, D. Liko, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz[1]

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

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

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

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, T. Reis, L. Thomas, G. Vander Marcken, 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, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco[2], J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul, J.M. Vizan Garcia

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Correa Martins Junior, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, 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. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
T.S. Anjos[3], C.A. Bernardes[3], F.A. Dias[4], T.R. Fernandez Perez Tomei, E.M. Gregores[3], C. Lagana, F. Marinho, P.G. Mercadante[3], S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev[5], P. Iaydjiev[5], 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, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, 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[6], D. Polic, I. Puljak[5]

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[7], S. Elgammal[8], A. Ellithi Kamel[9], M.A. Mahmoud[10], A. Radi[11,12]

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

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

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, 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[13], C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[14], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte[14], F. Drouhin[14], C. Ferro, J.-C. Fontaine[14], 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, CNRS/IN2P3, Villeurbanne, France, 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. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici[5], D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[15]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
G. Anagnostou, C. Autermann, 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[16]

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, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann[5], A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz[17], 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[17], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, 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[17], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
V. Blobel, J. Draeger, H. Enderle, J. Erfle, 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, J. Sibille[18], V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

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[5], C. Hackstein, F. Hartmann, T. Hauth[5], M. Heinrich, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov[16], J.R. Komaragiri, P. Lobelle Pardo, 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, 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[19], F. Sikler, V. Veszpremi, G. Vesztergombi[20]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, 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. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J.B. 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[5], L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, S. Ganguly, M. Guchait[21], M. Maity[22], 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[23], H. Bakhshiansohi, S.M. Etesami[24], A. Fahim[23], M. Hashemi, H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh[25], M. Zeinali

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], L. Barbone[a,b], C. Calabria[a,b,5], S.S. Chhibra[a,b], A. Colaleo[a], D. Creanza[a,c], N. De

Filippis[a,c,5], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], B. Marangelli[a,b], S. My[a,c], S. Nuzzo[a,b], N. Pacifico[a,b], A. Pompili[a,b], G. Pugliese[a,c], G. Selvaggi[a,b], L. Silvestris[a], G. Singh[a,b], R. Venditti[a,b], G. Zito[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], A.C. Benvenuti[a], D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b,5], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], M. Meneghelli[a,b,5], A. Montanari[a], F.L. Navarria[a,b], F. Odorici[a], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], R. Travaglini[a,b]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], G. Cappello[a,b], M. Chiorboli[a,b], S. Costa[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Frosali[a,b], E. Gallo[a], S. Gonzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,b]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Colafranceschi[26], F. Fabbri, D. Piccolo

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
P. Fabbricatore[a], R. Musenich[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a,b], F. De Guio[a,b], L. Di Matteo[a,b,5], S. Fiorendi[a,b], S. Gennai[a,5], A. Ghezzi[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], A. Martelli[a,b], A. Massironi[a,b,5], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], S. Sala[a], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli "Federico II" [b], Napoli, Italy
S. Buontempo[a], C.A. Carrillo Montoya[a], N. Cavallo[a,27], A. De Cosa[a,b,5], O. Dogangun[a,b], F. Fabozzi[a,27], A.O.M. Iorio[a,b], L. Lista[a], S. Meola[a,28], M. Merola[a], P. Paolucci[a,5]

INFN Sezione di Padova [a], Università di Padova [b], Università di Trento (Trento) [c], Padova, Italy
P. Azzi[a], N. Bacchetta[a,5], D. Bisello[a,b], A. Branca[a,b,5], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], K. Kanishchev[a,c], S. Lacaprara[a], I. Lazzizzera[a,c], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Passaseo[a], J. Pazzini[a,b], M. Pegoraro[a], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], S. Vanini[a,b], P. Zotto[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
M. Gabusi[a,b], S.P. Ratti[a,b], C. Riccardi[a,b], P. Torre[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], L. Fanò[a,b], P. Lariccia[a,b], G. Mantovani[a,b], M. Menichelli[a], A. Nappi[a,b†], F. Romeo[a,b], A. Saha[a], A. Santocchia[a,b], A. Spiezia[a,b], S. Taroni[a,b]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
P. Azzurri[a,c], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], G. Broccolo[a,c], R. Castaldi[a], R.T. D'Agnolo[a,c,5], R. Dell'Orso[a], F. Fiori[a,b,5], L. Foà[a,c], A. Giassi[a], A. Kraan[a], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,29], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A.T. Serban[a,30], P. Spagnolo[a], P. Squillacioti[a,5], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Università di Roma [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], D. Del Re[a,b], M. Diemoz[a], C. Fanelli[a,b], 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]

INFN 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], 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], A. Solano[a,b], A. Staiano[a], A. Vilela Pereira[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], 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, 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, 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.H. Ansari, M.I. Asghar, J. Butt, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

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

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

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

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
S. Evstyukhin, 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. Kossov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin[4], L. Dudko, A. Ershov, A. Gribushin, 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. Grishin[5], V. Kachanov, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[31], M. Djordjevic, M. Ekmedzic, D. Krpic[31], 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. Garcia-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[32], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, 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, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet[6], G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, 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. Girone, 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, N. Magini, T. Mäki, 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. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi[33], C. Rovelli[34], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas[35], D. Spiga, A. Tsirou, G.I. Veres[20], J.R. Vlimant, H.K. Wöhri, S.D. Worm[36], 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

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. Donegà, M. Dünser, 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[37], 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[38], 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
C. Amsler[39], V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, 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

Chulalongkorn University, Bangkok, Thailand
B. Asavapibhop, N. Srimanobhas

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci[40], S. Cerci[41], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar[42], A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk[43], A. Polatoz, K. Sogut[44], D. Sunar Cerci[41], B. Tali[41], H. Topakli[40], 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[45], M. Kaya[46], O. Kaya[46], S. Ozkorucuklu[47], N. Sonmez[48]

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
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[36], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso[49], K.W. Bell, A. Belyaev[49], 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. Futyan, 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[38], A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi[50], D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp[†], A. Sparrow, M. Stoye, 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, Z. Demiragli, A. Ferapontov, A. Garabedian, 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, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, D. Pellett, F. Ricci-Tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, R. Yohay

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. Schlein[†], P. Traczyk, 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. Jeng[51], 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. Wasserbaech[52], 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. Lowette, 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, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
B. Akgun, V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, 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, W.T. Ford, A. Gaz, 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. Tucker, 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, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko[53], C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, 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, T. Cheng, 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. Milenovic[54], G. Mitselmakher, L. Muniz, M. Park, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

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

Florida State University, Tallahassee, USA
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, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki[55], W. Clarida, F. Duru, J.-P. Merlo, H. Mermerkaya[56], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok[57], S. Sen, P. Tan, 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, 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. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, 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. Krajczar[58], P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, 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, Oxford, 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, 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
A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar

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, L. Lusito, 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, K.M. Chan, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

The Ohio State University, Columbus, USA
B. Bylsma, L.S. Durkin, 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
E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, USA
E. Alagoz, 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, W. Li, 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, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, 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, M. Walker

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[59], 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, C. Dragoiu, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, C. Florez, S. Greene, A. Gurrola, W. Johns, P. Kurt, C. Maguire, A. Melo, M. Sharma, P. Sheldon, B. Snook, 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

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, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, 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 British University in Egypt, Cairo, Egypt
12: Now at Ain Shams University, Cairo, Egypt
13: Also at National Centre for Nuclear Research, Swierk, Poland
14: Also at Université de Haute-Alsace, Mulhouse, France
15: Also 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 The University of Kansas, Lawrence, USA
19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
20: Also at Eötvös Loránd University, Budapest, Hungary
21: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
22: Also at University of Visva-Bharati, Santiniketan, India
23: Also at Sharif University of Technology, Tehran, Iran
24: Also at Isfahan University of Technology, Isfahan, Iran
25: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, 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 California, Los Angeles, Los Angeles, USA
33: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
34: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
35: Also at University of Athens, Athens, Greece
36: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
37: Also at Paul Scherrer Institut, Villigen, Switzerland
38: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
39: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
40: Also at Gaziosmanpasa University, Tokat, Turkey
41: Also at Adiyaman University, Adiyaman, Turkey
42: Also at Izmir Institute of Technology, Izmir, 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 Mimar Sinan University, Istanbul, Istanbul, Turkey
58: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
59: Also at Kyungpook National University, Daegu, Korea