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Search for resonant pair production of Higgs bosons decaying to two bottom quark-antiquark pairs in proton-proton collisions at 8 TeV

The CMS Collaboration*

Abstract

A model-independent search for a narrow resonance produced in proton-proton collisions at $\sqrt{s} = 8$ TeV and decaying to a pair of 125 GeV Higgs bosons that in turn each decays into bottom quark-antiquark pairs is performed by the CMS experiment at the LHC. The analyzed data correspond to an integrated luminosity of 17.9 fb^{-1} . No evidence for a signal is observed. Upper limits at a 95% confidence level on the production cross section for such a resonance, in the mass range from 270 to 1100 GeV, are reported. Using these results, a radion with decay constant of 1 TeV and mass from 300 to 1100 GeV, and a Kaluza–Klein graviton with mass from 380 to 830 GeV are excluded at a 95% confidence level.

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1 Introduction

Following the discovery of a Higgs boson (H) at the CERN LHC [1–3], with mass around 125 GeV and properties so far consistent with the standard model (SM) of particle physics, it has become important to search for new resonances that decay into pairs of such Higgs bosons. While non-resonant pair production of the Higgs boson is allowed in the SM, the theoretical production cross section is approximately 10 fb [4] and well beyond the sensitivity of currently acquired data. However, several well-motivated hypotheses of physics beyond the standard model posit narrow-width resonances that decay into pairs of Higgs bosons, and could be produced with large enough cross sections to be probed with existing data. The radion [5] and Kaluza–Klein (KK) gravitons in the Randall–Sundrum (RS1) [6] models of warped extra dimensions are examples of such resonances [7].

This letter reports the results of a model-independent search for the resonant pair production of Higgs bosons. The search for the narrow width resonance, denoted by X , is performed in the 270–1100 GeV mass range. Data from proton-proton collisions at the LHC and recorded by the CMS experiment corresponding to an integrated luminosity of $17.9 \pm 0.5 \text{ fb}^{-1}$ at $\sqrt{s} = 8 \text{ TeV}$ is used. We perform this search for the case where both Higgs bosons decay into bottom quark-antiquark pairs ($b\bar{b}$) [8]. The main challenge of this search is to distinguish the signal of four bottom quarks in the final state that hadronize into jets (b jets) from the copious multijet background described by quantum chromodynamics (QCD) in pp collisions. We address this challenge by suitable event selection criteria that include dedicated b-jet identification techniques and a model of the multijet background that is validated in data control regions. Our results may be compared with a search performed by the ATLAS experiment [9] that also probes the physics of resonant Higgs boson pair production, albeit in the channel where one Higgs boson decays to bottom quarks and the other decays to photons.

2 Detector and Event Reconstruction

A detailed description of the CMS detector, together with a description of the coordinate system used and the relevant kinematic variables, can be found in Ref. [10]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter that generates an axial magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Muons are detected and their properties measured in gas-ionization detectors embedded in a steel flux-return yoke outside the solenoid. Jets are reconstructed using the anti- k_T clustering algorithm [11, 12] with a distance parameter of 0.5 applied on the collection of particle candidates reconstructed by the particle-flow (PF) algorithm [13, 14]. The PF algorithm reconstructs and identifies each individual particle with a combination of information from the various elements of the CMS detector. To mitigate the effect of additional particles that do not originate from the hard interaction in jet reconstruction, we subtract charged hadrons that do not arise from the primary vertex associated with it from the collection of clustered particles. Further, an average neutral energy density from particles not arising from the primary vertex is evaluated and subtracted from the jets [15]. Energy corrections for the jets are determined as functions of the jet transverse momentum p_T and pseudorapidity $|\eta|$. Jet identification criteria [16] to reject detector noise misidentified as jets, and jets not originating from the hard interaction are also applied.

In order to identify (tag) b jets, we rely on the fact that bottom quarks hadronize into b hadrons which have decay lengths of the order of $c\tau = 450 \mu\text{m}$. Thus, their decay products originate

from secondary vertices made of tracks that have impact parameters with respect to the primary vertex of a similar scale. The pixel tracker provides an impact parameter resolution of about $15\ \mu\text{m}$ for charged tracks with $|\eta| < 2.4$. To maximize the b-tagging performance of the detector, we combine the output discriminants of several b-tagging algorithms described in Ref. [17] with a trained artificial neural network. This we call the combined multivariate (CMVA) algorithm. In particular, we combine the outputs of the combined secondary vertex (CSV) tagger that uses secondary vertices identified by the inclusive vertex finder (IVF) algorithm [18], the jet probability (JP) tagger, and the two soft lepton taggers. We choose a working point for the CMVA algorithm that maximizes the sensitivity of this search. This working point yields a 75% efficiency for tagging jets originating from b hadrons and a mistagging rate of 3% for light-flavor jets with $p_T > 40\ \text{GeV}$ and $|\eta| < 2.4$.

The first level of the trigger, consisting of customized processors, collects data for this analysis using information from the calorimeters and requires two jets to exceed p_T thresholds of 56 or 64 GeV, depending on luminosity conditions. The second level of the trigger, consisting of software algorithms executed on a farm of commercial processors, uses information from the entire detector to reconstruct PF jets, and requires four PF jets with $|\eta| < 2.4$ and $p_T > 30\ \text{GeV}$, of which two jets must have $p_T > 80\ \text{GeV}$. Further, to record signal events and reject background QCD multijet events, two jets are required to be tagged by the CSV b-tagging algorithm implemented at the trigger.

3 Simulated Samples

To model the production of a generic narrow-width spin-0 resonance, we use a Monte Carlo simulation of the RS1 radion produced through gluon fusion. The angular distributions of a spin-2 resonance are distinct from that of a spin-0 resonance, and result in different kinematic distributions. Therefore, we evaluate the signal efficiencies for a narrow-width spin-2 resonance from a separate simulation of the first excitation of the KK graviton produced through gluon fusion in the same extra dimension scenario as the radion. The resonance is forced to decay to a pair of Higgs bosons with parameters reported in Ref. [19], where both Higgs bosons decay to $b\bar{b}$. Samples of these signal events, as well as background events from diboson, W+jets, Z+jets and top-quark pair production ($t\bar{t}$) processes, are generated using the MADGRAPH 5.1 [20] program interfaced with PYTHIA 6.4 [21] for parton showering and hadronization. QCD multijet event samples are simulated with the PYTHIA 6.4 program. A sample of events where the Higgs boson is produced in association with a Zboson is simulated using the POWHEG event generator [22–24] interfaced with the HERWIG++ [25] program for showering and hadronization. We set the PYTHIA 6.4 parameters for the underlying event to the Z2* tune [26]. The response of the CMS detector is modeled using GEANT4 [27].

On average, 21 pp interactions occurred per bunch crossing in the data used in this analysis. Additional simulated pp interactions overlapping with the event of interest were added to the simulated samples to reproduce the distribution of the number of primary vertices per event reconstructed in data.

4 Event Selection

The trigger-level jet p_T thresholds confine our search for a narrow-width $X \rightarrow H(b\bar{b})H(b\bar{b})$ resonance to masses above 270 GeV. Beyond $m_X \approx 800\ \text{GeV}$, the selection efficiency is increasingly limited by the merging of jets from the same Higgs boson, and we curtail this search at 1100 GeV. The kinematic distributions of the decay products vary substantially over this mass

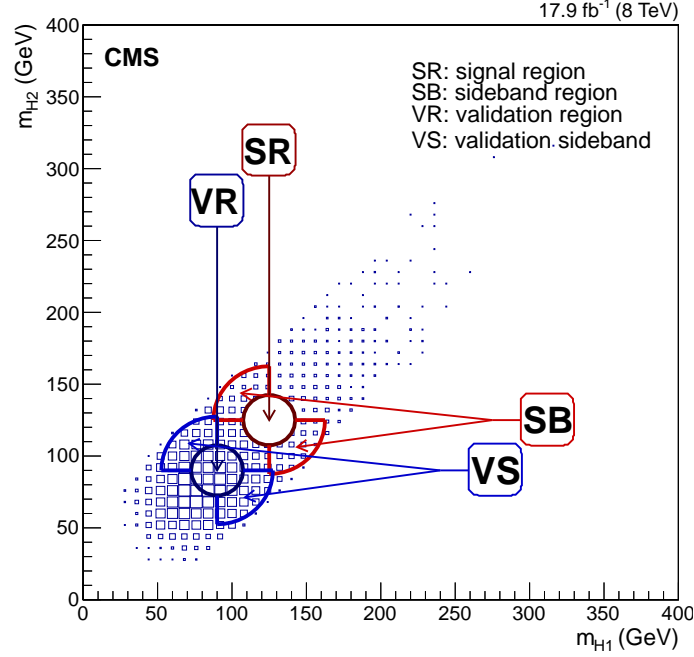


Figure 1: Illustration of the SR, SB, VR and VS kinematic regions in the (m_{H_1}, m_{H_2}) plane used to motivate and validate the parametric model for the QCD multijet background. The quantities m_{H_1} and m_{H_2} are the two reconstructed Higgs boson masses. The distribution in data events after b-tagging and kinematic selections is shown with the SR blinded.

range. Therefore, to optimize the search sensitivity, we use different event selection criteria in two main kinematic regions: the low-mass region (LMR) for mass hypotheses from 270 to 450 GeV, and the high-mass region (HMR) for masses from 450 to 1100 GeV.

Event selection begins with the identification of events containing at least four jets in the central region of the detector ($|\eta| < 2.4$) that are b-tagged and have $p_T > 40$ GeV. For the LMR, we combine these b jets into pairs to create HH candidates such that $|m_H - 125 \text{ GeV}| < 35$ GeV for each candidate Higgs boson. The mass resolution on the Higgs boson in the LMR is found to be approximately 9 GeV. Selected HH candidates are required to have at least two jets with $p_T > 90$ GeV. Signal events have large Lorentz factors for the Higgs boson candidates in the HMR, and therefore HH candidates for this case are constructed from four jets such that the $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ between the jets associated with an H candidate remain within 1.5, where $\Delta\eta$ and $\Delta\phi$ are the differences in the pseudorapidities and azimuthal angles of the two jets. For mass hypotheses from 740 to 1100 GeV, we impose an additional requirement of $p_T > 300$ GeV on one of the Higgs boson candidates to better discriminate signal events from background. In case of multiple HH candidates in an event, the combination with the smallest $|m_{H_1} - m_{H_2}|$ is chosen. Having identified the two Higgs boson candidates in each event, we plot their masses, m_{H_1} and m_{H_2} , on a two-dimensional histogram as shown in Fig. 1. H_1 and H_2 are chosen at random from the two reconstructed H candidates. As the final selection criterion, we require events to fall within the signal region (SR) defined as $\sqrt{\Delta m_{H_1}^2 + \Delta m_{H_2}^2} < 17.5$ GeV, where $\Delta m_{H_{1,2}} = m_{H_{1,2}} - 125$ GeV.

The efficiencies of these selection criteria for spin-0 and spin-2 resonances at representative masses are shown in Table 1. The major loss in efficiency for all mass hypotheses comes from the b-tagging requirement for 4 jets. For the 300 GeV mass hypothesis, this is compounded by

Table 1: Efficiencies of the event selection criteria for generic spin-0 and spin-2 resonances decaying to a pair of Higgs bosons in the four b jet final state at representative masses.

selection eff. (%)	Mass (GeV)				
	300	500	700	900	1100
spin-0	0.05	2.3	4.9	4.6	2.2
spin-2	0.09	3.4	6.6	5.4	2.3

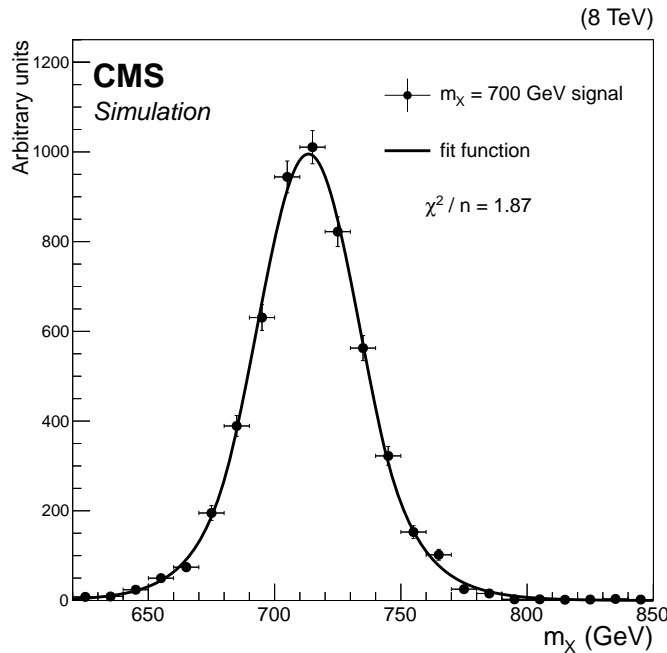


Figure 2: A maximum likelihood fit to the m_X distribution of simulated signal events for the 700 GeV mass hypothesis. The distribution is fitted to a Gaussian core smoothly extended on both sides to exponential tails. Here n is the number of degrees of freedom in the fit.

the trigger inefficiency. The distribution of the aforementioned ΔR between jets from a single Higgs boson is narrower for the spin-2 resonance, and thus requiring $\Delta R < 1.5$ results in a higher efficiency for it.

5 Signal Modeling

For signal events, the aforementioned event selection criteria are expected to produce a sharp peak in the m_X distribution over a relatively featureless background from events arising from SM processes. To search for signal events at various mass hypotheses, we fit the m_X distribution in data events in the SR to a parametric model for the signal peak on top of parametric models appropriate for components of the SM background. This procedure is performed for the LMR and the HMR separately.

To improve the mass resolution of the signal $X \rightarrow HH$ resonance, we perform a fit that constrains the invariant masses of the Higgs boson candidates. In the fit, the momenta of the reconstructed b jets are allowed to float within their expected resolutions. Since the uncertainty in the reconstructed mass of the Higgs boson candidate due to the measurement of jet direction is smaller than that due to the measurement of jet energy, this constraint mainly affects the latter. This fit improves the invariant mass resolution of the reconstructed signal resonance

by 20–40%, depending on the mass hypothesis. Extensive tests in background-dominated control regions in data show that no artificial structures are introduced in the background mass distributions by this procedure.

We build the parametric model for each signal mass hypothesis by fitting the shape of the m_X distribution of simulated events that are accepted by the selection criteria and corrected for differences between data and simulation. A sum of two Gaussian functions, requiring five parameters, is used for the LMR fit to account for tails in the distribution from incorrect combinations of jets. In the HMR, we fit a function with a Gaussian core smoothly extended on both sides to exponential tails, such that the function is continuous both in its value and its first derivative. This requires two parameters for the mean and width of the Gaussian function, and two other parameters for the exponential tails on both sides. An example of a parametric model for the HMR signal obtained through this procedure is shown in Fig. 2. While the model is constructed for the mass hypothesis of 700 GeV, its Gaussian core peaks at 714 GeV and has a width of 21 GeV. This mass shift is found to be linear in m_X and occurs due to the aforementioned constraint of jet momenta to m_H .

6 Background Modeling

While the composition of background events in the SR is expected to be dominated by QCD multijet processes, we find through simulation that $t\bar{t}$ production contributes approximately 22% and 27% in the LMR and HMR, respectively. We also find that Z+jets, ZZ, and ZH processes contribute less than 1% of the background and therefore neglect them in this analysis. The m_X distribution of these $t\bar{t}$ events is found to be somewhat different in shape from that of QCD multijet events, and therefore we treat it as a distinct component of the background and model it with a parametric form. We obtain this parametric form by fitting the shape of the m_X distribution of simulated $t\bar{t}$ events accepted by the event selection criteria to a function with a Gaussian core smoothly extended to an exponential tail on the high side. This function, henceforth referred to as GaussExp, is continuous in its value and its first derivative. It has two parameters for the mean and width of the Gaussian function and one parameter for the decay constant of the exponential tail. This model is normalized to a $t\bar{t}$ cross section of 234 pb [28], and is allowed to float with a systematic uncertainty of 15% in the final fit to account for theoretical and measurement uncertainties in our kinematically boosted region.

We use the GaussExp parametric model to fit the m_X distribution of the QCD multijet component of the background in the SR. With the SR kept blinded, we motivate and validate this choice of parametric model by the fact that it fits well the shape of the m_X QCD multijet background distributions in several different regions of the (m_{H_1}, m_{H_2}) plane depicted in Fig. 1 and described below. We do not aim to predict the parameters of the model in the SR from the other regions. These fits are performed for the LMR between 260 and 650 GeV, for the HMR between 400 and 900 GeV, and for the HMR with $H p_T > 300$ GeV between 600 and 1200 GeV. In each case the $t\bar{t}$ contribution, as expected from simulation, is subtracted.

We define a sideband region (SB) to the SR as $17.5 \text{ GeV} < \sqrt{\Delta m_{H_1}^2 + \Delta m_{H_2}^2} < 35 \text{ GeV}$ and $\Delta m_{H_1} \Delta m_{H_2} < 0$. For events in this region, the m_X distribution is expected to be kinematically similar to that for events in the SR—as in each of the sidebands one of the reconstructed Higgs boson masses is slightly higher in value than for events in the SR while the other is slightly lower. As an example, Fig. 3 top left shows the fit performed for events in the SB passing the HMR selection. Another set of events that pass the kinematic requirements of the event selection criteria in the SR region of the (m_{H_1}, m_{H_2}) plane but required to have one of the four jets

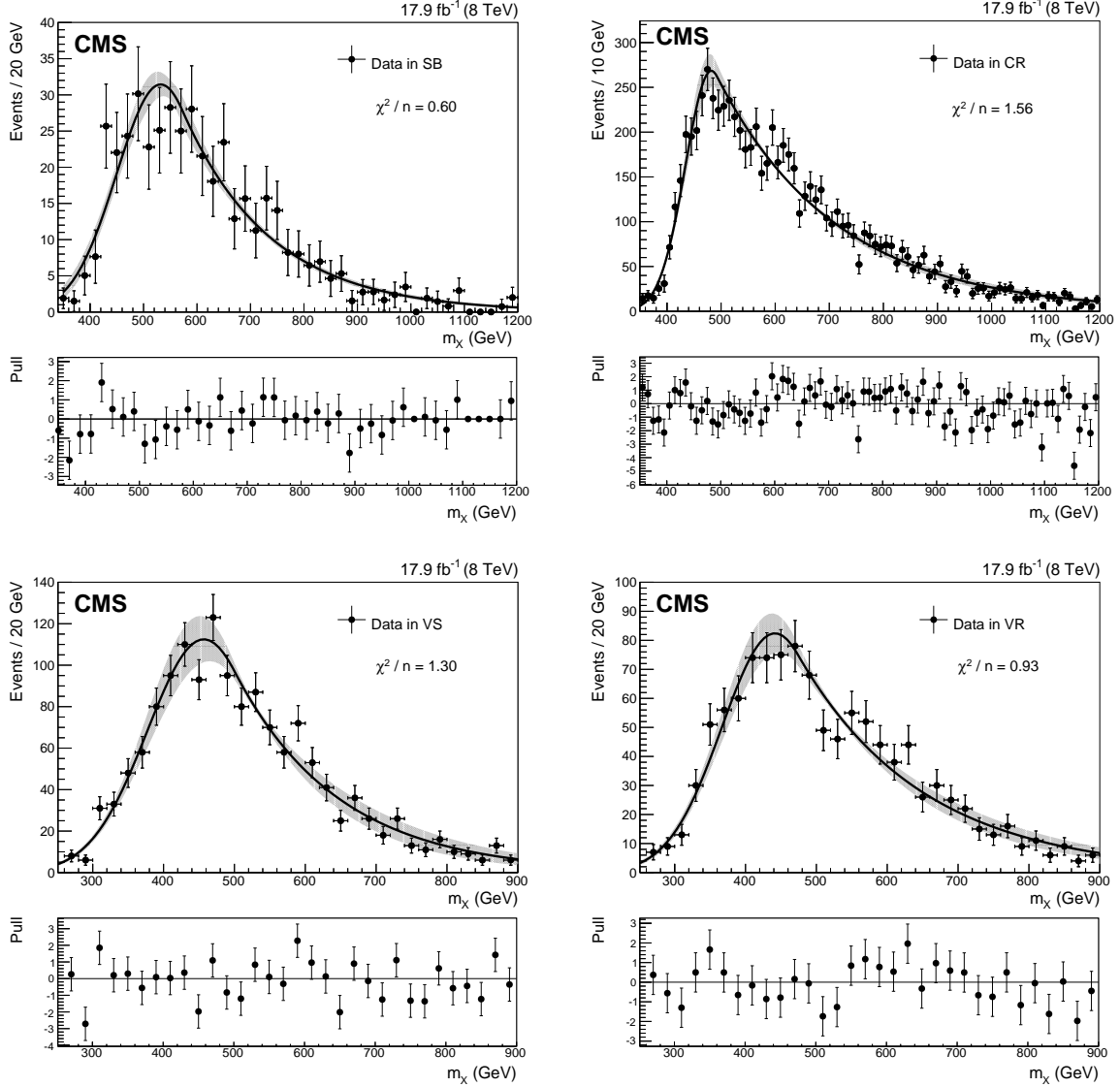


Figure 3: The m_X distributions in data (after the $t\bar{t}$ background has been subtracted) in the SB of the HMR (top-left), the CR of the HMR (top-right), the VS of the LMR (bottom-left), and the VR of the LMR (bottom-right). The distributions are fitted to the GaussExp parametric model. The shaded regions correspond to $\pm 1\sigma$ variations of this fit. Here n is the number of degrees of freedom in each fit. The pull, for a given bin, is defined as the number of data events minus the value of the fit model, divided by the uncertainty on the number of data events.

not be b-tagged is selected to further test the applicability of the GaussExp model in describing the m_X distribution of the QCD multijet background in a different but kinematically similar region. This is called the data Control Region (CR), and the fit for these events, that would have otherwise passed the HMR selection, is also shown in Fig. 3 on the top-right. In both cases, the goodness of the fit, characterized by the χ^2 per degree of freedom, is found to be reasonable.

These two cases already lend significant confidence to the choice of the GaussExp parametric model for the SR. However, we carry out further checks in neighboring validation regions (VR) with a corresponding sideband (VS) that are defined similarly to the SR and SB regions but with $m_{H_1} = m_{H_2}$ centered at different values. The good fits for the m_X distributions in these regions not only demonstrate the applicability of the GaussExp model to describe these kinematically distinct QCD multijet events, but also that events in the VR are in fact kinematically similar to those in the VS. As examples, Fig. 3 bottom-left and bottom-right plots show the results of these fits for the LMR selection for the VS and the VR, respectively, both centered at $m_{H_1} = m_{H_2} = 90$ GeV. We obtain similar results for the VR centered at $m_{H_1} = m_{H_2} = 107.5, 142.5$ and 160 GeV.

While the GaussExp function fits well the m_X distribution from QCD multijet events in all these distinct regions and therefore can be expected to be a good approximation of the parametric form of the true parent distribution for events in the SR, other similar parametric models could also be chosen instead of it. Therefore, a systematic uncertainty associated with the choice of this parametric model is evaluated by assuming a 7th order Bernstein polynomial, which also fits the m_X distribution well in the SB, to be the true distribution. Pseudo-datasets are generated from this polynomial function and fitted with the GaussExp function as well as other polynomial functions to compute biases in the reconstructed signal strength. This procedure is performed for each mass hypothesis. These biases are found to be of the order of 100 fb for the LMR and 10 fb for the HMR. We account for this bias as a signal-shaped systematic uncertainty on the background model with normalization centered at zero and a Gaussian uncertainty with standard deviation equal to the bias.

Table 2: Relative systematic uncertainties on the selection efficiencies for signal and $t\bar{t}$ events in the LMR and the HMR.

Source of systematic uncertainty	Impact in LMR (%)		Impact in HMR (%)	
	Signal	$t\bar{t}$	Signal	$t\bar{t}$
Jet energy scale	0.1–0.2	0.8	0.0–0.2	0.1
Jet energy resolution	2.4–7.0	2.7	5.5–6.7	2.1
b-tagging scale factor	12.7	12.7	12.7	12.7
Trigger scale factor	6.0–18.8	9.1	6.1–8.0	7.2

7 Systematic Uncertainties

Sources of systematic uncertainties that affect the selection efficiencies for signal and $t\bar{t}$ events are listed in Table 2 and described below. We vary the jet energy scale [29] by its uncertainty as a function of jet p_T and η and find that this affects signal efficiencies by a relative factor of up to 0.2% and $t\bar{t}$ efficiencies by up to 0.8%. We evaluate the effect of uncertainty in the jet energy resolution by varying the jet energies according to the measured uncertainty. This is found to affect signal efficiencies by 2–7%, and $t\bar{t}$ efficiencies by 2–3%. These uncertainties affect not only the normalizations but also the parameters of the signal and $t\bar{t}$ models, and are taken into account as nuisance parameters in the final fit.

The trigger efficiencies for signal and $t\bar{t}$ events are evaluated approximately by passing generated events through a trigger simulation. We then correct these efficiencies for differences between simulation and data by computing the difference in a $t\bar{t}$ -enriched control region obtained using a trigger that requires at least one muon with $p_T > 24$ GeV. Further, event selection criteria requiring at least one muon with $p_T > 40$ GeV and at least four jets in the central region of the detector with $p_T > 40$ GeV are applied. The data-to-simulation correction factor is characterized by the p_T and CMVA discriminants of the relevant jets. Uncertainties in this factor impact signal efficiencies by 6–18%, and $t\bar{t}$ efficiencies by 7–9%.

The b-tagging efficiencies of the CMVA algorithm for signal and $t\bar{t}$ events are also evaluated approximately through simulation and then corrected by a data-to-simulation comparison. The comparison is performed in the same $t\bar{t}$ -enriched control region as the calculation of the trigger efficiency. The correction factor for the b-tagging efficiencies is consistent with unity. The uncertainty on this factor is evaluated to be 13%.

Additionally, the yield of signal events for a given production cross section and $t\bar{t}$ events are both affected by a 2.6% uncertainty in the measurement of the integrated luminosity [30].

8 Results

The m_X distribution that we observe in data within the SR for both the LMR and HMR, along with a binned maximum-likelihood fit with the aforementioned parametric background models are shown in Fig. 4. We compute the observed and expected upper limits on the cross section for $pp \rightarrow X \rightarrow H(b\bar{b})H(b\bar{b})$ at a 95% confidence level (CL) using the modified frequentist CL_s method [31, 32] by fitting the data with the parametric signal, $t\bar{t}$, and QCD multijet models. This is done separately in the disjoint ranges of m_X for the LMR and the HMR described in Section 4, and the limits are presented together in Fig. 5. These limits are shown for the spin-0 resonance on the left, and the spin-2 resonance on the right. The green (dark) and yellow (light) bands represent the 1σ and 2σ confidence intervals around the expected limits. The observed upper limits lie within 2σ of the expected upper limits, and thus we conclude that there is no significant deviation from the background-only hypothesis.

The theoretical cross section for the production via gluon fusion of a radion that decays to a pair of Higgs bosons [33] that each in turn decays to a $b\bar{b}$ pair with a branching fraction of 58% [34], as calculated by MADGRAPH 5.1, is overlaid on the limit for the spin-0 resonance in the plot on the left. In this calculation, the correction factor used to account for next-to-leading-order amplitudes of the heavy-quark loop is identical to that used for Higgs boson production through gluon fusion [35]. The warped extra dimension scenario for this radion has the product of the curvature, k , and half the circumference of the extra dimension, L , set to 35, a radion decay constant of $\Lambda_R = 1$ TeV, and no radion-Higgs boson mixing. The theoretical cross section for the radion has an uncertainty of approximately 15% that is not used to compute the experimental limits on spin-0 resonance production shown in Fig. 5. Masses for the radion between 300 and 1100 GeV are excluded at a 95% CL. A similarly calculated theoretical cross section for the KK graviton as the resonance X , in the same warped extra dimension scenario, is overlaid on the limit for the spin-2 resonance in the plot on the right. Masses for such a graviton are excluded at a 95% CL between 380 and 830 GeV.

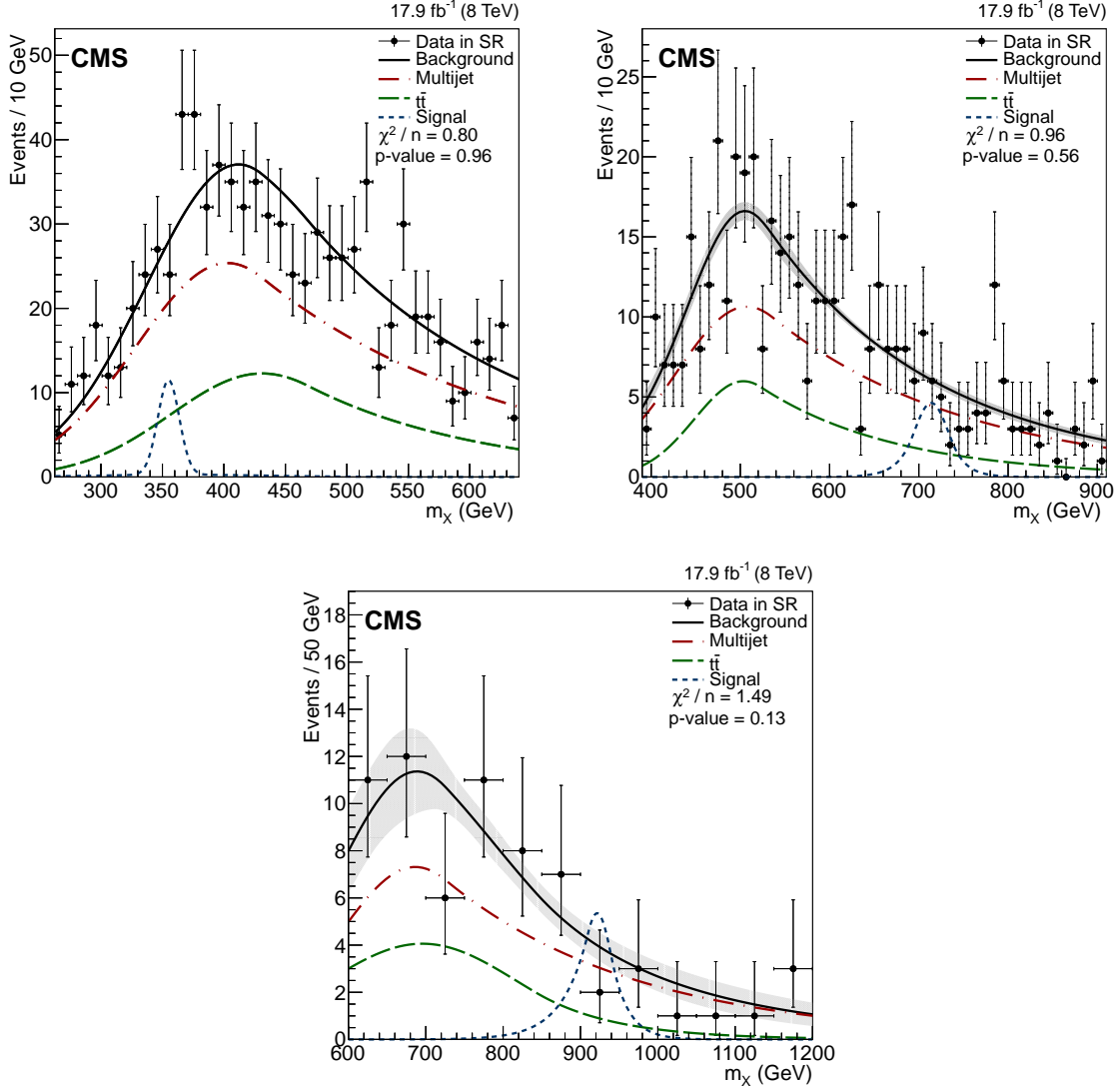


Figure 4: The m_X distribution in data in the SR between 260 and 650 GeV of the LMR (top-left), between 400 and 900 GeV of the HMR (top-right), and between 600 and 1200 GeV in the HMR where one of the Higgs boson candidates has $p_T > 300$ GeV (bottom). All distributions are fitted to the background-only hypothesis for illustration, showing the relative contributions of the QCD-multijet (dashed-dotted red) and $t\bar{t}$ (dashed green) processes. Also for illustration, we overlay the signal models of the spin-0 resonance (dotted blue) corresponding to mass hypotheses and production cross sections of 350 GeV and 653 fb for the LMR, 700 GeV and 17.6 fb for the HMR, and 900 GeV and 8.1 fb for the HMR with $H p_T > 300$ GeV on their respective plots. These cross sections correspond to the observed upper limits, which are computed for signal mass hypotheses from 270 to 450 GeV in the LMR, from 450 to 730 GeV in the HMR, and from 730 to 1100 GeV in the HMR with $H p_T > 300$ GeV.

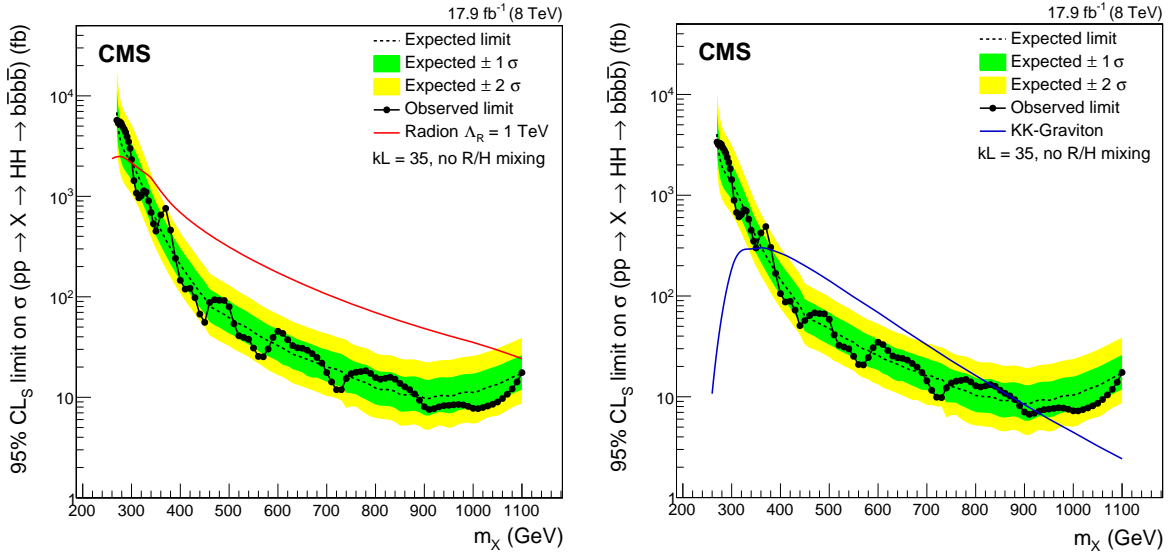


Figure 5: The observed and expected upper limits on the cross section for $pp \rightarrow X \rightarrow H(\bar{b}b)H(\bar{b}b)$ at a 95% confidence level, where the resonance X has spin-0 (left) and spin-2 (right). The theoretical cross section for the RS1 radion, with $\Lambda_R = 1$ TeV, $kL = 35$, and no radion-Higgs boson mixing, decaying to four b jets via Higgs bosons is overlaid on the left plot. The theoretical cross section for the first excitation of the KK-graviton for the same parameters is overlaid on the right plot.

9 Summary

We have presented a model-independent search by the CMS experiment at the LHC for a narrow resonance produced in proton-proton collisions at $\sqrt{s} = 8$ TeV and decaying to a pair of 125 GeV Higgs bosons that in turn each decays into bottom quark-antiquark pairs. The analyzed data correspond to an integrated luminosity of 17.9 fb^{-1} . No evidence for a signal is observed. Upper limits at a 95% CL on the production cross section for such spin-0 and spin-2 resonances, in the mass range from 270 to 1100 GeV, are reported. Using these results, a radion with decay constant of 1 TeV and mass from 300 to 1100 GeV, and a Kaluza–Klein graviton with mass from 380 to 830 GeV are excluded at a 95% confidence level.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, D. Rabadý², B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, W. Treberer-Treberspurg, W. Waltenberger, 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. Alderweireldt, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, J. Lauwers, S. Luyckx, S. Ochesanu, R. Rougny, M. Van De Klundert, H. Van Haeveermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, N. Daci, N. Heracleous, J. Keaveney, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Vilella

Université Libre de Bruxelles, Bruxelles, Belgium

C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Perniè², A. Randle-conde, T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang, F. Zenoni

Ghent University, Ghent, Belgium

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Crucy, A. Fagot, G. Garcia, J. Mccartin, A.A. Ocampo Rios, D. Poyraz, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis

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

S. Basegmez, C. Beluffi³, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco⁴, J. Hollar, A. Jafari, P. Jez, M. Komm, V. Lemaître, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, A. Popov⁵, L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

Université de Mons, Mons, Belgium

N. Bely, T. Caebergs, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, G.A. Alves, L. Brito, M. Correa Martins Junior, T. Dos Reis Martins, J. Molina, C. Mora Herrera, M.E. Pol, P. Rebello Teles

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

W. Carvalho, J. Chinellato⁶, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁶, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

C.A. Bernardes^b, S. Dogra^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Aleksandrov, V. Genchev², R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria

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

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, T. Cheng, R. Du, C.H. Jiang, R. Plestina⁷, F. Romeo, J. Tao, Z. Wang

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

C. Asawatangtrakuldee, Y. Ban, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

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

N. Godinovic, D. Lelas, D. Polic, I. Puljak

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, L. Sudic

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Bodlak, M. Finger, M. Finger Jr.⁸

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

Y. Assran⁹, A. Ellithi Kamel¹⁰, M.A. Mahmoud¹¹, A. Radi^{12,13}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

M. Kadastik, M. Murumaa, M. Raidal, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, 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, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

J. Talvitie, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

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

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, P. Busson, E. Chapon, C. Charlot, T. Dahms, M. Dalchenko, L. Dobrzynski, N. Filipovic, A. Florent, R. Granier de Cassagnac, L. Mastrolorenzo, P. Miné, I.N. Naranjo, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, C. Veelken, Y. Yilmaz, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram¹⁴, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte¹⁴, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, K. Skovpen, P. Van Hove

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

S. Gadrat

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

S. Beauceron, N. Beaupere, C. Bernet⁷, G. Boudoul², E. Bouvier, S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo², B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

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

Z. Tsamalaidze⁸

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

C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, A. Heister, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, J. Sammet, S. Schael, J.F. Schulte, H. Weber, B. Wittmer, V. Zhukov⁵

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

M. Ata, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, S. Knutzen, P. Kreuzer, M. Merschmeyer, A. Meyer, P. Millet, M. Olschewski, K. Padeken, P. Papacz, H. Reithler, S.A. Schmitz, L. Sonnenschein, D. Teyssier, S. Thüer

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

V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Künsken, J. Lingemann², A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, I. Asin, N. Bartosik, J. Behr, U. Behrens, A.J. Bell, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, G. Dolinska, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay Garcia, A. Geiser, A. Gizhko, P. Gunnellini, J. Hauk, M. Hempel¹⁵, H. Jung, A. Kalogeropoulos, O. Karacheban¹⁵, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, I. Korol,

D. Krücker, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁵, B. Lutz, R. Mankel, I. Marfin¹⁵, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, B. Roland, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, T. Schoerner-Sadenius, M. Schröder, C. Seitz, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, J. Erfle, E. Garutti, K. Goebel, M. Görner, J. Haller, M. Hoffmann, R.S. Höing, A. Junkes, H. Kirschenmann, R. Klanner, R. Kogler, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, J. Ott, T. Peiffer, A. Perieanu, N. Pietsch, J. Poehlsen, T. Poehlsen, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, A. Gilbert, F. Hartmann², T. Hauth, U. Husemann, I. Katkov⁵, A. Kornmayer², P. Lobelle Pardo, M.U. Mozer, T. Müller, Th. Müller, A. Nürnberg, G. Quast, K. Rabbertz, S. Röcker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, A. Psallidas, I. Topsis-Giotis

University of Athens, Athens, Greece

A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Stiliaris, E. Tziaferi

University of Ioánnina, Ioánnina, Greece

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath¹⁶, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁷, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi¹⁸, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary

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

National Institute of Science Education and Research, Bhubaneswar, India

S.K. Swain

Panjab University, Chandigarh, India

S.B. Beri, V. Bhatnagar, R. Gupta, U. Bhawandeep, A.K. Kalsi, M. Kaur, R. Kumar, M. Mittal, N. Nishu, J.B. Singh

University of Delhi, Delhi, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, D. Dutta, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik¹⁹, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²⁰, G. Kole, S. Kumar, M. Maity¹⁹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage²¹

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

S. Sharma

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami²², A. Fahim²³, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh²⁴, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, C. Calabria^{a,b}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, S. My^{a,c}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b,2}, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,2}, R. Venditti^{a,b}, P. Verwilligen^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}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^{a,b}, R. Travaglini^{a,b}

INFN Sezione di Catania ^a, Università di Catania ^b, CSFNSM ^c, Catania, Italy

S. Albergo^{a,b}, G. Cappello^a, M. Chiorboli^{a,b}, S. Costa^{a,b}, F. Giordano^{a,2}, 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}, E. Gallo^a, S. Gozzi^{a,b}, V. Gori^{a,b}, P. Lenzi^{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, F. Fabbri, D. Piccolo

INFN Sezione di Genova ^a, Università di Genova ^b, Genova, Italy

R. Ferretti^{a,b}, F. Ferro^a, M. Lo Vetere^{a,b}, E. Robutti^a, S. Tosi^{a,b}

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

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

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

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,2}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,2}, M. Merola^a, P. Paolucci^{a,2}

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

P. Azzi^a, N. Bacchetta^a, D. Bisello^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^a, P. Checchia^a, M. Dall'Osso^{a,b}, T. Dorigo^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, K. Kanishchev^{a,c}, S. Lacaprara^a, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, 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}, A. Zucchetta^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

M. Gabusi^{a,b}, S.P. Ratti^{a,b}, V. Re^a, C. Riccardi^{a,b}, P. Salvini^a, P. Vitulo^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

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

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

K. Androsov^{a,25}, P. Azzurri^a, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, M.A. Ciocci^{a,25}, R. Dell'Orso^a, S. Donato^{a,c,2}, G. Fedi, F. Fiori^{a,c}, L. Foà^{a,c}, A. Giassi^a, M.T. Grippo^{a,25}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, C.S. Moon^{a,26}, F. Palla^{a,2}, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,27}, A.T. Serban^a, P. Spagnolo^a, P. Squillacioti^{a,25}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a, C. Vernieri^{a,c}

INFN Sezione di Roma ^a, Università di Roma ^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, G. D'imperio^{a,b}, D. Del Re^{a,b}, M. Diemoz^a, C. Jorda^a, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, F. Micheli^{a,b,2}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}, L. Soffi^{a,b}, P. Traczyk^{a,b,2}

INFN Sezione di Torino ^a, Università di Torino ^b, Torino, Italy, Università del Piemonte Orientale ^c, Novara, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, S. Casasso^{a,b,2}, M. Costa^{a,b}, R. Covarelli, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b,2}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^a, M.M. Obertino^{a,c}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Potenza^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a, U. Tamponi^a

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

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

Kangwon National University, Chunchon, Korea

S. Chang, A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea

T.J. Kim, M.S. Ryu

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

J.Y. Kim, D.H. Moon, S. Song

Korea University, Seoul, Korea

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

Seoul National University, Seoul, Korea

H.D. Yoo

University of Seoul, Seoul, Korea

M. Choi, J.H. Kim, I.C. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y.K. Choi, J. Goh, D. Kim, E. Kwon, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

A. Juodagalvis

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

J.R. Komaragiri, M.A.B. Md Ali, W.A.T. Wan Abdullah

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

E. Casimiro Linares, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, A. Hernandez-Almada, R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Pedraza, H.A. Salazar Ibarquen

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler, S. Reucroft

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

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, 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, M. Misiura, M. Olszewski

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

P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, L. Lloret Iglesias, F. Nguyen, J. Rodrigues Antunes, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, V. Konoplyanikov, G. Kozlov, A. Lanev,

A. Malakhov, V. Matveev²⁸, P. Moiseenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim²⁹, E. Kuznetsova, 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, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁰, I. Dremin³⁰, M. Kirakosyan, A. Leonidov³⁰, G. Mesyats, S.V. Rusakov, A. Vinogradov

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

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin³¹, L. Dudko, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkin, 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. Adzic³², M. Ekmedzic, J. Milosevic, V. Rekovic

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

J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, A. Graziano, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez, 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, A. Benaglia,

J. Bendavid, L. Benhabib, J.F. Benitez, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi³³, M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, E. Di Marco, M. Dobson, M. Dordevic, B. Dorney, N. Dupont-Sagorin, A. Elliott-Peisert, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, L. Orsini, L. Pape, E. Perez, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pimiä, D. Piparo, M. Plagge, A. Racz, G. Rolandi³⁴, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁵, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, Y. Takahashi, D. Treille, A. Tsirou, G.I. Veres¹⁷, N. Wardle, H.K. Wöhri, H. Wollny, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

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

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, M.A. Buchmann, B. Casal, N. Chanon, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, J. Hoss, G. Kasieczka, W. Lustermann, B. Mangano, A.C. Marini, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, D. Meister, N. Mohr, P. Musella, C. Nägeli³⁶, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, L. Perrozzi, M. Peruzzi, M. Quittnat, L. Rebane, M. Rossini, A. Starodumov³⁷, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland

C. AMSLER³⁸, M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, B. Kilminster, C. Lange, J. Ngadiuba, D. Pinna, P. Robmann, F.J. Ronga, S. Taroni, Y. Yang

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y.H. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Petrakou, Y.M. Tzeng, R. Wilken

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

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

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci³⁹, S. Cerci⁴⁰, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, E.E. Kangal⁴¹, A. Kayis Topaksu, G. Onengut⁴², K. Ozdemir⁴³, S. Ozturk³⁹, A. Polatoz, D. Sunar Cerci⁴⁰, B. Tali⁴⁰, H. Topakli³⁹, M. Vergili, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan⁴⁴, B. Isildak⁴⁵, G. Karapinar⁴⁶, K. Ocalan⁴⁷, S. Sekmen, U.E. Surat, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E.A. Albayrak⁴⁸, E. Gülmez, M. Kaya⁴⁹, O. Kaya⁵⁰, T. Yetkin⁵¹

Istanbul Technical University, Istanbul, Turkey

K. Cankocak, F.I. Vardarli

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

L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold⁵², S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, S. Senkin, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁵³, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, A. Elwood, W. Ferguson, J. Fulcher, D. Futyan, G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas⁵², L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko³⁷, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Tapper, M. Vazquez Acosta, T. Virdee, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, N. Pastika, T. Scarborough, Z. Wu

The University of Alabama, Tuscaloosa, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA

A. Avetisyan, T. Bose, C. Fantasia, P. Lawson, C. Richardson, J. Rohlf, J. St. John, L. Sulak

Brown University, Providence, USA

J. Alimena, E. Berry, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, N. Dhingra, A. Ferapontov, A. Garabedian, U. Heintz, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Sagir, T. Sinthuprasith, T. Speer, J. Swanson

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, R. Erbacher, M. Gardner, W. Ko, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, M. Ivova Rikova, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, A. Luthra, M. Malberti, M. Olmedo Negrete, A. Shrinivas, S. Sumowidagdo, S. Wimpenny

University of California, San Diego, La Jolla, USA

J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, A. Holzner, R. Kelley, D. Klein, J. Letts,

I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, Y. Tu, A. Vartak, C. Welke, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, J. Bradmiller-Feld, C. Campagnari, T. Danielson, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Incandela, C. Justus, N. Mccoll, S.D. Mullin, J. Richman, D. Stuart, W. To, C. West, J. Yoo

California Institute of Technology, Pasadena, USA

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, A. Mott, H.B. Newman, C. Pena, M. Pierini, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, A. Gaz, M. Krohn, E. Luiggi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, A. Chatterjee, J. Chaves, J. Chu, S. Dittmer, N. Eggert, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, L. Skinnari, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Kwan[†], J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, P. Merkel, K. Mishra, S. Mrenna, S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, M. Carver, D. Curry, S. Das, M. De Gruttola, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, K. Matchev, H. Mei, P. Milenovic⁵⁴, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, M. Snowball, D. Sperka, J. Yelton, M. Zakaria

Florida International University, Miami, USA

S. Hewamanage, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA

J.R. Adams, T. Adams, A. Askew, J. Bochenek, B. Diamond, J. Haas, S. Hagopian, V. Hagopian, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva

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

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, C. Silkworth, P. Turner, N. Varelas

The University of Iowa, Iowa City, USA

B. Bilki⁵⁵, W. Clarida, K. Dilsiz, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁵⁶, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁴⁸, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA

I. Anderson, B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz, M. Xiao

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, D. Majumder, M. Malek, M. Murray, D. Noonan, S. Sanders, J. Sekaric, R. Stringer, Q. Wang, J.S. Wood

Kansas State University, Manhattan, USA

I. Chakaberia, A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, N. Skhirtladze, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

University of Maryland, College Park, USA

A. Baden, A. Belloni, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, Y. Lu, A.C. Mignerey, K. Pedro, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA

A. Apyan, R. Barbieri, K. Bierwagen, W. Busza, I.A. Cali, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, D. Velicanu, J. Veverka, B. Wyslouch, M. Yang, M. Zanetti, V. Zhukova

University of Minnesota, Minneapolis, USA

B. Dahmes, A. Gude, S.C. Kao, K. Klapöetke, Y. Kubota, J. Mans, S. Nourbakhsh, R. Rusack, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, R. Gonzalez Suarez, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, F. Meier, F. Ratnikov, G.R. Snow, M. Zvada

State University of New York at Buffalo, Buffalo, USA

J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, D. Trocino, R.-J. Wang, D. Wood, J. Zhang

Northwestern University, Evanston, USA

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA

A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, S. Lynch, N. Marinelli, Y. Musienko²⁸, T. Pearson, M. Planer, R. Ruchti, G. Smith, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, W. Luo, D. Puigh, M. Rodenburg, B.L. Winer, H. Wolfe, H.W. Wulsin

Princeton University, Princeton, USA

O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland², C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA

E. Brownson, S. Malik, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, USA

V.E. Barnes, D. Benedetti, D. Bortoletto, M. De Mattia, L. Gutay, Z. Hu, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D.H. Miller, N. Neumeister, F. Primavera, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, J. Zablocki

Purdue University Calumet, Hammond, USA

N. Parashar, J. Stupak

Rice University, Houston, USA

A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA

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

The Rockefeller University, New York, USA

R. Ciesielski, L. Demortier, K. Goulianos, 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, S. Kaplan, A. Lath, S. Panwalkar, M. Park, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

K. Rose, S. Spanier, A. York

Texas A&M University, College Station, USA

O. Bouhali⁵⁷, A. Castaneda Hernandez, S. Dildick, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁸, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, R. Patel, A. Perloff, J. Roe, A. Rose, A. Safonov, I. Suarez, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duderu, J. Faulkner, K. Kovitanggoon, S. Kunori, S.W. Lee, T. Libeiro, I. Volobouev

Vanderbilt University, Nashville, USA

E. Appelt, A.G. Delannoy, S. Greene, A. Gurrola, W. Johns, C. Maguire, Y. Mao, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Lin, C. Neu, E. Wolfe, J. Wood

Wayne State University, Detroit, USA

C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin, Madison, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, L. Dodd, S. Duric, E. Friis, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, C. Lazaridis, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, D. Taylor, C. Vuosalo, N. Woods

†: Deceased

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

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

3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

6: Also at Universidade Estadual de Campinas, Campinas, Brazil

7: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

8: Also at Joint Institute for Nuclear Research, Dubna, Russia

9: Also at Suez University, Suez, Egypt

10: Also at Cairo University, Cairo, Egypt

11: Also at Fayoum University, El-Fayoum, Egypt

12: Also at British University in Egypt, Cairo, Egypt

13: Now at Ain Shams University, Cairo, Egypt

14: Also at Université de Haute Alsace, Mulhouse, France

15: Also at Brandenburg University of Technology, Cottbus, Germany

16: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

17: Also at Eötvös Loránd University, Budapest, Hungary

18: Also at University of Debrecen, Debrecen, Hungary

19: Also at University of Visva-Bharati, Santiniketan, India

20: Now at King Abdulaziz University, Jeddah, Saudi Arabia

21: Also at University of Ruhuna, Matara, Sri Lanka

22: Also at Isfahan University of Technology, Isfahan, Iran

23: Also at University of Tehran, Department of Engineering Science, Tehran, Iran

24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran

25: Also at Università degli Studi di Siena, Siena, Italy

26: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France

27: Also at Purdue University, West Lafayette, USA

28: Also at Institute for Nuclear Research, Moscow, Russia

29: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia

30: Also at National Research Nuclear University 'Moscow Engineering Physics

Institute' (MEPhI), Moscow, Russia

31: Also at California Institute of Technology, Pasadena, USA

32: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia

33: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy

34: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy

35: Also at University of Athens, Athens, Greece

36: Also at Paul Scherrer Institut, Villigen, Switzerland

37: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia

38: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland

39: Also at Gaziosmanpasa University, Tokat, Turkey

40: Also at Adiyaman University, Adiyaman, Turkey

41: Also at Mersin University, Mersin, Turkey

42: Also at Cag University, Mersin, Turkey

43: Also at Piri Reis University, Istanbul, Turkey

44: Also at Anadolu University, Eskisehir, Turkey

45: Also at Ozyegin University, Istanbul, Turkey

46: Also at Izmir Institute of Technology, Izmir, Turkey

47: Also at Necmettin Erbakan University, Konya, Turkey

48: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey

49: Also at Marmara University, Istanbul, Turkey

50: Also at Kafkas University, Kars, Turkey

51: Also at Yildiz Technical University, Istanbul, Turkey

52: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom

53: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

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 Texas A&M University at Qatar, Doha, Qatar

58: Also at Kyungpook National University, Daegu, Korea