EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2022-020
2022/03/02

CMS-B2G-20-003

Search for new particles in an extended Higgs sector with four b quarks in the final state at $\sqrt{s} = 13\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

A search for an extended Higgs sector, characterized by a massive resonance X decaying to a pair of spin-0 bosons ϕ that themselves decay to pairs of bottom quarks, is presented. The analysis is restricted to the mass ranges m_ϕ from 25 to 100 GeV and m_X from 1 to 3 TeV. For these mass ranges, the decay products of each ϕ boson are expected to merge into a single large-radius jet. Jet substructure and flavor identification techniques are used to identify these jets. The search is based on CERN LHC proton-proton collision data at $\sqrt{s} = 13\,\mathrm{TeV}$, collected with the CMS detector in 2016–2018, corresponding to an integrated luminosity of $138\,\mathrm{fb}^{-1}$. Model-specific limits are set on the product of the production cross section and branching fraction for $\mathrm{X} \to \phi\phi \to (\mathrm{b\overline{b}})(\mathrm{b\overline{b}})$ as a function of mass, where both the $\mathrm{X} \to \phi\phi$ and $\phi \to \mathrm{b\overline{b}}$ branching fractions are assumed to be 100%. These limits are the first of their kind on this process, ranging between 30 and 1 fb at 95% confidence level for the considered mass ranges.

Submitted to Physics Letters B

*See Appendix A for the list of collaboration members

1 Introduction

The discovery [1–3] of a particle consistent with the standard model (SM) Higgs boson (H), by both the ATLAS and CMS Collaborations, does not preclude the existence of an extended Higgs sector. Such extensions, proposed in a variety of new physics models [4–10], generally postulate that an additional approximate global symmetry with spontaneous symmetry breaking is a sufficient condition for the existence of new spin-0 particles, X and ϕ, whose masses m_{X} and m_{ϕ} are not constrained. If $m_{\mathrm{X}} > 2m_{\phi}$, then $\mathrm{X} \to \phi\phi$ is the dominant decay of the heavier particle, and ϕ couples to fermions similarly to H.

This paper presents a search for the process $\mathrm{pp} \to \mathrm{X} \to \phi\phi \to (\mathrm{b\overline{b}})(\mathrm{b\overline{b}})$ for m_{X} between 1 and 3 TeV, and m_{ϕ} between 25 and 100 GeV (for which the $\phi \to \mathrm{b\overline{b}}$ decay is expected to dominate). The leading Feynman diagram for this process is shown in Fig. 1. In the considered model, the coupling of the boson X to gluons is evaluated by integrating over N flavors of quarks that receive all their mass from the X vacuum expectation value f, such that the cross section depends only on the quantity $m_{\mathrm{X}}N/f$. The search is based on proton-proton (pp) collision data at $\sqrt{s} = 13$ TeV collected with the CMS detector [11] at the LHC in 2016–2018, corresponding to a total integrated luminosity of 138 fb^{-1} [12–14]. In the mass ranges considered for the X and ϕ scalar bosons, the high momentum imparted to the ϕ boson causes the hadronic showers of the two b quarks to overlap, such that the signal is best reconstructed as a pair of large-radius jets each with substructure consistent with the decay to two b quarks. The ATLAS and CMS Collaborations have previously performed searches [15–19] for the process $\mathrm{X} \to \mathrm{HH} \to (\mathrm{b\overline{b}})(\mathrm{b\overline{b}})$ with similar topologies. However, requirements on the jet mass in those analyses make them less sensitive to m_{ϕ} below 100 GeV.

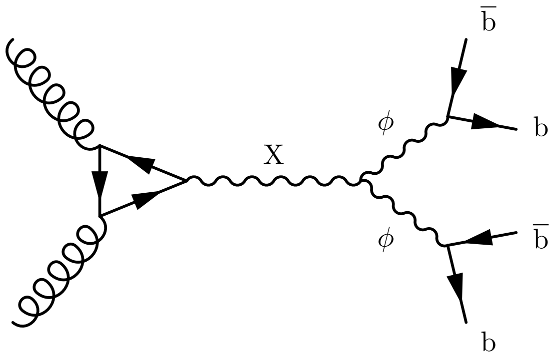

Figure 1: Feynman diagram of the production and decay of $\mathrm{X} \to \phi\phi \to (\mathrm{b\overline{b}})(\mathrm{b\overline{b}})$. The dominant production mechanism occurs via a fermion loop as shown in the diagram. Additional partons may be present, produced by initial-state or final-state radiation.

This analysis searches for a localized excess in the two-dimensional distributions of average jet mass and dijet mass for events with two large-radius jets with heavy-flavor jet substructure. The main background, from SM events composed uniquely of jets produced through the strong interaction, referred to as quantum chromodynamics (QCD) multijet events, is derived using control samples in data. Additional background from top quark pair ($\mathrm{t\overline{t}}$) events is estimated from simulation, with corrections obtained from control regions in data. Other SM backgrounds, namely single top quark, single vector boson, and paired vector boson processes, were found to be negligible. Tabulated results are provided in the HEPData record for this analysis [20].

2 The CMS detector

The CMS apparatus [11] is a multipurpose, nearly hermetic detector, designed to trigger on [21] and identify electrons, muons, photons, and (charged and neutral) hadrons [22–25]. A global reconstruction "particle-flow" (PF) algorithm [26] combines the information provided by the all-silicon inner tracker and by the lead-tungstate crystal electromagnetic (ECAL) and brass-scintillator hadron calorimeters (HCAL), operating inside a 3.8 T superconducting solenoid, with data from gas-ionization muon detectors interleaved with the solenoid return yoke, to build τ leptons, jets, missing transverse momentum, and other physics objects [27–29]. Events of interest are selected using a two-tiered trigger system [21]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast (online) processing, and reduces the event rate to around 1 kHz for use in (offline) analyses. A more detailed description of the CMS detector, including its coordinate system, can be found in Ref. [11].

3 Simulated samples

The benchmark signal model $\mathrm{X} \to \phi\phi \to (\mathrm{b\bar{b}})(\mathrm{b\bar{b}})$, where X is produced through gluon fusion, was generated to leading order with the MADGRAPH 2.6.0 [30] generator. Both the $\mathrm{X} \to \phi\phi$ and $\phi \to \mathrm{b\bar{b}}$ branching fractions are set to 100%. The samples are generated with up to two additional initial-state or final-state radiation jets. The total production cross section is calculated numerically at next-to-next-to-leading order (NNLO) in the infinite fermion mass limit using the HQT 2.0 program [31–33].

The MADGRAPH generator is used to model at leading order the QCD background, which was used to optimize the analysis procedure. The POWHEG 2.0 [34–36] generator is used to model $\mathrm{t\bar{t}}$ events at next-to-leading order [37].

The parton showering and fragmentation for all signal and background samples is done with PYTHIA 8 [38], and matching between the matrix element and parton shower jets relies on the MLM matching procedure [39]. The CUETP8M1 (CP5) [40, 41] underlying event tune is used for the simulated samples corresponding to the 2016 (2017–2018) data taking with the NNPDF3.0 (NNPDF3.1) [42] NNLO parton distribution function (PDF) sets.

The simulation of the CMS detector for all samples is handled by GEANT4 [43]. All samples include effects of additional pp interactions in the same or adjacent bunch crossings, referred to as pileup. The pileup distribution in simulation is weighted to match the one observed in data.

4 Event reconstruction

Jets used in this analysis are clustered using FASTJET [44] with the anti-k_{T} (AK) algorithm [45] and a distance parameter of 0.4 (AK4 jets) or 0.8 (AK8 jets). Particles produced in additional collisions within the same bunch crossing are suppressed by applying a weight to each PF candidate, calculated by the pileup-per-particle identification [46, 47] algorithm. Jets are corrected as a function of their p_{T} and pseudorapidity (η) to match the observed detector response [48].

Jets arising from the hadronization of a b quark-antiquark pair are identified using the "double-b tagger"algorithm [49], which uses a boosted decision tree (BDT) of several vertex- and trackrelated variables to identify jets containing two displaced vertices consistent with decays into $b\bar{b}$. The BDT was trained on simulated samples of boosted Higgs boson jets, where the jet showering may be different from the behavior of jets in real data. To correct for this, a scale factor is derived and applied to each jet in the signal simulation as a function of the jet p_T [49]. The lower bound on ϕ masses considered is due to uncertainty in the behavior of this algorithm for jet masses below 25 GeV. The training is sensitive to detector conditions, so the exact performance of the discriminator differs from year to year. The soft drop mass algorithm (with angular exponent $\beta = 0$ and soft threshold $z_{cut} = 0.1$) [50, 51] is used to remove soft and wide-angle radiation from jets before computing a "groomed jet mass" (m_j), which better reflects the mass of the particle that initiated the jet.

5 Event selection

Events are first selected by a trigger based on either the p_T of a single AK8 jet, or on the event H_T, defined as the scalar p_T sum of all AK4 jets with $p_T > 30$ GeV and $|\eta| < 2.5$. In 2016 the H_T threshold was set to 800 GeV for the early data-taking period and raised to 900 GeV for the last 8 fb^{-1}. This threshold was raised to 1050 GeV for data taken in 2017 and 2018. The AK8 jet threshold was set to 450 (500) GeV in 2016 (2017–2018). The efficiency of this trigger combination is measured in an orthogonal sample triggered on single-muon candidate events. To account for differences between the simulated and real responses of the detector, the ratio of the efficiency of the trigger between data and simulated samples is applied to all simulated events, with the uncertainty in the efficiencies considered as a systematic uncertainty.

Events are only considered if they pass the trigger for their given year, and if they contain two AK8 jets with $p_T > 300$ GeV and $|\eta| < 2.4$. An offline selection of $H_T > 900$ GeV is applied. Signals with m_X below 1 TeV do not produce events with H_T large enough to be considered in this analysis. The jets are ordered according to their p_T.

Events are divided between several search and control regions based on the mass asymmetry between the two leading jets j_1 and j_2 ($m_{asym} = |m_{j_1} - m_{j_2}|/(m_{j_1} + m_{j_2})$), the separation in η between these jets ($|\Delta\eta|$), and the values of the double-b tagger discriminant (D^{bb}) for each jet. Two signal enriched regions are used to extract the signal: the first, called the "tight search region" (TSR), requires $|\Delta\eta| < 1.5$, $m_{asym} < 0.1$, $D^{bb}_{j_1} > 0.8$, and $D^{bb}_{j_2} > 0.6$. The second, called the "loose search region" (LSR), differs only in the constraint on the mass asymmetry, requiring $m_{asym} \in [0.1, 0.25]$. This second region, while it has lower sensitivity to the signal, contains a large contribution from the $t\bar{t}$ background, allowing for strong constraints to be placed on that process, thus benefiting both search regions. These selections, including the two threshold values for D^{bb}, were optimized by maximizing the signal significance with respect to simulated backgrounds. Two control regions are defined with respect to each search region: the "$|\Delta\eta|$ sideband", where the $|\Delta\eta|$ requirement is replaced by $|\Delta\eta| > 1.5$, and the "double-b sideband", where the double-b discriminant on the leading jet becomes $-0.8 < D^{bb}_{j_1} < 0.3$. Both control regions are used to estimate the background in the search regions, as they are rich in background events, have similar kinematic distributions to the search regions, and are signal depleted. The categorization is summarized in Table 1. The background estimate, described in the next section, uses events from an additional category: the "failing region", defined for each search or control region, consisting of events fulfilling all selection criteria except that the subleading jet has $D^{bb}_{j_2} < 0.6$.

After all selection criteria are applied, the product of the acceptance and efficiency for the range of m_X and m_ϕ considered is between 5 and 20%. The efficiencies are lowest for signals with $m_X = 1.0\,\text{TeV}$, peak at $m_X = 1.5\,\text{TeV}$, and fall linearly to approximately 12% for $m_X = 3.0\,\text{TeV}$. The signal efficiencies have negligible dependence on m_ϕ.

Table 1: Search and control regions used in the analysis. A selection on the subleading jet double-b-tagger discriminant $D^{bb}_{j_2} > 0.6$ further separates each region into "passing" and "failing" categories.

	m_{asym}	$\lvert\Delta\eta\rvert$	$D^{bb}_{j_1}$
Tight search region	<0.1	<1.5	>0.8
Loose search region	$[0.1, 0.25]$	<1.5	>0.8
Tight $\lvert\Delta\eta\rvert$ sideband	<0.1	>1.5	>0.8
Loose $\lvert\Delta\eta\rvert$ sideband	$[0.1, 0.25]$	>1.5	>0.8
Tight double-b sideband	<0.1	<1.5	$[-0.8, 0.3]$
Loose double-b sideband	$[0.1, 0.25]$	<1.5	$[-0.8, 0.3]$

6 Background processes

The dominant QCD multijet background is modeled by exploiting the fact that the ratio of events for which the subleading jet passes or fails the $D^{bb}_{j_2} > 0.6$ requirement in each search region can be modeled by a smooth function of the subleading jet p_T and groomed jet mass, $R_{p/f}(p_{Tj_2}, m_{j_2})$. This pass-to-fail ratio is parameterized as $R_{p/f} = P_n(p_{Tj_2})F(m_{j_2})$, where P_n is a polynomial of order n and $F(m_{j_2})$ is the function $F(x) = p_0 \arctan(p_1 x + p_2) + p_3$. The parameters of each component of $R_{p/f}$ are measured in the control regions. The $\lvert\Delta\eta\rvert$ sidebands are used to determine $F(m_{j_2})$, whereas the double-b sidebands are used to determine $P_n(p_{Tj_2})$. In both cases the signal is negligible in the control regions. The QCD background in the "passing" search regions is estimated by weighting the events in the "failing" search regions by this $R_{p/f}$. This background estimate is also performed in each control region as a closure test.

Each year of data taking, as well as the TSR and LSR, is treated independently. The order of P_n is determined in the double-b control region by performing Fisher F-tests [52] on progressively higher-order polynomials. A P_2 (P_1) is found to be optimal for describing the data taken in 2016 (2017–2018). Uncertainties in the fit parameters for F and P_n are treated as systematic uncertainties in the shape of the background in the search regions.

The $t\bar{t}$ contribution to the total background is obtained from simulation, after a correction is applied to account for the differences [53–55] between the top quark pair transverse momentum distribution in fixed-order simulations and data. This variable is highly correlated with the dijet mass of the $t\bar{t}$ system. The correction is applied by weighting the simulated events with a term: $W = \exp[\alpha(p_T^t + p_T^{\bar{t}})]$, where α, initialized at 5×10^{-4}/GeV, controls the shape of the resulting $t\bar{t}$ distribution. The normalization of the $t\bar{t}$ background and the value of α are obtained by a simultaneous maximum likelihood fit of the TSR and LSR. The best fit values for both the overall normalization and the value of α may vary from year to year, so both are allowed to vary within large uncertainties (20 and 100%, respectively), separately for each year.

7 Fitting procedure

A two-dimensional mass spectrum is examined for localized excesses of events, since both m_ϕ and m_X for a potential signal are unknown. The two dimensions of this spectrum are the average jet mass $\hat{m} = (m_{\mathrm{j}_1} + m_{\mathrm{j}_2})/2$ and the dijet mass M_{jj} (the invariant mass of the sum of the two jet four-momenta). The signal is modeled analytically using a multivariate normal distribution whose five parameters (the mean and width of the distribution in $\hat{m}$ and M_{jj}, and the correlation between the two masses) are fit to the values observed in the generated signal samples. The signal is sharply peaked in both variables, with root-mean-square values of 12–16% and 6–9% of the resonance mass for the reconstructed ϕ and X masses, respectively. The range of average jet masses considered is $\hat{m} \in [15, 200]$ GeV, while M_{jj} between 0.9 and 5.0 TeV are considered. These ranges go beyond the signal masses considered in this analysis, with the events at high masses providing constraints on the $\mathrm{t\bar{t}}$ and QCD components. Both mass distributions use variable binnings to ensure that the background estimate prediction is nonzero in each mass interval.

The final fits, for both the background-only and signal-plus-background hypotheses, simultaneously maximize a binned maximum likelihood over the TSR and LSR in all years. When fitting for signal and background, the signal strength is the same in all regions. To validate the robustness of the fit, a goodness-of-fit test and bias tests are performed, where the bias tests use simulated data with a variety of simulated signals injected. No significant bias is observed for any ϕ and X mass combination. The results of the fit for the combined search regions are shown in Fig. 2 as projections onto the individual $\hat{m}$ and M_{jj} distributions, and in Fig. 3 as average jet mass distribution in consecutive dijet mass intervals, showing also the difference between the data and the background estimate. The largest excess corresponds to m_ϕ and m_X of about 75 GeV and 1 TeV, respectively, with a local significance of 3.1 standard deviations and a global significance of 1.3 standard deviations. Here the global significance takes into account the look-elsewhere effect, using pseudo-experiments to measure the probability that the background hypothesis produces a signal-like effect with at least the observed local significance, anywhere within the sensitive range of m_ϕ and m_X.

8 Systematic uncertainties

Systematic uncertainties are treated in the fit as nuisance parameters affecting the shapes and the normalization of signal and background processes. All uncertainties are quantified in Table 2. The dominant uncertainty is from the double-b tagger scale factor, which is described in Ref. [49] and applied as a function of the jet p_T. Differences between simulation and data on the jet energy calibration and p_T resolution of jets are corrected by applying scale factors to the simulation, derived from control regions in data [48]. The jet energy scale (JES) and resolution uncertainties are considered as uncertainties in the shape of the signal and $\mathrm{t\bar{t}}$ background. The JES uncertainties take into account correlated and uncorrelated components between all three years. Uncertainties pertaining to the trigger efficiency, the pileup distribution, the PDFs, and the integrated luminosity determination [12–14] are applied to the signal and $\mathrm{t\bar{t}}$ process simulations. The $\mathrm{t\bar{t}}$ background is additionally affected by the uncertainties in the normalization and the α parameter. The data-driven QCD background has two sources of uncertainty, from the determination of $R_{\mathrm{p/f}}$, and from the statistical uncertainty in the failing regions. The latter dominates for high dijet and average jet masses where the number of events in the failing region is low.

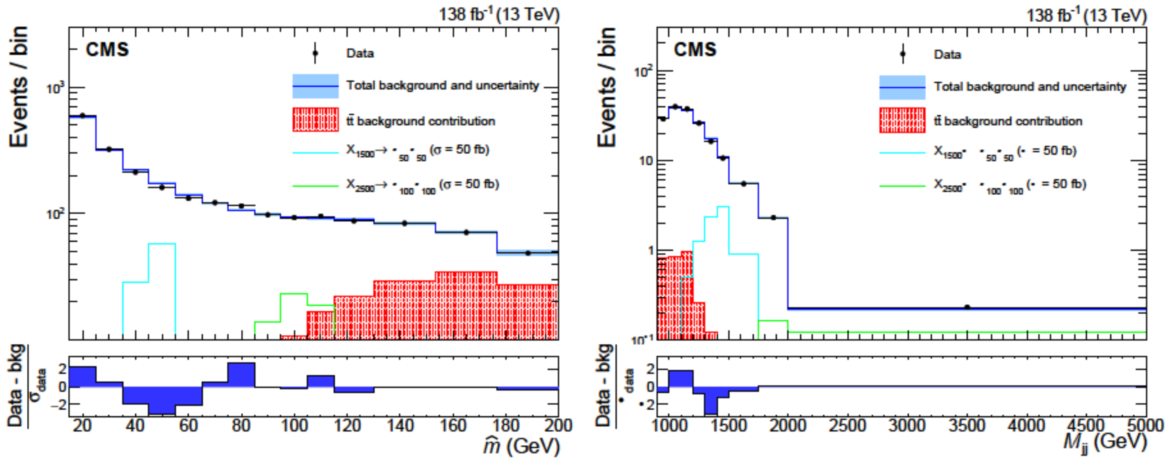

Figure 2: Distributions of average jet mass (left) and dijet mass (right), and background estimate of the combined search regions after the final fit is performed. The blue (solid) line represents the sum of the estimated QCD and $t\bar{t}$ backgrounds, and the red filled histogram shows the $t\bar{t}$ contribution alone. The shaded areas around the background estimate in the upper panels represent the total uncertainty in the total background estimate in that bin. The shapes of two representative signals, each normalized to cross sections of 50 fb, are indicated by solid colored lines. The lower panel shows the difference between the observed data and the background prediction, divided by σ_{data}, the statistical uncertainty of the data in each bin.

Table 2: Sources of systematic uncertainties considered in the analysis. The uncertainty in the integrated luminosity only affects the normalization; for the rest, both the shape and normalization are affected. The parameters affecting only the normalization have log-normal priors, and those affecting the shape (or both the shape and normalization) have Gaussian priors, except for the statistical uncertainty in the failing region, whose parameters were sampled from a Γ distribution. Uncertainties marked with R are correlated between the TSR and LSR for a given year of data-taking, and those marked with Y are correlated between both search regions in all three years. All other uncertainties are uncorrelated between search regions. The values indicated in the table represent the pre-fit values of the uncertainty in the parameter. When a range is given, it indicates the typical variation of the size of the uncertainty over the average jet mass and dijet mass distribution. We note that all $t\bar{t}$ uncertainties are propagated to the QCD estimate.

	Signal	Background		Corr.
		$t\bar{t}$	QCD	
Integrated luminosity	1.2–2.5%	1.2–2.5%		R
Double-b scale factor	19–46%			R
Trigger efficiency	1–5%	1–5%		R
PDF	4%	4%		R
Pileup	1–10%	1–10%		R
Jet energy scale (correlated)	2%	2%		RY
Jet energy scale (uncorrelated)	2%	2%		R
Jet energy resolution	10%	10%		R
$t\bar{t}$ shape (α)		100%		R
$t\bar{t}$ normalization		20%		R
$R_{p/f}$ fit			5–30%	—
Statistical uncertainty (failing region)			<1–100%	—

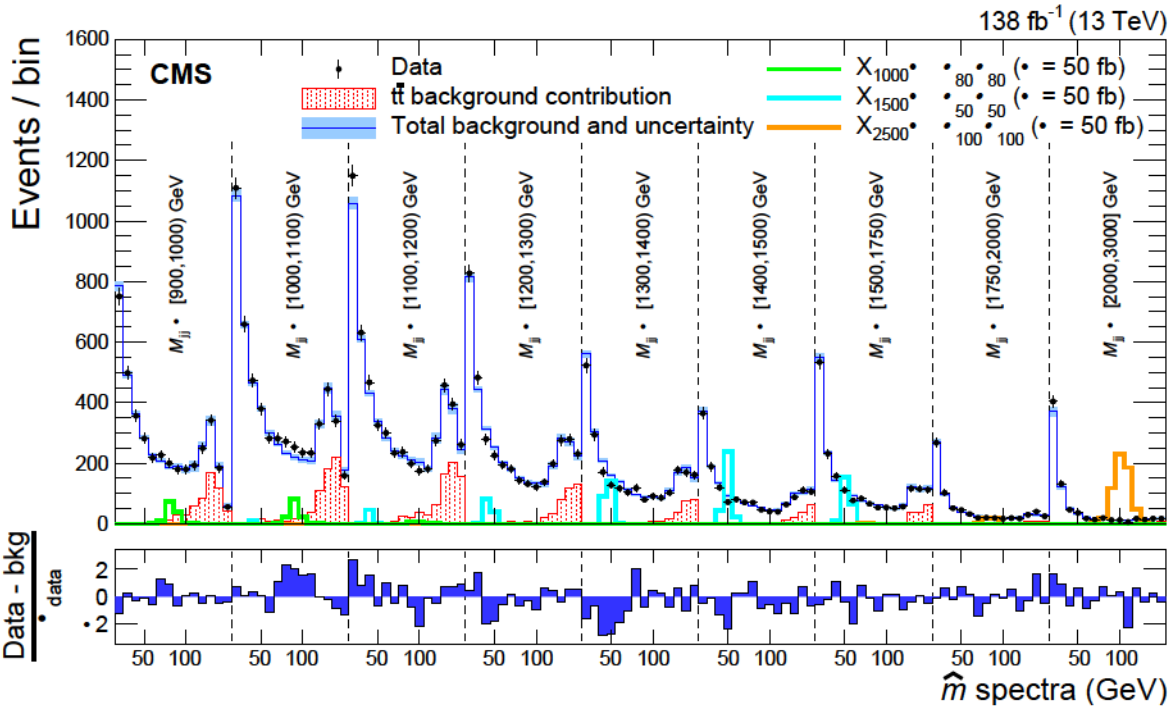

Figure 3: The average jet mass distributions in consecutive dijet mass intervals. The vertical dashed grey lines separate the average jet mass distributions in each bin of M_{jj}. The individual bins within such subdivisions correspond to the $\hat{m}$ spectrum (from 15 to 200 GeV), as seen in Fig. 2 (left). Representative signal shapes are also shown; we note that they peak in the $\hat{m}$ spectrum within subdivisions, and may appear in multiple M_{jj} bins. The blue (solid) line represents the sum of the estimated QCD and $t\bar{t}$ backgrounds, and the red filled histogram shows the $t\bar{t}$ contribution alone. The shaded areas around the background estimate in the upper panels represent the total uncertainty in the total background estimate in that bin. The shapes of three representative signals, each normalized to cross sections of 50 fb are indicated by solid colored lines. The lower panel shows the difference between the observed data and the background prediction, divided by σ_{data}, the statistical uncertainty of the data in each bin.

9 Results

The results of the fit are used to set 95% confidence level (CL) upper limits on $\sigma(pp \to X)$, assuming a 100% branching fraction for $X \to \phi\phi \to (b\bar{b})(b\bar{b})$. Upper limits are computed under a modified frequentist approach, using the CL_s criterion [56, 57] with the profile likelihood ratio used as the test statistic with the asymptotic approximation [58]. Observed limits are shown as a function of m_ϕ and m_X, and compared to the theoretical estimates of $\sigma(X \to \phi\phi)$ for a set of $(m_X N)/f$ values in Fig. 4. The upper limits on the process $X \to \phi\phi \to (b\bar{b})(b\bar{b})$ process range from 30 to 1 fb, depending on m_ϕ and m_X.

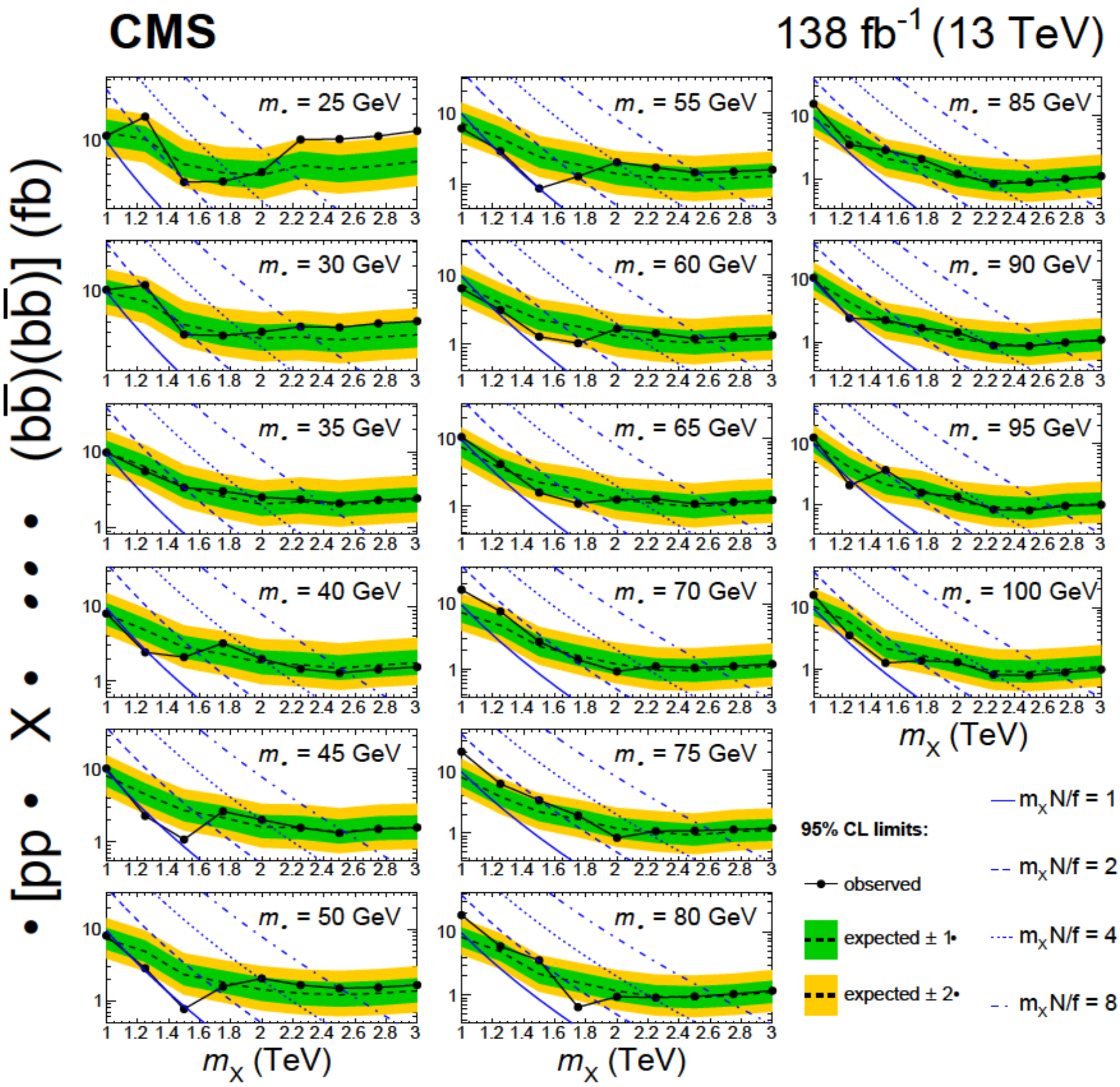

Figure 4: Upper limits at 95% CL on the cross section of the process pp $\rightarrow$ X $\rightarrow$ $\phi\phi$ $\rightarrow$ $(\mathrm{b\overline{b}})(\mathrm{b\overline{b}})$, as a function of the mass of m_{X}, for different values of m_{ϕ}. Both the X $\rightarrow$ $\phi\phi$ and ϕ $\rightarrow$ $\mathrm{b\overline{b}}$ branching fractions are assumed to be 100%. Each subpanel shows the limits for a fixed value of m_{ϕ}. The observed limits are shown as solid black lines with markers, while the expected limits are dotted. The yellow (outer) and green (inner) bands represent one and two standard deviation intervals. The theoretical cross section for different values of the parameter $m_{\mathrm{X}}N/f$ are shown with dotted and dashed curves.

10 Summary

A search for massive resonances (X) decaying to pairs of spin-0 bosons (ϕ) that themselves decay into b quark-antiquark pairs has been presented. The analysis is restricted to the case where the mass ratio of the resonance and the scalar bosons is such that each pair of b quarks is reconstructed as a single large-radius jet. Data from proton-proton collisions at the LHC at $\sqrt{s} = 13\,\text{TeV}$ collected in 2016–2018 with the CMS detector, corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$, have been used. Upper limits are set at 95% confidence level on the product of production cross section and branching fraction as a function of mass for $\text{X} \to \phi\phi \to (\text{b}\overline{\text{b}})(\text{b}\overline{\text{b}})$, where both the $\text{X} \to \phi\phi$ and $\phi \to \text{b}\overline{\text{b}}$ branching fractions are assumed to be 100%. These are the first limits on this process, and range between 30 and 1 fb for a ϕ mass in the range 25–100 GeV and an X mass in the range 1–3 TeV.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Science and Higher Education and the National Science Center, contracts Opus 2014/15/B/ST2/03998 and 2015/19/B/ST2/02861 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, projects no. 0723-2020-0041 and no. FSWW-2020-0008 (Russia); MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Stavros Niarchos Foundation (Greece); the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] CMS Collaboration, "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC", *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.

[2] CMS Collaboration, "Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV", *JHEP* **06** (2013) 081, doi:10.1007/JHEP06(2013)081, arXiv:1303.4571.

[3] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.

[4] G. C. Dorsch, S. J. Huber, K. Mimasu, and J. M. No, "Hierarchical versus degenerate 2HDM: The LHC Run 1 legacy at the onset of Run 2", *Phys. Rev. D* **93** (2016) 115033, doi:10.1103/PhysRevD.93.115033, arXiv:1601.04545.

[5] F. Kling, J. M. No, and S. Su, "Anatomy of exotic Higgs decays in 2HDM", *JHEP* **09** (2016) 093, doi:10.1007/JHEP09(2016)093, arXiv:1604.01406.

[6] S. Baum and N. R. Shah, "Two Higgs doublets and a complex singlet: disentangling the decay topologies and associated phenomenology", *JHEP* **12** (2018) 044, doi:10.1007/JHEP12(2018)044, arXiv:1808.02667.

[7] D. Barducci, G. Bélanger, C. Hugonie, and A. Pukhov, "Status and prospects of the nMSSM after LHC Run-1", *JHEP* **01** (2016) 050, doi:10.1007/JHEP01(2016)050, arXiv:1510.00246.

[8] U. Ellwanger and M. Rodríguez-Vázquez, "Simultaneous search for extra light and heavy Higgs bosons via cascade decays", *JHEP* **11** (2017) 008, doi:10.1007/JHEP11(2017)008, arXiv:1707.08522.

[9] S. Baum, N. R. Shah, and K. Freese, "The NMSSM is within reach of the LHC: mass correlations & decay signatures", *JHEP* **04** (2019) 011, doi:10.1007/JHEP04(2019)011, arXiv:1901.02332.

[10] T. Robens, T. Stefaniak, and J. Wittbrodt, "Two-real-scalar-singlet extension of the SM: LHC phenomenology and benchmark scenarios", *Eur. Phys. J. C* **80** (2020) 151, doi:10.1140/epjc/s10052-020-7655-x, arXiv:1908.08554.

[11] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[12] CMS Collaboration, "Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS", *Eur. Phys. J. C* **81** (2021) 800, doi:10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.

[13] CMS Collaboration, "CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.

[14] CMS Collaboration, "CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV", CMS Physics Analysis Summary CMS-PAS-LUM-18-002, 2019.

[15] ATLAS Collaboration, "Search for Higgs boson pair production in the $\mathrm{b\bar{b}b\bar{b}}$ final state from pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector", *Eur. Phys. J. C* **75** (2015) 412, doi:10.1140/epjc/s10052-015-3628-x, arXiv:1506.00285.

[16] ATLAS Collaboration, "Search for pair production of Higgs bosons in the $\mathrm{b\bar{b}b\bar{b}}$ final state using proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector", *Phys. Rev. D* **94** (2016) 052002, doi:10.1103/PhysRevD.94.052002, arXiv:1606.04782.

[17] ATLAS Collaboration, "Search for pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state using proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector", *JHEP* **01** (2019) 030, doi:10.1007/JHEP01(2019)030, arXiv:1804.06174.

[18] CMS Collaboration, "Search for a massive resonance decaying to a pair of Higgs bosons in the four b quark final state in proton–proton collisions at $\sqrt{s} = 13$ TeV", *Phys. Lett. B* **781** (2018) 244, doi:10.1016/j.physletb.2018.03.084, arXiv:1710.04960.

[19] CMS Collaboration, "Search for production of Higgs boson pairs in the four b quark final state using large-area jets in proton–proton collisions at $\sqrt{s} = 13$ TeV", *JHEP* **01** (2019) 040, doi:10.1007/JHEP01(2019)040, arXiv:1808.01473.

[20] "HEPData record for this analysis", 2022. doi:10.17182/hepdata.127245.

[21] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[22] CMS Collaboration, "Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV", *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.

[23] CMS Collaboration, "Performance of the CMS muon detector and muon reconstruction with proton–proton collisions at $\sqrt{s} = 13$ TeV", *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[24] CMS Collaboration, "Performance of photon reconstruction and identification with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV", *JINST* **10** (2015) P08010, doi:10.1088/1748-0221/10/08/P08010, arXiv:1502.02702.

[25] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[26] CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[27] CMS Collaboration, "Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV", *JINST* **13** (2018) P10005, doi:10.1088/1748-0221/13/10/P10005, arXiv:1809.02816.

[28] CMS Collaboration, "Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV", *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.

[29] CMS Collaboration, "Performance of missing transverse momentum reconstruction in proton–proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector", *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.

[30] J. Alwall et al., "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[31] G. Bozzi, S. Catani, D. de Florian, and M. Grazzini, "The q_T spectrum of the Higgs boson at the LHC in QCD perturbation theory", *Phys. Lett. B* **564** (2003) 65, doi:10.1016/S0370-2693(03)00656-7, arXiv:hep-ph/0302104.

[32] G. Bozzi, S. Catani, D. de Florian, and M. Grazzini, "Transverse-momentum resummation and the spectrum of the Higgs boson at the LHC", *Nucl. Phys. B* **737** (2006) 73, doi:10.1016/j.nuclphysb.2005.12.022, arXiv:hep-ph/0508068.

[33] D. de Florian, G. Ferrera, M. Grazzini, and D. Tommasini, "Transverse-momentum resummation: Higgs boson production at the Tevatron and the LHC", *JHEP* **11** (2011) 064, doi:10.1007/JHEP11(2011)064, arXiv:1109.2109.

[34] P. Nason, "A new method for combining NLO QCD with shower Monte Carlo algorithms", *JHEP* **11** (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[35] S. Frixione, P. Nason, and C. Oleari, "Matching NLO QCD computations with parton shower simulations: the POWHEG method", *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.

[36] S. Alioli, P. Nason, C. Oleari, and E. Re, "A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX", *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.

[37] S. Alioli, S.-O. Moch, and P. Uwer, "Hadronic top-quark pair-production with one jet and parton showering", *JHEP* **01** (2012) 137, doi:10.1007/JHEP01(2012)137, arXiv:1110.5251.

[38] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[39] J. Alwall et al., "Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions", *Eur. Phys. J. C* **53** (2008) 473, doi:10.1140/epjc/s10052-007-0490-5, arXiv:0706.2569.

[40] CMS Collaboration, "Event generator tunes obtained from underlying event and multiparton scattering measurements", *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.

[41] CMS Collaboration, "Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements", *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[42] NNPDF Collaboration, "Parton distributions for the LHC Run II", *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.

[43] GEANT4 Collaboration, "GEANT4– a simulation toolkit", *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[44] M. Cacciari, G. P. Salam, and G. Soyez, "FastJet user manual", *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

[45] M. Cacciari, G. P. Salam, and G. Soyez, "The anti-k_{T} clustering algorithm", *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[46] D. Bertolini, P. Harris, M. Low, and N. Tran, "Pileup per particle identification", *JHEP* **10** (2014) 059, doi:10.1007/JHEP10(2014)059, arXiv:1407.6013.

[47] CMS Collaboration, "Pileup mitigation at CMS in 13 TeV data", *JINST* **15** (2020) P09018, doi:10.1088/1748-0221/15/09/P09018, arXiv:2003.00503.

[48] CMS Collaboration, "Determination of jet energy calibration and transverse momentum resolution in CMS", *JINST* **6** (2011) 11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.

[49] CMS Collaboration, "Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV", *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.

[50] M. Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, "Towards an understanding of jet substructure", *JHEP* **09** (2013) 029, doi:10.1007/JHEP09(2013)029, arXiv:1307.0007.

[51] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, "Soft drop", *JHEP* **05** (2014) 146, doi:10.1007/JHEP05(2014)146, arXiv:1402.2657.

[52] R. A. Fisher, "On the interpretation of χ^2 from contingency tables, and the calculation of P", *J. Roy. Statis.* **85** (1922) 87, doi:10.2307/2340521.

[53] CMS Collaboration, "Measurement of differential cross sections for top quark pair production using the lepton+jets final state in proton–proton collisions at 13 TeV", *Phys. Rev. D* **95** (2017) 092001, doi:10.1103/PhysRevD.95.092001, arXiv:1610.04191.

[54] CMS Collaboration, "Measurement of normalized differential $\mathrm{t\bar{t}}$ cross sections in the dilepton channel from pp collisions at $\sqrt{s} = 13$ TeV", *JHEP* **04** (2018) 060, doi:10.1007/JHEP04(2018)060, arXiv:1708.07638.

[55] ATLAS Collaboration, "Measurements of normalized differential cross sections for $t\bar{t}$ production in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector", *Phys. Rev. D* **90** (2014) 072004, doi:10.1103/PhysRevD.90.072004, arXiv:1407.0371.

[56] T. Junk, "Confidence level computation for combining searches with small statistics", *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.

[57] A. L. Read, "Presentation of search results: the CL_s technique", *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.

[58] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, "Asymptotic formulae for likelihood-based tests of new physics", *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Tumasyan

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth[1], M. Jeitler[1], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck[1], R. Schöfbeck, D. Schwarz, S. Templ, W. Waltenberger, C.-E. Wulz[1]

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, A. Litomin, V. Makarenko

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[2], E.A. De Wolf, T. Janssen, T. Kello[3], A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
E.S. Bols, J. D'Hondt, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, L. Favart, A.K. Kalsi, K. Lee, M. Mahdavikhorrami, I. Makarenko, L. Moureaux, S. Paredes, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Rendón, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, B. Vermassen, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, A. Bethani, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Teklishyn, T.T. Tran, P. Vischia, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, C. Hensel, A. Moraes, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[4], E.M. Da Costa, G.G. Da Silveira[5], D. De Jesus Damiao, V. Dos Santos Sousa, S. Fonseca De Souza, C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[6], A. Vilela Pereira

Universidade Estadual Paulista (a), Universidade Federal do ABC (b), São Paulo, Brazil
C.A. Bernardes[5], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, D.S. Lemos, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China
T. Cheng, T. Javaid[7], M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, G. Bauer, C. Dozen[8], Z. Hu, J. Martins[9], Y. Wang, K. Yi[10,11]

Institute of High Energy Physics, Beijing, China
E. Chapon, G.M. Chen[7], H.S. Chen[7], M. Chen, F. Iemmi, A. Kapoor, D. Leggat, H. Liao, Z.-A. Liu[7], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. An, Y. Ban, C. Chen, A. Levin, Q. Li, X. Lyu, Y. Mao, S.J. Qian, D. Wang, J. Xiao, H. Yang

Sun Yat-Sen University, Guangzhou, China
M. Lu, Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[3], H. Okawa, Y. Zhang

Zhejiang University, Hangzhou, China, Zhejiang, China
Z. Lin, M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, J. Fraga

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov[12], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka

Charles University, Prague, Czech Republic
M. Finger[13], M. Finger Jr.[13], A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyp-

tian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim[14,15], S. Elgammal[16]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M.A. Mahmoud, Y. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, R.K. Dewanjee, K. Ehataht, M. Kadastik, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[17], M. Titov, G.B. Yu

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, O. Davignon, B. Diab, G. Falmagne, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, I. Kucher, J. Motta, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[18], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, J.-C. Fontaine[18], U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigira, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, S. Perries, K. Shchablo, V. Sordini, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
I. Bagaturia[19], I. Lomidze, Z. Tsamalaidze[13]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, J. Schulz, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Dodonova, D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, A. Pozdnyakov, Y. Rath, H. Reithler,

A. Schmidt, S.C. Schuler, A. Sharma, L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[20], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, D. Roy, A. Stahl[21], T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, F. Blekman, K. Borras[22], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, V. Danilov, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[23], A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Jafari[24], N.Z. Jomhari, H. Jung, A. Kasem[22], M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, D. Krücker, W. Lange, K. Lipka, W. Lohmann[25], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, M. Meyer, J. Mnich, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham[26], V. Scheurer, S. Schnake, P. Schütze, C. Schwanenberger[23], M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, N. Tonon, M. Van De Klundert, F. Vazzoler, R. Walsh, D. Walter, Q. Wang, Y. Wen, K. Wichmann, L. Wiens, C. Wissing, S. Wuchterl

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Albrecht, S. Bein, L. Benato, P. Connor, K. De Leo, M. Eich, K. El Morabit, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, M. Hajheidari, J. Haller, A. Hinzmann, G. Kasieczka, R. Klanner, T. Kramer, V. Kutzner, J. Lange, T. Lange, A. Lobanov, A. Malara, A. Mehta, A. Nigamova, K.J. Pena Rodriguez, M. Rieger, O. Rieger, P. Schleper, M. Schröder, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, A. Tews, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
J. Bechtel, S. Brommer, M. Burkart, E. Butz, R. Caspart, T. Chwalek, W. De Boer[†], A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann[21], C. Heidecker, U. Husemann, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, Th. Müller, M. Neukum, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, J. Van Der Linden, R.F. Von Cube, M. Wassmer, M. Weber, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis, D. Loukas, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, D. Karasavvas, P. Kontaxakis, C.K. Koraka, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece
G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos, J. Strologas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanad, K. Farkas, M.M.A. Gadallah[27], S. Lökös[28], P. Major, K. Mandal, G. Pasztor, A.J. Rádl, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[29], G. Bencze, C. Hajdu, D. Horvath[30,31], F. Sikler, V. Veszpremi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
S. Czellar, D. Fasanella, F. Fienga, J. Karancsi[29], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi[32], B. Ujvari[33]

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[34], F. Nemes[34], T. Novak

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[35], C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[36], A. Nayak[36], P. Saha, N. Sur, S.K. Swain, D. Vats[36]

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[37], R. Gupta, A. Kaur, H. Kaur, M. Kaur, P. Kumari, M. Meena, K. Sandeep, J.B. Singh[38], A.K. Virdi

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, B.C. Choudhary, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
M. Bharti[39], R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber[40], M. Maity[41], P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, P. Kalbhor, J.R. Komaragiri[42], D. Kumar[42], A. Muhammad, L. Panwar[42], R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar, P.C. Tiwari[42]

Bhabha Atomic Research Centre, Mumbai, India
K. Naskar[43]

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, S. Dugad, M. Kumar, G.B. Mohanty

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[44,45], E. Khazaie[45], M. Zeinali[46]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[47], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari [a], Bari, Italy, Università di Bari [b], Bari, Italy, Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,48], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], A. Di Pilato[a,b], W. Elmetenawee[a,b], F. Errico[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], G. Pugliese[a,c], D. Ramos[a], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna [a], Bologna, Italy, Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], L. Brigliadori[a], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], C. Ciocca[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,49], L. Lunerti[a,b], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania [a], Catania, Italy, Università di Catania [b], Catania, Italy
S. Albergo[a,b,50], S. Costa[a,b,50], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,50], C. Tuve[a,b]

INFN Sezione di Firenze [a], Firenze, Italy, Università di Firenze [b], Firenze, Italy
G. Barbagli[a], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], R. Seidita[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, D. Piccolo

INFN Sezione di Genova [a], Genova, Italy, Università di Genova [b], Genova, Italy
M. Bozzo[a,b], F. Ferro[a], R. Mulargia[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Milano, Italy, Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], G. Boldrini, F. Brivio[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], B.S. Pinolini, S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b], D. Valsecchi[a,b,21], D. Zuolo[a,b]

INFN Sezione di Napoli [a], Napoli, Italy, Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,51], S. Meola[a,d,21], P. Paolucci[a,21], B. Rossi[a], C. Sciacca[a,b]

INFN Sezione di Padova [a], Padova, Italy, Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], G. Grosso, L. Layer[a,52], E. Lusiani, M. Margoni[a,b],

A.T. Meneguzzo[a,b], J. Pazzini[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong[a], M. Tosi[a,b], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Pavia, Italy, Università di Pavia [b], Pavia, Italy
C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Perugia, Italy, Università di Perugia [b], Perugia, Italy
P. Asenov[a,53], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,53], A. Piccinelli[a,b], M. Presilla[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa [a], Pisa, Italy, Università di Pisa [b], Pisa, Italy, Scuola Normale Superiore di Pisa [c], Pisa, Italy, Università di Siena [d], Siena, Italy
P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], E. Bossini[a,b], R. Castaldi[a], M.A. Ciocci[a,b], V. D'Amante[a,d], R. Dell'Orso[a], M.R. Di Domenico[a,d], S. Donato[a], A. Giassi[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], D. Matos Figueiredo, A. Messineo[a,b], M. Musich[a], F. Palla[a], S. Parolia[a,b], G. Ramirez-Sanchez[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,c], A. Scribano[a], N. Shafiei[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Rome, Italy, Sapienza Università di Roma [b], Rome, Italy
P. Barria[a], M. Campana[a,b], F. Cavallari[a], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], E. Longo[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], R. Tramontano[a,b]

INFN Sezione di Torino [a], Torino, Italy, 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], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], J. Berenguer Antequera[a,b], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], F. Legger[a], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], M. Ruspa[a,c], K. Shchelina[a], F. Siviero[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], M. Tornago[a,b], D. Trocino[a], A. Vagnerini[a,b]

INFN Sezione di Trieste [a], Trieste, Italy, Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], G. Sorrentino[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea

S. Cho, S. Choi, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Republic of Korea, Seoul, Korea
J. Goh, A. Gurtu

Sejong University, Seoul, Korea
H.S. Kim, Y. Kim

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, S. Lee, B.H. Oh, M. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Jang, D.Y. Kang, Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, J.A. Merlin, I.C. Park, Y. Roh, M.S. Ryu, D. Song, I.J. Watson, S. Yang

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Egaila, Kuwait, Dasman, Kuwait
T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia
K. Dreimanis, V. Veckalns[54]

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Carvalho Antunes De Oliveira, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[55], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, R. Reyes-Almanza, A. Sánchez Hernández

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

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

University of Montenegro, Podgorica, Montenegro
J. Mijuskovic[56], N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, M. Gul, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, D. Budkouski, I. Golutvin, I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[57,58], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[59], A. Zarubin, I. Zhizhin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[60], E. Kuznetsova[61], V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, A. Toropin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Center 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[62], V. Popov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
O. Bychkova, M. Chadeeva[63], A. Oskin, P. Parygin, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, V. Bunichev, M. Dubinin[64], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, M. Perfilov, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov[65], T. Dimova[65], L. Kardapoltsev[65], A. Kozyrev[65], I. Ovtin[65], O. Radchenko[65], Y. Skovpen[65]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute',

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

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

Tomsk State University, Tomsk, Russia
V. Borshch, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[66], M. Dordevic, P. Milenovic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, L. Urda Gómez, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, N. Trevisani, C. Vico Villalba

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, C. Fernandez Madrazo, P.J. Fernández Manteca, A. García Alonso, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy[67], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
T.K. Aarrestad, D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Caillol, T. Camporesi, M. Capeans Garrido, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury, M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, F. Fallavollita[68], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, A. Lintuluoto, K. Long, C. Lourenço, B. Maier,

L. Malgeri, S. Mallios, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[69], S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk[70], K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[71], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli[71], L. Noehte[71], T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
K. Androsov[70], M. Backhaus, P. Berger, A. Calandri, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, F. Eble, K. Gedia, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, M.T. Meinhard, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, V. Stampf, J. Steggemann[70], R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[72], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

National Central University, Chung-Li, Taiwan
C. Adloff[73], C.M. Kuo, W. Lin, A. Roy, T. Sarkar[41], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, Y. Chao, K.F. Chen, P.H. Chen, P.s. Chen, H. Cheng, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

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

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
F. Boran, S. Damarseckin[74], Z.S. Demiroglu, F. Dolek, I. Dumanoglu[75], E. Eskut, Y. Guler[76], E. Gurpinar Guler[76], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[77], A. Polatoz, A.E. Simsek, B. Tali[78], U.G. Tok, S. Turkcapar, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
G. Karapinar, K. Ocalan[79], M. Yalvac[80]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gulmez, M. Kaya[81], O. Kaya[82], Ö. Özçelik, S. Tekten[83], E.A. Yetkin[84]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[75], Y. Komurcu, S. Sen[85]

Istanbul University, Istanbul, Turkey
S. Cerci[78], I. Hos[86], B. Isildak[87], B. Kaynak, S. Ozkorucuklu, H. Sert, C. Simsek,

D. Sunar Cerci[78], C. Zorbilmez

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

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

University of Bristol, Bristol, United Kingdom
D. Anthony, E. Bhal, S. Bologna, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[88], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[89], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[90], J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G.S. Chahal[91], D. Colling, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, D.G. Monk, J. Nash[92], M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, A. Tapper, K. Uchida, T. Virdee[21], M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
A. Buccilli, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio[93], C. West

Boston University, Boston, Massachusetts, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, E. Fontanesi, D. Gastler, S. May, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan, D. Zou

Brown University, Providence, Rhode Island, USA
G. Benelli, B. Burkle, X. Coubez[22], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[94], T. Kwon, G. Landsberg, K.T. Lau, D. Li, M. Lukasik, J. Luo, M. Narain, N. Pervan, S. Sagir[95], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

University of California, Davis, Davis, California, USA
J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok,

J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, B. Regnery, D. Taylor, Y. Yao, F. Zhang

University of California, Los Angeles, California, USA
M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, W.A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

University of California, Riverside, Riverside, California, USA
Y. Chen, R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, California, USA
J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
N. Amin, C. Campagnari, M. Citron, G. Collura, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, B. Marsh, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, F. Setti, J. Sheplock, P. Siddireddy, D. Stuart, S. Wang

California Institute of Technology, Pasadena, California, USA
A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, M. Paulini, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, R. Patel, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper

Cornell University, Ithaca, New York, USA
J. Alexander, S. Bright-Thonney, X. Chen, Y. Cheng, D.J. Cranshaw, S. Hogan, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, M. Reid, A. Ryd, W. Sun, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, K.F. Di Petrillo, J. Dickinson, V.D. Elvira, Y. Feng, J. Freeman, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[64], F. Ravera, A. Reinsvold Hall[96], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber

University of Florida, Gainesville, Florida, USA

P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R.D. Field, D. Guerrero, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu, E. Yigitbasi, X. Zuo

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Askew, R. Habibullah, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, O. Viazlo, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
M.M. Baarmand, S. Butalla, T. Elkafrawy[97], M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, Illinois, USA
M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, S. Dittmer, O. Evdokimov, C.E. Gerber, D.J. Hofman, A.H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Ye

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, K. Dilsiz[98], L. Emediato, R.P. Gandrajula, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[99], J. Nachtman, H. Ogul[100], Y. Onel, A. Penzo, C. Snyder, E. Tiras[101]

Johns Hopkins University, Baltimore, Maryland, USA
O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, R. Kowalski, S. Kyriacou, P. Maksimovic, J. Roskes, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, J. Anguiano, C. Baldenegro Barrera, P. Baringer, A. Bean, Z. Flowers, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, C. Rogan, C. Royon, R. Salvatico, S. Sanders, E. Schmitz, C. Smith, Q. Wang, Z. Warner, J. Williams, G. Wilson

Kansas State University, Manhattan, Kansas, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam

Lawrence Livermore National Laboratory, Livermore, California, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, USA
E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, M. Seidel, A. Skuja, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
D. Abercrombie, G. Andreassi, R. Bi, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez Ceballos, M. Goncharov, P. Harris, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, Minnesota, USA
R.M. Chatterjee, A. Evans, J. Hiltbrand, Sh. Jain, B.M. Joshi, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom, M. Bryson, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, C. Joo, I. Kravchenko, I. Reed, J.E. Siado, G.R. Snow†, W. Tabb, A. Wightman, F. Yan, A.G. Zecchinelli

State University of New York at Buffalo, Buffalo, New York, USA
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

Northeastern University, Boston, Massachusetts, USA
G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Hortiangtham, A. Krishna, J. Li, J. Lidrych, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, Illinois, USA
S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, Y. Liu, N. Odell, M.H. Schmitt, M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA
R. Band, R. Bucci, M. Cremonesi, A. Das, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, D. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko[57], R. Ruchti, A. Townsend, M. Wayne, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA
B. Bylsma, L.S. Durkin, B. Francis, C. Hill, M. Nunez Ornelas, K. Wei, B.L. Winer, B.R. Yates

Princeton University, Princeton, New Jersey, USA
F.M. Addesa, B. Bonham, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, Indiana, USA
A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic[17], J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, Indiana, USA
J. Dolen, N. Parashar

Rice University, Houston, Texas, USA
D. Acosta, A. Baty, T. Carnahan, M. Decaro, S. Dildick, K.M. Ecklund, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Rotter, W. Shi, A.G. Stahl Leiton, S. Yang, L. Zhang[102], Y. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus, G.P. Van Onsem

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, O. Karacheban[25], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson,

S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, Tennessee, USA
H. Acharya, A.G. Delannoy, S. Fiorendi, S. Spanier

Texas A&M University, College Station, Texas, USA
O. Bouhali[103], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[104], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, Virginia, USA
M.W. Arenton, B. Cardwell, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara, B. Tannenwald, S. White

Wayne State University, Detroit, Michigan, USA
N. Poudyal

University of Wisconsin - Madison, Madison, WI, Wisconsin, USA
S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-Reichert, W. Vetens

†: Deceased
1: Also at TU Wien, Wien, Austria
2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
3: Also at Université Libre de Bruxelles, Bruxelles, Belgium
4: Also at Universidade Estadual de Campinas, Campinas, Brazil
5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
6: Also at The University of the State of Amazonas, Manaus, Brazil
7: Also at University of Chinese Academy of Sciences, Beijing, China
8: Also at Department of Physics, Tsinghua University, Beijing, China
9: Also at UFMS, Nova Andradina, Brazil
10: Also at Nanjing Normal University Department of Physics, Nanjing, China
11: Now at The University of Iowa, Iowa City, Iowa, USA
12: Also at National Research Center 'Kurchatov Institute', Moscow, Russia
13: Also at Joint Institute for Nuclear Research, Dubna, Russia
14: Also at Helwan University, Cairo, Egypt
15: Now at Zewail City of Science and Technology, Zewail, Egypt
16: Now at British University in Egypt, Cairo, Egypt
17: Also at Purdue University, West Lafayette, Indiana, USA
18: Also at Université de Haute Alsace, Mulhouse, France
19: Also at Ilia State University, Tbilisi, Georgia
20: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
21: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

22: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
23: Also at University of Hamburg, Hamburg, Germany
24: Also at Isfahan University of Technology, Isfahan, Iran
25: Also at Brandenburg University of Technology, Cottbus, Germany
26: Also at Forschungszentrum Jülich, Juelich, Germany
27: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
28: Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
29: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
30: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
31: Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
32: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
33: Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
34: Also at Wigner Research Centre for Physics, Budapest, Hungary
35: Also at IIT Bhubaneswar, Bhubaneswar, India
36: Also at Institute of Physics, Bhubaneswar, India
37: Also at Punjab Agricultural University, Ludhiana, India
38: Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
39: Also at Shoolini University, Solan, India
40: Also at University of Hyderabad, Hyderabad, India
41: Also at University of Visva-Bharati, Santiniketan, India
42: Also at Indian Institute of Science (IISc), Bangalore, India
43: Also at Indian Institute of Technology (IIT), Mumbai, India
44: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
45: Now at Department of Physics, Isfahan University of Technology, Isfahan, Iran
46: Also at Sharif University of Technology, Tehran, Iran
47: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
48: Now at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
49: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
50: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
51: Also at Scuola Superiore Meridionale, Università di Napoli Federico II, Napoli, Italy
52: Also at Università di Napoli 'Federico II', Napoli, Italy
53: Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
54: Also at Riga Technical University, Riga, Latvia
55: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
56: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
57: Also at Institute for Nuclear Research, Moscow, Russia
58: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
59: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
60: Also at St. Petersburg Polytechnic University, St. Petersburg, Russia
61: Also at University of Florida, Gainesville, Florida, USA
62: Also at Imperial College, London, United Kingdom
63: Also at P.N. Lebedev Physical Institute, Moscow, Russia
64: Also at California Institute of Technology, Pasadena, California, USA
65: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia

66: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
67: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
68: Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
69: Also at National and Kapodistrian University of Athens, Athens, Greece
70: Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
71: Also at Universität Zürich, Zurich, Switzerland
72: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
73: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
74: Also at Şırnak University, Sirnak, Turkey
75: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
76: Also at Konya Technical University, Konya, Turkey
77: Also at Piri Reis University, Istanbul, Turkey
78: Also at Adiyaman University, Adiyaman, Turkey
79: Also at Necmettin Erbakan University, Konya, Turkey
80: Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
81: Also at Marmara University, Istanbul, Turkey
82: Also at Milli Savunma University, Istanbul, Turkey
83: Also at Kafkas University, Kars, Turkey
84: Also at Istanbul Bilgi University, Istanbul, Turkey
85: Also at Hacettepe University, Ankara, Turkey
86: Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
87: Also at Ozyegin University, Istanbul, Turkey
88: Also at Vrije Universiteit Brussel, Brussel, Belgium
89: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
90: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
91: Also at IPPP Durham University, Durham, United Kingdom
92: Also at Monash University, Faculty of Science, Clayton, Australia
93: Also at Università di Torino, Torino, Italy
94: Also at Bethel University, St. Paul, Minneapolis, USA
95: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
96: Also at United States Naval Academy, Annapolis, N/A, USA
97: Also at Ain Shams University, Cairo, Egypt
98: Also at Bingol University, Bingol, Turkey
99: Also at Georgian Technical University, Tbilisi, Georgia
100: Also at Sinop University, Sinop, Turkey
101: Also at Erciyes University, Kayseri, Turkey
102: Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
103: Also at Texas A&M University at Qatar, Doha, Qatar
104: Also at Kyungpook National University, Daegu, Korea