



ELSEVIER

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

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

The CMS Collaboration*

CERN, Geneva, Switzerland

ARTICLE INFO

Article history:

Received 1 March 2022

Received in revised form 10 September 2022

Accepted 10 November 2022

Available online 14 November 2022

Editor: M. Doser

Keywords:

CMS

Higgs

BSM

2HDM

ABSTRACT

A search for 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 $\sqrt{s} = 13$ TeV, collected with the CMS detector in 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1} . Model-specific limits, where the two new particles arise from an extended Higgs sector, are set on the product of the production cross section and branching fraction for $X \rightarrow \phi\phi \rightarrow (b\bar{b})(b\bar{b})$ as a function of the resonances' masses, where both the $X \rightarrow \phi\phi$ and $\phi \rightarrow b\bar{b}$ 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.

© 2022 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

The discovery, by both the ATLAS and CMS Collaborations [1–3], of a particle consistent with the Higgs boson (H) with standard model (SM) couplings, puts emphasis on searches for partners of this new boson, which are predicted in models with extended Higgs sectors. 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 $m_X > 2m_\phi$, then $X \rightarrow \phi\phi$ is the dominant decay of the heavier particle, and ϕ couples to fermions similarly to H.

This paper presents a search for the process $pp \rightarrow X \rightarrow \phi\phi \rightarrow (b\bar{b})(b\bar{b})$ for m_X between 1 and 3 TeV, and m_ϕ between 25 and 100 GeV (for which the $\phi \rightarrow b\bar{b}$ 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 $m_X N/f$. 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

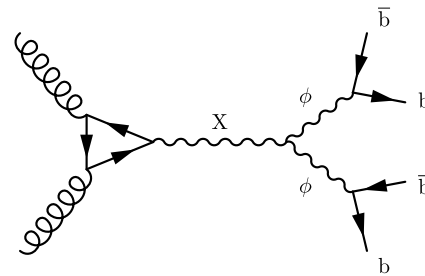


Fig. 1. Feynman diagram of the production and decay of $X \rightarrow \phi\phi \rightarrow (b\bar{b})(b\bar{b})$. The dominant production mechanism occurs via a fermion loop as shown in the diagram. Additional partons may be present, produced by initial-state or final-state radiation.

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 $X \rightarrow HH \rightarrow (b\bar{b})(b\bar{b})$ with similar topologies. However, requirements on the jet mass in those analyses make them less sensitive to m_ϕ below 100 GeV.

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.

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

ture. 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 ($t\bar{t}$) 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 μ s. 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. Monte Carlo simulation

The benchmark signal model $X \rightarrow \phi\phi \rightarrow (b\bar{b})(b\bar{b})$, where X is produced through gluon fusion, was generated to leading order with the MADGRAPH 2.6.0 [30] generator. Both the $X \rightarrow \phi\phi$ and $\phi \rightarrow b\bar{b}$ 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 $t\bar{t}$ 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 simulation 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. To account for any small differences noted above, systematic uncertainties associated with the simulations are treated as uncorrelated between years.

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 track-related variables to identify jets containing two displaced vertices consistent with decays into $b\bar{b}$. The BDT was trained on samples of simulated 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]. This measurement is performed using a sample of high- p_T jets enriched with gluon decays to b quark-antiquark pairs. To account for different data-taking conditions, this training is performed independently for each year. As a result, the exact performance of the discriminator differs from year to year. The soft drop mass algorithm (with angular exponent $\beta = 0$ and soft threshold $z_{\text{cut}} = 0.1$) [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. The lower bound on ϕ masses considered is due to uncertainty in the behavior of the double-b tagger for groomed jet masses below 25 GeV.

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, and ranges from 42% for samples with m_X of 1 TeV to 100% for m_X above 1.2 TeV. To account for differences between the simulated and real responses of the detector, the ratio of the efficiency of the trigger between data and simulation is applied to all simulated events, with the uncertainty in the efficiencies considered as a systematic uncertainty in the shape and normalization of the signal.

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 ($m_{\text{asym}} = |m_{j_1} - m_{j_2}| / (m_{j_1} + m_{j_2})$), 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 $|\Delta\eta| < 1.5$, $m_{\text{asym}} < 0.1$, $D_{j_1}^{\text{bb}} > 0.8$, and $D_{j_2}^{\text{bb}} > 0.6$. The second, called the “loose search region” (LSR), differs only in the constraint on the mass asymmetry, requiring $m_{\text{asym}} \in [0.1, 0.25]$. 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 [52] with respect to simulated backgrounds. Two control regions are defined with respect to each search region: the “ $|\Delta\eta|$

Table 1

Search and control regions used in the analysis. A selection on the subleading jet double-b-tagger discriminant $D_{j_2}^{bb} > 0.6$ further separates each region into “passing” and “failing” categories.

	m_{asym}	$ \Delta\eta $	$D_{j_1}^{bb}$
Tight search region	<0.1	<1.5	>0.8
Loose search region	$[0.1, 0.25]$	<1.5	>0.8
Tight $ \Delta\eta $ sideband	<0.1	>1.5	>0.8
Loose $ \Delta\eta $ 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	$[-0.8, 0.3]$

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 $-0.8 < D_{j_1}^{bb} < 0.3$. 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 $D_{j_2}^{bb} < 0.6$.

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 $m_X = 1.0$ TeV, peak at $m_X = 1.5$ TeV, and fall linearly to approximately 12% for $m_X = 3.0$ TeV. The signal efficiencies have negligible dependence on m_ϕ .

6. Background processes

The QCD and $t\bar{t}$ backgrounds are simultaneously evaluated in a maximum likelihood fit of the TSR and LSR in all years. In this section we describe the background estimation. In the following section we detail the maximum likelihood fit itself and the systematic uncertainties associated with it.

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 $5 \times 10^{-4}/\text{GeV}$, controls the shape of the resulting $t\bar{t}$ distribution. The normalization of the $t\bar{t}$ background and the value of α are constrained in the final 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. The uncertainty in the $t\bar{t}$ normalization covers that associated with the application of the double-b tagger to jets from that process, which may contain at most one genuine b quark.

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 $D_{j_2}^{bb} > 0.6$ 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 initialized from their values in the control regions. The $|\Delta\eta|$ sidebands are used for $F(m_{j_2})$, whereas the double-b sidebands are used for $P_n(p_{Tj_2})$. In both cases the signal is negligible in the control regions. Fig. 2 shows, in 2018 data, the groomed mass dependence of $R_{p/f}$ for both the TSR and the $\Delta\eta$ sidebands, as well as the fit from which

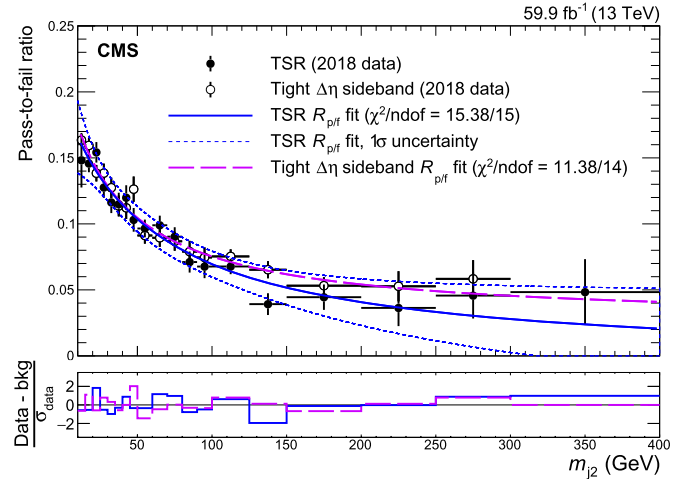


Fig. 2. Distributions of the ratio of event passing and failing the $D_{j_2}^{bb} > 0.6$ requirement, as a function of the subleading jet groomed mass m_{j_2} , in 2018 data, for the TSR (filled markers) and the tight $|\Delta\eta|$ sidebands (open markers). The arctangent $R_{p/f}$ fit from which the background is estimated is shown by the solid line in the case of the TSR, and by the thick dashed line for the sideband, with the resulting χ^2 and degrees of freedom indicated in the legend. The 1σ uncertainty band of the fit in the TSR, from which systematic uncertainties on the QCD background estimate are derived, is shown by the thin dashed lines. Similar results were obtained for 2016 and 2017 data and in the three LSRs. The lower panel shows the difference between the observed data and the fits, divided by the statistical uncertainty of the ratio of passing and failing events in the data for each bin.

the background estimate is extracted; similar results were obtained for the other years and in the LSR. The QCD background in the “passing” search regions is estimated by weighting the events in the “failing” search regions by this $R_{p/f}$, after subtracting the expected contribution from $t\bar{t}$ production. Systematic uncertainties in the $t\bar{t}$ estimate mentioned above are propagated through to the QCD background estimate. This background estimate is also performed in each control region as a closure test, the results of which indicates that no additional systematic uncertainties need to be applied to the QCD background estimate.

To account for differences in the implementation of the double-b tagger, each year of data taking, as well as the TSR and LSR, are treated independently. The order of P_n is determined in the double-b control region by performing Fisher F-tests [56] on progressively higher-order polynomials. A P_2 (P_1) is found to be optimal for describing the data taken in 2016 (2017–2018). A third-degree polynomial (with the order chosen by a similar F-test) was also considered for modeling $F(m_{j_2})$: as it did not lead to a significantly improved description of $R_{p/f}$, it was reserved for bias tests of the background estimate (described below). Uncertainties in the fit parameters for F and P_n in the signal regions are treated as systematic uncertainties in the shape and normalization of the QCD background in the search regions.

7. Fitting procedure and systematic uncertainties

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 $\hat{m} = (m_{j_1} + m_{j_2})/2$ 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 difference between

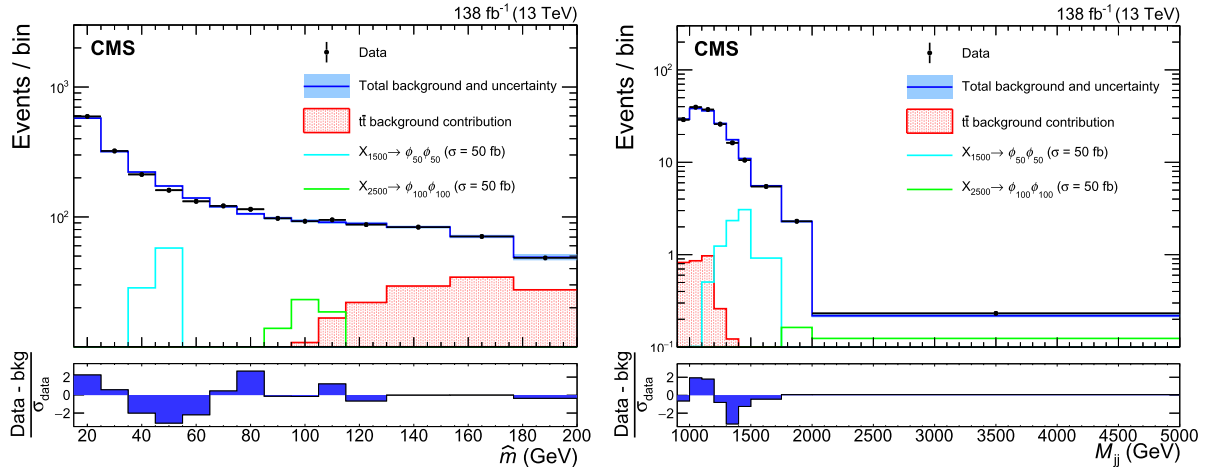


Fig. 3. Distributions of average jet mass (left) and dijet mass (right), and background estimate of the combined search regions after the final fit is performed. The blue (solid) line represents the sum of the estimated QCD and $t\bar{t}$ backgrounds, and the red filled histogram shows the $t\bar{t}$ 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 σ_{data} , the statistical uncertainty of the data in each bin.

generated signal shapes and those obtained from this functional form are negligible. The range of average jet masses considered is $\hat{m} \in [15, 200] \text{ GeV}$, while M_{jj} between 0.9 and 5.0 TeV are considered. The \hat{m} range extends beyond the signal masses considered in this analysis, with the events at high masses providing constraints on the $t\bar{t}$ and QCD background components. Both mass distributions use variable binning to ensure that the background estimate prediction is nonzero in each mass interval.

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 . To account for differences between simulation and data on the jet energy calibrations, the jet energy scale (JES) and resolution uncertainties are considered as uncertainties in the shape of the signal and $t\bar{t}$ background. The JES uncertainties take into account correlated and uncorrelated components between all three years. Uncertainty in the jet mass resolution was found to have a negligible effect on the result. Uncertainties pertaining to the trigger efficiency, the pileup distribution, the PDFs, and the integrated luminosity determination [12–14] are applied to the signal and $t\bar{t}$ process simulations. The $t\bar{t}$ 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_{pT} , 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.

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 utilizing a binned likelihood ratio with respect to the saturated model as the test statistic is performed, yielding an overall goodness-of-fit with a p -value of 0.3. Bias tests are also performed, where the bias tests use data simulated from the background estimate with a variety of simulated signals injected (including the null hypothesis). The simulated data used both the arctangent representation of $F(m_{j_2})$ and equivalent third-order polynomials. The mean of the distribution of signal strengths obtained from a large number of trials is found to deviate by less than 0.5 standard devi-

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 into the QCD background 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%	100%	R
$t\bar{t}$ normalization		20%	20%	R
R_{pT} fit			5–30%	–
Statistical uncertainty (failing region)			<1–100%	–

ations from the injected signal strength, confirming the absence of any significant bias. The results of the fit for the combined search regions are shown in Fig. 3 as projections onto the individual \hat{m} and M_{jj} distributions, and in Fig. 4 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_χ 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 [57], 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_χ .

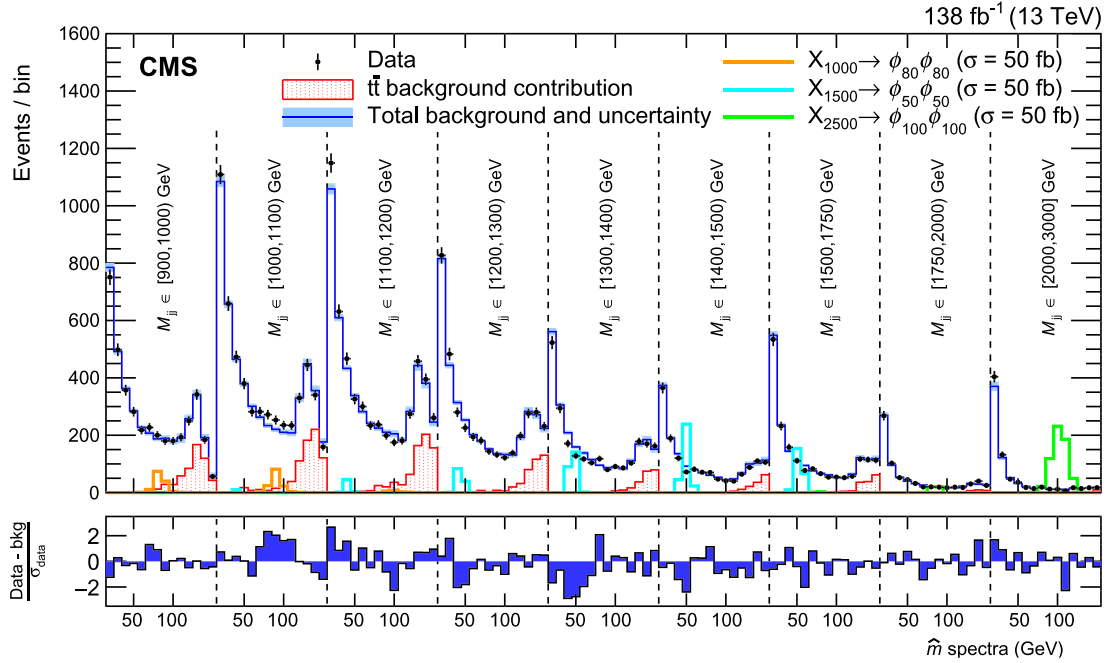


Fig. 4. The average jet mass distributions in consecutive dijet mass intervals. The vertical dashed lines separate the average jet mass distributions in each bin of M_{jj} . The individual bins within such subdivisions correspond to the \hat{m} spectrum (from 15 to 200 GeV), as seen in Fig. 3 (upper). 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.

8. Results

The results of the fit are used to set 95% confidence level (CL) upper limits on $\sigma(\text{pp} \rightarrow X)$, assuming a 100% branching fraction for $X \rightarrow \phi\phi \rightarrow (\text{b}\bar{\text{b}})(\text{b}\bar{\text{b}})$. Upper limits are computed under a modified frequentist approach, using the CL_s criterion [58,59] with the profile likelihood ratio used as the test statistic with the asymptotic approximation [60]. Observed limits are shown as a function of m_ϕ and m_X , and compared to the theoretical estimates of $\sigma(X \rightarrow \phi\phi)$ for a set of $(m_X N)/f$ values in Fig. 5. The upper limits on the process $X \rightarrow \phi\phi \rightarrow (\text{b}\bar{\text{b}})(\text{b}\bar{\text{b}})$ process range from 30 to 1 fb, depending on m_ϕ and m_X .

9. 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 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 $X \rightarrow \phi\phi \rightarrow (\text{b}\bar{\text{b}})(\text{b}\bar{\text{b}})$, where both the $X \rightarrow \phi\phi$ and $\phi \rightarrow \text{b}\bar{\text{b}}$ 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as stated in “[CMS data preservation, re-use and open access policy](#)”.

Acknowledgements

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); NK-FIA (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).

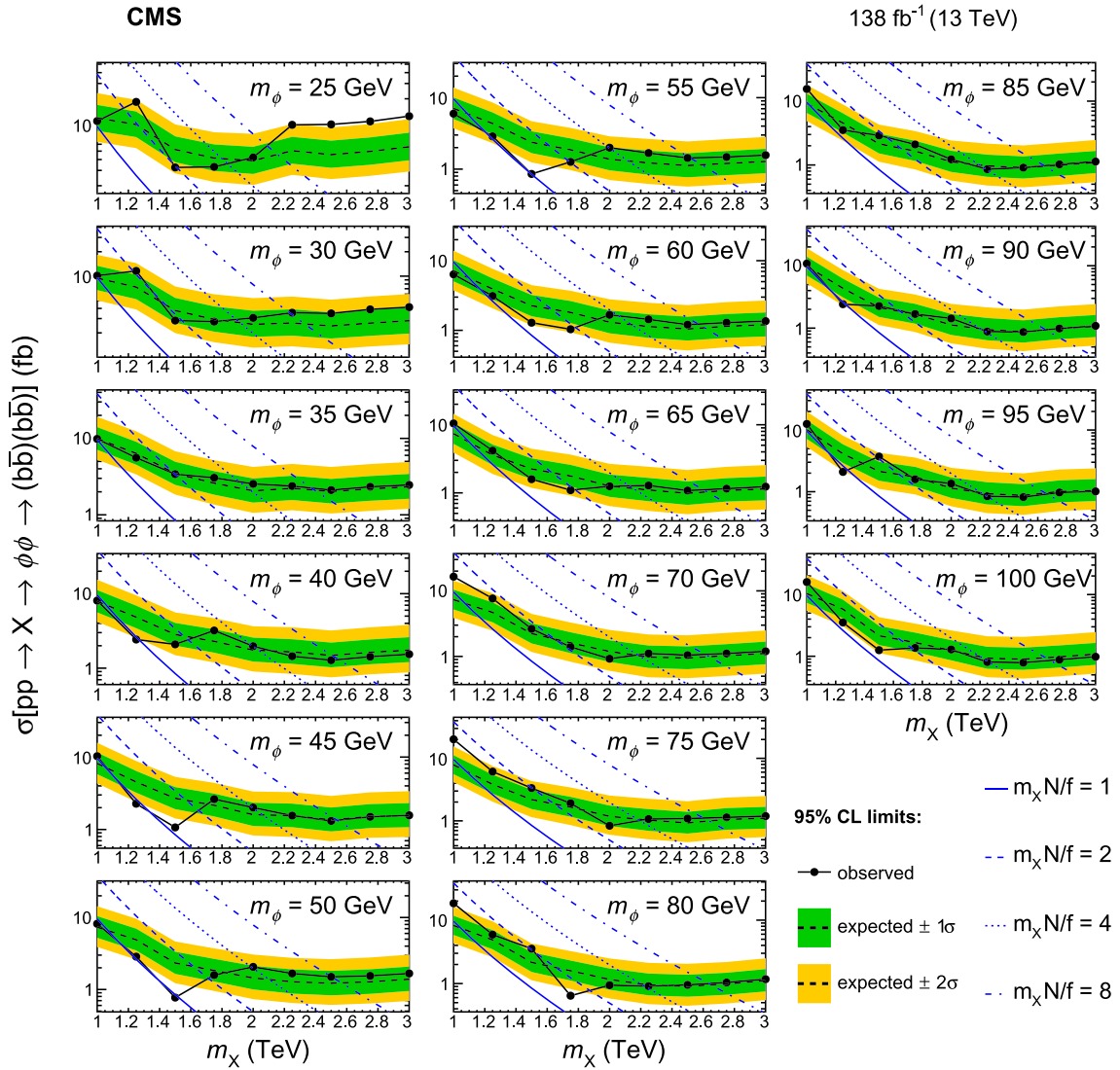


Fig. 5. Upper limits at 95% CL on the cross section of the process $pp \rightarrow X \rightarrow \phi\phi \rightarrow (b\bar{b})(b\bar{b})$, as a function of the mass of m_X , for different values of m_ϕ . Both the $X \rightarrow \phi\phi$ and $\phi \rightarrow b\bar{b}$ branching fractions are assumed 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 $m_X N/f$ are shown with dotted and dashed curves.

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 NKFI 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, <https://doi.org/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, *J. High Energy Phys.* 06 (2013) 081, [https://doi.org/10.1007/JHEP06\(2013\)081](https://doi.org/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, <https://doi.org/10.1016/j.physletb.2012.08.020>, arXiv:1207.7214.
- [4] G.C. Dorsch, S.J. Huber, K. Mimasu, J.M. No, Hierarchical versus degenerate 2HDM: the LHC Run 1 legacy at the onset of Run 2, *Phys. Rev. D* 93 (2016) 115033, <https://doi.org/10.1103/PhysRevD.93.115033>, arXiv:1601.04545.
- [5] F. Kling, J.M. No, S. Su, Anatomy of exotic Higgs decays in 2HDM, *J. High Energy Phys.* 09 (2016) 093, [https://doi.org/10.1007/JHEP09\(2016\)093](https://doi.org/10.1007/JHEP09(2016)093), arXiv:1604.01406.
- [6] S. Baum, N.R. Shah, Two Higgs doublets and a complex singlet: disentangling the decay topologies and associated phenomenology, *J. High Energy Phys.* 12 (2018) 044, [https://doi.org/10.1007/JHEP12\(2018\)044](https://doi.org/10.1007/JHEP12(2018)044), arXiv:1808.02667.
- [7] D. Barducci, G. Bélanger, C. Hugonie, A. Pukhov, Status and prospects of the mSMSSM after LHC Run-1, *J. High Energy Phys.* 01 (2016) 050, [https://doi.org/10.1007/JHEP01\(2016\)050](https://doi.org/10.1007/JHEP01(2016)050), arXiv:1510.00246.
- [8] U. Ellwanger, M. Rodríguez-Vázquez, Simultaneous search for extra light and heavy Higgs bosons via cascade decays, *J. High Energy Phys.* 11 (2017) 008, [https://doi.org/10.1007/JHEP11\(2017\)008](https://doi.org/10.1007/JHEP11(2017)008), arXiv:1707.08522.
- [9] S. Baum, N.R. Shah, K. Freese, The NMSSM is within reach of the LHC: mass correlations & decay signatures, *J. High Energy Phys.* 04 (2019) 011, [https://doi.org/10.1007/JHEP04\(2019\)011](https://doi.org/10.1007/JHEP04(2019)011), arXiv:1901.02332.
- [10] T. Robens, T. Stefaniak, J. Wittbrodt, Two-real-scalar-singlet extension of the SM: LHC phenomenology and benchmark scenarios, *Eur. Phys. J. C* 80 (2020) 151, <https://doi.org/10.1140/epjc/s10052-020-7655-x>, arXiv:1908.08554.
- [11] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* 3 (2008) S08004, <https://doi.org/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, <https://doi.org/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, <https://cds.cern.ch/record/2621960>.
- [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, <https://cds.cern.ch/record/2676164>.
- [15] ATLAS Collaboration, Search for Higgs boson pair production in the $b\bar{b}b\bar{b}$ final state from pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Eur. Phys. J. C* 75 (2015) 412, <https://doi.org/10.1140/epjc/s10052-015-3628-x>, arXiv:1506.00285.
- [16] 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, *Phys. Rev. D* 94 (2016) 052002, <https://doi.org/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, *J. High Energy Phys.* 01 (2019) 030, [https://doi.org/10.1007/JHEP01\(2019\)030](https://doi.org/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, <https://doi.org/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, *J. High Energy Phys.* 01 (2019) 040, [https://doi.org/10.1007/JHEP01\(2019\)040](https://doi.org/10.1007/JHEP01(2019)040), arXiv:1808.01473.
- [20] HEPData record for this analysis, <https://doi.org/10.17182/hepdata.127245.2022>.
- [21] CMS Collaboration, The CMS trigger system, *J. Instrum.* 12 (2017) P01020, <https://doi.org/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, *J. Instrum.* 10 (2015) P06005, <https://doi.org/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, *J. Instrum.* 13 (2018) P06015, <https://doi.org/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, *J. Instrum.* 10 (2015) P08010, <https://doi.org/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, *J. Instrum.* 9 (2014) P10009, <https://doi.org/10.1088/1748-0221/9/10/P10009>, arXiv:1405.6569.
- [26] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, *J. Instrum.* 12 (2017) P10003, <https://doi.org/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, *J. Instrum.* 13 (2018) P10005, <https://doi.org/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, *J. Instrum.* 12 (2017) P02014, <https://doi.org/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, *J. Instrum.* 14 (2019) P07004, <https://doi.org/10.1088/1748-0221/14/07/P07004>, arXiv:1903.06078.
- [30] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* 07 (2014) 079, [https://doi.org/10.1007/JHEP07\(2014\)079](https://doi.org/10.1007/JHEP07(2014)079), arXiv:1405.0301.
- [31] G. Bozzi, S. Catani, D. de Florian, M. Grazzini, The q_T spectrum of the Higgs boson at the LHC in QCD perturbation theory, *Phys. Lett. B* 564 (2003) 65, [https://doi.org/10.1016/S0370-2693\(03\)00656-7](https://doi.org/10.1016/S0370-2693(03)00656-7), arXiv:hep-ph/0302104.
- [32] G. Bozzi, S. Catani, D. de Florian, M. Grazzini, Transverse-momentum resummation and the spectrum of the Higgs boson at the LHC, *Nucl. Phys. B* 737 (2006) 73, <https://doi.org/10.1016/j.nuclphysb.2005.12.022>, arXiv:hep-ph/0508068.
- [33] D. de Florian, G. Ferrera, M. Grazzini, D. Tommasini, Transverse-momentum resummation: Higgs boson production at the Tevatron and the LHC, *J. High Energy Phys.* 11 (2011) 064, [https://doi.org/10.1007/JHEP11\(2011\)064](https://doi.org/10.1007/JHEP11(2011)064), arXiv:1109.2109.
- [34] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, *J. High Energy Phys.* 11 (2004) 040, <https://doi.org/10.1088/1126-6708/2004/11/040>, arXiv:hep-ph/0409146.
- [35] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, *J. High Energy Phys.* 11 (2007) 070, <https://doi.org/10.1088/1126-6708/2007/11/070>, arXiv:0709.2092.
- [36] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, *J. High Energy Phys.* 06 (2010) 043, [https://doi.org/10.1007/JHEP06\(2010\)043](https://doi.org/10.1007/JHEP06(2010)043), arXiv:1002.2581.
- [37] S. Alioli, S.-O. Moch, P. Uwer, Hadronic top-quark pair-production with one jet and parton showering, *J. High Energy Phys.* 01 (2012) 137, [https://doi.org/10.1007/JHEP01\(2012\)137](https://doi.org/10.1007/JHEP01(2012)137), arXiv:1110.5251.
- [38] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, *Comput. Phys. Commun.* 191 (2015) 159, <https://doi.org/10.1016/j.cpc.2015.01.024>, arXiv:1410.3012.
- [39] J. Alwall, S. Höche, F. Krauss, N. Lavesson, L. Lönnblad, F. Maltoni, M.L. Mangano, M. Moretti, C.G. Papadopoulos, F. Piccinini, S. Schumann, M. Treccani, J. Winter, M. Worek, Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions, *Eur. Phys. J. C* 53 (2008) 473, <https://doi.org/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, <https://doi.org/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, <https://doi.org/10.1140/epjc/s10052-019-7499-4>, arXiv:1903.12179.
- [42] R.D. Ball, V. Bertone, S. Carazza, C.S. Deans, L. Del Debbio, S. Forte, A. Guffanti, N.P. Hartland, J.J. Latorpe, J. Rojo, M. Ubiali, NNPDF, Parton distributions for the LHC Run II, *J. High Energy Phys.* 04 (2015) 040, [https://doi.org/10.1007/JHEP04\(2015\)040](https://doi.org/10.1007/JHEP04(2015)040), arXiv:1410.8849.
- [43] S. Agostinelli, et al., GEANT4, GEANT4- a simulation toolkit, *Nucl. Instrum. Methods A* 506 (2003) 250, [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8).
- [44] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, *Eur. Phys. J. C* 72 (2012) 1896, <https://doi.org/10.1140/epjc/s10052-012-1896-2>, arXiv:1111.6097.
- [45] M. Cacciari, G.P. Salam, G. Soyez, The anti- k_T clustering algorithm, *J. High Energy Phys.* 04 (2008) 063, <https://doi.org/10.1088/1126-6708/2008/04/063>, arXiv:0802.1189.
- [46] D. Bertolini, P. Harris, M. Low, N. Tran, Pileup per particle identification, *J. High Energy Phys.* 10 (2014) 059, [https://doi.org/10.1007/JHEP10\(2014\)059](https://doi.org/10.1007/JHEP10(2014)059), arXiv:1407.6013.
- [47] CMS Collaboration, Pileup mitigation at CMS in 13 TeV data, *J. Instrum.* 15 (2020) P09018, <https://doi.org/10.1088/1748-0221/15/09/P09018>, arXiv:2003.00503.
- [48] CMS Collaboration, Determination of jet energy calibration and transverse momentum resolution in CMS, *J. Instrum.* 6 (2011) 11002, <https://doi.org/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, *J. Instrum.* 13 (2018) P05011, <https://doi.org/10.1088/1748-0221/13/05/P05011>, arXiv:1712.07158.

- [50] M. Dasgupta, A. Fregoso, S. Marzani, G.P. Salam, Towards an understanding of jet substructure, *J. High Energy Phys.* 09 (2013) 029, [https://doi.org/10.1007/JHEP09\(2013\)029](https://doi.org/10.1007/JHEP09(2013)029), arXiv:1307.0007.
- [51] A.J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft drop, *J. High Energy Phys.* 05 (2014) 146, [https://doi.org/10.1007/JHEP05\(2014\)146](https://doi.org/10.1007/JHEP05(2014)146), arXiv:1402.2657.
- [52] G. Punzi, Sensitivity of searches for new signals and its optimization, in: L. Lyons, R.P. Mount, R. Reitmeyer (Eds.), *PHYSTAT2003: Statistical Problems in Particle Physics, Astrophysics, and Cosmology*, 2003, <https://www.slac.stanford.edu/econf/C030908/papers/MODT002.pdf>, arXiv:physics/0308063, eConf C030908 (2003) MODT002.
- [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, <https://doi.org/10.1103/PhysRevD.95.092001>, arXiv:1610.04191.
- [54] CMS Collaboration, Measurement of normalized differential $t\bar{t}$ cross sections in the dilepton channel from pp collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* 04 (2018) 060, [https://doi.org/10.1007/JHEP04\(2018\)060](https://doi.org/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, <https://doi.org/10.1103/PhysRevD.90.072004>, arXiv:1407.0371.
- [56] R.A. Fisher, On the interpretation of χ^2 from contingency tables, and the calculation of P, *J. R. Stat.* 85 (1922) 87, <https://doi.org/10.2307/2340521>.
- [57] E. Gross, O. Vitells, Trial factors for the look elsewhere effect in high energy physics, *Eur. Phys. J. C* 70 (2010) 525, <https://doi.org/10.1140/epjc/s10052-010-1470-8>.
- [58] T. Junk, Confidence level computation for combining searches with small statistics, *Nucl. Instrum. Methods A* 434 (1999) 435, [https://doi.org/10.1016/S0168-9002\(99\)00498-2](https://doi.org/10.1016/S0168-9002(99)00498-2), arXiv:hep-ex/9902006.
- [59] A.L. Read, Presentation of search results: the CL_s technique, *J. Phys. G* 28 (2002) 2693, <https://doi.org/10.1088/0954-3889/28/10/313>.
- [60] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* 71 (2011) 1554, <https://doi.org/10.1140/epjc/s10052-011-1554-0>, arXiv:1007.1727, <https://doi.org/10.1140/epjc/s10052-013-2501-z> (Erratum).

The CMS Collaboration

A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, R. Frühwirth¹, M. Jeitler¹, N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck¹, R. Schöffbeck, D. Schwarz, S. Templ, W. Waltenberger, C.-E. Wulz¹

Institut für Hochenergiephysik, Vienna, Austria

V. Chekhovsky, A. Litomin, V. Makarenko

Institute for Nuclear Problems, Minsk, Belarus

M.R. Darwish², E.A. De Wolf, T. Janssen, T. Kello³, A. Lelek, H. Rejeb Sfar, P. Van Mechelen, S. Van Putte, N. Van Remortel

Universiteit Antwerpen, Antwerpen, 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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, 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

Ghent University, Ghent, 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

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

G.A. Alves, C. Hensel, A. Moraes, P. Rebello Teles

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato⁴, E.M. Da Costa, G.G. Da Silveira⁵, 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 Araujo⁶, A. Vilela Pereira

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

C.A. Bernardes⁵, L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, D.S. Lemos, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

^a *Universidade Estadual Paulista, São Paulo, Brazil*

^b *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

University of Sofia, Sofia, Bulgaria

T. Cheng, T. Javaid⁷, M. Mittal, L. Yuan

Beihang University, Beijing, China

M. Ahmad, G. Bauer, C. Dozen⁸, Z. Hu, J. Martins⁹, Y. Wang, K. Yi^{10,11}

Department of Physics, Tsinghua University, Beijing, China

E. Chapon, G.M. Chen⁷, H.S. Chen⁷, M. Chen, F. Iemmi, A. Kapoor, D. Leggat, H. Liao, Z.-A. Liu⁷, V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

Institute of High Energy Physics, 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

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

M. Lu, Z. You

Sun Yat-Sen University, Guangzhou, China

X. Gao³, H. Okawa, Y. Zhang

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) – Fudan University, Shanghai, China

Z. Lin, M. Xiao

Zhejiang University, Hangzhou, China, Zhejiang, China

C. Avila, A. Cabrera, C. Florez, J. Fraga

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez

Universidad de Antioquia, Medellin, Colombia

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

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

Z. Antunovic, M. Kovac, T. Sculac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov¹², T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger¹³, M. Finger Jr.¹³, A. Kveton

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A.A. Abdelalim^{14,15}, S. Elgammal¹⁶

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

M.A. Mahmoud, Y. Mohammed

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

S. Bhowmik, R.K. Dewanjee, K. Ehataht, M. Kadastik, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, 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

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, H. Petrow, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

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-Navarro¹⁷, M. Titov, G.B. Yu

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, 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

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

J.-L. Agram¹⁸, J. Andrea, D. Apparù, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, J.-C. Fontaine¹⁸, U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigira, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, 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

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

I. Bagaturia¹⁹, I. Lomidze, Z. Tsamalaidze¹³

Georgian Technical University, Tbilisi, Georgia

V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, J. Schulz, M. Teroerde

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

C. Dziwok, G. Flügge, W. Haj Ahmad²⁰, O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, D. Roy, A. Stahl²¹, T. Ziemons, A. Zötz

RWTH Aachen University, III. Physikalisches Institut B, Aachen, 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. Borrás²², 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. Gallo²³, A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Jafari²⁴, N.Z. Jomhari, H. Jung, A. Kasem²², M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, D. Krücker, W. Lange, K. Lipka, W. Lohmann²⁵, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, M. Meyer, J. Mnich, A. Mussgiller, A. Nürnberg, Y. Otariid, D. Pérez Adán, D. Pitzl, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham²⁶, V. Scheurer, S. Schnake, P. Schütze, C. Schwanenberger²³, 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

Deutsches Elektronen-Synchrotron, 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. Schlepfer, M. Schröder, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, A. Tews, I. Zoi

University of Hamburg, Hamburg, 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. Hartmann²¹, 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. Savoie, 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. Wozniowski, S. Wunsch

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, A. Kyriakis, D. Loukas, A. Stakia

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

G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

National Technical University of Athens, Athens, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Giannelios, P. Katsoulis, P. Kokkas, N. Manthos, I. Papadopoulos, J. Strologas

University of Ioánnina, Ioánnina, Greece

M. Csanad, K. Farkas, M.M.A. Gadallah²⁷, S. Lökös²⁸, P. Major, K. Mandal, G. Pasztor, A.J. Rádl, O. Surányi, G.I. Veres

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Bartók²⁹, G. Bencze, C. Hajdu, D. Horvath^{30,31}, F. Sikler, V. Veszpremi

Wigner Research Centre for Physics, Budapest, Hungary

S. Czellar, D. Fasanella, F. Fienga, J. Karancsi²⁹, J. Molnar, Z. Szillasi, D. Teyssier

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi³², B. Ujvari³³

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo³⁴, F. Nemes³⁴, T. Novak

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

S. Bahinipati³⁵, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu³⁶, A. Nayak³⁶, P. Saha, N. Sur, S.K. Swain, D. Vats³⁶

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra³⁷, R. Gupta, A. Kaur, H. Kaur, M. Kaur, P. Kumari, M. Meena, K. Sandeep, J.B. Singh³⁸, A.K. Viridi

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

M. Bharti³⁹, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber⁴⁰, M. Maity⁴¹, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, S.C. Behera, P. Kalbhor, J.R. Komaragiri⁴², D. Kumar⁴², A. Muhammad, L. Panwar⁴², R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar, P.C. Tiwari⁴²

Indian Institute of Technology Madras, Madras, India

K. Naskar⁴³

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, M. Kumar, G.B. Mohanty

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee

Tata Institute of Fundamental Research-B, Mumbai, India

A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

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

H. Bakhshiansohi^{44,45}, E. Khazaie⁴⁵, M. Zeinali⁴⁶

Isfahan University of Technology, Isfahan, Iran

S. Chenarani⁴⁷, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

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

M. Grunewald

University College Dublin, Dublin, Ireland

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

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borghonovi^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. Diotallevi^{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}

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, 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}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, 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

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi, S. Bianco, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo^{a,b}, F. Ferro^a, R. Mulargia^a, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

A. Benaglia^a, G. Boldrini, F. Brivio^{a,b}, F. Cettorelli^{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}

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

^b Università di Milano-Bicocca, Milano, 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}

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Università G. Marconi, Roma, 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}

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, 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}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, 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}

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, 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

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

^d Università di Siena, Siena, 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}

^a INFN Sezione di Roma, Rome, Italy

^b Sapienza Università di Roma, Rome, 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}

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, 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}

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

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

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon

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

B. Francois, T.J. Kim, J. Park

Hanyang University, Seoul, Republic of Korea

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

Korea University, Seoul, Republic of Korea

J. Goh, A. Gurtu

Kyung Hee University, Department of Physics, Seoul, Republic of Korea, Seoul, Republic of Korea

H.S. Kim, Y. Kim

Sejong University, Seoul, Republic of 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

Seoul National University, Seoul, Republic of 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

University of Seoul, Seoul, Republic of Korea

S. Ha, H.D. Yoo

Yonsei University, Department of Physics, Seoul, Republic of Korea

M. Choi, H. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

T. Beyrouthy, Y. Maghrbi

College of Engineering and Technology, American University of the Middle East (AUM), Egaila, Kuwait, Dasman, Kuwait

K. Dreimanis, V. Veckalns⁵⁴

Riga Technical University, Riga, Latvia

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

Vilnius University, Vilnius, Lithuania

N. Bin Norjoharuddeen, Z. Zolkapli

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

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

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz⁵⁵, R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, R. Reyes-Almanza, A. Sánchez Hernández

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

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

J. Mijuskovic⁵⁶, N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

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

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

V. Avati, L. Grzanka, M. Malawski

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

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

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

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. Yuldashev⁵⁹, A. Zarubin, I. Zhizhin

Joint Institute for Nuclear Research, Dubna, Russia

G. Gavrilo, V. Golovtsov, Y. Ivanov, V. Kim⁶⁰, E. Kuznetsova⁶¹, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

V. Epshteyn, V. Gavrilo, N. Lychkovskaya, A. Nikitenko⁶², V. Popov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

National Research Center 'Kurchatov Institute', Moscow, Russia

O. Bychkova, M. Chadeeva⁶³, A. Oskin, P. Parygin, E. Popova, V. Rusinov

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁶⁴, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, M. Perfilov, V. Savrin

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

V. Blinov⁶⁵, T. Dimova⁶⁵, L. Kardapoltsev⁶⁵, A. Kozyrev⁶⁵, I. Ovtin⁶⁵, O. Radchenko⁶⁵, Y. Skovpen⁶⁵

Novosibirsk State University (NSU), Novosibirsk, 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

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

A. Babaev, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

V. Borshch, V. Ivanchenko, E. Tcherniaev

Tomsk State University, Tomsk, Russia

P. Adzic⁶⁶, M. Dordevic, P. Milenovic, J. Milosevic

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia

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

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

J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, 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

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, 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

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

M.K. Jayananda, B. Kailasapathy⁶⁷, D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

University of Ruhuna, Department of Physics, Matara, Sri Lanka

T.K. Aarrestad, D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon[†], D. Barney, J. Bendavid, M. Bianco, A. Bocchi, 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. Fallavollita⁶⁸, 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. Sphicas⁶⁹, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsiros, J. Wanczyk⁷⁰, K.A. Wozniak, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada⁷¹, A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, M. Missiroli⁷¹, L. Noehte⁷¹, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

K. Androsov⁷⁰, 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. Luster, 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. Reitspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, V. Stampf, J. Steggemann⁷⁰, R. Wallny

ETH Zurich – Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

C. Amsler⁷², P. Bäertschi, 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

Universität Zürich, Zurich, Switzerland

C. Adloff⁷³, C.M. Kuo, W. Lin, A. Roy, T. Sarkar⁴¹, S.S. Yu

National Central University, Chung-Li, 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

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

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

F. Boran, S. Damarsekkin⁷⁴, Z.S. Demiroglu, F. Dolek, I. Dumanoglu⁷⁵, E. Eskut, Y. Guler⁷⁶, E. Gulpinar Guler⁷⁶, C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir⁷⁷, A. Polatoz, A.E. Simsek, B. Tali⁷⁸, U.G. Tok, S. Turkcapar, I.S. Zorbakir

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

G. Karapinar, K. Ocalan⁷⁹, M. Yalvac⁸⁰

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gulmez, M. Kaya⁸¹, O. Kaya⁸², Ö. Özçelik, S. Tekten⁸³, E.A. Yetkin⁸⁴

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak⁷⁵, Y. Komurcu, S. Sen⁸⁵

Istanbul Technical University, Istanbul, Turkey

S. Cerci⁷⁸, I. Hos⁸⁶, B. Isildak⁸⁷, B. Kaynak, S. Ozkorucuklu, H. Sert, C. Simsek, D. Sunar Cerci⁷⁸, C. Zorbilmez

Istanbul University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk

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

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. Stylianou⁸⁸, K. Walkingshaw Pass, R. White

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁸⁹, C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg⁹⁰, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, V. Cepaitis, G.S. Chahal⁹¹, 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. Nash⁹², M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, A. Tapper, K. Uchida, T. Virdee²¹, M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

Imperial College, London, United Kingdom

K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid, L. Teodorescu, S. Zahid

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, TX, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

Catholic University of America, Washington, DC, USA

A. Buccilli, S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio⁹³, C. West

The University of Alabama, Tuscaloosa, AL, 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

Boston University, Boston, MA, USA

G. Benelli, B. Burkle, X. Coubez²², D. Cutts, M. Hadley, U. Heintz, J.M. Hogan⁹⁴, T. Kwon, G. Landsberg, K.T. Lau, D. Li, M. Lukasik, J. Luo, M. Narain, N. Pervan, S. Sagir⁹⁵, F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

Brown University, Providence, RI, 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, Davis, Davis, CA, 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, Los Angeles, CA, USA

Y. Chen, R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganeli, W. Si, S. Wimpenny, Y. Zhang

University of California, Riverside, Riverside, CA, 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, San Diego, La Jolla, CA, 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

University of California, Santa Barbara – Department of Physics, Santa Barbara, CA, 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

California Institute of Technology, Pasadena, CA, USA

J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, M. Paulini, A. Sanchez, W. Terrill

Carnegie Mellon University, Pittsburgh, PA, 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

University of Colorado Boulder, Boulder, CO, 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

Cornell University, Ithaca, NY, 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. Klijsma, 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. Pena⁶⁴, F. Ravera, A. Reinsvold Hall⁹⁶, 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

Fermi National Accelerator Laboratory, Batavia, IL, 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. Muthirakalayi Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu, E. Yigitbasi, X. Zuo

University of Florida, Gainesville, FL, 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 State University, Tallahassee, FL, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy⁹⁷, M. Hohlmann, R. Kumar Verma, D. Noonan, M. Rahmani, F. Yumiceva

Florida Institute of Technology, Melbourne, FL, 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

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

M. Alhousseini, K. Dilsiz⁹⁸, L. Emediato, R.P. Gandrajula, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili⁹⁹, J. Nachtman, H. Ogul¹⁰⁰, Y. Onel, A. Penzo, C. Snyder, E. Tiras¹⁰¹

The University of Iowa, Iowa City, IA, 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

Johns Hopkins University, Baltimore, MD, 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

The University of Kansas, Lawrence, KS, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam

Kansas State University, Manhattan, KS, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, CA, 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

University of Maryland, College Park, MD, 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

Massachusetts Institute of Technology, Cambridge, MA, 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 Minnesota, Minneapolis, MN, 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

University of Nebraska-Lincoln, Lincoln, NE, USA

G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

State University of New York at Buffalo, Buffalo, NY, 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

Northeastern University, Boston, MA, USA

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

Northwestern University, Evanston, IL, 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. Musienko⁵⁷, R. Ruchti, A. Townsend, M. Wayne, M. Zarucki, L. Zygala

University of Notre Dame, Notre Dame, IN, USA

B. Bylsma, L.S. Durkin, B. Francis, C. Hill, M. Nunez Ornelas, K. Wei, B.L. Winer, B.R. Yates

The Ohio State University, Columbus, OH, 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

Princeton University, Princeton, NJ, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, PR, 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. Stojanovic¹⁷, J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, IN, USA

J. Dolen, N. Parashar

Purdue University Northwest, Hammond, IN, 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. Zhang¹⁰², Y. Zhang

Rice University, Houston, TX, 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

University of Rochester, Rochester, NY, USA

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, O. Karacheban²⁵, 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

Rutgers, The State University of New Jersey, Piscataway, NJ, USA

H. Acharya, A.G. Delannoy, S. Fiorendi, S. Spanier

University of Tennessee, Knoxville, TN, USA

O. Bouhali¹⁰³, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon¹⁰⁴, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas A&M University, College Station, TX, 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

Texas Tech University, Lubbock, TX, USA

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

Vanderbilt University, Nashville, TN, 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

University of Virginia, Charlottesville, VA, USA

N. Poudyal

Wayne State University, Detroit, MI, 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

University of Wisconsin – Madison, Madison, WI, WI, USA

† 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 Babeş-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 Şirnak University, Şirnak, 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 Rektörlüğü, 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, Republic of Korea.