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

**A B S T R A C T**

A search for a massive resonance X decaying to a pair of spin-0 bosons $\phi$ that themselves decay to pairs of bottom quarks, is presented. The analysis is restricted to the mass ranges $m_{X}$ from 25 to 100 GeV and $m_{\phi}$ from 1 to 3 TeV. For these mass ranges, the decay products of each $\phi$ 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.

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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 $\phi$, whose masses $m_{X}$ and $m_{\phi}$ are not constrained. If $m_{X} > 2m_{b}$, then $X \rightarrow \phi\phi$ is the dominant decay of the heavier particle, and $\phi$ 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 $m_{\phi}$ 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 $m_{N}/f$. 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].

![Feynman diagram](https://example.com/feynman_diagram.png)

**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 $\phi$ scalar bosons, the high momentum imparted to the $\phi$ 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 $m_{b}$ 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 substruc-
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 $\tau$ 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 $\mu$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 $X \rightarrow \phi \rightarrow (b\bar{b})(b\bar{b})$, where $X$ is produced through gluon fusion, was generated to leading order with the MADGRAPH 2.6.0 [30] generator. Both the $X \rightarrow \phi$ 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 ($\eta$) 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” ($m_{\text{gj}}$), which better reflects the mass of the particle that initiated the jet. The lower bound on $m_{\text{gj}}$ 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 either on the $p_T$ of a single AK8 jet, or on the event $H_T$, defined as the scalar 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 $j_2$ ($m_{\text{sym}} = |m_{j_1} - m_{j_2}|/(m_{j_1} + m_{j_2})$), the separation in $\eta$ between these jets ($|\Delta \eta|$), and the values of the double-$b$ tagger discriminant ($D^{\text{bb}}$) for each jet. Two signal enriched regions are used to extract the signal: the first, called the “tight search region” (TSR), requires $|\Delta \eta| < 1.5$, $m_{\text{sym}} < 0.1$, $D^{\text{bb}}_1 > 0.8$, and $D^{\text{bb}}_2 > 0.6$. The second, called the “loose search region” (LSR), differs only in the constraint on the mass asymmetry, requiring $m_{\text{sym}} \in [0.1, 0.25]$. 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 $D^{\text{bb}}$, 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 $|\Delta \eta|$
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 $-0.8 < D_{bj}^{bb} < 0.3$. 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 $D_{bj}^{bb} < 0.6$.

After all selection criteria are applied, the product of the acceptance and efficiency for the range of $m_X$ and $m_\phi$ 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 $m_\phi$.

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: $W = \exp[\alpha(p_t^1 + p_t^2)]$, where $\alpha$, initialized at $5 \times 10^{-3}$/GeV, controls the shape of the resulting $t\bar{t}$ distribution. The normalization of the $t\bar{t}$ background and the value of $\alpha$ 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 $\alpha$ may vary from year to year, so both are allowed to vary within large uncertainties (20 and 100%, respectively) 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 $D_{bj}^{bb} > 0.6$ requirement in each search region can be modeled by a smooth function of the subleading jet $p_t$ and groomed jet mass, $R_{P_{\gamma}}(p_{t1}, p_{t2})$. This pass-to-fail ratio is parameterized as $R_{P_{\gamma}} = P_{\gamma}(p_{t1}, p_{t2})F(m_{\gamma})$, where $P_{\gamma}$ is a polynomial of order $n$ and $F(m_{\gamma})$ is the function $F(x) = \beta_0 \arctan(p_t^1 + p_t^2) + \beta_3$. The parameters of each component of $R_{P_{\gamma}}$ are initialized from their values in the control regions. The $|\Delta\eta|$ sidebands are used for $F(m_{\gamma})$, whereas the double-$b$ sidebands are used for $P_{\gamma}(p_{t1}, p_{t2})$. In both cases the signal is negligible in the control regions. Fig. 2 shows, in 2018 data, the groomed mass dependence of $R_{P_{\gamma}}$ for both the TSR and the $|\Delta\eta|$ sidebands, as well as the fit from which 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 $R_{P_{\gamma}}$, 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 $P_{\gamma}$ is determined in the double-$b$ control region by performing Fisher F-tests [36] on progressively higher-order polynomials. A $P_2$ ($P_4$) 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 $F(m_{\gamma})$: as it did not lead to a significantly improved description of $R_{P_{\gamma}}$, it was reserved for bias tests of the background estimate (described below). Uncertainties in the fit parameters for $F$ and $P_{\gamma}$ 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 $m_\phi$ and $m_X$ for a potential signal are unknown. The two dimensions of this spectrum are the average jet mass $\bar{m} = (m_1 + m_2)/2$ 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 $\bar{m}$ 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 $\phi$ and X masses, respectively. The difference between
generated signal shapes and those obtained from this functional form are negligible. The range of average jet masses considered is \( m \in [15, 200] \text{GeV} \), while \( M_{jj} \) between 0.9 and 5.0 TeV are considered. The \( m \) 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 \( \alpha \) parameter. The data-driven QCD background has two sources of uncertainty, from the determination of \( R_{ppf} \), 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 arc tangent representation of \( F(m_H) \) 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 deviations 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 \( m \) 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 \( m_H \) and \( m_X \) of about 75 GeV and 1 TeV, respectively, with a local significance of 3.1 standard deviations and a global significance of 1.3 standard deviations. Here the global significance takes into account the look-elsewhere effect [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 \( m_H \) and \( m_X \).

### 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 \( \Gamma \) 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.

<table>
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<th>Source</th>
<th>Signal</th>
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<th>Corr.</th>
</tr>
</thead>
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<td>1.2–2.5%</td>
<td>R</td>
</tr>
<tr>
<td>Double-b scale factor</td>
<td>19–46%</td>
<td>19–46%</td>
<td>R</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1–5%</td>
<td>1–5%</td>
<td>R</td>
</tr>
<tr>
<td>PDF</td>
<td>4%</td>
<td>4%</td>
<td>R</td>
</tr>
<tr>
<td>Pileup</td>
<td>1–10%</td>
<td>1–10%</td>
<td>R</td>
</tr>
<tr>
<td>Jet energy scale (correlated)</td>
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<td>2%</td>
<td>RY</td>
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<tr>
<td>Jet energy scale (uncorrelated)</td>
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<td>2%</td>
<td>R</td>
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<tr>
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<tr>
<td>(failing region)</td>
<td>&lt;1–100%</td>
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8. Results

The results of the fit are used to set 95% confidence level (CL) upper limits on $\sigma(pp \rightarrow X)$, assuming a 100% branching fraction for $X \rightarrow \phi \phi \rightarrow (b\bar{b})(b\bar{b})$. Upper limits are computed under a modified frequentist approach, using the $\text{CL}_{s}$ 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 $m_{b}$ 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 $X \rightarrow \phi \phi \rightarrow (b\bar{b})(b\bar{b})$ process range from 30 to 1 fb, depending on $m_{b}$ and $m_{X}$.

9. Summary

A search for massive resonances ($X$) decaying to pairs of spin-0 bosons ($\phi$) 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 $\sqrt{s} = 13$ 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 $X \rightarrow \phi \phi \rightarrow (b\bar{b})(b\bar{b})$, where both the $X \rightarrow \phi \phi$ and $\phi \rightarrow b\bar{b}$ branching fractions are assumed to be 100%. These are the first limits on this process, and range between 30 and 1 fb for a $\phi$ mass in the range 25–100 GeV and an $X$ mass in the range 1–3 TeV.

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".

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Fig. 5. Upper limits at 95% CL on the cross section of the process $p p \rightarrow X \rightarrow \phi \rightarrow (b\bar{b})(b\bar{b})$, as a function of the mass of $m_X$, for different values of $m_\phi$. Both the $X \rightarrow \phi$ and $\phi \rightarrow b\bar{b}$ branching fractions are assumed to be 100%. Each subpanel shows the limits for a fixed value of $m_\phi$. 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 $m_X / f$ are shown with dotted and dashed curves.

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The CMS Collaboration

A. Tumasyan
Yerevan Physics Institute, Yerevan, Armenia

Institut für Hochenergiephysik, Vienna, Austria

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

Universiteit Antwerpen, Antwerpen, Belgium

Vrije Universiteit Brussel, Brussel, Belgium

Université Libre de Bruxelles, Bruxelles, Belgium

Ghent University, Ghent, Belgium

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

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

C.A. Bernardes 5, L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, D.S. Lemos, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

Universidade Estadual Paulista, 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. Javaid 7, M. Mittal, L. Yuan

Beihang University, Beijing, China

M. Ahmad, G. Bauer, C. Dozen 8, Z. Hu, J. Martins 9, Y. Wang, K. Yi 10, 11

Department of Physics, Tsinghua University, Beijing, China


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. Gao 3, 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

Zhongnan 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. Starodumov 12, T. Susa
The CMS Collaboration

Institute Rudjer Boskovic, Zagreb, Croatia


University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr., 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, S. Elgammal

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


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


Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, H. Petrow, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland


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


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


Université de Strasbourg, CNRS, IPHC 7178, Strasbourg, France

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

University of Ioánnina, Ioánnina, Greece

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

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

University of Ioánnina, Ioánnina, Greece

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


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. Khazaie 45, M. Zeinali 46

Isfahan University of Technology, Isfahan, Iran

S. Chenarani 47, 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. Pompli a,b, G. Pugliese a,c, D. Ramos a, A. Ranieri a, G. Selvaggi a,b, L. Silvestris a, F.M. Simone a,b, U. Sözbilir a, R. Venditti a, P. Verwille44,45

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. Borgonovi a, L. Brigliadori a, R. Campanini a,b, P. Capiluppi a,b, A. Castro a,b, F.R. Cavallo a, C. Ciocca a, M. Cuffiani a,b, G.M. Dallavalle a, T. Diotalevi a,b, F. Fabbrini a, A. Fanfani a,b, P. Giacomelli a, L. Giommi a,b, C. Grandi a, L. Guiducci a,b, S. Lo Meo 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. Ross a,b, T. Rovelli a,b, G.P. Siroli a,b

a INFN Sezione di Bologna, Bologna, Italy
b Università di Bologna, Bologna, Italy

c INFN Sezione di Firenze, Firenze, Italy
b Università di Firenze, Firenze, 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. Bozio 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. Cetorelli a,b, F. De Guio a,b, M.E. Dinardo a,b, P. Dini a, S. Gennai a, A. Ghezzi a,b, P. Govoni a,b, L. Guzzi a,b, M.T. Lucchini a,b, M. Malberti a, S. Malvezzi a, A. Massironi a, D. Menasce a, L. Moroni a, M. Paganoni a,b, D. Pedrini a, B.S. Pinolini, S. Ragazzi a,b, N. Redaelli a, T. Tabarelli de Fatis a,b, D. Valsecchi a,b,21, D. Zuolo a,b

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


C. Aimè, A. Braghieri, S. Calzaferri, D. Fiorina, P. Montagna, S.P. Ratti, V. Re, C. Riccardi, P. Salvini, I. Vai, P. Vitullo


S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, A. Da Rold, G. Della Ricca, G. Sorrentino

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

J. Mijuskovic 56, N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand


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. Boimsha, M. Górska, 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


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


Joint Institute for Nuclear Research, Dubna, Russia


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


Institute for Nuclear Research, Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko 62, V. Popov, A. Stepenov, M. Toms, E. Vlasov, A. Zhokin

National Research Center ‘Kurchatov Institute’, Moscow, Russia

O. Bychkova, M. Chadeeva 63, A. Oskin, P. Parygin, E. Popova, V. Rusinov
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, V. Bunichev, M. Dubinin, 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. Blinov, T. Dimova, L. Kardapoltsev, A. Kozyrev, I. Ovtin, O. Radchenko, Y. Skovpen

Novosibirsk State University (NSU), Novosibirsk, Russia


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

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


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

J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain


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


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


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
The CMS Collaboration

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CERN, European Organization for Nuclear Research, Geneva, Switzerland


Paul Scherrer Institut, Villigen, Switzerland


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


Universität Zürich, Zurich, Switzerland

C. Adloff, C.M. Kuo, W. Lin, A. Roy, T. Sarkar, S.S. Yu

National Central University, Chung-Li, Taiwan


National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

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


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

G. Karapinar, K. Ocalan, M. Yalvac

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gulmez, M. Kaya, O. Kaya, Ö. Özçelik, S. Tekten, E.A. Yetkin

Bogazici University, Istanbul, Turkey
A. Cakir, K. Cankocak, Y. Komurcu, S. Sen
Istanbul Technical University, Istanbul, Turkey

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

University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom

Brunel University, Uxbridge, United Kingdom

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. Rumerio, C. West
The University of Alabama, Tuscaloosa, AL, USA

Boston University, Boston, MA, USA

Brown University, Providence, RI, USA

University of Florida, Gainesville, FL, USA


Florida State University, Tallahassee, FL, USA


Florida Institute of Technology, Melbourne, FL, USA


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


The University of Iowa, Iowa City, IA, USA


The University of Kansas, Lawrence, KS, USA


Johns Hopkins University, Baltimore, MD, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, CA, USA


University of Maryland, College Park, MD, USA


Massachusetts Institute of Technology, Cambridge, MA, USA


University of Minnesota, Minneapolis, MN, USA

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

University of Tennessee, Knoxville, TN, USA


Texas A&M University, College Station, TX, USA


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


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

1 Deceased.
2 Also at TU Wien, Wien, Austria.
3 Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.
4 Also at Université Libre de Bruxelles, Bruxelles, Belgium.
5 Also at Universidade Estadual de Campinas, Campinas, Brazil.
6 Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
7 Also at The University of the State of Amazonas, Manaus, Brazil.
8 Also at University of Chinese Academy of Sciences, Beijing, China.
9 Also at Department of Physics, Tsinghua University, Beijing, China.
10 Also at UFMS, Nova Andradina, Brazil.
11 Also at Nanjing Normal University Department of Physics, Nanjing, China.
12 Now at The University of Iowa, Iowa City, Iowa, USA.
13 Also at National Research Center ‘Kurchatov Institute’, Moscow, Russia.
14 Also at Joint Institute for Nuclear Research, Dubna, Russia.
15 Also at Helwan University, Cairo, Egypt.
16 Now at Zewail City of Science and Technology, Zewail, Egypt.
17 Now at British University in Egypt, Cairo, Egypt.
18 Also at Purdue University, West Lafayette, Indiana, USA.
19 Also at Université de Haute Alsace, Mulhouse, France.
20 Also at Ilia State University, Tbilisi, Georgia.
21 Also at Erzincan Binali Yıldırım University, Erzincan, Turkey.
22 Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
23 Also at RWTH Aachen University, II. Physikalisches Institut A, Aachen, Germany.
24 Also at University of Hamburg, Hamburg, Germany.
25 Also at Isfahan University of Technology, Isfahan, Iran.
26 Also at Brandenburg University of Technology, Cottbus, Germany.
27 Also at Forschungszentrum Jülich, Juelich, Germany.
28 Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
29 Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary.
30 Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
31 Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
32 Now at Universitatea Babes-Bolyai – Facultatea de Fizica, Cluj-Napoca, Romania.
33 Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
34 Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.