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

Abstract

A search for an extended Higgs sector, characterized by 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 $m_\phi$ from 25 to 100 GeV and $m_X$ 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 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 mass, 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.

Submitted to Physics Letters B

© 2022 CERN for the benefit of the CMS Collaboration. CC-BY-4.0 license

*See Appendix A for the list of collaboration members
1 Introduction

The discovery \cite{1-3} of a particle consistent with the standard model (SM) Higgs boson (H), by both the ATLAS and CMS Collaborations, does not preclude the existence of an extended Higgs sector. Such extensions, proposed in a variety of new physics models \cite{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 \( m_X > 2m_\phi \), 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 \( m_X N / f \). The search is based on proton-proton (pp) collision data at \( \sqrt{s} = 13 \) TeV collected with the CMS detector \cite{11} at the LHC in 2016–2018, corresponding to a total integrated luminosity of 138 fb\(^{-1} \) \cite{12-14}. In 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 \cite{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 \( m_\phi \) below 100 GeV.

![Figure 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.](image)

This analysis searches for a localized excess in the two-dimensional distributions of average jet mass and dijet mass for events with two large-radius jets with heavy-flavor jet substructure. The main background, from SM events composed uniquely of jets produced through the strong interaction, referred to as quantum chromodynamics (QCD) multijet events, is derived using control samples in data. Additional background from top quark pair (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 \cite{20}.
2 The CMS detector

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

3 Simulated samples

The benchmark signal model $X \rightarrow \phi \phi \rightarrow (b\bar{b})(b\bar{b})$, 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 CUEPT8M1 (CP5)[40, 41] underlying event tune is used for the simulated samples corresponding to the 2016 (2017–2018) data taking with the NNPDF3.0 (NNPDF3.1)[42] NNLO parton distribution function (PDF) sets.

The simulation of the CMS detector for all samples is handled by Geant4[43]. All samples include effects of additional pp interactions in the same or adjacent bunch crossings, referred to as pileup. The pileup distribution in simulation is weighted to match the one observed in data.

4 Event reconstruction

Jets used in this analysis are clustered using FastJet[44] with the anti-$k_T$ (AK) algorithm[45] and a distance parameter of 0.4 (AK4 jets) or 0.8 (AK8 jets). Particles produced in additional collisions within the same bunch crossing are suppressed by applying a weight to each PF candidate, calculated by the pileup-per-particle identification[46, 47] algorithm. Jets are corrected as a function of their $p_T$ and pseudorapidity ($\eta$) 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 simulated samples of boosted Higgs boson jets, where the jet showering may be different from the behavior of jets in real data. To correct for this, a scale factor is derived and applied to each jet in the signal simulation as a function of the jet $p_T$. The lower bound on $f$ masses considered is due to uncertainty in the behavior of this algorithm for jet masses below 25 GeV. The training is sensitive to detector conditions, so the exact performance of the discriminator differs from year to year. The soft drop mass algorithm (with angular exponent $\beta = 0$ and soft threshold $z_{cut} = 0.1$) [50, 51] is used to remove soft and wide-angle radiation from jets before computing a “groomed jet mass” ($m_j$), which better reflects the mass of the particle that initiated the jet.

5 Event selection

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

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

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

After all selection criteria are applied, the product of the acceptance and efficiency for the range
of \( m_X \) and \( m_f \) 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 \( m_f \).

Table 1: Search and control regions used in the analysis. A selection on the subleading jet double-b-tagger discriminant \( D_{bbj}^2 > 0.6 \) further separates each region into “passing” and “failing” categories.

| Region                        | \( m_{\text{asym}} \) | \( |\Delta \eta| \) | \( D_{bbj}^2 \) |
|-------------------------------|-------------------------|---------------------|----------------|
| 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]    |

6 Background processes

The dominant QCD multijet background is modeled by exploiting the fact that the ratio of events for which the subleading jet passes or fails the \( D_{bbj}^2 > 0.6 \) requirement in each search region can be modeled by a smooth function of the subleading jet \( p_T \) and groomed jet mass, \( R_{p/f}(p_T, m_{bbj}) \). This pass-to-fail ratio is parameterized as \( R_{p/f} = P_n(p_T) F(m_{bbj}) \), where \( P_n \) is a polynomial of order \( n \) and \( F(m_{bbj}) \) is the function \( F(x) = p_0 \arctan(p_1 x + p_2) + p_3 \). The parameters of each component of \( R_{p/f} \) are measured in the control regions. The \(|\Delta \eta|\) sidebands are used to determine \( F(m_{bbj}) \), whereas the double-b sidebands are used to determine \( P_n(p_T, m_{bbj}) \). In both cases the signal is negligible in the control regions. The QCD background in the “passing” search regions is estimated by weighting the events in the “failing” search regions by this \( R_{p/f} \). This background estimate is also performed in each control region as a closure test.

Each year of data taking, as well as the TSR and LSR, is treated independently. The order of \( P_n \) is determined in the double-b control region by performing Fisher F-tests on progressively higher-order polynomials. A \( P_2 \) \((P_3)\) is found to be optimal for describing the data taken in 2016 \((2017–2018)\). Uncertainties in the fit parameters for \( F \) and \( P_n \) are treated as systematic uncertainties in the shape of the background in the search regions.

The \( t\bar{t} \) contribution to the total background is obtained from simulation, after a correction is applied to account for the differences 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: \( W = \exp[a(p_T + p_T^\ell)] \), where \( a \), 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 \( a \) are obtained by a simultaneous maximum likelihood fit of the TSR and LSR. The best fit values for both the overall normalization and the value of \( a \) may vary from year to year, so both are allowed to vary within large uncertainties \((20 \text{ and } 100\%, \text{ respectively})\), separately for each year.
7 Fitting procedure

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 $\bar{m} = (m_{j_1} + m_{j_2})/2$ 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 $\bar{m}$ 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 range of average jet masses considered is $\bar{m} \in [15, 200]$ GeV, while $M_{jj}$ between 0.9 and 5.0 TeV are considered. These ranges go beyond the signal masses considered in this analysis, with the events at high masses providing constraints on the $t\bar{t}$ and QCD components. Both mass distributions use variable binnings to ensure that the background estimate prediction is nonzero in each mass interval.

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

8 Systematic uncertainties

Systematic uncertainties are treated in the fit as nuisance parameters affecting the shapes and the normalization of signal and background processes. All uncertainties are quantified in Table 2. The dominant uncertainty is from the double-b tagger scale factor, which is described in Ref. [49] and applied as a function of the jet $p_T$. Differences between simulation and data on the jet energy calibration and $p_T$ resolution of jets are corrected by applying scale factors to the simulation, derived from control regions in data [48]. The jet energy scale (JES) and resolution uncertainties are considered as uncertainties in the shape of the signal and $t\bar{t}$ background. The JES uncertainties take into account correlated and uncorrelated components between all three years. Uncertainties pertaining to the trigger efficiency, the pileup distribution, the PDFs, and the integrated luminosity determination [12–14] are applied to the signal and $t\bar{t}$ 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 $R_{pT}$, 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.
Figure 2: Distributions of average jet mass (left) and dijet mass (right), and background estimate of the combined search regions after the final fit is performed. The blue (solid) line represents the sum of the estimated QCD and tt backgrounds, and the red filled histogram shows the tt contribution alone. The shaded areas around the background estimate in the upper panels represent the total uncertainty in the total background estimate in that bin. The shapes of two representative signals, each normalized to cross sections of 50 fb, are indicated by solid colored lines. The lower panel shows the difference between the observed data and the background prediction, divided by $\sigma_{\text{data}}$, the statistical uncertainty of the data in each bin.

Table 2: Sources of systematic uncertainties considered in the analysis. The uncertainty in the integrated luminosity only affects the normalization; for the rest, both the shape and normalization are affected. The parameters affecting only the normalization have log-normal priors, and those affecting the shape (or both the shape and normalization) have Gaussian priors, except for the statistical uncertainty in the failing region, whose parameters were sampled from a $\Gamma$ 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 tt uncertainties are propagated to the QCD estimate.

<table>
<thead>
<tr>
<th>Source</th>
<th>Signal</th>
<th>Background</th>
<th>QCD</th>
<th>Corr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>1.2–2.5%</td>
<td>1.2–2.5%</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>Double-b scale factor</td>
<td>19–46%</td>
<td>19–46%</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1–5%</td>
<td>1–5%</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>PDF</td>
<td>4%</td>
<td>4%</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>Pileup</td>
<td>1–10%</td>
<td>1–10%</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>Jet energy scale (correlated)</td>
<td>2%</td>
<td>2%</td>
<td>R</td>
<td>RY</td>
</tr>
<tr>
<td>Jet energy scale (uncorrelated)</td>
<td>2%</td>
<td>2%</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>10%</td>
<td>10%</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>tt shape ($\alpha$)</td>
<td>100%</td>
<td>100%</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>tt normalization</td>
<td>20%</td>
<td>20%</td>
<td>R</td>
<td></td>
</tr>
<tr>
<td>$R_{p/t}$ fit</td>
<td>5–30%</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Statistical uncertainty (failing region)</td>
<td>&lt;1–100%</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>
9 Results

The results of the fit are used to set 95% confidence level (CL) upper limits on $\sigma(p\bar{p} \rightarrow X)$, 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 CL$_s$ criterion with the profile likelihood ratio used as the test statistic with the asymptotic approximation. Observed limits are shown as a function of $m_{\phi}$ 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. 4. 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 $m_{\phi}$ and $m_X$. 

Figure 3: The average jet mass distributions in consecutive dijet mass intervals. The vertical dashed grey lines separate the average jet mass distributions in each bin of $M_{jj}$. The individual bins within such subdivisions correspond to the $\hat{m}$ spectrum (from 15 to 200 GeV), as seen in Fig. 2 (left). Representative signal shapes are also shown; we note that they peak in the $\hat{m}$ spectrum within subdivisions, and may appear in multiple $M_{jj}$ bins. The blue (solid) line represents the sum of the estimated QCD and $t\bar{t}$ backgrounds, and the red filled histogram shows the $t\bar{t}$ contribution alone. The shaded areas around the background estimate in the upper panels represent the total uncertainty in the total background estimate in that bin. The shapes of three representative signals, each normalized to cross sections of 50 fb are indicated by solid colored lines. The lower panel shows the difference between the observed data and the background prediction, divided by $\sigma_{\text{data}}$, the statistical uncertainty of the data in each bin.
Figure 4: 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 $m_\phi$. 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 $m_\phi$. 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 $m_X N/f$ are shown with dotted and dashed curves.
10 Summary

A search for massive resonances (X) decaying to pairs of spin-0 bosons (φ) that themselves decay into b quark-antiquark pairs has been presented. The analysis is restricted to the case where the mass ratio of the resonance and the scalar bosons is such that each pair of b quarks is reconstructed as a single large-radius jet. Data from proton-proton collisions at the LHC at $\sqrt{s} = 13$ 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.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINGCIUS (Colombia); MSES and CSF (Croaita); RIF (Cyprus); SENESCYT (Ecuador); MoER, ECC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NFIA (Hungary); DAAD 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, IFST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science – EOS” – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Deutsche Forschungsgemeinschaft (DFG), under Germany’s Excellence Strategy – EXC 2121 “Quantum Universe” – 390833306, and under project number 400140256 - GRK2497; the Lendület (“Momenit”) Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIH research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hung-
gary); 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


reconstruction with the CMS tracker”, JINST 9 (2014) P10009,

[26] CMS Collaboration, “Particle-flow reconstruction and global event description with the
CMS detector”, JINST 12 (2017) P10003,

[27] CMS Collaboration, “Performance of reconstruction and identification of \( \tau \) leptons
decaying to hadrons and \( \nu_\tau \) in pp collisions at \( \sqrt{s} = 13 \) TeV”, JINST 13 (2018) P10005,

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

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

differential cross sections, and their matching to parton shower simulations”, JHEP 07

[31] G. Bozzi, S. Catani, D. de Florian, and M. Grazzini, “The \( q_T \) spectrum of the Higgs boson


resummation: Higgs boson production at the Tevatron and the LHC”, JHEP 11 (2011)

[34] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo

shower simulations: the POWHEG method”, JHEP 11 (2007) 070,

calculations in shower Monte Carlo programs: the POWHEG BOX”, JHEP 06 (2010) 043,

[37] S. Alioli, S.-O. Moch, and P. Uwer, “Hadronic top-quark pair-production with one jet and


[45] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-


A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Tumasyan

Institut für Hochenergiephysik, Vienna, Austria

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

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

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

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

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

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov
University of Sofia, Sofia, Bulgaria
A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

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

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, G. Bauer, C. Dozen, Z. Hu, J. Martins, Y. Wang, K. Yi

Institute of High Energy Physics, Beijing, China

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

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

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

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

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

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

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

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

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

University of Cyprus, Nicosia, Cyprus

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

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

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

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egypt
tian Network of High Energy Physics, Cairo, Egypt
A.A. Abdelalim\textsuperscript{14,15} and S. Elgamal\textsuperscript{16}

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M.A. Mahmoud\textsuperscript{17} and Y. Mohammed\textsuperscript{15}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik\textsuperscript{18}, R.K. Dewanjee\textsuperscript{19}, K. Ehtaha, M. Kadastik, S. Nandan, C. Nielsen, J. Pata, M. Raidal\textsuperscript{20}, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola\textsuperscript{21}, H. Kirschenmann\textsuperscript{22}, K. Osterberg\textsuperscript{23}, M. Voutilainen\textsuperscript{24}

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücker\textsuperscript{25}, F. García\textsuperscript{26}, J. Havukainen\textsuperscript{27}, M.S. Kim\textsuperscript{28}, R. Kinnunen, T. Lampén, K. Lassila-Perinti\textsuperscript{29}, S. Lehto\textsuperscript{30}, T. Lindén, M. Lotti, M. Martikainen, M. Myllymäki, J. Ott\textsuperscript{31}, H. Siikonen, E. Tuominen\textsuperscript{32}, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
P. Luukka\textsuperscript{33} and H. Petrow, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola\textsuperscript{34}, M. Besancon, F. Couderc\textsuperscript{35}, M. Dejardin, D. Denegri, J.L. Faure, F. Ferrig\textsuperscript{36}, S. Ganjour, P. Gras, G. Hamel de Monchenault\textsuperscript{37}, P. Jarry, B. Lenzi\textsuperscript{38}, E. Locci, J. Malcles, J. Rander, A. Rosowsky\textsuperscript{39}, M.Ö. Sahin\textsuperscript{40}, A. Savoy-Navarro\textsuperscript{41}, M. Titov\textsuperscript{42}, G.B. Yu\textsuperscript{43}

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
S. Ahuja\textsuperscript{44}, F. Beaudette\textsuperscript{45}, M. Bonanomi\textsuperscript{46}, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot\textsuperscript{47}, O. Davignon, B. Diab, G. Falmagne\textsuperscript{48}, S. Ghosh, R. Granier de Cassagnac\textsuperscript{49}, A. Hakimi, I. Kuchin\textsuperscript{50}, J. Motta, M. Nguyen\textsuperscript{51}, C. Ochando\textsuperscript{52}, P. Paganini\textsuperscript{53}, J. Rembser, R. Salerno\textsuperscript{54}, U. Sarkar\textsuperscript{55}, J.B. Sauvan\textsuperscript{56}, Y. Siros\textsuperscript{57}, A. Tarabini, A. Zabi, A. Zghiche\textsuperscript{58}

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram\textsuperscript{59}, J. Andrea, D. Apparu, D. Bloch\textsuperscript{60}, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard\textsuperscript{61}, D. Darej, J.-C. Fontaine\textsuperscript{62}, U. Goerlach, C. Grimault, A.-C. Le Bihan, E. Nibigire\textsuperscript{63}, P. Van Hove\textsuperscript{64}

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
E. Asilar\textsuperscript{65}, S. Beauceron\textsuperscript{66}, C. Bernet\textsuperscript{67}, G. Boudoul, C. Camen, A. Carle, N. Chanon\textsuperscript{68}, D. Contardo, P. Depasse\textsuperscript{69}, H. El Mamouni, J. Fay, S. Gascort\textsuperscript{70}, M. Gouzevitch, B. Ille, I.B. Laktineh, H. Lattaud\textsuperscript{71}, A. Lesaunier\textsuperscript{72}, M. Lethuillier\textsuperscript{73}, L. Mirabito, S. Perries, K. Shchablo, V. Sordini\textsuperscript{74}, L. Torretotot\textsuperscript{75}, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
I. Bagaturia\textsuperscript{19}, I. Lomidze, Z. Tsamaladze\textsuperscript{13}

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Bott, L. Feld\textsuperscript{87}, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, J. Schulz, M. Teroerde\textsuperscript{88}

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Dodonova, D. Eliseev, M. Erdmann\textsuperscript{89}, P. Fackeldey\textsuperscript{90}, B. Fischer, T. Hebbeker\textsuperscript{91}, K. Hoepfner, F. Ivone, L. Mastrolorenzo, M. Merschmeyr\textsuperscript{92}, A. Meyer\textsuperscript{93}, G. Mocellin, S. Mondal, S. Mukherjee\textsuperscript{94}, D. Noll\textsuperscript{95}, A. Novak, A. Pozdnyakov, Y. Rath, H. Reithler,
MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók, G. Bencze, C. Hajdu, D. Horváth, F. Sikler, V. Veszpremi

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

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

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

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

Panjab University, Chandigarh, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

Indian Institute of Technology Madras, Madras, India

Bhabha Atomic Research Centre, Mumbai, India
K. Naskar

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

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

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

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi, E. Khazaie, M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani, S.M. Etesami, M. Khazad, M. Mohammadi Najafabad
University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari
Bari, Italy, Università di Bari
Bari, Italy, Politecnico di Bari
Bari, Italy


INFN Sezione di Bologna
Bologna, Italy, Università di Bologna
Bologna, Italy


INFN Sezione di Catania
Catania, Italy, Università di Catania
Catania, Italy

S. Albergo, S. Costa, A. Di Mattia, R. Potenza, A. Tricomi, C. Tuve

INFN Sezione di Firenze
Firenze, Italy, Università di Firenze
Firenze, Italy


INFN Laboratori Nazionali di Frascati
Frascati, Italy

L. Benussi, S. Bianchi, D. Piccolo

INFN Sezione di Genova
Genova, Italy, Università di Genova
Genova, Italy

M. Bozzo, F. Ferro, R. Mulargia, E. Robutti, S. Tosi

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


INFN Sezione di Napoli
Napoli, Italy, Università di Napoli ‘Federico II’
Napoli, Italy, Università della Basilicata
Potenza, Italy, Università G. Marconi
Roma, Italy


INFN Sezione di Padova
Padova, Italy, Università di Padova
Padova, Italy, Università di Trento
Trento, Italy

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

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

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

Seoul National University, Seoul, Korea

University of Seoul, Seoul, Korea

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

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

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

Riga Technical University, Riga, Latvia
K. Dreimanis, V. Veckalns

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

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

Universidad de Sonora (UNISON), Hermosillo, Mexico

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

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

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

University of Montenegro, Podgorica, Montenegro
J. Mijuskovic, N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler

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

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

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

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

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

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

National Research Center ‘Kurchatov Institute’, Moscow, Russia
V. Epshteyn, V. Gavrilo, N. Lyakhovskyka, A. Nikolaenko, V. Popov, A. Stepenkov, M. Toms, E. Vlasov, A. Zhokin

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

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

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

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

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

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

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

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

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

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

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

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

University of Colombo, Colombo, Sri Lanka

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

Paul Scherrer Institut, Villigen, Switzerland

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

Universität Zürich, Zurich, Switzerland

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

National Taiwan University (NTU), Taipei, Taiwan

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

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

Middle East Technical University, Physics Department, Ankara, Turkey
G. Karapinar, K. Ocalan, M. Yalbac, K. Cankocak, Y. Komurcu, S. Sen

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

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

Istanbul University, Istanbul, Turkey
S. Cerci, I. Hos, B. Isilda, B. Kaynak, S. Ozkorucuklu, H. Sert, C. Simsek,
D. Sunar Cerci, C. Zorbilmez

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

B. Grynyov

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

L. Levchuk

University of Bristol, Bristol, United Kingdom


Rutherford Appleton Laboratory, Didcot, United Kingdom


Imperial College, London, United Kingdom


Brunel University, Uxbridge, United Kingdom


Baylor University, Waco, Texas, USA


Catholic University of America, Washington, DC, USA

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

The University of Alabama, Tuscaloosa, Alabama, USA

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

Boston University, Boston, Massachusetts, USA


Brown University, Providence, Rhode Island, USA


University of California, Davis, Davis, California, USA

J. Bonilla, C. Brainerd, R. Breeden, M. Calderon De La Barca Sanchez, M. Chertok,

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

Northeastern University, Boston, Massachusetts, USA

Northwestern University, Evanston, Illinois, USA

University of Notre Dame, Notre Dame, Indiana, USA

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

Princeton University, Princeton, New Jersey, USA

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

Purdue University, West Lafayette, Indiana, USA

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

Rice University, Houston, Texas, USA

University of Rochester, Rochester, New York, USA

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

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

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

Texas Tech University, Lubbock, Texas, USA

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

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

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

University of Wisconsin - Madison, Madison, WI, Wisconsin, USA

†: Deceased
1: Also at TU Wien, Wien, Austria
2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
3: Also at Université Libre de Bruxelles, Bruxelles, Belgium
4: Also at Universidade Estadual de Campinas, Campinas, Brazil
5: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
6: Also at The University of the State of Amazonas, Manaus, Brazil
7: Also at University of Chinese Academy of Sciences, Beijing, China
8: Also at Department of Physics, Tsinghua University, Beijing, China
9: Also at UFMS, Nova Andradina, Brazil
10: Also at Nanjing Normal University Department of Physics, Nanjing, China
11: Now at The University of Iowa, Iowa City, Iowa, USA
12: Also at National Research Center 'Kurchatov Institute', Moscow, Russia
13: Also at Joint Institute for Nuclear Research, Dubna, Russia
14: Also at Helwan University, Cairo, Egypt
15: Now at Zewail City of Science and Technology, Zewail, Egypt
16: Now at British University in Egypt, Cairo, Egypt
17: Also at Purdue University, West Lafayette, Indiana, USA
18: Also at Université de Haute Alsace, Mulhouse, France
19: Also at Ilia State University, Tbilisi, Georgia
20: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
21: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
22: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
23: Also at University of Hamburg, Hamburg, Germany
24: Also at Isfahan University of Technology, Isfahan, Iran
25: Also at Brandenburg University of Technology, Cottbus, Germany
26: Also at Forschungszentrum Jülich, Juelich, Germany
27: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
28: Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
29: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
30: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
31: Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
32: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
33: Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
34: Also at Wigner Research Centre for Physics, Budapest, Hungary
35: Also at IIT Bhubaneswar, Bhubaneswar, India
36: Also at Institute of Physics, Bhubaneswar, India
37: Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
38: Also at Shoolini University, Solan, India
39: Also at University of Hyderabad, Hyderabad, India
40: Also at University of Science and Technology of Mazandaran, Behshahr, Iran
41: Also at Indian Institute of Science (IISc), Bangalore, India
42: Also at Indian Institute of Technology (IIT), Mumbai, India
43: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
44: Also at University of Naples ‘Federico II’, Naples, Italy
45: Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
46: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
47: Also at Centro de Ciencia y Tecnología, Mexico City, Mexico
48: Also 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 University of Naples ‘Federico II’, Naples, 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 IFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
57: Also at University of Nuclear Research, Moscow, Russia
58: Also 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 Fédérable Lausanne, Lausanne, Switzerland
71: Also at Universität Zürich, Zurich, Switzerland
72: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
73: Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
74: Also at Şırnak University, Şırnak, 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 Üniversitesi 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 Bingöl University, Bingöl, Turkey
99: Also at Georgian Technical University, Tbilisi, Georgia
100: Also at Sinop University, Sinop, Turkey
101: Also at Erciyes University, Kayseri, Turkey
102: Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
103: Also at Texas A&M University at Qatar, Doha, Qatar
104: Also at Kyungpook National University, Daegu, Korea