Search for dark matter particles produced in association with a top quark pair at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A search is performed for dark matter particles produced in association with a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV. The data correspond to an integrated luminosity of 35.9 fb$^{-1}$ recorded by the CMS detector at the LHC. No significant excess over the standard model expectation is observed. The results are interpreted using simplified models of dark matter production via spin-0 mediators that couple to dark matter particles and to standard model quarks, providing constraints on the coupling strength between the mediator and the quarks. These are the most stringent collider limits to date for scalar mediators, and the most stringent for pseudoscalar mediators at low masses.

Published in Physical Review Letters as doi:10.1103/PhysRevLett.122.011803.
Astrophysical observations strongly motivate the existence of dark matter [1–4], which may originate from physics beyond the standard model. In a large class of models, dark matter consists of stable, weakly interacting massive particles ($\chi$) [4], which may be pair produced at the CERN LHC via mediators that couple both to dark matter particles and to standard model quarks. The dark matter particles would escape detection, thereby creating a transverse momentum imbalance ($\vec{p}_T^{\text{miss}}$) in the event. Searches at collider experiments can offer insights on the nature of the mediator and provide constraints on dark matter masses of $O(10 \text{ GeV})$ and below, a region that is difficult to explore in direct and indirect searches for dark matter. A favored class of models proposes a spin-0 mediator with standard model Higgs-like Yukawa coupling to quarks, which therefore couples preferentially to the top quark [5–9]. Consequently, in this class of models dark matter production in association with a top quark pair ($tt$) can offer better search sensitivity compared to other modes such as production in association with a jet [10–14]. At the LHC, the $tt+\chi\chi$ process is probed through the signature of $tt$ accompanied by $\vec{p}_T^{\text{miss}}$ [15, 16].

The top quark almost always decays to a W boson and a b quark. The W boson can decay leptonically (to a charged lepton and a neutrino) or hadronically (to a quark pair). The signal regions (SRs) of the search cover three $tt$ decay modes: the all-hadronic, lepton+jets ($\ell+\text{jets}$ where $\ell = e, \mu$), and dileptonic (ee, $e\mu$, $\mu\mu$) final states where neither, either, or both of the W bosons decay to leptons, respectively. This Letter presents a search for $tt+\chi\chi$ in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ with data recorded by the CMS experiment in 2016, corresponding to an integrated luminosity of 35.9 fb$^{-1}$. The analysis strategy is similar to Ref. [17], but includes additional SRs for the dileptonic mode.

The central feature of the CMS detector is a superconducting solenoid providing a magnetic field of 3.8 T. Within the solenoid volume are the silicon pixel and strip trackers, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. A steel and quartz-fiber Cherenkov forward hadron calorimeter extends the pseudorapidity ($\eta$) coverage. The muon system consists of gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A two-tiered trigger system [18] selects events at a rate of about 1 kHz for storage. A detailed description of the CMS detector is provided in Ref. [19].

The event reconstruction is based on the CMS particle-flow algorithm [20], which reconstructs and identifies individual particles using an optimized combination of the detector information. The $\vec{p}_T^{\text{miss}}$ vector is computed as the negative vector sum of the transverse momenta ($\vec{p}_T$) of all the particles in an event. Jets are formed from particles using the anti-$k_T$ algorithm [21, 22] with a distance parameter of 0.4. Corrections are applied to calibrate the jet momentum [23] and to remove energy from additional collisions in the same or adjacent bunch crossings (pileup) [24]. Jets in the analysis are required to have $p_T > 30 \text{ GeV}$ and $|\eta| < 2.4$, and to satisfy identification criteria [25] that minimize spurious detector effects. A combined secondary vertex b tagging algorithm [26] is used to identify jets originating from b quarks (b-tagged jets). A multivariate discriminant, the “resolved top tagger” (RTT) [17], based on jet properties and kinematic information, is used to identify top quarks that decay into three jets. Electrons and muons are selected using “tight” and “loose” requirements where the former applies more stringent identification criteria than the latter [27]. The tight leptons are used in the selection of specific final states, while loose leptons are used to veto events with extra leptons. The primary pp interaction vertex is taken to be the reconstructed vertex with the highest summed $p_T$ of its associated physics objects. Here, the physics objects are the jets, clustered with the tracks assigned to the vertex as inputs, plus the associated $\vec{p}_T^{\text{miss}}$.

The $tt+\chi\chi$ signal results in high-$p_T$ jets including b-tagged jets, leptons, and significant $\vec{p}_T^{\text{miss}}$. 
The background is dominated by $t\bar{t}$ and $V+$jets ($V=W, Z, \gamma^*$) production. The $t\bar{t}$ and single top quark backgrounds are simulated at next-to-leading order (NLO) accuracy in quantum chromodynamics (QCD) using POWHEG v2 and POWHEG v1 [28,31], respectively. Samples of $V+$jets and QCD multijet events are simulated at leading order (LO) in QCD using MADGRAPH5_aMC@NLO v2.2.2 [32] (MADGRAPH), with up to four additional partons in the matrix element (ME) calculations. The $V+$jets samples are corrected with boson $p_T$-dependent electroweak corrections [33–35] and QCD NLO/LO $K$ factors computed using MadGraph. Samples of $t\bar{t}+V$ and diboson processes (WW, WZ, and ZZ) are generated at NLO using either MADGRAPH or POWHEG v2. The initial-state partons are modeled with the NNPDF 3.0 [39] parton distribution function (PDF) sets at LO or NLO in QCD to match the ME calculation. Generated events are interfaced with PYTHIA 8.205 [40] for parton showering using the CUETP8M1 tune [41], except for the $t\bar{t}$ simulation which uses the CUETP8M2 tune customized by CMS with an updated strong coupling $\alpha_s$ for initial-state radiation. The simulation of the CMS detector is performed with GEANT4 [42]. Corrections derived from data are applied to account for any mismodeling of selection efficiencies in simulation.

The signal is simulated using simplified models of dark matter production [43]. The dominant mechanism is $s$-channel production of the mediator via gluon fusion, with the mediator then decaying to a pair of dark matter particles. The dark matter particles are assumed to be Dirac fermions, and the mediators are spin-0 particles with scalar ($\phi$) or pseudoscalar ($a$) interactions. The couplings between the mediator and standard model quarks are $g_{q\chi} = g_{q\chi} v_q$, where $y_q = \sqrt{2} m_q / v$ are the standard model Yukawa couplings, $m_q$ is the quark mass, and $v = 246$ GeV is the Higgs boson field vacuum expectation value. The $g_\chi$ parameter is assumed to be unity for all quarks. The direct coupling strength of the mediators to dark matter is denoted by $g_{\chi\chi}$. The model does not take into account possible mixing between $\phi$ and the standard model Higgs boson [44]. The $t\bar{t}+\chi\chi$ signal is generated at LO using MADGRAPH with up to one additional parton, and the mediator is forced to decay to a pair of dark matter fermions. The mediator width is computed according to partial-width formulas in Ref. [45] and assuming no additional interactions beyond those described here. The relative width of the scalar (pseudoscalar) mediator varies between 4% and 6% (4% and 8%) for masses in the range of $10$–$500$ GeV. The signal is normalized to the cross section computed at NLO in QCD.

Data are collected by triggering on events containing large $p_T^{\text{miss}}$ (the magnitude of $\vec{p}_T^{\text{miss}}$) or high-$p_T$ leptons. The triggers for the all-hadronic final state are based on the amount of $p_T^{\text{miss}}$ and $H_T^{\text{miss}}$ measured with the trigger-level reconstruction. The $H_T^{\text{miss}}$ variable is defined as the magnitude of the vector sum of $p_T$ over trigger-level jets with $p_T > 20$ GeV and $|\eta| < 5.0$ that pass identification requirements. During the period of data collection, the $p_T^{\text{miss}}$ and $H_T^{\text{miss}}$ trigger thresholds were increased as the instantaneous luminosity increased, in steps from 90 to 120 GeV. Events in the $\ell+$jets final state are obtained using single-lepton triggers that require an electron (muon) with $p_T > 27$ (24) GeV. Events in the dilepton final state are obtained using single-lepton and dilepton (ee, $e\mu$, $\mu\mu$) triggers. The trigger thresholds on the higher- and lower-$p_T$ electrons (muons) are 23 (17) GeV and 12 (8) GeV, respectively, and apply to all pairings of lepton object flavors.

Using additional selection requirements, two all-hadronic, one $\ell+$jets, and four dilepton SRs are defined. Several control regions (CRs) enriched in standard model processes are used to improve the simulation-based background estimates for the all-hadronic and $\ell+$jets SRs. There are no event overlaps among the regions. Together, the SRs and CRs associated with the individual $t\bar{t}+\chi\chi$ final states are referred to as “channels”. All three $t\bar{t}+\chi\chi$ channels are used in a simultaneous maximum-likelihood fit of $p_T^{\text{miss}}$ distributions to extract a potential dark matter signal. In the fit, the CRs constrain the contributions of $t\bar{t}$, $W+$jets, and $Z+$jets processes within
each channel via freely floating normalization parameters for each $p_T^{\text{miss}}$ bin.

The all-hadronic SRs require $p_T^{\text{miss}} > 200$ GeV, and four or more jets, of which at least one must be b tagged. Any event with a loose lepton of $p_T > 10$ GeV is vetoed. The dominant background consists of $t\bar{t}$ decays to $\ell+jets$, referred to as $t\bar{t}(1\ell)$, where the lepton is not identified as loose and therefore not vetoed, and the neutrino is the source of $p_T^{\text{miss}}$. The RTT is employed to define a category of events with two tagged hadronic top quark decays (2RTT), which suppresses the $t\bar{t}(1\ell)$ background, and a category with less than two top quark tags (0,1RTT) and at least two b-tagged jets. The RTT variable is essentially independent of $p_T^{\text{miss}}$; therefore, any bias on the $p_T^{\text{miss}}$ shape from requiring top tags is negligible. Spurious $p_T^{\text{miss}}$ can arise in multijet events as a result of jet energy mismeasurement. In such cases, the reconstructed $p_T^{\text{miss}}$ tends to align with a jet. The multijet background is suppressed by requiring the smallest azimuthal angle between the $p_T^{\text{miss}}$ and each jet in the event, $\Delta \phi \equiv \min \Delta \phi(p_T^{\ell}, p_T^{\text{miss}})$, to be greater than 0.4 (1.0) radians in the 2RTT (0,1RTT) category. The $\Delta \phi$ requirement also reduces the $t\bar{t}(1\ell)$ background, for which $p_T^{\text{miss}}$ can align with a bottom jet.

The CRs targeting the $t\bar{t}(1\ell)$ background, one for each category, are defined by selecting events with exactly one tight lepton with $p_T > 30$ GeV, and by requiring the transverse mass, $m_T$, given in terms of $p_T^{\text{miss}}$ and the lepton momentum ($p_T^{\ell}$) by the following expression:

$$m_T = \sqrt{2p_T^{\ell}p_T^{\text{miss}}[1 - \cos \Delta \phi(p_T^{\ell}, p_T^{\text{miss}})]},$$

(1)

to be less than 160 GeV, in order to avoid overlaps with the SR of the $\ell+jets$ channel. For ideal measurements, the $m_T$ quantity is bounded above by the W boson mass for $t\bar{t}(1\ell)$ and for $W(\ell\nu)+jets$ where the W boson is produced on shell.

There are also significant background contributions from $Z(v\bar{v})+jets$, and from $W(\ell\nu)+jets$ where the lepton is not identified. The CRs enriched in both W+jets and Z+jets are formed by modifying the SR selections to require no b-tagged jets. Additionally, dedicated W+jets CRs are defined by requiring a tight lepton with $p_T > 30$ GeV and $m_T < 160$ GeV. A CR enriched in Z+jets is defined by selecting two tight, oppositely charged, and same-flavor leptons, with the dilepton invariant mass between 60 and 120 GeV. This CR is not subdivided into categories based on the number of top quark tags because the event yield with two tags is negligible. The $p_T^{\text{miss}}$ calculation does not consider the two leptons in order to emulate the $Z(v\bar{v})+jets$ process.

Events in the $\ell+jets$ SR are selected by requiring $p_T^{\text{miss}} > 160$ GeV, exactly one tight lepton with $p_T > 30$ GeV, and three or more jets, of which at least one is b tagged. Events must not contain additional loose leptons with $p_T > 10$ GeV. A selection of $m_T > 160$ GeV is imposed to reduce the $t\bar{t}(1\ell)$ and W+jets backgrounds. Following these selections, the remaining background events primarily consist of dileptonic $t\bar{t}$ decays, referred to as $t\bar{t}(2\ell)$ events, where one of the leptons is not identified. This background is suppressed by requiring that the $m_W^{\ell\ell}$ variable [46] be larger than 200 GeV, and for the two highest $p_T$ jets in the event that $\Delta_{h,2} \equiv \min \Delta \phi(p_T^{h,2}, p_T^{\text{miss}}) > 1.2$. The $m_W^{\ell\ell}$ variable corresponds to the minimum mass of a particle consistent with being pair-produced and decaying to a bottom quark and a W boson, where both W bosons decay leptonically but one of the two leptons is not detected. The key characteristic of $m_W^{\ell\ell}$ is that for ideal measurements the distribution for $t\bar{t}(2\ell)$ events is bounded above by the top quark mass.

The CR targeting the $t\bar{t}(2\ell)$ background is defined by requiring an additional tight lepton of $p_T > 30$ GeV with respect to the SR selection and removing the selections on $m_T$, $m_W^{\ell\ell}$, and $\Delta_{h,2}$. To reduce the signal contamination and avoid overlap with the dileptonic SRs, the $m_{T2}^{\ell\ell}$ variable [47-49] is required to be less than 110 GeV. The $m_{T2}^{\ell\ell}$ variable is essentially the minimum
$m_T$ of a pair-produced particle that decays to a lepton and a neutrino. The $m_{T2}^\ell\ell$ distribution for $t\bar{t}(2\ell)$ events is bounded above by the W boson mass for ideal measurements. A W + jets CR for the $\ell+\text{jets}$ channel is defined by requiring no b-tagged jets and removing the selections on $m_W^T$ and $\Delta_{j}$. Events in the dilepton SRs are selected by requiring exactly two oppositely charged tight leptons with higher (lower) $p_T > 25 (15)$ GeV, two or more jets with at least one b-tagged jet, and $p_T^{\text{miss}} > 50$ GeV. The dilepton mass is required to be greater than 20 GeV, and for the dielectron and dimuon events, to be at least 15 GeV away from the Z boson pole mass ($m_Z$) [50]. Separate categories are considered for events with same- and different-flavor lepton pairs, and for events with $m_{T2}^\ell\ell$ greater or less than 110 GeV. Additionally, events with $m_{T2}^\ell\ell < 110$ GeV must not pass the selection for the $t\bar{t}(2\ell)$ CR of the $\ell+\text{jets}$ search channel. The SRs with large $m_{T2}^\ell\ell$ have significantly higher signal purity.

The estimates for the backgrounds from Drell–Yan production and from jets misidentified as leptons are performed using dedicated sideband regions not included in the fit. A $p_T^{\text{miss}}$ dependent correction to the Drell–Yan simulation in the same-flavor SRs is obtained by comparing data and simulation yields within 15 GeV of $m_Z$. The misidentified leptons background is estimated using data events with pairs consisting of one tight lepton plus a “nontight” lepton-like object passing a less stringent selection. The number of such combinations is scaled by misidentification rates, which are measured in a jet-enriched sample.

The dark matter signal, which would be observed as an excess of events compared to the predicted background at high $p_T^{\text{miss}}$, is extracted via a simultaneous maximum-likelihood fit to the binned $p_T^{\text{miss}}$ distributions of the signal and backgrounds, based on simulation with the exception of the misidentified leptons background, in the SRs and associated CRs. The fit is performed using the RooStats statistical package [51]. The template shapes and normalization are allowed to vary in the fit, constrained by the priors of the systematic uncertainties, parametrized as nuisance parameters.

The common sources of uncertainty are correlated across SRs and CRs and across channels. The sources of normalization uncertainty include the integrated luminosity (2.5%) [52], b tagging efficiency (1%–5%) [26], lepton efficiency (1.5%–2.2%) [27], and pileup simulation (0.8%–1.9%), where the range of values indicates variations across different physics processes. The common sources of shape uncertainty include $p_T^{\text{miss}}$ trigger efficiency, jet energy scale and resolution [25], PDF [39], uncertainty on the $K$ factors for $V+$jets, uncertainty from missing higher order QCD corrections for each simulated physics process, and the uncertainty in the modeling of top quark $p_T$ in $t\bar{t}$ simulation [53]. The jet energy scale uncertainties have the largest impact on the $\ell+\text{jets}$ and dilepton channels, while in the all-hadronic channel the top quark $p_T$ modeling and $p_T^{\text{miss}}$ trigger uncertainties are more important.

Within the all-hadronic and $\ell+\text{jets}$ search channels, additional nuisance parameters scale the yields of the $t\bar{t}$, W + jets, and Z + jets backgrounds independently in each $p_T^{\text{miss}}$ bin across the SRs and CRs of a given channel. For example, in each bin of $p_T^{\text{miss}}$ a single parameter is associated with the contribution of the W + jets process in the all-hadronic SRs and CRs, while another set of parameters distinct from those of the all-hadronic channel, is associated with the W + jets background in the $\ell+\text{jets}$ SRs and CRs. These nuisance parameters allow the data in the CRs to constrain the estimates of the dominant background processes in the corresponding SRs. Signal yields in all the SRs and CRs are scaled simultaneously by the signal strength parameter ($\mu$), defined as the ratio of the measured signal cross section to the theoretical cross section, $\mu = \sigma / \sigma_{\text{th}}$.
The fit is performed across all search channels and no significant excess is observed. Figure 1 shows the $p_T^{\text{miss}}$ distributions for three of the seven SRs, obtained after the background-only fit assuming the absence of any signal. Upper limits are set on the $t\bar{t} + \chi \chi$ production cross section using a modified frequentist approach (CL$_s$) with a test statistic based on the profile likelihood in the asymptotic approximation [54–56]. For each signal hypothesis, 95% confidence level (CL) upper limits on $\mu$ are determined. The all-hadronic channel provides the best sensitivity. The dileptonic channel is competitive with the all-hadronic channel for scalar mediator masses less than about 50 GeV, where the signal has a soft $p_T^{\text{miss}}$ spectrum, but is typically the least sensitive channel in other regions of the parameter space.

![Figure 1: Selected $p_T^{\text{miss}}$ distributions in SRs: 2RTT SR for the all-hadronic (upper left), the $\ell+\text{jets}$ (upper right), and the different-flavor, $M_{T2} > 110$ GeV SR in the dileptonic channel (lower). The solid red line shows the expectation for a signal with $m_\chi = 100$ GeV and $m_\phi = 1$ GeV. The last bin contains the overflow events. The lower panel shows the ratio of the observed to the fitted distribution (points), and the ratio of the background expectation before the fit to the fitted distribution (dashed magenta line). The vertical bars indicate the statistical uncertainty on the data. The horizontal bars on the rightmost plot indicate the bin width. The uncertainty bands in both panels include the statistical and systematic uncertainties on the total background.](image-url)

The limits are shown as a function of $m_\phi/\phi$ and $m_\chi$ in Fig. 2. The contours enclose the region where the upper limit on $\mu$ is less than 1. Because of the narrow width of the mediator, the
signal cross section drops rapidly across the \( m_{a/\phi} = 2m_\chi \) line, marking the boundary between the on-shell to the off-shell region. Therefore, the exclusion contour runs close to the \( m_{a/\phi} = 2m_\chi \) line but does not cross it. The observed (expected) upper limits on \( \mu \) exclude scalar and pseudoscalar masses of 160 (240) and 220 (320) GeV, respectively, at 95% CL. The observed exclusion is weaker than the expected because of tension in the fit between CRs and SRs of the all-hadronic channel, although the difference is not significant as the observed result lies only just outside the 68% probability interval. This arises because the a priori estimation of the background exceeds the number of events observed in the CRs, while the estimate is in better agreement with data in the SRs. Consequently, the signal-background fit, in contrast to the background-only fit, reduces this tension between CRs and SRs by accommodating for some signal, which contributes primarily to the SRs.

![Figure 2](image-url): The exclusion limits at 95% CL on the signal strength \( \mu = \sigma/\sigma_{th} \) computed as a function of the mediator and dark matter mass, assuming a scalar (left) and pseudoscalar (right) mediator. The mediator couplings are assumed to be \( g_q = g_\chi = 1 \). The dashed magenta lines represent the 68% probability interval around the expected limit. The observed limit contour is almost coincident with the boundary of the 68% probability interval.

The limits on \( \mu \) are also expressed in terms of the mediator coupling strength to quarks in Fig. 3. These results are obtained by fixing \( m_\chi = 1 \) GeV and \( g_\chi = 1 \), and then finding the value of \( g_q \) that corresponds to the upper limit on the cross section. This procedure is valid because the kinematic properties of the signal do not vary appreciably with \( g_q \). The width-to-mass ratio is around 4% for the \( g_q \) and \( m_{a/\phi} \) values considered.

In summary, a comprehensive search for dark matter particles produced in association with a top quark pair yields no significant excess over the predicted background. The results presented in this Letter provide 30%–60% better cross section limits compared to earlier searches targeting the same signature [57][59]. The analysis offers stronger constraints than direct and indirect experiments for dark matter masses of \( O(10 \) GeV\) and below. Over much of the parameter space, the \( t\bar{t} + \chi \chi \) signature has better sensitivity to spin-0 mediators than dark matter production in association with a jet [14] – previously considered to be the most sensitive signature. For the pseudoscalar model, the \( t\bar{t} + \chi \chi \) signature provides the most stringent cross section constraints for mediator masses of around 200 GeV and below. The observed (expected) limits exclude a pseudoscalar mediator with mass below 220 (320) GeV under the \( g_q = g_\chi = 1 \) benchmark scenario. The \( t\bar{t} + \chi \chi \) signature provides the best sensitivity for the scalar mediator model and is currently the only collider signature that is sufficiently sensitive to exclude regions of
Figure 3: The 95% observed and median expected CL upper limits on the coupling strength of the mediator to the standard model quarks under the assumption that $g_\chi = 1$. A dark matter particle with a mass of 1 GeV is assumed. The green and yellow bands indicate respectively the 68% and 95% probability intervals around the expected limit. The interpretations for a scalar (left) and a pseudoscalar (right) mediator are shown.

parameter space with these values of the couplings. The observed exclusion of a mediator with mass below 160 GeV (240 GeV expected) provides the most stringent constraint to date on this model.

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 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 and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).
References

[1] G. Bertone, D. Hooper, and J. Silk, “Particle dark matter: evidence, candidates and constraints”, Phys. Rept. 405 (2005) 279, doi:10.1016/j.physrep.2004.08.031, arXiv:hep-ph/0404175.

[2] J. L. Feng, “Dark matter candidates from particle physics and methods of detection”, Ann. Rev. Astron. Astrophys. 48 (2010) 495, doi:10.1146/annurev-astro-082708-101659, arXiv:1003.0904.

[3] T. A. Porter, R. P. Johnson, and P. W. Graham, “Dark matter searches with astroparticle data”, Ann. Rev. Astron. Astrophys. 49 (2011) 155, doi:10.1146/annurev-astro-081710-102528, arXiv:1104.2836.

[4] G. Bertone et al., “Identifying WIMP dark matter from particle and astroparticle data”, JCAP 03 (2018) 026, doi:10.1088/1475-7516/2018/03/026, arXiv:1712.04793.

[5] U. Haisch, F. Kahlhoefer, and J. Unwin, “The impact of heavy-quark loops on LHC dark matter searches”, JHEP 07 (2013) 125, doi:10.1007/JHEP07(2013)125, arXiv:1208.4605.

[6] T. Lin, E. W. Kolb, and L.-T. Wang, “Probing dark matter couplings to top and bottom quarks at the LHC”, Phys. Rev. D 88 (2013) 063510, doi:10.1103/PhysRevD.88.063510, arXiv:1303.6638.

[7] M. R. Buckley, D. Feld, and D. Gonçalves, “Scalar simplified models for dark matter”, Phys. Rev. D 91 (2015) 015017, doi:10.1103/PhysRevD.91.015017, arXiv:1410.6497.

[8] U. Haisch and E. Re, “Simplified dark matter top-quark interactions at the LHC”, JHEP 06 (2015) 078, doi:10.1007/JHEP06(2015)078, arXiv:1503.00691.

[9] C. Arina et al., “A comprehensive approach to dark matter studies: exploration of simplified top-philic models”, JHEP 11 (2016) 111, doi:10.1007/JHEP11(2016)111, arXiv:1605.09242.

[10] ATLAS Collaboration, “Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at √s = 8 TeV with the ATLAS detector”, Eur. Phys. J. C 75 (2015) 299, doi:10.1140/epjc/s10052-015-3517-3, arXiv:1502.01518 [Erratum: Eur. Phys. J. C 75 (2015) 408].

[11] CMS Collaboration, “Search for dark matter in proton-proton collisions at 8 TeV with missing transverse momentum and vector boson tagged jets”, JHEP 12 (2016) 083, doi:10.1007/JHEP12(2016)083, arXiv:1607.05764.

[12] ATLAS Collaboration, “Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at √s = 13 TeV using the ATLAS detector”, Phys. Rev. D 94 (2016) 032005, doi:10.1103/PhysRevD.94.032005, arXiv:1604.07773.

[13] CMS Collaboration, “Search for dark matter produced with an energetic jet or a hadronically decaying W or Z boson at √s = 13 TeV”, JHEP 07 (2017) 14, doi:10.1007/JHEP07(2017)014, arXiv:1703.01651.
[14] CMS Collaboration, “Search for new physics in final states with an energetic jet or a hadronically decaying W or Z boson and transverse momentum imbalance at $\sqrt{s} = 13$ TeV”, Phys. Rev. D 97 (2018) 092005, doi:10.1103/PhysRevD.97.092005, arXiv:1712.02345

[15] CMS Collaboration, “Search for the production of dark matter in association with top-quark pairs in the single-lepton final state in proton-proton collisions at $\sqrt{s} = 8$ TeV”, JHEP 06 (2015) 121, doi:10.1007/JHEP06(2015)121, arXiv:1504.03198

[16] ATLAS Collaboration, “Search for dark matter in events with heavy quarks and missing transverse momentum in pp collisions with the ATLAS detector”, Eur. Phys. J. C 75 (2015) 92, doi:10.1140/epjc/s10052-015-3306-z, arXiv:1410.4031

[17] CMS Collaboration, “Search for dark matter produced in association with heavy-flavor quark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV”, Eur. Phys. J. C 77 (2017) 845, doi:10.1140/epjc/s10052-017-5317-4, arXiv:1706.02581

[18] CMS Collaboration, “The CMS trigger system”, JINST 12 (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366

[19] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004

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

[21] M. Cacciari, G. P. Salam, and G. Soyez, “The anti-$k_T$ jet clustering algorithm”, JHEP 04 (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189

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

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

[24] M. Cacciari, G. P. Salam, and G. Soyez, “The catchment area of jets”, JHEP 04 (2008) 005, doi:10.1088/1126-6708/2008/04/005, arXiv:0802.1188

[25] CMS Collaboration, “Jet algorithms performance in 13 TeV data”, CMS Physics Analysis Summary CMS-PAS-JME-16-003, 2017.

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

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

[28] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms”, JHEP 11 (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146
[29] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, JHEP 11 (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092

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

[31] C. Oleari, “The POWHEG-BOX”, Nucl. Phys. Proc. Suppl. 205-206 (2010) 36, doi:10.1016/j.nuclphysbps.2010.08.016, arXiv:1007.3893

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

[33] A. Denner, S. Dittmaier, T. Kasprzik, and A. Muck, “Electroweak corrections to W+jet hadroproduction including leptonic W-boson decays”, JHEP 08 (2009) 075, doi:10.1088/1126-6708/2009/08/075, arXiv:0906.1656

[34] A. Denner, S. Dittmaier, T. Kasprzik, and A. Muck, “Electroweak corrections to dilepton+jet production at hadron colliders”, JHEP 06 (2011) 069, doi:10.1007/JHEP06(2011)069, arXiv:1103.0914

[35] A. Denner, S. Dittmaier, T. Kasprzik, and A. Maeck, “Electroweak corrections to monojet production at the LHC”, Eur. Phys. J. C 73 (2013) 2297, doi:10.1140/epjc/s10052-013-2297-x, arXiv:1211.5078

[36] J. H. Kuhn, A. Kulesza, S. Pozzorini, and M. Schulze, “Electroweak corrections to hadronic photon production at large transverse momenta”, JHEP 03 (2006) 059, doi:10.1088/1126-6708/2006/03/059, arXiv:hep-ph/0508253

[37] S. Kallweit et al., “NLO electroweak automation and precise predictions for W+multijet production at the LHC”, JHEP 04 (2015) 012, doi:10.1007/JHEP04(2015)012, arXiv:1412.5157

[38] S. Kallweit et al., “NLO QCD+EW predictions for V+jets including off-shell vector-boson decays and multijet merging”, JHEP 04 (2016) 021, doi:10.1007/JHEP04(2016)021, arXiv:1511.08692

[39] NNPDF Collaboration, “Parton distributions for the LHC Run II”, JHEP 04 (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849

[40] T. Sjöstrand, S. Mrenna, and P. Z. Skands, “A brief introduction to PYTHIA 8.1”, Comput. Phys. Commun. 178 (2008) 852, doi:10.1016/j.cpc.2008.01.036, arXiv:0710.3820

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

[42] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, Nucl. Instrum. Meth. A 506 (2003) 250, doi:10.1016/S0168-9002(03)01368-8

[43] D. Abercrombie et al., “Dark matter benchmark models for early LHC Run-2 searches: report of the ATLAS/CMS Dark Matter Forum”, (2015), arXiv:1507.00966
[44] A. Albert et al., “Towards the next generation of simplified dark matter models”, Phys. Dark Univ. 16 (2017) 49, doi:10.1016/j.dark.2017.02.002, arXiv:1607.06680

[45] P. Harris, V. V. Khoze, M. Spannowsky, and C. Williams, “Constraining dark sectors at colliders: Beyond the effective theory approach”, Phys. Rev. D 91 (2015) 055009, doi:10.1103/PhysRevD.91.055009, arXiv:1411.0535

[46] Y. Bai, H.-C. Cheng, J. Gallicchio, and J. Gu, “Stop the top background of the stop search”, JHEP 07 (2012) 110, doi:10.1007/JHEP07(2012)110, arXiv:1203.4813

[47] C. G. Lester and D. J. Summers, “Measuring masses of semi-invisibly decaying particles pair produced at hadron colliders”, Phys. Lett. B 463 (1999) 99, doi:10.1016/S0370-2693(99)00945-4, arXiv:hep-ph/9906349

[48] M. Burns, K. Kong, K. T. Matchev, and M. Park, “Using subsystem $M_{T2}$ for complete mass determinations in decay chains with missing energy at hadron colliders”, JHEP 03 (2009) 143, doi:10.1088/1126-6708/2009/03/143, arXiv:0810.5576

[49] H.-C. Cheng and Z. Han, “Minimal kinematic constraints and $m_{T2}$”, JHEP 12 (2008) 063, doi:10.1088/1126-6708/2008/12/063, arXiv:0810.5178

[50] Particle Data Group, “Review of particle physics”, Chin. Phys. C 40 (2016) 100001 and 2017 update, doi:10.1088/1674-1137/40/10/100001.

[51] L. Moneta et al., “The RooStats Project”, in Proceedings, 13th International Workshop on Advanced computing and analysis techniques in physics research (ACAT2010), p. 057. Jaipur, India, February, 2010. arXiv:1009.1003 [PoS(ACAT2010)057]. doi:10.22323/1.093.0057

[52] CMS Collaboration, “CMS luminosity measurements for the 2016 data taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017.

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

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

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

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

[57] CMS Collaboration, “Search for top squarks and dark matter particles in opposite-charge dilepton final states at $\sqrt{s} = 13$ TeV”, Phys. Rev. D 97 (2018) 032009, doi:10.1103/PhysRevD.97.032009, arXiv:1711.00752

[58] ATLAS Collaboration, “Search for top-squark pair production in final states with one lepton, jets, and missing transverse momentum using 36.1 fb$^{-1}$ of $\sqrt{s} = 13$ TeV pp collision data with the ATLAS detector”, (2017). arXiv:1711.11520 Submitted to JHEP.
[59] ATLAS Collaboration, “Search for dark matter produced in association with bottom or top quarks in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”, Eur. Phys. J. C 78 (2018) 18, doi:10.1140/epjc/s10052-017-5486-1, arXiv:1710.11412
A  The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, P. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth, V.M. Ghete, J. Hrubec, M. Jeitler, N. Krammer, I. Kräschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck, R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D’Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lovette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Varesio

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaître, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F.L. Alves, G.A. Alves, M. Correa Martins Junior, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato, E. Coelho, E.M. Da Costa, G.G. Da Silveira, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

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

Beihang University, Beijing, China
W. Fang, X. Gao, L. Yuan

Institute of High Energy Physics, Beijing, China
M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China
Y. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

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

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, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran, S. Elgamma, Y. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken
Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besançon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam, C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte, J.-C. Fontaine, D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Govzievitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov, V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, D. Duchardt, M. Endres, M. Erdmann, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, S. Knutzen, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, A. Schmidt, D. Teysseir
G. Bencze, C. Hajdu, D. Horvath, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Karancsi, A. Makovec, J. Molnar, Z. Szillasi

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

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati, C. Kar, P. Mal, K. Mandal, A. Nayak, D.K. Sahoo, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, B.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, G. Walia

University of Delhi, Delhi, India
A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
R. Bhardwaj, M. Bhattacharya, S. Bhattacharya, U. Bhawandeep, D. Bhowmik, S. Dey, S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, G. Saha, S. Sarkar, M. Sharan, B. Singh, S. Thakur

Indian Institute of Technology Madras, Madras, India
P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guhait, S. Jain, S. Karmakar, S. Kumar, M. Maity, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani, E. Eskandari Tadavani, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh, M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
M. Abbrescia, C. Calabria, A. Colaleo, D. Creanza, L. Cristella, N. De Filippis, M. De Palma, A. Di Florio, F. Errico, L. Fiore, A. Gelmí, G. Iselli, M. Ince, S. Lezki, G. Maggì, M. Maggi, G. Miniello, S. My, S. Nuzzo, A. Pompili.
G. Pugliese\textsuperscript{a,c}, R. Radogna\textsuperscript{a}, A. Ranieri\textsuperscript{a}, G. Selvaggi\textsuperscript{a,b}, A. Sharma\textsuperscript{a}, L. Silvestris\textsuperscript{a}, R. Venditti\textsuperscript{a}, P. Verwilligen\textsuperscript{a}, G. Zito\textsuperscript{d}

\textbf{INFN Sezione di Bologna \textsuperscript{a}, Università di Bologna \textsuperscript{b}, Bologna, Italy}

G. Abbiendi\textsuperscript{a}, C. Battilana\textsuperscript{a,b}, D. Bonacorsi\textsuperscript{a,b}, L. Borgonovi\textsuperscript{a,b}, S. Braibant-Giacomelli\textsuperscript{a,b}, R. Campanini\textsuperscript{a,b}, P. Capiluppi\textsuperscript{a,b}, A. Castro\textsuperscript{a,b}, F.R. Cavallo\textsuperscript{a}, S.S. Chhibra\textsuperscript{a,b}, C. Ciocca\textsuperscript{a}, G. Codispoti\textsuperscript{a,b}, M. Cuffiani\textsuperscript{a,b}, G.M. Dallavalle\textsuperscript{a}, F. Fabbri\textsuperscript{a}, A. Fanfani\textsuperscript{a,b}, P. Giacomelli\textsuperscript{a}, C. Grandi\textsuperscript{a}, L. Guiducci\textsuperscript{a,b}, F. Iemmi\textsuperscript{a,b}, S. Marcellini\textsuperscript{a}, G. Masetti\textsuperscript{a}, A. Montanari\textsuperscript{a}, F.L. Navarria\textsuperscript{a,b}, A. Perrottet\textsuperscript{a}, F. Primavera\textsuperscript{a,b,15}, A.M. Rossi\textsuperscript{a,b}, T. Rovelli\textsuperscript{a,b}, G.P. Siroli\textsuperscript{a,b}, N. Tosi\textsuperscript{a}

\textbf{INFN Sezione di Catania \textsuperscript{a}, Università di Catania \textsuperscript{b}, Catania, Italy}

S. Albergo\textsuperscript{a,b}, A. Di Mattia\textsuperscript{a}, R. Potenza\textsuperscript{a,b}, A. Tricomi\textsuperscript{a,b}, C. Tuve\textsuperscript{a,b}

\textbf{INFN Sezione di Firenze \textsuperscript{a}, Università di Firenze \textsuperscript{b}, Firenze, Italy}

G. Barbaglio\textsuperscript{a}, K. Chatterjee\textsuperscript{a,b}, V. Ciulli\textsuperscript{a,b}, C. Cividini\textsuperscript{a}, R. D'Alessandro\textsuperscript{a,b}, E. Focardi\textsuperscript{a,b}, G. Latino, P. Lenzi\textsuperscript{a,b}, M. Meschini\textsuperscript{a}, S. Paoletti\textsuperscript{a}, L. Russo\textsuperscript{a,28}, G. Sguazzoni\textsuperscript{a}, D. Strom\textsuperscript{a}, L. Viliani\textsuperscript{a}

\textbf{INFN Laboratori Nazionali di Frascati, Frascati, Italy}

L. Benucci, S. Bianco, F. Fabbrì, D. Piccolo

\textbf{INFN Sezione di Genova \textsuperscript{a}, Università di Genova \textsuperscript{b}, Genova, Italy}

F. Ferro\textsuperscript{a}, F. Ravera\textsuperscript{a,b}, E. Robutti\textsuperscript{a}, S. Tosi\textsuperscript{a,b}

\textbf{INFN Sezione di Milano-Bicocca \textsuperscript{a}, Università di Milano-Bicocca \textsuperscript{b}, Milano, Italy}

A. Benaglia\textsuperscript{a}, A. Beschi\textsuperscript{a}, L. Brianza\textsuperscript{a,b}, F. Brivio\textsuperscript{a,b}, V. Ciriolo\textsuperscript{a,b,15}, S. Di Guida\textsuperscript{a,d,15}, M.E. Dinardo\textsuperscript{a,b}, S. Fiorendi\textsuperscript{a,b}, S. Gennai\textsuperscript{a}, A. Ghezzi\textsuperscript{a,b}, P. Govoni\textsuperscript{a,b}, M. Malberti\textsuperscript{a,b}, S. Malvezzi\textsuperscript{a}, A. Massironi\textsuperscript{a,b}, D. Menasce\textsuperscript{a}, L. Moroni\textsuperscript{a}, M. Paganoni\textsuperscript{a,b}, D. Pedrini\textsuperscript{a}, S. Ragazzi\textsuperscript{a,b}, T. Tabarelli de Fatis\textsuperscript{a,b}, D. Zuolo

\textbf{INFN Sezione di Napoli \textsuperscript{a}, Università di Napoli 'Federico II' \textsuperscript{b}, Napoli, Italy, Università della Basilicata \textsuperscript{c}, Potenza, Italy, Università G. Marconi \textsuperscript{d}, Roma, Italy}

S. Buontempo\textsuperscript{a}, N. Cavallo\textsuperscript{a,c}, A. Di Crescenzo\textsuperscript{a,b}, F. Fabozzi\textsuperscript{a,c}, F. Fienga\textsuperscript{a}, G. Galati\textsuperscript{a}, A.O.M. Iorio\textsuperscript{a,b}, W.A. Khan\textsuperscript{a}, L. Lista\textsuperscript{a}, S. Meola\textsuperscript{a,d,15}, P. Paolucci\textsuperscript{a,15}, C. Sciacca\textsuperscript{a,b}, E. Voevodina\textsuperscript{a,b}

\textbf{INFN Sezione di Padova \textsuperscript{a}, Università di Padova \textsuperscript{b}, Padova, Italy, Università di Trento \textsuperscript{c}, Trento, Italy}

P. Azzi\textsuperscript{a}, N. Bacchetta\textsuperscript{a}, A. Boletti\textsuperscript{a,b}, A. Bragagnolo, R. Carlin\textsuperscript{a,b}, P. Checchia\textsuperscript{a}, P. De Castro Manzano\textsuperscript{a}, T. Dorigo\textsuperscript{a}, U. Dosselli\textsuperscript{a}, F. Gasparini\textsuperscript{a,b}, U. Gasparini\textsuperscript{a,b}, A. Gozzelino\textsuperscript{a}, S.Y. Hoh, S. Lacaprara\textsuperscript{a,b}, P. Lujan, M. Margoni\textsuperscript{a,b}, A.T. Meneguzzo\textsuperscript{a,b}, J. Pazzini\textsuperscript{a,b}, N. Pozzobon\textsuperscript{a,b}, P. Ronchese\textsuperscript{a,b}, R. Rossin\textsuperscript{a,b}, F. Simonetto\textsuperscript{a,b}, A. Tiko, E. Torassa\textsuperscript{a}, S. Ventura\textsuperscript{a}, M. Zanetti\textsuperscript{a,b}, P. Zotto\textsuperscript{a,b}, G. Zumerle\textsuperscript{a,b}

\textbf{INFN Sezione di Pavia \textsuperscript{a}, Università di Pavia \textsuperscript{b}, Pavia, Italy}

A. Braghieri\textsuperscript{a}, A. Magnani\textsuperscript{a}, P. Montagna\textsuperscript{a,b}, S.P. Ratti\textsuperscript{a,b}, V. Re\textsuperscript{a}, M. Ressegotti\textsuperscript{a,b}, C. Riccardi\textsuperscript{a,b}, P. Salvini\textsuperscript{a}, I. Vai\textsuperscript{a,b}, P. Vitulo\textsuperscript{a,b}

\textbf{INFN Sezione di Perugia \textsuperscript{a}, Università di Perugia \textsuperscript{b}, Perugia, Italy}

L. Alunni Solestizi\textsuperscript{a,b}, M. Biasini\textsuperscript{a,b}, G.M. Bilei\textsuperscript{c}, C. Cecchi\textsuperscript{a,b}, D. Ciangottini\textsuperscript{a,b}, L. Fano\textsuperscript{a,b}, P. Lariccia\textsuperscript{a,b}, R. Leonardi\textsuperscript{a,b}, E. Manoni\textsuperscript{a}, G. Mantovani\textsuperscript{a,b}, V. Mariani\textsuperscript{a,b}, M. Menichelli\textsuperscript{a}, A. Rossi\textsuperscript{a,b}, A. Santocchia\textsuperscript{a,b}, D. Spiga\textsuperscript{a}
INFIN Sezione di Pisa a, Università di Pisa b, Scuola Normale Superiore di Pisa c, Pisa, Italy
K. Androsov a, P. Azzurri a, G. Bagliesi a, L. Bianchini a, T. Boccali a, L. Borrello, R. Castaldi a,
M.A. Ciocci a,b, R. Dell’Orso a, G. Fedi a, F. Fiori a,c, L. Giannini a,c, A. Giassi a, M.T. Grippo a,
F. Ligabue a,c, E. Manca a,c, G. Mandorli a,c, A. Messineo a,b, F. Palla a, A. Rizzi a,b, P. Spagnolo a,
R. Tenchini a, G. Tonelli a,b, A. Venturi a, P.G. Verdini a

INFIN Sezione di Roma a, Sapienza Università di Roma b, Rome, Italy
L. Barone a,b, F. Cavallari a, M. Cipriani a,b, N. Daci a, D. Del Re a,b, E. Di Marco a,b, M. Diemoz a,
S. Gelli a,b, E. Longo a,b, B. Marzocchi a,b, P. Meridiani a, G. Organtini a,b, F. Pandolfi a,
R. Paramatti a,b, F. Preiato a,b, S. Rahatlou a,b, C. Rovelli a, F. Santanastasio a,b

INFIN Sezione di Torino a, Università di Torino b, Torino, Italy, Università del Piemonte Orientale c, Novara, Italy
N. Amapane a,b, R. Arcidiacono a,c, S. Argiro a,b, M. Arneodo a,c, N. Bartosik a, R. Bellan a,b,
C. Biino a, N. Cartiglia a, F. Cenna a,b, S. Cometti a, M. Costa a,b, R. Covarelli a,b, N. Demaria a,
B. Kiani a,b, C. Mariotti a,b, S. Maselli a,b, E. Migliore a,b, V. Monaco a,b, E. Montei a,b, M. Monteno a,
M.M. Obertino a,b, L. Pacher a,b, N. Pastrone a, M. Pelliccioni a, G.L. Pinna Angioni a,b,
A. Romero a,b, M. Ruspa a,c, R. Sacchi a,b, K. Shchelina a,b, V. Sola a, A. Solano a,b, D. Soldi a,b,
A. Staiano a

INFIN Sezione di Trieste a, Università di Trieste b, Trieste, Italy
S. Belforte a, V. Candelise a,b, M. Casarsa a, F. Cossutti a, G. Della Ricca a,b, F. Vazzoler a,b,
A. Zanetti a

Kyunpook National University
D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son,
Y.C. Yang

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

Hanyang University, Seoul, Korea
J. Goh *, T.J. Kim

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park,
Y. Roh

Sejong University, Seoul, Korea
H.S. Kim

Seoul National University, Seoul, Korea
J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo,
U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea
D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus
National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali, F. Mohamad Idris, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
A. Castaneda Hernandez, J.A. Murillo Quijada

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz, R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, M. Ramirez-Garcia, G. Ramirez-Sanchez, R Reyes-Almanza, A. Sanchez-Hernandez

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

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

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

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

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, S. Qazi, M.A. Shah, M. Shoail, M. Waqas

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, V. Alexakhin, P. Bunin, M. Gavrilenko, A. Golunov, I. Golutvin, N. Gorbounov, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sokonov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermeniev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin
Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

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

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
R. Chistov, M. Danilov, P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

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

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

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov, T. Dimova, L. Kardapoltsev, D. Shtol, Y. Skovpen

State Research Center of Russian Federation, Institute for High Energy Physics of NRC “Kurchatov Institute”, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bifiovuk, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

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

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto,
J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Priels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Guibaud, D. Guihan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban, H. Kieseler, A. Kornmayer, M. Krammer, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, G. Rolandi, M. Rovere, H. Sakulin, C. Schäfer, C. Schwik, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas, A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsirou, V. Vackalns, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Quittnat, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Schultska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amster, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan
Y.H. Chang, K.Y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Arun Kumar, Y.Y. Li, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

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

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
A. Bat, F. Boran, S. Cerci, S. Damarsekin, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos, C. Isik, E.E. Kanga, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir, S. Ozturk, B. Tali, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak, G. Karapinar, M. Yalvac, M. Zeyrek
Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya, O. Kaya, S. Ozkorucuklu, S. Tekten, E.A. Yetkin

Istanbul Technical University, Istanbul, Turkey
M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen

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
F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom
G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash, A. Nikitenko, V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. Mcmaster, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA
R. Bartek, A. Domínguez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Piperov, S. Sagir, R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang
Florida International University, Miami, USA
Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA
A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, C. Schiber, V. Sharma, R. Yohay

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA
M. Alhusseini, B. Bilki, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA
B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA
A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

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

University of Maryland, College Park, USA
A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, V. Azzolini, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D’Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

University of Minnesota, Minneapolis, USA
A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros
University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, S. Sevova, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
S. Cooperstein, P. Elmer, J. Hardenbrook, S. Higginbotham, A. Kalogeropoulos, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojulvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

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

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, R. Taus, M. Verzetti

Rutgers, The State University of New Jersey, Piscataway, USA
A. Agapitos, J.P. Chou, Y. Gerstein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker
University of Tennessee, Knoxville, USA
A.G. Delannoy, J. Heideman, G. Riley, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali\textsuperscript{72}, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon\textsuperscript{73}, S. Luo, R. Mueller, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA
M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

\( ^{\dagger} \): Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
6: Also at University of Chinese Academy of Sciences, Beijing, China
7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
8: Also at Joint Institute for Nuclear Research, Dubna, Russia
9: Also at Suez University, Suez, Egypt
10: Now at British University in Egypt, Cairo, Egypt
11: Now at Fayoum University, El-Fayoum, Egypt
12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
13: Also at Université de Haute Alsace, Mulhouse, France
14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
23: Also at Institute of Physics, Bhubaneswar, India
24: Also at Shoolini University, Solan, India
25: Also at University of Visva-Bharati, Santiniketan, India
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Università degli Studi di Siena, Siena, Italy
29: Also at Kyunghee University, Seoul, Korea
30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
31: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
32: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
33: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
34: Also at Institute for Nuclear Research, Moscow, Russia
35: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
36: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
37: Also at University of Florida, Gainesville, USA
38: Also at P.N. Lebedev Physical Institute, Moscow, Russia
39: Also at California Institute of Technology, Pasadena, USA
40: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
42: Also at INFN Sezione di Pavia a, Università di Pavia b, Pavia, Italy
43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
44: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Riga Technical University, Riga, Latvia
47: Also at Universität Zürich, Zurich, Switzerland
48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
49: Also at Adiyaman University, Adiyaman, Turkey
50: Also at Istanbul Aydin University, Istanbul, Turkey
51: Also at Mersin University, Mersin, Turkey
52: Also at Piri Reis University, Istanbul, Turkey
53: Also at Gaziosmanpasa University, Tokat, Turkey
54: Also at Ozyegin University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
59: Also at Istanbul Bilgi University, Istanbul, Turkey
60: Also at Hacettepe University, Ankara, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Monash University, Faculty of Science, Clayton, Australia
64: Also at Bethel University, St. Paul, USA
65: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
66: Also at Utah Valley University, Orem, USA
67: Also at Purdue University, West Lafayette, USA
68: Also at Beykent University, Istanbul, Turkey
69: Also at Bingol University, Bingol, Turkey
70: Also at Sinop University, Sinop, Turkey
71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
72: Also at Texas A&M University at Qatar, Doha, Qatar
73: Also at Kyungpook National University, Daegu, Korea