Search for supersymmetry in proton-proton collisions at √s = 13 TeV in events with high-momentum Z bosons and missing transverse momentum

Collaboration, CMS; Blekman, Freya; Bols, Emil Sørensen; Chhibra, Simranjit Singh; D'Hondt, Jorgen; De Clercq, Jarne; Lontkovskyi, Denys; Lowette, Steven; Marchesini, Ivan; Moortgat, Seth; Morton, Alexander; Python, Quentin; Tavernier, Stefaan; Van Doninck, Walter; Van Mulders, Petra

Published in:
JHEP

DOI:
10.1007/JHEP09(2020)149

Publication date:
2020

Citation for published version (APA):
Collaboration, CMS., Blekman, F., Bols, E. S., Chhibra, S. S., D'Hondt, J., De Clercq, J., Lontkovskyi, D., Lowette, S., Marchesini, I., Moortgat, S., Morton, A., Python, Q., Tavernier, S., Van Doninck, W., & Van Mulders, P. (2020). Search for supersymmetry in proton-proton collisions at √s = 13 TeV in events with high-momentum Z bosons and missing transverse momentum. *JHEP*, *2020*(9), [149]. https://doi.org/10.1007/JHEP09(2020)149

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2020-149
2020/09/25

CMS-SUS-19-013

Search for supersymmetry in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ in events with high-momentum Z bosons and missing transverse momentum

The CMS Collaboration[*]

Abstract

A search for new physics in events with two highly Lorentz-boosted Z bosons and large missing transverse momentum is presented. The analyzed proton-proton collision data, corresponding to an integrated luminosity of $137\,\text{fb}^{-1}$, were recorded at $\sqrt{s} = 13\,\text{TeV}$ by the CMS experiment at the CERN LHC. The search utilizes the substructure of jets with large radius to identify quark pairs from Z boson decays. Backgrounds from standard model processes are suppressed by requirements on the jet mass and the missing transverse momentum. No significant excess in the event yield is observed beyond the number of background events expected from the standard model. For a simplified supersymmetric model in which the Z bosons arise from the decay of gluinos, an exclusion limit of 1920 GeV on the gluino mass is set at 95% confidence level. This is the first search for beyond-standard-model production of pairs of boosted Z bosons plus large missing transverse momentum.

"Published in the Journal of High Energy Physics as `doi:10.1007/JHEP09(2020)149`*."*

---

[*] See Appendix A for the list of collaboration members

1 Introduction

The discovery of a Higgs boson in 2012 by the ATLAS and CMS experiments [1–3] at the CERN LHC fulfilled the predicted particle content of the standard model (SM). However, within the SM as a quantum field theory, the measured Higgs boson mass of around 125 GeV presents a special challenge as the calculated mass is unstable against corrections from loop processes when the theory is extended to higher mass scales. In the absence of extreme fine tuning [4–7] that would precisely cancel the divergent terms, the mass value can run up to the ultraviolet cutoff of the model at the Planck scale. This instability of the Higgs boson mass and the entire electroweak scale is known as the gauge hierarchy problem.

One widely studied extension of the SM is supersymmetry (SUSY) [8–10], which posits a partner for each SM particle differing in spin by one-half unit. For example, squarks $\widetilde{\mathrm{q}}$ and gluinos $\widetilde{\mathrm{g}}$ are the SUSY partners of quarks and gluons, respectively. Depending on the mass hierarchy of these new particles, they could resolve the gauge hierarchy problem by providing necessary radiative corrections to partly cancel the SM contributions. Furthermore, in R-parity conserving models [11, 12], SUSY particles are produced in pairs, while the lightest of them is neutral, stable, and weakly interacting. This lightest SUSY particle (LSP) provides a suitable candidate for dark matter [12], which is not described in the SM. The typical experimental signatures of pair-produced SUSY particles with R-parity conserving decay chains are jets, leptons, and large missing transverse momentum ($p_{\mathrm{T}}^{\text{miss}}$).

As gluinos and squarks carry color charge, like their SM partners, they can be produced via the strong interaction; therefore among SUSY particles they have the highest production cross sections at hadron colliders for a given mass. Searches for direct decays of gluinos to quarks and the LSP have excluded $m(\widetilde{\mathrm{g}}) \lesssim 2\,\mathrm{TeV}$ [13–16], depending on the model. The search described in this paper focuses on gluino decay cascades to Z bosons and the LSP via the next-to-lightest SUSY particle (NLSP). We consider a picture in which the NLSP and LSP are respectively the neutralinos $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$, mixed states of SUSY partners of the neutral Higgs and gauge bosons. Such a situation arises in SUSY scenarios like those described in Ref. [17] that seek to preserve "naturalness," that is, minimal fine tuning of the SM to solve the gauge hierarchy problem, by admitting large mass splittings among the neutralinos (and charginos), leading to experimental signatures with vector bosons and $p_{\mathrm{T}}^{\text{miss}}$ in the final state. Figure 1 shows our signal process, expressed within the framework of simplified models [18–21], and referred to as T5ZZ. We further assume a heavy $\widetilde{\chi}_2^0$, (with mass below that of the $\widetilde{\mathrm{g}}$), and a light $\widetilde{\chi}_1^0$. This gives rise to energetic Z bosons along with large $p_{\mathrm{T}}^{\text{miss}}$ and additional soft quarks in the final state. In our model calculations we set the branching fraction for $\widetilde{\chi}_2^0 \to \mathrm{Z}\widetilde{\chi}_1^0$ to 100%, the $\widetilde{\chi}_1^0$ mass to 1 GeV, and the difference in mass between the $\widetilde{\mathrm{g}}$ and $\widetilde{\chi}_2^0$ to 50 GeV, though any set of mass parameters with a large [$\mathcal{O}$(TeV)] mass difference between the $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$ will result in highly energetic Z bosons. For the dominant $\mathrm{Z} \to \mathrm{q}\overline{\mathrm{q}}$ decay at large momentum, the decay products can be contained in a single reconstructed jet with a large angular radius (wide-cone jet).

In this paper, we present a search in proton-proton (pp) collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ for events with two highly Lorentz-boosted, hadronically decaying Z bosons and large $p_{\mathrm{T}}^{\text{miss}}$. The analysis is based on the LHC Run 2 data set with an integrated luminosity of $137\,\mathrm{fb}^{-1}$, recorded by the CMS experiment during 2016–2018. The signature for a signal is a pair of wide-cone jets, each having a reconstructed mass consistent with the Z boson mass. This selection, in combination with large $p_{\mathrm{T}}^{\text{miss}}$, greatly suppresses backgrounds from SM processes.

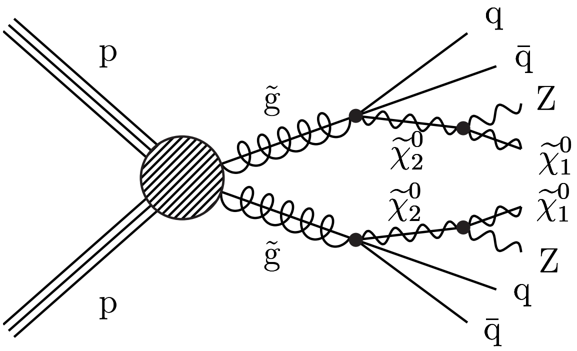

Figure 1: Signal diagram for the T5ZZ simplified model process. The assumed small mass splitting between the $\tilde{g}$ and $\tilde{\chi}_2^0$ implies a massive $\tilde{\chi}_2^0$. We further assume a 100% branching fraction for the $\tilde{\chi}_2^0$ decay to the Z boson and $\tilde{\chi}_1^0$, leading to an energetic Z boson and large $p_{\mathrm{T}}^{\mathrm{miss}}$.

2 The CMS detector and trigger

A detailed description of the CMS detector and the associated coordinate system and kinematic variables is given in Ref. [22]. The main components of the apparatus are briefly discussed here. The core of CMS is a cylindrical superconducting solenoid with an inner diameter of 6 m that provides a 3.8 T axial magnetic field. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter are placed within the volume enclosed by the solenoid. Gas-ionization detectors are embedded in the steel flux-return yoke outside the solenoid to identify muons. The detector is nearly hermetic, permitting accurate measurements of $p_{\mathrm{T}}^{\mathrm{miss}}$.

The CMS trigger system is described in Ref. [23]. For this analysis, signal candidate events were recorded by requiring $p_{\mathrm{T}}^{\mathrm{miss}}$ at the trigger level to exceed a threshold that varied between 100 and 120 GeV, depending on the LHC instantaneous luminosity. The efficiency of this trigger is measured in data to be greater than 97% for events satisfying the selection criteria described in Section 5. Additional triggers based on an isolated lepton or photon are used to select control samples for the background predictions.

3 Simulated event samples

The estimation of yields for the most prominent backgrounds is based on data in orthogonal signal-depleted control regions and is described in Section 6. Samples of Monte Carlo (MC) simulated events are used to test the background estimation, as well as to optimize the selection criteria. These samples include events with top quark pair production ($\mathrm{t\bar{t}}$), and photon, W boson, or Z boson production accompanied by jets, denoted γ+jets, W+jets, or Z+jets, respectively.

The SM production of $\mathrm{t\bar{t}}$, γ+jets, W+jets, Z+jets, and quantum chromodynamics (QCD) multijet events is simulated using the MADGRAPH5_aMC@NLO 2.2.2 [24, 25] generator for 2016 samples and MADGRAPH5_aMC@NLO 2.4.2 for 2017 and 2018 samples, all with leading order (LO) precision. The $\mathrm{t\bar{t}}$ events are generated with up to three additional partons in the matrix element calculations, while the γ+jets, W+jets, and Z+jets events are generated with up to four additional partons. Single top quark events produced via the s channel, diboson events originating from WW, ZZ, or ZH production, and events from $\mathrm{t\bar{t}W}$, $\mathrm{t\bar{t}Z}$, and WWZ production, are generated with MADGRAPH5_aMC@NLO 2.2.2 at next-to-leading order (NLO) [26], except that WW events in which both W bosons decay leptonically are generated using POWHEG 2.0 [27–31] at NLO. The POWHEG generator is also used to describe t-channel production of single top quarks as well as tW events. Normalization of the simulated background samples is derived from the most accurate cross section calculations available [24, 30–40], which generally correspond to NLO or next-to-NLO (NNLO) precision.

Samples of simulated signal events are generated at LO using MADGRAPH5_aMC@NLO 2.2.2 (2.4.2) for the 2016 (2017 and 2018) samples, with up to two additional partons included in the matrix element calculations. The production cross sections are normalized to approximate NNLO plus next-to-next-to-leading logarithmic (NNLL) precision [41–52].

All simulated samples make use of PYTHIA 8.205 (2016) or 8.230 (2017 and 2018) [53] to describe parton showering and hadronization. The CUETP8M1 [54] tune was used to simulate both the SM background and signal samples for the 2016 simulation. To generate the 2017 and 2018 samples, PYTHIA was used, with the CP5 tune [55] for the backgrounds and the CP2 tune [55] for signals. Simulated samples generated at LO (NLO) with the CUETP8M1 tune use the NNPDF3.0LO (NNPDF3.0NLO) [56] PDF set, while those generated with the CP2 or CP5 tune use the NNPDF3.1LO (NNPDF3.1NNLO) [57] PDF set. Here PDF refers to the parton distribution function. The detector response is modeled with GEANT4 [58]. The simulated events are generated with a distribution of pp interactions per bunch crossing (“pileup”) that is adjusted to match the corresponding distribution measured in data.

To improve the description of initial-state radiation (ISR), the MADGRAPH5_aMC@NLO prediction of the jet multiplicity distribution is compared with data in a control sample enriched in $t\bar{t}$ events [13]. A correction factor derived therefrom is subsequently applied to the simulated $t\bar{t}$ and signal events. The correction is found to be unnecessary for $t\bar{t}$ samples that are generated with the CP5 tune, so it is not applied to those samples.

4 Event reconstruction

Individual particles are reconstructed with the CMS particle-flow (PF) algorithm [59], which identifies them as photons, charged or neutral hadrons, electrons, or muons. These objects are characterized kinematically by their transverse momentum p_T, pseudorapidity η, and azimuthal angle ϕ. Photon and electron candidates are required to satisfy $|\eta| < 2.5$, and muon candidates $|\eta| < 2.4$, within the fiducial coverage of the tracking and muon system, respectively.

The missing transverse momentum vector $\vec{p}_T^{\,miss}$ is computed as the negative vector sum of the p_T of all of the PF candidates in an event, and its magnitude is denoted as p_T^{miss} [60]. The $\vec{p}_T^{\,miss}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event.

The reconstructed vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex, where the physics objects are the jets, clustered using the anti-k_T algorithm [61, 62] with the charged particle tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector p_T sum of those jets. Charged particle tracks associated with vertices other than the primary vertex are removed from further consideration.

Jets are defined as clusters of PF candidates formed by the anti-k_T algorithm with a distance parameter of 0.4 or 0.8. Quality criteria [63, 64] are imposed to suppress jets from spurious sources such as electronics noise in the calorimeters. The jet energies are corrected for the nonlinear response of the detector [65]. Jets with $p_T > 30\,\text{GeV}$, $|\eta| < 2.4$, and a distance parameter of 0.4 (AK4) are used as specified in Section 5 to calculate some of the selection variables. For these jets, charged particles that emerge from vertices other than the primary one are removed from the list of PF candidates used for the jet clustering. The expected contribution from neutral particles from pileup is removed using the effective area technique [64, 66].

The hadronically decaying Z boson candidates are reconstructed as wide-cone jets with a distance parameter of 0.8 (AK8). These AK8 jets are reclustered from their original constituents using the "soft drop" method [67] to remove soft, wide-angle radiation that can adversely impact the mass measurement of the jet. Contributions from pileup in these jets are removed with the PUPPI technique [68]. The soft drop mass m_{jet} is then used to identify jets from $\mathrm{Z} \to \mathrm{q\overline{q}}$ decays. No requirements on their flavor content are imposed.

The identification of b jets (b jet tagging) is performed by applying, to the AK4 jets, a version of the combined secondary vertex algorithm based on deep neural networks [69] (DeepCSV). A working point ("medium") of this algorithm is used that has a tagging efficiency for b jets of 68%, and a misidentification probability of approximately 1% for gluon and light-flavor quark jets and 12% for charm quark jets.

As described in Section 5, events with leptons or photons are vetoed in the search sample selection. Electron and muon candidates are identified as described in Refs. [70] and [71], respectively. To suppress jets erroneously identified as leptons or genuine leptons from hadron decays, electron and muon candidates are subjected to an isolation requirement. The isolation criterion is based on a variable I, which is the scalar p_{T} sum of charged hadron, neutral hadron, and photon PF candidates within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ around the lepton direction, divided by the lepton p_{T}. The expected contributions of neutral particles from pileup are subtracted [64, 66]. The radius of the cone, in radians, is 0.2 for lepton $p_{\mathrm{T}} < 50\,\text{GeV}$, $10\,\text{GeV}/p_{\mathrm{T}}$ for $50 \leq p_{\mathrm{T}} \leq 200\,\text{GeV}$, and 0.05 for $p_{\mathrm{T}} > 200\,\text{GeV}$. The decrease in cone size with increasing lepton p_{T} accounts for the increased collimation of the decay products from the lepton's parent particle as the Lorentz boost of the latter increases [72]. The isolation requirement is $I < 0.1$ (0.2) for electrons (muons).

To further suppress events with leptons from hadron decays and single-prong hadronic τ lepton decays, the event selection veto is extended to include isolated charged-particle tracks not identified as electrons or muons by the criteria of the previous paragraph. For these candidates the scalar p_{T} sum of all other charged-particle tracks within $\Delta R = 0.3$ around the track direction, divided by the track p_{T}, is required to be less than 0.2 if the track is identified as a PF electron or muon, and less than 0.1 otherwise. Isolated tracks are required to satisfy $|\eta| < 2.4$.

Photon candidates are identified as described in Ref. [73], using the "loose" working point, and with an isolation requirement based on the individual sums of energy from charged and neutral hadrons and electromagnetically interacting particles, excluding the photon candidate itself, within $\Delta R = 0.3$ around the direction of the photon candidate. Each of the three individual sums, corrected for pileup, is required not to exceed a threshold that depends on the calorimeter geometry.

5 Event selection

We select events with large jet activity and $p_{\mathrm{T}}^{\text{miss}}$, no leptons or photons, and wide-cone jets from Lorentz-boosted, hadronically decaying Z bosons. Control regions for the determination of backgrounds are also defined.

The observables used to characterize candidate events are:

- N_{jet}, the number of AK4 jets in the event;

- $p_{\mathrm{T}}^{\mathrm{miss}}$;
- $H_{\mathrm{T}} = \sum_{\mathrm{AK4\,jets}} |\vec{p}_{\mathrm{T}}|$;
- $\Delta\phi_{j,\vec{H}_{\mathrm{T}}^{\mathrm{miss}}}$, the azimuthal angle between the $\vec{p}_{\mathrm{T}}$ of the j^{th} AK4 jet and $\vec{H}_{\mathrm{T}}^{\mathrm{miss}} = -\sum_{\mathrm{AK4\,jets}} \vec{p}_{\mathrm{T}}$;
- ${m_{\mathrm{T}}}^{i}$, the transverse mass [74] of a system comprising the i^{th} isolated track and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$;
- $\Delta R_{\mathrm{Z,b}}$, the angular separation between a wide-cone jet and a b-tagged jet.

The following requirements define the event selection:

1. $N_{\text{jet}} \geq 2$;
2. $p_{\mathrm{T}}^{\mathrm{miss}} > 300\,\mathrm{GeV}$;
3. $H_{\mathrm{T}} > 400\,\mathrm{GeV}$;
4. $|\Delta\phi_{j,\vec{H}_{\mathrm{T}}^{\mathrm{miss}}}| > 0.5$ (0.3) for the first two (up to next two, if $N_{\text{jet}} > 2$) AK4 jets ranked in descending order of p_{T};
5. no identified isolated photon, electron, or muon candidate with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$;
6. no isolated track with $m_{\mathrm{T}} < 100\,\mathrm{GeV}$ and
$$p_{\mathrm{T}} > \begin{cases} 5\,\mathrm{GeV} & \text{if the track is identified as a PF electron or muon,} \\ 10\,\mathrm{GeV} & \text{otherwise.} \end{cases}$$
7. at least two AK8 jets with $p_{\mathrm{T}} > 200\,\mathrm{GeV}$;
8. m_{jet} of the two highest p_{T} AK8 jets between 40 and 140 GeV;
9. $\Delta R_{\mathrm{Z,b}} > 0.8$, for the second-highest p_{T} AK8 jet and any b-tagged jet.

The $\Delta\phi_{j,\vec{H}_{\mathrm{T}}^{\mathrm{miss}}}$ requirements suppress background from QCD multijet events, as well as those from hadronic Z and W boson decay, for which $\vec{H}_{\mathrm{T}}^{\mathrm{miss}}$ is usually aligned along a jet direction. The m_{T} requirement restricts the isolated track veto to situations consistent with a W boson decay.

The first six requirements define an inclusive "hadronic baseline" selection, and the last three specify the further selection of events with jet pairs that include pairs of hadronically decaying Z boson candidates. The accepted range in m_{jet} is chosen to reject the bulk of nonresonant SM processes on the low side, and the peak from boosted top quark jets on the high side, while including sidebands around the Z boson peak to facilitate the determination of the background. The $\Delta R_{\mathrm{Z,b}}$ requirement suppresses backgrounds from $\mathrm{t\bar{t}}$ and single top quark events in which a top quark is reconstructed as a b-tagged jet together with a W boson reconstructed as an AK8 jet.

Figure 2 shows the simulated SM background components and two example signal mass points for events selected without and with the three Z boson requirements. The main sources of SM background are Z+jets, W+jets, and $\mathrm{t\bar{t}}$, which can yield large $p_{\mathrm{T}}^{\mathrm{miss}}$ accompanied by AK8 jets formed from random combinations of hadrons. In the case of Z+jets, large $p_{\mathrm{T}}^{\mathrm{miss}}$ comes from the $\mathrm{Z} \to \nu\bar{\nu}$ decay. For W+jets and $\mathrm{t\bar{t}}$, $p_{\mathrm{T}}^{\mathrm{miss}}$ arises from a leptonically decaying W boson where the charged lepton is undetected. Smaller background contributions arise from the QCD multijet

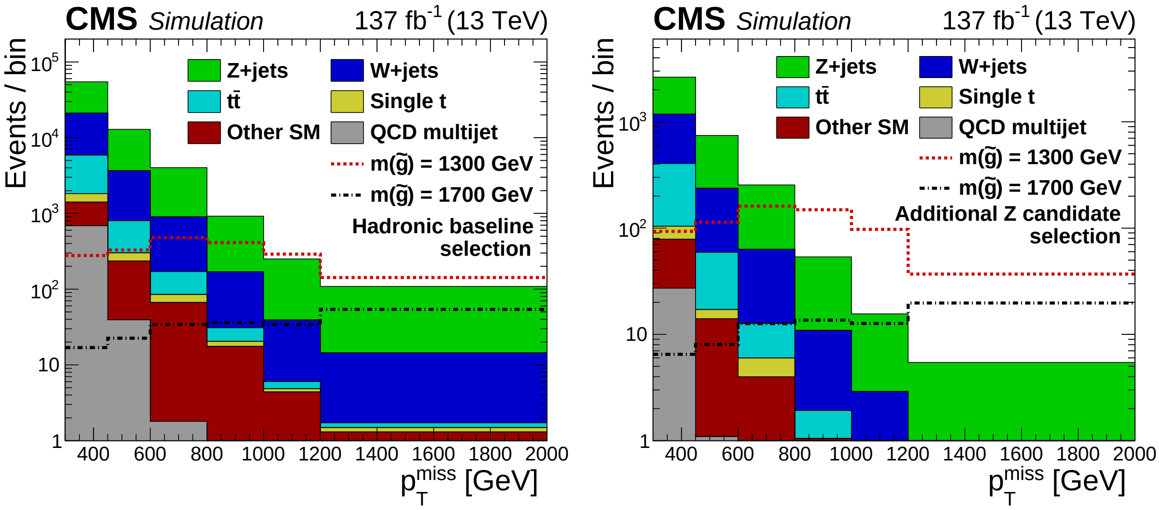

Figure 2: Distributions of $p_{\mathrm{T}}^{\mathrm{miss}}$ for simulated SM backgrounds (stacked histograms), with only the hadronic baseline selection (left), and after the additional Z candidate selection (right). Expected signal contributions for two example mass points (dotted lines) are also shown. The last bin includes the overflow events.

events in which the measurement of a jet's energy suffers a large fluctuation, production of single top quarks, and other SM processes, such as diboson production and $\mathrm{t\bar{t}}$ pairs accompanied by vector bosons.

An event satisfying the above criteria lies in the search region (SR) if, in addition, both of the two highest p_{T} AK8 jets have m_{jet} values in the range [70,100] GeV (as discussed in Section 6.1). Relative to the hadronic baseline selection, about 21% of signal events are retained in the SR, along with 0.5% of background events. The $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the SR is divided into six bins, with lower boundaries at 300, 450, 600, 800, 1000, and 1200 GeV.

6 Background estimation

This section focuses on the estimation of SM backgrounds in each $p_{\mathrm{T}}^{\mathrm{miss}}$ bin. We first describe the method based on control samples in data, then follow with a description of the performance of the method in simulation (MC closure), and lastly deal with the uncertainty in the $p_{\mathrm{T}}^{\mathrm{miss}}$ dependence (shape uncertainty) based on the data observed in the validation samples.

6.1 Background estimation method

Control regions (CRs) are formed from the events in which one or both of the highest p_{T} (leading) and second-highest p_{T} (subleading) jets lie in the m_{jet} sideband $[40, 70] \vee [100, 140]$ GeV. Figure 3 shows the definition of the SR and CRs in the plane of jet masses of the leading and subleading jets. In addition, validation samples are selected by inverting the lepton or photon veto requirement.

The first step of the method is to determine the background normalization $\mathcal{B}_{\mathrm{norm}}$ integrated over all $p_{\mathrm{T}}^{\mathrm{miss}}$ bins above 300 GeV. We fit the m_{jet} distribution for the leading jet in the leading-jet mass sideband, defined as the sample having the subleading jet m_{jet} within, and the leading jet m_{jet} outside, the Z signal window. The bulk of the background is from nonresonant SM contributions, which can be modeled with a smoothly falling shape. The nominal fit is performed with a linear function, as shown in Fig. 4.

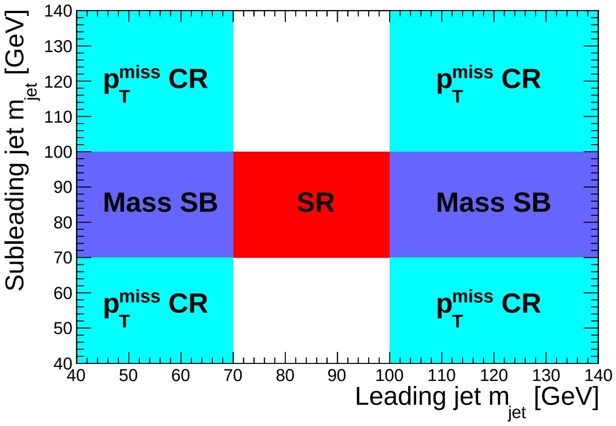

Figure 3: Definition of the search and control regions in the plane of subleading vs. leading jet mass. The search region (red central box), with both m_{jet} values lying within the Z signal window, defines the acceptance for potential signal; the leading-jet mass sideband (dark blue), with subleading jet within and leading jet outside the signal window, is used to measure the background normalization; the $p_{\mathrm{T}}^{\text{miss}}$ CR (light blue), with both leading- and subleading-jet m_{jet} values lying outside the signal window, is used to derive the $p_{\mathrm{T}}^{\text{miss}}$ shape in the search region.

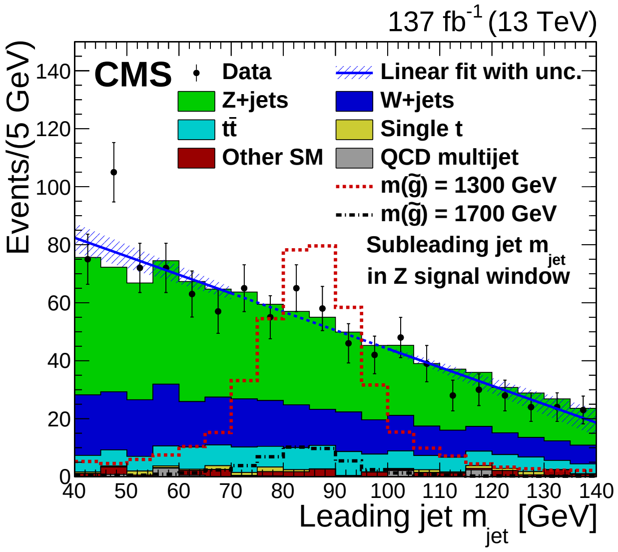

Figure 4: Leading AK8 jet m_{jet} shape fit in the mass sidebands. The Z candidate selection is applied and the subleading AK8 jet m_{jet} value is required to lie in the Z signal window. The blue hatched region represents the ±1 standard deviation uncertainty in the fit to the mass sideband performed with a linear function, which is indicated by the blue line. The stacked histogram shows the background from simulation scaled to the data. Expected signal contributions for two example mass points are also shown.

The uncertainties in $\mathcal{B}_{\text{norm}}$ include a statistical component from the fit, and a systematic one due to the choice of the fitting function. To obtain the statistical uncertainty due to the interpolation of the fit into the SR, pseudo-experiments generated from the background model are fitted using a linear function with free slope and normalization. The Gaussian width of the resulting distribution of the yields in the Z signal window, 10.7 events, is taken as the statistical uncertainty in the total background prediction.

To test if the linear function is adequate to represent the m_{jet} distribution, we consider higher-order polynomials as alternative functions. We check Chebyshev polynomials of up to the fourth order. The largest variation in the fitted yield with respect to the nominal one, 10.9 events, comes from a fit with a third-order Chebyshev polynomial, and is taken as an additional uncertainty attributable to the fit shape. Considering the statistical uncertainty described above, this results in $\mathcal{B}_{\text{norm}} = 325 \pm 15$.

To determine the distribution of background events in the $p_{\mathrm{T}}^{\text{miss}}$ bins, we rely on an underlying assumption that $p_{\mathrm{T}}^{\text{miss}}$ and m_{jet} have minimal correlation. To derive the $p_{\mathrm{T}}^{\text{miss}}$ shape in the SR, a nonoverlapping CR is used in which both leading and subleading AK8 jets have m_{jet} in the mass sideband. This is referred to as the $p_{\mathrm{T}}^{\text{miss}}$ CR (Fig. 3). In each of the six $p_{\mathrm{T}}^{\text{miss}}$ bins, we calculate the background prediction as

$$\mathcal{B}_i = \mathcal{T} N_i^{\text{CR}}, \tag{1}$$

where N_i^{CR} is the yield in $p_{\mathrm{T}}^{\text{miss}}$ bin i in the $p_{\mathrm{T}}^{\text{miss}}$ CR, and the transfer factor,

$$\mathcal{T} \equiv \frac{\mathcal{B}_{\text{norm}}}{\sum_i N_i^{\text{CR}}} = 0.198 \pm 0.009, \tag{2}$$

scales the $p_{\mathrm{T}}^{\text{miss}}$ CR yield to that of the SR. The uncertainty in $\mathcal{T}$ includes both statistical and systematic uncertainties in $\mathcal{B}_{\text{norm}}$.

6.2 Background closure in simulation

The background estimation method based on control samples in data is tested by applying the procedure to MC simulation. We perform this closure test in two steps.

The main assumption to verify is the lack of correlation between the AK8 jet mass and $p_{\mathrm{T}}^{\text{miss}}$ shape. Figure 5 shows the results of a test of this assumption, where the simulated sample size permits a distribution in relatively fine steps. The plots compare the $p_{\mathrm{T}}^{\text{miss}}$ shape in the search and control regions, for the two main background processes. In both cases we see that the $p_{\mathrm{T}}^{\text{miss}}$ shapes are consistent between the two regions.

For the closure test of the background estimation method we calculate the background prediction in each $p_{\mathrm{T}}^{\text{miss}}$ bin [Eq. (1)] and compare these predictions with the background yields taken directly from simulation. The results of this test, shown in Fig. 6, demonstrate good agreement within the statistical precision of the test. To account for the uncertainties in the comparison, we assign the relative difference between the prediction and direct observation as a nonclosure systematic uncertainty in the $p_{\mathrm{T}}^{\text{miss}}$ shape. This difference ranges from 1 to 20%, where the variations in the four lower $p_{\mathrm{T}}^{\text{miss}}$ bins are treated as being anti-correlated with those in the higher $p_{\mathrm{T}}^{\text{miss}}$ bins to give a systematic uncertainty in the $p_{\mathrm{T}}^{\text{miss}}$ shape that does not affect the overall normalization of the background estimation.

6.3 The $p_{\mathrm{T}}^{\text{miss}}$ shape uncertainty

While the background estimation method is shown to close well in simulation, we additionally verify in data how well the $p_{\mathrm{T}}^{\text{miss}}$ CR models the $p_{\mathrm{T}}^{\text{miss}}$ shape in the Z signal window. In

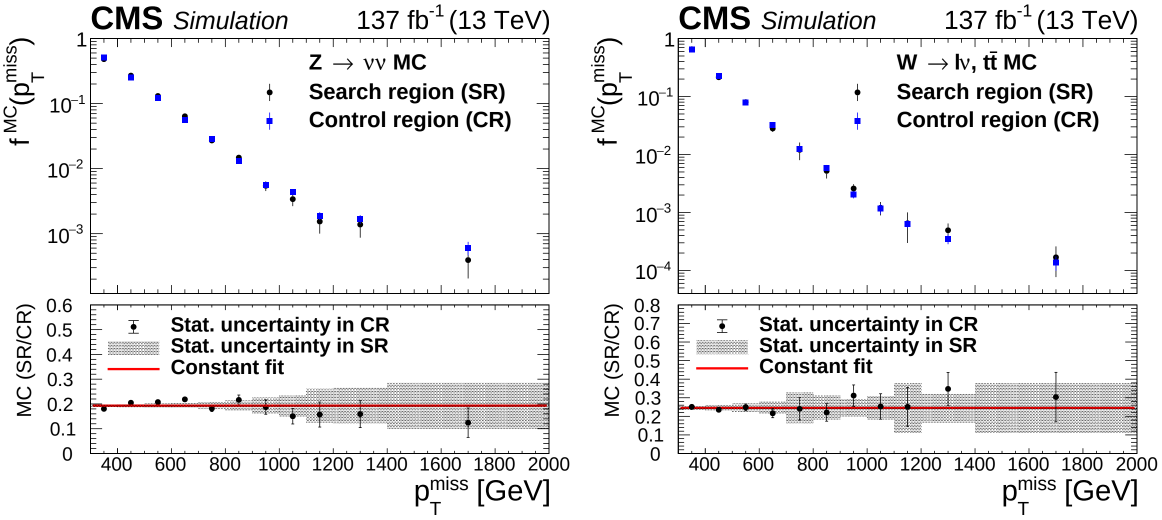

Figure 5: Comparison of the $p_{\mathrm{T}}^{\mathrm{miss}}$ shape in the search and control regions in simulation. The upper panels show the unit-normalized $p_{\mathrm{T}}^{\mathrm{miss}}$ distributions $f^{\mathrm{MC}}(p_{\mathrm{T}}^{\mathrm{miss}})$ in the two regions, while the lower panels show the ratio of the number of events in the search region to that in the control region. This comparison is done for two main background components: $\mathrm{Z} \to \nu\overline{\nu}$ (left) and $\mathrm{t\bar{t}}$ plus W+jets (right). In the lower panel the statistical uncertainties in the search and control region yields are denoted by the shading and vertical bars, respectively, and a fit to a constant is included to show the average ratio.

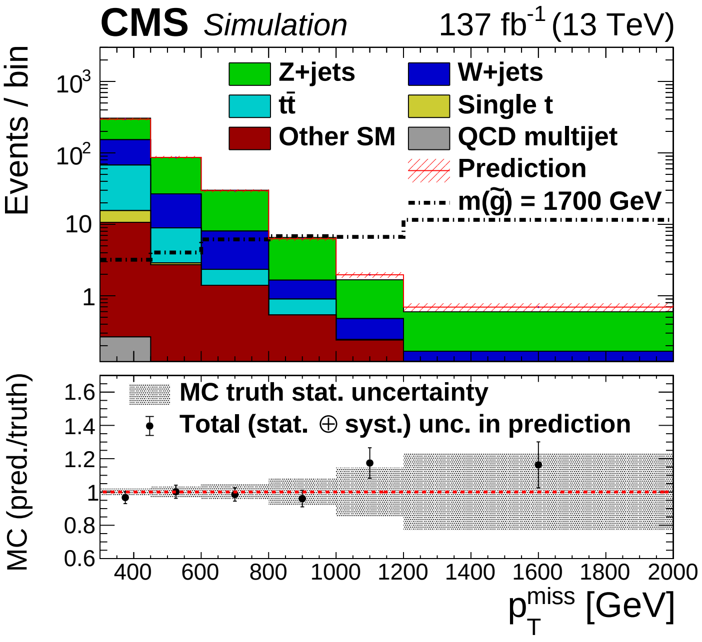

Figure 6: Results of the closure test in which the background estimation method based on control samples in data is applied to simulation and compared with the direct yield, in the analysis search bins. Expected signal contribution for one example mass point is also shown. The lower panel shows the ratio of the prediction to the direct yield. The gray band shows the statistical uncertainty in the direct yield, and the error bars on the points represent the total uncertainty in the prediction.

particular, two validation samples are used to compare the $p_{\mathrm{T}}^{\mathrm{miss}}$ shape obtained from the $p_{\mathrm{T}}^{\mathrm{miss}}$ CR with the one obtained in the Z signal window, used to define our SR, for the main background components. A photon validation sample is used as a proxy for the Z+jets background component, while a single-lepton sample is used to validate the modeling of $\mathrm{t\bar{t}}$ and W+jets combined.

We select the photon validation sample from events recorded with a single-photon trigger, replacing the photon veto with the requirement of exactly one photon, defined as in Section 4. The photon p_{T} is used to emulate the $p_{\mathrm{T}}^{\mathrm{miss}}$ from the Z boson when the latter decays to neutrinos. The lower-p_{T} trigger threshold for the photon compared with the $p_{\mathrm{T}}^{\mathrm{miss}}$ threshold in the signal trigger allows us to consider the photon validation sample down to 200 GeV in photon p_{T} as a proxy for $p_{\mathrm{T}}^{\mathrm{miss}}$. To enhance the event count in this sample, we do not require a threshold on $\Delta R_{\mathrm{Z,b}}$ since there is a low risk of heavy flavor contamination. All other event selection requirements are the same as for the SR of the analysis.

For the single-lepton sample, the same $p_{\mathrm{T}}^{\mathrm{miss}}$ trigger is used as for the SR. The same offline criteria are also applied, with the exception that the $p_{\mathrm{T}}^{\mathrm{miss}}$ requirement is relaxed to 200 GeV to gain a longer lever arm for the $p_{\mathrm{T}}^{\mathrm{miss}}$ shape comparison, and the lepton vetoes are applied only after selecting exactly one electron or muon.

Figure 7 shows the $p_{\mathrm{T}}^{\mathrm{miss}}$ shape comparison for the photon and single-lepton data. Both ratios are consistent with being independent of $p_{\mathrm{T}}^{\mathrm{miss}}$, as expected from the MC closure test, albeit within the limited statistical precision of the data. To account for possible shape differences between the search and control regions, we apply a systematic uncertainty in the $p_{\mathrm{T}}^{\mathrm{miss}}$ shape calculated using the photon and single-lepton samples. The uncertainty is the difference with respect to a uniform distribution of a fit to the SR/CR distribution with a linear function having a free slope parameter. This results in uncertainties ranging from 0–33% in the Z+jets background based on the photon validation sample, and 1–14% in the combined $\mathrm{t\bar{t}}$ and W+jets background based on the single-lepton validation sample. Weighting these by the proportions of those components in the total background yields uncertainties of 2–30%, depending on the $p_{\mathrm{T}}^{\mathrm{miss}}$ bin.

7 Systematic uncertainties

The uncertainties in the SM background prediction are described in Section 6, along with the description of the background estimation method. The uncertainties in the background normalization include the statistical uncertainty from the mass sideband fit interpolation as well as the systematic one derived from alternative fit functions. The uncertainties in the $p_{\mathrm{T}}^{\mathrm{miss}}$ shape include the statistical uncertainties of the $p_{\mathrm{T}}^{\mathrm{miss}}$ CR. The systematic uncertainties only affect the $p_{\mathrm{T}}^{\mathrm{miss}}$ shape without changing the background normalization. These are derived from the MC closure test and data validation samples. All of these systematic uncertainties are summarized in the upper section of Table 1.

The sources of uncertainty in the signal efficiency affect the signal normalization, the signal $p_{\mathrm{T}}^{\mathrm{miss}}$ shape, or both, as indicated in Table 1. The uncertainties in the integrated luminosity are 2.5% [75], 2.3% [76], and 2.5% [77] for 2016, 2017, and 2018, respectively. The trigger, lepton veto, and isolated-track veto efficiencies are measured in data validation samples and their statistical uncertainties propagated to the signal yields. The ISR modeling in the simulation is adjusted to match the efficiencies measured in data events enriched in dileptonic $\mathrm{t\bar{t}}$ production and decay, and the uncertainty in this correction is propagated to the signal yields. To evaluate the uncertainty associated with the renormalization (μ_{R}) and factorization (μ_{F}) scales, each

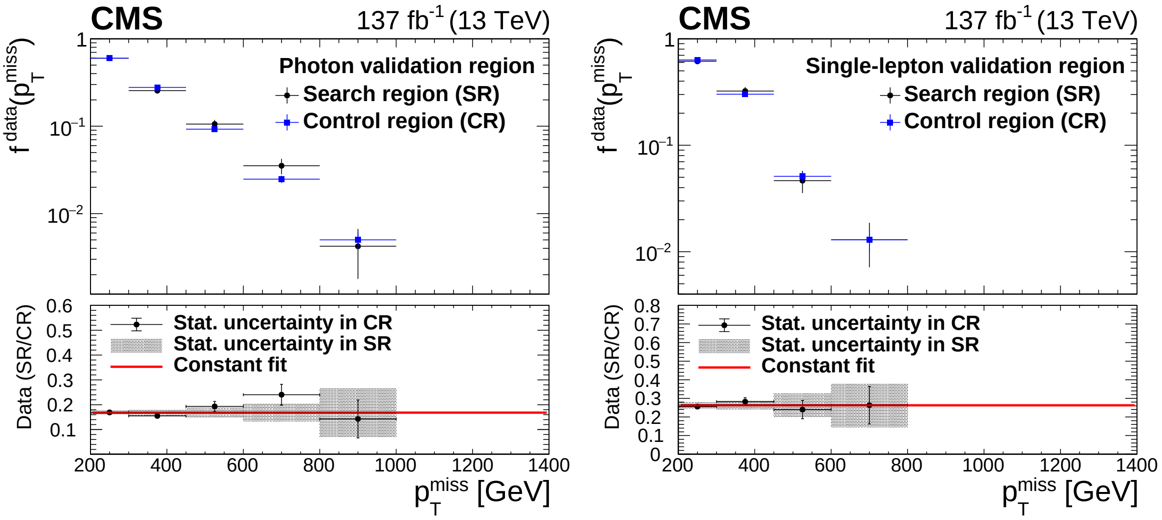

Figure 7: Comparison of the $p_{\mathrm{T}}^{\mathrm{miss}}$ shape between the Z signal window and $p_{\mathrm{T}}^{\mathrm{miss}}$ control region for the photon (left) and single-lepton (right) validation samples in data. The upper panels show the unit-normalized $p_{\mathrm{T}}^{\mathrm{miss}}$ distributions $f^{\mathrm{data}}(p_{\mathrm{T}}^{\mathrm{miss}})$ in the two regions, while the lower panels show the ratio of the number of events in the search region to that in the control region. A fit to a constant is included in the lower panels to show the average ratio. The horizontal bars on the markers indicate the widths of the search bins. In the lower panel the statistical uncertainties in the search and control region yields are denoted by the shading and vertical bars, respectively.

Table 1: Summary of systematic uncertainties, where the ranges refer to different $p_{\mathrm{T}}^{\mathrm{miss}}$ bins. In the last column we distinguish uncertainties that affect the normalizations (”norm.”), the shapes of distributions, or both.

Source of uncertainty	Effect on yields (%)	norm. or shape
Uncertainties in the background predictions		
Fit, normalization	3.3	norm.
Fit, shape	3.4	norm.
m_{jet} CR statistics	3–100	shape
MC closure	2–13	shape
Data validation	2–30	shape
Uncertainties in the signal yields		
Integrated luminosity	2.3–2.5	norm.
Trigger efficiency	2.0	both
Isolated lepton and track vetoes	2.0	norm.
Jet quality requirements	1.0	norm.
ISR modeling	1–2	both
μ_{R} and μ_{F} scales	0.2–0.5	both
JEC	2–4	both
JER	5–6	both
MC statistics	1–2	both
m_{jet} resolution	1–3	norm.

scale is varied independently by a factor of 2.0 and 0.5 [78, 79]. Uncertainties in the simulation of pileup are found to be of the order of 0.02%; thus no associated uncertainty is applied.

The jet momenta in MC samples are smeared to match the jet energy resolution (JER) in data. The jet energy corrections (JECs) are varied using p_{T}- and η-dependent uncertainties. Both effects are propagated to the jet-dependent variables, including $p_{\mathrm{T}}^{\mathrm{miss}}$, H_{T}, and $\Delta\phi_{j,\vec{H}_{\mathrm{T}}^{\mathrm{miss}}}$, and are varied within the uncertainty of the corrections to derive a systematic uncertainty in the signal yields. The efficiency of the jet quality requirements used to suppress events with misreconstructed jets is found to differ by 1% between data and simulation, and this is applied as a systematic uncertainty. The difference in the resolution of m_{jet} between data and simulation is applied as a smearing factor to the MC events, and the statistical uncertainty in the size of the correction is included as a systematic uncertainty in the corresponding selection efficiency. Lastly, the statistical precision due to the limited event count in the simulated samples is accounted for as an uncertainty.

The systematic uncertainties associated with the signal yields are evaluated assuming that the contributions from the three years of data taking are fully correlated. The total systematic uncertainties in the signal yields range from 0.2 to 6%.

8 Results

The background predictions and observed yields for each $p_{\mathrm{T}}^{\mathrm{miss}}$ bin are shown in Fig. 8 and Table 2. The table also gives the inputs to the prediction calculation, Eq. (1). The observations are found to be consistent with the SM predictions within uncertainties, and no evidence for SUSY is observed. We calculate upper limits on the gluino pair-production cross section using a maximum-likelihood fit in which the free parameters are the signal strength μ and the nuisance parameters associated with the systematic uncertainties in the background and signal model. The uncertainty in the normalization of the background is represented with a lognormal function correlated across all $p_{\mathrm{T}}^{\mathrm{miss}}$ bins, while the $p_{\mathrm{T}}^{\mathrm{miss}}$ CR statistical uncertainties are assigned as uncorrelated. The MC closure and data-MC agreement uncertainties are assigned as correlated across $p_{\mathrm{T}}^{\mathrm{miss}}$ bins.

We evaluate 95% confidence level (CL) upper limits based on the asymptotic form of a likelihood ratio test statistic [80], in conjunction with the $\mathrm{CL_s}$ criterion described in Refs. [81–83]. The test statistic is $q(\mu) = -2\ln(\mathcal{L}_{\mu}/\mathcal{L}_{\mathrm{max}})$, where $\mathcal{L}_{\mu}$ is the maximum likelihood for fixed μ, and $\mathcal{L}_{\mathrm{max}}$ is the same determined by allowing all parameters, including μ, to vary.

Expected and observed 95% CL upper limits, and the predicted gluino pair-production cross sections, are shown in Fig. 9, taking $m(\tilde{\chi}_1^0) = 1\,\mathrm{GeV}$ and $m(\tilde{\mathrm{g}}) - m(\tilde{\chi}_2^0) = 50\,\mathrm{GeV}$. The observed (expected) gluino mass limits reach as high as 1920 (2060) GeV. The observed limit is 1.4 standard deviations weaker than the expected one due to the mild excesses observed in the two highest $p_{\mathrm{T}}^{\mathrm{miss}}$ bins. The sensitivity of the search is independent of $m(\tilde{\chi}_1^0)$ values that are small compared with $m(\tilde{\chi}_2^0)$, and of $m(\tilde{\chi}_2^0)$ values large enough to ensure Lorentz-boosted Z boson daughters. A gradual loss of signal efficiency occurs with increasing $\Delta m(\tilde{\mathrm{g}}, \tilde{\chi}_2^0)$ as quarks from the gluino decay that form AK8 jets with p_{T} above the 200 GeV threshold displace Z jets as leading or subleading in p_{T}.

9 Summary

Results are presented of a search for events with two hadronically decaying, highly energetic Z bosons and large transverse momentum imbalance, in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$. The sample corresponds to an integrated luminosity of $137\,\mathrm{fb}^{-1}$. The signature for a Z boson candidate is a wide-cone jet having a measured mass compatible with the Z boson mass. Yields

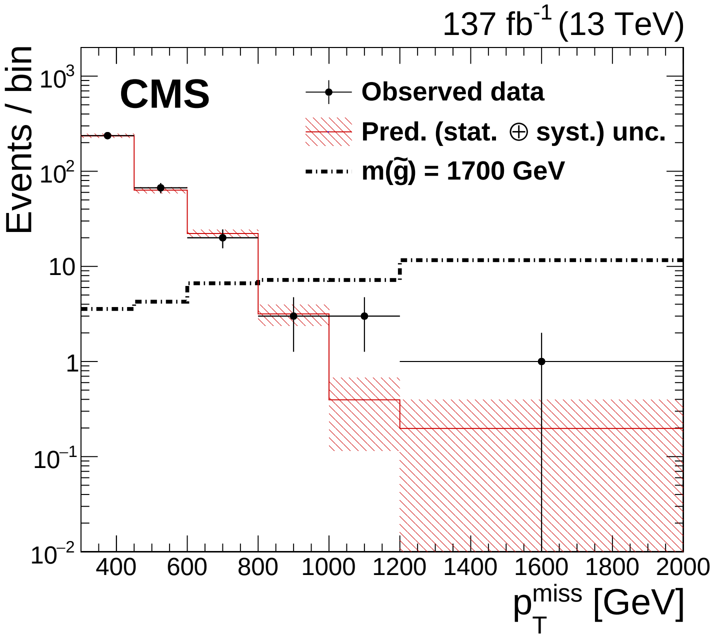

Figure 8: Observed data and background prediction as functions of $p_{\mathrm{T}}^{\mathrm{miss}}$. The horizontal bar associated with each data point represents the width of the corresponding bin. The red hatched region denotes the expected statistical and systematic uncertainties added in quadrature. Expected signal contribution for one example mass point is also shown.

Table 2: Number of events in the $p_{\mathrm{T}}^{\mathrm{miss}}$ CR, transfer factor, background prediction, and observed yield in each of the six $p_{\mathrm{T}}^{\mathrm{miss}}$ bins. Where two uncertainties are quoted, the first is statistical and the second systematic. The systematic uncertainties in the background prediction include the shape uncertainties in addition to the uncertainty in $\mathcal{T}$. Also listed in the last column is the number of expected signal events and corresponding statistical uncertainties for one example mass point.

$p_{\mathrm{T}}^{\mathrm{miss}}$ bin (GeV)	$p_{\mathrm{T}}^{\mathrm{miss}}$ CR yield N^{CR} (events)	Transfer factor $\mathcal{T}$	Background prediction $\mathcal{B}$ (events)	Observed yield (events)	Exp. signal $m(\tilde{g})$ = 1700 GeV (events)
300–450	1191	0.198 ± 0.009	$236 \pm 7 \pm 16$	237	3.5 ± 0.1
450–600	320		$63.3 \pm 3.6 \pm 3.3$	67	4.3 ± 0.1
600–800	112		$22.2 \pm 2.0 \pm 1.9$	20	6.6 ± 0.1
800–1000	16		$3.2 \pm 0.8 \pm 0.5$	3	7.2 ± 0.1
1000–1200	2		$0.40 \pm 0.29 \pm 0.11$	3	7.2 ± 0.1
>1200	1		$0.20 \pm 0.20 \pm 0.06$	1	11.6 ± 0.1

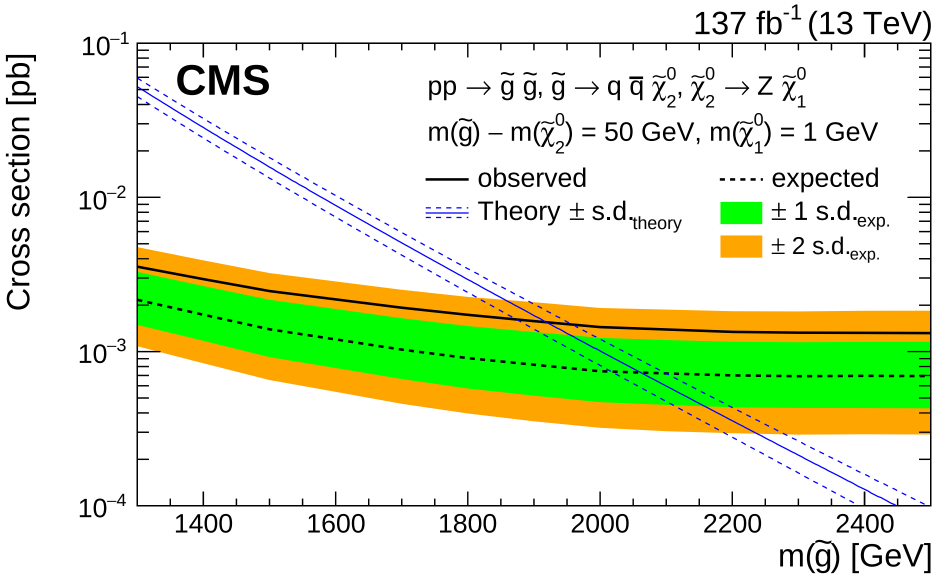

Figure 9: The 95% CL upper limit on the production cross section for the T5ZZ signal model as a function of the gluino mass. The solid black curve shows the observed exclusion limit. The dashed black curve presents the expected limit while the green and yellow bands represent the ±1 and ±2 standard deviation uncertainty ranges. The approximate-NNLO+NNLL cross sections [41–45] are shown in the solid blue curve while the dashed blue curves show their theoretical uncertainties [84]. The T5ZZ model assumes a 100% branching fraction for the $\tilde{\chi}^0_2$ to decay to the Z boson and $\tilde{\chi}^0_1$.

from standard model background processes, which are small for events with the largest transverse momentum imbalance, are estimated from the data in jet mass sidebands. No evidence for physics beyond the standard model is observed. The reach of the search is interpreted in a simplified supersymmetric model of gluino pair production in which each gluino decays to a low-momentum quark pair and the next-to-lightest supersymmetric particle (NLSP), and the latter decays to a Z boson and the lightest supersymmetric particle (LSP). With the further assumption of a large mass splitting between the NLSP and LSP, the data exclude gluino masses below 1920 GeV at 95% confidence level. This is the first search for beyond-standard-model production of pairs of boosted Z bosons plus large missing transverse momentum.

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: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM

(Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 752730, and 765710 (European Union); the Leventis Foundation; the A.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; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, project no. 02.a03.21.0005 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

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

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

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

[4] R. Barbieri and G. F. Giudice, "Upper bounds on supersymmetric particle masses", *Nucl. Phys. B* **306** (1988) 63, `doi:10.1016/0550-3213(88)90171-X`.

[5] S. Dimopoulos and G. F. Giudice, "Naturalness constraints in supersymmetric theories with nonuniversal soft terms", *Phys. Lett. B* **357** (1995) 573, `doi:10.1016/0370-2693(95)00961-J`, `arXiv:hep-ph/9507282`.

[6] R. Barbieri and D. Pappadopulo, "S-particles at their naturalness limits", *JHEP* **10** (2009) 061, `doi:10.1088/1126-6708/2009/10/061`, `arXiv:0906.4546`.

[7] M. Papucci, J. T. Ruderman, and A. Weiler, "Natural SUSY endures", *JHEP* **09** (2012) 035, `doi:10.1007/JHEP09(2012)035`, `arXiv:1110.6926`.

[8] P. Fayet and S. Ferrara, "Supersymmetry", *Phys. Rept.* **32** (1977) 249, `doi:10.1016/0370-1573(77)90066-7`.

[9] H. P. Nilles, "Supersymmetry, supergravity and particle physics", *Phys. Rept.* **110** (1984) 1, `doi:10.1016/0370-1573(84)90008-5`.

[10] S. P. Martin, "A supersymmetry primer", *Adv. Ser. Direct. High Energy Phys.* **21** (2010) 1, `doi:10.1142/9789814307505_0001`, `arXiv:hep-ph/9709356`.

[11] P. Fayet, "Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino", *Nucl. Phys. B* **90** (1975) 104, `doi:10.1016/0550-3213(75)90636-7`.

[12] G. R. Farrar and P. Fayet, "Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry", *Phys. Lett. B* **76** (1978) 575, `doi:10.1016/0370-2693(78)90858-4`.

[13] CMS Collaboration, "Search for supersymmetry in proton-proton collisions at 13 TeV in final states with jets and missing transverse momentum", *JHEP* **10** (2019) 244, `doi:10.1007/JHEP10(2019)244`, `arXiv:1908.04722`.

[14] CMS Collaboration, "Searches for physics beyond the standard model with the M_{T2} variable in hadronic final states with and without disappearing tracks in proton-proton collisions at $\sqrt{s} = 13$ TeV", *Eur. Phys. J. C* **80** (2020) 3, `doi:10.1140/epjc/s10052-019-7493-x`, `arXiv:1909.03460`.

[15] CMS Collaboration, "Search for supersymmetry in pp collisions at $\sqrt{s} = 13$ TeV with 137 fb^{-1} in final states with a single lepton using the sum of masses of large-radius jets", *Phys. Rev. D* **101** (2020) 052010, `doi:10.1103/PhysRevD.101.052010`, `arXiv:1911.07558`.

[16] CMS Collaboration, "Search for physics beyond the standard model in events with jets and two same-sign or at least three charged leptons in proton-proton collisions at $\sqrt{s} =$ 13 TeV", *Eur. Phys. J. C* **80** (2020) 752, `doi:10.1140/epjc/s10052-020-8168-3`, `arXiv:2001.10086`.

[17] H. Baer et al., "Natural SUSY with a bino- or wino-like LSP", *Phys. Rev. D* **91** (2015) 075005, `doi:10.1103/PhysRevD.91.075005`, `arXiv:1501.06357`.

[18] N. Arkani-Hamed et al., "MARMOSET: The path from LHC data to the new standard model via on-shell effective theories", (2007). `arXiv:hep-ph/0703088.`.

[19] J. Alwall, M.-P. Le, M. Lisanti, and J. G. Wacker, "Model-independent jets plus missing energy searches", *Phys. Rev. D* **79** (2009) 015005, `doi:10.1103/PhysRevD.79.015005`, `arXiv:0809.3264`.

[20] J. Alwall, P. Schuster, and N. Toro, "Simplified models for a first characterization of new physics at the LHC", *Phys. Rev. D* **79** (2009) 075020, `doi:10.1103/PhysRevD.79.075020`, `arXiv:0810.3921`.

[21] D. Alves et al., "Simplified models for LHC new physics searches", *J. Phys. G* **39** (2012) 105005, `doi:10.1088/0954-3899/39/10/105005`, `arXiv:1105.2838`.

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

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

[24] 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`.

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

[26] R. Frederix and S. Frixione, "Merging meets matching in MC@NLO", *JHEP* **12** (2012) 061, `doi:10.1007/JHEP12(2012)061`, `arXiv:1209.6215`.

[27] 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`.

[28] 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`.

[29] 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`.

[30] S. Alioli, P. Nason, C. Oleari, and E. Re, "NLO single-top production matched with shower in POWHEG: s- and t-channel contributions", *JHEP* **09** (2009) 111, `doi:10.1088/1126-6708/2009/09/111`, `arXiv:0907.4076`. [Erratum: `doi:10.1007/JHEP02(2010)011`].

[31] E. Re, "Single-top Wt-channel production matched with parton showers using the POWHEG method", *Eur. Phys. J. C* **71** (2011) 1547, `doi:10.1140/epjc/s10052-011-1547-z`, `arXiv:1009.2450`.

[32] T. Melia, P. Nason, R. Rontsch, and G. Zanderighi, "W^+W^-, WZ and ZZ production in the POWHEG BOX", *JHEP* **11** (2011) 078, `doi:10.1007/JHEP11(2011)078`, `arXiv:1107.5051`.

[33] M. Beneke, P. Falgari, S. Klein, and C. Schwinn, "Hadronic top-quark pair production with NNLL threshold resummation", *Nucl. Phys. B* **855** (2012) 695, `doi:10.1016/j.nuclphysb.2011.10.021`, `arXiv:1109.1536`.

[34] M. Cacciari et al., "Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation", *Phys. Lett. B* **710** (2012) 612, `doi:10.1016/j.physletb.2012.03.013`, `arXiv:1111.5869`.

[35] P. Bärnreuther, M. Czakon, and A. Mitov, "Percent-level-precision physics at the Tevatron: next-to-next-to-leading order QCD corrections to $\mathrm{q\overline{q}} \to \mathrm{t\overline{t}} + X$", *Phys. Rev. Lett.* **109** (2012) 132001, `doi:10.1103/PhysRevLett.109.132001`, `arXiv:1204.5201`.

[36] M. Czakon and A. Mitov, "NNLO corrections to top-pair production at hadron colliders: the all-fermionic scattering channels", *JHEP* **12** (2012) 054, `doi:10.1007/JHEP12(2012)054`, `arXiv:1207.0236`.

[37] M. Czakon and A. Mitov, "NNLO corrections to top pair production at hadron colliders: the quark-gluon reaction", *JHEP* **01** (2013) 080, `doi:10.1007/JHEP01(2013)080`, `arXiv:1210.6832`.

[38] M. Czakon, P. Fiedler, and A. Mitov, "Total top-quark pair-production cross section at hadron colliders through $O(\alpha_S^4)$", *Phys. Rev. Lett.* **110** (2013) 252004, `doi:10.1103/PhysRevLett.110.252004`, `arXiv:1303.6254`.

[39] R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, "W physics at the LHC with FEWZ 2.1", *Comput. Phys. Commun.* **184** (2013) 208, `doi:10.1016/j.cpc.2012.09.005`, `arXiv:1201.5896`.

[40] R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, "FEWZ 2.0: A code for hadronic Z production at next-to-next-to-leading order", *Comput. Phys. Commun.* **182** (2011) 2388, `doi:10.1016/j.cpc.2011.06.008`, `arXiv:1011.3540`.

[41] W. Beenakker, R. Höpker, M. Spira, and P. M. Zerwas, "Squark and gluino production at hadron colliders", *Nucl. Phys. B* **492** (1997) 51, `doi:10.1016/S0550-3213(97)00084-9`, `arXiv:hep-ph/9610490`.

[42] A. Kulesza and L. Motyka, "Threshold resummation for squark-antisquark and gluino-pair production at the LHC", *Phys. Rev. Lett.* **102** (2009) 111802, `doi:10.1103/PhysRevLett.102.111802`, `arXiv:0807.2405`.

[43] A. Kulesza and L. Motyka, "Soft gluon resummation for the production of gluino-gluino and squark-antisquark pairs at the LHC", *Phys. Rev. D* **80** (2009) 095004, `doi:10.1103/PhysRevD.80.095004`, `arXiv:0905.4749`.

[44] W. Beenakker et al., "Soft-gluon resummation for squark and gluino hadroproduction", *JHEP* **12** (2009) 041, `doi:10.1088/1126-6708/2009/12/041`, `arXiv:0909.4418`.

[45] W. Beenakker et al., "Squark and gluino hadroproduction", *Int. J. Mod. Phys. A* **26** (2011) 2637, `doi:10.1142/S0217751X11053560`, `arXiv:1105.1110`.

[46] W. Beenakker et al., "NNLL-fast: predictions for coloured supersymmetric particle production at the LHC with threshold and Coulomb resummation", *JHEP* **12** (2016) 133, `doi:10.1007/JHEP12(2016)133`, `arXiv:1607.07741`.

[47] W. Beenakker et al., "NNLL resummation for squark-antisquark pair production at the LHC", *JHEP* **01** (2012) 076, `doi:10.1007/JHEP01(2012)076`, `arXiv:1110.2446`.

[48] W. Beenakker et al., "Towards NNLL resummation: hard matching coefficients for squark and gluino hadroproduction", *JHEP* **10** (2013) 120, `doi:10.1007/JHEP10(2013)120`, `arXiv:1304.6354`.

[49] W. Beenakker et al., "NNLL resummation for squark and gluino production at the LHC", *JHEP* **12** (2014) 023, `doi:10.1007/JHEP12(2014)023`, `arXiv:1404.3134`.

[50] W. Beenakker et al., "Stop production at hadron colliders", *Nucl. Phys. B* **515** (1998) 3, `doi:10.1016/S0550-3213(98)00014-5`, `arXiv:hep-ph/9710451`.

[51] W. Beenakker et al., "Supersymmetric top and bottom squark production at hadron colliders", *JHEP* **08** (2010) 098, `doi:10.1007/JHEP08(2010)098`, `arXiv:1006.4771`.

[52] W. Beenakker et al., "NNLL resummation for stop pair-production at the LHC", *JHEP* **05** (2016) 153, `doi:10.1007/JHEP05(2016)153`, `arXiv:1601.02954`.

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

[54] 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`.

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

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

[57] NNPDF Collaboration, "Parton distributions from high-precision collider data", *Eur. Phys. J. C* **77** (2017) 663, `doi:10.1140/epjc/s10052-017-5199-5`, `arXiv:1706.00428`.

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

[59] 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`.

[60] 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`.

[61] 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`.

[62] 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`.

[63] CMS Collaboration, "Jet performance in pp collisions at $\sqrt{s} = 7$ TeV", CMS Physics Analysis Summary CMS-PAS-JME-10-003, 2010.

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

[65] 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`.

[66] M. Cacciari and G. P. Salam, "Pileup subtraction using jet areas", *Phys. Lett. B* **659** (2008) 119, `doi:10.1016/j.physletb.2007.09.077`, `arXiv:0707.1378`.

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

[68] D. Bertolini, P. Harris, M. Low, and N. Tran, "Pileup Per Particle Identification", *JHEP* **10** (2014) 059, `doi:10.1007/JHEP10(2014)059`, `arXiv:1407.6013`.

[69] 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`.

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

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

[72] K. Rehermann and B. Tweedie, "Efficient identification of boosted semileptonic top quarks at the LHC", *JHEP* **03** (2011) 059, `doi:10.1007/JHEP03(2011)059`, `arXiv:1007.2221`.

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

[74] UA1 Collaboration, "Experimental observation of isolated large transverse energy electrons with associated missing energy at $\sqrt{s} = 540$ GeV", *Phys. Lett. B* **122** (1983) 103, `doi:10.1016/0370-2693(83)91177-2`.

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

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

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

[78] S. Catani, D. de Florian, M. Grazzini, and P. Nason, "Soft gluon resummation for Higgs boson production at hadron colliders", *JHEP* **07** (2003) 028, `doi:10.1088/1126-6708/2003/07/028`, `arXiv:hep-ph/0306211`.

[79] M. Cacciari et al., "The $\mathrm{t\bar{t}}$ cross-section at 1.8 TeV and 1.96 TeV: a study of the systematics due to parton densities and scale dependence", *JHEP* **04** (2004) 068, `doi:10.1088/1126-6708/2004/04/068`, `arXiv:hep-ph/0303085`.

[80] 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`].

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

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

[83] ATLAS and CMS Collaborations, "Procedure for the LHC Higgs boson search combination in Summer 2011", Technical Report CMS-NOTE-2011-005, ATL-PHYS-PUB-2011-11, 2011.

[84] C. Borschensky et al., "Squark and gluino production cross sections in pp collisions at $\sqrt{s}$ = 13, 14, 33 and 100 TeV", *Eur. Phys. J. C* **74** (2014) 3174, `doi:10.1140/epjc/s10052-014-3174-y`, `arXiv:1407.5066`.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan[†], A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, R. Frühwirth[1], M. Jeitler[1], N. Krammer, L. Lechner, D. Liko, T. Madlener, I. Mikulec, F.M. Pitters, N. Rad, J. Schieck[1], R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz[1], M. Zarucki

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

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

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, A. Morton, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, M. Gruchala, I. Khvastunov[4], M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Teklishyn, P. Vischia, S. Wuyckens, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, E. Belchior Batista Das Chagas, H. BRANDAO MALBOUISSON, W. Carvalho, J. Chinellato[5], E. Coelho, E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, J. Martins[7], D. Matos Figueiredo, M. Medina Jaime[8], M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, E.J. Tonelli Manganote[5], F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

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

Beihang University, Beijing, China
W. Fang[3], Q. Guo, H. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China
E. Chapon, G.M. Chen[9], H.S. Chen[9], M. Chen, A. Kapoor, D. Leggat, H. Liao, Z. Liu, R. Sharma, A. Spiezia, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang[9], J. Zhao

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

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

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

Zhejiang University, Hangzhou, China
M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia
J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, 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, D. Majumder, M. Roguljic, A. Starodumov[10], T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger[11], M. Finger Jr.[11], A. Kveton, J. Tomsa

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
H. Abdalla[12], S. Khalil[13], A. Mohamed[13]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M.A. Mahmoud, Y. Mohammed[14]

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, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

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

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[15], M. Titov, G.B. Yu

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

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[16], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine[16], D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze[11], Z. Tsamalaidze[11]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee,

D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[17], O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[18], T. Ziemons

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras[19], V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, A. De Wit, M.M. Defranchis, L. Didukh, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, L.I. Estevez Banos, E. Gallo[20], A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari[21], N.Z. Jomhari, H. Jung, A. Kasem[19], M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann[22], R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otarid, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, P. Schütze, C. Schwanenberger, A. Singh, R.E. Sosa Ricardo, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, A. Ebrahimi, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, V. Kutzner, J. Lange, T. Lange, A. Malara, C.E.N. Niemeyer, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
M. Baselga, S. Baur, J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, A. Gottmann, F. Hartmann[18], C. Heidecker, U. Husemann, M.A. Iqbal, I. Katkov[23], P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, D. Müller, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, D. Schäfer, M. Schnepf, M. Schröder, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, R. Wolf, S. Wozniewski

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

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

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

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

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Bartók[24], R. Chudasama, M. Csanad, M.M.A. Gadallah[25], S. Lökös[26], P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[27], F. Sikler, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
S. Czellar, J. Karancsi[24], J. Molnar, Z. Szillasi, D. Teyssier

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

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
T. Csorgo, F. Nemes, T. Novak

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

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[28], D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak[29], D.K. Sahoo[28], N. Sur, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra[30], R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
M. Bharti[31], R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber[32], M. Maity[33], S. Nandan, P. Palit, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh[31], S. Thakur[31]

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India
D. Dutta, V. Kumar, K. Naskar[34], P.K. Netrakanti, L.M. Pant, P. Shukla

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

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy, N. Sahoo

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

Department of Physics, Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[35]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[36], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

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

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,37], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], A. Di Pilato[a,b], W. Elmetenawee[a,b], L. Fiore[a], A. Gelmi[a,b], M. Gul[a], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], J.A. Merlin[a], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a,b], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], C. Ciocca[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi[a,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,38], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b,39], S. Costa[a,b], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,39], C. Tuve[a,b]

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

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

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

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], A. Beschi[a,b], F. Brivio[a,b], F. Cetorelli[a,b], V. Ciriolo[a,b,18], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M. Malberti[a], S. Malvezzi[a], D. Menasce[a], F. Monti[a,b], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Valsecchi[a,b,18], D. Zuolo[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], F. Fienga[a], A.O.M. Iorio[a,b], L. Lista[a,b], S. Meola[a,d,18], P. Paolucci[a,18], B. Rossi[a], C. Sciacca[a,b], E. Voevodina[a,b]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], A. Boletti[a,b], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], P. De Castro Manzano[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], S.Y. Hoh[a,b], L. Layer[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Presilla[b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong, A. Tiko[a], M. Tosi[a,b], H. YARAR[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

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

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

INFN 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], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], M.R. Di Domenico[a,b], S. Donato[a], 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], G. Ramirez-Sanchez[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,c], A. Scribano[a], N. Shafiei[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a], A. Venturi[a], P.G. Verdini[a]

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

INFN 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], A. Bellora[a,b], C. Biino[a], A. Cappati[a,b], N. Cartiglia[a], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], F. Legger[a], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], M. Ruspa[a,c], R. Salvatico[a,b], F. Siviero[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], D. Trocino[a,b]

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

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

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

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

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, S. Ha, 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
J. Goh, A. Gurtu

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

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

University of Seoul, Seoul, Korea
D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson

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

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

Riga Technical University, Riga, Latvia
V. Veckalns[40]

Vilnius University, Vilnius, Lithuania
A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[41], R. Lopez-Fernandez, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, 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 Montenegro, Podgorica, Montenegro
J. Mijuskovic[4], N. Raicevic

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.I. Asghar, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

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

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[42], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

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

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev[43,44], P. Moisenz, V. Palichik, V. Perelygin, M. Savina, D. Seitova, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, A. Zarubin, I. Zhizhin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[45], E. Kuznetsova[46], V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

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

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[47], V. Popov, G. Safronov, A. Spiridonov, A. Stepennov, 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
O. Bychkova, M. Chadeeva[48], D. Philippov, 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, M. Dubinin[49], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov[50], T. Dimova[50], L. Kardapoltsev[50], I. Ovtin[50], Y. Skovpen[50]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, V. Kachanov, A. Kalinin, D. Konstantinov, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

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

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[51], P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic

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

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, S. Sanchez Cruz, A. Trapote

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, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
MK Jayananda, B. Kailasapathy[52], D.U.J. Sonnadara, DDC Wickramarathna

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland
T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, G. Cerminara, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita[53], D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Guilbaud, D. Gulhan, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Orfanelli, L. Orsini, F. Pantaleo[18], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[54], J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[55], W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
C. Amsler[56], C. Botta, D. Brzhechko, M.F. Canelli, R. Del Burgo, J.K. Heikkilä, M. Huwiler, A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, K. Schweiger, Y. Takahashi, S. Wertz

National Central University, Chung-Li, Taiwan
C. Adloff[57], C.M. Kuo, W. Lin, A. Roy, T. Sarkar[33], S.S. Yu

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

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

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
F. Boran, S. Damarseckin[58], Z.S. Demiroglu, F. Dolek, C. Dozen[59], I. Dumanoglu[60], E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler[61], I. Hos[62], C. Isik, E.E. Kangal[63], O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[64], A. Polatoz, A.E. Simsek, B. Tali[65], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[66], G. Karapinar[67], K. Ocalan[68], M. Yalvac[69]

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya[70], O. Kaya[71], Ö. Özçelik, S. Tekten[72], E.A. Yetkin[73]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[60], Y. Komurcu, S. Sen[74]

Istanbul University, Istanbul, Turkey
F. Aydogmus Sen, S. Cerci[65], B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci[65]

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
E. Bhal, S. Bologna, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[75], C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder,

S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, V. Cepaitis, G.S. Chahal[76], D. Colling, P. Dauncey, G. Davies, M. Della Negra, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash[77], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee[18], N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

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

Baylor University, Waco, USA
A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, C. Madrid, B. McMaster, N. Pastika, S. Sawant, C. Smith, J. Wilson

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

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

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

Brown University, Providence, USA
G. Benelli, B. Burkle, X. Coubez[19], D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan[78], K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir[79], R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko[†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Y. Yao, F. Zhang

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

University of California, Riverside, Riverside, USA
K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, USA
J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, J. Duarte, R. Gerosa, D. Gilbert, B. Hashemi, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

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

Carnegie Mellon University, Pittsburgh, USA
J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, Y. Cheng, J. Chu, D.J. Cranshaw, A. Datta, A. Frankenthal, K. Mcdermott, J. Monroy, J.R. Patterson, D. Quach, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena[49], O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, A. Woodard

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

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

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, S. Butalla, T. Elkafrawy[80], M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

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

The University of Iowa, Iowa City, USA
M. Alhusseini, K. Dilsiz[81], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[82], A. Moeller, J. Nachtman, H. Ogul[83], Y. Onel, F. Ozok[84], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi[85]

Johns Hopkins University, Baltimore, USA

O. Amram, B. Blumenfeld, L. Corcodilos, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, C. Mantilla, J. Roskes, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, USA
C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

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

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

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

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

University of Minnesota, Minneapolis, USA
R.M. Chatterjee, A. Evans, S. Guts[†], P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, I. Kravchenko, J.E. Siado, G.R. Snow[†], B. Stieger, W. Tabb, F. Yan

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

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

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

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko[43], R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf, L. Zygala

The Ohio State University, Columbus, USA
J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

Princeton University, Princeton, USA
P. Das, G. Dezoort, P. Elmer, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

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

Purdue University, West Lafayette, USA
V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, M. Stojanovic[15], N. Trevisani, F. Wang, R. Xiao, W. Xie

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

Rice University, Houston, USA
A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts[†], J. Rorie, W. Shi, A.G. Stahl Leiton

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

Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban[22], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

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

Texas A&M University, College Station, USA
O. Bouhali[86], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[87], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov, J. Sturdy

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

Vanderbilt University, Nashville, USA
E. Appelt, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

University of Virginia, Charlottesville, USA
M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
P.E. Karchin, N. Poudyal, P. Thapa

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

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at Department 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 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
5: Also at Universidade Estadual de Campinas, Campinas, Brazil
6: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
7: Also at UFMS, Nova Andradina, Brazil
8: Also at Universidade Federal de Pelotas, Pelotas, Brazil
9: Also at University of Chinese Academy of Sciences, Beijing, China
10: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
11: Also at Joint Institute for Nuclear Research, Dubna, Russia
12: Also at Cairo University, Cairo, Egypt
13: Also at Zewail City of Science and Technology, Zewail, Egypt
14: Now at Fayoum University, El-Fayoum, Egypt
15: Also at Purdue University, West Lafayette, USA
16: Also at Université de Haute Alsace, Mulhouse, France
17: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
18: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
19: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
20: Also at University of Hamburg, Hamburg, Germany
21: Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran
22: Also at Brandenburg University of Technology, Cottbus, Germany
23: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
24: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
25: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
26: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
27: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
28: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
29: Also at Institute of Physics, Bhubaneswar, India
30: Also at G.H.G. Khalsa College, Punjab, India
31: Also at Shoolini University, Solan, India
32: Also at University of Hyderabad, Hyderabad, India
33: Also at University of Visva-Bharati, Santiniketan, India
34: Also at Indian Institute of Technology (IIT), Mumbai, India
35: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
36: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran

37: Now at INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
38: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
39: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
40: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
41: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
42: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
43: Also at Institute for Nuclear Research, Moscow, Russia
44: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
45: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
46: Also at University of Florida, Gainesville, USA
47: Also at Imperial College, London, United Kingdom
48: Also at P.N. Lebedev Physical Institute, Moscow, Russia
49: Also at California Institute of Technology, Pasadena, USA
50: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
51: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
52: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
53: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy, Pavia, Italy
54: Also at National and Kapodistrian University of Athens, Athens, Greece
55: Also at Universität Zürich, Zurich, Switzerland
56: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
57: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
58: Also at Şırnak University, Sirnak, Turkey
59: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China
60: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
61: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
62: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
63: Also at Mersin University, Mersin, Turkey
64: Also at Piri Reis University, Istanbul, Turkey
65: Also at Adiyaman University, Adiyaman, Turkey
66: Also at Ozyegin University, Istanbul, Turkey
67: Also at Izmir Institute of Technology, Izmir, Turkey
68: Also at Necmettin Erbakan University, Konya, Turkey
69: Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
70: Also at Marmara University, Istanbul, Turkey
71: Also at Milli Savunma University, Istanbul, Turkey
72: Also at Kafkas University, Kars, Turkey
73: Also at Istanbul Bilgi University, Istanbul, Turkey
74: Also at Hacettepe University, Ankara, Turkey
75: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
76: Also at IPPP Durham University, Durham, United Kingdom
77: Also at Monash University, Faculty of Science, Clayton, Australia
78: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
79: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

80: Also at Ain Shams University, Cairo, Egypt
81: Also at Bingol University, Bingol, Turkey
82: Also at Georgian Technical University, Tbilisi, Georgia
83: Also at Sinop University, Sinop, Turkey
84: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
85: Also at Nanjing Normal University Department of Physics, Nanjing, China
86: Also at Texas A&M University at Qatar, Doha, Qatar
87: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea