



Search for displaced leptons in $\sqrt{s} = 13$ TeV and 13.6 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

A search for leptons displaced from the primary vertex is performed with the ATLAS detector at the Large Hadron Collider. The search includes the full proton–proton collision dataset collected during Run 2 at $\sqrt{s} = 13$ TeV and a partial dataset collected during Run 3 in 2022–2023 at $\sqrt{s} = 13.6$ TeV, corresponding to integrated luminosities of 140 fb^{-1} and 56.3 fb^{-1} , respectively. Final states with displaced electrons or muons are considered, and novel triggers introduced in Run 3 are employed that use large impact parameter tracking to reconstruct displaced tracks with low momentum. In addition, photon reconstruction and multivariate techniques are employed to broaden the sensitivity to channels with large background rates or highly displaced electrons, respectively. The results are consistent with the Standard Model background expectations and are used to set model-independent limits on the production of displaced electrons and muons. The analysis is also interpreted in the context of a gauge-mediated supersymmetry breaking model with pair-produced long-lived sleptons, and a dark sector model with pair-produced chargino-like states. The results include 95% CL exclusions of selectrons with lifetimes from 4 ps to 60 ns and a mass of 150 GeV, and exclusions of selectrons, smuons, and staus with a lifetime of 0.3 ns for masses up to 740 GeV, 830 GeV, and 440 GeV, respectively. Dark charginos with masses up to 380 GeV are excluded for a mass difference with the neutral state of 40 GeV, and mass differences down to 17 GeV are excluded for dark charginos with a 100 GeV mass.

1 Introduction

Long-lived particles (LLPs) occur in the Standard Model (SM), and are predicted in a wide variety of beyond-the-SM (BSM) scenarios, including both R -parity-conserving [1–7] and R -parity-violating supersymmetry (SUSY) [8, 9], split-SUSY [10, 11], gauge-mediated SUSY breaking (GMSB) [12–14], universal extra dimensions [15, 16], and Hidden Valley models [17]. Most searches for BSM physics at the Large Hadron Collider (LHC) [18] experiments assume that BSM particles decay promptly, producing final state particles with trajectories consistent with an origin at the primary proton–proton (pp) interaction point. By contrast, LLPs with lifetimes longer than a few picoseconds travel at least hundreds of microns before decaying. Their decay products can thus be displaced from the primary vertex (PV), the vertex with the largest sum of squared track transverse momentum, or delayed with respect to the bunch crossing. Reconstruction of the decay products can pose technical challenges that could have caused them to elude detection in prior searches.

This paper presents a search for BSM physics producing events with two displaced light leptons (electrons or muons). The search is performed with inclusive selection criteria to enable broad sensitivity to BSM models producing LLPs, with lifetimes from a few ps up to of order 100 ns, that decay into electrons or muons. The sensitivity of the search is illustrated using a GMSB SUSY model [19–21] in which the lightest SUSY particle (LSP) is a nearly massless gravitino (\tilde{G}) and the next-to-lightest SUSY particle (NLSP) is a slepton ($\tilde{\ell}$), which can be either a selectron (\tilde{e}), smuon ($\tilde{\mu}$), or stau ($\tilde{\tau}$). The slepton can acquire a long lifetime due to its small gravitational coupling to the gravitino LSP. As shown in Figure 1, the NLSP can be pair-produced, and then each decays into a charged SM lepton (ℓ) of the same flavor and a gravitino LSP, yielding events containing two displaced leptons. GMSB models often predict that staus are the NLSP [22].

Previous results setting limits on these processes include an ATLAS search using the full Run 2 dataset, consisting of 140 fb^{-1} of pp collisions collected at $\sqrt{s} = 13 \text{ TeV}$, which excluded selectrons, smuons, and staus with masses up to 720 GeV, 680 GeV, and 340 GeV, respectively, for a slepton lifetime of 0.1 ns [23], dramatically enhancing the sensitivity with respect to prior constraints from the LEP experiments [24–28]. A CMS search based on 113–118 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ pp collision data extended the stau mass reach to 405 GeV for a similar lifetime [29]. A subsequent full Run 2 ATLAS search for muons with intermediate displacements, in between those of the displaced and prompt lepton searches, extended the sensitivity to GMSB smuons with lifetimes below about 0.01 ns [30].

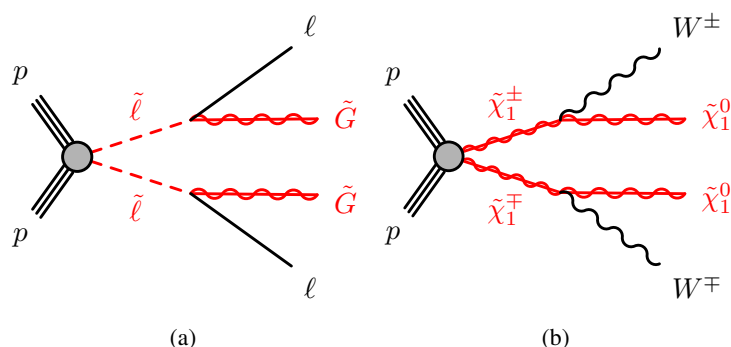


Figure 1: Diagrams of the (a) GMSB slepton and (b) dark sector models.

Interpretations are also performed using a Higgs portal model that introduces a dark sector consisting of a charged state ($\tilde{\chi}^\pm$) and neutral state ($\tilde{\chi}^0$) with mass difference $\Delta m \equiv m(\tilde{\chi}^\pm) - m(\tilde{\chi}^0)$ [31], which can produce the observed dark matter relic density for $10 \lesssim \Delta m \lesssim 40$ GeV [32]. For the signal process $\tilde{\chi}^+ \tilde{\chi}^- \rightarrow W^+ W^- \tilde{\chi}^0 \tilde{\chi}^0$ shown in Figure 1, the charged state can acquire a non-negligible lifetime due to the weak coupling between the dark states and the W boson. This results in events with two displaced leptons if the W bosons decay leptonically, the same final state as with the GMSB slepton model. However, with this model the leptons tend to have lower p_T since the lighter neutral state is massive, highlighting the need for improved low-momentum lepton acceptance. In SUSY models, as assumed here, the chargino and neutralino play the roles of the new charged and neutral states, respectively, and chargino-pair production cross-section is used for the signal model.

This result enhances the discovery reach for displaced leptons beyond that of prior searches through several novel additions. It includes data collected by the ATLAS detector at a center-of-mass energy of 13.6 TeV, new triggers introduced in Run 3 that exploit improved tracking capabilities of the high-level trigger (HLT) to enable lower lepton transverse momentum (p_T) thresholds, as well as improved offline tracking performance that greatly lowers the rate of incorrectly reconstructed displaced tracks [33]. Precision information from the ATLAS Liquid Argon (LAr) electromagnetic (EM) calorimeter is introduced for sensitivity to highly displaced electrons, which may fail to include reconstructed tracks and be reconstructed as photons. Finally, the analysis includes a first consideration of single displaced electron channels, which were previously inaccessible due to high background rates and are enabled using multivariate Boosted Decision Trees (BDTs).

The analysis combines two approaches with mutually exclusive selections: the ‘‘ABCD’’ search and the ‘‘EM-BDT’’ search. In both cases, backgrounds are determined with entirely data-driven methods, and Monte Carlo (MC) simulation is only used for signal models. The ABCD search targets dilepton events, requiring at least two electrons, two muons, or an electron and a muon, and uses similar techniques as the prior Run 2 ATLAS displaced leptons search [23] for the estimation of backgrounds from fake and heavy-flavor (FHF) leptons and cosmic-ray muons. The ABCD search is performed in two orthogonal sets of signal regions (SRs) with different triggers and lepton p_T thresholds. The ‘‘high- p_T ’’ SRs use a similar selection as the prior Run 2 search [23], and the new large-radius tracking (LRT) SRs use novel Run 3 triggers that employ LRT [34] (see Section 2.2) to extend the trigger tracking to large transverse impact parameter ($|d_0|$) values, thus enabling reduced lepton thresholds with respect to Run 2. A separate EM-BDT search also exploits the new LRT trigger for electrons, and leverages precision tracking and electromagnetic calorimeter information (see Section 2.3) to improve the displaced e/γ selection, building on previous ATLAS Run 2 searches for displaced photons [35, 36]. The LRT channel of the ABCD search and the EM-BDT search both use 56.3 fb^{-1} of Run 3 data collected at $\sqrt{s} = 13.6$ TeV in 2022–2023, while the ABCD high- p_T channel also uses the full Run 2 dataset of 140 fb^{-1} collected at $\sqrt{s} = 13$ TeV.

The paper is organized as follows. Section 2 describes the ATLAS detector, with specific emphasis on the unique LRT and LAr reconstruction techniques employed in the analysis. Section 3 describes the data and simulated samples used, and selections for objects and analysis events are given in Section 4. Descriptions of the ABCD (Section 5) and EM-BDT (Section 6) analyses follow, including detailed event selections, background estimations, and systematic uncertainties. Finally, results and interpretations are presented in Section 8, followed by brief conclusions.

2 ATLAS detector

The ATLAS detector [37, 38] at the LHC covers nearly the entire solid angle around the collision point.¹ It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnet systems.

2.1 Detector subsystems

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the interaction region and typically provides four measurements per track, the first hit generally being in the insertable B-layer (IBL). It is followed by the SemiConductor Tracker (SCT), which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to $|\eta| = 2.0$. The TRT also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy-deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, EM calorimetry is provided by barrel and endcap high-granularity lead/LAr calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for electromagnetic and hadronic energy measurements, respectively.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, cover the region $|\eta| < 2.7$, except in the innermost layer of the endcap region, where layers of small-strip thin-gap chambers and Micromegas chambers both provide precision tracking in the region $1.3 < |\eta| < 2.7$. The muon trigger system covers the range $|\eta| < 2.4$ with resistive-plate chambers in the barrel, thin-gap chambers in the endcap regions, and the aforementioned small-strip thin-gap chambers and Micromegas chambers in the innermost layer of the endcap. These replaced cathode-strip chambers that were used through Run 2.

The luminosity is measured mainly by the LUCID-2 detector that records Cherenkov light produced in the quartz windows of photomultipliers located close to the beampipe.

Events are selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the HLT [34, 39]. The first-level trigger accepts events

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the center of the LHC ring, and the y -axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$.

from the 40 MHz bunch crossings at a rate below 100 kHz, which the high-level trigger further reduces in order to record complete events to disk.

The Run 3 detector configuration benefits from several upgrades compared with that of Run 2 to maintain high detector performance at the higher pileup levels of Run 3. The improvements include a new innermost layer of the muon spectrometer in the endcap region, which provides higher redundancy and a large reduction in fake muon triggers. The trigger system also benefits from new LAr digital electronics with significantly increased granularity. Other updates and further details are provided in Ref. [38]. A software suite [40] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

As described in more detail below, this analysis exploits some specialized capabilities of the ATLAS detector and its TDAQ system. These include LRT (see Section 2.2), which is the ability to reconstruct tracks with a large impact parameter with respect to the PV, and the ability of the EM calorimeter to measure the flight direction and time-of-arrival of particles causing EM showers (see Section 2.3).

2.2 Large radius tracking

The standard ATLAS tracking algorithm is designed to reconstruct the trajectory of promptly produced charged particles. It is efficient out to a $|d_0|$ of 5 mm, limiting its usefulness for LLPs that decay into charged particles after traversing part of the detector. The LRT [41] is a configuration of the tracking algorithm designed to increase the tracking efficiency for decay products of LLPs. Figure 2(a) shows an example $|d_0|$ distribution, extending well past 5 mm, for several models in the EM-BDT search, which combines both standard and LRT tracking. For the offline reconstruction of data, it is implemented as a second pass, running on the remaining hits that were not used by the standard tracking, with a looser restriction on the impact parameters and other optimizations, e.g. in the seeding step. Large radius tracks are reconstructed out to a $|d_0|$ of 300 mm, the first layer of the SCT. Compared to previous searches during Run 2, the LRT configuration in the reconstruction software was improved to greatly reduce the number of incorrectly reconstructed tracks as well as to reduce the computation time, allowing LRT tracks to be reconstructed in all events.

In Run 3, LRT is run in the HLT for the first time [34]. For signal-like electrons and muons, the LRT used in the HLT is expected to be more than 80% efficient with respect to offline reconstruction for $|d_0| < 125$ mm. This is possible due to improvements in the LRT computation time, the HLT tracking algorithms, and the HLT computing resources. LRT for leptons in the trigger is implemented as a single pass, running on all hits in small regions around lepton candidates from the first-level trigger, with the same looser restrictions on impact parameters and similar optimizations as the offline reconstruction.

2.3 Electromagnetic calorimeter timing and pointing measurements

Electrons from the decays of massive LLPs could reach the LAr calorimeter with a slight delay compared to prompt electrons. This delay arises mostly from the LLP time-of-flight, which corresponds to a relativistic speed ($\beta = v/c$) that can be substantially less than one.

In addition, the opening angle in the LLP decay causes the electron to be “non-pointing”, arriving at the calorimeter from a direction that does not point directly back to the PV. This effect results in the geometrical path to the calorimeter being longer than that for a prompt electron from the PV, further increasing the

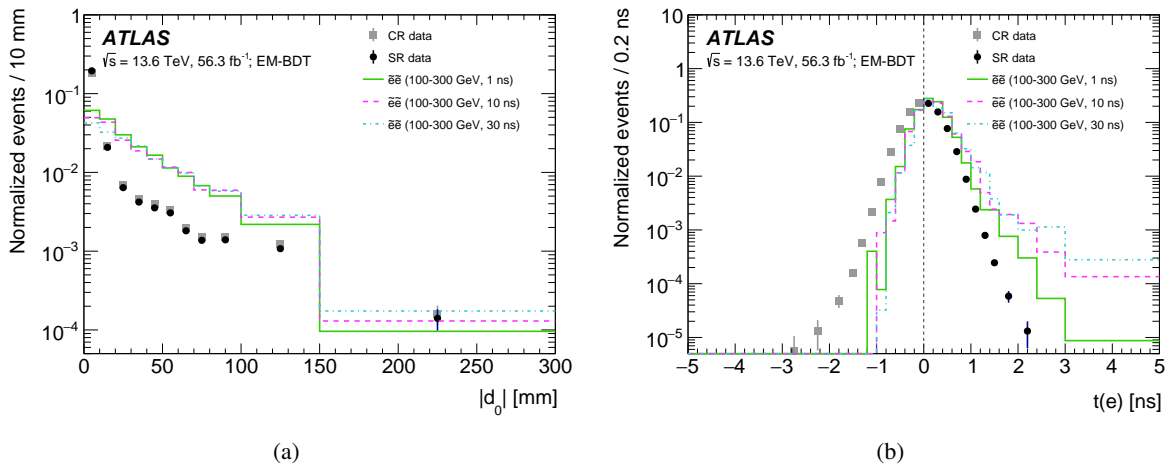


Figure 2: Distributions of the (a) $|d_0|$ and (b) LAr timing using the EM-BDT search regions with Run 3 data and selected signal samples with slepton masses of 100, 200, and 300 GeV. The LAr timing measurement was calibrated to zero for promptly produced particles traveling near the speed of light. The data events with negative times (gray squares) represent the signal-depleted control region (CR) used to determine the background estimate, while the data events with positive times (black circles) represent the signal region (SR) events on which the final search is performed. The SR data were blinded until the analysis strategy was finalized and the data were unblinded to determine the results.

delay in its arrival time. Figure 2(b) illustrates the delay in the timing distribution of several signal models in the EM-BDT SR.

As described in Refs. [35, 36] and references therein, the fine segmentation of the LAr EM calorimeter can be used to measure the flight direction of a particle (electron or photon) that produces an EM shower, while its accordion structure and fast readout allows precise measurement of the particle’s arrival time at the calorimeter. A line drawn through the centroids of the EM shower in the first two longitudinal layers is used to calculate the pointing value, defined as the difference between the position on the z -axis where the line crosses the beamline and the position of the PV. The resolution on the pointing measurement is ≈ 15 mm for an EM shower with energy of ≈ 50 – 100 GeV in the barrel. The arrival time is determined using the energy deposit from the second-layer EM calorimeter cell with the maximum energy deposit among cells in the associated EM shower ($E_{\text{cell}}^{\text{max}}$). For an electron with an energy in the range of interest, this cell typically contains about 20%–50% of the total energy deposited in the EM shower. The timing resolution is approximately 200 ps for EM showers with $E_{\text{cell}}^{\text{max}}$ greater than 20 GeV, and is dominated by the LHC beamsread.

3 Data and Simulation samples

Collision data collected by the ATLAS detector from the LHC’s $\sqrt{s} = 13$ TeV pp Run 2 (2015–2018) and $\sqrt{s} = 13.6$ TeV pp Run 3 (2022–2023) are used, with luminosities corresponding to 140 fb^{-1} and 56.3 fb^{-1} , respectively, after applying detector conditions and data quality requirements [42]. The uncertainty in the Run 2 integrated luminosity is 0.83% [43], for 2022 it is 2.2% [44], and for 2023 it is 2.0% [45], following the methodology discussed in Ref. [43], using the LUCID–2 detector [46] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters. The ABCD

Table 1: Summary of trigger thresholds used for the ABCD and EM-BDT analyses, based on the object topology. Trigger objects are denoted as γ for photons, e for electrons, and μ for muons, preceded by the multiplicity and followed by the p_T threshold in GeV. “MS-only” indicates triggers that only rely on the Muon Spectrometer (MS), and not the inner detector. For example, $2\gamma 50$ means a trigger requiring the presence of two photons with $p_T > 50$ GeV. The $1\mu 60$ MS-only trigger has a restriction of $|\eta| < 1.05$. The large-radius tracking (LRT) electron (muon) trigger has a $|d_0| > 3(2)$ mm requirement. None of the triggers have an isolation requirement. “OR” indicates a logical OR of multiple triggers.

Topology	Trigger Thresholds [GeV]
ABCD high- p_T	
if $\geq 1e$, $p_T > 160$ GeV	$1\gamma 140$
else if $\geq 2e$, $p_T > 60$ GeV	$2\gamma 50$
else if $\geq 1\mu$, $p_T > 60$ GeV, $ \eta < 1.07$	$1\mu 60$ (MS-only)
else if $e\mu$ (Run 3 only)	$\gamma 40\mu 40$ (MS-only)
else if $\mu\mu$ (Run 3 only)	$2\mu 50$ (MS-only)
ABCD LRT	
e , $p_T > 31$ GeV	$1e 30$ (LRT)
μ , $p_T > 21$ GeV	$1\mu 20$ (LRT)
EM-BDT	
$= 1e, 0\gamma$	$1e 30$ (LRT) OR $1\gamma 140$
$\geq 2e$ OR $(1e, 1\gamma)$	$1e 30$ (LRT) OR $2\gamma 50$ OR $1\gamma 140$
$\geq 2\gamma$	$2\gamma 50$ OR $1\gamma 140$

high- p_T search uses the Run 2 and Run 3 datasets. The ABCD LRT and EM-BDT searches use only the Run 3 data. Run 2 data was reconstructed with a consistent software suite [40] as used for Run 3 data to take advantage of developments, such as the improved LRT described in Section 2.2.

Data were collected with several triggers [34, 39] with signatures and thresholds that would accept events from displaced decays of leptons. Electron [47] and muon [48] triggers based on standard tracking [49] are efficient out to $|d_0|$ values of approximately 5 or 10 mm, respectively. Thus they are not optimal for saving events with LLPs of moderate lifetime. Photon triggers accept events with electrons, even if they are too displaced to reconstruct a track, but have higher energy thresholds than electron triggers. MS-only triggers accept events based on muon tracks in the MS, without the need for an inner-detector track; these also have higher thresholds and some have restrictions in η to additionally reduce the trigger rate. Thanks to the requirement of an inner detector track, LRT-based lepton triggers are able to save events with lower momentum thresholds of 30 and 20 GeV for electrons and muons, with $|d_0|$ thresholds of 3 and 2 mm, respectively. Table 1 lists the triggers used based on the analysis region and lepton topology.

For the baseline GMSB-motivated slepton signal model in Figure 1, MC simulation events are used to determine the lepton selection criteria and estimate the sensitivity in a simplified GMSB SUSY model with light sleptons and a 1 GeV gravitino LSP. The signal models are given by the slepton flavor, mass, and lifetime. For each slepton mass value, several slepton lifetimes were simulated, typically ranging from 1 ps to 30 ns. Since the distribution of particle flight distances follows an exponential distribution, it is possible to reweight the shape of that curve and thus generalize from the simulated samples to other lifetime values. Each event is assigned a weight according to a source signal lifetime, target signal lifetime, and the decay

of the event in question.

For the dark sector model in Figure 1(b), MC simulation is used to perform two scans of parameter space: varying the mass difference Δm and chargino mass for a fixed chargino lifetime of $\tau = 0.3$ ns, and varying the chargino lifetime and mass for a fixed $\Delta m = 40$ GeV. This choice was motivated by the analysis having the best expected sensitivity to the GMSB model for a lifetime of 0.3 ns, and a mass splitting of 40 GeV is the most favorable in terms of lepton p_T that is still consistent with the dark matter relic density. The W bosons are forced to decay into an electron or muon in the simulation.

Signal model MC simulation events with up to two additional partons at leading order are simulated using MADGRAPH5_aMC@NLO v2.6.1 [50] interfaced to PYTHIA 8.230 [51] with the A14 parameter set (tune) [52] along with the NNPDF2.31o parton distribution function (PDF) set [53]. GEANT4 [54] is used to simulate the propagation and decay of the slepton, but without preserving information about its chirality. To model the impact of multiple interactions that occur in the same and neighboring bunch crossings (pileup), each hard-scattering event is overlaid [55] with simulated minimum bias events generated by EPOS 2.0.1.4 [56, 57] with the EPOS LHC tune and PYTHIA 8.307 [58] with the NNPDF2.3 LO set of PDFs and A3 tune [59]. The 13 TeV wino-like chargino-pair and slepton-pair production cross-sections and uncertainties were calculated at next-to-leading-order (NLO) in α_s , with soft-gluon emission effects at next-to-leading-logarithm [60–67]. At 13.6 TeV, these were calculated at approximate next-to-next-to-leading-order in α_s matched with threshold resummation at the next-to-next-to-leading-logarithmic accuracy (aNNLO+NNLL) using an envelope of predictions with different factorization and renormalization scales and PDF sets [68]. The superpartners of the left- and right-handed leptons are assumed to have equal mass. The slepton-pair cross-section for a single flavor of $\tilde{\ell}$ with mass 100 GeV (800 GeV) is 0.37 ± 0.01 pb (0.059 ± 0.004 fb) at 13 TeV and 0.41 ± 0.01 pb (0.069 ± 0.008 fb) at 13.6 TeV. The chargino-pair cross-section for a mass of 300 GeV is 190 ± 13 fb at 13 TeV and 216 ± 9 fb at 13.6 TeV. A factor of 0.0642 is included to account for the branching ratio of the two W boson decays into electrons and muons.

4 Object selections and event preselections

The main objects used in this analysis are electrons and muons, including those produced in the decays of τ -leptons, and photons. Jets, including those from hadronically decaying τ -leptons, are also used in the procedure to remove ambiguities between nearby reconstructed objects (“overlap removal”) and to construct the magnitude of the missing transverse momentum (E_T^{miss}), which is used in the EM-BDT analysis.

For electrons, muons, and photons, a baseline selection is used for the overlap removal procedure. For electrons and muons, additional kinematic requirements are imposed before separating events into the ABCD and EM-BDT regions; these are referred to as high- d_0 leptons in the paragraphs below. Analysis dependent selections are then applied to high- d_0 leptons to define signal leptons that are used to construct SRs, which are used to search for signal-like excesses above SM expectations. Table 2 summarizes the baseline and signal lepton selection requirements, with more details in the following text.

Electrons are reconstructed from ID tracks matched to clusters of energy deposited in the EM calorimeter. If a standard and large-radius track both point to the same EM cluster and lead to the reconstruction of a standard and LRT electron with the same cluster, the electron satisfying the stricter identification requirement is kept, and in case of a tie, the electron reconstructed with a standard track is kept. Baseline electrons must have $p_T > 10$ GeV, $|\eta| < 2.47$, and satisfy a modified version of the *VeryLoose* identification working point (WP) [69] that does not depend on $|d_0|$, $|d_0|$ significance, or the number of pixel hits, to

Table 2: Overview of electron and muon baseline and signal selections. The signal selection is applied on top of the baseline selection. The ABCD identification and p_T requirements depend on the SR and on which triggers are used. $\Delta p_T/p_T = (p_T^{\text{track}} - p_T^e)/p_T^e$ is the relative difference between the track p_T and the calorimeter E_T . N_{miss} is the number of missing hits. The χ^2 variables are all reduced by the number of degrees of freedom (n.d.f.), and are for the Inner Detector (ID) track or Combined Muon (CB) track. N_{prec} is the number of precision layers, and N_ϕ is the number of ϕ layers. The TRT barrel selection is only applied for 2023 data.

Selection	Electrons	Muons	
	Baseline		
p_T (GeV)	> 10	> 21	
$ d_0 $ (mm)	< 300	$2 < d_0 < 300$	
$ z_0 $ (mm)	< 500	< 500	
$ \eta $	$ \eta < 1.37$ OR $1.52 < \eta < 2.47$	< 2.5	
Identification	LLP VeryLoose	LLP Medium	
	ABCD Signal (LRT / high- p_T)	EM-BDT Signal	ABCD Signal (LRT / high- p_T)
Isolation	Tight_VarRad	Tight_VarRad	PFlow_Loose_VarRad
Identification	LLP Loose / -	LLP Loose	-
p_T (GeV)	> 31 / > 65	-	- / > 65
$ d_0 $ (mm)	> 3	> 3	- / > 3
$(p_T^{\text{track}} - p_T^e)/p_T^e$	≥ -0.5	-	-
$\chi_{\text{ID}}^2/\text{n.d.f.}$	< 2	-	< 2
N_{miss}	≤ 1	-	≤ 1
N_{prec}	-	-	≥ 3
$\chi_{\text{CB}}^2/\text{n.d.f.}$	-	-	< 3
N_ϕ	-	-	> 0
Pass cosmic veto	-	-	True
Pass TRT barrel (2023)	True	True	True

avoid suppressing displaced electrons, referred to here as LLP VeryLoose. Figure 3(a) shows the efficiency of electrons from a selection region definition to satisfy the standard and LLP electron identification WP as a function of the true lepton $|d_0|$ value.

High- d_0 electrons, for the purpose of analysis region definition, must additionally satisfy the object overlap removal, have $p_T > 31$ GeV, $3 < |d_0| < 300$ mm, $|z_0| < 500$ mm, and fall outside of the EM calorimeter barrel-endcap transition region ($1.37 < |\eta| < 1.52$). The ABCD signal electron selection additionally requires that the electrons are isolated from nearby tracks and calorimeter energy deposits. The sum of the p_T of all prompt tracks within a cone, shrinking with p_T (max $\Delta R = 0.2$), and E_T of all energy deposits within $\Delta R = 0.3$ of the electron must each be less than 6% of the electron p_T (Tight_VarRad). To suppress electrons from random overlaps of hadronic tracks and photon energy deposits, the relative difference between the electron track p_T measurement and that of the electron p_T measured when accounting for the calorimeter energy must satisfy $(p_T^{\text{track}} - p_T^e)/p_T^e \equiv \Delta p_T \geq -0.5$. To suppress combinatoric fake tracks, the ID track must have a χ^2 per degree of freedom satisfying $\chi_{\text{ID}}^2/\text{n.d.f.} < 2$, where χ^2 is the sum of the squares of the distances between each hit and the track position extrapolated to the given sensor divided by the resolution on this difference, and at most one missing cluster that is included in the track fit (track “hit”) at a larger radius than the innermost hit. Signal electrons in regions triggered by the LRT trigger require the stricter LLP Loose identification WP to be consistent with the trigger, with the same modifications as above to the standard *Loose* WP [69]. The EM-BDT signal electron selection requires the baseline selection, $3 < |d_0| < 300$ mm, the same isolation criterion, and the same LLP Loose identification WP.

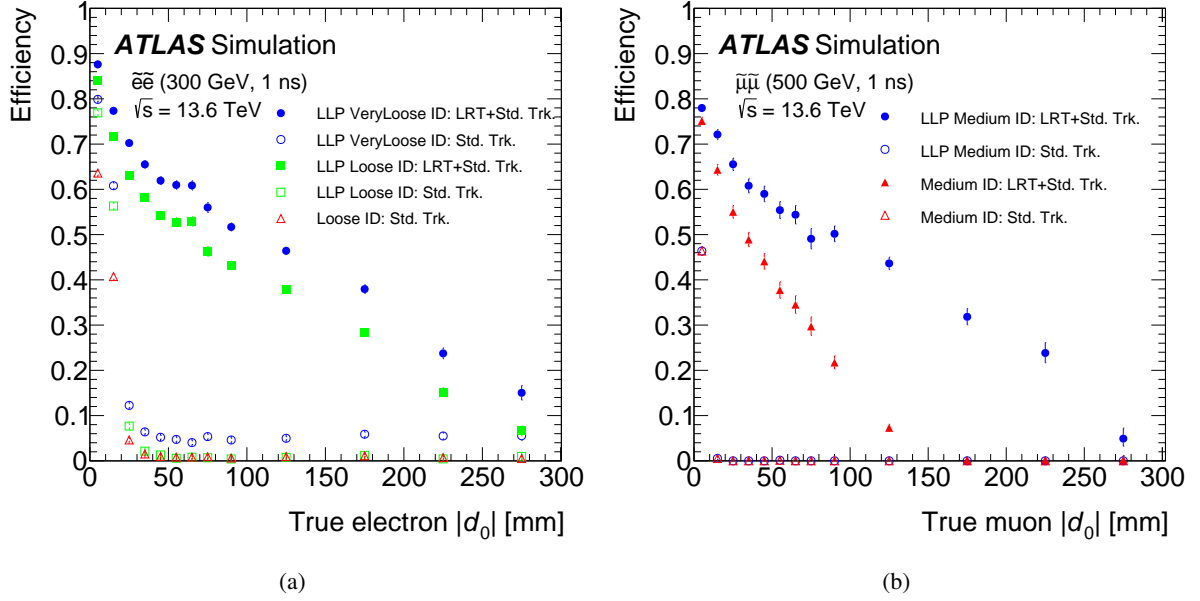


Figure 3: Efficiency to reconstruct and identify (a) electrons and (b) muons using large-radius tracking (LRT) and standard tracking (Std. Trk.) with respect to generator-level leptons in simulated GMSB slepton signal models with a slepton lifetime of 1 ns and a selectron (smuon) mass of 300 (500) GeV. The efficiencies for the various LLP working points are shown as a function of the true transverse impact parameter $|d_0|$ of the daughter lepton.

Muons are reconstructed from ID tracks matched to muon track segments. If a standard and LRT track both point to the same muon segment and lead to the reconstruction of a standard and LRT muon with the same segment, the duplication is resolved by keeping the muon with the smaller difference in η between the ID track and the muon track segment extrapolated to the PV. Baseline muons must have $p_T > 21$ GeV, $|\eta| < 2.5$, and satisfy a modified version of the *Medium* identification WP [70] without requirements on the number of pixel and TRT hits, referred to here as LLP Medium; though, the standard tracks used to reconstruct muons still have a requirement of at least one pixel hit. Figure 3(b) shows the efficiency of muons from a smuon signal model to satisfy the standard and LLP muon medium identification WP as a function of the true lepton $|d_0|$ value.

High- d_0 muons must additionally satisfy the object overlap removal, $2 < |d_0| < 300$ mm, and $|z_0| < 500$ mm. Signal muons are required to additionally be isolated from nearby tracks and calorimeter energy depositions using an algorithm that exploits particle flow to associate tracks with their energy clusters [70]. The sum of the p_T of all prompt tracks within a cone, shrinking in p_T (max $\Delta R = 0.3$), of the muon is added to 40% of the sum of the E_T of energy depositions within $\Delta R = 0.2$ that are not matched to tracks and the total is required to be less than 16% of the muon p_T (PFlow_Loose_VarRad). Several additional requirements are imposed to reject spurious muons from combinatoric fake tracks. Muons must be measured in at least three MS precision tracking layers and have at least one high-precision ϕ measurement. The ID track must have $\chi_{\text{ID}}^2/\text{n.d.f.} < 2$ and at most one missing hit at a larger radius than the innermost hit, and the combined muon track must satisfy $\chi_{\text{CB}}^2/\text{n.d.f.} < 3$. To reject cosmic-ray muons, a cosmic muon veto is applied that is similar to the one used in the ATLAS Run 2 displaced leptons search [23] and originally developed in the ATLAS Run 2 search for a displaced vertex and a displaced muon [71]. A muon is tagged as originating from a cosmic-ray muon, and thus vetoed, if there are MS segments on the opposite side of the detector along its trajectory, within η and ϕ windows of $|\eta_\mu + \eta_{\text{MS}}| < 0.01$ and $\pi - |\phi_\mu - \phi_{\text{MS}}| < 0.08$, where the μ

and MS subscripts refer to the reconstructed muon and MS segments, respectively.

Photons are reconstructed from EM calorimeter depositions. Baseline photons must have $E_T > 30$ GeV, fall within the barrel ($|\eta| < 1.37$) or endcap ($1.52 < |\eta| < 2.5$) regions, and satisfy the *Loose* photon identification WP [69]. Signal photons must also be isolated from nearby tracks and calorimeter depositions [69]. The sum of the p_T of all prompt tracks (E_T of all energy depositions) within $\Delta R = 0.2$ of the photon must be less than 5% (6.5%) of the photon E_T .

Jets are reconstructed with the particle-flow technique [72, 73] using the anti- k_t algorithm with a radius parameter of 0.4 [74]. In this analysis, jets are only used for overlap removal and, for the EM-BDT search only, to evaluate the E_T^{miss} . Baseline jets must satisfy $p_T > 20$ GeV and $|\eta| < 2.8$. To reject jets from pileup interactions, a jet vertex tagger algorithm employing a neural network is applied using a WP with an approximately fixed efficiency as a function of jet p_T [75].

The value of E_T^{miss} is defined as the magnitude of the negative vector sum of the transverse momenta of all distinct reconstructed objects as well as tracks not associated with any reconstructed objects [75]. When calculating the value of E_T^{miss} , both prompt and displaced leptons are included.

The analysis requires one of the following three conditions to be true: at least one baseline electron, at least two baseline muons, or at least two baseline photons. Events must pass one of the triggers described in Section 3, which depend on the final state and the p_T of the leptons and photons. During 2023, part of the TRT barrel was not in operation, in a region defined by $-1.759 < \phi < -1.257$ and $|\eta| < 1.37$. Events with electrons or muons in this $\eta - \phi$ region are vetoed in 2023 data only.

Events are categorized into orthogonal ABCD high- p_T , ABCD LRT, and EM-BDT regions in cascading order based on the number of high- d_0 leptons, as defined above. If there are at least two such leptons with

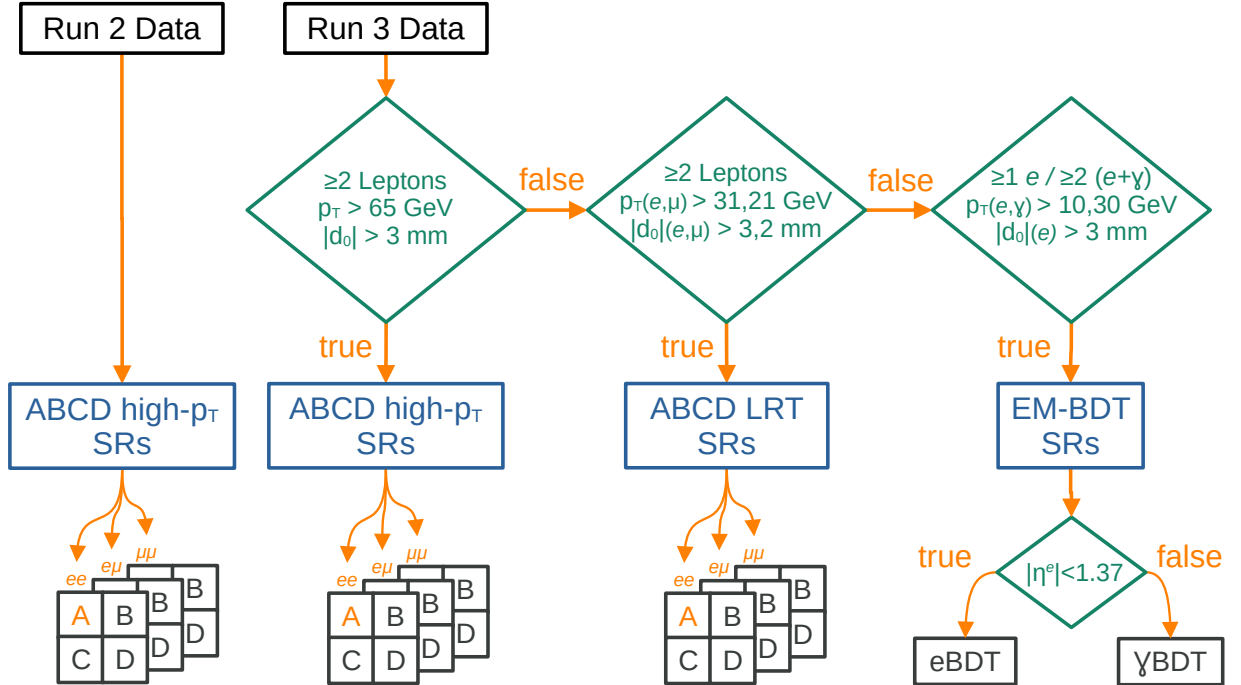


Figure 4: Flowchart of the event categorization into the ABCD high- p_T , ABCD LRT, and EM-BDT SRs. The Run 2 and Run 3 ABCD high- p_T SRs are separate.

$p_T > 65$ GeV, events fall into the ABCD high- p_T regions. Failing that, if events have at least two such leptons with $p_T > 31(21)$ GeV for electrons (muons), events fall into the ABCD LRT regions. Remaining events fall into the EM-BDT regions. The flowchart in Figure 4 illustrates the categorization of events. Additional selections, defined in Sections 5 and 6 for the ABCD and EM-BDT approaches, respectively, are used to define SRs that are sensitive to BSM signals, control regions (CRs) that are used to estimate the backgrounds in the SRs, and validation regions (VRs) that are used to test the robustness of the background estimation methodology. The SRs, CRs, and VRs for each channel are mutually orthogonal.

5 ABCD analysis

The ABCD analysis defines SRs for three dilepton flavor combinations, ee , $\mu\mu$, and $e\mu$, using the flavors of the two leptons with the highest p_T . Backgrounds are estimated using two ABCD-based estimations, one for FHF leptons and one for cosmic-ray muons, which make use of leptons passing and failing certain quality criteria. These are estimated separately because, while they are uncorrelated with each other, different sets of background suppressing requirements need to be inverted to populate the background estimation regions. Cosmic-ray muons are only relevant for the $\mu\mu$ final state. Region A, shared for the FHF and cosmic-ray muon estimates, is the SR where both leptons pass all analysis requirements, regions B and C have one lepton passing the criteria and the other one failing them, and region D contains events where both leptons fail the criteria, which are different for the FHF and cosmic-ray muon estimates. When the criteria used on each lepton are uncorrelated, the estimate of the background in the SRs reduces to

$$N_A^{\text{predicted}} = \frac{N_B^{\text{FHF}} \times N_C^{\text{FHF}}}{N_D^{\text{FHF}}} + \frac{N_B^{\text{Cosmics}} \times N_C^{\text{Cosmics}}}{N_D^{\text{Cosmics}}},$$

where $N_{B/C/D}^{\text{FHF}}$ and $N_{B/C/D}^{\text{Cosmics}}$ are the event yields in the various control regions for the FHF and cosmic-ray backgrounds, respectively, for a given lepton flavor combination. The B, C, and D regions for a given SR are included in the fits to determine the backgrounds for model-independent limits and BSM exclusions, as described further in Section 8.

5.1 ABCD event selection

The selection of events for the ABCD analysis begins with the common preselection requirements described in Section 4. The ABCD search requires the presence of at least two signal leptons (e or μ) separated by $\Delta R(\ell_1, \ell_2) > 0.2$ and considers two orthogonal sets of SRs. The high- p_T SRs use a similar selection as the Run 2 search, relying on photon and MS-only muon triggers and requiring both leptons to have $p_T > 65$ GeV and $|d_0| > 3$ mm. The Run 3 high- p_T SRs benefit from the addition of new photon plus MS-only and di-MS-only-muon triggers, listed in Table 1. Separate SRs are defined for ee , $\mu\mu$, and $e\mu$ events in Run 2 and Run 3, resulting in six orthogonal ABCD high- p_T SRs.

The ABCD LRT SRs use the novel LRT triggers that were introduced in Run 3 and require electrons (muons) with $p_T > 31$ (21) GeV. The muon $|d_0|$ threshold is also reduced to 2 mm. Electrons are required to pass the stricter LLP Loose WP to be consistent with the LRT trigger. Events satisfying the high- p_T SR selection are vetoed. Three SRs exploiting the LRT triggers are defined for ee , $\mu\mu$, and $e\mu$ events, in Run 3 only, leading to a total of nine orthogonal SRs considered in the ABCD search. For the three $\mu\mu$ SRs, an additional cosmic-ray veto rejects events with back-to-back fully reconstructed muons, μ_1 and μ_2 , with

$|\eta(\mu_1) + \eta(\mu_2)| < 0.02$ and $\pi - |\phi(\mu_1) - \phi(\mu_2)| < 0.01$, taking advantage of the better angular resolution of fully reconstructed muons at the PV, compared to extrapolated MS segments.

To maintain broad sensitivity to BSM physics scenarios besides the GMSB long-lived slepton and dark sector models considered in this paper, no additional kinematic selections are applied. Due to the low rates of displaced leptons in data, these selection criteria are enough to reduce the expected background yields in all SRs to less than one event.

Example total acceptances, summing over the ABCD SRs lepton flavors, for the stau model with a 100 GeV mass and 0.01 ns lifetime in the high- p_T and LRT SRs are 0.001 and 0.012, respectively. For the smuon model with 800 GeV mass and 0.1 ns lifetime, the total acceptances are 0.19 and 0.06 for the high- p_T and LRT SRs, respectively.

5.2 ABCD background estimation

Two sources of background are considered in the ABCD analyses. The FHF lepton background contributes to all three lepton flavor channels and includes combinatoric fake tracks, random overlaps of hadronic tracks with EM clusters or MS tracks, photon conversions, and decays of heavy-flavor bottom and charm mesons. The cosmic-ray muon background contributes to $\mu\mu$ events only. Since these processes are not necessarily well-modeled in simulation, they are estimated from data CRs using ABCD methods that closely follow the methodology of the Run 2 ATLAS displaced leptons search [23]. The final background estimates and results for each SR are obtained from a simultaneous fit of the four ABCD regions.

The background estimate for FHF leptons uses CRs in which some of the quality criteria for one lepton, the other lepton, or both, are inverted. A failing electron is one that fails at least one of the requirements on Δp_T , ID track $\chi_{ID}^2/n.d.f.$, and the number of missing track hits, while satisfying all other ABCD signal electron requirements of Section 4. A failing muon is one that fails at least one of the requirements on the number of precision tracking layers, the presence of a high-precision ϕ measurement, ID track $\chi_{ID}^2/n.d.f.$, combined muon $\chi_{CB}^2/n.d.f.$, and the number of missing track hits, while satisfying all other ABCD signal muon requirements of Section 4. In the $\mu\mu$ high- p_T regions only, the observed yields in the ABCD CRs are too small to provide individual predictions for Run 2 and Run 3. Therefore the yields in the ABCD regions for these two datasets are combined and the predicted FHF background is scaled by the fractions of the total luminosity accounted for by each dataset, namely 0.71 for Run 2 and 0.29 for Run 3. The predicted SM background yields in each of the nine ABCD SRs is less than 0.2 events. As an example, for the high- p_T Run 3 ee SR, the FHF B, C, and D region yields are 3, 6, and 278 respectively. This results in a predicted background of $3 \cdot 6/278 = 0.067^{+0.092}_{-0.041}$ assuming no signal and ignoring the SR yields, which are included as a constraint in the fit.

This method assumes that the quality criteria of the two FHF leptons are uncorrelated with each other. Two sets of VRs are defined to account for any systematic biases of the background estimation methodology, including potential correlations between the quality criteria of the leptons. The VR-fake regions are enriched in fake-lepton backgrounds by inverting the requirement on Δp_T for electrons and the CB track $\chi_{CB}^2/n.d.f.$ requirement for muons. The VR-HF regions are enriched in heavy-flavor leptons by inverting the lepton isolation criteria. The observed yields in the nine VR-fake and VR-HF regions corresponding to the nine SRs are consistent with the background expectations obtained by performing the ABCD estimate in these VRs.

For cosmic-ray muons, the ABCD CRs are defined by inverting the MS quality requirements (number of precision tracking layers, number of high-precision ϕ measurements, or combined muon $\chi_{\text{CB}}^2/\text{n.d.f.}$) or by inverting the cosmic veto relying on the presence of MS segments on the opposite side of the detector. These are inverted for the muon in the top half of the detector, which is more likely to be mis-reconstructed than the muon in the bottom half since it travels in the opposite direction of particles that originate from the PV. Applying the additional cosmic-ray veto on back-to-back fully reconstructed muons eliminates almost all of the events in these regions. Therefore the cosmic-ray muon background is estimated without this additional cosmic-ray veto applied and then scaled by the expected efficiency $T = (3.7 \pm 2.6) \times 10^{-3}$ for muons to survive the veto, evaluated using the events that fall in the superset of regions B, C, and D. The expected background yields are of the order 10^{-3} in the three $\mu\mu$ SRs.

This background method is validated in VRs enriched in cosmic-ray muons, in which the cosmic veto relying on the presence of MS segments on the opposite side of the detector as the bottom muon is replaced by the requirement that this muon has MS segments satisfying $|\eta_\mu + \eta_{\text{MS}}| < 0.01$ and $\pi - |\phi_\mu - \phi_{\text{MS}}| < 0.08$ but no such segments satisfying $|\eta_\mu + \eta_{\text{MS}}| < 0.002$ and $\pi - |\phi_\mu - \phi_{\text{MS}}| < 0.02$. To enrich the VR in cosmic-ray muons, the additional cosmic-ray veto based on the two fully reconstructed muons is not applied. The observed yields are consistent with the background expectations.

5.3 ABCD systematic uncertainties

While the sensitivity of the ABCD analysis is dominated by statistical uncertainties, several sources of systematic uncertainty are considered. Additional uncertainties common with the EM-BDT analysis are described in Section 7.

The systematic uncertainty in the FHF lepton background is based on the agreement between observed yields versus expected backgrounds in the VR-fake and VR-HF regions. For each region, the larger of two quantities is taken as the systematic uncertainty: the deviation from one of the ratio of the observed yield to the expected background, or the statistical uncertainty in the expected background. The values are extracted from VR-fake and VR-HF separately and then added in quadrature. Uncertainties in the range of 20–240% are applied in the corresponding SRs, with the larger uncertainties occurring in regions with very small observed yields.

Two sources of systematic uncertainty in the cosmic-ray muon background are considered. The first source is due to the assumption that the muon in the top half of the detector is the one that is mismeasured. The background is estimated by instead inverting the cosmic veto and/or MS quality variables of the bottom muon and taking the relative difference with respect to the nominal result, resulting in uncertainties of 2–41%. The cosmic-ray background is also estimated by inverting any two of the three MS quality variables and taking the relative difference with respect to the nominal estimate, resulting in uncertainties of 20–82%.

6 EM-BDT analysis

The EM-BDT analysis seeks to discriminate between displaced electrons and the background, which is dominated by prompt particles. In the interpretation of the results for the GMSB long-lived slepton model used as a benchmark (see the diagram in Figure 1), the EM-BDT analysis is applied to the selectron and stau channels, since either can produce displaced electrons in the final state.

As an electron arising from the decay of a long-lived parent is both displaced and delayed, there exist significant correlations between many relevant observables, motivating the introduction of machine learning techniques in the development of a multivariate discriminant. An electron from an LLP decay that occurs too far into the detector may not have an identifiable track. In such a case, the electron is reconstructed as a photon, provided the decay is before the calorimeter. Two different BDTs are employed, each using variables that are verified with comparisons of $Z \rightarrow ee$ data and MC simulation to be reasonably well modeled. The “ e BDT” seeks to identify displaced electrons from among those particles reconstructed as electrons, while the “ γ BDT” seeks to identify displaced electrons from among those particles initially reconstructed as photons. The γ BDT extends the sensitivity of the analysis to events where the decay producing the electron occurs in front of the EM calorimeter but farther from the beamline than the 300 mm limit where LRT is applied; in such cases, it is still possible to identify the displaced electron from the EM calorimeter information only.

The discriminating variables for the e BDT include tracking information, EM calorimeter variables, and combinations of the ID and LAr measurements. The tracking variables include the track fit quality χ^2 value, the number of pixel hits on the track, the number of missing layers in the track, and the transverse and longitudinal impact parameters with respect to the PV position. The EM calorimeter variables include the LAr pointing measurement (z_{EM}), the absolute value of the LAr timing measurement, and two LAr shower shape variables, namely the fraction of the EM shower energy in the first and third longitudinal layers (f_1 and f_3 , respectively). The combined variables include Δp_T and the difference between z_0 and z_{EM} ; both of these combined variables are intended to help reject backgrounds from fake electrons. The background rejection of the e BDT is enough that the analysis can be performed with only one reconstructed electron in the event, thereby greatly extending the analysis sensitivity to longer slepton lifetime values, where only one selectron (or stau) has decayed before reaching the EM calorimeter. In events with more than one reconstructed electron, or with one electron and one or more photons, the e BDT is applied to the leading electron. Thus, the e BDT is an “object-level” discriminant, using only measurements of the electron itself and not of other properties of the event, and thereby functions as a “displaced electron tagger.” This feature of the e BDT makes it rather model-independent.

The γ BDT searches for displaced electrons reconstructed as photons. The lack of tracking information and higher background rates for photons than electrons makes a single photon region infeasible. Instead, the γ BDT requires at least one additional electron or photon. The variables used are the pointing and timing measurements of the two objects, as well as the differences between them. In addition, the value of E_T^{miss} in the event is used. This choice is motivated by the gravitinos produced in the baseline slepton model in order to extend the reach of the analysis to longer slepton lifetime values, but does make the γ BDT more model-dependent than the e BDT.

6.1 EM-BDT event selection

The selection of events for the EM-BDT analysis begins with the common preselection requirements described in Section 4. The EM-BDT event selection is made orthogonal to that of the ABCD analysis regions by vetoing dielectron events passing the ABCD p_T and $|d_0|$ requirements. The selected EM-BDT events are divided into several distinct final states, according to the multiplicity of reconstructed EM objects (electrons or photons) in the event. Each final state is selected by a set of triggers, as described in Table 1.

The e BDT is used to analyze events with at least one electron in the barrel calorimeter ($|\eta| < 1.37$). These include single-electron events, but also events with an electron in the barrel calorimeter plus either

additional electrons or photons. In events with more than one reconstructed electron, the leading electron in the barrel is selected as the input object to the e BDT algorithm. The electron is required to have $E_{\text{cell}}^{\text{max}} > 5$ GeV to reduce the impact of noise on the calorimeter timing, and an absolute value of its calorimeter time less than 12.5 ns, to reject backgrounds from other bunch crossings.

Given the large backgrounds in single-photon event samples as well as the lack of tracking information for photons, the γ BDT is used to analyze only events with at least two reconstructed EM objects; the first must be a photon passing the baseline requirement, while the second can be another photon or an electron which fails the e BDT requirements. At least one EM object must be in the barrel calorimeter ($|\eta| < 1.37$). Both EM objects are required to have $E_{\text{cell}}^{\text{max}} > 5$ GeV and an absolute value of its calorimeter time less than 12.5 ns. A requirement of $|z| < 2000$ mm for both EM objects eliminates beam-induced backgrounds that can fake the photon signature.

For a selectron with a mass of 200 GeV and a lifetime of 30 ns, total acceptances of the EM-BDT event selection are 0.0022 for the γ BDT and 0.01 for the e BDT. The sum of these are two orders of magnitude larger than the sum of the ABCD SR acceptances.

6.2 EM-BDT background estimation

The background in the EM-BDT analysis is dominated by prompt particles that are mismeasured or poorly reconstructed. Such effects cannot be sufficiently precisely simulated, and therefore the background estimation is necessarily entirely data-driven. The estimate is generated by dividing the data into three orthogonal regions: a CR, which can be used estimate the background normalization and BDT distribution shape, a VR, which can be used to validate the background estimate before unblinding the SR data, and the SR, in which the search will ultimately be performed.

The EM-BDT analysis exploits the fact that, for prompt background, the distribution of the arrival time at the EM calorimeter should, due to resolution effects, be symmetric about zero, as seen in Figure 2. In contrast, signal events should be delayed, and therefore have primarily positive arrival times. As a result, the CR can be defined for the e BDT (γ BDT) by events where the leading electron has (both photons have) a negative time, while the SR is defined by events where the leading electron has (both photons have) a positive time. The VR is defined by kinematic selections that aim to achieve a dominance of background over signal by selecting events with enhanced SM W or Z boson production; the VR includes single-electron events with a transverse mass of the lepton and $E_{\text{T}}^{\text{miss}}$ system in the range from 60–100 GeV, and dielectron events with a dielectron mass in the range from 80–100 GeV. To guarantee orthogonality among the three regions, the CR and SR definitions include vetoes of any events that fall within the VR selection.

For both the e BDT and the γ BDT, the BDT is trained to separate the signal, as modeled with MC simulation, from the background, as modeled by the CR data. Signal models of various masses and lifetimes ≥ 1 ns were used for training in order to maximize the sensitivity to longer lifetimes. To make use of the entire sample of the MC simulation and the CR data, the signal sample and data used for training are split randomly into three “folds” and training is performed on each group individually. It is then required that the score assigned to a particular event during evaluation is determined using a fold other than the one assigned to that event in training. The final EM-BDT results for various slepton masses and lifetimes are obtained by signal-plus-background fits, including associated statistical and systematic uncertainties, of the unblinded SR data to the weighted sum of the CR-derived background template and signal template shape from MC simulation. The signal contamination in the CR is found to be less than one percent of the yield. Still, to

account for signal contamination in the CR, particularly at low lifetimes where the signal has a similar shape in the CR and SR, the signal template in the fit is set to be the difference of the positive and negative timing BDT score distributions, i.e. the difference between the SR and CR templates. Before unblinding the SR data, the BDT distributions were validated by performing fits to the background-dominated VR.

The BDTs are defined such that their output values range from -1 to $+1$, with signal-like (background-like) events skewed toward positive (negative) BDT scores. The final statistical analysis uses a simultaneous fit to binned e BDT and γ BDT distributions, where the normalization is allowed to float. Before unblinding, the binning used for the BDT scores was subject to an optimization procedure that sought to maximize the signal sensitivity. To ensure a non-zero background estimate could be made for each bin, the choice of bins was subject to the constraint that there exist at least one CR event in each bin. The e BDT and γ BDT binnings were optimized separately. However, for both BDTs the very background-like events with BDT scores less than zero are not used in the fit, and the events with positive BDT scores are divided into five non-overlapping bins.

6.3 EM-BDT systematic uncertainties

While the sensitivity of the EM-BDT analysis is dominated by statistical uncertainties, several sources of systematic uncertainty are considered. The background normalization is determined in the fit, and therefore no corresponding systematic uncertainty is needed. However, systematic uncertainties that are considered can impact the results of the final fit by either impacting the shapes of the BDT score distribution of the signal or the background, or by affecting only the signal normalization. Additional uncertainties common with the ABCD analysis are described in Section 7.

The largest systematic uncertainty in the shape of the background BDT distribution arises due to the assumption that the CR data, which has negative time values, describes accurately the expected background in the SR region, which has positive times. The systematic uncertainty in this assumption is determined by using the VR data, where the signal contribution is negligible and therefore the symmetry of the background around $t = 0$ ns can be tested quantitatively. Comparing the BDT distribution of the VR data with negative times with that of the VR data with positive times, the relative discrepancies increase monotonically toward the higher BDT score bins, and reach as high as 33% (84%) in the highest bin of the e BDT (γ BDT) score. These “non-closure” uncertainties are symmetrized about the central prediction and included as systematic uncertainties in the BDT background shape.

A systematic uncertainty in the shape of the signal BDT distribution arises due to uncertainties in the smearing of the time resolution. The MC simulation does not accurately describe the timing resolution in data, and therefore the signal MC events are subjected to an additional smearing of the time. The smearing procedure consists of taking the raw time from the MC simulation, which already contains a model of the observed noise in the calorimeter, and adding additional correlated and uncorrelated components. The correlated component corresponds to the beam spread, and is therefore shared by all objects in the same event. The uncorrelated component is applied separately to each object and corresponds to different electronic and pileup noise assumptions and other global effects observed in comparisons between data and MC simulation. To determine an uncertainty in the signal BDT shape, the smearing is varied up and down within the experimental uncertainties, and the signal BDT shape is re-evaluated.

7 Common systematic uncertainties

Several sources of systematic uncertainties are evaluated for the prediction of signal model yields, both from the theoretical and experimental sides. The factorization and renormalization scales, α_S , parton distribution functions, and QCD radiation models are all varied to assess the impact on the simulated acceptance in the SRs. For the GMSB slepton model in the EM-BDT SR a 12% theory acceptance uncertainty is applied on the yield, while in the ABCD SRs the uncertainty varies between 10–30% in the excluded region. For the dark sector model, theory acceptance uncertainties in the yield in the ABCD SRs also vary between 10–30% in the excluded regions. The theory uncertainty in the total predicted cross-section is not included as an additional uncertainty in the fit.

Experimental-based uncertainties in the modeling of leptons are determined in two parts. Electrons and muons are reconstructed with a track and calorimeter or MS information, respectively. These sub-detectors are sufficiently far from the PV relative to the displacements targeted in this search that the sub-detectors performance, and simulation of said performance, should not differ by much from that for prompt leptons. Thus uncertainties in the tracking and calorimeter or MS information are separated in order to determine each in the most robust way. Additional uncertainties for displaced leptons are added to those derived for prompt leptons, which cover the calorimeter and MS portion of the leptons. Standard uncertainties in the modeling of photons are included; there are no additional displacement based uncertainties applied for photons other than that for the smearing of the time resolution described in Section 6.3.

Uncertainties in reconstructed objects are propagated to the reconstruction of E_T^{miss} . Additional uncertainties in E_T^{miss} come from varying the scale and resolution of the soft term, parallel and perpendicular to the hard term [75]. As E_T^{miss} is used in selecting events with enhanced SM W production to define the EM-BDT VR, a systematic is assessed on the impact of E_T^{miss} -reconstruction uncertainties in the fitted EM-BDT score distributions. The migration of events from EM-BDT SRs to the EM-BDT VR was studied after redefining the VR using variations in E_T^{miss} . Based on this a 2% uncertainty in the signal yields in the EM-BDT SRs was assigned. For the γ BDT, which uses E_T^{miss} as an input variable, an additional uncertainty is evaluated by propagating the E_T^{miss} systematic uncertainties into the γ BDT score calculation and re-evaluating the γ BDT shape. Uncertainties in E_T^{miss} have no impact in the ABCD analysis since it is not used in the event selection.

The uncertainty in the modeling of LRT in offline reconstruction was determined from comparisons of data and MC simulation using K_S^0 vertices in Ref. [41]. These are parameterized in p_T and radius of the first hit on the track, and vary from 0.3–16.8% per large-radius track.

Uncertainties in the simulated acceptance of the trigger for standard prompt leptons and photons are considered. Additional uncertainties in the LRT-based trigger acceptance are computed by comparing the trigger tracking efficiency with respect to offline tracks in data and MC simulation, as done in Ref. [34]. This amounts to an additional uncertainty of 11% for electrons and 2% for muons on top of the standard trigger uncertainties.

Corrections to the modeling of identification and isolation requirements for leptons were computed with prompt $Z \rightarrow \ell\ell$ events using the same methods as described for electrons in Ref. [69] and muons in Ref. [70]. Uncertainties in the corrections for electrons are generally less than 11% for $p_T > 30$ GeV; they rise to 70% for electrons with $p_T < 20$ GeV. For muons the uncertainties in the corrections are generally less than 3%. An additional uncertainty in electron identification as a function of $|d_0|$ is assessed by comparing the relative loss in efficiency between the VeryLoose and Loose WPs of signal MC simulation; this amounts to an uncertainty of 16% per electron. For muons, the MS is sufficiently far away from

the PV, and their identification does not make use of a likelihood discriminant. Thus, no additional displacement-based uncertainty is applied.

The uncertainties in the ABCD background predictions come from the propagation of statistical uncertainties in the yield in each region, which ranges from 20–120%, except for the high- p_T $\mu\mu$ regions where this is up to 1100%, and the uncertainties described in Section 5.3 on the FHF background prediction, which ranges from 30–210%. The dominant uncertainty in the signal prediction in the ABCD SRs depends on the region and signal model. Typical ranges for uncertainties are: 11–40% for the number of MC simulation events, 25% for the signal theory acceptance, 10–40% for the uncertainty in LRT, 1–15% for muon modeling, and 20–30% for electron modeling. The uncertainty in the BDT backgrounds are dominated by the shape uncertainties, except for the most sensitive bin where the number of CR events is low and the statistical uncertainty is large. The dominant uncertainties for the e BDT are the electron modeling at 21%, the theory acceptance uncertainty at 12%, and the statistical uncertainty in the number of simulated events in the most sensitive bins at 7%. The dominant uncertainties for the γ BDT are the signal acceptance uncertainty of 12%, and the statistical uncertainty in the number of simulated events in the two most sensitive bins at 11 and 4%. For both the ABCD and EM-BDT regions, the uncertainty in the lifetime reweighting, discussed in the next section, may be the dominant uncertainty when used.

8 Results

Each of the orthogonal ABCD signal regions is used individually to compare the observed data yield with the expected background, the results of which are used as “discovery regions” to set model-independent limits on the production of displaced leptons; for the ABCD high- p_T analyses, these are quoted separately for the Run 2 and Run 3 data, due to the different center-of-mass energies, resulting in a total of nine orthogonal ABCD discovery regions. An EM-BDT discovery region is defined as the most signal-like bin of the e BDT distribution (e BDT score > 0.46), and is used to set model-independent limits on the production of displaced electrons. All model-independent limits are derived using pseudo-experiments. Model-dependent limits on the long-lived slepton model are obtained by performing a simultaneous fit to the e BDT and γ BDT distributions, as well as the nine ABCD SRs. Only the ABCD SRs are used for the dark sector model as the EM-BDT SRs are not sensitive to muons, and therefore have a lower sensitivity to the dark sector model which has two leptons of any flavor in the final state.

Only one event is observed among the nine orthogonal ABCD signal regions, namely in the SR_{ee} -LRT region. The observed and expected yields in the orthogonal ABCD signal regions are presented in Table 3. Corresponding model-independent upper limits on the visible BSM cross-sections, the observed and expected limits on the number of non-SM events, and the p -values and corresponding local Z scores are also shown. The one event observed in the SR_{ee} -LRT region, compared to the background expectation of $0.0016^{+0.0029}_{-0.0016}$ events corresponds to a local significance of 2.2σ .

The observed BDT distributions in the SRs of the e BDT and γ BDT analyses are shown in Figure 5. Shown superimposed are the background shapes as determined using the CR data, and example GMSB signal models with selectrons. The lower panels in the figures show the bin-by-bin ratios of the data divided by the background, and illustrate that the observed SR data are consistent with the background expectation. Defining the EM-BDT discovery region as the most signal-like bin of the e BDT yields a background expectation of one event. The uncertainty in this background estimate is dominated by the statistical uncertainty resulting from the fact that it is determined from a single CR event in this bin of the e BDT, plus a systematic uncertainty of ± 0.33 from the other sources of uncertainty described previously. A total

Table 3: Expected and observed yields in the signal regions and model-independent upper limits derived using pseudo-experiments. Left to right: total expected background after a background-only fit, with the combined statistical and systematic uncertainties; number of events observed in data; 95% CL upper limits on the visible cross-section ($\langle A\epsilon\sigma \rangle_{\text{obs}}^{95}$) and on the number of signal events (S_{obs}^{95}). The sixth column (S_{exp}^{95}) shows the expected 95% CL upper limit on the number of signal events, given the expected number (and $\pm 1\sigma$ excursions of the expectation) of background events. The last two columns indicate the confidence level of the background-only hypothesis (CL_b) and discovery p -value with the corresponding Gaussian significance ($Z(s=0)$). CL_b provides a measure of compatibility of the observed data with the signal strength hypothesis at the 95% CL limit relative to fluctuations of the background, and $p(s=0)$ measures compatibility of the observed data with the background-only hypothesis relative to fluctuations of the background. The p -value is capped at 0.5.

Signal Region	Total Bkg.	N_{obs}	$\langle A\epsilon\sigma \rangle_{\text{obs}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}	CL_b	$p(s=0)$ (Z)
ee high- p_T (Run 2)	0.031 ± 0.031	0	0.02	3.0	$3.0^{+0.0}_{-0.0}$	0.46	0.5 (0)
ee high- p_T (Run 3)	0.06 ± 0.05	0	0.05	3.0	$3.0^{+0.0}_{-0.1}$	0.45	0.5 (0)
ee LRT	$0.0016^{+0.0029}_{-0.0016}$	1	0.07	4.1	$3.0^{+0.0}_{-0.1}$	0.97	0.01 (2.2)
$\mu\mu$ high- p_T (Run 2)	$0.02^{+0.22}_{-0.02}$	0	0.02	3.0	$3.0^{+0.0}_{-0.0}$	0.49	0.5 (0)
$\mu\mu$ high- p_T (Run 3)	$0.01^{+0.11}_{-0.01}$	0	0.05	3.0	$3.0^{+0.0}_{-0.0}$	0.48	0.5 (0)
$\mu\mu$ LRT	$0.02^{+0.04}_{-0.02}$	0	0.05	3.0	$3.0^{+0.0}_{-0.0}$	0.49	0.5 (0)
$e\mu$ high- p_T (Run 2)	$0.0016^{+0.0033}_{-0.0016}$	0	0.02	3.0	$3.0^{+0.0}_{-0.1}$	0.50	0.5 (0)
$e\mu$ high- p_T (Run 3)	$0.004^{+0.010}_{-0.004}$	0	0.05	3.0	$3.0^{+0.0}_{-0.0}$	0.50	0.5 (0)
$e\mu$ LRT	$0.2^{+0.4}_{-0.2}$	0	0.05	3.0	$3.0^{+0.1}_{-0.1}$	0.45	0.5 (0)
EM-BDT	$1.0^{+2.3}_{-0.9}$	3	0.13	7.1	$5.7^{+1.9}_{-0.8}$	0.77	0.2 (0.9)

of 3 events are observed in the EM-BDT discovery region, corresponding to a local significance of 0.9σ ; this result is included as the last row of Table 3.

The combined ABCD and EM-BDT results are used to set exclusion contours on the GMSB stau and selectron models, in the two-dimensional plane of slepton lifetime versus slepton mass. Only the ABCD results are used for the smuon and dark sector models. The combination is obtained by simultaneously fitting all included regions, using a single fit parameter to describe the signal strength. Thus the 13.6 TeV to 13 TeV cross-section ratio is taken from the theoretical prediction. To improve the interpolation between generated signal models with different lifetimes, a reweighting procedure is used to estimate the signal acceptances for lifetimes that were not included in the MC sample described in Section 3 and corresponding uncertainties in the signal yields are included in the fit. A 20% signal normalization uncertainty was assessed for reweighting to lifetimes up to 100 ns, increasing to 50% for reweighting to even higher lifetimes, where the uncertainties are based on comparing reweighted samples to simulated samples with the same lifetime.

The 95% CL exclusion contours for long-lived selectrons, smuons, and staus are shown in Figure 6. Results from the prior Run 2 analysis [23] are also included. The excluded regions from the current analysis extend to significantly higher slepton masses and much higher slepton lifetimes. For example, selectrons with a mass of 150 GeV are excluded for lifetime values ranging from 4 ps to 60 ns, while selectrons, smuons, and staus with a lifetime of 0.3 ns are excluded up to 740 GeV, 830 GeV, and 440 GeV, respectively. The improvement in sensitivity for long lifetimes for selectrons with lower masses is due to the EM-BDT and

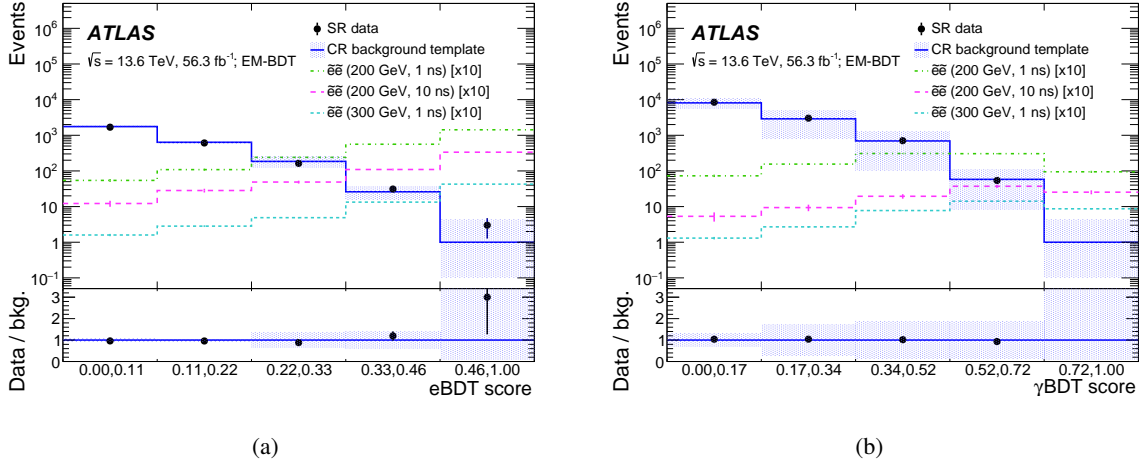


Figure 5: BDT score distributions for the (a) e BDT and (b) γ BDT comparing the expected yields from the control region to the observed data. Selectron pair-production models with a mass of 300 GeV and lifetime of 1 ns, and mass of 200 GeV with lifetime of 1 ns or 10 ns are overlaid with 10 times the expected yield. The lower panel is the ratio of the observed data over the expected background.

new LRT-based triggers. For smuons, in addition to the LRT-based triggers, the improved sensitivity is due to better trigger acceptance for muons in the forward region. The sensitivity to stau models benefits from all of the improvements above and especially from the new LRT triggers since the leptons tend to have lower p_T . This is illustrated in Figure 7, which overlays the exclusion contours for the ABCD high- p_T , ABCD LRT, and EM-BDT SRs. The difference between the expected and observed exclusion contours for the stau model comes from the observed event in the ABCD LRT region as the EM-BDT sensitivity is sub-dominant for the mixed flavor final-state from the staus. All models benefit at high masses from the additional Run 3 data.

The 95% CL exclusion contours for the dark sector model are shown in Figure 8. For a lifetime of $\tau = 0.3$ ns, mass differences down to $\Delta m = 16$ GeV are excluded for a chargino mass of 100 GeV, and charginos with masses up to 900 GeV are excluded for large values of Δm . For a mass difference of $\Delta m = 40$ GeV, charginos with masses up to 380 GeV are excluded and chargino lifetimes of $0.006 < \tau < 10$ ns for a chargino mass of 100 GeV are excluded. Similar to the exclusion contour overlays for the slepton models, Figure 9 illustrates the sensitivity to the chargino models for the ABCD high- p_T SRs at larger masses and sensitivity of the ABCD LRT SRs to the theoretically-preferred small-mass-splittings between 10–40 GeV [32].

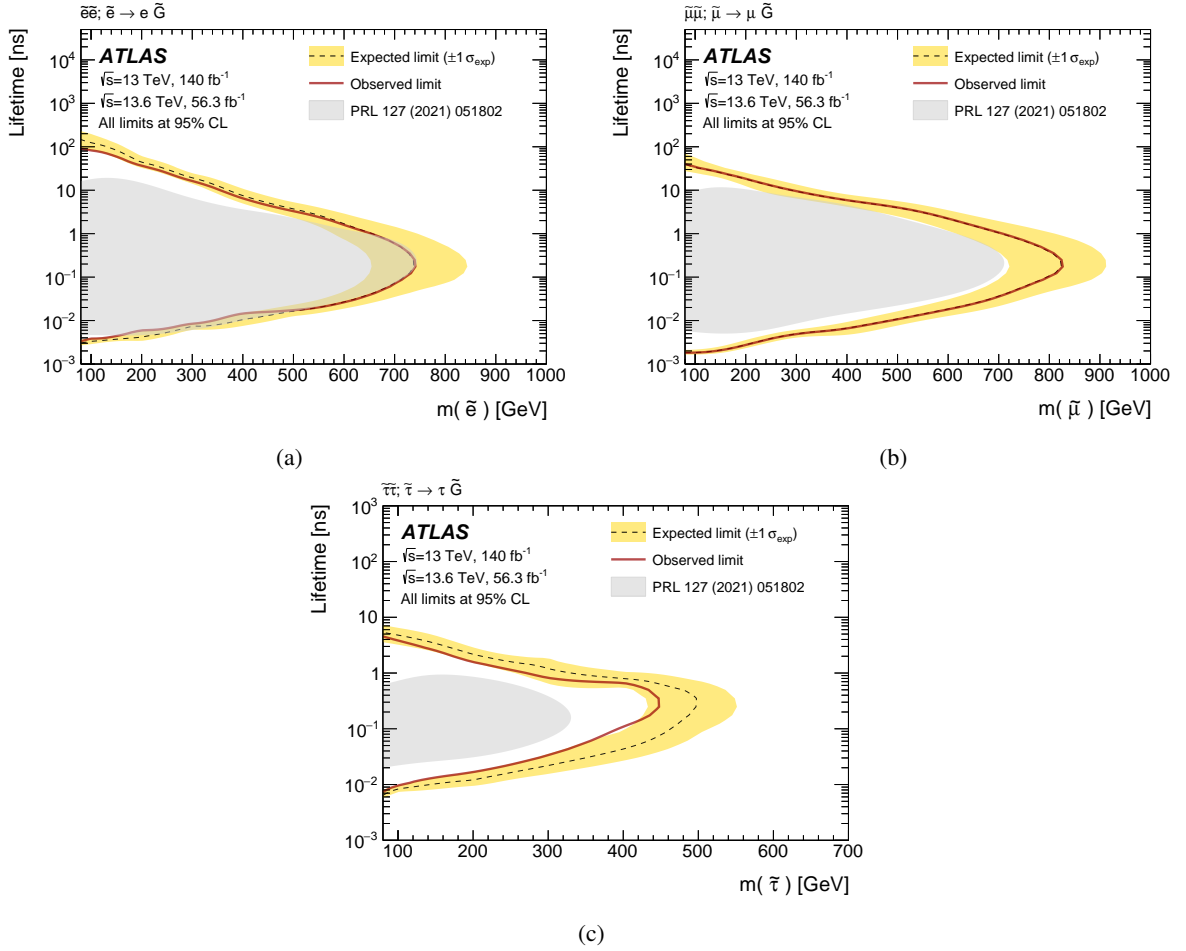


Figure 6: Expected and observed 95% CL exclusion contours for the (a) selectron, (b) smuon, (c) and stau models. The selectron and stau limits are computed using both the ABCD and EM-BDT regions, while the smuon limits are from the ABCD regions only. The dashed line indicates the expected limit and the surrounding band shows the 1σ variation of the expected limit due to uncertainties in the background prediction and experimental uncertainties in the signal modeling. The gray shaded area illustrates the observed exclusion obtained in the prior ATLAS Run 2 analysis [23].

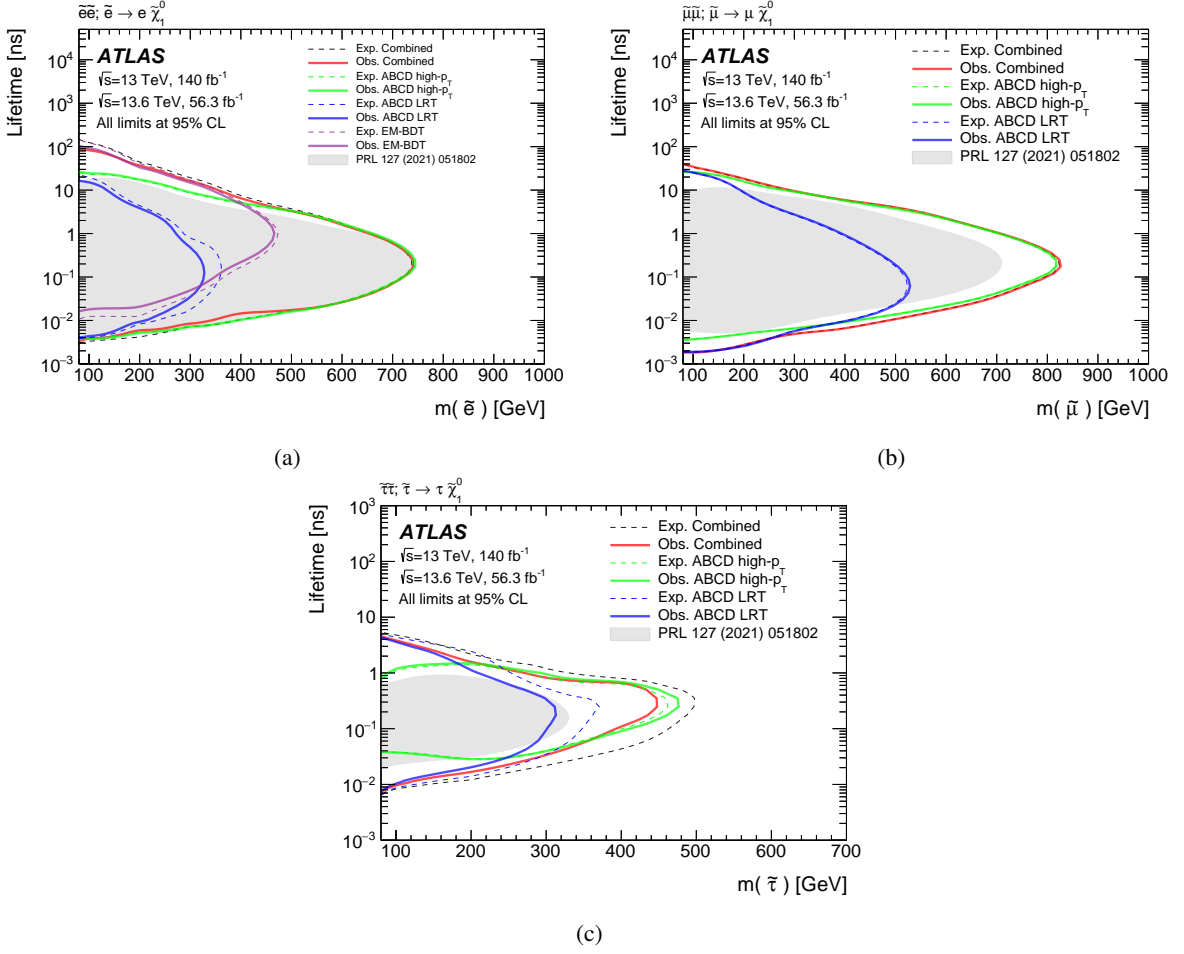


Figure 7: Comparison of expected and observed 95% CL exclusion contours for the (a) selectron, (b) smuon, and (c) stau models for subsets of the analysis regions: ABCD high- p_T , ABCD LRT, and EM-BDT. For the stau model, the EM-BDT SRs do not exclude any points by themselves. The dashed lines indicate the expected limits. The gray shaded area illustrates the observed exclusion obtained in the prior ATLAS Run 2 analysis [23].

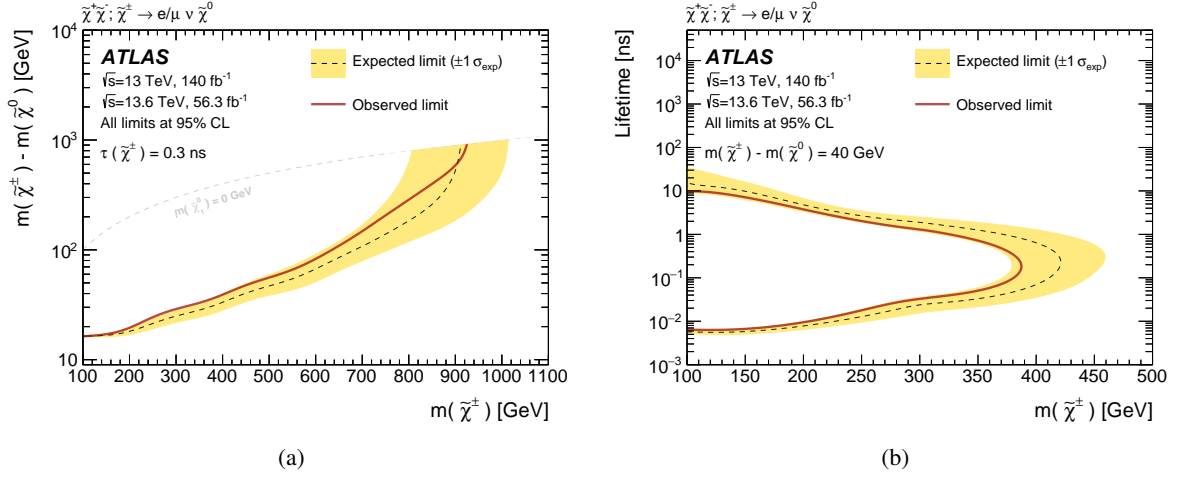


Figure 8: Expected and observed 95% CL exclusion contours for the dark sector model with a (a) fixed lifetime and (b) fixed mass splitting. The dashed line indicates the expected limit and the surrounding band shows the 1σ variation of the expected limit due to uncertainties in the background prediction and experimental uncertainties in the signal modeling.

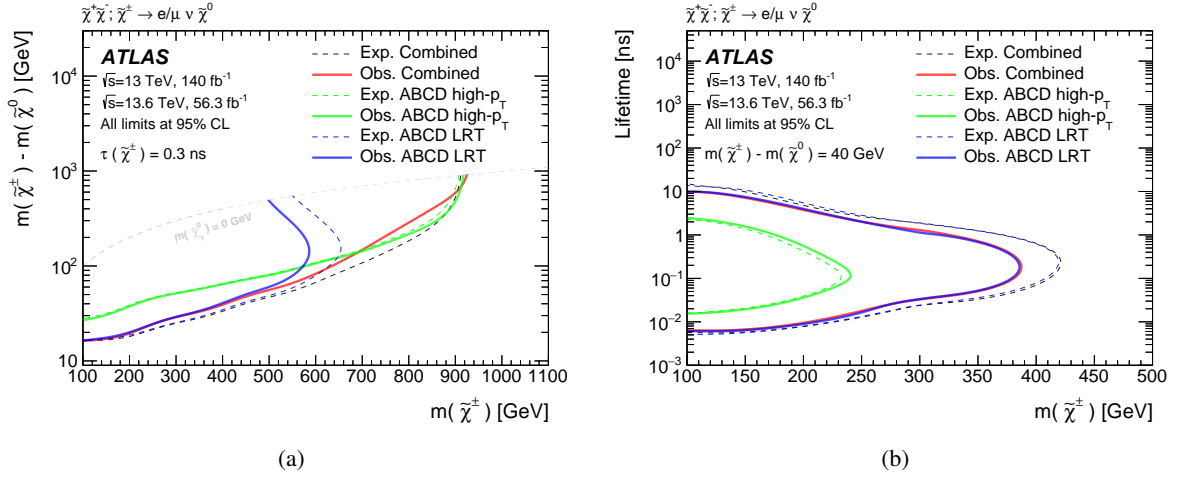


Figure 9: Comparison of expected and observed 95% CL exclusion contours for the dark sector model with a (a) fixed-lifetime and (b) fixed-mass-splitting for subsets of the analysis regions: ABCD high- p_T and ABCD LRT. The dashed lines indicate the expected limits.

9 Conclusion

A search for BSM physics using 56.3 fb^{-1} of proton–proton collision data collected by the ATLAS detector at the LHC during 2022–2023 with $\sqrt{s} = 13.6 \text{ TeV}$, combined with the full Run 2 dataset in some regions, was presented. The analysis focuses on the signature of displaced electrons or muons, consistent with the decay of a long-lived BSM particle. The event selection exploits new Run 3 triggers that employ LRT for sensitivity to lower momentum final state particles. Two orthogonal approaches are used, one focusing on dilepton events and another using LAr measurements and multivariate techniques for expanded sensitivity to single-electron and photon-reconstructed events.

The observed event yields in the various signal regions are consistent with the SM background expectations. The results are therefore used to set model-independent limits on the production of displaced electrons and muons. The combined analysis results are interpreted with two models. The first is a GMSB model with pair-produced long-lived sleptons that decay into the lepton of the same flavor and a nearly massless gravitino, providing exclusion contours that extend significantly beyond previous results. For example, 95% CL exclusions are obtained for selectrons with a mass of 150 GeV and lifetime values ranging from 4 ps to 60 ns, and selectrons, smuons, and staus with a 0.3 ns lifetime are excluded up to masses of 740 GeV, 830 GeV, and 440 GeV, respectively. The second model is pair-produced dark charginos decaying into a W boson and neutralino, where small mass splittings of 10–40 GeV result in a dark matter relic density consistent with observations. Similarly, 95% CL are set for charginos with masses up to 380 GeV for a mass difference with the neutralino of 40 GeV, and mass differences down to 17 GeV are excluded for dark charginos with a 100 GeV mass.

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The ATLAS Collaboration

G. Aad ¹⁰⁵, E. Aakvaag ¹⁷, B. Abbott ¹²⁴, S. Abdelhameed ^{120a}, K. Abeling ⁵⁷, N.J. Abicht ⁵¹, S.H. Abidi ³⁰, M. Aboeela ⁴⁶, A. Aboulhorma ^{36e}, H. Abramowicz ¹⁵⁶, H. Abreu ¹⁵⁵, Y. Abulaiti ¹²¹, B.S. Acharya ^{71a,71b,k}, A. Ackermann ^{65a}, C. Adam Bourdarios ⁴, L. Adamczyk ^{88a}, S.V. Addepalli ²⁷, M.J. Addison ¹⁰⁴, J. Adelman ¹¹⁹, A. Adiguzel ^{22c}, T. Adye ¹³⁸, A.A. Affolder ¹⁴⁰, Y. Afik ⁴¹, M.N. Agaras ¹³, A. Aggarwal ¹⁰³, C. Agheorghiesei ^{28c}, F. Ahmadov ^{40,y}, S. Ahuja ⁹⁸, X. Ai ^{64e}, G. Aielli ^{78a,78b}, A. Aikot ¹⁶⁸, M. Ait Tamliah ^{36e}, B. Aitbenkikh ^{36a}, M. Akbiyik ¹⁰³, T.P.A. Åkesson ¹⁰¹, A.V. Akimov ¹⁵⁰, D. Akiyama ¹⁷³, N.N. Akolkar ²⁵, S. Aktas ^{22a}, K. Al Houry ⁴³, G.L. Alberghi ^{24b}, J. Albert ¹⁷⁰, P. Albicocco ⁵⁵, G.L. Albouy ⁶², S. Alderweireldt ⁵⁴, Z.L. Alegria ¹²⁵, M. Aleksa ³⁷, I.N. Aleksandrov ⁴⁰, C. Alexa ^{28b}, T. Alexopoulos ¹⁰, F. Alfonsi ^{24b}, M. Algren ⁵⁸, M. Alhroob ¹⁷², B. Ali ¹³⁶, H.M.J. Ali ^{94,s}, S. Ali ³², S.W. Alibocus ⁹⁵, M. Aliev ^{34c}, G. Alimonti ^{73a}, W. Alkakh ⁵⁷, C. Allaire ⁶⁸, B.M.M. Allbrooke ¹⁵¹, J.S. Allen ¹⁰⁴, J.F. Allen ⁵⁴, C.A. Allendes Flores ^{141f}, P.P. Allport ²¹, A. Aloisio ^{74a,74b}, F. Alonso ⁹³, C. Alpigiani ¹⁴³, Z.M.K. Alsolami ⁹⁴, M. Alvarez Estevez ¹⁰², A. Alvarez Fernandez ¹⁰³, M. Alves Cardoso ⁵⁸, M.G. Alvigi ^{74a,74b}, M. Aly ¹⁰⁴, Y. Amaral Coutinho ^{85b}, A. Ambler ¹⁰⁷, C. Amelung ³⁷, M. Amerl ¹⁰⁴, C.G. Ames ¹¹², D. Amidei ¹⁰⁹, B. Amini ⁵⁶, K.J. Amirie ¹⁵⁹, S.P. Amor Dos Santos ^{134a}, K.R. Amos ¹⁶⁸, D. Amperiadou ¹⁵⁷, S. An ⁸⁶, V. Ananiev ¹²⁹, C. Anastopoulos ¹⁴⁴, T. Andeen ¹¹, J.K. Anders ³⁷, A.C. Anderson ⁶¹, S.Y. Andrean ^{49a,49b}, A. Andreazza ^{73a,73b}, S. Angelidakis ⁹, A. Angerami ⁴³, A.V. Anisenkov ³⁹, A. Annovi ^{76a}, C. Antel ⁵⁸, E. Antipov ¹⁵⁰, M. Antonelli ⁵⁵, F. Anulli ^{77a}, M. Aoki ⁸⁶, T. Aoki ¹⁵⁸, M.A. Aparo ¹⁵¹, L. Aperio Bella ⁵⁰, C. Appelt ¹⁵⁶, A. Apyan ²⁷, S.J. Arbiol Val ⁸⁹, C. Arcangeletti ⁵⁵, A.T.H. Arce ⁵³, J-F. Arguin ¹¹¹, S. Argyropoulos ¹⁵⁷, J.-H. Arling ⁵⁰, O. Arnaez ⁴, H. Arnold ¹⁵⁰, G. Artoni ^{77a,77b}, H. Asada ¹¹⁴, K. Asai ¹²², S. Asai ¹⁵⁸, N.A. Asbah ³⁷, R.A. Ashby Pickering ¹⁷², K. Assamagan ³⁰, R. Astalos ^{29a}, K.S.V. Astrand ¹⁰¹, S. Atashi ¹⁶³, R.J. Atkin ^{34a}, M. Atkinson ¹⁶⁷, H. Atmani ^{36f}, P.A. Atmasiddha ¹³², K. Augsten ¹³⁶, A.D. Auriol ²¹, V.A. Austrup ¹⁰⁴, G. Avolio ³⁷, K. Axiotis ⁵⁸, G. Azuelos ^{111,ac}, D. Babal ^{29b}, H. Bachacou ¹³⁹, K. Bachas ^{157,o}, A. Bachiu ³⁵, E. Bachmann ⁵², A. Badea ⁴¹, T.M. Baer ¹⁰⁹, P. Bagnaia ^{77a,77b}, M. Bahmani ¹⁹, D. Bahner ⁵⁶, K. Bai ¹²⁷, J.T. Baines ¹³⁸, L. Baines ⁹⁷, O.K. Baker ¹⁷⁷, E. Bakos ¹⁶, D. Bakshi Gupta ⁸, L.E. Balabram Filho ^{85b}, V. Balakrishnan ¹²⁴, R. Balasubramanian ⁴, E.M. Baldin ³⁹, P. Balek ^{88a}, E. Ballabene ^{24b,24a}, F. Balli ¹³⁹, L.M. Baltes ^{65a}, W.K. Balunas ³³, J. Balz ¹⁰³, I. Bamwidhi ^{120b}, E. Banas ⁸⁹, M. Bandieramonte ¹³³, A. Bandyopadhyay ²⁵, S. Bansal ²⁵, L. Barak ¹⁵⁶, M. Barakat ⁵⁰, E.L. Barberio ¹⁰⁸, D. Barberis ^{59b,59a}, M. Barbero ¹⁰⁵, M.Z. Barel ¹¹⁸, T. Barillari ¹¹³, M-S. Barisits ³⁷, T. Barklow ¹⁴⁸, P. Baron ¹²⁶, D.A. Baron Moreno ¹⁰⁴, A. Baroncelli ^{64a}, A.J. Barr ¹³⁰, J.D. Barr ⁹⁹, F. Barreiro ¹⁰², J. Barreiro Guimarães da Costa ¹⁴, M.G. Barros Teixeira ^{134a}, S. Barsov ³⁹, F. Bartels ^{65a}, R. Bartoldus ¹⁴⁸, A.E. Barton ⁹⁴, P. Bartos ^{29a}, A. Basan ¹⁰³, M. Baselga ⁵¹, A. Bassalat ^{68,b}, M.J. Basso ^{160a}, S. Bataju ⁴⁶, R. Bate ¹⁶⁹, R.L. Bates ⁶¹, S. Batlamous ¹⁰², B. Batool ¹⁴⁶, M. Battaglia ¹⁴⁰, D. Battulga ¹⁹, M. Bauce ^{77a,77b}, M. Bauer ⁸¹, P. Bauer ²⁵, L.T. Bazzano Hurrell ³¹, J.B. Beacham ⁵³, T. Beau ¹³¹, J.Y. Beaucamp ⁹³, P.H. Beauchemin ¹⁶², P. Bechtel ²⁵, H.P. Beck ^{20,n}, K. Becker ¹⁷², A.J. Beddall ⁸⁴, V.A. Bednyakov ⁴⁰, C.P. Bee ¹⁵⁰, L.J. Beemster ¹⁶, T.A. Beermann ³⁷, M. Begalli ^{85d}, M. Begel ³⁰, A. Behera ¹⁵⁰, J.K. Behr ⁵⁰, J.F. Beirer ³⁷, F. Beisiegel ²⁵, M. Belfkir ^{120b}, G. Bella ¹⁵⁶, L. Bellagamba ^{24b}, A. Bellerive ³⁵, P. Bellos ²¹, K. Beloborodov ³⁹, D. Benckekroun ^{36a}, F. Bendebba ^{36a}, Y. Benhammou ¹⁵⁶,

K.C. Benkendorfer ⁶³, L. Beresford ⁵⁰, M. Beretta ⁵⁵, E. Bergeaas Kuutmann ¹⁶⁶, N. Berger ⁴,
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 P. Bhattarai ¹⁴⁸, Z.M. Bhatti ¹²¹, K.D. Bhide ⁵⁶, V.S. Bhopatkar ¹²⁵, R.M. Bianchi ¹³³,
 G. Bianco ^{24b,24a}, O. Biebel ¹¹², R. Bielski ¹²⁷, M. Biglietti ^{79a}, C.S. Billingsley ⁴⁶, Y. Bimgdi ^{36f},
 M. Bindi ⁵⁷, A. Bingham ¹⁷⁶, A. Bingul ^{22b}, C. Bini ^{77a,77b}, G.A. Bird ³³, M. Birman ¹⁷⁴,
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 C. Bohm ^{49a}, V. Boisvert ⁹⁸, P. Bokan ³⁷, T. Bold ^{88a}, M. Bomben ⁵, M. Bona ⁹⁷,
 M. Boonekamp ¹³⁹, A.G. Borbély ⁶¹, I.S. Bordulev ³⁹, G. Borissov ⁹⁴, D. Bortoletto ¹³⁰,
 D. Boscherini ^{24b}, M. Bosman ¹³, K. Bouaouda ^{36a}, N. Bouchhar ¹⁶⁸, L. Boudet ⁴,
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 J. Boyd ³⁷, D. Boye ³⁰, P.R. Boyella ¹⁶⁷, I.R. Boyko ⁴⁰, L. Bozianu ⁵⁸, J. Bracik ²¹,
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 R. Brenner ¹⁷⁴, L. Brenner ¹¹⁸, R. Brenner ¹⁶⁶, M. Bressan ⁴³, S. Bressler ¹⁷⁴, G. Brianti ^{80a,80b},
 D. Britton ⁶¹, D. Britzger ¹¹³, I. Brock ²⁵, R. Brock ¹¹⁰, G. Brooijmans ⁴³, A.J. Brooks ⁷⁰,
 E.M. Brooks ^{160b}, E. Brost ³⁰, L.M. Brown ¹⁷⁰, L.E. Bruce ⁶³, T.L. Bruckler ¹³⁰,
 P.A. Bruckman de Renstrom ⁸⁹, B. Brüers ⁵⁰, A. Bruni ^{24b}, G. Bruni ^{24b}, D. Brunner ^{49a,49b},
 M. Bruschi ^{24b}, N. Bruscinò ^{77a,77b}, T. Buanes ¹⁷, Q. Buat ¹⁴³, D. Buchin ¹¹³, A.G. Buckley ⁶¹,
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 J.M. Butterworth ⁹⁹, W. Buttinger ¹³⁸, C.J. Buxo Vazquez ¹¹⁰, A.R. Buzykaev ³⁹,
 S. Cabrera Urbán ¹⁶⁸, L. Cadamuro ⁶⁸, D. Caforio ⁶⁰, H. Cai ¹³³, Y. Cai ^{14,115c}, Y. Cai ^{115a},
 V.M.M. Cairo ³⁷, O. Cakir ^{3a}, N. Calace ³⁷, P. Calafiura ^{18a}, G. Calderini ¹³¹, P. Calfayan ³⁵,
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 Y.C. Cekmecelioglu ⁵⁰, E. Celebi ⁸⁴, S. Cella ³⁷, V. Cepaitis ⁵⁸, K. Cerny ¹²⁶,
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 G. Cesarini ⁵⁵, S.A. Cetin ⁸⁴, D. Chakraborty ¹¹⁹, J. Chan ^{18a}, W.Y. Chan ¹⁵⁸, J.D. Chapman ³³,
 E. Chapon ¹³⁹, B. Chargeishvili ^{154b}, D.G. Charlton ²¹, M. Chatterjee ²⁰, C. Chauhan ¹³⁷,
 Y. Che ^{115a}, S. Chekanov ⁶, S.V. Chekulaev ^{160a}, G.A. Chelkov ^{40,a}, A. Chen ¹⁰⁹, B. Chen ¹⁵⁶,
 B. Chen ¹⁷⁰, H. Chen ^{115a}, H. Chen ³⁰, J. Chen ^{64c}, J. Chen ¹⁴⁷, M. Chen ¹³⁰, S. Chen ⁹⁰,
 S.J. Chen ^{115a}, X. Chen ^{64c}, X. Chen ^{15,ab}, Y. Chen ^{64a}, C.L. Cheng ¹⁷⁵, H.C. Cheng ^{66a},
 S. Cheong ¹⁴⁸, A. Cheplakov ⁴⁰, E. Cheremushkina ⁵⁰, E. Cherepanova ¹¹⁸,
 R. Cherkaoui El Moursli ^{36e}, E. Cheu ⁷, K. Cheung ⁶⁷, L. Chevalier ¹³⁹, V. Chiarella ⁵⁵,
 G. Chiarelli ^{76a}, N. Chiedde ¹⁰⁵, G. Chiodini ^{72a}, A.S. Chisholm ²¹, A. Chitan ^{28b},

M. Chitishvili ¹⁶⁸, M.V. Chizhov ^{40,q}, K. Choi ¹¹, Y. Chou ¹⁴³, E.Y.S. Chow ¹¹⁷, K.L. Chu ¹⁷⁴,
M.C. Chu ^{66a}, X. Chu ^{14,115c}, Z. Chubinidze ⁵⁵, J. Chudoba ¹³⁵, J.J. Chwastowski ⁸⁹,
D. Cieri ¹¹³, K.M. Ciesla ^{88a}, V. Cindro ⁹⁶, A. Ciocio ^{18a}, F. Cirotto ^{74a,74b}, Z.H. Citron ¹⁷⁴,
M. Citterio ^{73a}, D.A. Ciubotaru ^{28b}, A. Clark ⁵⁸, P.J. Clark ⁵⁴, N. Clarke Hall ⁹⁹, C. Clarry ¹⁵⁹,
J.M. Clavijo Columbie ⁵⁰, S.E. Clawson ⁵⁰, C. Clement ^{49a,49b}, Y. Coadou ¹⁰⁵, M. Cobal ^{71a,71c},
A. Coccaro ^{59b}, R.F. Coelho Barrue ^{134a}, R. Coelho Lopes De Sa ¹⁰⁶, S. Coelli ^{73a},
L.S. Colangeli ¹⁵⁹, B. Cole ⁴³, J. Collot ⁶², P. Conde Muiño ^{134a,134g}, M.P. Connell ^{34c},
S.H. Connell ^{34c}, E.I. Conroy ¹³⁰, F. Conventi ^{74a,ad}, H.G. Cooke ²¹, A.M. Cooper-Sarkar ¹³⁰,
F.A. Corchia ^{24b,24a}, A. Cordeiro Oudot Choi ¹³¹, L.D. Corpe ⁴², M. Corradi ^{77a,77b},
F. Corriveau ^{107,x}, A. Cortes-Gonzalez ¹⁹, M.J. Costa ¹⁶⁸, F. Costanza ⁴, D. Costanzo ¹⁴⁴,
B.M. Cote ¹²³, J. Couthures ⁴, G. Cowan ⁹⁸, K. Cranmer ¹⁷⁵, L. Cremer ⁵¹,
D. Cremonini ^{24b,24a}, S. Crépe-Renaudin ⁶², F. Crescioli ¹³¹, M. Cristinziani ¹⁴⁶,
M. Cristoforetti ^{80a,80b}, V. Croft ¹¹⁸, J.E. Crosby ¹²⁵, G. Crosetti ^{45b,45a}, A. Cueto ¹⁰², H. Cui ⁹⁹,
Z. Cui ⁷, W.R. Cunningham ⁶¹, F. Curcio ¹⁶⁸, J.R. Curran ⁵⁴, P. Czodrowski ³⁷,
M.J. Da Cunha Sargedas De Sousa ^{59b,59a}, J.V. Da Fonseca Pinto ^{85b}, C. Da Via ¹⁰⁴,
W. Dabrowski ^{88a}, T. Dado ³⁷, S. Dahbi ¹⁵³, T. Dai ¹⁰⁹, D. Dal Santo ²⁰, C. Dallapiccola ¹⁰⁶,
M. Dam ⁴⁴, G. D'amen ³⁰, V. D'Amico ¹¹², J. Damp ¹⁰³, J.R. Dandoy ³⁵, D. Dannheim ³⁷,
M. Danninger ¹⁴⁷, V. Dao ¹⁵⁰, G. Darbo ^{59b}, S.J. Das ³⁰, F. Dattola ⁵⁰, S. D'Auria ^{73a,73b},
A. D'Avanzo ^{74a,74b}, C. David ^{34a}, T. Davidek ¹³⁷, I. Dawson ⁹⁷, H.A. Day-hall ¹³⁶, K. De ⁸,
R. De Asmundis ^{74a}, N. De Biase ⁵⁰, S. De Castro ^{24b,24a}, N. De Groot ¹¹⁷, P. de Jong ¹¹⁸,
H. De la Torre ¹¹⁹, A. De Maria ^{115a}, A. De Salvo ^{77a}, U. De Sanctis ^{78a,78b}, F. De Santis ^{72a,72b},
A. De Santo ¹⁵¹, J.B. De Vivie De Regie ⁶², J. Debevc ⁹⁶, D.V. Dedovich ⁴⁰, J. Degens ⁹⁵,
A.M. Deiana ⁴⁶, F. Del Corso ^{24b,24a}, J. Del Peso ¹⁰², L. Delagrangé ¹³¹, F. Deliot ¹³⁹,
C.M. Delitzsch ⁵¹, M. Della Pietra ^{74a,74b}, D. Della Volpe ⁵⁸, A. Dell'Acqua ³⁷,
L. Dell'Asta ^{73a,73b}, M. Delmastro ⁴, C.C. Delogu ¹⁰³, P.A. Delsart ⁶², S. Demers ¹⁷⁷,
M. Demichev ⁴⁰, S.P. Denisov ³⁹, L. D'Eramo ⁴², D. Derendarz ⁸⁹, F. Derue ¹³¹, P. Dervan ⁹⁵,
K. Desch ²⁵, C. Deutsch ²⁵, F.A. Di Bello ^{59b,59a}, A. Di Ciaccio ^{78a,78b}, L. Di Ciaccio ⁴,
A. Di Domenico ^{77a,77b}, C. Di Donato ^{74a,74b}, A. Di Girolamo ³⁷, G. Di Gregorio ³⁷,
A. Di Luca ^{80a,80b}, B. Di Micco ^{79a,79b}, R. Di Nardo ^{79a,79b}, K.F. Di Petrillo ⁴¹,
M. Diamantopoulou ³⁵, F.A. Dias ¹¹⁸, T. Dias Do Vale ¹⁴⁷, M.A. Diaz ^{141a,141b}, A.R. Didenko ⁴⁰,
M. Didenko ¹⁶⁸, E.B. Diehl ¹⁰⁹, S. Díez Cornell ⁵⁰, C. Díez Pardos ¹⁴⁶, C. Dimitriadi ¹⁶⁶,
A. Dimitrievska ²¹, J. Dingfelder ²⁵, T. Dingley ¹³⁰, I-M. Dinu ^{28b}, S.J. Dittmeier ^{65b},
F. Dittus ³⁷, M. Divisek ¹³⁷, B. Dixit ⁹⁵, F. Djama ¹⁰⁵, T. Djobava ^{154b}, C. Doglioni ^{104,101},
A. Dohnalova ^{29a}, J. Dolejsi ¹³⁷, Z. Dolezal ¹³⁷, K. Domijan ^{88a}, K.M. Dona ⁴¹,
M. Donadelli ^{85d}, B. Dong ¹¹⁰, J. Donini ⁴², A. D'Onofrio ^{74a,74b}, M. D'Onofrio ⁹⁵,
J. Dopke ¹³⁸, A. Doria ^{74a}, N. Dos Santos Fernandes ^{134a}, P. Dougan ¹⁰⁴, M.T. Dova ⁹³,
A.T. Doyle ⁶¹, M.A. Dragnet ¹³⁰, M.P. Drescher ⁵⁷, E. Dreyer ¹⁷⁴, I. Drivas-koulouris ¹⁰,
M. Drnevich ¹²¹, M. Drozdova ⁵⁸, D. Du ^{64a}, T.A. du Pree ¹¹⁸, F. Dubinin ³⁹, M. Dubovsky ^{29a},
E. Duchovni ¹⁷⁴, G. Duckeck ¹¹², O.A. Ducu ^{28b}, D. Duda ⁵⁴, A. Dudarev ³⁷, E.R. Duden ²⁷,
M. D'uffizi ¹⁰⁴, L. Duflost ⁶⁸, M. Dührssen ³⁷, I. Duminica ^{28g}, A.E. Dumitriu ^{28b},
M. Dunford ^{65a}, S. Dungs ⁵¹, K. Dunne ^{49a,49b}, A. Duperrin ¹⁰⁵, H. Duran Yildiz ^{3a},
M. Düren ⁶⁰, A. Durglishvili ^{154b}, B.L. Dwyer ¹¹⁹, G.I. Dyckes ^{18a}, M. Dyndal ^{88a},
B.S. Dziedzic ³⁷, Z.O. Earnshaw ¹⁵¹, G.H. Eberwein ¹³⁰, B. Eckerova ^{29a}, S. Eggebrecht ⁵⁷,
E. Egidio Purcino De Souza ^{85e}, L.F. Ehrke ⁵⁸, G. Eigen ¹⁷, K. Einsweiler ^{18a}, T. Ekelof ¹⁶⁶,
P.A. Ekman ¹⁰¹, S. El Farkh ^{36b}, Y. El Ghazali ^{64a}, H. El Jarrari ³⁷, A. El Moussaouy ^{36a},
V. Ellajosyula ¹⁶⁶, M. Ellert ¹⁶⁶, F. Ellinghaus ¹⁷⁶, N. Ellis ³⁷, J. Elmsheuser ³⁰, M. Elsayy ^{120a},
M. Elsing ³⁷, D. Emelianov ¹³⁸, Y. Enari ⁸⁶, I. Ene ^{18a}, S. Epari ¹³, P.A. Erland ⁸⁹,

D. Ernani Martins Neto [ID⁸⁹](#), M. Errenst [ID¹⁷⁶](#), M. Escalier [ID⁶⁸](#), C. Escobar [ID¹⁶⁸](#), E. Etzion [ID¹⁵⁶](#),
 G. Evans [ID^{134a}](#), H. Evans [ID⁷⁰](#), L.S. Evans [ID⁹⁸](#), A. Ezhilov [ID³⁹](#), S. Ezzarqtouni [ID^{36a}](#), F. Fabbri [ID^{24b,24a}](#),
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 A.D. Gentry [ID¹¹⁶](#), S. George [ID⁹⁸](#), W.F. George [ID²¹](#), T. Geralis [ID⁴⁸](#), P. Gessinger-Befurt [ID³⁷](#),
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 B. Giacobbe [ID^{24b}](#), S. Giagu [ID^{77a,77b}](#), T. Giani [ID¹¹⁸](#), A. Giannini [ID^{64a}](#), S.M. Gibson [ID⁹⁸](#), M. Gignac [ID¹⁴⁰](#),
 D.T. Gil [ID^{88b}](#), A.K. Gilbert [ID^{88a}](#), B.J. Gilbert [ID⁴³](#), D. Gillberg [ID³⁵](#), G. Gilles [ID¹¹⁸](#), L. Ginabat [ID¹³¹](#),
 D.M. Gingrich [ID^{2,ac}](#), M.P. Giordani [ID^{71a,71c}](#), P.F. Giraud [ID¹³⁹](#), G. Giugliarelli [ID^{71a,71c}](#), D. Giugni [ID^{73a}](#),
 F. Giuli [ID^{78a,78b}](#), I. Gkialas [ID^{9,i}](#), L.K. Gladilin [ID³⁹](#), C. Glasman [ID¹⁰²](#), G.R. Gledhill [ID¹²⁷](#), G. Glemža [ID⁵⁰](#),
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 B. Gokturk [ID^{22a}](#), S. Goldfarb [ID¹⁰⁸](#), T. Golling [ID⁵⁸](#), M.G.D. Gololo [ID^{34g}](#), D. Golubkov [ID³⁹](#),
 J.P. Gombas [ID¹¹⁰](#), A. Gomes [ID^{134a,134b}](#), G. Gomes Da Silva [ID¹⁴⁶](#), A.J. Gomez Delegido [ID¹⁶⁸](#),
 R. Gonçalves [ID^{134a}](#), L. Gonella [ID²¹](#), A. Gongadze [ID^{154c}](#), F. Gonnella [ID²¹](#), J.L. Gonski [ID¹⁴⁸](#),
 R.Y. González Andana [ID⁵⁴](#), S. González de la Hoz [ID¹⁶⁸](#), R. Gonzalez Lopez [ID⁹⁵](#),
 C. Gonzalez Renteria [ID^{18a}](#), M.V. Gonzalez Rodrigues [ID⁵⁰](#), R. Gonzalez Suarez [ID¹⁶⁶](#),
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 M. Greco [ID^{72a,72b}](#), M.J. Green [ID¹](#), C. Grefe [ID²⁵](#), A.S. Grefsrud [ID¹⁷](#), I.M. Gregor [ID⁵⁰](#), K.T. Greif [ID¹⁶³](#),

P. Grenier ¹⁴⁸, S.G. Grewe ¹¹³, A.A. Grillo ¹⁴⁰, K. Grimm ³², S. Grinstein ^{13,t}, J.-F. Grivaz ⁶⁸,
 E. Gross ¹⁷⁴, J. Grosse-Knetter ⁵⁷, L. Guan ¹⁰⁹, J.G.R. Guerrero Rojas ¹⁶⁸, G. Guerrieri ³⁷,
 R. Gugel ¹⁰³, J.A.M. Guhit ¹⁰⁹, A. Guida ¹⁹, E. Guilloton ¹⁷², S. Guindon ³⁷, F. Guo ^{14,115c},
 J. Guo ^{64c}, L. Guo ⁵⁰, L. Guo ¹⁴, Y. Guo ¹⁰⁹, A. Gupta ⁵¹, R. Gupta ¹³³, S. Gurbuz ²⁵,
 S.S. Gurdasani ⁵⁶, G. Gustavino ^{77a,77b}, P. Gutierrez ¹²⁴, L.F. Gutierrez Zagazeta ¹³²,
 M. Gutsche ⁵², C. Gutschow ⁹⁹, C. Gwenlan ¹³⁰, C.B. Gwilliam ⁹⁵, E.S. Haaland ¹²⁹,
 A. Haas ¹²¹, M. Habedank ⁶¹, C. Haber ^{18a}, H.K. Hadavand ⁸, A. Hadeef ⁵², A.I. Hagan ⁹⁴,
 J.J. Hahn ¹⁴⁶, E.H. Haines ⁹⁹, M. Haleem ¹⁷¹, J. Haley ¹²⁵, G.D. Hallewell ¹⁰⁵, L. Halser ²⁰,
 K. Hamano ¹⁷⁰, M. Hamer ²⁵, E.J. Hampshire ⁹⁸, J. Han ^{64b}, L. Han ^{115a}, L. Han ^{64a},
 S. Han ^{18a}, Y.F. Han ¹⁵⁹, K. Hanagaki ⁸⁶, M. Hance ¹⁴⁰, D.A. Hangal ⁴³, H. Hanif ¹⁴⁷,
 M.D. Hank ¹³², J.B. Hansen ⁴⁴, P.H. Hansen ⁴⁴, D. Harada ⁵⁸, T. Harenberg ¹⁷⁶,
 S. Harkusha ¹⁷⁸, M.L. Harris ¹⁰⁶, Y.T. Harris ²⁵, J. Harrison ¹³, N.M. Harrison ¹²³,
 P.F. Harrison ¹⁷², N.M. Hartman ¹¹³, N.M. Hartmann ¹¹², R.Z. Hasan ^{98,138}, Y. Hasegawa ¹⁴⁵,
 F. Haslbeck ¹³⁰, S. Hassan ¹⁷, R. Hauser ¹¹⁰, C.M. Hawkes ²¹, R.J. Hawkings ³⁷,
 Y. Hayashi ¹⁵⁸, D. Hayden ¹¹⁰, C. Hayes ¹⁰⁹, R.L. Hayes ¹¹⁸, C.P. Hays ¹³⁰, J.M. Hays ⁹⁷,
 H.S. Hayward ⁹⁵, F. He ^{64a}, M. He ^{14,115c}, Y. He ⁵⁰, Y. He ⁹⁹, N.B. Heatley ⁹⁷, V. Hedberg ¹⁰¹,
 A.L. Heggelund ¹²⁹, N.D. Hehir ^{97,*}, C. Heidegger ⁵⁶, K.K. Heidegger ⁵⁶, J. Heilman ³⁵,
 S. Heim ⁵⁰, T. Heim ^{18a}, J.G. Heinlein ¹³², J.J. Heinrich ¹²⁷, L. Heinrich ^{113,aa}, J. Hejbal ¹³⁵,
 A. Held ¹⁷⁵, S. Hellesund ¹⁷, C.M. Helling ¹⁶⁹, S. Hellman ^{49a,49b}, R.C.W. Henderson ⁹⁴,
 L. Henkelmann ³³, A.M. Henriques Correia ³⁷, H. Herde ¹⁰¹, Y. Hernández Jiménez ¹⁵⁰,
 L.M. Herrmann ²⁵, T. Herrmann ⁵², G. Herten ⁵⁶, R. Hertenberger ¹¹², L. Hervas ³⁷,
 M.E. Hesping ¹⁰³, N.P. Hessey ^{160a}, J. Hessler ¹¹³, M. Hidaoui ^{36b}, N. Hidic ¹³⁷, E. Hill ¹⁵⁹,
 S.J. Hillier ²¹, J.R. Hinds ¹¹⁰, F. Hinterkeuser ²⁵, M. Hirose ¹²⁸, S. Hirose ¹⁶¹,
 D. Hirschbuehl ¹⁷⁶, T.G. Hitchings ¹⁰⁴, B. Hiti ⁹⁶, J. Hobbs ¹⁵⁰, R. Hobincu ^{28e}, N. Hod ¹⁷⁴,
 M.C. Hodgkinson ¹⁴⁴, B.H. Hodgkinson ¹³⁰, A. Hoecker ³⁷, D.D. Hofer ¹⁰⁹, J. Hofer ¹⁶⁸,
 T. Holm ²⁵, M. Holzbock ³⁷, L.B.A.H. Hommels ³³, B.P. Honan ¹⁰⁴, J.J. Hong ⁷⁰, J. Hong ^{64c},
 T.M. Hong ¹³³, B.H. Hooberman ¹⁶⁷, W.H. Hopkins ⁶, M.C. Hoppesch ¹⁶⁷, Y. Horii ¹¹⁴,
 M.E. Horstmann ¹¹³, S. Hou ¹⁵³, M.R. Housenga ¹⁶⁷, A.S. Howard ⁹⁶, J. Howarth ⁶¹, J. Hoya ⁶,
 M. Hrabovsky ¹²⁶, A. Hrynevich ⁵⁰, T. Hryn'ova ⁴, P.J. Hsu ⁶⁷, S.-C. Hsu ¹⁴³, T. Hsu ⁶⁸,
 M. Hu ^{18a}, Q. Hu ^{64a}, S. Huang ³³, X. Huang ^{14,115c}, Y. Huang ¹⁴⁴, Y. Huang ¹⁰³,
 Y. Huang ¹⁴, Z. Huang ¹⁰⁴, Z. Hubacek ¹³⁶, M. Huebner ²⁵, F. Huegging ²⁵, T.B. Huffman ¹³⁰,
 M. Hufnagel Maranha De Faria ^{85a}, C.A. Hugli ⁵⁰, M. Huhtinen ³⁷, S.K. Huiberts ¹⁷,
 R. Hulskén ¹⁰⁷, N. Huseynov ^{12,f}, J. Huston ¹¹⁰, J. Huth ⁶³, R. Hyneman ¹⁴⁸, G. Iacobucci ⁵⁸,
 G. Iakovidis ³⁰, L. Iconomidou-Fayard ⁶⁸, J.P. Iddon ³⁷, P. Iengo ^{74a,74b}, R. Iguchi ¹⁵⁸,
 Y. Iiyama ¹⁵⁸, T. Iizawa ¹³⁰, Y. Ikegami ⁸⁶, N. Ilic ¹⁵⁹, H. Imam ^{85c}, G. Inacio Goncalves ^{85d},
 T. Ingebretsen Carlson ^{49a,49b}, J.M. Inglis ⁹⁷, G. Introzzi ^{75a,75b}, M. Iodice ^{79a}, V. Ippolito ^{77a,77b},
 R.K. Irwin ⁹⁵, M. Ishino ¹⁵⁸, W. Islam ¹⁷⁵, C. Issever ¹⁹, S. Istin ^{22a,ag}, H. Ito ¹⁷³,
 R. Iuppa ^{80a,80b}, A. Ivina ¹⁷⁴, J.M. Izen ⁴⁷, V. Izzo ^{74a}, P. Jacka ¹³⁵, P. Jackson ¹,
 C.S. Jagfeld ¹¹², G. Jain ^{160a}, P. Jain ⁵⁰, K. Jakobs ⁵⁶, T. Jakoubek ¹⁷⁴, J. Jamieson ⁶¹,
 W. Jang ¹⁵⁸, M. Javurkova ¹⁰⁶, P. Jawahar ¹⁰⁴, L. Jeanty ¹²⁷, J. Jejelava ^{154a}, P. Jenni ^{56,e},
 C.E. Jessiman ³⁵, C. Jia ^{64b}, H. Jia ¹⁶⁹, J. Jia ¹⁵⁰, X. Jia ^{14,115c}, Z. Jia ^{115a}, C. Jiang ⁵⁴,
 S. Jiggins ⁵⁰, J. Jimenez Pena ¹³, S. Jin ^{115a}, A. Jinaru ^{28b}, O. Jinnouchi ¹⁴², P. Johansson ¹⁴⁴,
 K.A. Johns ⁷, J.W. Johnson ¹⁴⁰, F.A. Jolly ⁵⁰, D.M. Jones ¹⁵¹, E. Jones ⁵⁰, K.S. Jones ⁸,
 P. Jones ³³, R.W.L. Jones ⁹⁴, T.J. Jones ⁹⁵, H.L. Joos ^{57,37}, R. Joshi ¹²³, J. Jovicevic ¹⁶,
 X. Ju ^{18a}, J.J. Junggeburth ³⁷, T. Junkermann ^{65a}, A. Juste Rozas ^{13,t}, M.K. Juzek ⁸⁹,
 S. Kabana ^{141e}, A. Kaczmarzka ⁸⁹, M. Kado ¹¹³, H. Kagan ¹²³, M. Kagan ¹⁴⁸, A. Kahn ¹³²,
 C. Kahra ¹⁰³, T. Kaji ¹⁵⁸, E. Kajomovitz ¹⁵⁵, N. Kakati ¹⁷⁴, I. Kalaitzidou ⁵⁶, C.W. Kalderon ³⁰,

N.J. Kang ¹⁴⁰, D. Kar ^{34g}, K. Karava ¹³⁰, M.J. Kareem ^{160b}, E. Karentzos ²⁵, O. Karkout ¹¹⁸,
 S.N. Karpov ⁴⁰, Z.M. Karpova ⁴⁰, V. Kartvelishvili ⁹⁴, A.N. Karyukhin ³⁹, E. Kasimi ¹⁵⁷,
 J. Katzy ⁵⁰, S. Kaur ³⁵, K. Kawade ¹⁴⁵, M.P. Kawale ¹²⁴, C. Kawamoto ⁹⁰, T. Kawamoto ^{64a},
 E.F. Kay ³⁷, F.I. Kaya ¹⁶², S. Kazakos ¹¹⁰, V.F. Kazanin ³⁹, Y. Ke ¹⁵⁰, J.M. Keaveney ^{34a},
 R. Keeler ¹⁷⁰, G.V. Kehris ⁶³, J.S. Keller ³⁵, J.J. Kempster ¹⁵¹, O. Kepka ¹³⁵, B.P. Kerridge ¹³⁸,
 S. Kersten ¹⁷⁶, B.P. Kerševan ⁹⁶, L. Keszezhova ^{29a}, S. Ketabchi Haghghat ¹⁵⁹, R.A. Khan ¹³³,
 A. Khanov ¹²⁵, A.G. Kharlamov ³⁹, T. Kharlamova ³⁹, E.E. Khoda ¹⁴³, M. Kholodenko ^{134a},
 T.J. Khoo ¹⁹, G. Khoriauli ¹⁷¹, J. Khubua ^{154b,*}, Y.A.R. Khwaira ¹³¹, B. Kibirige ^{34g}, D. Kim ⁶,
 D.W. Kim ^{49a,49b}, Y.K. Kim ⁴¹, N. Kimura ⁹⁹, M.K. Kingston ⁵⁷, A. Kirchhoff ⁵⁷, C. Kirfel ²⁵,
 F. Kirfel ²⁵, J. Kirk ¹³⁸, A.E. Kiryunin ¹¹³, S. Kita ¹⁶¹, C. Kitsaki ¹⁰, O. Kivernyk ²⁵,
 M. Klassen ¹⁶², C. Klein ³⁵, L. Klein ¹⁷¹, M.H. Klein ⁴⁶, S.B. Klein ⁵⁸, U. Klein ⁹⁵,
 A. Klimentov ³⁰, T. Klioutchnikova ³⁷, P. Kluit ¹¹⁸, S. Kluth ¹¹³, E. Kneringer ⁸¹,
 T.M. Knight ¹⁵⁹, A. Knue ⁵¹, D. Kobylanski ¹⁷⁴, S.F. Koch ¹³⁰, M. Kocian ¹⁴⁸, P. Kodyš ¹³⁷,
 D.M. Koeck ¹²⁷, P.T. Koenig ²⁵, T. Koffas ³⁵, O. Kolay ⁵², I. Koletsou ⁴, T. Komarek ⁸⁹,
 K. Köneke ⁵⁶, A.X.Y. Kong ¹, T. Kono ¹²², N. Konstantinidis ⁹⁹, P. Kontaxakis ⁵⁸,
 B. Konya ¹⁰¹, R. Kopeliansky ⁴³, S. Koperny ^{88a}, K. Korcyl ⁸⁹, K. Kordas ^{157,d}, A. Korn ⁹⁹,
 S. Korn ⁵⁷, I. Korolkov ¹³, N. Korotkova ³⁹, B. Kortman ¹¹⁸, O. Kortner ¹¹³, S. Kortner ¹¹³,
 W.H. Kostecka ¹¹⁹, V.V. Kostyukhin ¹⁴⁶, A. Kotsokechagia ³⁷, A. Kotwal ⁵³, A. Koulouris ³⁷,
 A. Kourkoumeli-Charalampidi ^{75a,75b}, C. Kourkoumelis ⁹, E. Kourlitis ^{113,aa}, O. Kovanda ¹²⁷,
 R. Kowalewski ¹⁷⁰, W. Kozanecki ¹²⁷, A.S. Kozhin ³⁹, V.A. Kramarenko ³⁹, G. Kramberger ⁹⁶,
 P. Kramer ²⁵, M.W. Krasny ¹³¹, A. Krasznahorkay ³⁷, A.C. Kraus ¹¹⁹, J.W. Kraus ¹⁷⁶,
 J.A. Kremer ⁵⁰, T. Kresse ⁵², L. Kretschmann ¹⁷⁶, J. Kretschmar ⁹⁵, K. Kreul ¹⁹,
 P. Krieger ¹⁵⁹, K. Krizka ²¹, K. Kroeninger ⁵¹, H. Kroha ¹¹³, J. Kroll ¹³⁵, J. Kroll ¹³²,
 K.S. Krowpman ¹¹⁰, U. Kruchonak ⁴⁰, H. Krüger ²⁵, N. Krumnack ⁸³, M.C. Kruse ⁵³,
 O. Kuchinskaia ³⁹, S. Kuday ^{3a}, S. Kuehn ³⁷, R. Kuesters ⁵⁶, T. Kuhl ⁵⁰, V. Kukhtin ⁴⁰,
 Y. Kulchitsky ⁴⁰, S. Kuleshov ^{141d,141b}, M. Kumar ^{34g}, N. Kumari ⁵⁰, P. Kumari ^{160b},
 A. Kupco ¹³⁵, T. Kupfer ⁵¹, A. Kupich ³⁹, O. Kuprash ⁵⁶, H. Kurashige ⁸⁷, L.L. Kurchaninov ^{160a},
 O. Kurdysh ⁶⁸, Y.A. Kurochkin ³⁸, A. Kurova ³⁹, M. Kuze ¹⁴², A.K. Kvam ¹⁰⁶, J. Kvita ¹²⁶,
 T. Kwan ¹⁰⁷, N.G. Kyriacou ¹⁰⁹, L.A.O. Laatu ¹⁰⁵, C. Lacasta ¹⁶⁸, F. Lacava ^{77a,77b},
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 M.P.J. Landon ⁹⁷, V.S. Lang ⁵⁶, O.K.B. Langrekken ¹²⁹, A.J. Lankford ¹⁶³, F. Lanni ³⁷,
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 E.M. Le Boulicaut ¹⁷⁷, L.T. Le Pottier ^{18a}, B. Leban ^{24b,24a}, A. Lebedev ⁸³, M. LeBlanc ¹⁰⁴,
 F. Ledroit-Guillon ⁶², S.C. Lee ¹⁵³, S. Lee ^{49a,49b}, T.F. Lee ⁹⁵, L.L. Leeuw ^{34c}, M. Lefebvre ¹⁷⁰,
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 A. Leisos ^{157,r}, M.A.L. Leite ^{85c}, C.E. Leitgeb ¹⁹, R. Leitner ¹³⁷, K.J.C. Leney ⁴⁶, T. Lenz ²⁵,
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 M. Levchenko ³⁹, J. Levêque ⁴, L.J. Levinson ¹⁷⁴, G. Levrini ^{24b,24a}, M.P. Lewicki ⁸⁹,
 C. Lewis ¹⁴³, D.J. Lewis ⁴, L. Lewitt ¹⁴⁴, A. Li ³⁰, B. Li ^{64b}, C. Li ^{64a}, C-Q. Li ¹¹³, H. Li ^{64a},
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 S. Li ^{14,115c}, S. Li ^{64d,64c}, T. Li ⁵, X. Li ¹⁰⁷, Z. Li ¹⁵⁸, Z. Li ^{14,115c}, Z. Li ^{64a}, S. Liang ^{14,115c},
 Z. Liang ¹⁴, M. Liberatore ¹³⁹, B. Liberti ^{78a}, K. Lie ^{66c}, J. Lieber Marin ^{85e}, H. Lien ⁷⁰,
 H. Lin ¹⁰⁹, K. Lin ¹¹⁰, L. Linden ¹¹², R.E. Lindley ⁷, J.H. Lindon ², J. Ling ⁶³, E. Lipeles ¹³²,

A. Lipniacka ¹⁷, A. Lister ¹⁶⁹, J.D. Little ⁷⁰, B. Liu ¹⁴, B.X. Liu ^{115b}, D. Liu ^{64d,64c},
 E.H.L. Liu ²¹, J.B. Liu ^{64a}, J.K.K. Liu ³³, K. Liu ^{64d}, K. Liu ^{64d,64c}, M. Liu ^{64a}, M.Y. Liu ^{64a},
 P. Liu ¹⁴, Q. Liu ^{64d,143,64c}, X. Liu ^{64a}, X. Liu ^{64b}, Y. Liu ^{115b,115c}, Y.L. Liu ^{64b}, Y.W. Liu ^{64a},
 S.L. Lloyd ⁹⁷, E.M. Lobodzinska ⁵⁰, P. Loch ⁷, E. Lodhi ¹⁵⁹, T. Lohse ¹⁹, K. Lohwasser ¹⁴⁴,
 E. Loiacono ⁵⁰, J.D. Lomas ²¹, J.D. Long ⁴³, I. Longarini ¹⁶³, R. Longo ¹⁶⁷, I. Lopez Paz ⁶⁹,
 A. Lopez Solis ⁵⁰, N.A. Lopez-canelas ⁷, N. Lorenzo Martinez ⁴, A.M. Lory ¹¹², M. Losada ^{120a},
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 J. Martin ⁹⁹, T.A. Martin ¹³⁸, V.J. Martin ⁵⁴, B. Martin dit Latour ¹⁷, L. Martinelli ^{77a,77b},
 M. Martinez ^{13,t}, P. Martinez Agullo ¹⁶⁸, V.I. Martinez Outschoorn ¹⁰⁶, P. Martinez Suarez ¹³,
 S. Martin-Haugh ¹³⁸, G. Martinovicova ¹³⁷, V.S. Martoiu ^{28b}, A.C. Martyniuk ⁹⁹, A. Marzin ³⁷,
 D. Mascione ^{80a,80b}, L. Masetti ¹⁰³, J. Masik ¹⁰⁴, A.L. Maslennikov ³⁹, S.L. Mason ⁴³,
 P. Massarotti ^{74a,74b}, P. Mastrandrea ^{76a,76b}, A. Mastroberardino ^{45b,45a}, T. Masubuchi ¹²⁸,
 T.T. Mathew ¹²⁷, T. Mathisen ¹⁶⁶, J. Matousek ¹³⁷, D.M. Mattern ⁵¹, J. Maurer ^{28b},
 T. Maurin ⁶¹, A.J. Maury ⁶⁸, B. Maček ⁹⁶, D.A. Maximov ³⁹, A.E. May ¹⁰⁴, R. Mazini ^{34g},
 I. Maznas ¹¹⁹, M. Mazza ¹¹⁰, S.M. Mazza ¹⁴⁰, E. Mazzeo ^{73a,73b}, J.P. Mc Gowan ¹⁷⁰,
 S.P. Mc Kee ¹⁰⁹, C.A. Mc Lean ⁶, C.C. McCracken ¹⁶⁹, E.F. McDonald ¹⁰⁸, A.E. McDougall ¹¹⁸,
 J.A. Mcfayden ¹⁵¹, R.P. McGovern ¹³², R.P. Mckenzie ^{34g}, T.C. Mclachlan ⁵⁰, D.J. Mclaughlin ⁹⁹,
 S.J. McMahan ¹³⁸, C.M. Mcpartland ⁹⁵, R.A. McPherson ^{170,x}, S. Mehlhase ¹¹², A. Mehta ⁹⁵,
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 A.M. Mendes Jacques Da Costa ¹⁰⁴, H.Y. Meng ¹⁵⁹, L. Meng ⁹⁴, S. Menke ¹¹³, M. Mentink ³⁷,
 E. Meoni ^{45b,45a}, G. Mercado ¹¹⁹, S. Merianos ¹⁵⁷, C. Merlassino ^{71a,71c}, L. Merola ^{74a,74b},
 C. Meroni ^{73a,73b}, J. Metcalfe ⁶, A.S. Mete ⁶, E. Meuser ¹⁰³, C. Meyer ⁷⁰, J-P. Meyer ¹³⁹,
 R.P. Middleton ¹³⁸, L. Mijović ⁵⁴, G. Mikenberg ¹⁷⁴, M. Mikestikova ¹³⁵, M. Mikuž ⁹⁶,
 H. Mildner ¹⁰³, A. Milic ³⁷, D.W. Miller ⁴¹, E.H. Miller ¹⁴⁸, L.S. Miller ³⁵, A. Milov ¹⁷⁴,
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 P.S. Miyagawa ⁹⁷, T. Mkrtychyan ^{65a}, M. Mlinarevic ⁹⁹, T. Mlinarevic ⁹⁹, M. Mlynarikova ³⁷,
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 G. Mokgatitswane ^{34g}, L. Moleri ¹⁷⁴, B. Mondal ¹⁴⁶, S. Mondal ¹³⁶, K. Mönig ⁵⁰,
 E. Monnier ¹⁰⁵, L. Monsonis Romero ¹⁶⁸, J. Montejo Berlingen ¹³, A. Montella ^{49a,49b},
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N. Morange ⁶⁸, A.L. Moreira De Carvalho ⁵⁰, M. Moreno Llácer ¹⁶⁸, C. Moreno Martinez ⁵⁸,
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 Y. Moyal ¹⁷⁴, E.J.W. Moyse ¹⁰⁶, O. Mtintsilana ^{34g}, S. Muanza ¹⁰⁵, J. Mueller ¹³³,
 D. Muenstermann ⁹⁴, R. Müller ³⁷, G.A. Mullier ¹⁶⁶, A.J. Mullin ³³, J.J. Mullin ¹³², A.E. Mulski ⁶³,
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 A.M. Nairz ³⁷, Y. Nakahama ⁸⁶, K. Nakamura ⁸⁶, K. Nakkalil ⁵, H. Nanjo ¹²⁸,
 E.A. Narayanan ⁴⁶, I. Naryshkin ³⁹, L. Nasella ^{73a,73b}, S. Nasri ^{120b}, C. Nass ²⁵, G. Navarro ^{23a},
 J. Navarro-Gonzalez ¹⁶⁸, R. Nayak ¹⁵⁶, A. Nayaz ¹⁹, P.Y. Nechaeva ³⁹, S. Nechaeva ^{24b,24a},
 F. Nechansky ¹³⁵, L. Nedic ¹³⁰, T.J. Neep ²¹, A. Negri ^{75a,75b}, M. Negrini ^{24b}, C. Nellist ¹¹⁸,
 C. Nelson ¹⁰⁷, K. Nelson ¹⁰⁹, S. Nemecek ¹³⁵, M. Nessi ^{37,g}, M.S. Neubauer ¹⁶⁷, F. Neuhaus ¹⁰³,
 J. Neundorf ⁵⁰, J. Newell ⁹⁵, P.R. Newman ²¹, C.W. Ng ¹³³, Y.W.Y. Ng ⁵⁰, B. Ngair ^{120a},
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 J. Niermann ⁵⁷, N. Nikiforou ³⁷, V. Nikolaenko ^{39,a}, I. Nikolic-Audit ¹³¹, K. Nikolopoulos ²¹,
 P. Nilsson ³⁰, I. Ninca ⁵⁰, G. Ninio ¹⁵⁶, A. Nisati ^{77a}, N. Nishu ², R. Nisius ¹¹³,
 N. Nitika ^{71a,71c}, J-E. Nitschke ⁵², E.K. Nkadimeng ^{34g}, T. Nobe ¹⁵⁸, T. Nommensen ¹⁵²,
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 R. Novotny ¹¹⁶, L. Nozka ¹²⁶, K. Ntekas ¹⁶³, N.M.J. Nunes De Moura Junior ^{85b}, J. Ocariz ¹³¹,
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 I. Oleksiyuk ⁵⁸, S.A. Olivares Pino ^{141d}, G. Oliveira Correa ¹³, D. Oliveira Damazio ³⁰,
 J.L. Oliver ¹⁶³, Ö.O. Öncel ⁵⁶, A.P. O'Neill ²⁰, A. Onofre ^{134a,134e}, P.U.E. Onyisi ¹¹,
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 M. Ouchrif ^{36d}, F. Ould-Saada ¹²⁹, T. Ovsianikova ¹⁴³, M. Owen ⁶¹, R.E. Owen ¹³⁸,
 V.E. Ozcan ^{22a}, F. Ozturk ⁸⁹, N. Ozturk ⁸, S. Ozturk ⁸⁴, H.A. Pacey ¹³⁰, A. Pacheco Pages ¹³,
 C. Padilla Aranda ¹³, G. Padovano ^{77a,77b}, S. Pagan Griso ^{18a}, G. Palacino ⁷⁰, A. Palazzo ^{72a,72b},
 J. Pampel ²⁵, J. Pan ¹⁷⁷, T. Pan ^{66a}, D.K. Panchal ¹¹, C.E. Pandini ¹¹⁸,
 J.G. Panduro Vazquez ¹³⁸, H.D. Pandya ¹, H. Pang ¹⁵, P. Pani ⁵⁰, G. Panizzo ^{71a,71c},
 L. Panwar ¹³¹, L. Paolozzi ⁵⁸, S. Parajuli ¹⁶⁷, A. Paramonov ⁶, C. Paraskevopoulos ⁵⁵,
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 F. Parodi ^{59b,59a}, V.A. Parrish ⁵⁴, J.A. Parsons ⁴³, U. Parzefall ⁵⁶, B. Pascual Dias ¹¹¹,
 L. Pascual Dominguez ¹⁰², E. Pasqualucci ^{77a}, S. Passaggio ^{59b}, F. Pastore ⁹⁸, P. Patel ⁸⁹,
 U.M. Patel ⁵³, J.R. Pater ¹⁰⁴, T. Pauly ³⁷, F. Pauwels ¹³⁷, C.I. Pazos ¹⁶², M. Pedersen ¹²⁹,
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 K.E. Pensi ¹¹², M. Penzin ³⁹, B.S. Peralva ^{85d}, A.P. Pereira Peixoto ¹⁴³, L. Pereira Sanchez ¹⁴⁸,
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 N. Vranjes [ID16](#), M. Vranjes Milosavljevic [ID16](#), M. Vreeswijk [ID118](#), N.K. Vu [ID64d,64c](#), R. Vuillermet [ID37](#),
 O. Vujanovic [ID103](#), I. Vukotic [ID41](#), I.K. Vyas [ID35](#), S. Wada [ID161](#), C. Wagner [ID148](#), J.M. Wagner [ID18a](#),
 W. Wagner [ID176](#), S. Wahdan [ID176](#), H. Wahlberg [ID93](#), C.H. Waits [ID124](#), J. Walder [ID138](#), R. Walker [ID112](#),
 W. Walkowiak [ID146](#), A. Wall [ID132](#), E.J. Wallin [ID101](#), T. Wamorkar [ID6](#), A.Z. Wang [ID140](#), C. Wang [ID103](#),
 C. Wang [ID11](#), H. Wang [ID18a](#), J. Wang [ID66c](#), P. Wang [ID99](#), R. Wang [ID63](#), R. Wang [ID6](#), S.M. Wang [ID153](#),
 S. Wang [ID14](#), T. Wang [ID64a](#), W.T. Wang [ID82](#), W. Wang [ID14](#), X. Wang [ID115a](#), X. Wang [ID167](#),
 X. Wang [ID64c](#), Y. Wang [ID64d](#), Y. Wang [ID115a](#), Y. Wang [ID64a](#), Z. Wang [ID109](#), Z. Wang [ID64d,53,64c](#),
 Z. Wang [ID109](#), A. Warburton [ID107](#), R.J. Ward [ID21](#), N. Warrack [ID61](#), S. Waterhouse [ID98](#), A.T. Watson [ID21](#),
 H. Watson [ID54](#), M.F. Watson [ID21](#), E. Watton [ID61,138](#), G. Watts [ID143](#), B.M. Waugh [ID99](#), J.M. Webb [ID56](#),
 C. Weber [ID30](#), H.A. Weber [ID19](#), M.S. Weber [ID20](#), S.M. Weber [ID65a](#), C. Wei [ID64a](#), Y. Wei [ID56](#),
 A.R. Weidberg [ID130](#), E.J. Weik [ID121](#), J. Weingarten [ID51](#), C. Weiser [ID56](#), C.J. Wells [ID50](#), T. Wenaus [ID30](#),
 B. Wendland [ID51](#), T. Wengler [ID37](#), N.S. Wenke [ID113](#), N. Wermes [ID25](#), M. Wessels [ID65a](#), A.M. Wharton [ID94](#),

A.S. White ⁶³, A. White ⁸, M.J. White ¹, D. Whiteson ¹⁶³, L. Wickremasinghe ¹²⁸, W. Wiedenmann ¹⁷⁵, M. Wielers ¹³⁸, C. Wiglesworth ⁴⁴, D.J. Wilbern ¹²⁴, H.G. Wilkens ³⁷, J.J.H. Wilkinson ³³, D.M. Williams ⁴³, H.H. Williams ¹³², S. Williams ³³, S. Willocq ¹⁰⁶, B.J. Wilson ¹⁰⁴, P.J. Windischhofer ⁴¹, F.I. Winkel ³¹, F. Winklmeier ¹²⁷, B.T. Winter ⁵⁶, J.K. Winter ¹⁰⁴, M. Wittgen ¹⁴⁸, M. Wobisch ¹⁰⁰, T. Wojtkowski ⁶², Z. Wolffs ¹¹⁸, J. Wollrath ³⁷, M.W. Wolter ⁸⁹, H. Wolters ^{134a,134c}, M.C. Wong ¹⁴⁰, E.L. Woodward ⁴³, S.D. Worm ⁵⁰, B.K. Wosiek ⁸⁹, K.W. Woźniak ⁸⁹, S. Wozniowski ⁵⁷, K. Wraight ⁶¹, C. Wu ²¹, M. Wu ^{115b}, M. Wu ¹¹⁷, S.L. Wu ¹⁷⁵, X. Wu ⁵⁸, Y. Wu ^{64a}, Z. Wu ⁴, J. Wuerzinger ^{113,aa}, T.R. Wyatt ¹⁰⁴, B.M. Wynne ⁵⁴, S. Xella ⁴⁴, L. Xia ^{115a}, M. Xia ¹⁵, M. Xie ^{64a}, S. Xin ^{14,115c}, A. Xiong ¹²⁷, J. Xiong ^{18a}, D. Xu ¹⁴, H. Xu ^{64a}, L. Xu ^{64a}, R. Xu ¹³², T. Xu ¹⁰⁹, Y. Xu ¹⁴³, Z. Xu ⁵⁴, Z. Xu ^{115a}, B. Yabsley ¹⁵², S. Yacoob ^{34a}, Y. Yamaguchi ⁸⁶, E. Yamashita ¹⁵⁸, H. Yamauchi ¹⁶¹, T. Yamazaki ^{18a}, Y. Yamazaki ⁸⁷, S. Yan ⁶¹, Z. Yan ¹⁰⁶, H.J. Yang ^{64c,64d}, H.T. Yang ^{64a}, S. Yang ^{64a}, T. Yang ^{66c}, X. Yang ³⁷, X. Yang ¹⁴, Y. Yang ⁴⁶, Y. Yang ^{64a}, W-M. Yao ^{18a}, H. Ye ^{115a}, H. Ye ⁵⁷, J. Ye ¹⁴, S. Ye ³⁰, X. Ye ^{64a}, Y. Yeh ⁹⁹, I. Yeletsikh ⁴⁰, B. Yeo ^{18b}, M.R. Yexley ⁹⁹, T.P. Yildirim ¹³⁰, P. Yin ⁴³, K. Yorita ¹⁷³, S. Younas ^{28b}, C.J.S. Young ³⁷, C. Young ¹⁴⁸, C. Yu ^{14,115c}, Y. Yu ^{64a}, J. Yuan ^{14,115c}, M. Yuan ¹⁰⁹, R. Yuan ^{64d,64c}, L. Yue ⁹⁹, M. Zaazoua ^{64a}, B. Zabinski ⁸⁹, E. Zaid ⁵⁴, Z.K. Zak ⁸⁹, T. Zakareishvili ¹⁶⁸, S. Zambito ⁵⁸, J.A. Zamora Saa ^{141d,141b}, J. Zang ¹⁵⁸, D. Zanzi ⁵⁶, O. Zaplatilek ¹³⁶, C. Zeitnitz ¹⁷⁶, H. Zeng ¹⁴, J.C. Zeng ¹⁶⁷, D.T. Zenger Jr ²⁷, O. Zenin ³⁹, T. Ženiš ^{29a}, S. Zenz ⁹⁷, S. Zerradi ^{36a}, D. Zerwas ⁶⁸, M. Zhai ^{14,115c}, D.F. Zhang ¹⁴⁴, J. Zhang ^{64b}, J. Zhang ⁶, K. Zhang ^{14,115c}, L. Zhang ^{64a}, L. Zhang ^{115a}, P. Zhang ^{14,115c}, R. Zhang ¹⁷⁵, S. Zhang ¹⁰⁹, S. Zhang ⁹², T. Zhang ¹⁵⁸, X. Zhang ^{64c}, Y. Zhang ¹⁴³, Y. Zhang ⁹⁹, Y. Zhang ^{115a}, Z. Zhang ^{18a}, Z. Zhang ^{64b}, Z. Zhang ⁶⁸, H. Zhao ¹⁴³, T. Zhao ^{64b}, Y. Zhao ¹⁴⁰, Z. Zhao ^{64a}, Z. Zhao ^{64a}, A. Zhemchugov ⁴⁰, J. Zheng ^{115a}, K. Zheng ¹⁶⁷, X. Zheng ^{64a}, Z. Zheng ¹⁴⁸, D. Zhong ¹⁶⁷, B. Zhou ¹⁰⁹, H. Zhou ⁷, N. Zhou ^{64c}, Y. Zhou ¹⁵, Y. Zhou ^{115a}, Y. Zhou ⁷, C.G. Zhu ^{64b}, J. Zhu ¹⁰⁹, X. Zhu ^{64d}, Y. Zhu ^{64c}, Y. Zhu ^{64a}, X. Zhuang ¹⁴, K. Zhukov ⁷⁰, N.I. Zimine ⁴⁰, J. Zinsser ^{65b}, M. Ziolkowski ¹⁴⁶, L. Živković ¹⁶, A. Zoccoli ^{24b,24a}, K. Zoch ⁶³, T.G. Zorbas ¹⁴⁴, O. Zormpa ⁴⁸, W. Zou ⁴³, L. Zwalinski ³⁷.

¹Department of Physics, University of Adelaide, Adelaide; Australia.

²Department of Physics, University of Alberta, Edmonton AB; Canada.

³(^a)Department of Physics, Ankara University, Ankara; (^b)Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye.

⁴LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.

⁵APC, Université Paris Cité, CNRS/IN2P3, Paris; France.

⁶High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.

⁷Department of Physics, University of Arizona, Tucson AZ; United States of America.

⁸Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.

⁹Physics Department, National and Kapodistrian University of Athens, Athens; Greece.

¹⁰Physics Department, National Technical University of Athens, Zografou; Greece.

¹¹Department of Physics, University of Texas at Austin, Austin TX; United States of America.

¹²Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.

¹³Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.

¹⁴Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; China.

¹⁵Physics Department, Tsinghua University, Beijing; China.

¹⁶Institute of Physics, University of Belgrade, Belgrade; Serbia.

- ¹⁷Department for Physics and Technology, University of Bergen, Bergen; Norway.
- ¹⁸(^a)Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; (^b)University of California, Berkeley CA; United States of America.
- ¹⁹Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
- ²⁰Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
- ²¹School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
- ²²(^a)Department of Physics, Bogazici University, Istanbul; (^b)Department of Physics Engineering, Gaziantep University, Gaziantep; (^c)Department of Physics, Istanbul University, Istanbul; Türkiye.
- ²³(^a)Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; (^b)Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia.
- ²⁴(^a)Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; (^b)INFN Sezione di Bologna; Italy.
- ²⁵Physikalisches Institut, Universität Bonn, Bonn; Germany.
- ²⁶Department of Physics, Boston University, Boston MA; United States of America.
- ²⁷Department of Physics, Brandeis University, Waltham MA; United States of America.
- ²⁸(^a)Transilvania University of Brasov, Brasov; (^b)Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (^c)Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (^d)National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (^e)National University of Science and Technology Politehnica, Bucharest; (^f)West University in Timisoara, Timisoara; (^g)Faculty of Physics, University of Bucharest, Bucharest; Romania.
- ²⁹(^a)Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (^b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
- ³⁰Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
- ³¹Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina.
- ³²California State University, CA; United States of America.
- ³³Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
- ³⁴(^a)Department of Physics, University of Cape Town, Cape Town; (^b)iThemba Labs, Western Cape; (^c)Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (^d)National Institute of Physics, University of the Philippines Diliman (Philippines); (^e)University of South Africa, Department of Physics, Pretoria; (^f)University of Zululand, KwaDlangezwa; (^g)School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
- ³⁵Department of Physics, Carleton University, Ottawa ON; Canada.
- ³⁶(^a)Faculté des Sciences Ain Chock, Université Hassan II de Casablanca; (^b)Faculté des Sciences, Université Ibn-Tofail, Kénitra; (^c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (^d)LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; (^e)Faculté des sciences, Université Mohammed V, Rabat; (^f)Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- ³⁷CERN, Geneva; Switzerland.
- ³⁸Affiliated with an institute formerly covered by a cooperation agreement with CERN.
- ³⁹Affiliated with an institute covered by a cooperation agreement with CERN.
- ⁴⁰Affiliated with an international laboratory covered by a cooperation agreement with CERN.
- ⁴¹Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.
- ⁴²LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
- ⁴³Nevis Laboratory, Columbia University, Irvington NY; United States of America.

- ⁴⁴Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
- ⁴⁵(^a)Dipartimento di Fisica, Università della Calabria, Rende; (^b)INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
- ⁴⁶Physics Department, Southern Methodist University, Dallas TX; United States of America.
- ⁴⁷Physics Department, University of Texas at Dallas, Richardson TX; United States of America.
- ⁴⁸National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
- ⁴⁹(^a)Department of Physics, Stockholm University; (^b)Oskar Klein Centre, Stockholm; Sweden.
- ⁵⁰Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.
- ⁵¹Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany.
- ⁵²Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.
- ⁵³Department of Physics, Duke University, Durham NC; United States of America.
- ⁵⁴SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.
- ⁵⁵INFN e Laboratori Nazionali di Frascati, Frascati; Italy.
- ⁵⁶Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
- ⁵⁷II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
- ⁵⁸Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ⁵⁹(^a)Dipartimento di Fisica, Università di Genova, Genova; (^b)INFN Sezione di Genova; Italy.
- ⁶⁰II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.
- ⁶¹SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.
- ⁶²LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.
- ⁶³Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.
- ⁶⁴(^a)Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; (^b)Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; (^c)School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; (^d)Tsung-Dao Lee Institute, Shanghai; (^e)School of Physics, Zhengzhou University; China.
- ⁶⁵(^a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; (^b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
- ⁶⁶(^a)Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (^b)Department of Physics, University of Hong Kong, Hong Kong; (^c)Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.
- ⁶⁷Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.
- ⁶⁸IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France.
- ⁶⁹Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain.
- ⁷⁰Department of Physics, Indiana University, Bloomington IN; United States of America.
- ⁷¹(^a)INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (^b)ICTP, Trieste; (^c)Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
- ⁷²(^a)INFN Sezione di Lecce; (^b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
- ⁷³(^a)INFN Sezione di Milano; (^b)Dipartimento di Fisica, Università di Milano, Milano; Italy.
- ⁷⁴(^a)INFN Sezione di Napoli; (^b)Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
- ⁷⁵(^a)INFN Sezione di Pavia; (^b)Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
- ⁷⁶(^a)INFN Sezione di Pisa; (^b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
- ⁷⁷(^a)INFN Sezione di Roma; (^b)Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
- ⁷⁸(^a)INFN Sezione di Roma Tor Vergata; (^b)Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.

- ^{79(a)}INFN Sezione di Roma Tre;^(b)Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
- ^{80(a)}INFN-TIFPA;^(b)Università degli Studi di Trento, Trento; Italy.
- ⁸¹Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.
- ⁸²University of Iowa, Iowa City IA; United States of America.
- ⁸³Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
- ⁸⁴Istinye University, Sariyer, Istanbul; Türkiye.
- ^{85(a)}Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;^(b)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;^(c)Instituto de Física, Universidade de São Paulo, São Paulo;^(d)Rio de Janeiro State University, Rio de Janeiro;^(e)Federal University of Bahia, Bahia; Brazil.
- ⁸⁶KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
- ⁸⁷Graduate School of Science, Kobe University, Kobe; Japan.
- ^{88(a)}AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow;^(b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
- ⁸⁹Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
- ⁹⁰Faculty of Science, Kyoto University, Kyoto; Japan.
- ⁹¹Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
- ⁹²L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
- ⁹³Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
- ⁹⁴Physics Department, Lancaster University, Lancaster; United Kingdom.
- ⁹⁵Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
- ⁹⁶Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
- ⁹⁷School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
- ⁹⁸Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
- ⁹⁹Department of Physics and Astronomy, University College London, London; United Kingdom.
- ¹⁰⁰Louisiana Tech University, Ruston LA; United States of America.
- ¹⁰¹Fysiska institutionen, Lunds universitet, Lund; Sweden.
- ¹⁰²Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
- ¹⁰³Institut für Physik, Universität Mainz, Mainz; Germany.
- ¹⁰⁴School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
- ¹⁰⁵CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
- ¹⁰⁶Department of Physics, University of Massachusetts, Amherst MA; United States of America.
- ¹⁰⁷Department of Physics, McGill University, Montreal QC; Canada.
- ¹⁰⁸School of Physics, University of Melbourne, Victoria; Australia.
- ¹⁰⁹Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
- ¹¹⁰Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
- ¹¹¹Group of Particle Physics, University of Montreal, Montreal QC; Canada.
- ¹¹²Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
- ¹¹³Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
- ¹¹⁴Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
- ^{115(a)}Department of Physics, Nanjing University, Nanjing;^(b)School of Science, Shenzhen Campus of Sun Yat-sen University;^(c)University of Chinese Academy of Science (UCAS), Beijing; China.
- ¹¹⁶Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of

America.

¹¹⁷Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.

¹¹⁸Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.

¹¹⁹Department of Physics, Northern Illinois University, DeKalb IL; United States of America.

¹²⁰(^a)New York University Abu Dhabi, Abu Dhabi;(^b)United Arab Emirates University, Al Ain; United Arab Emirates.

¹²¹Department of Physics, New York University, New York NY; United States of America.

¹²²Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.

¹²³Ohio State University, Columbus OH; United States of America.

¹²⁴Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.

¹²⁵Department of Physics, Oklahoma State University, Stillwater OK; United States of America.

¹²⁶Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.

¹²⁷Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.

¹²⁸Graduate School of Science, Osaka University, Osaka; Japan.

¹²⁹Department of Physics, University of Oslo, Oslo; Norway.

¹³⁰Department of Physics, Oxford University, Oxford; United Kingdom.

¹³¹LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.

¹³²Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.

¹³³Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.

¹³⁴(^a)Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;(^b)Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;(^c)Departamento de Física, Universidade de Coimbra, Coimbra;(^d)Centro de Física Nuclear da Universidade de Lisboa, Lisboa;(^e)Departamento de Física, Universidade do Minho, Braga;(^f)Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);(^g)Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.

¹³⁵Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.

¹³⁶Czech Technical University in Prague, Prague; Czech Republic.

¹³⁷Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.

¹³⁸Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.

¹³⁹IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.

¹⁴⁰Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.

¹⁴¹(^a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;(^b)Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;(^c)Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;(^d)Universidad Andres Bello, Department of Physics, Santiago;(^e)Instituto de Alta Investigación, Universidad de Tarapacá, Arica;(^f)Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.

¹⁴²Department of Physics, Institute of Science, Tokyo; Japan.

¹⁴³Department of Physics, University of Washington, Seattle WA; United States of America.

¹⁴⁴Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

¹⁴⁵Department of Physics, Shinshu University, Nagano; Japan.

¹⁴⁶Department Physik, Universität Siegen, Siegen; Germany.

- ¹⁴⁷Department of Physics, Simon Fraser University, Burnaby BC; Canada.
- ¹⁴⁸SLAC National Accelerator Laboratory, Stanford CA; United States of America.
- ¹⁴⁹Department of Physics, Royal Institute of Technology, Stockholm; Sweden.
- ¹⁵⁰Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.
- ¹⁵¹Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
- ¹⁵²School of Physics, University of Sydney, Sydney; Australia.
- ¹⁵³Institute of Physics, Academia Sinica, Taipei; Taiwan.
- ¹⁵⁴(^a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (^b)High Energy Physics Institute, Tbilisi State University, Tbilisi; (^c)University of Georgia, Tbilisi; Georgia.
- ¹⁵⁵Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
- ¹⁵⁶Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
- ¹⁵⁷Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
- ¹⁵⁸International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
- ¹⁵⁹Department of Physics, University of Toronto, Toronto ON; Canada.
- ¹⁶⁰(^a)TRIUMF, Vancouver BC; (^b)Department of Physics and Astronomy, York University, Toronto ON; Canada.
- ¹⁶¹Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
- ¹⁶²Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
- ¹⁶³Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
- ¹⁶⁴University of West Attica, Athens; Greece.
- ¹⁶⁵University of Sharjah, Sharjah; United Arab Emirates.
- ¹⁶⁶Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
- ¹⁶⁷Department of Physics, University of Illinois, Urbana IL; United States of America.
- ¹⁶⁸Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
- ¹⁶⁹Department of Physics, University of British Columbia, Vancouver BC; Canada.
- ¹⁷⁰Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
- ¹⁷¹Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
- ¹⁷²Department of Physics, University of Warwick, Coventry; United Kingdom.
- ¹⁷³Waseda University, Tokyo; Japan.
- ¹⁷⁴Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.
- ¹⁷⁵Department of Physics, University of Wisconsin, Madison WI; United States of America.
- ¹⁷⁶Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
- ¹⁷⁷Department of Physics, Yale University, New Haven CT; United States of America.
- ¹⁷⁸Yerevan Physics Institute, Yerevan; Armenia.
- ^a Also Affiliated with an institute covered by a cooperation agreement with CERN.
- ^b Also at An-Najah National University, Nablus; Palestine.
- ^c Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
- ^d Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
- ^e Also at CERN, Geneva; Switzerland.
- ^f Also at CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC); Azerbaijan.

- ^g Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
- ^h Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
- ⁱ Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
- ^j Also at Department of Physics, California State University, Sacramento; United States of America.
- ^k Also at Department of Physics, King's College London, London; United Kingdom.
- ^l Also at Department of Physics, Stanford University, Stanford CA; United States of America.
- ^m Also at Department of Physics, Stellenbosch University; South Africa.
- ⁿ Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
- ^o Also at Department of Physics, University of Thessaly; Greece.
- ^p Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
- ^q Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia; Bulgaria.
- ^r Also at Hellenic Open University, Patras; Greece.
- ^s Also at Imam Mohammad Ibn Saud Islamic University; Saudi Arabia.
- ^t Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
- ^u Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
- ^v Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
- ^w Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
- ^x Also at Institute of Particle Physics (IPP); Canada.
- ^y Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
- ^z Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
- ^{aa} Also at Technical University of Munich, Munich; Germany.
- ^{ab} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
- ^{ac} Also at TRIUMF, Vancouver BC; Canada.
- ^{ad} Also at Università di Napoli Parthenope, Napoli; Italy.
- ^{ae} Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
- ^{af} Also at Washington College, Chestertown, MD; United States of America.
- ^{ag} Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
- * Deceased